



# *A Unified Model of NS interior : EoS, superfluidity gaps and thermal states*

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based on Taranto, Burgio, Schulze, MNRAS **456**, 1451 (2016)

Fortin, Taranto, Burgio, Haensel, Schulze, Zdunik, arXiv:1709.04855

NSAA\_2017

Nuclear Structure and Astrophysical Applications

September 19<sup>th</sup>-20<sup>th</sup>, 2017

# The Neutron Star Mystery

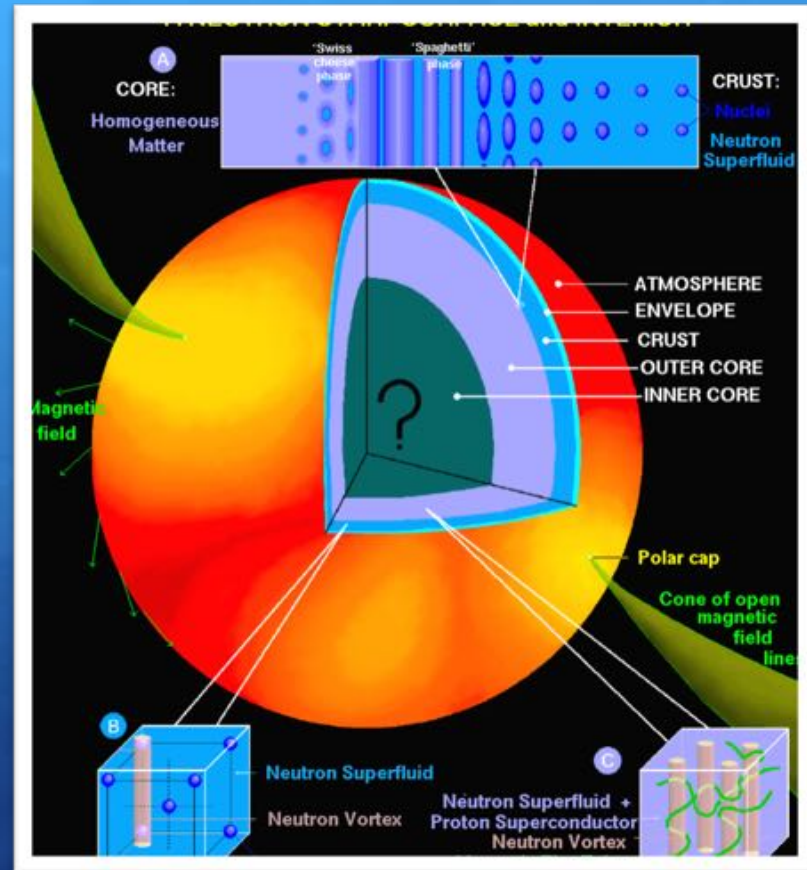
## Four main layers

1. Outer crust
2. Inner crust
3. Outer core
4. Inner core

## (A) Composition of the core

1. Nucleon matter
2. Nucleons and hyperons
3. Pion condensates
4. Kaon condensates
5. Quarks (u,d,s)

## (B) The pressure of dense matter

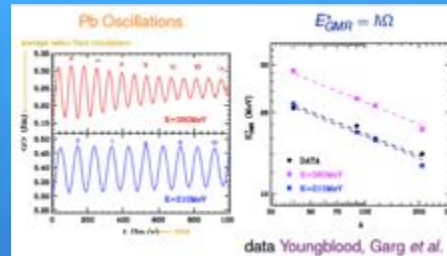
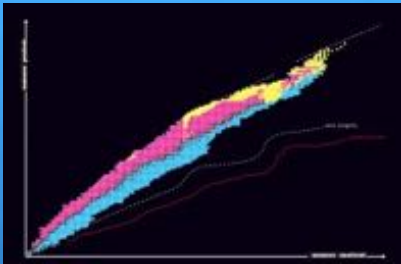


by Dany Page, UNAM Mexico City

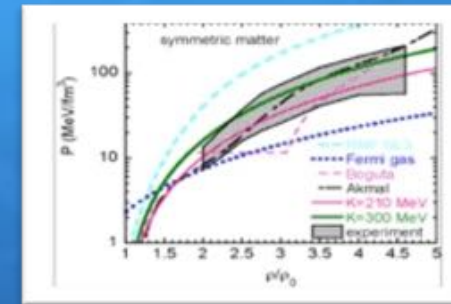
$(A) + (B) = \text{The problem of the equation of state}$

# ☞ The EoS : where do we stand ?

- Structure prop. of about 3339 nuclides. GMR. K+ mult. in HIC (Kaos coll.). Collective flow in Au+Au collisions.

