Nuclei in Core-Collapse Supernovae

・Nuclei in supernova central engines

・Their roles in supernova dynamics

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Evolutions of Stellar objects

Stellar formation

Stars

White Dwarf
⇒Thermonuclear
(Type Ia) Supernovae

Core-Collapse Supernovae (CCSNe)

Compact Star mergers

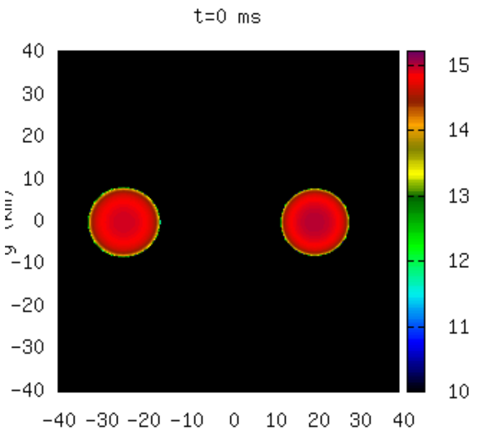
Neutron Stars

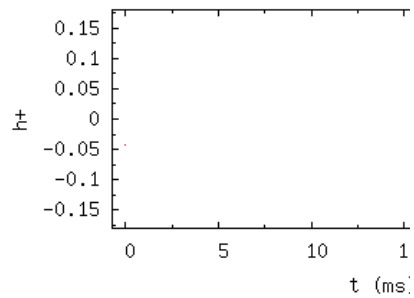
Black Holes

Gravitational Wave & Stiffness of Nuclear matter Equation of State

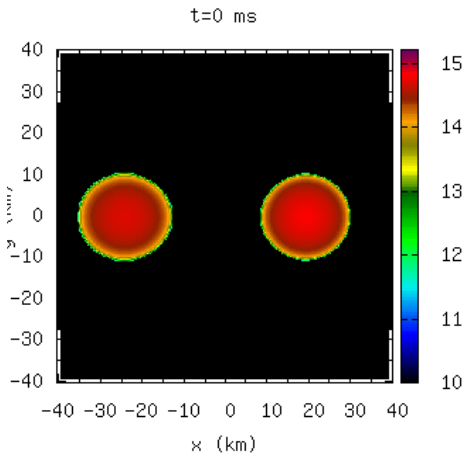
Gravitational Wave Signal (Hotokezaka '11)

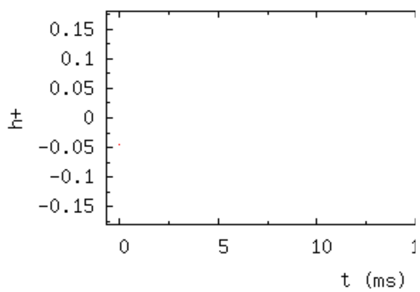
Soft EOS (APR4)

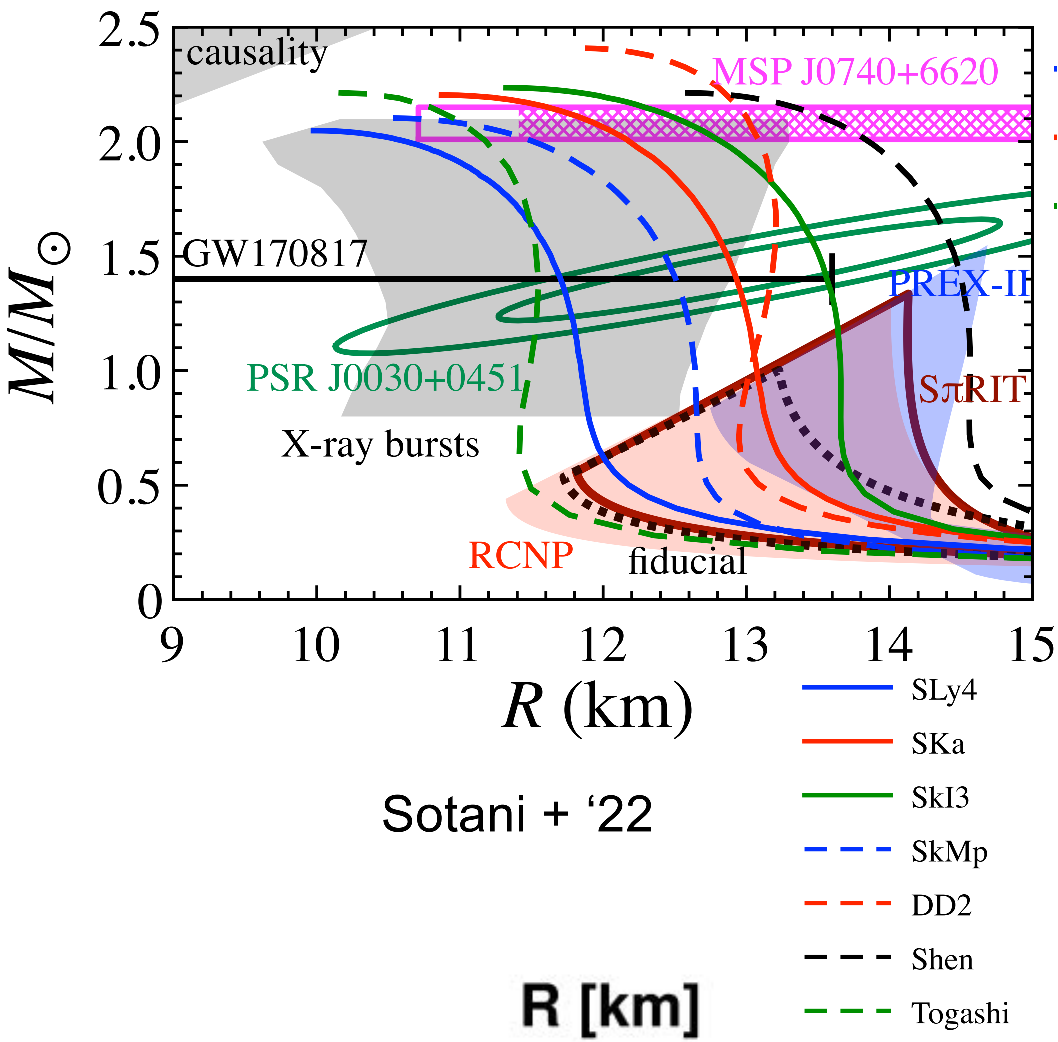




Stiff EOS (H4)







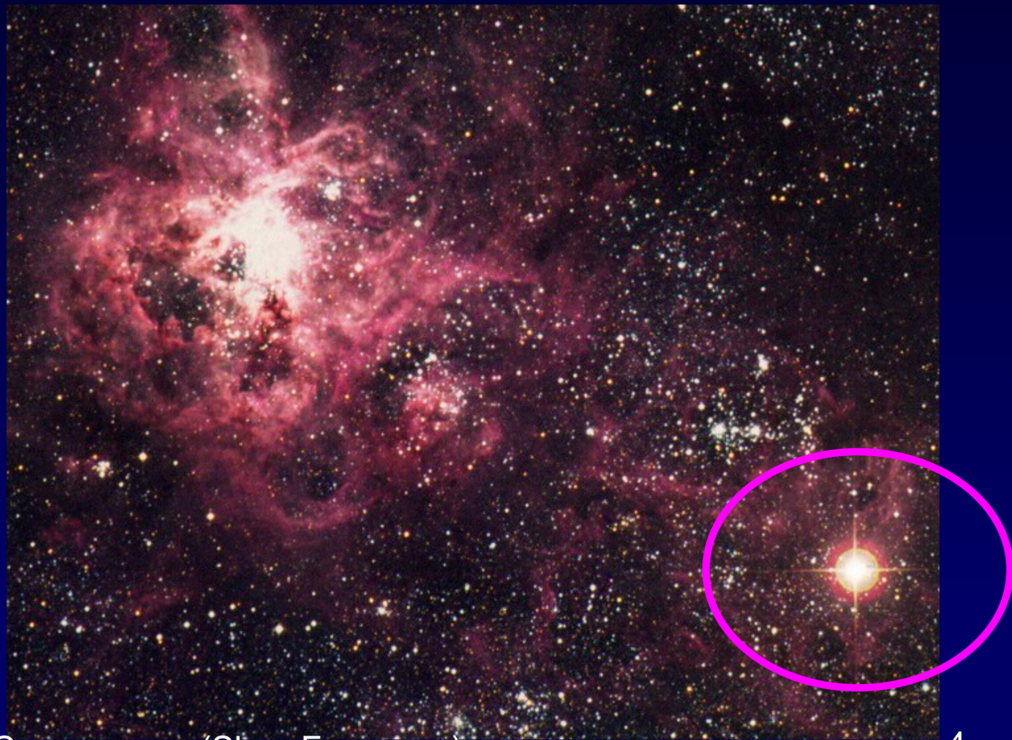
Sotani + '22

Neutron star matter (zero temperature & beta equilibrium) EOS may be constrained. ⇒ finite temperature and arbitrary proton fraction ?

