Jan. 24-26, Hadrons under Extreme Condition @ JAERI

On a Possible Importance of Nuclear Liquid-Gas Phase Transition in Supernova Nucleosynthesis

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1. Heavy Element Synthesis
   — When, Where and How ?
   - ⋆ s- and r-processes
   - ⋆ A-distribution in the Universe
   - ⋆ Phase Diagram of Nuclear Matter
   - ⋆ Possible Importance of LG-process
2. Simple Model Calculation
   - ⋆ Adiabatic Path of "Neutron" Matter Evolution
   - ⋆ Does it hit Spinodal Region ?
3. Summary and Discussion

Synthesis of Heavy Elements
– When, Where and How ?

- **Slow Neutron Capture process (s-process)**
  - ⋆ Stable Nuclei upto ^{209}Bi
  - ⋆ Neutron Flux in Stars: Understanding is not complete
- **Rapid Neutron Capture process (r-process)**
  - ⋆ Heavy Neutron Rich Nuclei
  - ⋆ Most Probable Site
    = Hot bubble region of Massive Supernovae
  - ⋆ Requires Very High Entropy/Baryon, $S/B \simeq (110-400)$
    (Woosley et al. 1994, Meyer and Brown 1997,
    Terasawa and Kajino 1999)

→ **SOMETHING ELSE ?**

- **Hints ?**
  - ⋆ Background A-distribution in the Universe:
    ⋯ Power Law Behavior in addition to Exponential
  - ⋆ Phase Diagram of Nuclear Matter
    ⋯ Unstable (L-G coexistence) Region

→ **Fragm. through LG Phase Tr.
may be important**

Simple Model Calculation at High Densities ($\rho_B/\rho_0 > 0.05$)

Assumption:

- ⋆ Lepton to Baryon ratio is conserved. (νs are still trapped.)
- ⋆ Entropy per Baryon is conserved.

