THERMAL EVOLUTION OF ISOLATED AND ACCRETING NEUTRON STARS. . . AND MORE

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Astro-PF
Polish-French collaboration in astrophysics

NARODOWE CENTRUM NAUKI

PHAROS
THE MULTI-MESSENGER PHYSICS AND ASTROPHYSICS OF NEUTRON STARS

Thermal evolution of isolated and accreting neutron stars

Cooling of isolated NSs

$t = 0$: $T \sim 10^9 - 10^{10}$ K.

$t \lesssim 10^2$ years
  - the core cools by ν-emission,
  - the crust by heat diffusion.

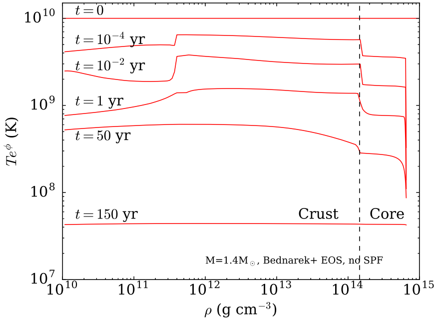
→ crust properties.

$t \lesssim 10^5$ years
  - thermal balance between the core and the crust,
  - cooling by ν-emission;

→ core properties.

$t \gtrsim 10^5$ years
  - cooling via emission of photons from the surface.

Evolution of the temperature profile



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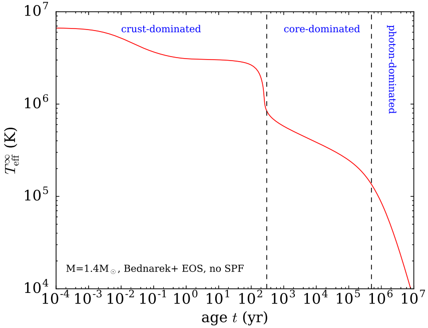
Evolution of the surface temperature



Heat equation

integrated over the whole star

$$C(T_{\rm i})\frac{{\rm d}T_{\rm i}}{{\rm d}t} = -L_\nu^\infty(T_{\rm i}) - L_\gamma^\infty(T_{\rm s}) + \underbrace{L_{\rm h}^\infty}_{=0}.$$

with $T_{\rm i} = Te^\phi$ and $T_{\rm s}(T_{\rm i})$ is given by a model for the heat blanketing envelope.

Observations of isolated NSs

Biases

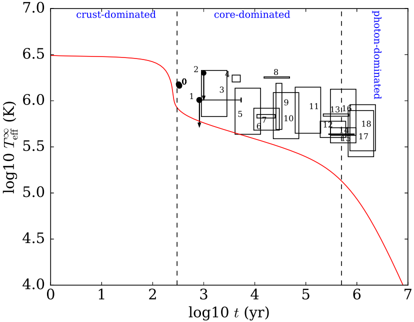
- small objects: detection of NSs with $T \sim 10^5 - 10^7$ K within few kpc
- middle-aged NSs with extended supernova remnant.

Age and temperature determination

- age: uncertain unless the supernova as been observed in the past (cf. Crab pulsar): estimation from spin-down or modelling the expansion of the supernova.
- temperature: composition of the envelope unknown: H, He, . . . Fe?

Observational data

X-ray telescopes eg. XMM-Newton, Chandra, Athena, . . .



Heat equation

All observed NSs are in the core and photon dominated stages → dependence on core and envelope properties.

$$C(T_\mathrm{i})\frac{\mathrm{d}T_\mathrm{i}}{\mathrm{d}t} = -L_\nu^\infty(T_\mathrm{i}) - L_\gamma^\infty(T_\mathrm{s}).$$

Neutrino emission

See eg. Table 1 of Potekhin et al. SSR (2015) - arXiv:1507.06186

Slow processes with $Q_\nu \propto T^8$

- modified Urca

$$n + N \rightarrow p + N + l + \nu_l$$

  with N a spectator nucleon to ensure momentum conservation.

- NN-bremsstrahlung

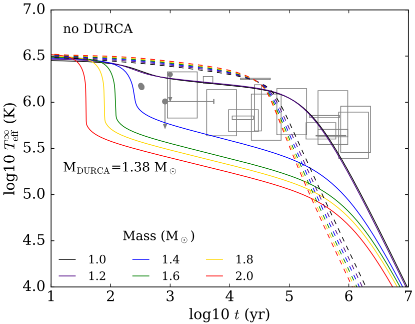
$$N + N \rightarrow N + N + \nu_l + \bar{\nu}_l$$

Fast process: direct Urca with $Q_\nu \propto T^6$

$$n \rightarrow p + l + \bar{\nu}_l$$

with $l = e^-, \mu^-$.
Momentum conservation imposes EOS-dependent density/mass threshold above which it operates.

