Compact Stars and Heavy-Ion Collisions

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HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

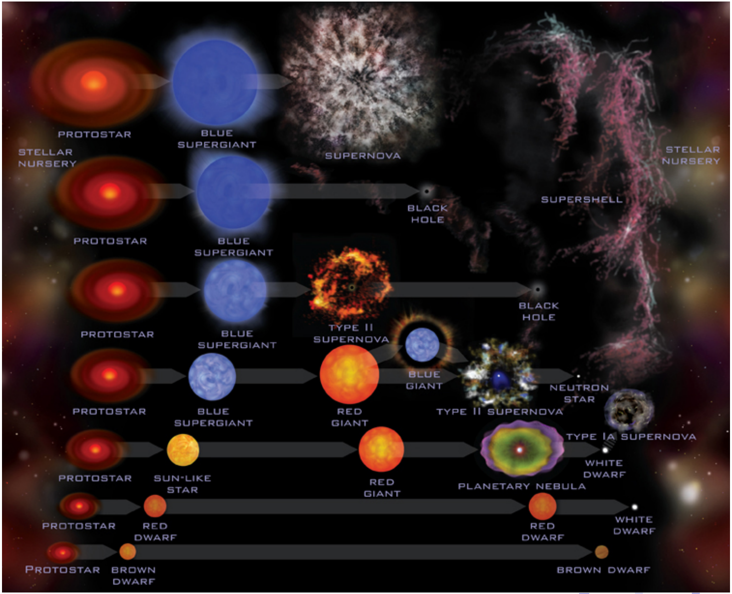
CRC-TR 211
Strong-interaction matter under extreme conditions

DFG

Outline

Outline

Stellar Evolution (Credit: NASA/CXC/M.Weiss)



Formation of Compact Objects

endpoints of stellar evolution:

$M < 0.08 M_\odot$: no stable nuclear burning $\rightarrow$ brown dwarfs

$M < 0.4 M_\odot$: hydrogen burning $\rightarrow$ H-He white dwarfs

$M < 8 M_\odot$: helium burning $\rightarrow$ C-O white dwarfs (our Sun!)

$8 < M < 10 M_\odot$: carbon burning, degenerate Ne-O-Mg core,
core collapse supernova $\rightarrow$ neutron star

$M > 10 M_\odot$: Ne-O-Si burning, degenerate Fe core,
core collapse supernova $\rightarrow$ neutron star

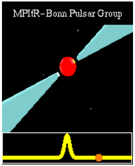
$M \gtrsim 25 M_\odot$: core collapse supernova $\rightarrow$ black hole

$M \sim 100 M_\odot$: upper mass limit for stars

(formation of black holes also by supermassive stars (first stars), primordial black holes ('mini black holes' with $M > 10^{15}$g) or collision of compact stars in binary systems)

Neutron Stars – the Crab Nebula

Hubble Space Telescope (green), Spitzer (red), Chandra (blue)



- produced in core collapse supernova explosions
- compact, massive objects: radius $\approx$ 10 km, mass $1 - 2M_\odot$
- extreme densities, several times nuclear density: $n \gg n_0 = 2.5 \cdot 10^{14}$ g/cm^3
- in the middle of the crab nebula: a pulsar, a rotating neutron star!

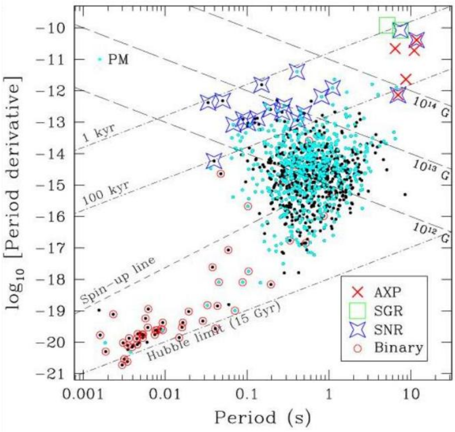
Comparison of compact objects

	mass ($M_\odot$)	radius (km)	density (g/cm^3)	GM/R
Sun	1	695.700	1.4	10^{-6}
white dwarf	$0.5 - 1$	~ 10.000	$\sim 10^6$	$\sim 10^{-4}$
neutron star	$1 - 2$	~ 10	$\sim 10^{15}$	$0.1 - 0.3$
black hole	$10 - 10^{10}$	$30 - 3 \times 10^9$	N/A	0.5

($M_\odot = 1.98848(9) \cdot 10^{33}$g)

huge range of densities, involves all four fundamental forces (strong, weak, electromagnetic, gravity)

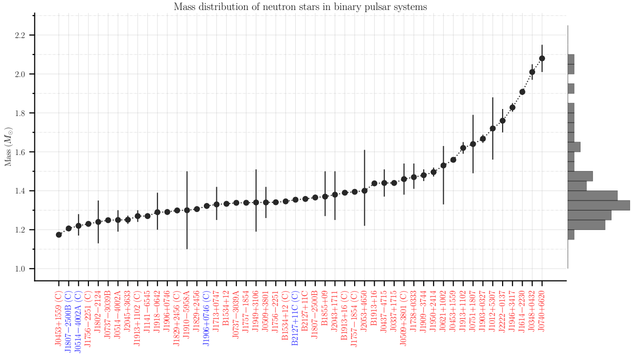
The Pulsar Diagram



(ATNF pulsar catalog)

- the diagram for pulsars: period versus period change (P-$\dot{P}$)
- dipole model for pulsars: characteristic age: $\tau = P/(2\dot{P})$ and magnetic field $B = 2 \cdot 10^{19}(P \cdot \dot{P})^{1/2}$ Gauss
- anomalous x-ray pulsars: AXP, soft-gamma ray repeaters: SGR, young pulsars in supernova remnants: SNR
- rapidly rotating pulsars (millisecond pulsars): mostly in binary systems (old recycled pulsars!)

