Pairing Gaps and Neutron Star Cooling

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- Motivation
- Cooling processes
- Pairing gaps
- Cooling scenarios
- Results

PRC 70, 048802 (2004)

PRL 95, 051101 (2005)

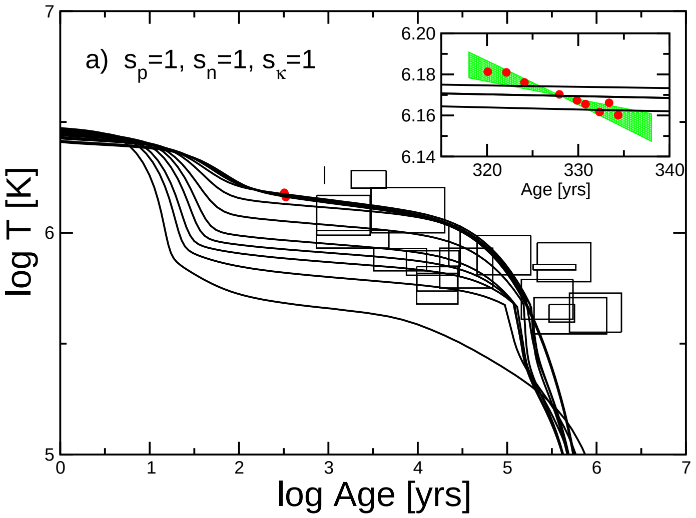
PRC 75, 025802 (2007)

PRC 89, 048801 (2014)

MNRAS 456, 1451 (2016)

Neutron Star cooling:

- Objective: “Explain” the objects in the *Temp.* vs. *Age* plot:



After ~ 20s SN remnant becomes neutrino transparent
Isothermal after $\lesssim 100y$, $T_{\text{core}} \approx (10...100)T_{\text{surface}}$
Neutrino cooling for $t \lesssim 10^5$yr, then photon cooling

Data for 19+1 isolated NS from
Beznogov & Yakovlev, MNRAS 447, 1598 (2015)
Klochkov et al., A&A 573, A53 (2015)

Fast cooling of Cas A NS (Disputed !):
Heinke & Ho, ApJ 719, L167 (2010)
Elshamouty et al., ApJ 777, 22 (2013)

Theoretical cooling simulations for fixed NS mass
$M/M_\odot = 1.0, 1.1, \ldots, 2.0$

- Major problems:
  - Stellar atmosphere is unknown, distance not well known
    → Uncertain temperature
  - Most NS masses are unknown
    → Verification of theoretical models currently impossible

- Models can be falsified when unable to cover all data
- Theoretical input required:
  - EOS for core, crust, atmosphere
    → composition of stellar matter
  - Effective masses, Heat capacities and conductivities
  - Cooling rates for different processes
  - Pairing gaps for all channels
- We use standard cooling code **NSCool** of D. Page with consistent BHF EOS, eff. masses, pairing gaps as input (checked by independent code of P. Haensel)
- We assume purely nucleonic NS: no hyperons, no QM !

Cooling Processes:

Yakovlev,Kaminker,Gnedin,Haensel, Phys. Rep. 354, 1 (2001)

- Neutrino emissivities without pairing [erg cm^{-3} s^{-1}] :
  - Direct Urca $n \to p + l + \overline{\nu}\,;\, p + l \to n + \nu$:

$$Q^{(DU)} \approx 4.0 \times 10^{27} M_{11} T_9^6 \, \Theta\left(k_{F_p} + k_{F_e} - k_{F_n}\right)$$

  - Modified Urca $N + N \to N + N + l + \overline{\nu}\,;\, N + N + l \to N + N + \nu$:

$$Q^{(Mn)} \approx 8.1 \times 10^{21} M_{31} T_9^8 \alpha_n \beta_n$$

$$Q^{(Mp)} \approx 8.1 \times 10^{21} M_{13} T_9^8 \alpha_p \beta_p \left(1 - k_{F_e}/4k_{F_p}\right) \Theta_{Mp}$$

$\alpha_p = \alpha_n = 1.13$, $\beta_p = \beta_n = 0.68$: in-medium corrections of matrix elements

  - Bremsstrahlung $N + N \to N + N + \nu + \overline{\nu}$:

$$Q^{(Bnn)} \approx 2.3 \times 10^{20} M_{40} T_9^8 \alpha_{nn} \beta_{nn} (\rho_n/\rho_p)^{1/3}$$

