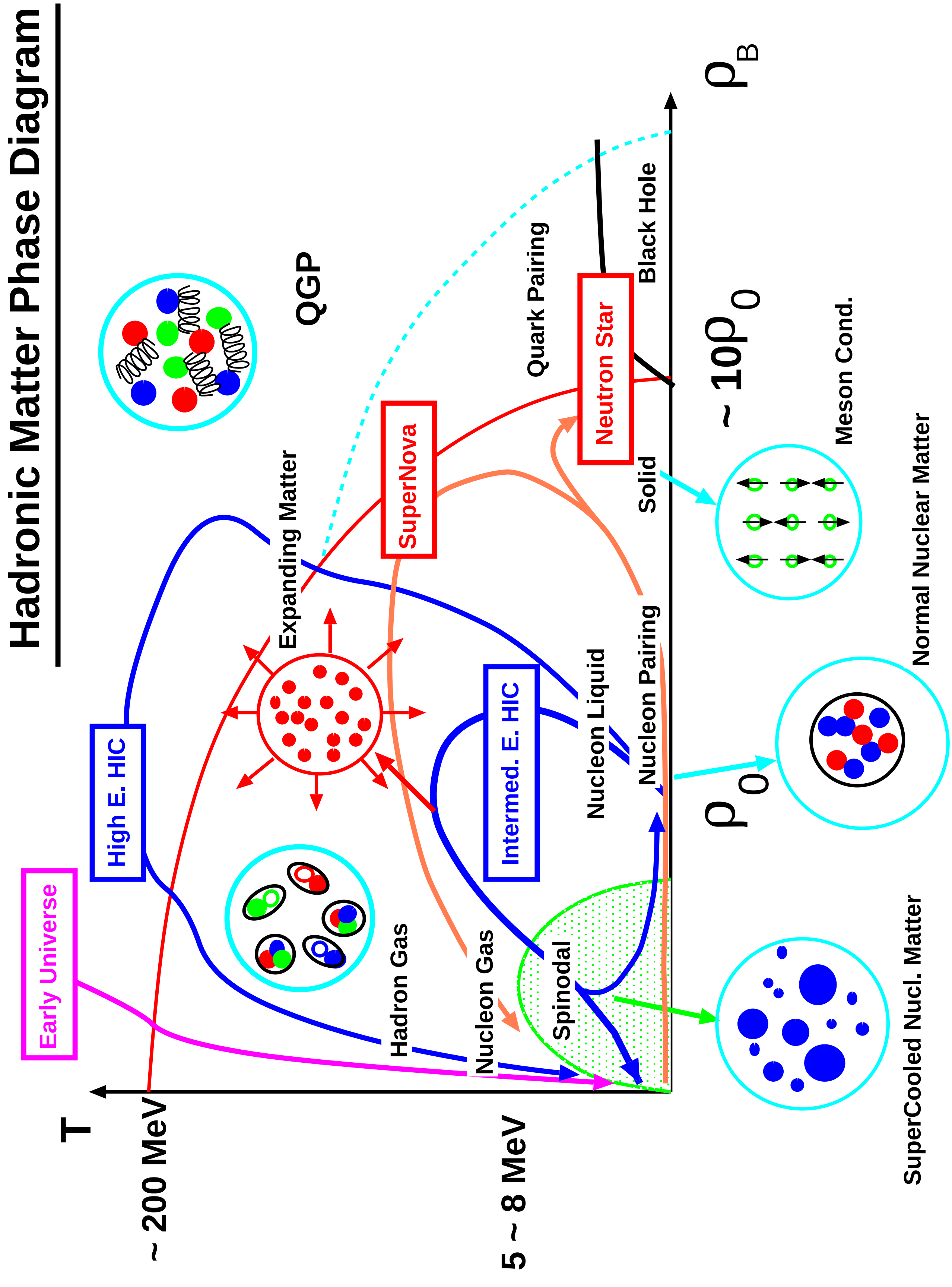
Fragment Distribution in Coexistent Phase of Supernova Matter

C. Ishizuka, A. Ohnishi (Hokkaido)
K. Sumiyoshi (Numazu)

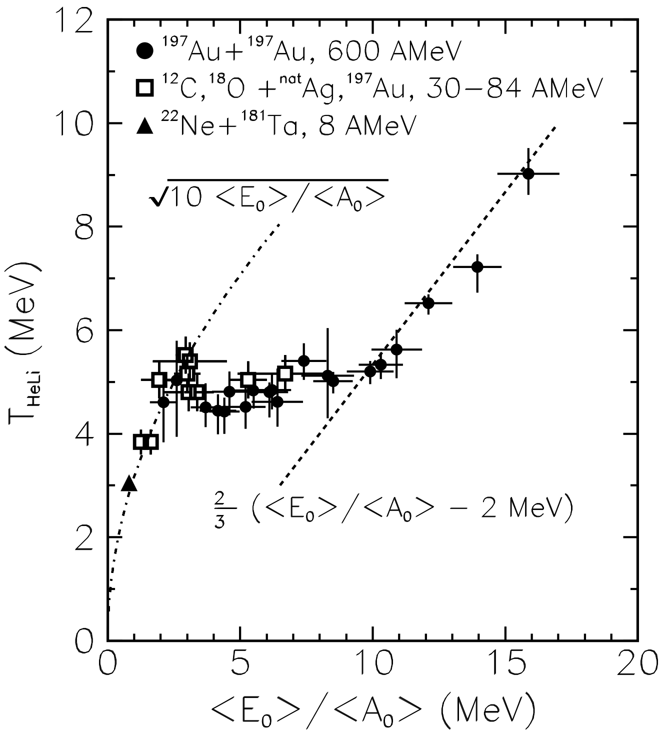
1. Phen. Study of Hadronic Matter Phase Diagram
2. Heavy Element Synthesis
   — When, Where and How ?
   - ⋆ Phase Diagram of Nuclear Matter
   - ⋆ s- and r-processes
   - ⋆ A-distribution in the Universe
   - ⋆ Possible Importance of LG-process
3. Simple Model Calculation
   - ⋆ Model (I): Relativistic Mean Field (RMF)
   - ⋆ Model (II): Statistical Model of Fragments
   - ⋆ Does the Supernova Evolution Path hit LG Coexistence Region ?
   - ⋆ Isotope Distribution in the Universe
4. Summary and Discussion


Hadronic Matter Phase Diagram
QGP
Expanding Matter
SuperNova
Quark Pairing
Neutron Star
Black Hole
ρ_B
~ $10\rho_0$
Meson Cond.
Solid
Normal Nuclear Matter
Nucleon Liquid
Nucleon Pairing
Intermed. E. HIC
High E. HIC
Early Universe
ρ_0
Hadron Gas
Nucleon Gas
Spinodal
SuperCooled Nucl. Matter
T
~ 200 MeV
5 ~ 8 MeV

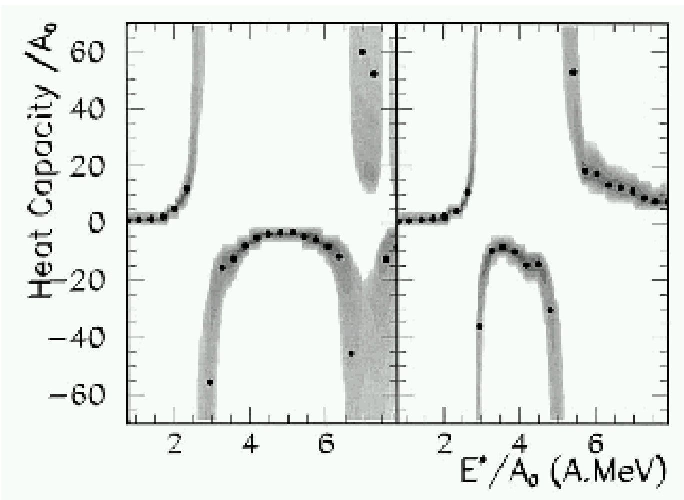
⋆ Phen. Study of Hadronic Matter Phase Diagram

↔ Microscopic Study of Nucleon Matter EOS

- Hadronic Matter Phase Diagram → Figure
- Recent Progress: L-G Phase Trans. is almost confirmed



Caloric Curve
J. Pochadzalla et al. (GSI-ALLADIN collab.),
PRL 75 (1995) 1040.



Negative Heat Capacity
M. D'Agostino et al.
MSU Exp.
INFN-IN2P3 Collab.
PLB 473 (2000) 219.

Two Indep. Exp. on Two Indep. Observables
Gave the Same Conclusion.

