Thermal evolution of neutron stars and the role of their superfluidity

Review of Part I

- Energy loss is mainly due to neutrino emission from the core
  - dUrca, mUrca, bremsstrahlung, Cooper pair formation and breaking
- neutron pairing in the crust ($^1S_0$), neutron ($^3P_2$) and proton ($^1S_0$) pairing in the core, hyperonic ($^1S_0$ and $^3P_2$) pairing in the core
- NS's thermal evolution is intimately related to the core composition

Part II:

- Cooling relevant effects of pairing
- Hypernuclear compact stars: EoS, constraints, properties
- Cooling Simulations
- What do we learn from data?

Thermal evolution

According to [Thorne, Astrophys. J. 212, 825 (1977)] thermal evolution is governed by two equations:

Thermal balance:

$$\frac{1}{4\pi r^2 e^{2\Phi}}\sqrt{1-\frac{2Gm}{c^2 r}}\frac{\partial}{\partial r}\left(e^{2\Phi}L_r\right) = -Q_\nu - \frac{C_v}{e^\Phi}\frac{\partial T}{\partial t}; \quad Q_\nu = \sum_i Q_{\nu,i}, \quad C_V = \sum_j C_{V,j},$$

$i = \mathrm{dUrca},\ \mathrm{mUrca},\ \mathrm{brem},\ \mathrm{PBF},$
$j = n, p, \Lambda, \Xi^-, \Xi^0, \Sigma^-$, etc.

Heat transport:

$$\frac{L_r}{4\pi k r^2} = -\sqrt{1-\frac{2Gm}{c^2 r}}e^{-\Phi}\frac{\partial}{\partial r}\left(Te^\Phi\right)$$

For isothermal cores, i.e. $\left(Te^\Phi\right) = \mathrm{ct.}$, $C_v \partial T e^{-\Phi}/\partial t = -Q_\nu$

EoS dependence via Q_ν, C_V, k, Φ

Thermal evolution from superfluid cores

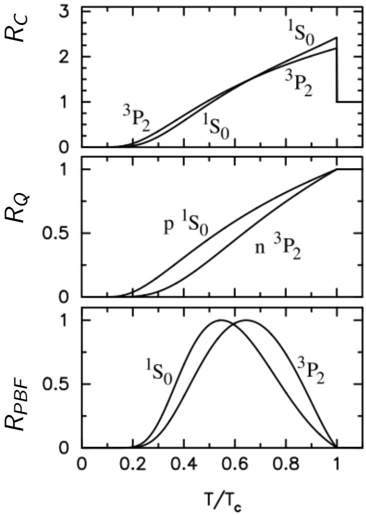
1. C_V is modified, see talk by N. Chamel
   ○ $C_V \to 0$ for $T \ll T_c$ **enhances cooling** in the γ-cooling era
   ○ maximum effect comes from neutrons, which are the dominant component

2. gaps reduce the phase space,
   ○ neutrino emissivities of all processes which involve paired particles are reduced,
   ○ though dependent on T, Δ, type of pairing, number of paired species, $Q_\nu \to 0$ for $T \ll T_c$ [Yakovlev et al., Phys. Rep. 354 (2001)],
   ○ **SF slows down the cooling**; the consequences are most visible in the ν-cooling era,

   ○ pairing turns dUrca into an intermediate cooling process

3. opens up, for $T < T_c$, a new ν-emission process,
   the formation and breaking of Cooper pairs
   $B + B \to [BB] + \nu + \tilde{\nu}$ and $[BB] \to B + B + \nu + \tilde{\nu}$,
   ○ maximum emissivity at $T/T_c \approx 0.5$;
   ○ **SF speeds up the cooling**,
   ○ the consequences are most visible in the ν-cooling era.

Suppression of Q_ν and C_V by pairing



[Page+, ApJSS 155(2004)]

a pairing gap in the s.p. excitation spectrum results in a Boltzmann-like $\approx \exp(-\Delta/k_B T)$ suppression of C_V and Q_ν

- specific heat [Levenfish & Yakovlev (1994)]
  ○ for $T \lesssim T_C$, $C_v > C_{V,0}$, due to increased correlation length around T_C;
  ○ for $T \ll T_C$, $C_V \to 0$
- emissivity of mUrca, $Q_\nu^{mD} = Q_{\nu,0}^{mD} \alpha \exp(-\beta T_c/T)$; similar qualitative behavior for dUrca, bremsstrahlung, etc.
- emissivity of PBF, maximum efficiency around $T_C/2$

Cooling of neutron stars

• purely nucleonic stars
[Kaminker+, A&A373 (2001); Page+, ApJSS (2004); Yakovlev & Pethick, Ann. Rev. Astron. Astrophys. (2004); Page+, ApJ (2009); Fortin+, MNRAS (2017)]

• nucleonic stars with hyperonic admixtures
[Haensel & Gnedin (1994); Schaab+, ApJ (1998); Tsuruta+, ApJ (2009); Raduta+, MNRAS (2018); MNRAS (2019); Grigorian+, NPA (2018); Negreiros+, ApJ (2018)]

• neutron stars with π and K-condensates [Schaab+, NPA605 (1996); Yakovlev & Pethick, Ann. Rev. Astron. Astrophys. (2004)]

• quark stars
[Blaschke+, A&A (2001); Schaab+, NPA605 (1996); Page+, PRL85 (2000); Page & Usov, PRL89 (2002); Alford+, PRD71 (2005); Hess & Sedrakian, PRD84 (2011); Negreiros+, PRC85 (2012); de Carvalho+, PRC92 (2015); Sedrakian, EPJA52 (2016)]

• NS built upon phenomenological EoS, mainly meant to constrain the dUrca threshold and/or neutron and proton SF gaps
[Beznogov & Yakovlev, MNRAS (2015); Beloin+, PRC97 (2018)]

