Nuclear equation-of-state and Nuclei in Core-Collapse Supernovae

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iTHEMS

reference: SF & H. Nagakura (2023) Progress in Particle and Nuclear Physics 129, 104018, (Nucl-th: arXiv:2211.01050)

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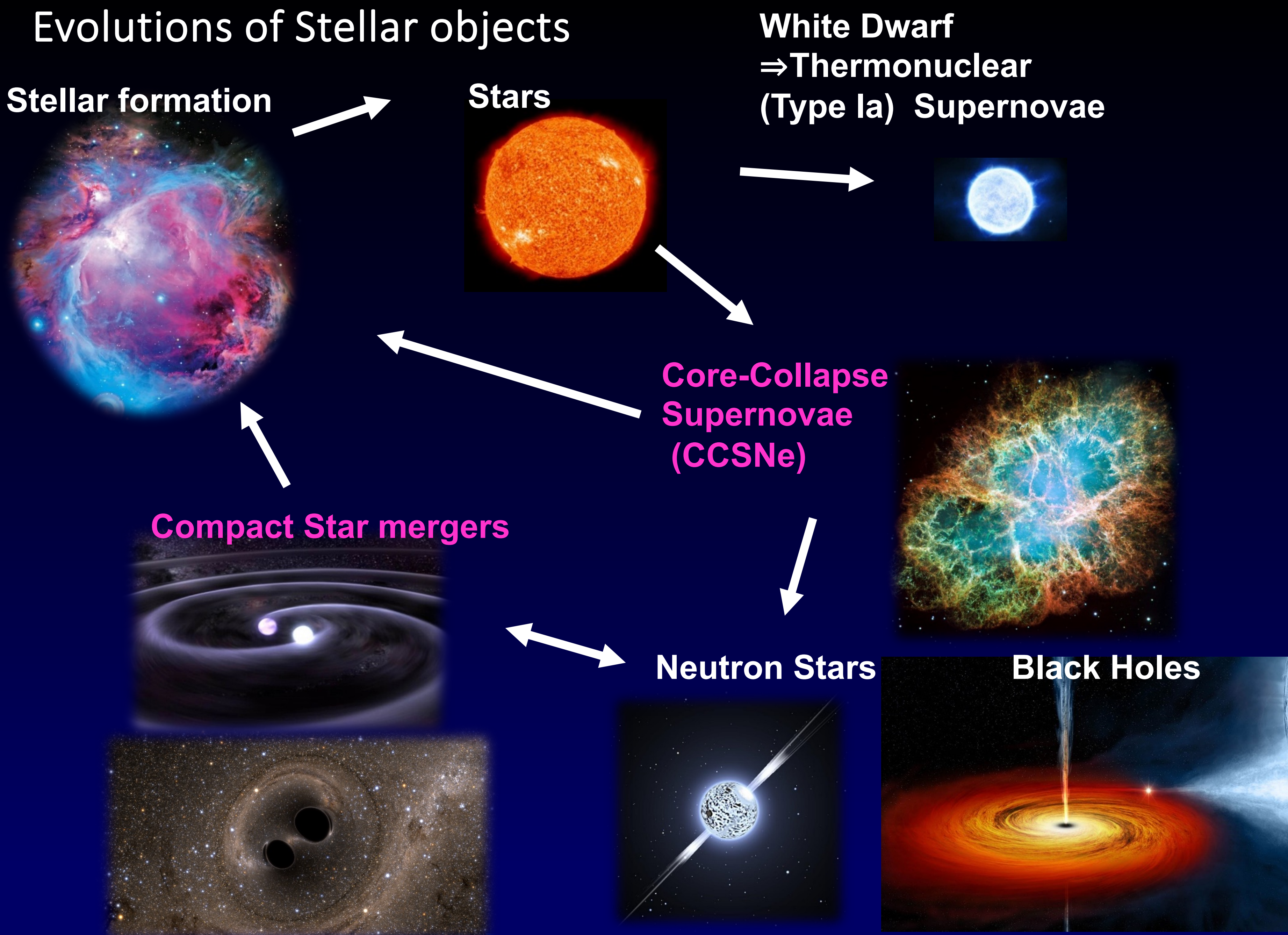
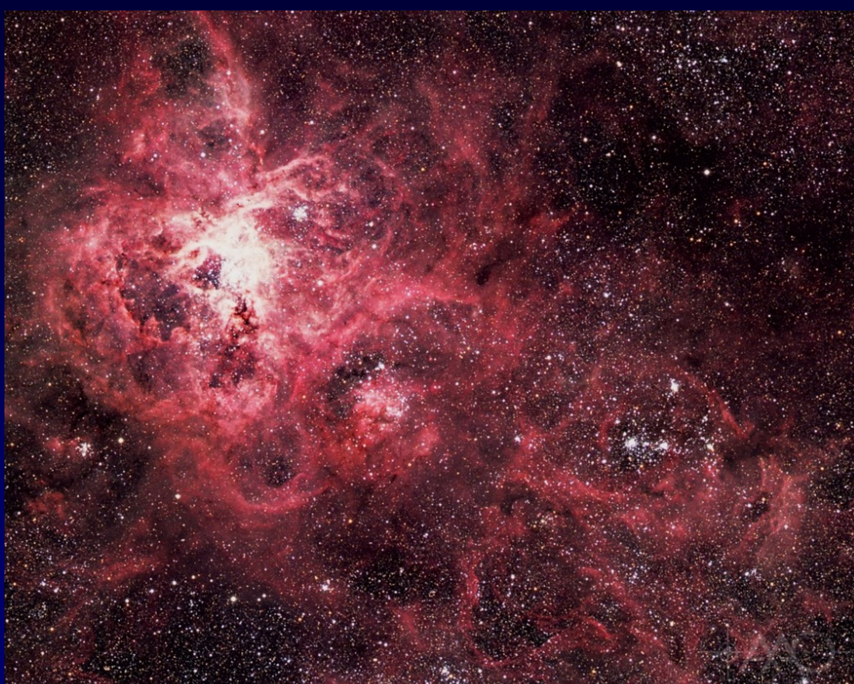
Evolutions of Stellar objects

