Quark Structure of Hadrons, Nuclei, and Neutron Stars

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Overview

- Motivation
- Framework: QMC Model
- Finite Nuclei
- Neutron Stars
  - NS Phenomenology
  - Mass and Radius
  - Gravitational Waves
  - Isovector-Scalar Effects
  - Delta Isobars

Motivation

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- There could be quark effects on the physics of nuclei

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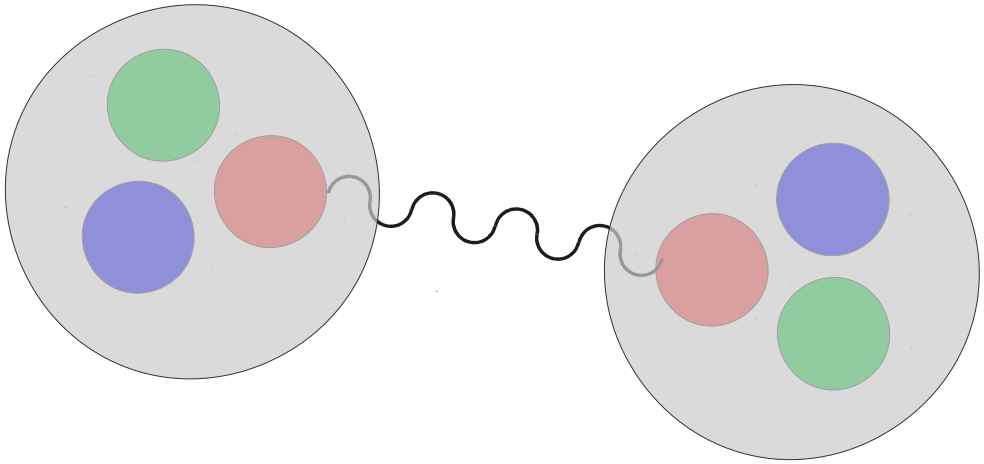
- There could be quark effects on the physics of nuclei
- There could be quark effects on the physics of neutron stars

QMC Model

QMC

- The Quark-Meson Coupling model describes the baryons as bags of three quarks that couple directly to meson fields (P.A.M Guichon, J.R. Stone A.W.Thomas (2018))



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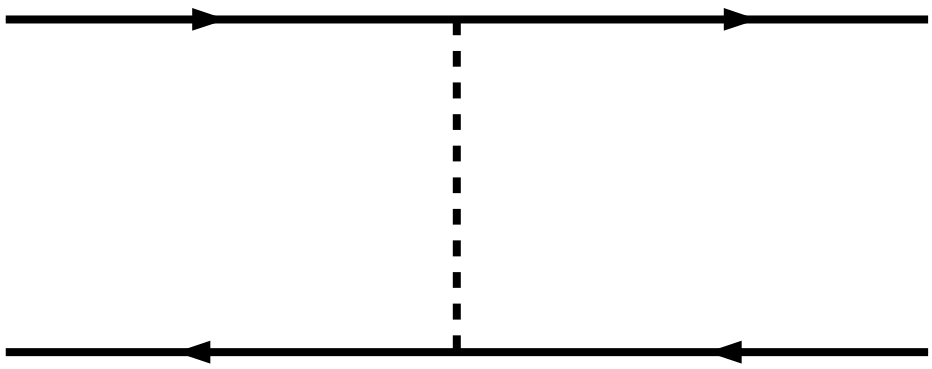

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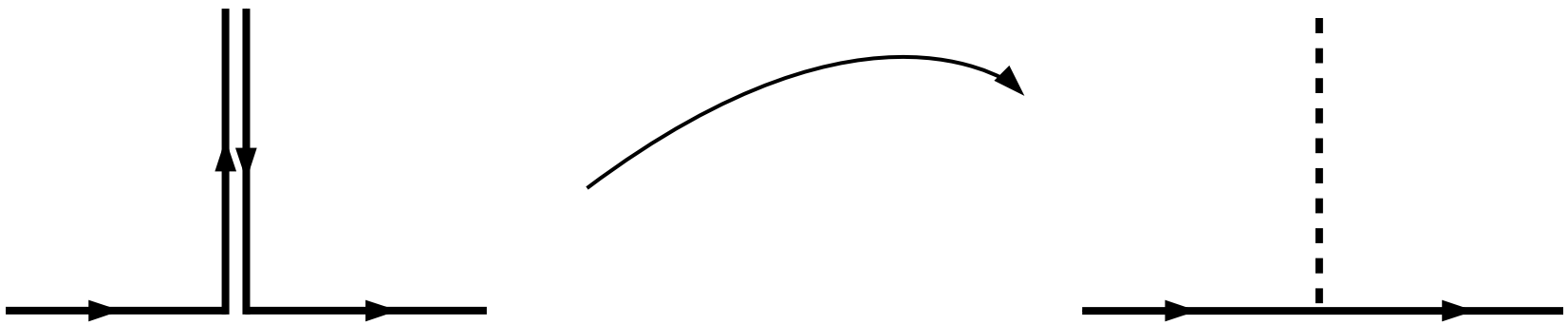

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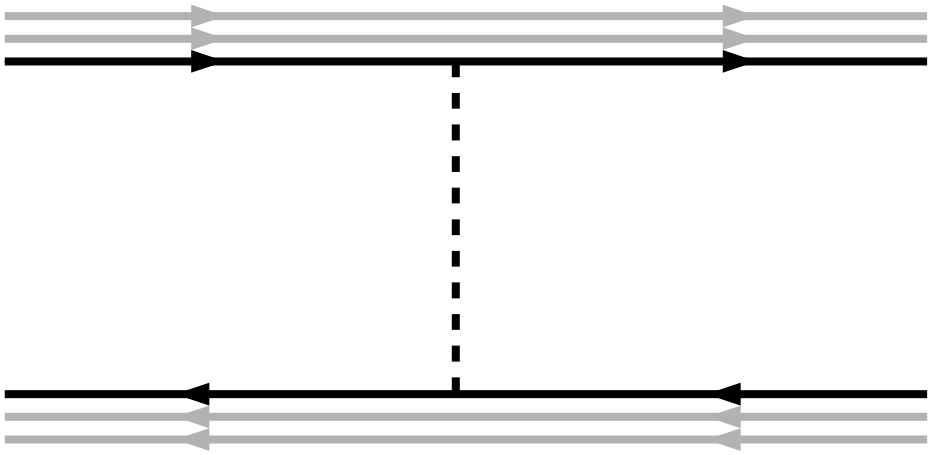
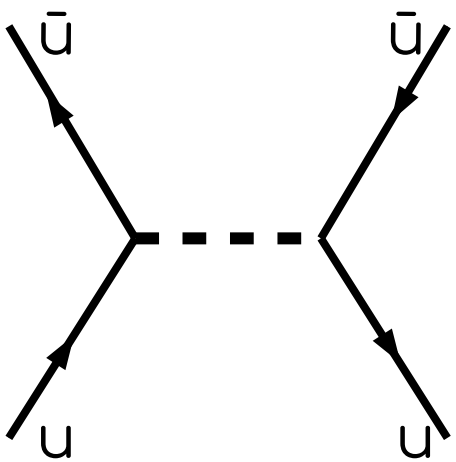


QMC

- So on the quark level we have the following lagrangian

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m_q + g_\sigma^q \hat{\sigma} + g_\omega^q \hat{\omega\!\!\!/} + g_\rho^q \hat{\boldsymbol{\rho}} \cdot \boldsymbol{\tau} + g_\delta^q \hat{\boldsymbol{\delta}} \cdot \boldsymbol{\tau})\psi + \mathcal{B}$$

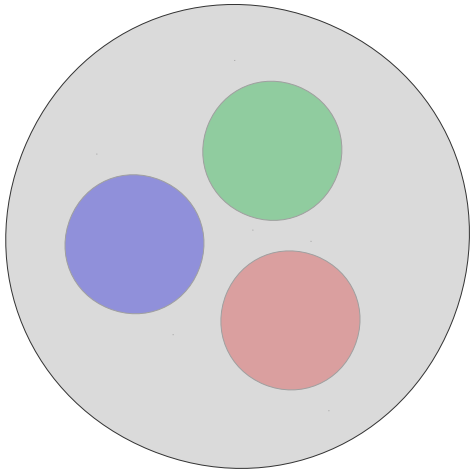


QMC

- We solve the equations for the bag model

$$(i\gamma \cdot \partial - m_q)\psi = 0, \ \forall r < R_B$$

$$(1 + i\gamma \cdot \hat{r})\psi\Big|_{r=R_B} = 0$$



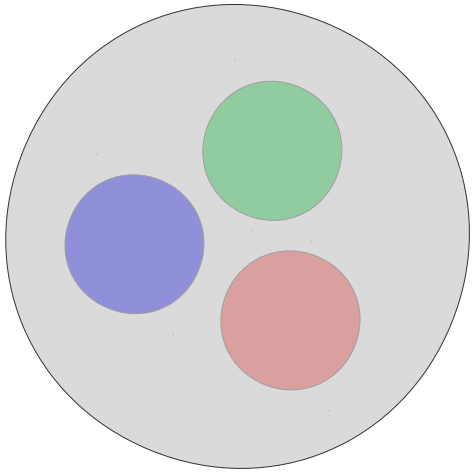
QMC

- The lowest positive energy mode with spin m

$$\phi_m(\vec{r}) = N \begin{pmatrix} j_0(xr/R_B) \\ i\beta_q \vec{\sigma} \cdot \hat{r} j_1(xr/R_B) \end{pmatrix} \times \frac{\chi_m}{\sqrt{4\pi}}$$

- Where

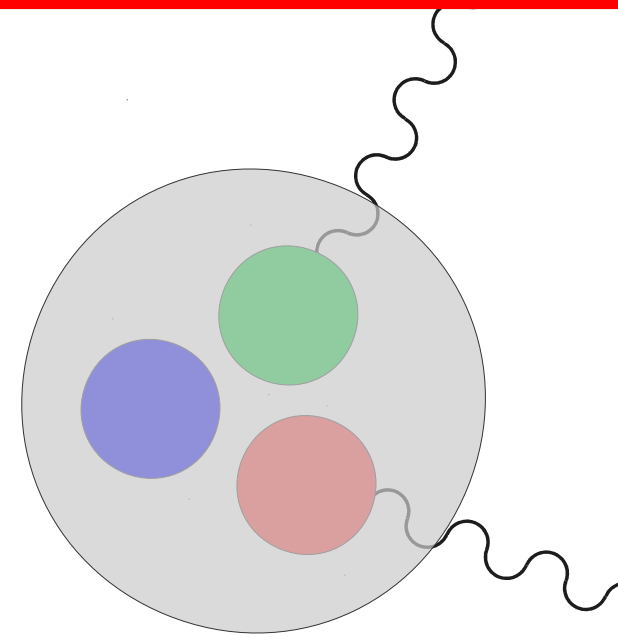
$$\beta = \sqrt{\frac{\Omega - m_q R_B}{\Omega + m_q R_B}}$$



$$\Omega = \sqrt{x^2 + (m_q R_B)^2}$$

QMC

- Now in our case, the quarks couple to the mesons.



- The solution is the same only with effective mass and momentum

$$m_q^\star = m_q - g_\sigma^q \sigma + g_\delta^q \delta_\times I^q$$

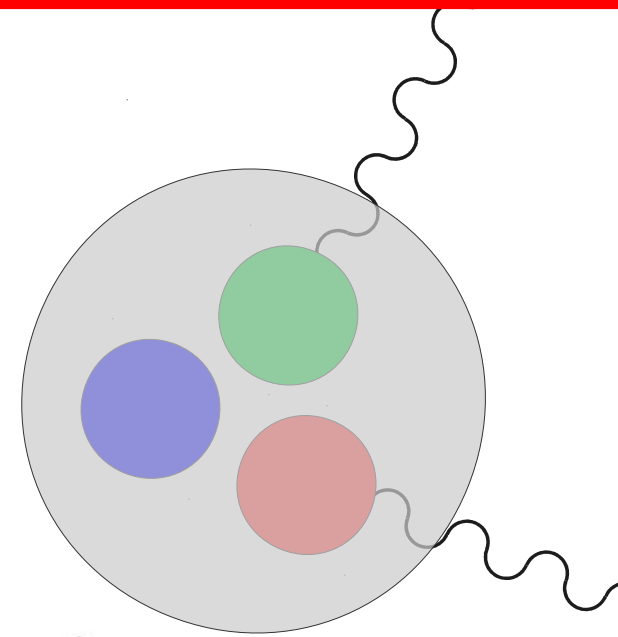
$$\vec{k}_q^\star = (g_\omega^q \omega(\vec{R}) + g_\rho^q \rho(\vec{R})_\times I^q)\hat{v} \cosh \xi$$

- And

$$\Omega = \sqrt{x^2 + (m_q^\star R_B)^2} \quad \beta = \sqrt{\frac{\Omega - m_q^\star R_B}{\Omega + m_q^\star R_B}}$$

Now depend on the meson fields

QMC



- Ok, now, the quarks are sources of meson fields:

$$(\partial^2 + m_\sigma^2)\hat{\sigma} = g_\sigma^q \bar{\psi}_q \psi_q$$

- Or the baryons are sources of meson fields:

$$(\partial^2 + m_\sigma^2) \langle A | \hat{\sigma} | A \rangle = g_\sigma^q \langle A | \bar{\psi}_q \psi_q | A \rangle$$

- Which at the baryonic level becomes field dependent

$$g_\sigma^q \langle A | \bar{\psi}_q \psi_q | A \rangle \rightarrow g_\sigma(\sigma, \delta) \bar{\Psi} \Psi$$

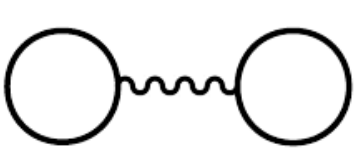
QMC

- If we have Baryons as sources for Meson fields we can write:

$$\mathcal{L} = \bar{\Psi}(i\partial\!\!\!/ - M_B)\Psi + g_\sigma(\sigma,\delta)\bar{\Psi}\Psi + \cdots$$

- So we have an effective Lagrangian, describing the physics of Baryons, but including effects of their quark internal structure!!!

- All there is left to do is solve the many body problem for this system...

$\mathcal{E} = \sum_i$ $+ \sum_{i,j} \Big($  $+$ $+ \cdots \Big)$

$\mu_i = \sqrt{k_F^2 + m_i^2} + \sum_{j,l} \Big($ $+$ $+ \cdots \Big)$

QMC

- We can see the system as baryons with effective mass.

$$M_B^\star(\sigma,\delta) = M_B - g_\sigma(\sigma,\delta)\sigma + g_\delta(\sigma,\delta)\delta_\times I^q$$

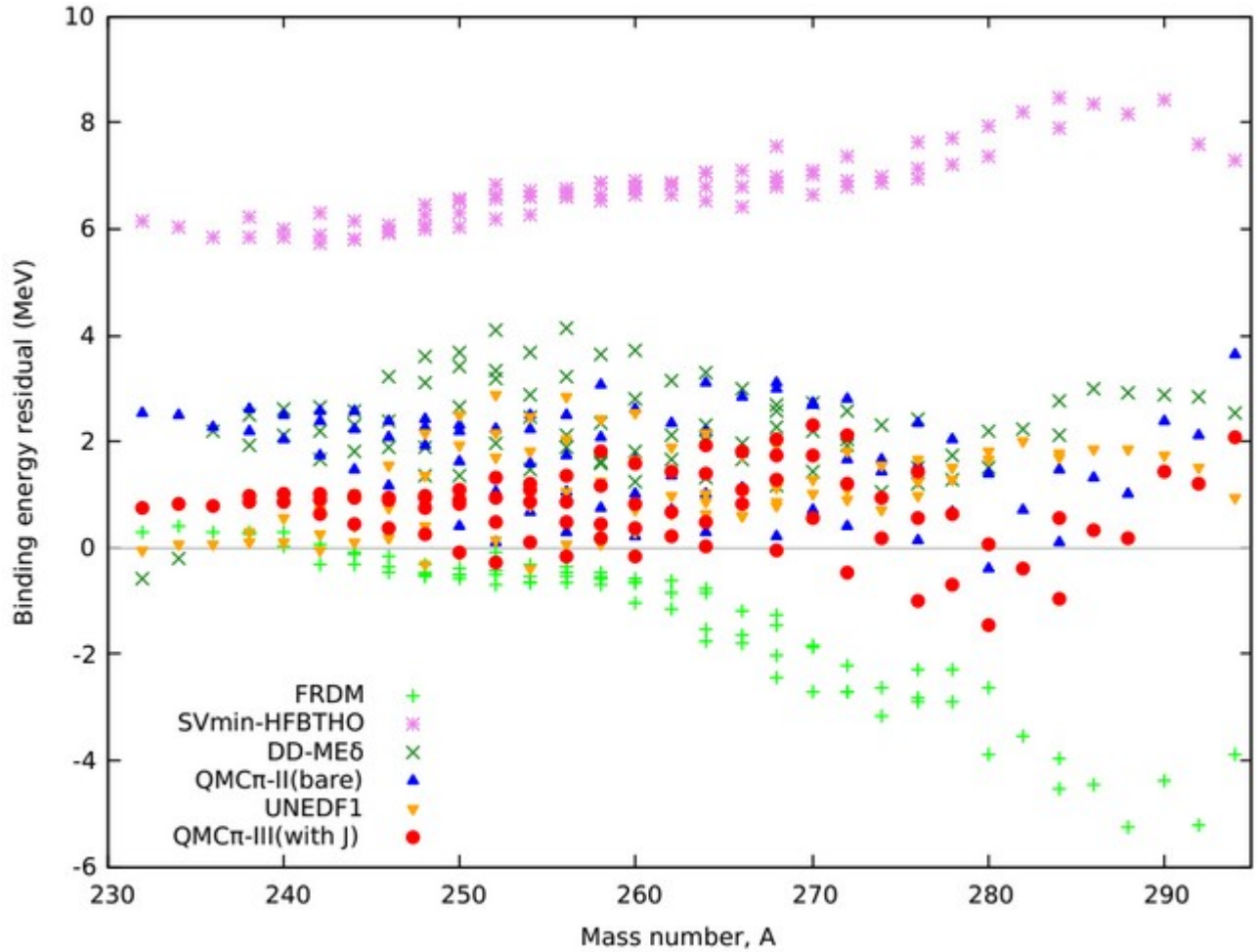
- Where the meson fields are the respective mean field values.

- In order to connect the quark-level theory to the nuclear-level theory we fit this values to the mass derived from the MIT bag model solution:

$$M_B^\star = \sum_f \frac{n_f\Omega_0 - z_0}{R_B} + \mathcal{B}V_B + \Delta_{EM}$$

Finite Nuclei

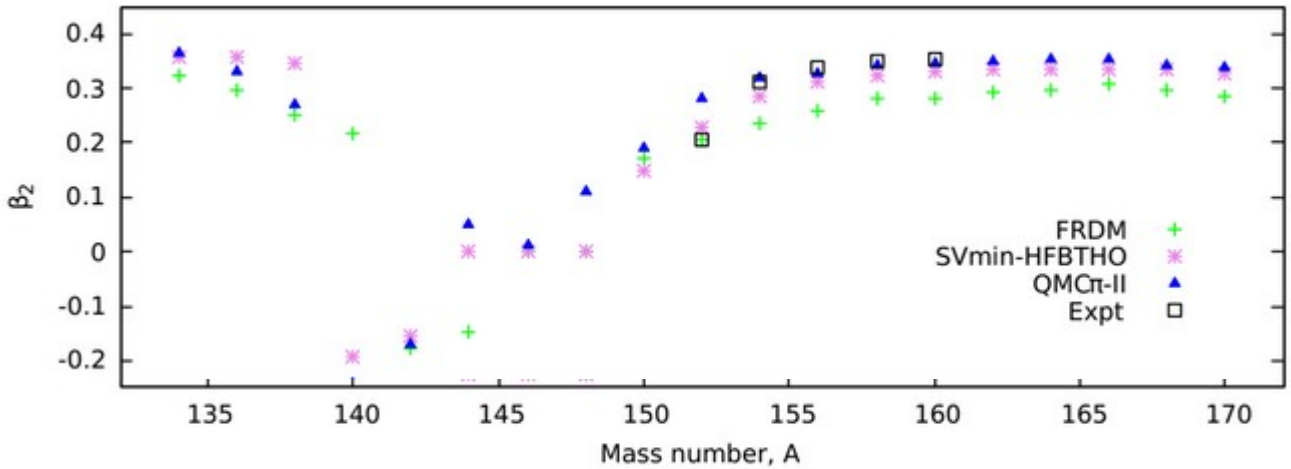
- Binding energies for heavy nuclei



Martinez, K. L. et al. Physical Review C, 100 024333.

