Stability and collapse of strange white dwarfs

Alessandro Drago – Ferrara University

F. Di Clemente, A.D., P. Char, G. Pagliara, e-Print: 2207.08704

- Are strange white dwarfs stable or unstable?
  - The analyses of Glendenning et al., of Alford et al. and of the Armenian group
- They are stable if nuclear matter cannot transform into strange quark matter!
  - Based on the techniques developed by Pereira et al. and by Di Clemente et al.
- Have they been «discovered»?
  - The data analysed by Kurban et al.
- What if the core of the star is perturbed so that $\rho_{drip} = 4 \times 10^{11}$ g/cm^3 is reached?
  - Can this facilitate the collapse of the white dwarf to a «neutron star» ?
  - How large must the quark core be in order to significantly change the dynamics?
  - Is that compatible with what we know about dark matter?
  - Can this help in explaining the gamma emission from the galactic center?
  - What type of object is then produced? Can it be SAX J1808.4-3658?

Possible New Class of Dense White Dwarfs

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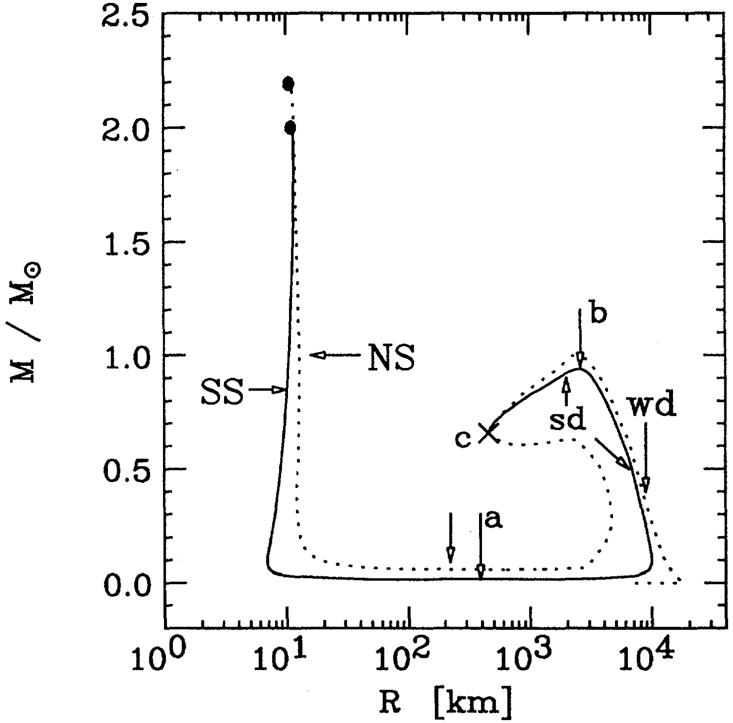
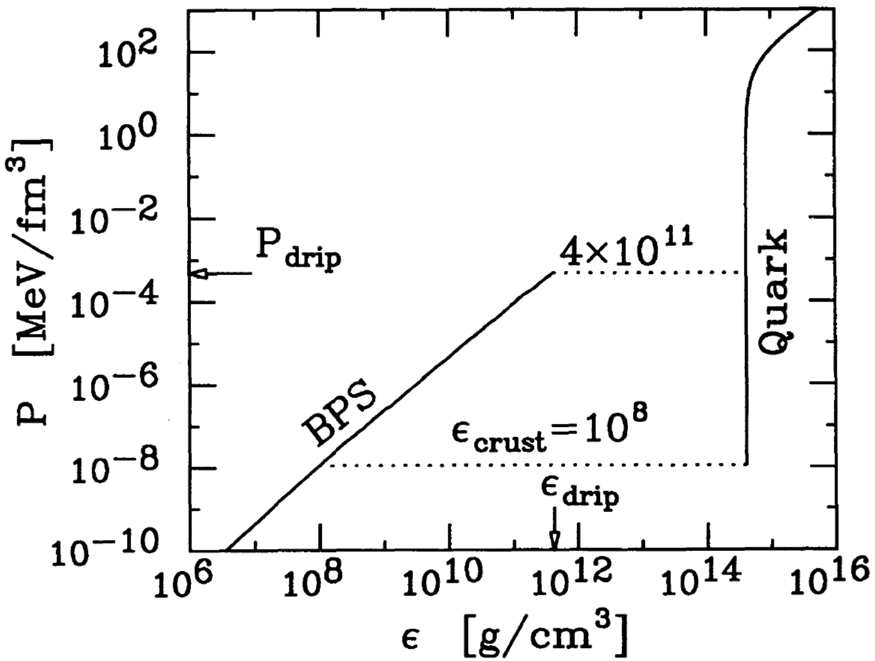
(Received 17 October 1994)

If the strange matter hypothesis of Bodmer and Witten is true, then a new class of white dwarfs can exist whose nuclear material in their deep interiors can have a density as high as the neutron drip density, a few hundred times the density in maximum-mass white dwarfs and 4×10^4 the density in dwarfs of typical mass, $M \sim 0.6 M_\odot$. Their masses fall in the approximate range $10^{-4}-1 M_\odot$. They are stable against acoustical modes of vibration. A strange quark core stabilizes these stars, which otherwise would have central densities that would place them in the unstable region of the sequence between white dwarfs and neutron stars.





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On the Stability of Strange Dwarf Hybrid Stars