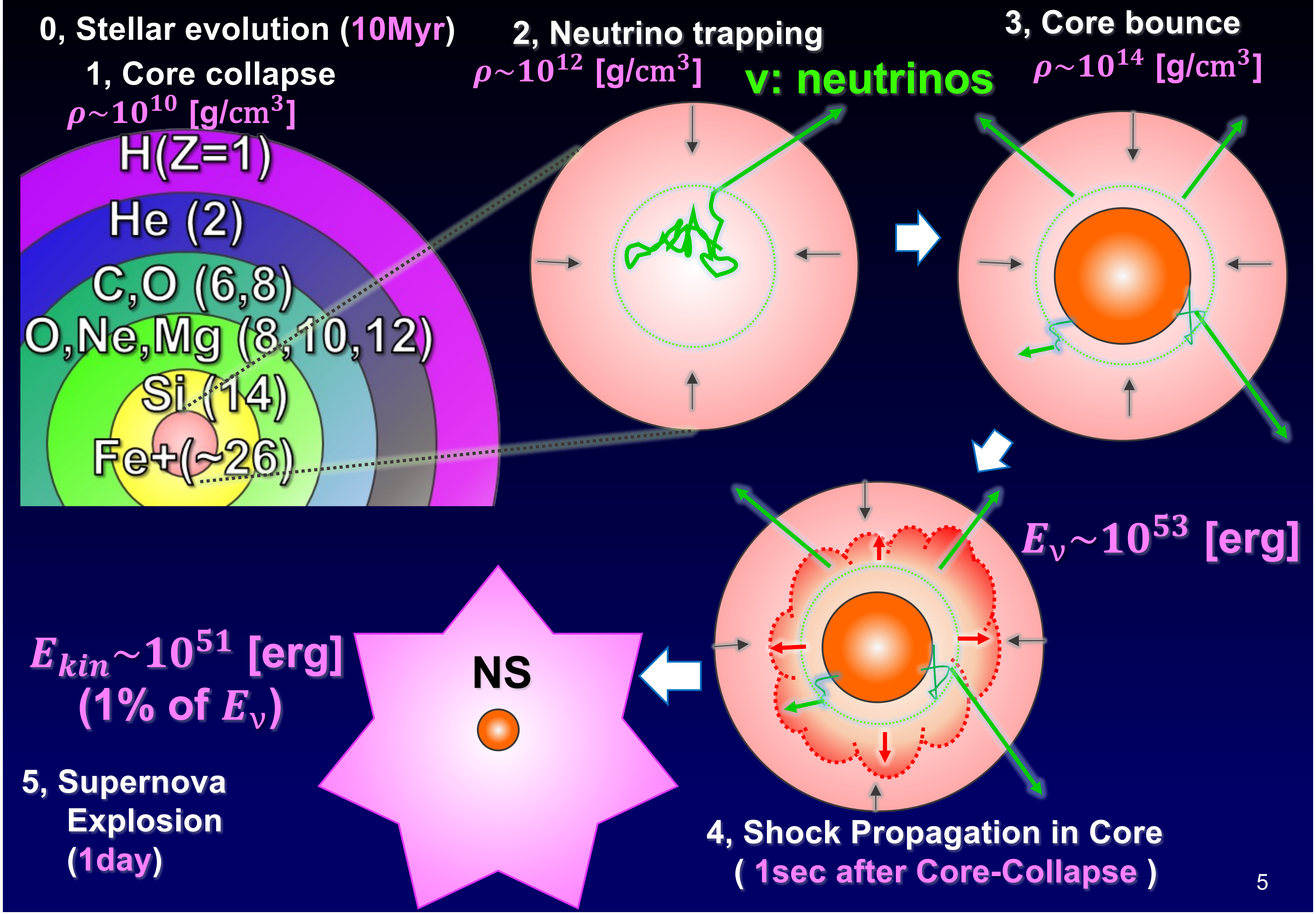
Core-Collapse Supernovae

- **Energetic evets 10^{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

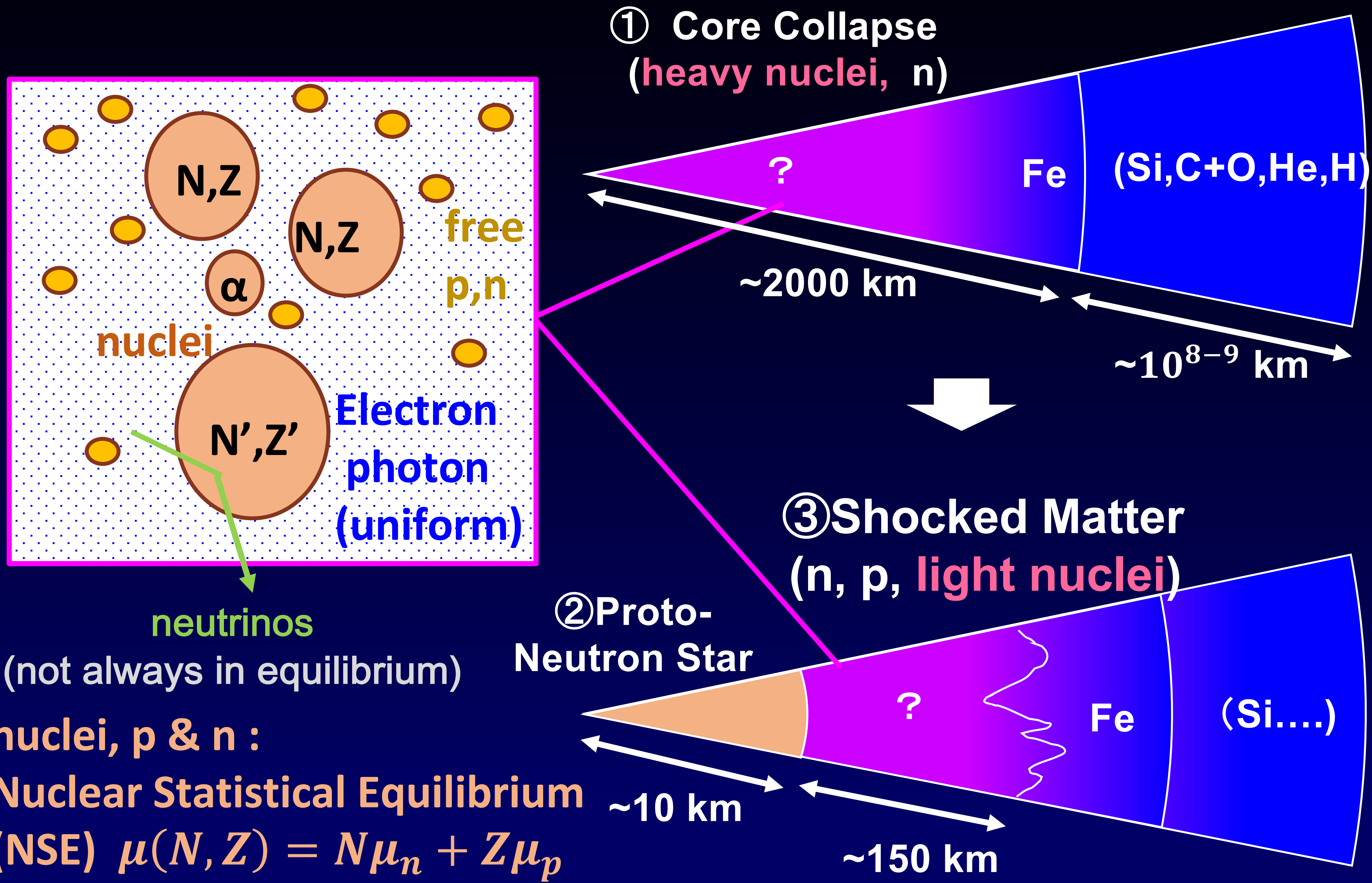
SN 1987A



Core-Collapse Supernovae



Supernova matter and Nuclear Statistical Equilibrium



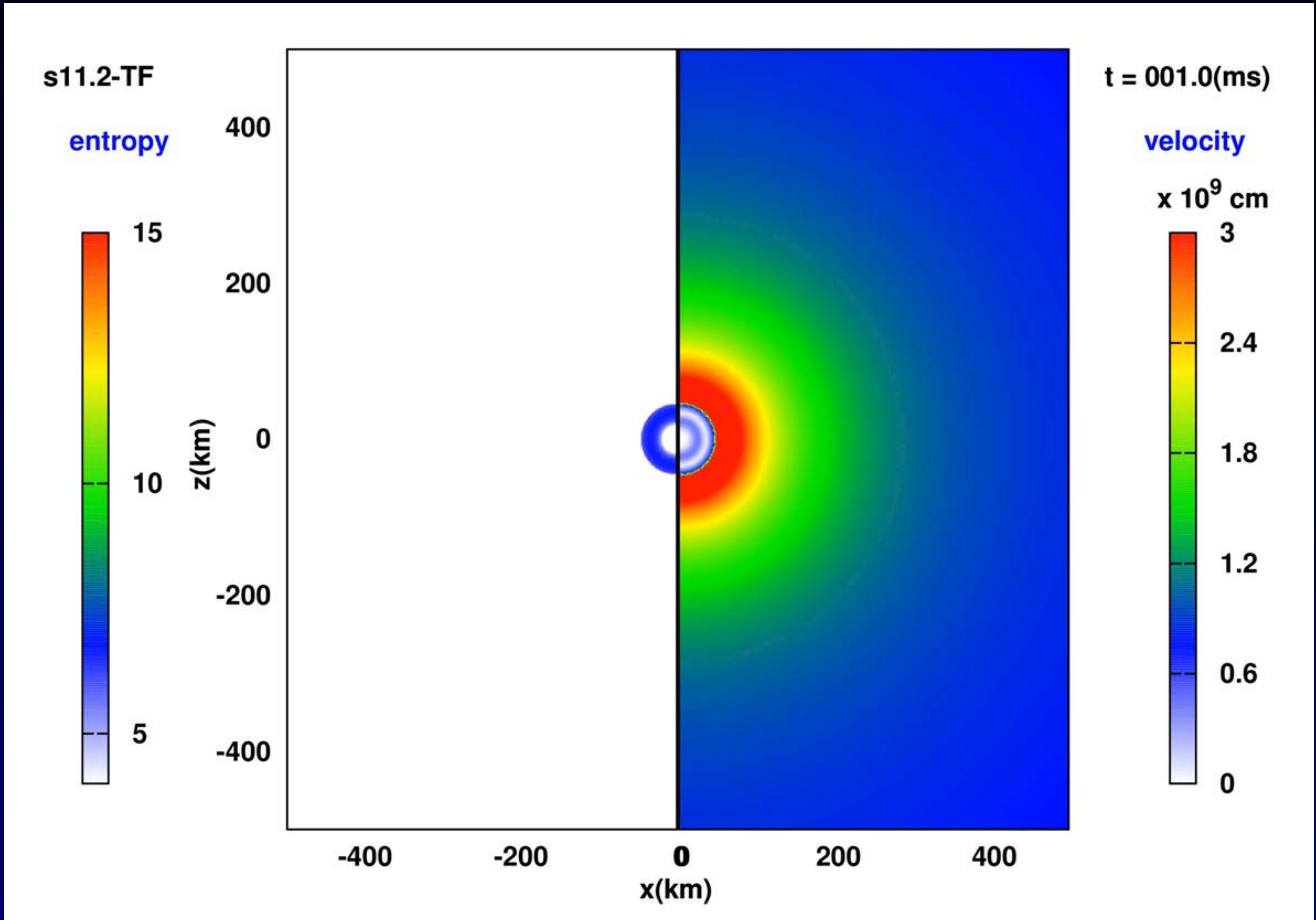