Finite Nuclei

- Binding energies for heavy nuclei
- Deformation



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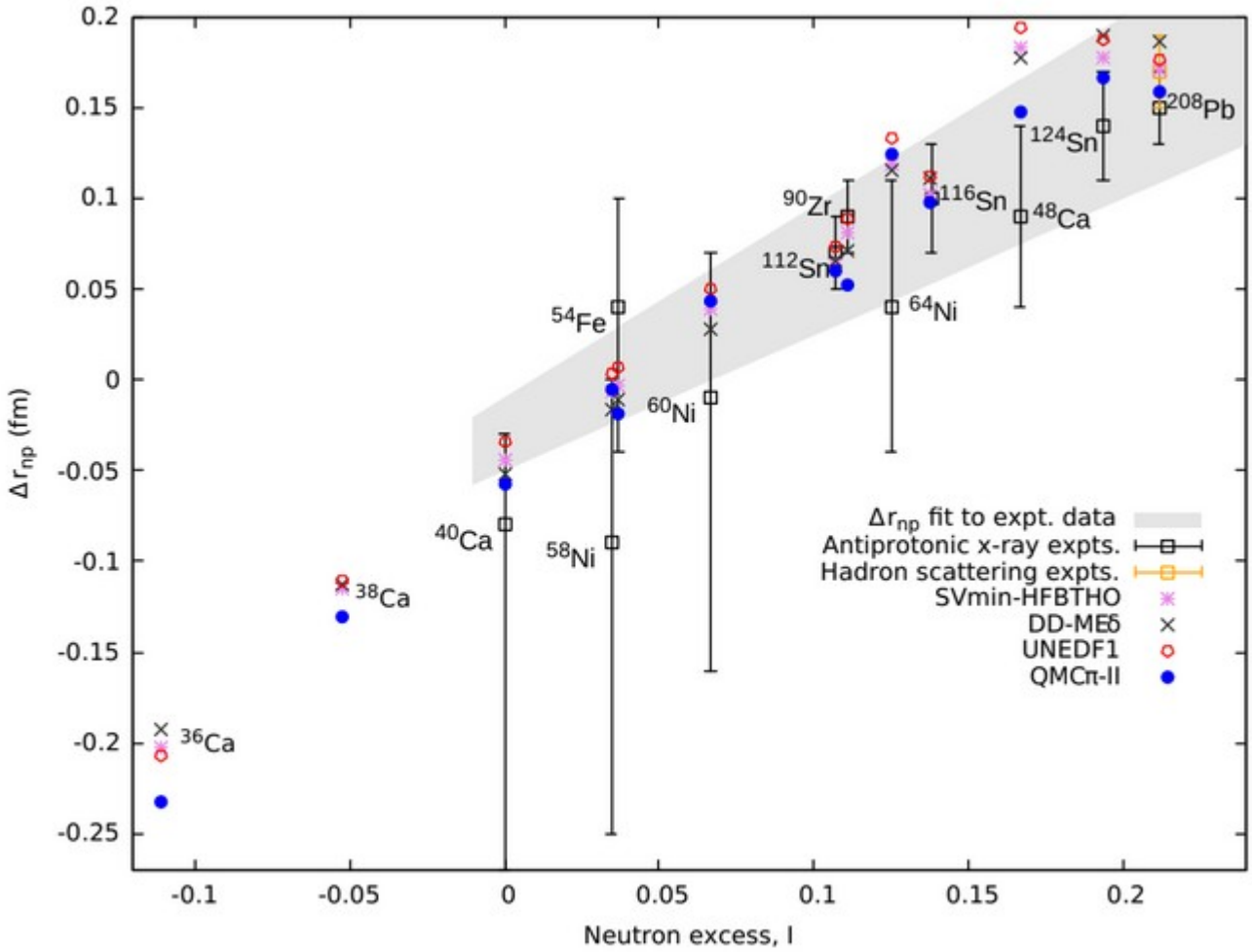
Finite Nuclei

- Binding energies for heavy nuclei
- Deformation
- Neutron Skin Thickness



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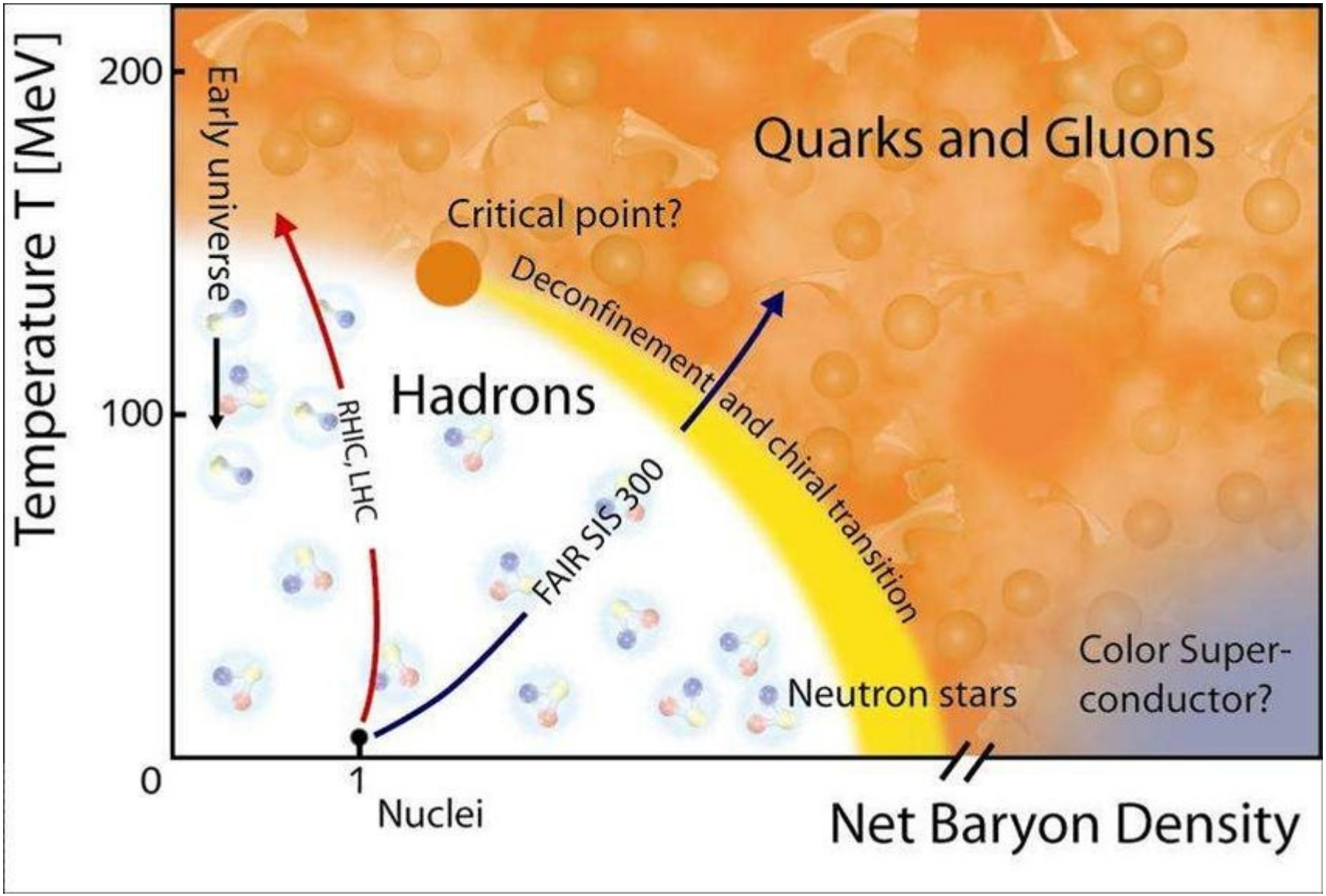
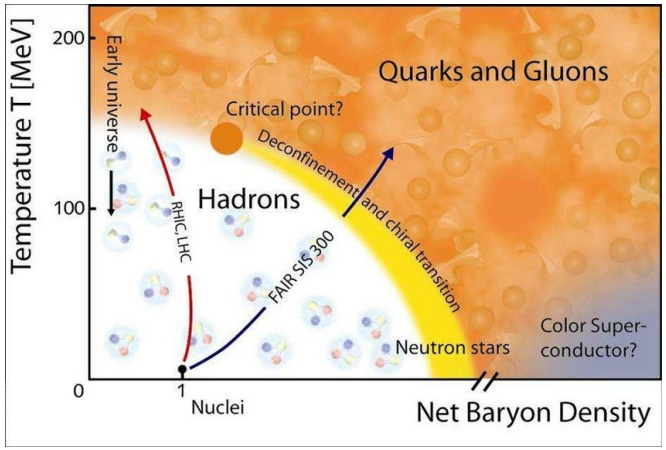
Neutron Stars

Why Neutron Stars?



Why Neutron Stars?

- Expected density around ~1 fm^{-3}.
  (If the star's mass is large!!!)



Why Neutron Stars?

- Expected density around ~1 fm^{-3}.
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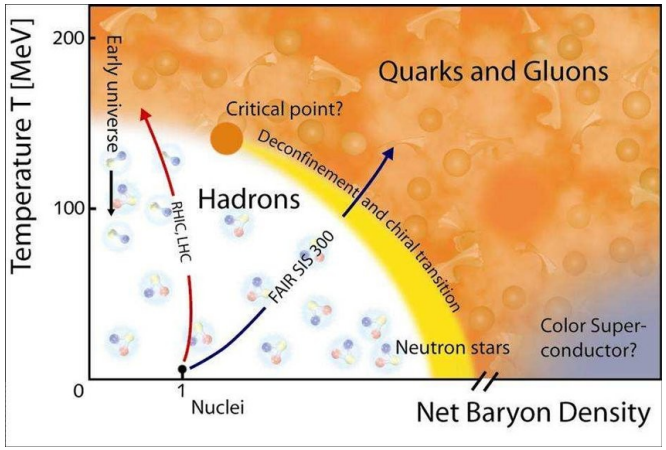
- If you take the baryon to be a spherical object of avg radius ~0.8fm

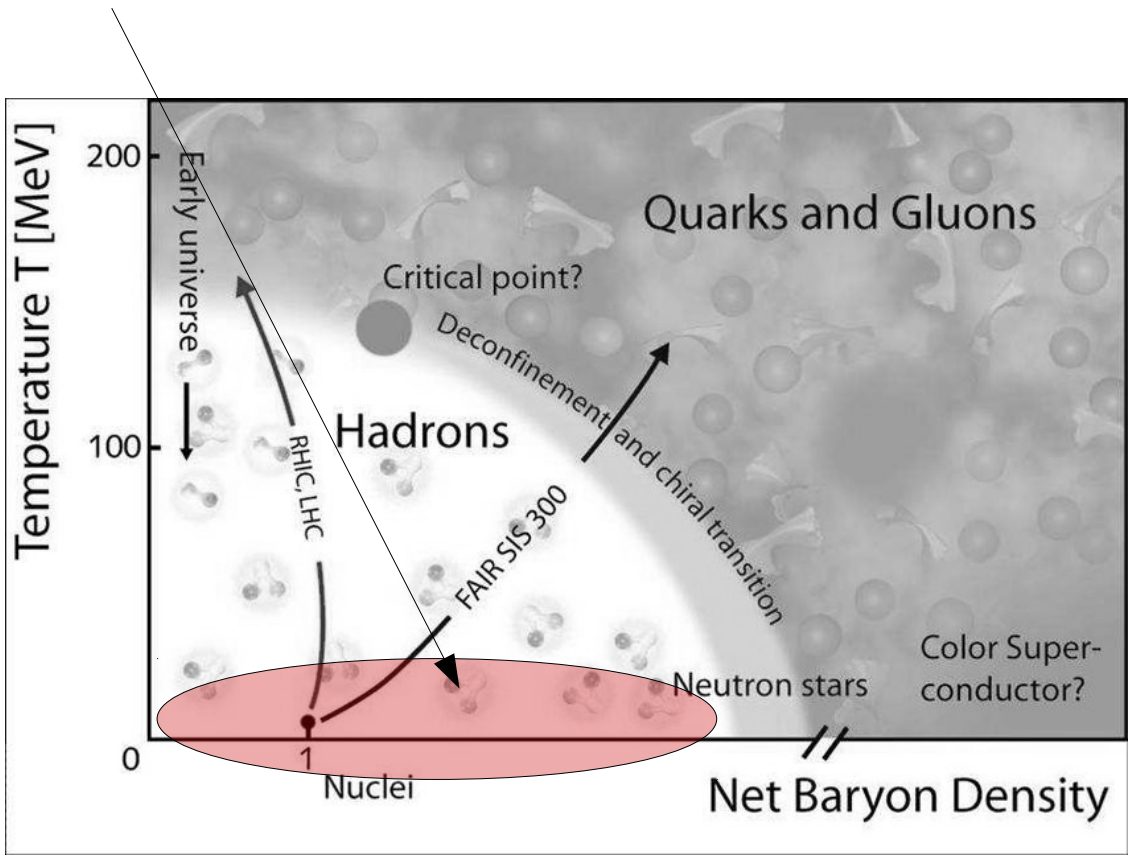
  Then the volume of the baryon is around 2.1 fm^3.



Why Neutron Stars?

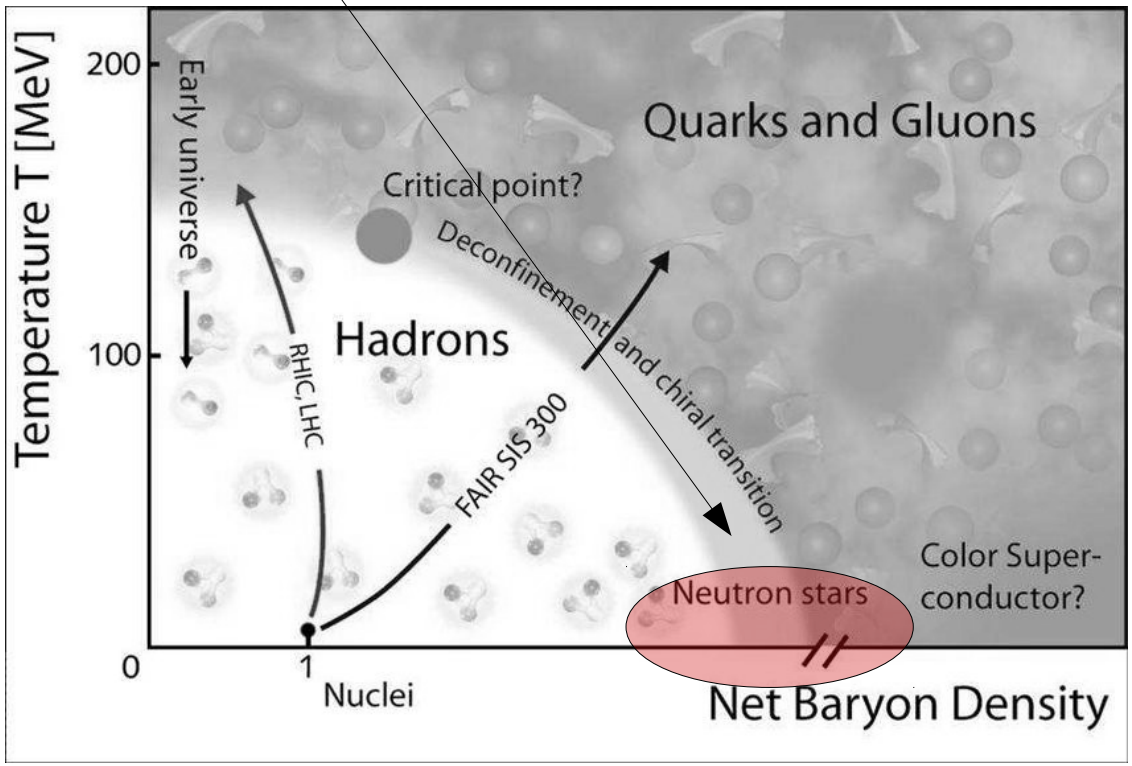
- How does matter look like at such high densities?

- QCD at **low densities** has only two flavours of quark (u,d)



Why Neutron Stars?

- But if density increases it should generate strangeness



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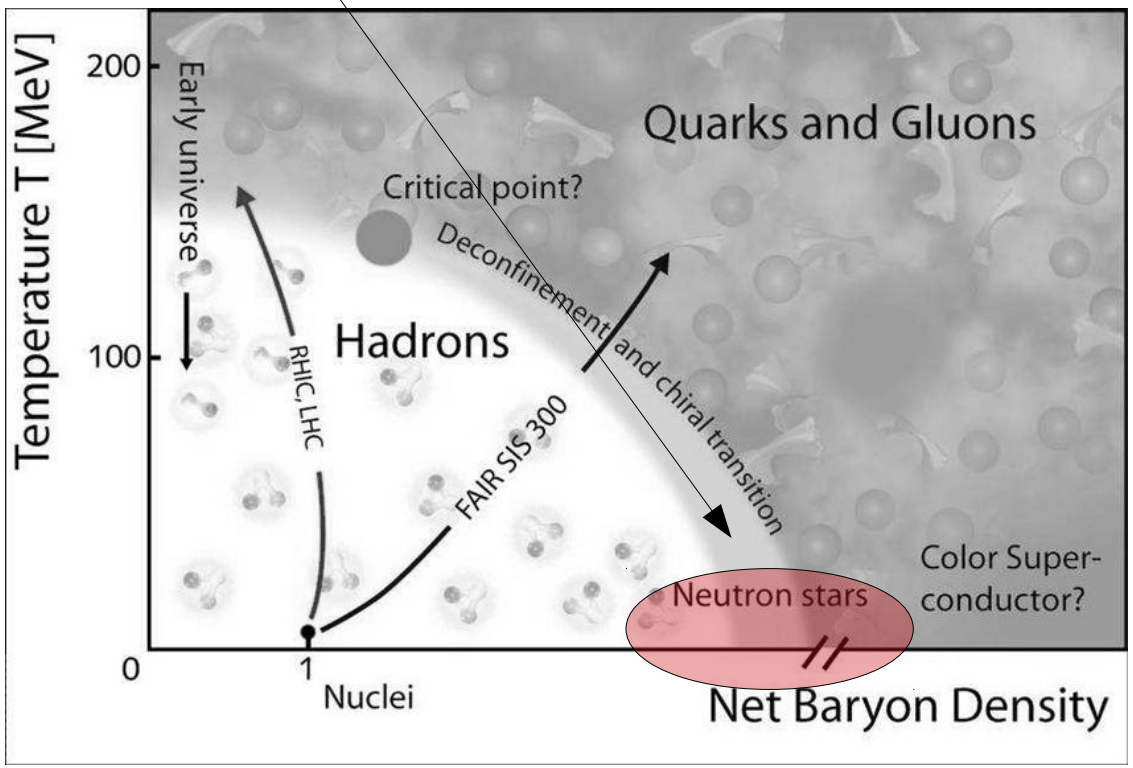
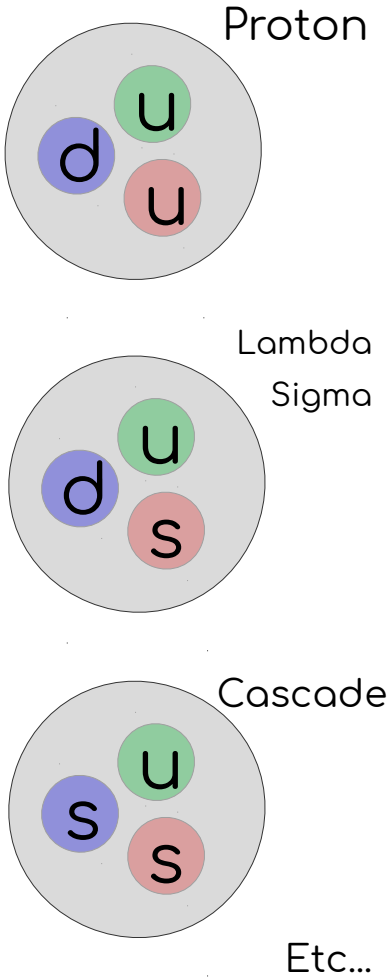
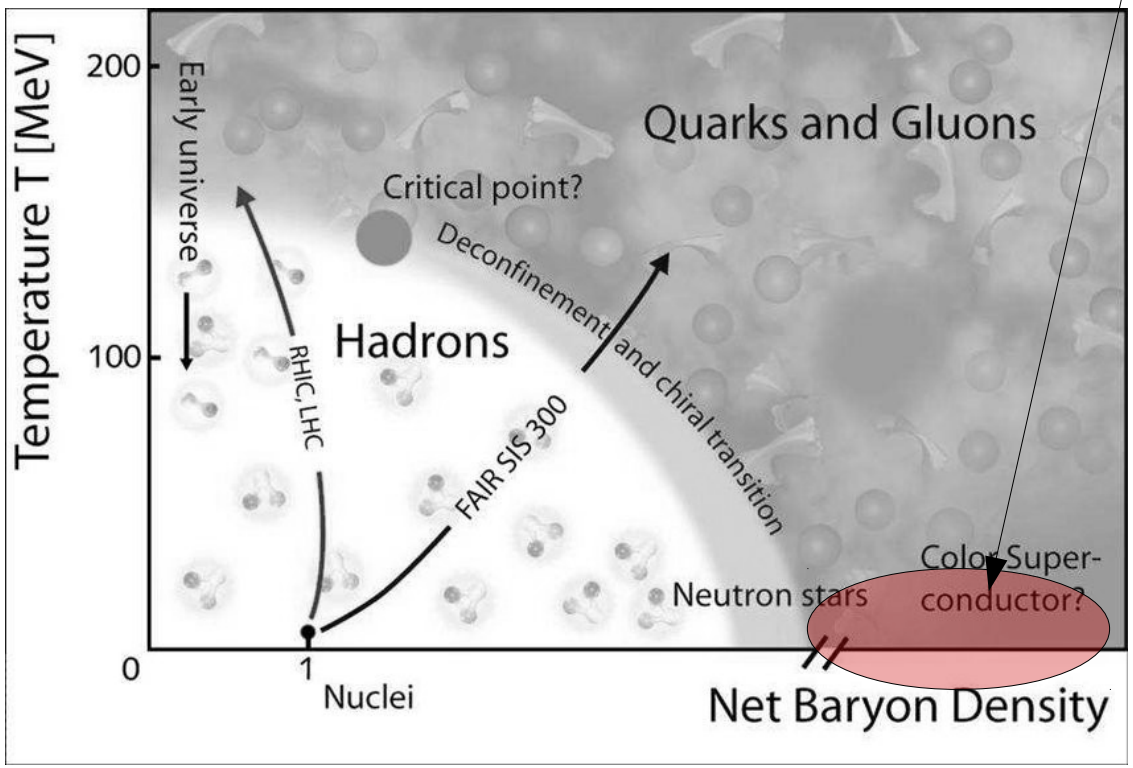




Why Neutron Stars?

