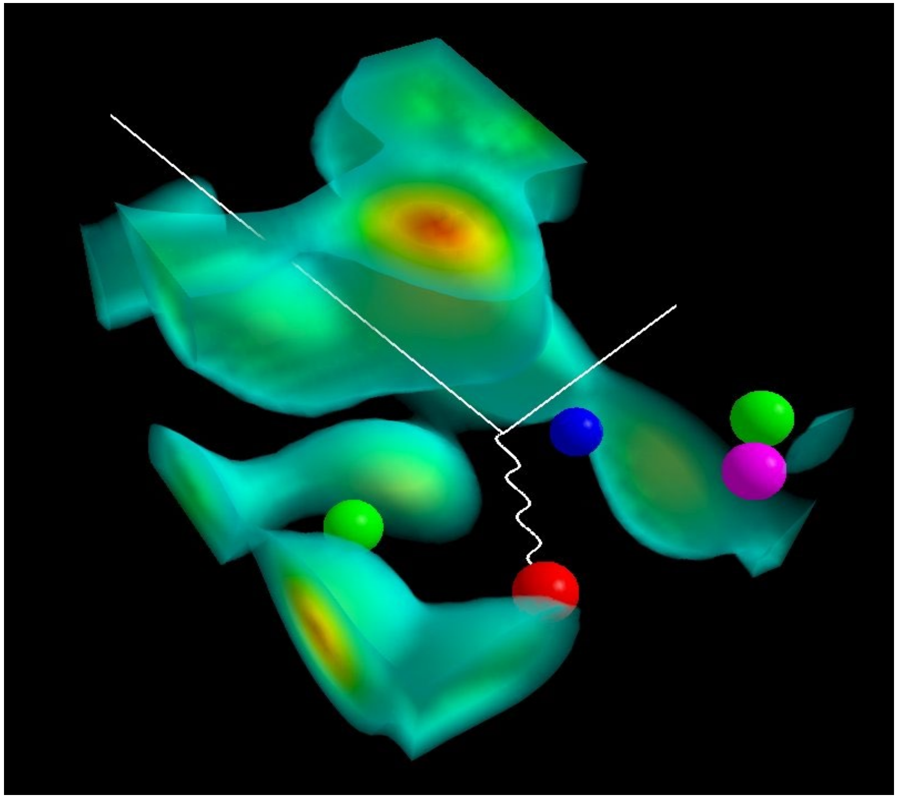
From Quarks to Nuclei and Neutron Stars



Anthony W. Thomas

QCHSC 2024

Cairns : August 21st 2024

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SPECIAL RESEARCH CENTRE FOR THE SUBATOMIC STRUCTURE OF MATTER

Outline

I. Why the quark-meson coupling (QMC) model?
   - vital role of changing baryon structure in-medium

II. Application of EDF derived from QMC to nuclear properties across the periodic table

III. Neutron stars: role of hyperons

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Insights into nuclear structure

– what is the atomic nucleus?

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Quark Structure matters/doesn't matter

- **Nuclear femtography: the science of mapping the quark and gluon structure of *atomic nuclei* is just beginning (EIC motivation)**

- **"Considering quarks is in contrast to our modern understanding of nuclear physics… the basic degrees of freedom of QCD (quarks and gluons) have to be considered only at higher energies. The *energies relevant for nuclear physics are only a few* MeV"**

What do we know?

- Since 1970s: Dispersion relations → intermediate range NN attraction is a strong Lorentz scalar

- In relativistic treatments (RHF, RBHF, QHD…) this leads to mean scalar field on a nucleon ~300 to 500 MeV!!

- *This is not small* – up to half the nucleon mass
  - death of "wrong energy scale" arguments

- Largely cancelled by large vector mean field BUT these have totally different dynamics: ω^0 just shifts energies, σ seriously modifies internal hadron dynamics

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Self-consistent solution for confined quarks in a hadron in nuclear matter

Guichon 1988

$$[i\gamma^\mu \partial_\mu - (m_q - g_\sigma{}^q \bar{\sigma}) - \gamma^0 g_\omega{}^q \bar{\omega}]\psi = 0$$

Source of σ changes: $\int_{Bag} d\vec{r}\,\bar{\psi}(\vec{r})\psi(\vec{r})$

SELF-CONSISTENCY

and hence mean scalar field changes…

and hence quark wave function changes….

THIS PROVIDES A NATURAL SATURATION MECHANISM (VERY EFFICIENT BECAUSE QUARKS ARE LIGHT)

source is suppressed as mean scalar field increases (i.e. as density increases)

Quark-Meson Coupling Model (QMC):
Role of the Scalar Polarizability of the Nucleon

The response of the nucleon internal structure to the scalar field is of great interest… and importance

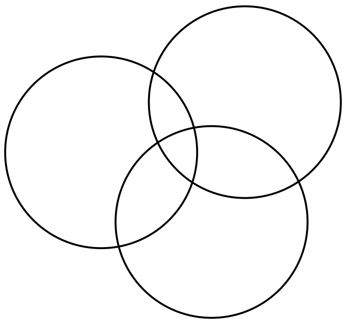
$$M^*(\vec{r}) = M - g_\sigma \sigma(\vec{r}) + \frac{d}{2}\left(g_\sigma \sigma(\vec{r})\right)^2$$

Non-linear dependence through the scalar polarizability
d ~ 0.22 R in original QMC (MIT bag)

Indeed, in nuclear matter at mean-field level, this is the ONLY place the response of the internal structure of the nucleon enters.

Summary : Scalar Polarizability

- Consequence of polarizability in atomic physics is many-body forces:



$$V = V_{12} + V_{23} + V_{13} + V_{123}$$

  – same is true in nuclear physics

- Three-body forces (for ALL baryons: NNN, HNN, HHN…) generated with NO new parameters

  – critical in neutron stars

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DARK MATTER

Guichon & Thomas, Phys. Rev. Lett. 93 (2004) 132502

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Application to nuclear structure

Initial Derivation of Density Dependent Effective Force

Physical origin of density dependent forces of Skyrme type within the quark meson coupling model

P.A.M. Guichon [a,*], H.H. Matevosyan [b,c], N. Sandulescu [a,d,e], A.W. Thomas [b]

Nuclear Physics A 772 (2006) 1–19

- **Start with classical theory of MIT-bag nucleons with structure modified in medium to give M_{eff} (σ).**
- **Quantise nucleon motion (non-relativistic), expand in powers of derivatives**
- **Derive equivalent, local energy density functional:**

$$\langle H(\vec{r}\,)\rangle = \rho M + \frac{\tau}{2M} + \mathcal{H}_0 + \mathcal{H}_3 + \mathcal{H}_{\mathrm{eff}} + \mathcal{H}_{\mathrm{fin}} + \mathcal{H}_{\mathrm{so}}$$

Derivation of EDF (cont.)

$$\mathcal{H}_0+\mathcal{H}_3=\rho^2\left[\frac{-3G_\rho}{32}+\boxed{\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}}-\frac{G_\sigma}{2(1+d\rho G_\sigma)}+\frac{3G_\omega}{8}\right]$$
$$+(\rho_n-\rho_p)^2\left[\frac{5G_\rho}{32}+\boxed{\frac{G_\sigma}{8(1+d\rho G_\sigma)^3}}-\frac{G_\omega}{8}\right],$$

$$\mathcal{H}_{\text{eff}}=\left[\left(\frac{G_\rho}{8m_\rho{}^2}-\frac{G_\sigma}{2m_\sigma{}^2}+\frac{G_\omega}{2m_\omega{}^2}+\frac{G_\sigma}{4M_N{}^2}\right)\rho_n+\left(\frac{G_\rho}{4m_\rho^2}+\frac{G_\sigma}{2M_N^2}\right)\rho_p\right]\tau_n$$
$$+p\leftrightarrow n,$$

$$\mathcal{H}_{\text{fin}}=\left[\left(\frac{3G_\rho}{32m_\rho{}^2}-\frac{3G_\sigma}{8m_\sigma{}^2}+\frac{3G_\omega}{8m_\omega{}^2}-\frac{G_\sigma}{8M_N{}^2}\right)\rho_n\right.$$
$$\left.+\left(\frac{-3G_\rho}{16m_\rho{}^2}-\frac{G_\sigma}{2m_\sigma{}^2}+\frac{G_\omega}{2m_\omega{}^2}-\frac{G_\sigma}{4M_N{}^2}\right)\rho_p\right]\nabla^2(\rho_n)+p\leftrightarrow n,$$

$$\mathcal{H}_{\text{so}}=\nabla\cdot J_n\left[\left(\frac{-3G_\sigma}{8M_N{}^2}-\frac{3G_\omega(-1+2\mu_s)}{8M_N{}^2}-\frac{3G_\rho(-1+2\mu_v)}{32M_N{}^2}\right)\rho_n\right.$$
$$\left.+\left(\frac{-G_\sigma}{4M_N{}^2}+\frac{G_\omega(1-2\mu_s)}{4M_N{}^2}\right)\rho_p\right]+p\leftrightarrow n.$$

Spin-orbit force predicted!