Cooling of hypernuclear compact stars

• **"History":** due to activation of hyperonic dUrca, hypernuclear compact stars were considered [Haensel & Gnedin (1994); Schaab+, ApJ (1998); Tsuruta+, ApJ (2009)] incompatible with thermal data, even if hyperonic pairing was accounted for

• **Context:** Measurements of several $\approx 2M_{\odot}$ pulsars motivated research on hyperonic d.o.f. in NS core

• **Recent results:** [Raduta+, MNRAS (2018, 2019); Grigorian+, NPA (2018); Negreiros+, ApJ (2018)] shown that hypernuclear stars are not incompatible with present data

• **Status:** results are much dependent on EoS, including the nucleonic sector, nucleonic and hyperonic pairing, ν-emission channels even in the simplified hypotheses that no heating source is present

• **Today:** thermal evolution of NS built upon various EoS, accounting for Λ and Ξ-pairing

Equation of State: the astrophysics perspective

- structure and composition of NS depend on the EoS, $P(\epsilon)$
  - the simplest case: static, spherically symmetric NS built by solving TOV eqs.
- $P(\epsilon)$ depends on effective interactions over a wide range of dens.
  - radii of canonical mass NS, $M \approx 1.4 M_\odot$, depend on EoS at interm. dens., in particular on the symmetry energy, expr. in terms of E_{sym}, L_{sym}, K_{sym} recent measurements: millisecond pulsar PSR J0030+0451 (NICER): $M = 1.34^{+0.15}_{-0.16} M_\odot$, $R_e = 12.71^{+1.14}_{-1.19}$ km (Riley+, 2019) and $M = 1.44^{+0.15}_{-0.14} M_\odot$, $R_e = 13.02^{+1.24}_{-1.06}$ km (Miller+, 2019)
  - tidal deform. constrain both intermediate and high dens.; GW170817(Abbott+, 2017) rules out stiff EoS(Most+; Paschalidis+, 2018)
  - moment of inertia depend on EoS
- $P(\epsilon)$ depends on particle degrees of freedom
  - hyperons soften $P(\epsilon)$, which diminishes $M_{\rm max}$
  - Δ soften/stiffen $P(\epsilon)$ for intermediate/high densities, which diminishes the radii of NS with $1M_\odot \lesssim M \lesssim M_{\rm max}$
- $P(\epsilon)$ does not provide info on composition
- (some) info on composition can be extracted from thermal data

Equation of State: the nuclear physics perspective

- ϵ and P are derived quantities, under phys. cond. relevant for NS, i.e. β-equil.
- a more general description would require particle densities, $P(\{n_i\})$, $\epsilon(\{n_i\})$

Simplest case:
nuclear matter = charge neutral, homogeneous, infinitely large system made of neutrons and protons

Energy per nucleon:
expressed as a Taylor expansion around $(n_s, 0)$, in terms of departure from saturation $\chi = (n - n_0)/3n_0$ and isospin symmetry $\delta = (n_n - n_p)/n$

$$E(n,\delta) = E_0 + \frac{K_0}{2!}\chi^2 + \left[J_{sym} + L_{sym}\chi + \frac{K_{sym}}{2!}\chi^2\right]\delta^2$$

○ all parameters have physical meaning (saturation density n_s, en. per nucleon at saturation E_0, compression modulus K_0, symmetry energy E_{sym}, etc.)

○ can be expressed analytically in terms of forces parameters

○ their values are constrained by nuclear experiments (binding energies, charge rms radii, neutron skin thickness, charge radii of mirror nuclei, energy of giant monopole/dipole/quadrupole resonances, dipole polarizability, etc.)

Equation of State: State of art

$$E(n,\delta) = E_0 + \frac{K_0}{2!}\chi^2 + \left[J_{sym} + L_{sym}\chi + \frac{K_{sym}}{2!}\chi^2\right]\delta^2$$

from the analyses of 55 Skyrme and relativistics mean-filed models, whose parameters have been tuned on different properties of atomic nuclei [Margueron+, PRC97 (2018)] it comes out that:

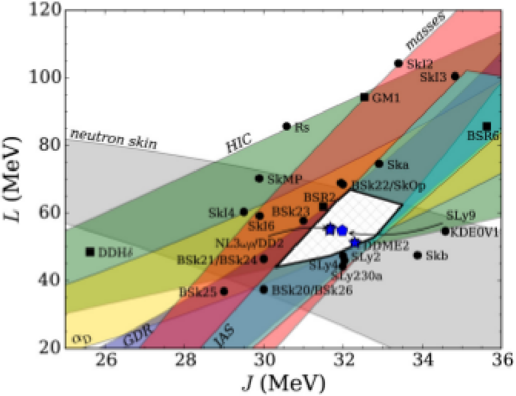
- good constraints on: $n_s = 0.1543 \pm 0.0054\ \mathrm{fm}^{-3}$, $E_0 = -16.03 \pm 0.20\ \mathrm{MeV}$, $J_{sym} = 33.30 \pm 2.65\ \mathrm{MeV}$
- loose constraints on: $K_0 = 251 \pm 29\ \mathrm{MeV}$, $L_{sym} = 76.6 \pm 29.2\ \mathrm{MeV}$
- no constraints on $K_{sym} = -3 \pm 132\ \mathrm{MeV}$ [Margueron+, PRC97 (2018)] and param. of high order terms

reason? nuclei are close to saturation and isospin symmetry

Extra constraints on neutron rich matter:

- *ab initio* calculations of pure neutron matter (L_{sym}),
- NS measurements (L_{sym}, K_{sym})