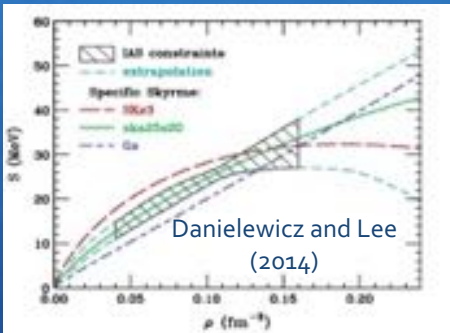


$K_0 = 240 \pm 10 \text{ MeV}$  (Colo' 2004)  
 $= 248 \pm 8 \text{ MeV}$  (Piekarewicz 2004)

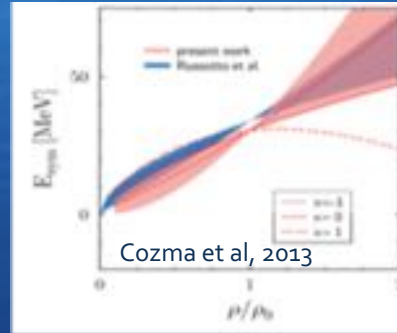


P. Danielewicz,  
 Science **298**, 1592  
 (2002)

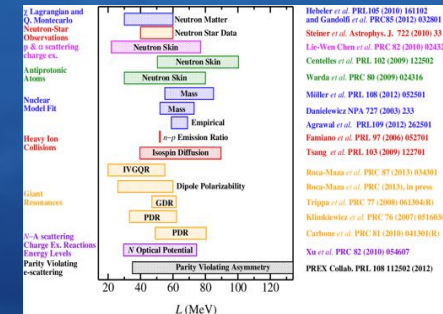
- Symmetry energy S and slope L.



Danielewicz and Lee  
 (2014)



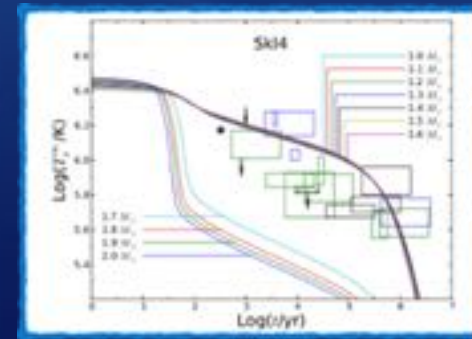
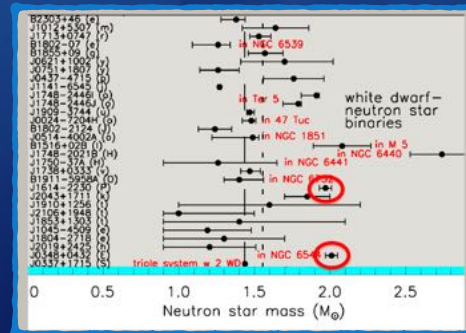
Cozma et al, 2013



X. Vinas et al.,  
 EPJA 50:27 (2014)

- Astrophysical observations of WD-NS binaries → Masses → stiff EoS at large density.

J. Lattimer & D. Nice



Cooling of INS.  
 Role of  
 superfluidity  
 Yakovlev 2001.

# 👉 Towards a unified picture from the crust to the core

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★ **Our goal** : to construct a unified theory which is able to describe the overall structure of Neutron Stars, from the outer crust to the inner core. A few of such EoS are available :

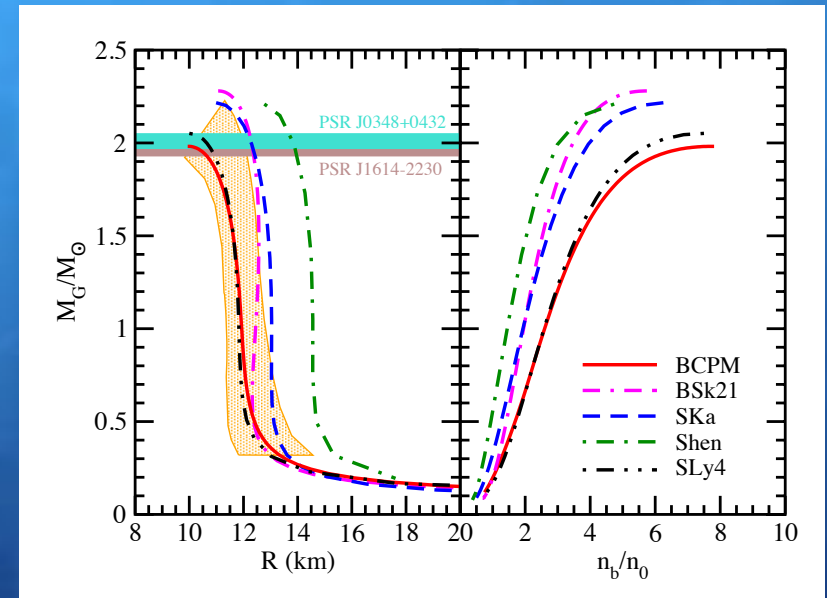
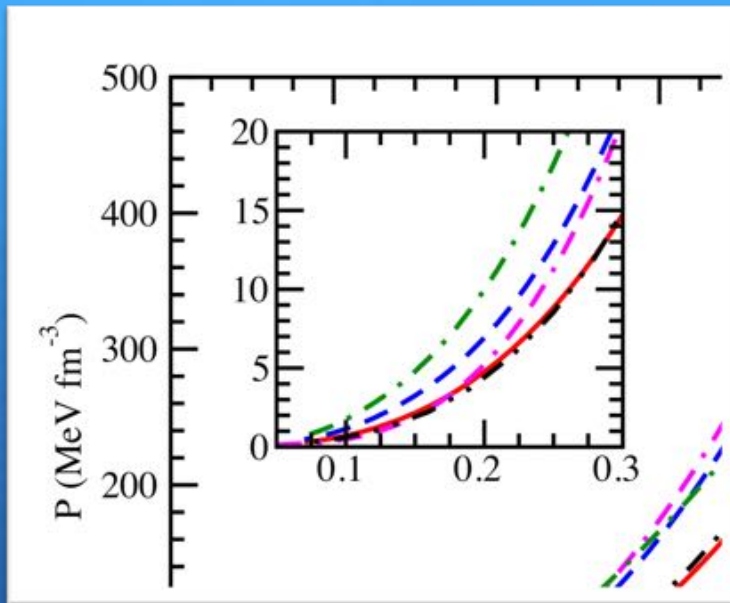
- **Lattimer-Swesty** (CLDM with a Skyrme effective force)
- **Shen** (TF scheme and RMF model)
- **Douchin-Haensel** (CLDM, SLy<sub>4</sub> force fitted to microscopic neutron matter calculations)
- **BSk** (ETF, Skyrme force fitted to known masses of nuclei and microscopic neutron matter calculations with different stiffness)
- **Hempel-Schaffner-Bielich** (NSE, supernova matter)

