

ASTROPHYSICAL CONSTRAINTS ON THE EQUATION OF STATE?

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HECOLS
Polish-French
collaboration
in astrophysics



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Constraints on the EOS from the NS thermal emission?

Cooling of isolated NSs

$t = 0$

- ▶ $T \sim 10^9 - 10^{10}$ K.

$t \sim 1$ year

- ▶ the core cools by ν -emission,
- ▶ the crust by heat diffusion.

→ crust properties.

$t \lesssim 10^5$ years

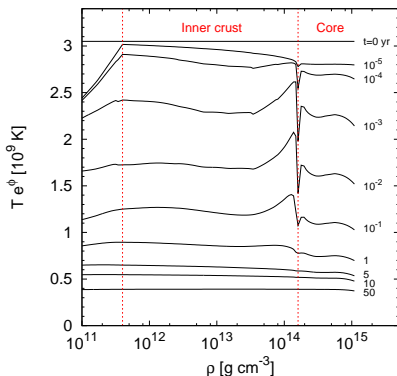
- ▶ thermal balance between the core and the crust,
- ▶ cooling by ν -emission;

→ core properties.

$t \gtrsim 10^5$ years

- ▶ cooling via emission of photons from the surface.

Evolution of the temperature profile



Non-superfluid $1.4 M_\odot$ NS model.

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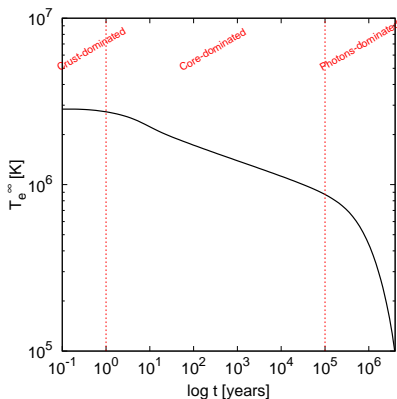
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Evolution of the surface temperature



Non-superfluid $1.4 M_\odot$ NS model.

Observations of isolated NSs

X-ray telescopes eg. XMM-Newton, Chandra, AstroH(?), NuStar, Athena, ...

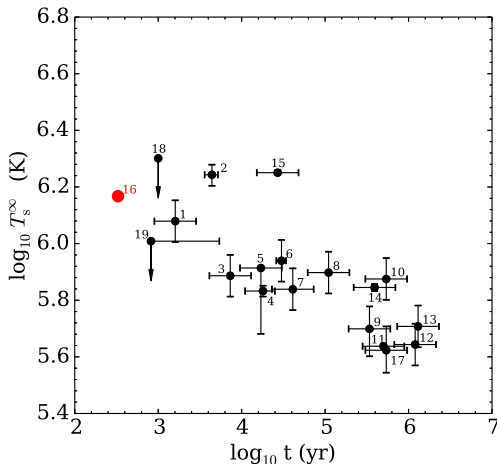
Biases

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

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 remnant.
- ▶ temperature: composition of the envelope unknown: H, He, non-accreted?

Observational data



Observations of isolated NSs

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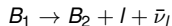
Modelling

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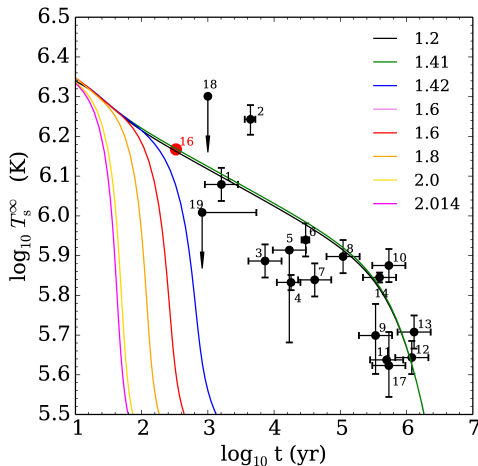
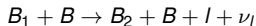
Neutrino processes in a nutshell

- ▶ Fast processes (DUrca):
 $Q_\nu \propto T^6$



momentum conservation \rightarrow
density n_{DU} and mass M_{DU}
thresholds

- ▶ Slow processes (MUrca):
 $Q_\nu \propto T^8$



BM165 + non-accreted envelope + no SPF + no hyperons
 $M_{\text{DU}} = 1.43 M_\odot$

Observations of isolated NSs

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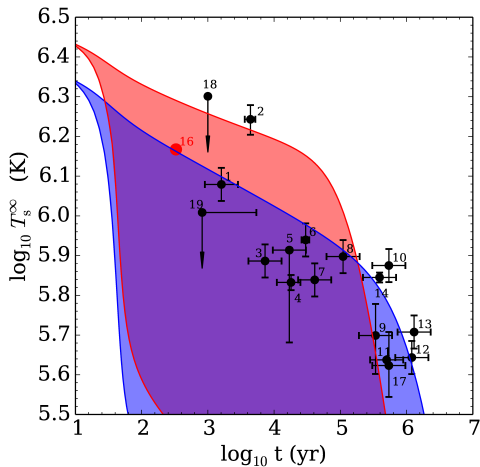
Constraints?