Lab constraints on $J_{sym} - L_{sym}$ and MR diagram

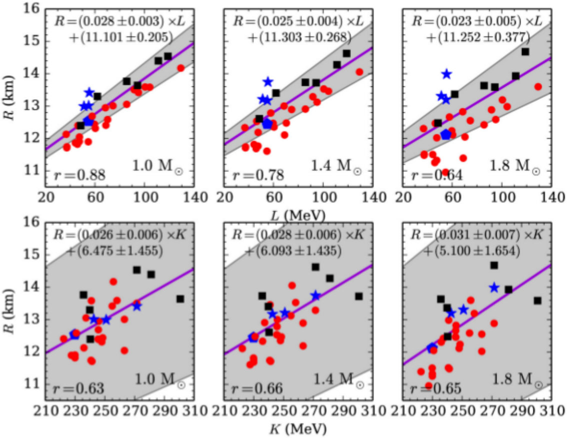


Tsang et al., PRC86, 015803 (2012)
Lattimer & Lim, ApJ771, 51 (2013)
Lattimer & Steiner, EPJA50, 40 (2014)

for most interactions J_{sym}, L_{sym} fall outside the intersection of constraints originatong from various type of experiments

$E_{sym}(n)$ and NS properties

[Lattimer & Prakash], Phys. Rep. 442 (2007):
i) empirical correlation between R and $RP_*^{-1/4}$, $P_* = P(1.5n_0)$
ii) $P(1.5n_0) = 2.25n_0 \left[K/18 - K_{sym}/216 + n_0(1-2x)^2 L_{sym}(1.5n_0)\right]$
[Fortin et al., Phys. Rev. C94, 035804 (2016)]



(n, p, e, μ)-EoS

red dots: Skyrme,
black squares: RMF

correl. $L_{\rm sym}$, $K_{\rm sym}$ - R strongest effect for $1M_\odot$,

Recent constraints on K_{sym} from NICER and LIGO/Virgo

- until recently, no constraint on K_{sym}
  example: based on 50 Skyrme and RMF models,
  $K_{sym} = -3 \pm 132$ MeV [Margueron+, PRC97 (2018)]

- based on correlation between $K_{sym} - R_{1.4M_\odot}$ and $\Lambda - R_{1.4M_\odot}$ NICER radius measurements and LIGO/Virgo GW170817 measurements were exploited to constrain $K_{sym} = -102^{+71}_{-72}$ MeV [Zimmerman+, arXiv:2002.03210]

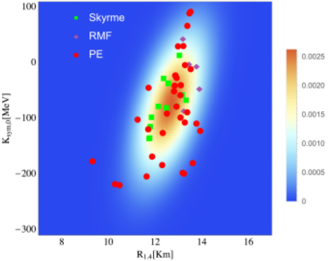


FIG. 3. Correlation between $K_{sym,0}$ and the NS radius with mass $1.4M_\odot$. We show the scattering with Skyrme (green), RMF (purple) and PE (red) EoSs. The colored contour shows the two-dimensional Gaussian distribution fit.

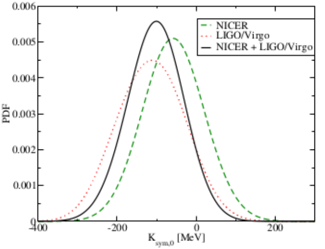


FIG. 4. Comparison of probability distributions for $K_{sym,0}$ with various observations: PSR J0030+0451 with NICER using the 3-spot model, GW170817 with LIGO/Virgo, and NICER + LIGO/Virgo combined.

NS with admixture of hyperons

• exotic degrees of freedom are expected to nucleate at supra-saturation densities based on energetic arguments (hyperons, Δ resonances, condensates, quarks)

▷ the first candidates are the hyperons=baryons with one or two strange quarks

Baryon	B	Q	S	I	J^{Π}	rest mass (MeV)		mean life (s)
Λ	1	0	-1	0	$1/2^{+}$	1115.683	uds	$2.60 \cdot 10^{-10}$
Σ^{+}	1	1	-1	1	$1/2^{+}$	1189.37	uus	$8.02 \cdot 10^{-11}$
Σ^{0}	1	0	-1	1	$1/2^{+}$	1192.642	uds	$7.4 \cdot 10^{-20}$
Σ^{-}	1	-1	-1	1	$1/2^{+}$	1197.449	dds	$1.48 \cdot 10^{-10}$
Ξ^{0}	1	0	-2	1/2	$1/2^{+}$	1314.83	uss	$2.90 \cdot 10^{-10}$
Ξ^{-}	1	-1	-2	1/2	$1/2^{+}$	1321.31	dss	$1.64 \cdot 10^{-10}$

NS with admixture of hyperons

- heavy baryons are expected to be populated at supra-saturation densities based on energetic arguments

- onset density depends on NY and YY interactions

- no scattering data

- experimental data on the binding energy of hyperons in single-Λ hypernuclei in $s,\ p,\ d,\ f,\ g$ shells, with $7 \leq A \leq 208$, double-Λ hypernuclei [Gal+, RMP (2016)] and two Ξ^- hypernuclei ($^{12}_{\Xi^-}\mathrm{Be}$ [Khaustov+, PRC61 (2000)], $^{15}_{\Xi^-}\mathrm{C}$ [Nakazawa+, PTEP (2015)])

- ΛN and ΞN interactions are tuned such as to reproduce experimental data [van Dalen & Sedrakian, PLB (2013); Sun+, PRC(2016); Fortin+, PRC(2017); Fortin+, PRD (2020)]

- values are converted in $U_Y^{(N)}(n_s)$, with $U_\Lambda^{(N)}(n_s) \approx -28\ \mathrm{MeV}$, $U_\Xi^{(N)}(n_s) \approx -18\ \mathrm{MeV}$, $U_\Sigma^{(N)}(n_s)$ [Gal+, RMP (2016)]

- $U_\Lambda^{(\Lambda)}(n_s) \approx -1\ \mathrm{MeV}$

How to "build" a NS?

I. Nuclear physics job:

- assume particle degrees of freedom (*eg.* (n, p, e), (n, p, e, μ), (n, p, e, μ, Λ), $(n, p, e, \mu, \Lambda, \Xi^-, \Xi^0, \Sigma^-, \Sigma^0, \Sigma^+)$, etc.)

