Thermal evolution of neutron stars

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- Overview
- Observational Data (Isolated/Accreting stars, luminosity, composition of the atmosphere)
- Cooling (ν and γ emission in various sectors and by different agents)
- Heating (magnetic field decay, nuclear reactions from accreted matter)
- Where does nuclear physics enter?
- Some results - isolated NS

Neutron stars - as we view them today

- NS are extraordinary objects (very compact, very fast spinning, huge magnetic fields, possibly accommodate exotic degrees of freedom in the core, source of gravitational waves, involved in synthesis of elements heavier than iron, etc., etc., etc.)

- involve extraordinary tasks (instrumentation, astronomical missions, interdisciplinarity: astrophysics, nuclear/particle/atomic/plasma physics, optics, magnetism, transport properties, general relativity)

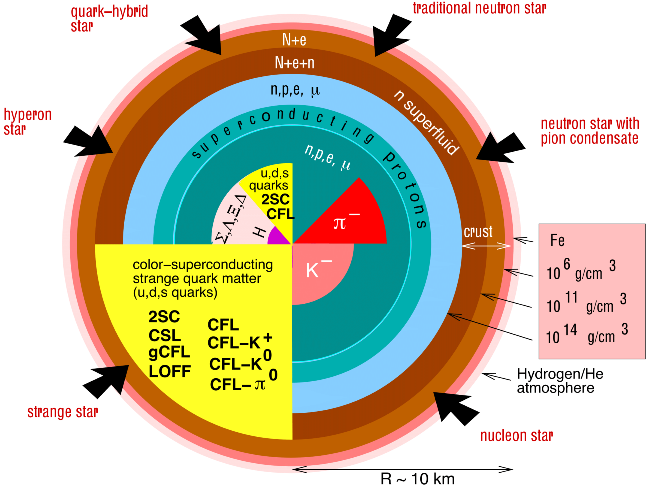
- data: mass, radius (??), age (??), surface temperature (??), rotation frequency

- nuclear physics determines the structure (mass and radius, via $P(\epsilon)$), composition (particles, abundances), thermal evolution (temperature vs. age)

- except the crust, matter is very different from what *exists* or *can be produced* in labs. ($n >> n_0$, $\delta >> 0$, strange component)

- large *uncertainties* **but also** the hope of a *benefit*

Neutron Stars - Structure and Composition



Good knowledge of the crust

High uncertainties related to interactions in the supra-saturated domain

Neutron stars = residues of supernoave explosions

- are born hot $T \approx 10^{11}\ \mathrm{K} \approx 20\ \mathrm{MeV}$,
- cool down by **conduction** and **radiation**
- the cooling lasts 10^6 yr, after which the NS spends its life being cold
- understanding cooling assumes:
  - *accurately measure* the age and effective surface temperature
  - *correctly* model the composition of the atmosphere which acts as a *insulating* heat blancket
    - depending on the spectra several comp. are proposed: H, He, C, Fe
    - light/heavy elements are associated with young/old stars
    - different conductivity prop. lead to different $T_b - T_s$ relations
  - *correctly* model the composition of the star, especially its core
  - *correctly* model superfluid properties of *every* species, which modifies emissivities and transport prop.
  - account for all cooling/heating agents
- uncertainties arise at every step

Heat transfer

Textbooks:

1. **conduction:** transfer of heat by microscopic collisions and/or movement of particles as molecules and electrons (eg. from an electric stove to the saucepan)
2. **convection:** transfer of heat from one place to another by the movement of fluids (eg. draft in a chimney or around any fire)
3. **radiation:** emission of electromagnetic radiation generated by the thermal motion of particles in matter (eg. the Sun heats the Earth)

Neutron stars:

1. radiation (ν and γ) from the whole volume
2. conduction towards the surface

Emissivities and *transport coefficients* depend on: composition, in-medium properties (Landau effective mass), superfluid properties, temperature

Cooling stages of an isolated NS

1. thermal relaxation: the crust and core are thermally decoupled,
   $T_{eff,s}$ reflects the the crust's thermal state,
   it lasts $t \lesssim 10 - 100$ yrs.,
   is affected by both crust and core prop.
2. neutrino-cooling era: the star is isothermal,
   the cooling is due to ν-emission from the core,
   it lasts $t \lesssim 10^5$
3. photon-cooling era: the cooling wave moves toward the surface,
   it lasts $t \gtrsim 10^5$

Global thermal balance:

$$C(T_i)dT_i/dt = -L_\nu^{\rm inf}(T_i) - L_\gamma^{\rm inf}(T_s);\; T_i(t) = T(r,t)\exp\left[\Phi(r)\right],$$

EOS enters: C, L_i, Φ. Bref, everywhere!