☞ Can it affect Nucleosynthesis ?

⋆ 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)
- Problems
  - ⋆ Why is the Elements Dist. Universal ?
  - ⋆ How are the Heavy Proton Rich Nuclei formed ?

SOMETHING ELSE ?

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

Fragm. through LG Phase Tr.
may be important

We propose LG process as a preprocess of usual r-process.

1. During SN Explosion, up to some time Statistical Equilibirum is kept at constant $S/B, Y_L = L/B$.
2. SN Matter would Freeze Out just below $T_c(\rho_B)$, where
   - ⋆ Abundant Fragments are Formed,
   - ⋆ Fragment Number Density becomes thin,
   - ⋆ Large Z Suppresses Nuclear Reactions between Chaged Fragments.
3. Equilibrium Fragment Yields at Freeze-Out will be the initial condition of the r-process.
   - ⋆ Evaporation of Neutrons and Fission
   - ⋆ Weak Decays
   - ⋆ Neutron Captures
   - ⋆ Interaction with Neutrinos and Electrons

In this work,

- ⋆ First, we investigate the LG coex. region with

  Relativistic Mean Field (RMF)

  - ∘ Comparison with Hydro. Calc. (Ejection: $S/B \geq 10$)
- ⋆ Next, we evaluate Fragment Formation in the LG Coex. region with

  Statistical Model

  - ∘ Estimate of $T_c(\rho_B)$.
  - ∘ Fragment Yield around $T_c(\rho_B)$.
    $\sim$ Approx. Power Law Behavior
  - ∘ Comparison with Solar Abundance

⋆ Simple Model (I): RMF + Adiabatic Path

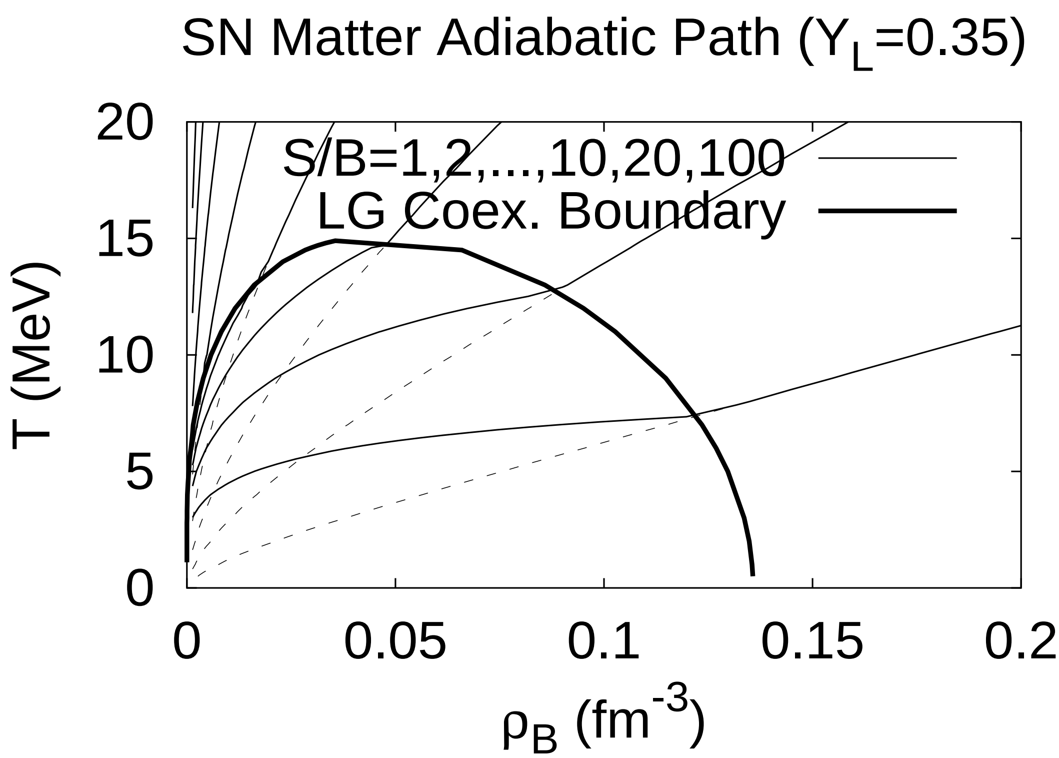
Assumption:

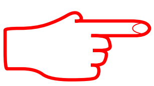
- ⋆ Infinitely Large Liquid and Gas phase coexist.
- ⋆ Lepton to Baryon ratio is conserved.
  (νs are still trapped.)
- ⋆ Entropy per Baryon is conserved.

- Relativistic Mean Field (RMF)

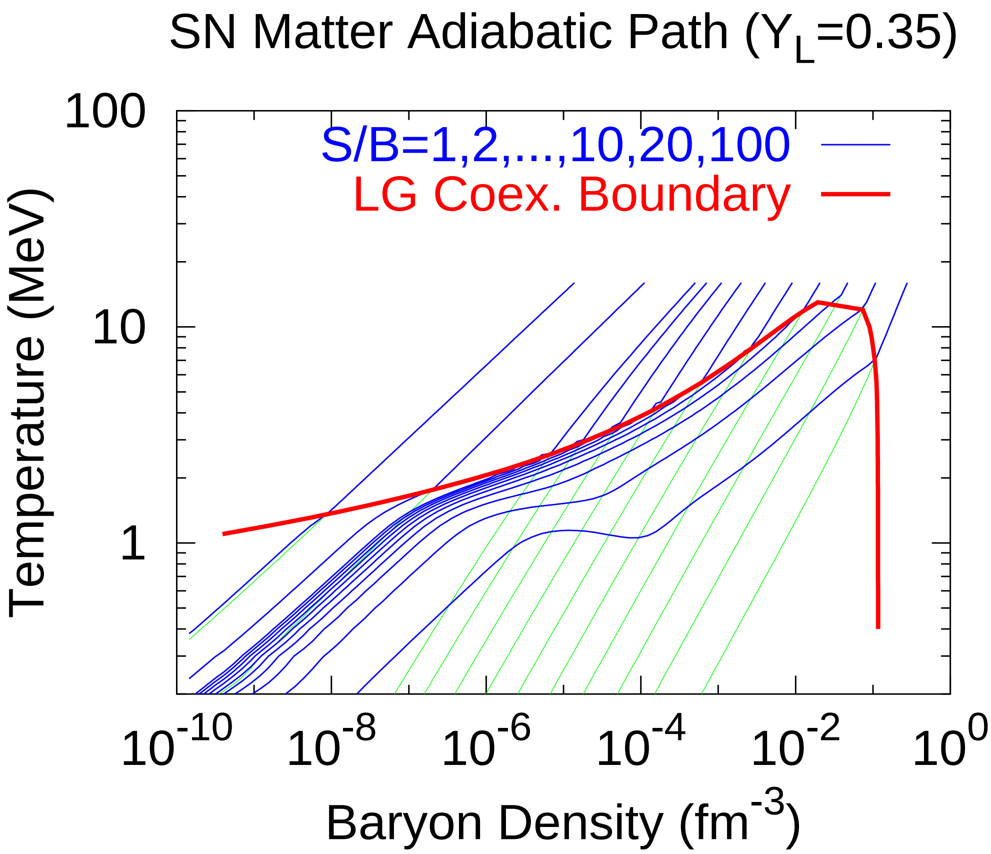
⋆ Tokyo Metro. Univ. Parameter (TM1)
→ B.E. of n-rich nuclei / SN Explosion

⋆ Phase Coexistence $(n, p, e, \nu_e ...)$
→ Gibbs Condition



 Does it hit LG Coex. Region ?

Adiabatic Path at Low Densities



Yes, it hits LG Coex. Region even at $S/B > 10$!

- Why, Problems and To Do

  ⋆ At low T, Entropy is mainly carried by Leptons $(e^{\pm}, \nu, \bar{\nu})$.
  $\leftrightarrow$ $S/B \sim (3-6)$ at 1 A GeV HIC

  ⋆ With lepton chemical pot., larger proton ratio can be supported than in neutron star matter.
  $\rightarrow$ Gains Sym. Energy in Liquid phase

  ⋆ p/n ratios in L and G are different, and phases are assumed to be of infinite size.
  $\rightarrow$ Coulomb Energy !

☞ Estimate based on Finite Nuclei is necessary.

⋆ Simple Model (II): Statistical Model

Stat. Model in HIC
$\simeq$ Nuclear Stat. Equil. (NSE) in Astrophys.

