Self consistent calculation of nuclear composition in hot and dense stellar matter

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Composition of Supernova matter

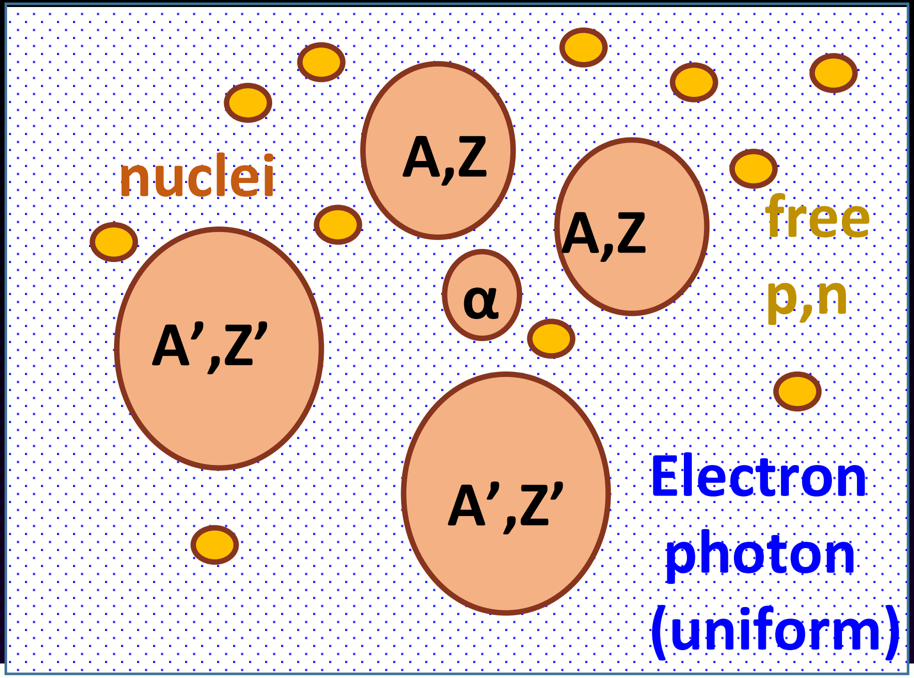
Supernova matter

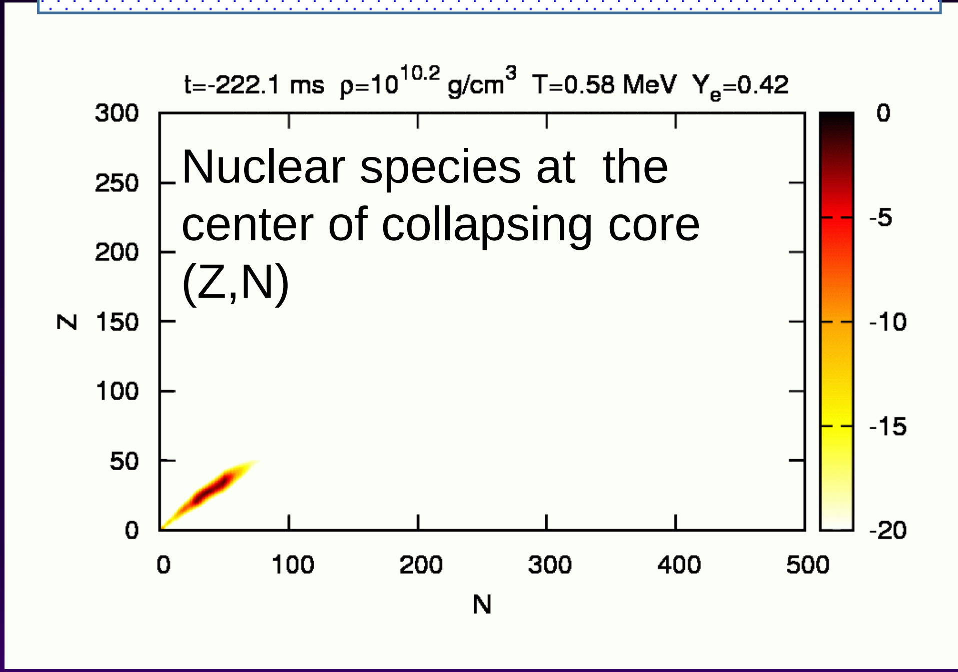
- **neutrons and protons**
- **light and heavy nuclei**
- **electrons, positrons, muons** (Bolling et al. '17)
- **photons**

(Easy, ideal Fermi or Bose gasses)

- **neutrinos**

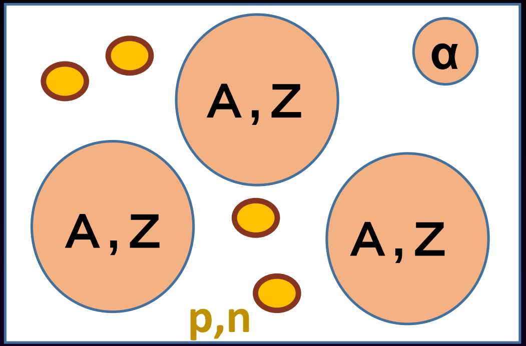
(not always thermalized, Boltzmann Transport Part)





