Neutron stars: Part 1
Introduction to NS structure

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Outline

Part 1

- Neutron star observations and structure
- Overview of neutrino cooling processes
- Composition and equation of state of neutron star matter – hadronic model

Part 2

- Neutrino emission processes luminosities
- Description of pions in dense hadronic matter
- Effects of the medium on neutrino emission processes
- Comparison of results for several cooling scenarios

History

Early theoretical suggestions

- 1932 – discovery of neutron by Chadwick
- 1931 – before neutron – anticipation of NSs by L. Landau
- 1933 – Baade and Zwicky APS meeting, Stanford coined the terms supernova and neutron star
- 1939 – GR calculation of NS hydrostatic equilibrium assuming free degenerate neutron gas
  $\Rightarrow M_{\max} \simeq 0.7\, M_{\odot}$
  [Oppenheimer Volkoff Phys.Rev. 85 (1939)]

> *...in February—March 1931, in Copenhagen, one year before the discovery of the neutron, Landau, Bohr and Rosenfeld discussed a not published paper written by Landau about a possible existence of very dense stars, where atomic nuclei form one giant nucleus.*

[Yakovlev et al. UFN 183 (2013)]

> *...we advance the view that a super-nova represents the transition of an ordinary star into a neutron star, consisting mainly of neutrons.*

[Baade and Zwicky PNAS USA 20 (1934)]

First discovery

- 1967 – observation by chance by Jocelyn Bell (A. Hewish's graduate student) of very stable radio pulses with $P \simeq 1.34\,\mathrm{s}$
- First label – LGM-1 (Little Green Men)
  - After more sources found – Pulsar (Pulsating Source of Radio)
- 1974 – Nobel Prize for the discovery of pulsars to Hewish (only)

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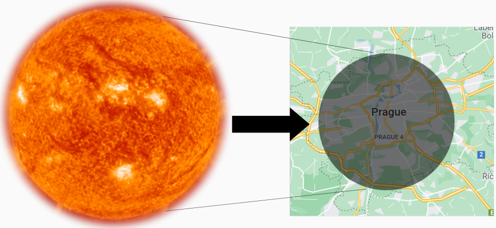
Current knowledge

Born in supernova explosions of $\sim$ $10 - 20\,M_\odot$ stars



Star with the size of a city

Properties summary

- Mass $M \sim (1-2)\,M_\odot$, $M_\odot \simeq 1.46\,\mathrm{km}$
  $G = c = 1$
- Radius $R \sim 10\,\mathrm{km}$
- Compactness $= 2GM/Rc^2 \simeq 0.3$
- Average density $\bar{\rho} \sim 10^{15}\mathrm{g/cm^3}$

Relativistic objects sustained by strong interactions

Pulsars

Lighthouse model

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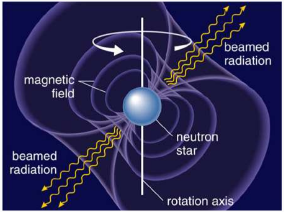


T. Gold Nature 218 (1968)

- Pulse period – period of NS rotation
- All pulsars are NSs, but not NS are seen as pulsars
- 3177 for tonight [ATNF Pulsar Catalogue]
- $\sim 5\%$ in binaries

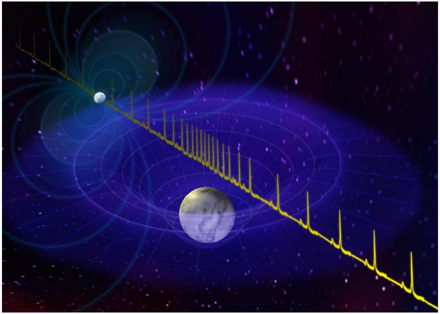
Most of the NSs are seen as pulsars

Isolated cooling NS

- ~ 40 objects with limits on the surface temperature

NS mass measurements

asfasdf



Shapiro delay

- Time delay of pulsar signal in a binary system
- Precise NS mass measurements

Most massive NSs

- $M = 2.14^{+0.10}_{-0.09}\, M_\odot$
  Cromartie et al. Nature Astronomy (2019)
- $M = 2.01 \pm 0.04\, M_\odot$
  Antoniadis et al. Science 340 (2013)
  (another method)

Much larger than canonical NS mass value
$M \simeq 1.4\, M_\odot$
Challenge for the EoS studies

Radius measurements

- Typical NS: same angular size as a proton from human length scale
- How to measure and constrain?
  see talks of D. Alvarez-Castillo this week

sorry...