Note the totally new, subtle density dependence

Latest Nuclear Structure Results

Includes some unpublished results for QMC π-III from

PhD thesis of Kay Martinez

- now at Silliman University (Philippines)
(publications in preparation)

- in collaboration with Pierre Guichon and Jirina Stone

QMC π-II and III incorporate a much more accurate evaluation of H^{σ}

QMC π-III

- **Just 5 parameters***: m_σ , quark couplings to σ, ω and ρ mesons and λ_3 - the strength of σ^3 term

- **Tensor term included:**

$$H^J_{\sigma,\omega,\rho} = \left(\frac{G_\sigma(1-dv_0)^2}{4m_\sigma^2} - \frac{G_\omega}{4m_\omega^2}\right)\sum_m \vec{J}_m^2 - \frac{G_\rho}{4m_\rho^2}\sum_{m,m'} S_{m,m'}\vec{J}_m \cdot \vec{J}_{m'},$$

and

$$H_S^J = -\frac{G_\sigma - G_\omega}{16M^2}\sum_m \vec{J}_m^2 + \frac{G_\rho}{16M^2}\sum_{mm'} S_{m,m'}\vec{J}_m \cdot \vec{J}_{m'}.$$

with

$$\vec{J}_m = i\sum_{i\in F_m}\sum_{\sigma\sigma'}\vec{\sigma}_{\sigma'\sigma} \times [\vec{\nabla}\phi^i(\vec{r},\sigma,m)]\phi^{i*}(\vec{r},\sigma',m), \quad \vec{J} = \vec{J}_p + \vec{J}_n,$$

- **Pairing interaction (simple BCS) derived in the model**

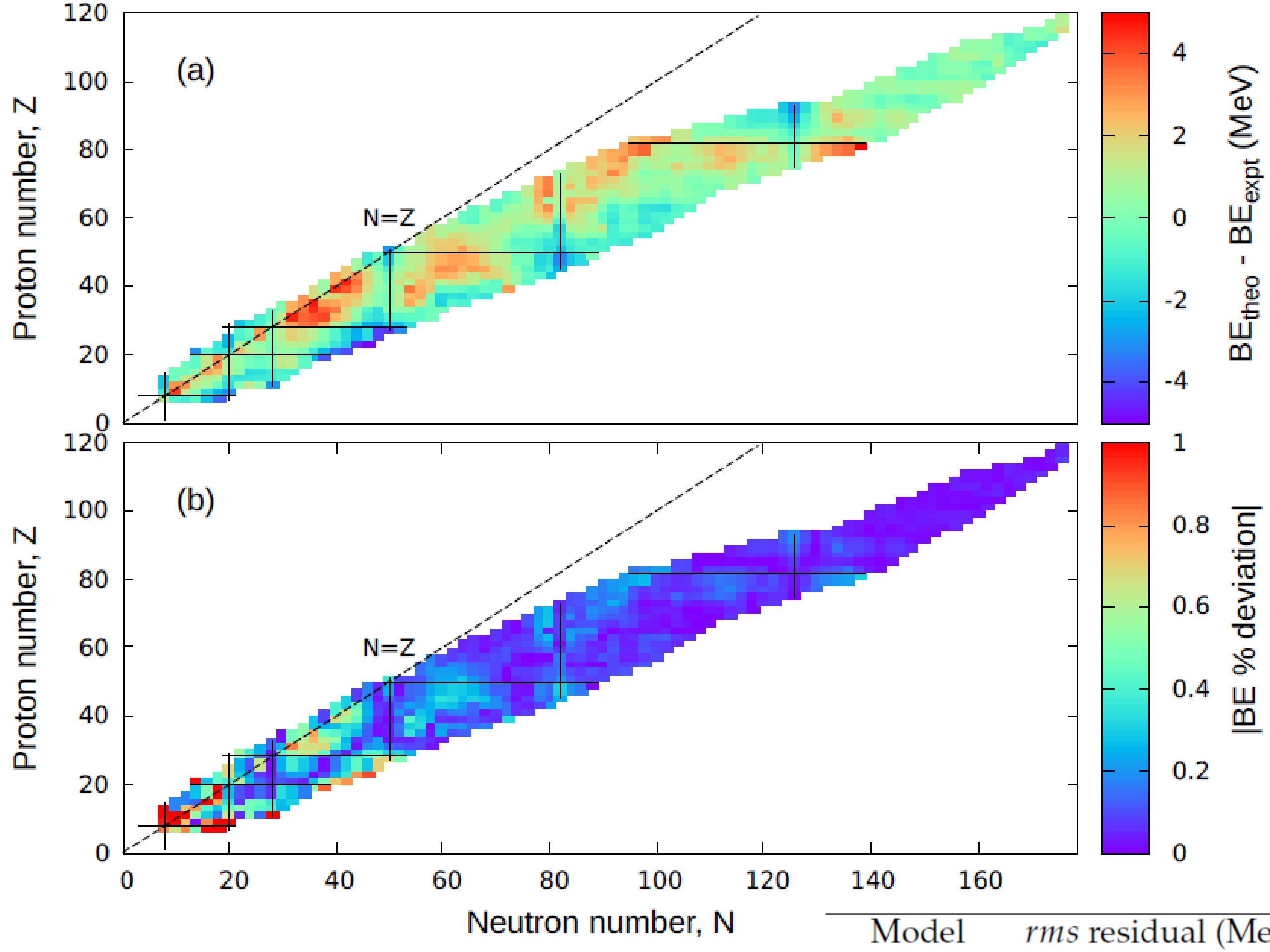
$$V^{\rm QMC}_{\rm pair} = -\left(\frac{G_\sigma}{1 + d'G_\sigma\rho(\vec{r})} - G_\omega - \frac{G_\rho}{4}\right)\delta(\vec{r} - \vec{r}\,')$$