Single Nucleus VS Multi-nucleus

● Single-Nucleus EOSs (optimize the nuclear structure)



LS ('91) , STOS ('98, '11) , Togashi ('17)

Compressible Liquid Drop model (LDM)

or Thomas Fermi approximation

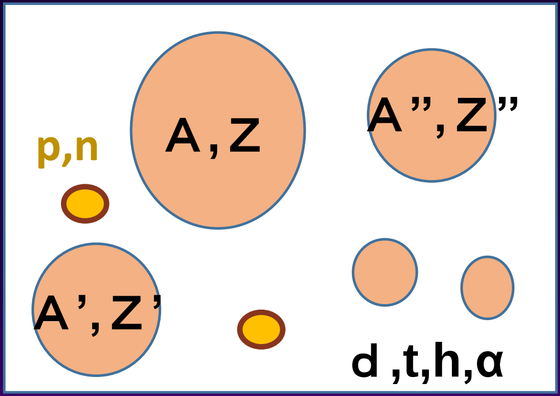
Only one representative heavy nucleus

(Single Nucleus Approximation(SNA))

⇒Only He4 of light nuclei

● Multi-Nucleus EOSs (optimize the nuclear ensemble)

- SMSM('13) HS('11,'13), FYSS (13,17a,17d) , Pais and Typel ('17) (SHO('13), SRO('17))

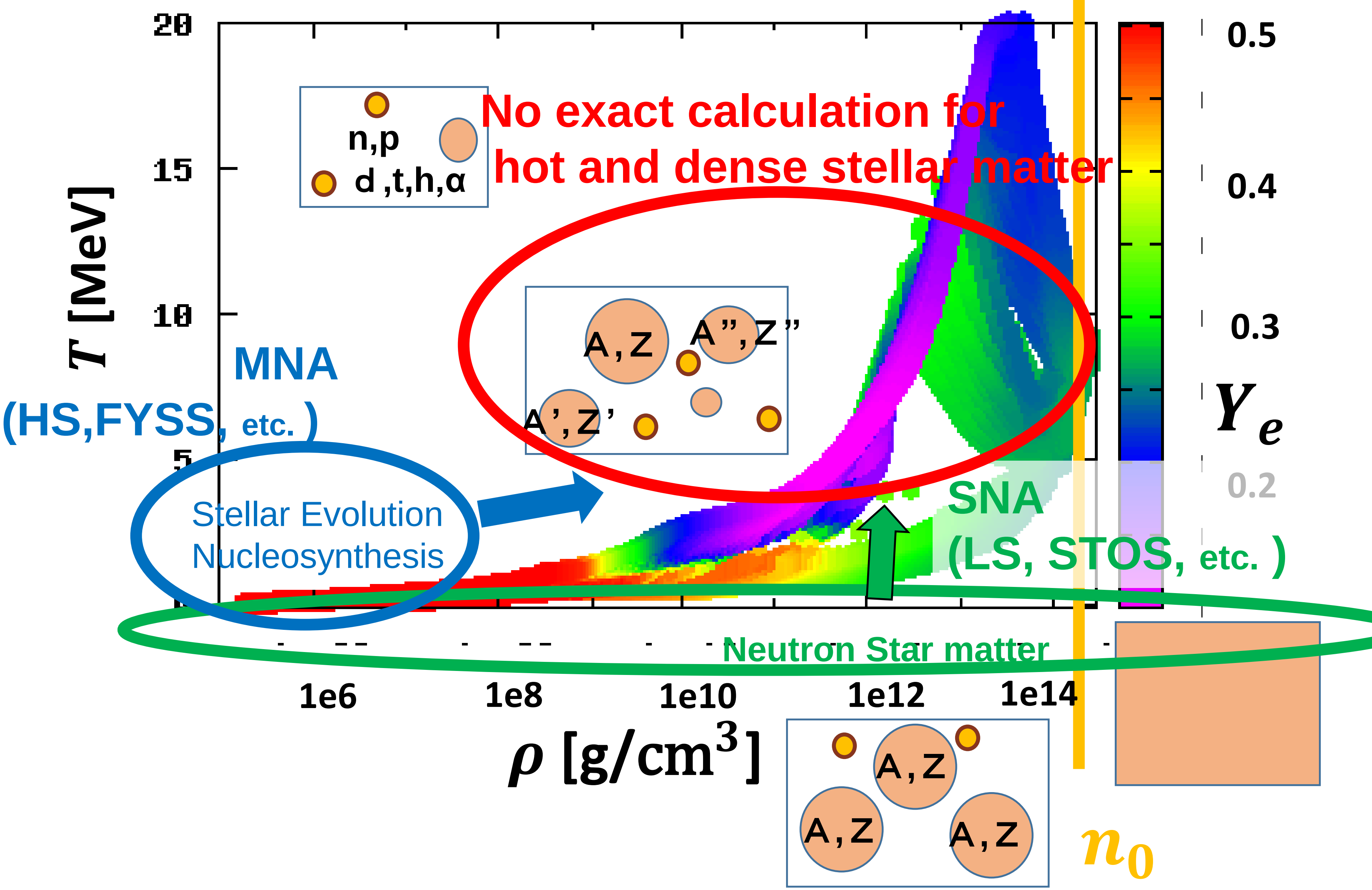


Incompressible LDM or nuclear mass data

⇒Simple evaluation of nuclear binding energies to solve full nuclear ensemble

(Multi Nucleus Approximation(MNA))

