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?

Modeling NSs' thermal evolution - Why?

- **Context** (a nuclear physicist's perspective): the ultimate goal of nuclear physics is to understand nuclear interactions
- **Status:** (phenomenologically) well understood under physical conditions (isovector and isoscalar densities) existent on Earth, i.e. $n \approx n_0$ and $\delta = (n_n - n_p)/n \approx 0$
- **Conjecture:** complementary information, i.e. $n \gg n_0$ and $\delta \gg 0$, can be provided by NS
- **Sought for quantities:**
  - $P(e)$, generically called equation of state;
    it impacts NS radii, moments of inertia, tidal deformability, maximum NS mass;
  - thermal evolution mostly dependent on composition and superfluidity
- **Methodology:** simulated thermal evolution is confronted with data
- **Questions to be answered:** a) can we identify a most plausible EoS? b) can we infer the most probable composition of some NS?

Modeling NSs' thermal evolution - What does it assume?

Nuclear

- core composition (Which particles? How many? In which stars?)
- superfluidity (bare NN- and YY- interactions; in-medium effects; correlations)
- emissivities of all heat loss processes (ν emission from the core)
- deep crustal heating by a series of nuclear reactions, for XRT
- transport properties

Plasma

- composition of the envelope (H/He/C/Fe; stratified), which acts as an insulating blanket, and fixes $T_b - T_s$

Astro

- accurately measure $t - T_{eff}^{\infty}$ (INS) or $\langle \dot{M} \rangle - T_{eff}^{\infty}$ (XRT)

Extra

- heating due to evolution of magnetic field
- frictional dissipation of rotational energy
- etc.

UNCERTAINTIES evrywhere

Observational data:

1. isolated middle aged NS (INS)

   • NS are born hot ($T \approx 50$ MeV $\approx 10^{11}$ K) in a supernova explosion;

   • cool down by ◦ neutrino emission from the core, $t \lesssim 10^5 - 10^6$ yr and
   ◦ heat transport from the core to the surface, resulting in thermal emission of photons $t \lesssim 10^5 - 10^6$ yr

   • thermal evolution is followed as a function of time

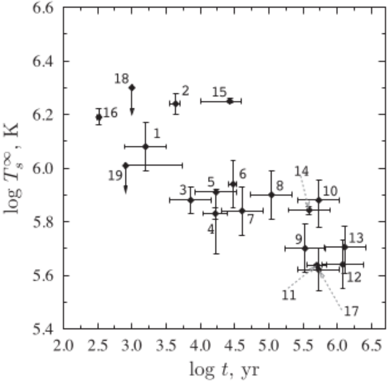
2. transiently accreting quasi-stationary NS in low-mass X-ray binaries (XRT)

   • heat-up because of the energy deposited in the bottom layers of the crust by the material which is intermittently accreted from the low mass companion

   • the heating is due to a series of nuclear reactions (electron capture, neutron absorption and emission, pycnonuclear reactions) and its rate is estimated at $\approx 1 - 2$ MeV per accreted nucleon

   • thermal evolution is followed as a function of average accreted mass rate

Isolated middle aged neutron stars (INS)



Beznogov&Yakovlev, MNRAS (2015)

- preeminence of thermal radiation in the measured total radiation spectrum and thermal relaxation throughout the volume allow one to bridge measured temperatures/luminosities to the multi-source neutrino emission from the core

- measured L_γ^∞ is converted into $T_s^\infty = \left(L_\gamma^\infty/4\pi R_\infty^2 \sigma_{SB}\right)^{1/4}$ by assuming a certain composition of the atmosphere ($T_b - T_s$) and emission from the whole surface

- 19 objects with $10^2 \lesssim t \lesssim 10^6$ yr, $10^{32} \lesssim L_\gamma^\infty \lesssim 10^{34}$ erg $\cdot$ s^{-1}, $T_s^\infty \approx 10^6$ K

- T_s^∞ is negatively correlated with t

- $T_s^\infty - t$ domain uniformly populated

Isolated middle aged NS: composition of the atmosphere

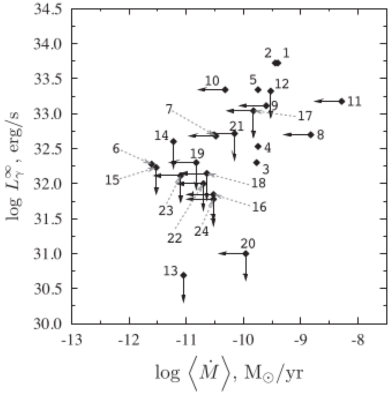
Table 1. Middle-aged cooling isolated neutron stars whose thermal surface emission has been detected or constrained; see the text for details.