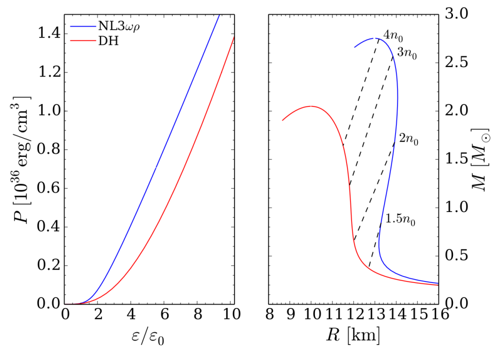
Global NS structure

Static NS hydrodynamic equilibrium – Tollman-Oppenheimer-Volkoff equation

Equation of state $P(E)$ as an input

$$\frac{dP(r)}{dr} = -\frac{Gm(r)E(r)}{r}\left[1+\frac{P(r)}{E(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{m(r)}\right]\left[1-2\frac{Gm(r)}{r}\right]^{-1},$$

$$\frac{dm(r)}{dr} = 4\pi r^2 E(r)$$



- Various central densities n_{cen} ↔ various masses and radii, $n_0 \simeq 0.16\,\mathrm{fm}^{-3}$ – nuclear saturation density
  $P(E) \rightarrow M - R$ diagram
- Each EoS corresponds to a maximum NS mass it can support from collapse into a black hole
- $dM/dn_{\mathrm{cen}} < 0 \Rightarrow$ hydrodynamically unstable

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Determination of age

Spindown age
Toy model:

Pulsar rotation frequency changes with time due to e/m emission and gravitational wave emission

$$\dot{\Omega} = -\frac{B^2 R^6}{6c^3 I}\sin^2\alpha\Omega^3 - G\frac{32\varepsilon^2}{5c^2}\Omega^5$$

α - angle between rotational and mag. field axes,

ε - eccentricity of a NS

$$\dot{\Omega} = \kappa\Omega^n, \quad P = \frac{2\pi}{\Omega} \Rightarrow$$

$$(n-1)\frac{\dot{P(t)}}{P(t)}t = 1 - \left(\frac{P_0}{P(t)}\right)^{n-1}, \frac{P_0}{P(t)} \ll 1$$

$n = \frac{\ddot{\Omega}\Omega}{\dot{\Omega}^2}$ – braking index measurable from observations

$$t = \frac{1}{n-1}\frac{P}{\dot{P}}$$

Historical SN

- Crab: 1054 AD
- Cassiopeia A: 1680 AD
- Tycho's SN: 1572 AD

Pulsar kicks

- NS distance from SN remnant
- NS velocity relative to the remnant
  ⇒ estimate of the kinematic age

NS cooling after birth

$$C_V \frac{\partial T}{\partial t} = -L_\gamma - \sum_{\text{reaction } r} \int dV\, Q_v^{(r)}$$

Thermal evolution of proto-NS

- $T_{\text{birth}} \sim (10-20)\,\text{MeV} \sim 10^2 T_9$, $T_9 = T/10^9 K \sim 0.1\,\text{MeV}$

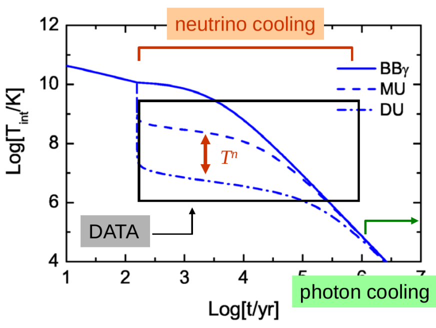
Neutrino transparency

- $t \gtrsim 20\,\text{s}$: $T \lesssim 1\,\text{MeV}$ – NS core transparent for neutrinos
- $t \sim 10^2$ yr – core cooling wave reaches the surface
- Cooling for $t \sim 10^2 - 10^5$yr is governed by neutrino emission from NS volume

Photon cooling

- Black-body radiation from the surface

$$L_\gamma^{\text{BB}} = 4\pi R^2 \sigma_{SB} T_{\text{ext}}^4 \simeq 7.8{\cdot}10^{43} T_{\text{ext},9}^{4} \frac{\text{erg}}{\text{s}}$$



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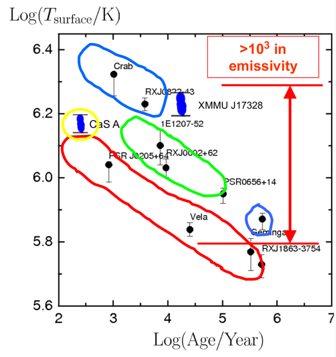
Problem of NS cooling

$$C_V \frac{\partial T}{\partial t} = -L_\gamma - \sum_{\text{reaction } r} \int dV Q_v^{(r)}$$



$\sim$ 40 cooling NSs
+ Cas A – young (1681±19 AD) X-ray source

Tasks for cooling modeling

- Different cooling rate: slow, intermediate and fast
- The data for $T_{\text{surface}}(t)$ should be described in a unified scenario

Main difference in scenarios –

assumed reason for such a large discrepancy in cooling rates

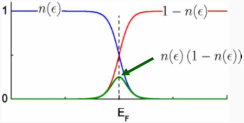
For instance – are the cooling NS masses close to each other?