Single-Nucleus vs Multi-Nucleus



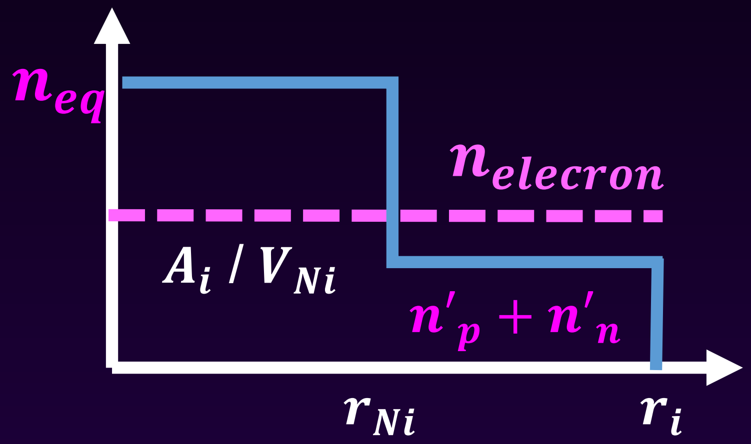
Self-Consistent Calculation of nuclear ensemble and equilibrium density

S.F and I. Mishustin ('17, '18)

Mixture of Compressible nuclei (6<A<2000), n, p, light clusters

- Free bulk energy (Oyamatsu Iida Skrme Type interactions)
- Liquid Drop model (FYSS, Surface tension (Agrawal '14))
- Excluded Volume effect for translational energy (HS EOS)

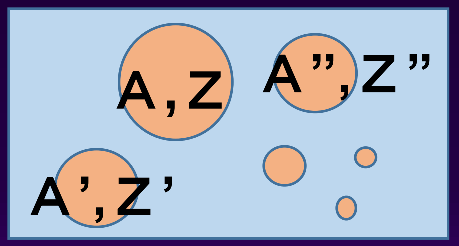
1, Solve the structure (n_{eq}) of all nuclei
(minimize the individual binding energy)



dripped nucleons
n'_p, n'_n

binding energies
of all nuclei

2, Solve the ensemble $\mu_p, \mu_n, n'_p\ n'_n$
(minimize the total free energy)

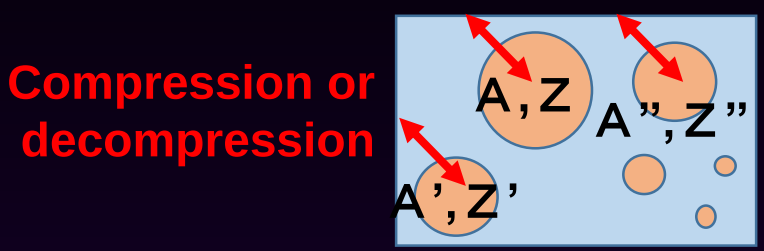


Convergence of all quantities
= the equilibrium state at given $n_B,\ T,\ Y_p$

Models (SF et al. '17)

Model Multi-nucleus Compressible (the new model)

solve $n_p, n_n, n_\alpha, \{n_i\}$, $\{\boldsymbol{n_{eqi}}\}$

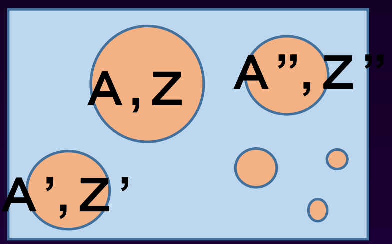


Model Multi-nucleus Incompressible

~HS,FYSS etc. **(MNA)**

solve $n_p, n_n, n_\alpha, \{n_i\}$

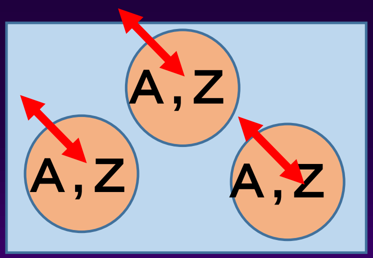
$\boldsymbol{n_{eqi}}$=$\boldsymbol{n_{eqi}(T=0, n'_p=0, n'_n=0, n_e=0)}$



