Introduction to the physics of neutron stars

Lecture 1

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FLAD LUSO-AMERICAN DEVELOPMENT FOUNDATION

Overview of lectures

Lecture 1: Introduction to the **Physics of Neutron Stars**

- What are they, how do they form, and what are they made up of?

Lecture 2: (Electromagnetic) **Observations of Neutron Stars**

- Neutron star masses, radii, and how these measurements constrain the equation of state

Lecture 3: **Gravitational Wave Astronomy**: a new window into neutron star interiors

- Introduction to gravitational waves (astro)physics
- Introduction to the LIGO experiment: how it works and what has been measured to date
- What to expect from neutron star mergers over the next ~decade

Introduction to Neutron Stars

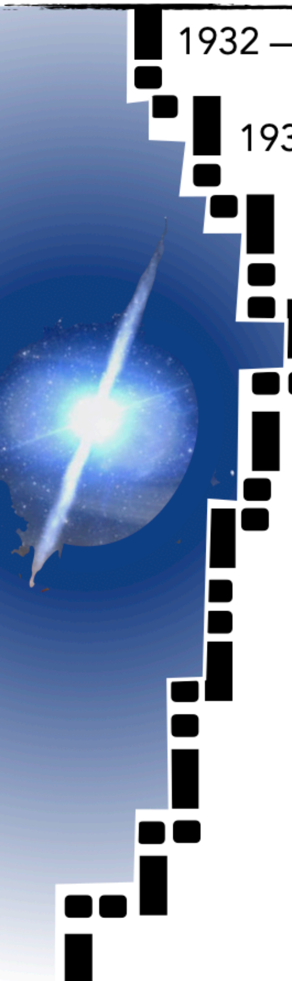
A (biased and incomplete) history of neutron stars

1932 — James Chadwick discovers the neutron

1934 — Baade & Zwicky **predict existence of neutron stars**, as the end product of core-collapse supernovae

> "With all reserve, we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons. Such a star may possess a very small radius and an extremely high density. As neutrons can be packed much more closely than ordinary nuclei and electrons, the "gravitational packing" energy in a cold neutron star may become very large, and, under certain circumstances may far exceed the ordinary nuclear packing fractions. …"

A (biased and incomplete) history of neutron stars



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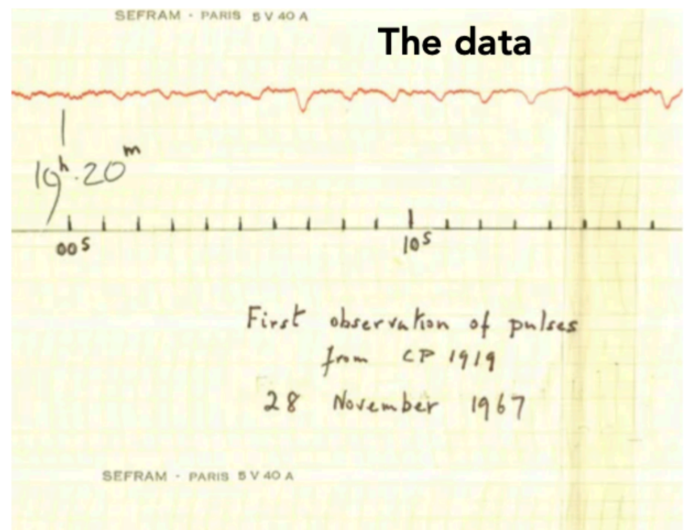
1967 — Jocelyn Bell Burnell discovers the first pulsar (leads to 1974 Nobel for Anthony Hewish)



Signal repeats every 1.3373 seconds!

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1968 — Discovery of a pulsar in the Crab Nebula; cements association of NS with supernovae

Signal repeats every ***33 milliseconds****!*

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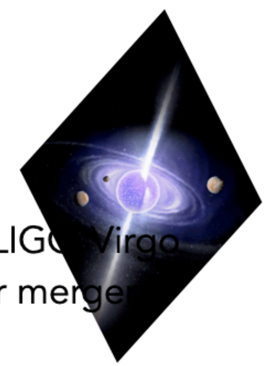
1974 — First binary pulsar (B1913+16) discovered by Hulse & Taylor (leads to 1993 Nobel prize)

1979 — Orbital decay of B1913+16 by Weisberg & Taylor; **proves existence of gravitational waves**

1982 — First *millisecond (!)* pulsar discovered by Backer et al.