$$d' = d + \tfrac{1}{3}G_\sigma\lambda_3.$$

*cf. More than 15 in FRDM and typical Skyrme forces

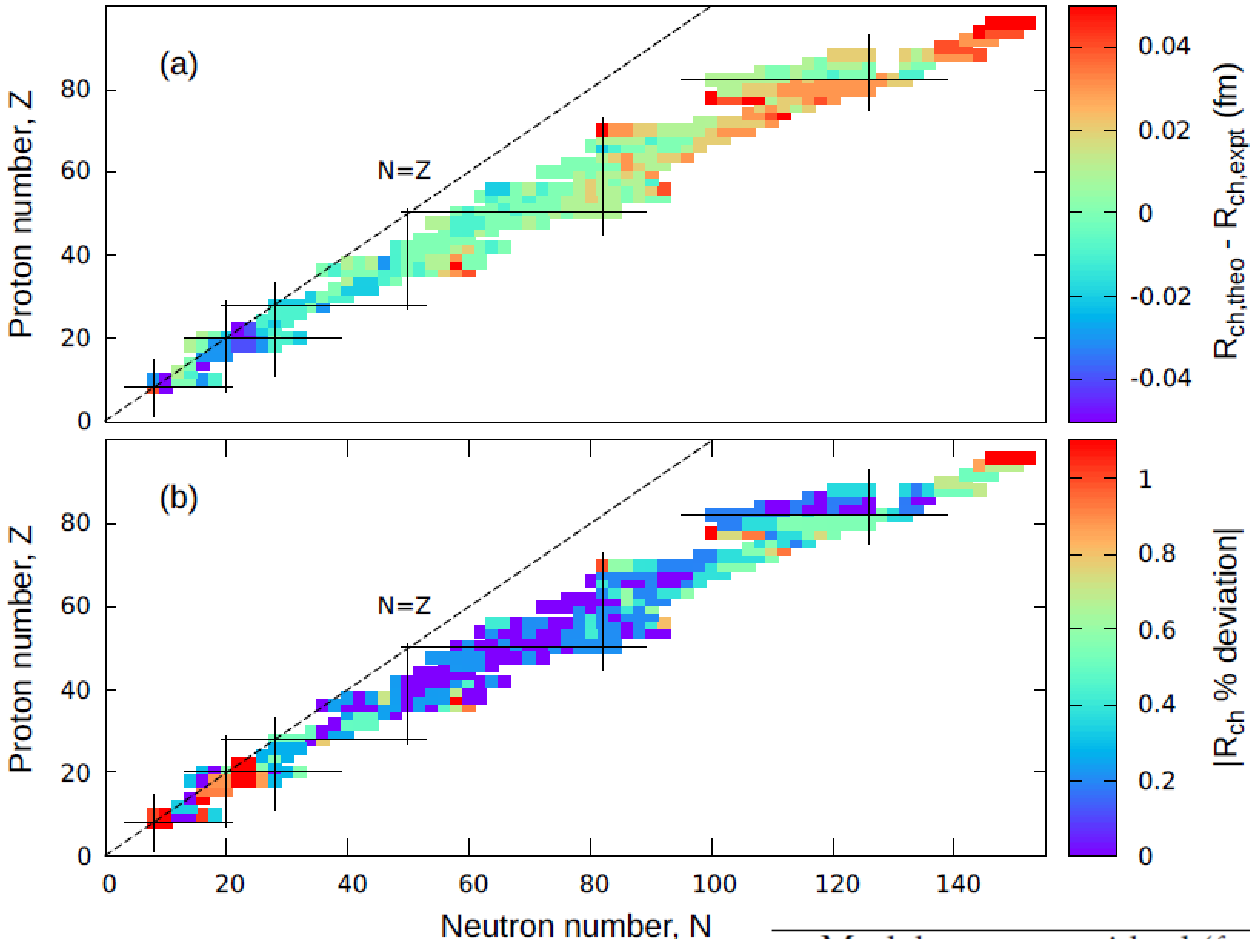
Binding Energies – 820 Known Even-Even Nuclei

2020



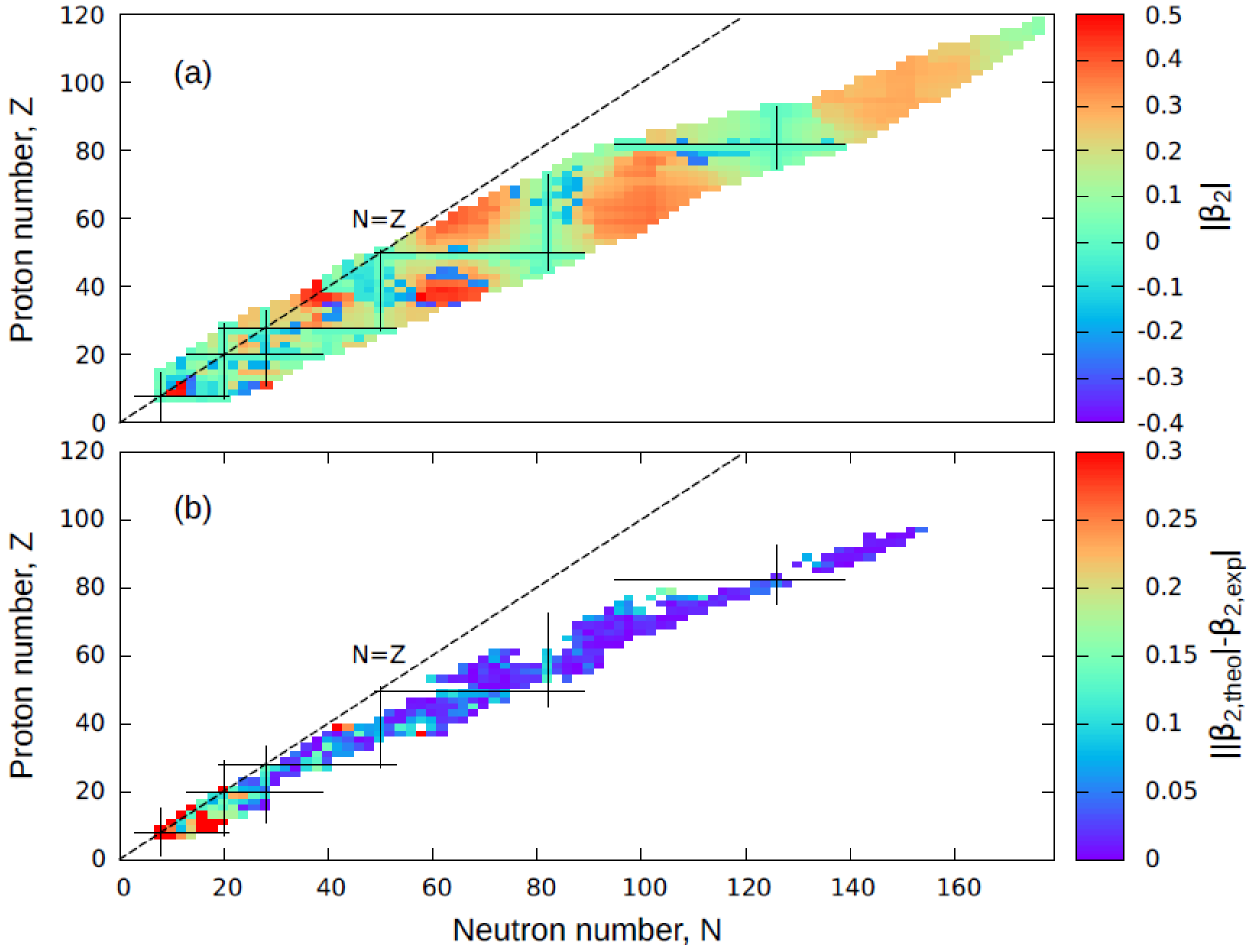
Model	*rms* residual (MeV)	*rms* % deviation
QMCπ-III	1.59	0.29
QMCπ-II	2.34	0.39
QMCπ-I	2.78	0.50
QMC-I	3.84	0.69
SV-min	3.64	0.38
UNEDF1	2.06	0.55
DD-MEδ	2.41	0.42
FRDM	0.89	0.18

Charge Radii



Model	*rms* residual (fm)	*rms* % deviation
QMCπ-III	0.024	0.50
QMCπ-II	0.029	0.66
QMCπ-I	0.028	0.65
QMC-I	0.030	0.66
SV-min	0.024	0.61
UNEDF1	0.029	0.65
DD-MEδ	0.035	0.78

Deformation



Model	*rms* residual	*rms* % deviation
QMCπ-III	0.11	28
SV-min	0.16	59
UNEDF1	0.15	53
DD-MEδ	0.14	40
FRDM	0.11	30

Hypernuclei

No new parameters as σ, ω and ρ
mesons do not couple to the strange quark.

One could add extra mesons with more
free parameters but let's see what we find…..