$$Q^{(Bnp)} \approx 4.5 \times 10^{20} M_{22} T_9^8 \alpha_{np} \beta_{np}$$

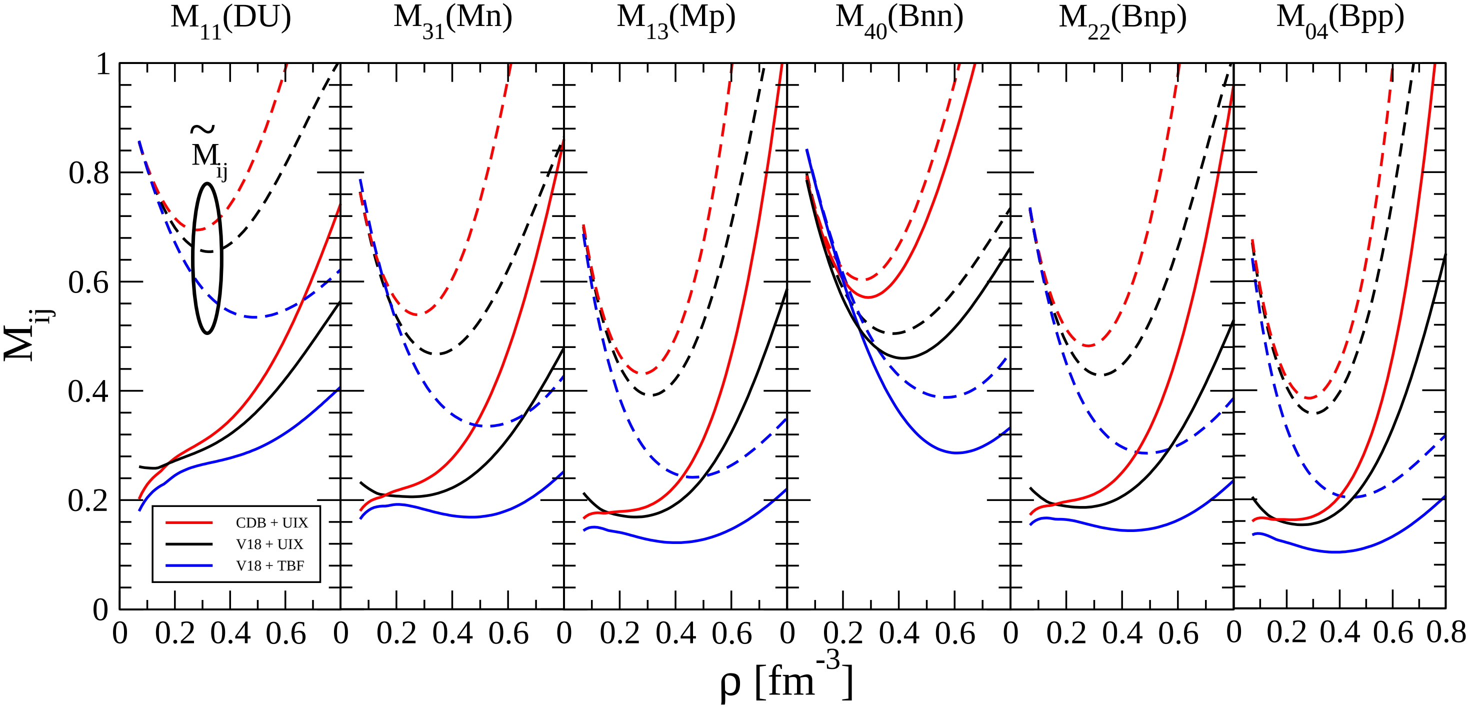
$$Q^{(Bpp)} \approx 2.3 \times 10^{20} M_{04} T_9^8 \alpha_{pp} \beta_{pp}$$

$\alpha_{nn} = 0.59$, $\alpha_{np} = 1.06$, $\alpha_{pp} = 0.11$, $\beta_{nn} = 0.56$, $\beta_{np} = 0.66$, $\beta_{pp} = 0.70$

- Effective mass prefactors:

$$M_{ij} \equiv \left(\frac{\rho_p}{\rho_0}\right)^{1/3} \left(\frac{m_n^*}{m_n}\right)^i \left(\frac{m_p^*}{m_p}\right)^j , \quad \frac{m^*}{m} = \frac{k}{m}\left[\frac{de(k)}{dk}\right]^{-1}_{k=k_F}$$

BHF results:



Effects of Pairing:

Yakovlev,Kaminker,Gnedin,Haensel, Phys. Rep. 354, 1 (2001)

- Damping of DU,MU,BNN reactions:

$$Q^{(DU)} \to Q^{(DU)} \times R(v_n, v_p)\ ; \quad v = \frac{\bar{\Delta}(T)}{T}\ ; \quad R(v) \approx e^{-v_0}$$

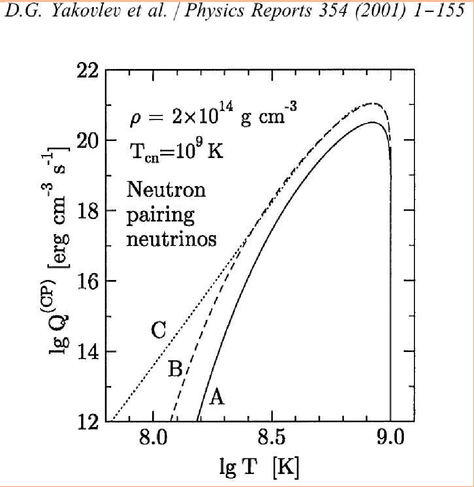
$$v_0 = \frac{\bar{\Delta}(T=0)}{T} = 1.746\frac{T_c}{T}$$

- A new cooling process: Pair Breaking and Formation:

