Nuclear equations of state for supernova simulations

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(1, Systematical Comparison of nuclear physics inputs for SN EOSs, '18 PRC)

2, New EOSs (DBHF and χEFT) for SN simulations

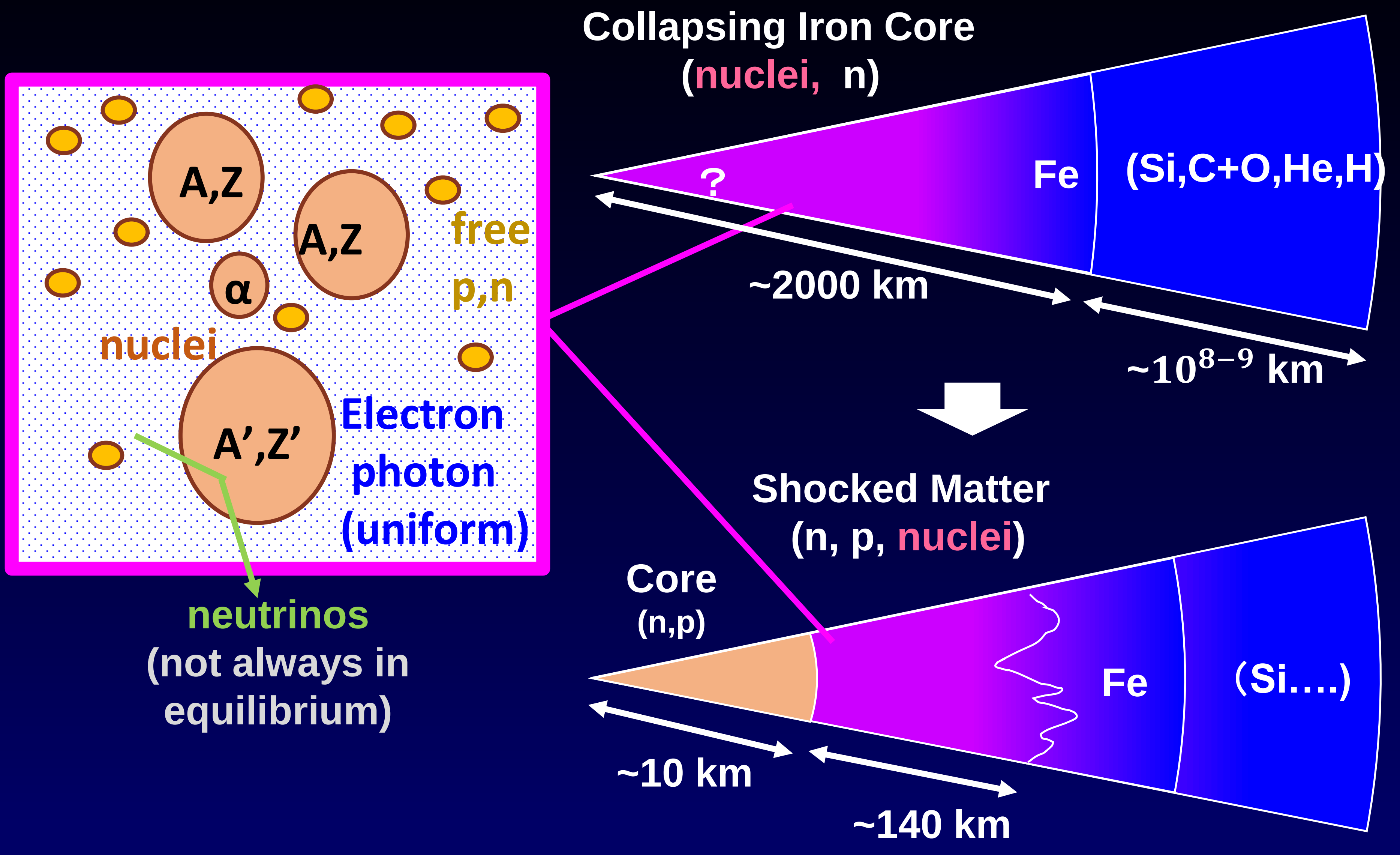
(3, light cluster condensation in hot and dense matter, submitted to PRC)

(and other collaboration works)

H. Nagakura, J. Holt, H. Togashi, K. Saito,

K. Sumiyoshi, I. Mishustin, S. Yamada, H. Suzuki

Supernova matter in Core-Collapse Supernovae



Nuclear Statistical Equilibrium (NSE, 核統計平衡)