★ **A new Energy Density Functional** : *BCPM* (*Barcelona-Catania-Paris-Madrid*), based on the nuclear matter EoS derived in the **BHF scheme**. (*M. Baldo talk*)

*More in Sharma, Centelles, Vinas, Baldo, Burgio, A&A 584, A103 (2015)*

*Burgio & Fantina, The NewCompStar White Book, Chap.6, Springer 2018*

# BCPM EoS and NS structure



Comparing with currently used unified EoS :

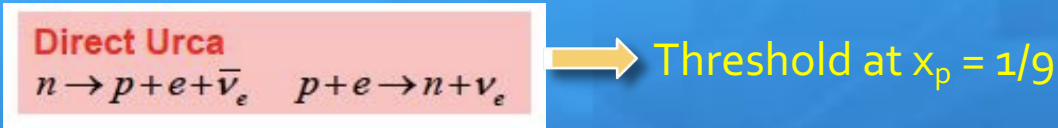
- Total agreement with the SLy<sub>4</sub> EoS
- Large discrepancy with LS and Shen .
- EoS compatible with observations and current limits on the radius (except Shen ...)
- Smaller radii for stars with BCPM and SLy<sub>4</sub> EoS.
- Future obs. from NICER.



*A unified approach extended to cooling simulations*

# ☞ Neutrino Emissivities in non-superfluid dense matter

The most efficient mechanism of NS cooling is the direct Urca process

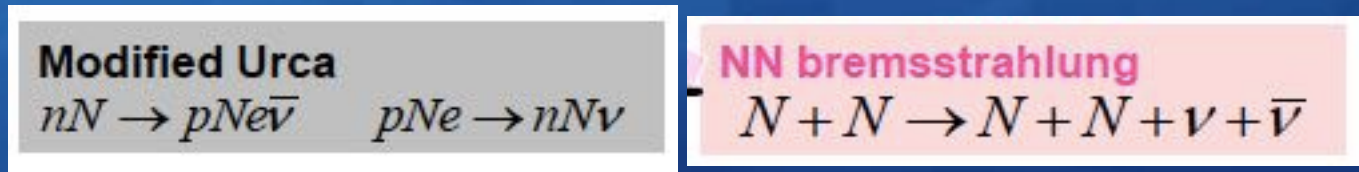


Units of  $10^9 \text{K}$

$$Q^{(DU)} \approx 4.0 \times 10^{27} \left( \frac{n_p}{n_0} \right)^{1/3} \left( \frac{m_n^*}{m_n} \right) \left( \frac{m_p^*}{m_p} \right) T_9^6 \Theta(k_{F_p} + k_{F_e} - k_{F_n}) \quad \text{erg cm}^{-3} \text{ s}^{-1}$$

Similarly for the less efficient modified Urca and NN brems.

D.G. Yakovev, A.D. Kaminker, O. Y. Gnedin and P. Haensel, Phys. Rep. **354**, 1 (2001)