Non-superfluid NSs



Two EOS, one allowing for DURCA.

- Hot (luminous) objects: low-mass NSs;
- Cold objects: high-mass NSs.

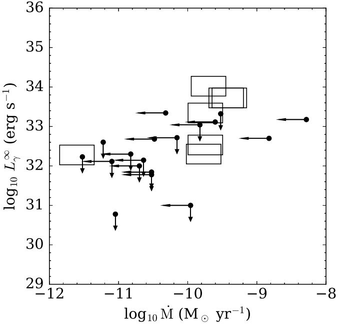
Thermal evolution of accreting NSs

Soft X-ray Transients

NSs in close binaries with a low-mass companion undergoing:

- repeated short periods of accretion;
- long quiescent phases.

Observations



Thermal equilibrium

Quasi-stationary state:

$$\underbrace{C(T_\mathrm{i})\frac{\mathrm{d}T_\mathrm{i}}{\mathrm{d}t}}_{=0} = -L_\nu^\infty(T_\mathrm{i}) - L_\gamma^\infty(T_\mathrm{s}) + \underbrace{L_\mathrm{h}^\infty}_{\neq 0}.$$

Heating

During the accretion phases, deep crustal heating.
$\Rightarrow L_\mathrm{h}^\infty = L_\mathrm{DCH}^\infty(\langle \dot{M} \rangle)$
with $\langle \dot{M} \rangle$ estimated, averaged over periods of accretion and quiescence.

Ingredients

- Properties of the core: EOS and baryon superfluidity
- envelope models.

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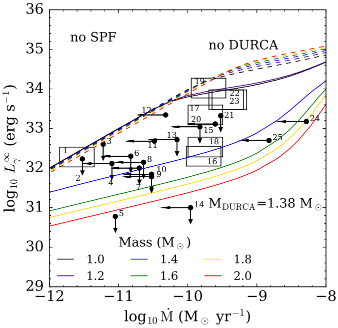
Modelling



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Constraints

Low photon luminosity:

- very high ν losses ie. large L_ν;
- the most efficient ν-process DUrca is necessary: not all EoS allow for it.
- necessary to go beyond the minimal cooling model

Thermal evolution of isolated and accreting NSs

eg. Levenfish & Haensel (2007), Beznogov & Yakovlev (2015a,b)

Fortin, Taranto, Burgio, Haensel, Schulze and Zdunik, MNRAS 475 (2018)

- BHF EOS of Taranto et al. 2016 (AV18+Urbana) with a DURCA onset at $1.1 M_\odot$
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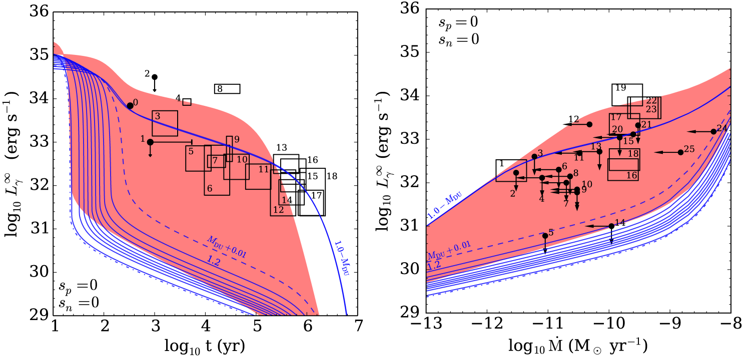
Non superfluid matter



Consistent with the coolest SXT but not the middle-aged hot INS
+ problematic mass distribution (see also Beznogov & Yakovlev (2015a,b))

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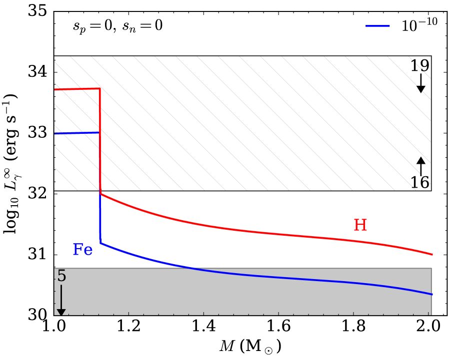