- nuclear equation of state model, governed by interactions among particles

- solve the equilibrium equations
    - net charge neutrality: $\sum_{\alpha \in baryons} n_\alpha + \sum_{\beta \in leptons} n_\beta = 0$,
    - chemical equilibrium: $\mu_\alpha = Q_B \mu_B + Q_Q \mu_Q + Q_S \mu_s$,
      $\mu_\beta = Q_Q \mu_Q + Q_L \mu_L$
    - particles with non-vanishing densities, $\mu_i > m_i c^2$

- result: equations of state $P(n_b)$, $e(n_b)$,
  typically at $T = 0$, $\mu_{Lepton} = 0$ (cold catalized matter)
    - rule out EoS with violate causality,
      maximum mass, $2M_\odot$ (since 2010),
      tidal deformability, $\lambda < 800$ (since 2017)

Relativistic mean field model

- covariant Lagrangian density:
$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_Y + \mathcal{L}_M$, N=nucleons, Y=hyperons, M=mesons

$\mathcal{L}_B = \bar{\Psi} \left[\gamma_\mu D_B^\mu - M_B^* \right] \Psi$, with $D_B^\mu = i\partial^\mu - g_{\omega B}\omega^\mu - g_{\rho B}\tau_B\rho^\mu$, $M_B^* = M_B - g_{\sigma B}\sigma$

- interactions among nucleons are mediated by the exchange of scalar-isoscalar (σ), vector-isoscalar (ω), vector-isovector (ρ) mesons

- the meson-nucleon coupling constants are determined from properties of atomic nuclei; for a review, see [Dutra+, PRC90 (2014)]

- interactions between hyperons and nucleons are mediated by the same mesonic fields

- the σ-hyperon coupling constants are determined from values of $U_Y^{(N)}(n_s)$

- the couplings of the hyperons with the vector fields are expressed in terms of nucleonic couplings and determined based on flavor symmetry arguments

Key nuclear properties of some relativistic DF models

Model	n_{s} (fm^{-3})	E_{s} (MeV)	K (MeV)	J (MeV)	L (MeV)	K_{sym} (MeV)	n_{DU} (fm^{-3})	M_{DU} ($M_{\odot}$)
NL3	0.149	-16.2	271.6	37.4	118.9	101.6	0.20	0.84
GM1A	0.154	-16.3	300.7	32.5	94.4	18.1	0.28	1.10
DDME2	0.152	-16.1	250.9	32.3	51.2	-87.1	-	-
DD2	0.149	-16.0	242.7	31.7	55.0	-93.2	-	-
FSU2H	0.150	-16.3	238.0	30.5	44.5	n.a.	0.53	1.86
NL3$\omega\rho$	0.148	-16.2	271.6	31.5	55.0	-7.6	0.53	2.22
SWL	0.150	-16.0	260.0	31.0	55.0	n.a.	0.90	2.00

NL3 [Lalazissis et al., PRC55 (1997); GM1A [Glendenning et al., PRL67 (1991); DDME2 [Lalazissis et al., PRC71 (2005); DD2 [Typel et al., PRC81 (2010)]; FSU2H [Tolos et al., PASA (2017); Negreiros et al., ApJ863 (2018)]; NL3$\omega\rho$ [Horowitz+, PRL86 (2001); Pais+, PRC94 (2016)] SWL [Spinella, PhD Thesis, Univ. San Diego (2017)]

Constraints: $40 \lesssim L \lesssim 62$ MeV [Lattimer & Lim, ApJ771 (2013)] or
$30 \lesssim L \lesssim 86$ MeV [Oertel+, RMP89 (2017)]
$K_{sym} = -102 \pm 71$ MeV [Zimmerman+ (2020)]

Key astrophysical charact. of some relativistic DF models

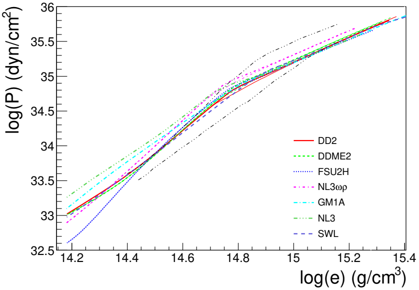
Model	$n_{\rm max}$ (fm^{-3})	$M^{\rm Y}_{\rm max}$ ($M_\odot$)	Y$_1$	$n_{{\rm Y}_1}$ (fm^{-3})	$M_{{\rm Y}_1}$ ($M_\odot$)	Y$_2$	$n_{{\rm Y}_2}$ (fm^{-3})	$M_{{\rm Y}_2}$ ($M_\odot$)	Y$_3$	$n_{{\rm Y}_3}$ (fm^{-3})	$M_{{\rm Y}_3}$ ($M_\odot$)
NL3	0.77	2.07	Λ	0.28	1.47	Ξ^-	0.33	1.73	Ξ^0	0.57	2.02
GM1A	0.92	1.994	Λ	0.35	1.49	Ξ^-	0.41	1.67	-	-	-
DDME2	0.93	2.12	Λ	0.34	1.39	Ξ^-	0.37	1.54	Σ^-	0.39	1.60
DD2	1.00	2.00	Λ	0.34	1.29	Σ^-	0.37	1.45	Ξ^-	0.37	1.46
FSU2H	0.90	1.99	Λ	0.33	1.41	Σ^-	0.43	1.71	Ξ^-	0.49	1.81
NL3$\omega\rho$	0.76	2.31	Λ	0.32	1.68	Ξ^-	0.36	1.89	Σ^-	0.42	2.05
SWL	0.97	2.00	Λ	0.41	1.51	Ξ^-	0.45	1.65	Ξ^0	0.90	2.00

all models provide $M_{\rm max} \approx 2M_\odot$, in agreement with
PSR J1614 - 2230, $M = 1.908 \pm 0.016 M_\odot$ [Demorest+, Nature (2010);
Arzoumanian+, ApJS235 (2018)],
PSR J0348 + 0432, $M = 2.01 \pm 0.04 M_\odot$ [Antoniadis+, Science340 (2013)],
MSP J0740+6620, $M = 2.14^{+0.10}_{-0.09} M_\odot$ [Cromartie+, (2019)]

