CONSTRAINTS ON THE EQUATION OF STATE FROM NEUTRON STAR OBSERVATIONS

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Astro-PF
Polish-French collaboration in astrophysics

comp star

NATIONAL SCIENCE CENTRE
POLAND

Neutron stars: general aspects

Constraints from mass measurements

Constraints from radius measurements

Others. . .

Radius uncertainty

Hyperons in neutron stars?

Neutron stars: general aspects

Constraints from mass measurements

Constraints from radius measurements

Equation of state

Oertel et al. arXiv:1610.03361 RMP (2017), Haensel et al. book (2007)

Mystery : equation of state (EoS)

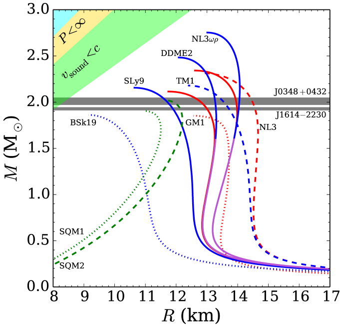
- Neutron star matter: many-body system of strongly-interacting particles (e, p, n, μ, more?) at T=0.
- EoS: describes its composition and properties;
- $P(\rho)$ with P the pressure, ρ the energy density.

Key point

How to constrain the EoS thanks to NS observations and experiments ?

Mass-radius plot

An EoS + Tolman and Oppenheimer & Volkoff (TOV) equations for hydrostatic equilibrium in GR = a specific mass-radius relation.



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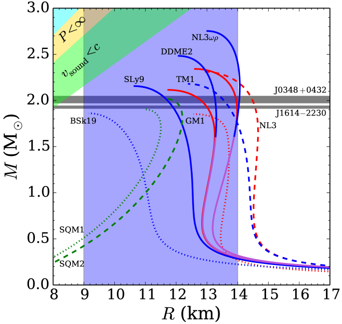
Constraints

- Mass: 2 $M_\odot$ NS (PSR J1614-2230 & J0348+0432)
- Radius: uncertainties in the modeling and the observations. Consensus $R = 9 - 14$ km. . .

Mass-radius plot

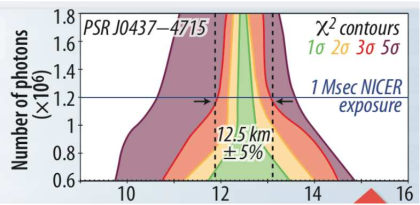
An EoS + Tolman and Oppenheimer & Volkoff (TOV) equations for hydrostatic equilibrium in GR = a specific mass-radius relation.



Perspectives

NICER

- Neutron star Interior Composition ExploreR Mission
- NASA project
- On the ISS
- Launch on June 3
- First light on July 17
- Rotating hot spots from non-accreting MSPs
- $M - R$ constraints with a precision of $\sim 5\%$ for ~ 3 NS.



Athena

- Advanced Telescope for High ENergy Astrophysics
- ESA project
- L2 point
- in 2028
- X-ray emission from MSPs;
- quiescent thermal emission of accreting NSs;
- PRE bursts from accreting NSs.

$M - R$ measurements

- rule out EoS
- reconstruct the EoS (see H. Grigorian's talk).

Others. . .

Rotational frequency

Theory

Haensel et al., A&A (1995)
Mass shedding limit:

$$f_{\mathrm{MS}} \simeq 1220\,\mathrm{Hz} \left(\frac{M_{\mathrm{max}}^{\mathrm{NR}}}{\mathrm{M}_\odot}\right)^{1/2} \left(\frac{R_{\mathrm{max}}^{\mathrm{NR}}}{10\ \mathrm{km}}\right)^{-3/2}.$$

Consistency with the fastest rotating NS:

$$\left(\frac{M_{\mathrm{max}}^{\mathrm{NR}}}{\mathrm{M}_\odot}\right) \left(\frac{R_{\mathrm{max}}^{\mathrm{NR}}}{10\ \mathrm{km}}\right)^{-3} > 0.67 \left(\frac{f_{\mathrm{max}}^{\mathrm{obs}}}{1000\,\mathrm{Hz}}\right)$$

PSR J1748-2446ad

Hessels et al., Science (2006)
Eclipsing binary MSP in Terzan 5 globular cluster.