Neutrino emission in the core

Strongly degenerate matter

- $T \ll \varepsilon_{F,npe}$
- Each line on Fermi surface ↔ T
- Neutrino energy and phase space

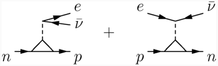
$$\omega_\nu \times \delta(\omega_\nu - \dots) 4\pi\omega_\nu^2 d\omega_\nu \sim T^3$$



One-nucleon processes

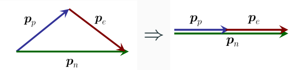
- Ordinary β-decay

"Direct URCA (DU)"



Operative only if the triangle inequality for $p_{\mathrm{F},n}$, $p_{\mathrm{F},p}$, $p_{\mathrm{F},e}$ is fulfilled

$p_{\mathrm{F,i}} = (3\pi^2 n_i)^{1/3} \Rightarrow$ threshold proton density



$$Q_\nu^{\mathrm{DU}} \sim 10^{27} T_9^6 \theta(n - n_{c,N}^{\mathrm{DU}}) \frac{\mathrm{erg}}{\mathrm{s}\cdot\mathrm{cm}^3}$$

Has threshold density $n_{c,N}^{\mathrm{DU}}$ strongly dependent on the NS composition

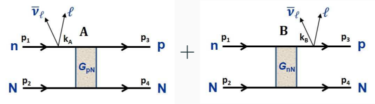
Two-nucleon processes

- Nucleon bremstrahlung (NB):

$$n + n \to n + n + \nu + \bar{\nu} + \dots$$

- Modified URCA process (MU, "MURCA"):

$$n + n \to n + p + e + \bar{\nu} + \dots$$



$$Q_\nu^{MU} \sim T^8$$

Strongly depends on the nucleon interaction G_{pN}, G_{nN}

Need to care about the detailed composition of the medium

NS composition

Cold NS

$T \sim 1\,\mathrm{MeV} \ll \varepsilon_{\mathrm{F},npe} \sim (60 - \mathrm{hundreds})\,\mathrm{MeV} \Rightarrow T \to 0$ for constructing the EoS

Charge neutrality

Any object bound by gravity should be electrically neutral

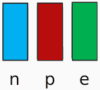
Local charge neutrality:

$$\sum_i Q_i n_i = 0$$

Should be loosened to global charge neutrality if the 1st order phase transition is present

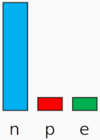
Symmetry energy

- Weak decays ⇒ not only neutrons
- Pauli principle + interactions: two Fermi surfaces are better than one
- Electrons are present



Energy minimization

- Ultrarelativistic electrons ⇒ rapidly rising energy
- Upper bound for n_e, n_p
- Neutronized matter with relatively small admixture of protons and electrons

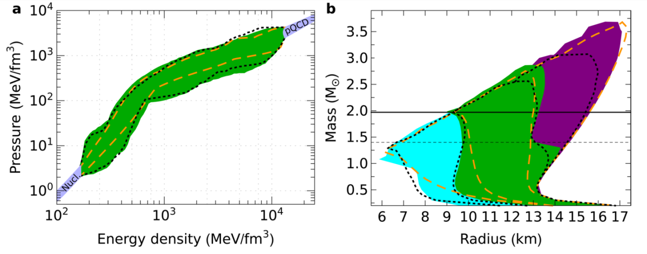


Particle fractions $n_{n,p,e,\ldots}$ are functions of the total density inside the NS

EoS vs. global NS properties

Model-independent consideration

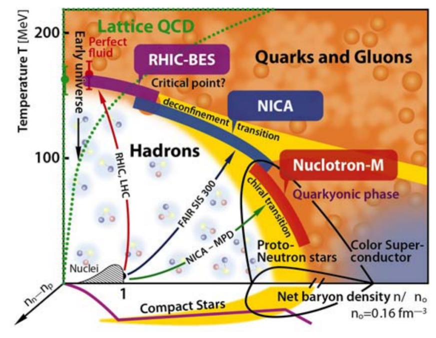
- Parameterize all possible EoS in terms of $P(n)$ or speed of sound $c_S^2(n) = \dfrac{dP}{dE}$ and impose well-established theoretical and observational constraints
- $\Rightarrow$ “cloud” of possible EoS behaviors



[Annala et al. Nature Physics 16 (2020)] and refs. therein

- No information on NS composition $\Rightarrow$ cannot study neutrino emission

Strong interactions



NICA White Paper Eur. Phys. J. A (2016) 52

Confinement problem

- No description of confinement from QCD lagrangian
  - For describing NSs we need an EoS based on hadronic degrees of freedom at least at low n
- Some regions of phase diagram can be explored experimentally ⇒ verification of models

QCD phase diagram

Baryonic matter –

condensed matter with strong interactions

- Baryon number density $n = (0 - 10)\, n_0$, $n_0 \simeq 0.16\,\mathrm{fm}^{-3}$
- Temperature $T = (0 - 200)\,\mathrm{MeV}$
- Isotopic asymmetry $\beta = (n_p - n_n)/n, 0 \leq \beta \leq 1$.