NL3 [Miyatsu et al. PRC 88 (2013)]; GM1A [Gusakov et al., MNRAS439 (2014)]; DDME2 [Fortin et al., PRC94 (2016)]; DD2, FSU2H, NL3$\omega\rho$ [Fortin+, PRD (2020)]; SWL [Spinella, PhD Thesis, Univ. San Diego (2017)]

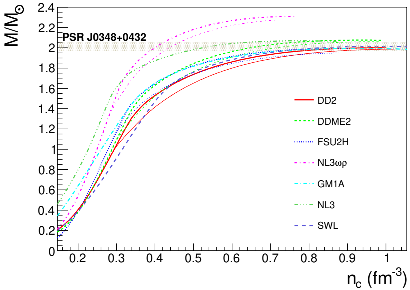
NS EoS and NS properties (I)

$P(e)$



dot-dashed curves=limits of the domain extracted by [Raaijmakers+, (2019)] from NICER and LIGO/Virgo data on PSR J0030+0451 and GW170817

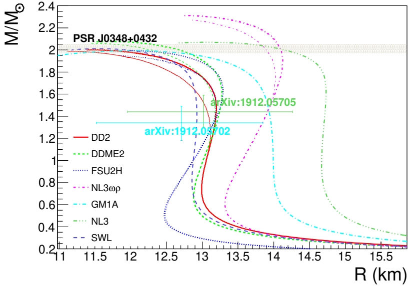
$M_G(n_{B,c})$



horizontal band: PSR J0348+0432, $M = 2.01 \pm 0.04 M_\odot$ [Antoniadis+, Nature (2013)].

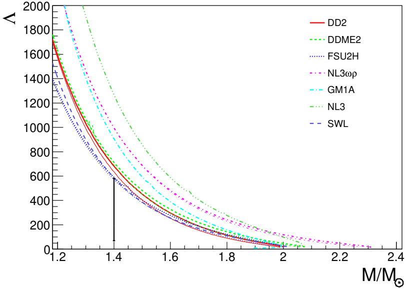
NS EoS and NS properties (II)

$M_G(R)$



data: the experimental constraints on mass-radius relation based on NICER measurements of the millisecond pulsar PSR J0030+0451 [Miller+, Riley+, (2019)]

$\Lambda(M_G)$



GW170817 data [Abbott+, 2017]

Thermal evolution by `NSCool`* by D. Page

Physical situations:

- ∘ Cooling of isolated NS
- ∘ Heating of accreting NS

ν-emission processes:

∘ **crust:** bremsstrahlung, Cooper pair formation & breaking, plasmon decay, pair annihilation, $\gamma - \nu$ processes

∘ **core:** dUrca, mUrca, bremsstrahlung, Cooper pair formation & breaking

Atmosphere model: Fe or H

Crust model:

- ∘ outer crust [Negele&Vautherin 1973],
- ∘ inner crust [Haensel+ (1989)]

Extra heating: none

Input

- ∘ EoS
- ∘ NS mass and radial profiles of particle densities
- ∘ SF gaps in various channels
- ∘ ν-emission processes (crust/core)
- ∘ atmosphere model
- ∘ initial temperature profile
- ∘ accretion rate, for XRT

Output

- ∘ radial temp. profiles at different moments
- ∘ luminosity of all ν and γ-processes
- ∘ $T_s^\infty = T_s\sqrt{1 - 2GM/c^2R}$

* available at: http://www.astroscu.unam.mx/neutrones/NSCool/ + upgrading

Cooling of INS

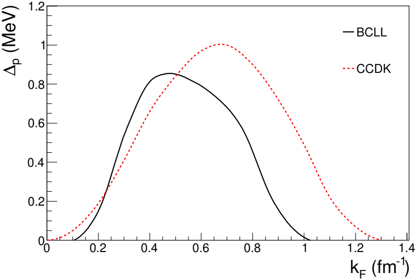
Phenomenology

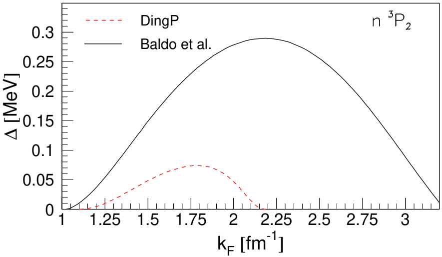
- born hot in SN explosions, $T \approx 50\ \mathrm{MeV} \approx 5 \cdot 10^{11}\ \mathrm{K}$
- $t \lesssim 10 - 100$ yr: the core cools down by ν-emission; the crust stays hot; the crust and the core are thermally decoupled; if measured, T_s would reflect crust's state
- $t \approx 10 - 100$ yr: NS is isothermal
- $10^2 \lesssim t \lesssim 10^5$ yr: ν-emission from the core; $\underline{\nu\text{-cooling era}}$; $\underline{\text{dominated by } Q_\nu}$
- $t \gtrsim 10^5$ yr: the cooling wave moves toward the surface; $\underline{\gamma\text{-cooling era};}$ $\underline{\text{dominated by } C_V}$