Model Single-nucleus compressible

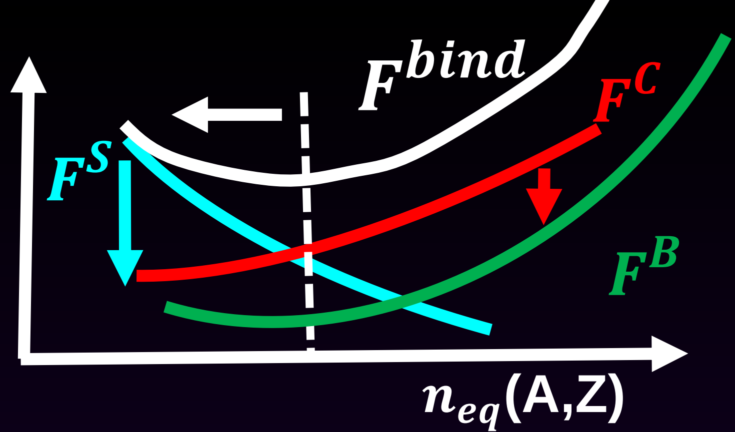
~LS, STOS etc. **(SNA)**

solve $n_p, n_n, n_\alpha, n_{rep}$, $n_{eq\,rep}, \boldsymbol{Z_{rep}}, \boldsymbol{A_{rep}}$

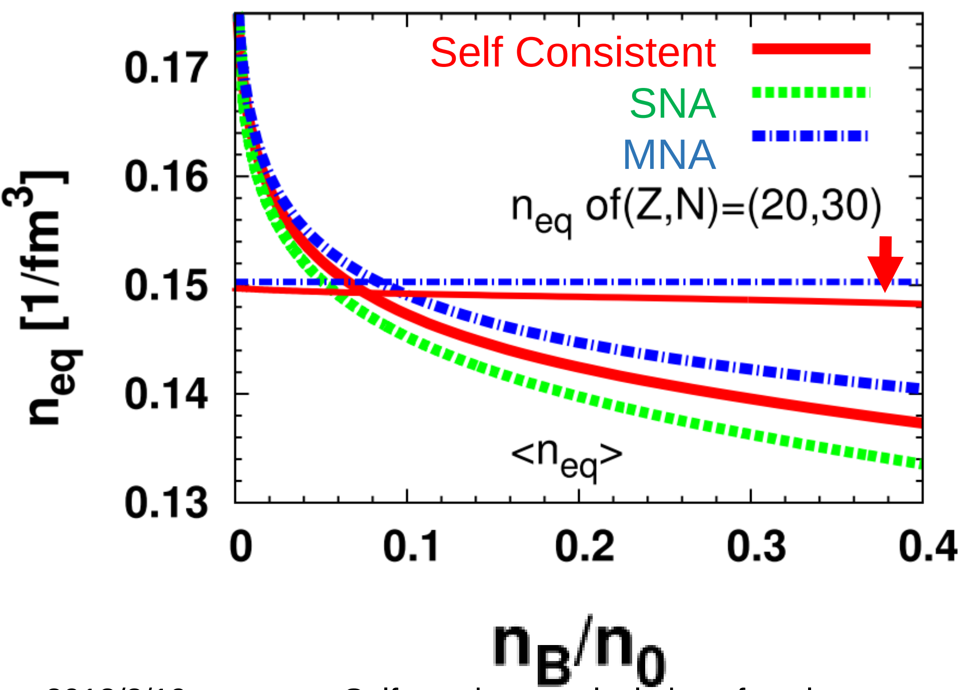


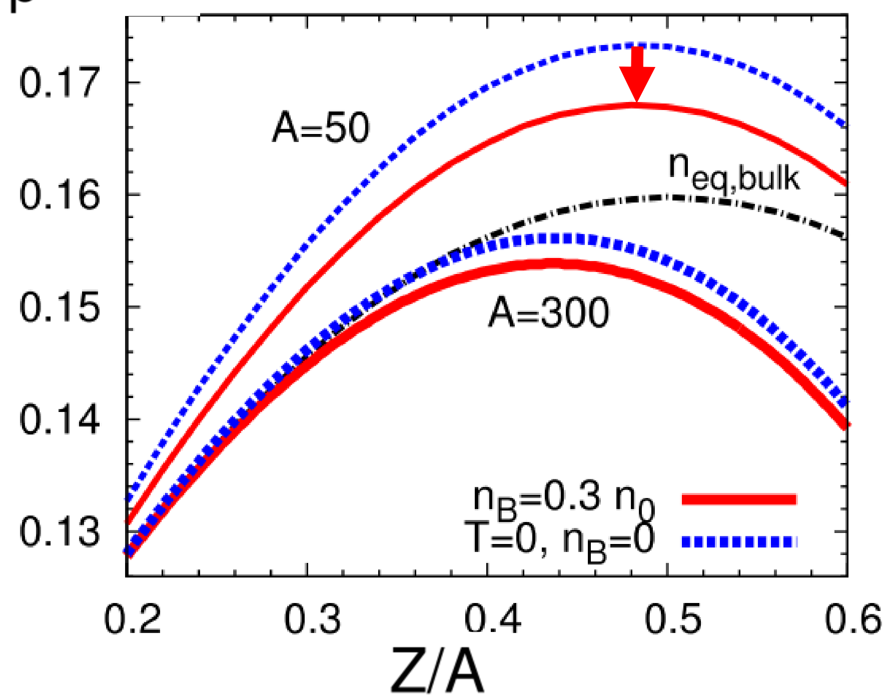
ρ-Dependence of n_{eq} (SF et al. '17)

①nucleons-dripped conditions
⇒dripped neutrons reduce
surface energies F_i^S
⇒ Decompression of individual nuclei
(Average or representative $\langle n_{eq} \rangle$ always decreases.)