1992 — Pulsars are used to discover the **first exo-planets** by Wolszczan & Frail



2017 — First **direct detection of gravitational waves from a neutron star merger** by LIGO/Virgo collaboration; first kilonova, first evidence of r-process nucleosynthesis from neutron star mergers

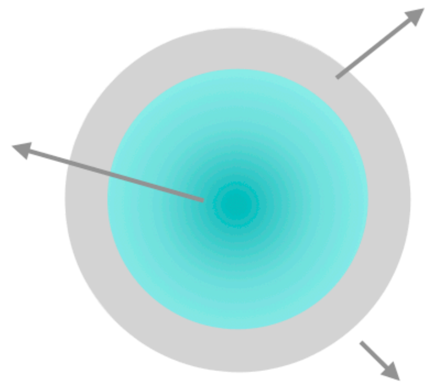
2020 — First NS-black hole mergers observed

Temperature of neutron stars

Proto-neutron stars are born with T ~ 10^{11} - 10^{12} K (~50 MeV)

Crust cools by conduction

Isothermal core cools by neutrino emission; dominates cooling for first 10^4-10^5 years



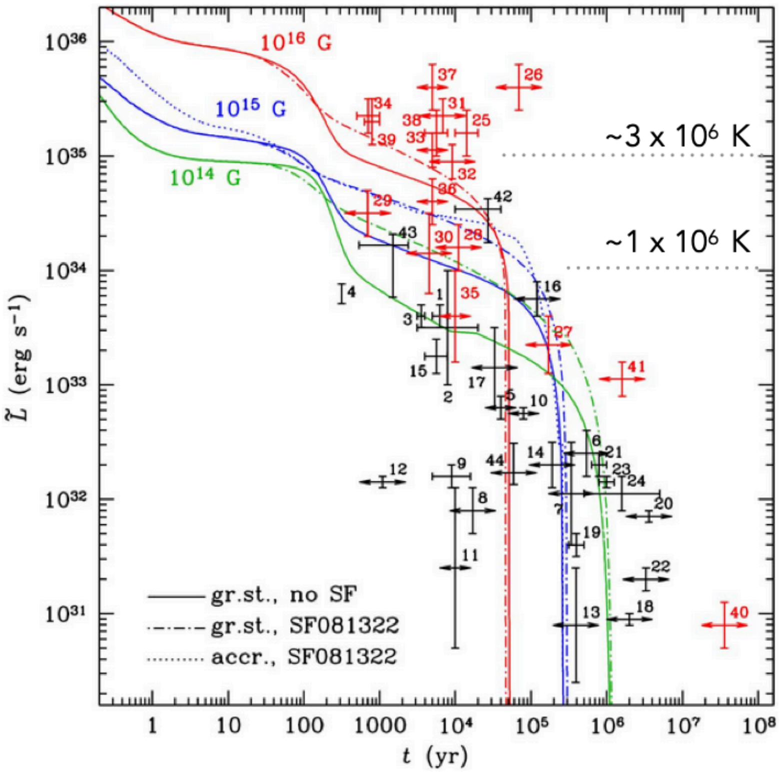
PNS cooling is regulated by neutrino emission, heat capacity, superfluidity of interior, and heat-insulating properties of the outer layers

Surface photon emission dominates at late time t > 10^6 yrs

Data from young neutron stars can help constrain these processes

Neutron star cooling curves

Redshifted thermal luminosity as a function of stellar age *t*



Potekhin and Chabrier 2017

Observations show neutron stars cool to T≲10^6 K within the first ~10^5 years

Very approximately:

$$T_{\rm interior} = 10^2\ \alpha\ T_{\rm surface},\ \ 0.1 \lesssim \alpha \lesssim 1$$

