CASS Co-learnium, 31st Jan. 2019

Are neutron stars* actually quark stars?

Shi Dai

* A neutron star is the collapsed core of a giant star which before collapse had a mass between ~10 and ~40 solar masses. Neutron stars have a radius of the order of 10 km and a mass of ~1.4 solar masses. For more about neutron stars and pulsars, see previous Co-learnium talks given by Dick Manchester and Andrew Cameron.

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Are neutron stars actually strange* quark stars?

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* Quark stars (consist of u, d quarks) don't exist, but **strange quark**** stars might.
  General audience: This is a **strange** question! Doesn't make any sense!
  Pulsar astronomers: This is a **strange** question! We love neutron stars (≈ we don't care about particle physics) !

** **strange quark** or s quark is the third lightest of all six types (flavors) of quarks.

Please no questions about these phrases or particles

- **Color:** a property of quarks and gluons that is related to the strong interactions
- **Quantum chromodynamics:** QCD, theory of the strong interaction between quarks and gluons
- **Color confinement:** the phenomenon that color charged particles cannot be isolated
- **Asymptotic freedom:** interactions between particles to become asymptotically weaker as the energy scale increases
- **Hyperons** (strange baryons, $\Lambda^0, \Sigma^0, \Sigma^+, \Sigma^-, \Sigma^{*+}, \Sigma^{*-}, \Sigma^{*0}, \Xi^0, \Xi^-, \Xi^{*0}, \Xi^{*-}, \Omega^-$), **free quarks** ($six\ flavors$, u, d, c ,s, t, b), **gluons** (force carries, bosons)

35 years before the discovery of pulsar

- In 1932, Sir James Chadwick discovered neutron
- At the American Physical Society meeting in December 1933, Walter Baade and Fritz Zwicky proposed the existence of ***neutron stars*** to explain the origin of a supernova.

"…… with all reserve we advance the view that supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of closely packed neutrons."

"…… neutrons are produced on the surface of an ordinary star" [under the effect of cosmic rays] and "rain down towards the centre as we assume that the light pressure on neutrons is practically zero."

(Baade W, Zwicky F, 1934, Phys. Rev. 46, 76)

Los Angeles Times of 19 January 1934
(Yakovlev et al. 2013, Phys. Usp, 56, 289)

Lev Landau's "gigantic nucleus"

- **Even before the discovery of neutron**, in 1931, Lev Landau speculated his "gigantic nucleus: atomic nuclei come in close contact, forming one gigantic nucleus"

"Following a beautiful idea of Professor Niels Bohr's we are able to believe that the stellar radiation is due simply to a violation of the law of energy, which law, as Bohr has first pointed out, is no longer valid in the relativistic quantum theory, when the laws of ordinary quantum mechanics break down"

Landau, Lev D. 1932, Phys. Z. Sowjetunion. 1: 285, 288

- Independently derived the Chandrasekhar mass limit (mass limit of white dwarf)

Lev Landau 1929

Lev Landau's "gigantic nucleus"

- Landau proposed that in ordinary stars of masses greater than a critical mass $0.001M_{sun}$, a neutron core must exist.

"…… it is easy to see that matter can go into another state which is much more compressible – the state where all the nuclei and electrons have combined to form neutrons."

"Thus we can regard a star as a body which has a neutronic core the steady growth of which liberates the [gravitational] energy which maintains the star at its high temperature."

Landau, 1938, Nature, 141 333

- Thorne-Zytkow (TZ) objects

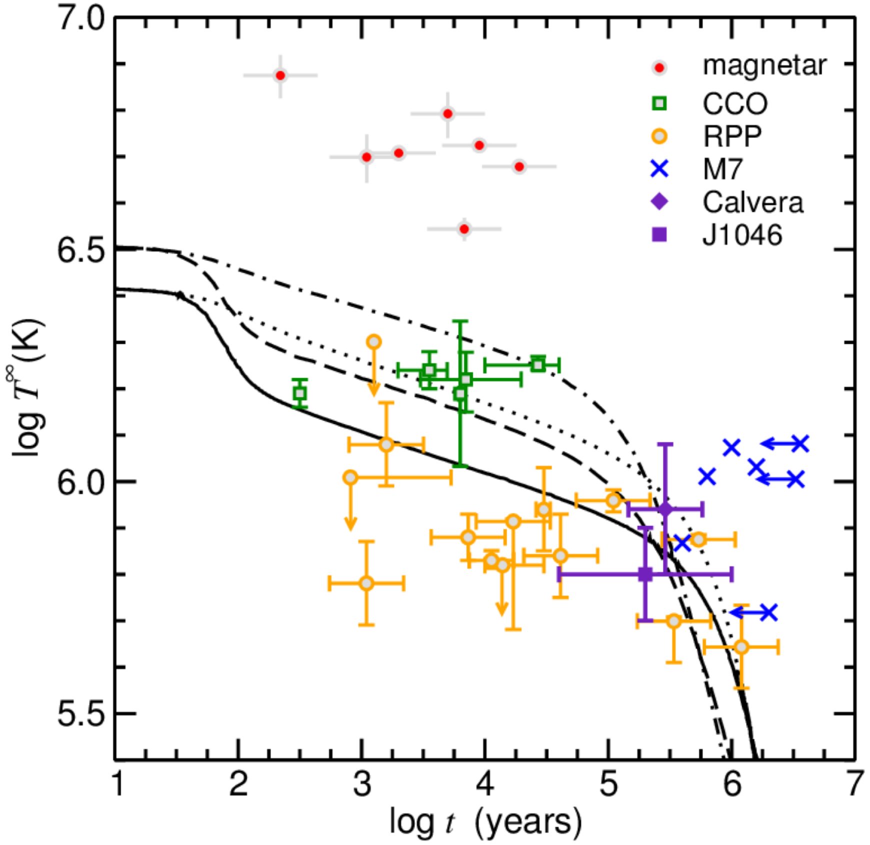
Lev Landau 1929

The Golden Age of particle physics

- Bardeen, Cooper, and Schrieffer (BCS) in 1957 proposed the pairing mechanism to explain the superconductivity of some metals at low temperatures