Neutrino emission processes

name	process	emissivity erg $\mathrm{cm}^{-3}\mathrm{s}^{-1}$	efficiency	occurence cond.
modified Urca	$N + n \rightarrow N + p + l + \tilde{\nu}_l$ $N + p + l \rightarrow N + n + \nu_l$	$\sim 10^{21}\, T_9^8$	slow	
bremsstrahlung	$n + n \rightarrow n + n + \nu + \tilde{\nu}$ $n + p \rightarrow n + p + \nu + \tilde{\nu}$ $p + p \rightarrow p + p + \nu + \tilde{\nu}$	$\sim 10^{19}\, T_9^8$	slow	
Cooper pair formation	$n + n \rightarrow [nn] + \nu + \tilde{\nu}$	$\sim 10^{21}\, T_9^7$	medium	$T < T_{C,n}$
	$p + p \rightarrow [pp] + \nu + \tilde{\nu}$	$\sim 10^{19}\, T_9^7$	medium	$T < T_{C,p}$
direct Urca	$n \rightarrow p + l + \tilde{\nu}_l$ $p + l \rightarrow n + \nu_l$ $\Lambda \rightarrow p + l + \tilde{\nu}_l$ $p + l \rightarrow \Lambda + \nu_l$ $\Xi^- \rightarrow \Lambda + l + \tilde{\nu}_l$ $\Lambda + l \rightarrow \Xi^- + \nu_l$ etc.	$\sim 10^{27}\, T_9^6$	fast	$p_{F,i} + p_{F,j} \geq p_{F,k}$

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

The most efficient is dUrca.

Triangle ineq. for dUrca entails a threshold!

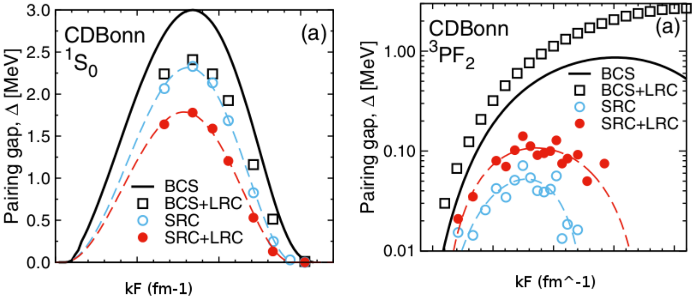
All processes are affected by SF.

Cooling of nucleonic neutron stars

- intensively studied (Page et al, ApJSS 155, 623 (2004); Page et al., ApJ 707, 1131 (2009); Yakovlev & Pethick, Annu. Rev. Astron. Astrophys. 42, 169 (2004); many others)
- subject to uncertainties from
  - the isovector channel, linked to the symmetry energy at supra-saturation densities
  - superfluid prop. of protons ($^1S_0$) and neutrons ($^3P_2 - ^3F_2$) in the core, due to short-range NN interaction potential and many body correlations
- "minimum paradigm", often prefered
- effects of different SF channels well understood **qualitatively**

Superfluidity in the crust and core: $^1S_0$ and $^3P_2 - ^3F_2$

Neutrons (Ding et al., PRC94, 025802 (2016))



Short range correlations diminish the gap;
Long range correl. act differently at low/high densities;
At high densities, extra uncertainty from the potential
Proton $^1S_0$-SF in the core is equally affected by manybody correl. (see Baldo+, Clark+, Sedrakian+, etc.)

As any fermion with attractive interactions, hyperons can pair; high uncertainties!