nuclei, p & n :

Nuclear Statistical Equilibrium

(NSE) $\mu(N,Z) = N\mu_n + Z\mu_p$

Supernova Simulations

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



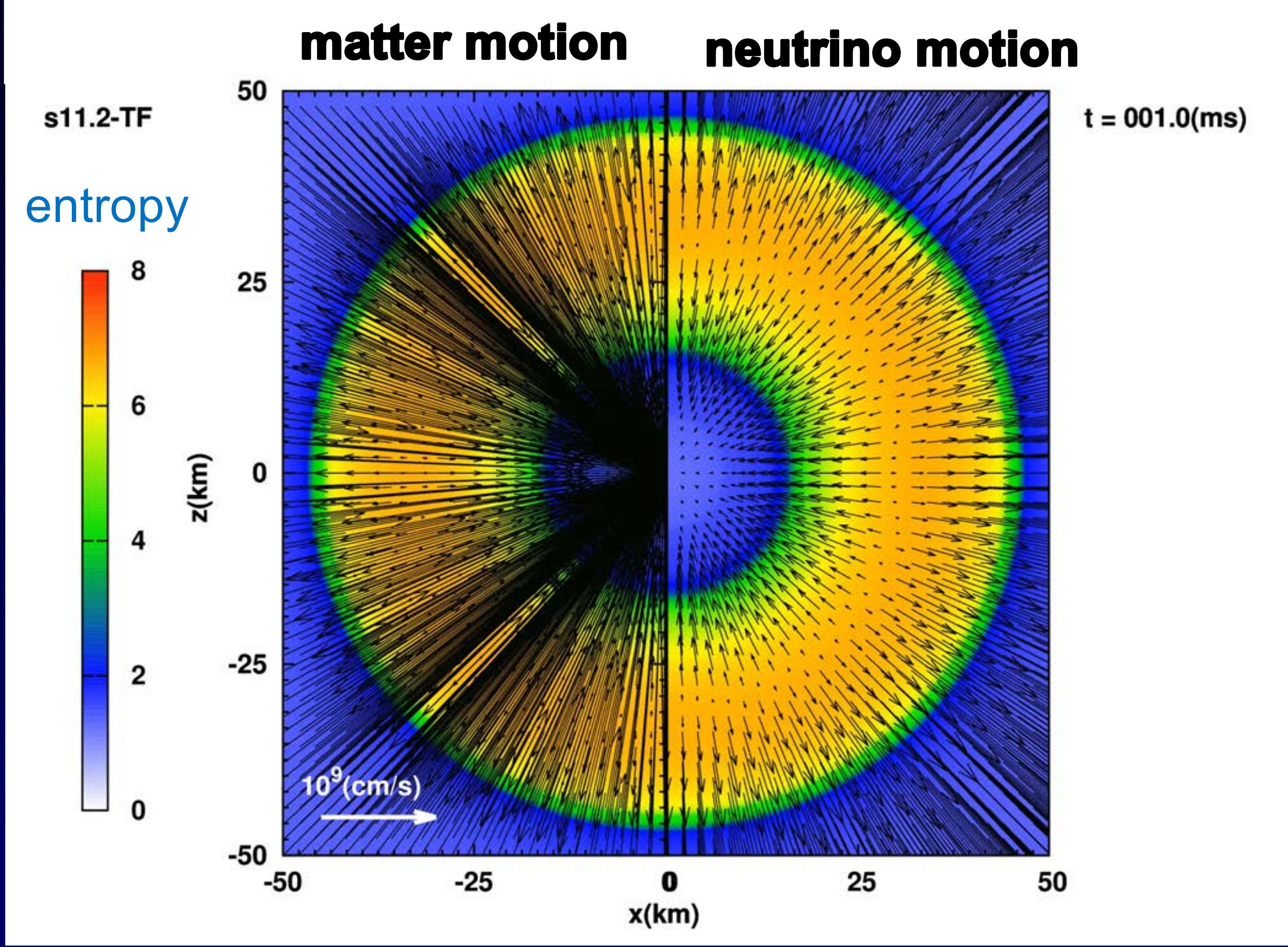
2D (axisymmetric) simulation（Nagakura+ 18）
based on Furusawa-Togashi EOS (SF+17d)

