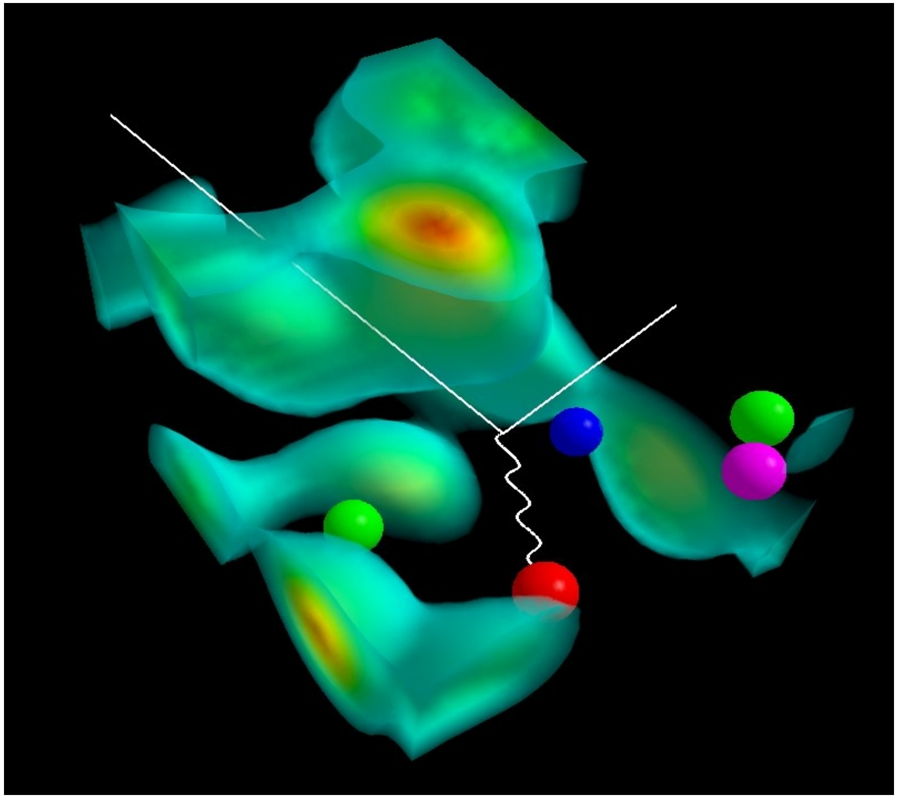
Studies in Dark Matter Particle Physics



Anthony W. Thomas

Annual Workshop CDMPP
November 2020

Outline

I. Nuclei from Quarks
- start from a QCD-inspired model of *hadron* structure
- develop a quantitative theory of nuclear structure

II. Neutron Stars
- role of hyperons and insights from GW170817

III. Dark Matter:

Use insights from I and II to investigate and constrain properties of Dark Matter and its interactions
- proposed explanation for neutron lifetime anomaly
- capture of DM by neutron stars
- effects of captured DM on neutron stars
- scattering of DM from nuclei (eg. in SABRE)

D. Alan Bromley (Yale) to Stan Brodsky in 1982

"Stan, you have to understand -- in nuclear physics we are only interested in how protons and neutrons make up a nucleus.

We are <u>not</u> interested in what is inside of a proton."

Like this beautiful scene – very relaxing

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"Stan, you have to understand -- in nuclear physics we are only interested in how protons and neutrons make up a nucleus.

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Moral: A comfortable picture is not necessarily the right one.....

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

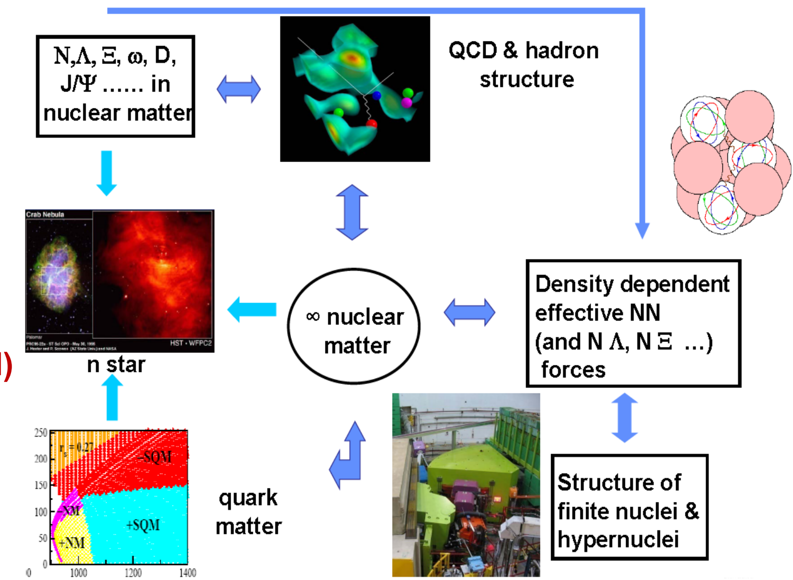
- **Largely cancelled by large vector mean field BUT these have totally different dynamics: ω^0 just shifts energies, σ seriously modifies internal hadron dynamics**

Suggests a different approach : QMC Model

(Guichon, Saito, Tsushima et al., Rodionov et al.
- see Saito et al., Prog. Part. Nucl .Phys. 58 (2007) 1 and
Prog. Part. Nucl. Phys. 100 (2018) 262-297 for reviews)

- **Start with quark model (MIT bag/NJL...) for all hadrons**

- **Introduce a relativistic Lagrangian with σ, ω and ρ mesons coupling to non-strange quarks**



- **Hence <u>only 3 parameters</u> (4 if σ mass not fixed)**

  − determine by fitting to:
  ρ_0 , E/A and symmetry energy

  − same in dense matter & finite nuclei

- **Must solve <u>self-consistently</u> for the internal structure of baryons in-medium**

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Self-consistent solution of nuclear matter