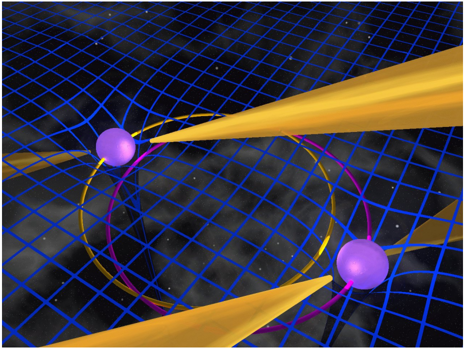
Masses of Pulsars

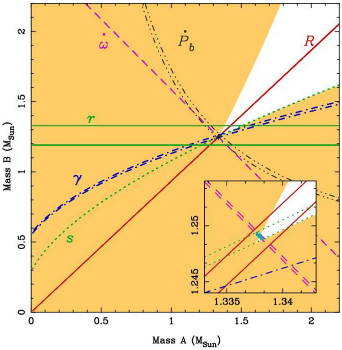


(figure: Vivek V. Krishnan, 2021)

- more than 2000 pulsars known with 140 binary pulsars
- up-to-date list of pulsar masses by Paolo Freire at: `https://www3.mpifr-bonn.mpg.de/staff/pfreire/NS_masses.html`
- most massive pulsars: PSR 0740+6620 with $M = 2.08(7) M_\odot$ (Fonseca et al. 2021) and PSR 0348+0432 $M = 2.01(4) M_\odot$ (Antoniadis et al. 2013)

The Double Pulsar PSR J0737-3039

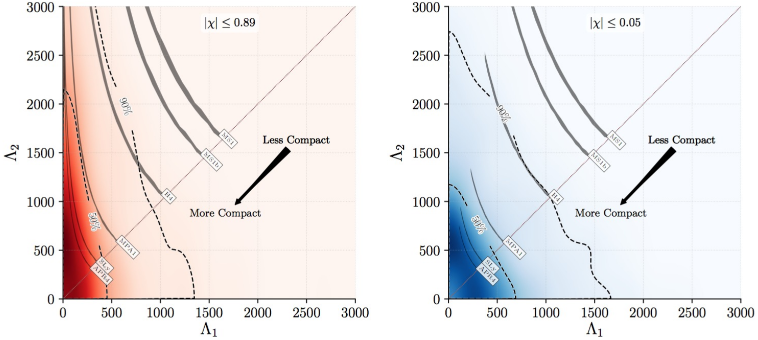




- sensational discovery of two pulsars orbiting each other (Lyne et al. 2004)
- measured five post-Keplerian parameters: Shapiro delay r and s, redshift γ, periastron advance $\dot{\omega}$, decrease in orbital period $\dot{P}_b$ (Kramer et al. 2006)
- all in agreement with the prediction of GR to within 0.05% !
- fundamental tests of General Relativity in STRONG fields

animation (credit: Michael Kramer)

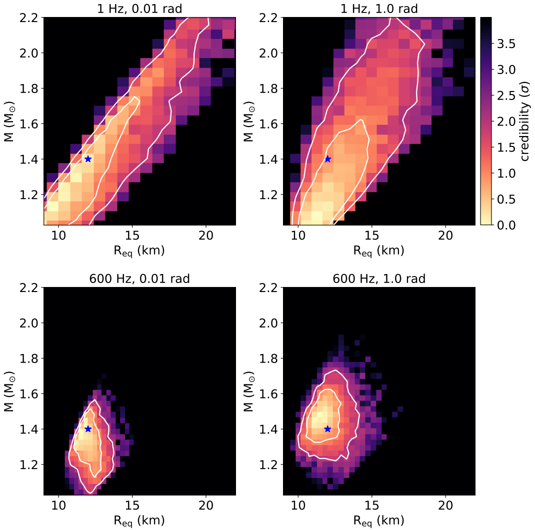
Constraint from gravitational wave event GW170817



(LIGO and Virgo collaboration 2017)

- limits on the tidal deformability of two merging neutron stars ($\Lambda < 720$)
- for high-spin (left plot) and low-spin (right plot) scenario
- rules out several models for neutron star matter (equations of state)
- more compact neutron stars (with higher mass-to-radius-ratio) are favoured

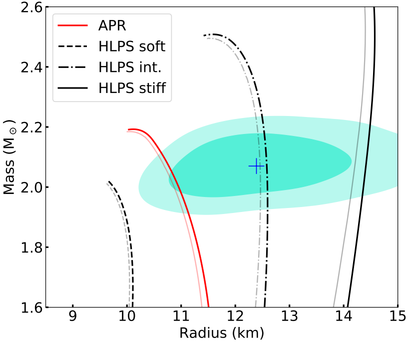
NICER constraint on neutron stars: proof of concept



(Bogdanov et al. 2021)

- observing hot spots on neutron stars in x-rays
- modulated by the curvature of spacetime
- constraints on compactness $C = GM/R$ (upper plots) or mass and radius (lower plots, fastly rotating) possible