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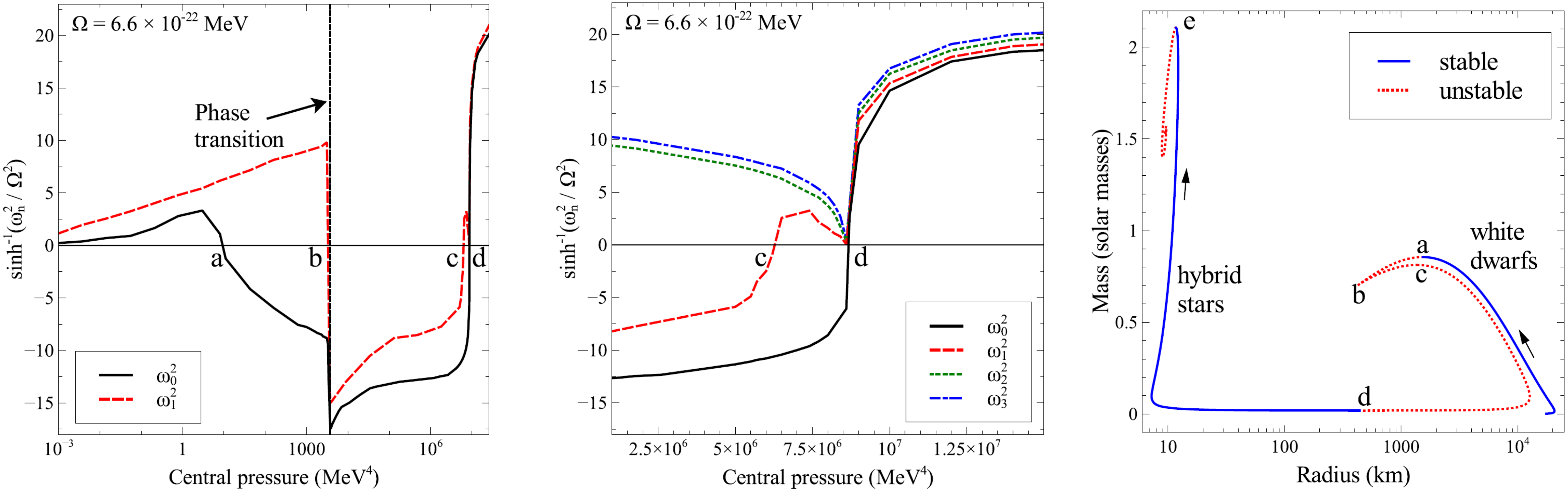
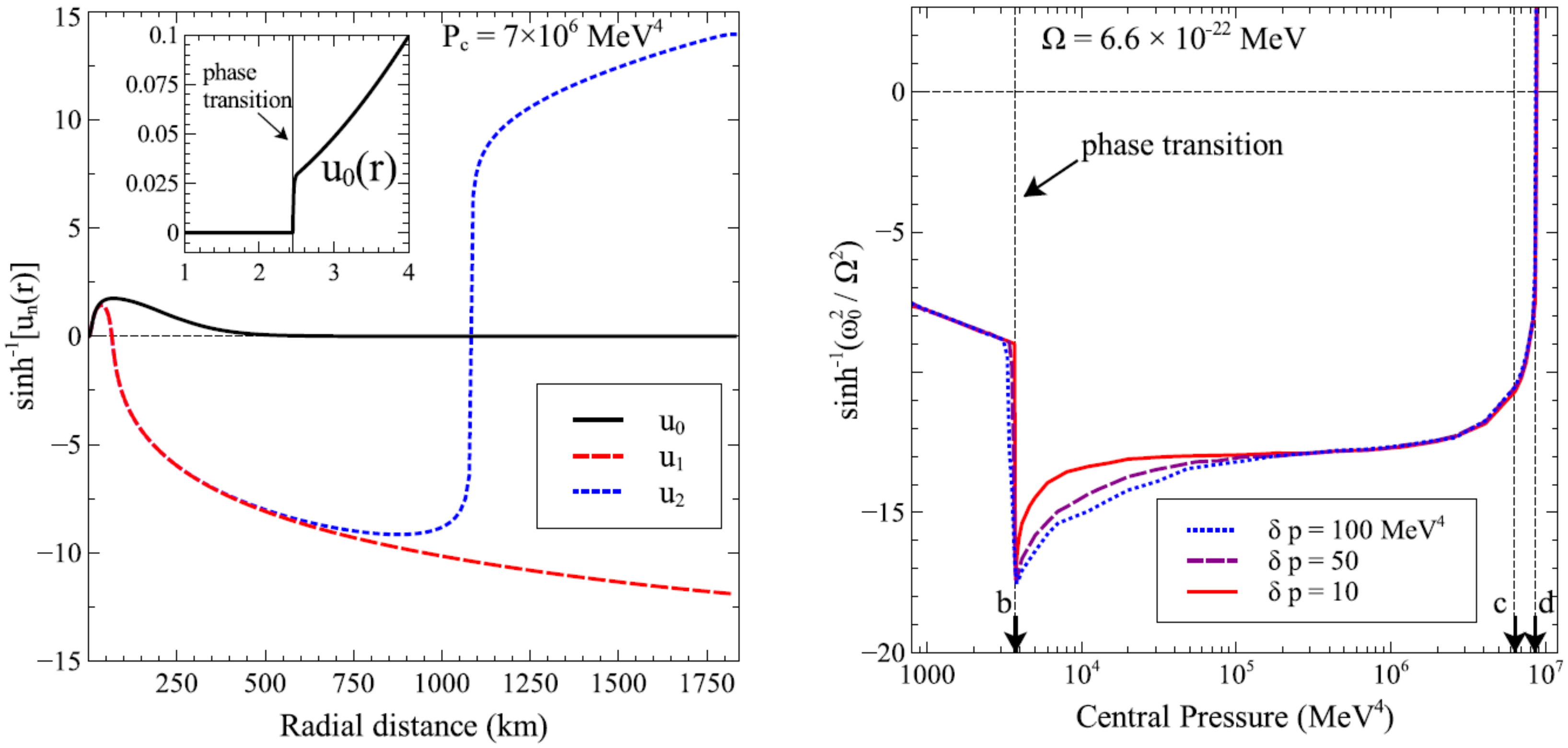
Abstract

We investigate the stability of "strange dwarfs": white-dwarf-sized stars with a density discontinuity between a small dense core of quark matter and a thick low-density mantle of degenerate electrons. Previous work on strange dwarfs suggested that such a discontinuity could stabilize stars that would have been classified as unstable by the conventional criteria based on extrema in the mass–radius relation. We investigate the stability of such stars by numerically solving the Sturm–Liouville equations for the lowest-energy modes of the star. We find that the conventional criteria are correct, and strange dwarfs are not stable.



Making the EOS smooth, a la Alford

$$\varepsilon(P) = \frac{1}{2}\left(1 - \tanh\left(\frac{P - P_{\rm crit}}{\delta P}\right)\right)\varepsilon_{\rm BPS}(P) + \frac{1}{2}\left(1 + \tanh\left(\frac{P - P_{\rm crit}}{\delta P}\right)\right)(kP + 4B)$$



Armenian papers!

- - Alaverdyan et al. Astronomy Letters, 28 (2002) 24
- - Vartanyan et al. Astrophysics, 52 (2009) 300
- - Vartanyan et al. Astrophysics, 52 (2009) 440
- - Vartanyan et al. Astrophysics, 55 (2012) 98
- - Vartanyan et al. Journal of Physics: Conference Series 496 (2014) 012009

They suggest that **strange white dwarfs need to be studied for a given and frozen quark content**, since the transition from nucleons to quarks is suppressed due to the huge density jump. On the other hand, above $\rho_{drip} = 4\text{x}10^{11}$ g/cm^3 neutrons can fall directly onto the quark central ball and be absorbed, destabilizing the strange white dwarf.

What they do not do is to show that the radial oscillations are stable IF the quark content is kept frozen. Actually, they do not study at all radial oscillations.