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

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

SELF-CONSISTENCY

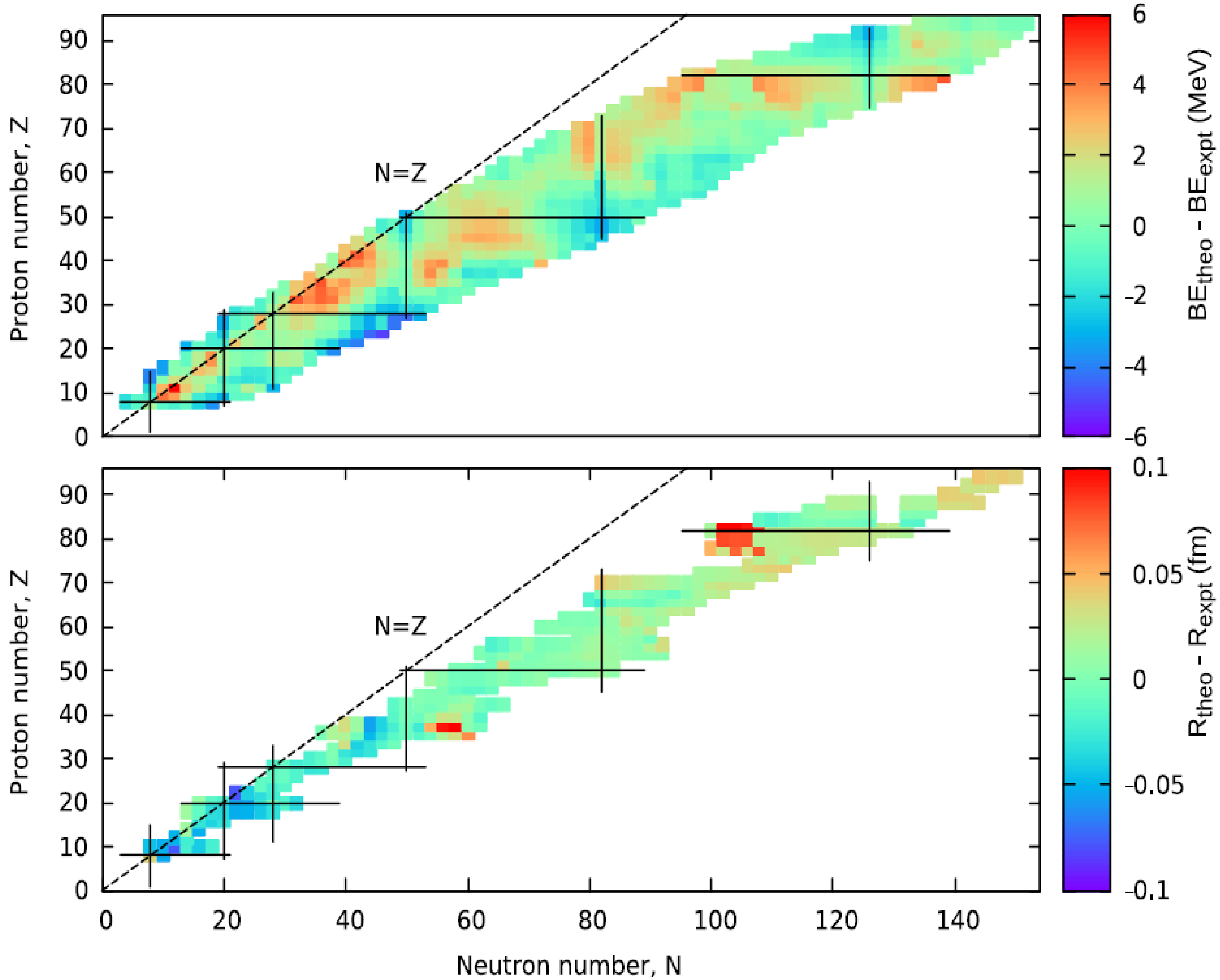
and hence mean scalar field changes…

and hence quark wave function changes….

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

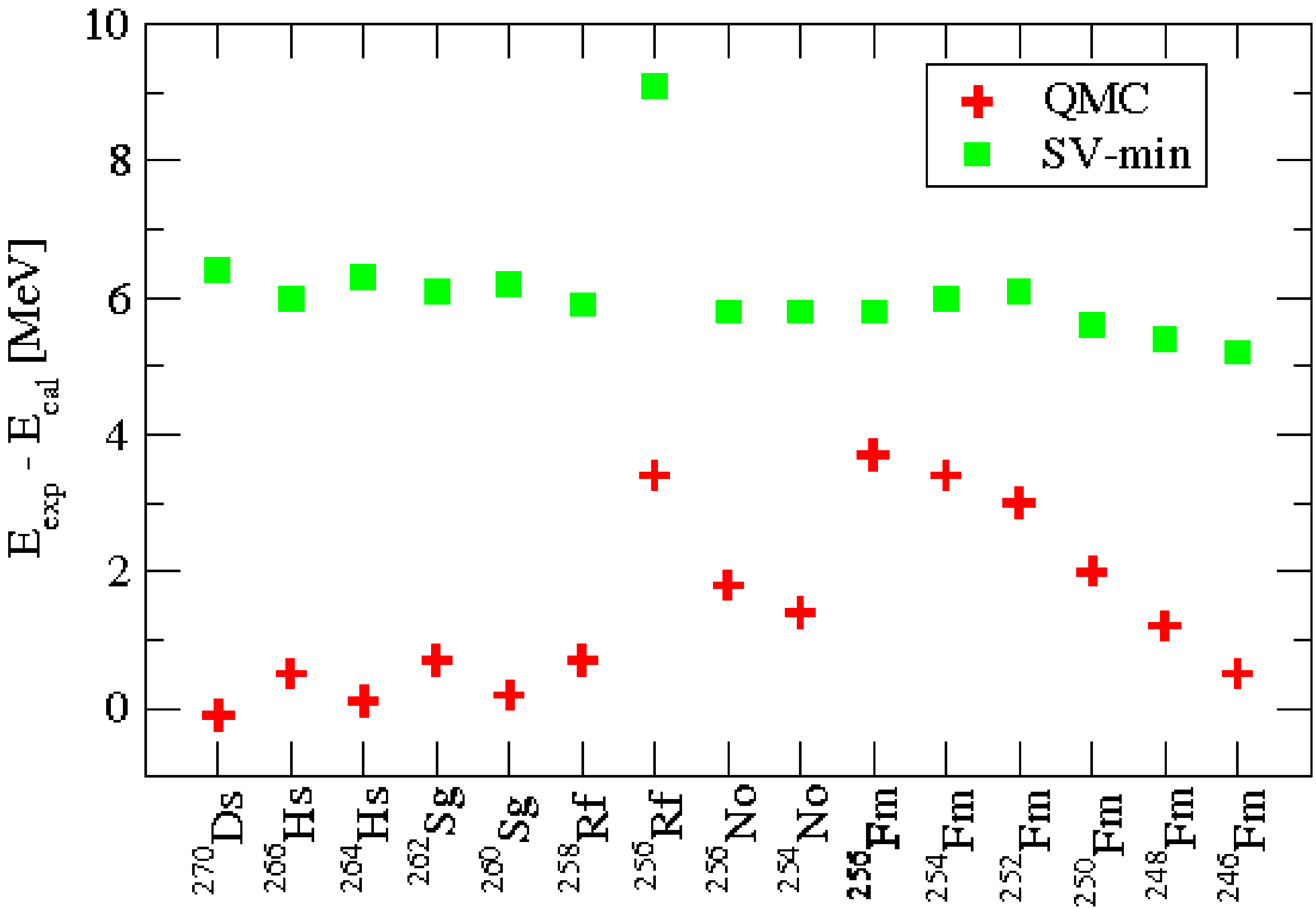
source is suppressed as mean scalar field increases
(i.e. as density increases)