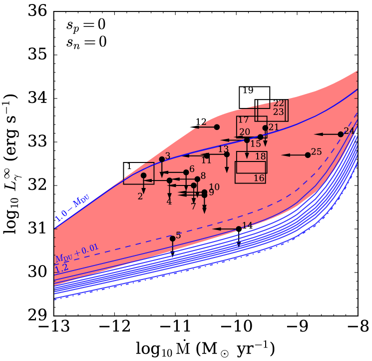

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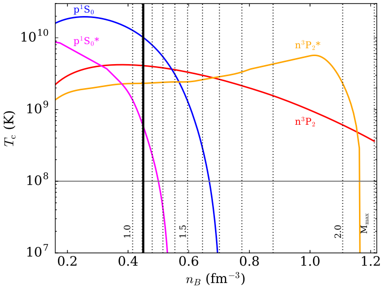
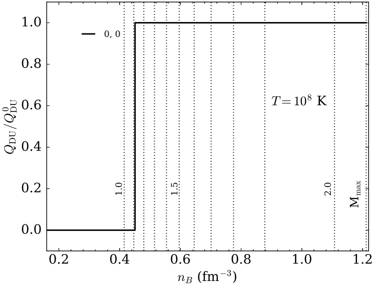
Superfluidity (SPF)



- Zhou et al. (2004): calculated with the same nucleon interaction as the EOS.
- SPF $*$: BHF approximation for the SP potential.

When $T \leq T_c$, formation of Cooper pairs → superfluidity.

DURCA threshold



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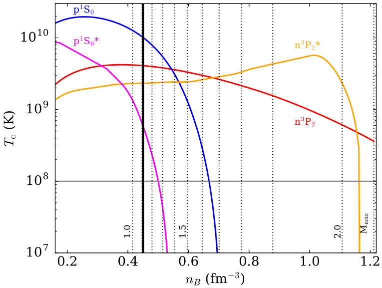

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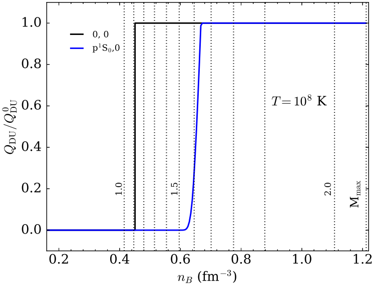

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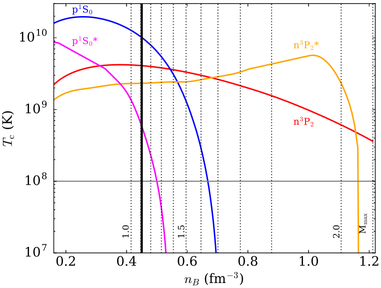

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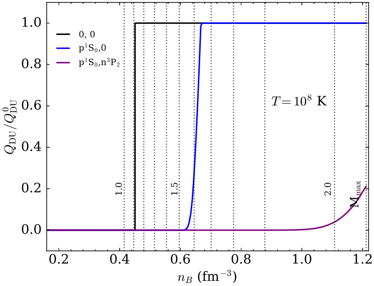

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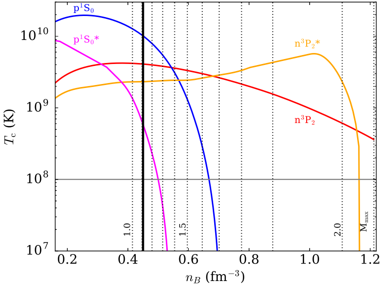

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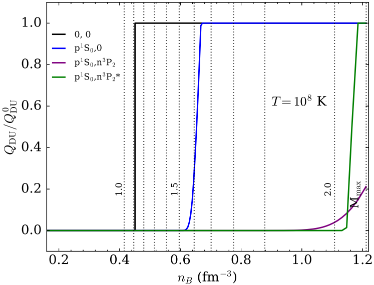

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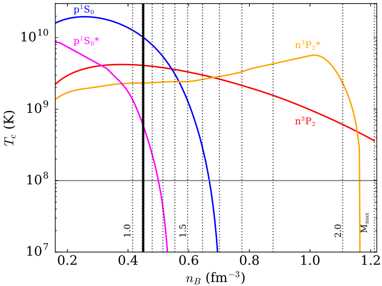

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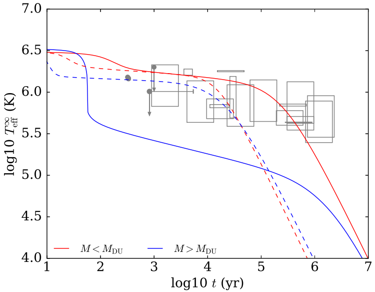
When $T \leq T_c$, formation of Cooper pairs $\rightarrow$ superfluidity.