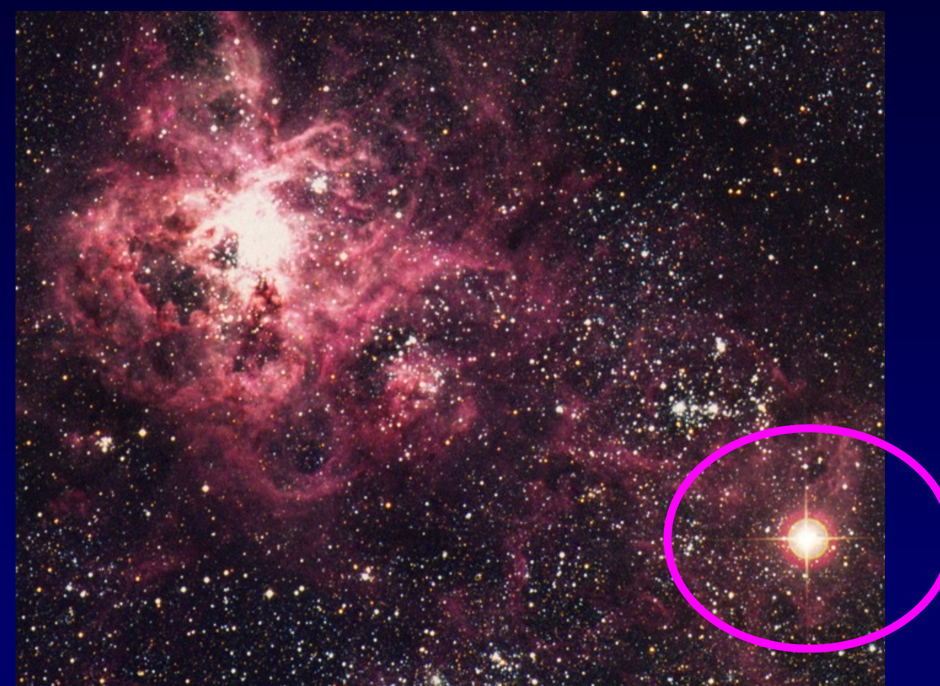


Core-Collapse Supernovae

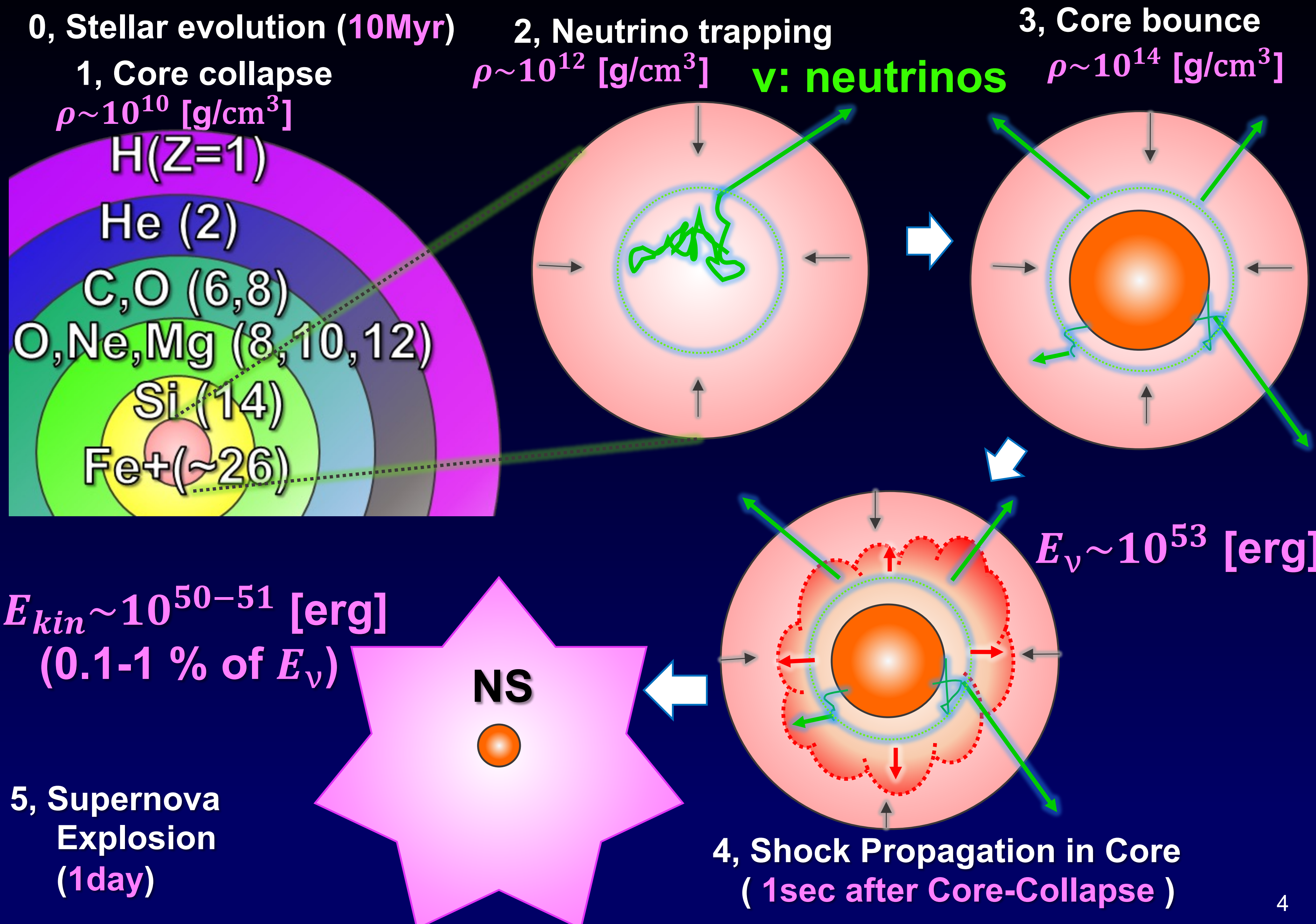
- **Energetic evets 10^{50-51} erg (ejecta), 10^{53} erg (neutrino)**
- **Emissions of neutrinos and gravitational Waves**
- **Formations of a neutron star or a black hole**
- **Nucleosynthesis site of heavy elements**
- Extreme test for nuclear physics