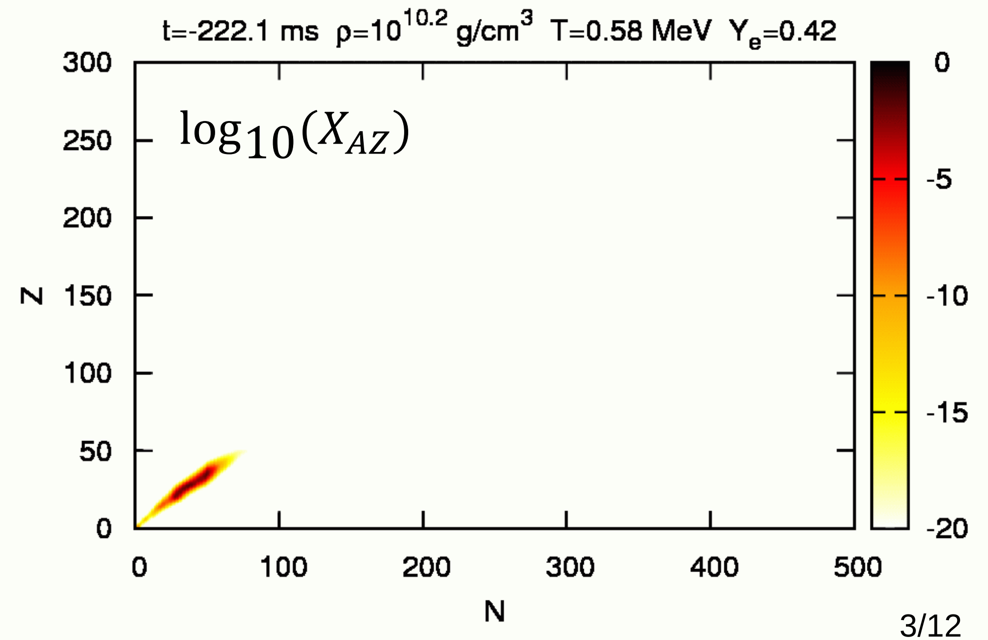
- $\tau_{\text{nuclear reaction}} \ll \tau_{\text{dynamics}}$
- All nuclear components in chemical equilibrium @T>~0.4 MeV

$$(A, Z) \leftrightarrow (A-1, Z) + n$$
$$(A, Z) \leftrightarrow (A-1, Z-1) + p$$