Application to nuclear structure



Martinez et al., Phys Rev C106, 034304 (2020)

Superheavy Binding : 0.1% accuracy



Stone et al., PRL 116 (2016) 092501

For detailed study of SHE see: arXiv:1901.06064

Summary: Finite Nuclei

- The effective force was *derived* at the quark level *based upon the changing structure of a bound nucleon*

- Has many less parameters but reproduces nuclear properties at a level comparable with the best phenomenological Skyrme forces

- Looks like standard nuclear force

- BUT underlying theory also predicts modified internal structure and hence modified
  - DIS structure functions – notably explains EMC effect
  - elastic form factors......

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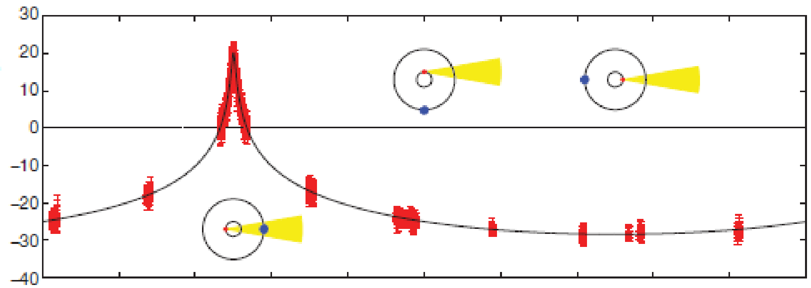
Neutron Stars

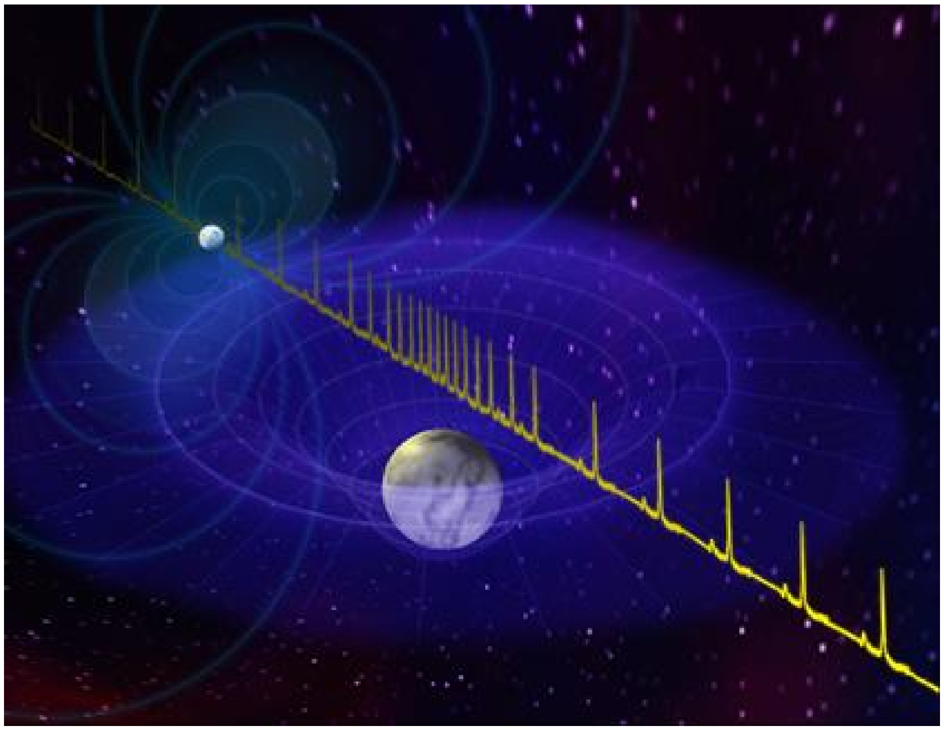
LETTER (2010)

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]



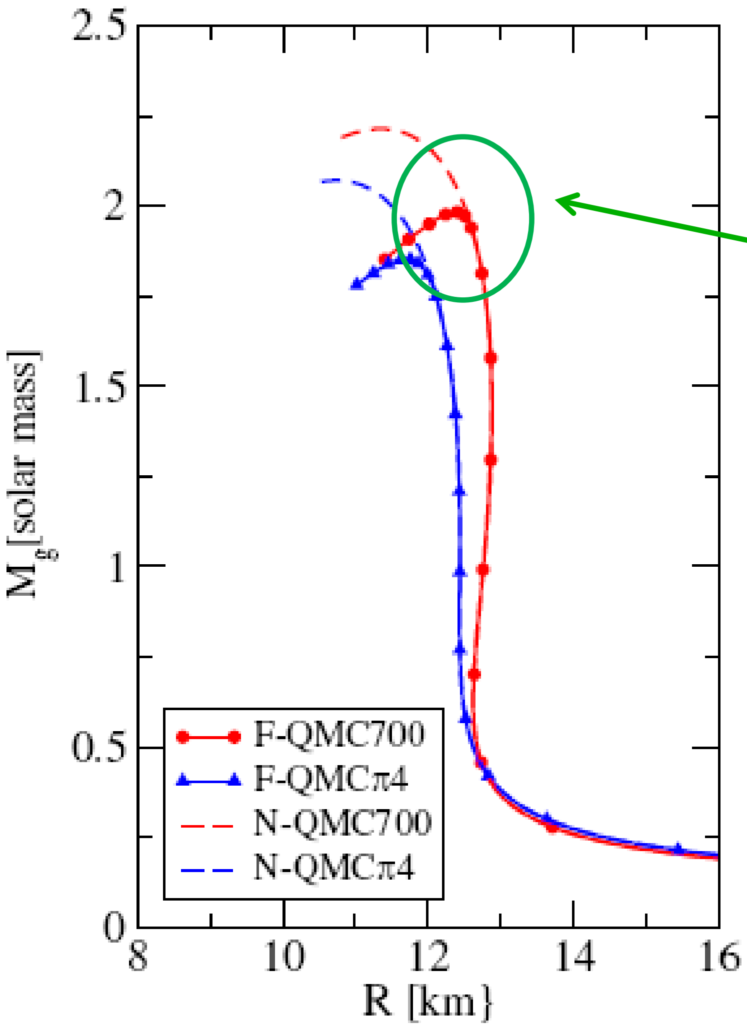


Reports a very accurate pulsar mass much larger than seen before : 1.97 ± 0.04 solar mass