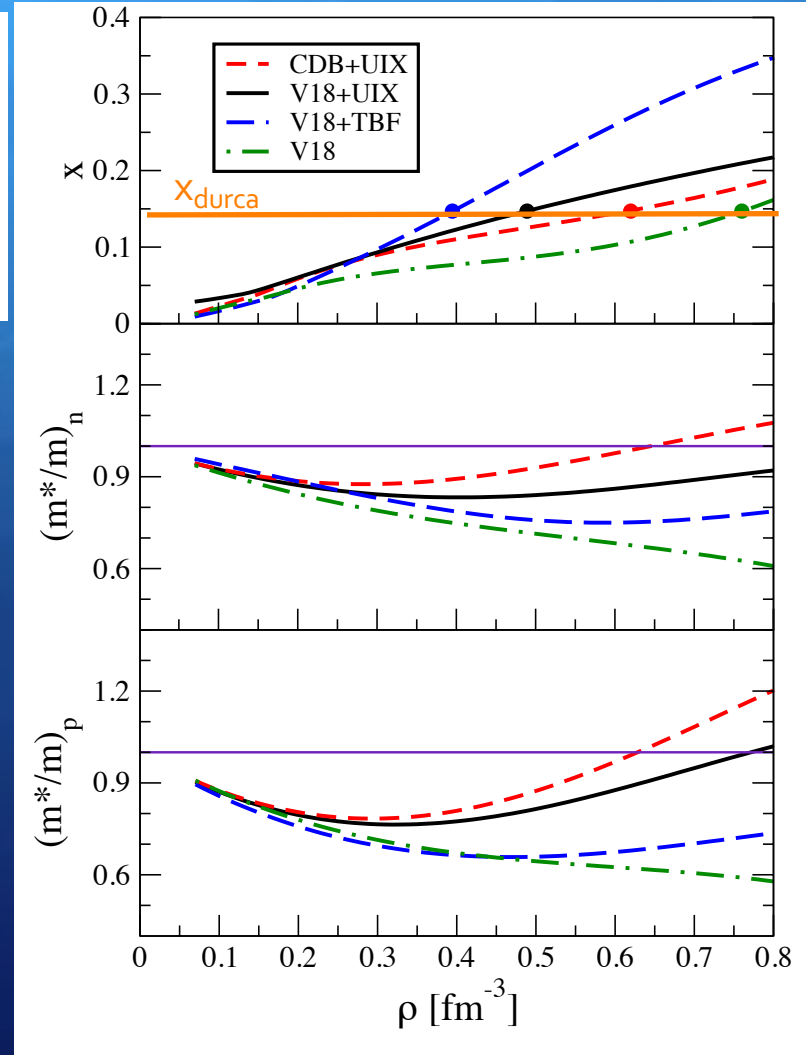
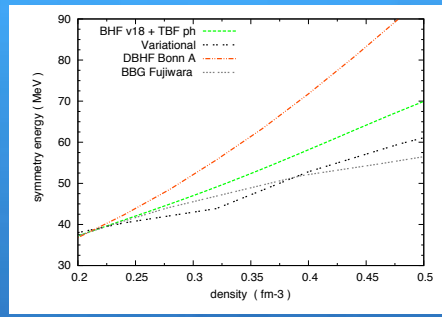
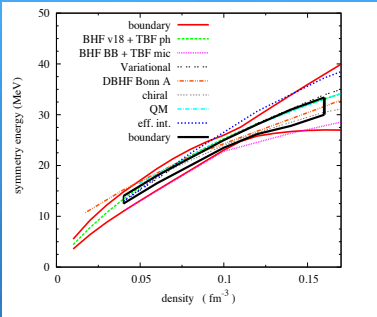
$$Q^{(Mn)} \approx 8.1 \times 10^{21} \left( \frac{n_p}{n_0} \right)^{1/3} \left( \frac{m_n^*}{m_n} \right)^3 \left( \frac{m_p^*}{m_p} \right) T_9^8 \quad \text{erg cm}^{-3} \text{ s}^{-1}$$

*The EoS enters through the proton fraction and the effective masses.*



# Proton fraction and Effective Mass

$$X \longrightarrow E_{\text{sym}}(\rho) \simeq BE(\rho, x=0) - BE(\rho, x=0.5)$$



$$\frac{m^*(k)}{m} = \frac{k}{m} \left[ \frac{de(k)}{dk} \right]^{-1}$$

$$e(k) = e(k; \rho) = \frac{k^2}{2m} + U(k; \rho)$$

from the G-matrix in BHF approach

- Relevant effects of TBF's due to repulsion
- Strong dependence on TBF's models

# 👉 Global thermal balance equation

$$C(T_i) \frac{dT_i}{dt} = -L_\nu^\infty(T_i) - L_\gamma^\infty(T_s)$$

Thorne (1977)

$$L_\nu^\infty(T_i) = 4\pi \int_0^R dr r^2 e^{2\phi} Q_\nu / \sqrt{1 - 2Gm/r}$$

$$L_\gamma^\infty(T_s) = 4\pi R^2 \sigma_{SB} T_s^4 (1 - 2GM/R)$$

$Q_\nu$  = neutrino emissivity

$C_\nu$  = total specific heat

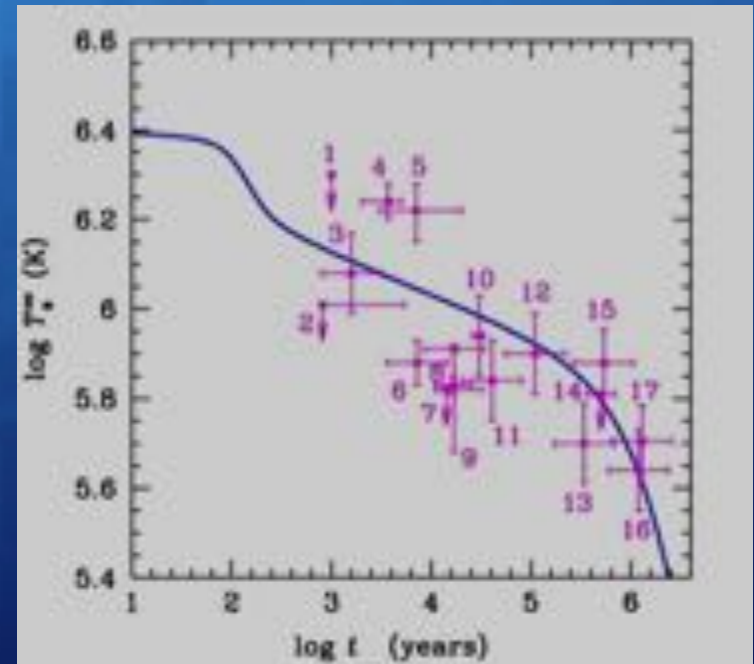
$m(r)$  = grav. mass enclosed in a sphere of radius  $r$

