NuSYM10
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Symmetry Energy Effects on Superfluidity of Neutron Stars

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☐ Introduction

- ○ As a conventional picture, liquid inner core of neutron stars (NSs) is taken to be composed of n, p, e^- and μ^- .
- ○ By a pairing correlation due to the attractive NN interaction, both of n and p are in the superfluid state (*);
  n → 3P2-superfluid, p → 1S0-superfluid, in the density region
  $\rho \sim (1\text{-}4)\,\rho_{0}$ with ρ_{0} = nuclear density.
- ○ At present, however, following two points should be taken into account;

  ① Hyperon (Y) mixing surely occurs → So, as a standard picture, NSs are composed of n, p, Y (=Λ, Σ^- ,---), e^- and μ^- .

  ② Uncertainty of nuclear symmetry energy (E_{sym}), the high light of this symposium.

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*) As a review article, T. Takatsuka and R. Tamagaki, Prog. Theor. Suppl. No.112 (1993) 27-65.

- In this talk, we discuss how the superfluidity of baryons (N,Y) is affected by E_{sym}, trying to use larger E_{sym} in neutron star matter calculations.
- We consider two cases

  CASE-1 → without Y degrees of freedom
  (n, p, e^-, μ^-)

  CASE-2 → with Y-mixing
  ($n, p, \Lambda, \Sigma^-, e^-, \mu^-$)

□ Three elements in gap equations

- ○ Here, we note the 3-elements (Fermi momentum k_{FB}, effective mass m*_{B} and pairing interaction) to control the energy gap.

$$\Delta_B(k) = -\frac{1}{\pi}\int k'^2 dk' \langle k' | V_{BB}({}^1S_0) | k \rangle \times \frac{\Delta_B(k')}{\sqrt{\tilde{\varepsilon}_B^2(k') + \Delta_B^2(k')}}$$

$$\tilde{\varepsilon}_B(k') \equiv \varepsilon_B(k') - \varepsilon_B(k_{FB}) \simeq \hbar^2(k'^2 - k_{FB}^2)/2m_B^*$$

#) For 3P2 NN pairing, the situation is similar, although the gap equation becomes complex due to the 3P2-3F2 tensor-coupling.

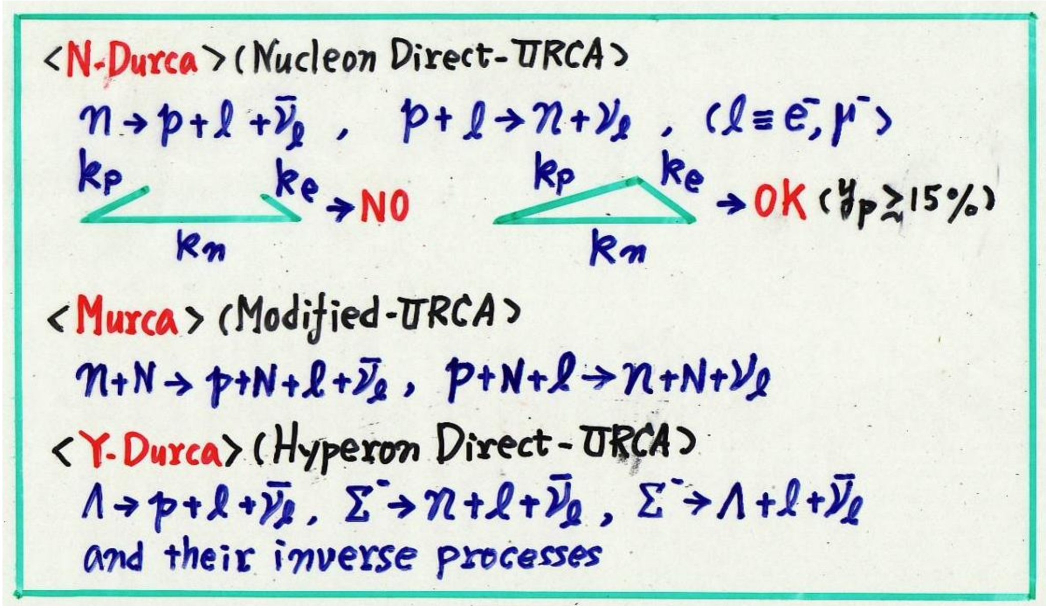
- That is, E_{sym} affects y_{B} (fraction of baryon components) at a given ρ
  $\rightarrow$ affects $k_{FB}^{2} = (3\pi \rho y_{B})^{1/3}$, and also m^*_{B}
  ($B=N,Y$)