- A. B. Migdal first proposed the idea that superfluidity exists inside neutron stars (A. B. Migdal, 1959, Nucl. Phys. A, 655–674).

- Superfluidity and superconductivity has been invoked to explain the dynamical (e.g., pulsar glitch, Anderson & Itoh, 1975, Nature 256, 25, 27) and thermal evolution of a neutron star.



Credit: S. Popov

Here comes the quarks!

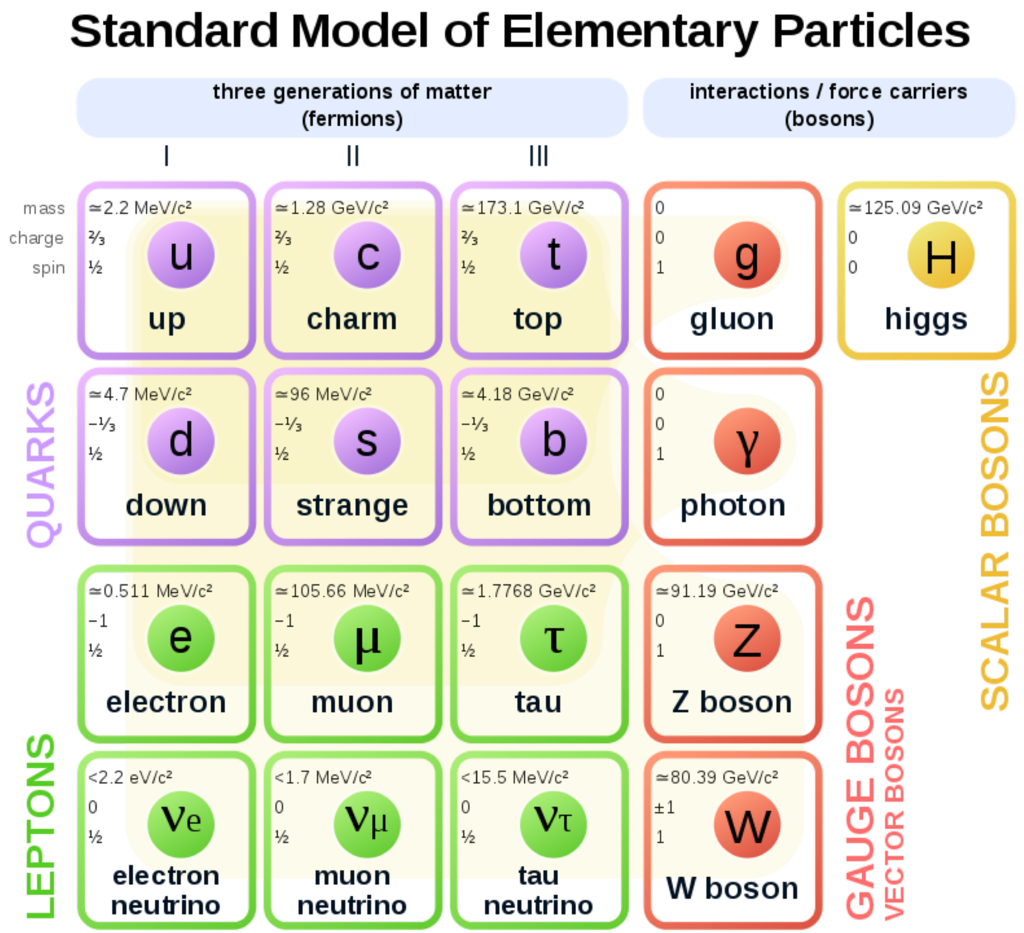
- The quark model was independently proposed by physicists Murray Gell-Mann and George Zweig in 1964.

- The hypothesis about quark stars was first proposed in 1965 by Soviet physicists D. D. Ivanenko* and D. F. Kurdgelaidze.

"It is not impossible that in the central regions of some of the recently discovered astronomical objects (quasars, exploding galaxies), some part is played by processes in which quarks (or other subparticles) participate."