• Statistical Model of Fragments

Stat. Equil. between Fragments
$\cdots$ Fragment-based Grandcanonical Model

$$\begin{aligned}
\rho_f(A,Z) &= g(T)\int \frac{d^3p}{(2\pi\hbar)^3}\exp(-(E_f-\mu_f)/T) \\
E_f &= \frac{p^2}{2M_f} - B_f(A,Z) + V_c(A,Z) \\
\mu_f &= Z\,\mu_p + N\,\mu_n
\end{aligned}$$

$g(T)$: g.s (+ Disc. Levels) + Bethe formula
V_c : Average Interfrag. Coulomb Pot.

(μ_p, μ_n): Fixed from (ρ_p, ρ_n)

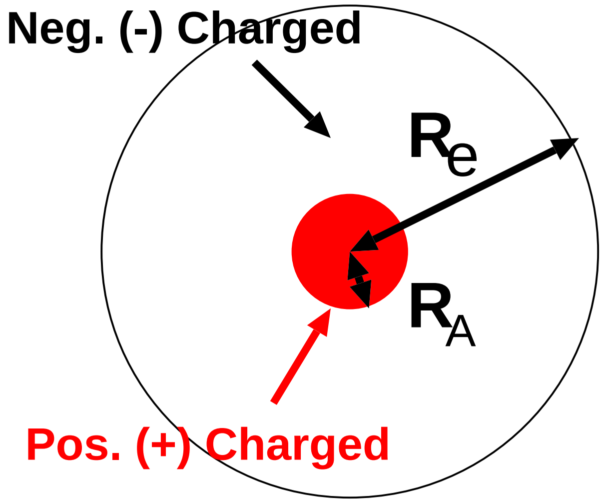
In SN Matter, Extension of Mass Table is needed.

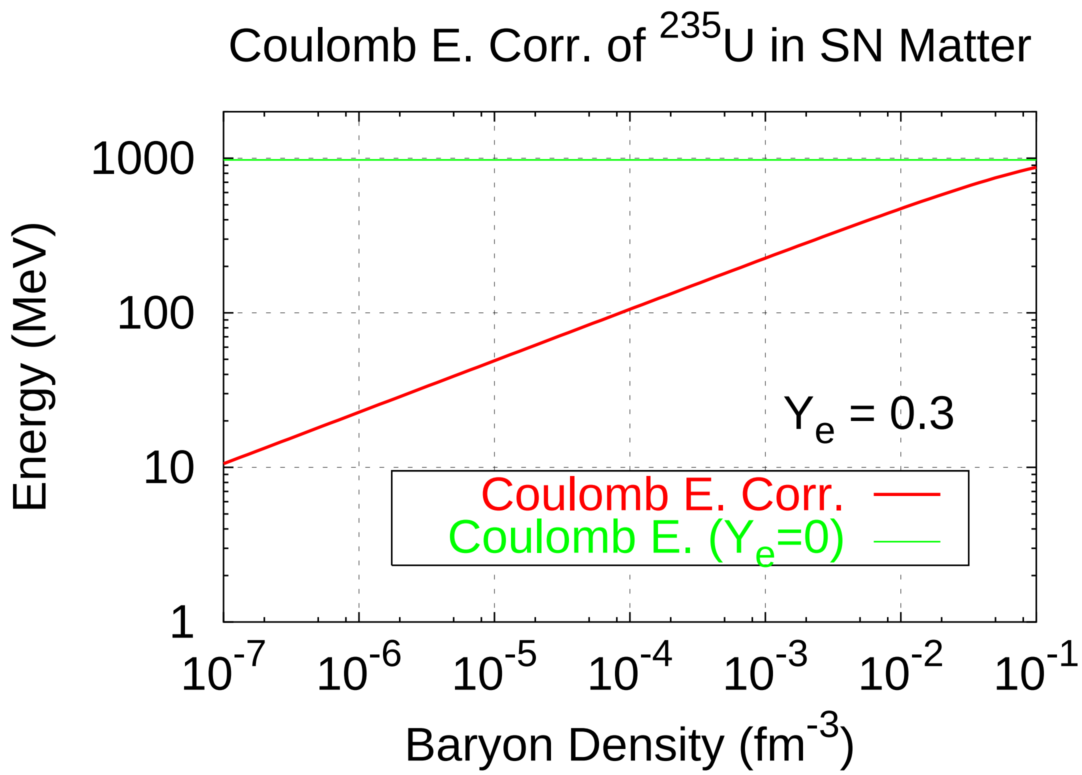
- ⋆ Electron Screening
  $\rightarrow$ Stabilize Proton Rich nuclei
- ⋆ Large Neutron Chem. Pot.
  $\rightarrow$ Stabilize Neutron Rich nuclei

• Binding Energy Correction in SN Matter

Coulomb E. Correction from Electron Screening

$$\Delta V_c(A,Z) = a_c \frac{Z^2}{A}\left(\frac{3}{2}\eta - \frac{1}{2}\eta^3\right) \quad , \qquad \eta = R_A/R_e \propto \rho_e^{1/3}$$