- As for the pairing interaction for the baryon pair,
  We use
  - OPEG-A (Tamagaki pot.) for NN
  - ND-soft (soft-core version of Nijmegen hard-core D-type pot.) for YY

□ Influence on NS cooling

- Usually, direct URCA process (β-decay) is forbidden and modified URCA process becomes an efficient ν- emission process.
- However, if y_{p} exceeds ∼15%, β-decay can be possible and extremely efficient ν-emission provides a very rapid cooling scenario of NSs.

<Cooling processes due to ν-emission>*



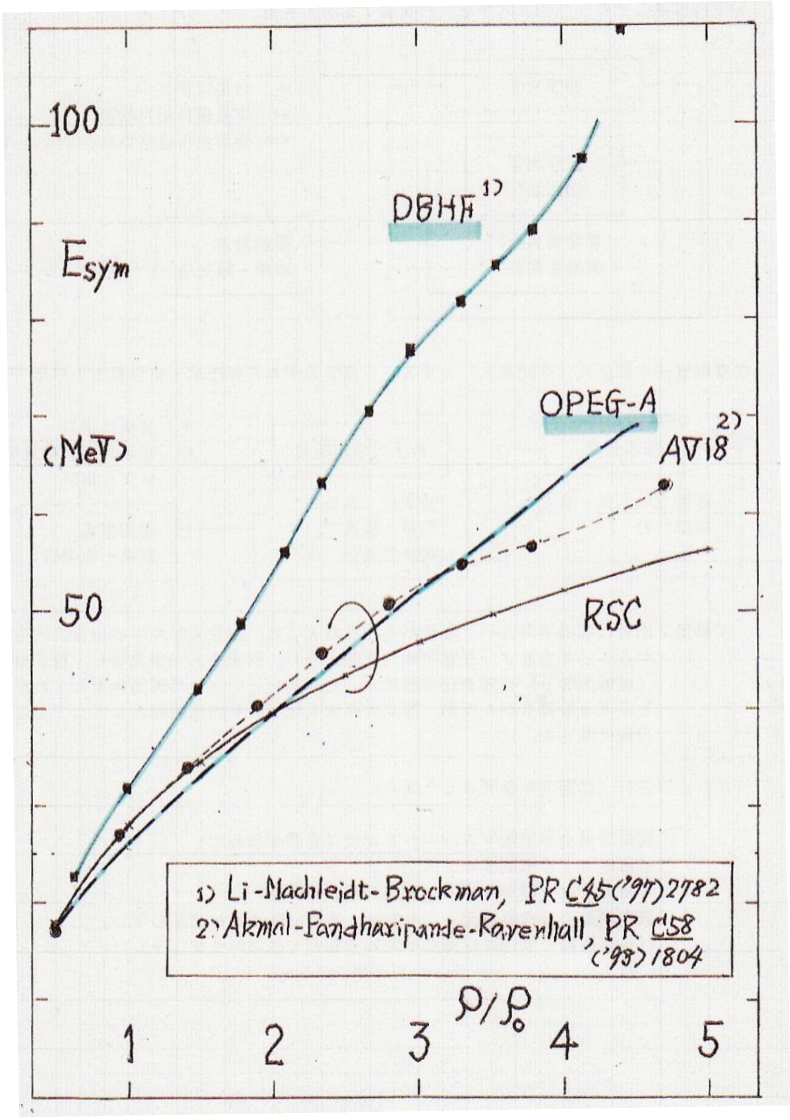
*) J.M. Lattimer, C.J. Pethick, M. Prakash and P. Haensel, PRL66(1991) 2701