How to study radial oscillations in a two-component system

Pereira, Flores, Lugones, ApJ 860 (2018) 12
Di Clemente, Mannarelli, Tonelli, PRD 101 (2020) 103003

Eqs for $\xi \equiv \Delta r/r$ and for Δp

$$\frac{d\xi}{dr} = V(r)\xi + W(r)\Delta p,$$

$$\frac{d\Delta p}{dr} = X(r)\xi + Y(r)\Delta p,$$

with the coefficients given by

$$V(r) = -\frac{3}{r} - \frac{dp}{dr}\frac{1}{(p+\epsilon)},$$

$$W(r) = -\frac{1}{r}\frac{1}{\Gamma p}$$

$$X(r) = \omega^2 e^{\lambda-\nu}(p+\epsilon)r - 4\frac{dp}{dr} + \left(\frac{dp}{dr}\right)^2\frac{r}{(p+\epsilon)} - 8\pi e^{\lambda}(p+\epsilon)pr$$

$$Y(r) = \frac{dp}{dr}\frac{1}{(p+\epsilon)} - 4\pi(p+\epsilon)re^{\lambda},$$

Boundary conditions at the interface

Mechanical equilibrium implies

$$[\Delta p]^{+}_{-} = 0.$$

“Slow” transitions: no mass transfer from one phase to the other. This is similar to what Glendening et al. did. The displacement is continuous across the transition:

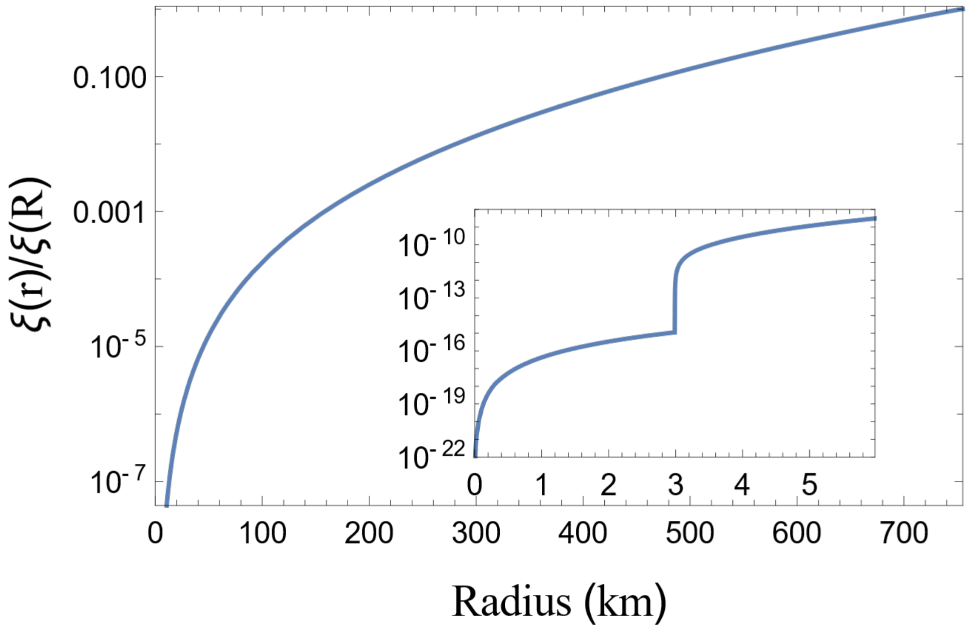
$$[\xi]^{+}_{-} \equiv \xi^{+} - \xi^{-} = 0$$

“Rapid” transitions: instantaneous change of the nature of matter

$$\left[\xi - \frac{\Delta p}{r p_0'}\right]^{+}_{-} = 0$$

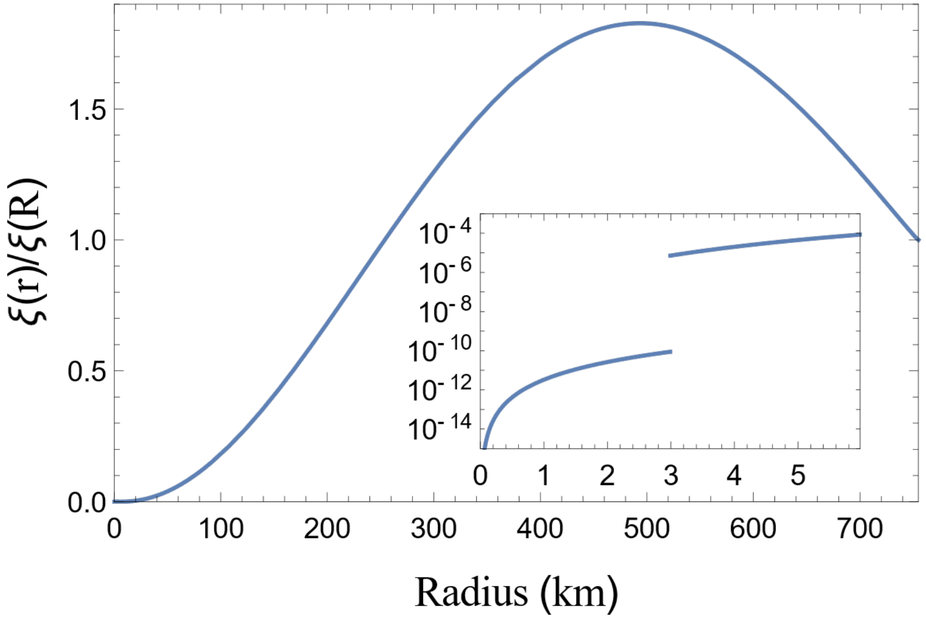
This is similar to what Alford et al did.

Eigenfunctions in the “slow” and in the “rapid” scenario



First eigenfunction of radial modes in the ”slow” scenario in which, during the oscillation time-scale, hadrons do not deconfine into quarks (and viceversa).