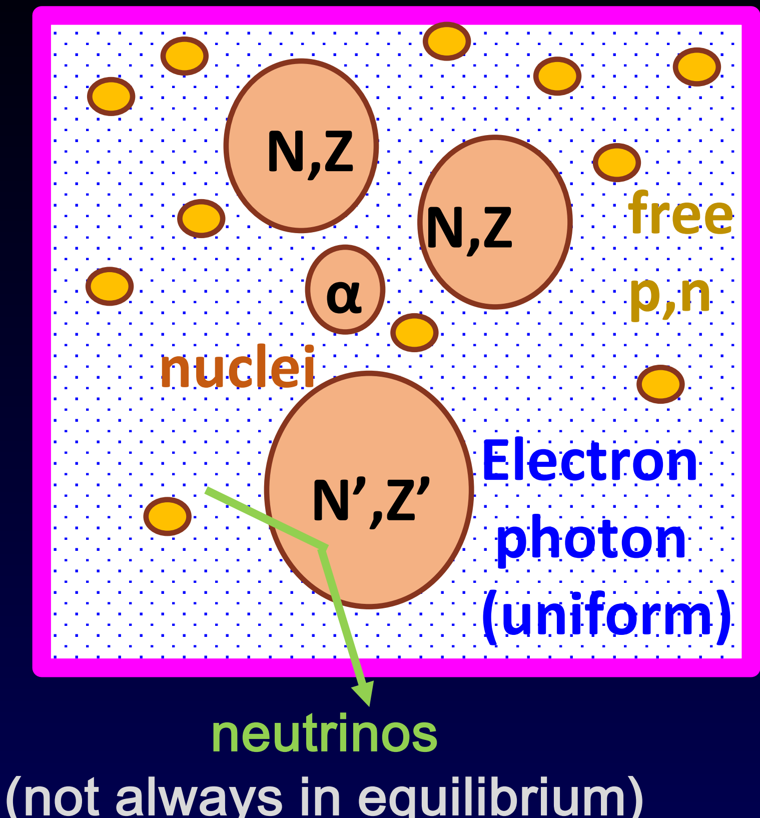
SN 1987A

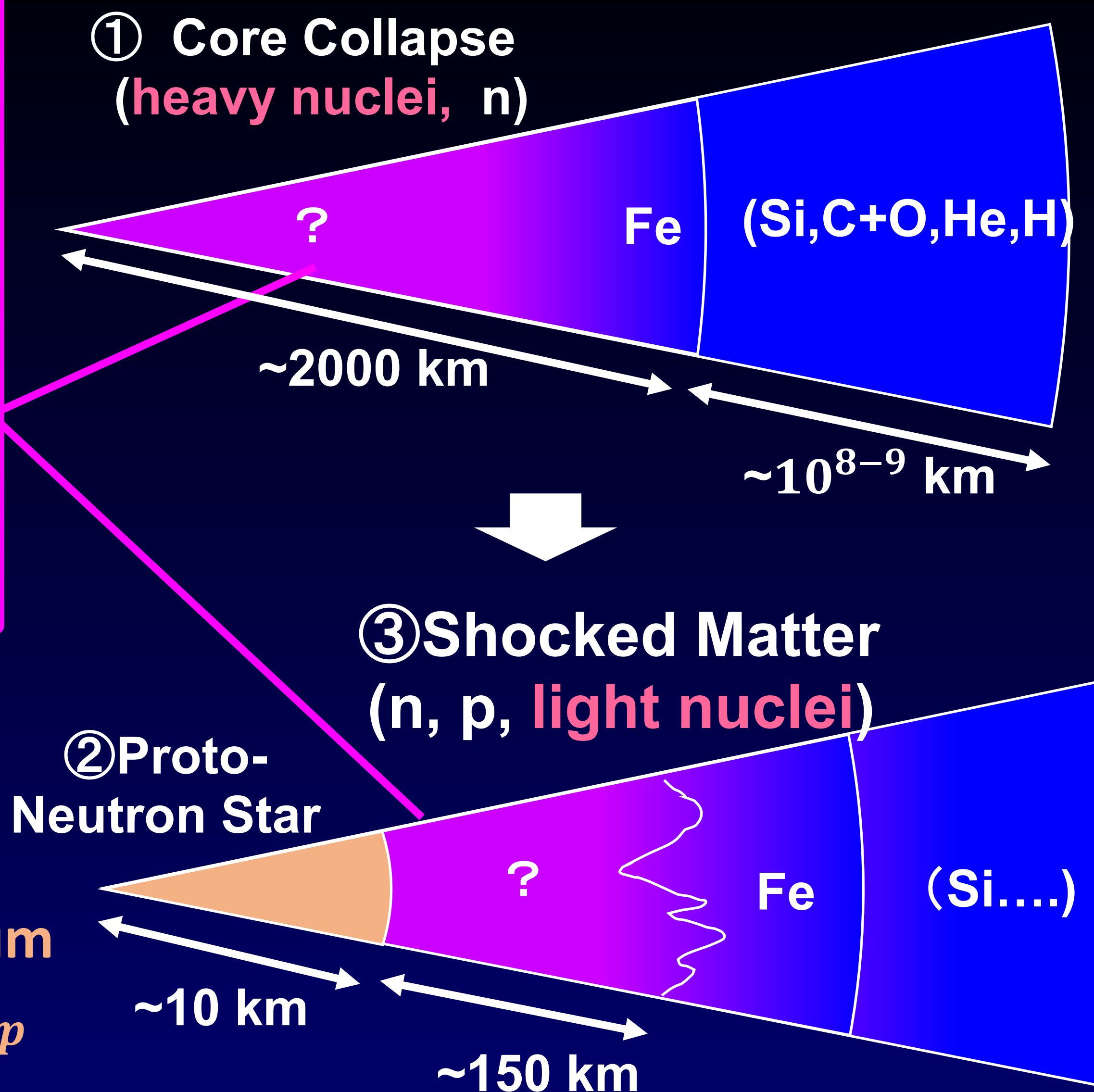


Core-Collapse Supernovae



Supernova matter and Nuclear Statistical Equilibrium



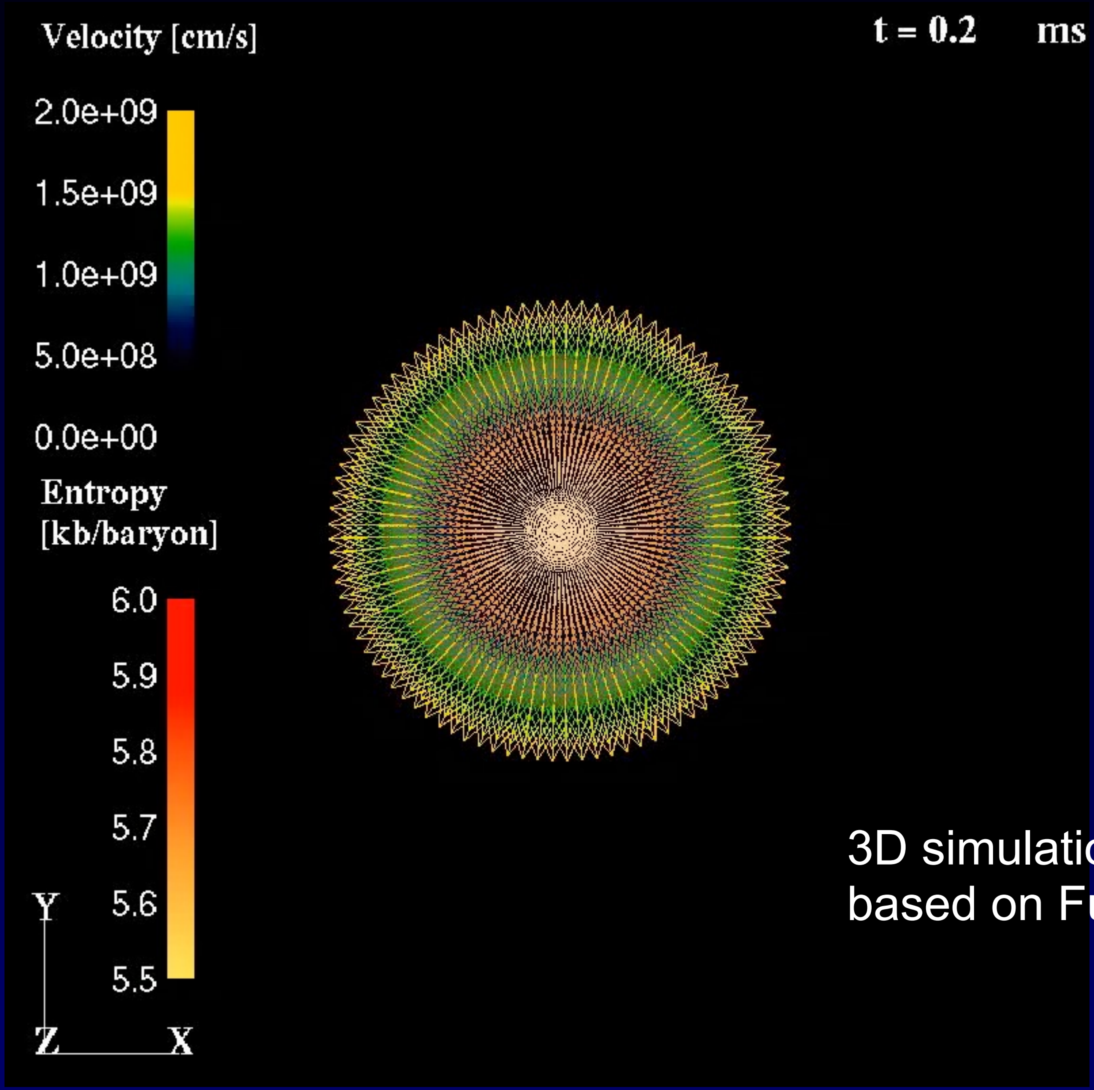


nuclei, p & n :
Nuclear Statistical Equilibrium
(NSE) $\mu(N,Z) = N\mu_n + Z\mu_p$

$$(N,Z) \pm n \leftrightarrow (N \pm 1, Z)$$
$$(N,Z) \pm p \leftrightarrow (N, Z \pm 1)$$

Supernova Simulations

① Hydrodynamics of matter in 3D space
② Neutrino transport in 3D space + 3D momentum space



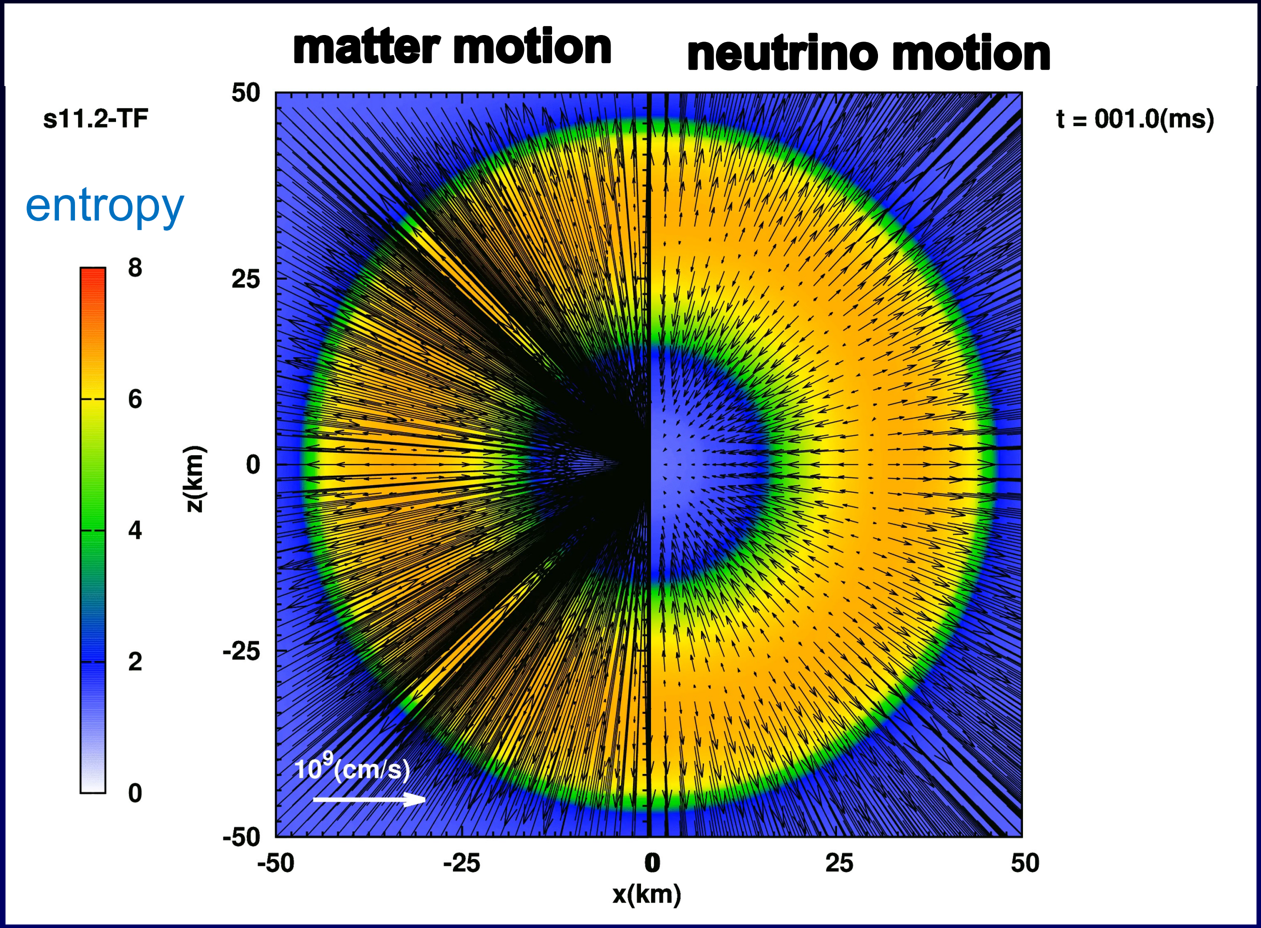
3D simulation（Iwakami+ 22）
based on Furusawa-Togashi EOS (SF+17d)

Nuclear Physics Inputs of Supernova Simulations

① Equation of State(EOS) Nuclear matter model (stiffness), Nuclear model (Which nuclei ?)

② Weak interaction rates (Neutrino emissions, absorptions, and scattering)

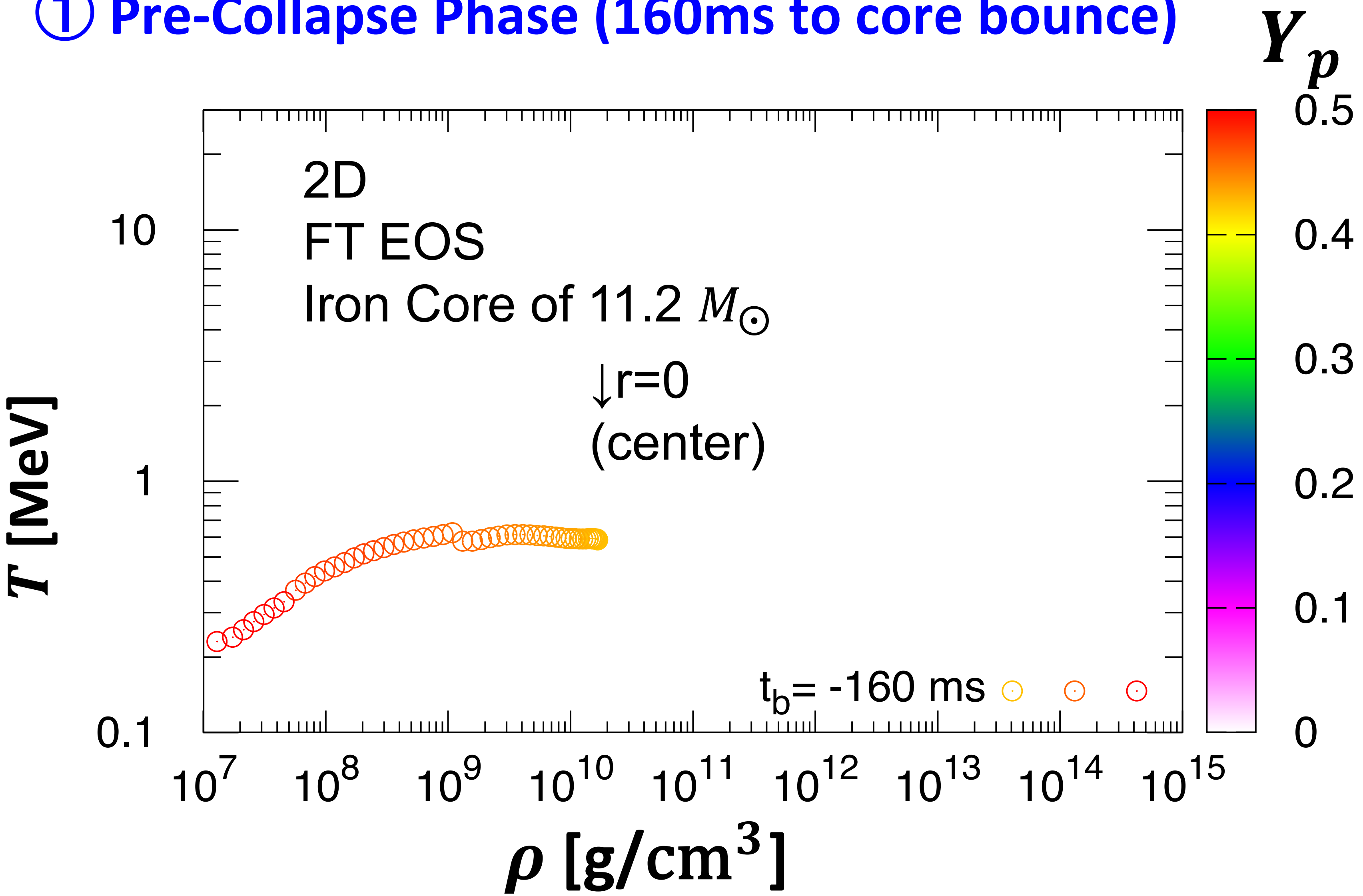
Ex. $(N, Z) + e^{-} \leftrightarrow (N+1, Z-1) + \nu_e$