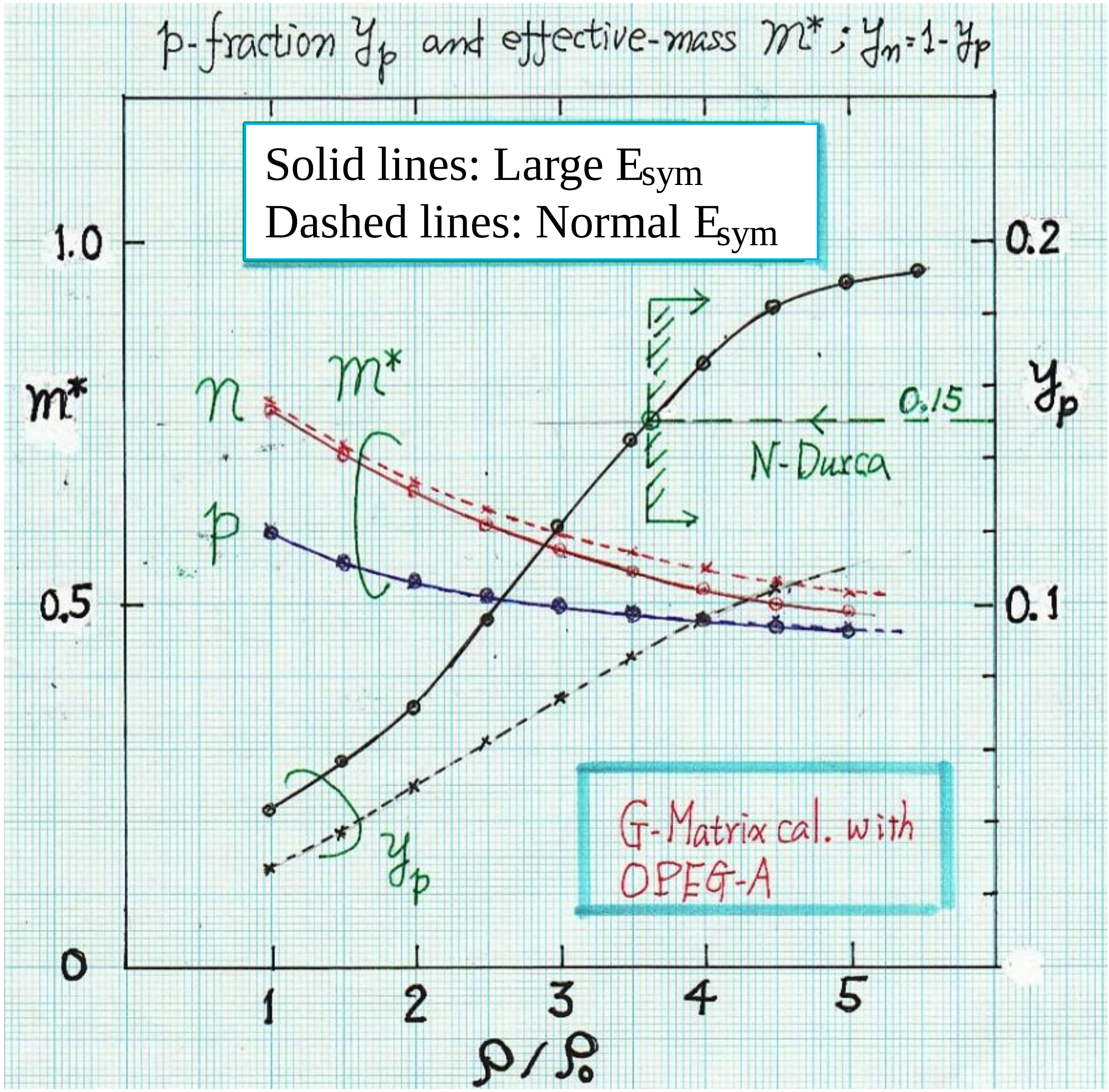
- But, if directly applied, it causes a serious problem of " too rapid cooling " incompatible with NS surface-temperature observations.
- This problem is resolved if baryon superfluidity to suppress "two rapid cooling" is realized.
  → Coexistence of direct URCA and superfluidity of associated baryons is essential for a fast cooling scenario to be compatible with observations.

