NEUTRON STAR PROPERTIES, NUCLEAR PARAMETERS, (HYPER)NUCLEI, AND GRAVITATIONAL WAVES

Dr. Morgane FORTIN
N. Copernicus Astronomical Center, Warsaw - Poland
fortin@camk.edu.pl

8th International Symposium on Nuclear Symmetry Energy
Sept. 10, 2018

Astro-PF
Polish-French collaboration in astrophysics

NATIONAL SCIENCE CENTRE
POLAND

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

Neutron star radius

Astrophysical constraints on the EOS

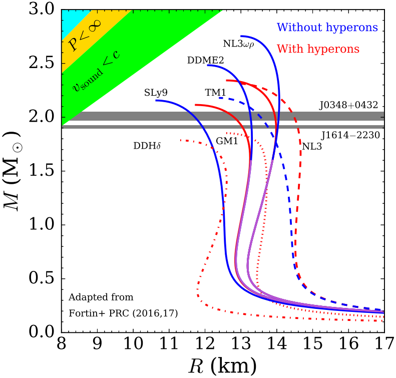
Mass

- each EOS has a maximum mass $M_{\rm max}$;
- $M_{\rm max} \geq M^{\rm obs}_{\rm max}$.

eaviest NSs:

- PSR J1614-2230: $M = 1.908 \pm 0.016\, M_\odot$ (Arzoumanian+ ApJS 2018).
- PSR J0348+0432: $M = 2.01 \pm 0.04\, M_\odot$ (Antoniadis+ Science 2013)

Mass-radius plot



Radius

e.g. Miller & Lamb EpJA, Ozel & Freire ARAA (2016), Fortin+ A&A (2015) ldots

$$R \simeq 9 - 14 \text{ km}.$$

Current and future instruments:

- NICER (NASA): on board of the ISS, currently operating.
- Athena (ESA): launch in 2028;

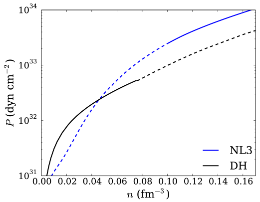
$\Rightarrow$ **simultaneous** (M, R) for several NSs with a $\sim 5\%$ uncertainty on R...

NS EOSs and radius

NS EOSs

- core: homogeneous mixture;
- crust: lattice of nuclei $\rightarrow$ non-uniform.

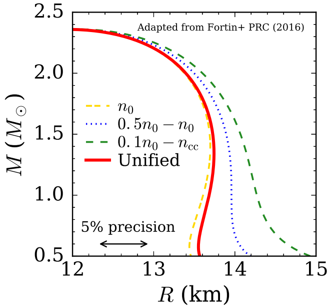
$\Rightarrow$ many more core EOS than crust EOS.



How to glue core and crust EOSs?

Fortin, Providência, Raduta, Gulminelli, Zdunik, Haensel, & Bejger, PRC 94 (2016)

- transition at $n_0 = 0.16$ fm^{-3};
- crust below $0.5n_0$ and core above n_0;
- crust below $0.1n_0$ and core above n_t;
- reference: unified EOS.

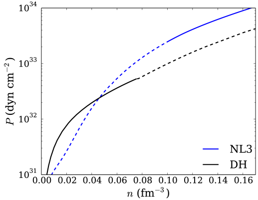


NS EOSs and radius

NS EOSs

- core: homogeneous mixture;
- crust: lattice of nuclei → non-uniform.

⇒ many more core EOS than crust EOS.



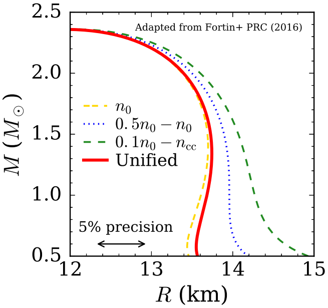
Uncertainty on R

- due to the treatment of the core-crust transition: up ∼ 4% (up to ∼ 30% on the crust thickness),
- with NICER, Athena: expected precision ∼ 5% . . . .
- how to, if not solve, at least handle this problem?