(Too?) many uncertainties:

- ▶ the mass
- ▶ the atmosphere composition
- ▶ the age
- ▶ the distance
- ▶ ...

Plus effect of the magnetic field (see eg. Viganó et al. MNRAS 2013) → modeling of the magneto-thermal evolution.

Modelling



BM165 + non-accreted and H envelope + no SPF + no hyperons

Cas A NS

- ▶ age = 330 ± 20 yr,
- ▶ distance $d = 3.4^{+0.3}_{-0.1}$ kpc,
- ▶ C atmosphere (Ho & Heinke, 2009).

Direct observations of the cooling

- ▶ 10 years of X-ray observations
- ▶ Temperature decline of $\sim 3.5\% \pm 0.5\%$ (Heinke & Ho, 2010; Elshamouty et al. 2013)

Neutrino process in SPF matter

- ▶ for $T^B \ll T_C^B$ exponential suppression of the process involving the baryon B
- ▶ new 'PBF' process: $Q_\nu \propto T^7$

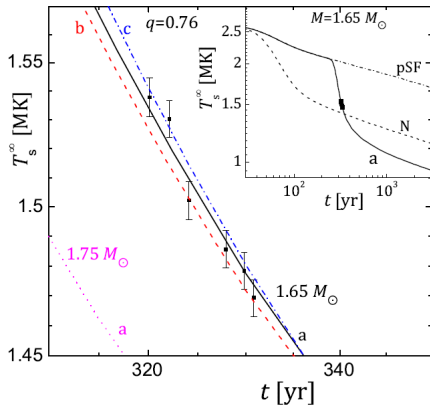
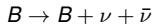


Figure : Cooling curves of a $1.65 M_\odot$ star for different superfluid properties in the core. From Shternin et al., MNRAS (2011)

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Modelling

Two ingredients (Shternin et al., MNRAS 2011; Page et al., PRL 2011):

- ▶ recent triggering of the PBF process due to neutron ${}^3\text{P}_2$ superfluidity :
 $T_C \sim 5 - 9 \times 10^8$ K,
- ▶ the protons are already superfluid (in the ${}^1\text{S}_0$ channel) : $T_C \sim 10^9$ K.
- ▶ Constraints on the core superfluid properties ☺

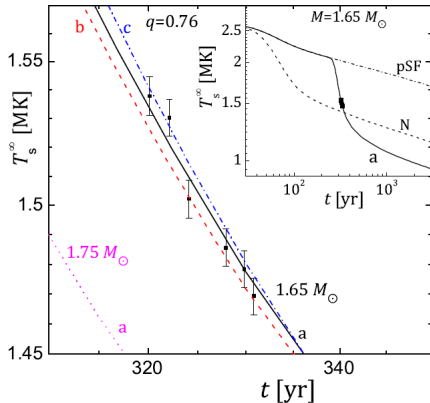


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- ▶ talk by B. Posselt: maybe not in fact ☺

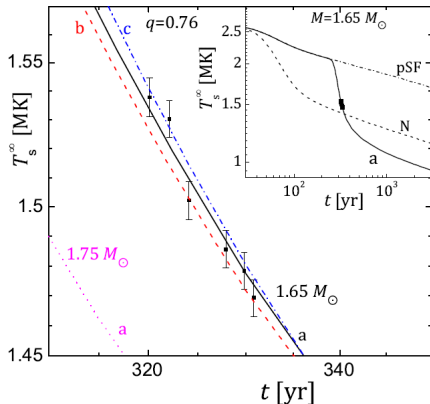
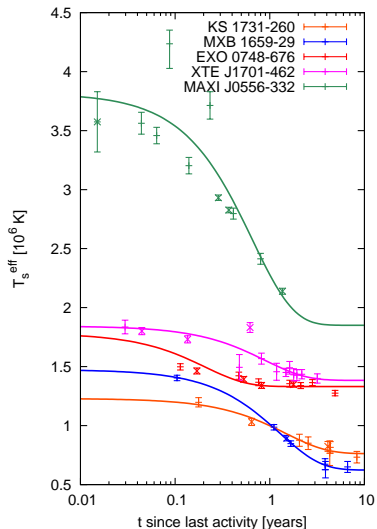


Figure : Cooling curves of a $1.65 M_{\odot}$ star for different superfluid properties in the core. From Shternin et al., MNRAS (2011)

Thermal evolution of accreting NSs

Thermal relaxation

= after end of accretion



MORGANE FORTIN (CAMK)

Quasi-Persistent X-Ray Transients

Two phases:

- ▶ accretion during \sim years to decades,
- ▶ quiescence when accretion stops.