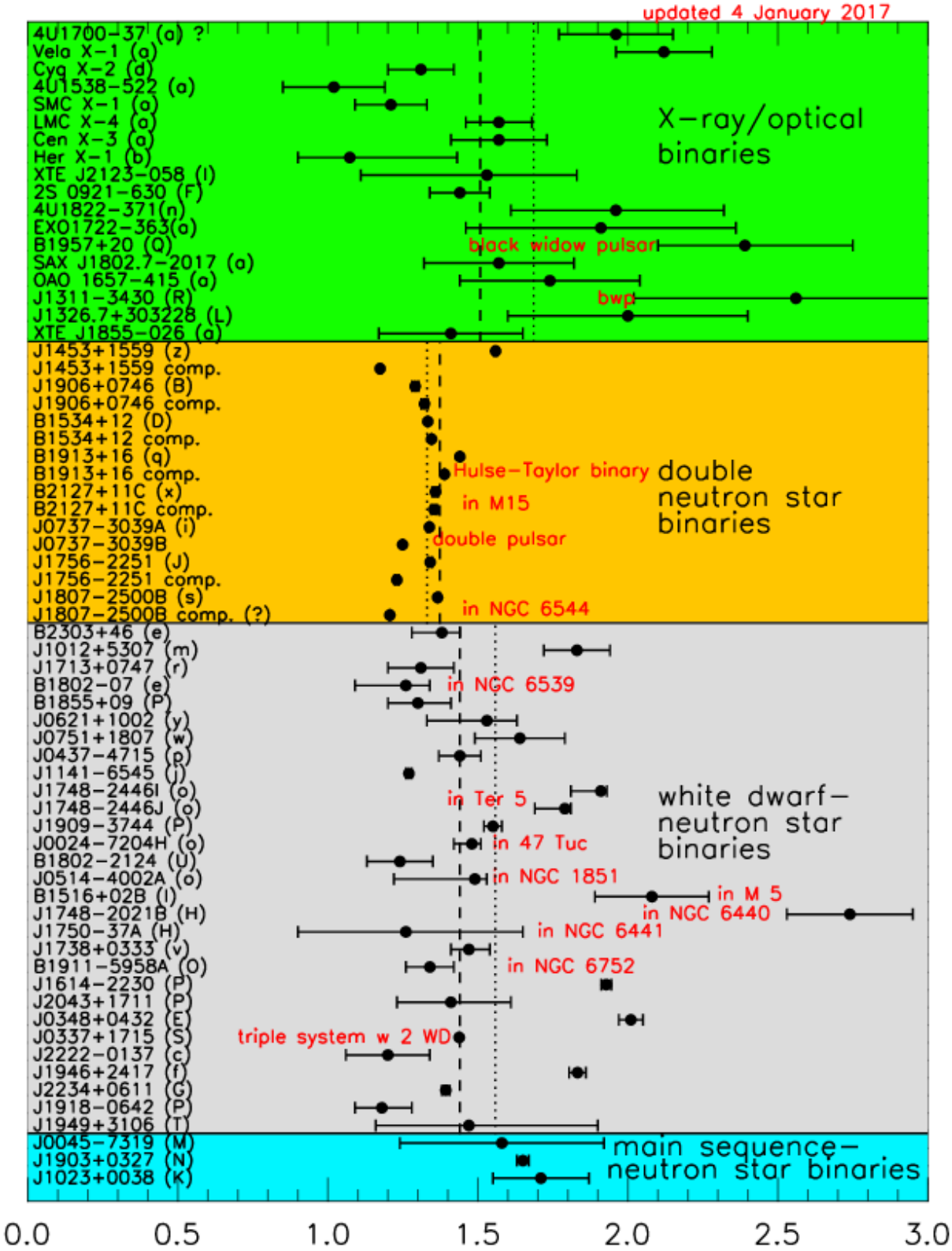
- And at high enough densities the baryons deconfine



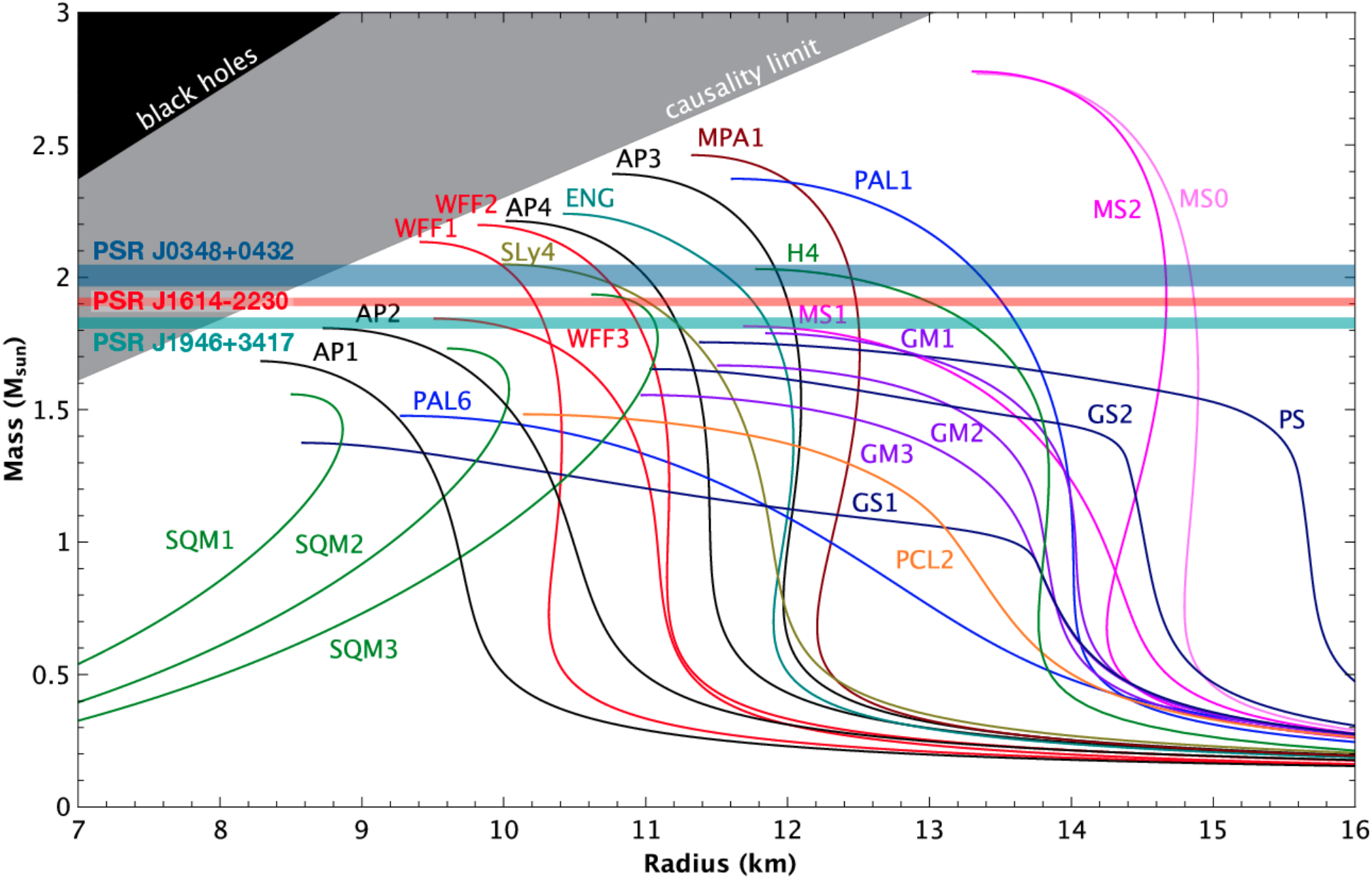
Mass - Radius

Mass

- Measuring masses is hard!
  Most data points have **large errors**
- Suspected to have large **systematic uncertainties**
- Each measurement is done **differently**

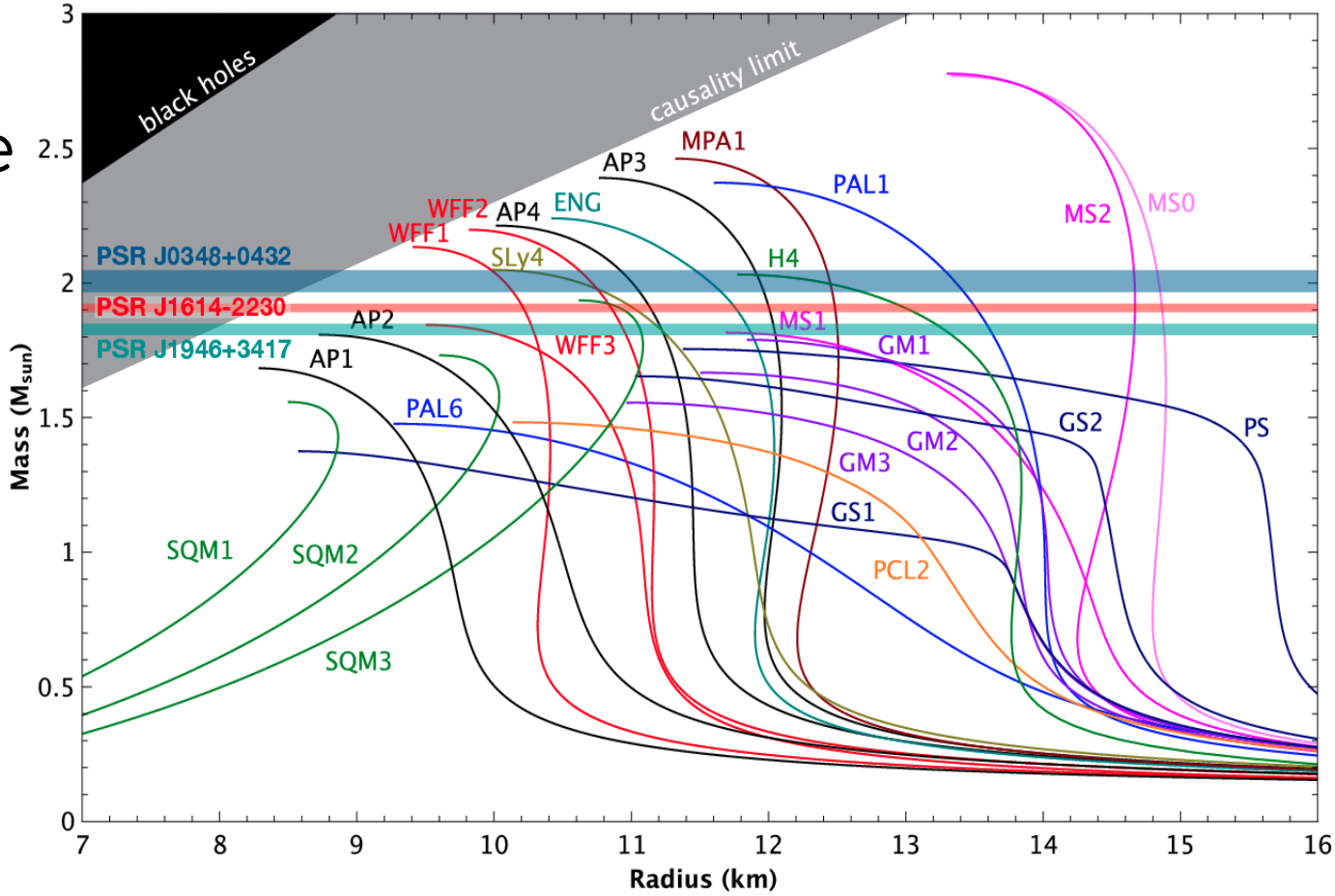


Mass-Radius


black holes
causality limit
PSR J0348+0432
PSR J1614-2230
PSR J1946+3417
MPA1
AP3
PAL1
WFF2
AP4
ENG
WFF1
SLy4
H4
MS2
MS0
AP2
MS1
WFF3
GM1
AP1
PAL6
GS2
PS
GM2
GM3
GS1
PCL2
SQM1
SQM2
SQM3
Mass (M_{sun})
Radius (km)
0
0.5
1
1.5
2
2.5
3
7
8
9
10
11
12
13
14
15
16

Mass-Radius

- Hyperon puzzle
- Quark puzzle
- Delta puzzle



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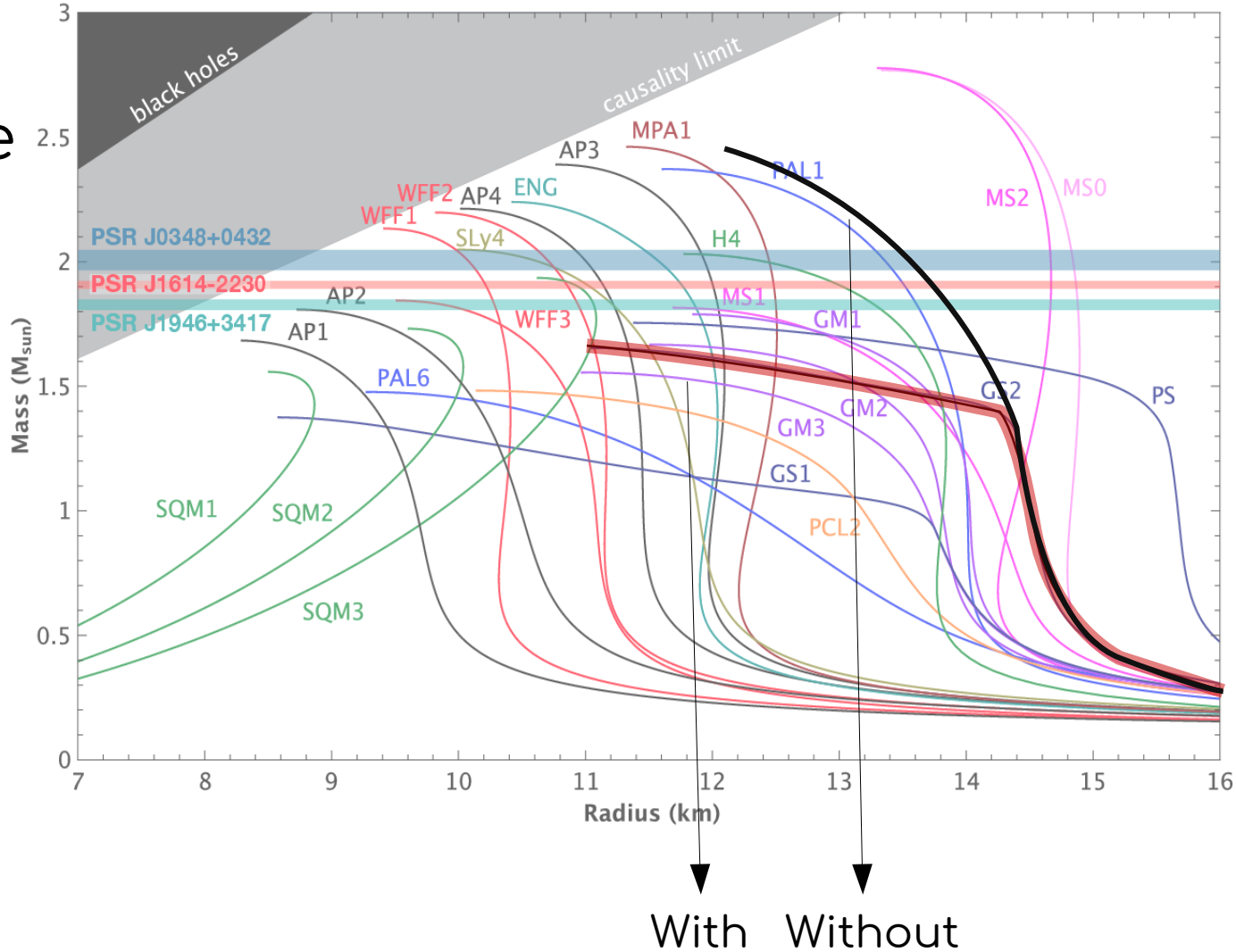

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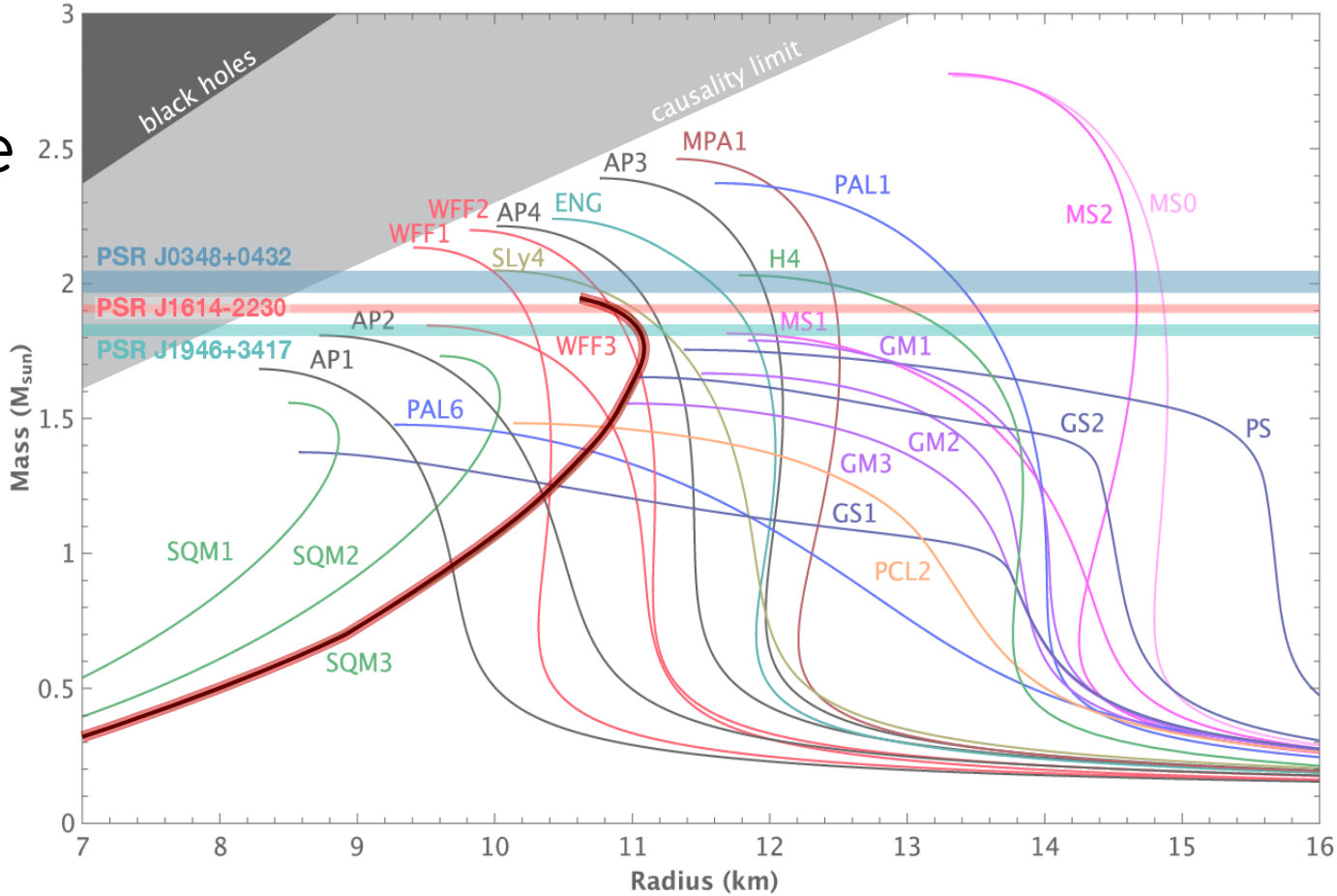