How to glue core and crust EOSs?

Fortin, Providência, Raduta, Gulminelli, Zdunik, Haensel, & Bejger, PRC 94 (2016)

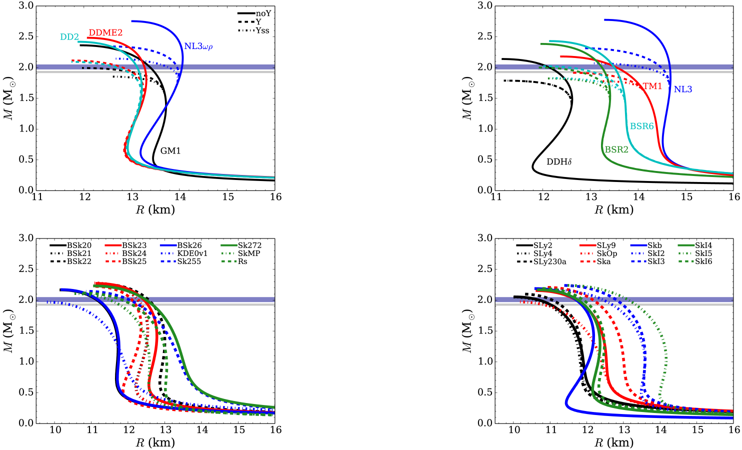
- transition at $n_0 = 0.16$ fm^{-3};
- crust below $0.5n_0$ and core above n_0;
- crust below $0.1n_0$ and core above n_t;
- reference: unified EOS.



1. Unified equations of state

Very few unified EOSs for NSs exist eg. Douchin & Haensel 2001, BSk (Brussels Uni.), Sharma et al. 2015

Fortin, Providência, Raduta, Gulminelli, Zdunik, Haensel, & Bejger, PRC 94 (2016)



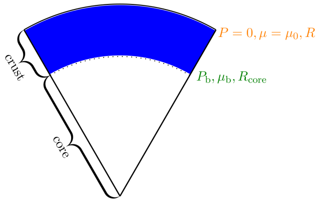
33 nucleonic EOSs (9 RMF and 24 Skyrme) and 15 RMF hyperonic EOSs, all consistent with 2 $M_{\odot}$ (and causal).

EOS tables as supplemental material to the paper (can also provide $M - R$) and also soon on the open-source database Compose: `compose.obspm.fr`

2. Approximate formula for the radius and crust thickness

Zdunik, Fortin, and Haensel, A&A (2017)

- All you need is . . . : the core EOS down to a chosen density $n_{\rm b}$ with $\mu(n_{\rm b}) = \mu_{\rm b}$.
- Obtain the $M(R_{\rm core})$ relation solving the TOV equations.
- Obtain $M(R)$ with
  $$R = R_{\rm core} / \left(1 - (\frac{\mu_{\rm b}{}^2}{\mu_0{}^2} - 1)(\frac{R_{\rm core} c^2}{2GM} - 1)\right).$$



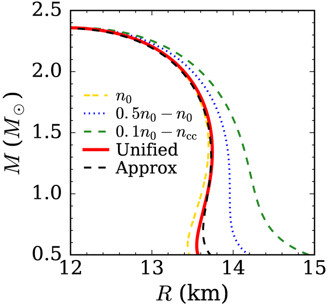
2 unknowns

- $\mu_0 = 930.4$ MeV - minimum energy per nucleon of a bcc lattice of ^{56}Fe.
- $\mu_{\rm b}$ at the core-crust transition? For $L \in [30, 120]$ MeV, $n_{\rm b} \in [0.06, 0.10]$ fm^{-3} (Ducoin+ PRC 2011)
- $\mu_{\rm b} = (P + \rho)/n$ at $n_0/2 = 0.08$ fm^{-3}

Results

- $\Delta R \lesssim 0.2\%$ for $M > 1\ M_\odot$
- $\Delta l^{\rm cr} \lesssim 1\%$ for $M > 1\ M_\odot$