Deep crustal heating scenario

While the accreted matter sinks into the crust, it undergoes a series of reactions that heats the crust.

KS & MXB

Shternin et al., MNRAS (2007); Brown & Cumming, ApJ (2009) :

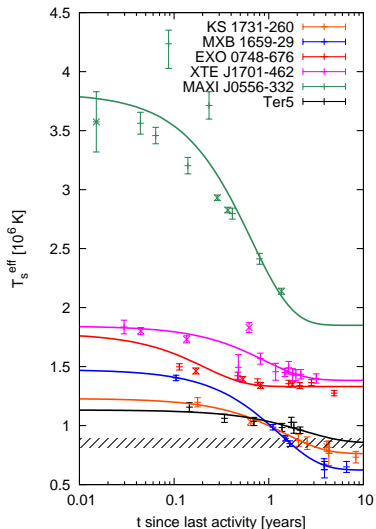
- ▶ exclude DUrca in the core,
- ▶ crystalline crust with superfluid neutrons.

ASTROPHYSICAL CONSTRAINTS ON THE EQUATION OF STATE?

Thermal evolution of accreting NSs

Thermal relaxation

= after end of accretion



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New type of source: normal transient

IGR J17480-2446 in Terzan 5 (Degenaar et al., ApJ 2013):

accreted during ~ 10 weeks only.

	τ (d)
KS	540 ± 125
MXB	465 ± 35
EXO	165 ± 60
XTE	95 ± 15
MAXI	240 ± 60
Ter 5	100 ± 10

Constraints

on the crust properties:

- ▶ composition,
- ▶ nuclear reactions due to accretion,
- ▶ neutron superfluidity.

ASTROPHYSICAL CONSTRAINTS ON THE EQUATION OF STATE?

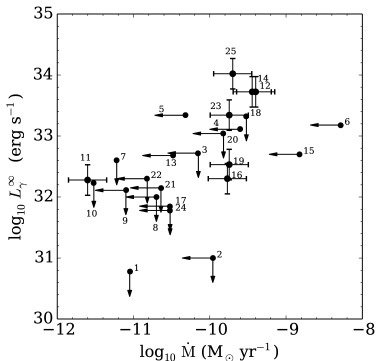
Thermal evolution of accreting NSs

Soft X-ray Transients

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

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

Observations



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Luminosity in quiescent state

Assuming a quasi-stationary evolution:

Luminosity of photons emitted at the surface L_{γ}

= power from the heat generated in the interior by nuclear reactions ($\langle \dot{M} \rangle$)

– luminosity of neutrinos emitted from the whole interior L_{ν} .

Uncertainties

- ▶ observations for at most several decades:
 $\langle \dot{M} \rangle$ estimated but large uncertainties;
- ▶ uncertainty on the distance.

Ingredients

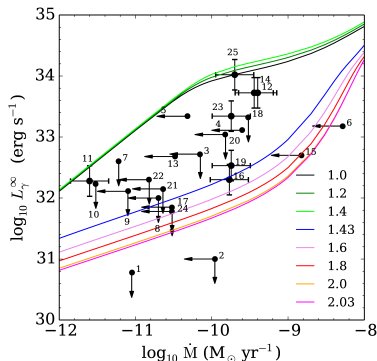
Properties of the core:

- ▶ EoS,
- ▶ baryon superfluidity.

ASTROPHYSICAL CONSTRAINTS ON THE EQUATION OF STATE?

Thermal evolution of accreting NSs

Modelling



BM165 + H envelope + no SPF + no hyperons

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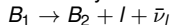
– luminosity of neutrinos emitted from the whole interior L_ν .

Constraints

Low quiescent luminosity:

→ very high ν losses ie. large L_ν ;

▶ the most efficient process: DUrca is necessary:

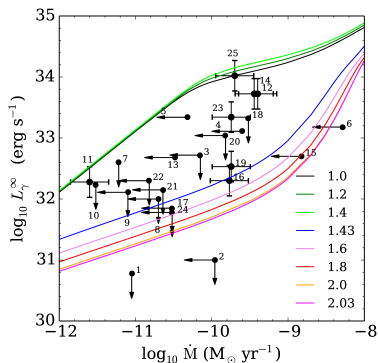
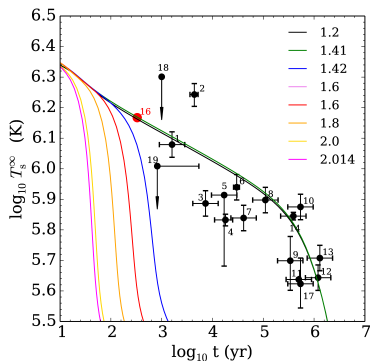


Conservation of momentum → density threshold.