Many phase transitions (PT)

Hadronic degrees of freedom:

- nuclear liquid-gas PT
- pairing of nucleons
- Bose-condensation of π, K, ρ –mesons
- appearance of heavier baryonic states (hyperons, Δ-isobars)
  [this talk]

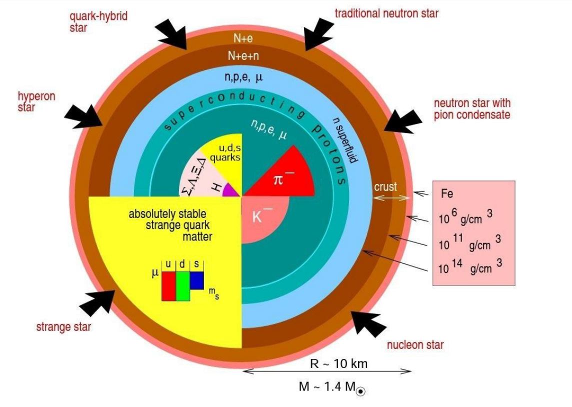
Including the quark substructure:

- chiral symmetry restoration
- hadron-quark transition
- color superconductivity
- possible existence of the QCD critical endpoint – RHIC Beam-Energy Scan, NICA, FAIR, J-PARC

NS structure

NS matter not accessible on Earth!

Many possibilities for internal structure



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F. Weber J.Phys.G27 (2001)

More or less known:

- Composition of crust
- EoS up to $2\,n_0$
- EoS for $n \gtrsim 40\,n_0$ not realized in NSs

This talk:

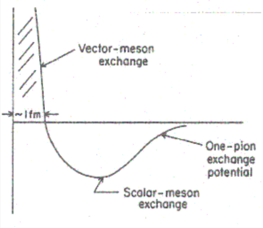
- Nucleonic stars
- Hyperonization

Many orders of magnitude in:

- density: $(1 - 10^{15}$ g/cm^3
-

Phenomenology near nuclear saturation density

Nuclear interaction

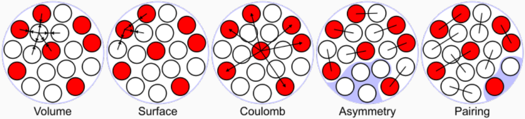


Several scales

- *vector mesons*
  $m_{\omega,\rho} \sim 800\,\mathrm{MeV},\ r \sim 0.2\,\mathrm{fm}$
- *correlated* 2π *exchange* $\sim$ scalar meson
  $m_\sigma \sim 200 - 600\,\mathrm{MeV}\ r \sim 0.3 - 1\,\mathrm{fm}$
- 1π *exchange*
  $m_\pi = 140\,\mathrm{MeV},\ r \sim 1.4\mathrm{fm}$

Saturation property: volume of nuclear droplet $\sim$ number of particles A

Liquid drop model



Semi-empirical Weizsaecker mass formula

$$E_B = a_V A - a_S A^{2/3} - a_C \frac{Z(Z-1)}{A^{1/3}} - a_A \frac{(N-Z)^2}{A} + \delta(N,Z)$$

Saturation properties

Infinite volume limit – *nuclear matter*

Energy per baryon

EoS up to $n \lesssim 2\,n_0$ parametrized in terms of experimentally available quantities

$$E_B/A \equiv \mathcal{E}(n) = \mathcal{E}_0 + \frac{K}{18}\epsilon^2 - \frac{K'}{162}\epsilon^3 + \cdots + \beta^2 \mathcal{E}_{\rm sym}(n)$$

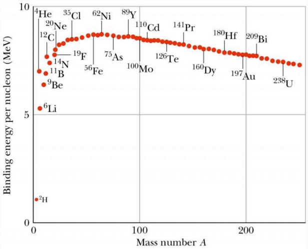
$$\epsilon = (n - n_0)/n_0, \quad \beta = (n_n - n_p)/n \quad n_0 \simeq 0.16\,\mathrm{fm}^{-3}$$

Isospin-symmetric matter (ISM) – $\beta = 0$:

Nuclear matter binding energy

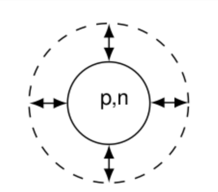
Global fit of nuclear masses:

$\mathcal{E}_0 = a_V \simeq -16\,\mathrm{MeV}$



Nuclear incompressibility

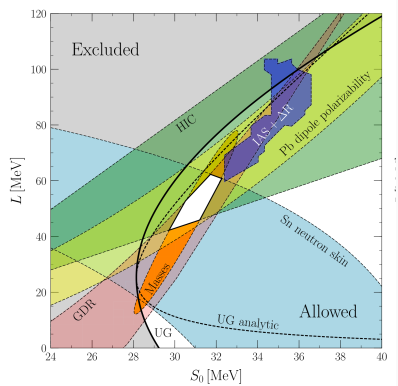
Giant monopole resonance in nuclei



$K \simeq (240 \pm 20)\,\mathrm{MeV}$

Nuclear symmetry energy

$$\mathcal{E}_{\rm sym}(n) = \mathcal{E} - \mathcal{E}(\beta = 0) \simeq \beta^2 \left(J + \frac{L}{3}\epsilon + \dots \right)$$