Num.	Source	Age, kyr	T_s^∞, MK	Confid. level for T_s^∞	Model	Refs.
1	PSR J1119−6127	∼1.6	≈1.2	–	mHA	Z09
2	RX J0822−4300 (in Pup A)	4.4 ± 0.8	1.6–1.9	90 percent	HA	Z99, B12
3	PSR J1357−6429	∼7.3	≈0.77	–	mHA	Z07
4	PSR B0833−45 (Vela)	11–25	0.68 ± 0.03	68 percent	mHA	P01
5	PSR B1706−44	∼17	$0.82^{+0.01}_{-0.34}$	68 percent	mHA	MG04
6	PSR J0538+2817	30 ± 4	∼0.87	–	mHA	Z04
7	PSR B2334+61	∼41	∼0.69	–	mHA	Z09
8	PSR B0656+14	∼110	∼0.79	–	BB	Z09
9	PSR B0633+1748 (Geminga)	∼340	0.5 ± 0.1	–	BB	K05
10	PSR B1055−52	∼540	∼0.75	–	BB	PZ03
11	RX J1856.4−3754	∼500	0.434 ± 0.003	68 percent	mHA*	Ho07, P14
12	PSR J2043+2740	∼1200	∼0.44	–	mHA	Z09
13	RX J0720.4−3125	∼1300	∼0.51	–	HA*	M03
14	PSR J1741−2054	∼391	0.70 ± 0.02	90 percent	BB	Ka14
15	XMMU J1731−347	∼27	$1.78^{+0.04}_{-0.02}$	–	CA	K14
16	Cas A NS	0.33	≈1.6	–	CA	H09
17	PSR J0357+3205 (Morla)	∼540	$0.42^{+0.09}_{-0.07}$	90 percent	mHA	M13, Ki14
18	PSR B0531+21 (Crab)	1	<2.0	99.8 percent	BB	W04, W11
19	PSR J0205+6449 (in 3C 58)	0.82–5.4	<1.02	99.8 percent	BB	S04, S08

Notes. [Z09] Zavlin (2009); [Z99] Zavlin, Trümper & Pavlov (1999); [B12] Becker et al. (2012); [Z07] Zavlin (2007); [P01] Pavlov et al. (2001); [MG04] McGowan et al. (2004); [Z04] Zavlin & Pavlov (2004); [K05] Kargaltsev et al. (2005); [PZ03] Pavlov & Zavlin (2003); [Ho07] Ho et al. (2007); [P14] Potekhin (2014); [M03] Motch, Zavlin & Haberl (2003); [Ka14] Karpova et al. (2014); [K14] Klochkov et al. (2014); [H09] Ho & Heinke (2009); [M13] Marelli et al. (2013); [Ki14] Kirichenko et al. (2014); [W04] Weisskopf et al. (2004); [W11] Weisskopf et al. (2011); [S04] Slane et al. (2004); [S08] Shibanov et al. (2008).

Beznogov & Yakovlev, MNRAS (2015)

Transiently accreting quasi-stationary NS in low-mass X-ray binaries (XRT)



Beznogov&Yakovlev, MNRAS (2015)

- 24 objects
- large error bars on L_γ^∞ and $\langle \dot{M} \rangle$
- $4.9 \times 10^{30} \leq L_\gamma^\infty \leq 5.3 \times 10^{33}$ erg/s and $2.5 \times 10^{-12} \leq \langle \dot{M} \rangle / M_\odot \leq 5.2 \times 10^{-9}$
- positive correlation between the surface photon luminosity and the accretion rate
- with the exception of SAX J1808.4-3658 and 1H 1905+000 the domain $L_\gamma^\infty - \langle \dot{M} \rangle$ is uniformly populated

composition of the atmosphere is little known; (probably) light (heavy) elements from new (old) accreted material

NS Structure and Composition

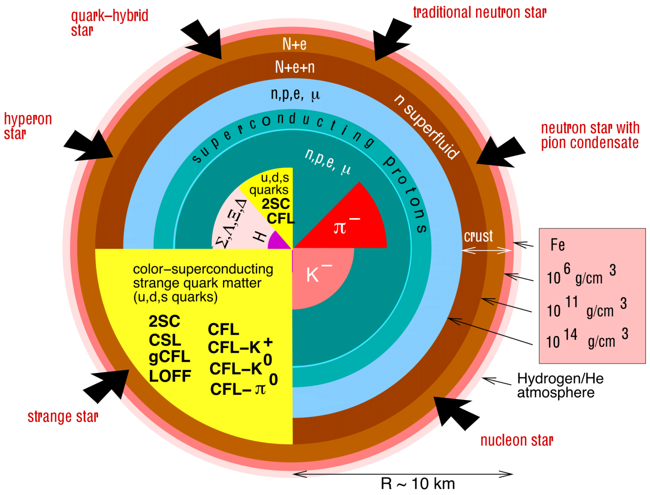


Image credit: F. Weber

Uncertainties in the high density domain are reflected in alternative scenarios on the composition.