• Adiabatic Path in "Supernova" Matter Evolution

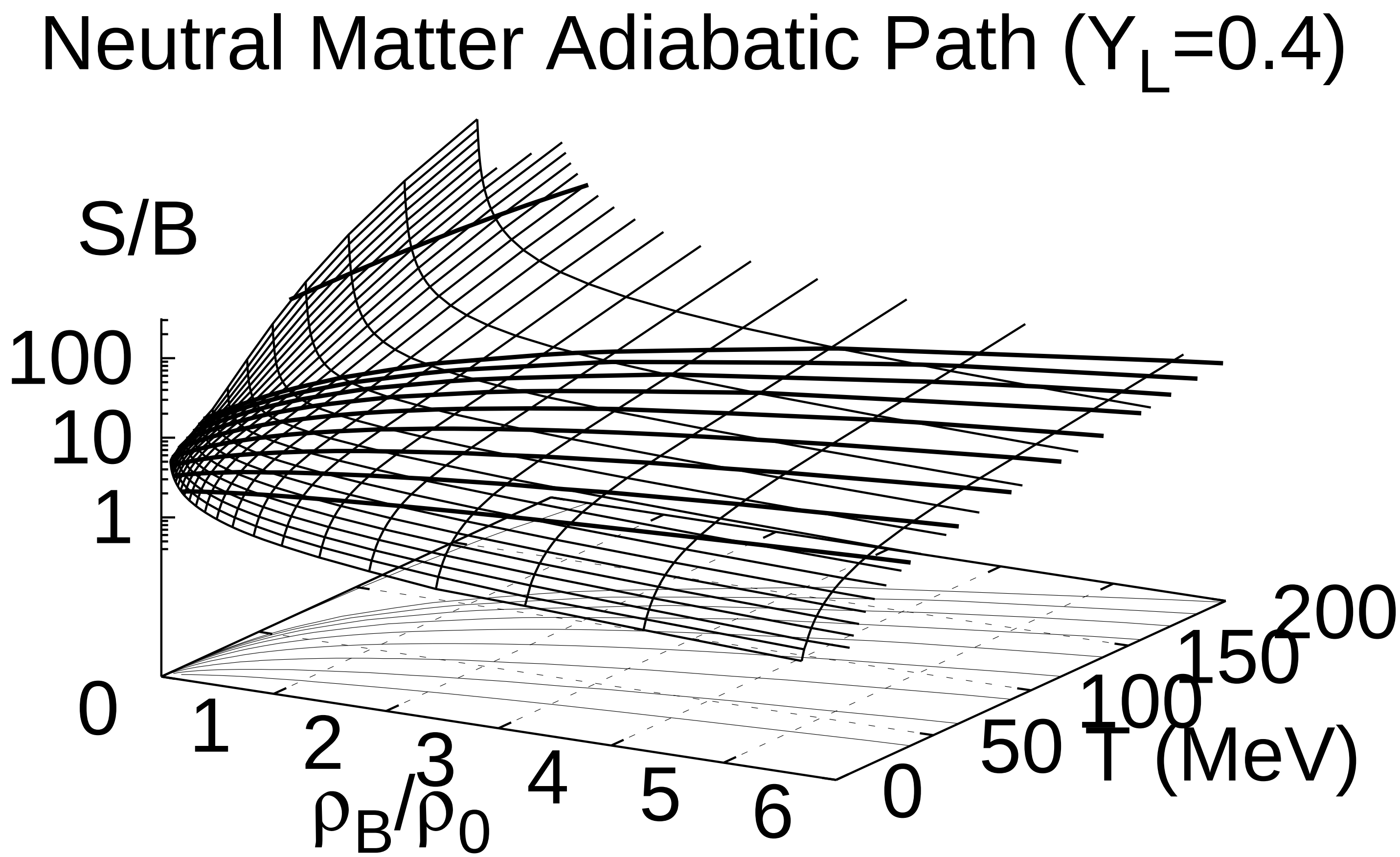
⋆ **Important Parameters:**

- ∘ **Lepton to Baryon Ratio:** $Y_l \equiv N_l/B = (0.3 - 0.4)$ **(Takatsuka)**
- ∘ **Entropy per Baryon:** S/B
  $\leftarrow$ **Initial** (ρ_B, T) **in Supernova Simulation**
  Example: $\rho_B/\rho_0 = (5 - 8)\rho_0, T = (50 - 80)$ **MeV**