[Tews et. al. ApJ 848 (2017)]

Experimental constraints

- Structure of nuclei
- Heavy-ion collisions of asymmetric nuclei
- Comparison with unitary Fermi-gas – lower bound on symmetry energy density behavior

β–equilibrium in NS matter

- $n \leftrightarrow p + e^- + \bar{\nu}$ – escaping
- Equilibrium: $\mu_e = \mu_n - \mu_p$, $\mu_i = \dfrac{\partial \mathcal{E}}{\partial n_i}$

$$\mu_e \simeq p_{\mathrm{F}e} = 4\mathcal{E}_{\rm sym}(n)(1 - 2\frac{n_p}{n})$$

Crucial for determining the NS composition

Approaches to NS EoS

Microscopic

- Based on baryon-baryon potential + a many-body method
- Sometimes controllable theoretical uncertainties
- Robust in some density range, but large uncertainties outside

Phenomenological

- Relatively simple models with parameters fitted to describe the experimental data / robust theoretical results
- Extrapolatable and causal for all densities - important for NSs and HICs

from A.B. Migdal “Searching for the truth” (“Поиски истины”), in Russian

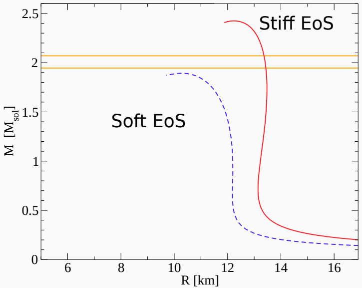
Contradicting constraints

Maximum NS mass constraint

Any EoS corresponds to some $M_{\max}$

$$M_{\max} > 2.01 \pm 0.04\, M_{\odot}$$

$$M_{\max} > 2.14^{+0.10}_{-0.09}\, M_{\odot}$$



$M_{\max} \gtrsim 2\, M_{\odot}$ – requires a stiff EoS

Must be reconciled within a single approach

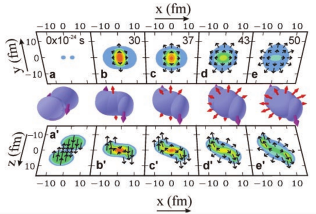
Stiff EoS ⇒ large NS radii

Possible contradiction with GW observations

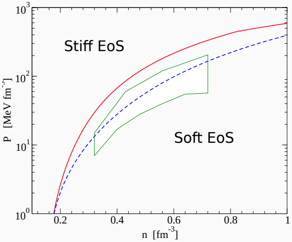
[talk of D. Alvarez-Castillo]

Particles flows in ion collisions

Comressed ISM (N = Z) – can be extracted from heavy-ion experiments



Constraint for the pressure $P(n)$ at $2\, n_0 \lesssim n \lesssim 4.5\, n_0$



Danielewicz et al. Science 298 (2002)

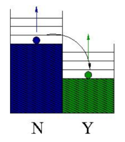
Requires a soft EoS in ISM

Apparent conflict with large $M_{\max}$

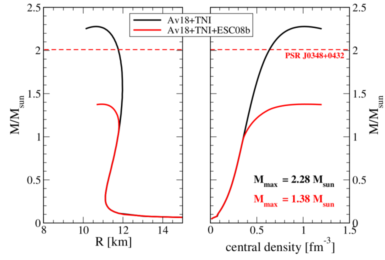
Hyperon puzzle I

Hyperon in β-equilibrium matter

- Lightest strange baryons: $\Lambda^0(1116), \Sigma^{\pm,0}(1193), \Xi^{-,0}(1318)$
- Can appear by weak processes at $T = 0$ in long-living NS matter (not in dense ISM)
- Do not appear without taking their interaction with the medium into account
  Ambartsumyan Saakyan Soviet Astronomy 4 (1960)



- Data on hypernuclei: attractive hyperon interactions with the medium
  - $\Rightarrow$ at $n \gtrsim (2-3)\, n_0$ – nucleons partly converted to Λ, Σ, Ξ
    Glendenning ApJ (1985) “Neutron stars are giant hypernuclei?”
    - Strong softening of the EoS
    Not a problem before $2\, M_\odot$ NSs, but...
  - For standard EoSs leads to M_max decreasing below observable limits



[Bombaci JPS Conf.Proc.17 (2017)]

Possible solutions

- Very stiff EoS without hyperons – contradicts the flow constraint
- Deconfinement phase transition before the hyperon appearance
  Needs very stiff EoS of quark matter ⇒ reconfinement problem
  for purely thermodynamic description
- Microscopic approaches – N-hyperon and hyperon-hyperon three-body forces
- Withing phenomenological models – e.g. accounting for in-medium modification of hadron properties

Hyperon puzzle II

Hyperons can affect NS cooling

Direct URCA-type reactions with hyperons

Weak reactions with strangeness change

Some of them do not include neutron, e.g.