Λ- and Ξ-Hypernuclei in QMC

	$^{89}_{\Lambda}$Yb (Expt.)	$^{91}_{\Lambda}$Zr	$^{91}_{\Xi^0}$Zr	$^{208}_{\Lambda}$Pb (Expt.)	$^{209}_{\Lambda}$Pb	$^{209}_{\Xi^0}$Pb
$1s_{1/2}$	-22.5	-24.0	-9.9	-27.0	-26.9	-15.0
$1p_{3/2}$		-19.4	-7.0		-24.0	-12.6
$1p_{1/2}$	-16.0 ($1p$)	-19.4	-7.2	-22.0 ($1p$)	-24.0	-12.7
$1d_{5/2}$		-13.4	-3.1	—	-20.1	-9.6
$2s_{1/2}$		-9.1	—	—	-17.1	-8.2
$1d_{3/2}$	-9.0 ($1d$)	-13.4	-3.4	-17.0 ($1d$)	-20.1	-9.8
$1f_{7/2}$		-6.5	—	—	-15.4	-6.2
$2p_{3/2}$		-1.7	—	—	-11.4	-4.2
$1f_{5/2}$	-2.0 ($1f$)	-6.4	—	-12.0 ($1f$)	-15.4	-6.5
$2p_{1/2}$		-1.6	—	—	-11.4	-4.3

Also predicts Ξ – hypernuclei bound by 5-15 MeV − being tested at J-PARC

"The first evidence of a bound state of Ξ^{-} ^{14}N system",
K. Nakazawa et al.,
Prog. Theor. Exp. Phys. (2015)

Guichon *et al.*, Nucl.Phys. A814 (2008) 66; see also 1998

Neutron Stars

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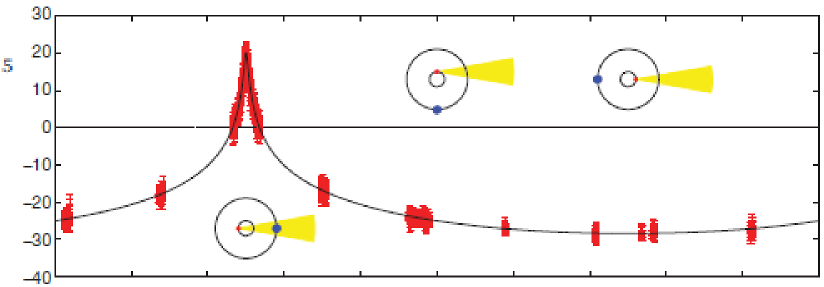
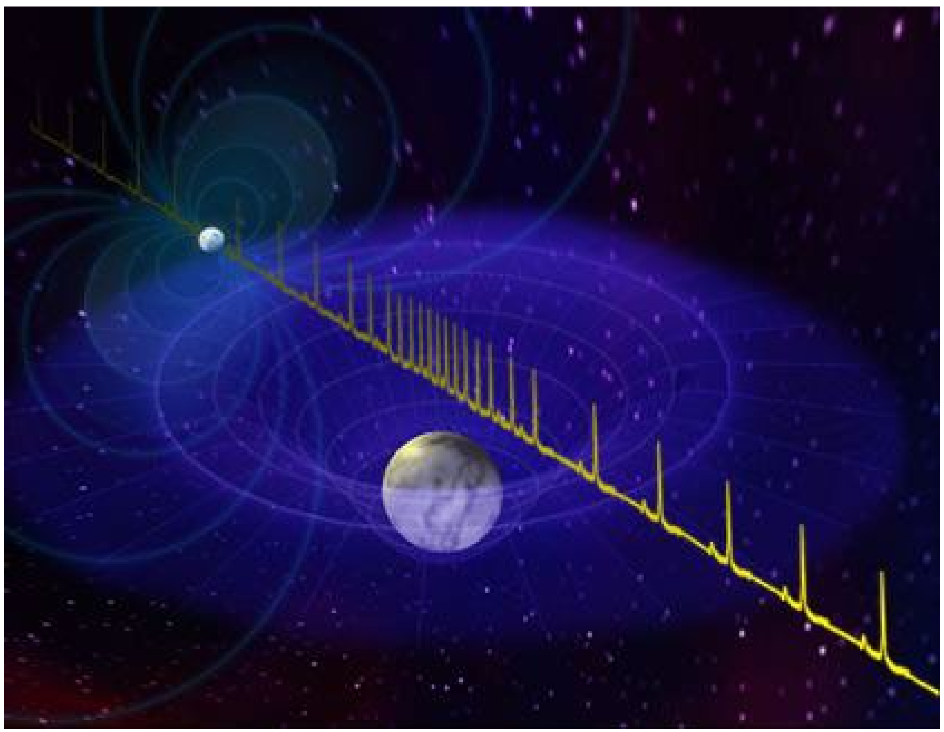
LETTER (2010)

doi:10.1038/nature09466

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]





Reported a very accurate pulsar mass much larger than seen before : 1.97 ± 0.04 solar mass

Claim: it rules out hyperon occurrence

- ignored work *published* three years before using QMC!

Rikovska-Stone *et al.*, NP A792 (2007) 341

J1614-2230

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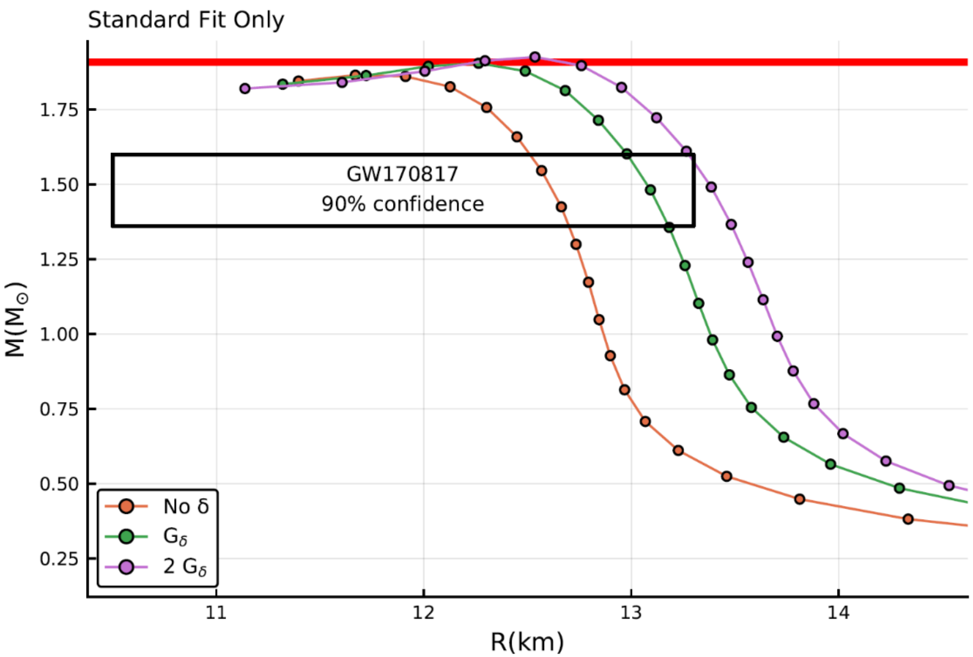
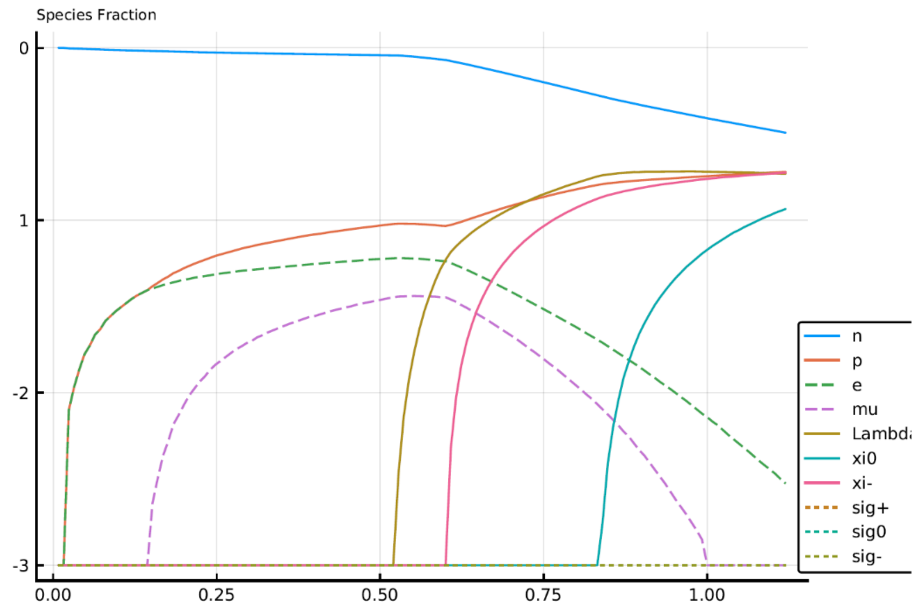
Neutron Stars with hyperons in β-equilibrium