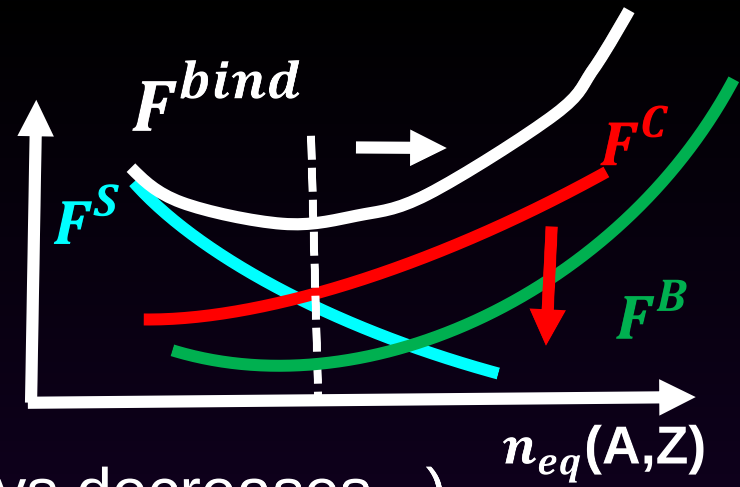
T=3 MeV Y_p=0.2



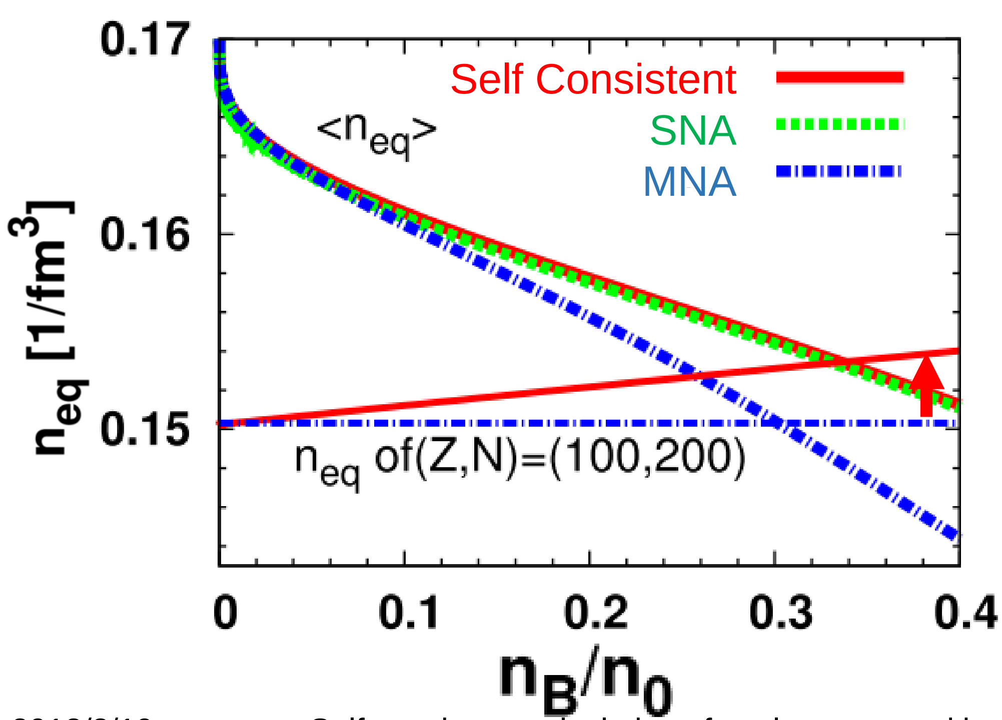


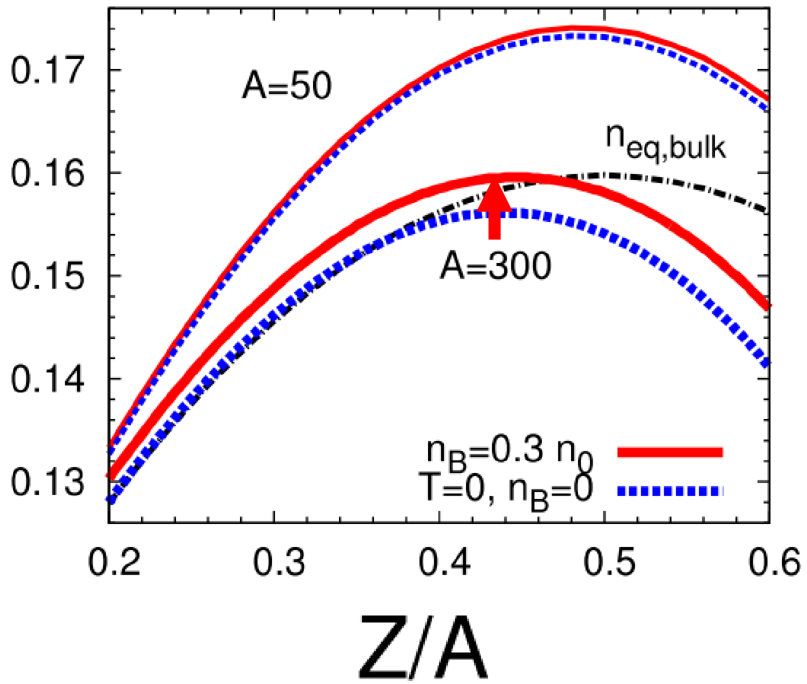
ρ-Dependence of n_{eq} (SF et al. '17)