- $\Lambda \rightleftarrows p + e + \bar{\nu}$
- $\Xi^0 \rightleftarrows p + e + \bar{\nu}$

$\Rightarrow$ (almost) no “triangle inequality” threshold density

Efficient reactions become operative but less than DU by factor ~ 0.01

Typical situation with an efficient reaction

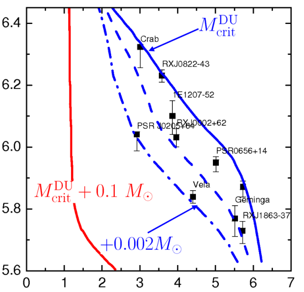
Cooling curves are:

- Almost insensitive to NS mass before

$$n_{\text{cen}} > n^{DU}_{\text{crit}} \leftrightarrow M^{\text{DU}}_{\text{crit}}$$

in some approaches – see part II

- $M \gtrsim M^{\text{DU}}_{\text{crit}}$ – superfast cooling
- Seemingly all observed cooling NS have almost the same masses...
- But they are different; is this inevitable?



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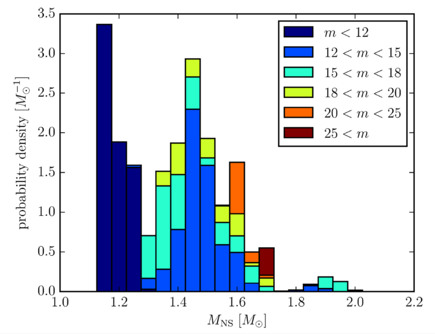


Phenomenological example: Relativistic mean-field (RMF) models

Degrees of freedom

"Quantum" field theory-based phenomenology of hadronic degrees of freedom

Minimum Yukawa coupling of mesons to baryons $\mathcal{L}_{\text{int}} = g\sigma\bar{\Psi}\Psi + \ldots$

Scalar meson $\sigma \leftrightarrow$ attraction, vector mesons $\omega, \rho, \phi \leftrightarrow$ repulsion

Mean-field approximation

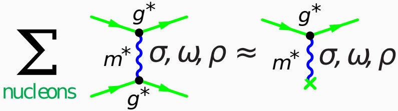
Mesons

- Baryon sources $\Rightarrow$ non-zero mean-field solutions for the fields $\sigma,\ \omega,\ \rho^0,\ \phi$
- Effect of quantum fluctuations and medium – in-medium parameters of the interactions
- Analogous to order parameters in Ginzburg-Landau theory

Pseudoscalar pion mean-field $\pi = 0$

if no charged pion condensation

Baryons



Quasiparticle approximation – baryons in a self-consistent mean field

- Coupling constants g^* – from nuclear phenomenology around $n \simeq n_0 \leftrightarrow$ Landau Fermi-liquid theory

Succesful applications

Even the simplest non-linear Walecka model

[Boguta Bodmer NPA 292 (1977)] (see also talk of R.N. del Alamo 1st week)

– acceptable description of nuclear matter and finite nuclei

Hyperonization in simplest models → $M_{\max} <$ observable limits

Hadron masses and couplings in medium

Chiral symmetry

Spontaneous chiral symmetry breaking:

constituent quark masses and hadron masses $\sim \langle \bar{q}q \rangle$ –
chiral condensate as an order parameter for the chiral phase transition

Hadron mass change in the medium $\rightleftarrows$ partial chiral symmetry restoration.

Theoretical hints

- QCD sum rules: for all hadrons $m^*(n)/m \simeq 1 - 0.18\,(n/n_0)$

Hatsuda, Lee Phys. Rev. C 46 (1992)

- Brown-Rho scaling conjecture:

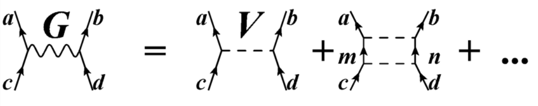
$$m_N^*/m_N \simeq m_\omega^*/m_\omega \simeq m_\rho^*/m_\rho \simeq \ldots$$

Brown, Rho Phys.Rev.Lett 66 (1991)

Lots of controversy, but allows to constrain phenomenological models

Modification of coupling constants

Nucleon interactions *in the medium* – resummation of ladder diagrams



Can be expressed in RMF language as effective couplings g^* in the medium

Generalized RMF models

E. E. Kolomeitsev and D. N. Voskresensky NPA 759 (2005) 373

Hadron mass change in the medium

Scalar field σ – analogous to the chiral condensate $\langle \bar{q}q \rangle$

$\Rightarrow$ all hadron masses depend on σ

$$m_N \to m_N^*(\sigma) \equiv m_N \Phi_N(\sigma)$$
$$m_\omega \to m_\omega^*(\sigma) \equiv m_\omega \Phi_\omega(\sigma)$$
$$\ldots$$