$M = m(R)$

$\Phi$  = metric function

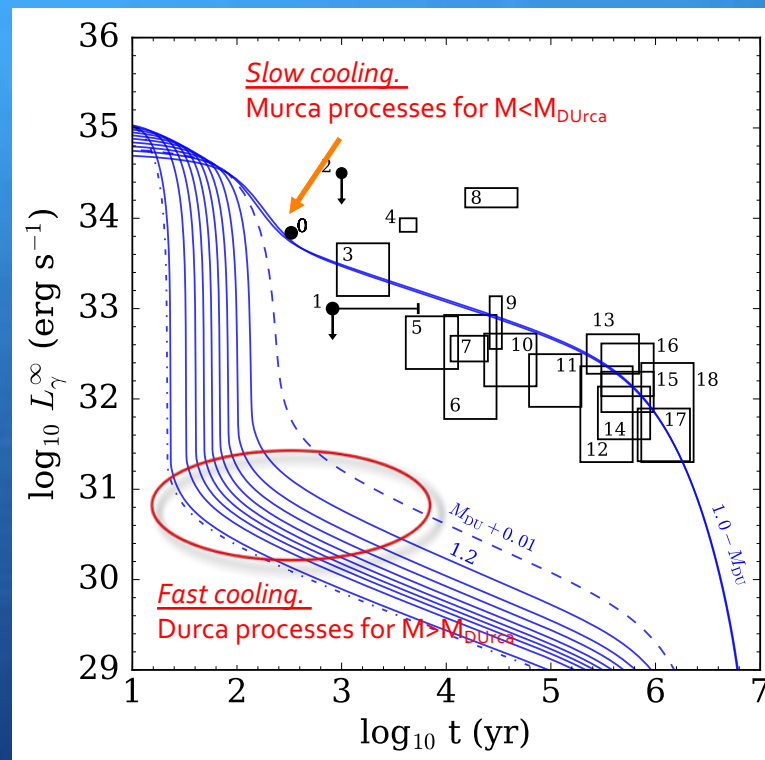
$$\frac{dP}{dr} = -\frac{Gm}{r^2} \frac{(\epsilon + P)(1 + 4\pi r^3 P/m)}{1 - \frac{2Gm}{r}}$$

$$\frac{dm}{dr} = 4\pi r^2 \epsilon(r)$$



## Obs. data on isolated NS

- 0 - CasA NS,
- 1 - PSR J0205+6449 (in 3C58),
- 2 - PSR B0531+21 (Crab),
- 3 - PSR J1119-6127,
- 4 - RX J0822-4300 (in PupA),
- 5 - PSR J1357-6429,
- 6 - PSR B1706-44,
- 7 - PSR B0833-45 (Vela),
- 8 - XMMU J1731-347,
- 9 - PSR J0538+2817,
- 10 - PSR B2334+61,
- 11 - PSR B0656+14,
- 12 - PSR B0633+1748 (Geminga),
- 13 - PSR J1741-2054,
- 14 - RX J1856.4-3754,
- 15 - PSR J0357+3205 (Morla),
- 16 - PSR B1055-52,
- 17 - PSR J2043+2740,
- 18 - RX J0720.4-3125.



1. Models of cooling via Murca don't explain some obs. data.
2. The data require both slower and faster cooling.
3. Transition from slow to fast in a narrow range of masses (Durca threshold).
4. Some sources fall in the transition zone  $\rightarrow$  same mass? Unlikely ....

$\longrightarrow$  *Nucleon superfluidity*

# Pairing Gaps and Critical Temperatures

## Superfluidity effects:

1. Suppresses traditional neutrino processes ( $e^{-\Delta/kT}$ )
2. Creates specific neutrino emission due to Cooper pairing of nucleons

In most of current cooling simulations the EoS and superfluidity gaps obtained in different theoretical frameworks and using different input interactions *not consistent!*

## Our improvement :

Solving the gap equation in the channels  $^1S_0$  and  $^3P_F_2$  using the same BHF s.p. spectra and Av18+UVIX interaction as in the EoS. Zhou, Schulze et al. PRC70,(2004).