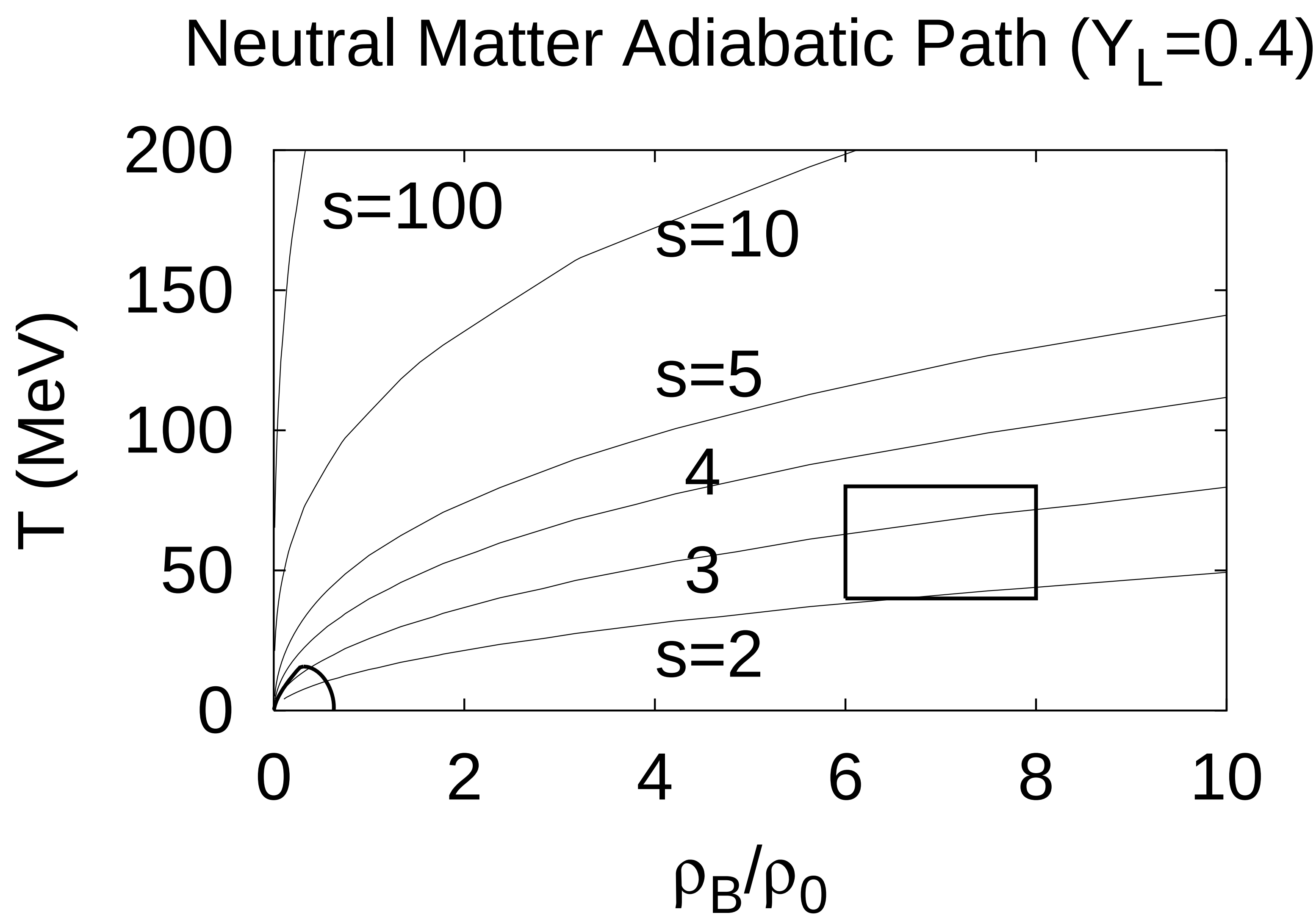
⋆ **Constituents**

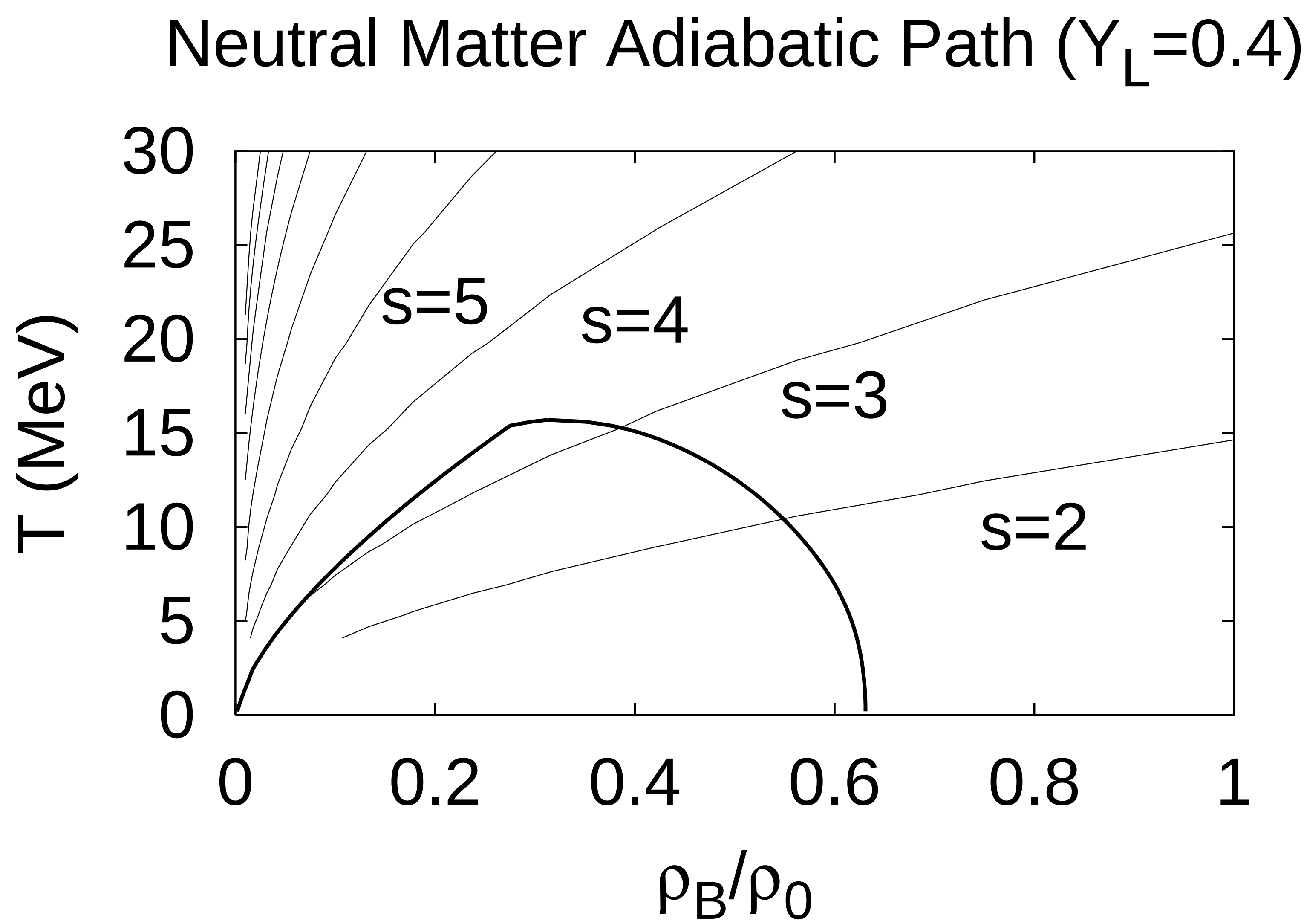
- ∘ $n, p, e, \nu_e, \mu, \nu_\mu, \ldots$
- ∘ π