NICER measurement for PSR J0740+6620

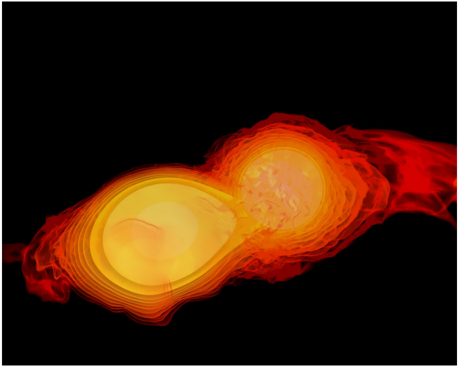


(Riley et al. 2021)

- newest data from a pulsar with known mass!
- constraint: $R = 11.4 - 13.7$ km (Riley et al. 2021) and $R = 12.2 - 16.3$ km (Miller et al. 2021)
- ruling out softer EOS (without a phase transition)

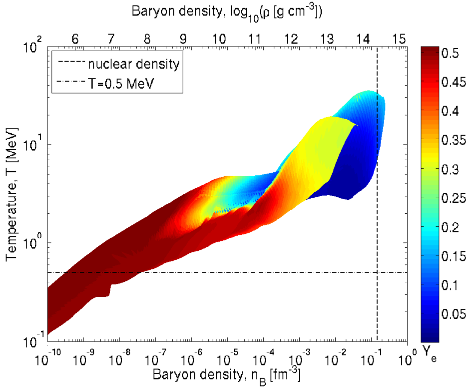
Outline

Nuclear Equation of State as Input in Astrophysics



(Koppitz/Giacomazzo/Rezzolla (AEI/ZIB))

- supernovae simulations: $T = 1$–50 MeV, $n = 10^{-10}$–$2n_0$
- proto-neutron star: $T = 1$–50 MeV, $n = 10^{-3}$–$10n_0$
- global properties of neutron stars: $T = 0$, $n = 10^{-3}$–$10n_0$
- neutron star mergers: $T = 0$–100 MeV, $n = 10^{-10}$–$10n_0$

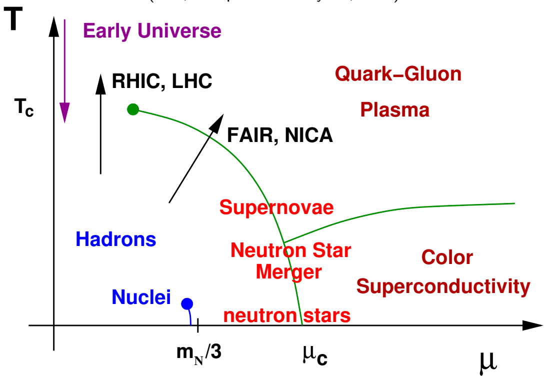


(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- wide range in densities, temperatures and electron fraction needed for the EoS in core-collapse supernova simulations
- densities: $n = 10^{-10} - 10^{-1}$ fm^{-3}, temperatures: $T = 0.5 - 50$ MeV, electron to baryon fraction: $Y_e = 0 - 0.5$

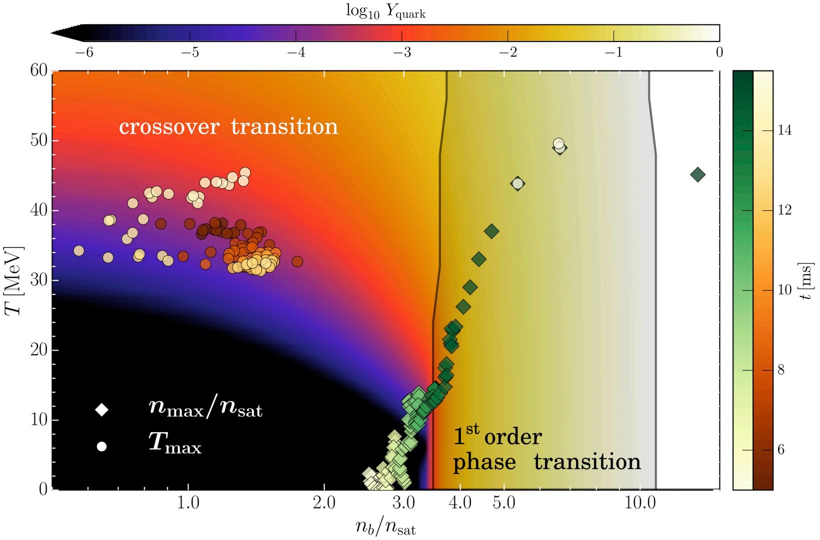
Phase Diagram of Quantum Chromodynamics QCD

(JSB, Compact Star Physics, 2020)



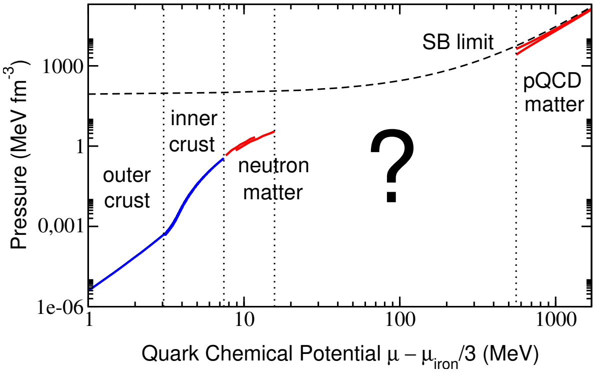
- early universe at zero density and high temperature
- heavy-ion collisions at high temperature and density
- neutron star matter at small temperature and high density
- first order phase transition to quark matter at high density?