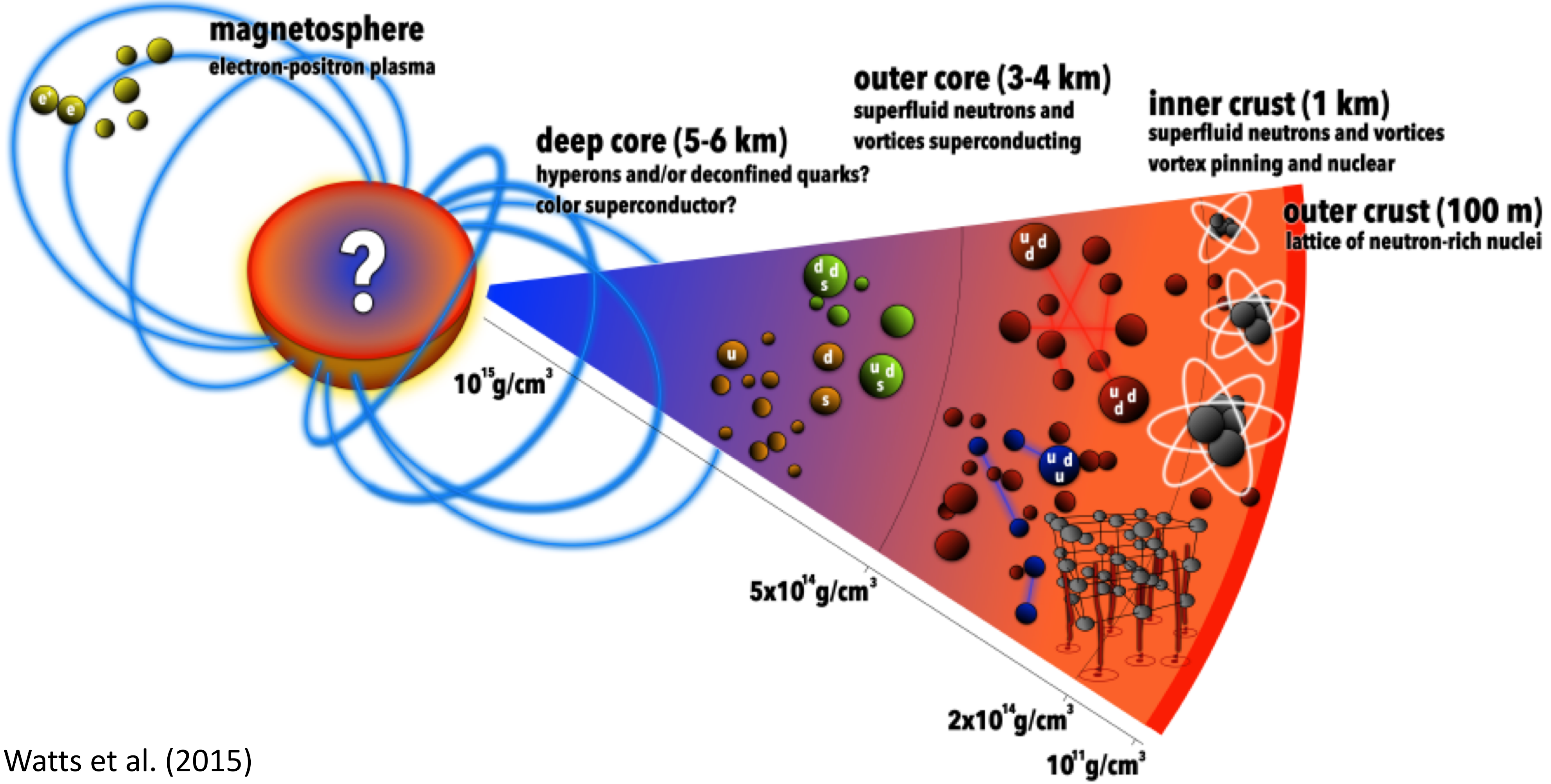
(Ivanenko & Kurdgelaidze, 1965, Astrofizika, 1, 479, 482)

* D. D. Ivanenko first proposed the proton-neutron model of the atomic nucleus (Ivanenko, 1932, Nature, 129, 798)



Credit: Wikipedia

Here comes the quarks!



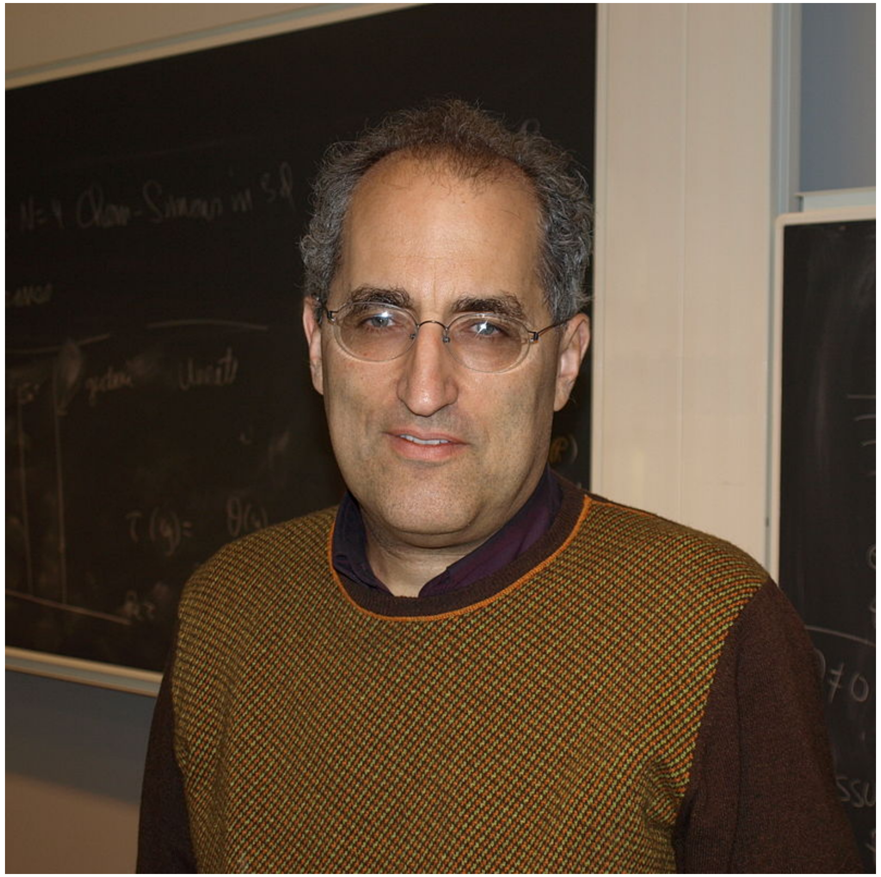
Watts et al. (2015)

Is strange quark matter more stable?