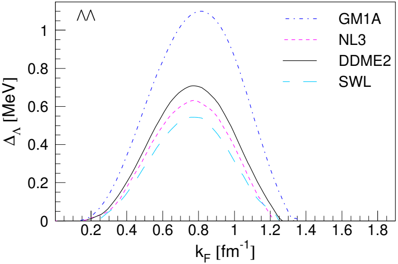
Setup & Strategy

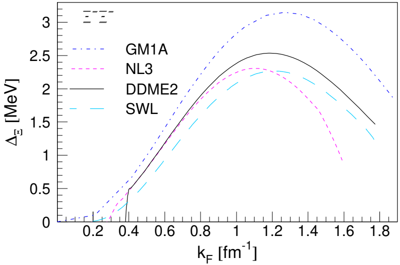
- **fix:** crust EoS, atmosphere model (mostly Fe), neutron ${}^1S_0$ pairing in the crust
- **explore:**
  - ○ core EoS (DDME2, SWL, GM1A),
  - ○ NS mass ($1 \leq M/M_\odot \leq M_{\max}$),
  - ○ proton ${}^1S_0$ pairing in the core:
    - i) BCLL [Baldo+, NPA536 (1992)]
    - ii) CCDK [Chen+, NPA555 (1993)]
  - ○ neutron ${}^3PF_2$ in the core:
    - i) "b" [Page+, ApJ (2004)]
    - ii) Av18 [Ding+, PRC (2016)]
    - iii) $\Delta_{3P2} = 0$
  - ○ Λ ${}^1S_0$ from BCS
  - ○ Ξ ${}^1S_0$ from BCS
  - ○ p and Λ high dens. pairing

Pairing gaps - Overview

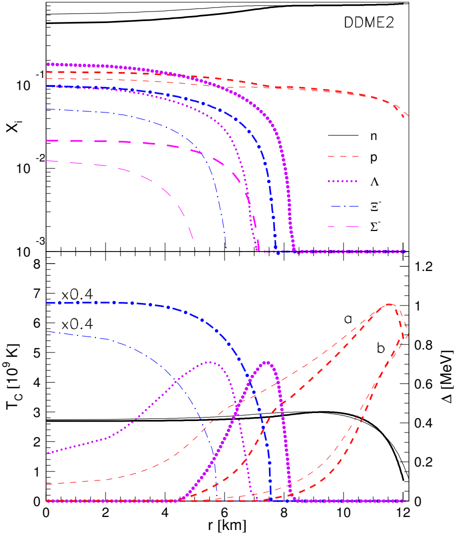








NS Composition and pairing: DDME2



thin: 1.8$M_\odot$, thick: 2$M_\odot$

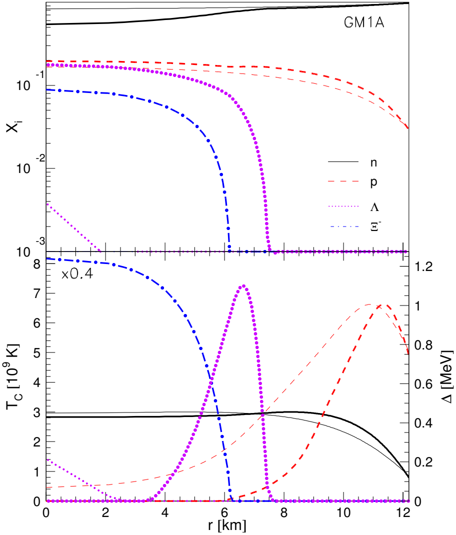
$^3P_2 - ^3F_2$ n: gaps "b" of Page+, ApJSS155
$^1S_0$ proton: a) Chen+, NPA555 (1993),
b) Baldo+, NPA536 (1992)

1.8$M_\odot$: n, p, Λ, Ξ SF everywhere in the core
$\Lambda \rightarrow p + l + \tilde{\nu}$ part. suppressed
$\Xi^- \rightarrow \Lambda + l + \tilde{\nu}$ part. suppressed
$\Sigma^- \rightarrow \Lambda + l + \tilde{\nu}$ part. suppressed
$\Sigma^- \rightarrow n + l + \tilde{\nu}$ not allowed

2$M_\odot$: p, n, Ξ SF over the whole volume
Λ SF in the outer core, only
$\Lambda \rightarrow p + l + \tilde{\nu}$ active!
$\Xi^- \rightarrow \Lambda + l + \tilde{\nu}$ part. suppressed
$\Sigma^- \rightarrow \Lambda + l + \tilde{\nu}$ active!
$\Sigma^- \rightarrow n + l + \tilde{\nu}$ not allowed

[AR, Sedrakian & Weber, MNRAS (2018)]

NS Composition and pairing: GM1A



thin: $1.5M_\odot$, thick: $1.9M_\odot$

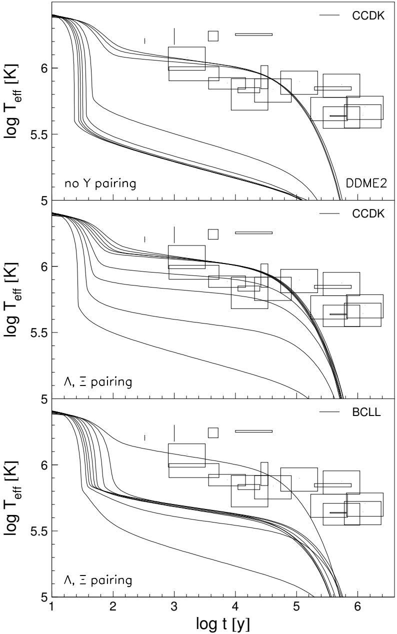
${}^3P_2 - {}^3F_2$ n: gaps "b" of Page+, ApJSS155
${}^1S_0$ proton: Chen+, NPA555 (1993)

$1.5M_\odot$: n, p, Λ SF everywhere in the core
$n \to p + l + \tilde{\nu}$ part. suppressed
$\Lambda \to p + l + \tilde{\nu}$ part. suppressed

$1.9M_\odot$: n, Ξ SF over the whole volume
p, Λ SF in the outer core, only
$n \to p + l + \tilde{\nu}$ part. suppressed
$\Lambda \to p + l + \tilde{\nu}$ active!
$\Xi^- \to \Lambda + l + \tilde{\nu}$ part. suppressed

[AR, Sedrakian & Weber, MNRAS (2018)]

INS Cooling by DDME2



DDME2: no nucleonic dUrca;

$M_{(\Lambda,n)} = 1.39 M_\odot$; $M_{(\Xi^-,\Lambda)} = 1.55 M_\odot$

data: Beznogov & Yakovlev, MNRAS (2015)

cooling curves:

M=1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.85, 1.9, 2$M_\odot$

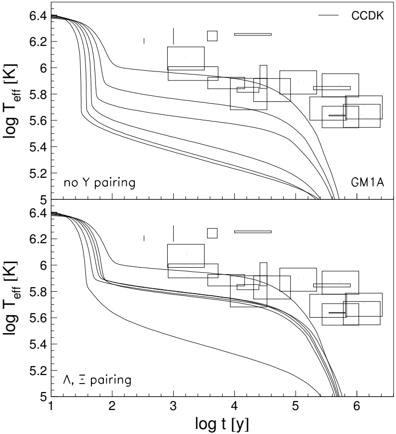
p(CCDK) & no Y-SF: $M > 1.55 M_\odot$ too cold

p(CCDK) & Y-SF: OK up to $1.85 M_\odot$

p(BCLL) & Y-SF: $M \gtrsim 1.4 M_\odot$ too cold

[AR, Sedrakian & Weber, MNRAS (2018)]

INS Cooling by GM1A



[AR, Sedrakian & Weber, MNRAS (2018)]

GM1A: $M_{dU} = 1.10 M_\odot$
$M_\Lambda = 1.49 M_\odot$; $M_{\Xi^-} = 1.67 M_\odot$;

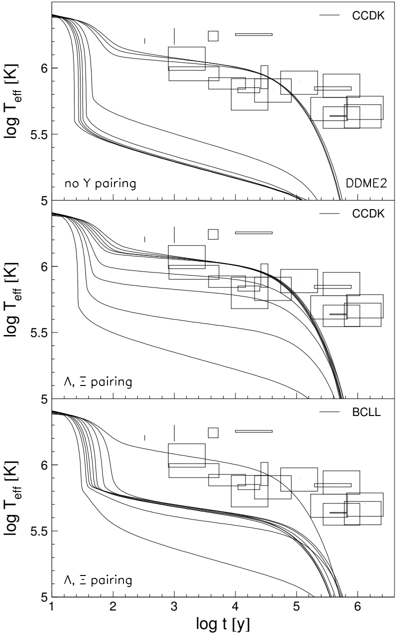
data: Beznogov & Yakovlev, MNRAS (2015)

cooling curves:
M=1.4, 1.5, 1.6, 1.7, 1.8, 1.9$M_\odot$

p(CCDK) & no Y-SF: $M \gtrsim 1.5 M_\odot$ too cold

p(CCDK) & Y-SF: OK up to 1.8$M_\odot$

INS Cooling by DDME2



cooling curves:
M=1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.85, 1.9, 2$M_\odot$

What do we learn from data?

- had the criterium to decide the agreement with data been that CC of hypernuclear INS pass through **some** data, the agreement would be good
- had it been that **all** data have to be passed through, the agreement would be bad

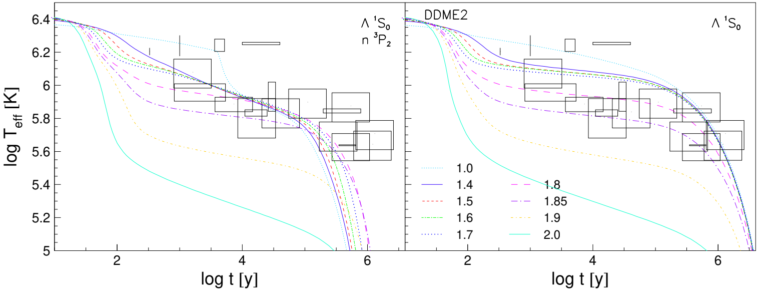
○ oldest and coolest INSs' T_{eff} are not described; reason? the neutron $^3P_2$ pairing which makes $C_v \rightarrow 0$

→ (common practice) suppress neutron $^3P_2$ pairing, though there is no much theoretical support

INS Cooling - effect of neutron $^3P_2 - ^3F_2$

gap as in [Ding+, PRC (2016)]

no gap



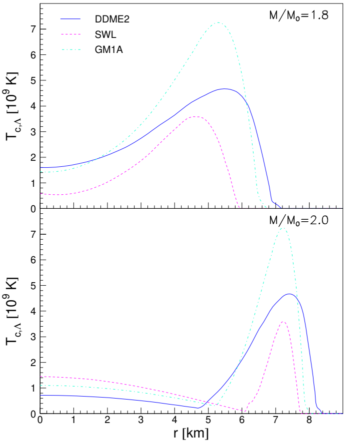
Observation: All data are reproduced

Conclusion: INS with hyperonic admixtures are compatible with thermal data

Comment: This is not a proof in favor of hyperons in the core, as other EoS (e.g. purely nucleonic EoS) do as well

[AR, Li, Sedrakian & Weber, MNRAS (2019)]

High density proton and Λ pairing



[AR, Li, Sedrakian & Weber, MNRAS (2019)]

A weak coupling estimation:

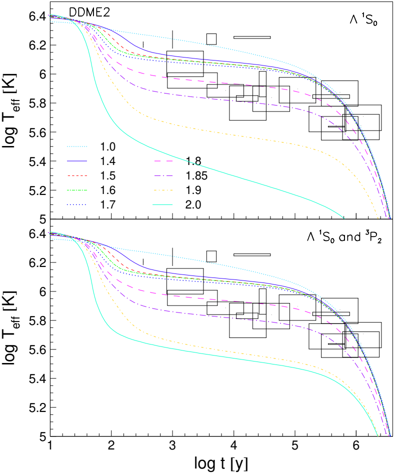
$$\Delta_p = \epsilon_{F,p} \left(\frac{\Delta_n}{\epsilon_{F,n}} \right)^{\alpha_p}, \qquad \alpha_p = \frac{m_n^*}{m_p^*},$$

$$\Delta_\Lambda = \epsilon_{F,\Lambda} \left(\frac{\Delta_n}{\epsilon_{F,n}} \right)^{\alpha_\Lambda}, \qquad \alpha_\Lambda = \frac{3}{2} \frac{m_n^*}{m_\Lambda^*}.$$