CASE-1

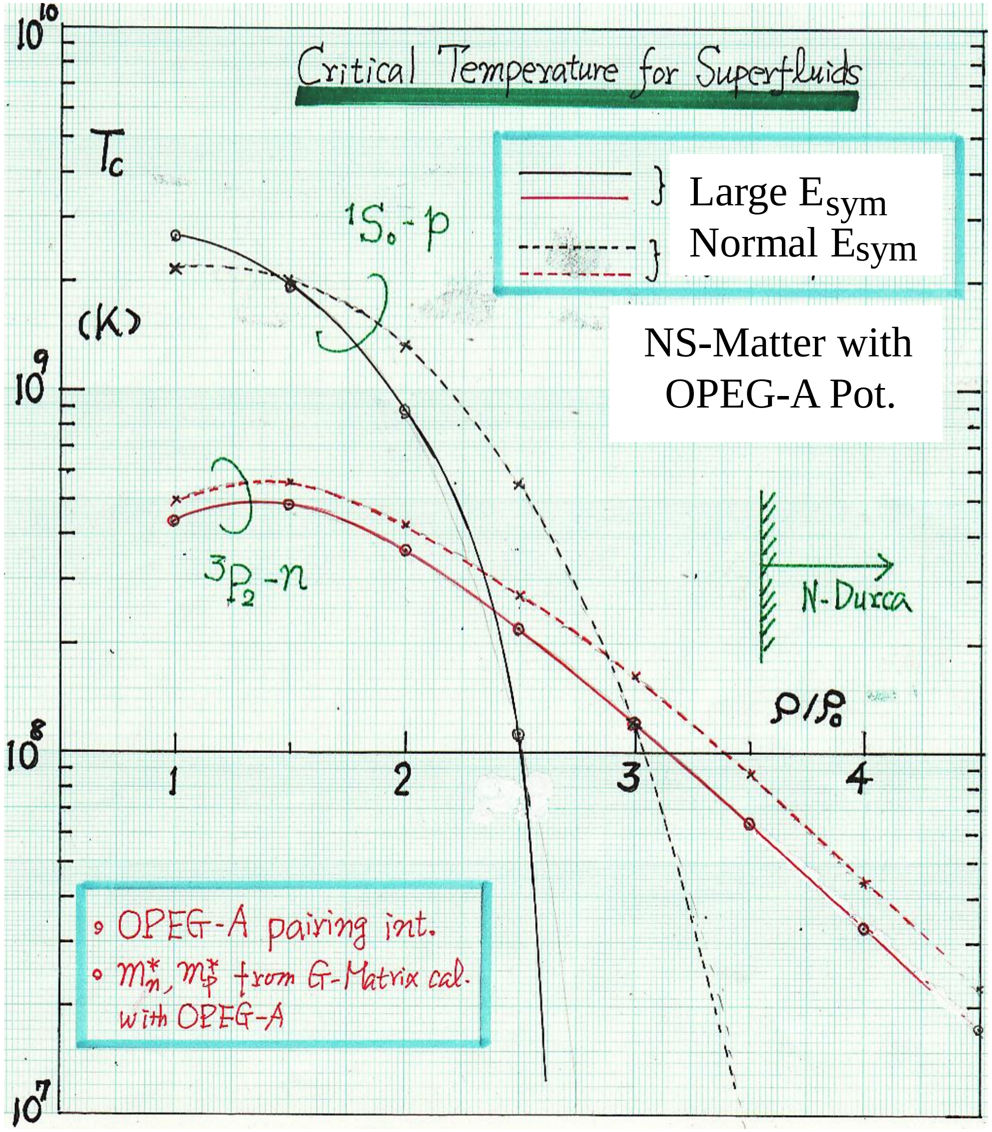
(n, p, e^- , μ^-)