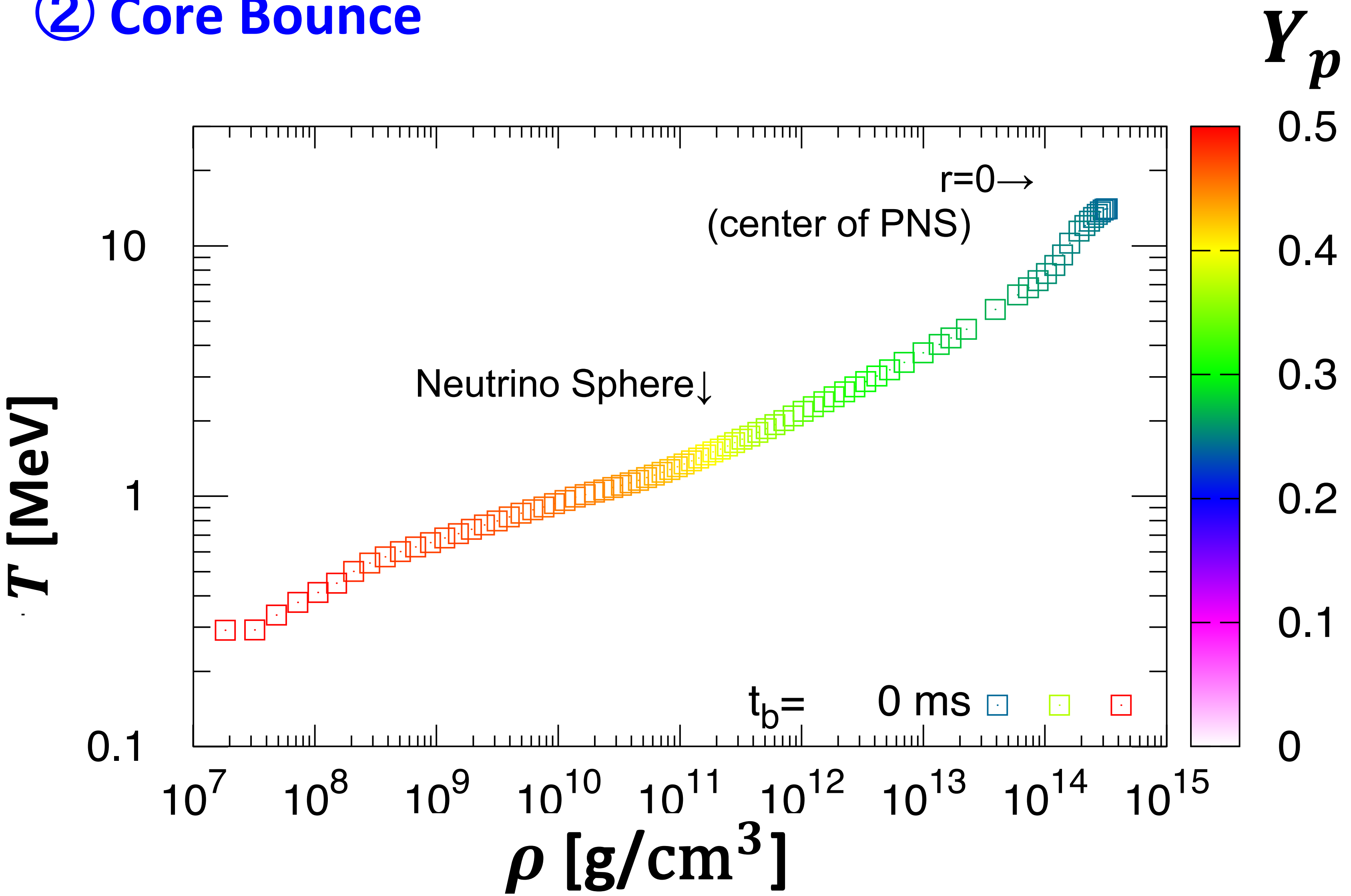
Motions of neutrinos and matter around Proto-Neutron Star （Nagakura+18）

Togashi-Furusawa EOS (SF+17d)

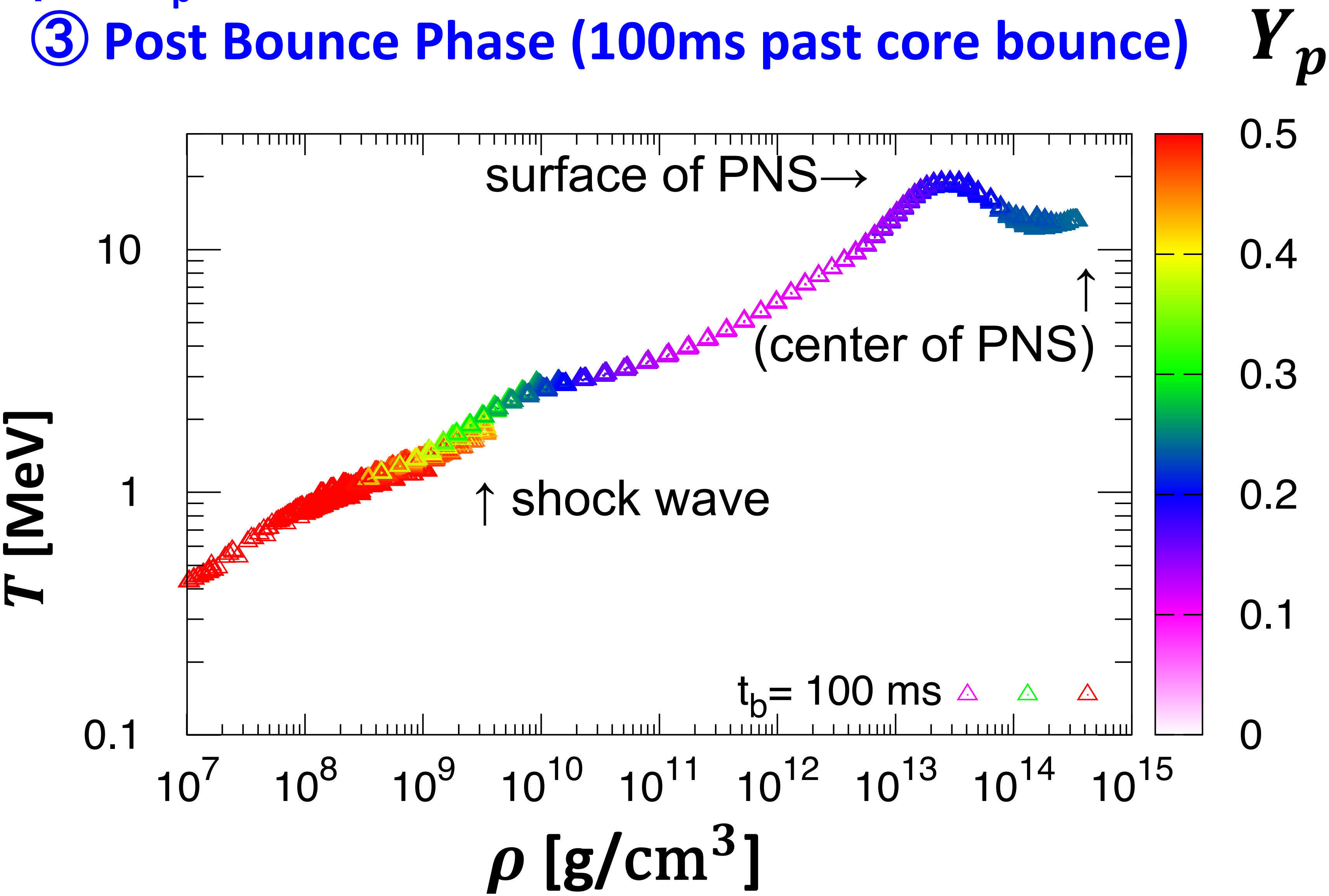
(ρ, T, Y_p) in Core-Collapse Supernova Simulations
① Pre-Collapse Phase (160ms to core bounce)



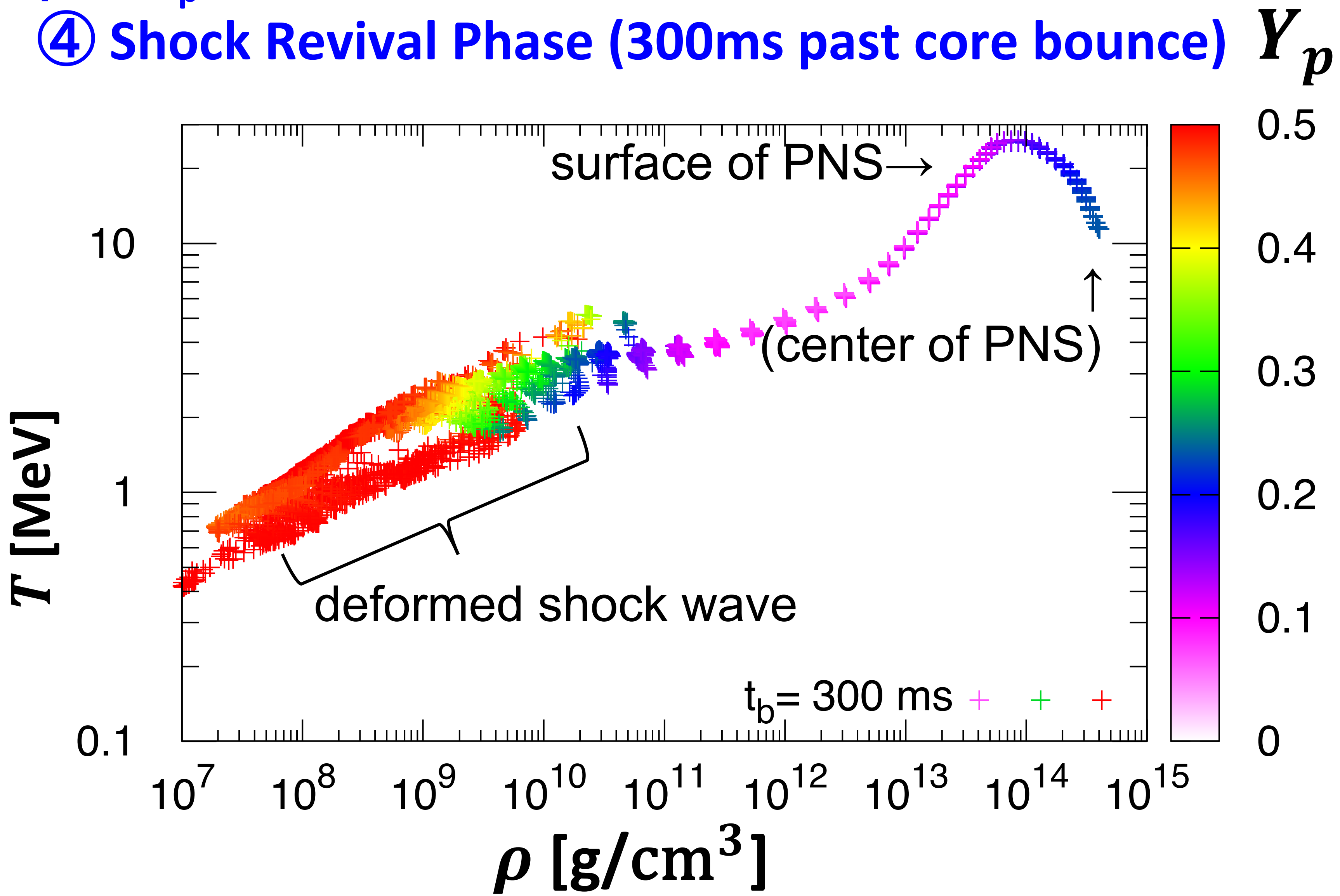
(ρ,T,Y_p) in Core-Collapse Supernova Simulations
② Core Bounce