- The "Bodmer-Witten conjecture"

"The most extreme possibility is that macroscopic [strange] quark matter is bound and stable at zero temperature and pressure. At first sight, one might think that this is excluded by the fact that ordinary nuclei do not spontaneously turn into the hypothetical dense quark state. This is not quite so, however······ For quark matter, the story is different. The likely Fermi momentum in quark matter is 300 to 350 MeV, more than the strange quark mass, so it is energetically favoured for some of the non-strange quarks to become strange quarks, lowering the Fermi momentum and the energy."

(E. Witten, 1984, Phys. Rev. D. 30, 272)



Edward Witten, April 29, 2008 (credit: wikipedia)

Is strange quark matter more stable?

- The "Bodmer-Witten conjecture"

  "······ One way or another, neutron stars almost surely contain a quark-matter component······ Once a quark-matter component is present in a neutron star, two things will rapidly happen. It will quickly develop the equilibrium strangeness content via weak interactions······ Even more important, quark matter component can rapidly grow in a neutron star by absorbing free neutrons, since there is no Coulomb barrier."

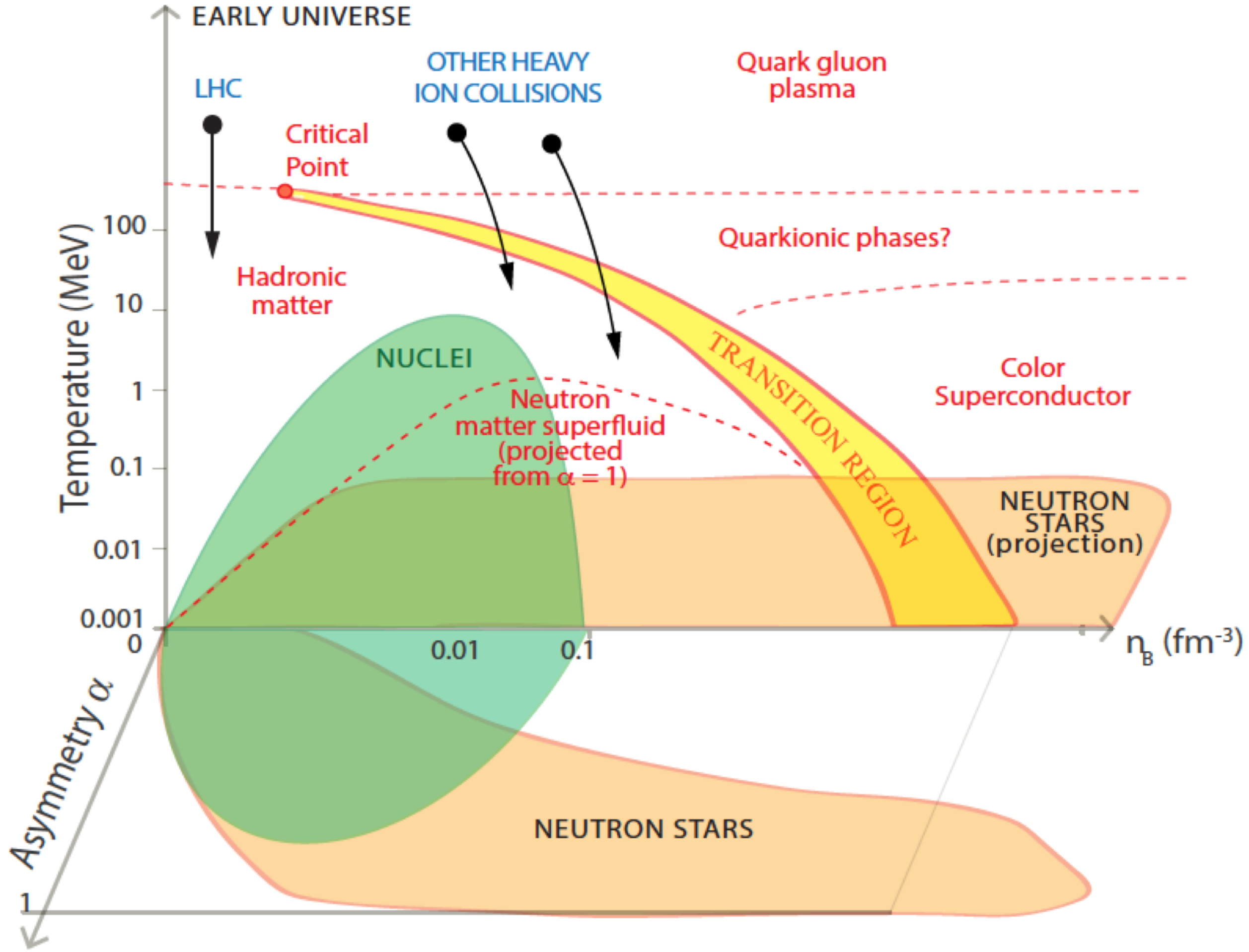
  (E. Witten, 1984, Phys. Rev. D 30, 272)

- Implications:

  ✓ Neutron stars are all strange quark stars (without complex structures)

  ✓ Strange quark star can be self-bound (strong interaction), rather than gravity-bound

Is strange quark matter more stable?