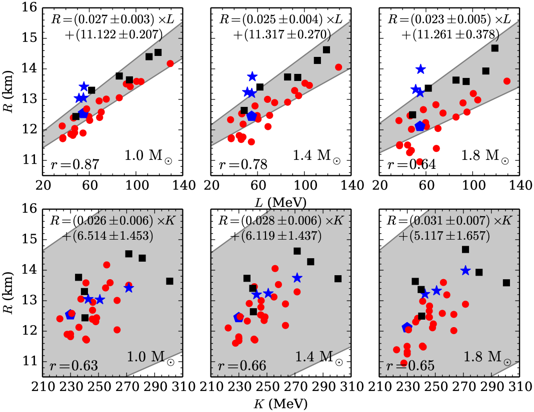
+ Formulas for NSs with an accreted crust.



Correlations

NS radius and nuclear parameters

Fortin+ PRC 94 (2016): 33 unified RMF and Skyrme models

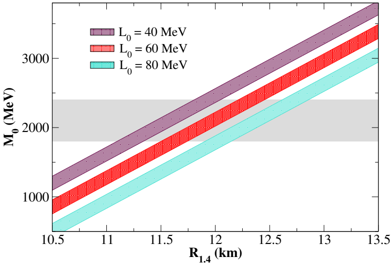


- R vs L (see also eg. Horowitz & Piekarewicz 2001, . . . works): dispersion larger for higher masses due to higher order terms
- R vs K: for isoscalar properties higher order terms can not be neglected

NS radius and nuclear parameters II

- 42 RMF and Skyrme unified EOSs + 2 microscopic ones: all consistent with 2 $M_\odot$
- Nuclear parameters: L_0 the slope of the symmetry energy, $K_{\rm sym}$ its curvature, K_0 the incompressibility and $M_0 = Q_0 + 12K_0$ its slope with Q_0 the skewness.

R $\propto$ linear combination of L_0 and M_0



Alam, Agrawal, Fortin et al. PRC 94 (2016)

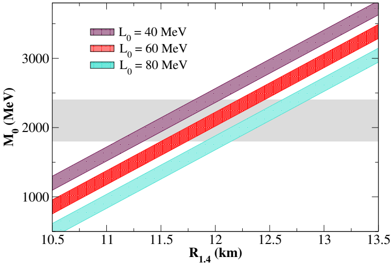
- Color strips: $L_0 = 40 - 80$ MeV
- Gray strip: experimental constraint from giant monopole resonance (De+ PRC 92, 2015)

$\Rightarrow R_{1.4} = 11.09 - 12.86$ km

NS radius and nuclear parameters II

- 42 RMF and Skyrme unified EOSs + 2 microscopic ones: all consistent with $2\,M_\odot$
- Nuclear parameters: L_0 the slope of the symmetry energy, $K_{\rm sym}$ its curvature, K_0 the incompressibility and $M_0 = Q_0 + 12K_0$ its slope with Q_0 the skewness.

R $\propto$ linear combination of L_0 and M_0

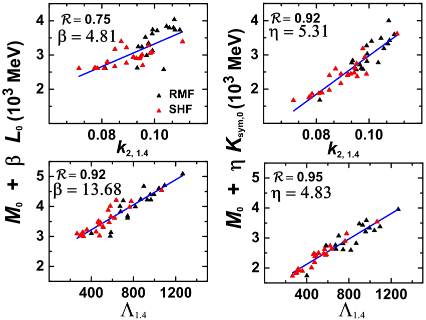


Alam, Agrawal, Fortin et al. PRC 94 (2016)

- Color strips: $L_0 = 40 - 80$ MeV
- Gray strip: experimental constraint from giant monopole resonance (De+ PRC 92, 2015)

$\Rightarrow R_{1.4} = 11.09 - 12.86$ km

$\Lambda \propto$ linear combination of L_0 and M_0, $K_{\rm sym}$



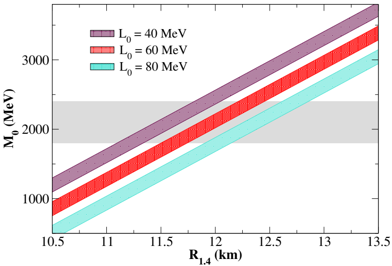
Similarly

- $1900 < M_0 < 3800$ MeV
- $-141 < K_{\rm sym} < +16$ MeV, not constrained experimentally

NS radius and nuclear parameters II

- 42 RMF and Skyrme unified EOSs + 2 microscopic ones: all consistent with 2 $M_\odot$
- Nuclear parameters: L_0 the slope of the symmetry energy, $K_{\rm sym}$ its curvature, K_0 the incompressibility and $M_0 = Q_0 + 12K_0$ its slope with Q_0 the skewness.