Here the mode is stable: $\omega^2 = 0.78\ \text{Hz}^2$

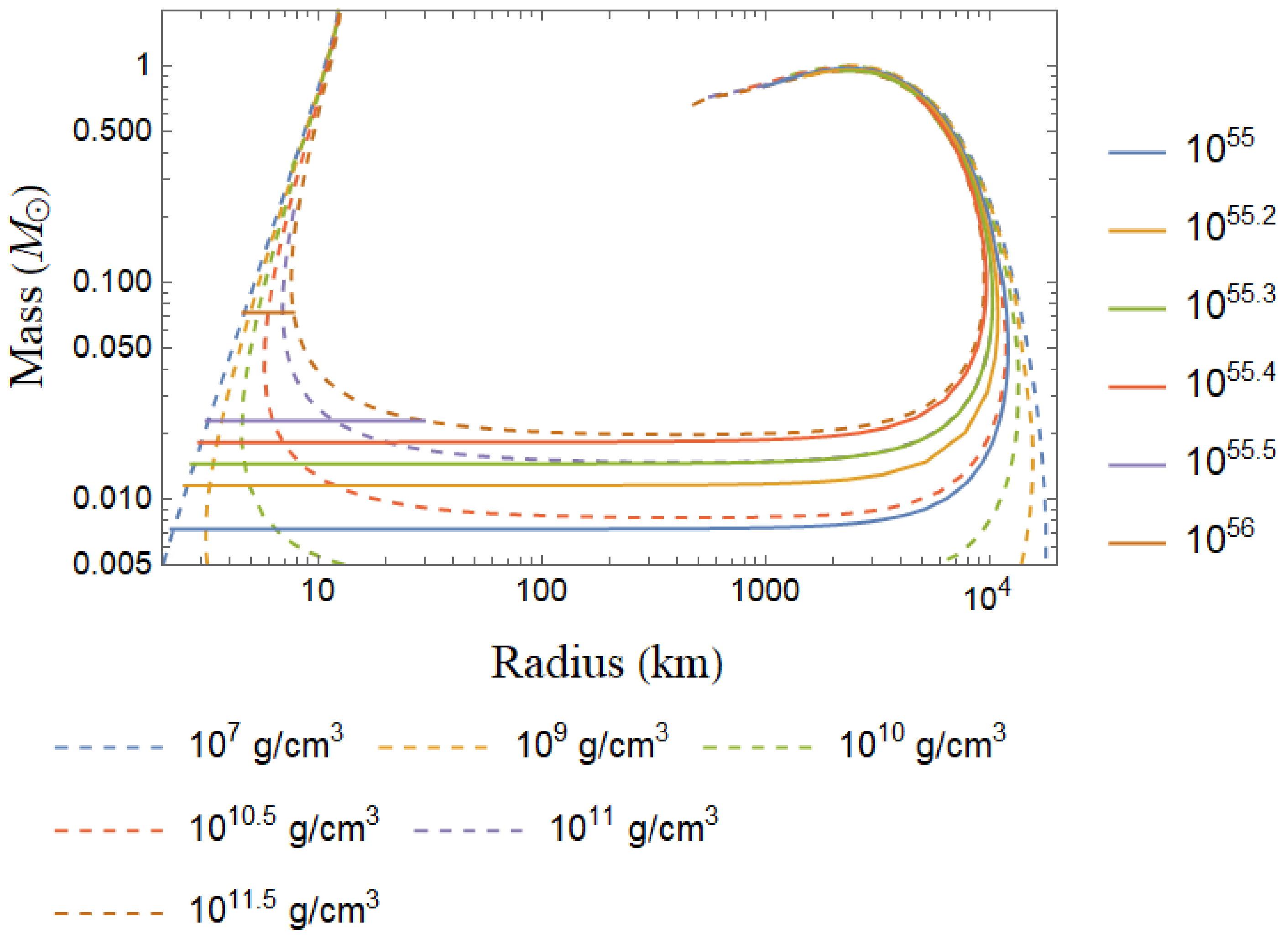


First eigenfunction of radial modes in the ”rapid” scenario in which, during the oscillation time-scale, hadrons can deconfine into quarks (and viceversa).

Here the mode is unstable: $\omega^2 = -1.67\ \text{Hz}^2$

M-R relations obtained by either keeping fixed ρ_{trans} (dashed) or B_{quark} (solid)

The M-R curves of SWDs are followed
1) clockwise if ρ_{trans} is kept fixed (Alford)
2) counter-clockwise if B_{quark} is kept fixed (Glendenning).
In both cases the general criterium of stability/instability is respected!



Relation between composition, central density and Chandrasekhar mass

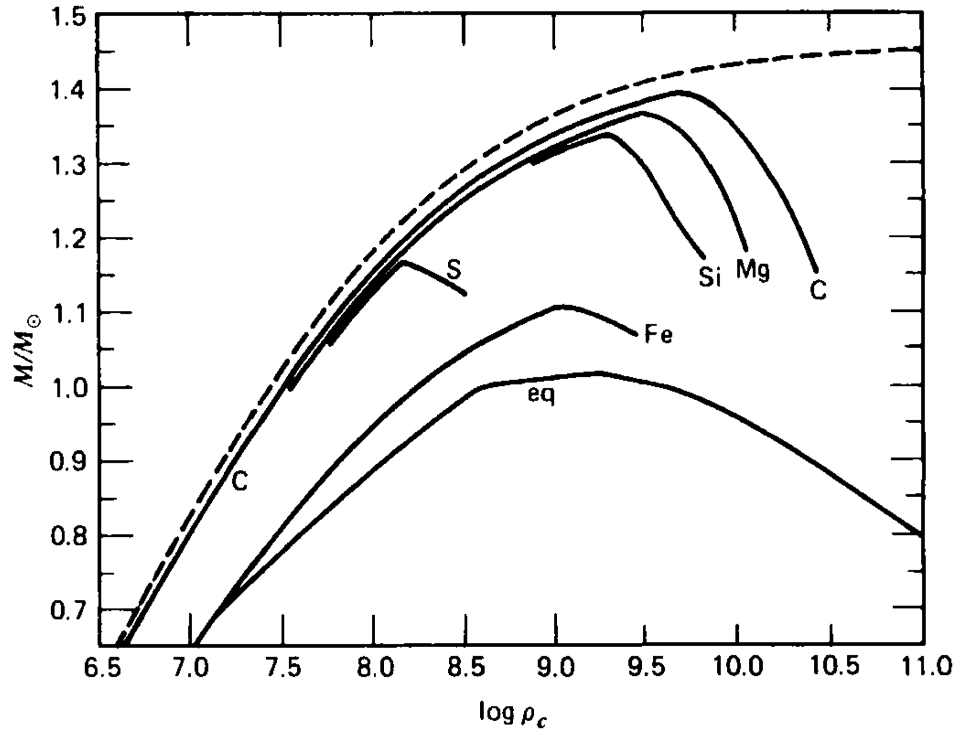
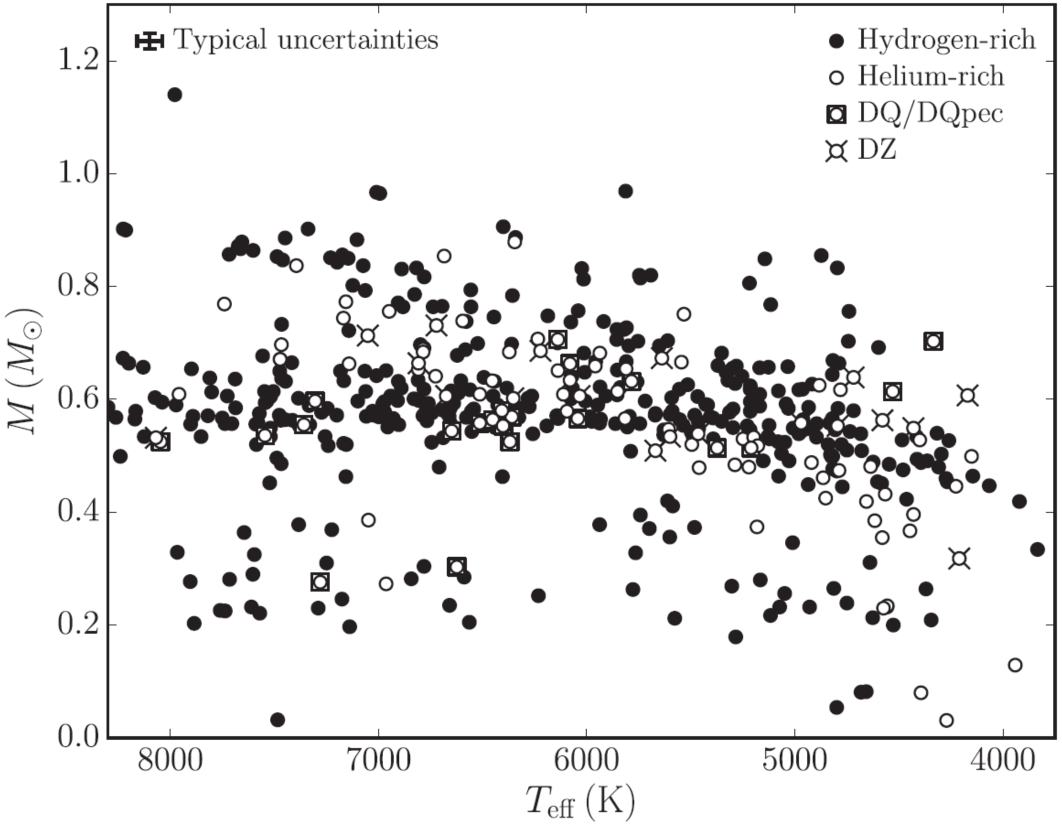