Nuclear Physics Inputs of Supernova Simulations

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

②Weak 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)

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)

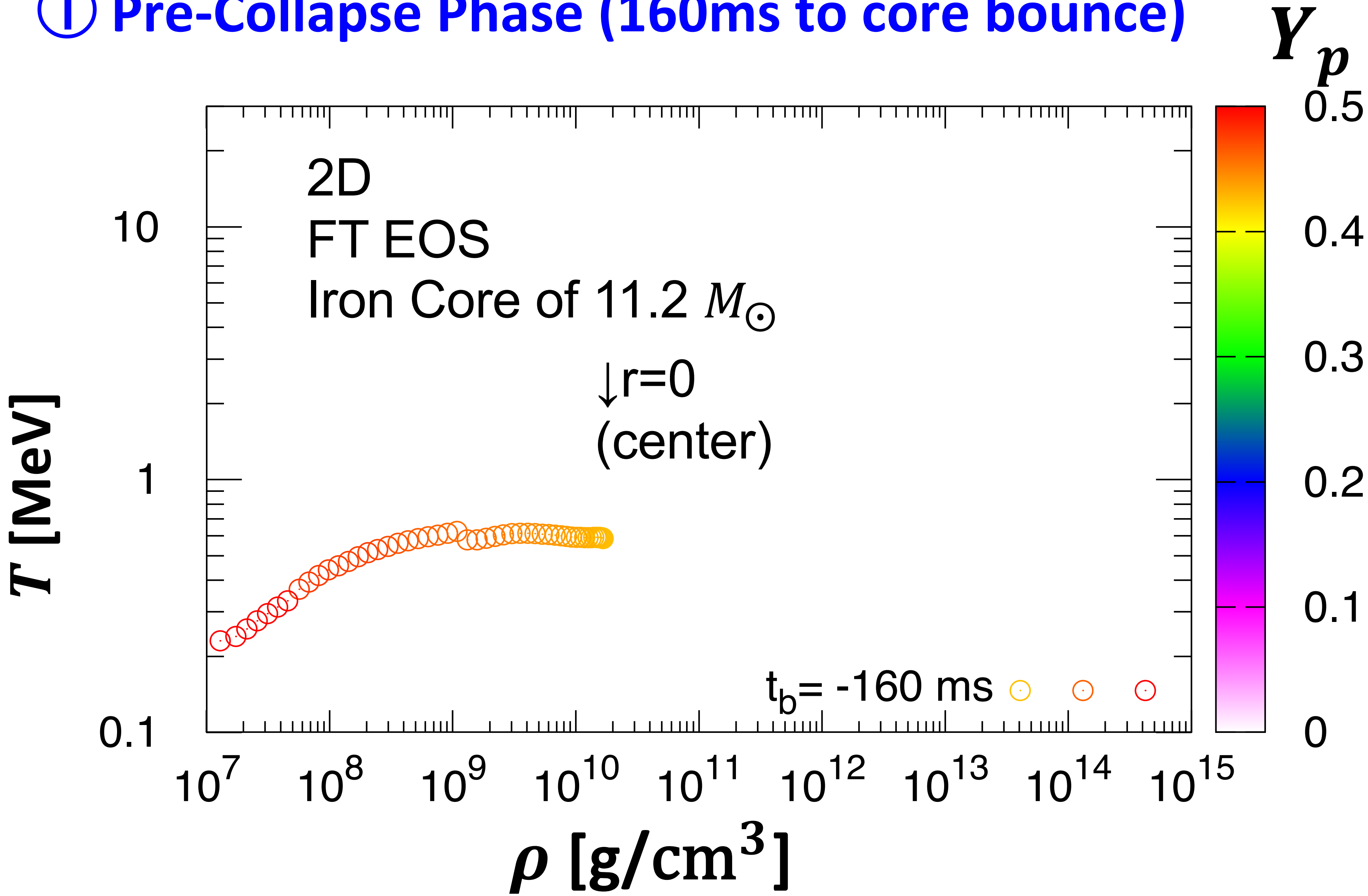
・Nuclear Statistical Equilibrium EOS : n, p & all nuclei

- HS - SFHo, DD2, TM1, ... (Hempel+'11, Steiner+'13)
- FYSS – Variational method (SF+'17, FT EOS) DBHF (SF+,'20) TM1 (SF+'17)
- RG – SLy4 (Raduta & Gulminelli'18)
- PT –DD2 (Typel'18)
- UTK (Du+ '22)