Effectively takes into account partial chiral symmetry restoration

In-medium coupling constants

Scalar field dependence can be introduced into the Lagrangian directly

Minimization of energy $\to \sigma = \sigma(n)$

$$g_{\sigma N} \to g_{\sigma N}^*(\sigma) \equiv g_{\sigma N} \chi_\sigma(\sigma),$$
$$g_{\omega N} \to g_{\omega N}^*(\sigma) \equiv g_{\omega N} \chi_\omega(\sigma),$$
$$\ldots$$

Explicit thermodynamic consistency

KVOR model (Kolomeitsev Voskresensky $\omega - \rho$)

- Nice model passing many constraints from nuclear physics and NS observations
- ......without hyperons
- With hyperons – $M_{\max}$ violated

Generalized RMF models with σ–dependence

E. E. Kolomeitsev, D.N. Voskresensky, Nucl.Phys. A 759 (2005)

K. A. M, Kolometsev, Voskesensky, Phys. Lett. B 748 (2015), Nucl.Phys. A961 (2017)

$$\mathcal{L} = \mathcal{L}_{\text{bar}} + \mathcal{L}_{\text{mes}} + \mathcal{L}_l$$

Барионы $\{b\} = (N, \Lambda, \Sigma^{\pm,0}, \Xi^{-,0})$

$$\mathcal{L}_{\text{bar}} = \sum_{i=b\cup r} (\bar{\Psi}_i \left(iD_\mu^{(i)}\gamma^\mu - m_i \Phi_i(\sigma) \right) \Psi_i,$$

$$D_\mu^{(i)} = \partial_\mu + ig_{\omega i}\chi_{\omega i}(\sigma)\omega_\mu + ig_{\rho i}\chi_{\rho i}(\sigma)\vec{t}\vec{\rho}_\mu + ig_{\phi i}\chi_{\phi i}(\sigma)\phi_\mu,$$

Coupling to $\vec{\rho}_\mu$ determines the symmetry energy

Мезоны $\{m\} = (\sigma, \omega, \rho, \phi)$

$$\mathcal{L}_{\text{mes}} = \frac{\partial_\mu\sigma\partial^\mu\sigma}{2} - \frac{m_\sigma^2\Phi_\sigma^2(\sigma)\sigma^2}{2} - U(\sigma) + \frac{m_\omega^2\Phi_\omega^2(\sigma)\omega_\mu\omega^\mu}{2} - \frac{\omega_{\mu\nu}\omega^{\mu\nu}}{4} + \frac{m_\rho^2\Phi_\rho^2(\sigma)\vec{\rho}_\mu\vec{\rho}^\mu}{2} -$$

$$-\frac{\rho_{\mu\nu}\rho^{\mu\nu}}{4} + \frac{m_\phi^2\Phi_\phi^2(\sigma)\phi_\mu\phi^\mu}{2} - \frac{\phi_{\mu\nu}\phi^{\mu\nu}}{4}, \quad U(\sigma) = b\sigma^3/3 + c\sigma^4/4$$

$$\omega_{\mu\nu} = \partial_\nu\omega_\mu - \partial_\mu\omega_\nu, \quad \vec{\rho}_{\mu\nu} = \partial_\nu\vec{\rho}_\mu - \partial_\mu\vec{\rho}_\nu, \quad \phi_{\mu\nu} = \partial_\nu\phi_\mu - \partial_\mu\phi_\nu$$

Vector meson ϕ with hidden strangeness ($\bar{s}s$): additional repulsion between hyperons

leptons $\{l\} = (e, \mu)$ ← **in the beta-equilibrium model**

$$\mathcal{L}_l = \sum_l \bar{\psi}_l(i\partial_\mu\gamma^\mu - m_l)\psi_l.$$

Equation of state

Energy density at $T = 0$

$$E = \frac{m_N^4 f^2}{2C_\sigma^2}\eta_\sigma(f) + U(f) + \frac{C_\omega^2}{2m_N^2\eta_\omega(f)}\Big(\sum_b x_{\omega b} n_b\Big)^2 + \frac{C_\rho^2}{2m_N^2\eta_\rho(f)}\Big(\sum_b x_{\rho b} t_{3b} n_b\Big)^2 +$$

$$+\frac{C_\omega^2}{2m_N^2\eta_\phi(f)}\frac{m_\omega^2}{m_\phi^2}\Big(\sum_H x_{\phi H} n_H\Big)^2 + \sum_b \int\limits_0^{p_{\mathrm{F},b}} \frac{p^2\,dp}{\pi^2}\sqrt{p^2 + m_b^2\Phi_b^2(f)} + E_l,$$

$$E_l = \sum_{l=e,\mu}\int\limits_0^{p_{\mathrm{F},l}} \frac{p^2\,dp}{\pi^2}\sqrt{p^2+m_l^2}\,, \quad C_i = \frac{g_{iN} m_N}{m_i}, \quad i = \sigma, \omega, \rho, \quad f = \frac{g_{\sigma N}\chi_{\sigma N}(\sigma)}{m_N}\sigma$$