Cooling of hyper-neutron stars

Pioneering papers:

Haensel & Gnedin, A&A290, 290 (1994)
Schaab, Balberg & Schaffner-Bielich, ApJ504, L99 (1998)
Tsuruta et al., ApJ691, 621 (2009)

Criticism: obsolete EoS and YY potentials,
Conclusion: fast cooling due to H-DURCA despite hyperon SF

Recently:

Raduta, Sedrakian & Weber, MNRAS 475, 4347 (2018)
Negreiros et al., ApJ863, 104 (2018)
Grigorian et al., NPA980, 105 (2018)
Raduta, Li, Sedrakian & Weber, MNRAS (2019)

Features: EoS agreement with various present constraints; n and p SF gaps; hyperon SF; different cooling mechanisms; different models for the envelope

Conclusion: hyper-NS are not incompatible with data

RMF Equations of State

Nuclear Properties

Model	$n_{\rm s}$ (fm^{-3})	$E_{\rm s}$ (MeV)	K (MeV)	J (MeV)	L (MeV)	$K_{\rm sym}$ (MeV)	$n_{\rm DU}$ (fm^{-3})	$M_{\rm DU}$ ($M_\odot$)
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	-	-
SWL	0.150	-16.0	260.0	31.0	55.0	n.a.	0.90	2.00

Astrophysical Properties

Model	$n_{\rm max}$ (fm^{-3})	$M_{\rm max}^{\rm Y}$ ($M_\odot$)	$\rm Y_1$	$n_{\rm Y_1}$ (fm^{-3})	$M_{\rm Y_1}$ ($M_\odot$)	$\rm Y_2$	$n_{\rm Y_2}$ (fm^{-3})	$M_{\rm Y_2}$ ($M_\odot$)	$\rm Y_3$	$n_{\rm Y_3}$ (fm^{-3})	$M_{\rm Y_3}$ ($M_\odot$)
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
SWL	0.97	2.003	Λ	0.41	1.5	Ξ^-	0.45	1.65	Ξ^0	0.90	2.00

GM1A (Gusakov et al., MNRAS439 (2014)); DDME2 (Fortin et al., PRC94 (2016)); SWL (Spinella, PhD thesis (Univ. of San Diego); Weber, private com.)

Pairing Gap Equations and YY Potentials

Pairing equation:

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

Single-particle energy:

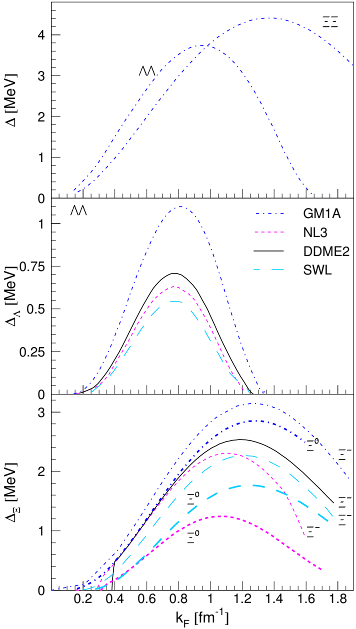
$$e(k) = \sqrt{(\hbar c)^2 k^2 + M^{*2}} + g_{\omega Y}\omega + g_{\phi Y}\phi + \tau_{3Y} g_{\rho Y}\rho + \Sigma_R,$$

Effective mass: $M^* = M - g_{\sigma B}\sigma - g_{\sigma^* B}\sigma^*$,
Interaction potential in the ${}^1S_0$ channel, due to low densities of hyperons:

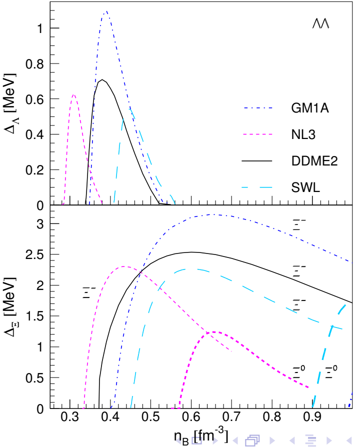
$$V(k,k') = 4\pi \int dr r^2 j_0(kr) V(r) j_0(k'r)$$