Thermal evolution

Approximation: NS structure is temperature independent $\rightarrow$ eqs. of stellar structure are decoupled from eqs. of thermal evolution

Thermal balance:

$$\frac{1}{4\pi r^2 e^{2\Phi}}\sqrt{1-\frac{2Gm}{c^2 r}}\frac{\partial}{\partial r}\left(e^{2\Phi}L_r\right)=-Q_\nu-\frac{C_v}{e^\Phi}\frac{\partial T}{\partial t}$$

Heat transport:

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

[Thorne, Astrophys. J. 212, 825 (1977)]

r=radial coordinate

$m(r)$ gravitational mass

$\Phi=\Phi(r)$ the metric function

Q_ν=ν emissivity (energy/volume/time)

C_v=specific heat at const. vol. (energy/volume/temperature)

L_r=local luminosity =non-ν heat flux (energy/time)

k=thermal conductivity

Thermal evolution

Thermal balance:

$$\frac{1}{4\pi r^2 e^{2\Phi}} \sqrt{1-\frac{2Gm}{c^2 r}} \frac{\partial}{\partial r}\left(e^{2\Phi} L_r\right) = -Q_\nu - \frac{C_v}{e^{\Phi}} \frac{\partial T}{\partial t}$$

Heat transport:

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

Particular case: isothermal stars $\left(Te^{\Phi}\right) = \mathrm{ct.}$

Thermal balance:

$$C_v \frac{\partial T e^{-\Phi}}{\partial t} = -Q_\nu$$

two unknowns: $L_r(r,t)$, $T(r,t)$

thermal evolution depends on: Q_ν, C_V, k

EoS dependent quantities: $\Phi = \ln\left(\sqrt{1-2GM/c^2 r}\right)$, C_V, k, Q_ν

SF-dependent quantities: C_V, Q_ν

Moral: Thermal evolution depends on microphysics (EoS and SF)

Effective and apparent surface temperatures

- effective surface temperature = the temperature at the surface of the heat blanketing envelope
- heat blanketing envelope: thin, tiny mass layer with no sources of energy sink and generation, short thermal relaxation time, which serves as thermal insulator
- $T_b - T_s$ relation depends on the composition of the envelope; H/He/C/Fe compositions are used; light (heavy) elements have large (small) thermal conductivity
- effective surface temperature determines the photon luminosity $L_\gamma = L_r(R,t) = 4\pi\sigma R^2 T_s^4$
- **Apparent** luminosity L_γ^∞, **apparent** effective surface temperature T_s^∞ and **apparent** radius R_∞, as would be registered by a distant observer

  $L_\gamma^\infty = L_\gamma (1 - r_g/R) = 4\pi\sigma \left(T_s^\infty\right)^4 R_\infty^2$,
  $T_s^\infty = T_s\sqrt{1 - r_g/R}$, $R_\infty = R/\sqrt{1 - r_g/R}$,
  $r_g = 2GM/c^2$ Schwarzschild radius

Neutrino emission processes in the core

name	process	emissivity $\mathrm{erg\ cm^{-3}s^{-1}}$	efficiency	occurrence cond.
direct Urca	$B_1 \to B_2 + l + \tilde{\nu}_l$ $B_2 + l \to B_1 + \nu_l$	$\sim 10^{23-27}\, T_9^6$	fast	$p_{F,i} + p_{F,j} \geq p_{F,k}$
modified Urca	$B_1 + B_3 \to B_2 + B_3 + l + \tilde{\nu}_l$ $B_2 + B_3 + l \to B_1 + B_3 + \nu$	$\sim 10^{18-21}\, T_9^8$	slow	-
ν bremsstrahlung in baryon-baryon coll.	$B_1 + B_2 \to B_1 + B_2 + \nu + \tilde{\nu}$	$\sim 10^{16-20}\, T_9^8$	slow	-
ν bremsstrahlung Coulomb coll.	$l + C \to l + C + \nu + \tilde{\nu}$	$\sim 10^{13-15}\, T_9^8$	slow	-
Cooper pair formation and breaking	$B + B \to [BB] + \nu + \tilde{\nu}$ $[BB] \to B + B + \nu + \tilde{\nu}$	$\sim 10^{19-21}\, T_9^7$	medium	$T < T_{C,B}$

[Yakovlev et al., Phys. Rep. 354 (2001)]

$T_9 = T(K)/10^9$; $\quad i, j, k = B_1, B_2, l$

B=baryon; C=charged fermion; l=lepton; ν_l =neutrino of l type

dUrca examples: $n \to p + e + \tilde{\nu}_e$ (beta decay of the neutron)