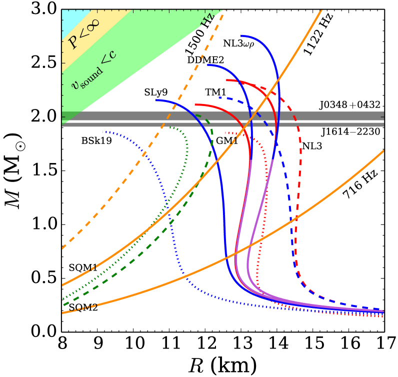
$$f_{\mathrm{max}}^{\mathrm{obs}} = 716\ \mathrm{Hz}.$$

XTE J1739-285

Kaaret et al., ApJ (2007)
Oscillations in an X-ray burst.

$$f = 1122\ \mathrm{Hz} \rightarrow \text{not confirmed.}$$

Mass-radius diagram



Perspectives

New radiotelescopes (FAST, SKA)

Redshift

Surface gravitational redshift z_g

$$\frac{M}{R} = \frac{c^2}{2G}\left[1 - (1 + z_g)^{-2}\right]$$

If M known → a single point in the (M, R) plane.

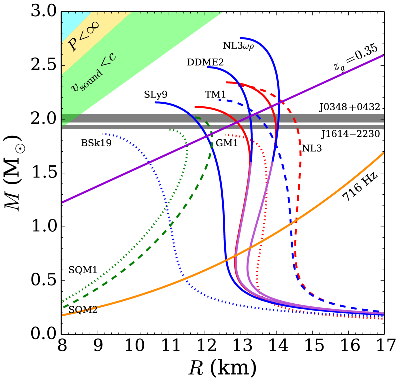
EXO 0748-676

- Cottam et al., Nature (2002) : **narrow** absorption lines in the spectra of X-ray bursts with
$$z_g = 0.35.$$
- Lin et al., ApJ (2010) : lines do not come from the surface.

Hohle et al., MNRAS (2012)

Narrow absorption lines detected in the X-ray spectra of 2 thermally emitting and slowly rotating isolated neutron stars → NS surface, circumstellar or interstellar origin?

Mass-radius plot



Perspectives

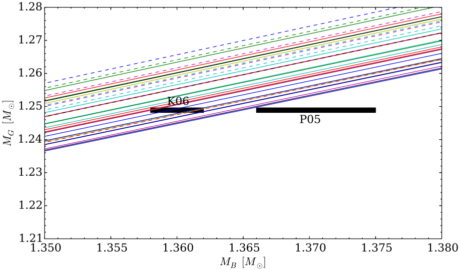
Athena (ESA, 2028).

Double pulsar PSR J0737−3039

NS baryon mass

Pulsar B:

- Very low mass:
  $M_{\mathrm{G}} = 1.2489 \pm 0.0007\ \mathrm{M}_{\odot}$.
- *IF* originates from an O-Ne-Mg electron capture supernova then loss of matter during the NS formation negligible.
- Total number of baryons A_{b} or NS baryon mass $M_{\mathrm{B}} = A_{\mathrm{b}} m_{\mathrm{b}}$ constrained from the properties of the WD progenitor.



Podsiadlowski et al. MNRAS (2005)

$M_{\mathrm{B}} = 1.336 - 1.375\ \mathrm{M}_{\odot}$

Kitaura et al. A&A (2006)

$M_{\mathrm{B}} = 1.36 \pm 0.002\ \mathrm{M}_{\odot}$

But...

see Oertel et al. arXiv:1610.03361 RMP (2017)
No consensus it originates from an O-Ne-Mg electron capture supernova.

Double pulsar PSR J0737−3039

Moment of inertia

Pulsar A

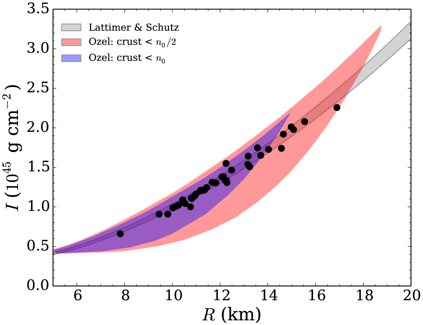
- $M = 1.3381 \pm 0.0007$ $M_\odot$.
- moment of inertia I measurable from the periastron advance of the binary orbit $\dot{omega}$ with the decay of the orbital period $\dot{P}_\mathrm{b}$
- expected with up to 10% within the next years

Lattimer & Schutz ApJ (2005)

Fitting a sample of EoS

Raithel et al. PRC93 (2016)

Simple model of constant densities in the core.