Interaction potentials: $\Lambda\Lambda$: ESC00 [Rijken 2001; Filikhin & Gal 2002]
$\Xi\Xi$: NSC08c [Rijken et al. 2013; Garcilazzo et al., 2016]
they are both very attractive

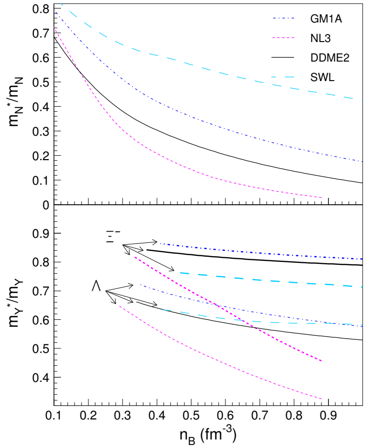
Pairing Gaps

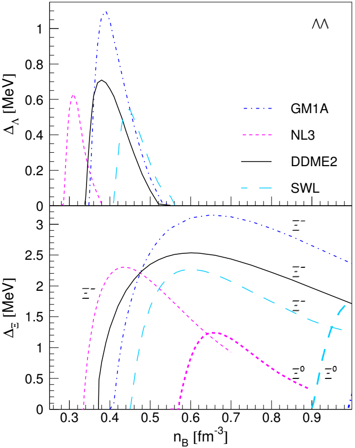


- strong EoS dependence
- Λs are paired over a narrow density range, probably in the outer core only
- Ξs are paired over a wide density range, probably in the whole core
- (strong V_{YY} dependence)



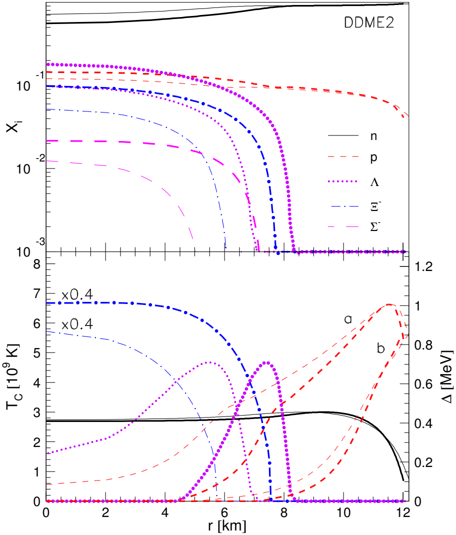
Pairing Gaps





- correlation M^* - Δ_F

NS Composition and pairing: DDME2



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

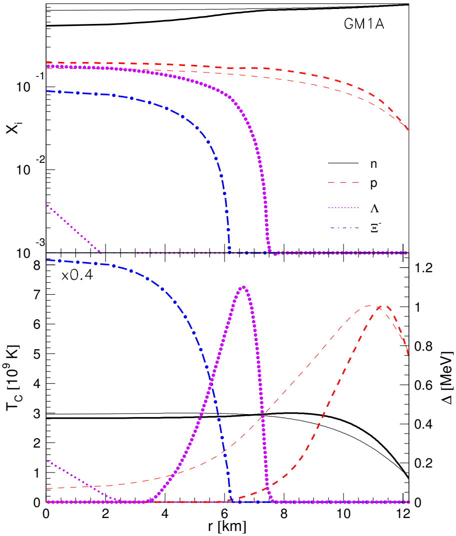
$^3P_2 - ^3F_2$ n: gaps "b" of Page et al., ApJSS155 (2004)
$^1S_0$ p: a) Chen et al., NPA555 (1993),
b) Baldo et al., NPA536 (1992)

$1.8M_\odot$: n, p, Λ, Ξ SF everywhere in the core
$\Lambda \to p + l + \tilde{\nu}$ suppressed
$\Xi^- \to \Lambda + l + \tilde{\nu}$ suppressed
$\Sigma^- \to n + l + \tilde{\nu}$ suppressed
$\Sigma^- \to \Lambda + l + \tilde{\nu}$ suppressed

$2M_\odot$: p, n, Ξ SF over the whole volume
Λ SF in the outer core
$\Lambda \to p + l + \tilde{\nu}$ active!
$\Xi^- \to \Lambda + l + \tilde{\nu}$ suppressed
$\Sigma^- \to n + l + \tilde{\nu}$ suppressed
$\Sigma^- \to \Lambda + l + \tilde{\nu}$ active!