Not all EoS allow for the DUrca.

Thermal evolution of isolated and accreting NSs

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



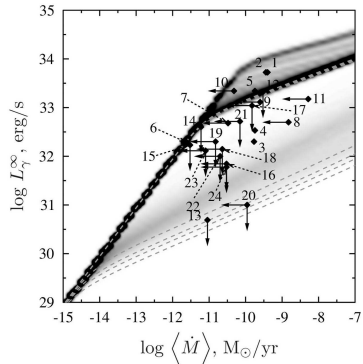
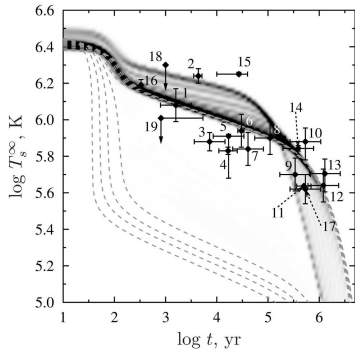
Problem

2 'populations' of NS:

- ▶ $M < M_{DU}$: warm NS
- ▶ $M > M_{DU}$: cold NS
- ▶ intermediate NS require extreme fine-tuning of the mass.

Thermal evolution of isolated and accreting NSs

Beznogov & Yakovlev (2015a,b)

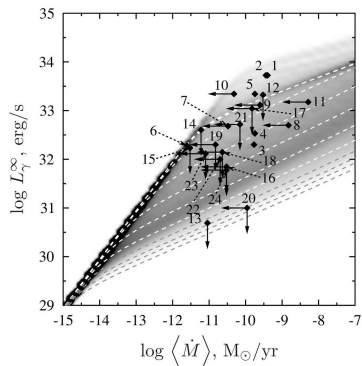
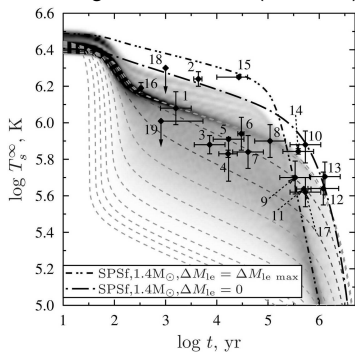


Ingredients

- ▶ EOS: Heiselberg & Hjorth-Jensen (1999) with $M_{\text{DU}} = 1.77 M_\odot$
- ▶ H and non-accreted envelopes
- ▶ no superfluidity
- ▶ assume mass distribution functions with most probable mass: $M_{\text{iso}} = 1.4 M_\odot$ and $M_{\text{acc}} = 1.5 M_\odot$

Thermal evolution of isolated and accreting NSs

Beznogov & Yakovlev (2015a,b)



Ingredients

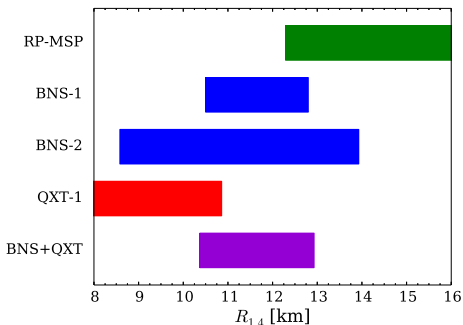
- ▶ gap due to the fact that DUrca process is on or off
- ▶ introduce ad-hoc broadening of the DUrca threshold
- smooth mass distribution
- ▶ mimics effects of proton superfluidity
- not too strong proton superfluidity at high density.

NS radii and hyperons

Astrophysical constraints: radius

Fitting the spectrum of

- ▶ X-ray emission from radio millisecond pulsars (RP-MSP);
- ▶ X-bursts from accreting NSs (BNS);
- ▶ the quiescent thermal emission of accreting NSs (QXT).



Summary

Based on most recent publications.