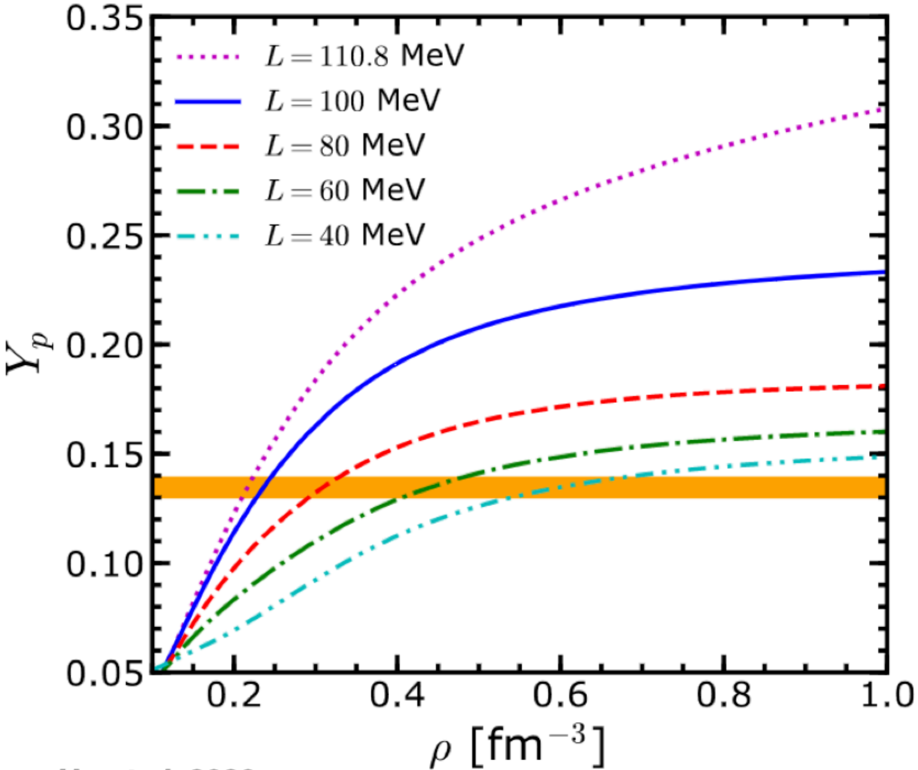
Even at core temperatures of ~10^8 K ~ 0.01 MeV,

$T_{\rm core} << T_{Fermi}$

Conclusion: matter is thermodynamically cold

Composition of neutron stars

Proton fraction for different values of the symmetry energy slope, *L*, for the TM1 parameter set



Hu et al. 2020

Composition at the core determines what pathways are available for NS cooling:

- **Direct Urca**: $n \rightarrow p + e^- + \bar{\nu}_e$

  $p \rightarrow n + e^+ + \nu_e$

  - Requires a minimal proton fraction of $\mathbf{Y_p \gtrsim 1/9}$
- At lower proton fractions, **modified Urca** is possible, but neutrino cooling is *~10⁶ x less efficient*

Constraints on the nuclear symmetry energy

$$E_{\rm nucl}(n, Y_p, T) = E_{\rm nucl}(n, Y_p = {}^1\!/\!_2, T) + E_{\rm sym}(n, T)(1 - 2Y_p)^2 + \ldots$$