Phase diagram for neutron star merger



(Dexheimer, Constantinou, Most, Papenfort, Hanauske, Schramm, Stöcker, Rezzolla, 2019)

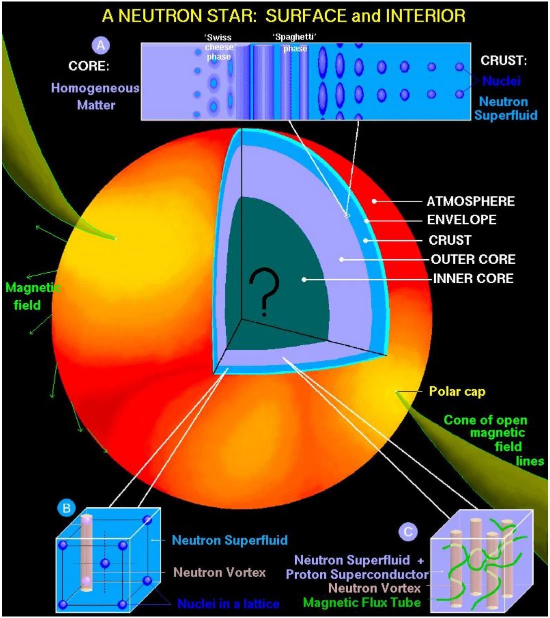
What we know about the EoS for neutron star matter



(Kurkela, Fraga, JSB, Vuorinen, 2014))

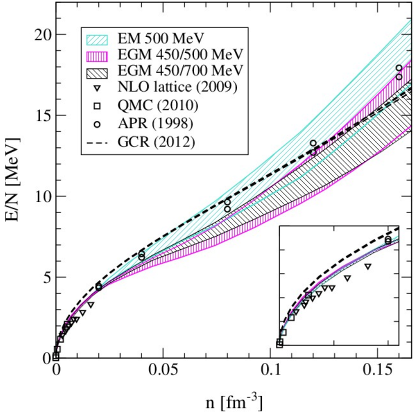
- pressure versus the quark chemical potential (above the one of ^{56}Fe)
- low-density regime: outer crust (lattice of nuclei), inner crust (lattice of nuclei in a neutron fluid), neutron matter
- high-density regime: pQCD, close to Stefan-Boltzmann limit

Structure of Neutron Stars — the Crust (Dany Page)



- $n \leq 10^4$ g/cm^3: atmosphere (atoms)
- $n = 10^4 - 4 \cdot 10^{11}$ g/cm^3: outer crust or envelope (free e^-, lattice of nuclei)
- $n = 4 \cdot 10^{11} - 10^{14}$ g/cm^3: Inner crust (lattice of nuclei with free neutrons and e^-)

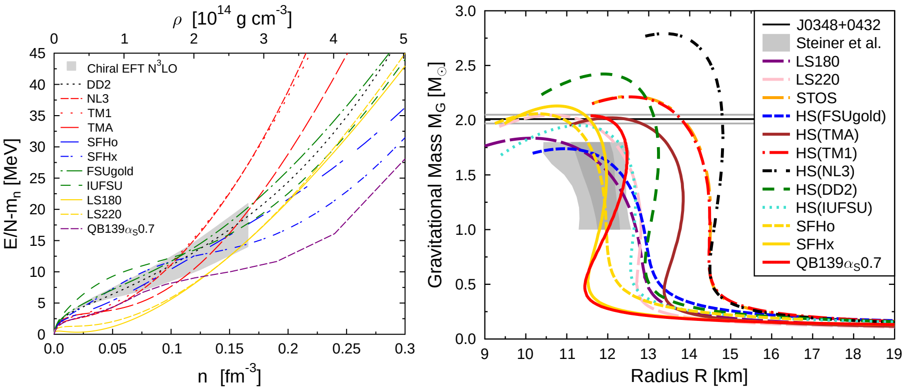
Pure Neutron Matter: EOS known



(Tews, Krüger, Hebeler, Schwenk 2012)

- chiral effective field theory including N^{3}LO terms with 3N and 4N forces
- comparison to Quantum Monte Carlo Simulations QMC and GCR
- band of uncertainty for the neutron equation of state up to saturation density

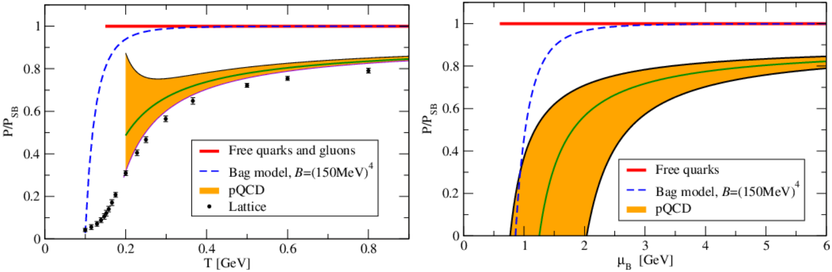
Properties of available Supernovae EoS



(Fischer, Hempel, Sagert, Suwa, JSB 2014)

- widely used: Lattimer and Swesty (LS220) and Shen et al. (STOS), fail to describe neutron matter (Krüger, Tews, Hebeler, Schwenk 2013)
- mass-radius relation depends on SLOPE of EoS (see e.g. IUFSU and LS220) which determines the pressure

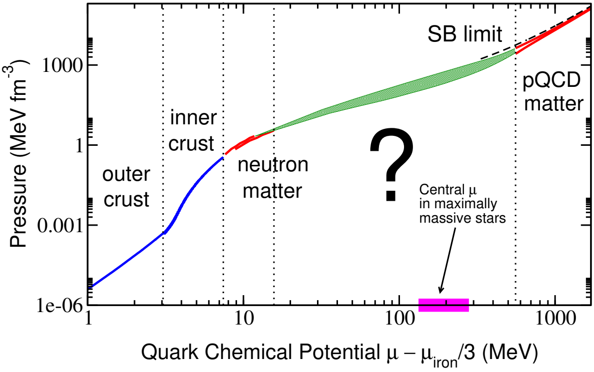
High-Density Side: perturbative QCD



(Fraga, Kurkela, Vuorinen, 2013)