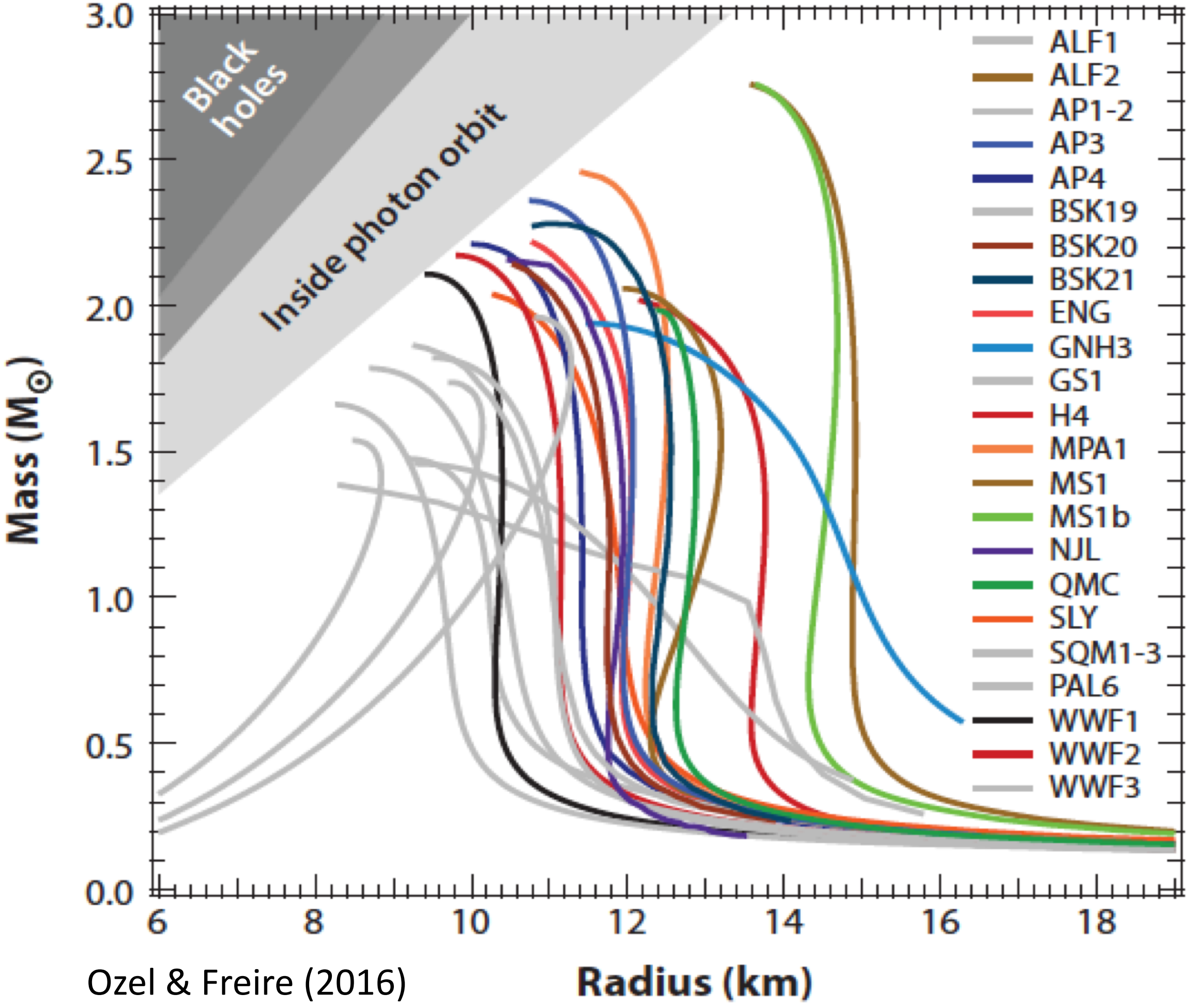


Watts et al. (2015)

Is strong interaction very strong at zero temperature and high density?

State of matter at zero temperature and high density is unknown.