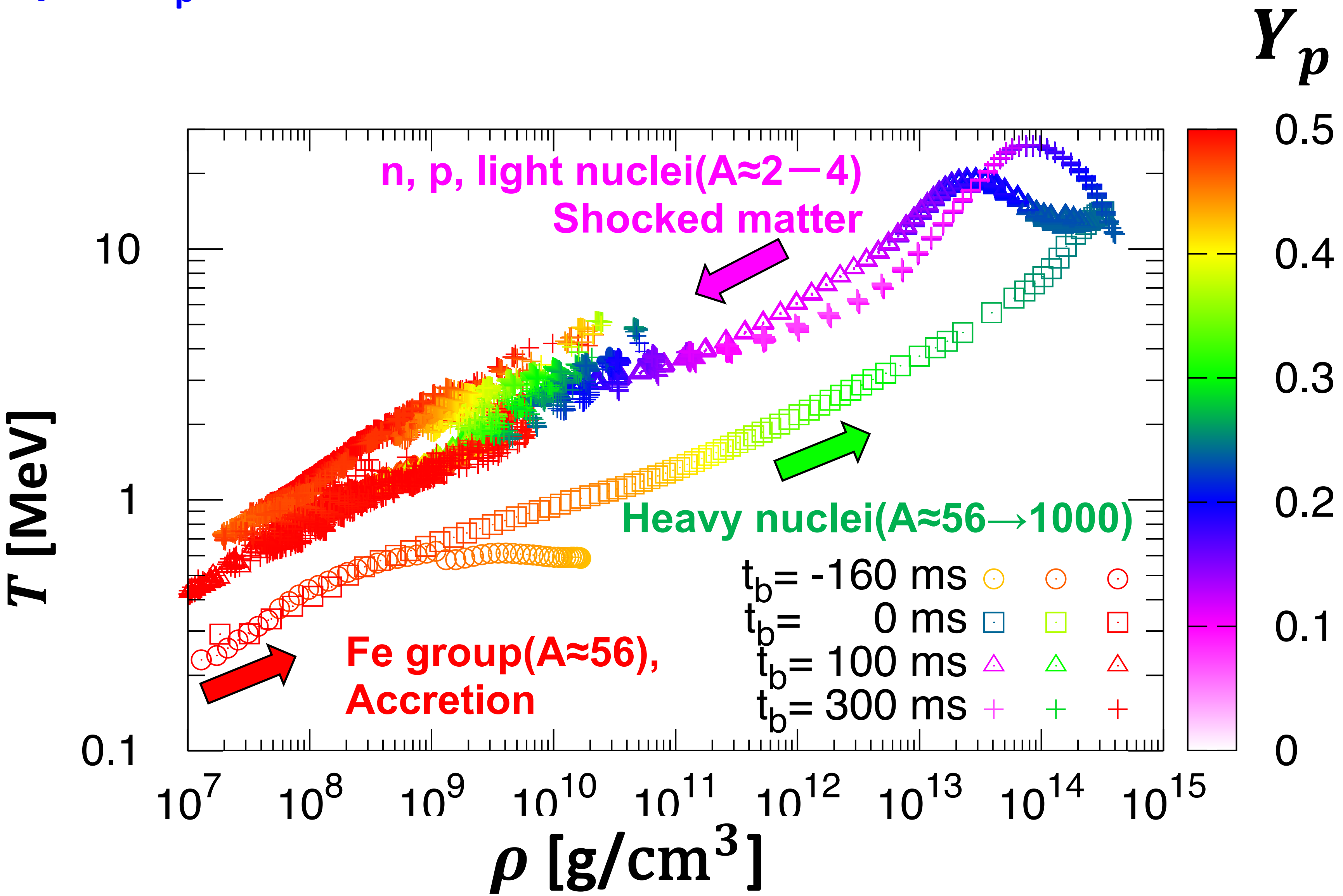
(ρ,T,Y_p) in Core-Collapse Supernova Simulations
③ Post Bounce Phase (100ms past core bounce)



(ρ, T, Y_p) in Core-Collapse Supernova Simulations
④ Shock Revival Phase (300ms past core bounce)



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



EOS tables as functions of (ρ, T, Yp)

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

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

- Compressible LDM (LS)- Skyrme 180, 220, 375 (Latimer+’91)
- Thomas-Fermi (STOS) –TM1e (H. Shen+’21) , TM1(H. Shen+’98),
  - Variational method (Togashi+’17)

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

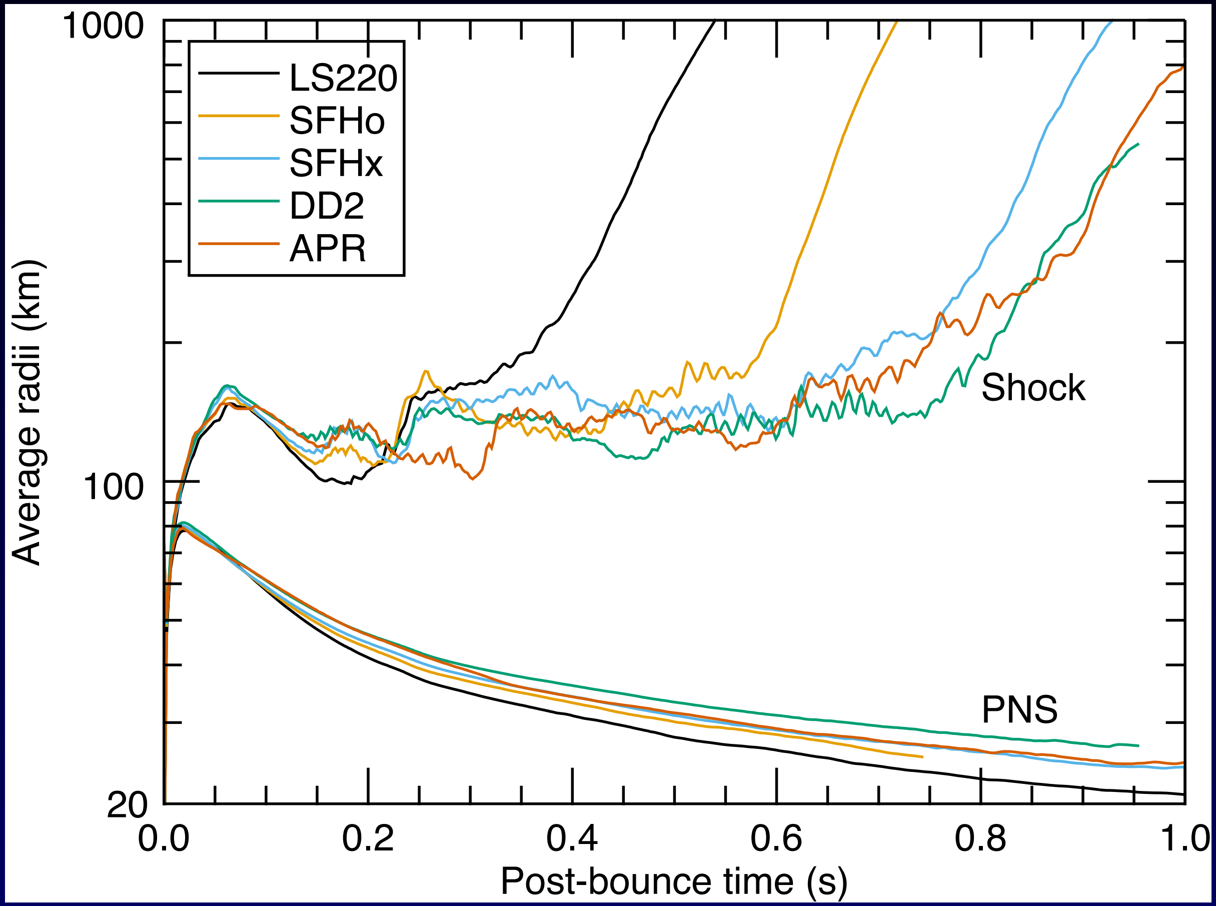
- HS - SFHo, DD2, TM1, ... (Hempel+’11, Steiner+’13)
- FYSS – Variational method (SF+’17d) DBHF (SF+,’20) TM1 (SF+’17a)
- RG – SLy4 (Raduta & Gulminelli‘18)
- GRDF1, GRDF2 –DD2 (Pais’17, Typel’18)
- UTK (Du+ ’19, ’22): HS NSE &Skyrme based on χ EFT, 9 version