- **Free energy minimization ⇒ NSE EOS**

$$\mu_{AZ} = Z\,\mu_p + (A-Z)\,\mu_n$$

Ex1) Central mass fraction of stellar core collapse →



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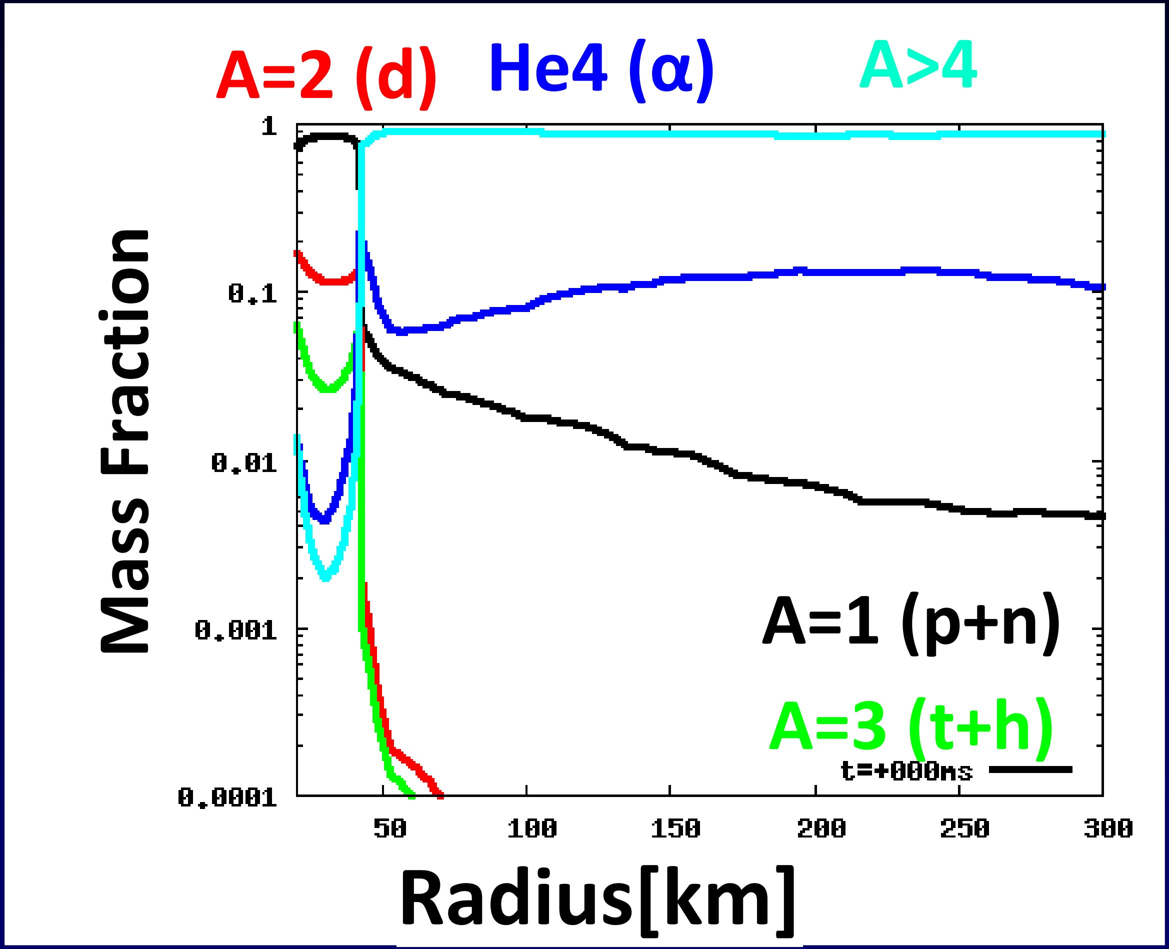
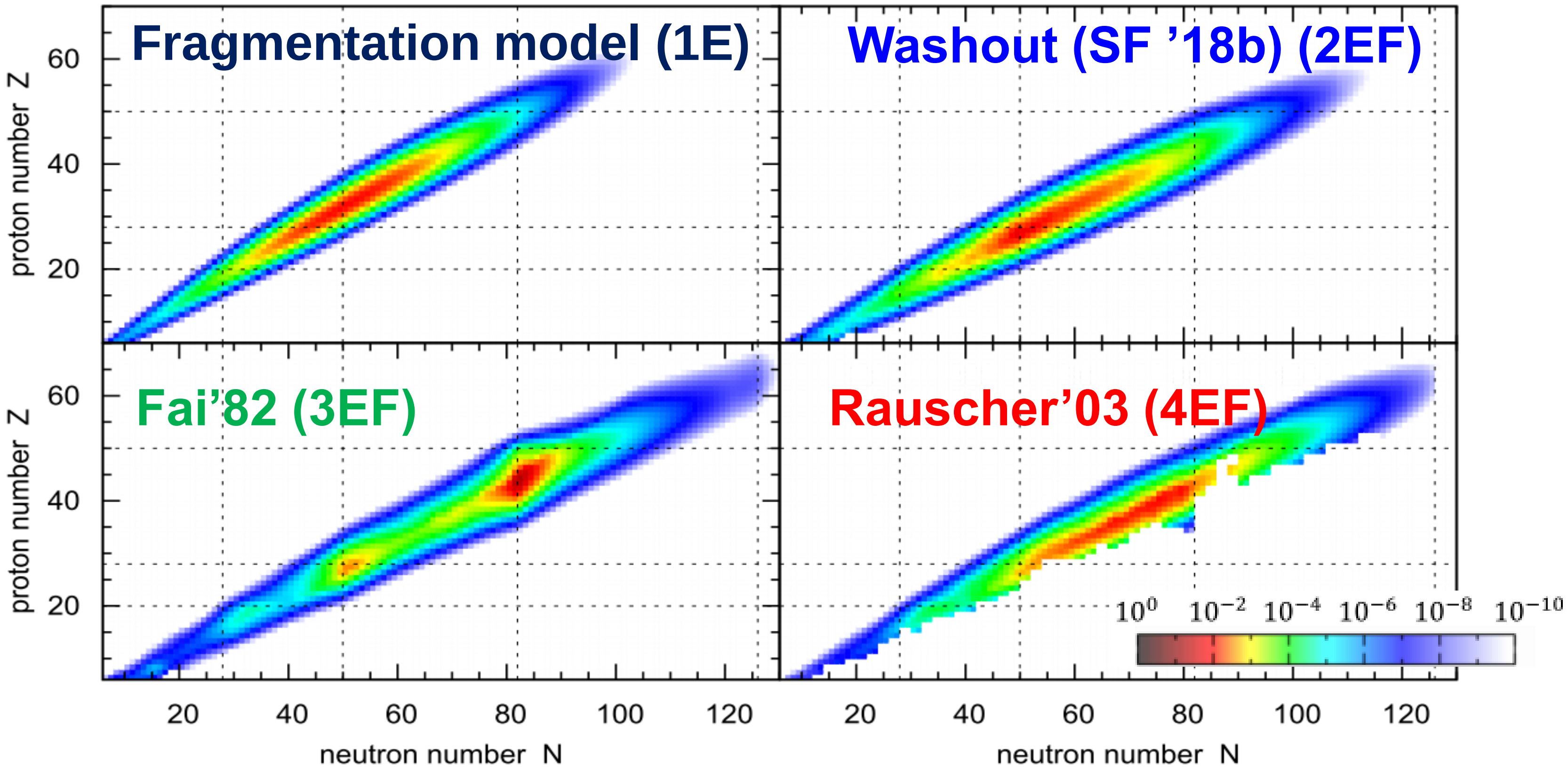
Ex2) Mass fraction of shocked matter →