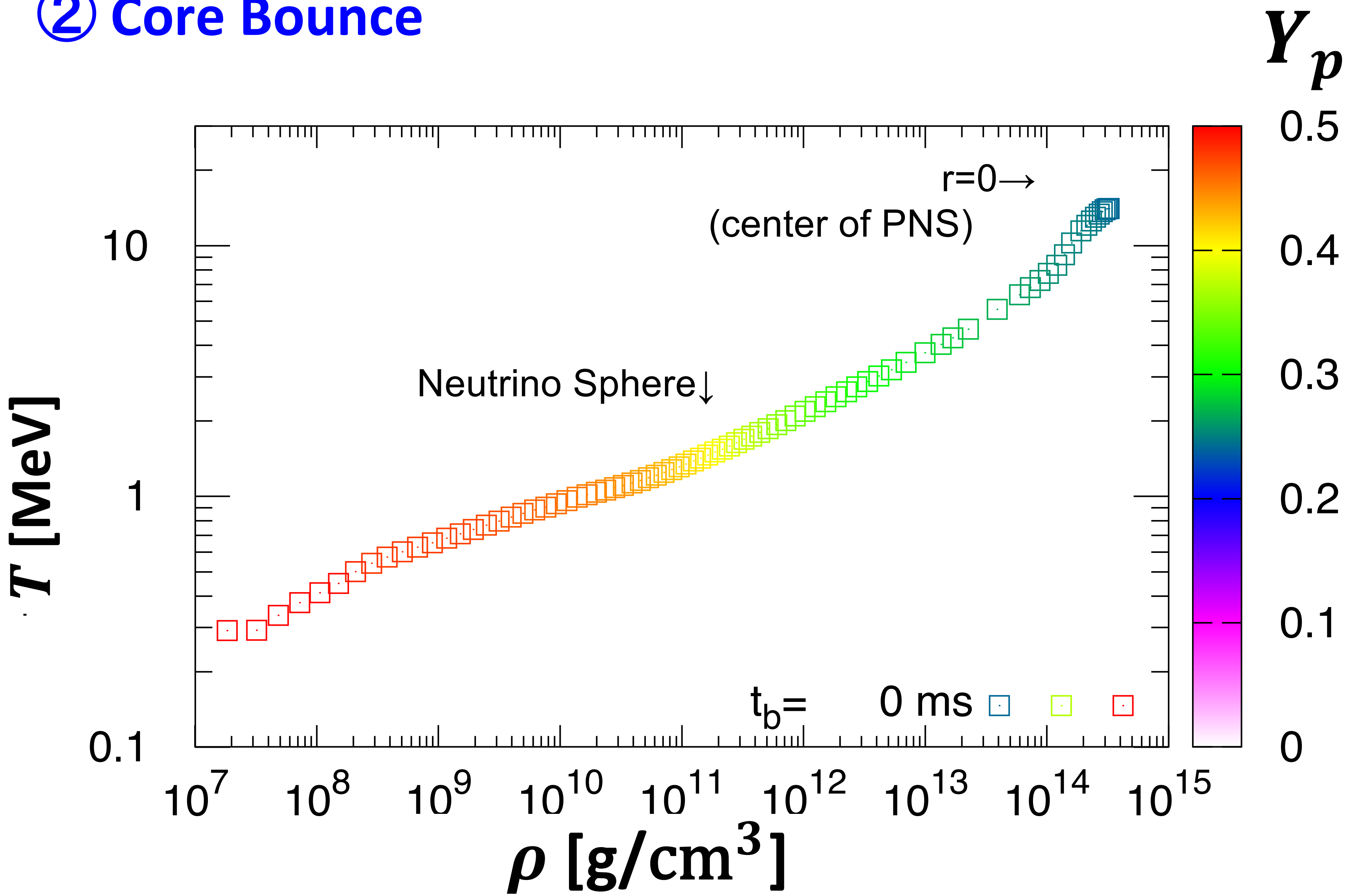
・Hybrid EOS : NSE @low ρ & SNA @high ρ

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

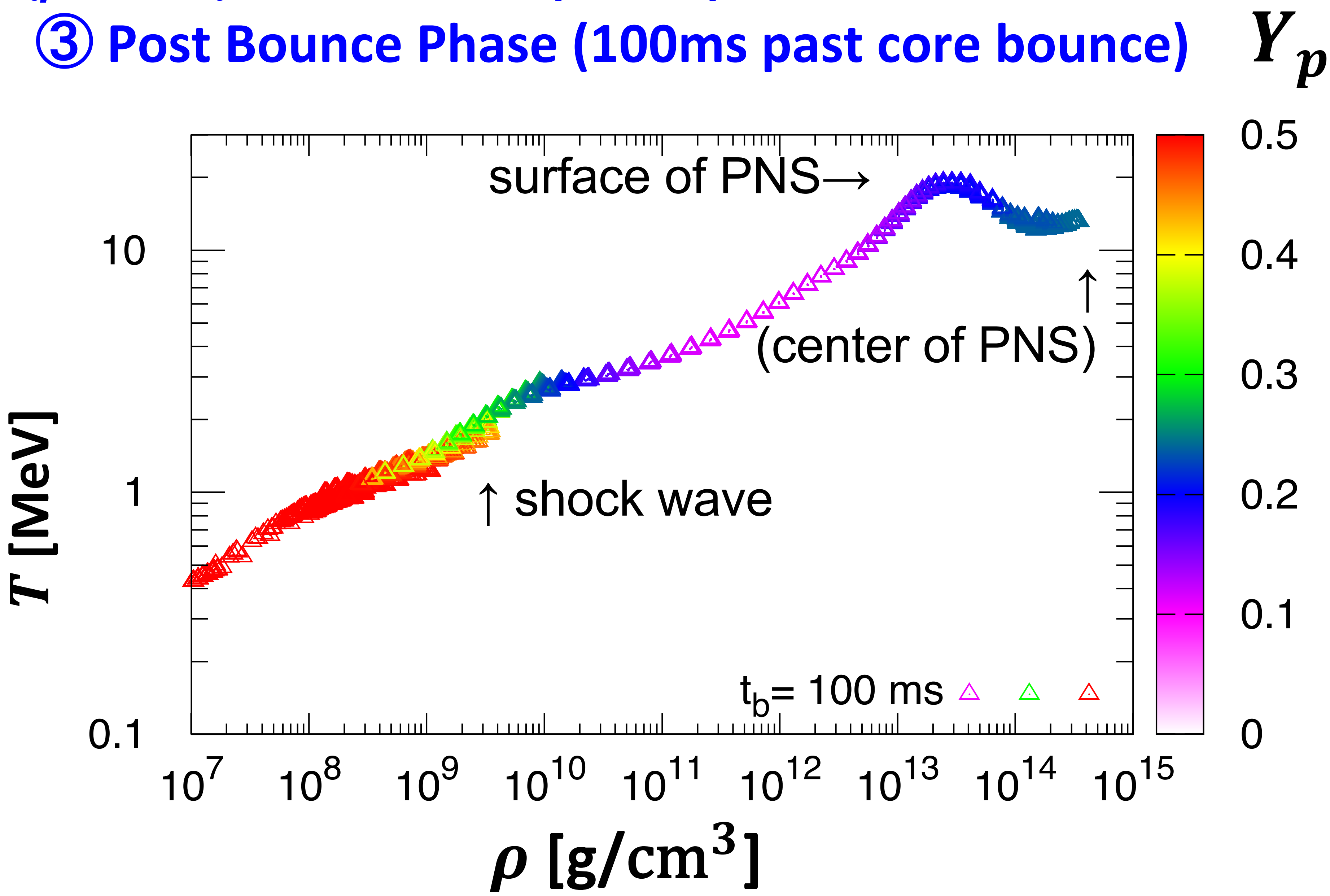
(ρ, T, Ye) in Core-Collapse Supernova Simulations
① Pre-Collapse Phase (160ms to core bounce)



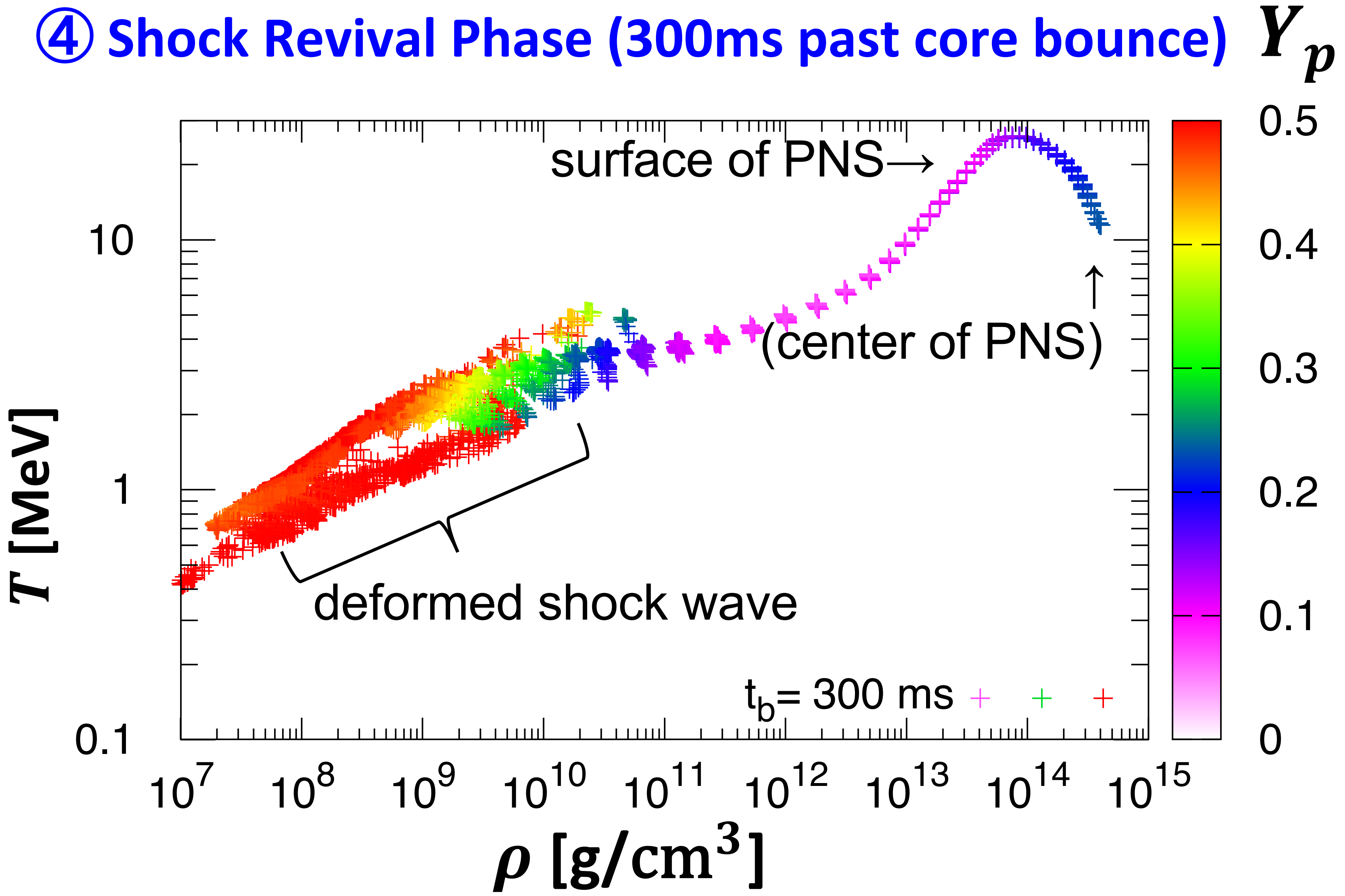
(ρ, T, Ye) in Core-Collapse Supernova Simulations
② Core Bounce