- Large E_{sym}
  → DBHF
- Normal E_{sym}
  → OPEG-A





p-fraction y_p and effective-mass m^* ; y_n=1-y_p
Solid lines: Large E_{sym}
Dashed lines: Normal E_{sym}
1.0
0.5
0
m^*
n
p
m^*
0.2
0.1
y_p
0.15
N-Durca
y_p
G-Matrix cal. with
OPEG-A
1
2
3
4
5
ρ / ρ_0



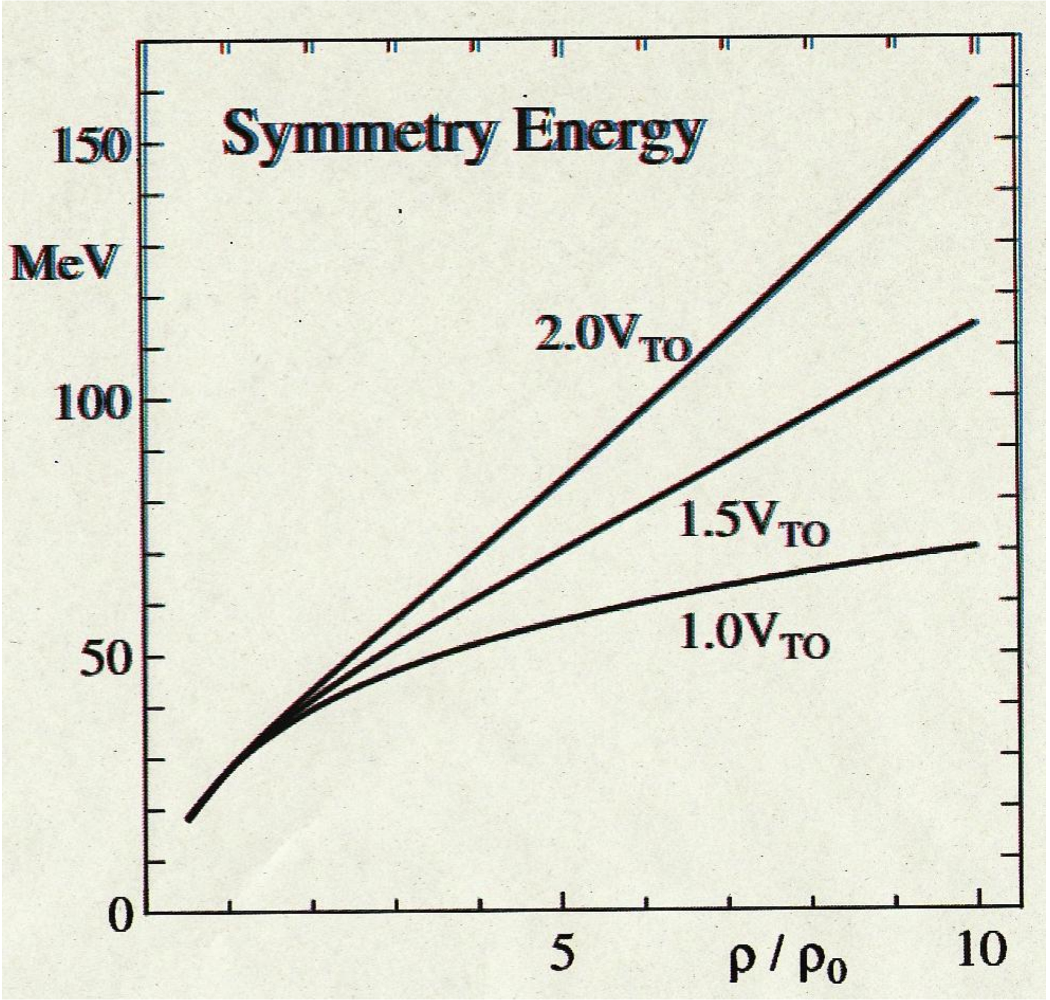
Critical Temperature for Superfluids
Tc
(K)
10^{10}
10^{9}
10^{8}
10^{7}
$^1S_0$-p
$^3P_2$-n
Large E_{sym}
Normal E_{sym}
NS-Matter with OPEG-A Pot.
N-Durca
ρ/ρ0
1
2
3
4
∘ OPEG-A pairing int.
∘ m_n^*, m_p^* from G-Matrix cal. with OPEG-A