$\rightarrow$ **Does it hit Spinodal Region ?**

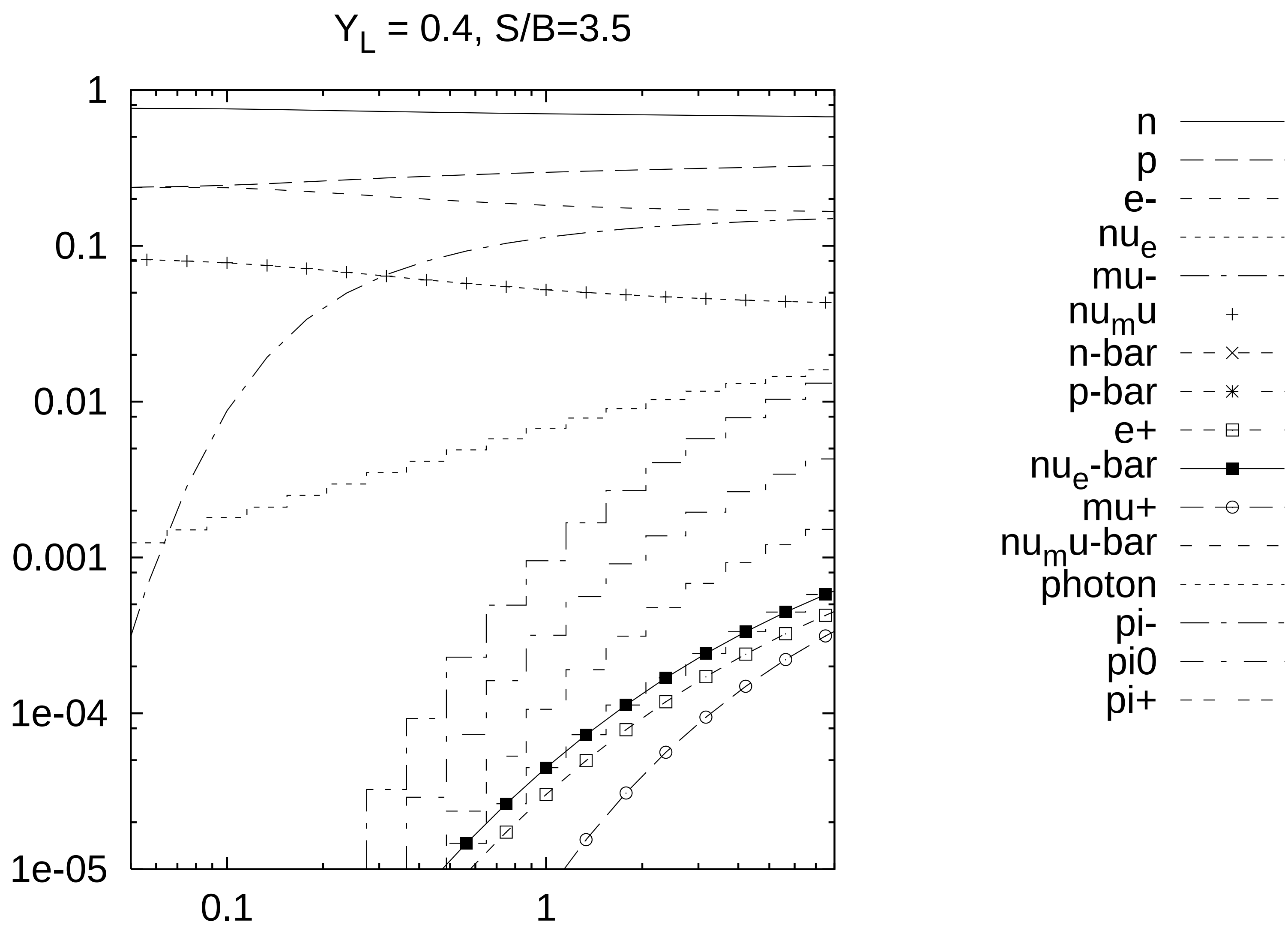


Neutral Matter Adiabatic Path (Y_L=0.4)
S/B
100
10
1
0
1
2
3
4
5
6
ρ_B/ρ_0
0
50
100
150
200
T (MeV)