Core collapse of massive stars

- (ρ, T, Y_e): $(10^{10}$ g/cc, 0.5 MeV, **0.46**$)\Rightarrow(10^{14}$ g/cc, 5.0 MeV, **0.25**$)$
- Iron group nuclei ⇒ **neutron-rich heavy nuclei**
- **Nuclear excitation model affects NSE ambiguities (SF 18b) ↓**

Mass fraction at $\rho = 2.0 \times 10^{12}$ g/cc, $T = 1.8$ MeV, $Y_e = 0.28$



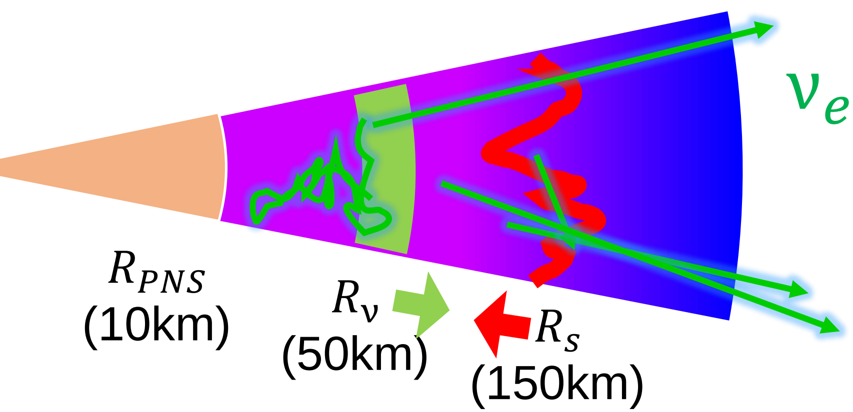
- **NSE ambiguities affect up to 40% of Electron Captures**
  $(N, Z) + e^- \leftrightarrow (N+1, Z-1) + \nu_e$ **(SF+ 17b)**

Electron captures on nuclei reduce neutrino bursts
(Sullivan et al.16, see also Hix '03, Lentz '13)