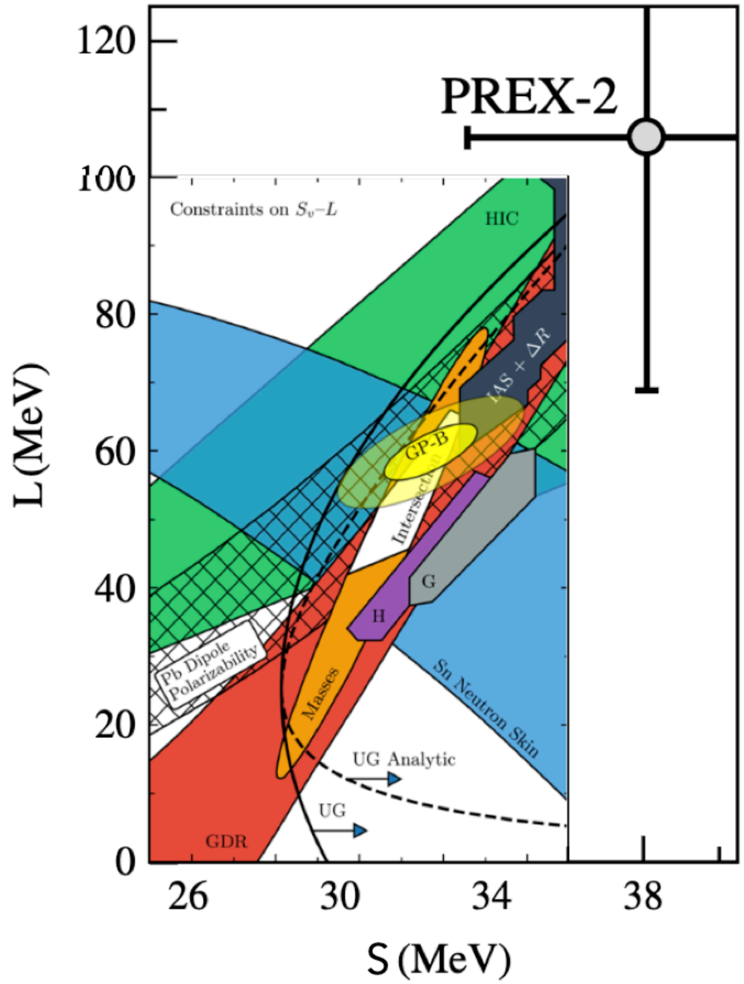
Total energy for arbitrary composition

Symmetric nuclear matter

Neutron excess

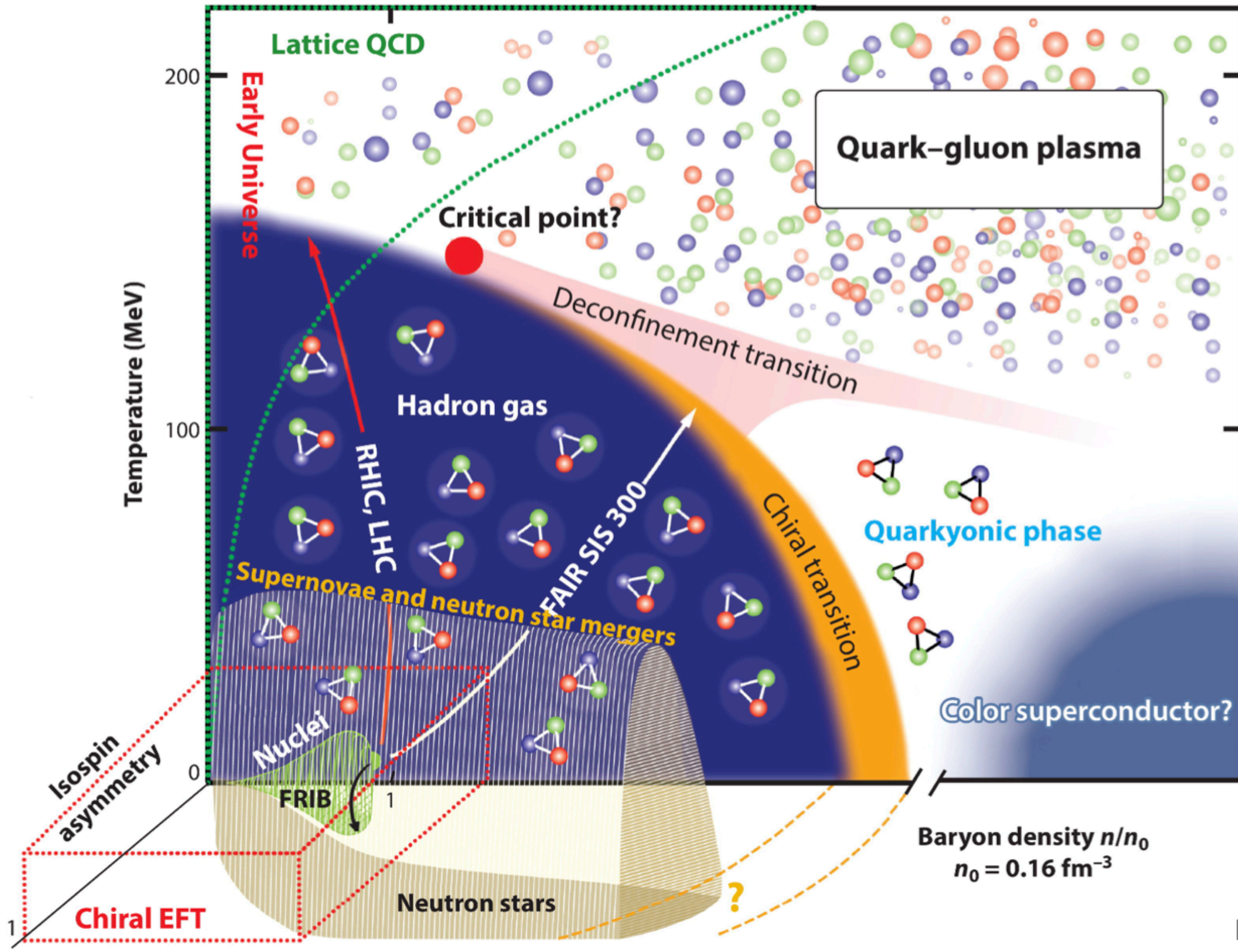
$$E_{\rm sym}(n) = S_0 + \frac{L_0}{3}u + \frac{K_{\rm sym}}{18}u^2 + \frac{Q_{\rm sym}}{162}u^3 + \mathcal{O}\left(u^4\right)$$