Nuclear parameters

At given density $n_{\rm b} = n_n + n_p$ and asymmetry $\delta = (n_n - n_p)/n_{\rm b}$,
the energy per nucleon is

$$E(n_{\rm b},\delta) = E_0(n_{\rm b},0) + E_{\rm sym}(n_{\rm b})\delta^2 + +\mathcal{O}(\delta^4)$$

which can be expanded around n_0 the saturation density, with $u = (n_{\rm b} - n_0)/3n_0$:

- the energy per nucleon in symmetric matter

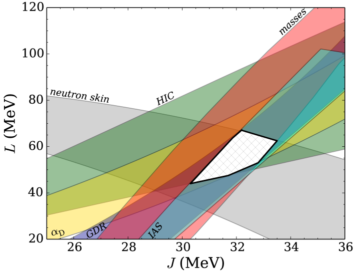
  $$E_0(n_{\rm b},0) = E(n_0) + K/2u^2 + Q/6u^3 + \ldots$$

  with K the incompressibility, Q the skewness coefficient, and $M = Q + 12K$ its slope;
- the symmetry energy

  $$E_{\rm sym}(n_{\rm b}) = J + Lu + K_{\rm sym}/2u^2 + \ldots$$

  with J the symmetry energy, L its slope, and $K_{\rm sym}$ its curvature.

Nuclear constraints



- neutron skin thickness of ^{208}Pb
- heavy ion collisions (HIC)
- electric dipole polarizability α_D
- giant dipole resonance of ^{208}Pb
- measured nuclear masses
- isobaric analog states (IAS)

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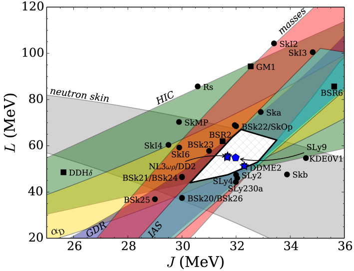
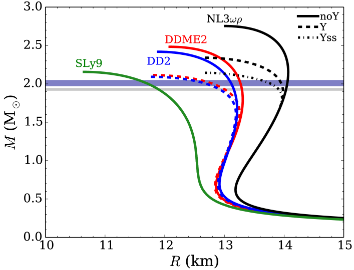


Fortin et al. PRC 94 (2016)



33 EoS; $R_{1.4} = 12.45 - 13.75$ km.

Nuclear parameters

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$$E(n_\mathrm{b}, \delta) = E_0(n_\mathrm{b}, 0) + E_\mathrm{sym}(n_\mathrm{b})\delta^2 + +\mathcal{O}(\delta^4)$$

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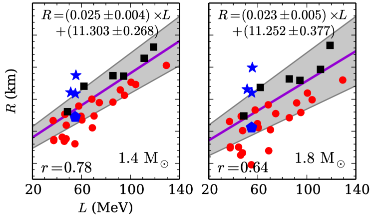
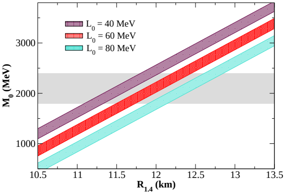


L also correlated to ^{48}Ca and ^{208}Pb neutron skin thickness (PREX & CREX)

Alam et al. PRC 94 (2016)



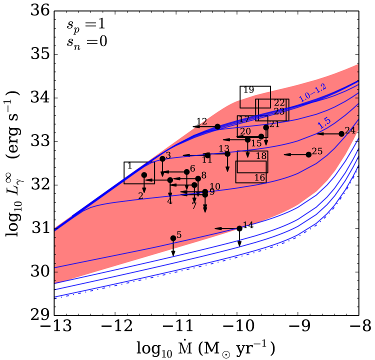
Gray strip: GMR experimental constraint (De+, PRC 92 2015)

$R_{1.4} = 11.09 - 12.86$ km

Nucleonic DUrca process

- $n \rightarrow p + e^- + \bar{\nu}_e \quad \text{and} \quad p + e^- \rightarrow n + \nu_e$
- momentum conservation → density n_{DU} and mass M_{DU} threshold

Fortin, Taranto et al., submitted (2017)

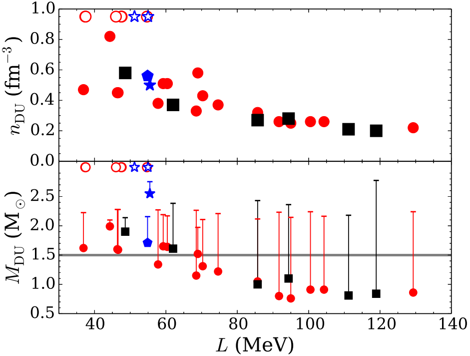


- eg. Beznogov & Yakovlev MNRAS (2015): DUrca process needed to explain the thermal emission of isolated and accreting NS.