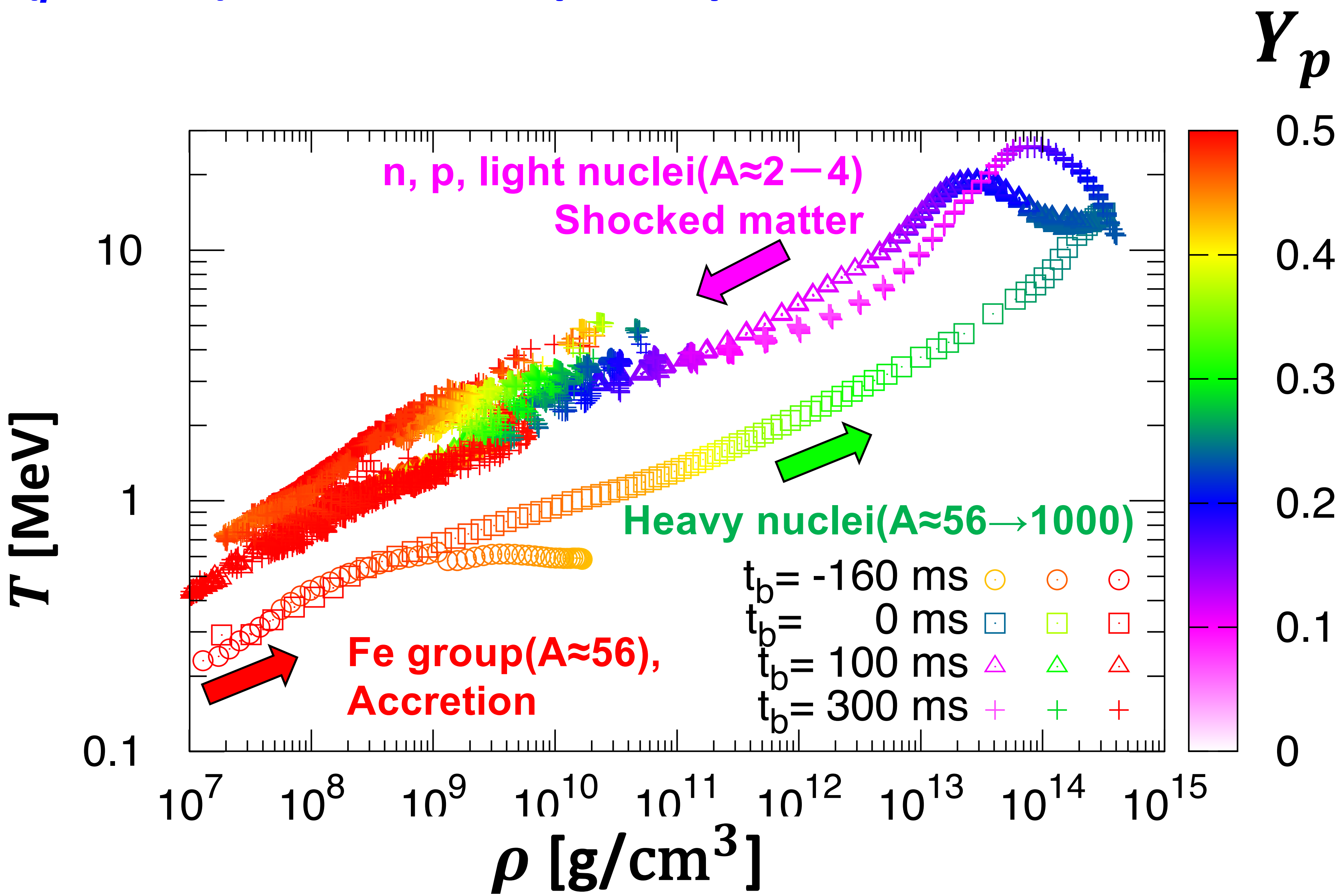
(ρ,T,Ye) in Core-Collapse Supernova Simulations
③ Post Bounce Phase (100ms past core bounce)



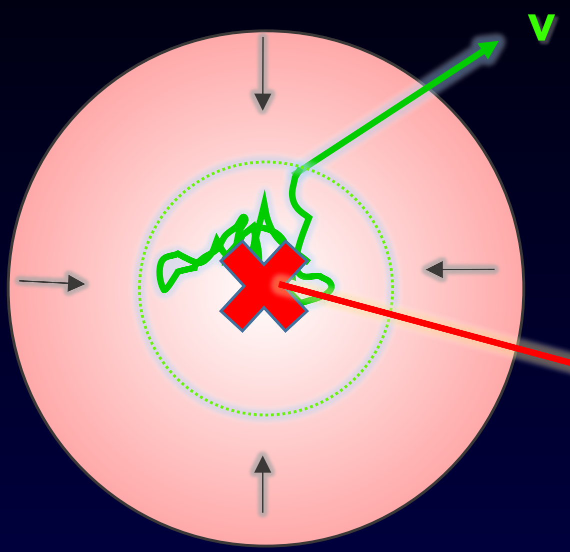
(ρ, T, Ye) in Core-Collapse Supernova Simulations
④ Shock Revival Phase (300ms past core bounce)