- asymptotic freedom of strong interactions (QCD): weakly interacting at large scales (temperature and/or chemical potential)
- perturbative calculations up to $\mathcal{O}(\alpha_s^2)$: follows lattice data at nonzero temperature
- band of uncertainty for the pQCD equation of state at nonzero μ (from choice of renormalization scale)

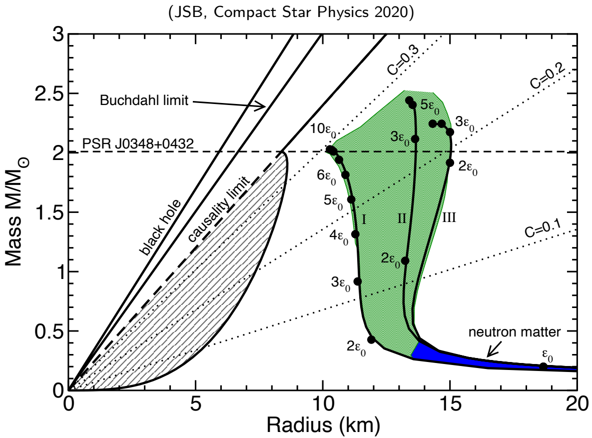
QCD Matter in Compact Stars



(Kurkela, Fraga, JSB, Vuorinen, 2014))

- green band: interpolated region compatible with pulsar mass constraint
- only pretty narrow region allowed for the EOS (without a phase transition)!
- note: we do not know what the matter within the green band is made of!

Mass-radius relation (smooth interpolation)

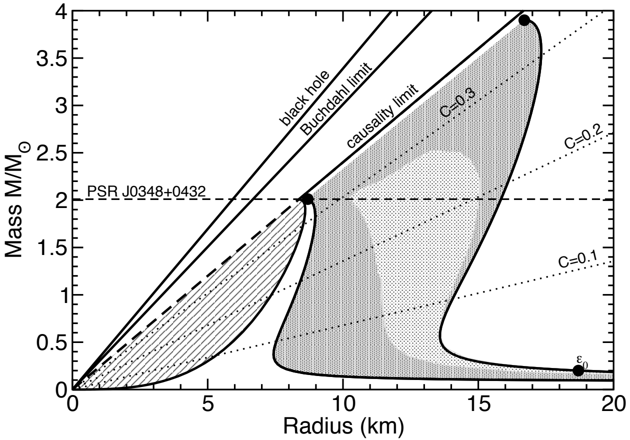


- Buchdahl limit: incompressible fluid ($C = GM/R = 4/9$)
- causality limit: $P = \epsilon - \epsilon_0$ ($C = 0.354$)
- interpolated EOS: $R = 10 - 15$ km ($M = 2M_\odot$)

Outline

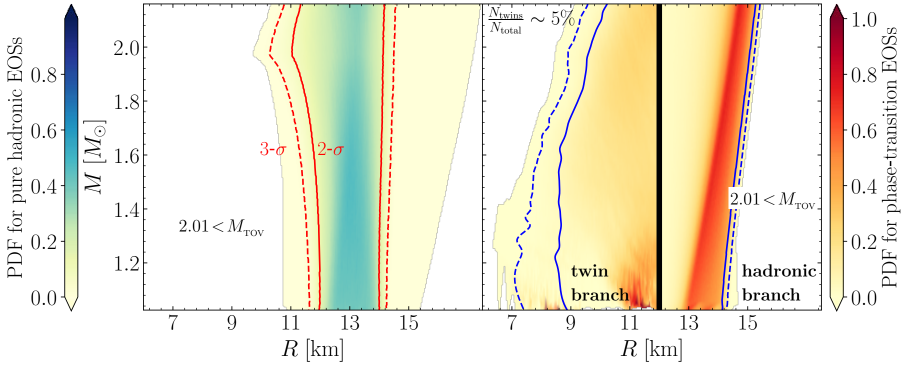
Mass-radius relation (causal EOS)

(JSB, Compact Star Physics 2020)



- causal EOS $p = \epsilon$ ($\Delta\epsilon = 0$): right bound in mass-radius relation
- causal EOS with jump $\Delta\epsilon$: left bound in mass-radius relation with $M_{\text{max}} = 2M_\odot$

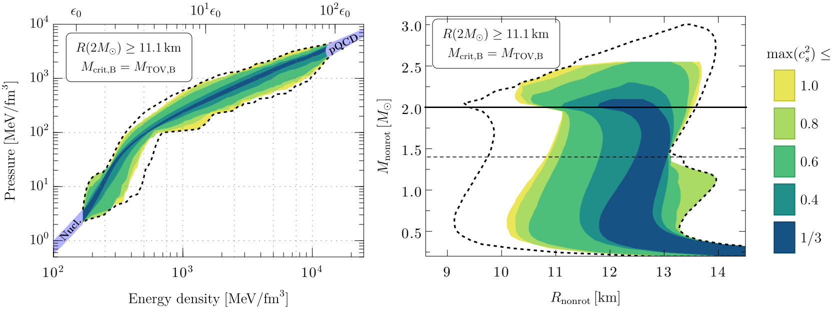
Mass-radius constraints from GW170817



(Most, Weih, Rezzolla, JSB, 2018)