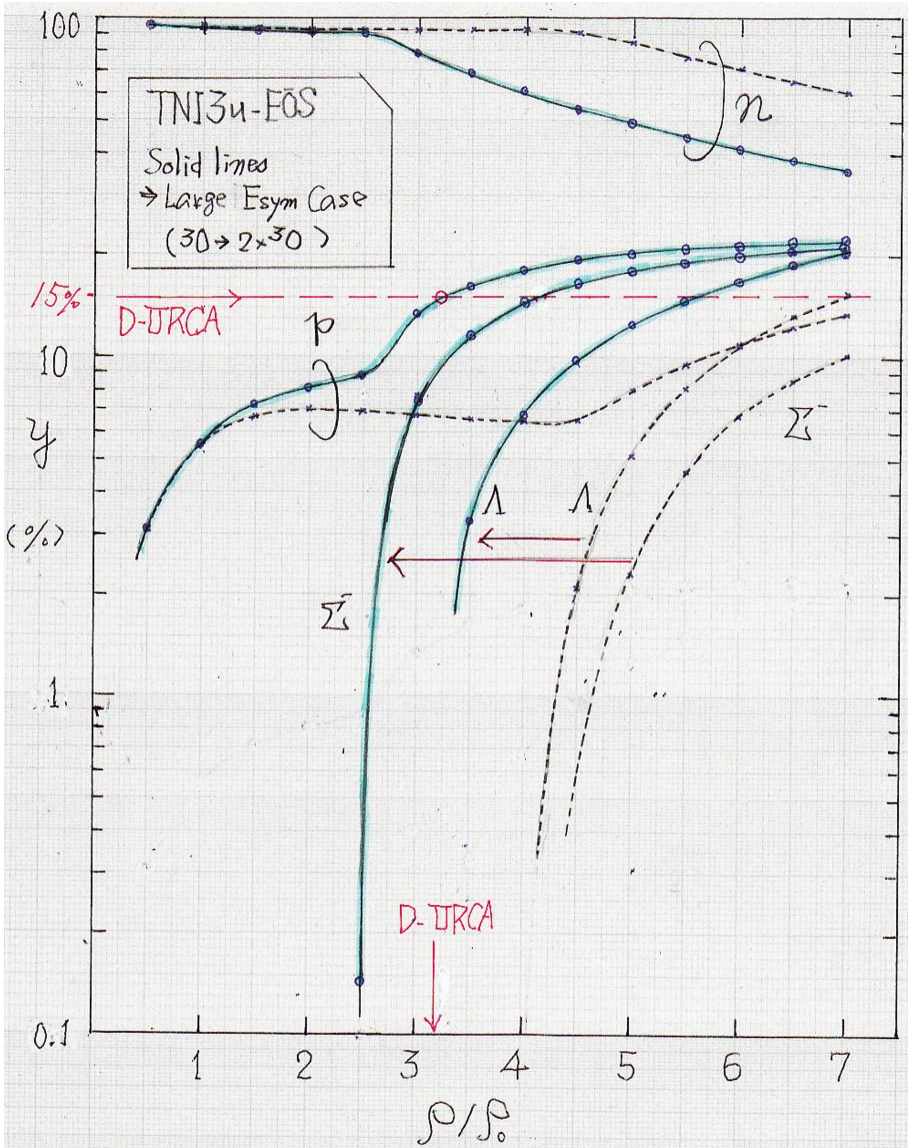
CASE-2

(n, p, Λ, Σ^- , e^- , μ^-)