$p + e \to n + \nu_e$ (electron capture on a proton)

$\Lambda \to p + e + \tilde{\nu}_e$; $\quad \Xi^- \to n + e + \tilde{\nu}_e$; $\quad \Xi^- \to \Lambda + e + \tilde{\nu}_e$;

$\Sigma^- \to n + e + \tilde{\nu}_e$

Fast versus Slow Cooling

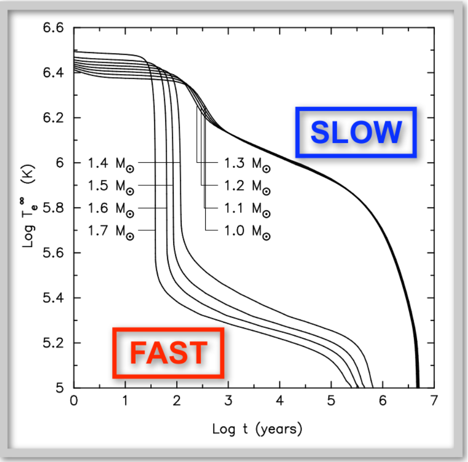


fig. by D. Page, CompStar School (2010)

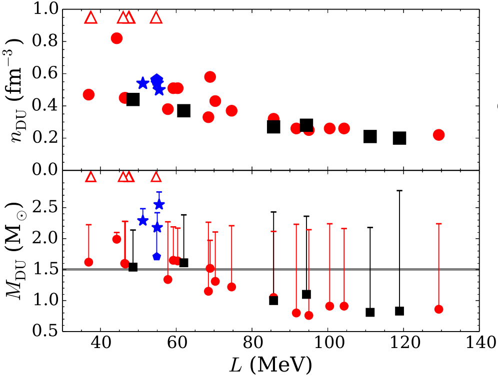
$M_{dU} = 1.35 M_\odot$

- models with $M < M_{dU}$ cool down by slow processes (bremsstrahlung, mUrca)
- models with $M > M_{dU}$ cool down by fast processes (dUrca)
- **mass hierarchy:** more massive stars cool down faster than less massive stars, as they accommodate more matter that participate in cooling processes
- the region in between fast and slow is filled by intermediate, Cooper pair breaking and formation active in paired matter

Nucleonic dUrca

Two weak-interaction reactions: $n \to p + l + \tilde{\nu}_l$ (beta decay of the neutron),
$p + l \to n + \nu_l$ (lepton capture on a proton),
$l = e, \mu$

Threshold cond.: $p_{F,i} + p_{F,j} \geq p_{F,k}$, $i, j, k = n, p, l$ [Prakash et al., ApJ (1992)].
in (n, p, e) matter, $x_p = 1/9 = 0.111$.
in (n, p, e, μ) matter, $x_p = 1/(1 + (1 + x_e^{1/3}))^3$.



Occurrence on nucleonic dUrca depends on $E_{sym}(n)$.

E_{sym} is not constrained at $n \gg n_0$, much dispersion in predictions.

[Fortin et al., PRC (2016)]

Hyperonic dUrca

Similarly to the neutron, also hyperons suffer weak-interaction decays:

$$\begin{array}{ll}
\Lambda \to p + l + \bar{\nu}_l; & \text{R=0.0394,} \\
\Sigma^- \to n + l + \bar{\nu}_l; & \text{R=0.0125,} \\
\Sigma^- \to \Lambda + l + \bar{\nu}_l; & \text{R=0.2055,} \\
\Sigma^- \to \Sigma^0 + l + \bar{\nu}_l; & \text{R=0.6052,} \\
\Xi^- \to \Lambda + l + \bar{\nu}_l; & \text{R=0.0175,} \\
\Xi^- \to \Xi^0 + l + \bar{\nu}_l; & \text{R=0.2218,} \\
\Xi^- \to \Sigma^0 + l + \bar{\nu}_l; & \text{R=0.0282,} \\
\Xi^0 \to \Sigma^+ + l + \bar{\nu}_l; & \text{R=0.0564.}
\end{array}$$

which, in addition to chemical compo., change also the strangeness.