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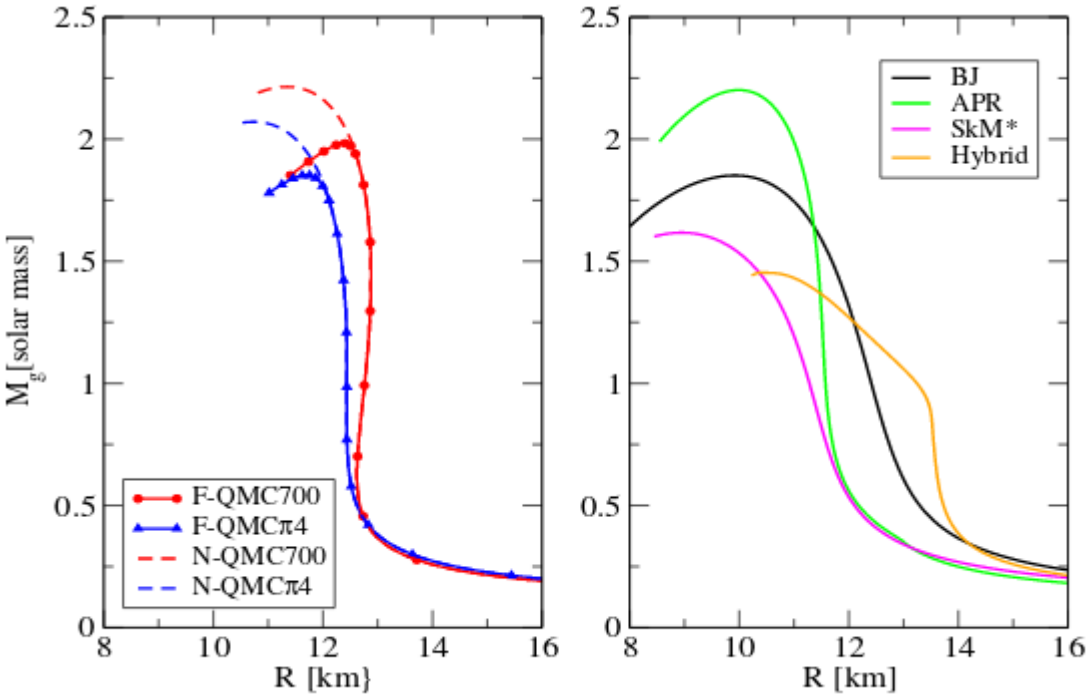
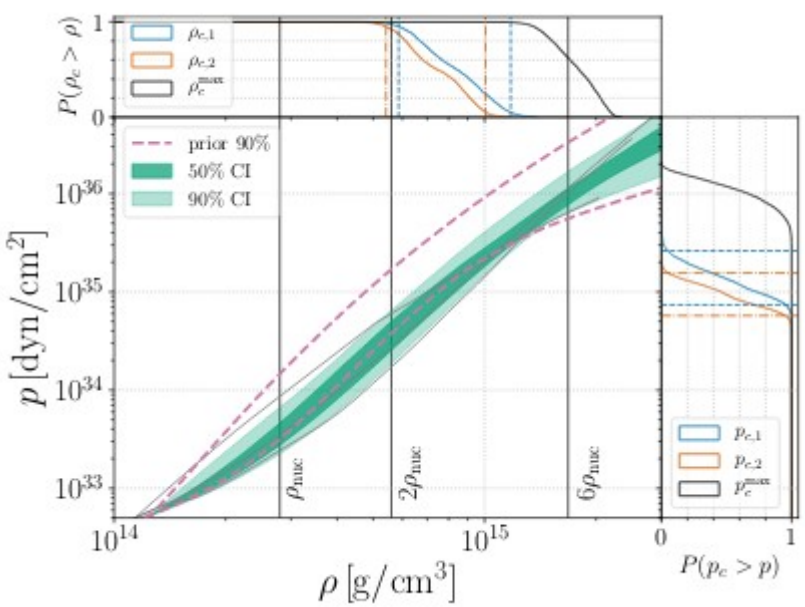


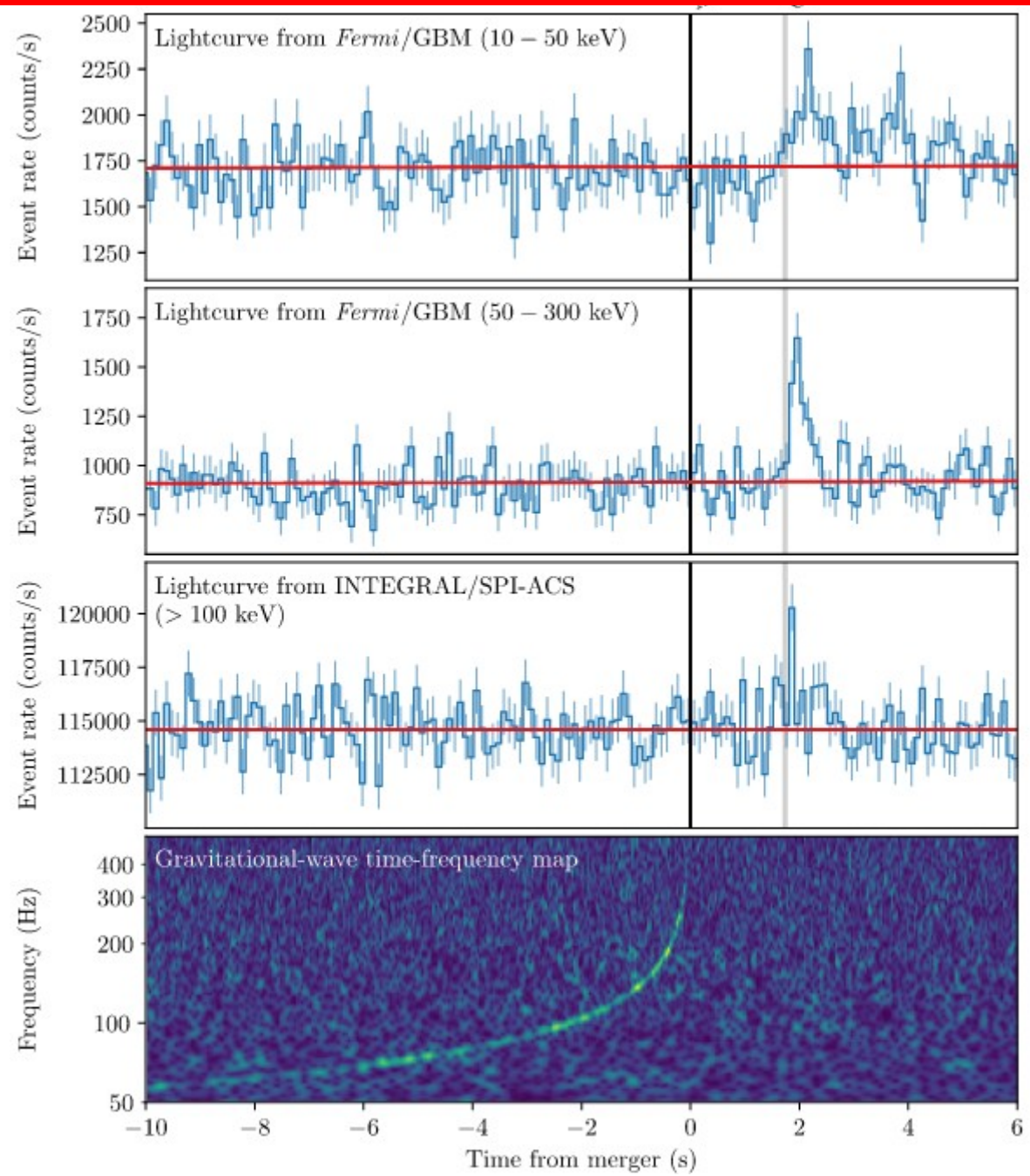
J.R. Stone, Nuclear Physics A 792 (2007)

Gravitational Waves

GW170817

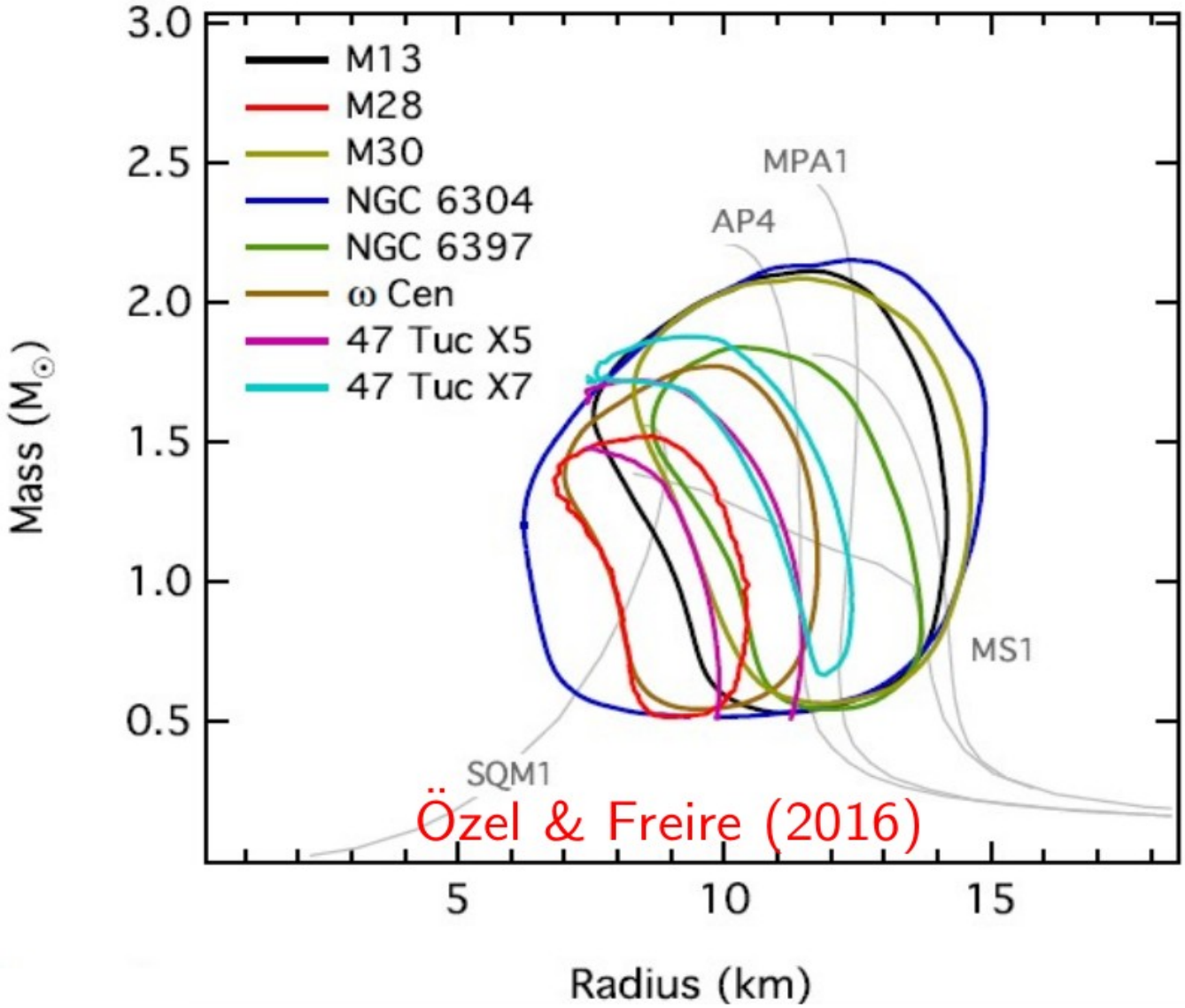
- Abbot et al (2017) measured a GW event of NS-NS merger
- From that they deduced the EOS to 90% confidence.





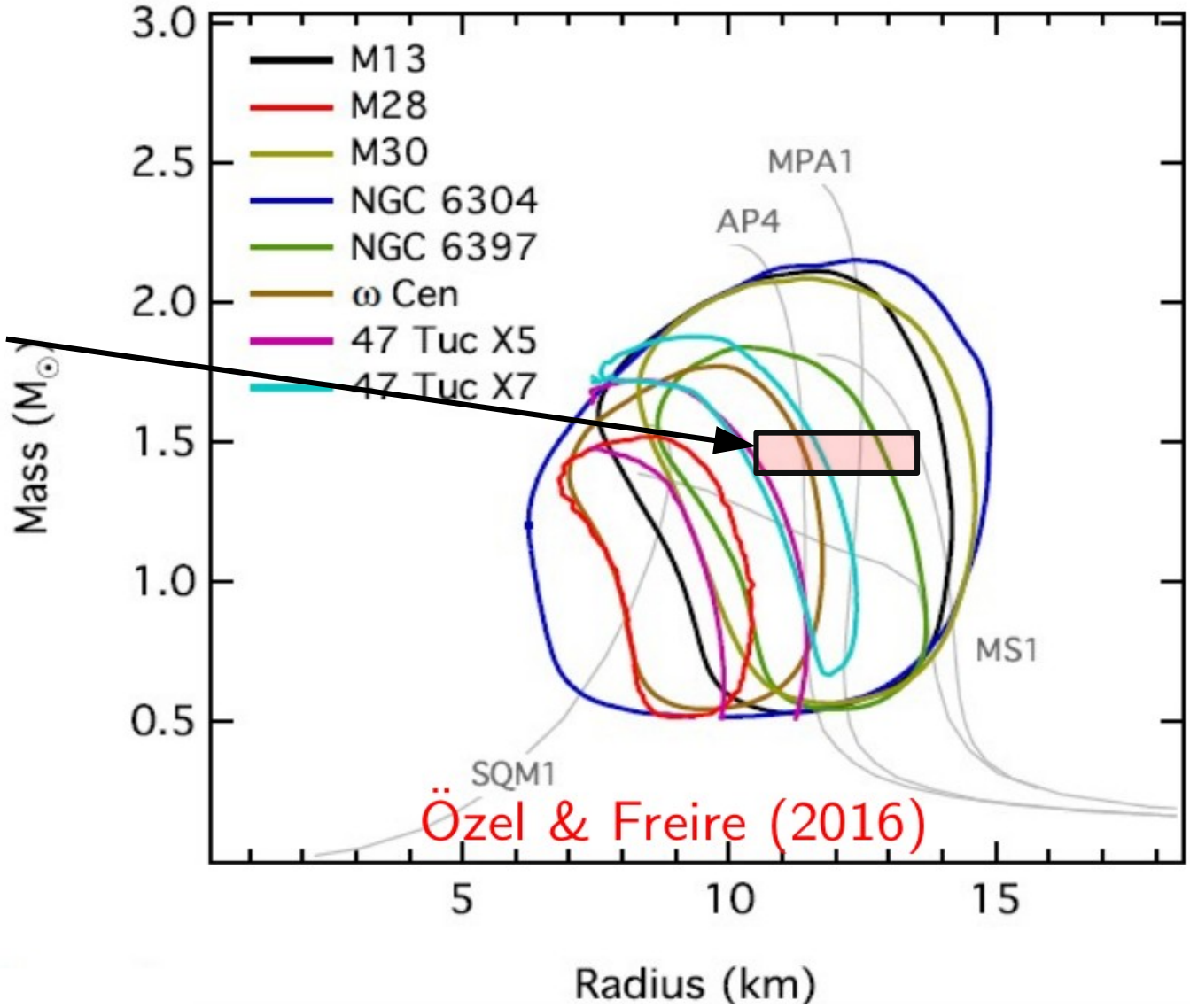
Radius

- Predictions go from 7 to 15 km

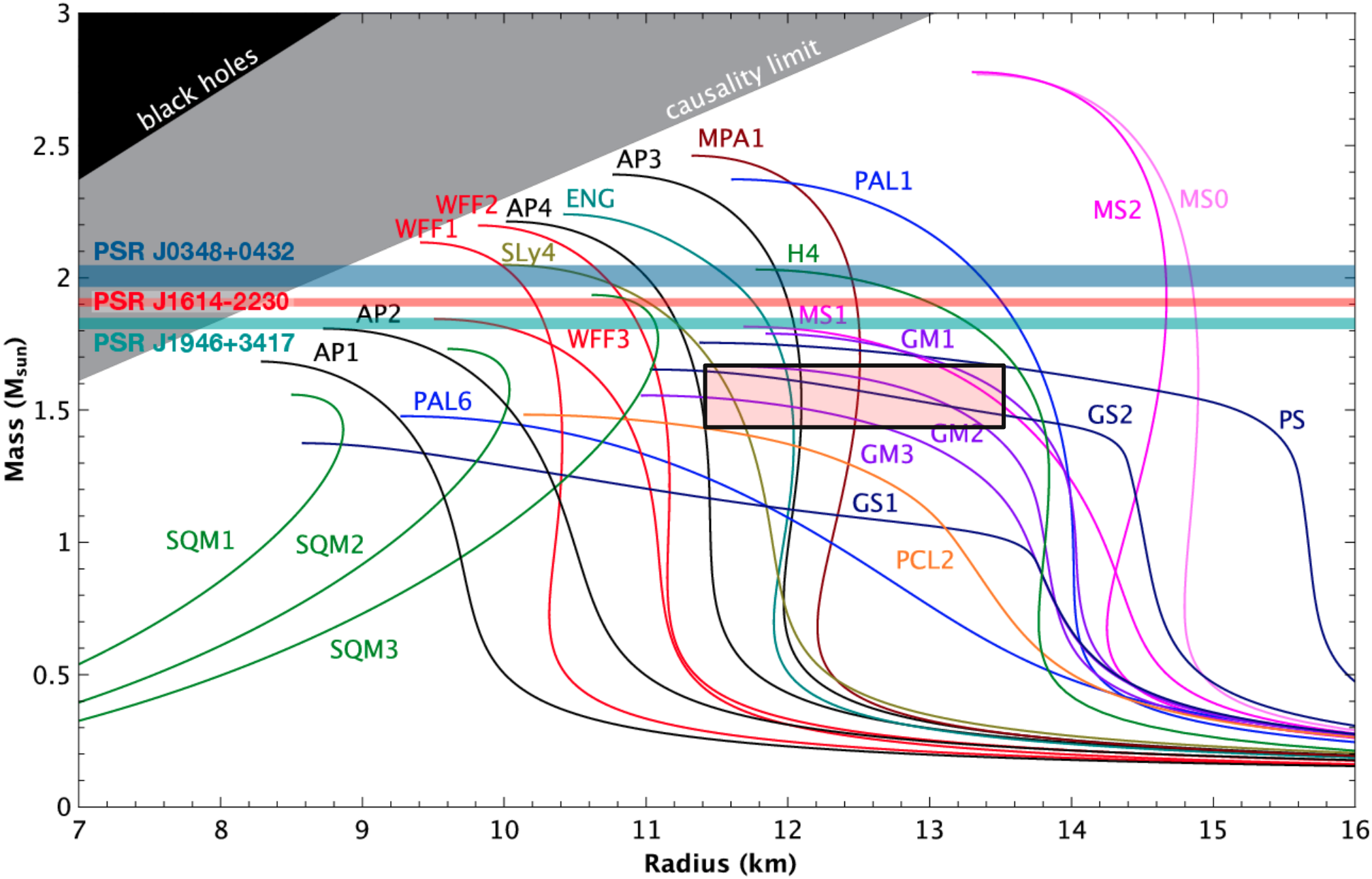


Radius

- Predictions go from 7 to 15 km
- GW170817 restricts that to 90% confidence



Mass-Radius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Mass (M_{sun})
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Forthcoming

NICER: The Neutron star Interior Composition Explorer

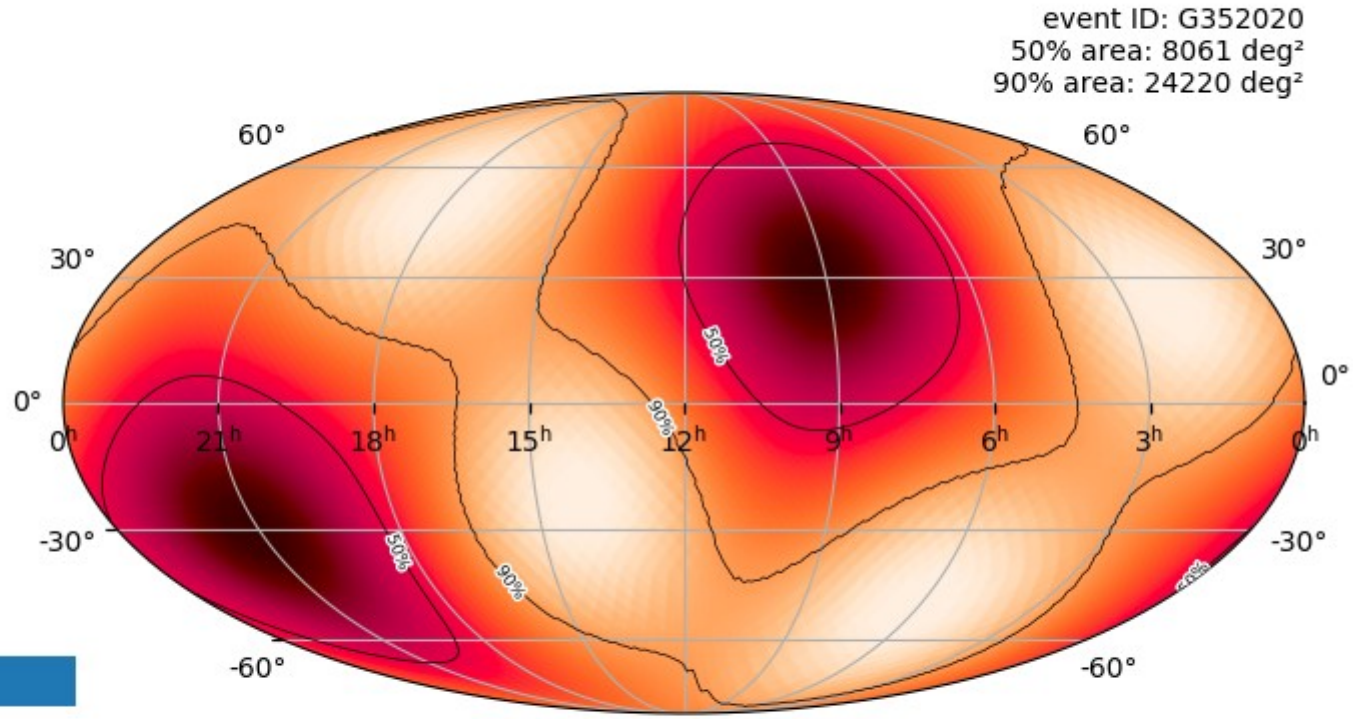
"NICER observations will achieve an accuracy of $\simeq$ 2% in the measurement of radius (Gendreau, Arzoumanian, and Okajima, 2012; Bogdanov, 2013). In practice, the measurement will be limited by uncertainties in these two requirements. The uncertainty in the mass measurement of NICER's primary target, the bright pulsar PSR J0437−4715, is ~5% (Reardonet al., 2016)."