Neutron star is the best laboratory



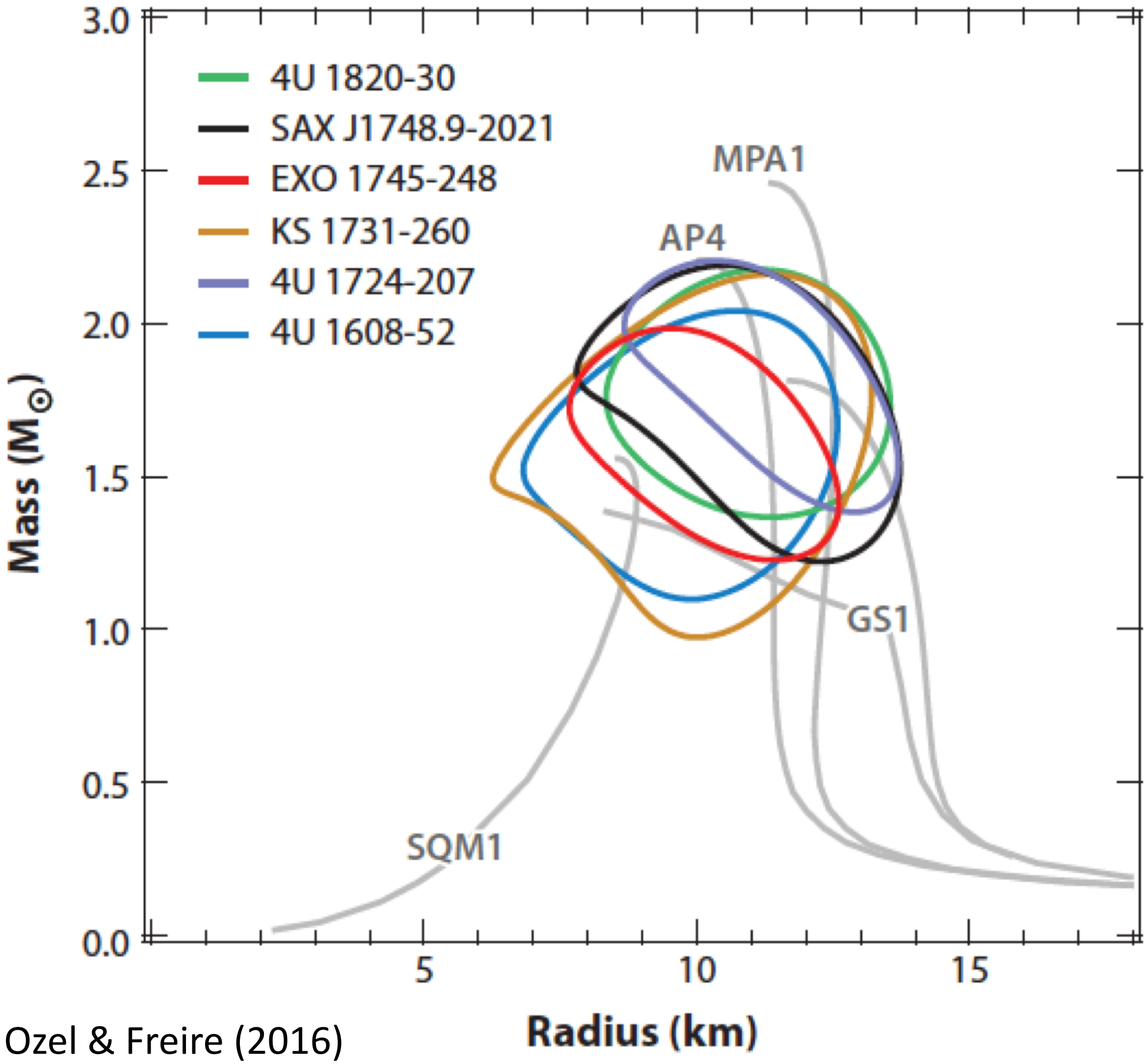
Ozel & Freire (2016)

- Equation of state (EoS) – relation between pressure and density as a function of radius.
- Mass-radius relation can be determined by the state of matter and stiffness of EoS
- Current highest precise measurement of neutron star mass

$$M_{NS} = 2.01 \pm 0.04\, M_\odot$$

(Antoniadis et al. 2013)

Neutron star is the best laboratory



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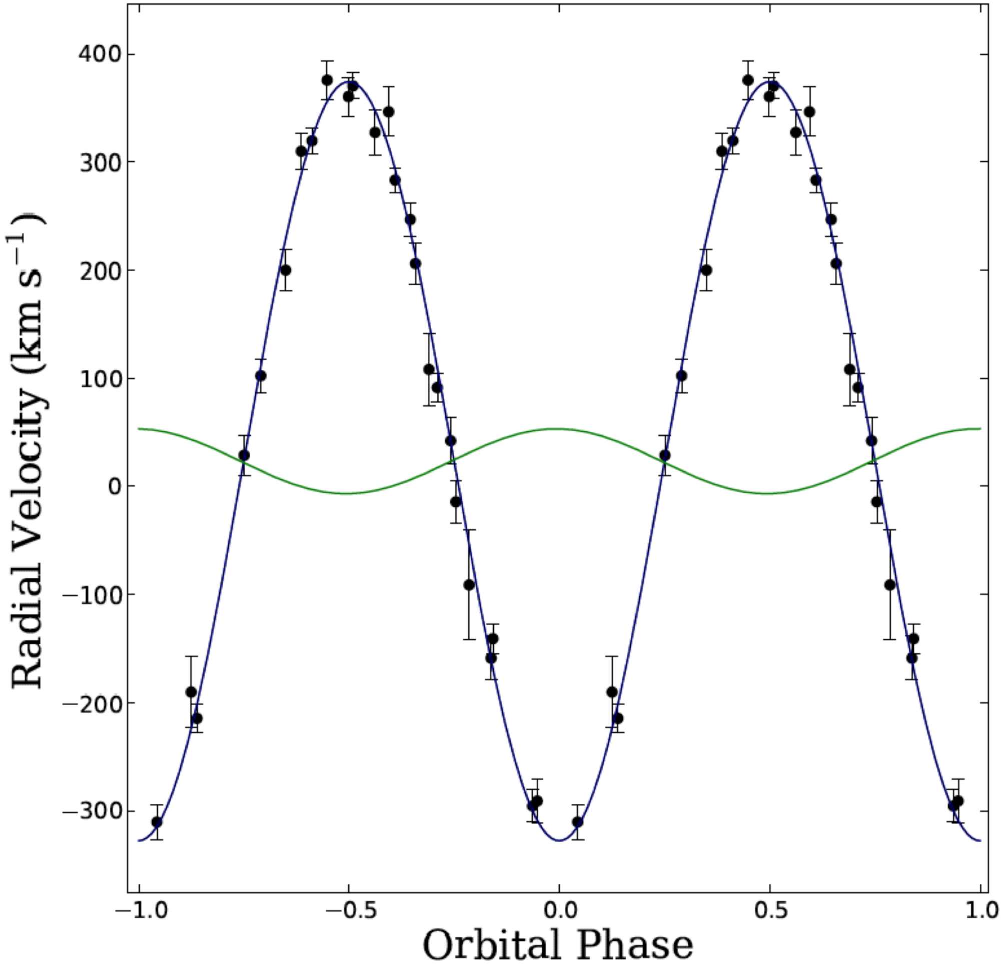
(Antoniadis et al. 2013)