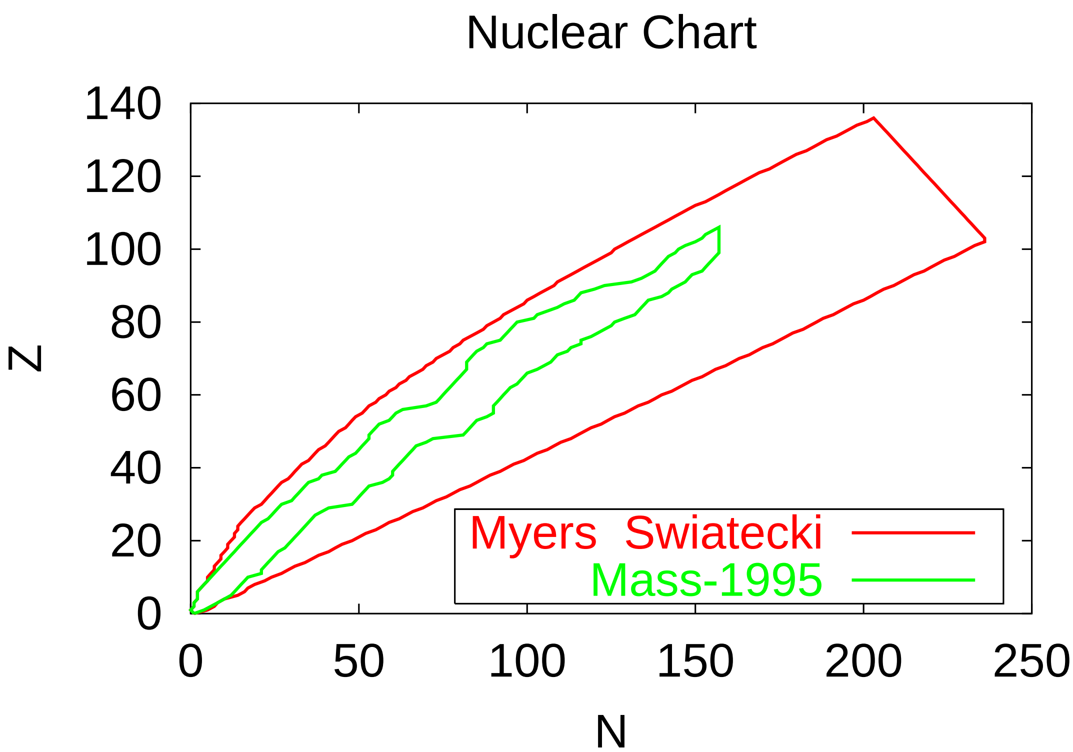




☞ Large Binding Energy Corr. even at low ρ_B

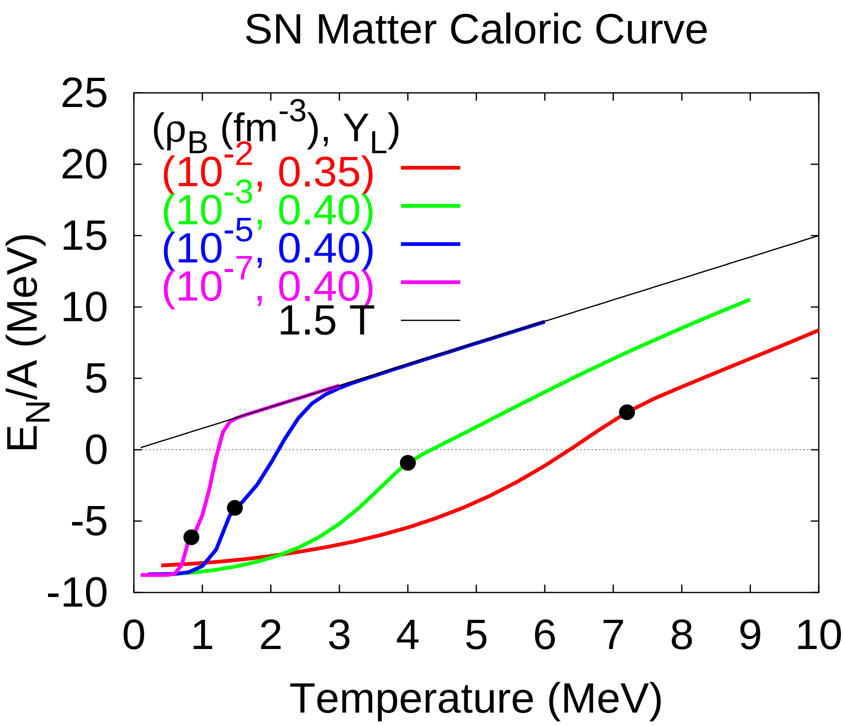
- Mass Table Extension

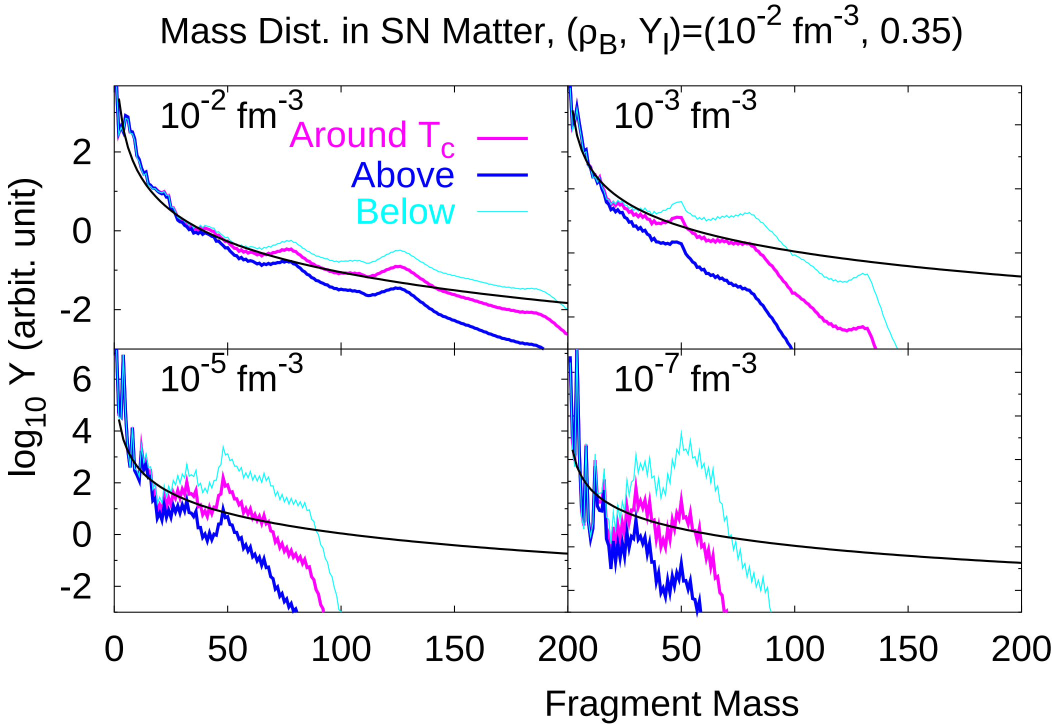
Mass Formula: Myers & Swiatecki 1995
Extended Thomas-Fermi + Shell corr.
→ 9000 nuclei