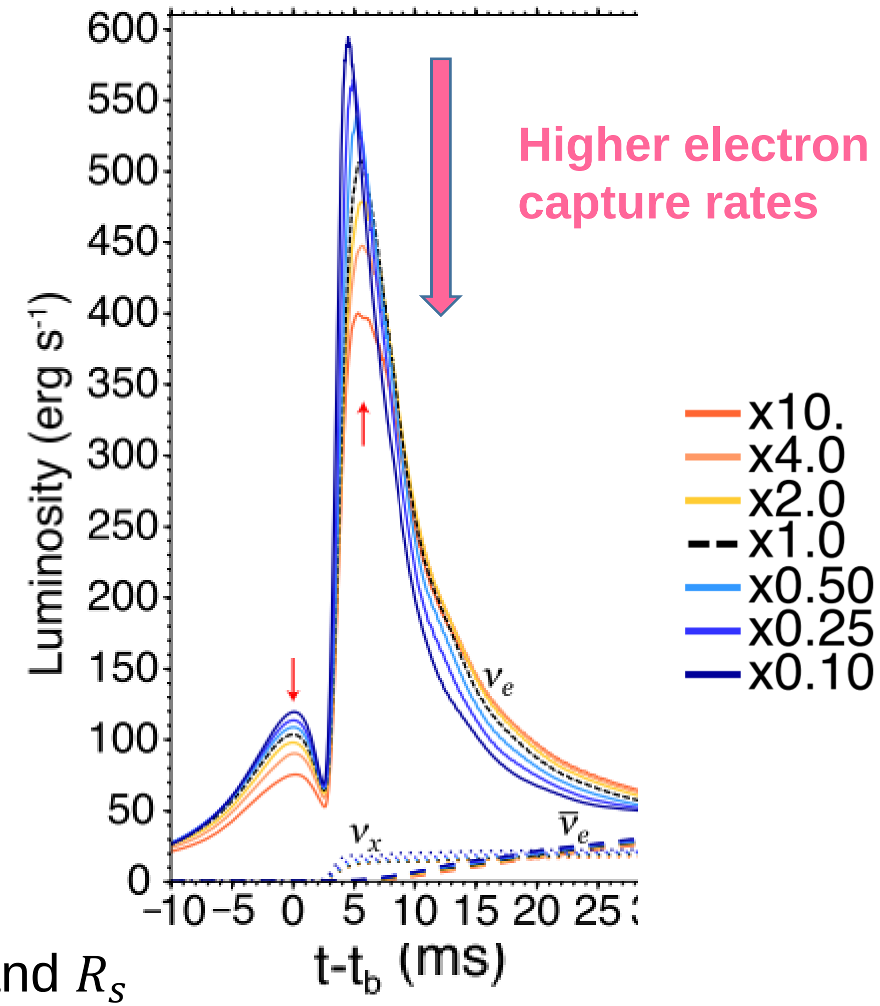
More electron captures on nuclei

1, less lepton degeneracy pressure
⇒smaller proto neutron star
⇒**smaller shock radius R_s**