Claim: it rules out hyperon occurrence
- ignored our work *published* three years before!

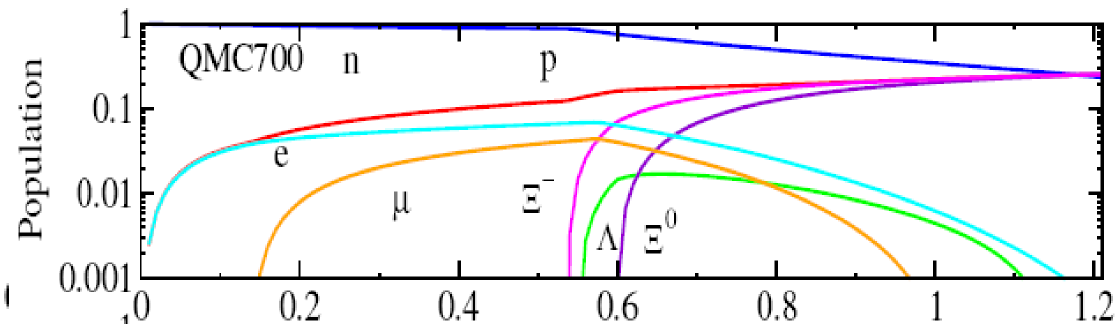
J1614-2230

Consequences of QMC for Neutron Star



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

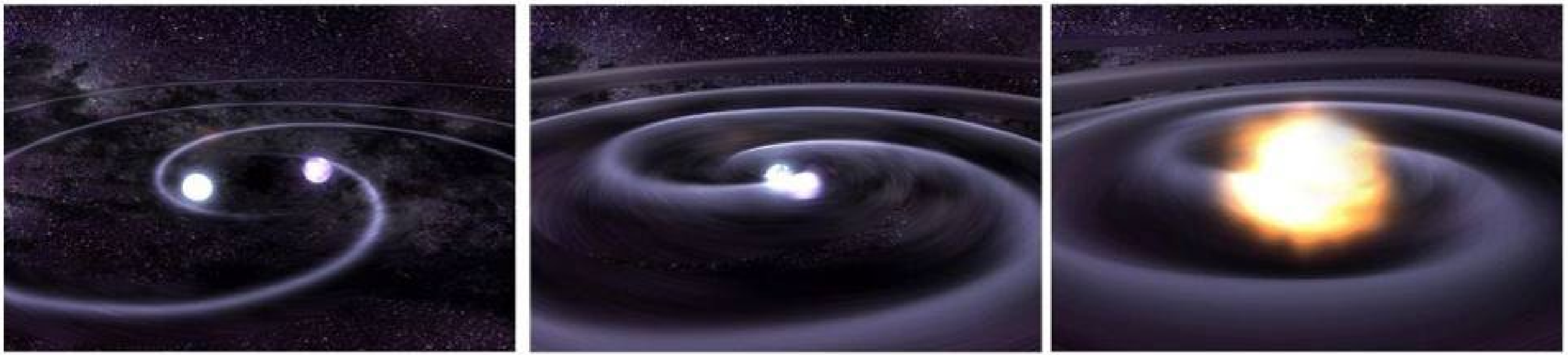
2 Solar mass stars predicted with hyperons present:



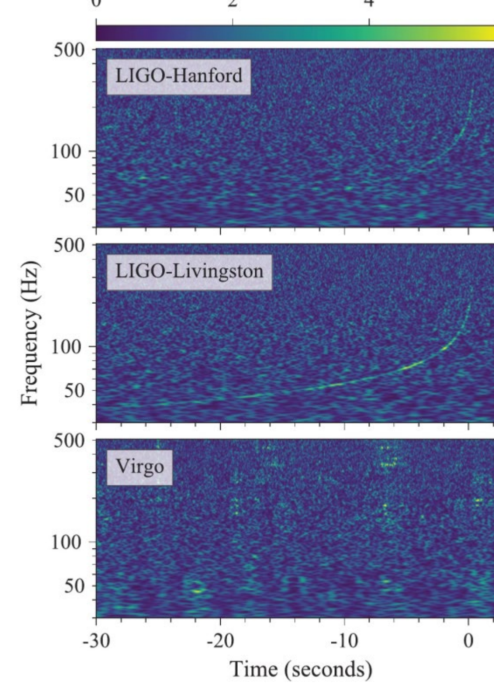
<u>Predicted</u> HNN forces crucial!

Later work: Saito et al., Whittenbury et al.....