Raduta, 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 et al., ApJSS155 (2004)
$^1S_0$ p: Chen et al., NPA555 (1993)

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

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

Raduta, Sedrakian & Weber, MNRAS (2018)

Cooling by `NSCool`*

ν**-emission processes** (standard choice):
crust: bremsstrahlung ($N + N' \to N + N' + \nu + \tilde{\nu}$), Cooper pair formation ($N + N \to [NN] + \nu + \tilde{\nu}$), plasmon decay ($\Gamma \to \nu + \tilde{\nu}$), pair annihilation ($\gamma + \gamma \leftrightarrow e^+ + e^- \to \nu + \tilde{\nu}$), $\gamma - \nu$ processes ($\gamma + e^- \to e^- + \nu + \tilde{\nu}$)
core: N-DURCA & H-DURCA, N-MURCA, bremsstrahlung, Cooper pair formation (neutrons, protons)

- at $T < T_C$: ϵ_ν, C_v suppressed by a Boltzmann-like factor
- *H-DURCA emissivities as in Prakash et al. ApJ390 (1992)*

Present calculations:

- no heating sources, no magnetic field, no accretion, Fe-envelope

- crust EoS: [Haensel-Zdunik-Dobaczewski, 1989 + Negele-Vautherin, 1973] smoothly merged with the core EoS

- PBF of hyperons

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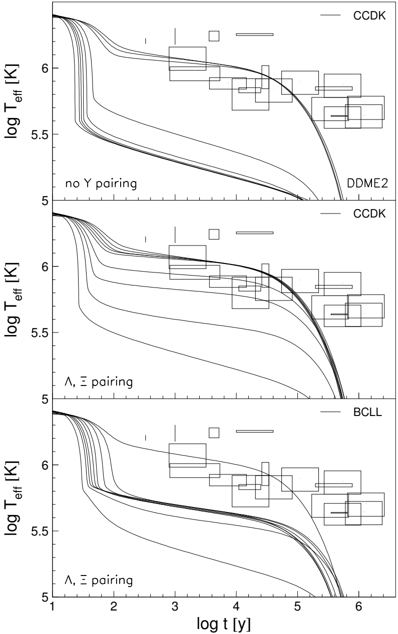
[*] by D. Page, publicly available at: http://www.astroscu.unam.mx/neutrones/NSCool/

Cooling curves: DDME



M=1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.85, 1.9, 2$M_\odot$
data: Beznogov & Yakovlev, MNRAS (2015)

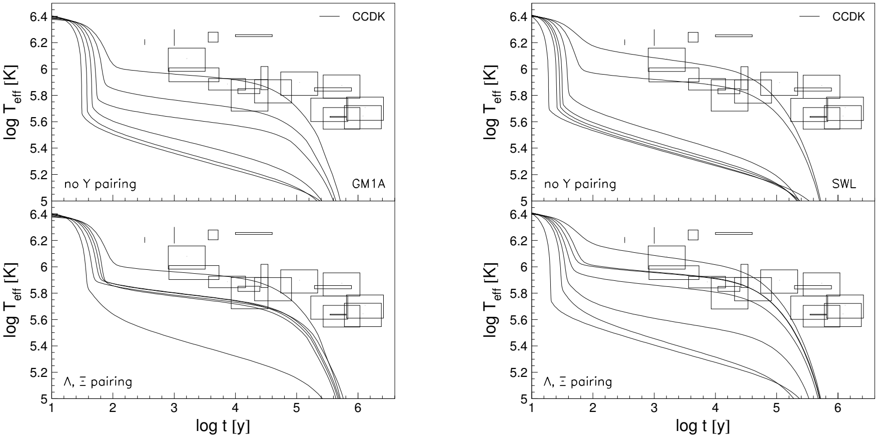
p(CCDK), no Y-SF: $M > 1.55 M_\odot$ too cold

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

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

Raduta, Sedrakian & Weber, MNRAS (2018)