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

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

Impact of EOSs on Supernova Simulations 1/3

① Softer EOSs give smaller PNS radii and larger shock radii.
(e.g. Suwa+ ’13, Harada+’20, Bolling+ 17)



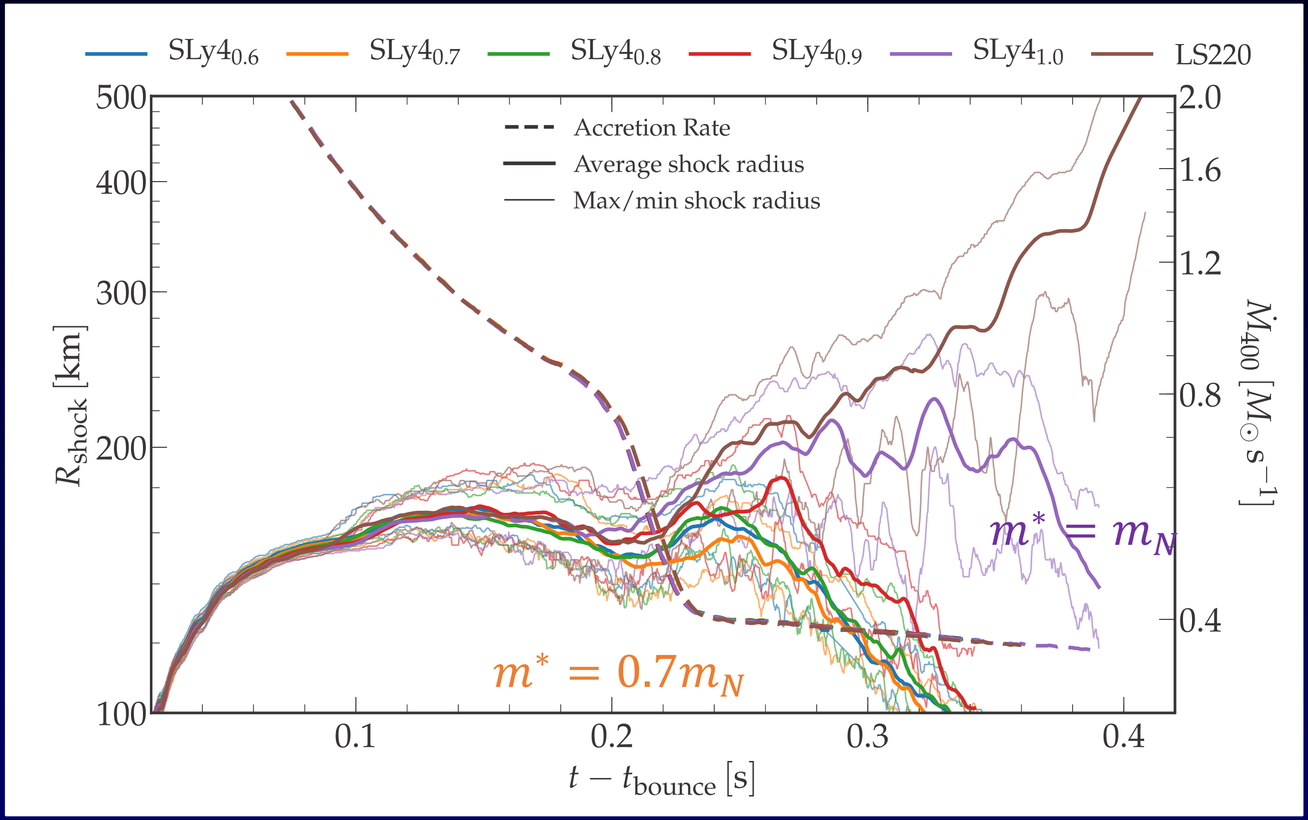
Janaka & Bauswein ‘22

② Effective mass and/or entropy densities are key ?
③ Nuclear model affects the dynamics more than stiffness.

Impact of EOSs on Supernova Simulations 2/3

① Softer EOSs give smaller PNS radii and larger shock radii.
② Effective mass (Schneider +'19) and/or entropy densities (Boccioli+ '22) may be key parameters for PNS structure, convection, and dynamics.

$m^*/m_N = 0.6, \quad 0.7, \quad 0.8, \quad 0.9, \quad 1.0, \quad LS220$



Schneider+ '19

see also
Yasin+ '20 PRL

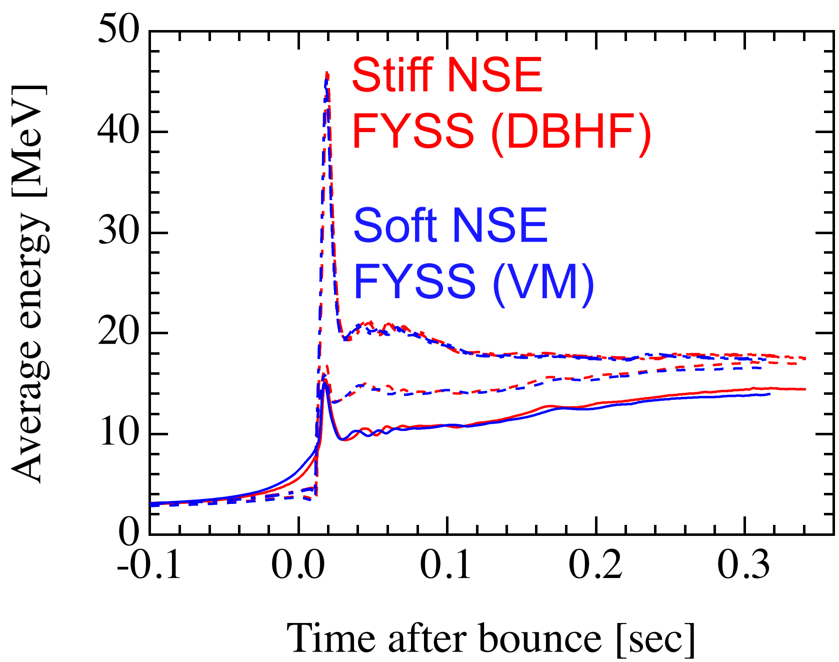
Large effective mass ⇨ small thermal pressure ⇨ compact PNS

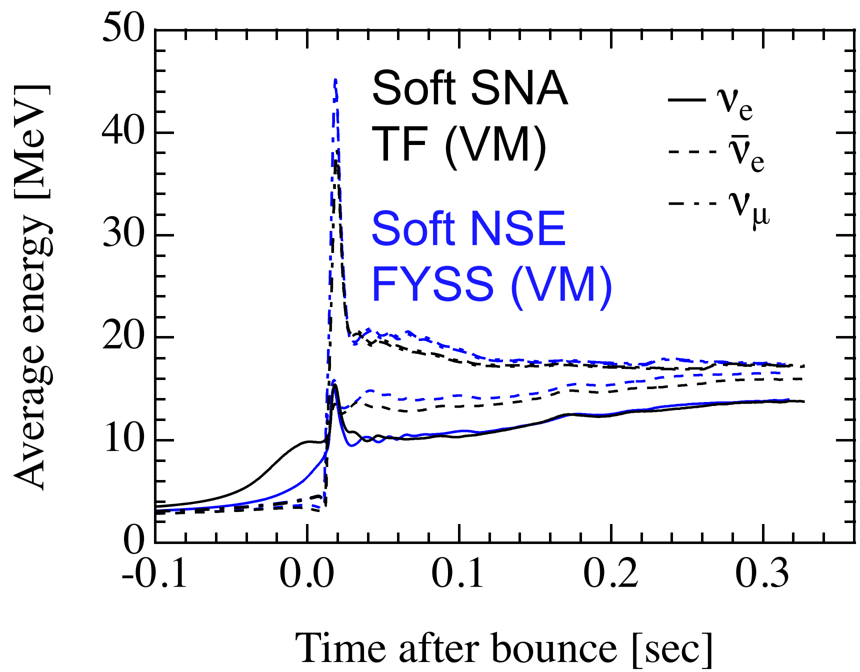
③ Nuclear model affects the dynamics more than stiffness

Impact of EOSs on Supernova Simulations 3/3

① Softer EOSs give smaller PNS radii and larger shock radii.
② Effective mass and/or entropy densities are key ?
③ Nuclear model affects the dynamics more than nuclear matter model

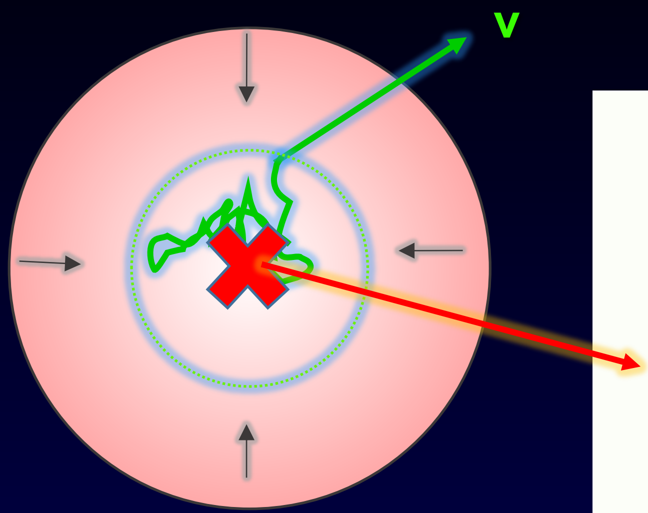
nuclear matter difference (Soft or Stiff) < Nuclear model diiference (NSE or SNA)