Triangle ineq.:
$p_{F,i} + p_{F,j} \geq p_{F,k}$, $i, j, k = n, p, l$
[Prakash et al., ApJ (1992)]

- Modern EoS for hypernuclear compact stars predict only nucleation of $(\Lambda, \Xi^-, \Sigma^-)$ or (Λ, Ξ^-, Ξ^0)
- threshold densities and minimum NS mass which accommodate hyperonic dUrca depend on $U_Y^{(N)}$ potential and nucleonic effective interaction
- more details later on

dUrca processes involving exotic phases

Pion condensation

- pion condensation represents a macroscopic condensed field, whose excitation is favored at $n > n_0$; no free π is created; a coherent field excitation is created with the same quantum numbers as the pions; the pion field is thought to be non-stationary and non-uniform; the pion field mixes the n and p states; treatment of these states requires quasi-particle formalism.
- dUrca: $\tilde{n} \to \tilde{p} + e + \bar{\nu}$; $\tilde{p} + e \to \tilde{n} + \nu$; no threshold
- $Q^{(\pi)} \approx 10^{-2} - 10^{-1} Q^{(dU)} \gg Q^{(mU)}$

Kaon condens.

- macroscopic field excited at $n > n_0$; the excitations are characterized by the same quantum numbers as K^-; the K-condensate is thought to be stationary and uniform; the condensate affects the nucleon states; the quasiparticles are coherent superpositions of states of N and hyperon-like excitations.
- dUrca: no threshold
- $Q^{(K)} \approx 10^{-3} Q^{(dU)} \gg Q^{(mU)}$

Quark matter

- deconfined degenerate u, d and s quarks with admixture of e;
- β-equilibrium $\mu_d = \mu_s = \mu_u + \mu_e$
- dUrca: $d \to u + e + \tilde{\nu}_e$ and $u + e \to d + \nu_e$
- threshold; $Q^{(Dd)} < Q^{(dU)}$, $Q^{(Dd)} \gg Q^{(mU)}$

Neutrino emissivity: the nucleonic dUrca case

$n \rightarrow p + e + \tilde{\nu}_e$ and $p + e \rightarrow n + \nu_e$,

the most efficient cooling process, if energetically allowed

ν_e emissivity under the condition of β-equilibrium:

$$Q^{(D)} = 2 \int \frac{d\mathbf{p_n}}{(2\pi)^3} dW_{i\rightarrow f} \epsilon_\nu f_n (1 - f_p)(1 - f_e)$$

$dW_{i\rightarrow f} = \beta$ decay differential probability (Fermi Golden Rule):

$$dW_{i\rightarrow f} = 2\pi\delta(\epsilon_n - \epsilon_p - \epsilon_e - \epsilon_\nu) \sum_{\rm spins} |H_{fi}|^2 \frac{d\mathbf{p}_p}{(2\pi)^3} \frac{d\mathbf{p}_e}{(2\pi)^3} \frac{d\mathbf{p}_\nu}{(2\pi)^3}$$

Nucleon and electron gas are highly degenerate: $p_i \rightarrow p_{F,i}$, $i = n, p, e$

$\epsilon_\nu \propto T \rightarrow p_\nu \ll p_{F,i}$,

$$dW_{i\rightarrow f} \frac{d\mathbf{p_n}}{(2\pi)^3} = \frac{(2\pi)^4}{(2\pi)^{12}} \delta(\epsilon_n - \epsilon_n - \epsilon_e - \epsilon_\nu) \delta(\mathbf{p}_n - \mathbf{p}_p - \mathbf{p}_e) |M_{fi}|^2 4\pi\epsilon_\nu^2 d\epsilon_\nu \prod_{j=1}^{3} p_{F,j} m_j^* d\epsilon_j d\Omega_j.$$

After some algebra,

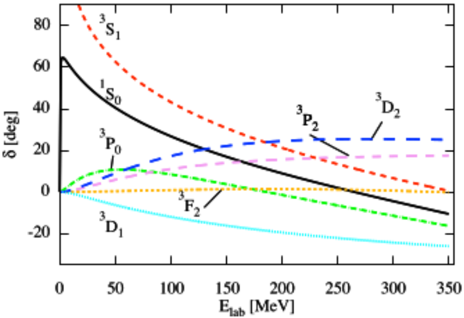
$$Q^{(D)} \approx 4 \times 10^{27} \left(\frac{n_e}{n_s}\right)^{1/3} \frac{m_n^* m_p^*}{m_n^2} T_9^6 \Theta_{npe} \ \mathrm{erg} \cdot \mathrm{cm}^{-3} \cdot \mathrm{s}^{-1} \quad \text{EoS dependent}$$

[Yakovlev et al., Phys. Rep. 354 (2001)]

Pairing

- a generic **quantum** feature for fermions with attractive interactions

- found to manifest in atomic nuclei between identical nucleons that occupy the same single particle level, $(B/A)_{\rm ee} > (B/A)_{\rm oe} > (B/A)_{\rm oo}$; due to spin-coupling



NN scattering phase shifts
[Sedrakian & Clark, EPJA (2019)]