①non-drip conditions
⇒electrons reduce
Coulomb energies F^C (A,Z)
⇒ Compression of individual nuclei
(Average or representative $<n_{eq}>$ always decreases.)



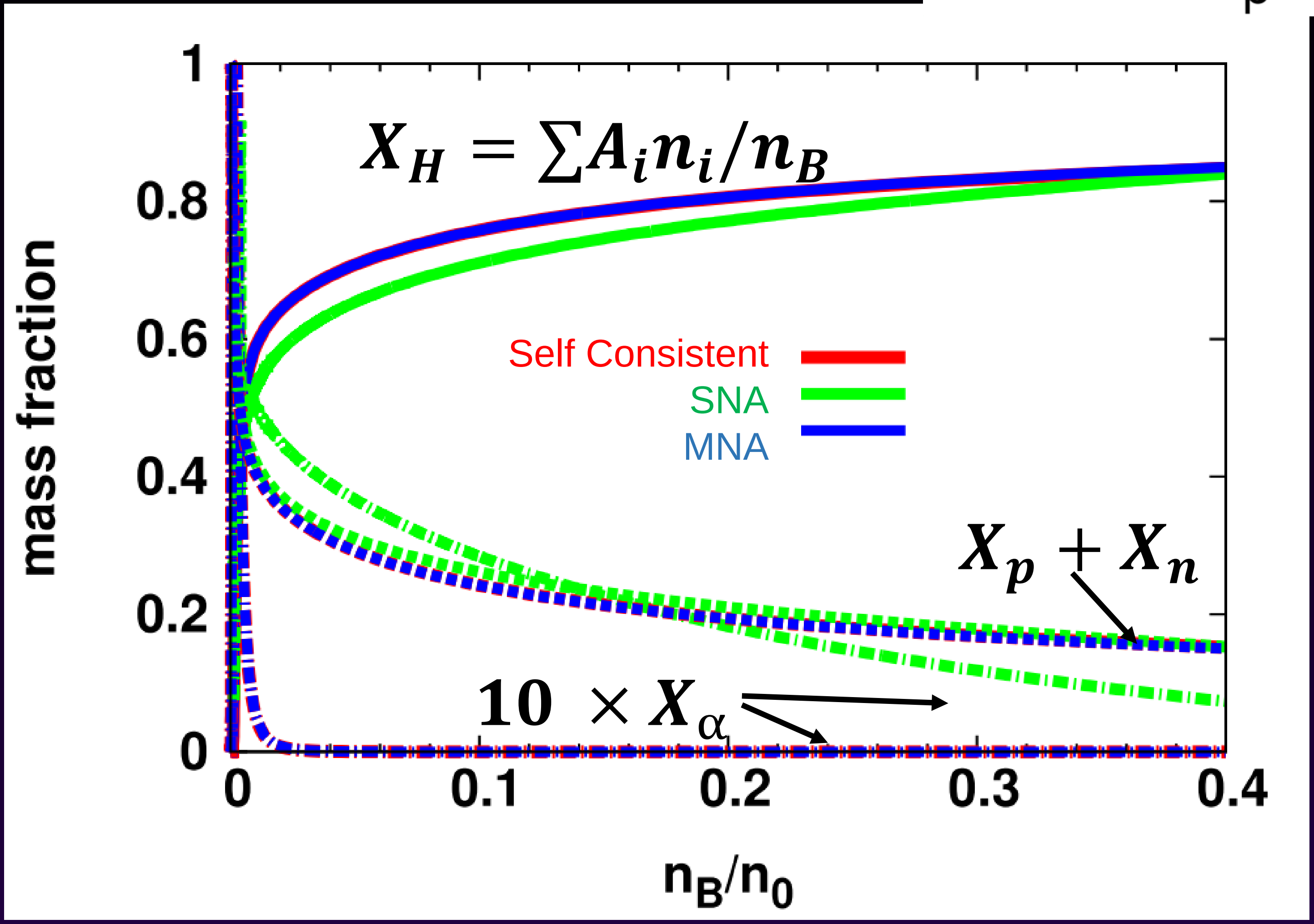
T=1 MeV Y_p=0.4





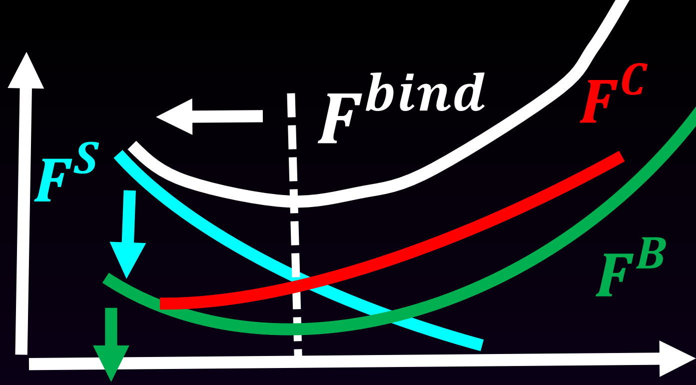
Mass Fraction (SF et al. '17)

T=3 MeV Y_p=0.2