$N \to N + \nu + \overline{\nu}$:

$$Q^{(PBF)} \approx 3.5 \times 10^{21} \frac{m^*}{m}\frac{k_F}{m} T_9^7 a F(v)$$

Provides rapid cooling close to below the critical temperature

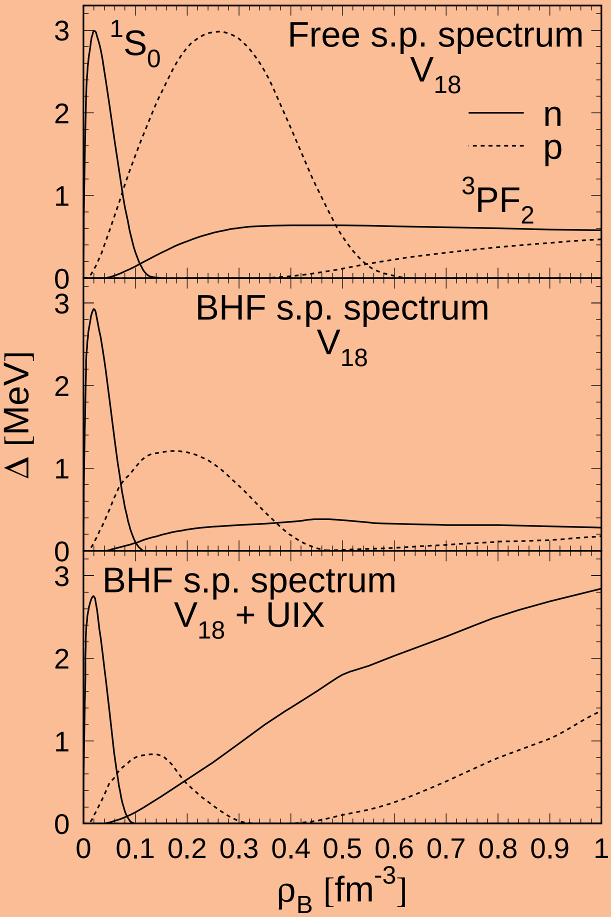

D.G. Yakovlev et al. / Physics Reports 354 (2001) 1–155

Intermezzo:

- No pairing:
  - If DU is active ($x_p \gtrsim 13\%$), it dominates all other processes
  - Too fast cooling of most NS
- Yes pairing:
  - All cooling processes are comparable and must be used
  - Competition between blocking and PBF
  - All gaps have to be known

Gaps in Neutron Star Matter:

X.-R. Zhou, H.-J. S., E.-G. Zhao, Feng Pan, J.P. Draayer; PRC 70, 048802 (2004)



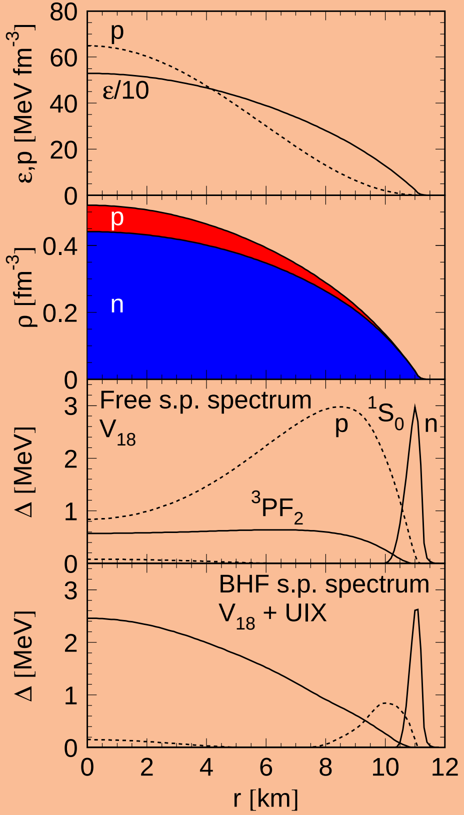
EOS: BHF (V18 + UIX)

- Self-energy effects suppress gaps
- TBF suppress *pp* $^1S_0$ but strongly enhance $^3PF_2$ gaps !
- No polarization corrections included here

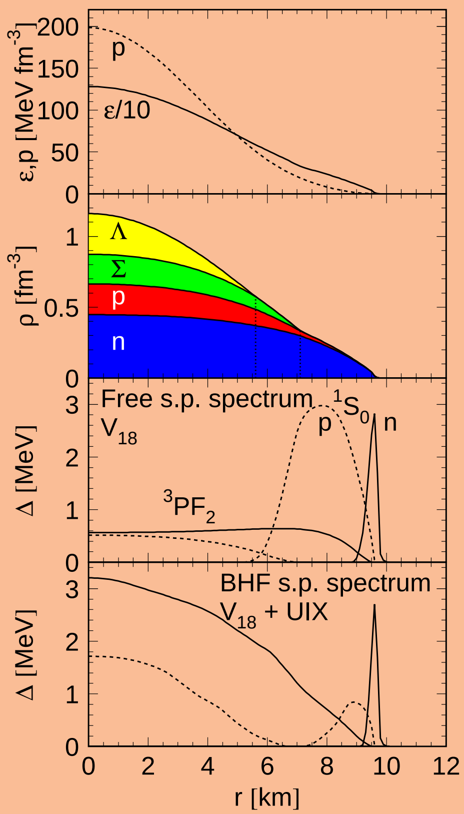
Neutron Star Profile: Particle Densities & Gaps:

EOS: BHF (V18 + UIX + NSC89) , $M = 1.2\ M_\odot$

without hyperons:



with hyperons:



Polarization effects (including *pn* interaction) ?