- mass-radius constraint from GW170817
- left plot: smooth interpolation
- right plot: allowing for a phase transition (twin stars)

Newest constraints on mass-radius relation

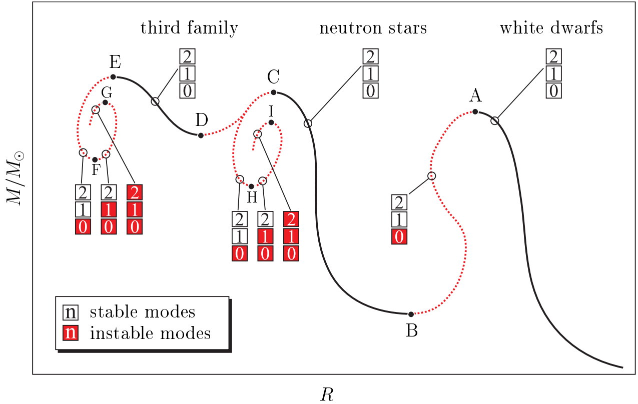


(Annala, Gorda, Katerini, Kurkela, Nättilä, Paschalidis, Vuorinen 2021)

- left plot: constraints on EOS from GW170817 and newest NICER data
- right plot: constraints on mass-radius relation
- dominant constraints: $\Lambda < 720$ ($R \leq 13.4$ km) at $1.4M_\odot$ and $R \geq 11.4$ km for $2M_\odot$

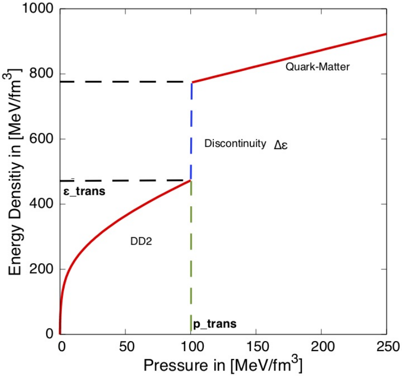
Third Family of Compact Stars

(Gerlach 1968; Kämpfer 1981; Glendenning, Kettner 2000; Schertler, C. Greiner, JSB, Thoma 2000)



- third solution to the TOV equations besides white dwarfs and neutron stars, solution is stable!
- generates stars more compact than neutron stars
- possible for any first order phase transition or rapid crossover!

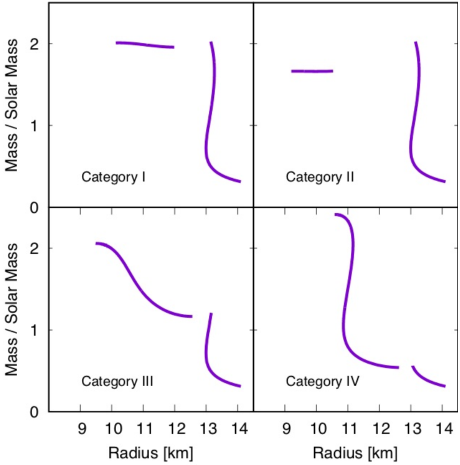
Equation of state with a phase transition



(Christian, Zacchi, JSB 2018)

- model phase transition by two parameters:
  transition pressure $p_{\rm trans}$ and jump in energy density $\Delta\epsilon$
- choose stiffest possible equation of state for the quark phase
  (speed of sound $c_s^2 = 1$)

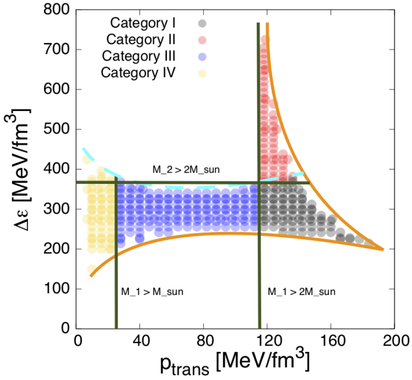
Classification of twin star solutions



(Christian, Zacchi, JSB 2018)

- four different classes of separate compact star branches
- category I: both branches reach $2M_\odot$
- category II: only first branch reaches $2M_\odot$
- category III: only second branch reaches $2M_\odot$ and first branch is above $1M_\odot$
- category IV: only second branch reaches $2M_\odot$ and first branch is below $1M_\odot$ (unobservable)

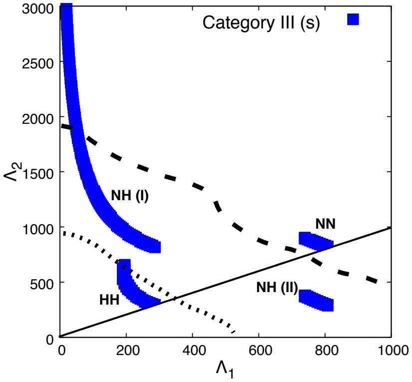
Classes of solution for twin stars



(Christian, Zacchi, JSB 2018)

- twin stars: two compact stars with the same mass but different radii
- twin star solutions exist for certain values of transition pressure $p_{\rm trans}$ and energy density jump $\Delta\epsilon$
- pulsar mass measurement of $M_{\rm max} > 2M_\odot$ can be fulfilled

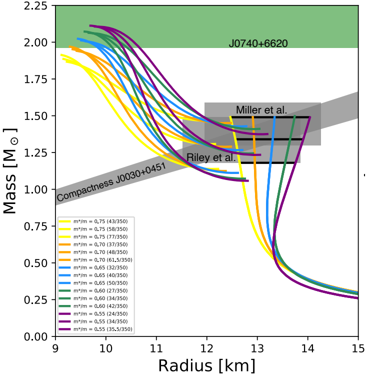
Unusual tidal deformabilities for twin stars