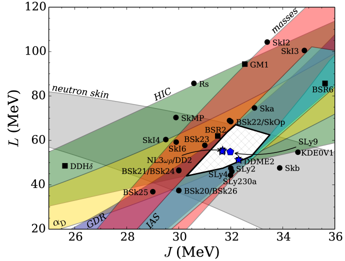
Nucleonic DUrca process

- $n \to p + e^- + \bar{\nu}_e$ and $p + e^- \to n + \nu_e$
- momentum conservation → density $n_{\rm DU}$ and mass $M_{\rm DU}$ threshold

Fortin et al., PRC 94 (2016)



- eg. Beznogov & Yakovlev MNRAS (2015): DUrca process needed to explain the thermal emission of isolated and accreting NS.
- For $L \lesssim 70$ MeV, EoS with DUrca and others without.
- $L - J$ plane: the intersection of all constraints gives $L \lesssim 70$ MeV.



Radius uncertainty

Equation of state

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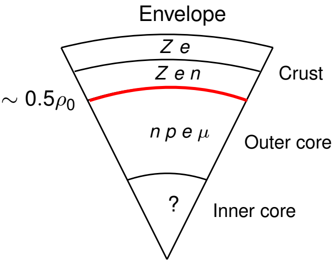
NS structure



Envelope

$Z\ e$

$Z\ e\ n$

Crust

$\sim 0.5\rho_0$

$n\ p\ e\ \mu$

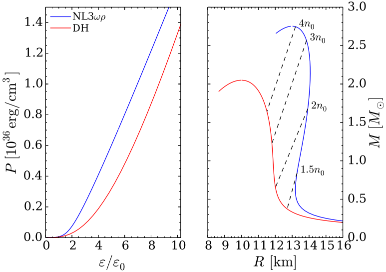
Outer core

?

Inner core

Mass-radius plot

EoS + TOV equations



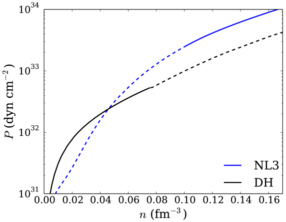
EoS

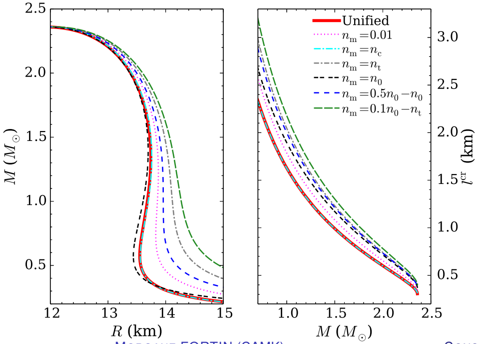
- core: homogeneous mixture
- crust: lattice of neutron rich atomic nuclei → non-uniform.

⇒ many more core EoS than crust EoS.

How to glue an EoS for the core to one for the crust?

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





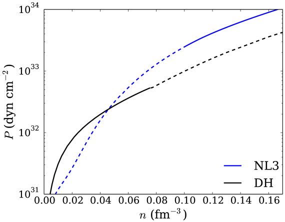
- core glued to BPS+BBP EoS at 0.01 fm^{-3};
- transition at the crossing density between the 2 EoSs;
- transition at the core-crust transition density n_t;
- transition at $n_0 = 0.16\ \mathrm{fm}^{-3}$;
- crust below $0.5n_0$ and core above n_0;
- crust below $0.1n_0$ and core above n_t;
- reference: unified EoS.

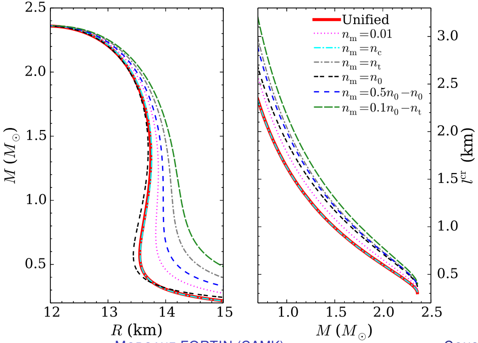
Uncertainty on R

- due to the treatment of the core-crust transition: up $\sim$ 4% (up to $\sim$ 30% on the crust thickness),
- decreases if crust and core EoSs with similar saturation properties.

How to glue an EoS for the core to one for the crust?

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





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

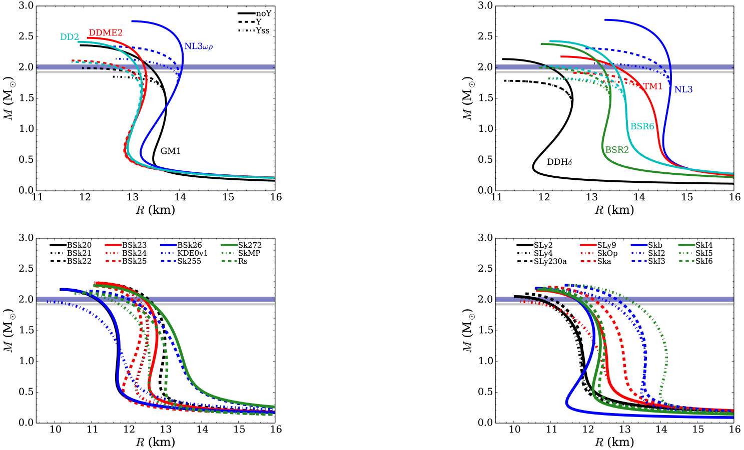
Uncertainty on *R*

- due to the treatment of the core-crust transition: up $\sim$ 4%
- with NICER, Athena or LOFT(?): expected precision $\sim$ 5% . . . .
- how to, if not solve, at least handle this problem?