Proton $^1S_0$ Pairing in Neutron Stars:

M. Baldo, H.-J. S.; PRC 75, 025802 (2007)

- Strong in-medium effects on protons due to large neutron background
- Consider complete set of medium effects: m*, Z, TBF, Polarization:

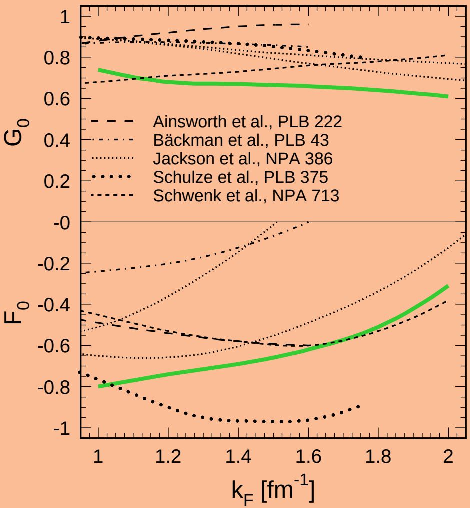
$$\Delta(k') = -\sum_k \frac{Z(k)[V + V_{TBF} + V_{Pol}](k',k)}{2\sqrt{M_s(k)^2 + \Delta(k)^2}} \Delta(k)$$

- Weak-coupling approximation:

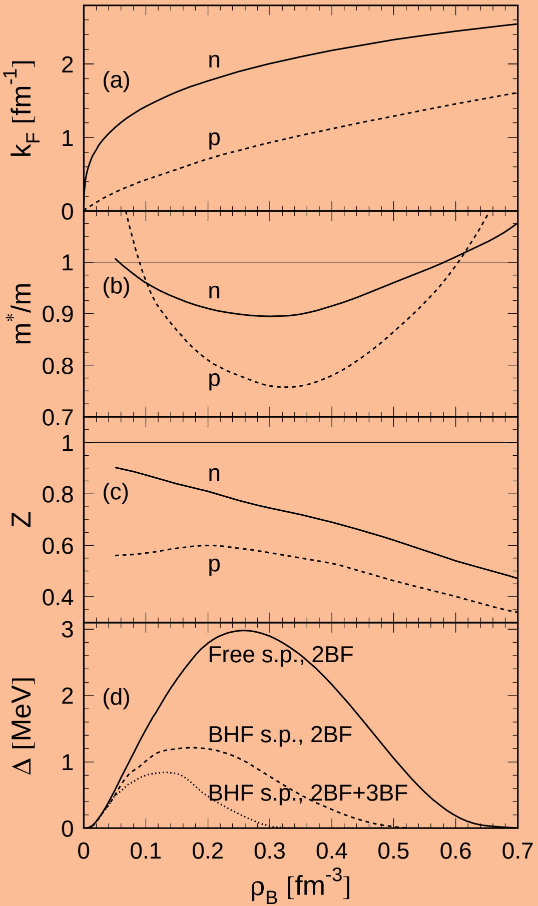
$$\Delta = c\,\mu\, e^{1/\lambda} \;, \quad \lambda = k_F m^* Z^2 V_{\text{eff}}$$

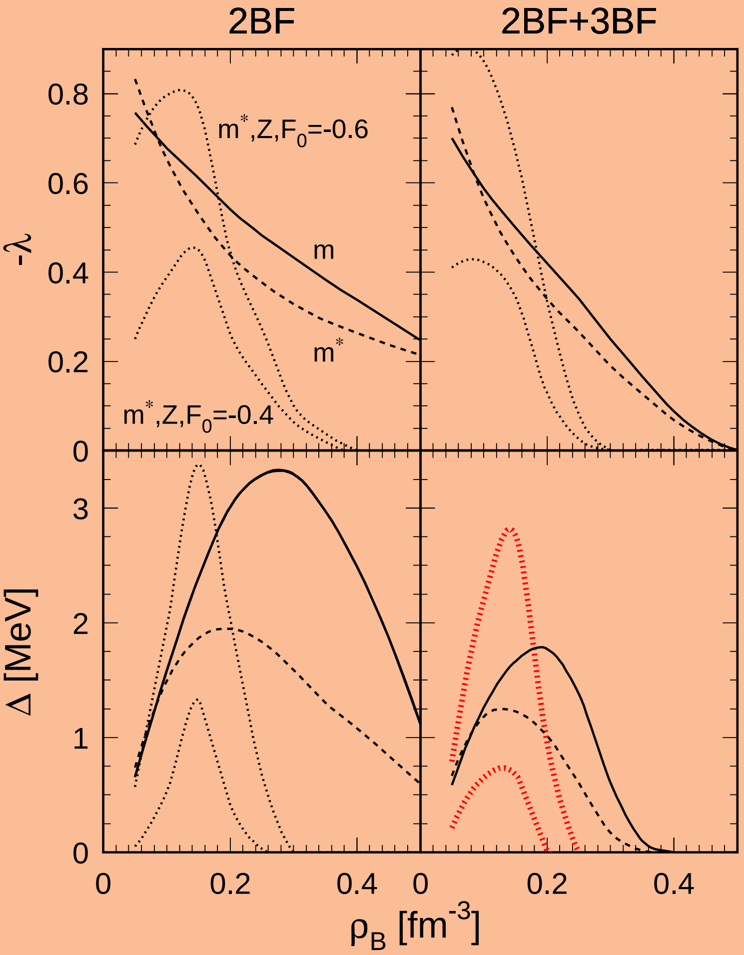
- Approximation for Landau parameters:

$$G_0 = 0.7 \;;\; F_0 = -0.4, -0.6$$



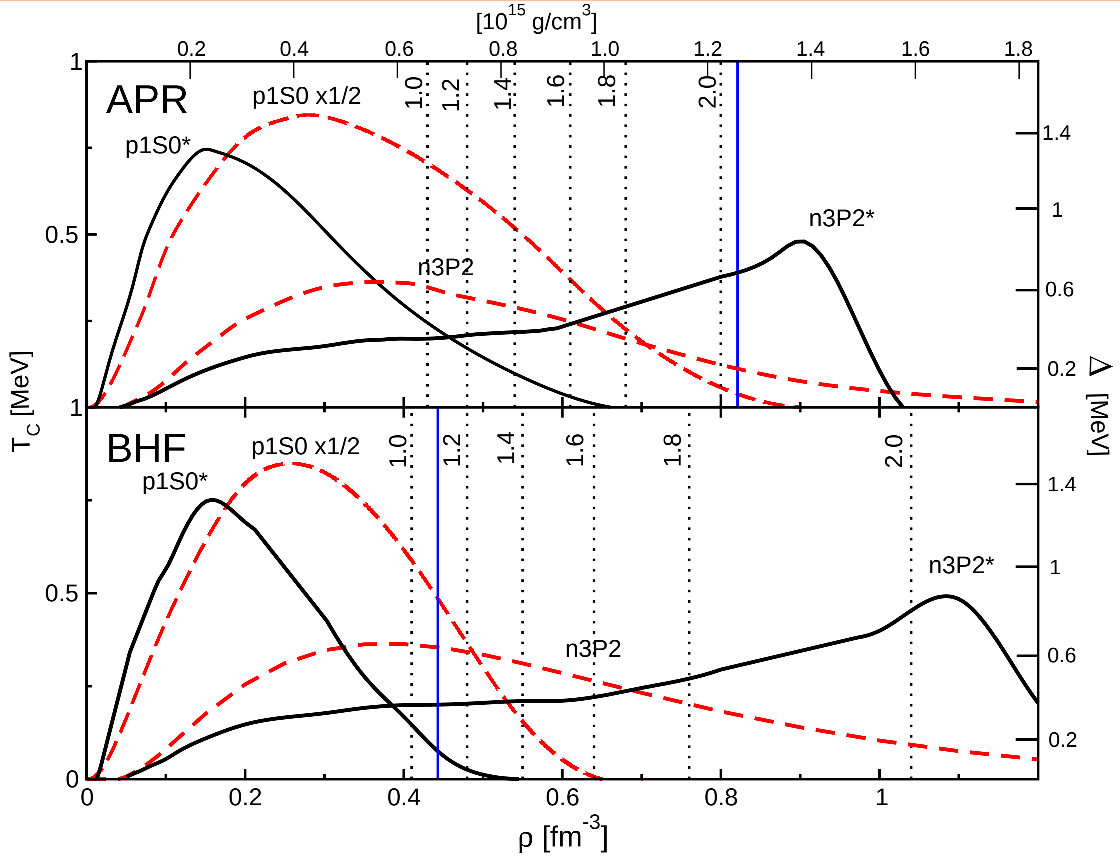
• Results:





→ Reduction by m^*, Z, TBF; Enhancement by polarization!

Pairing gaps used for cooling simulation:



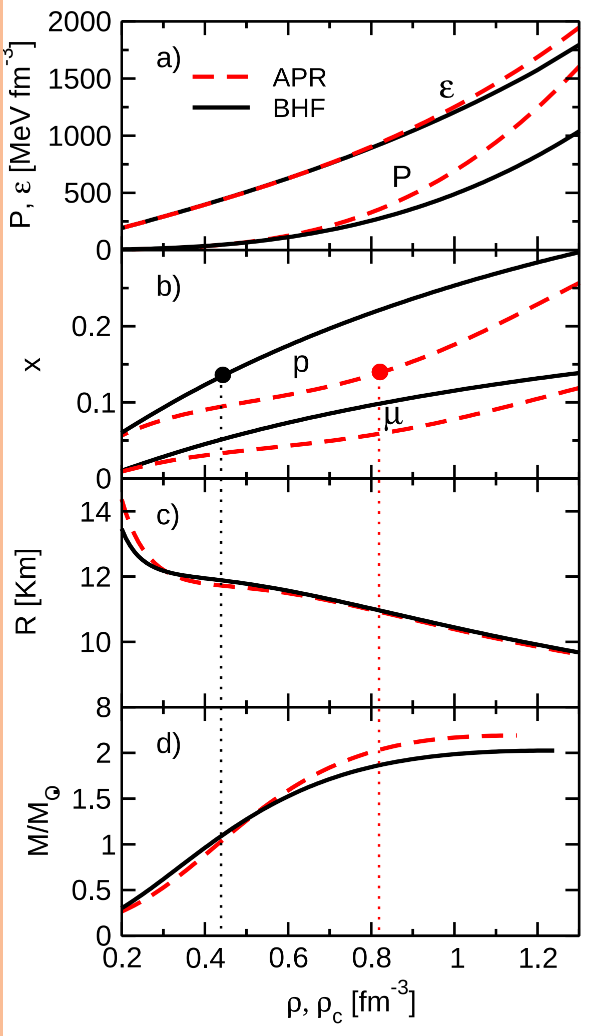
DU onset:

$$\rho = 0.82\,\mathrm{fm}^{-3}$$
$$x_p = 0.140$$
$$M/M_\odot = 2.03$$

$$\rho = 0.44\,\mathrm{fm}^{-3}$$
$$x_p = 0.136$$
$$M/M_\odot = 1.10$$

We employ BCS and BCS+m^* gaps
with global scaling factors s, s^*

● Nuclear EOS and NS Structure:



Compare APR and BHF(V18+UIX) EOS :

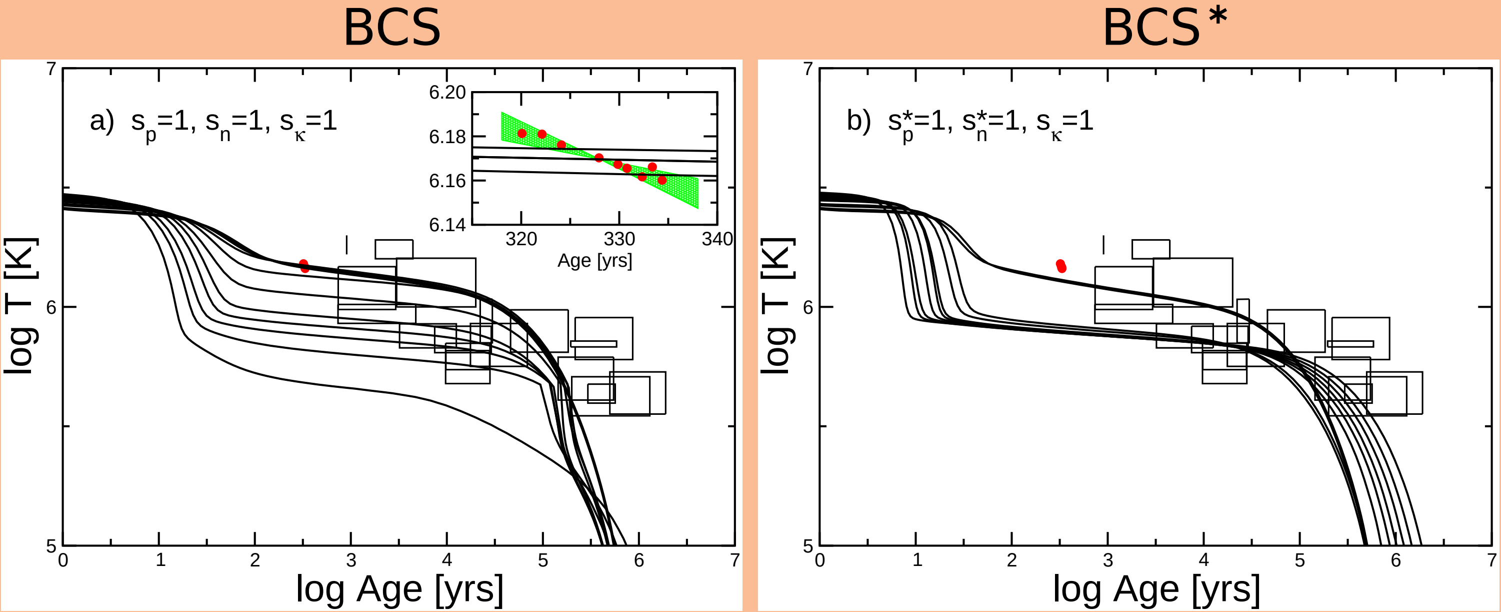
BHF has large x_p and early DU onset

$M_{\max} > 2M_\odot$ for both EOSs

DU thresholds: $M/M_\odot = 1.10, 2.03$ (BHF,APR)

Cooling Scenarios:

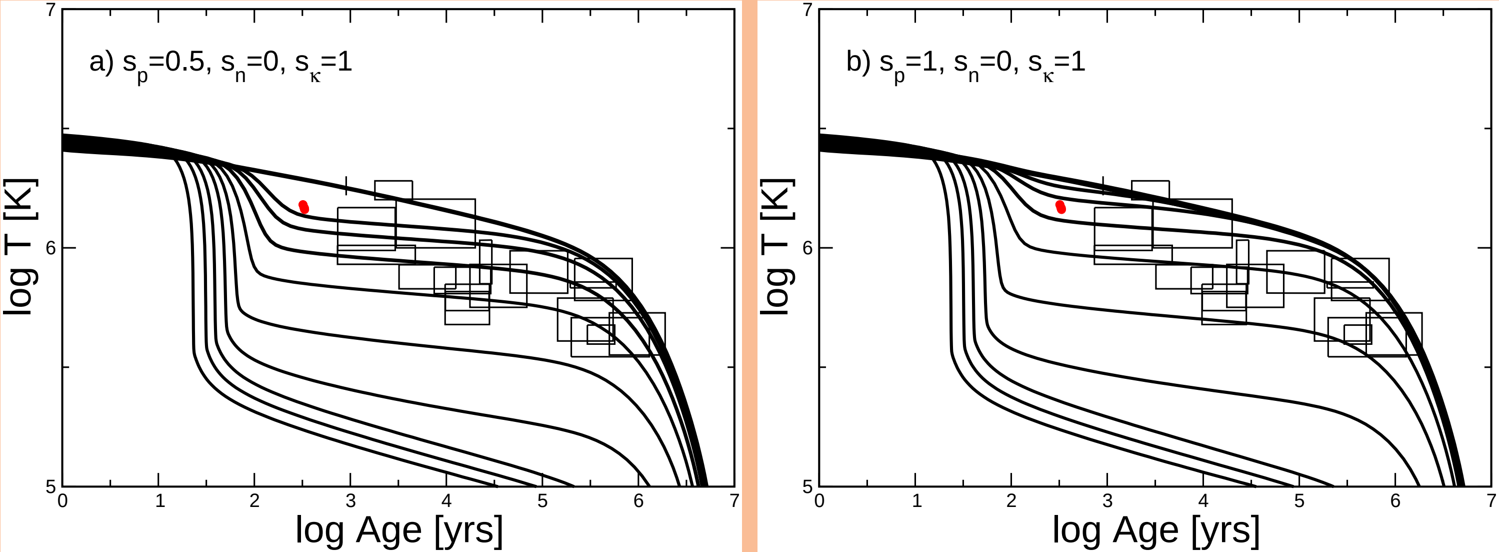
- Results: BCS gaps, no scaling:



  - Cooling too fast, hot old NS not reproduced
  - Cas A fast cooling not reproduced
  - BCS/BCS*: fast DU cooling blocked for $M/M_\odot \lesssim 1.5/1.2$

- Results: Global fit of all data:

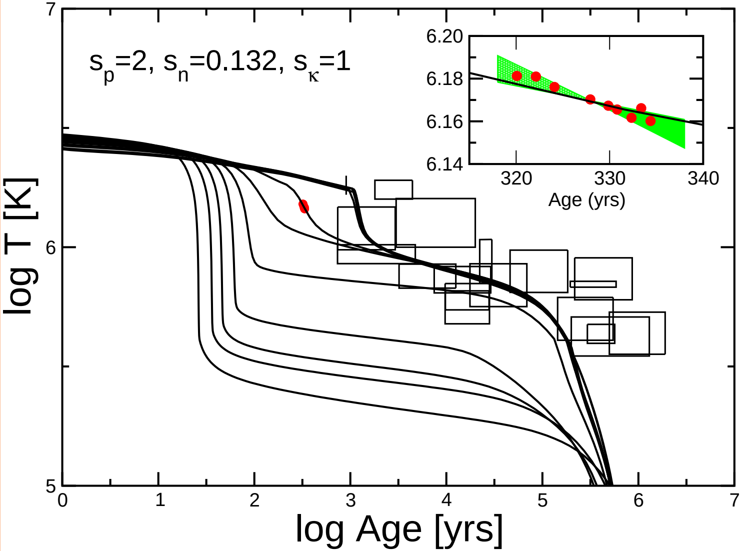
No n3P2 cooling, only p1S0 BCS gap



- No n3P2 gap, otherwise PBF process cools too much
- Magnitude of p1S0 nearly arbitrary
- p1S0 gap must extend to large density to inhibit DU for many sources
- Cas A fast cooling not possible

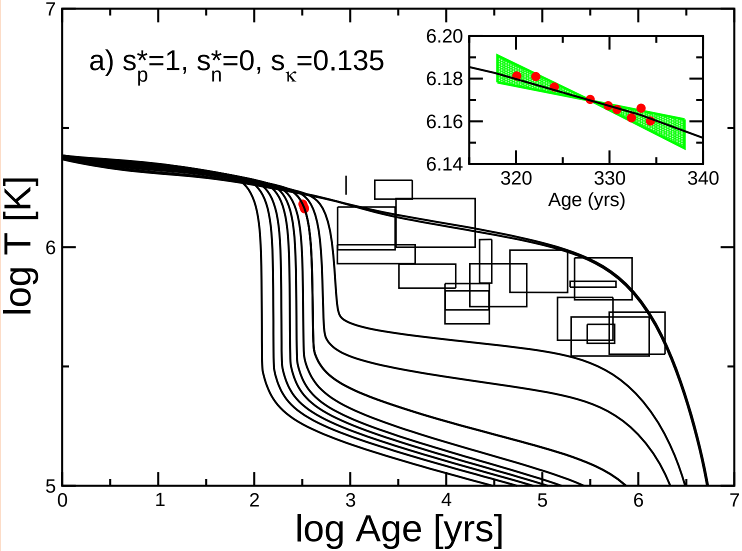
- Results: Two ways to fit Cas A cooling:

PBF cooling



Fine-tuned n3P2 PBF cooling at current age/temperature of Cas A: $\Delta_{n3P2} \approx 0.1\mathrm{MeV}$

Delayed cooling



Suppressed thermal conductivity and delayed heat propagation

↪ Difficult to fit ALL other sources in this case

Recent Progress on n3PF2 Pairing

- ApJ 817, 6 (2016): J.M. Dong et al.
  Role of nucleonic Fermi surface depletion in neutron star cooling
  - No Polarization

- PRC 94, 025802 (2016): D. Ding et al.
  Pairing in high-density neutron matter including short- and long-range correlations
  - PNM, No TBF

- PRC 95, 024302 (2017): C. Drischler et al.
  Pairing in neutron matter: New uncertainty estimates and three-body forces
  - PNM, No Polarization

Summary:

- Quantitative knowledge of *all* pairing gaps is required
- n3P2 PBF cooling clashes with existence of hot old NS
  Quantitative theoretical calculation still missing
- DU cooling possible if damped for most NS
  → p1S0 gap must extend to large density
- Rapid Cas A and cooling of all other objects are difficult to reconcile
- Need masses of cooling NS to verify models !