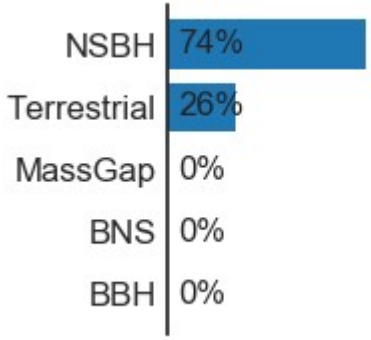
-*Watts et al. (2016)*

Forthcoming

Ligo is still measuring!

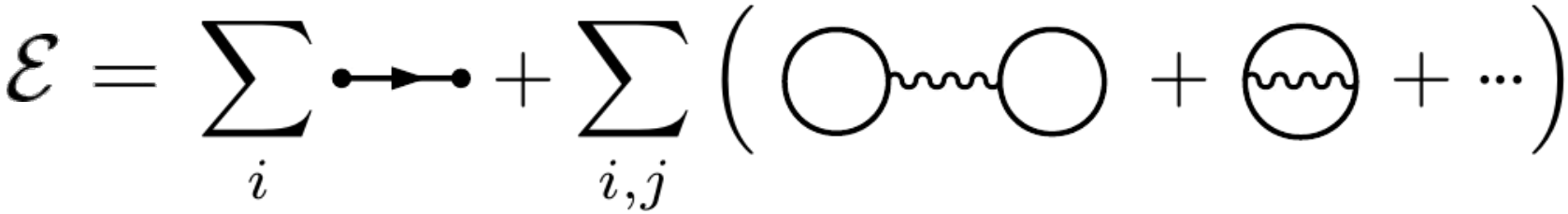
September 30th:



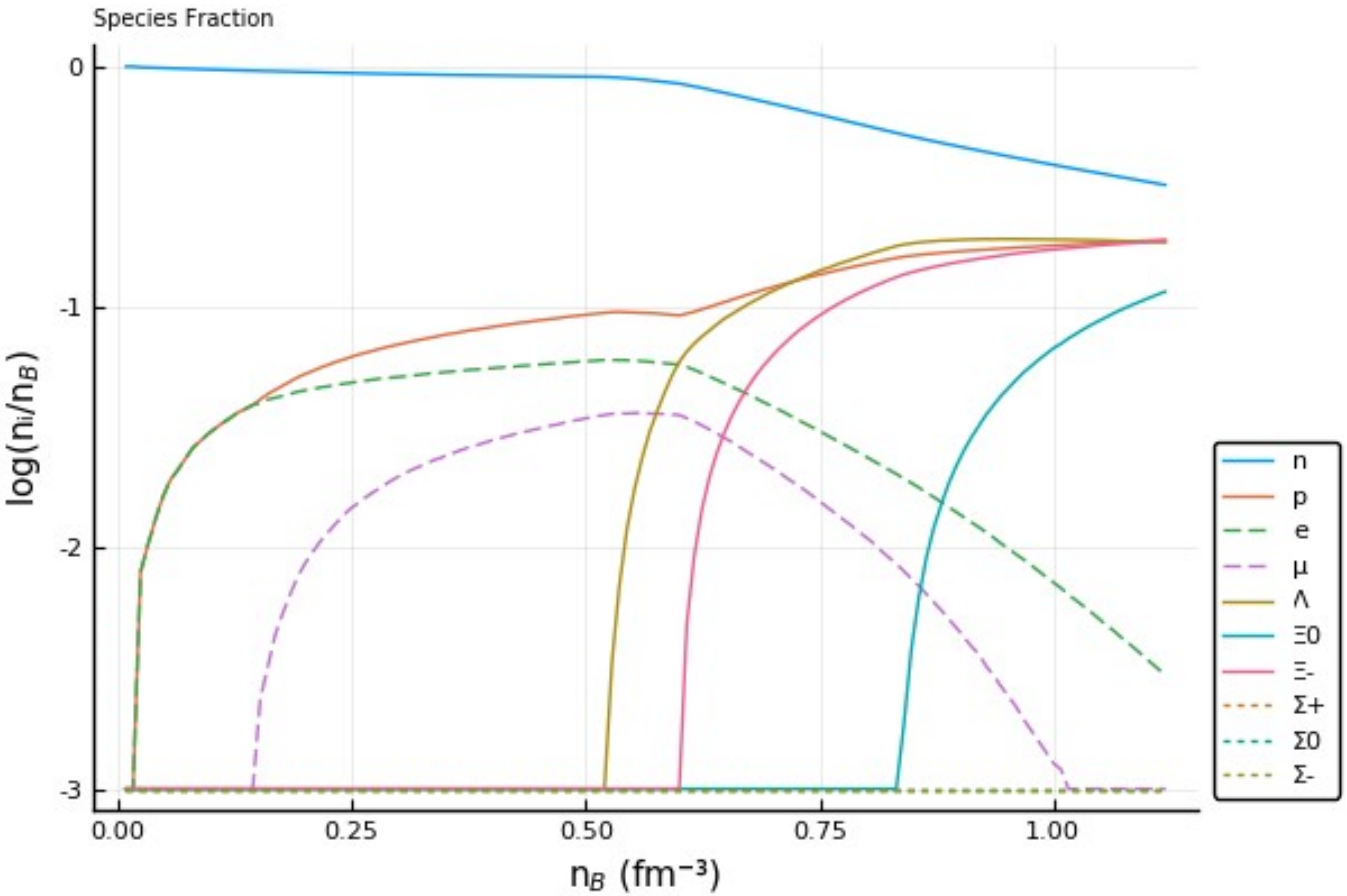


QMC Applied to NS

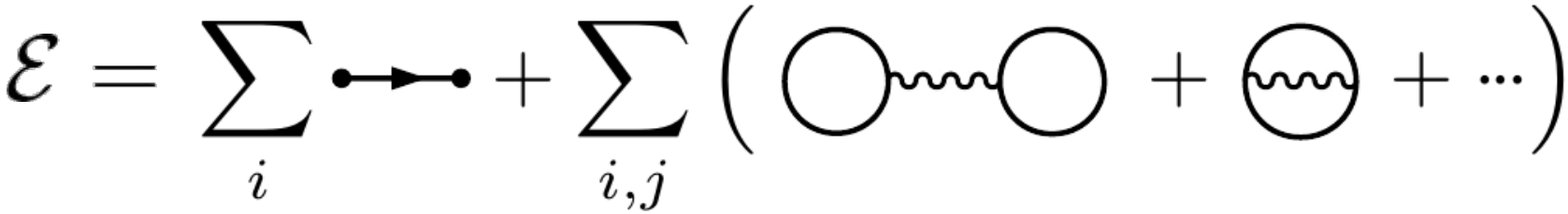
Population



- Minimize energy density (β-equilibrium)
- Get Population chart
- Get Energy and Pressure for each baryon density (EOS)



Population



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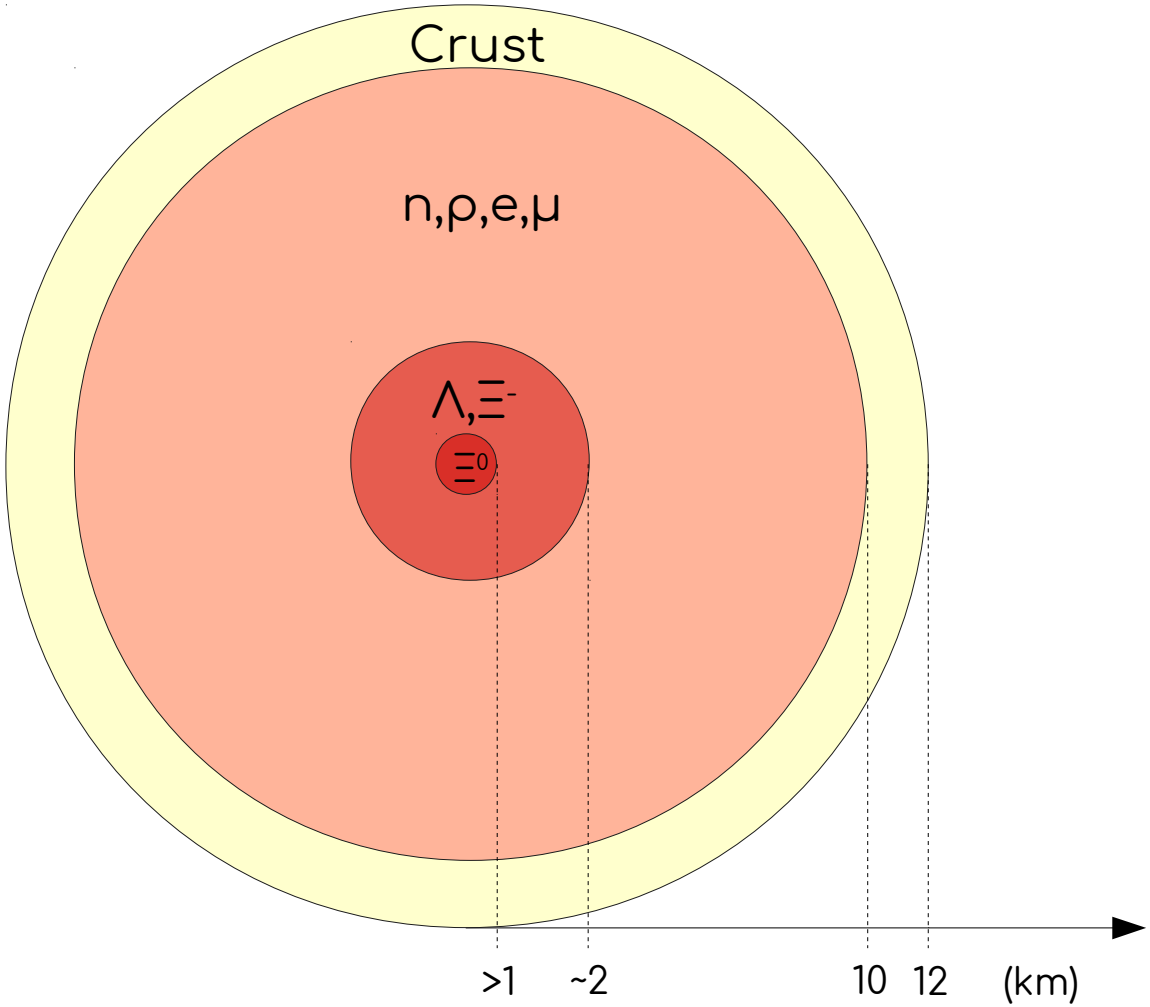
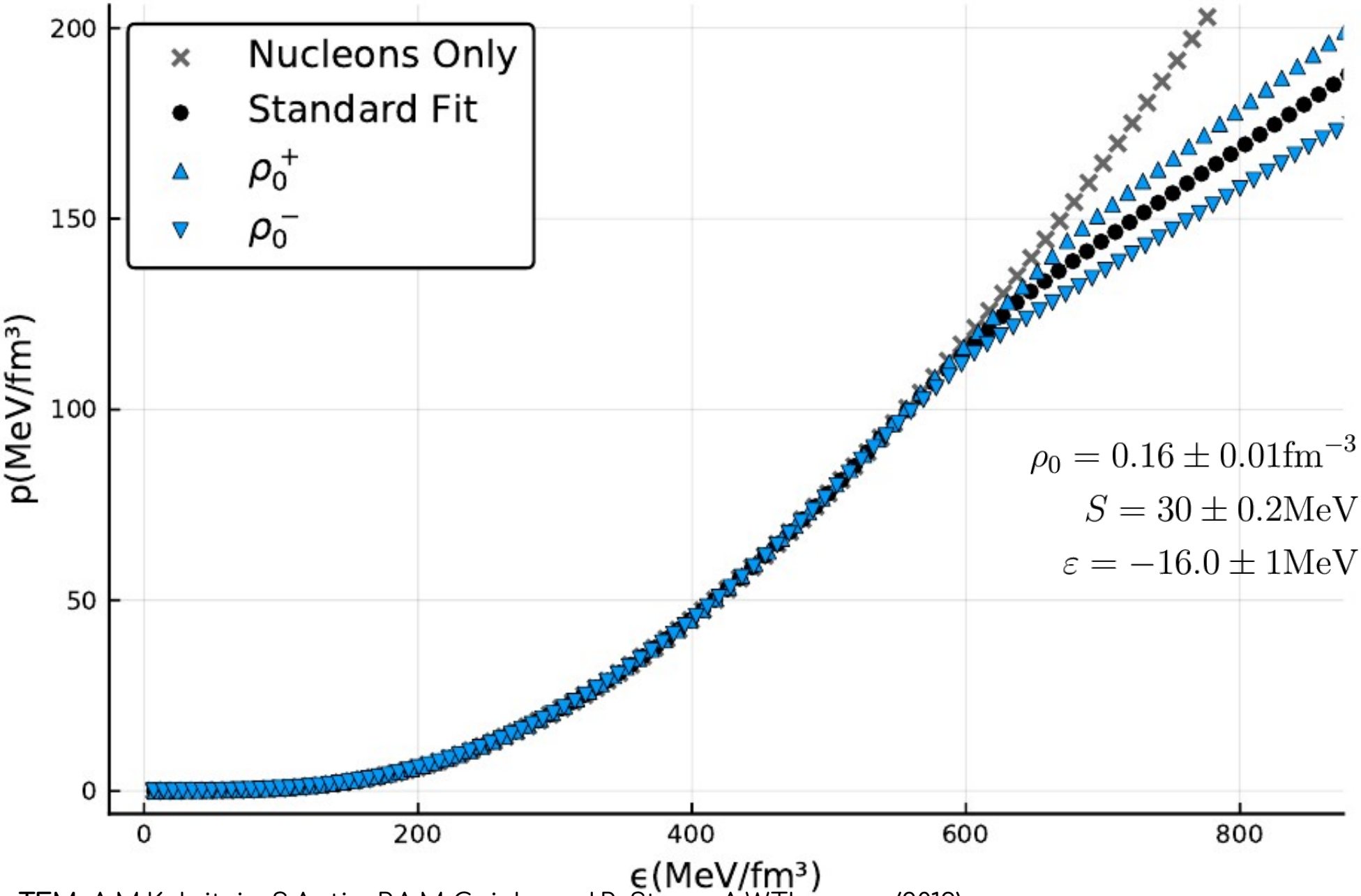
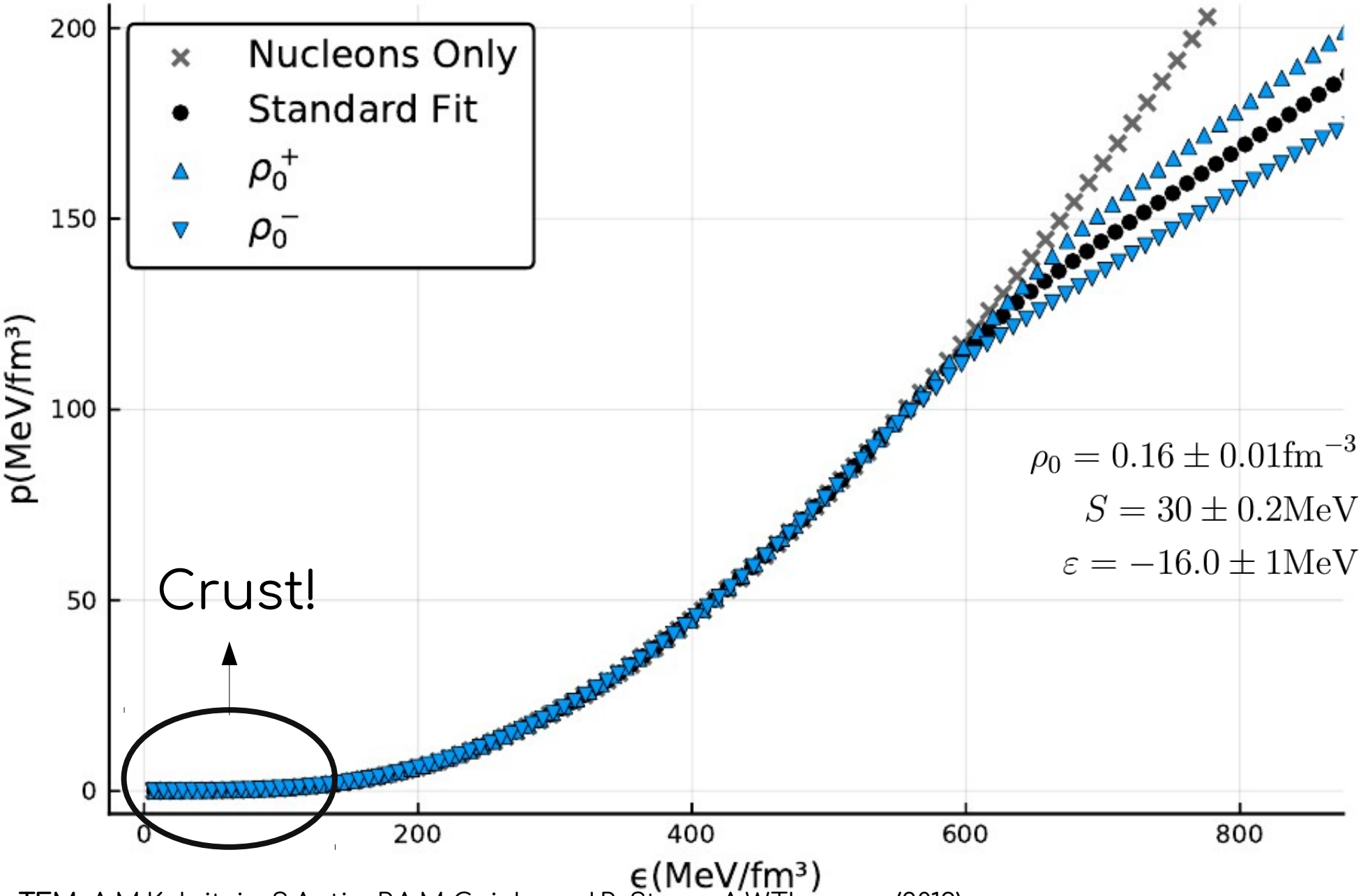


EOS



TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

EOS



TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

TOV

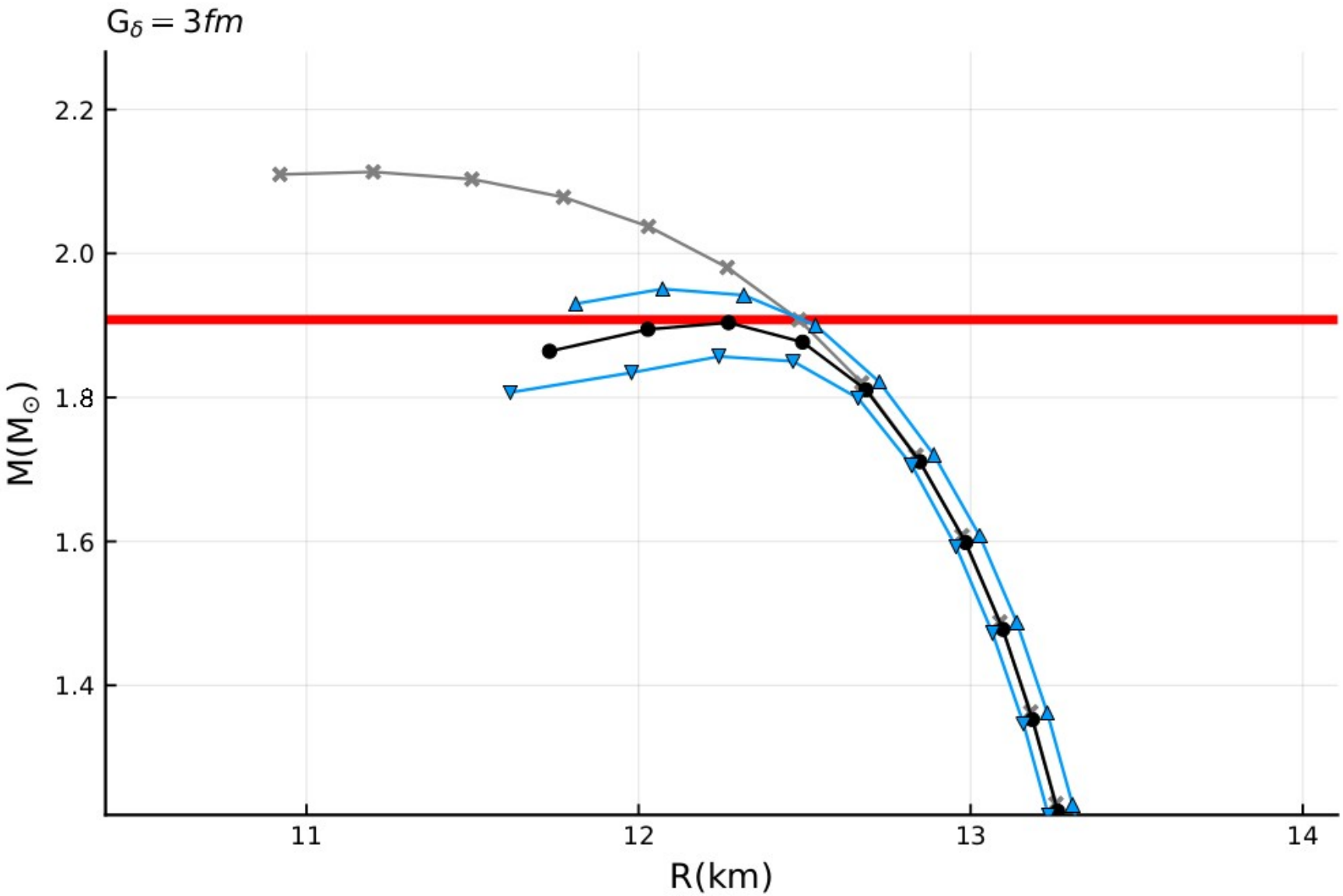
$$\frac{8\pi G}{c^4} T_{\mu\nu} = G_{\mu\nu}$$