Compression or decompression hardly affects the total Mass Fraction.
(Self Consistent model agrees with MNA model)
The dripped nucleons and α particles are overestimated in SNA EOS

T-Dependence of n_{eq} and Vaporization (SF et al. '18)

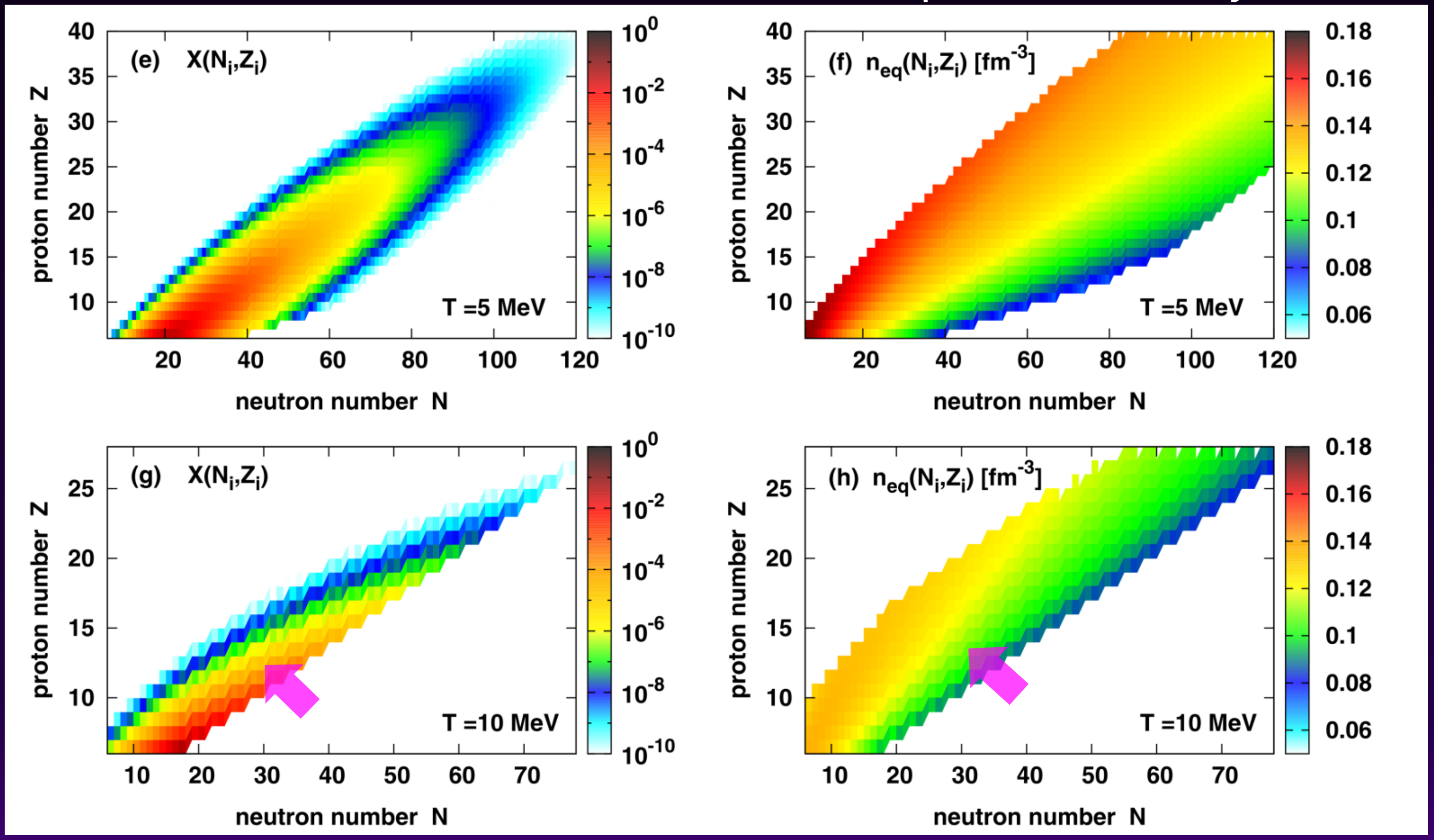


Weakly-bound neutron-rich nuclei become unstable and disappear one after another as T increases