1. Unified equations of state

Very few unified EoSs for NSs exist

eg. Douchin & Haensel 01, BSk EoS (Chamel+), Sharma+ 15



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

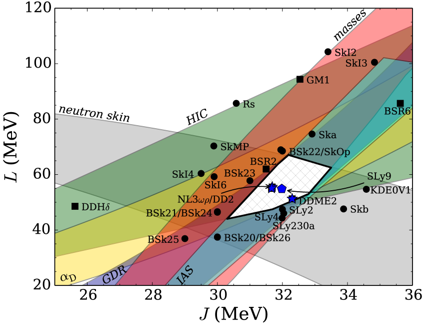
33 nucleonic EoSs and 15 hyperonic EoSs

Tables with n, ρ, P as supplemental material to the paper + soon on Compose

1. Unified equations of state

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

Nuclear constraints



- neutron skin thickness of ^{208}Pb
- heavy ion collisions (HIC)
- electric dipole polarizability α_{D}
- giant dipole resonance of ^{208}Pb
- measured nuclear masses
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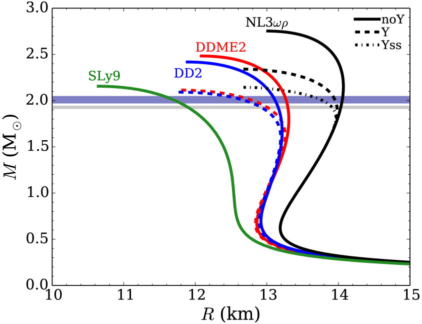
Low-density: $n_{\mathrm{b}} < n_0$

Hebeler et al. ApJ (2013): chiral effective field theory;

Gandolfi et al. PRC (2012): Quantum Monte Carlo technique

Selected EoSs

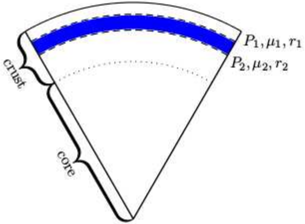


$R_{1.4} = 13.10 \pm 0.65$ km.

2. Approximate formula for the radius and crust thickness

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

Thickness of a shell in a catalyzed crust



Assuming that in the crust $m \approx M$ and $4\pi r^3 P/mc^2 \ll 1$ in the TOV equation one obtains:

$$\frac{\mathrm{d}P}{\rho + P/c^2} = -GM \frac{\mathrm{d}r}{r^2(1 - 2GM/rc^2)} \ .$$

With

$$\frac{\mathrm{d}P}{\rho c^2 + P} = \frac{\mathrm{d}\mu}{\mu} \qquad \text{one gets} \qquad \frac{\sqrt{1 - 2GM/r_2 c^2}}{\sqrt{1 - 2GM/r_1 c^2}} = \frac{\mu_2}{\mu_1}$$

valid for no jump in the chemical potential.

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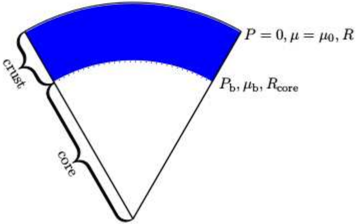

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valid for no jump in the chemical potential.
Taking $r_1 = R$ and $r_2 = R_\mathrm{core}$

$$\frac{\sqrt{1 - 2GM/Rc^2}}{\sqrt{1 - 2GM/R_\mathrm{core} c^2}} = \frac{\mu_\mathrm{b}}{\mu_0}$$

with $\mu_0 = \mu(P = 0) = 930.4$ MeV - minimum energy per nucleon of a bcc lattice of ^{56}Fe and μ_b at the core-crust transition.