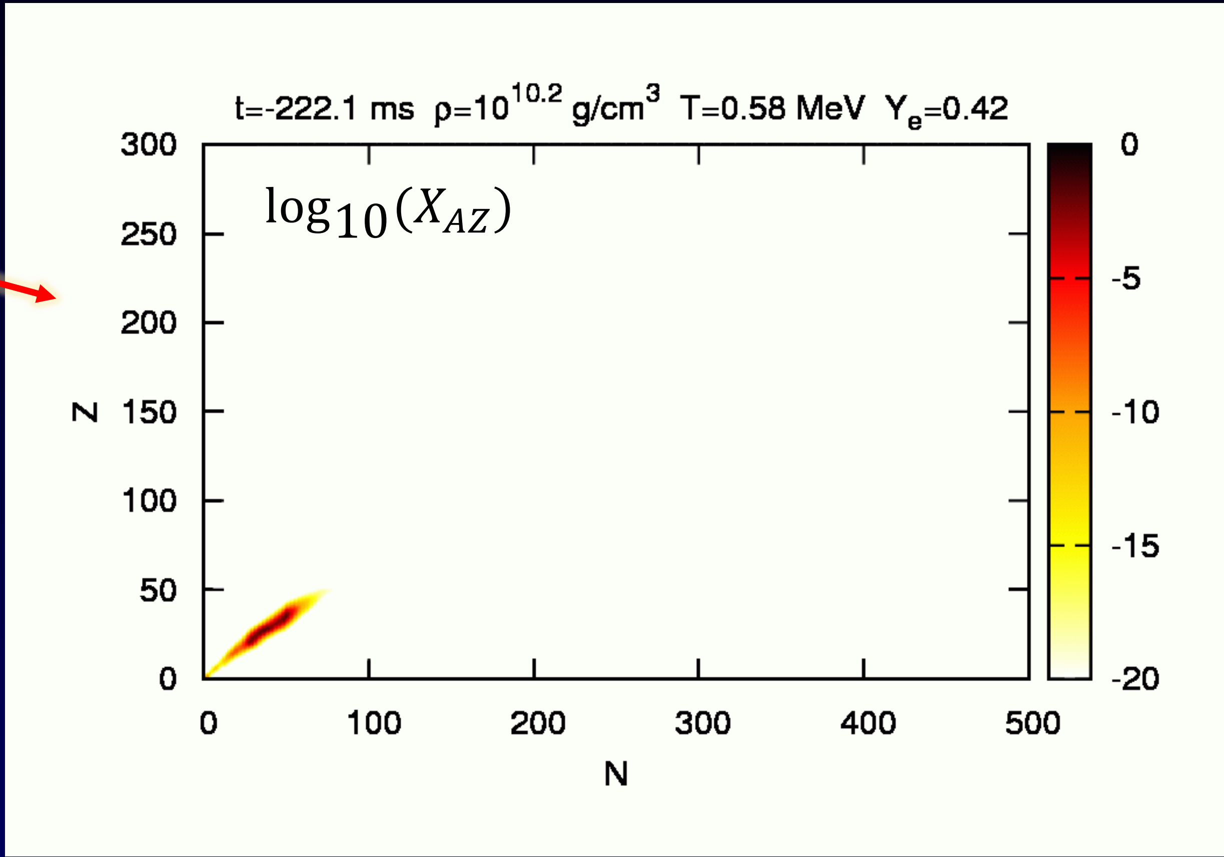
(ρ, T, Ye) in Core-Collapse Supernova Simulations



Nuclei in stellar core collapse



mass fractions of nuclei at center

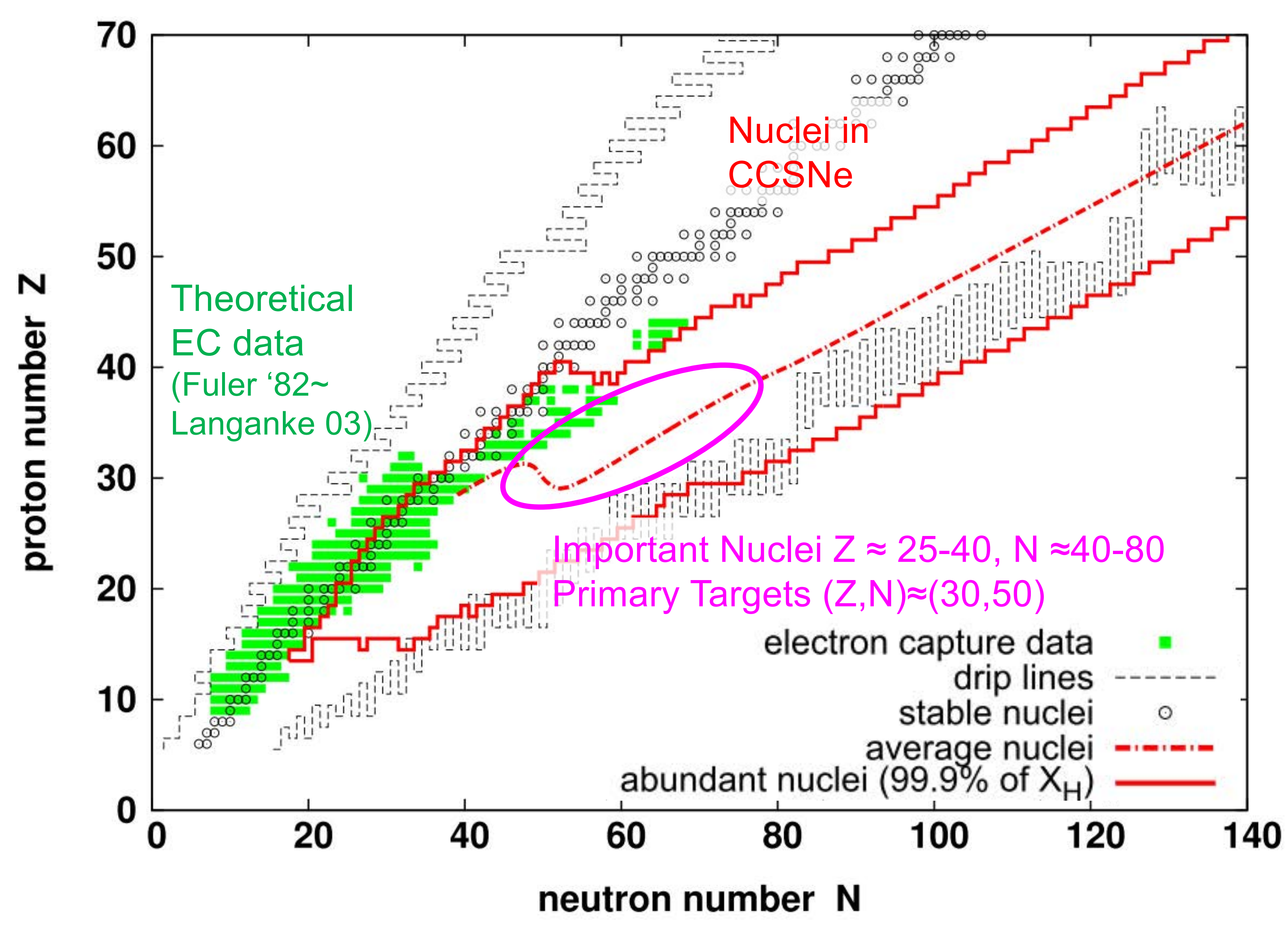


- Dense electrons reduce nuclear Coulomb energy.
  → **large mass nuclei**
- $\mu_n > \mu_p$
  → **neutron-rich nuclei**

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

Lack of Electron Capture Data $(N, Z) + e^- \rightarrow (N+1, Z-1) + \nu_e$

(+ partition function level densities for Equation of State)