$$n_B = 0.3\, n_0, Y_p = 0.2$$

Mass Fraction

Equilibrium density

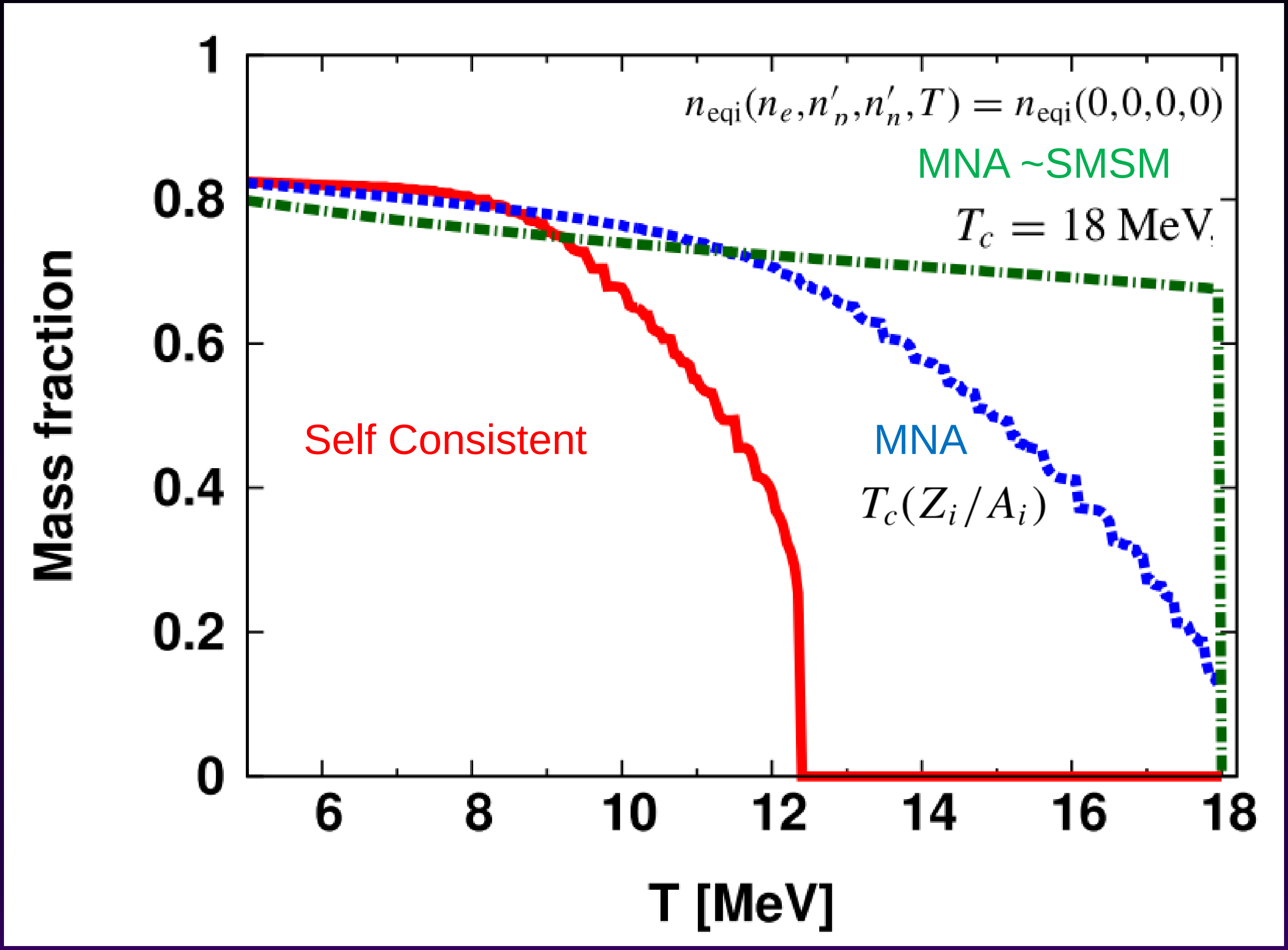


T=5MeV

T=10MeV

T-Dependence of total Mass Fraction of Heavy Nuclei

$n_B = 0.3\ n_0, \qquad Y_p = 0.2$



Summary

- Current SN EOS models are based on Single Nucleus Approximation (SNA) or Multi-nucleus Approximation (MNA).
- In our self-consistent calculations individual nuclei are decompressed at nucleons-dripped conditions (low Yp & high T) or compressed at the non-drip conditions (high Yp & low T)
- These optimizations do not greatly affect the binding energies, the mass fractions and average mass numbers.
- The MNA EOS models are rather good at $n_B \leq 0.3\, n_0$

- Neutron-rich nuclei disappear one after another from T ~ 3 -14 MeV

Future tasks

- Application to Heavy Ion Collision Experiment
- Multi-nucleus oblate / prolate deformation
- Multi-nucleus Thomas Fermi Calculation (See also Gulminelli and Oertel ('17))