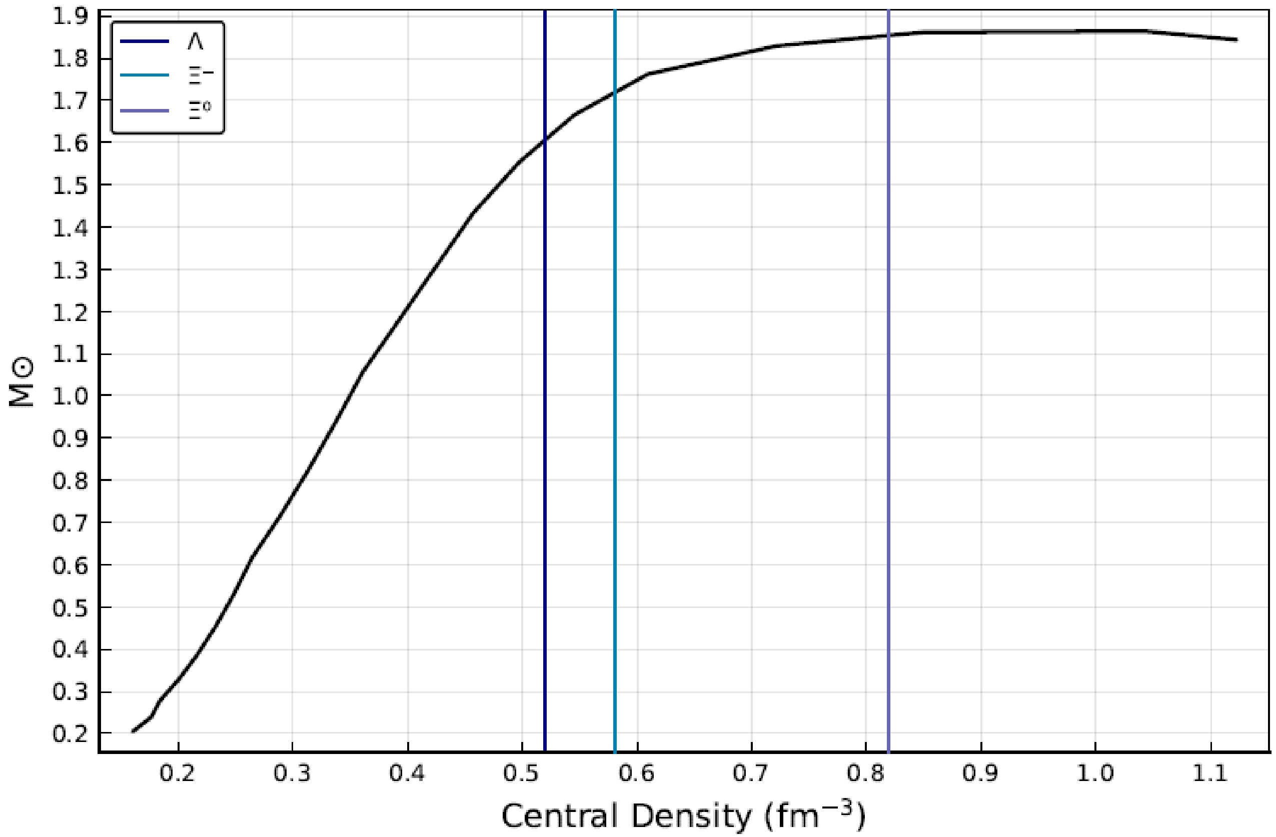




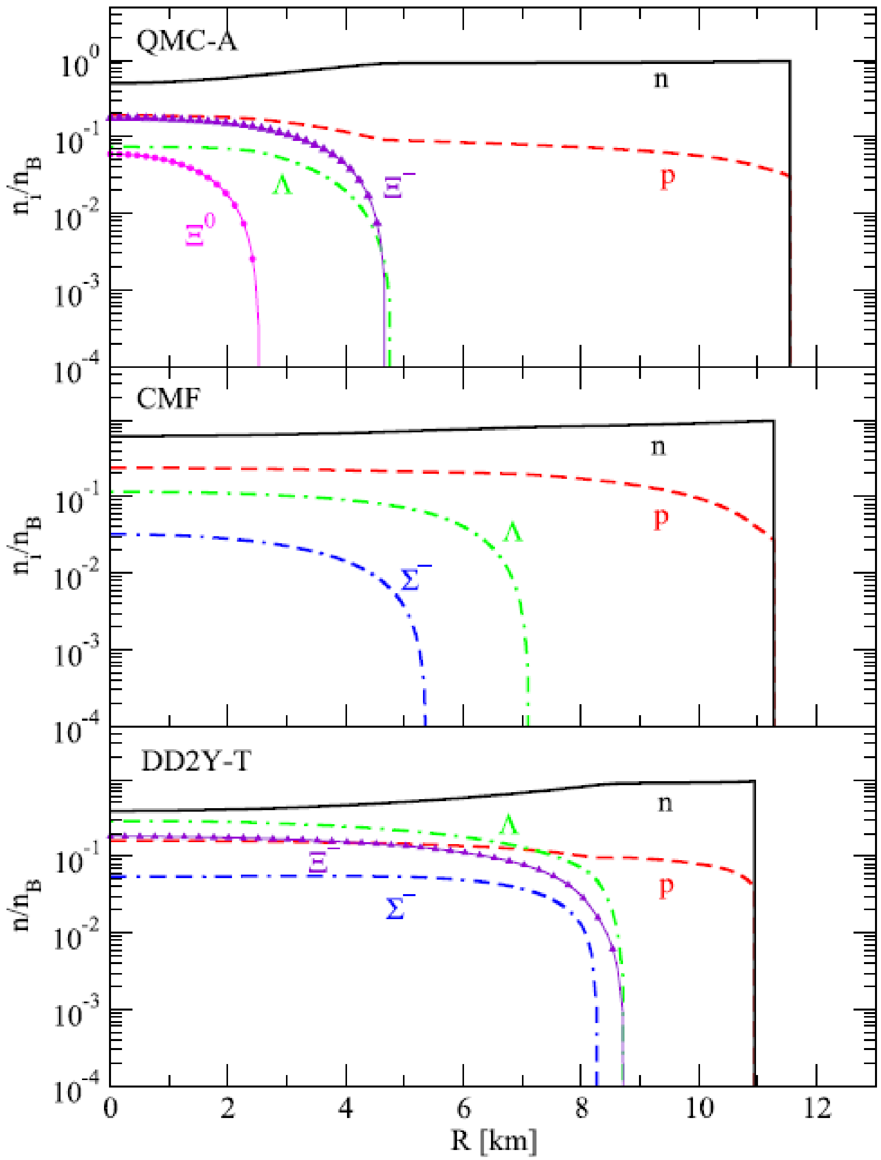
n_B

Motta, Kalaitzis *et al.*, Ap J 878 (2019) 159

Hadron Content versus NS Mass



Radial Distribution of Hyperons (T=0)



Stone *et al.*, MNRAS **502,** 3476–3490 (2021)