Adapted from Fortin et al. A&A (2015)

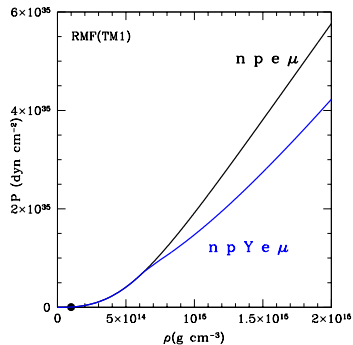
- ▶ RP-MSP: Bodganov, ApJ (2013)
- ▶ BNS-1: Nättilä et al. arXiv:1509.06561
- ▶ BNS-2: Güver & Özel, ApJ (2013)
- ▶ QXT-1: Guillot & Rutledge, ApJ (2014)
- ▶ BNS+QXT: Steiner et al., ApJ (2013)

Conclusion

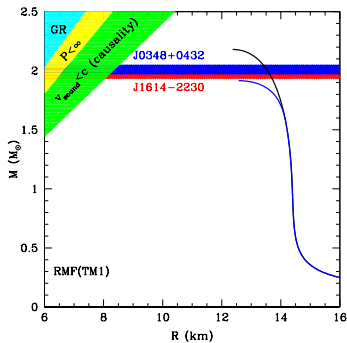
- ▶ marginally consistent (see QXT-1 and RP-MSP),
- ▶ many remaining uncertainties in the modelling,
- ▶ inclusion of rotation: effect $\simeq 10\%$.
- ▶ future X-ray telescopes (NICER, Athena, LOFT?): $M - R$ constraints with a precision of $\sim 5\%$

Context: equation of state (EoSs) and hyperons (Y)

Equation of state



$M - R$ plot



Hyperons

- reduce the pressure in the inner core. ie. softening of the EoS;
- reduce the maximum mass.

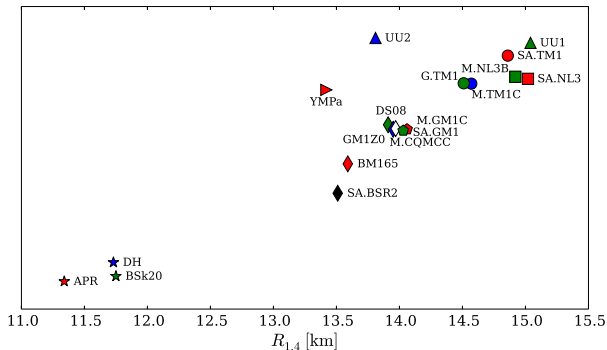
Claims that $M_{\text{max}} \geq 2 M_{\odot}$ rules out hyperonic equations of state ...

Hyperonic equations of state and radii

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

Set of EOSs

- 14 hyperonic with $M_{\max} \geq 2 M_{\odot}$, all but one (Yamamoto et al. PRC 2014) are RMF models;
- 3 nucleonic as reference.



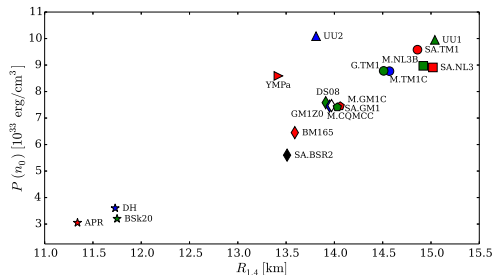
Hyperonic EOS

for $M \in [1.0 - 1.6] M_{\odot}$, $R > 13$ km.

Hyperonic equations of state and radii

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

Pressure at $n_0 = 0.16 \text{ fm}^{-3}$ near the core-crust transition



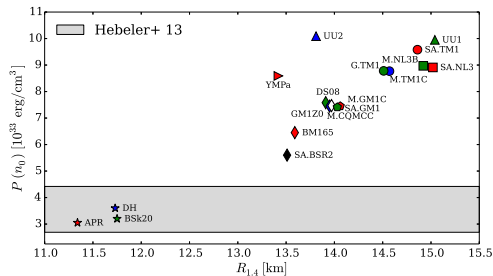
▶ large radius for Y.EoSs correlated with a large pressure at n_0 .

→ $M_{\text{max}} \geq 2 M_{\odot}$ possible if the decrease in the pressure at high density due to Y is compensated by a large pressure at low density.

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• gray strip: chiral effective field theory calculations up to n_0 (Hebeler et al. ApJ 2013).

▶ over-pressure at n_0 for hyperonic EOS inconsistent with this constraint.

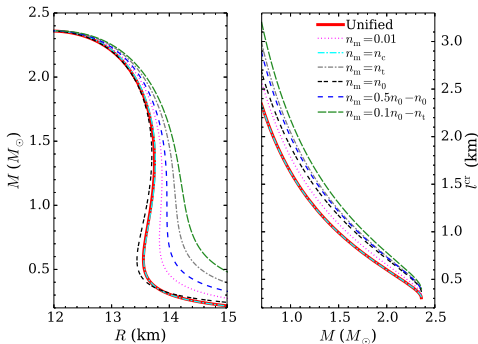
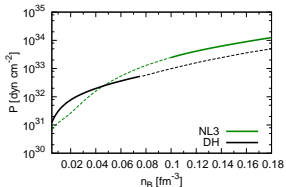
Recent work

Oertel et al. JPG (2015): hyperonic EoS consistent with Hebeler et al. constraint and with $M_{\text{max}} \geq 2 M_{\odot}$.