(Christian, Zacchi, JSB 2019)

- tidal deformabilities Λ_1 and Λ_2 of merging neutron stars
- normal neutron stars: $\Lambda_2 > \Lambda_1$ (the more massive neutron star has a smaller radius)
- twin stars: $\Lambda_1 > \Lambda_2$ (the more massive neutron star has a LARGER radius)

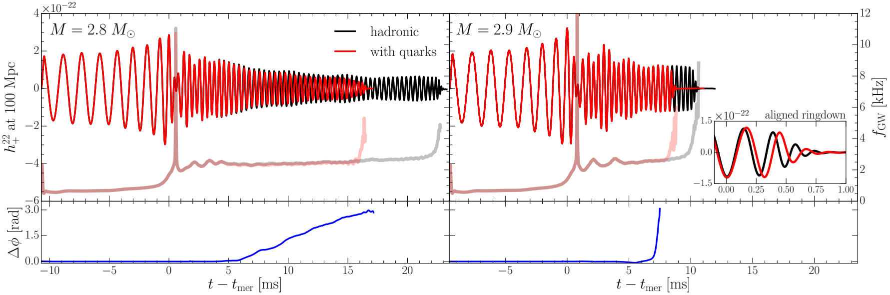
Radius constraints: limit on phase transition density



(Christian, JSB 2020)

- radius constraint on J0030+0451 from NICER: $R = 12.71^{+1.14}_{-1.19}$ km (Riley et al. 2019) and $R = 13.02^{+1.24}_{-1.06}$ km (Miller et al. 2019)
- strong phase transitions for $\epsilon < 1.7\epsilon_0$ are ruled out
- new constraints from J0740+6620 from 2021: work in progress!

Neutron-star merger and QCD phase transition

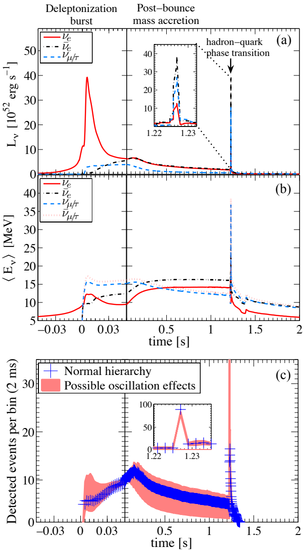


(Most, Papenfort, Dexheimer, Hanauske, Schramm, Stöcker, Rezzolla, 2019)

- First full GR calculation of neutron-star mergers with a phase transition to quark matter
- Produces a very hot and dense quark core
- Strong effects on the gravitational wave signal

(see also Bauswein, Bastian, Blaschke, Chatziioannou, Clark, Fischer, Oertel 2019)

Implications for Supernova – Neutrino-Signal!



- temporal profile of the emitted neutrinos out of the supernova
- pronounced second peak of anti-neutrinos from a phase transition (Sagert, Hempel, Pagliara, JSB, Fischer, Mezzacappa, Thielemann, Liebendörfer, 2009)
- peak location and height determined by the critical density and strength of the QCD phase transition
- update: compatible with pulsar masses, works for blue giants (Fischer, Bastian, Wu, Baklanov, Sorokina, Blinnikov, Typel, Klähn, Blaschke 2019)

Outline

Experimental Status of Hypernuclear Systems

NΛ: attractive $\rightarrow$ Λ-hypernuclei for $A = 3 - 209$
$U_\Lambda = -30$ MeV at $n = n_0$

NΣ: ${}^4_\Sigma$He hypernucleus bound by isospin forces
Σ^- atoms: potential is repulsive

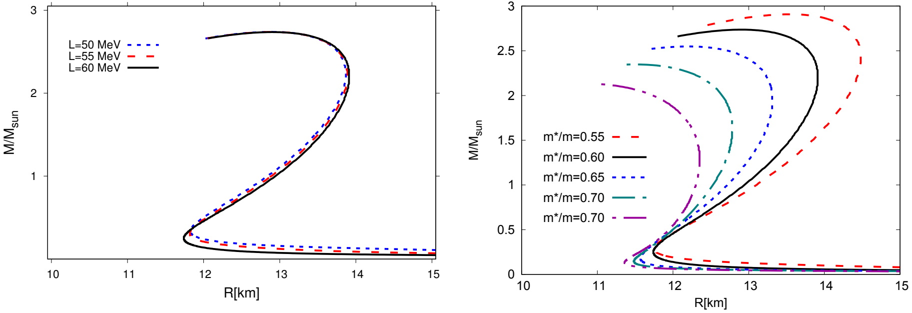
NΞ: attractive $\rightarrow$ 5 new Ξ hypernuclear events
$U_\Xi \leq -20$ MeV at $n = n_0$ (Friedmann and Gal 2021)
quasi-free production of Ξ: $U_\Xi = -18$ MeV

$\Lambda\Lambda$: attractive $\rightarrow$ one unambiguous $\Lambda\Lambda$ hypernucleus (Nagara event ${}^{\ 6}_{\Lambda\Lambda}$He)

YY: Y$= \Lambda, \Sigma, \Xi$ starting to be explored via femtoscopy!
(see e.g. Fabbietti, Sarti, Doce 2021)

hypernuclear programs: JLab, J-PARC, STAR, ALICE, FAIR: PANDA, HYPHI, CBM $\longrightarrow$ access to strange dibaryons, multi-hypernuclei!