- exponentially suppresses of all reactions involving the SPF baryons;
- broadens the onset of the DURCA threshold.
- initiates a new neutrino processes: "PBF" (pair breaking and formation processes): $B \rightarrow B + \nu + \bar{\nu}$; $Q_\nu \propto T^7$ very strongly reduced for $^1S_0$ pairing by in-medium effects,
  $\Rightarrow$ only operating for $^3P_2$ neutron pairing.

Cooling curves (similar trends for SXTs)



Thermal evolution of isolated and accreting NSs

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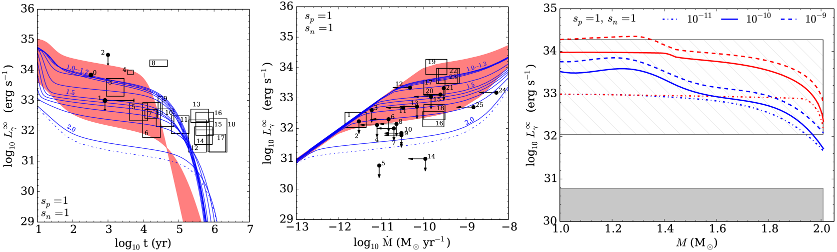
SPF gaps consistent with the EOS



- smooth mass distribution
- but too strong SPF reduction of the DURCA process and PBF processes.

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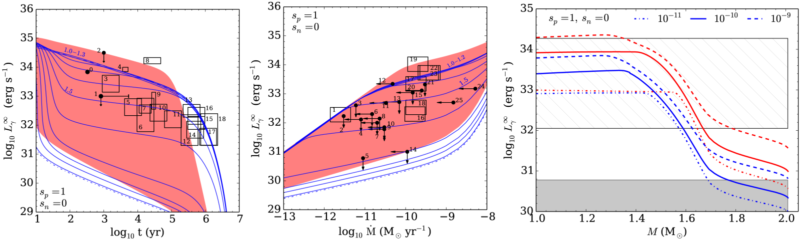
Consistency with the data



- middle aged INSs and hot SXTs = low-mass NSs where proton SPF suppresses slow ν-processes and no neutron SPF hence no PBF process.
- cold SXTs = massive NSs with fully operating DURCA process: protons and neutrons not superfluid at the center of massive stars
- smooth mass distribution: protons and neutrons SPF at the center of medium-mass NSs.

see also Beznogov & Yakovlev (2015a,b), Han & Steiner PRC (2017)

Conclusions

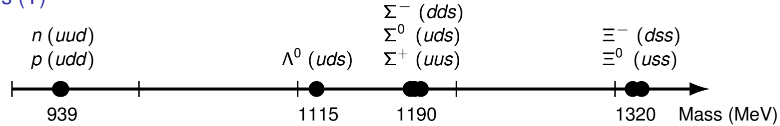
- joint modeling of INSs and SXTs required;
- modeling of SXTs indicates that the DURCA is required: go beyond the minimal cooling model + constrain on the EOS;
- some general trends on baryon SPF can be derived;

- more observations of INSs and SXTs;
- determination of the mass of some of these NSs.
- consistent calculations of the EOS and the SPF gaps.

…and more: (hyper)nuclei and neutron stars

Hyperonic equations of state

Hyperons (Y)



n (uud)
p (udd)

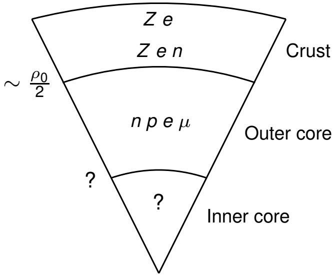
Λ^0 (uds)

Σ^- (dds)
Σ^0 (uds)
Σ^+ (uus)

Ξ^- (dss)
Ξ^0 (uss)

939 1115 1190 1320 Mass (MeV)

Structure



$Z\ e$

$Z\ e\ n$

Crust

$\sim \frac{\rho_0}{2}$

$n\ p\ e\ \mu$

Outer core

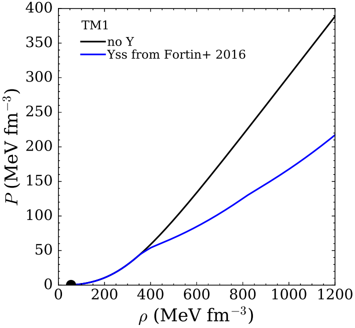
?