Core-crust matching and unified EOS

How to glue core and crust: NL3 & DH?

Fortin, Providência, Raduta, Gulminelli, Zdunik, Haensel, & Bejger, arXiv:1604.01944



MORGANE FORTIN (CAMK)

- ▶ 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 $n_0 = 0.16 \text{ fm}^{-3}$;
- ▶ crust below $0.5n_0$ and core above n_0 ;
- ▶ crust below $0.1n_0$ and core above n_t ;
- ▶ reference: unified EoS.

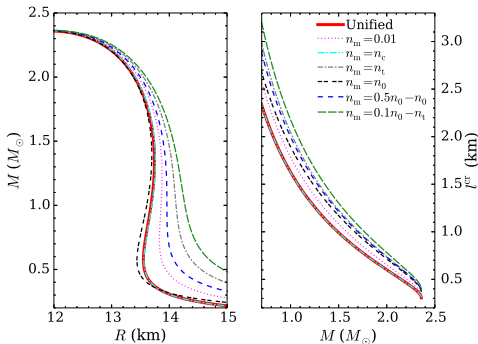
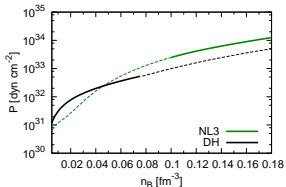
Uncertainty on R

- ▶ 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 EOS with similar saturation properties.

ASTROPHYSICAL CONSTRAINTS ON THE EQUATION OF STATE?

How to glue core and crust: NL3 & DH?

Fortin, Providência, Raduta, Gulminelli, Zdunik, Haensel, & Bejger, arXiv:1604.01944



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- ▶ 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 $\sim 4\%$
- ▶ with NICER, Athena or LOFT(?): expected precision $\sim 5\% \dots$
- ▶ how to, if not solve, at least handle this problem?

ASTROPHYSICAL CONSTRAINTS ON THE EQUATION OF STATE?

Approximate formulae for the radius and crust thickness

Zdunik, Fortin, and Haensel, in prep.

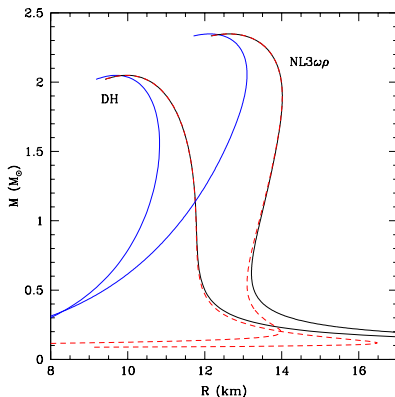
How?

- ▶ All you need is . . . : the core EOS.
- ▶ Obtain the $M(R_{\text{core}})$ relation solving the TOV equations
- ▶ Using a simple (secret!) formula $R(M, R_{\text{core}})$, obtain $M(R)$.

Results

- ▶ uncertainty in the radius: $\lesssim 1\%$ for $M > 1 M_{\odot}$
- ▶ uncertainty in the crust thickness: $\sim 1\%$ for $M > 1 M_{\odot}$

Stay tuned ☺



Black: exact solution of the TOV equation
Blue: exact $M(R_{\text{core}})$
Red: approximate $M(R)$

Unified equations of state

Very few unified EoSs for NSs exist eg. DH (Douchin & Haensel 2001), BSk (Brussels Uni.) Fortin, Providência, Raduta, Gulminelli, Zdunik, Haensel, & Bejger, arXiv:1604.01944