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However:

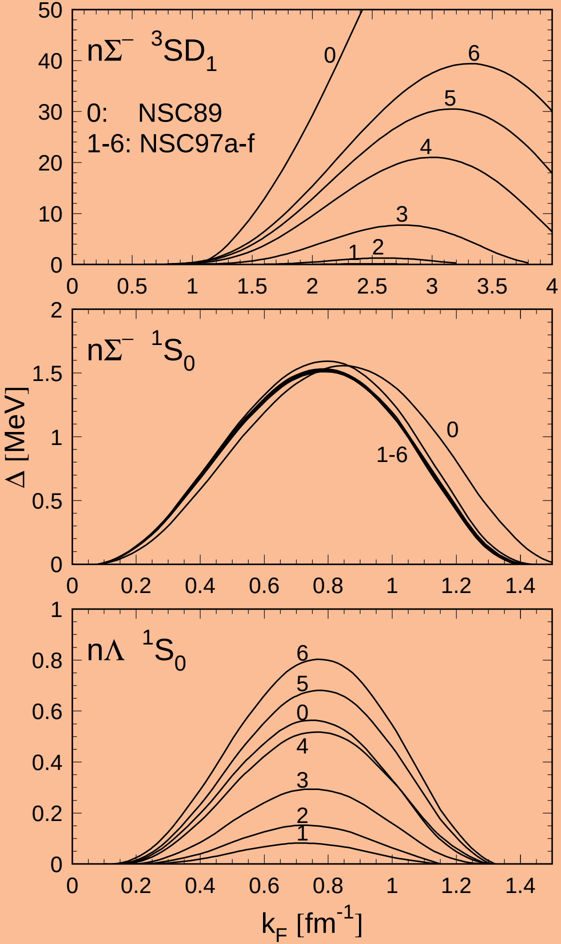
- Purely nucleonic picture is too naive:
  Quark matter, hyperons, etc. must be considered . . .

Hyperon-Nucleon Pairing in Neutron Stars:

Xian-Rong Zhou, H.-J. S., Feng Pan, J.P. Draayer; PRL 95, 051101 (2005)

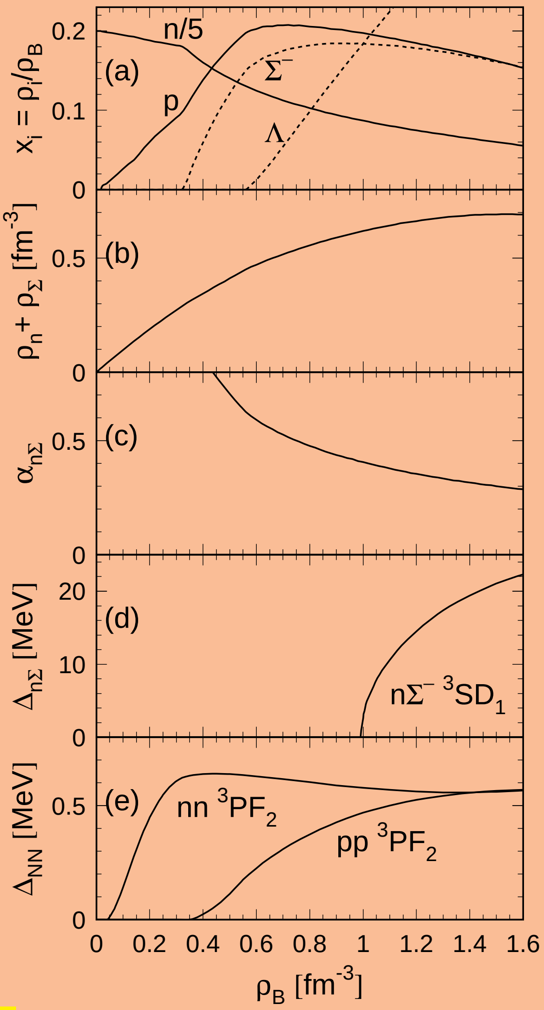
- NY gaps in symmetric hyperon-nucleon matter:

  YY pairing unknown due to unknown potentials



↪ Nijmegen potentials predict very large $n\Sigma^-$ $^3SD_1$ gaps !
(no hard core, very attractive)

• $n\Sigma^-\ {}^3SD_1$ pairing in neutron star matter:



with V18+UIX+NSC89 BHF EOS

↪ Suppression of *nn* $^3PF_2$ pairing !

Suppression of direct Urca Σ^- cooling !

But, at high density many uncertainties:

- EOS, composition of matter ?
- NY potentials ?
- Medium effects on pairing ?
- Separation of paired/unpaired phases ?

↪ Presently YN pairing cannot be excluded