- $V_{NN}(\mathbf{r}, \mathbf{p}_1, \mathbf{s}_1, \tau_1, \mathbf{p}_2, \mathbf{s}_2, \tau_2,)$, with long-range attraction and short-range repulsion, spin-orbit interaction, tensor component
- partial wave analyses on NN scattering data reveals the properties of V_{NN}
- (spectroscopic notation) ${}^{2S+1}L_J$ with S, L, J =total spin, relative angular momentum (L=0,1,2,3 are mapped to S, P, D, F, ...), total angular momentum
- (scattering theory) attractive potentials are signaled by positive phase shifts

Pairing

• nucleonic pairing might occur for *nn*, *pp*, *np*, for various energies and spin orientations and mainly depends on V_{NN}

• the pair is characterized by quantum numbers: T, S, L, J, with

  ∘ $T = 0, 1$ is total isospin number ($T = T_1 + T_2$, $T_{1,2} = \pm 1/2$ for n, p),

  ∘ $\vec{S} = \vec{S}_1 + \vec{S}_2$ is the total spin;
  given that $S_{1,2} = 1/2$ only two possible states: $S = 0$ ($\uparrow\downarrow$ or $\uparrow\downarrow$) singlet state
  $S = 1$ ($\uparrow\uparrow$ or $\downarrow\downarrow$) triplet state

  ∘ $\vec{L} = 0, 1, 2, 3, ...$ is relative angular momentum;
  L states are mapped to S, P, D, F, G

  ∘ $\vec{J} = \vec{L} + \vec{S}$ is total angular momentum, $L - S \leq J \leq L + S$

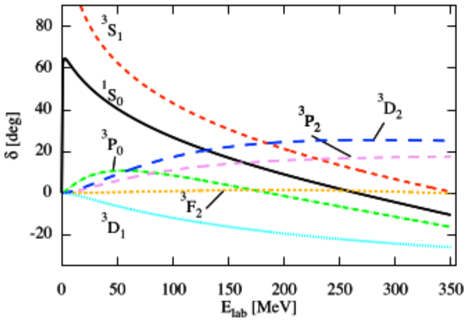
• spectroscopic notation $^{2S+1}L_J$,

In order for pairing to occur, two conditions have to be fulfilled:
1) interaction potential is attractive
2) total wave function is antisymmetric; $\Pi = (-1)^{T+S+L}$, i.e. $T + S + L$=odd

Results: $^1S_0$, ~~$^3S_1 - ^3D_1$~~, $^3P_2 - ^3F_2$ (SD and PF coupling due to tensor force)

for more see [Sedrakian & Clark, EPJA (2019)]

Pairing in neutron stars



NN scattering phase shifts
[Sedrakian & Clark, EPJA (2019)]

- phase shifts are given of E_{lab}
- conversion into particle number densities requires:

  1) change the reference frame from lab to CM, which attributes to each particle $E_{lab}/2$,

  2) computation of energies at the Fermi level, $k_F = \left(2\pi^2 n\right)^{1/3}$

Results:

- neutron $^1S_0$ pairing in the crust, $0 \lesssim k_{F,n} \lesssim 1.6\ \mathrm{fm}^{-1}$
- proton $^1S_0$ pairing in the core, $0 \lesssim k_{F,p} \lesssim 1.6\ \mathrm{fm}^{-1}$
- neutron pairing in $^3P_2 -^3 F_2$ for $1(??) \lesssim k_{F,n} \lesssim 3(??)\ \mathrm{fm}^{-1}$

The Bardeen-Cooper-Schrieffer (BCS) theory

Pairing gap equation:

$$\Delta(k) = -\frac{1}{4\pi^2} \int dk' k'^2 \frac{V(k,k')\Delta(k')}{\sqrt{[e(k') - \mu(k)]^2 + \Delta^2(k')}}, \quad \text{where}$$

k = the particle's momentum, μ = the chemical potential,
$V(k,k')$ = the bare interaction potential in momentum space,

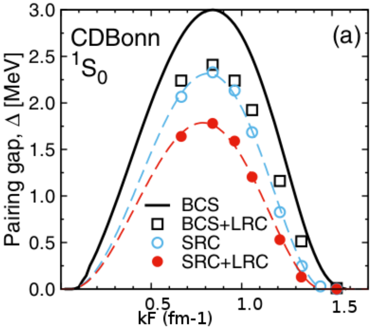
$$V^{(^1S_0)}(k,k') = 4\pi \int dr r^2 j_0(kr) V(r) j_0(k'r),$$

$e(k)$ = the single-particle energy; $e(k)$ may contain, via M^*, **in-medium effects**.

Characteristic shape: bell-like: competition among the increase in the density of states and the decreasing attraction as k_F increases

EoS effects enter via M^* and μ; whenever in-medium effects are accounted for, Δ is quenched.