2, more neutrino captures(CC)
⇒**larger neutrino spheres R_ν**



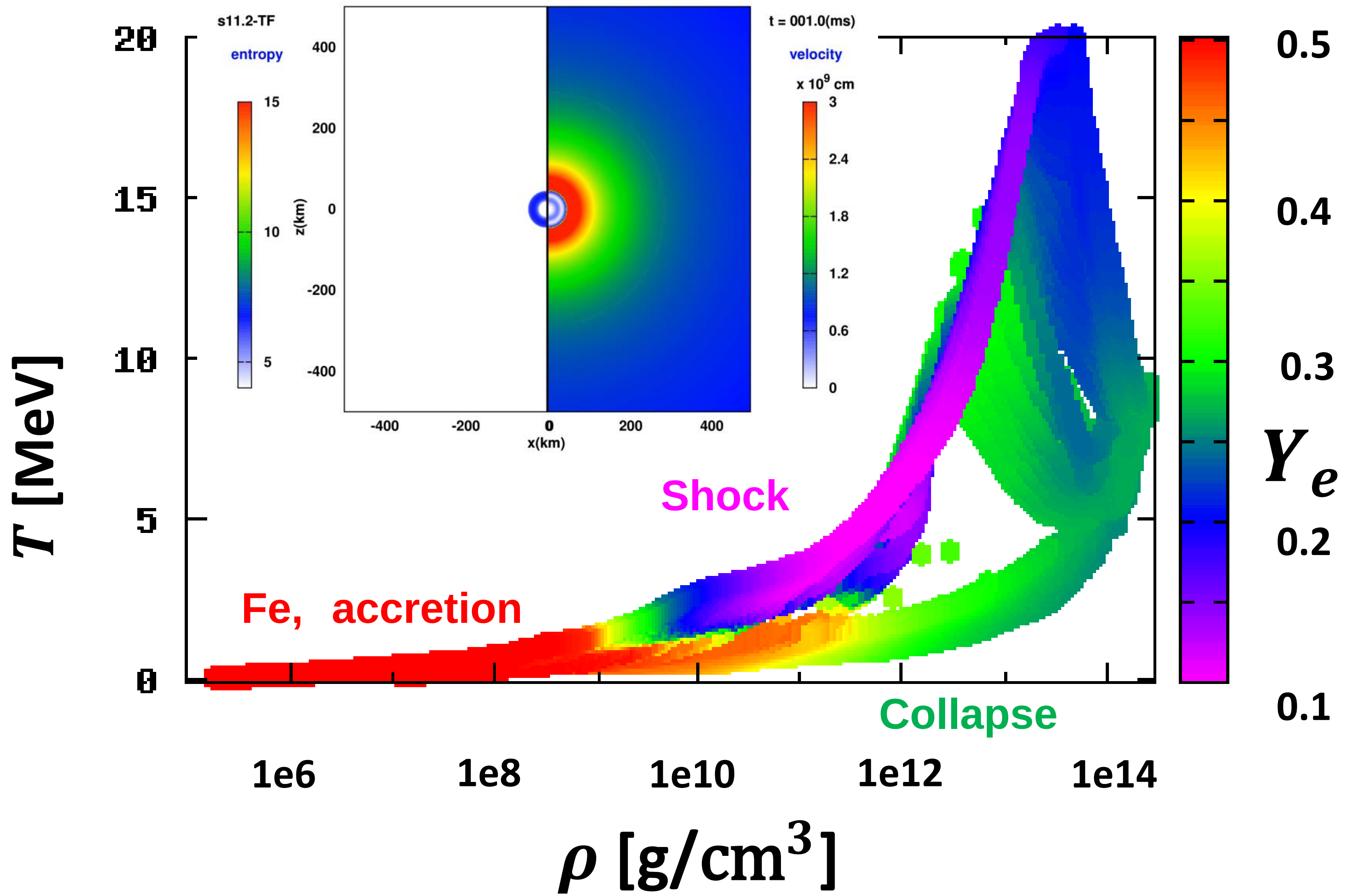
Neutrino Luminosity



⇒smaller mass shell between R_ν and R_s
⇒ **lower peak neutrino luminosity**

(ρ,T,Ye) in Core-Collapse Supernova Simulations

2D CCSN with Togashi-Furusawa EOS (Nagakura+)



Current EOS tables as functions of (ρ, T, Ye)

Soft $R_{1.4}$<12.5 km, $R_{1.4}$=12.5-13.5 km, $R_{1.4}$>13.5 km stiff

・ Single Nucleus Approximation EOS : n, p, α, <A>

- Compressible LDM (LS)- Skyrme 180, 220, 375 (Latimer+'91)
- Thomas-Fermi (STOS) –RMF TM1e (in prep.) , TM1(H. Shen+'98),
  - Variational method with AV18 & UIX (Togashi+'17)

・ Nuclear Statistical Equilibrium EOS : n, p & all nuclei

- HS - SFHo, DD2, TM1, ... (Hempel+'11, Steiner+'13)
- FYSS – AV18 & UIX (SF, Togashi+'17) , TM1 (SF+'13,'17) ,
  - χEFT , DBHF with Bonn A (SF+'19, TM1e (SF+ in prep.)
- RG – SLy4 (Raduta & Gulminelli'18)

・Hybrid EOS : NSE @low ρ & SNA @high ρ

- SHO - FSU, FSU2.1, NL3 (G.Shen et al. '11)
- SRO - SLy4, KDE0v1, NRAPR, LS220 (Schneider et al. '17)

Three modern Nuclear matter theory

1, Variational Method (VM): Togashi+13, 17

- AV18 two-body potential ・UIX three-body potential
- Non-Relativistic formulation for single particle energy
- **Full range of (ρ, T, Y_p)**

2, Dirac Bruckner Hartree Fock (DBHF) Katayama+13

- Bonn A two-body potential
- **Rela.**
- Extrapolation to Finite temperature (SF+'19 accepted in PTEP)

3, chiral Effective Field Theory (**χEFT**) J. Holt+ 18'

- **N2LO ・NN scattering data, ・ ^{3}H βdecay**
- Non-Rela.
- Extrapolation to high density ($\geq 2\, n_0$)

Model	n_{s0} (fm^{-3})	E_0 (MeV)	K_0 (MeV)	J_0 (MeV)	L_0 (MeV)
VM	0.160	-16.0	245	30.0	35.0
DBHF	0.179	-16.6	232	34.5	66.8
χEFT	0.166	-15.9	250	31.3	41.9

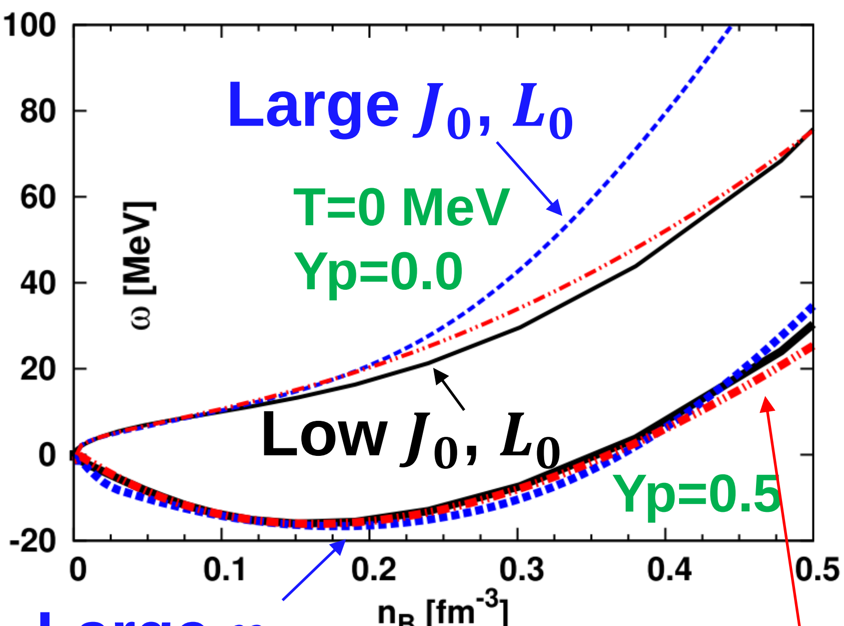
Modern EOSs based on **realistic nuclear forces (NN scattering data)**