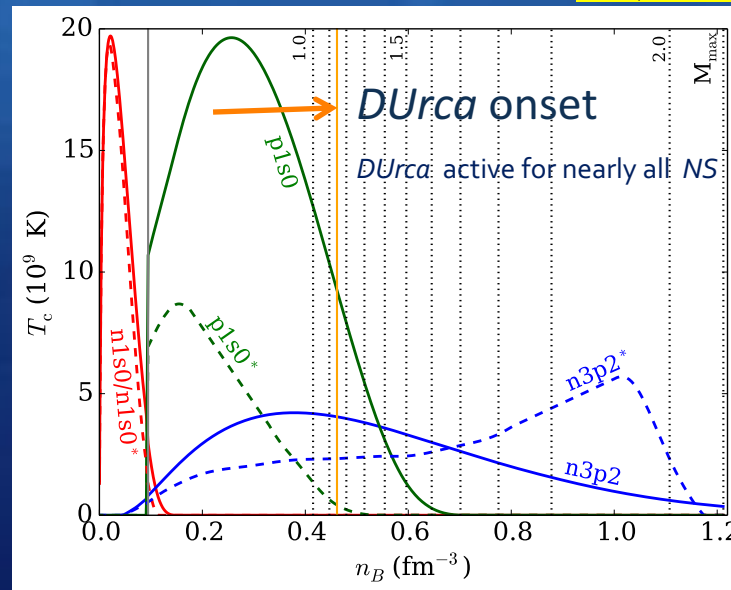
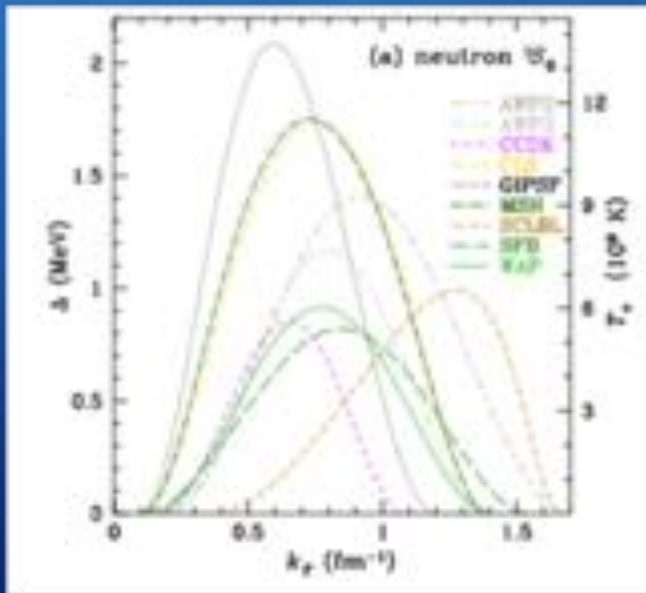
$$\begin{pmatrix} \Delta_1 \\ \Delta_3 \end{pmatrix}(k) = -\frac{1}{\pi} \int_0^{\infty} dk' k'^2 \frac{1}{E(k')} \begin{pmatrix} V_{11} & V_{13} \\ V_{31} & V_{33} \end{pmatrix}(k, k') \begin{pmatrix} \Delta_1 \\ \Delta_3 \end{pmatrix}(k') \quad (6)$$

with

$$E(k)^2 = [e(k) - \mu]^2 + \Delta_1(k)^2 + \Delta_3(k)^2, \quad (7)$$

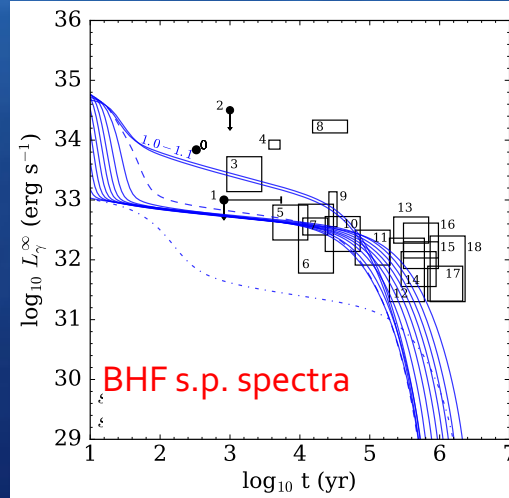
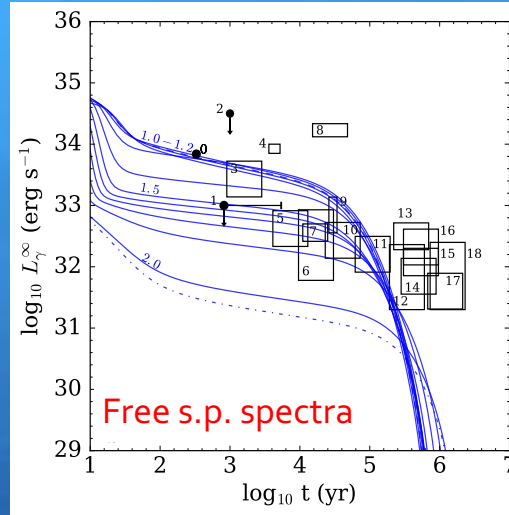
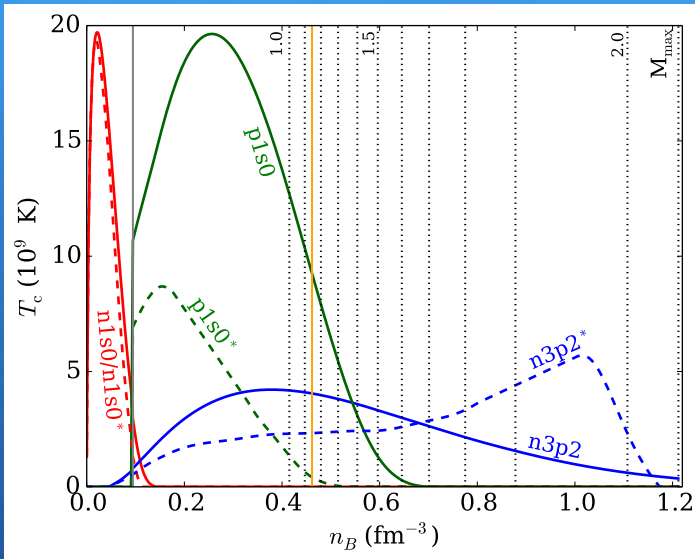
$$n = \frac{k_F^3}{3\pi^2} = 2 \sum_k \frac{1}{2} \left[ 1 - \frac{e(k) - \mu}{E(k)} \right]$$