Ideal Fluid

$$T^0_0 = \varepsilon$$
$$T^i_i = -P$$

$$\frac{dP}{dr} = -\frac{Gm}{r^2}\rho\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$

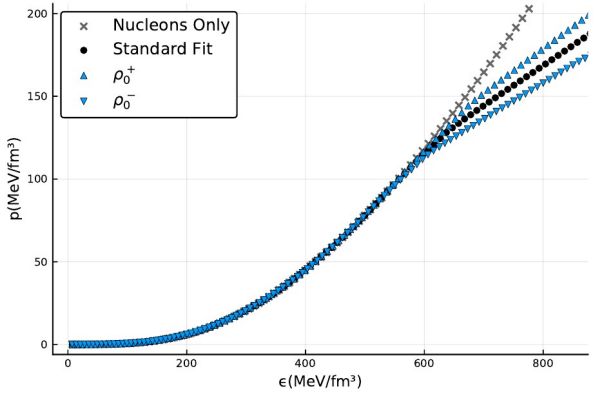
EOS

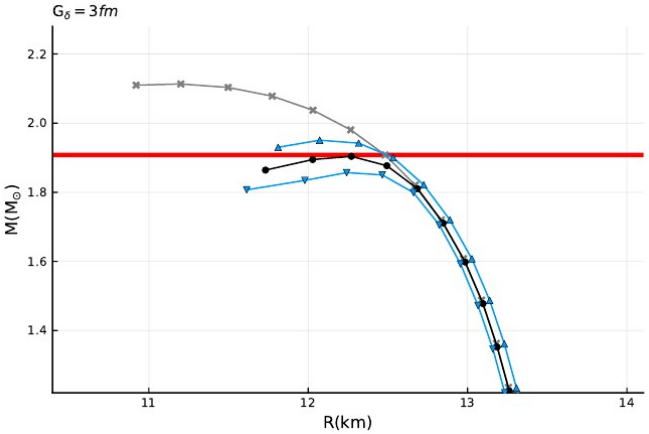


TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

EOS

- Equation of state does produce stars with masses of up to 1.9 solar masses for all values of delta coupling

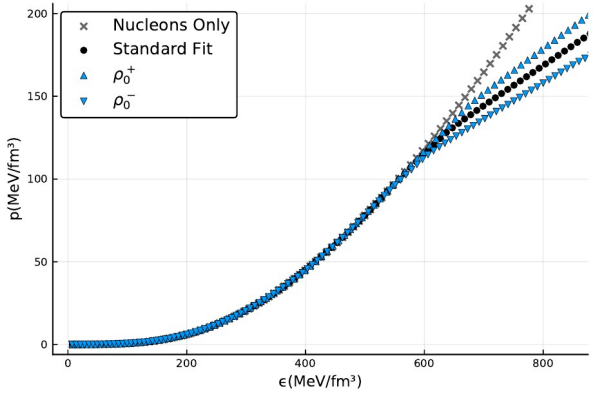


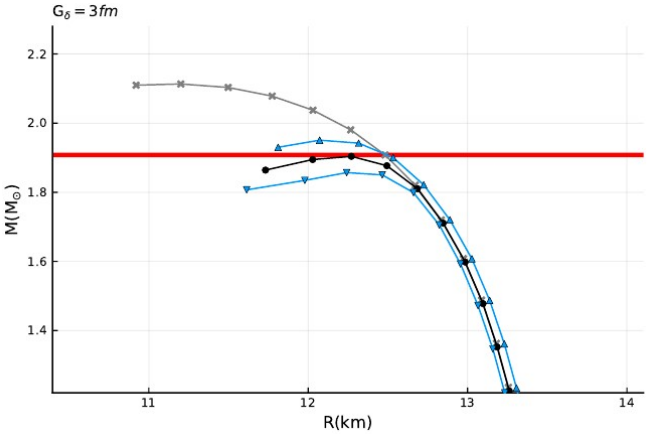


EOS

- Equation of state does produce stars with masses of up to 1.9 solar masses for all values of delta coupling

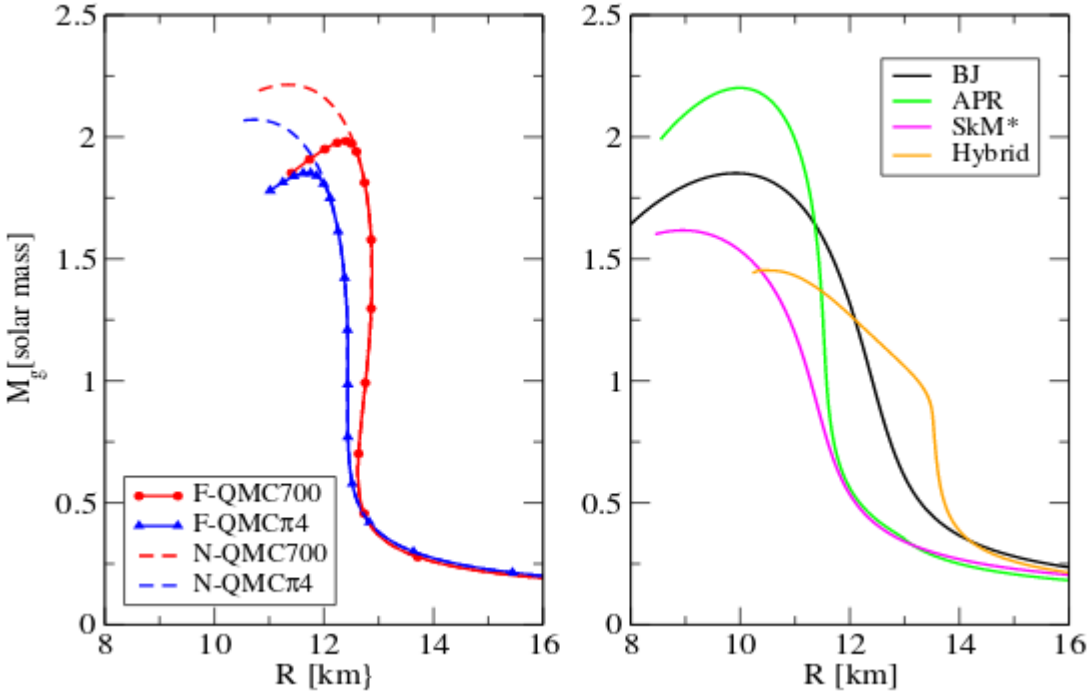
- Variations on saturation density give rise to small variations in mass-radius





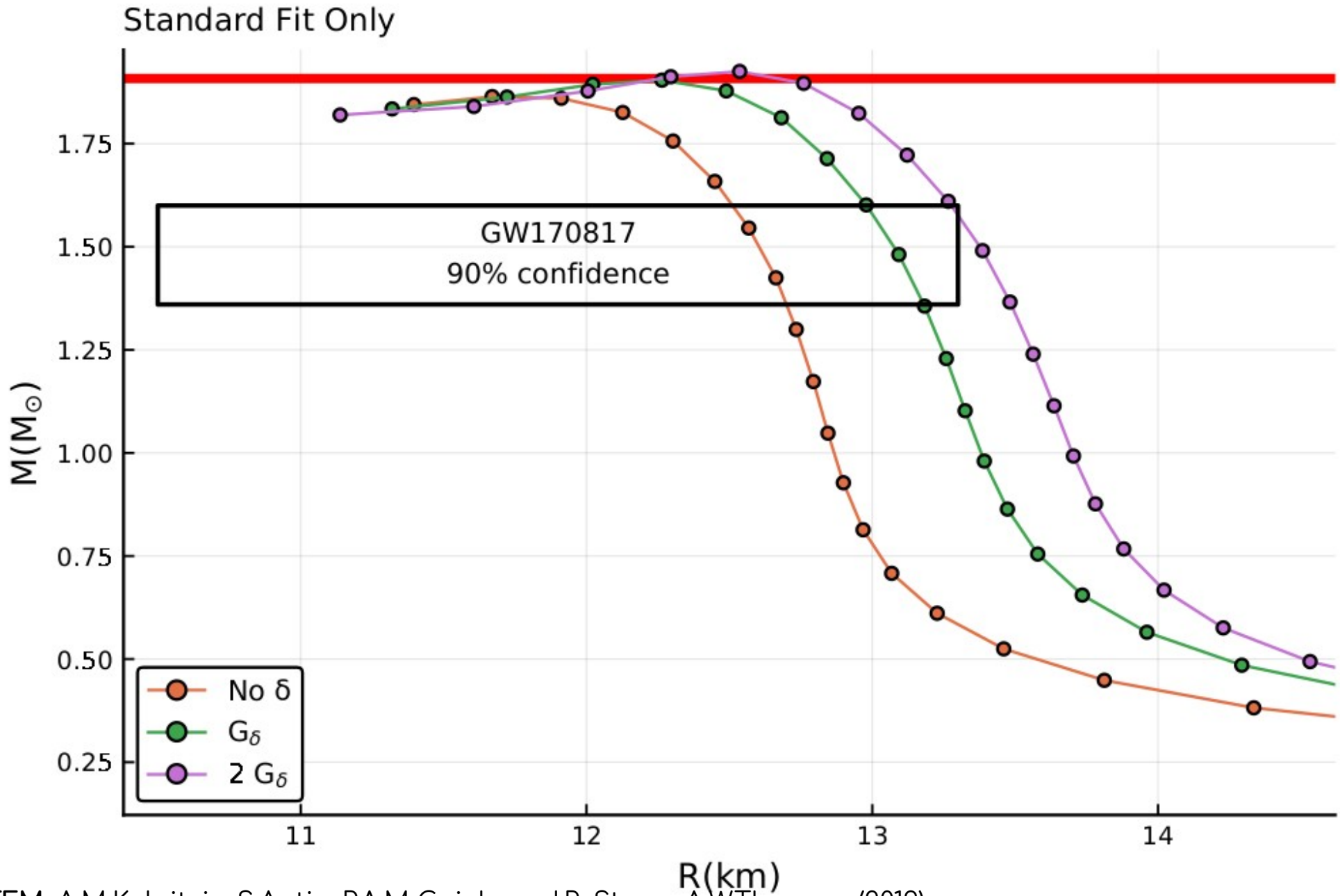
Delta

- Why wasn't it there in the first place?
  - It's mass is large and coupling is small
  - Wasn't likely to change the maximum mass
  - We only had mass to think about!



Stone, J. R. et al (2007)

Mass-Radius



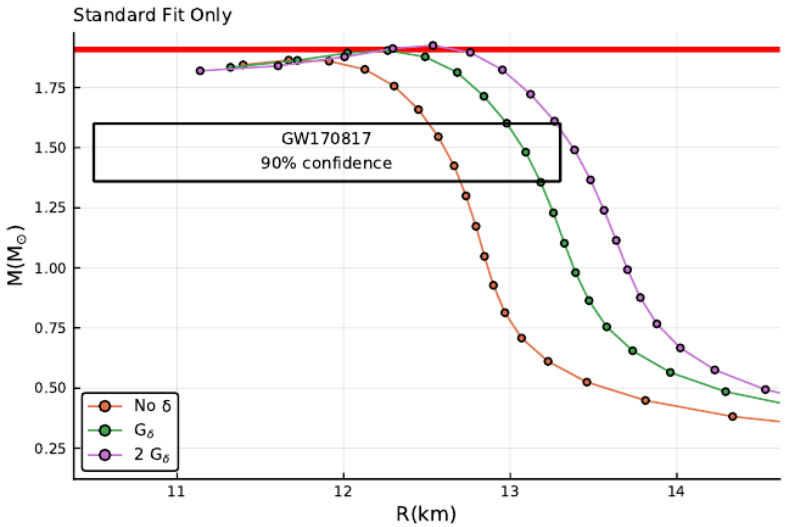
TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

Mass-Radius

- We find that the delta coupling **changes the radius** very significantly!

- With the upcoming NICER mission such a result is quite important.

- Effects of **variations in baryon density** are much **smaller than delta** effects

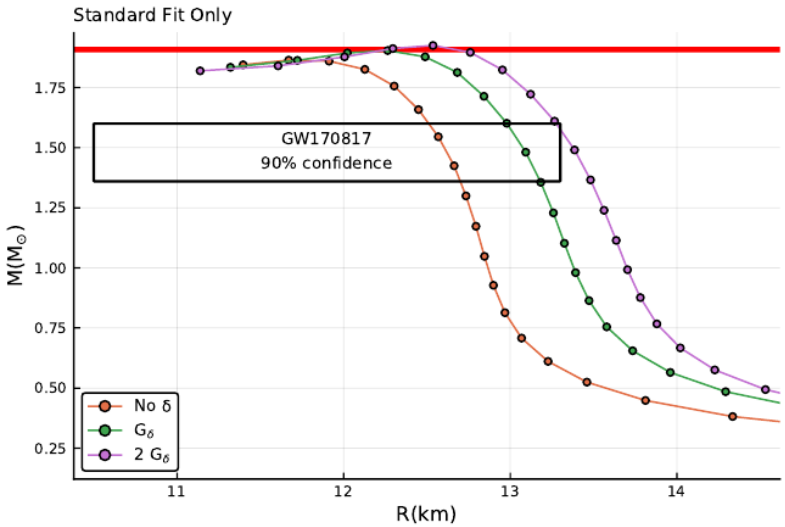


Mass-Radius

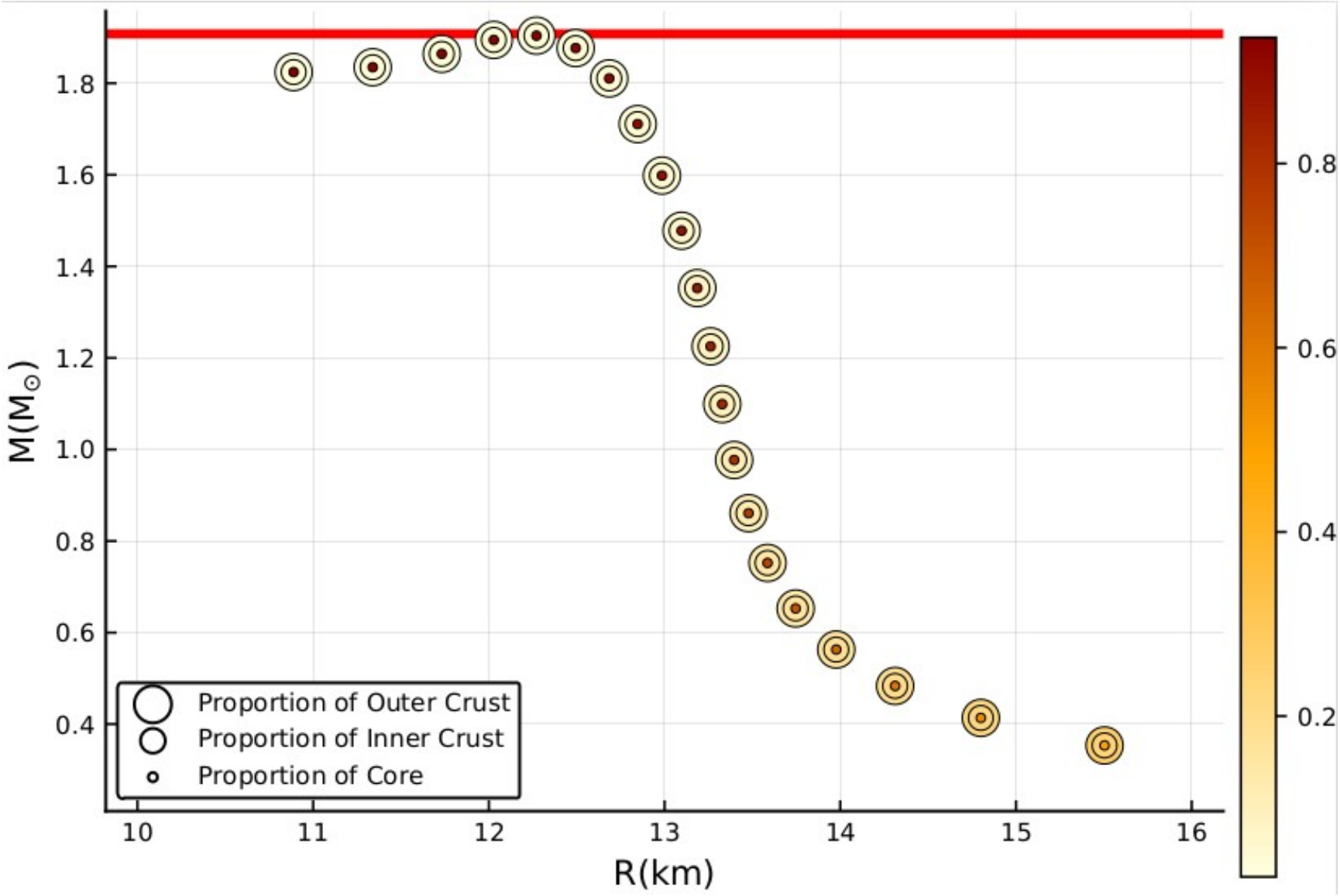
- But couldn't it be that such results are inconsistent?

  E.g. we use the same crust EoS all throughout this study

- Doesn't the crust contribute much more to the radius than the core does?

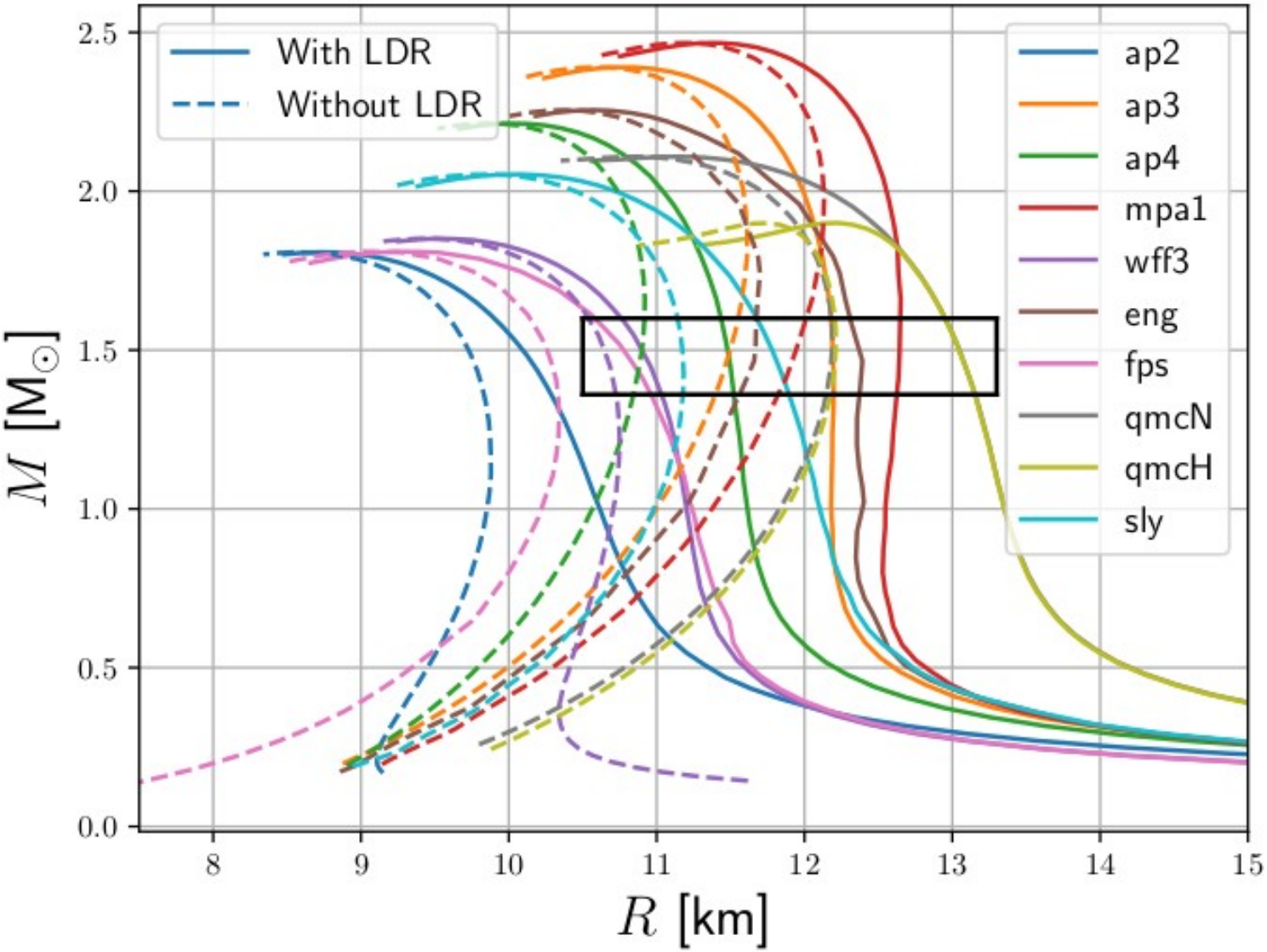


Mass-Radius



TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

Mass-Radius

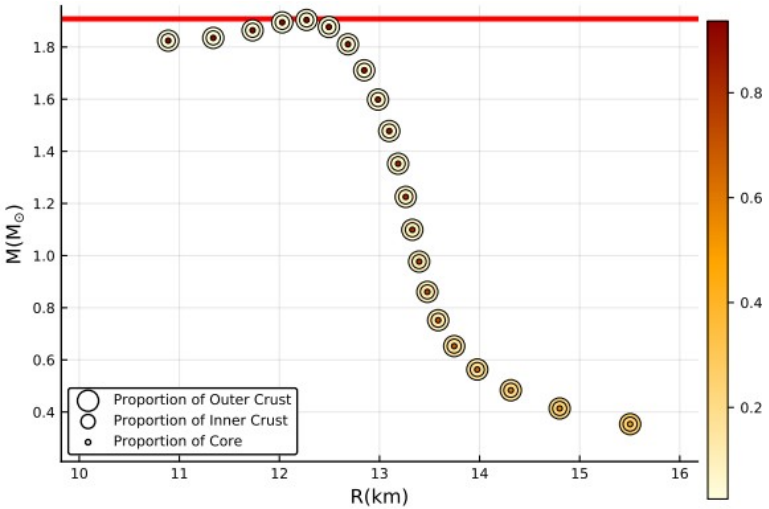


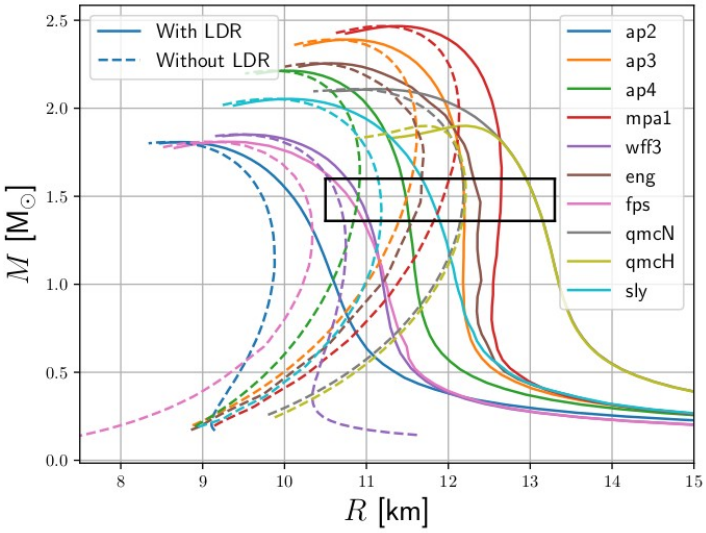
A.M Kalaitzis, **TFM**, A.W.Thomas (2019)