Gravity Waves from Neutron Star Mergers



LIGO



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

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arXiv:1805.11581

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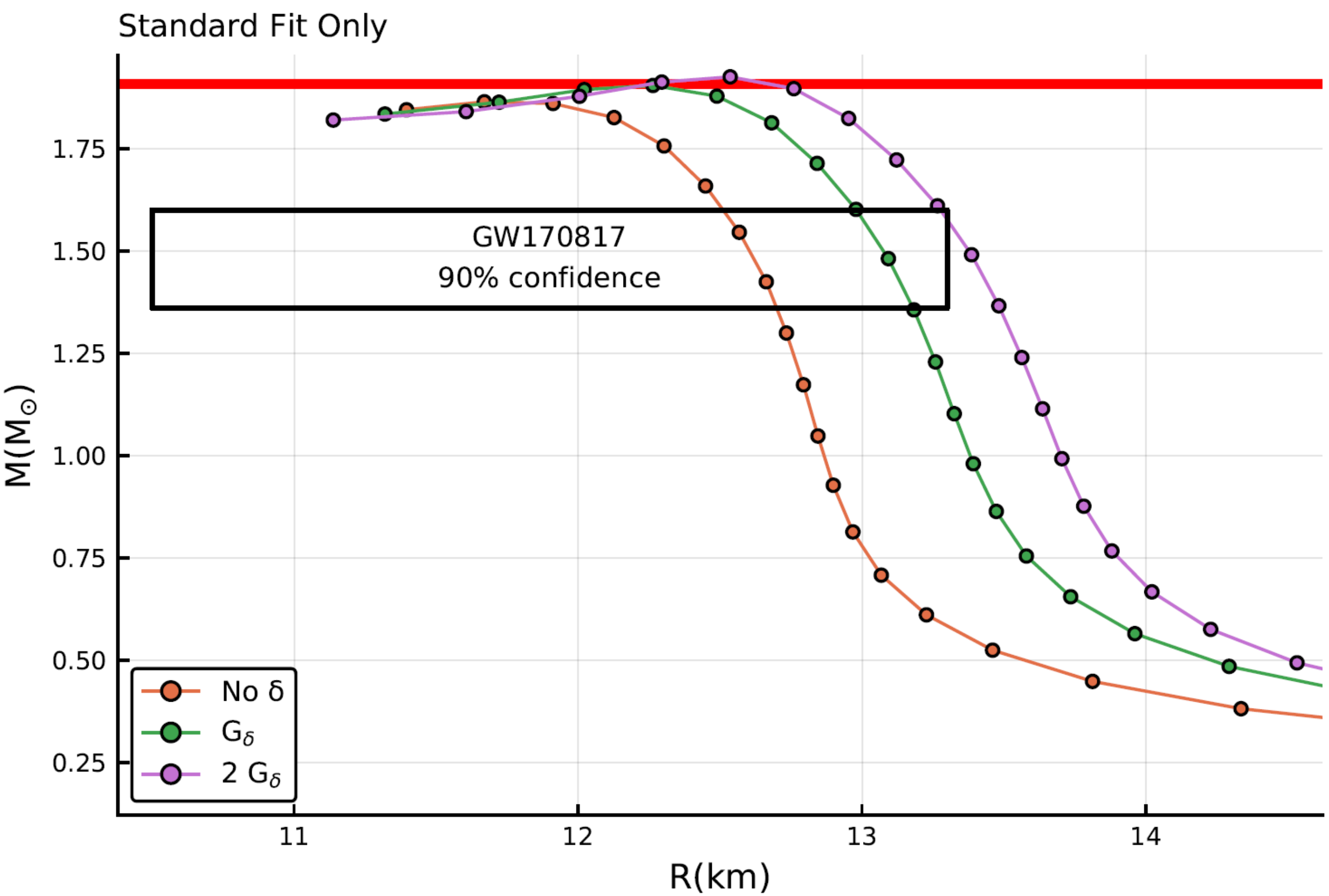
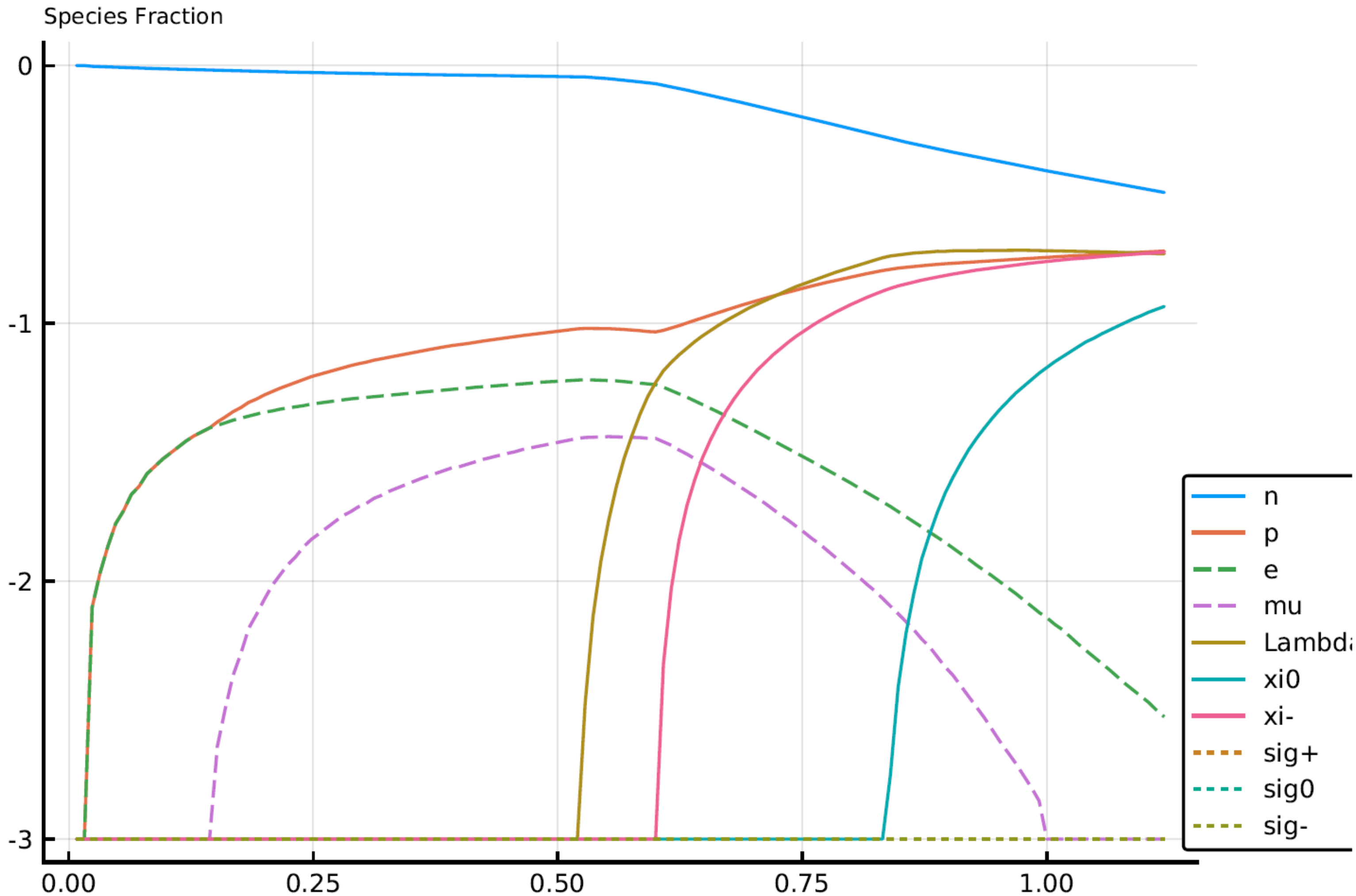
Recent Study Motivated by GW170817