Equilibrium conditions

$$\underbrace{\frac{\partial E}{\partial f} = 0}_{\text{scalar field e.o.m}}\,, \underbrace{\sum_{i=b\cup l} Q_i n_i = 0}_{\text{electroneutrality}}, \underbrace{\mu_b = \mu_n - Q_b\mu_e}_{\beta\text{-equilibrium}}$$

Meson-baryon couplings

$x_{mb} = g_{mb}/g_{mN}$:

- Symmetries of quark models of hadrons
- Hyeron potentials in nuclei

Meson masses and couplings

Enter only in combinations C_i and

$$\eta_m(f) = \frac{\Phi_m^2(f)}{\chi_m^2(f)}$$

In infinite matter g_{mb}^* and m_m^* can't be determined independently

C_i – from saturation properties

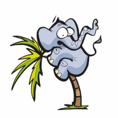
von Neuman elephant?

E. Fermi: "...my friend Johnny von Neumann used to say, with four parameters I can fit an elephant, and with five I can make him wiggle his trunk." [F. Dyson Nature (2004)]

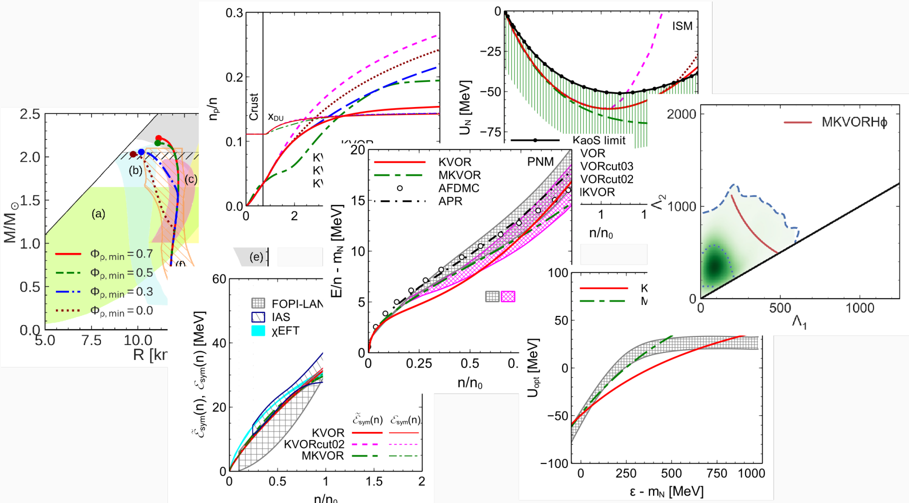
Many constraints in a continuous interval, some contradicting – need of this much flexibility

The elephant...

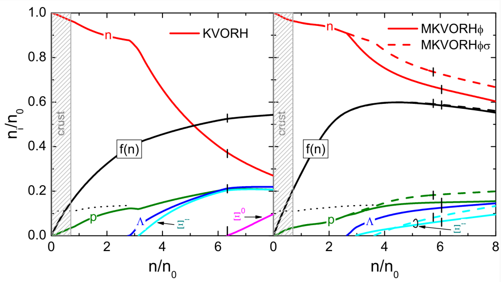
asdasd

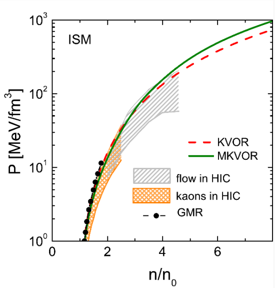


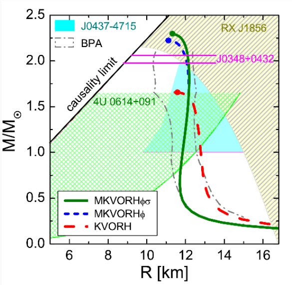
- ...describes a lot of constraints...
- even including more possible PTs (Δ-resonances, ρ^- condensation)
  [K.A.M, Kolometsev, Voskesensky, Nucl.Phys.A(2016, 2017, 2018)]



Resulting NS properties







[K.A.M., E.E. Kolomeitsev, D.N. Voskresensky, Physics Letters B 748 (2015)]

Results

Hyperons are there at $n \gtrsim (2-3)\, n_0$

- MKVOR*HΔϕ:
  $M_{\rm max} = 2.22\, M_\odot$ with hyperons
- Flow constraint satisfied
- + many other constraints
  [K.A.M., E.E. Kolomeitsev, D.N.Voskresensky Nucl.Phys.A 950 (2015)]

No NS-mass hyperon puzzle in this kind of models

End of part 1

Summary

- Neutron stars are natural laboratories for studying matter under extreme conditions
- NS surface temperature evolution is governed by neutrino emission from the whole volume
- Neutrino luminosity depends on the composition of the strongly interacting dense NS core

- New constraints ⇒ better models of strong interactions inside NS core
Possible phase transitions:
- new puzzles for EoS studies
- new channels of neutrino emission

Part 2

Contribution to the NS cooling rates – hyperon puzzle II?