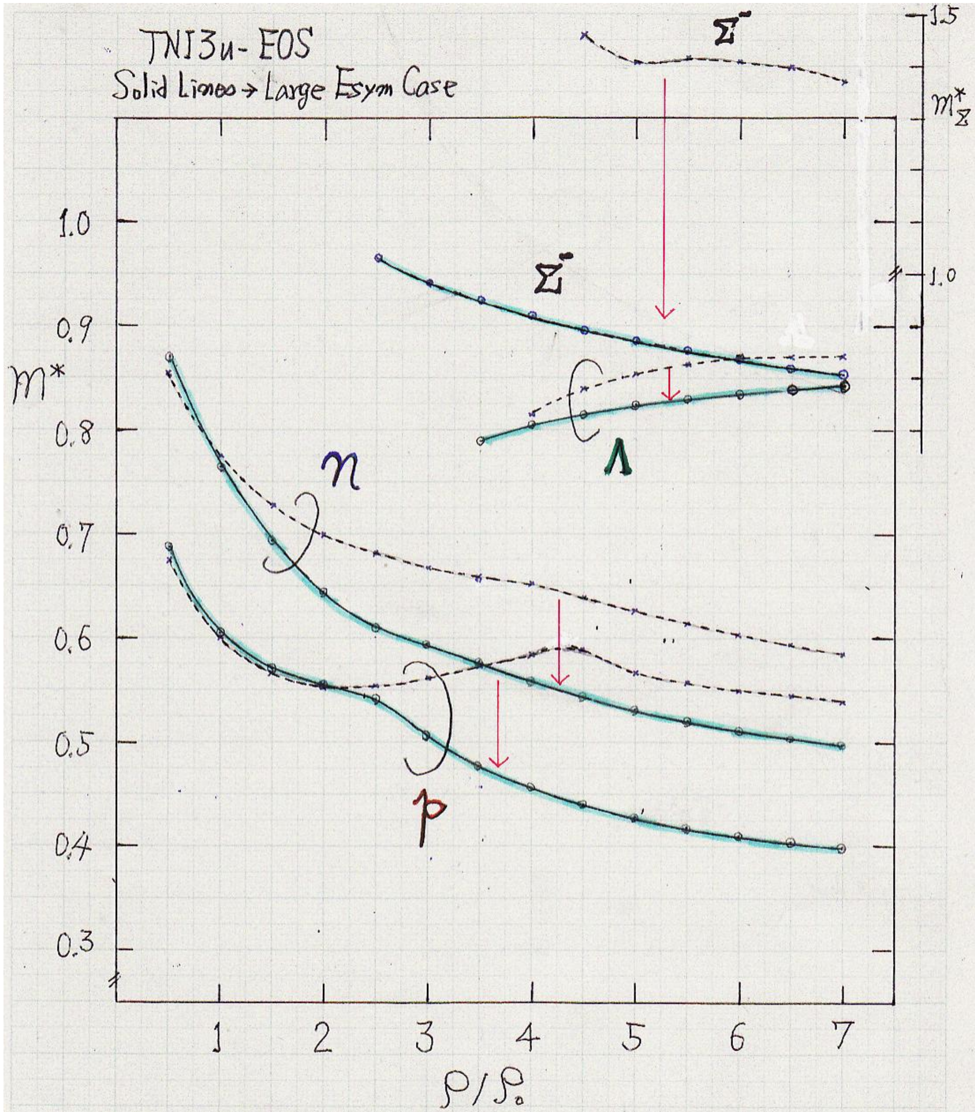
- Large E_{sym}
  → 2.0 V_{T0} (RSC)
- Normal E_{sym}
  → 1.0 V_{T0} (RSC)

(*) Details of our approach are given by S. Nishizaki's Talk in this symposium (session V, tomorrow morning)