Mass-Radius

- Crust consists of a **low percentage** of the radius for stars with M>1.4

- We also expect that, IF the model we used for the crust turns out to be incorrect, **variations would probably be much smaller** than this





Tidal Deformability

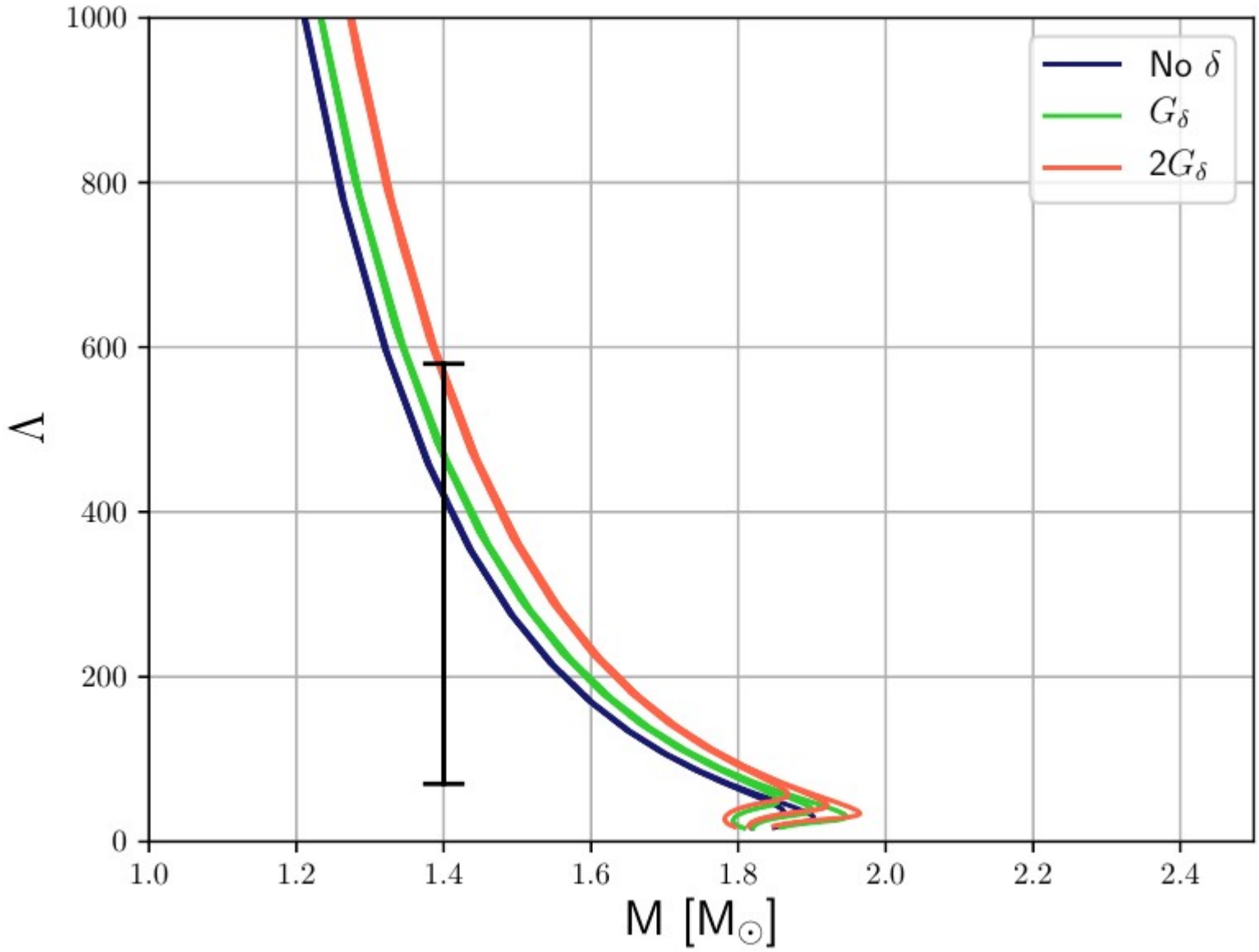
- Tidal deformability (or equivalently, the Love number)

$$\Lambda^{\mathrm{Tid}} = \frac{2}{3} k_2^{\mathrm{Tid}} \beta^{-5}$$

- Give the ratio between Quadrupole moment and tidal potential induced by the companion

$$\Lambda^{Tid} \propto \frac{Q^{Tid}}{\mathcal{E}^{Tid}}$$

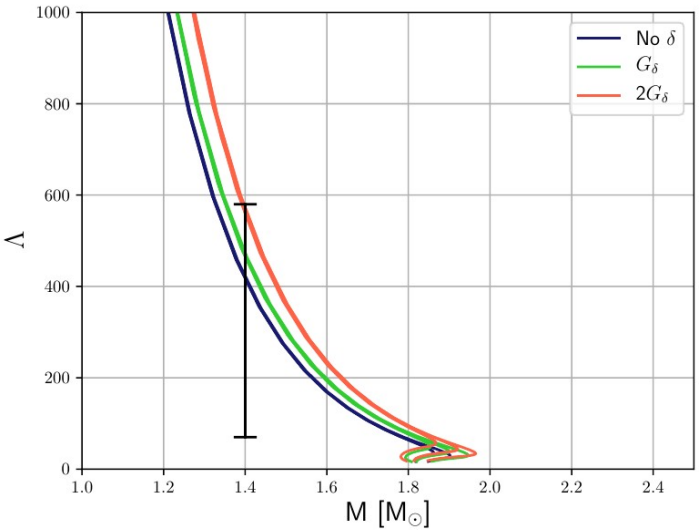
Tidal Deformability



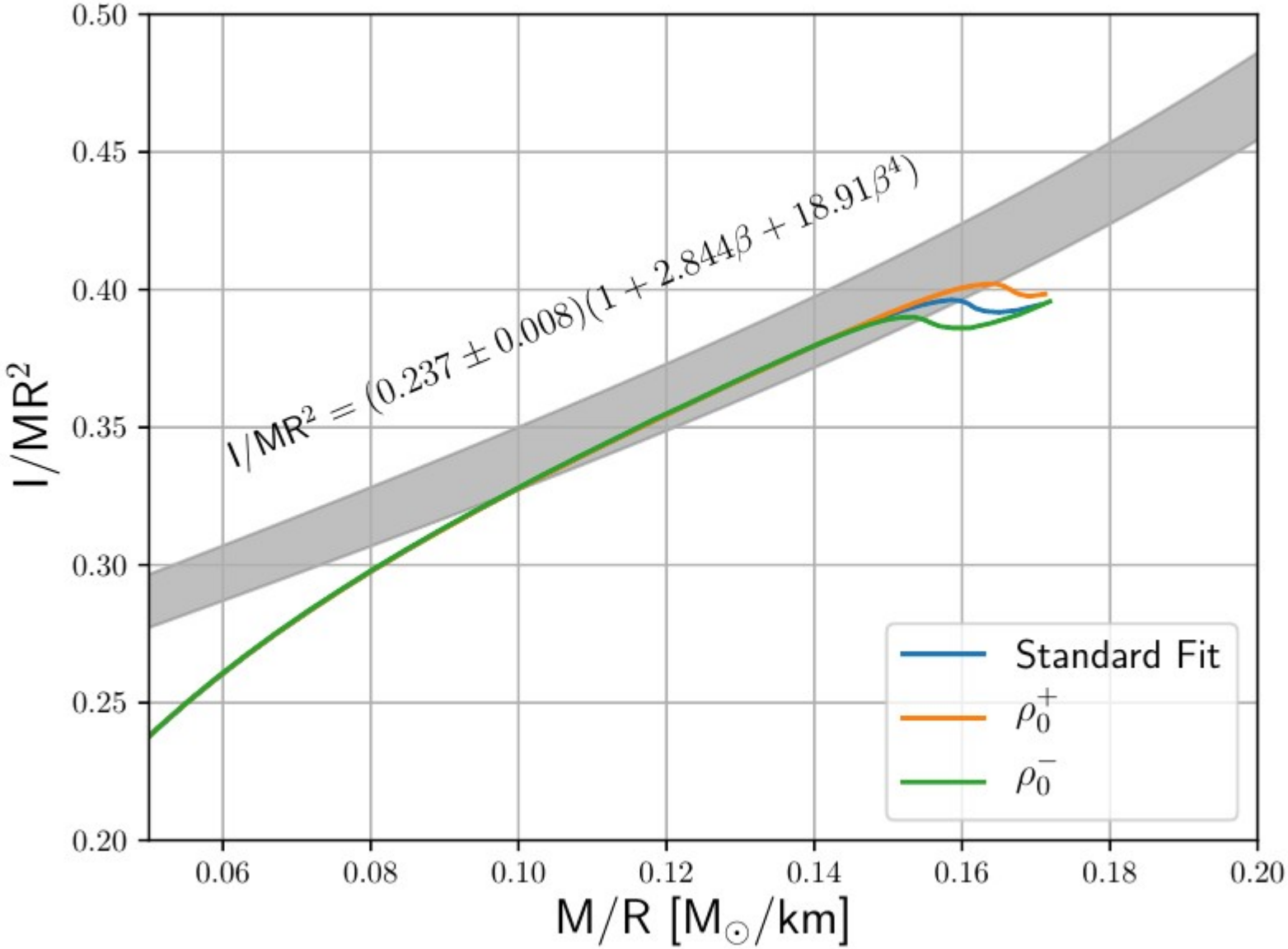
TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

Tidal Deformability

- Delta meson **changes little** the Tidal Deformability
- Still all values of δ coupling **fit to GW's band**
- Again the case with double delta coupling is in most tension with GW constraints



Moment of Inertia

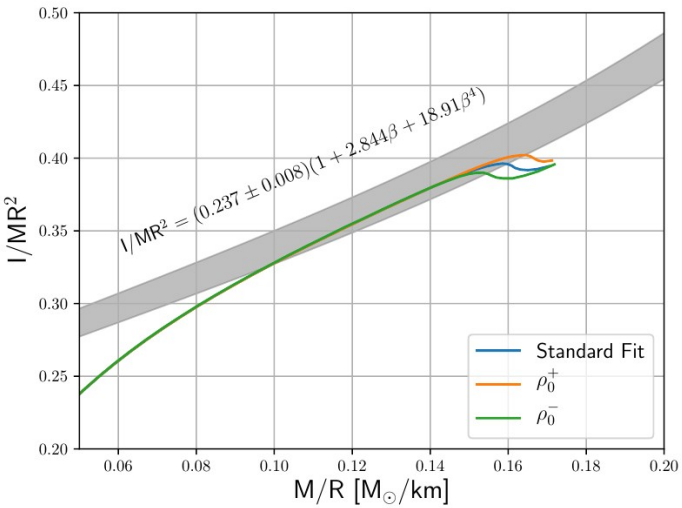


TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

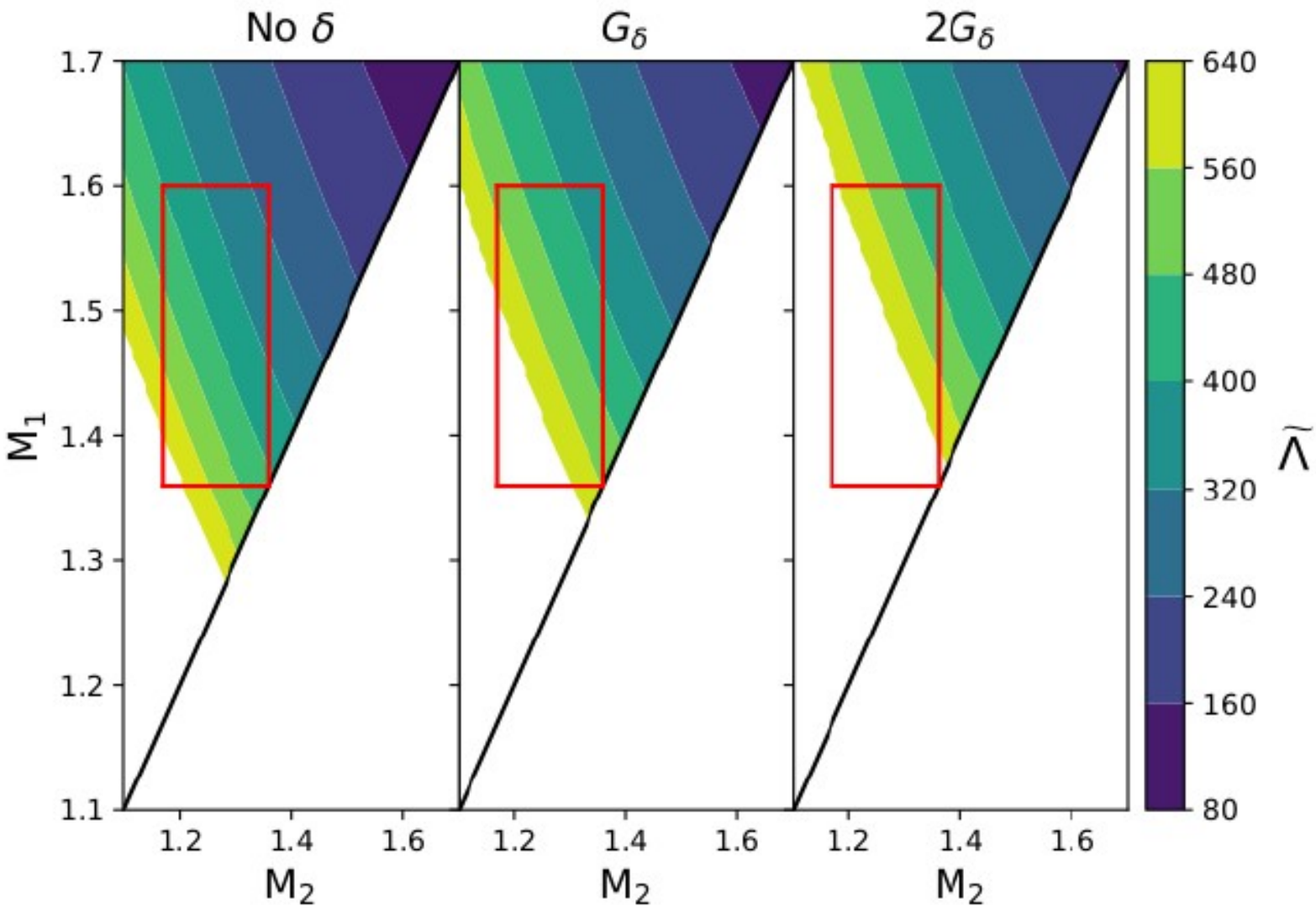
Moment of Inertia

- Delta **doesn't change at all** the moment of inertia for most (M,R) points.

- All parametrizations **agree with band** from Zhao and Lattimer (2018)

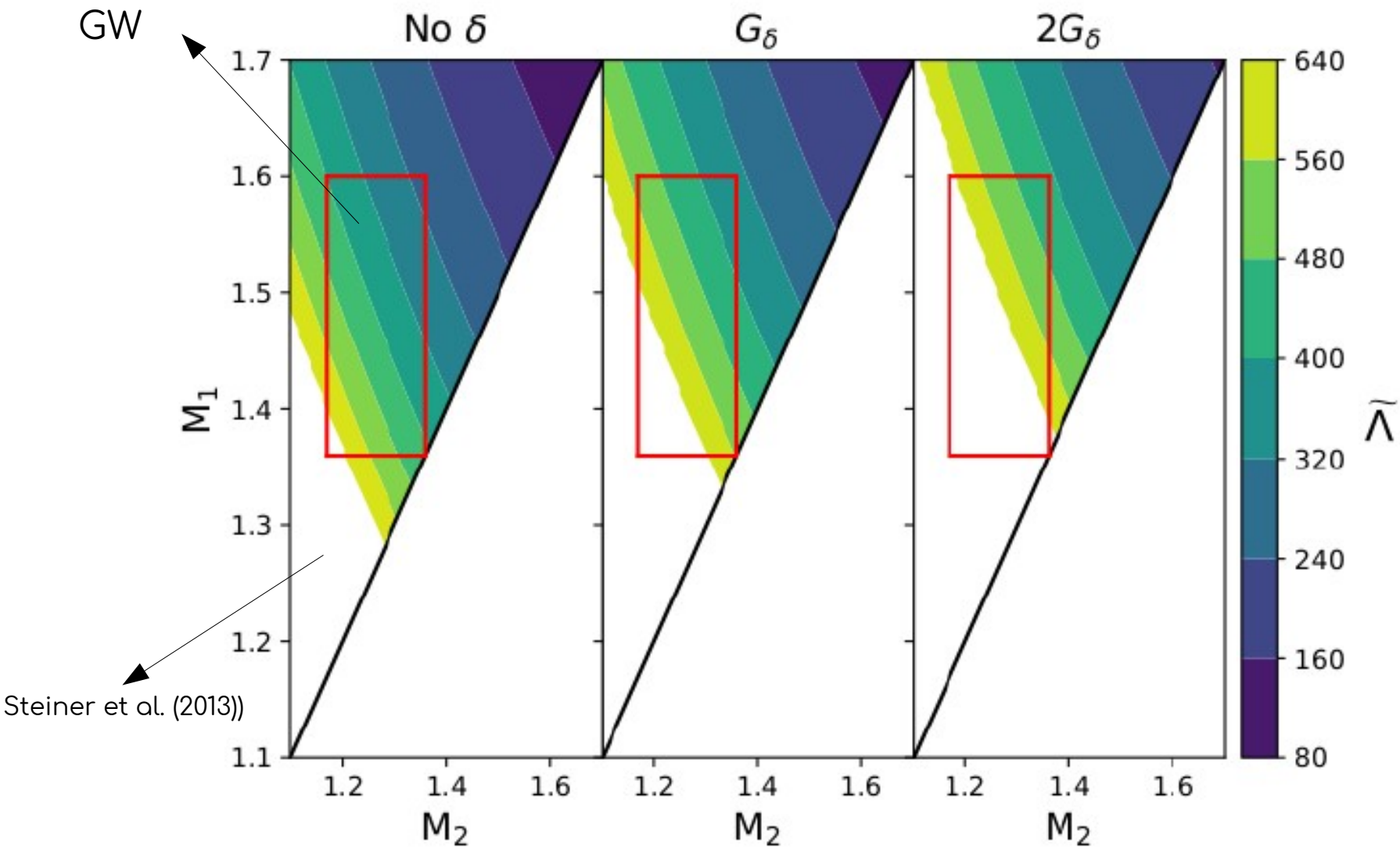


Binary Λ



TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

Binary Λ

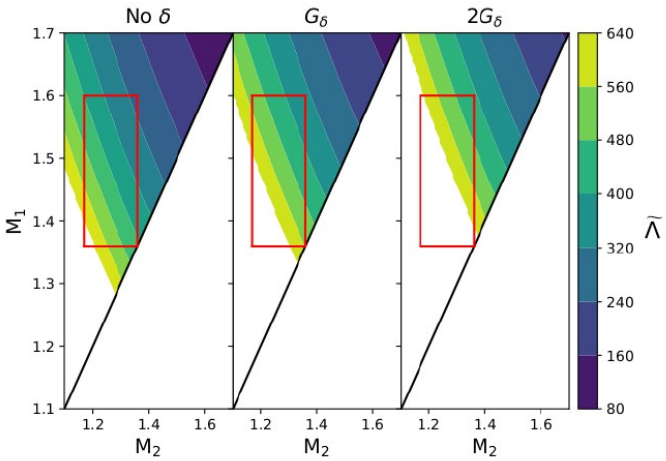


TFM, A.M.Kalaitzis, S.Antic, P.A.M Guichon, J.R. Stone, A.W.Thomas (2019)