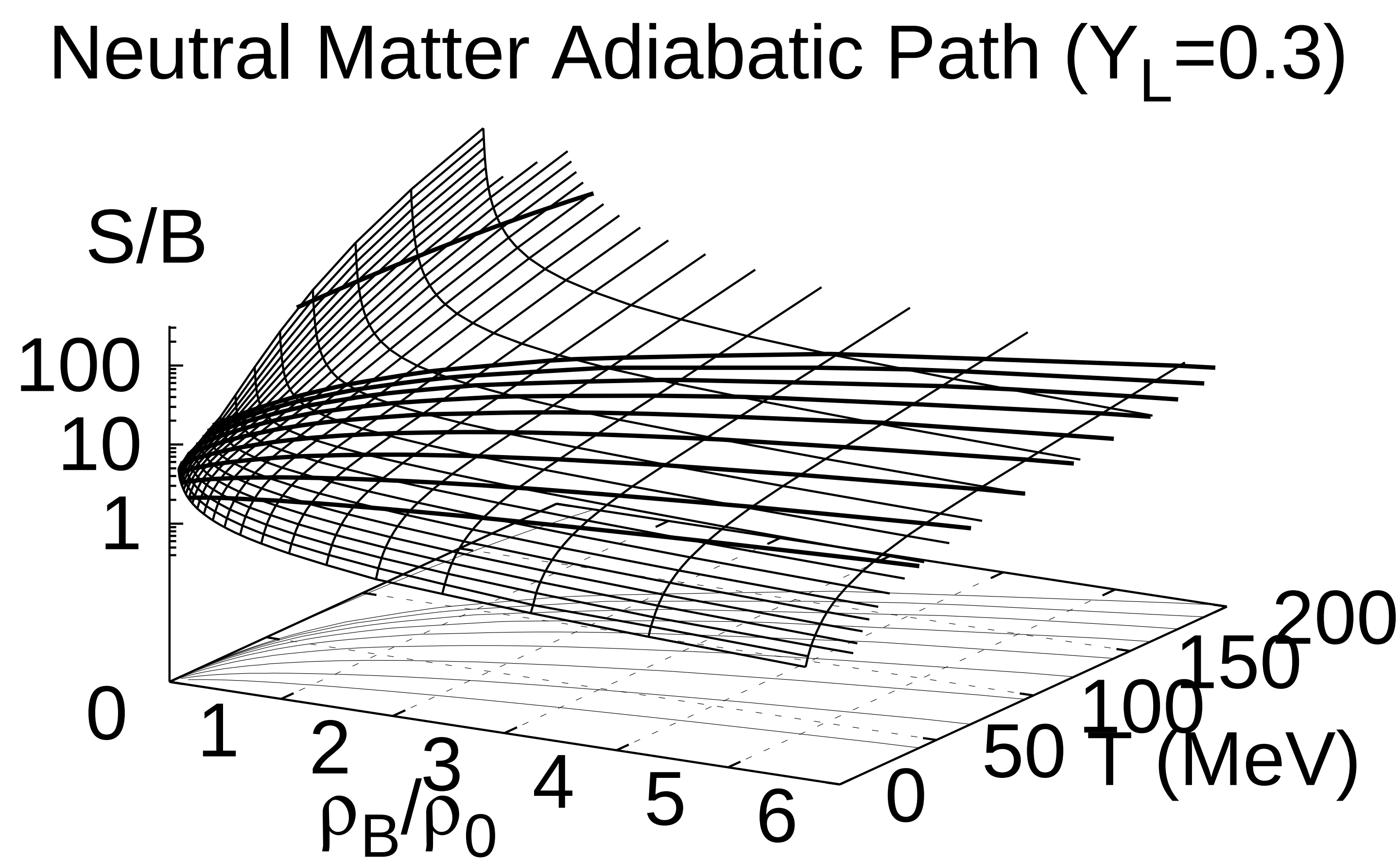

Neutral Matter Adiabatic Path (Y_L=0.4)
T (MeV)
200
150
100
50
0
0
2
4
6
8
10
ρ_B/ρ_0
s=100
s=10
s=5
4
3
s=2