?

Inner core

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

Equation of state



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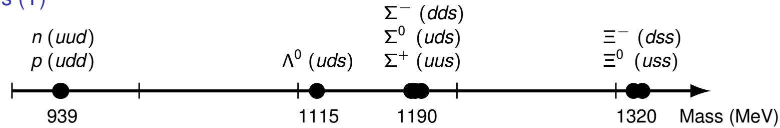

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939

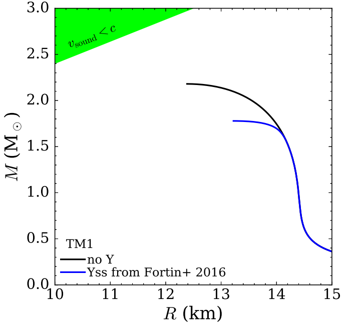
1115

1190

1320

Mass (MeV)

$M - R$ plot



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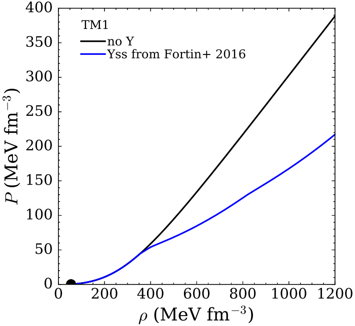

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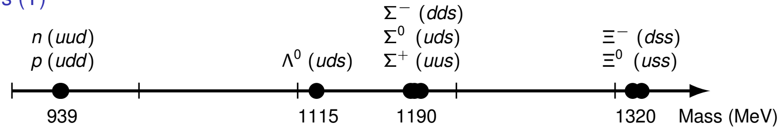


$n\ (uud)$
$p\ (udd)$

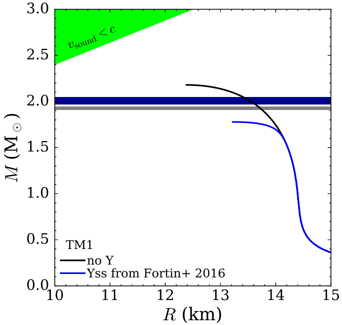
$\Lambda^0\ (uds)$

$\Sigma^-\ (dds)$
$\Sigma^0\ (uds)$
$\Sigma^+\ (uus)$

$\Xi^-\ (dss)$
$\Xi^0\ (uss)$

939 1115 1190 1320 Mass (MeV)

$M - R$ plot



Observational constraint:

- each EoS has a maximum mass $M_{\rm max}$;
- $M_{\rm max}$ reduced when Y are included;
- consistency with the observations: $M_{\rm max} \geq M_{\rm max}^{\rm obs}$.
- Largest masses observed:
  PSR J1614-2230 & PSR J0348+0432

$$M_{\rm max}^{\rm obs} \simeq 2\ M_\odot.$$

- Hyperon puzzle: Can hyperons be present in NSs and yet $M_{\rm max} \geq 2\ M_\odot$?

Experimentally calibrated hyperonic EoS

Experimental properties of hypernuclei

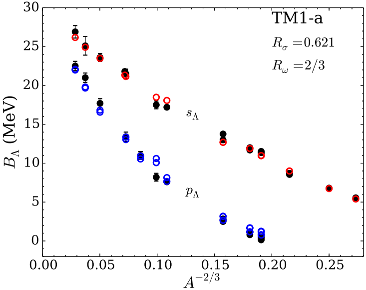
Gal et al., RMP (2016)

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

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



Usual approach to hyperons

Adjust the couplings for the 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 $U_\Lambda^\Lambda(n_0/5)$

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

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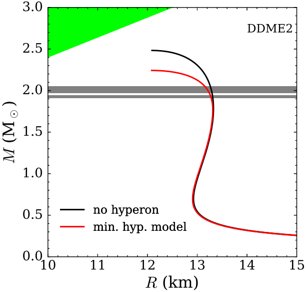