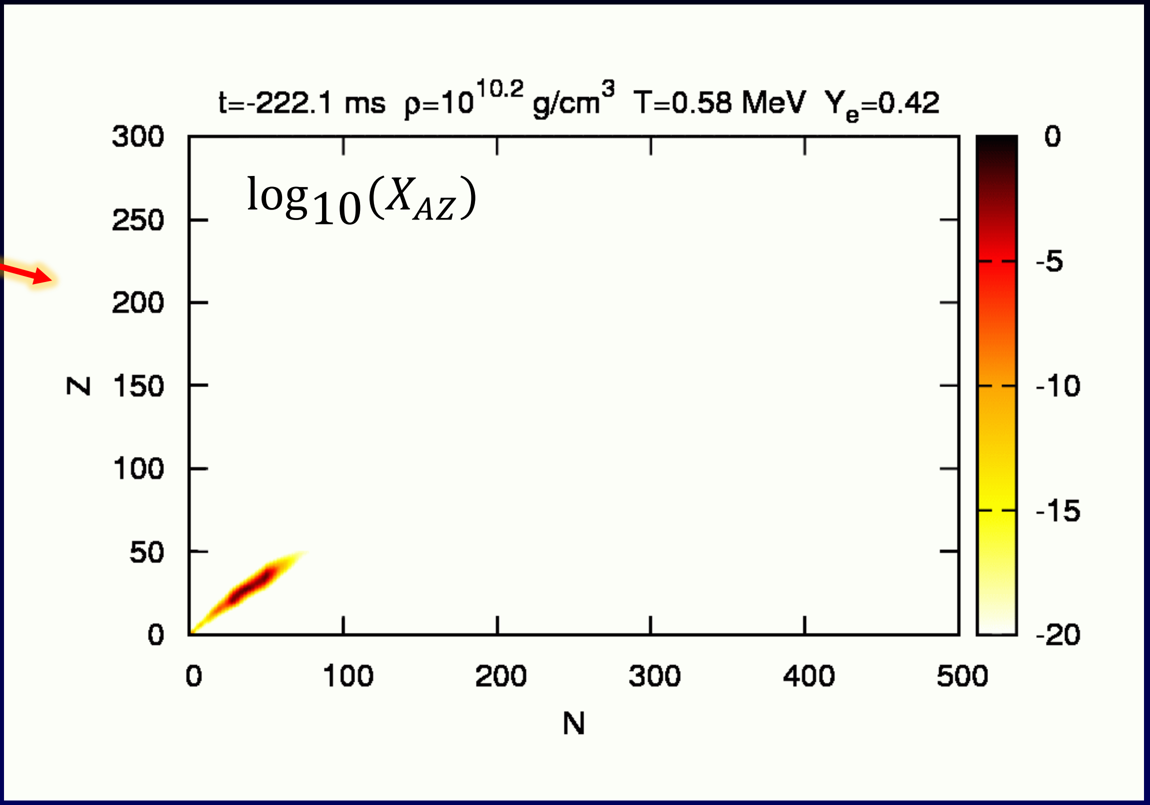


1D systematic EOS comparison
Sumiyoshi, SF+ '22 (see also Hempel+' 12, Suwa +13)

Nuclei in stellar core collapse



mass fractions of nuclei at center

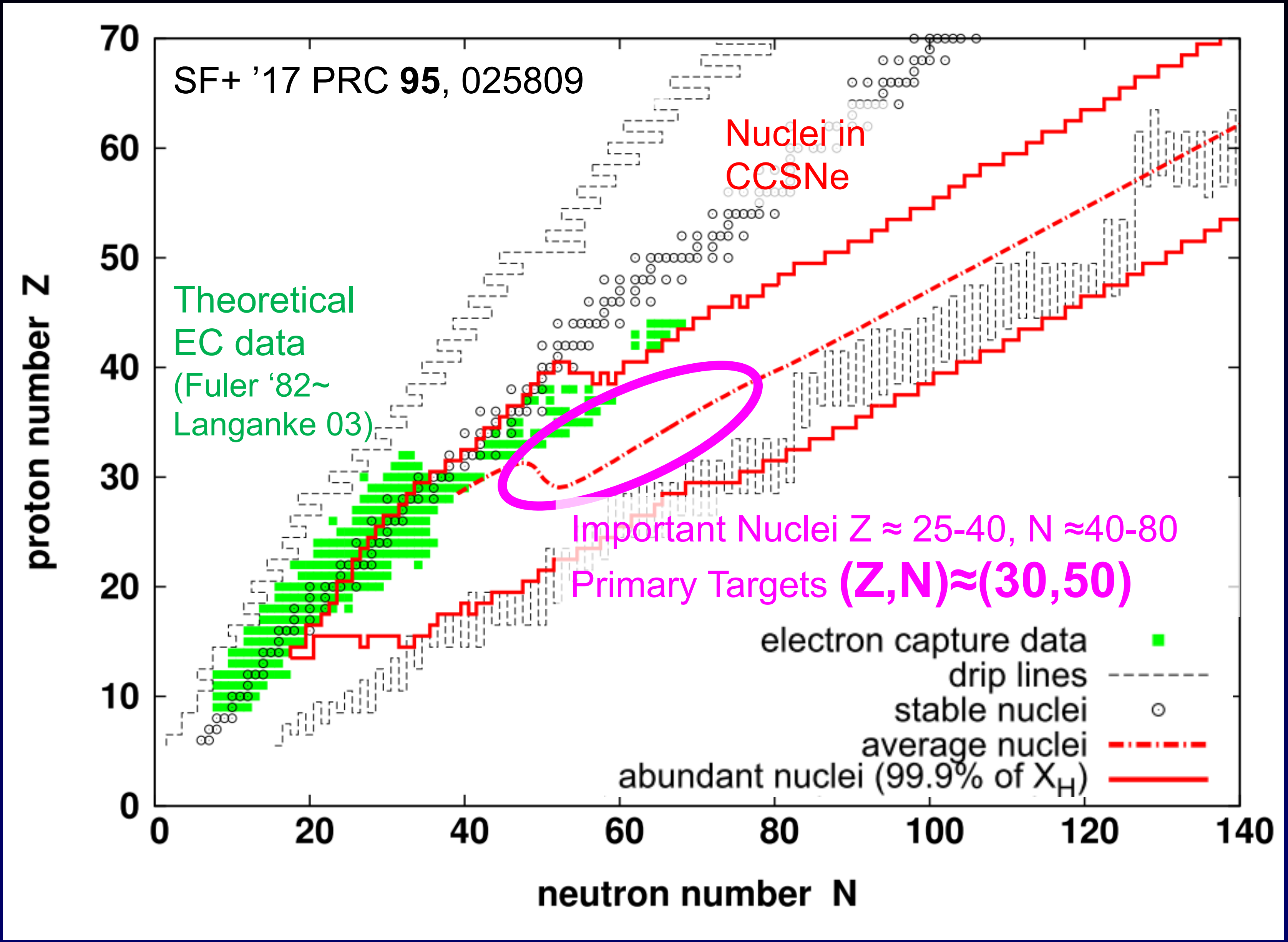


- Dense electrons reduce nuclear Coulomb energy.
  → **large mass nuclei**
- $\mu_n > \mu_p$
  → **neutron-rich nuclei**

Sensitive to **nuclear excitation models** in NSE calculations.
Mass data and nuclear interaction are trivial **(Furusawa** ’18 PRC 98, 065802**)**