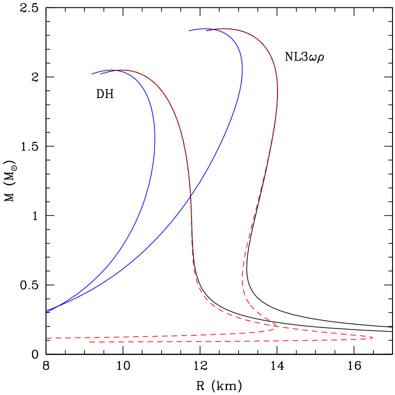
2. Approximate formula for the radius and crust thickness

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

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

Results

- uncertainty in the radius: $\lesssim 0.2\%$ for $M > 1\ M_\odot$
- uncertainty in the crust thickness: $\lesssim 1\%$ for $M > 1\ M_\odot$



Solution of the TOV equation with a unified EoS
TOV solution for the core $M(R_\mathrm{core})$
Approximate $M(R)$ for $n_\mathrm{b} = 0.077\ \mathrm{fm}^{-3}$

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_b with $\mu(n_\mathrm{b}) = \mu_\mathrm{b}$.
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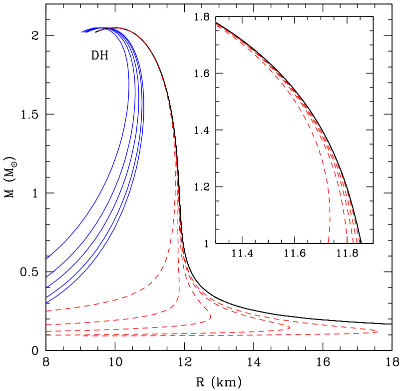
How to choose the core-crust transition density n_b?

- inversely proportional to L (Horowitz & Piekarewicz 2001)
- Ducoin et al. (2011): for EOSs with $30 \leq L \leq 120$ MeV, obtain: $0.06 \lesssim n_\mathrm{b} \lesssim 0.10\ \mathrm{fm}^{-3}$

$\Rightarrow$ $n_\mathrm{b} \simeq n_0/2 = 0.08\ \mathrm{fm}^{-3}$

+ approximate approach for a NS with an accreted crust.

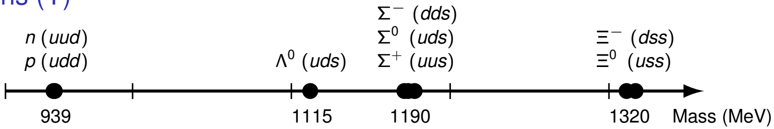


Solution of the TOV equation with a unified EoS
TOV solution for the core $M(R_\mathrm{core})$
Approximate $M(R)$ for $n_\mathrm{b} = 0.16, 0.13, 0.11, 0.09, 0.077\ \mathrm{fm}^{-3}$ from left to right.

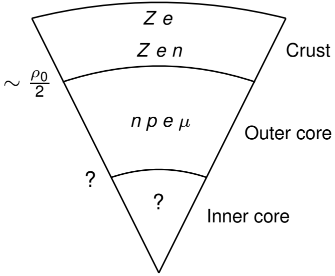
Hyperons in neutron stars?

Hyperonic equations of state

Hyperons (Y)

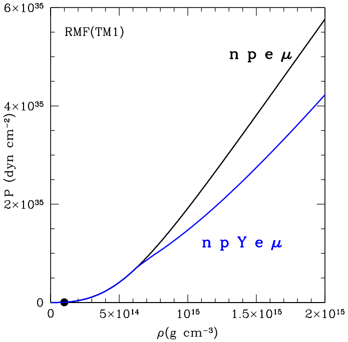


Structure



$\rho_0 \simeq 3 \times 10^{14}$ g cm^{-3}

Equation of state



Hyperonic equations of state

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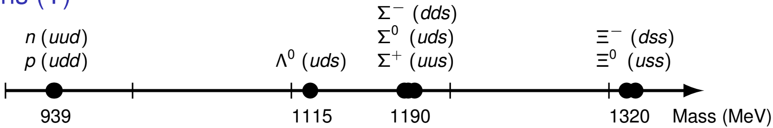


n (*uud*)
p (*udd*)

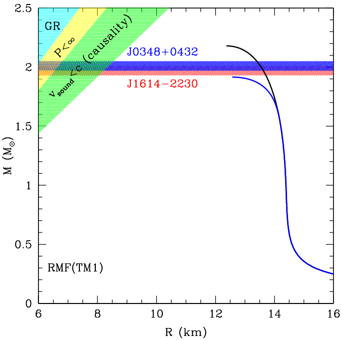
Λ^0 (*uds*)

Σ^- (*dds*)
Σ^0 (*uds*)
Σ^+ (*uus*)

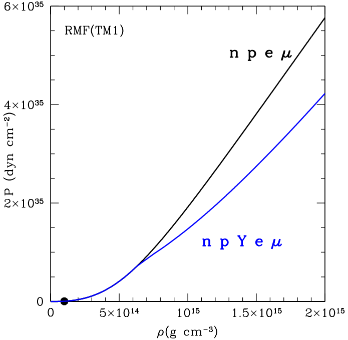
Ξ^- (*dss*)
Ξ^0 (*uss*)