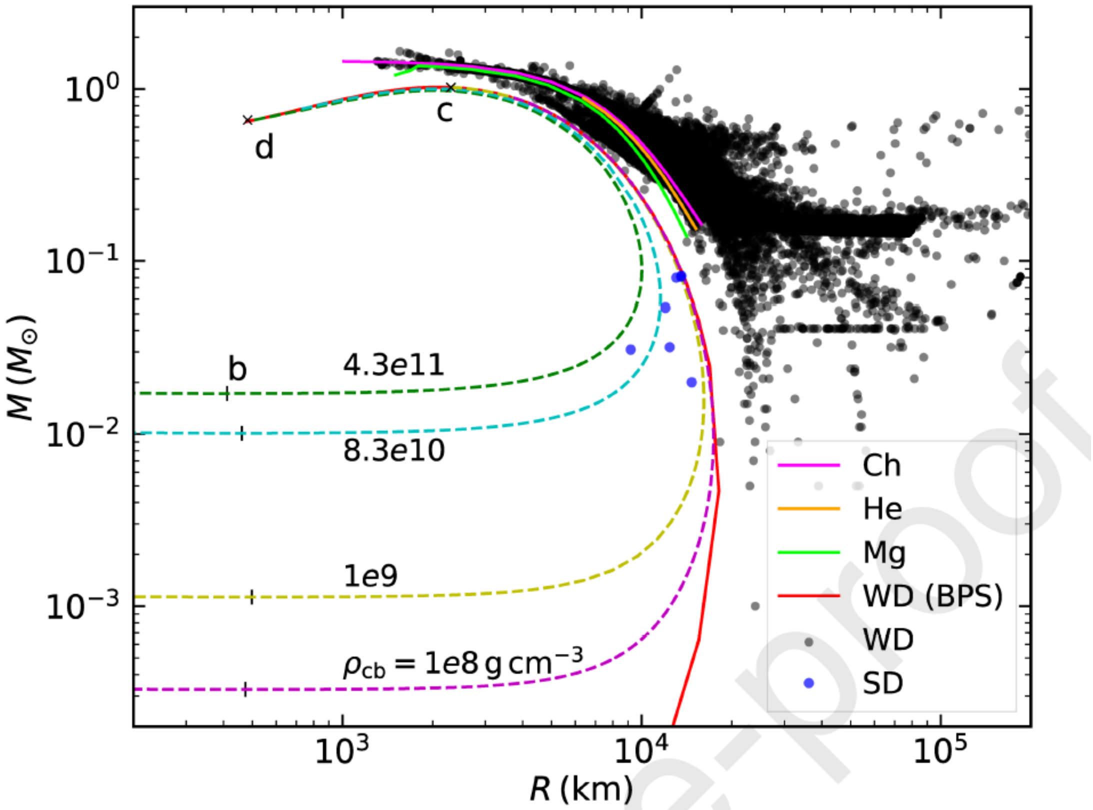
Figure 3.2 The relation between mass M and central density ρ_c (in g cm^{-3}) for zero-temperature stars composed of ^{12}C, ^{24}Mg, ^{28}Si, ^{32}S, and ^{56}Fe and for equilibrium (*eq*) conditions. The *dashed* curve denotes the Chandrasekhar model for $\mu_e = 2$. [After Hamada and Salpeter (1961). Reprinted courtesy of the authors and *The Astrophysical Journal*, published by the University of Chicago Press; © 1961 The American Astronomical Society.]

Have strange white dwarfs been discovered?