R $\propto$ linear combination of L_0 and M_0

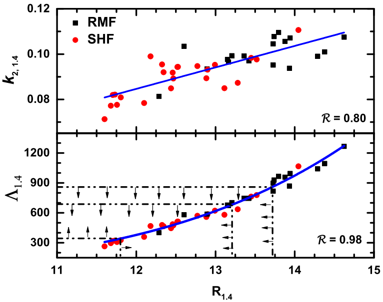


Alam, Agrawal, Fortin et al. PRC 94 (2016)

- Color strips: $L_0 = 40 - 80$ MeV
- Gray strip: experimental constraint from giant monopole resonance (De+ PRC 92, 2015)

$\Rightarrow R_{1.4} = 11.09 - 12.86$ km

R $\propto$ tidal deformability Λ



Malik, Alam, Fortin et al. arXiv 1805.11963

- arrow: bounds on Λ from GW170817 event: GW observations (LIGO-Virgo collab' and De et al. PRL 2018) and EM counterpart (Radice et al. ApJL 2018)

$\Rightarrow R_{1.4} = 11.82 - 13.72$ km

Mirror nuclei and NS radii

Yang & Piekarewicz PRC (2018)

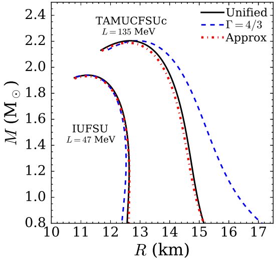
$$R_{\mathrm{mirr}}(Z,N) = R_p(N,Z) - R_p(Z,N)$$

- inspired by Brown PRL (2017) for Skyrme models
- 14 RMF models
- $R_{\mathrm{mirr}}(^{50}\text{Ni-Ti})$: correlated with the radius of low-mass stars.

Fortin, Providência, Pais, in prep.

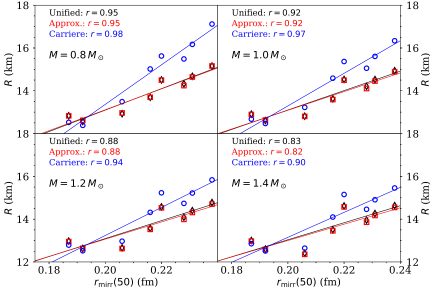
For 9 of these models:

- Unified EOSs
- Approximate approach



EOS construction à la Carriere et al. ApJ (2003):

- outer crust from BPS
- core down to the core-crust transition density from RPA
- in between polytrope with $\Gamma = 4/3$.



$\Rightarrow$ Correlations are weaker.

Mirror nuclei and NS radii

Yang & Piekarewicz PRC (2018)

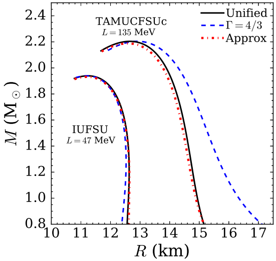
$R_{\rm mirr}(Z,N) = R_p(N,Z) - R_p(Z,N)$

- inspired by Brown PRL (2017) for Skyrme models
- 14 RMF models
- $R_{\rm mirr}(^{50}\text{Ni-Ti})$: correlated with the radius of low-mass stars.

Fortin, Providência, Pais, in prep.