939
1115
1190
1320
Mass (MeV)

$M - R$ plot



Equation of state



Hyperonic equations of state

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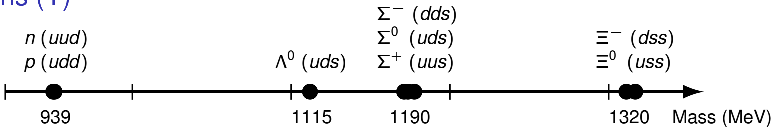


$n\,(uud)$

$p\,(udd)$

$\Lambda^0\,(uds)$

$\Sigma^-\,(dds)$

$\Sigma^0\,(uds)$

$\Sigma^+\,(uus)$

$\Xi^-\,(dss)$

$\Xi^0\,(uss)$

939

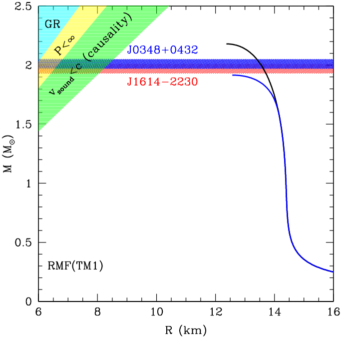
1115

1190

1320

Mass (MeV)

$M - R$ plot



- each EoS has a maximum mass $M_{\rm max}$;
- $M_{\rm max}$ strongly reduced when Y are included;
- consistency with the observations: $M_{\rm max} \geq M_{\rm max}^{\rm obs}$.

Hyperon puzzle

Can hyperons be present in NSs and yet $M_{\rm max} \geq M_{\rm max}^{\rm obs}$ with $M_{\rm max}^{\rm obs} \simeq 2\,M_\odot$?

Hyperonic equations of state

Fortin, Zdunik, Haensel and Bejger, A&A 576 (2015)

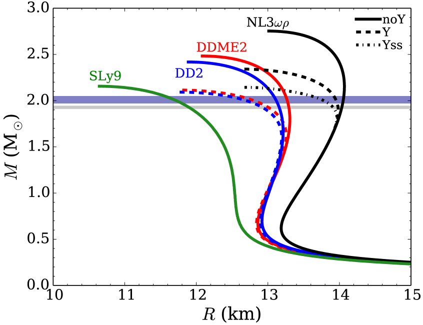
14 hyperonic EoSs consistent with 2 $M_\odot$:

- large radius for hyperonic EoSs correlated with a large pressure at n_0
- over-pressure at n_0 for hyperonic EoSs inconsistent with up-to-date microscopic calculations by Hebeler et al. (2013)

→ 2 $M_\odot$ is reach by compensating the decrease of the pressure at high density due to Y by a large pressure at low density

Fortin et al. PRC 94 (2016)

Hyperonic EoSs consistent with Hebeler et al. constraint and with $M_{\max} \geq 2\,M_\odot$.

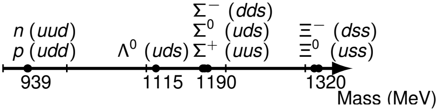


+ eg. Oertel et al. JPG (2015)

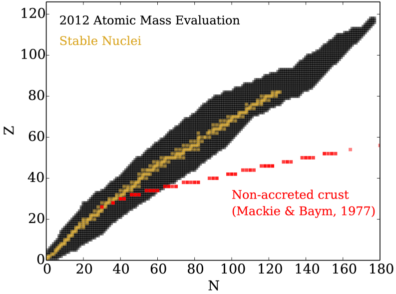
Experimentally calibrated hyperonic EoS

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

Hyperons (Y)



From nuclei to hypernuclei



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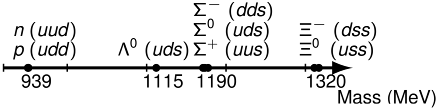

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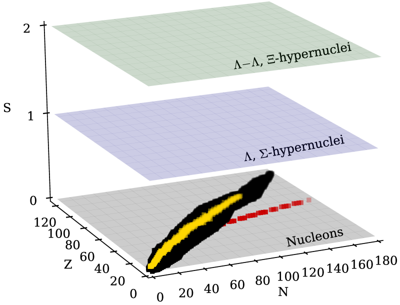


Experimentally calibrated hyperonic EoS

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

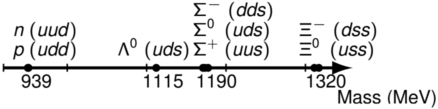
Experimental hypernuclei data

Gal et al., RMP (2016)