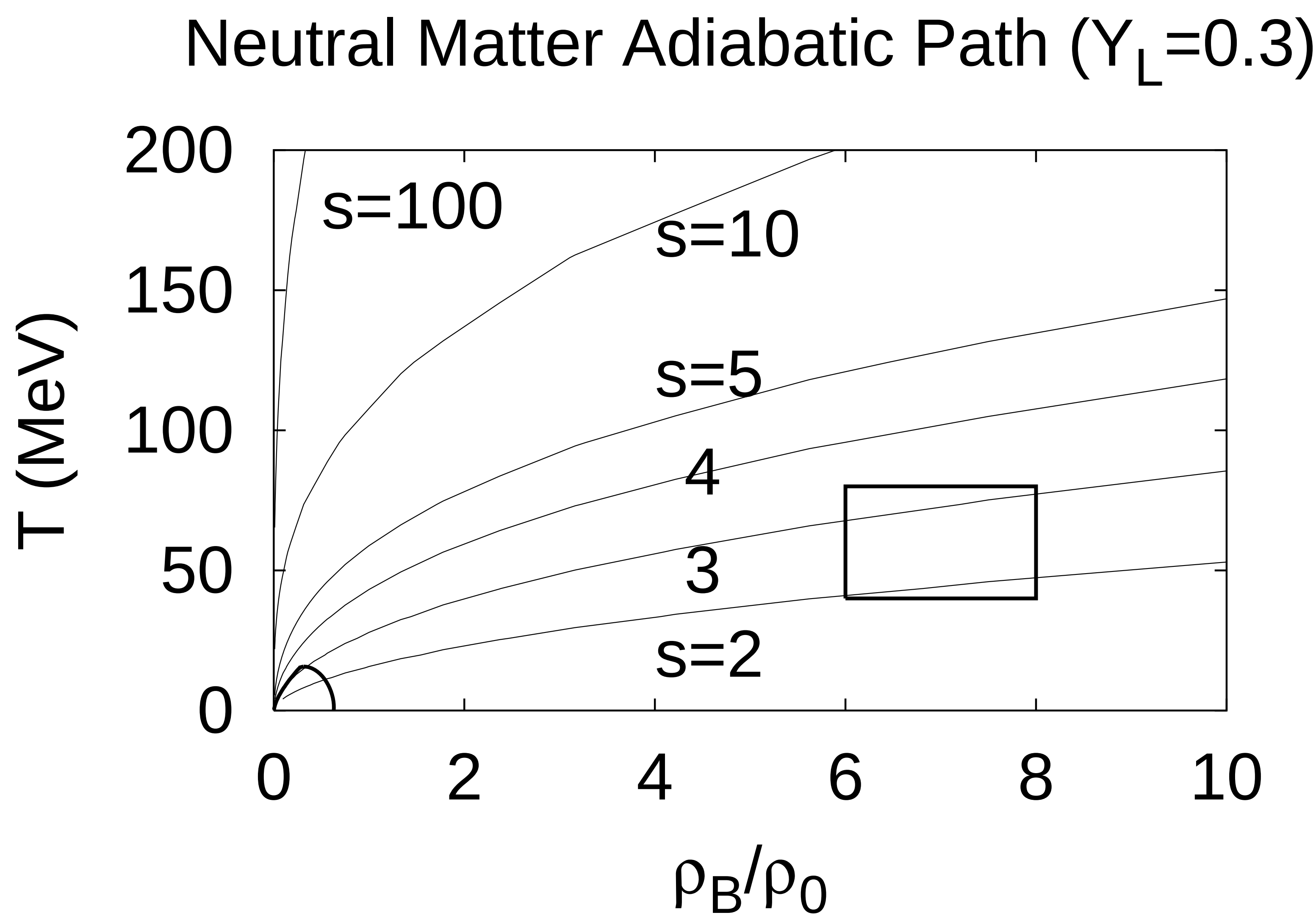


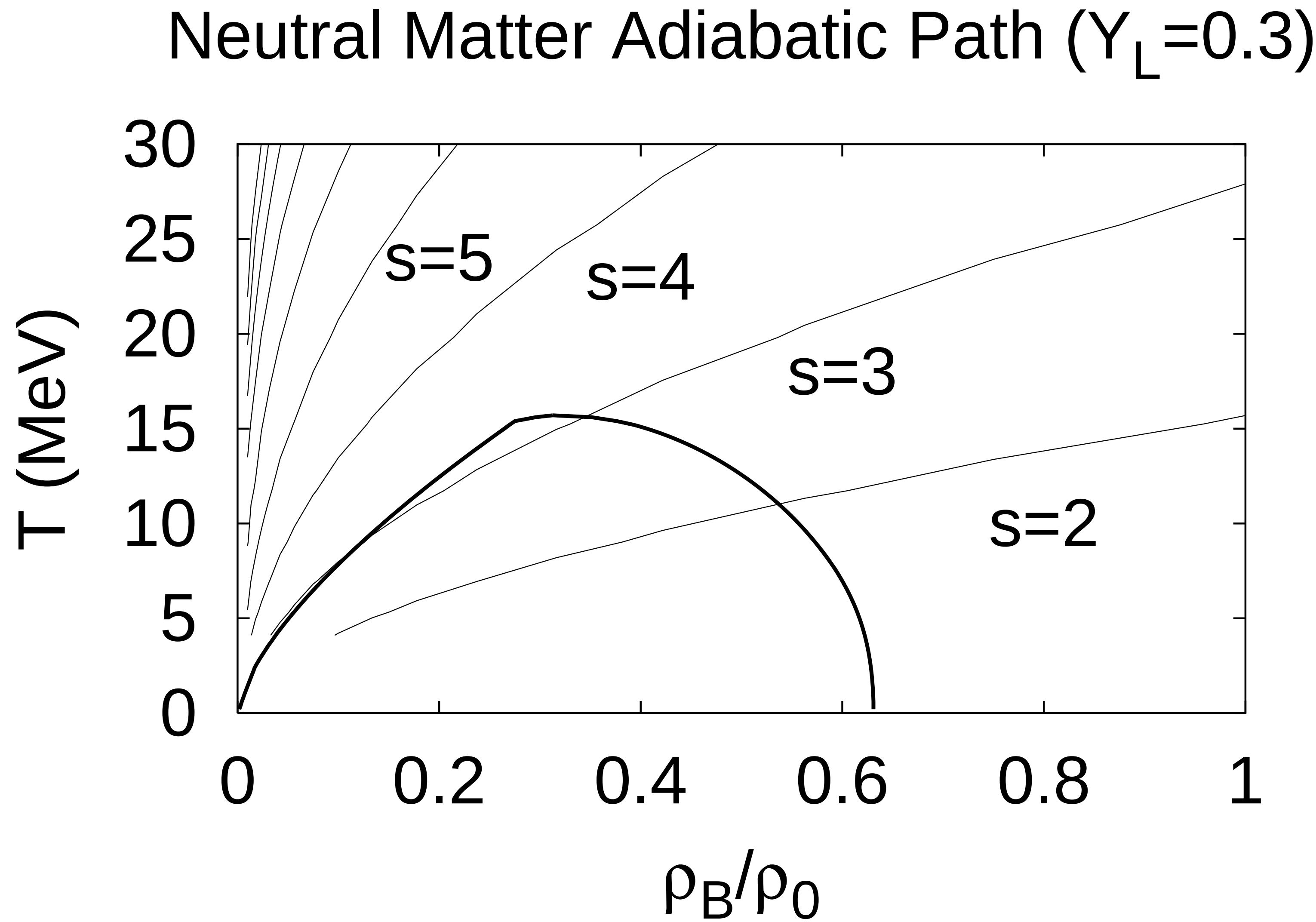
Neutral Matter Adiabatic Path (Y_L=0.4)
T (MeV)
30
25
20
15
10
5
0
0
0.2
0.4
0.6
0.8
1
ρ_B/ρ_0
s=5
s=4