Cooling curves: GM1A and SWL



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

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

Thermal states of INS compatible with hypernuclear stars

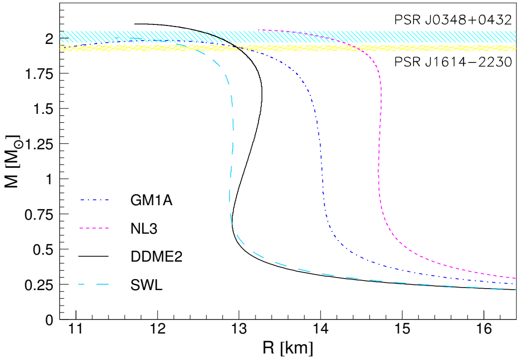
Conclusions

- hyperonic pairing gaps of up to few MeV are obtained for RMF EoS compatible with present constraints *if* the YY potentials are attractive enough

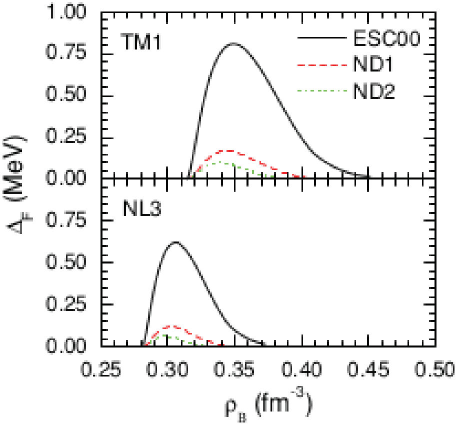
- hyperonic superfluidity is necessary for hyperonic stars up to a certain, EoS-dependent mass, to agree with thermal data

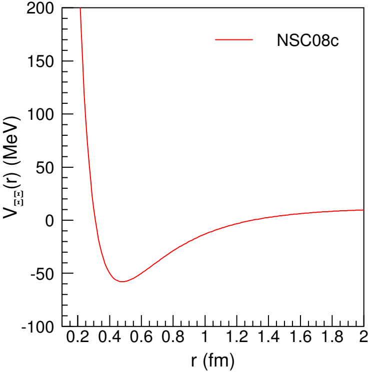
- rapid cooling properties of most massive stars depend of the closing of $^1S_0$ gaps for Λ and protons at high densities,
- high densities pairing in $^3P_2 -^3 F_2$ or D channels is, in principle, possible if the potential is attractive enough.

M-R


PSR J0348+0432
PSR J1614−2230
M [$M_\odot$]
0
0.25
0.5
0.75
1
1.25
1.5
1.75
2
R [km]
11
12
13
14
15
16
GM1A
NL3
DDME2
SWL

$\Lambda\Lambda$ and $\Xi\Xi$ $^1S_0$ potentials

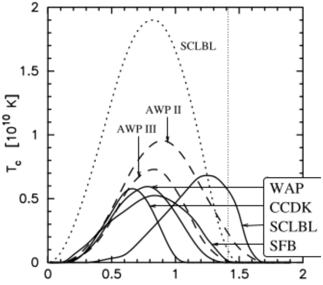


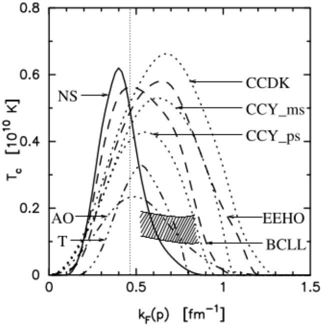


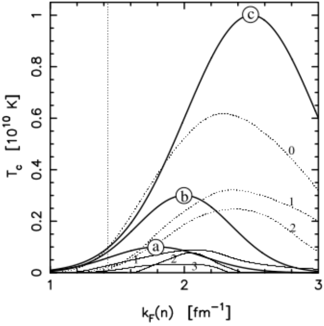
Wang & Shen, PRC81 (2010) Filikhin et al. (2017)

- no scattering data, much uncertainties
- $\Lambda\Lambda$ and $\Xi\Xi$ potentials are attractive
- pairing might occur