- **Includes isovector scalar meson**



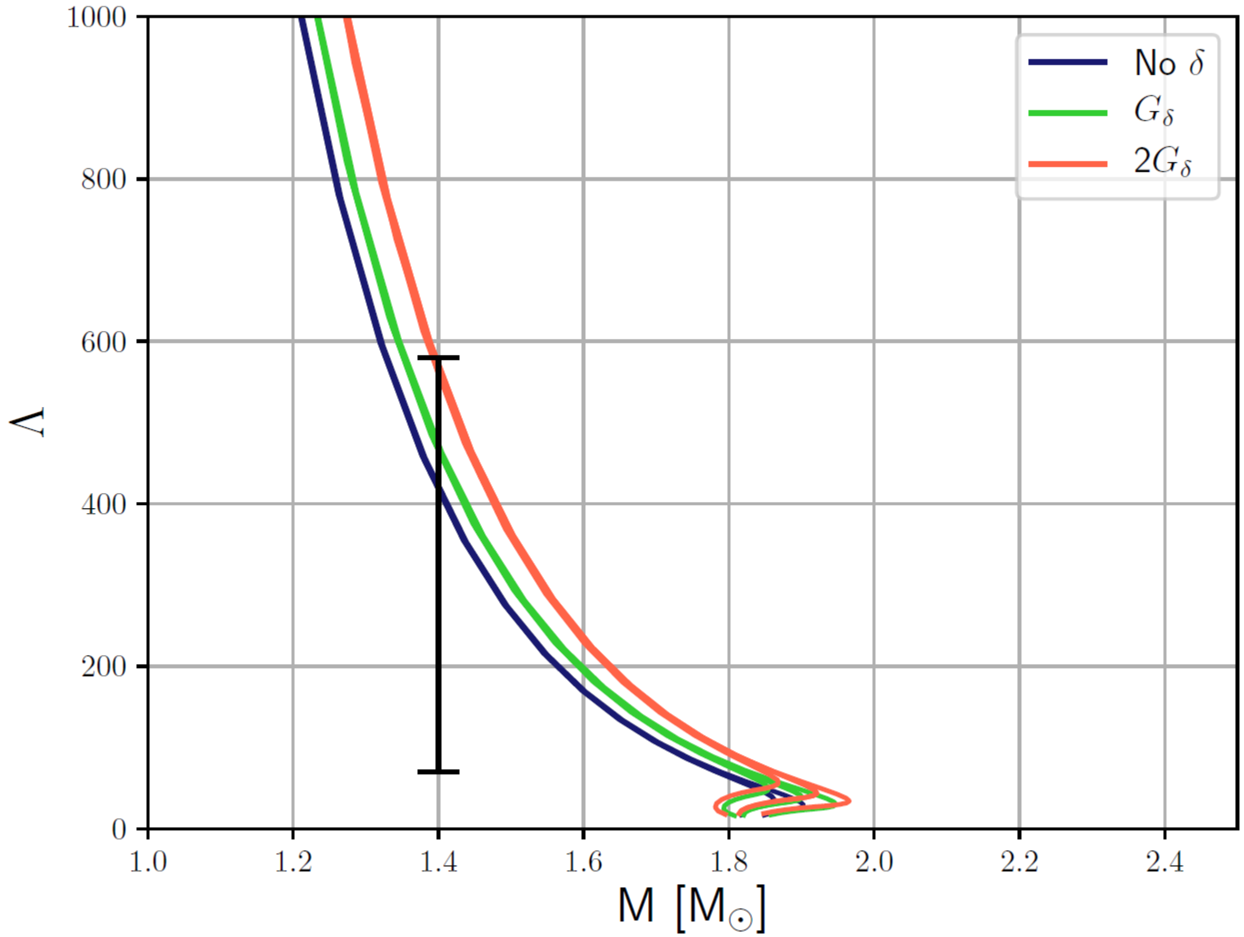
Motta, Kalaitzis et al., arXiv tomorrow

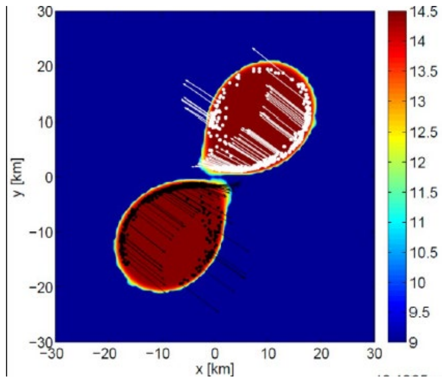
Species Fractions: in β-equilibrium



Tidal deformability

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





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

Light Dark Matter

Recently there was a very interesting proposal from Fornal and Grinstein (1801.01124).

Originated in long-standing puzzle concerning free neutron lifetime:

- **Measurement for trapped n's: 879.6 ± 0.6 sec**
- **Measurement in beam decay : 888.0 ± 2.0 sec**

This *4σ discrepancy* solved by existence of new decay mode, which would not be seen in the beam decay experiment