Let's Go

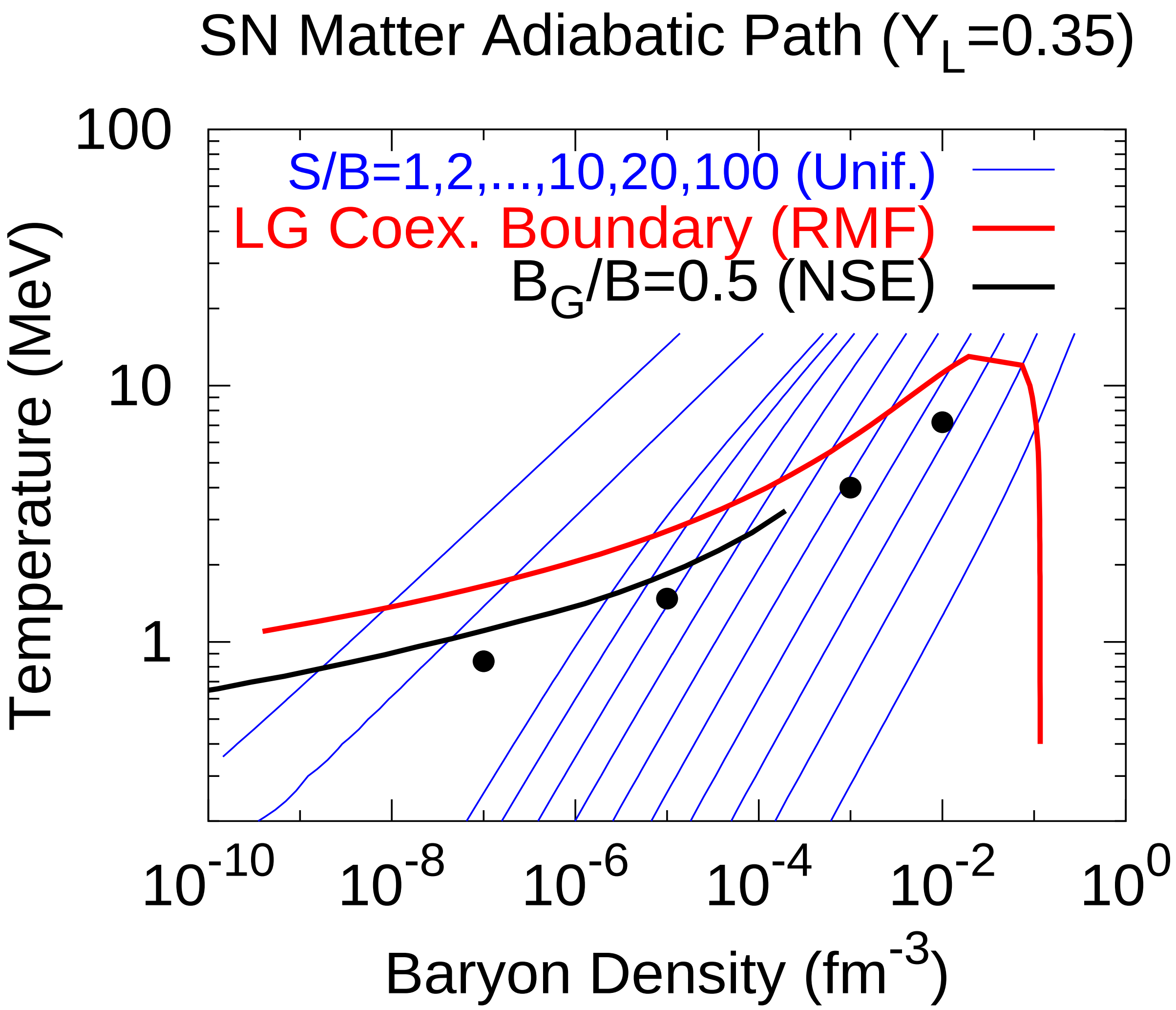
- Critical Tempertures in SN Matter





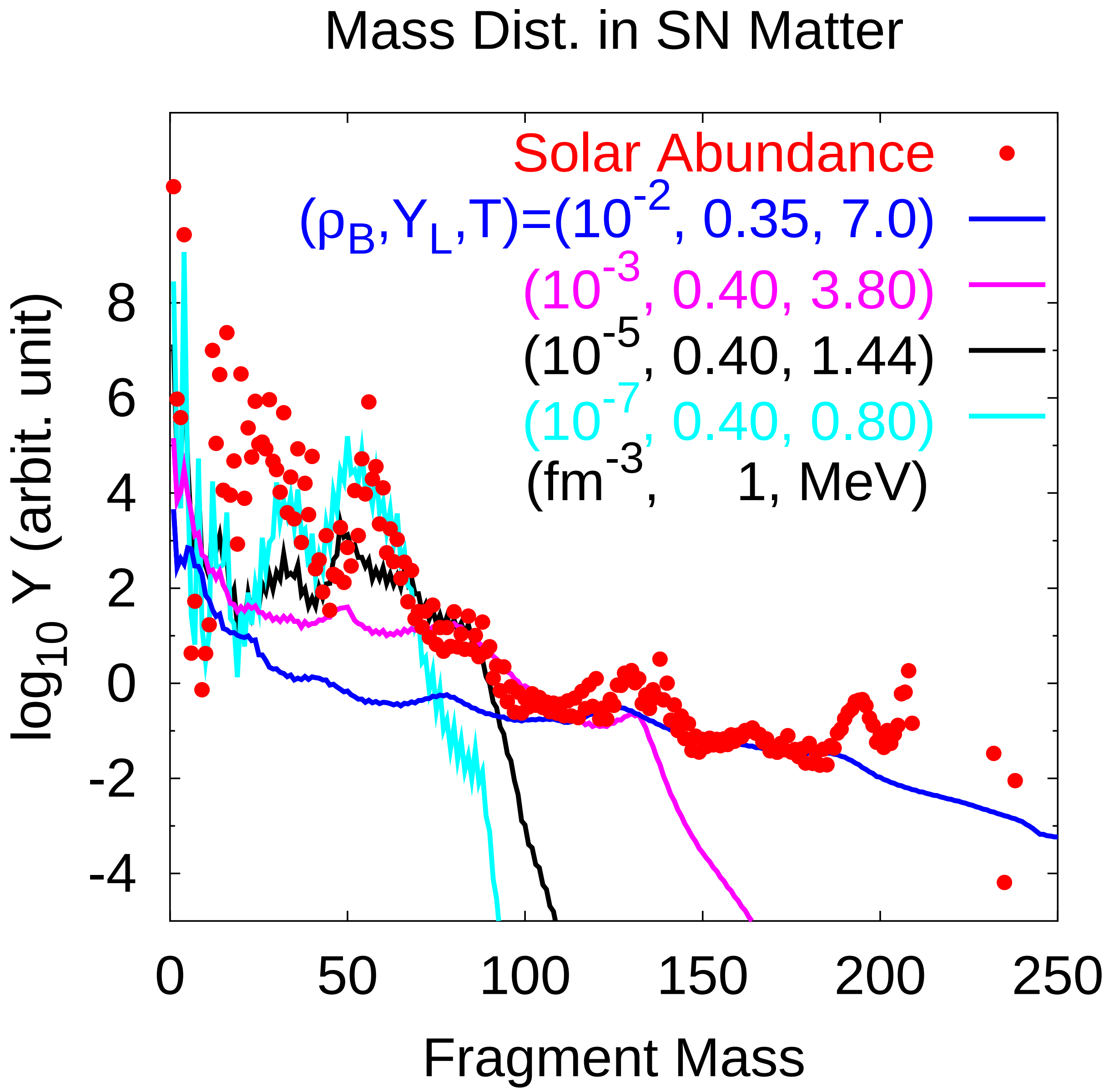
Kink in Caloric Curve
$\leftrightarrow$ Power Law Behavior in Mass Dist.

- (ρ_B, T) Diagram



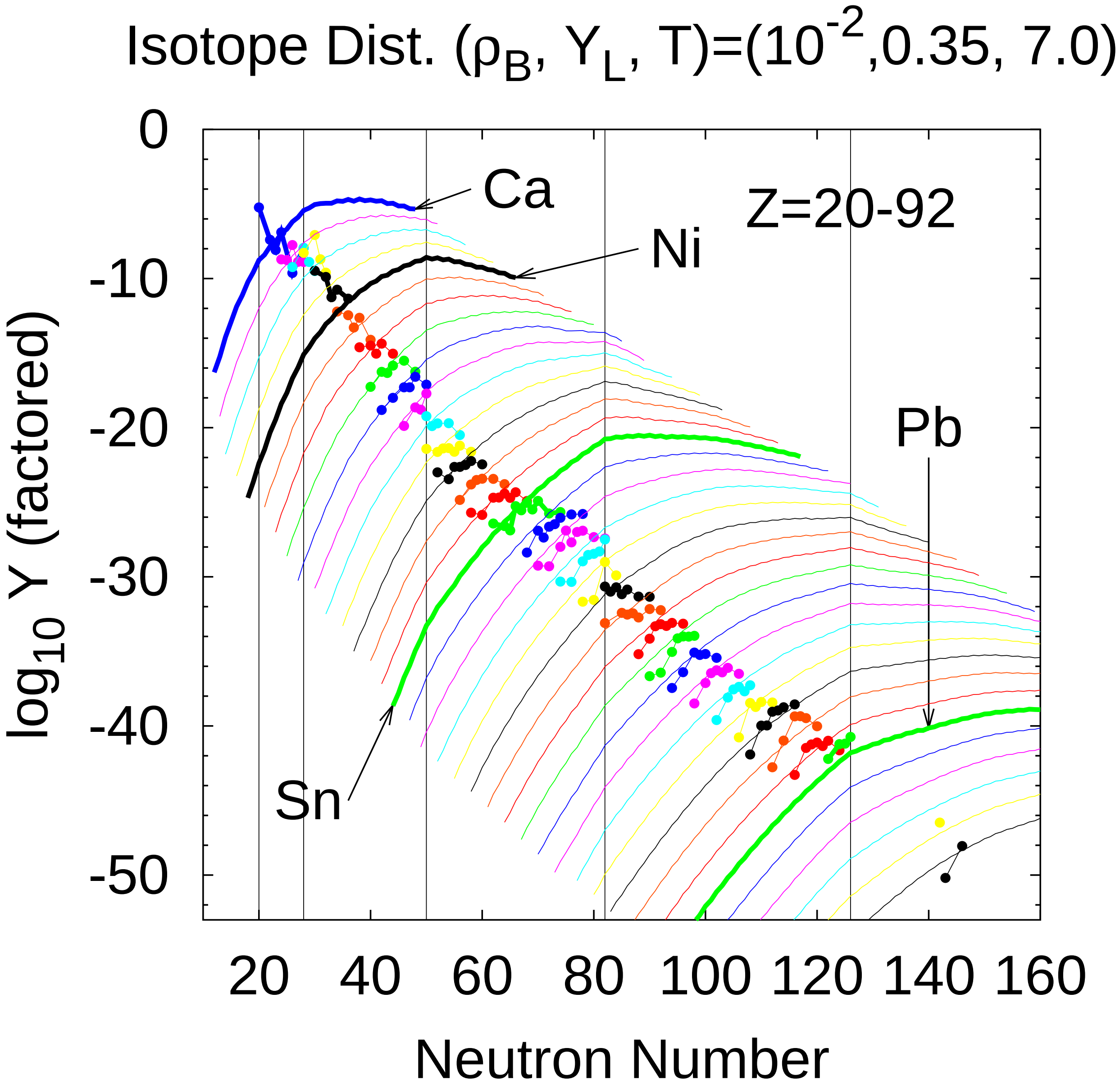
Finite Size: Reduce T_c,
but still in the Ejectable Range

- Mass Distribution just below T_c



Freeze Out Density (fm^{-3})	Temperture (T_c) (MeV)	r-process peak
10^{-2}	7.0 (7.2)	3rd Peak
10^{-3}	3.8 (4.0)	2nd Peak
10^{-5}	1.44 (1.48)	1st Peak
10^{-7}	0.80 (0.84)	Fe, Ni + 1st Peak

- Isotope Distribution



Isotope Dist. from Ca to U
can be explained with one normalization para.
→ Isotope Dist. in the Univ. seems to be Statistical.

⋆ Summary and Discussion

• Summary

1. Heavy Elements Form. through LG phase transition at around the surface of Supernova Core — LG process — may be important.

   ··· Phase Diagram / A Distribution / Heavy p-rich Nuclei

2. Simple Model Calc. (I): — RMF + Ad. Path —
   ··· TM1 → Large Critical Temperature in SN: $T_c \simeq 16$ MeV

   ⋆ Ejection Path goes through LG coex. region.

3. Simple Model Calc. (II): — Statistical Model —
   ··· Mass Table Ext. + Coulomb Energy Corr.

   ⋆ Finite Size effects reduces T_c,
   but still in the Ejection Range

   ⋆ Solar Isotope Dist. can be explained
   with NSE at High ρ_B and T.

Freeze Out Density (fm^{-3})	Temperture (T_c) (MeV)	r-process peak
10^{-2}	7.0 (7.2)	3rd Peak
10^{-3}	3.8 (4.0)	2nd Peak
10^{-5}	1.44 (1.48)	1st Peak
10^{-7}	0.80 (0.84)	Fe, Ni + 1st Peak

   ⋆ Very Neutron Rich Nuclei beyond the Dripline
   are formed abundantly at Equilibrium.
   → Neutron Source after Equil. is Lost.