For 9 of these models:

- Unified EOSs
- Approximate approach



EOS construction à la Carriere et al. ApJ (2003):

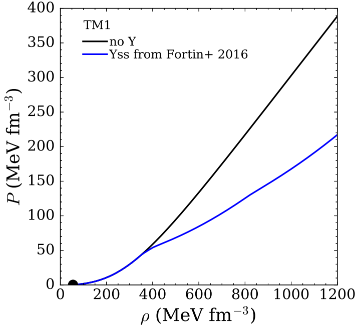
- outer crust from BPS
- core down to the core-crust transition density from RPA
- in between polytrope with $\Gamma = 4/3$.

- 50 RMF models in total: $\omega\rho$ and $\sigma\rho$ families of the NL3, Z271, TM1 parametrizations (Pais & Providência PRC 2016)
- Preliminary: much weaker correlations between R and $R_{\rm mir}$: $r = 0.76$ for $M = 0.8\,M_\odot$.
- Confirm correlations between ^{208}Pb and ^{48}Ca neutron skin thickness and L, and $R_{\rm mir}$ and L.
- Extensive study of correlations in progress. . . stay tuned!

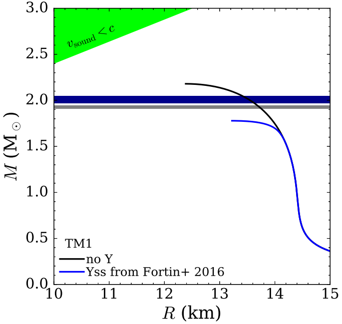
Hypernuclei and neutron stars

Hyperonic equations of state

Equation of state



$M - R$ plot



Hyperon puzzle

- $M_{\rm max}$ reduced when Y are included;
- consistency with the observations:
  $M_{\rm max} \geq M_{\rm max}^{\rm obs} \simeq 2\,{\rm M}_\odot$ (PSR J1614-2230 & J0348+0432)

$\Rightarrow$ Can hyperons be present in NSs and yet $M_{\rm max} \geq 2\ M_\odot$?

Experimentally calibrated hyperonic EOS

Usual approach to hyperons

Adjust the couplings for e.g. Λ to reproduce:

- the Λ-potential in symm. NM $U_\Lambda^N(n_0)$
- the Λ-potential in pure Λ matter $U_\Lambda^\Lambda(n_0)$ or $U_\Lambda^\Lambda(n_0/5)$

Experimental properties of hypernuclei

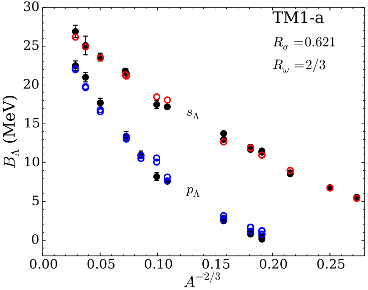
Gal et al., RMP (2016)

- $\sim$ 40 Λ-hypernuclei
  + measurement of binding energy
- only one unambiguous $\Lambda\Lambda$-hypernuclei:
  measurement of the bond energy:

  $$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\text{He}) = 0.67 \pm 0.17 \text{ MeV}.$$
- few Ξ-hypernuclei
  but no measurement of binding energy
- no Σ-hypernuclei
  repulsive Σ-nucleon interaction?

Fortin, Avancini, Providência, Vidaña, PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei



Experimentally calibrated hyperonic EOS

Usual approach to hyperons

Adjust the couplings for e.g. Λ to reproduce:

- the Λ-potential in symm. NM $U_\Lambda^N(n_0)$
- the Λ-potential in pure Λ matter $U_\Lambda^\Lambda(n_0)$ or $U_\Lambda^\Lambda(n_0/5)$

Experimental properties of hypernuclei

Gal et al., RMP (2016)

- $\sim$ 40 Λ-hypernuclei + measurement of binding energy
- only one unambiguous $\Lambda\Lambda$-hypernuclei: measurement of the bond energy:

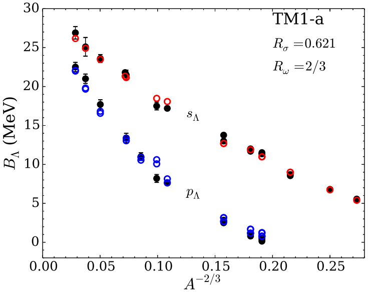
  $\Delta B_{\Lambda\Lambda}({}^6_{\Lambda\Lambda}\mathrm{He}) = 0.67 \pm 0.17$ MeV.
- few Ξ-hypernuclei but no measurement of binding energy
- no Σ-hypernuclei repulsive Σ-nucleon interaction?