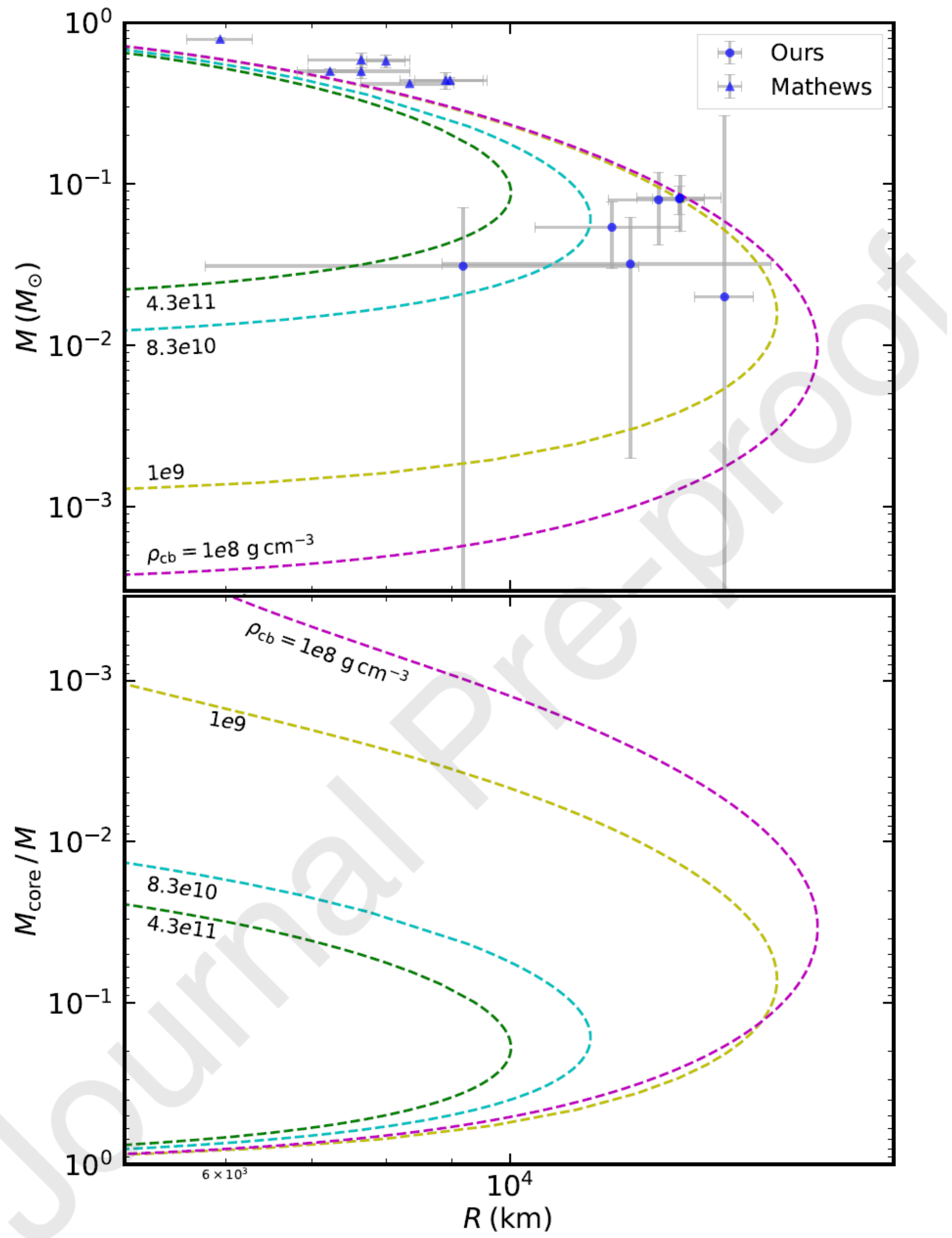
Blouin et al, ApJ 878 (2019) 63
Very small mass objects having anomalously large temperatures

Kurban et al. in print on PLB

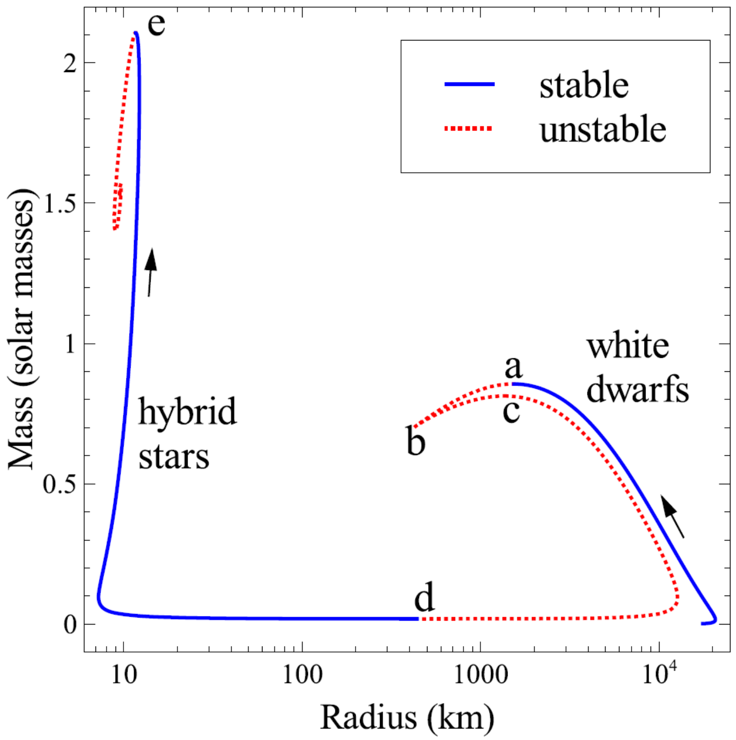




Reasons to be skeptical:
1) error bars are large
2) at least one of the objects was analyzed by another group obtaining rather different M and R
3) the quark content is rather large, B_{quark} of the order of 10^{53}, difficult to justify

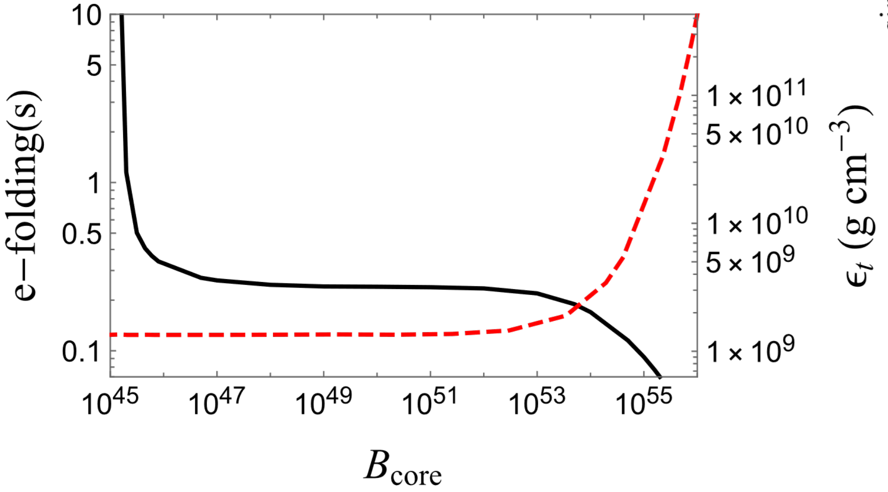


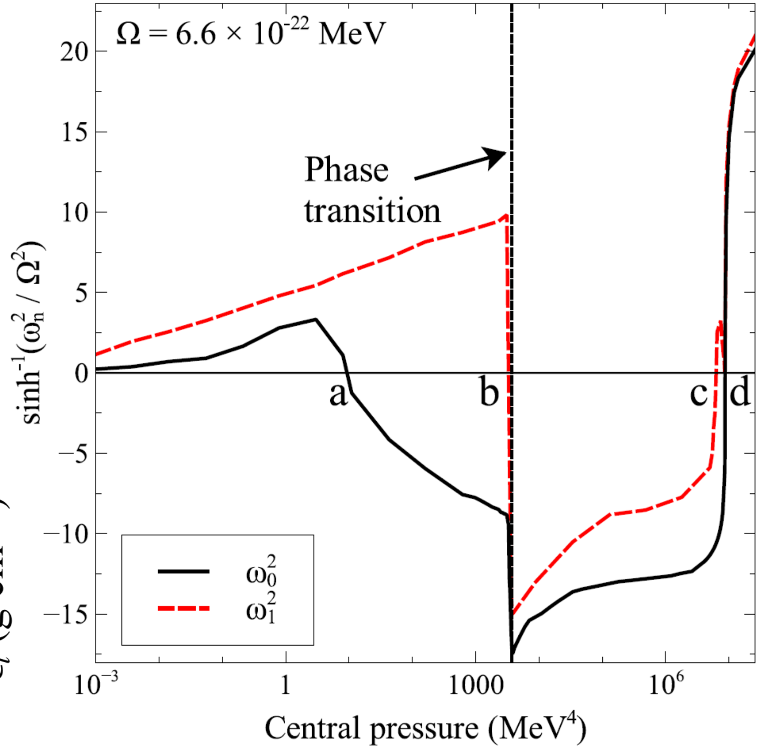
Instability time-scale



In normal WDs at “a” the frequency vanishes.