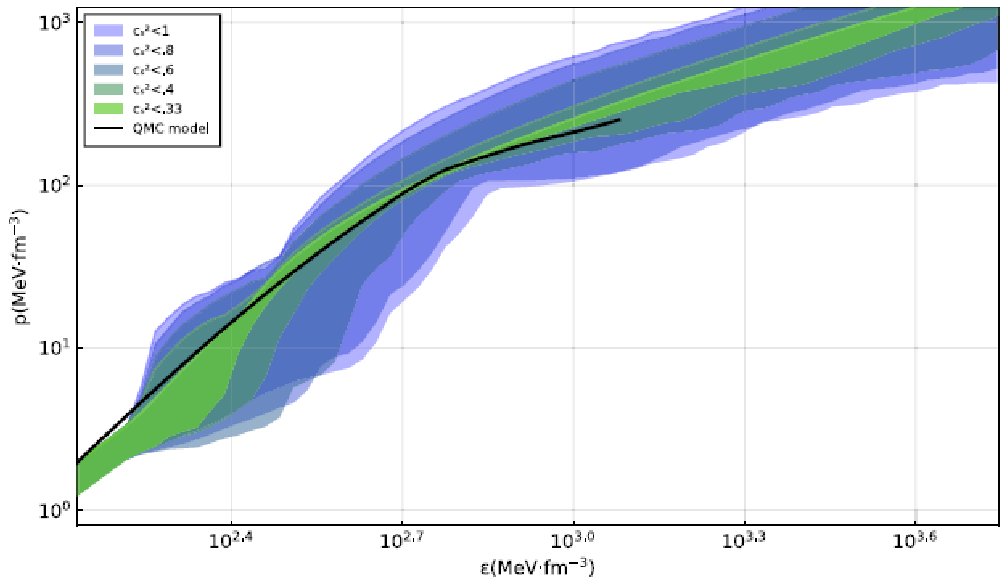
ELSEVIER

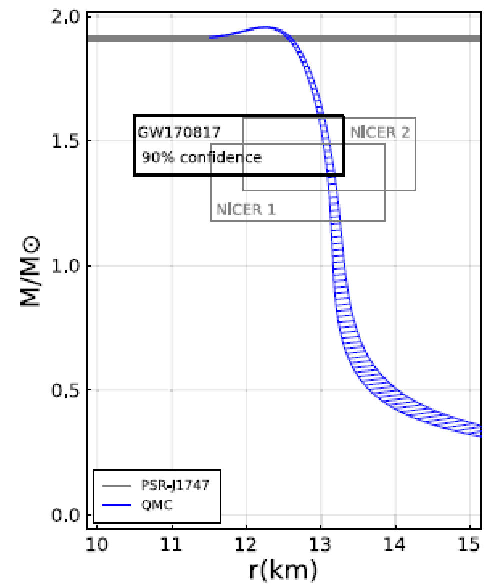
Nuclear Physics A 1009 (2021) 122157

www.elsevier.com/locate/nuclphysa

On the sound speed in hyperonic stars

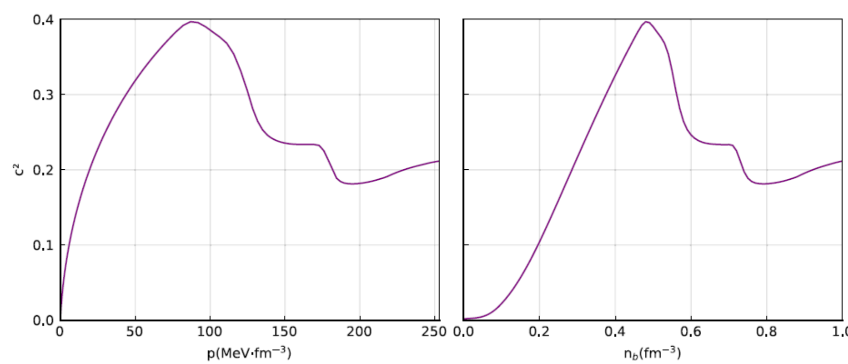
T.F. Motta [a,*], P.A.M. Guichon [b], A.W. Thomas [a]





Follow up on Annala et al., Nature Physics (2020) model independent EoS based on speed of sound interpolation between low and high density

- claim low value implies quark matter



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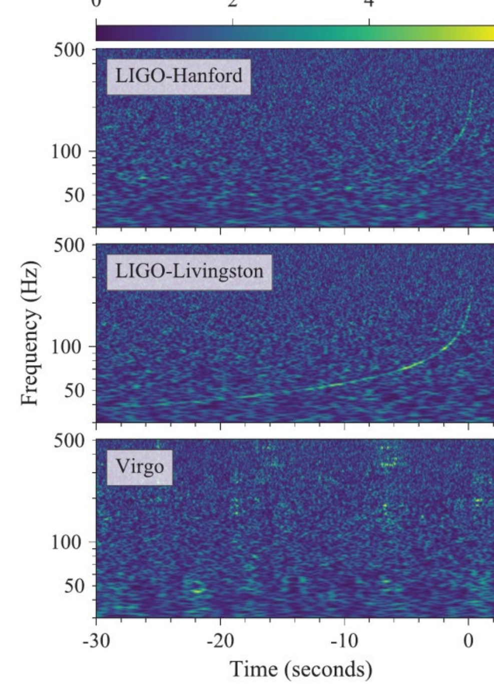


GW170817: Measurements of neutron star radii and equation of state

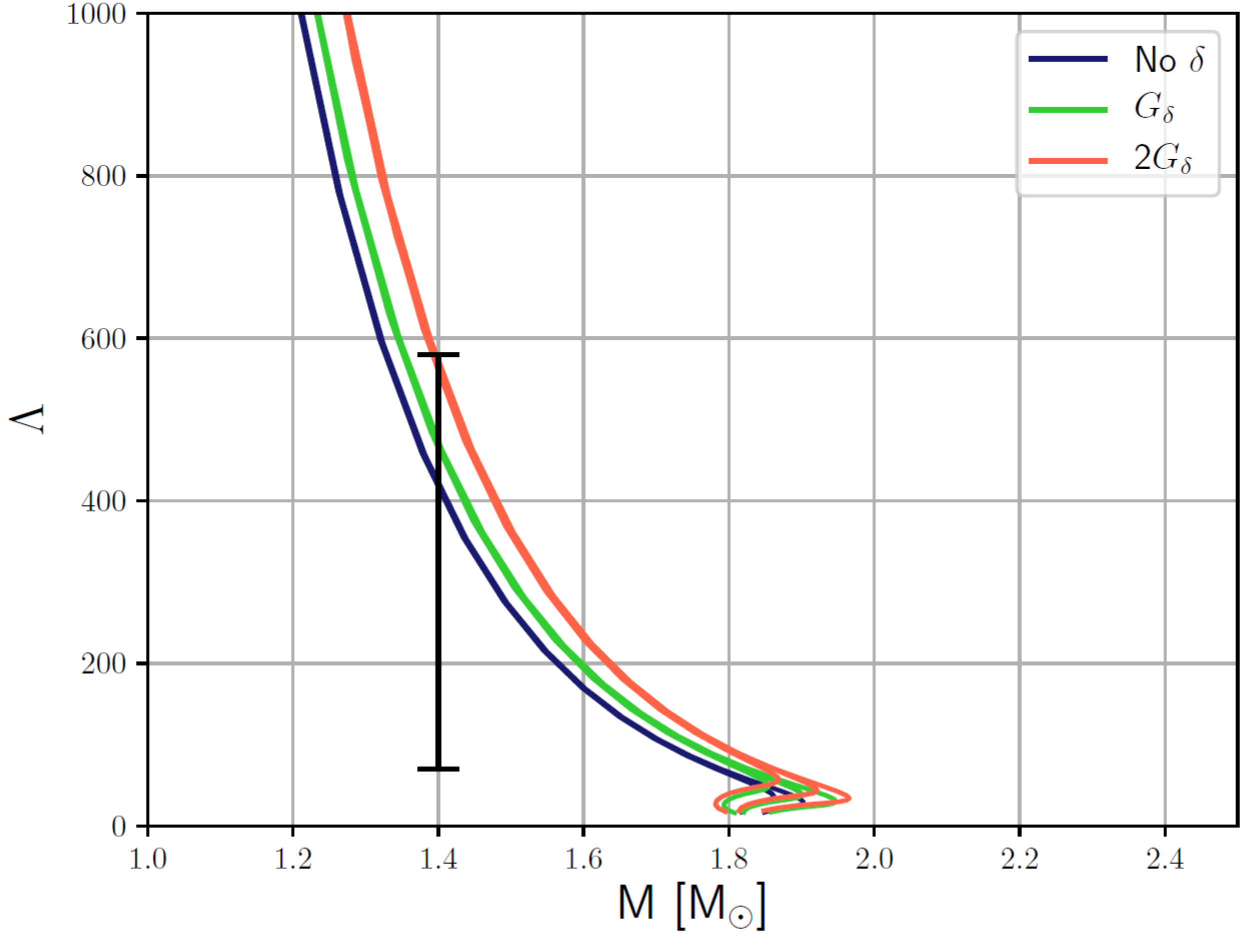
The LIGO Scientific Collaboration and The Virgo Collaboration
(compiled 30 May 2018)