s=3
s=2



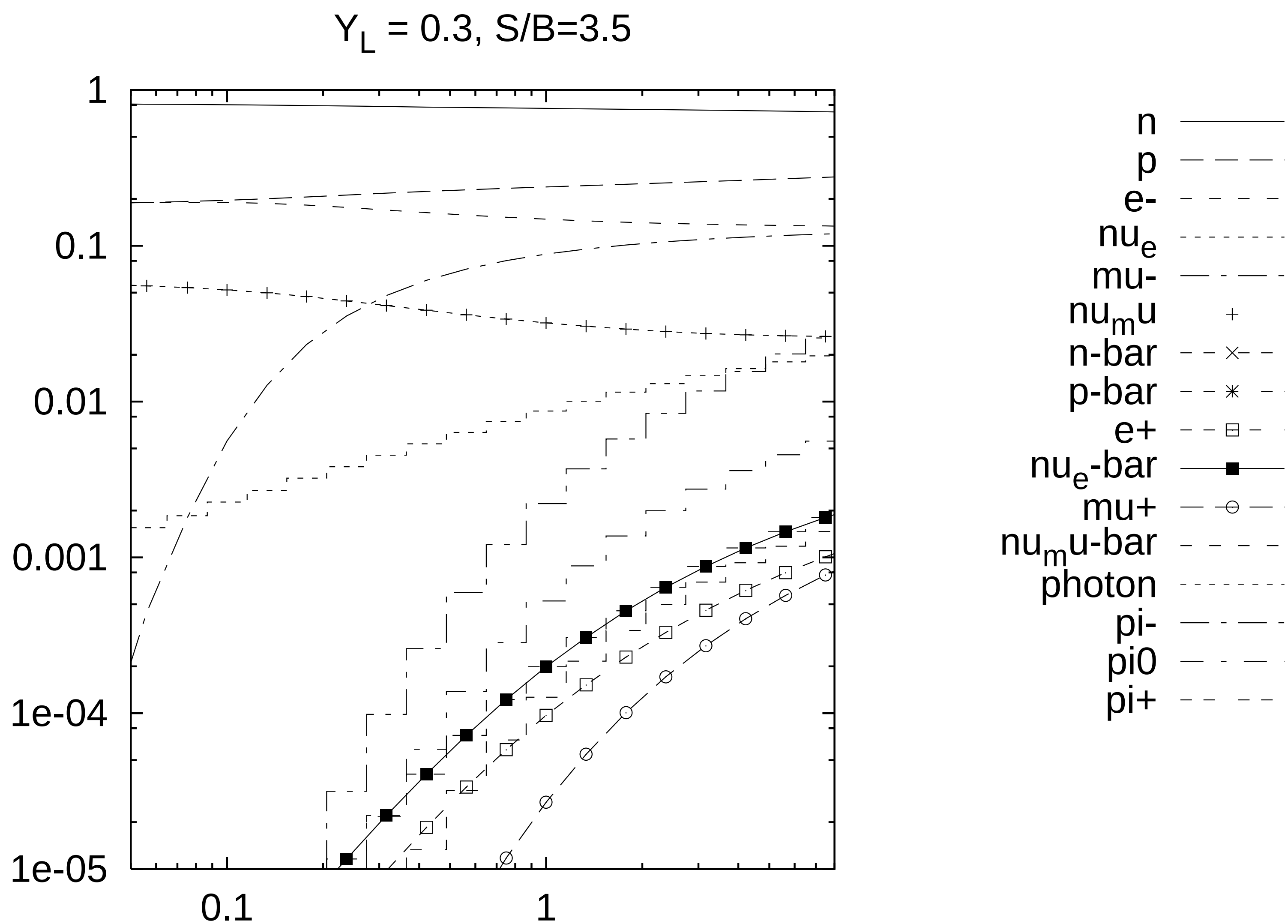
Y_L = 0.4, S/B=3.5
1
0.1
0.01
0.001
1e-04
1e-05
0.1
1
n
p
e-
nu_e
mu-
nu_mu
n-bar
p-bar
e+
nu_e-bar
mu+
nu_mu-bar
photon
pi-
pi0
pi+