- $\sim$ 40 Λ-hypernuclei
  + measurement of binding energy B_Λ
- few Ξ-hypernuclei
  but no measurement of binding energy
- no Σ-hypernuclei
  repulsive Σ-nucleon interaction?
- only one unambiguous $\Lambda\Lambda$-hypernuclei:
  measurement of the bond energy:

$$\Delta B_{\Lambda\Lambda}({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 0.67 \pm 0.17\ \mathrm{MeV}.$$

Hyperons (Y)



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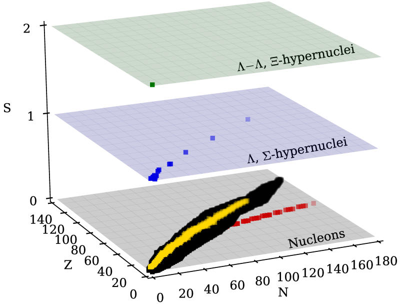

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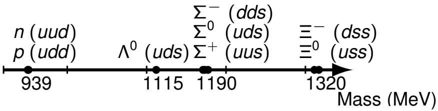
Usual approach to hyperons

Adjust the couplings for the Λ to reproduce:

- the Λ-potential in symmetry nuclear matter
  $U_\Lambda^N(n_0)$: usually (-30, -28) MeV
- the Λ-potential in pure Λ matter
  $U_\Lambda^\Lambda(n_0, n_0/5)$: usually (-5, -1) MeV

Hyperons (Y)



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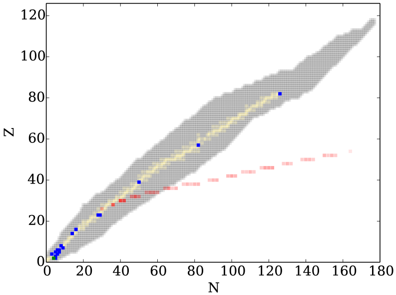

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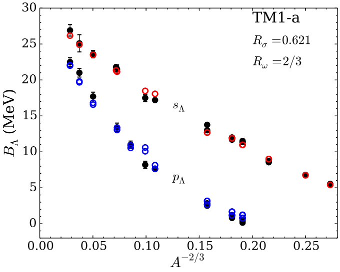
Modeling of hypernuclei

- for the TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2 RMF models.
- adjust the Λ-couplings to reproduce:
  1. Λ-hypernuclei:



$$U_\Lambda^N(n_0) \in [-36, -30]\ \mathrm{MeV}$$

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

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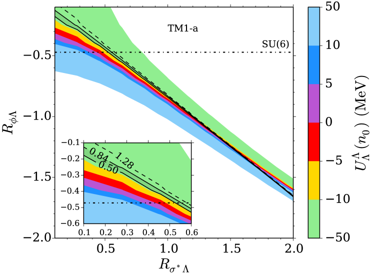
  2. ΛΛ-hypernuclei



$$U_\Lambda^\Lambda(n_0) \in [-14, -9] \text{ MeV}$$
$$U_\Lambda^\Lambda(n_0/5) \in [-7, -5] \text{ MeV}$$

Experimentally calibrated hyperonic EoS

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

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Modeling of hypernuclei

- for the TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2 RMF models.
- adjust the Λ-couplings to reproduce:
  1. Λ-hypernuclei:
  2. ΛΛ-hypernuclei
- build calibrated hyperonic EoSs including the other hyperons and the current experimental uncertainty of their properties: two hyperonic models:
  1. 'minimal hyperonic model': only Λ included
  2. 'maximal hyperonic model': Λ, Σ, and Ξ included with:
     $U_\Xi^N(n_0 \text{ or } 2/3 n_0) = -14$ MeV
     suggested by experiments
     $U_\Sigma^N(n_0) = 0, 30$ MeV.

Experimentally calibrated hyperonic EoSs

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

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Conclusions

- models are consistent with 2 $M_\odot$
- because lack of constraints on the nuclear model at high density
- thus no solution to the hyperon puzzle at the moment.

NSs are at the interface between astrophysics and nuclear physics

- Goal: constrain the properties of the nuclear force with astrophysical observations and *vice-versa*.
- Currently: only constraints from mass measurements;
- Hopefully more to come in the next few years thanks to new instruments.
- More constraints thanks to nuclear experiments.
- Be careful when gluing an EoS for the core to one for the crust:
  - Use unified equations of state eg. Fortin+ PRC 94 (2016)
  - Approximate formula for $M(R)$ with no crust needed (Zdunik+ A&A, 2017).
- Hyperonic equations of state are *not* ruled out by the existence of 2 $M_\odot$ neutron stars.