Neutron $^1S_0$ pairing

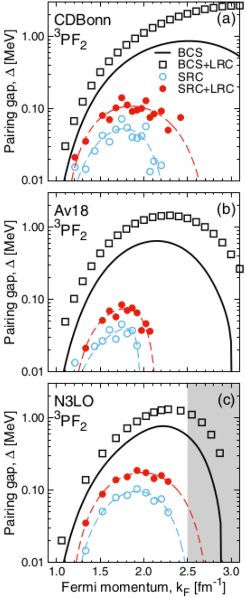


(pure neutron matter)
[Ding et al., PRC 94 (2016)]

- at low densities, V_{nn} is well constrained (by *nn* scattering data)
- uncertainties may arise **only** from many body correlations
- The gap Δ has a bell-like shape
- accounting for correlations leads to a diminish of Δ (SRC vs. BCS)
- long range correlations (LRC), when added on the top of BCS or calc. accounting for SRC, quench the gap
- maximum quenching with respect to BCS by a factor of 1.7

Inner crust = lattice of neutron-rich nuclei embedded in a gas of neutrons and (charge neutralizing) electrons
example: $n_{cc} \approx 0.07\ \mathrm{fm}^{-3}$, $Y_p = 0.2$, $n_{n,cc} = 0.056\ \mathrm{fm}^{-3}$, $k_{F,n} = 1.18\ \mathrm{fm}^{-1}$
Conclusion: Neutrons in the crust are paired in $^1S_0$, well known for decades!

Neutron $^3P_2 -^3 F_2$ pairing

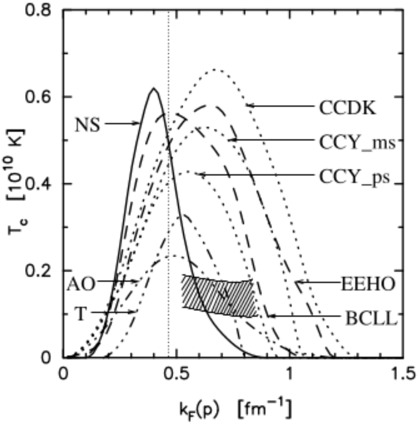


- at low densities, V_{nn} is **not** constrained
- uncertainties on Δ arise from V_{nn} **and** many body correlations
- $\Delta_{\max}$ is reduced by a factor of 3 when calc. with Av18 with respect to N3LO
- $\Delta_{\max}$ is reduced by a factor of 50 when diff. correl. are accounted for
- similarly to what happens at low n, SRC quench the gap
- contrary to what happens at low n, LRC enhance the gap

Conclusions: neutron $^3P_2$ pairing occurs in the core of NS but **it is highly uncertain**

(pure neutron matter)
[Ding et al., PRC 94 (2016)]

Proton $^1S_0$ pairing



[Page et al., ApJS 155, 623 (2004)]

$T_c \approx 0.57\Delta$, $1\ \mathrm{eV} = 1.15 \cdot 10^4\ \mathrm{K}$,

$T_c[10^{10}\mathrm{K}] \approx 0.66\Delta$

- $V_{pp} \approx V_{nn}$
- protons pair in $^1S_0$ over $0.1 \lesssim k_{F,p} \lesssim 1.4\ \mathrm{fm}^{-1}$, i.e. in the **core**
- as for neutrons, large uncertainties related to correlations
- if one additionally accounts for uncertainties related to EoS which play on the n_p radial profile, it is difficult to say where in the NS core, protons are paired

Hyperon pairing ??

• no experimental data for YY scattering, no constrain on Y_{YY}

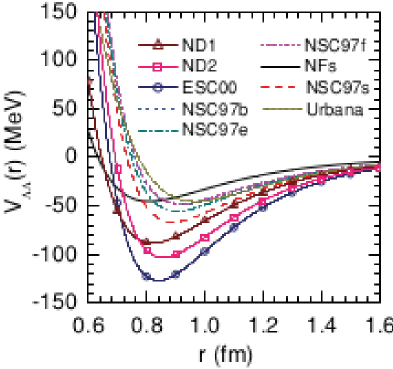
• theoretical calculations of V_{YY} differ much

• (according to some authors) $V_{\Lambda\Lambda}$,

$V_{\Xi\Xi}$ and $V_{\Sigma\Sigma}$ are attractive over a certain density range

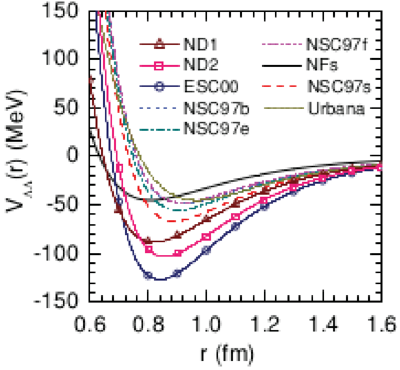
• if V_{YY} is attractive, YY may, in principle, pair