- Mass + Radius measurements provide the most stringent constraint

How to measure the mass of neutron stars?

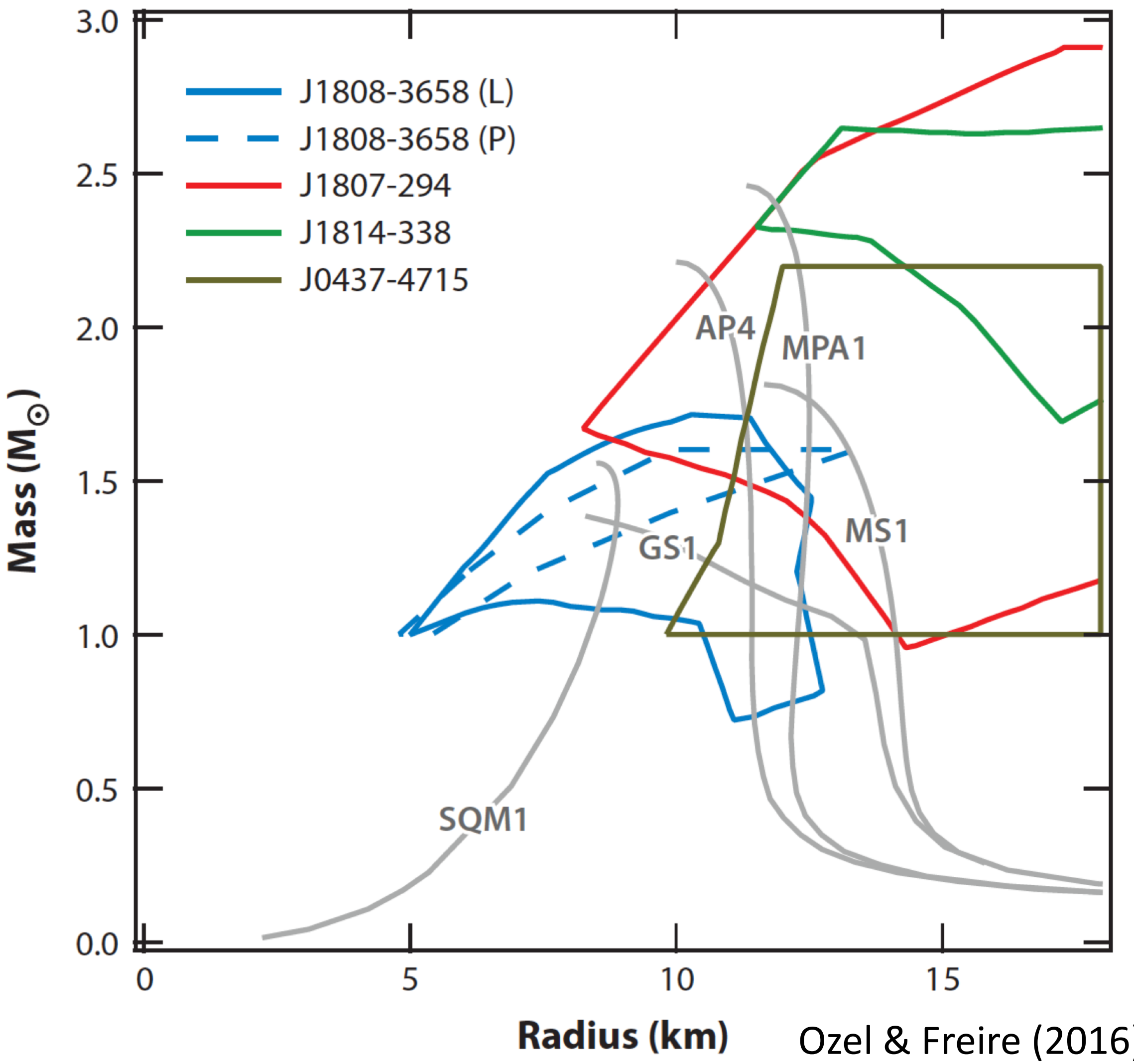
- High precision timing of pulsars in binary systems
  - ✓ Measurements of post-Keplerian (PK) parameters
  - ✓ Shapiro delay (e.g., PSR + WD systems)
- Optical spectroscopy of the companion + timing of the pulsar
  - ✓ Radio pulsars + WD/MS: very precise
  - ✓ X-ray pulsars + MS: not precise
- Gravitational microlensing → mass of isolated neutron stars (e.g., Dai et al. 2015)



(Antoniadis et al. 2013)

How to measure the radius of neutron stars?