Neutral Matter Adiabatic Path (Y_L=0.3)
S/B
100
10
1
0
1
2
3
4
5
6
ρ_B/ρ_0
0
50
100
150
200
T (MeV)


Neutral Matter Adiabatic Path (Y_L=0.3)
s=100
s=10
s=5
4
3
s=2
200
150
100
50
0
T (MeV)
0
2
4
6
8
10
ρ_B/ρ_0



Neutral Matter Adiabatic Path (Y_L=0.3)
T (MeV)
0
5
10
15
20
25
30
0
0.2
0.4
0.6
0.8
1
ρ_B/ρ_0
s=5
s=4
s=3
s=2



Y_L = 0.3, S/B=3.5
1
0.1
0.01
0.001
1e-04
1e-05
0.1
1
n
p
e-
nu_e
mu-
nu_mu
n-bar
p-bar
e+
nu_e-bar
mu+
nu_mu-bar
photon
pi-
pi0
pi+

Summary and Discussion

- **Summary**

1. **Heavy Elements production**
   through Nuclear Liquid-Gas phase transition
   at around the surface of Supernova Core (LG process)
   may be important.

   ⋆ A **Distribution in the Universe**

   ⋆ **Phase Diagram of Nuclear Matter**

2. **Simple Model Calculation**

   ⋆ $Y_l, S/B$ **are constant along the path**

   ⋆ **Critical Temperature of Nuclear LGpt**
   $T_c \simeq 16$ **MeV**

   $\rightarrow$ **Adiabatic Path hits Spinodal Region**
   for $Y_l > 0.35$**,** $S/B < 3.5$
   (c.f. $S/B = (110 - 400)$ **in standard scenarios)**

• Discussion

1. **Asymmetry dependence of T_c:**
   - ⋆ **Weak in the range $Y \equiv (N-Z)/A < 0.4$ (Chomaz and Gulminelli 1999)**
2. **T_c: How High ?**
   - ⋆ **Skyrme int.: $T_c \simeq 16$ MeV for Symmetric Matter**
   - ⋆ **GSI-Aladin: $T_c \simeq 5$ MeV for Finite Nuclei**
   - ⋆ **Instability from α boiling (Ohta and Abe)**
   - ⋆ **Microcan. AMD-MF (Sugawa and Horiuchi)**
   - ⋆ **Canonical QL (Ohnishi and Randrup)**
   - ⋆ **...**
3. **Importance of Density Fluctuation**
   - ⋆ **Static: Negele-Vautherin (1973), Oyamatsu(1993), Maruyama et al.(1998)**
   - ⋆ **Non-Static: Kajino-Mathews-Boyd (QCD)**

• To do...($\rightarrow$ Chikako Ishizuka)

1. **Dynamics: Supernova Simulation**
2. **Mean Field Effects**
3. **Fragmentation and Entropy Production**
4. **After burner: Combination with the Standard r-process**