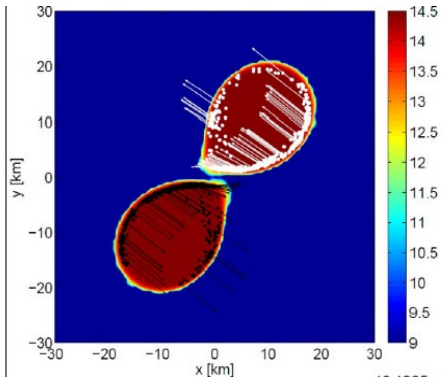
On August 17, 2017, the LIGO and Virgo observatories made the first direct detection of gravitational waves from the coalescence of a neutron star binary system. The detection of this gravitational wave signal, GW170817, offers a novel opportunity to directly probe the properties of matter at the extreme conditions found in the interior of these stars. The initial, minimal-assumption analysis of the LIGO and

arXiv:1805.11581

Tidal deformability

- **Band deduced by LIGO-Virgo analysis of GW170817**





$$Q_{ij} = -\lambda(M)\, E_{ij}$$

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Motta, Kalaitzis *et al.*, Ap J 878 (2019) 159

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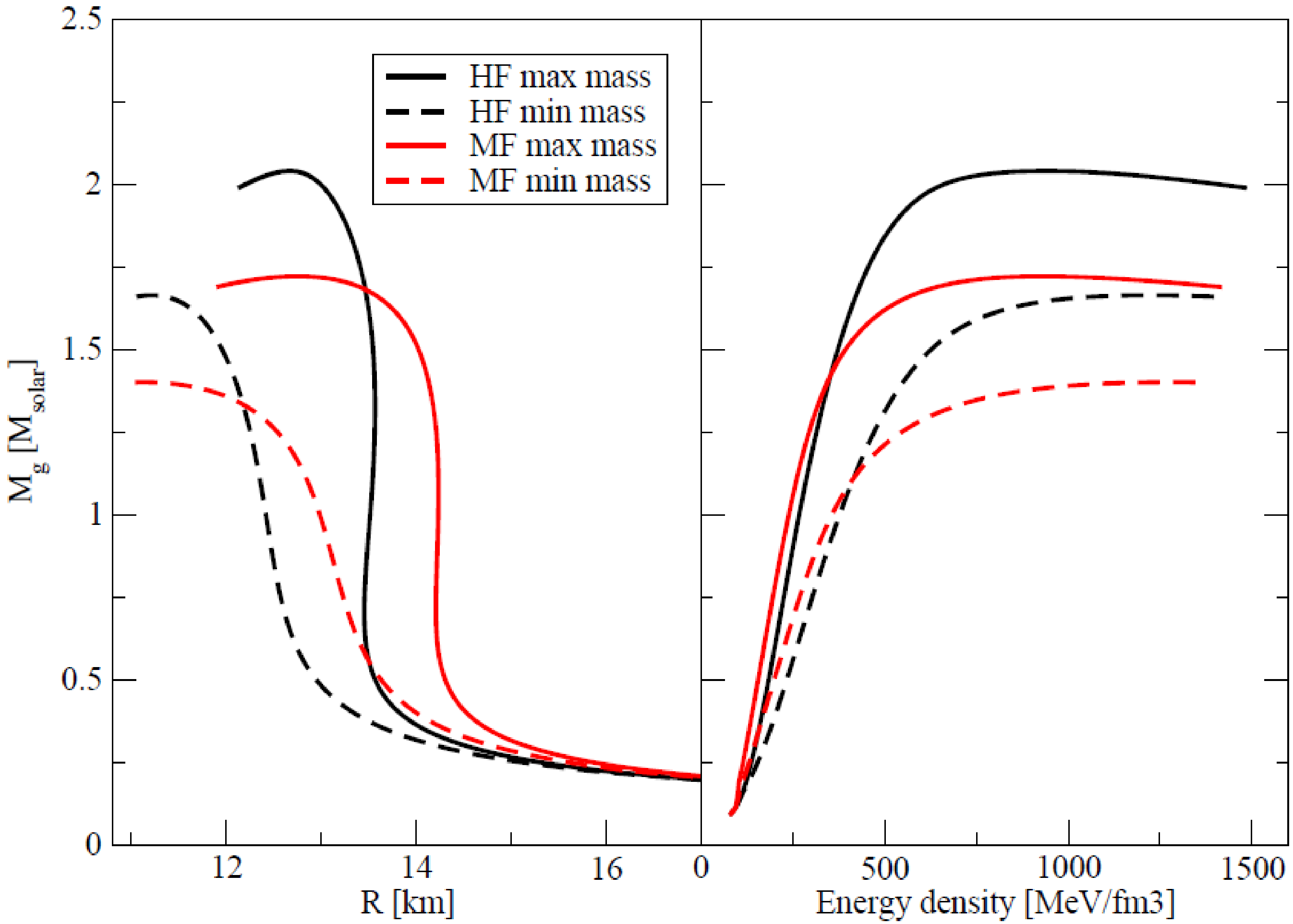
What maximum mass is possible?