where $u = (n/n_{sat}) - 1$



Drischler et al. 2021; Lattimer et al. 2012

PREX result from Reed et al. 2021



Drischler et al. 2021

Equation of state

Generically: ***P(n, T, Y_p)***

For assumption of cold, equilibrated matter, this simplifies to: ***P(n)***

Early model (considered by Oppenheimer, Volkoff 1939) was a *degenerate, ideal, Fermi gas:*

Non-relativistic: $P = c_{\text{nonrel.}}\, \rho^{5/3}$

Relativistic: $P = c_{\text{rel.}}\, \rho^{4/3}$

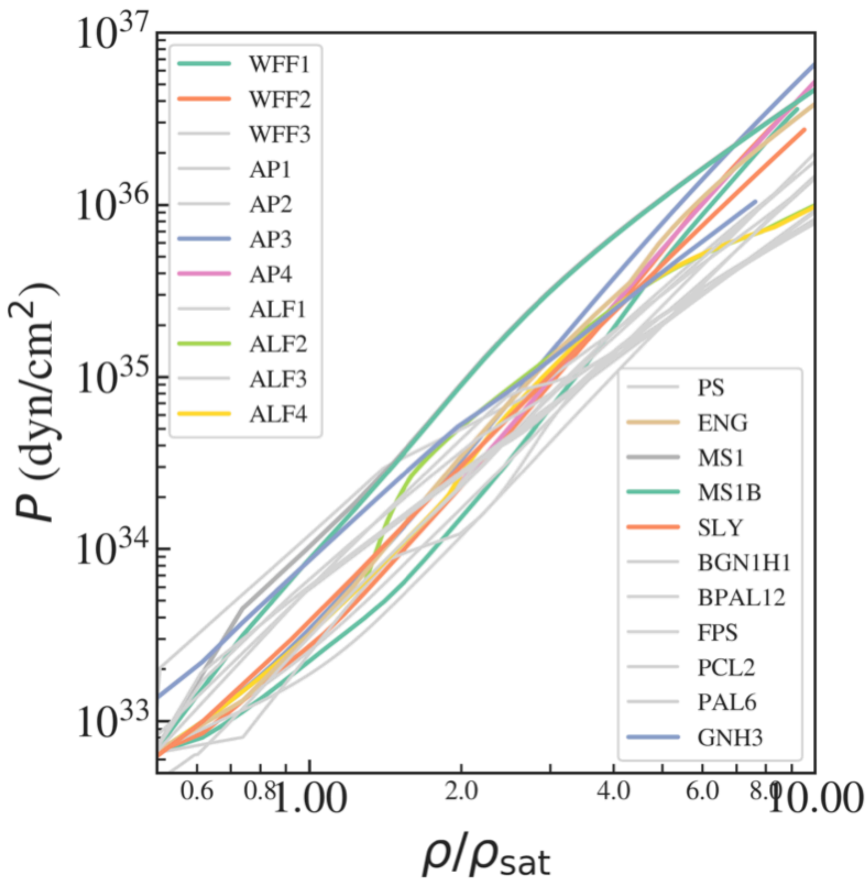
More accurate model needs to take into account:

- **Electrostatic corrections** — important in crust, where charge is not uniformly distributed
- **Composition** of not just neutrons, but protons and electrons (required to inhibit neutron decays)
- **Nuclear interactions**, which are a significant contribution to the energy density
- **Exotic degrees of freedom** at high densities

Above ρ_{sat}, there are two key challenges:

1. Determining the **nuclear potential** for nucleon-nucleon interactions
2. Finding an appropriate computational technique for **solving the (relativistic) quantum many-body problem**

Theoretical models of the equation of state*



* for cold, β-equilibrated matter

Nuclear models (npeμ matter only):

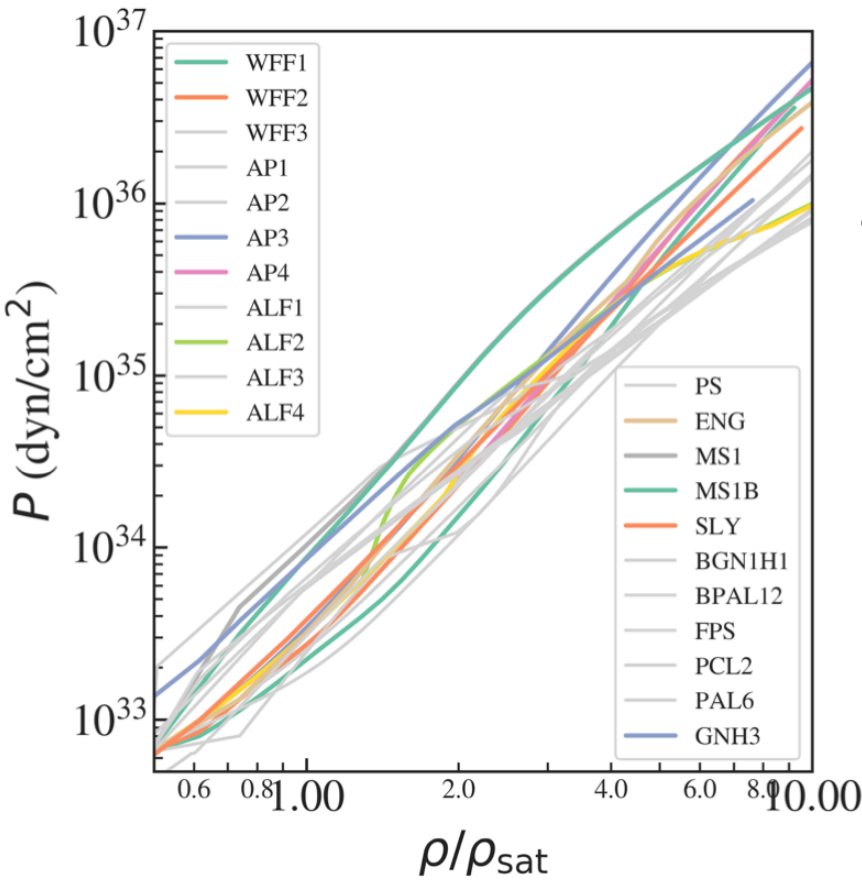
- Potential-method EOSs (PAL6 and SLy)
- Variational-method EOSs (AP1-4, FPS, and WFF1-3)
- Relativistic Brueckner-Hartree-Fock EOSs (BPAL12 and ENG)
- Relativistic mean field theory EOSs (MS1, MS1b)