Result: Λs are paired **also** in the inner core, $T_{c,3P2} \ll T_{c,1S0}$, $\Delta_{3P2} \approx 0.1 - 0.2$ MeV

Expectation: cooling by $\Lambda \to p + e + \tilde{\nu}_e$ is much reduced

INS Cooling - effect of high density Λ pairing



[AR, Li, Sedrakian & Weber, MNRAS (2019)]

$\Delta_\Lambda^{3P2} \approx 0.1 - 0.2$ MeV

though small, high density pairing is efficient in slowing down the cooling

strongest effect: $2M_\odot$, where $\Lambda \to p + e + \tilde{\nu}_e$ is supressed **also** in the inner core

Heating of transiently accreting quasi-stationary NS in low mass X-binaries (XRT)

- old ($t \gtrsim 10^8 - 10^9$ yr) NS which accrete matter from time to time (in the active states of XRT) from the low mass companion,

- the accreted matter is compressed by the weight of new material and sinks in the deeper layers of the crust,

- nuclear reactions (capture of electrons, neutron capture and emission, pressure-induced fusion) heat up the deep crust; deposited energy $\approx 1 - 2$ MeV/nucleon [Haensel & Zdunik, AA (1990); *ibid.* (2008)],

- the accretion episodes last months-weeks; the accretion rate is weak enough to not destroy the thermal equilibrium with the core; it is strong enough to keep NS warm and produce obs. thermal emission during quiescence

- mean heating rate is determined by the average mass accretion rate $\langle \dot{M} \rangle$; the average is performed over characteristic cooling times of these stars, $\gtrsim 10^3$ yr

Heating of transiently accreting quasi-stationary NS in low mass X-binaries (XRT)

Steady state approximation [Yakovlev, Levenfish & Haensel (2003)]

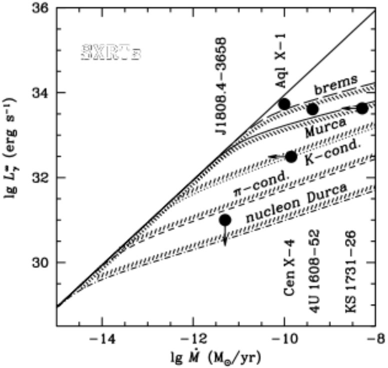
Starting from an arbitrary initial thermal state, the accreting NS reaches a stationary state supported by the deep crustal heating. This state is reached when $L_{\rm tot}^{\infty} = L_{\nu}^{\infty} + L_{\gamma}^{\infty}$ is balanced by $L_{\rm dh}^{\infty}$:

$$L_{\rm dh}^{\infty}\left(\dot{M}\right) = L_{\nu}^{\infty}\left(T_i\right) + L_{\gamma}^{\infty}\left(T_s\right)$$

γ emission regime: the energy deposited in the deep crust is transported to the surface, and then radiated away; T_S depends on the accretion rate and does not depend on the internal structure

ν emission regime: the energy is spread all over the volume; T_S depends on the internal structure (ν-emission reactions, SF)

Heating of transiently accreting quasi-stationary NS in low mass X-binaries (XRT)



[Yakovlev+, AA407 (2003)]

- low L_γ require small acc. rate and/or fast ν emission

- high L_γ require high acc. rate and low ν emission

- XRT heating is equivalent to INS cooling, **except** that XRT do not depend on heat capacity and thermal conductivity of the isothermal interior

- as INS, XRTs' T_S depends on the composition of the atmosphere (light elements lead to higher T_S); most probably, the atmosphere is stratified (H/He/C....Fe) [Beznogov+, MNRAS (2016)]

EoS constraints from thermal data

Recent works:

• purely nucleonic EoS, allowing or not dUrca; neutron $^3P2$ and proton $^1S_0$ gaps determined, via a Bayesian analyses, from thermal data [Beloin+, PRC97 (2018); Beznogov & Yakovlev, MNRAS (2015)]

• phenomenological EoS, nucleonic matter, dUrca threshold and SF gaps determined, via a Bayesian analyses, from thermal data [Beloin+, PRC100 (2019)]

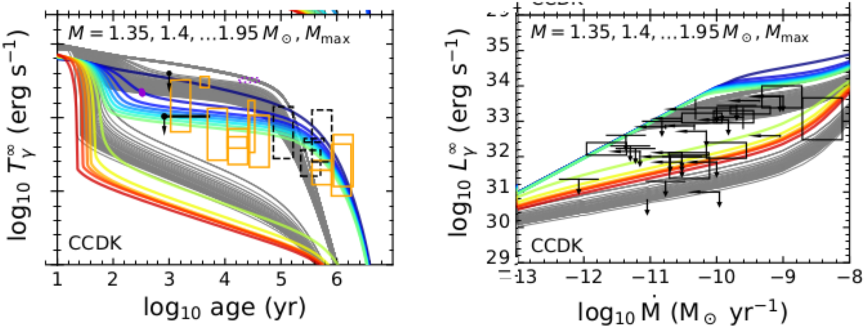
• compatibility of thermal data with π and K condensates [Beznogov & Yakovlev, MNRAS (2015)]

Conclusion: agreement with data is obtained by construction; many simplifing hypotheses are done, including on a composition

Alternative perspective: take EoS which agree with all availabled data, vary the SF gaps between limits provided by theoretical calculations; try to identify the EoS and SF gaps which offer the best agreement; try to predict the most probable composition, at least in some cases; do INS and XRT give the same answer? [Fortin+, in prep.]

INS Cooling versus XRT Heating

FSU2H effective interaction [Tolos+, 2016]



courtesy of Morgane Fortin

Thermal evolution of neutron stars and the role of their superfluidity

Overview

Part I:

- Why?
- Observational data
- Heat loss processes
- NS composition and Equation of State
- Pairing in neutron stars (NS)

Part II:

- Simulations: Cooling of isolated NS and heating of accreting NS
- What do we learn from data?