Variational Method (VM)

Dirac Bruckner Hartree Fock (DBHF)

chiral Effective Field Theory (χEFT)

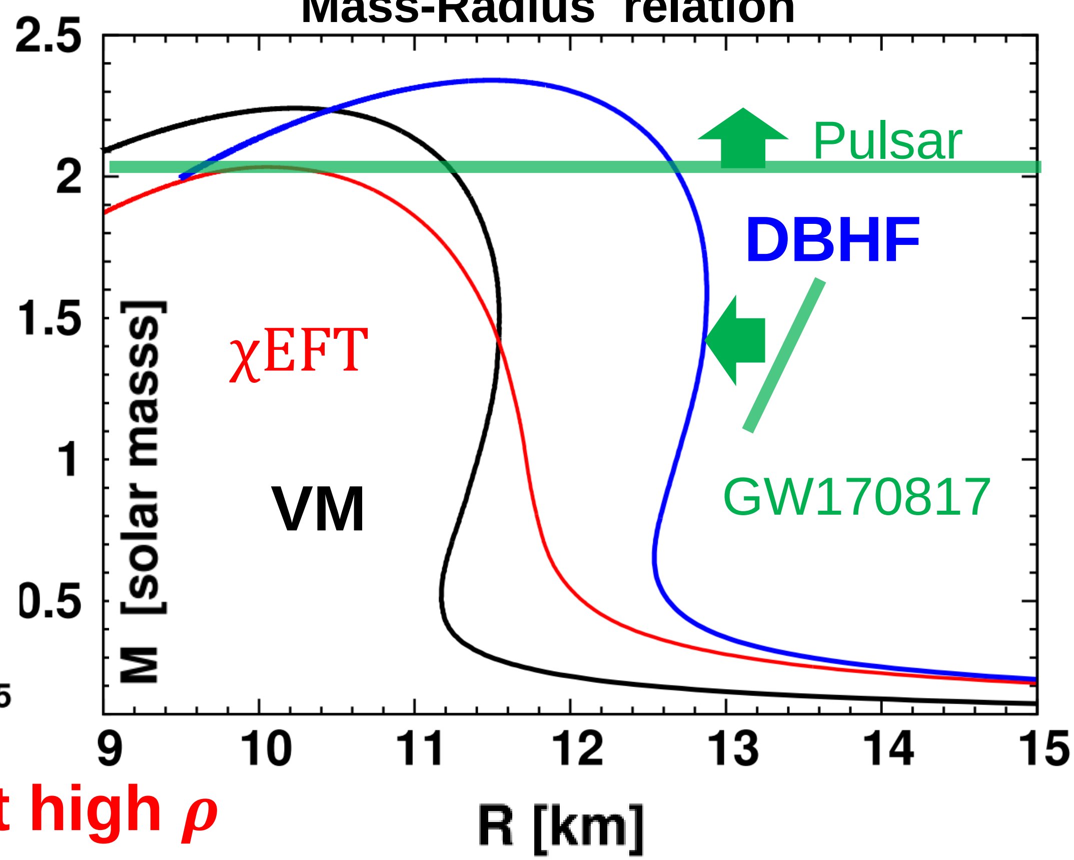
Energy per baryon



Large n_0
Low E_0

Softest at high ρ

Mass-Radius relation



Three Extended Nuclear Statistical Equilibrium EOS

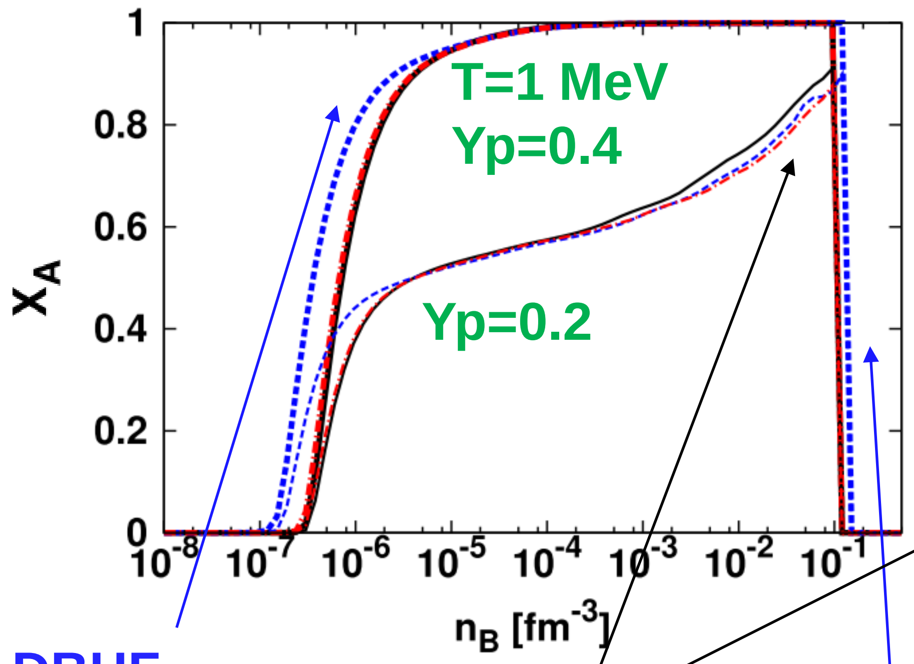
(Liquid Drop model with mass data for heavy nuclei and quantum approach for light nuclei)

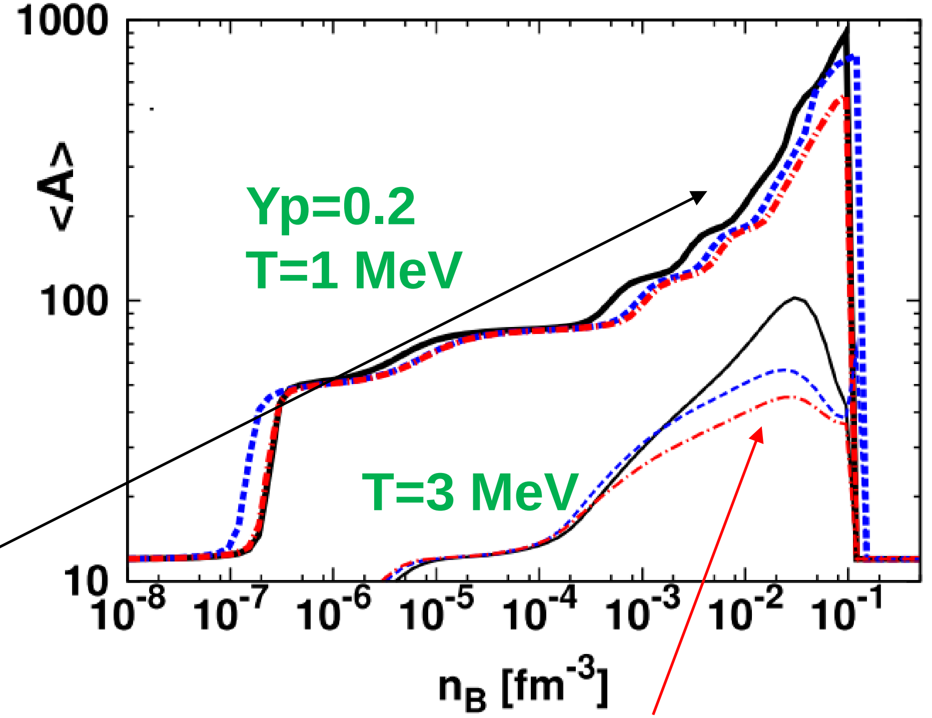
・Variational Method (VM) (SF+'17d, JPG)

・Dirac Bruckner Hartree Fock (DBHF) (SF+'19, PTEP)

・chiral Effective Field Theory (χEFT) (in prep)

& consistent weak interaction rates for nuclei (SF+'17c, H. Nagakura, SF '19)





DBHF Low E_0

VM low J_0

DBHF Large n_0

χEFT **low surface tension**

Summary

- We construct 3 data sets of EOS and consistent weak rate based on realistic nuclear **forces (NN scattering data)**
  ① Variational method (Togashi+),
  ② Dirac Bruckner Hartree Fock (Katayama +), and
  ③ chiral Effective Field Theory(Holt+)

- VM is soft at $Y_p = 0.0$ and gives large mass fractions of large mass neutron-rich nuclei
- DBHF is soft at $Y_p = 0.5$ and stiff for at $Y_p = 0.0$ and gives large mass fractions of medium mass symmetric nuclei
- χEFT is between the two and show low average mass number

- We compare them in SN simulations.