Define two limiting hyperonic NS EOS:

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

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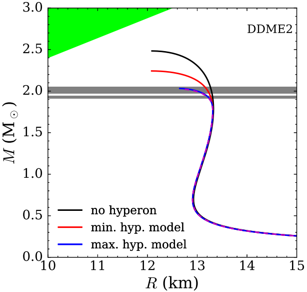

Define two limiting hyperonic NS EOS:

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

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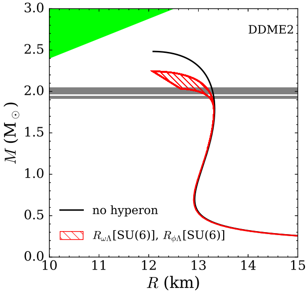

Define two limiting hyperonic NS EOS:

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

→ $\Delta M_{\max} \simeq 0.2\, M_\odot$.

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:

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

Usual approach to hyperons

Adjust the couplings for the Λ to reproduce:

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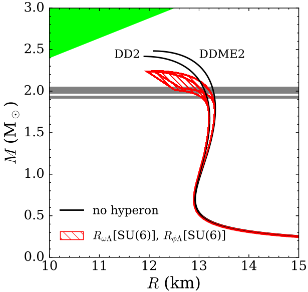

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$\Delta M_{\max} \sim 0.4\,M_\odot \ldots$

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

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

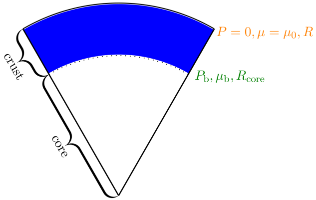
Hyperons in NSs NOT ruled out by the observations of $2\, M_\odot$ PSRs.

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

$$R = R_{\rm core} / \left(1 - \left(\frac{{\mu_{\rm b}}^2}{{\mu_0}^2} - 1\right)\left(\frac{R_{\rm core}\, c^2}{2GM} - 1\right)\right).$$



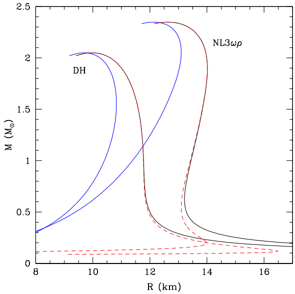
2 unknowns

- $\mu_0 = 930.4$ 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 $M > 1\, M_\odot$
- $\Delta I^{\rm cr} \lesssim 1\%$ for $M > 1\, M_\odot$

+ Formulas for NSs with an accreted crust.



TOV solution for the unified EoS, for the core EOS

Approximate $M(R)$

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
- $R_{\rm mirr}(^{50}\mathrm{Ni}\text{-Ti})$: correlated with the radius of low-mass stars.

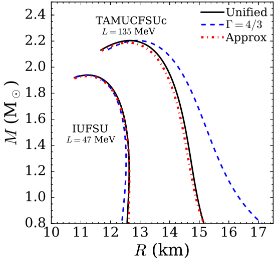
Fortin, Providência, Pais, in prep.

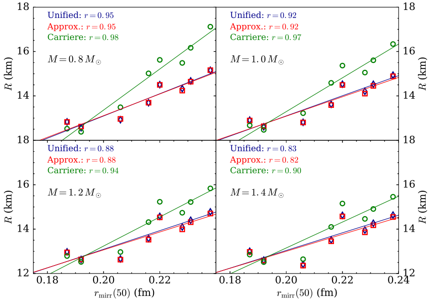
- 9 out of 14 RMF models
- Unified EOSs
- Approximate approach

EOS construction

From Carriere et al. ApJ (2003):

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





More correlations studied employing ∼ 50 EOS. Stay tuned!

Conclusions

- joint modeling of INSs and SXTs required;
- modeling of SXTs indicates that the DURCA is required: go beyond the minimal cooling model + constrain on the EOS;
- some general trends on baryon SPF can be derived;

- more observations of INSs and SXTs;
- determination of the mass of some of these NSs.
- consistent calculations of the EOS and the SPF gaps.

- Fortin et al. PRC 94 (2017): hyperonic RMF EoSs consistent by the existence of $2\,M_\odot$ NSs.
- More experimental constraints for hyperons necessary to reduce the $\Delta M_{\rm max}$.
- 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.
- Fortin, Providência, Pais, *in prep.*: extensive study of correlations between properties of nuclei and of neutron stars.