$$\Delta = \sqrt{\Delta_1^2(k_F) + \Delta_3^2(k_F)} \approx 1.76 T_c$$

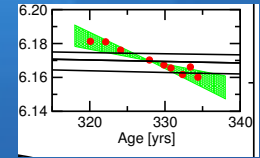


G. Taranto et al., MNRAS (2016)

# ☞ Cooling scenarios : inclusion of superfluidity



o – CasA NS

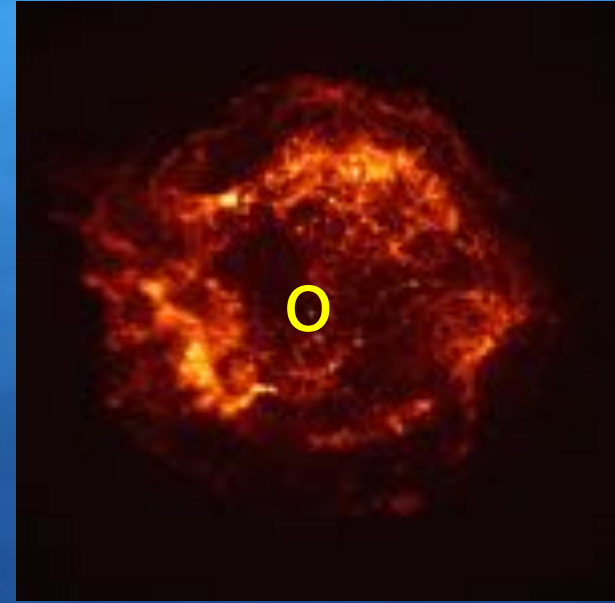


Temperature decline of 4% in the last 10 years

- Results in line with the features of the pairing gaps ☺
- Problems with old and warm NS and CasA data. ☹

# ☞ Cooling scenarios : the CasA constraint

- First discovered in radio in 1947
- Distance to the SNR  $3.4_{-0.1}^{+0.4}$  kpc
- Current age **335 yrs**
- Surface temperature  $T \approx 2 \cdot 10^6$  K
- Mass and Radius  $M \geq 1.4M_{\odot}$   
 $R = (8 - 18)$ km  
Ho & Heinke (2009)
- Temperature decline of 4% from 2000 to 2009
- Observed flux decrease by 21%



Chandra, August 1999. ©NASA.

☞ *The youngest known NS whose cooling is observed in real time !*

## ➡ Proposed solutions

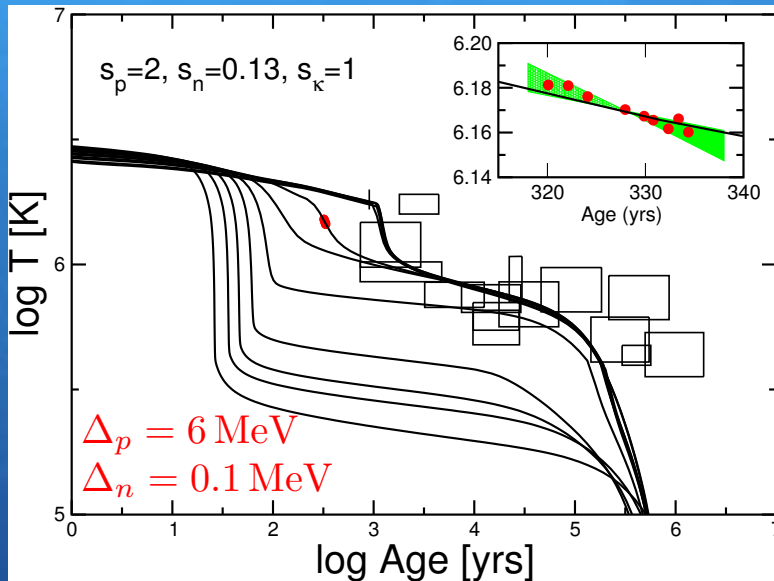
*A neutron  ${}^3\text{PF}_2$  pairing phase transition is triggered*

*To assume a strongly reduced thermal conductivity*

*Both scenarios exclude from the beginning the possibility of  $d$ Urca cooling.*

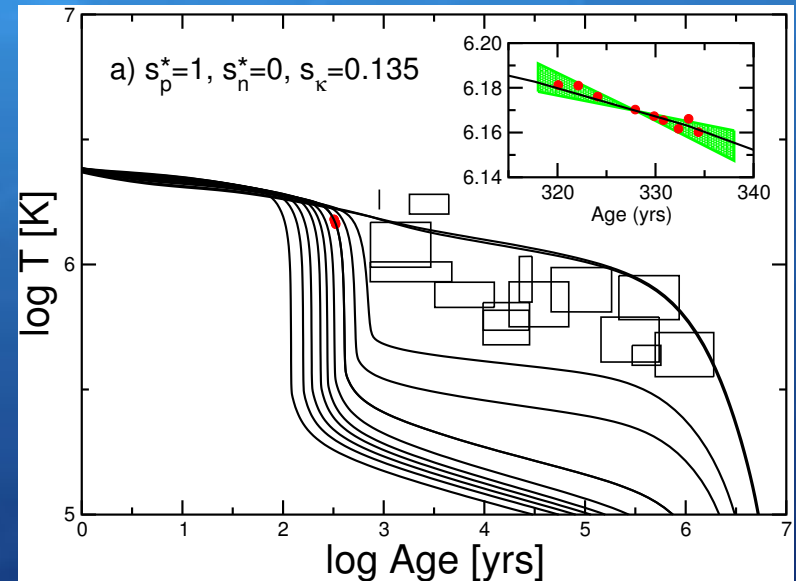
## Neutron ${}^3\text{PF}_2$ Cooling

CasA  $M = 1.4M_\odot$  by construction



- Large  ${}^1\text{S}_0$  proton gap to block Durca
- Small  $n3\text{P}_2$  PBF  $\rightarrow$  rapid cooldown
- No reproduction of old hot stars