Lack of Electron Capture Data

$$(N, Z) + e^- \rightarrow (N + 1, Z - 1) + \nu_e$$



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

$(N, Z) + e^- \leftrightarrow (N+1, Z-1) + \nu_e$

More electron capture rates

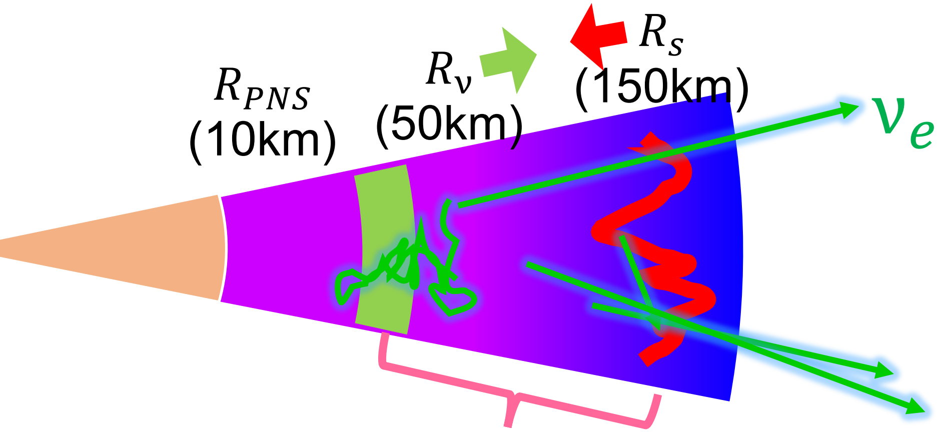
⇒ ①fewer leptons in PNS

⇒smaller mass of PNS

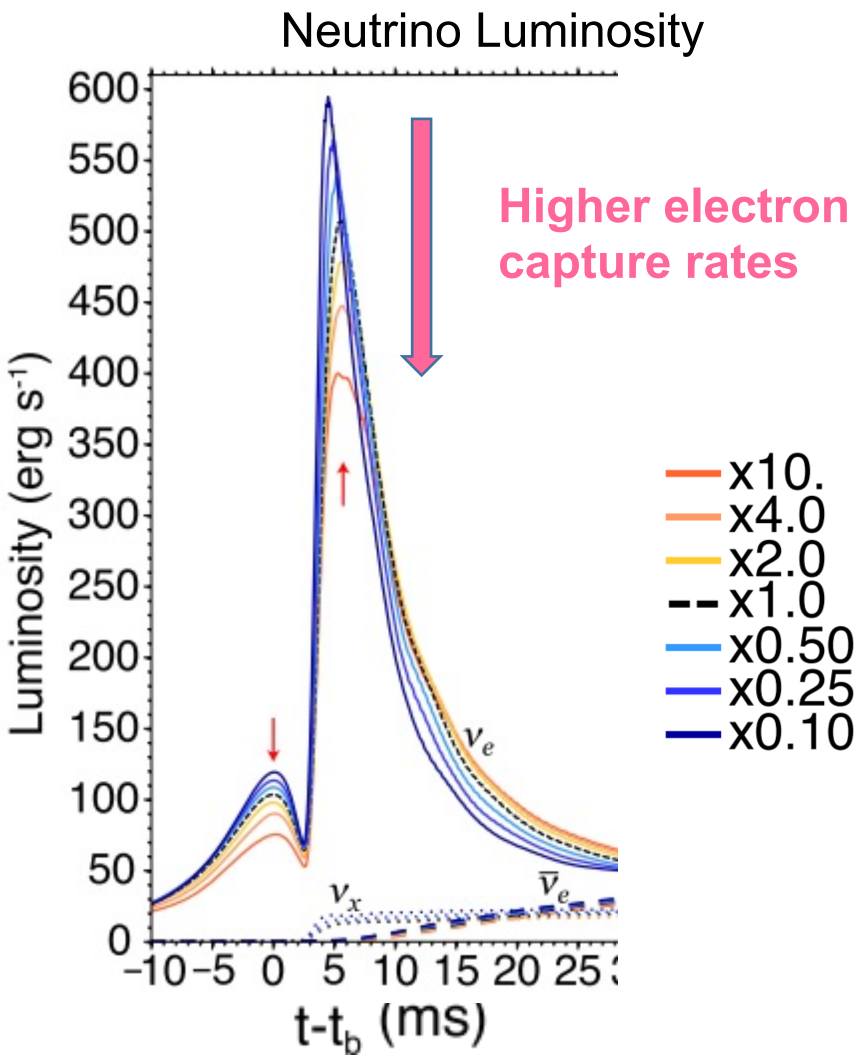
⇒**smaller shock radius R_s**

⇒② more neutrino captures around R_ν

⇒**larger neutrino sphere R_ν**

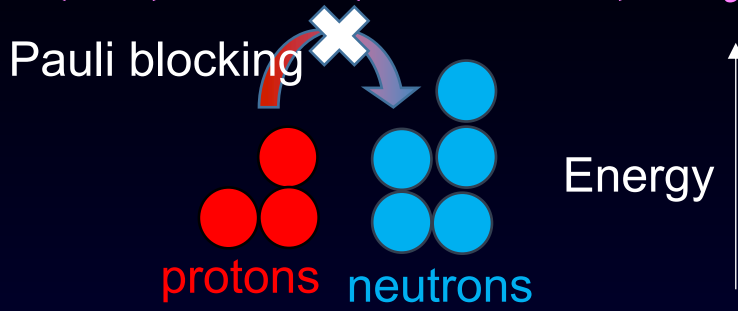


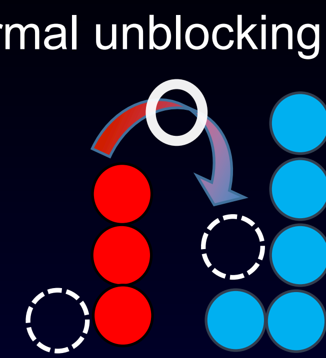
⇒ **smaller neutrino emissions**



Electron Capture rates in Supernovae

$(N,Z) + e^- \leftrightarrow (N+1, Z-1) + \nu_e$

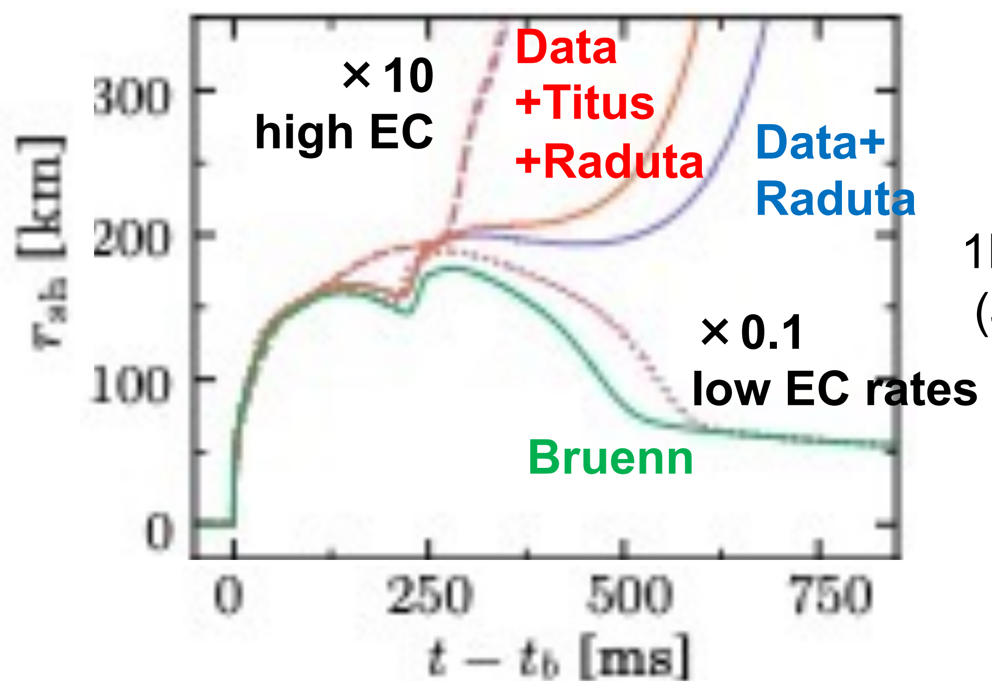




1. Bruenn+'85, N>40 reaction rate=0 Pauli blocking
2. Langanke+'03, fitting formula with thermal unblocking (for pf nuclei(N~30))
3. Raduta+'17, Titus+'18, Dzhioev+'20, Litvinova'21 Giraud+ '22

   revisit thermal unblocking for nuclei , N~50

Larger EC rate
⇨more ν heating
(Larger ν_eC rate?
faster PNS
contraction?)
⇨faster Shock revival

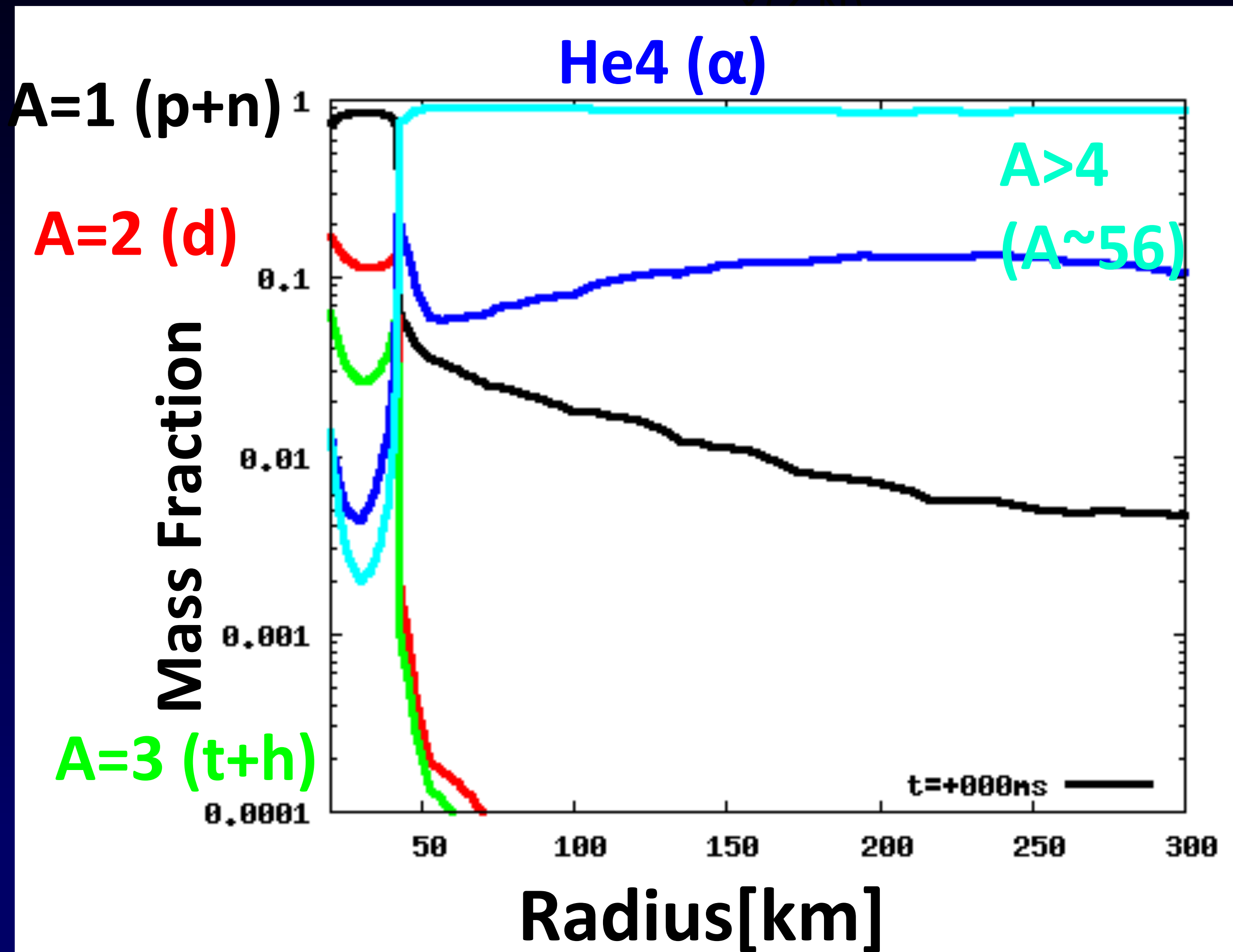


1D comparison
(Johnston+ '22)

Nuclei after bounce.

Light cluster (especially deuteron) physics
may affect shock dynamics
(SF+13, Fischer+'18, Nagakura+ 19)

Mass fraction of shocked matter



Summary

- Core-Collapse Supernovae (CCSNe) greatly depend on equation of state (EOS) and weak interaction data.
- The faster Proto-Neutron Star Contraction leads to faster shock revival (Janka+22)
  ex. fewer ν scattering (Melson+'15), Muons (Bolling+ '17), Softer EOS (Harada +20), larger m^*(Schneider+'18, Yasin+20) larger electron capture rates? (Johnston+ '22)
- The Nuclear model has greater impacts on the shock revival more than nuclear matter model. (Sumiyoshi +22)
- Nuclei with (N,Z)≈(50,30) appear at $\rho\sim10^{11-12}$g/cc.
  The most ambiguous parts in the nuclear model is nuclear excitation model (SF '18 PRC)

Key Question: What does determine CCSNe dynamics in nuclear matter theory and in nuclear model?