Models with hyperons, pion condensates, or quarks:

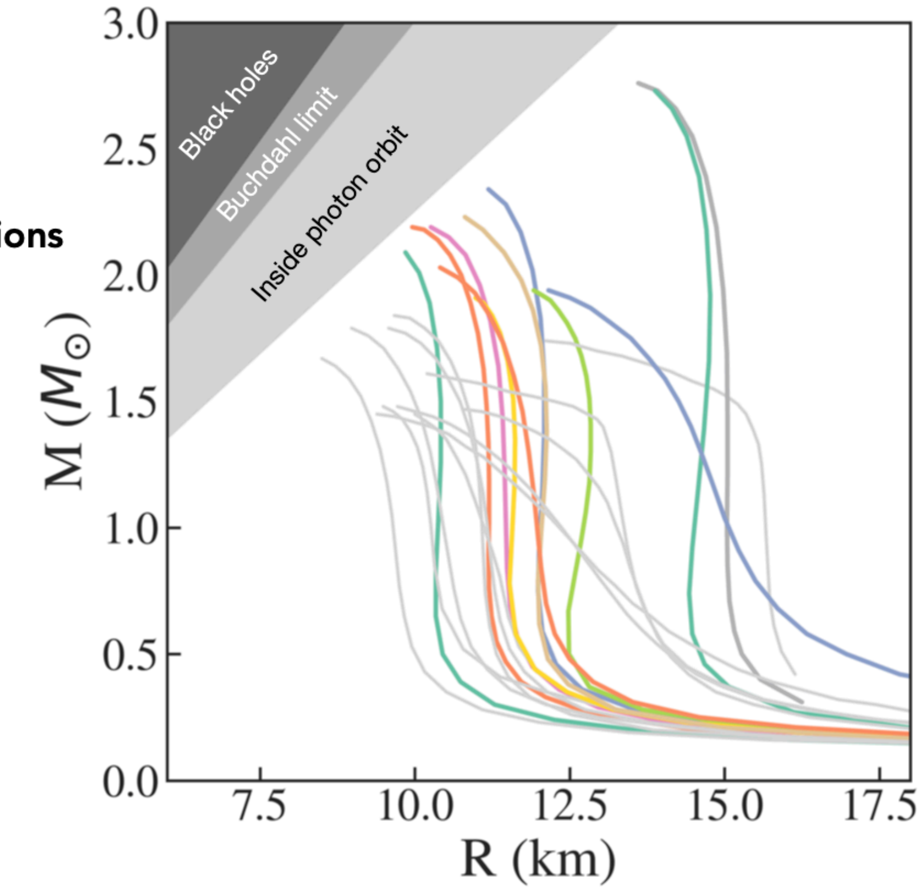
- Neutron-only EOS with pion condensates (PS)
- Effective potential EOS including hyperons (BGN1H1)
- Relativistic mean field theory EOS with hyperons (GNH3)
- Relativistic mean field theory EOS with hyperons and quarks (PCL2)
- Hybrid EOSs with mixed APR nuclear matter and colour-flavor-locked quark matter (ALF1-4)

Nomenclature and descriptions from Read et al. 2009

Mass-radius relations for theoretical EOSs



TOV equations



Further reading

Textbooks:

- “Compact Stars: Nuclear Physics, Particle Physics, and General Relativity” by Glendenning
- “Black Holes, White Dwarfs, and Neutron Stars” by Shapiro & Teukolsky

Reviews:

- “Neutron Stars and the Nuclear Equation of State” — Burgio, Schulze, Vidana, and Wei (2021, Progress in Particle and Nuclear Physics)
- “Neutron Stars and the Nuclear Matter Equation of State” — Lattimer (2021, Annual Reviews of Nuclear and Particle Science)
- “Masses, Radii, and the Equation of State of Neutron Stars” — Ozel & Friere (2016, Annual Reviews of Astronomy & Astrophysics)