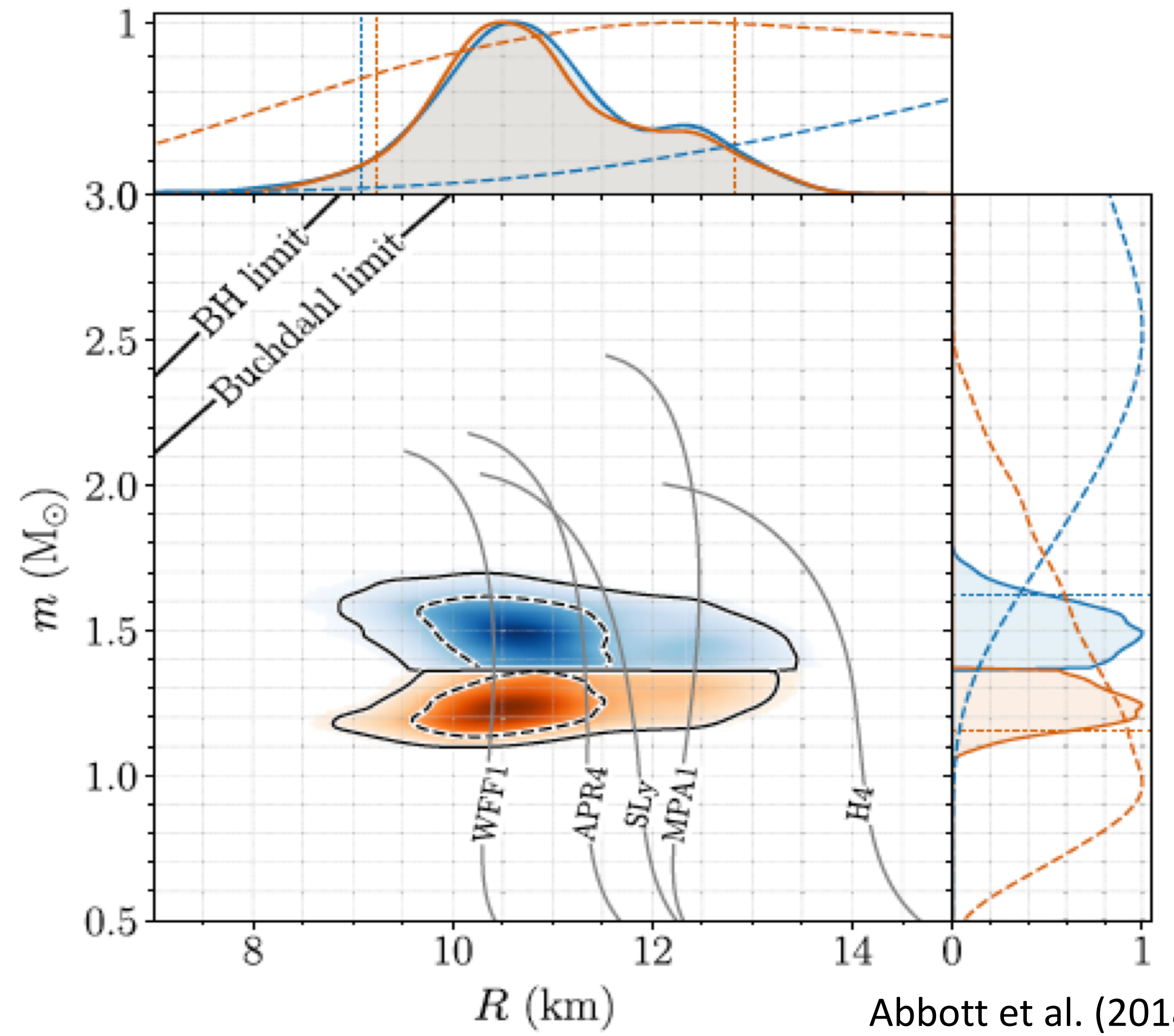
- Thermal emission from neutron stars
  - ✓ model the thermal spectrum and combine this with a distance measurement (e.g., Quiescent low-mass X-ray binaries)
  - ✓ Thermonuclear (Type-I) X-ray bursts (accreted material undergoes a helium flash)
- X-ray pulse profile modelling (e.g., NICER)
  - ✓ Determined by gravitational light bending, temperature profile and beaming
  - ✓ Constraints on both radius and mass



Ozel & Freire (2016)

A new window to probe the state of matter

- On 17 August 2017, the LIGO and Virgo observatories made the first direct detection of gravitational waves from the coalescence of a neutron star binary system.
- As the network of GW observatories expands and their sensitivity improves, future detections of binary NS and NS-BH mergers will be very exciting!



Abbott et al. (2018)

Summary

- The state of dense matter at zero temperature is still an open question
- Neutron star is the best laboratory to test different theories
- Mass and radius measurements are the best ways to constrain different model (pulsar glitches and cooling are also important)
- This is the most exciting field in pulsar astronomy (personal opinion), and future telescopes (SKA, LIGO, optical, X-ray…) are very likely to make breakthroughs in coming years.