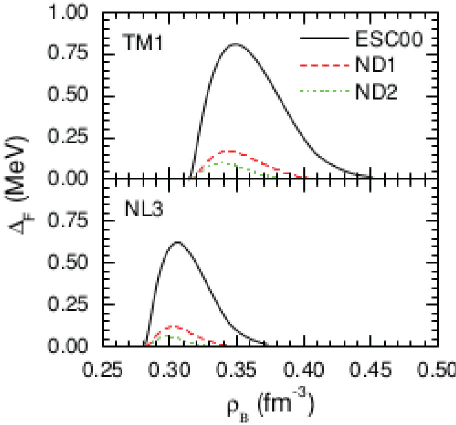
• for low densities, ${}^1S_0$ pairing



[Wang&Shen, PRC81 (2010)]

Hyperon pairing ??





[Wang&Shen, PRC81 (2010)]

Attractive potential is a necessary condition; it is not sufficient!

<u>e.g.:</u> NSC97b, NSCe, NSCf, NFs, NF97s, Urbana provide $\Delta = 0$.

Hyperon pairing in NS

- Select **the most attractive** the potentials:

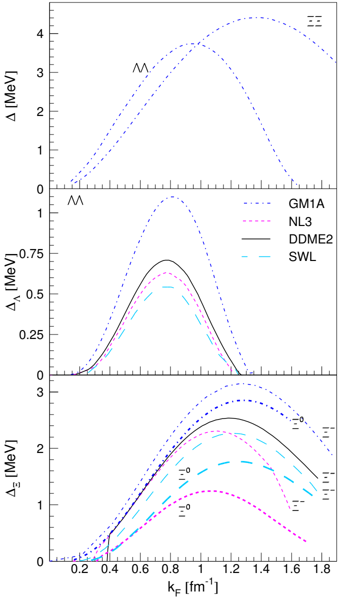
ΛΛ: ESC00 [Rijken 2001; Filikhin&Gal 2002],
ΞΞ: NSC08c [Rijken et al. 2013; Garcilazzo et al., 2016],

- Select modern EoS with hyperons

- Compute pairing gap within BCS

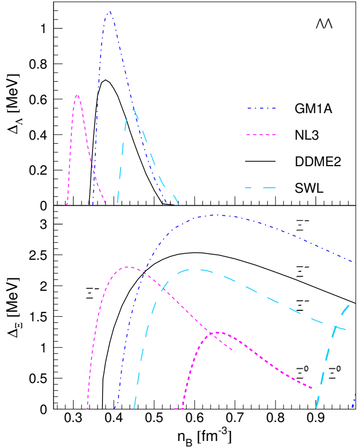
$$\Delta(k) = -\frac{1}{4\pi^2}\int dk' k'^2 \frac{V(k,k')\Delta(k')}{\sqrt{[e(k')-\mu(k)]^2+\Delta^2(k')}},$$

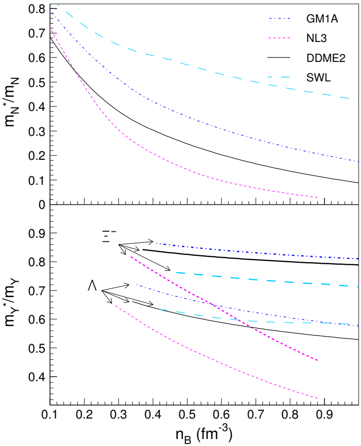
- Results:
  - $0.5 \lesssim \Delta_\Lambda \lesssim 1$ MeV,
  - $1 \lesssim \Delta_{\Xi^-}, \Delta_{\Xi^0} \lesssim 3$ MeV,
  - strong dependence on EoS-dependence.



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

Hyperon pairing in NS





- Δ extension in density depends strongly on the EoS
- correlation between M^* - Δ_F

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

P wave pairing for protons and Λ

Conjecture: on the basis of the (approximate) isospin invariance of nuclear forces, it is natural to anticipate that $^3P_2 -^3 F_2$ pairing occurs also in the proton component, for the range of densities where this channel dominates the attraction

Considering:

$$\Delta_i = \epsilon_{F,i} \exp\left[-1/\left(\nu_i V_i\right)\right],$$

with $\nu_i(P_{F,i}) = p_{F,i} m/\pi^2 =$ density of states, V_i=pairing matrix element.

A weak coupling estimation: $\Delta_p = \epsilon_{F,p} \left(\frac{\Delta_n}{\epsilon_{F,n}}\right)^{\alpha_p}, \quad \alpha_p = \frac{m_n^*}{m_p^*}.$

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

$n(udd)$ and $\Lambda(uds)$.

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