$$n \longrightarrow \text{Dark Matter } (\chi) + \text{something}$$

"Something" not a photon : Tang *et al*., Los Alamos 1802.01595

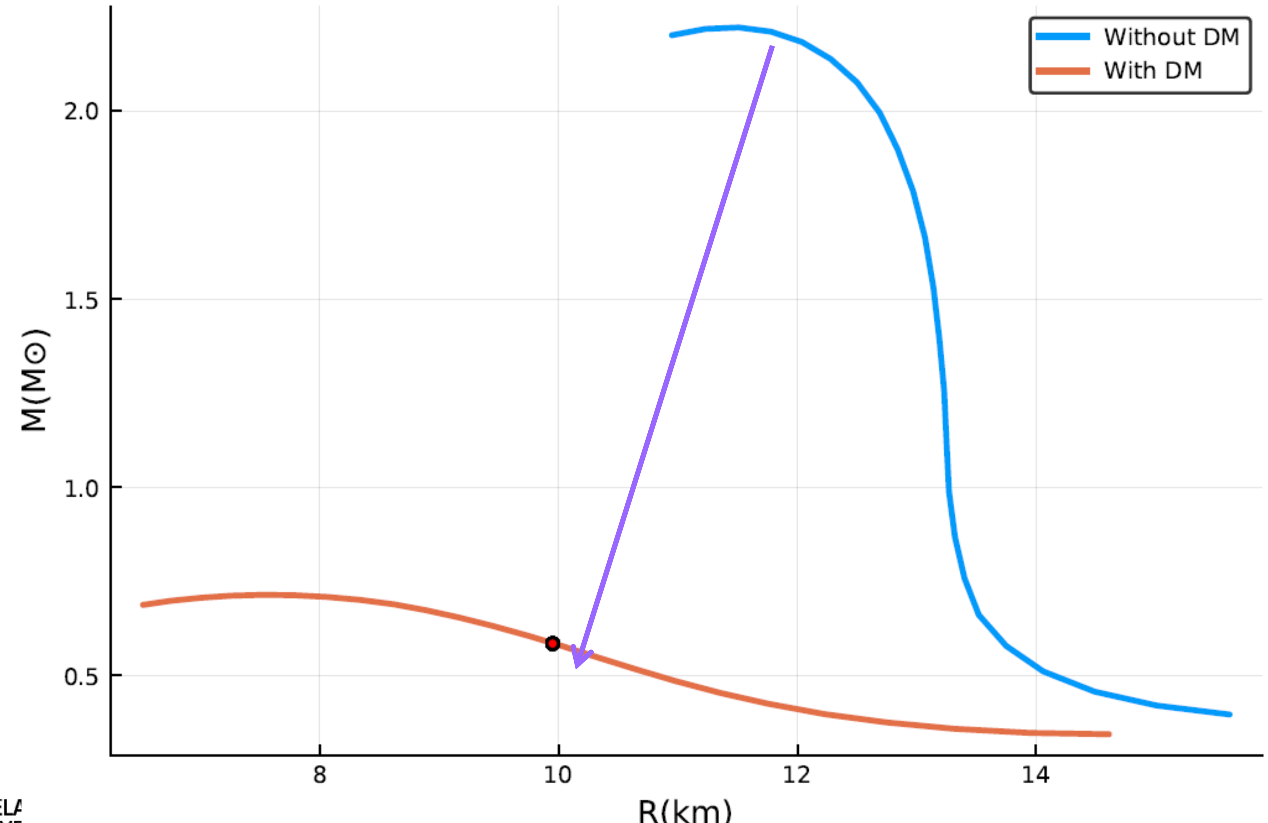
Compatibility of Fornal-Grinstein Hypothesis with Neutron Star Properties?

- **In just 2 weeks a rush of papers**
  - **McKeen *et al.*, 1802.08244**
  - **Motta *et al.*, 1802.08427**
  - **Baym *et al.*, 1802.08282**
- **All reach a similar conclusion**
- **I follow the work of Motta, Guichon and Thomas (1802.08427)**
- **If such a dark matter particle exists neutrons high in the Fermi sea of a neutron star will be unstable**
- **This will replace high energy/pressure neutrons with lower energy/pressure dark matter particles: Consequences?**

Solve Tolman-Oppenheimer-Volkoff Equations

- **Maximum allowed mass for stable neutron star drops from 2.21 $M_{\odot}$ to 0.7 $M_{\odot}$**

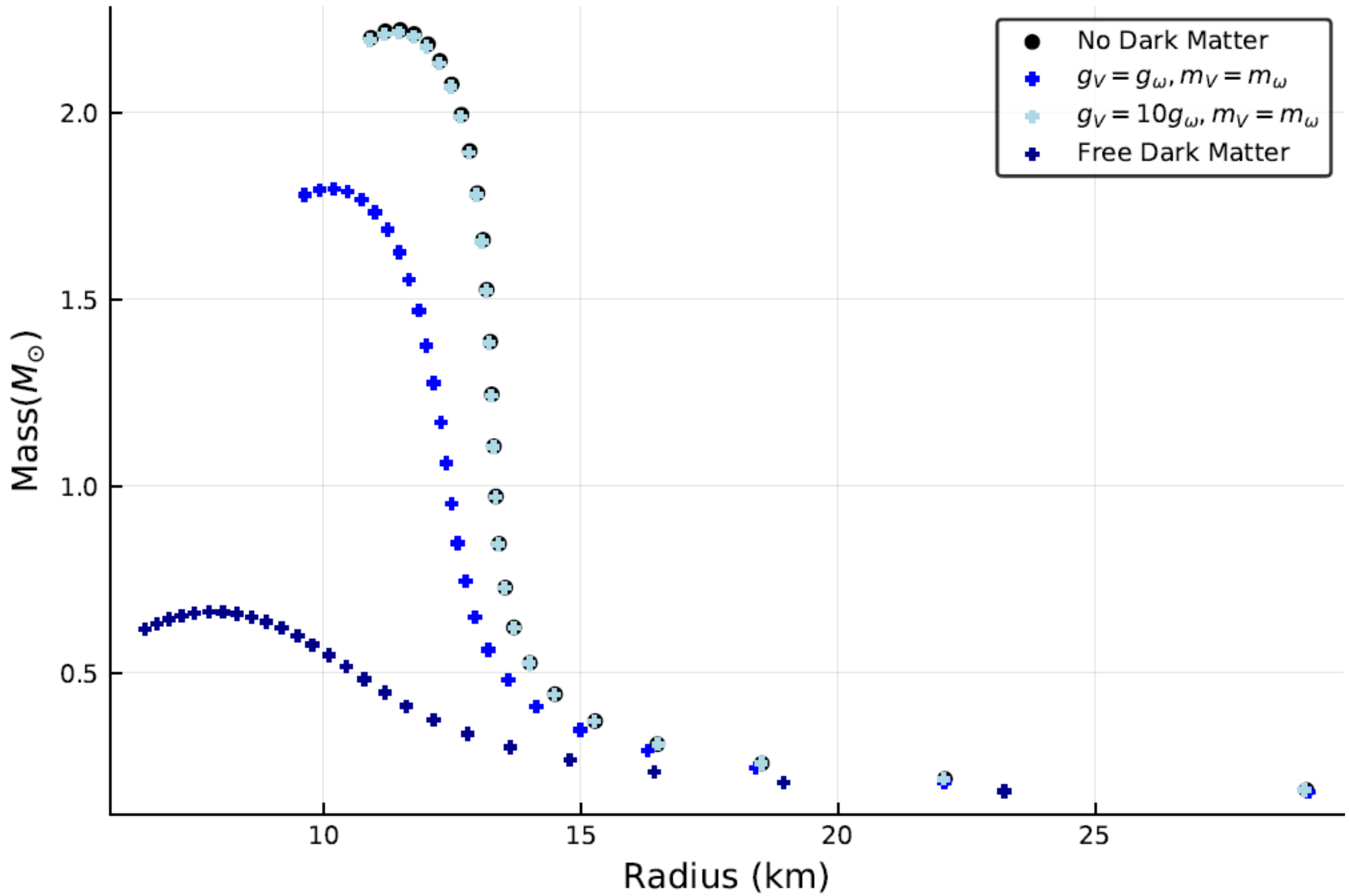
- **But cannot even get that as maximum stable star goes to just 0.58 $M_{\odot}$**