Experimentally calibrated potentials

- $U_\Lambda^N(n_0) \in [-36, -30]$ MeV usually (-30, -28) MeV
- $U_\Lambda^\Lambda(n_0) \in [-14, -9]$ MeV
- or $U_\Lambda^\Lambda(n_0/5) \in [-6, -5]$ MeV usually (-5, -1) MeV

Fortin, Avancini, Providência, Vidaña, PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei



Experimentally calibrated hyperonic EOS

Experimental properties of hypernuclei

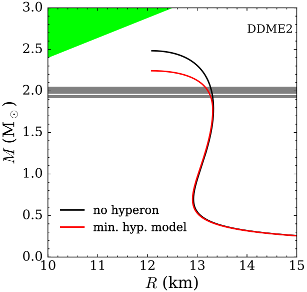
Gal et al., RMP (2016)

- ~ 40 Λ-hypernuclei
  + measurement of binding energy
- only one unambiguous $\Lambda\Lambda$-hypernuclei: measurement of the bond energy:

  $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 0.67 \pm 0.17$ MeV.
- few Ξ-hypernuclei
  but no measurement of binding energy
- no Σ-hypernuclei
  repulsive Σ-nucleon interaction?

Fortin, et al. PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei



Define two limiting hyperonic NS EOS:

- 'minimal hyperonic model': only Λ, calibrated to hypernuclear data.

Experimentally calibrated hyperonic EOS

Experimental properties of hypernuclei

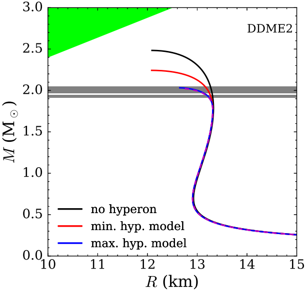
Gal et al., RMP (2016)

- $\sim$ 40 Λ-hypernuclei
  + measurement of binding energy
- only one unambiguous ΛΛ-hypernuclei: measurement of the bond energy:

  $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\text{He}) = 0.67 \pm 0.17$ MeV.
- few Ξ-hypernuclei
  but no measurement of binding energy
- no Σ-hypernuclei
  repulsive Σ-nucleon interaction?

Fortin, et al. PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei



Define two limiting hyperonic NS EOS:

- 'minimal hyperonic model': only Λ, calibrated to hypernuclear data.
- 'maximal hyperonic model': Σ and Ξ included too without $\sigma*$ and ϕ-mesons:
  - with $U^N_\Xi(n_0, 2/3n_0) = -14$ MeV suggested by experiments
  - $U^N_\Sigma(n_0) = 0, 30$ MeV

Experimentally calibrated hyperonic EOS

Experimental properties of hypernuclei

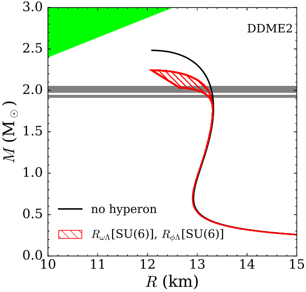
Gal et al., RMP (2016)

- $\sim$ 40 Λ-hypernuclei
  + measurement of binding energy
- only one unambiguous ΛΛ-hypernuclei: measurement of the bond energy:

  $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\text{He}) = 0.67 \pm 0.17$ MeV.
- few Ξ-hypernuclei
  but no measurement of binding energy
- no Σ-hypernuclei
  repulsive Σ-nucleon interaction?

Fortin, et al. PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei



Define two limiting hyperonic NS EOS:

- 'minimal hyperonic model': only Λ, calibrated to hypernuclear data.
- 'maximal hyperonic model': Σ and Ξ included in addition.