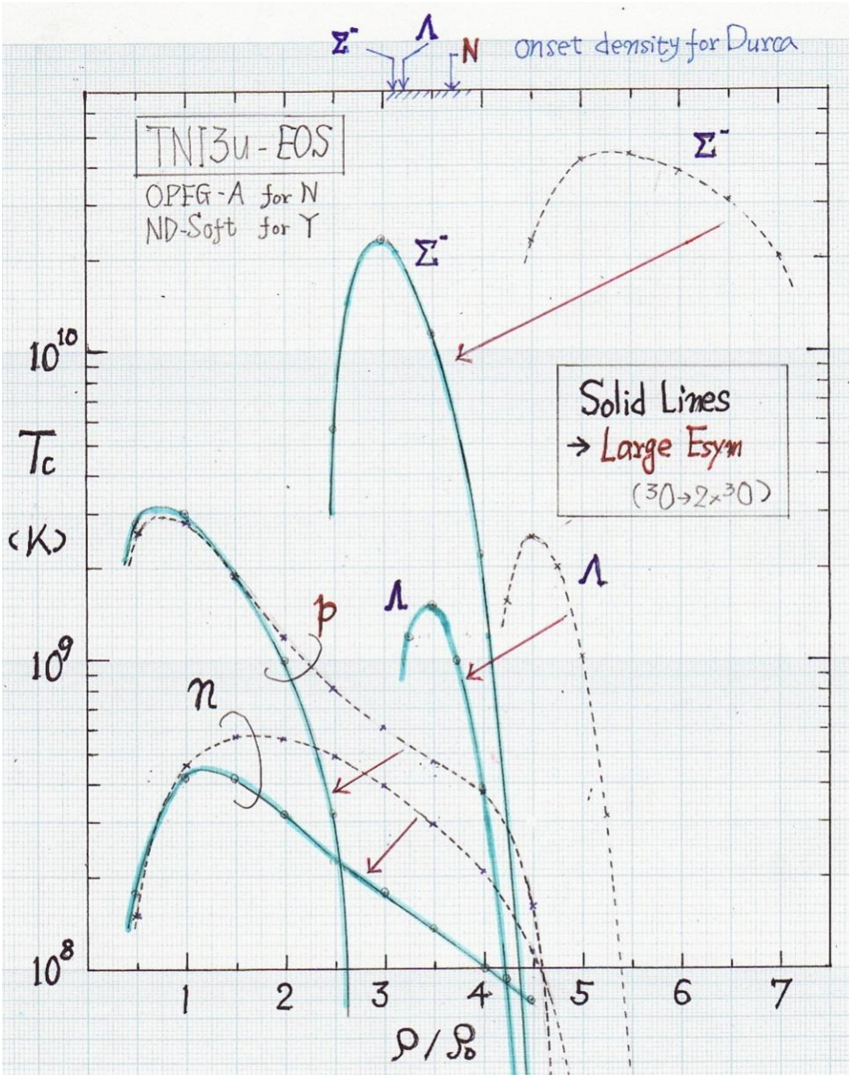




TNI3u-EOS
Solid lines
→ Large Esym Case
(30 → 2×30)
n
p
15%
D-URCA
Λ
Λ
Σ⁻
Σ⁻
D-URCA
y
(%)
100
10
1.
0.1
1
2
3
4
5
6
7
ρ/ρ₀



TNI3u-EOS
Solid Lines → Large Esym Case
Σ⁻
$m^*_{\Sigma^-}$
1.5
1.0
m^*
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
n
p
Λ
1
2
3
4
5
6
7
ρ/ρ₀



Σ⁻
Λ
N
onset density for Durca
TNI3u-EOS
OPEG-A for N
ND-Soft for Y
Σ⁻
Σ⁻
Solid Lines
→ Large Esym
(³O→2×³O)
Λ
Λ
p
n
T_c
(K)
10^{10}
10^9
10^8
1
2
3
4
5
6
7
ρ/ρ₀

☐ Summary

- ○ For NSs composed of (n, p, e^-, μ^-), a large E_{sym} increases proton fraction and thereby the onset density for N-Durca is made lower ($\sim 3.5\rho_{0}$). However, at that density-region, N-superfluidity disappears, leading to "too rapid cooling" and so N-Durca cannot be a candidate for the cooling scenario of colder class NSs.
- ○ For NSs composed of $(n, p, e^-, \Lambda, \Sigma^-)$, a large E_{sym} increases y_{p} and also works for the appearance of hyperons at lower densities. The change of fractional density for baryon components ($\rho_{B} = y_{B} \rho$) causes the change of k_{FB} and m^*_{B}. The net effect is the weakening of baryon superfluidities.
- ○ N-Durca fails to coexist with N-super. In addition, Λ-super disappears when information from "NAGARA event" is taken into account. This situation indicates that a serious problem of "too rapid cooling" cannot be resolved even by a large E_{sym}, requesting further studies on the cooling scenario consistent with observations.