- FAQ

1. Why are Fragments Formed Abundantly at Density as Low as $\rho_B \sim 10^{-7}$ fm^{-3} ?

   → Fragment Window: $Y_p \sim 0.5$ (Poster by C. Ishizuka)

2. Required S/B is too low. They do not come out.

   → Adiabatic Index $< 4/3$ in Coex. Region.
   There may be the Turbulence in SN Explosion.

3. What is the diff. from Normal NSE ?

   → Mass Table Ext. and Coulomb Corr.
   Modifies the Dist.
   (Talk by C. Ishizuka at PostYK01)
   → Freeze-Out T is NOT a Indep. Var. of ρ_B

4. You wrote that you discuss mass mod. by nucl. int.

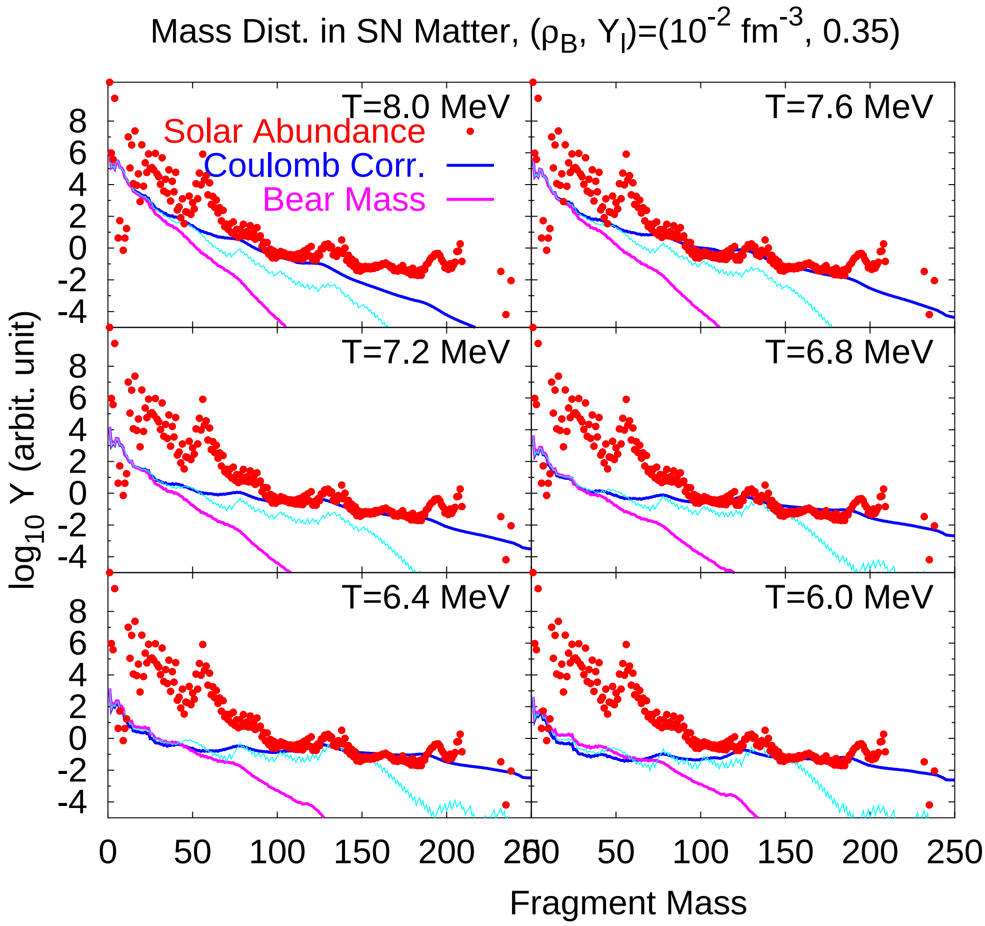
   → Sorry, We will do it in the future.