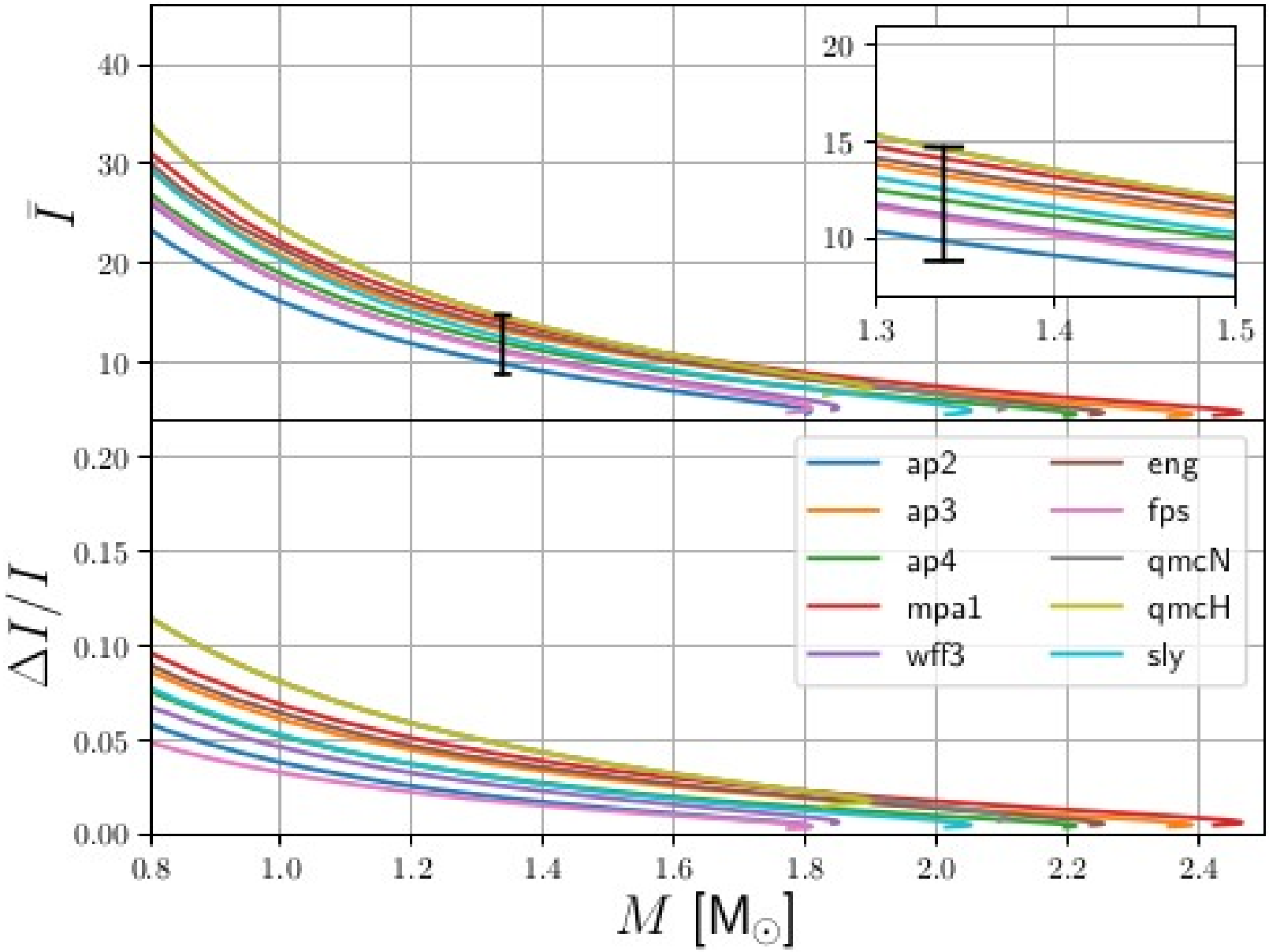
Binary Λ

- For binary tidal deformability we also have **QMC compatible with the GW** measurement

- Same pattern with delta coupling

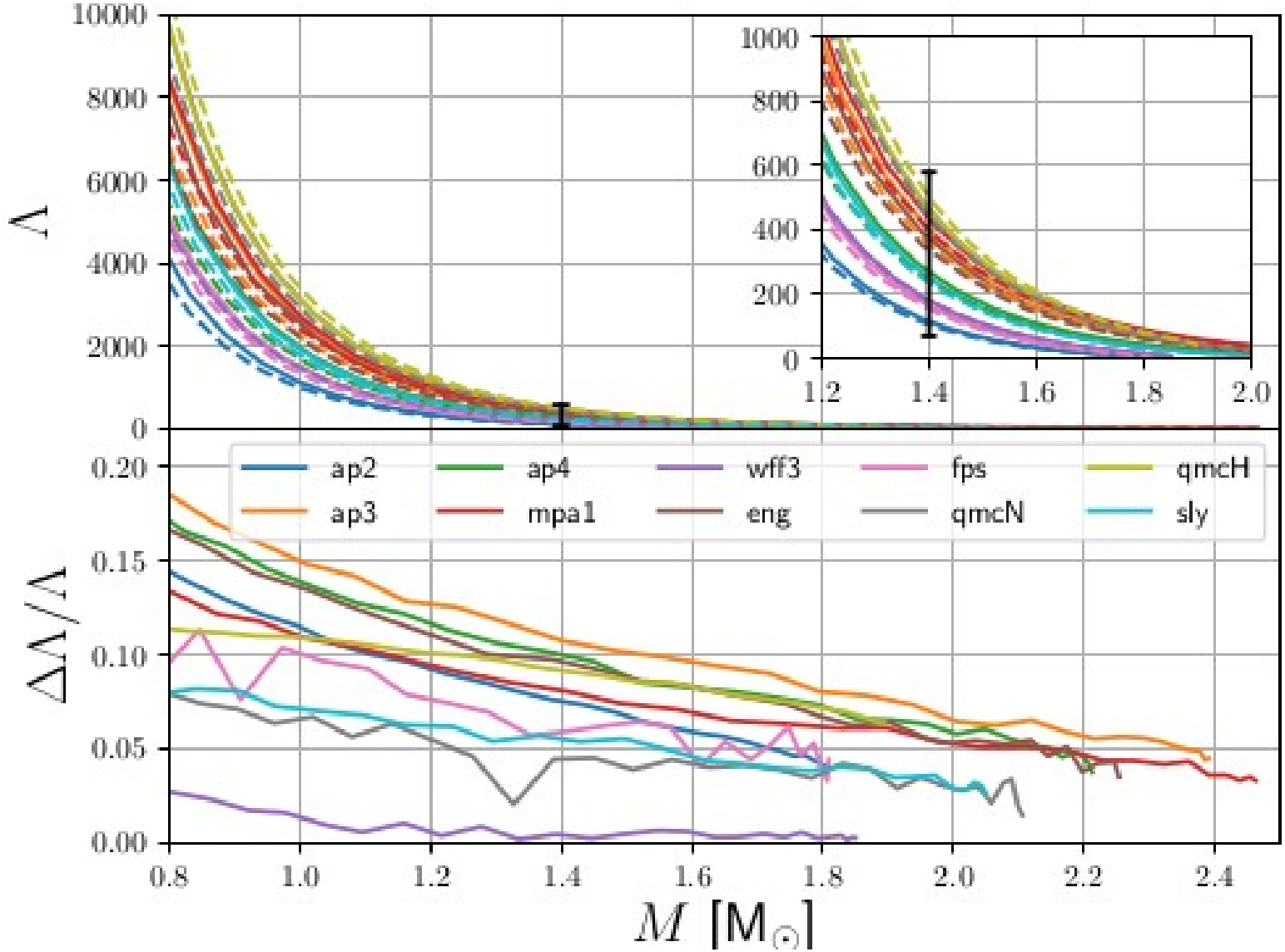


Crust



A.M Kalaitzis, **TFM**, A.W.Thomas (2019)

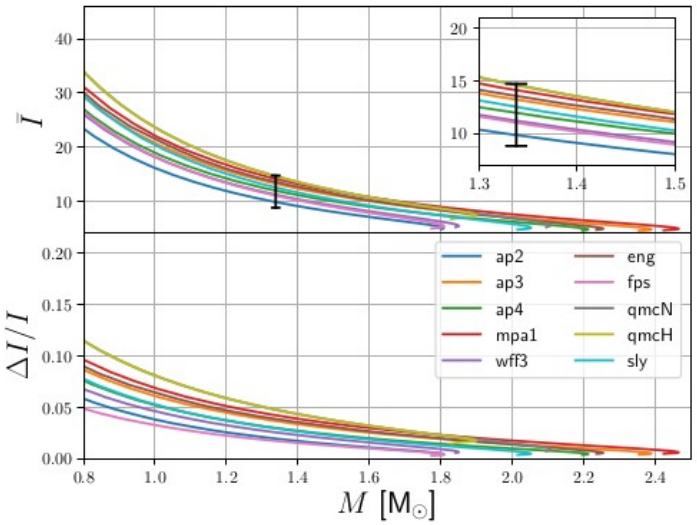
Crust

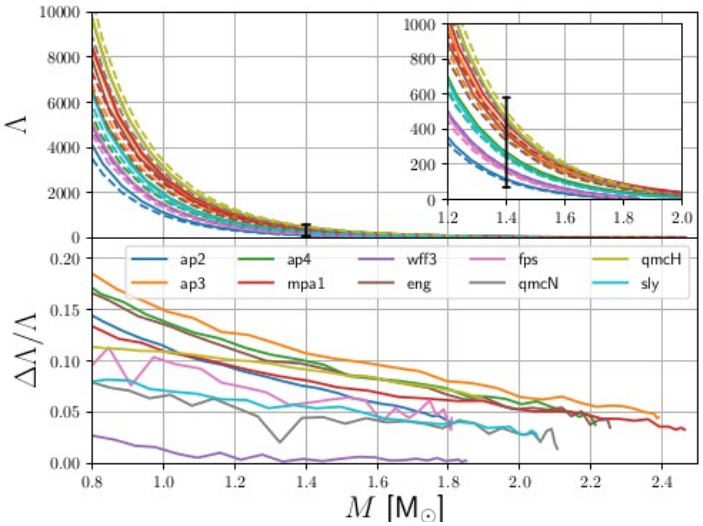


A.M Kalaitzis, **TFM**, A.W.Thomas (2019)

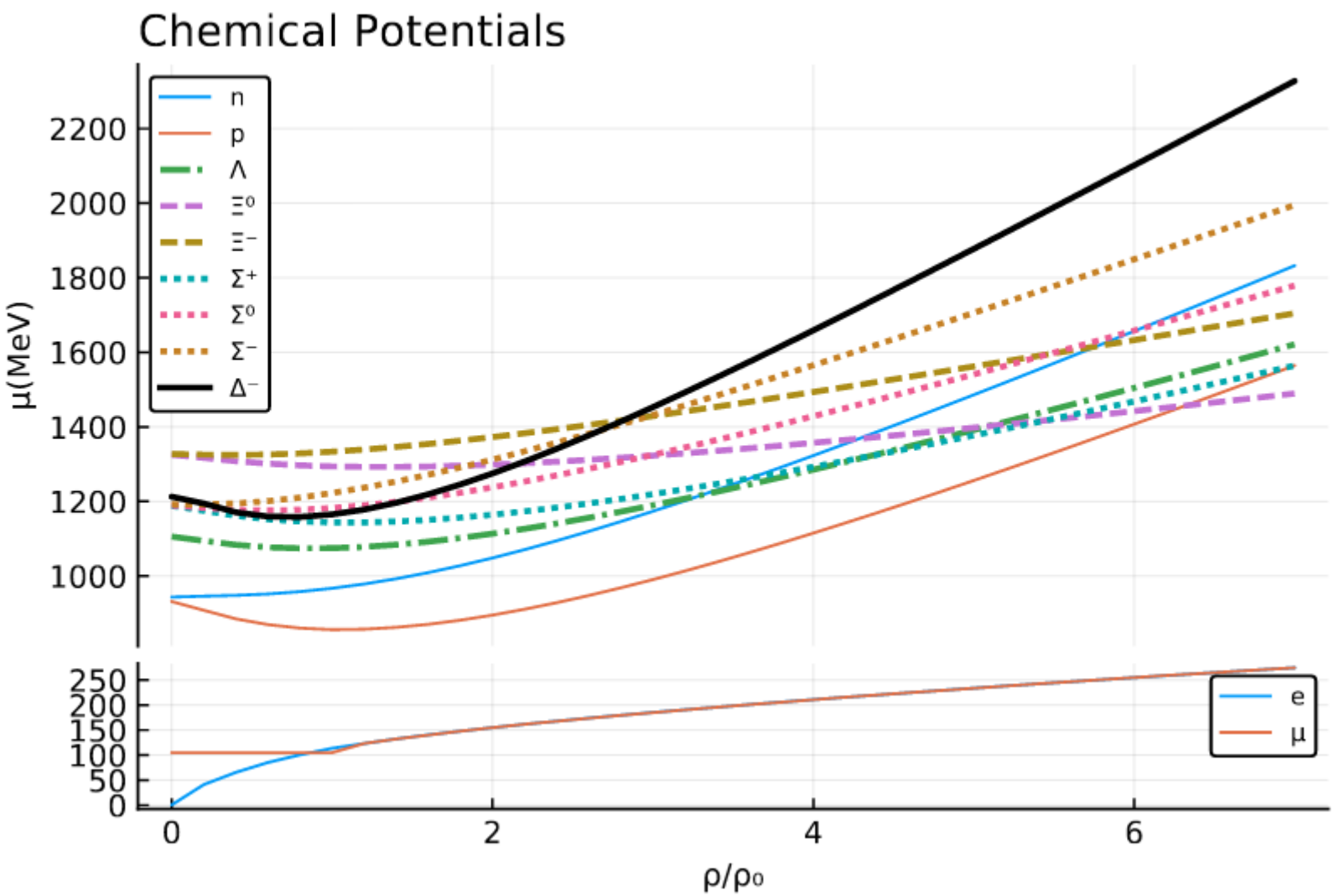
Crust

- **Moment of inertia** contribution to the crust is **small**
- Surprisingly, **so is the Λ** contribution
- Both below 10% for the QMC model



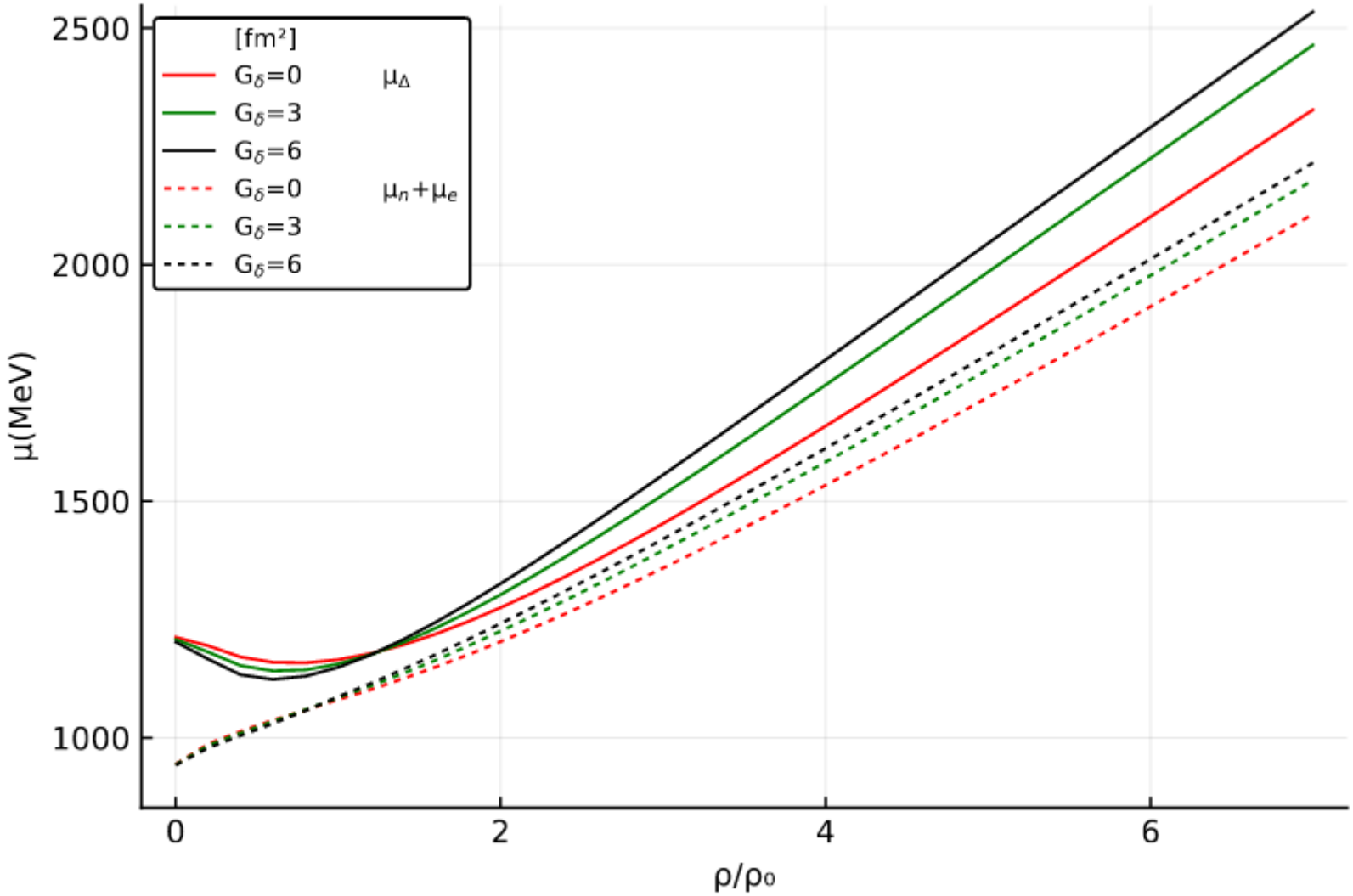


Delta Isobars



TFM, A.W.Thomas, P.A.M Guichon (2019)

Delta Isobars

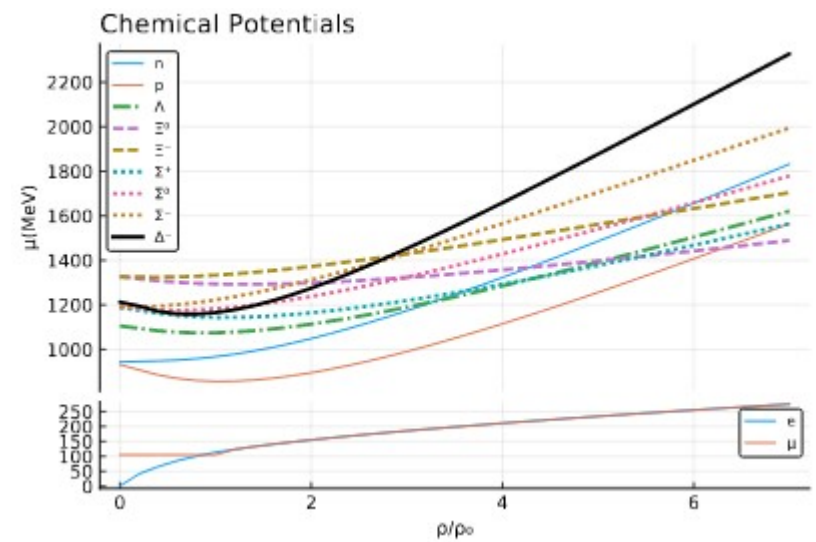


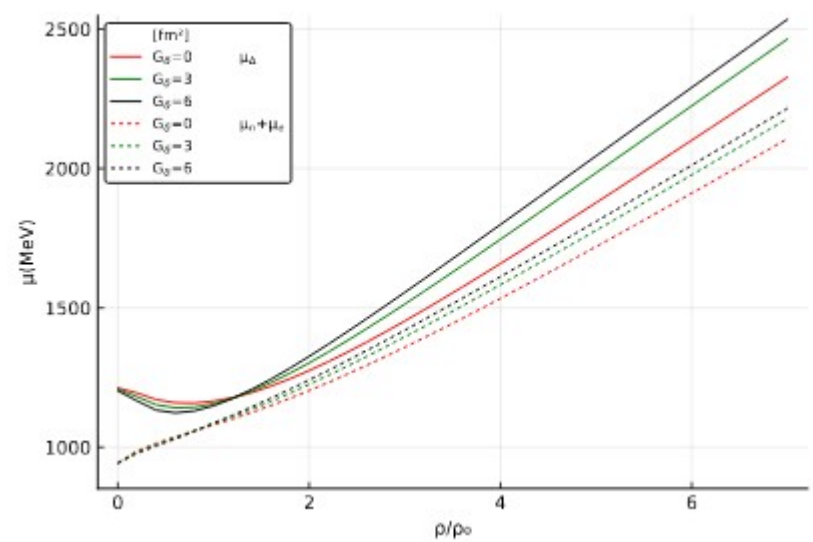
TFM, A.W.Thomas, P.A.M Guichon (2019)

Delta Isobars

- The QMC model predicts no **Delta isobars** in the core of neutron stars

- This can be seen as a natural **ΔNN three body repulsion**





Summary and Conclusions

Summary

- QMC agrees with GW constraints for all studied values of δ coupling
- QMC agrees with existent measurements for radius (preferring larger radius than most models)
- Measurements of the radius will give us strength of δ coupling
- Values for GW quantities depend little on the crust EOS
- QMC proposes a solution for both the "hyperon puzzle" and the "Delta puzzle"