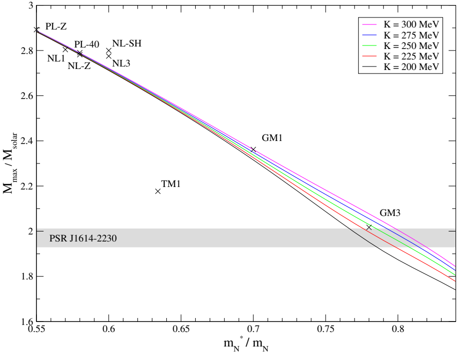
Mass-radius relation and nuclear parameters



(Hornick, Tolos, Zacchi, Christian, JSB 2018)

- relativistic mean field model fitted to nuclear matter and neutron matter
- different slope parameters L: small impact on mass-radius relation
- effective mass m^*: dominant impact on mass-radius relation

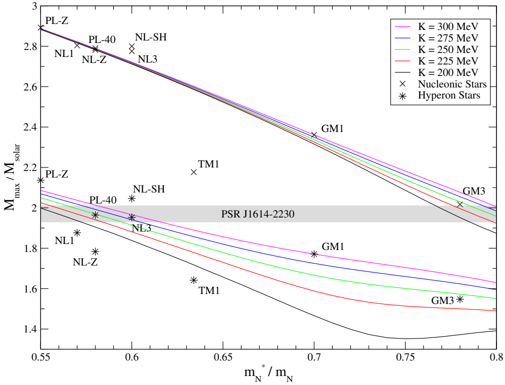
Maximum mass with nucleons only



(Weissenborn, Chatterjee, JSB 2011)

- maximum mass for different effective masses m^*/m and compressibility K
- change in maximum mass for different incompressibilities: at most $0.1 M_\odot$
- change in maximum mass for different m^*/m: up to $1 M_\odot$!
- values of $M > 2 M_\odot$ possible for reasonable values of m^*/m

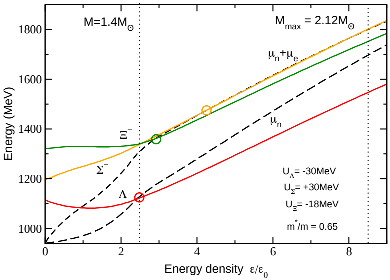
Maximum mass with hyperons: hyperon puzzle

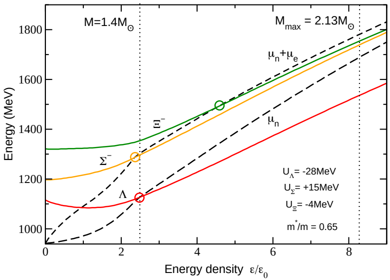


(Weissenborn, Chatterjee, JSB 2011)

- maximum mass for different effective masses of RMF parameter sets
- stars: parameter sets with standard SU(6) baryon couplings (no ϕ meson)
- values of $M > 2M_{\odot}$ possible with hyperons for stiff nuclear EoS

Onset of hyperons in neutron star matter

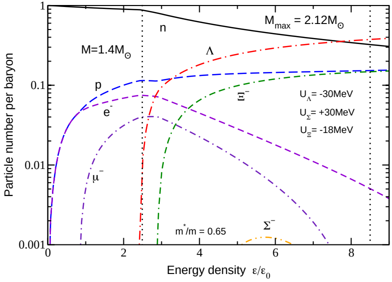




(JSB 2021)

- condition for appearance of hyperons: in-medium energy lower than the chemical potential
- left plot: hyperon potentials from hypernuclear data
- right plot: hyperon potentials from lattice data (HAL QCD collaboration 2019)
- onset of Σ^- and Ξ^- very different

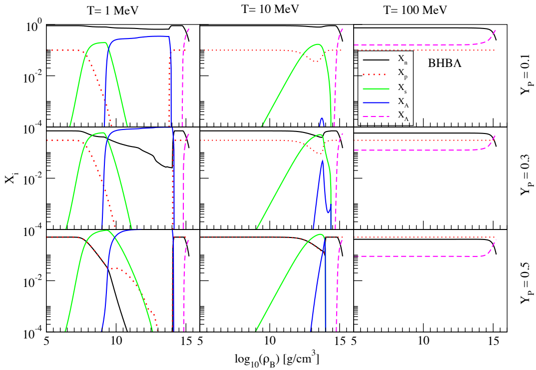
Hyperon composition in neutron star matter



(JSB 2021)

- left plot: with hypernuclear potentials
  right plot: with lattice potentials
- fraction of Σ^- hyperons widely different
- new input from heavy-ion data?

Hyperons in supernovae and neutron star merger



(Banik, Hempel, Bandyopadhyay 2014)

- equation of state at nonzero T and Y_p with hyperons
- for core-collapse supernovae and neutron star merger simulations
- high hyperon fractions seen at low electron fraction Y_e and high temperature

Outline

Observing Dense Matter in the Sky

Two different types of modification from high-density QCD matter

- equation of state, phase transition(s):
  - mass-radius relation (third family of compact stars?)
  - dynamics of core-collapse supernovae (second shock wave?)
  - proto-neutron star evolution (collapse to a black hole?)
  - neutron star merger (gravitational wave signal)
- transport properties:
  - bulk and shear viscosity (r-mode instability)
  - neutrino reactions (cooling of (proto-) neutron stars, neutron star merger)

X-ray satellites (NuSTAR, NICER, eRosita, ATHENA), optical (JWST), radio (SKA), gravitational wave (LIGO, Virgo, KAGRA, LIGO-India!) and neutrino detectors (Super-K, IceCube)