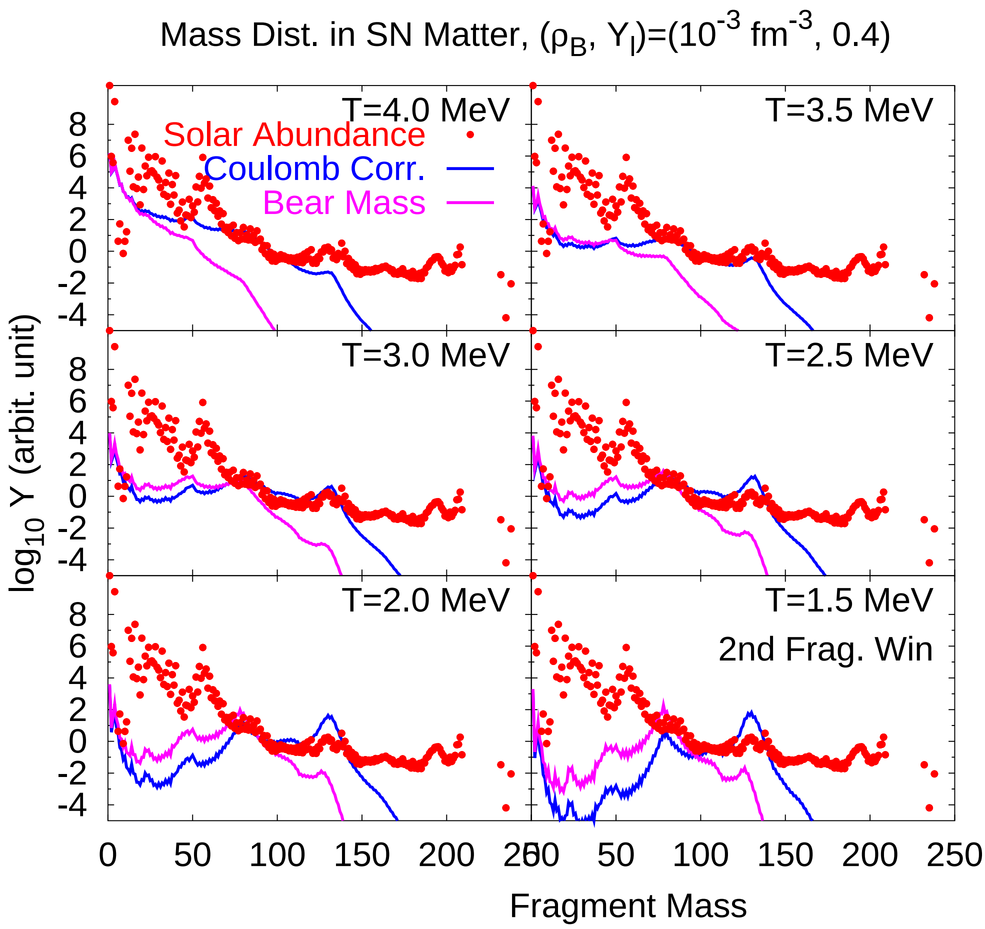
- Future Work

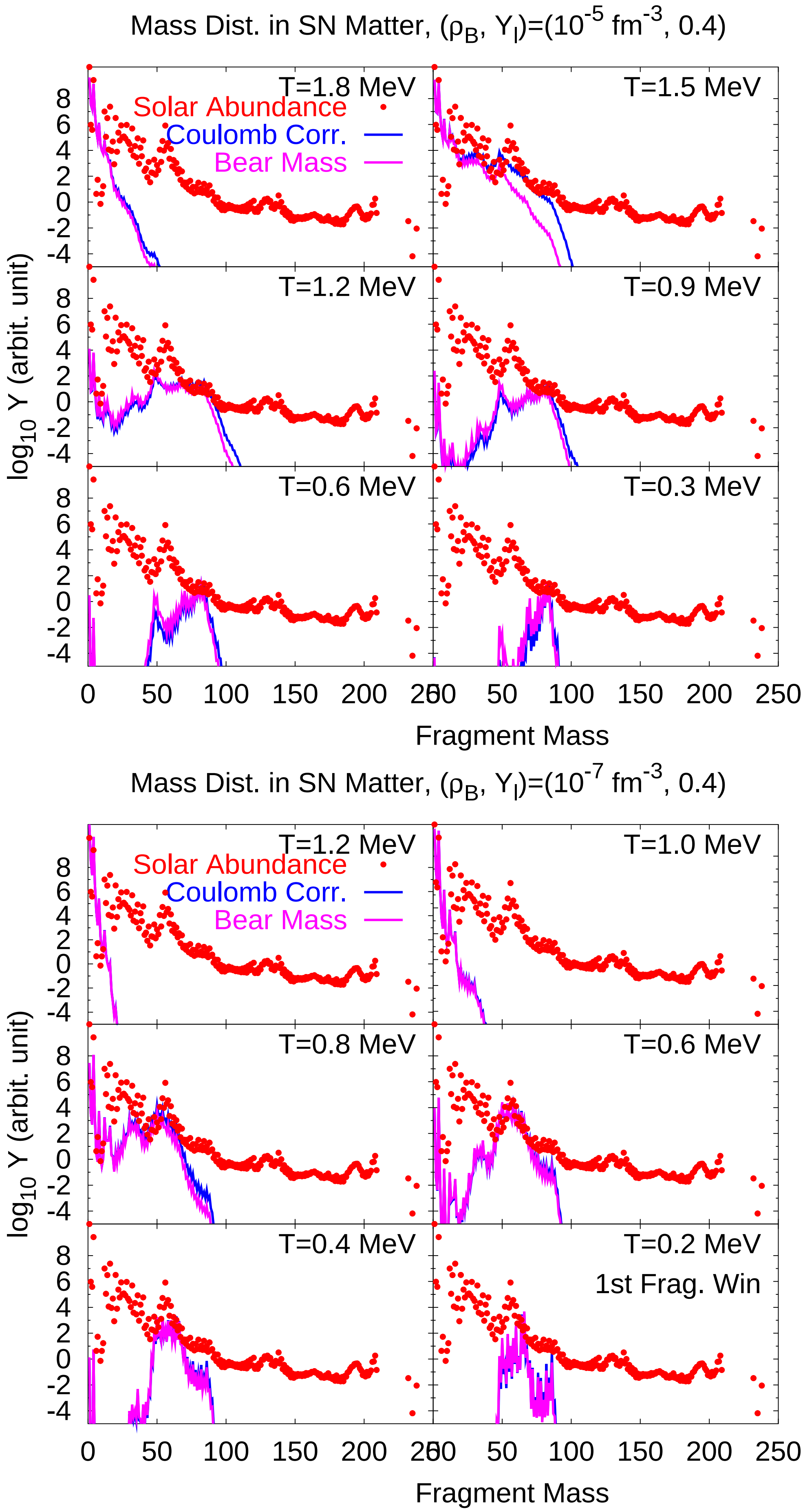
1. Nucl. Mass Mod. by Nuclear Int.
2. Unified Treatment of Mean Field and Statistics
3. Freeze Out Condition
4. Symmetry Energy (Rel. vs. Non-Rel., c.f. Takatsuka)
5. Decay of Nuclei beyond Neutron Driplines / Stability Line against Fission
6. Combination with SN Explosion and Later r-process
7. Comparison with HIC with n-rich Nuclei

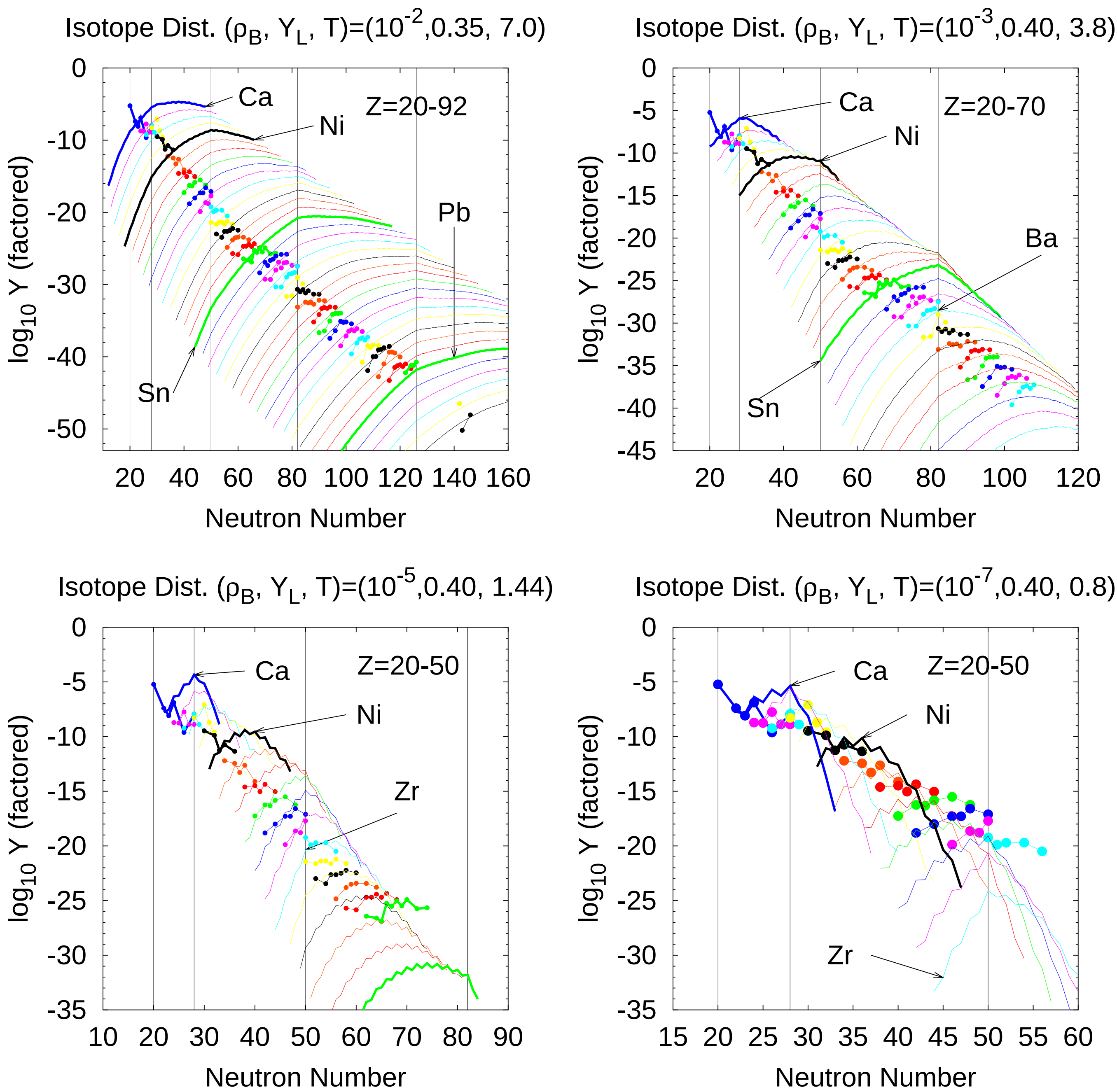
- Discussion

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)

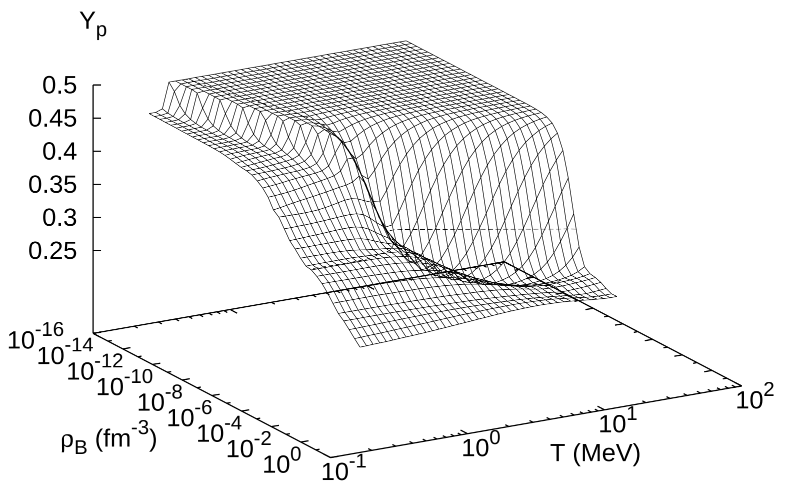

Mass Dist. in SN Matter, (ρB, Yl)=(10-2 fm-3, 0.35)
T=8.0 MeV
Solar Abundance
Coulomb Corr.
Bear Mass
T=7.6 MeV
T=7.2 MeV
T=6.8 MeV
T=6.4 MeV
T=6.0 MeV
log10 Y (arbit. unit)
Fragment Mass


Mass Dist. in SN Matter, (ρB, Yl)=(10-3 fm-3, 0.4)
T=4.0 MeV
Solar Abundance
Coulomb Corr.
Bear Mass
T=3.5 MeV
T=3.0 MeV
T=2.5 MeV
T=2.0 MeV
T=1.5 MeV
2nd Frag. Win
log10 Y (arbit. unit)
Fragment Mass