Pairing in neutron stars



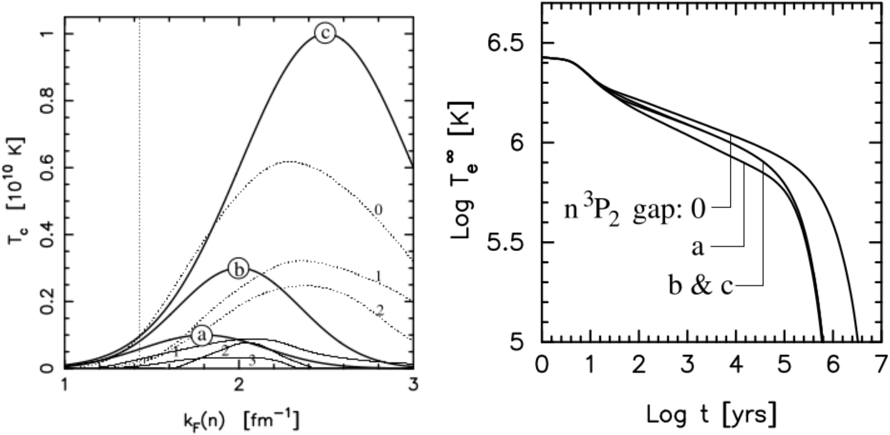




Page et al., ApJ 155 (2004)

1 GK = 86.21738 keV

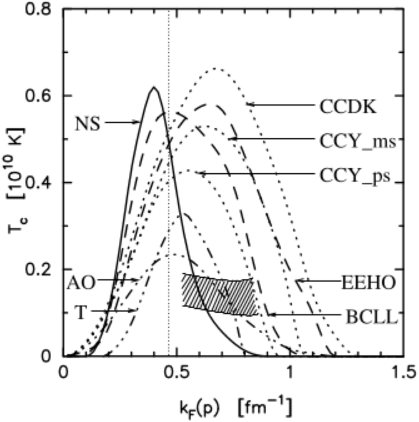
Neutron $^3P_2$ gap - effect on cooling

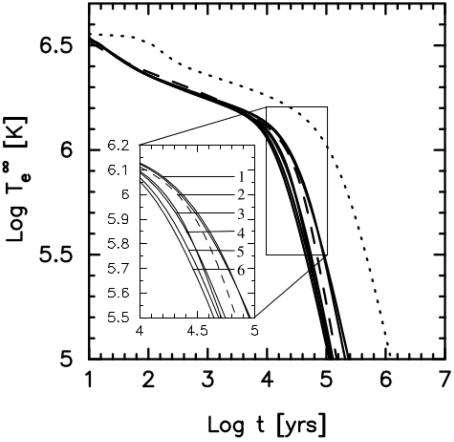


$1.4M_\odot$, APR

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

Proton ${}^1S_0$ gap - effect on cooling





$1.1M_\odot$, APR

1=NS, 2=T, 3=AO, 4=BCLL, 5=CCY_ms, 6=CCDK

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

Magnetic field

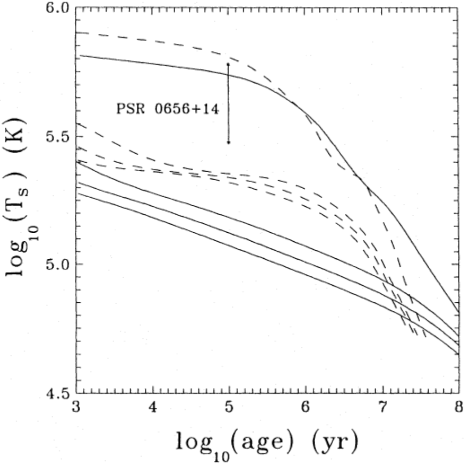


Fig. 2. Cooling curves in the presence of nucleon superfluidity, with $T_{\rm c,n} = T_{\rm c,p} = 10^9$ K. Solid curves: no magnetic field. Dashed curves: $B = 3 \times 10^{12}$ G. The curves correspond to a set of neutron star models with $M/M_\odot = 1.3,\ 1.4,\ 1.5,\ 1.7$, lower temperature corresponding to higher mass

[Haensel & Gnedin, AA290, 458 (1994)]