In strange WDs at “c” the frequency vanishes if nuclear matter cannot transform into quark matter, but is instead large (and imaginary) if nucleons can transform into quarks.





Properties of maximum mass stars as a function of their quark content. Solid black: time-scale of the mechanical instability as a function of B_{core}. Dashed red: interface density of the nuclear matter. The static structure of a SD having $M \sim M_{\odot}$ does not change till $B_{core} > 10^{52}$. For smaller values of B_{core}, ϵ_t equals the central density of a white dwarf having a Chandrasekhar mass, indicating that the quark core affects the stability of the star for values of B_{core} smaller than those needed to affect its static properties.

Accretion induced collapse
from Canal et al. Ann. Rev. A&A 1990. 28:183

WDs are often members of close binary systems. In a fraction of these systems mass transfer is taking place.

IF the WD could retain this mass and grow up to the Chandrasekhar limit **without first exploding**, it should collapse and a neutron star would form.

Not all the compositions can be involved in AIC. Helium WDs can immediately be discarded. Their mass growth would lead to explosive helium ignition at $\rho_c < 4 \times 10^8$ g cm^{-3}, at a mass of about 1.30 M_s, well below Chandrasekhar mass. This leaves CO and ONeMg WDs as possible candidates.

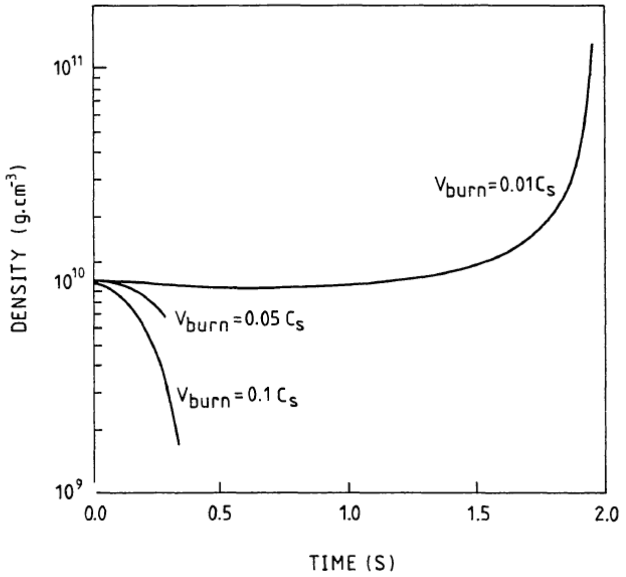


Figure 1 Time evolution of central density following explosive carbon ignition at the center of a C+O white dwarf ($X_C = X_O = 0.50$), for $\rho_c^{ign} = 10^{10}$ g cm^{-3}. The velocity of the burning front is taken to be a constant fraction of the local sound speed: $v_{burn} = \alpha c_s$ (a parameterization that would approximate the behavior of a conductive burning front). Cases $\alpha = 0.01$, 0.05, and 0.1 are displayed. We see here that bifurcation between collapse and explosion happens for $0.01 \leq \alpha \leq 0.05$.

Table 1 Outcome of explosive carbon ignition at high densities for several combinations of ignition density and velocity of the burning front

Model	ρ_{ign} (10^9 g cm^{-3})	v_{burn}/c_s	Outcome	t_{11}[a] (s)
A	9.50	0.005	Collapse	3.08
A	9.50	0.010	Explosion	—
B	10.00	0.010	Collapse	1.95
B	10.00	0.050	Explosion	—
C	15.00	0.010	Collapse	0.70
C	15.00	0.100	Explosion	—

[a] t_{11} is the time elapsed between explosive ignition and when the central density becomes $\simeq 10^{11}$ g cm^{-3}.

How to collect strange quark matter?

Strangelets produced by QS-QS mergers are not sufficient: they produce order of 1 M_s per galaxy per GYear.

What if strangelets constitute dark matter? Burdin et al. Phys.Rept.582 (2015) ; Jacobs et al. Mon.Not.Roy.Astron.Soc. 450 (2015) 4; J. Singh Sidhu and G. D. Starkman, Phys. Rev. D 101 083503 (2020); Caloni et al. JCAP 07 (2021) 027.

object mass (g)	Eros	Moon	Earth	Jupiter	Sun
1	10^4	$3\cdot10^8$	$4\cdot10^9$	$4\cdot10^{11}$	$5\cdot10^{13}$
10^3	10	$3\cdot10^5$	$4\cdot10^6$	$4\cdot10^8$	$5\cdot10^{10}$
10^6	10^{-2}	$3\cdot10^2$	$4\cdot10^3$	$4\cdot10^5$	$5\cdot10^7$
10^9	10^{-5}	0.3	4	$4\cdot10^2$	$5\cdot10^4$
10^{12}	10^{-8}	$3\cdot10^{-4}$	$4\cdot10^{-3}$	0.4	50
10^{15}	10^{-11}	$3\cdot10^{-7}$	$4\cdot10^{-6}$	$4\cdot10^{-4}$	$5\cdot10^{-2}$
10^{18}	10^{-14}	$3\cdot10^{-10}$	$4\cdot10^{-9}$	$4\cdot10^{-7}$	$5\cdot10^{-5}$

From Burdin et al. Phys.Rept.582 (2015) 1

Table 5: Expected number of collisions per year between an object of given mass and various bodies in the Solar System, assuming that the object constitutes 100% of the local dark matter density and that it possesses a typical galactic velocity.

A more explicit formula estimating the capture rate due to gravity (Madsen PRL 61 (1988) 2909):
$F = (1.39 \times 10^{30}\ s^{-1})\ A^{-1}\ M/M_s\ R/R_s$

A WD close to the Chandrasekhar mass, with a radius of ~ 3000 km, during 5 Gy can reach $B_{core} \sim 10^{45}$, just slightly smaller than the one needed to affect the dynamics of AIC.
The density distribution of dark matter grows rapidly towards the center, so that in the most central regions of the Milky Way B_{core} can easily be large enough to favor AIC.

nature astronomy
LETTERS
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Millisecond pulsars from accretion-induced collapse as the origin of the Galactic Centre gamma-ray excess signal

Anuj Gautam[1], Roland M. Crocker[1]✉, Lilia Ferrario[2], Ashley J. Ruiter[3], Harrison Ploeg[4], Chris Gordon[4] and Oscar Macias[5,6]

Dark matter (strangelets) could be more dense in the galactic bulge, making the mechanism of AIC based on strangelets extremely efficient.