9 RMF models

NL3, NL3 $_{\omega\rho}$, DDME2, GM1, TM1, DDH δ , DD2, BSR2, and BSR6 with

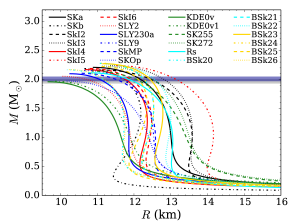
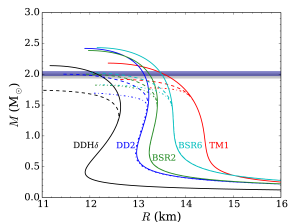
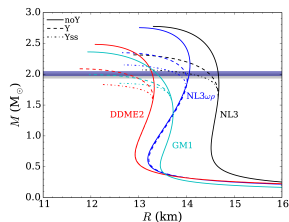
- ▶ outer-crust non consistently calculated but hardly affect the $M - R$ relations
- ▶ inner-crust with pasta phase from Thomas-Fermi calculations
- ▶ noY: a purely nucleonic core
- ▶ Y: a transition to hyperonic matter in the core: SU(6) with the ϕ meson;
 $U_{\Lambda}^N(n_0) = -28$ MeV, $U_{\Sigma}^N(n_0) = 30$ MeV, $U_{\Xi}^N(n_0) = -18$ MeV
- ▶ Yss: a transition to hyperonic matter in the core: SU(6) with the ϕ and σ^* mesons;
 $U_{\Lambda}^{\Lambda}(n_0) = -5$ MeV, $U_{\Xi}^{\Xi} \simeq 2U_{\Lambda}^{\Lambda}$, $g_{\sigma^*\Sigma} = g_{\sigma^*\Lambda}$

24 Skyrme models

SKa, SKb, SkI2, SkI3, SkI4, SkI5, SkI6, Sly2, Sly230a, Sly9, SkMP, SKOp, KDE0V, KDE0V1, SK255, SK272, Rs, BSk20, BSk21, BSk22, BSk23, BSk24, BSk25, and BSk26 with

- ▶ purely nucleonic core, causal up to $2 M_{\odot}$
- ▶ compressible liquid drop model
- ▶ no shell effect and curvature terms

Unified equations of state



33 nucleonic EoSs and 17 hyperonic EoSs

- ▶ tables with n , ρ , P as supplemental material to the paper (for observers mainly)
- ▶ available on the open-source COMPOSE database: <http://compose.obspm.fr/>

Fits by piecewise polytropes à la Read et al. PRD (2009)

In progress

Potential applications to:

- ▶ I -Love- Q relations
- ▶ modelling of binary neutron star systems

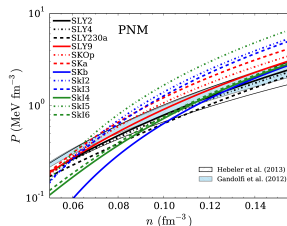
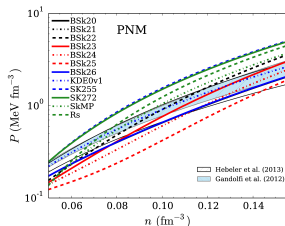
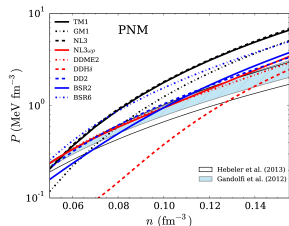
with different crust models and thus consistent models.

Comparison with nuclear constraints

1. Low-density

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

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



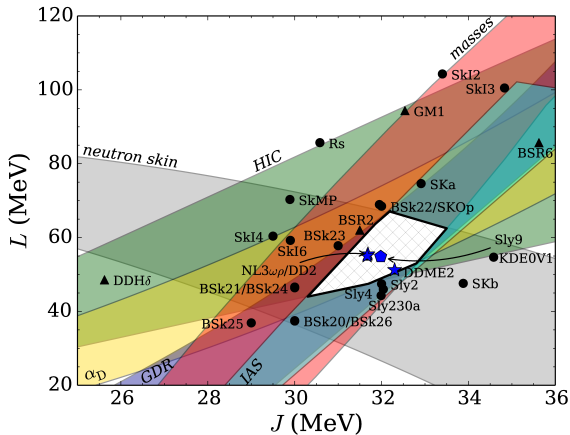
- RMF: DDME2; $\pm 10\%$: NL3 $\omega\rho$, DD2
- Skyrme: SLY2, KDE0v, KDE0v1; $\pm 10\%$: SLY9

2. Incompressibility

$K = 230 \pm 40$ MeV: all but GM1 and TM1

Comparison with nuclear constraints

3. $L - J$ plane



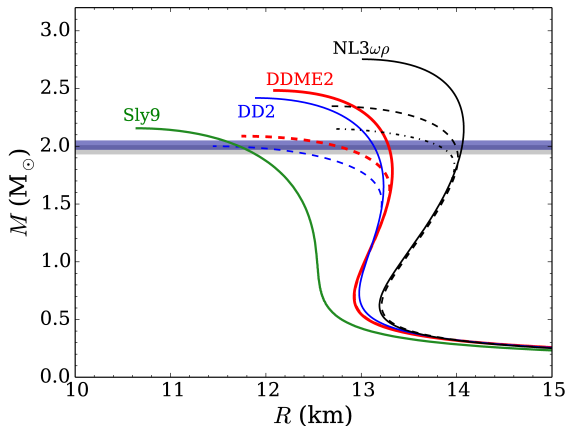
- ▶ neutron skin thickness of ^{208}Pb
- ▶ heavy ion collisions (HIC)
- ▶ electric dipole polarizability α_D
- ▶ giant dipole resonance (GDR) of ^{208}Pb
- ▶ measured nuclear masses
- ▶ isobaric analog states (IAS)