## Suppressed thermal conductivity



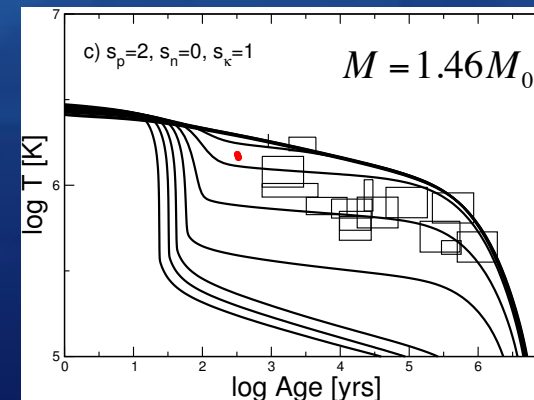
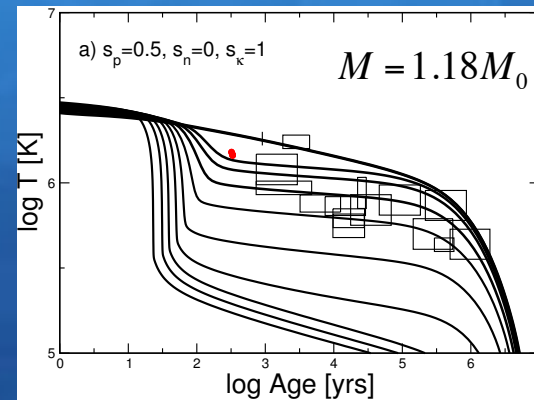
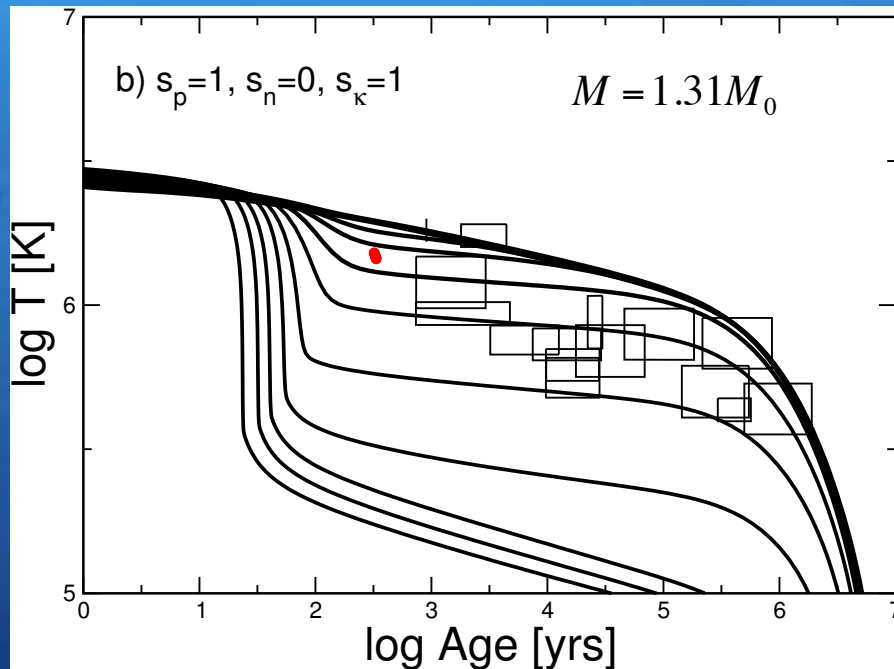
- Reduced conductivity due to medium effects.
- Delay of the temperature decline up to the current CasA age.
- No reproduction of young cold stars

The model can reproduce many alternative scenarios  
 (Page, 2009; Yakovlev & Shternin 2007,2008; Blaschke, PRC 2012)

# ☞ Relaxing the CasA constraint

Difficult to satisfy simultaneously the rapid cooling of CasA and the slow cooling of old NS.

Posselt et al. , ApJ 2013--→ revision of CasA data analysis. Much slower cooling ?



- Perfect coverage of all current cooling data.
- BCS 1po gap alone suppress sufficiently Durca if it extends to large enough densities.
- Need of precise information on the masses of the NS in the cooling diagram!

## Conclusions

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- Model of NS cooling : microscopic BHF EoS with strong Urca processes plus consistent effective masses and superfluidity gaps.
- Cas A : large and extended proton  $^1S_0$  and fine tuned neutron  $^3P_2$  gaps or a reduced thermal conductivity.
- Strong dUrca processes cannot be excluded from the cooling analysis.
- No need of exotic scenarios (hyperons, quarks).
- Same conclusions in the analysis of thermal states of accreting NS in X-ray transients in quiescence (Fortin, Taranto, Burgio, Haensel, Schulze, Zdunik, arXiv:1709.04855)

Minimal model : probably it is not reality, but might be killed if new theoretical calculations find a nonvanishing neutron gap at large density.