Motta et al., J. Phys. G45 (2018) no.5, 05LT01

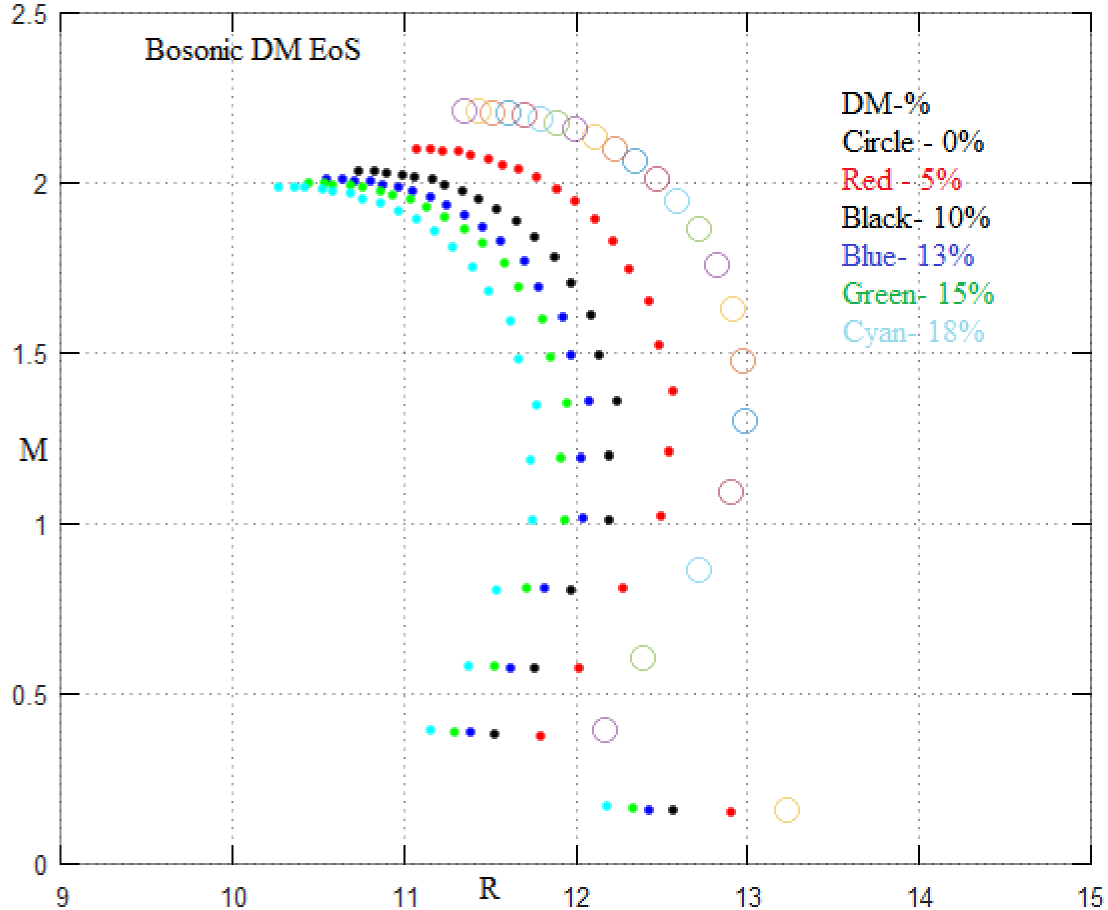
Is there a way out?

- **If the dark matter has a strong repulsive interaction with other dark matter we can lift the pressure and hence the maximum neutron star mass**



Motta et al., Conf. on Particles and Cosmology Singapore 2018 - arXiv:1806.00903

What about effect of DM on Neutron Stars?



- Effect of bosonic DM – Wasif Husain

Further work

- **Nicole Bell and collaborators:**
  DM capture rate on NS

- **Xuangong Wang:**
  Effective non-relativistic operators for DM interaction with nuclei

Latest papers

- **Review:**
  Guichon *et al.*, PPNP 100 (2018) 262

- **SHE:**
  Stone *et al.*, arXiv: 1901.06064

- **Systematic application to finite nuclei:**
  Stone *et al.*, Phys Rev Lett 116 (2016) 092501

Key papers on QMC

- **Many-body forces:**

    1. Guichon, Matevosyan, Sandulescu, Thomas, Nucl. Phys. A772 (2006) 1.
    2. Guichon and Thomas, Phys. Rev. Lett. 93 (2004) 132502

- **Built on earlier work on QMC: e.g.**

    3. Guichon, Phys. Lett. B200 (1988) 235
    4. Guichon, Saito, Rodionov, Thomas, Nucl. Phys. A601 (1996) 349

- **Major review of applications of QMC to many nuclear systems:**

    5. Saito, Tsushima, Thomas, Prog. Part. Nucl. Phys. 58 (2007) 1-167 (hep-ph/0506314)

References to: Covariant Version of QMC

- Basic Model: (Covariant, chiral, confining version of NJL)

•Bentz & Thomas, Nucl. Phys. A696 (2001) 138

- Bentz, Horikawa, Ishii, Thomas, Nucl. Phys. A720 (2003) 95

- Applications to DIS:

- Cloet, Bentz, Thomas, Phys. Rev. Lett. 95 (2005) 052302
- Cloet, Bentz, Thomas, Phys. Lett. B642 (2006) 210

- Applications to neutron stars – including SQM:

- Lawley, Bentz, Thomas, Phys. Lett. B632 (2006) 495
- Lawley, Bentz, Thomas, J. Phys. G32 (2006) 667

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