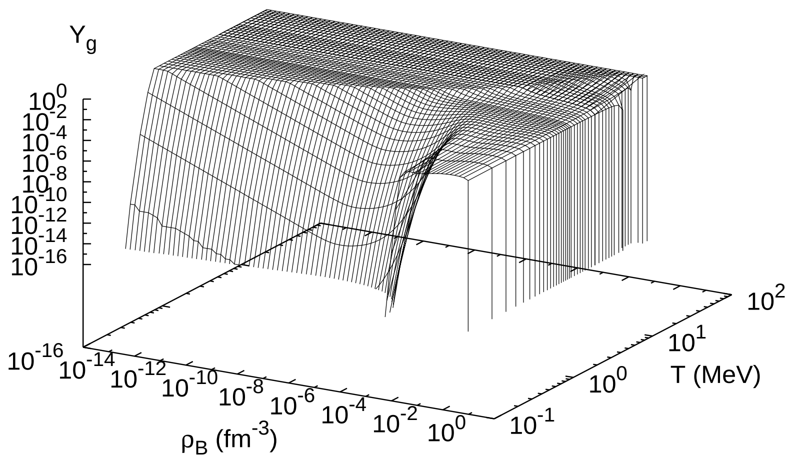

Mass Dist. in SN Matter, (ρB, Yl)=(10-5 fm-3, 0.4)
T=1.8 MeV
T=1.5 MeV
T=1.2 MeV
T=0.9 MeV
T=0.6 MeV
T=0.3 MeV
Solar Abundance
Coulomb Corr.
Bear Mass
log10 Y (arbit. unit)
Fragment Mass
Mass Dist. in SN Matter, (ρB, Yl)=(10-7 fm-3, 0.4)
T=1.2 MeV
T=1.0 MeV
T=0.8 MeV
T=0.6 MeV
T=0.4 MeV
T=0.2 MeV
1st Frag. Win
Solar Abundance
Coulomb Corr.
Bear Mass
log10 Y (arbit. unit)
Fragment Mass


Isotope Dist. (ρ_B, Y_L, T)=(10^{-2},0.35, 7.0)
Ca
Ni
Z=20-92
Pb
Sn
$\log_{10}$ Y (factored)
Neutron Number
Isotope Dist. (ρ_B, Y_L, T)=(10^{-3},0.40, 3.8)
Ca
Ni
Z=20-70
Ba
Sn
$\log_{10}$ Y (factored)
Neutron Number
Isotope Dist. (ρ_B, Y_L, T)=(10^{-5},0.40, 1.44)
Ca
Z=20-50
Ni
Zr
$\log_{10}$ Y (factored)
Neutron Number
Isotope Dist. (ρ_B, Y_L, T)=(10^{-7},0.40, 0.8)
Ca
Z=20-50
Ni
Zr
$\log_{10}$ Y (factored)
Neutron Number

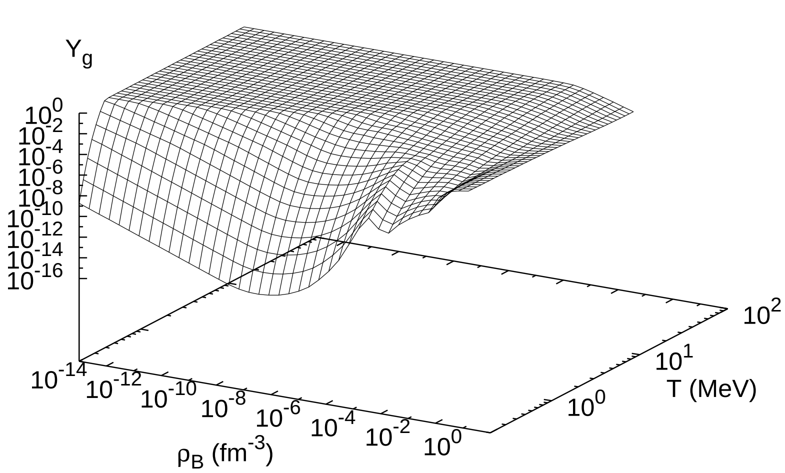
Yp (NSE) (Y_L = 0.35)

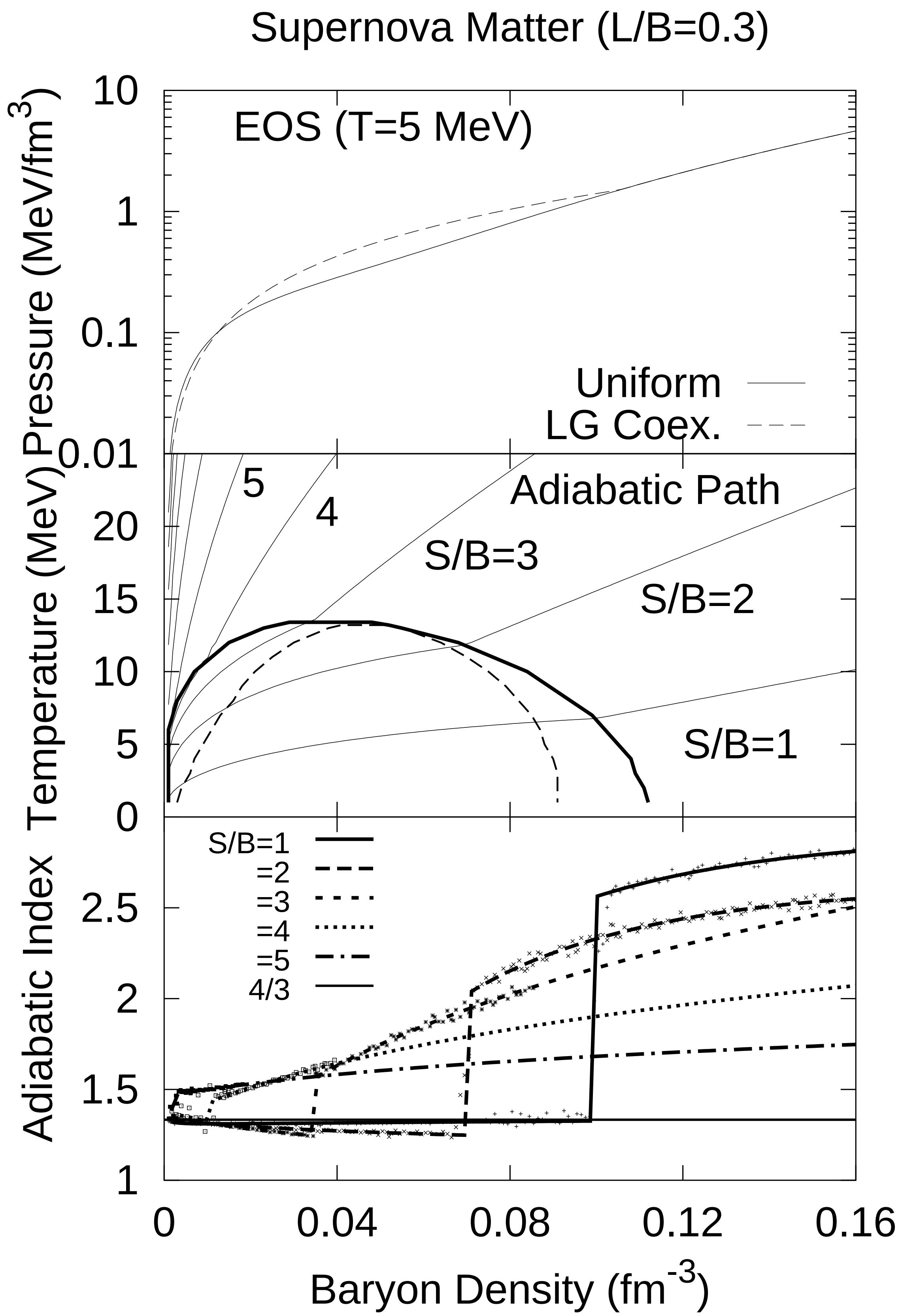


Yg = B_G/B (RMF)



Yg = B_G/B (NSE)




Supernova Matter (L/B=0.3)
EOS (T=5 MeV)
Pressure (MeV/fm^3)
Uniform
LG Coex.
Adiabatic Path
5
4
S/B=3
S/B=2
S/B=1
Temperature (MeV)
S/B=1
=2
=3
=4
=5
4/3
Adiabatic Index
Baryon Density (fm^{-3})