In Leung et al Phys. Rev. D 87, 123506 (2013) the impact of dark matter on AIC of WDs is also discussed. The main difference is that in that paper dark matter and normal matter cannot transform into each other and therefore a huge amount of dark matter is needed to affect the structure of the WD only through gravity.

Gamma-ray data from the Fermi Large Area Telescope reveal an unexplained, apparently diffuse, signal from the Galactic bulge[1-3] that peaks near ~2 GeV with an approximately spherical[4] intensity profile $\propto r^{-2.4}$ (refs. [3,5]), where r is the radial distance to the Galactic centre, that extends to angular radial scales of at least ~10° and possibly to ~20° (refs. [6,7]). The origin of this 'Galactic Centre excess' (GCE) has been debated, with proposed sources prominently including self-annihilating dark matter[1,4] and a hitherto undetected population of millisecond pulsars (MSPs)[8]. However, the conventional channel for the generation of MSPs has been found to predict too many low-mass X-ray binary (LMXB) systems[9] and, because of the expected large natal kicks, may not accommodate[10] the close spatial correspondence[11-13] between the GCE signal and stars in the bulge. Here we report a binary population synthesis (BPS) forward model that demonstrates that an MSP population arising from the accretion-induced collapse (AIC) of O–Ne white dwarfs in Galactic bulge binaries can naturally reproduce the morphology, spectral shape and intensity of the GCE signal while also obeying LMXB constraints. Synchrotron emission from MSP-launched cosmic ray electrons and positrons may simultaneously explain the mysterious microwave 'haze'[14] from the inner Galaxy.

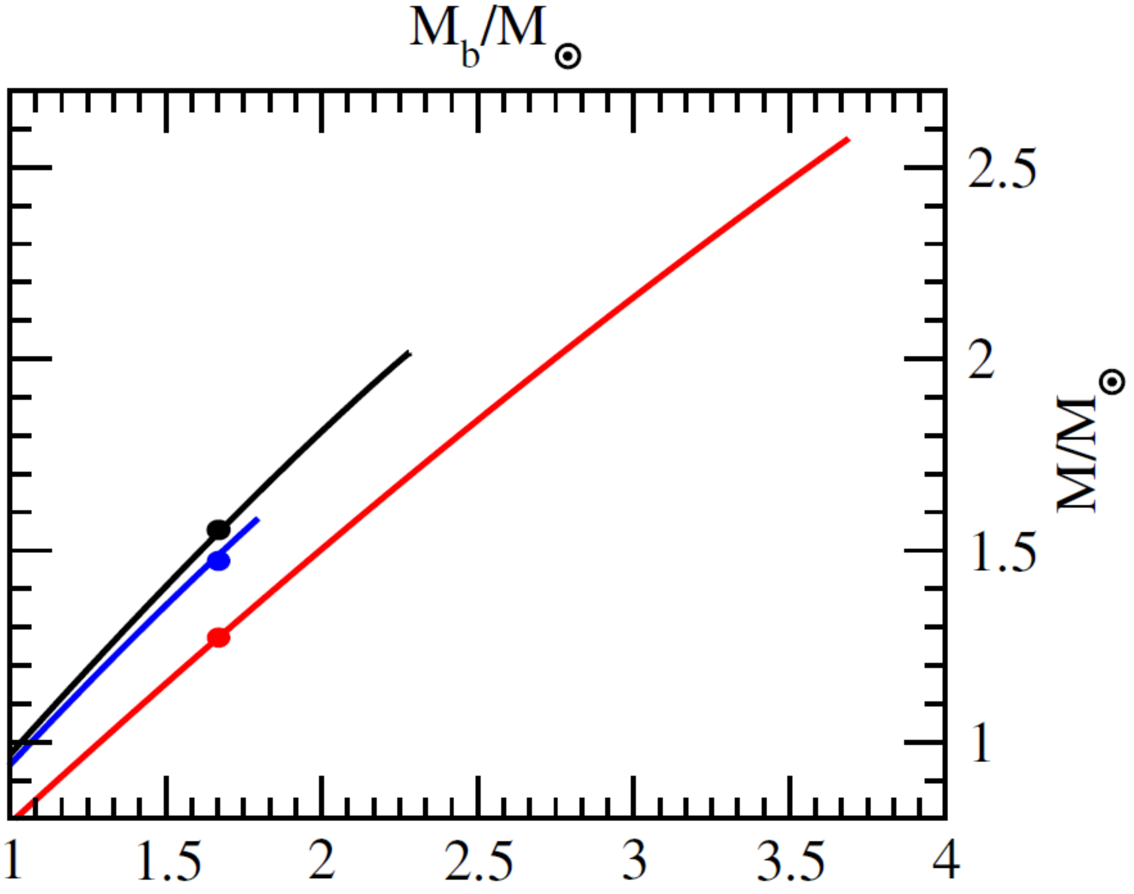
What type of object is produced by collapse of strange WDs?

From Bombaci et al. PRL 126 (2021) 162702

The binding energy of a strange quark star having a baryon mass of about 1.3 M_s can be so large that its gravitational mass is about 1 M_s.

The binding energy is released mostly in neutrinos, although a bare strange quark star can also release a significant fraction of energy in photons and in electron-positron pairs.

The energy released can be 3-4 times as large as the one released in the formation of a neutron star. It is therefore possible that the final object has a gravitational mass significantly smaller than 1 M_s due to mass ejection.



SAX J1808.4 - 3658

Discovered in 1996

More than 85 articles studying this object

Several articles pointing to its odd properties:

Small radius:

- X. D. Li, I. Bombaci, M. Dey, J. Dey, and E. P. J. van den Heuvel, Phys. Rev. Lett. 83, 3776 (1999)
- J. Poutanen and M. Gierlinski, Mon. Not. Roy. Astron. Soc. 343, 1301 (2003)
- D. A. Leahy, S. M. Morsink, and C. Cadeau, Astrophys. J. 672, 1119 (2008)

Accelerated cooling:

- C. O. Heinke, P. G. Jonker, R. Wijnands, C. J. Deloye, and R. E. Taam, Astrophys. J. 691, 1035 (2009)

Subsolar mass:

- T. Di Salvo, A. Sanna, L. Burderi, A. Papitto, R. Iaria, A. F. Gambino, and A. Riggio, Mon. Not. Roy. Astron.Soc. 483, 767 (2019)

Is SAX J1808.4-3658 a strange quark star produced by AIC?