References: see eg. Lattimer & Steiner, EPJA (2015)

Comparison with nuclear constraints

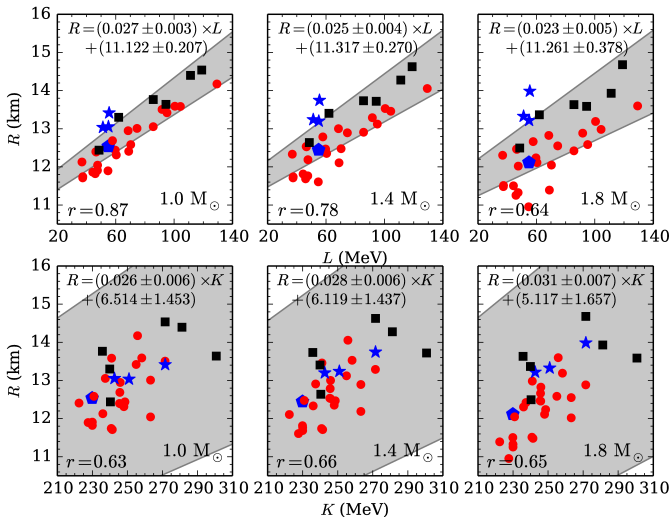
EOS fulfilling:

- ▶ all constraints 1.+2.+3.: DDME2
- ▶ constraint 1.±10%+ constraints 2.+3.: DD2, NL3 $\omega\rho$ and Sly9.



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

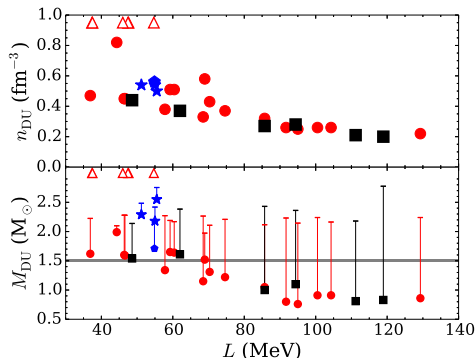
Correlations



- ▶ R vs L : dispersion larger for higher masses due to higher order terms
- ▶ R vs K : for isoscalar properties higher order terms can not be neglected

Nucleonic DUrca process

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



Additional DUrca processes for hyperonic EOS.

- ▶ Beznogov & Yakovlev MNRAS (2015): DUrca process needed to explain the thermal emission of isolated and accreting accreting NS.
- ▶ For $L \gtrsim 70$ MeV, DUrca process always on for $M > 1.5 M_{\odot}$.
- ▶ For $L \lesssim 70$ MeV, EOS with DUrca and others without.
- ▶ $L - J$ plane: the intersection of all constraints gives $L \lesssim 70$ MeV.
- ▶ Popov et al. A&A (2006): population synthesis of isolated NS requires $M_{\text{DU}} > 1.5 M_{\odot}$.

Conclusions

- ▶ DUrca process and superfluidity necessary to explain thermal states of isolated and accreting NS;
- ▶ thermal relaxation of accreting NS constrains on the properties of accreted crust.
- ▶ Most hyperonic EoSs consistent with $2 M_{\odot}$ have a large $R_{1.4}$ and overpressure close to saturation density;
- ▶ inconsistency with the constraint by Hebeler et al. (2013).
- ▶ Treatment of the gluing of non-unified core and crust EoSs introduces an uncertainty on the radius that can be as large as the expected precision from NICER, Athena or LOFT(?).
- ▶ Development of unified nucleonic and hyperonic EoSs based on 9 RMF and 24 Skyrme models;
- ▶ available on the CompOSE database: <http://compose.obspm.fr> and as supplemental material to the paper;
- ▶ confrontation with nuclear constraints and selection of 4 EoS.

Perspectives

- ▶ calculation of fits by piecewise polytropes for various applications,
- ▶ confrontation of the unified EOS with astrophysical constraints,
- ▶ study of rotating NS (Keplerian frequency, minimum mass, ...) with LORENE,
- ▶ study of the surface gravitational redshift (spectral lines),
- ▶ development of more EOS consistent with Hebeler et al. constraint and $2 M_{\odot}$.

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