→ $\Delta M_{\max} \simeq 0.2\, M_\odot$ (up to $0.4\, M_\odot$ if SU(6) symmetry broken).

Experimentally calibrated hyperonic EOS

Experimental properties of hypernuclei

Gal et al., RMP (2016)

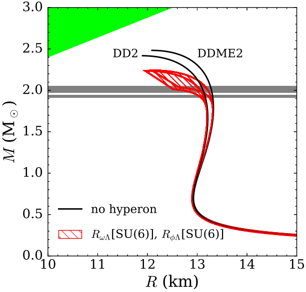
- $\sim$ 40 Λ-hypernuclei
  + measurement of binding energy
- only one unambiguous $\Lambda\Lambda$-hypernuclei: measurement of the bond energy:

  $\Delta B_{\Lambda\Lambda}(^{6}_{\Lambda\Lambda}\text{He}) = 0.67 \pm 0.17$ MeV.
- few Ξ-hypernuclei
  but no measurement of binding energy
- no Σ-hypernuclei
  repulsive Σ-nucleon interaction?

Hyperons in NSs NOT ruled out by the observations of 2 $M_\odot$ PSRs.
- see Also Fortin et al. PASA (2018): finite-T EOSs).

Fortin, et al. PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei



Define two limiting hyperonic NS EOS:

- 'minimal hyperonic model': only Λ, calibrated to hypernuclear data.
- 'maximal hyperonic model': Σ and Ξ included in addition.

$\rightarrow$ $\Delta M_{\rm max} \simeq 0.2\, M_\odot$ (up to 0.4 $M_\odot$ if SU(6) symmetry broken).

Experimentally calibrated hyperonic EOS

Experimental properties of hypernuclei

Gal et al., RMP (2016)

- $\sim$ 40 Λ-hypernuclei
  + measurement of binding energy
- only one unambiguous ΛΛ-hypernuclei: measurement of the bond energy:

  $\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 0.67 \pm 0.17$ MeV.
- few Ξ-hypernuclei
  but no measurement of binding energy
- no Σ-hypernuclei
  repulsive Σ-nucleon interaction?

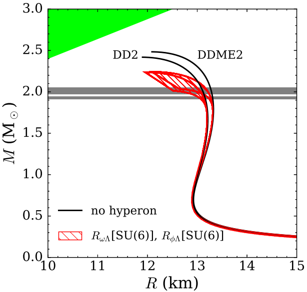
Hyperons in NSs NOT ruled out by the observations of 2 $M_{\odot}$ PSRs.
- see Also Fortin et al. PASA (2018): finite-T EOSs).

How to reduce $\Delta M_{\max}$?

- experimental constraints on the Ξ and Σ hyperons
- astrophysical constraints?

Fortin, et al. PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei



Define two limiting hyperonic NS EOS:

- 'minimal hyperonic model': only Λ, calibrated to hypernuclear data.
- 'maximal hyperonic model': Σ and Ξ included in addition.

$\rightarrow$ $\Delta M_{\max} \simeq 0.2\, M_{\odot}$ (up to 0.4 $M_{\odot}$ if SU(6) symmetry broken).

Conclusions

- Be careful when gluing an EOS for the core to one for the crust!
- Use unified EOS:
  - eg. Douchin & Haensel A&A 2001, BSk EOS (Chamel, Fantina et al.), Sharma et al. A&A 2015
  - Fortin et al. PRC 94 (2016): 48 unified nucleonic and hyperonic EOSs as supplemental material + confrontation with nuclear constraints.
- Zdunik et al. A&A (2017): very precise formula for $M(R)$ just with the EOS for the core.
- Alam et al. PRC (2016), Malik et al. arXiv 1805.11963: interesting correlations between neutron stars properties (radius, tidal deformability) and nuclear parameters.
- Fortin, Providência, Pais, *in prep.*: extensive study of correlations between properties of mirror and neutron-rich nuclei and of neutron stars.
- Fortin et al. PRC 94 (2017), Fortin et al. PASA (2018): hyperonic RMF EOSs consistent by the existence of 2 $M_\odot$ NSs taking account current experimental constraints.