Relativistic Hartree-Fock vs RMF

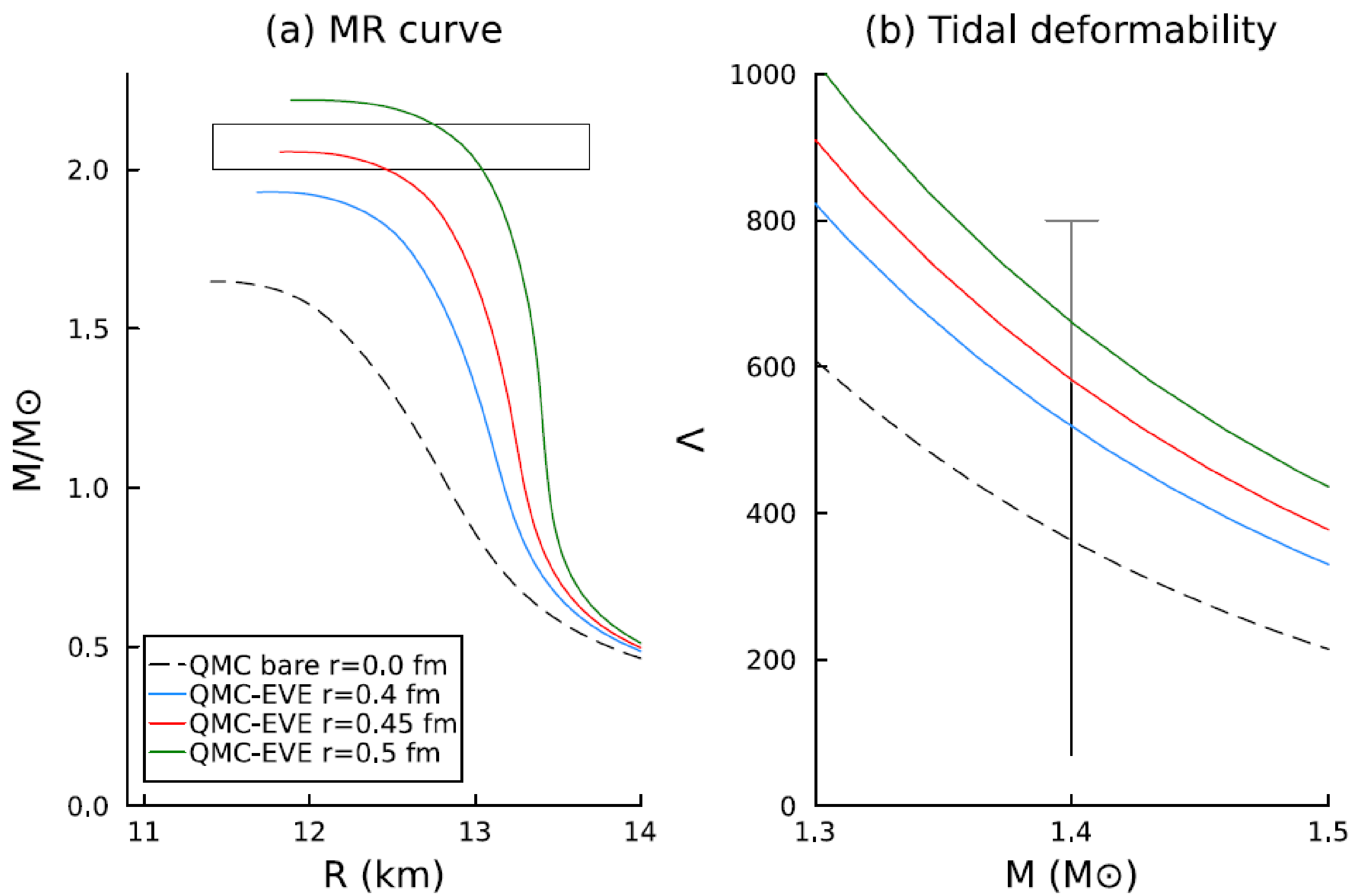
Upper and lower limits vs nuclear matter parameters:



Guichon et al., PHYSICAL REVIEW D **109**, 083035 (2024)

Excluded volume approach

Introduced by Rischke et al. (1991) and for QMC see Panda et al., 2002
It allows one to account for short-distance repulsion and obtain higher mass stars with low incompressibility at ρ_0



Leong et al., Nucl Phys A1050 (2024) 122928

Finite Temperature

Finite Temperature

After BNS mergers the temperature in the time-frame relevant to Gravitational Waves is 10-100 MeV (e.g. Bauswein, Perego, Kochankovski, Jakobus and others this meeting)

The composition is then very different from a cold star

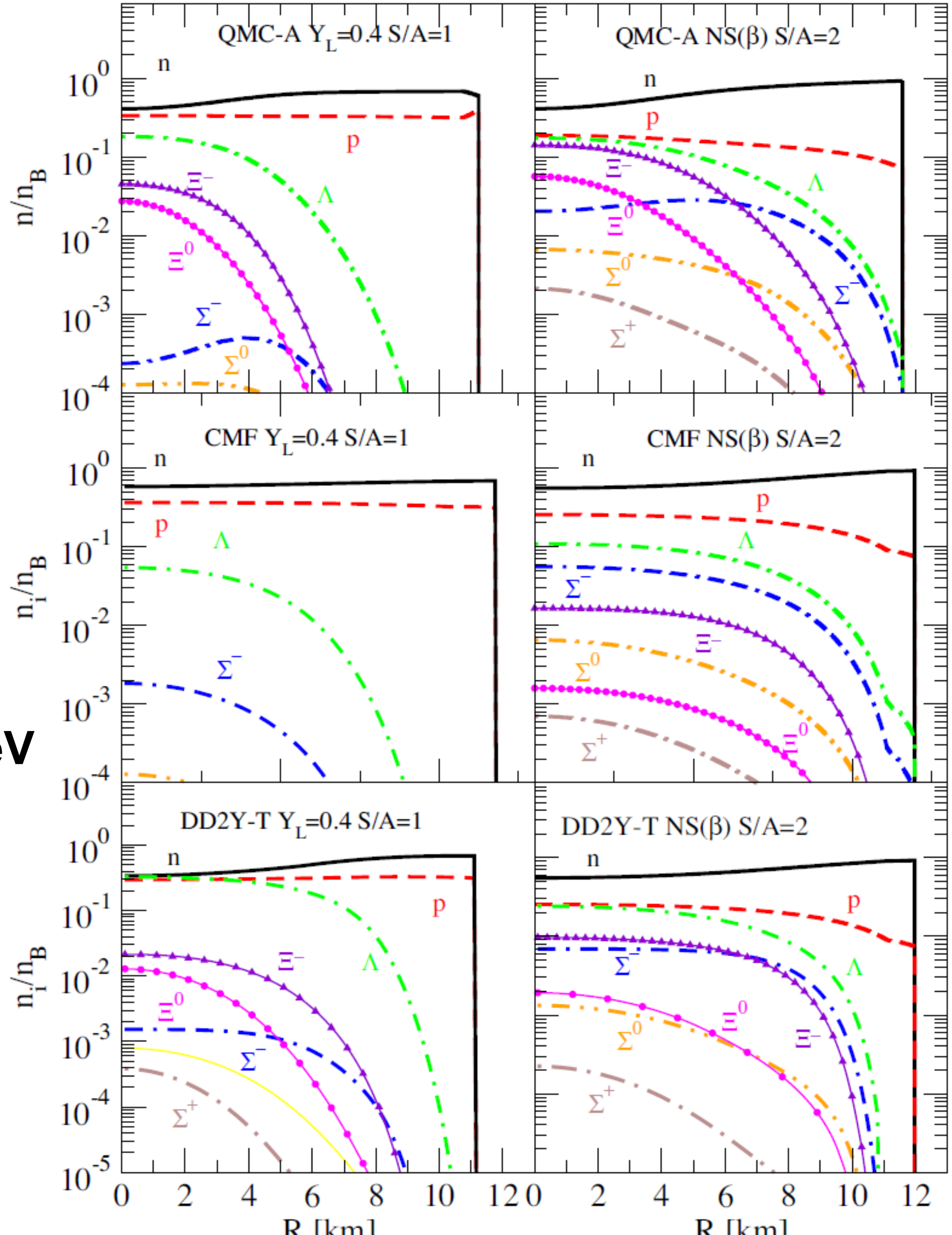
For example, Σ hyperons which play no role in QMC at T=0 because of the enhancement of the color hyperfine repulsion now play an important role

See: Stone et al., MNRAS **502**, 3476–3490 (2021)

and Guichon et al., PHYSICAL REVIEW D **109**, 083035 (2024)

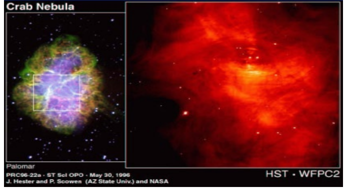
Hyperon content at finite Temperature

T = 10-20 MeV



T = 20-40 MeV

Summary



- Intermediate range NN attraction is STRONG Lorentz scalar

- This modifies the intrinsic structure of the bound nucleon
  - profound change in shell model :

    what occupies shell model states are NOT free nucleons

- Scalar polarizability is a natural source of three-body forces (NNN, HNN, HHN…)
  - clear physical interpretation

- Naturally generates effective HN and HNN forces with no new parameters and predicts heavy neutron stars

- Difficult to get mass beyond 2.2 $M_{\odot}$. Radii and tidal deformability consistent with current data

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Special Mentions……

Guichon

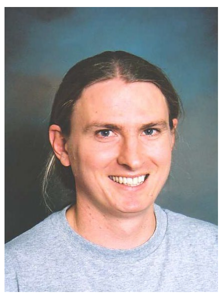
Tsushima

Saito

Stone

Krein

Matevosyan



Cloët

Whittenbury

Simenel

Bentz

Martinez

Motta

Antic

Kalaitzis

Leong

P. G. Reinhard
Skyax

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DARK MATTER PARTICLE PHYSICS

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