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

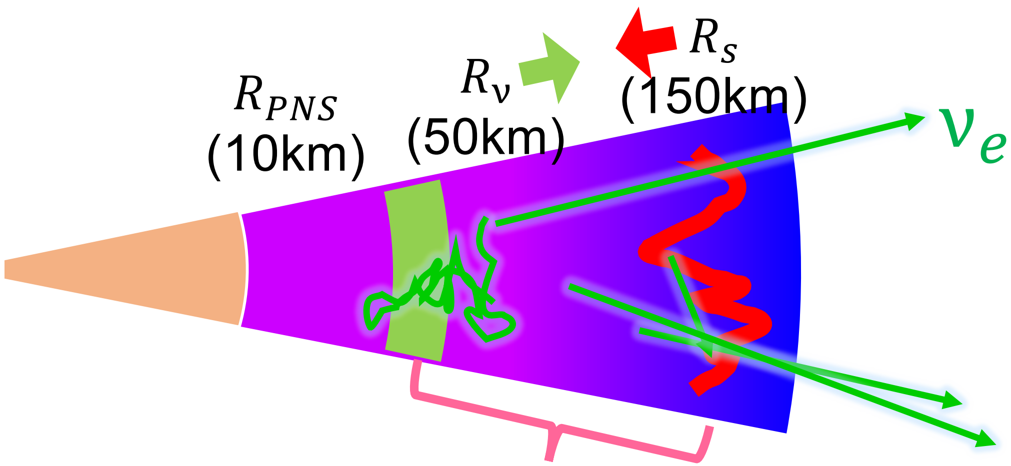
⇒ ①fewer leptons in PNS

⇒smaller mass of PNS

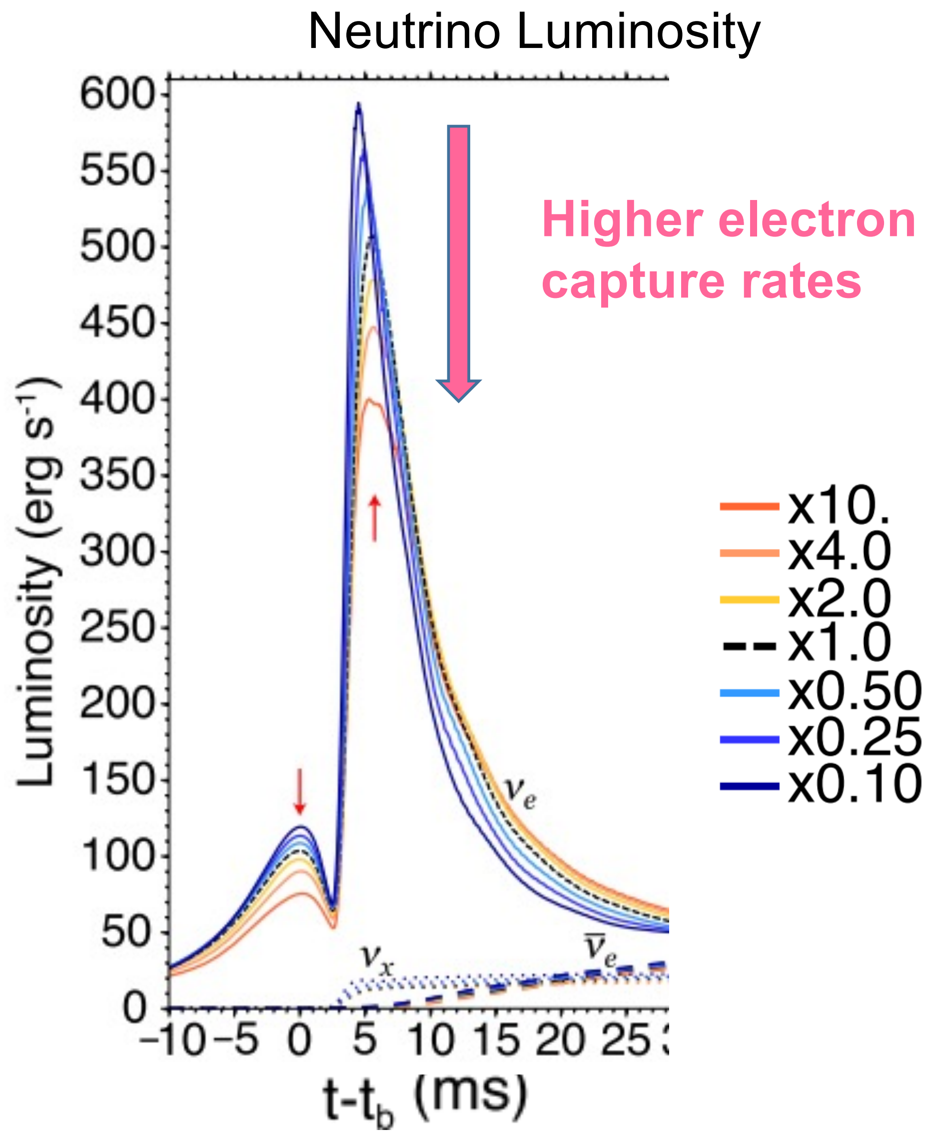
⇒**smaller shock radius** R_s

⇒② more neutrino captures around R_ν

⇒**larger neutrino sphere** R_ν



⇒ **smaller neutrino emissions**



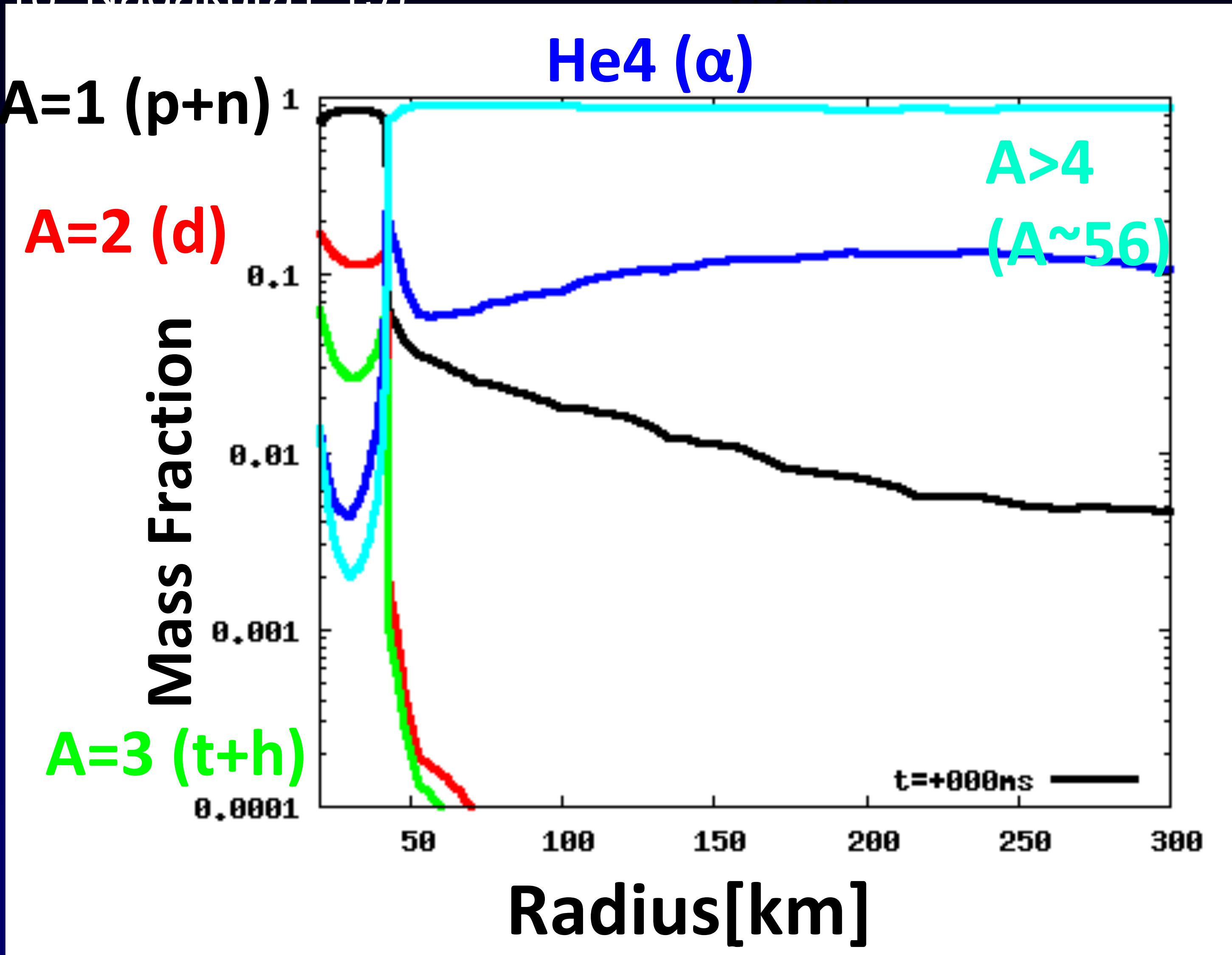
Rate improvements: Raduta+'17, Titus+'18, Dzhioev+'20, Giraud+ '21 , Johnston+ '22

Johnston+'22

Nuclei after bounce.

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

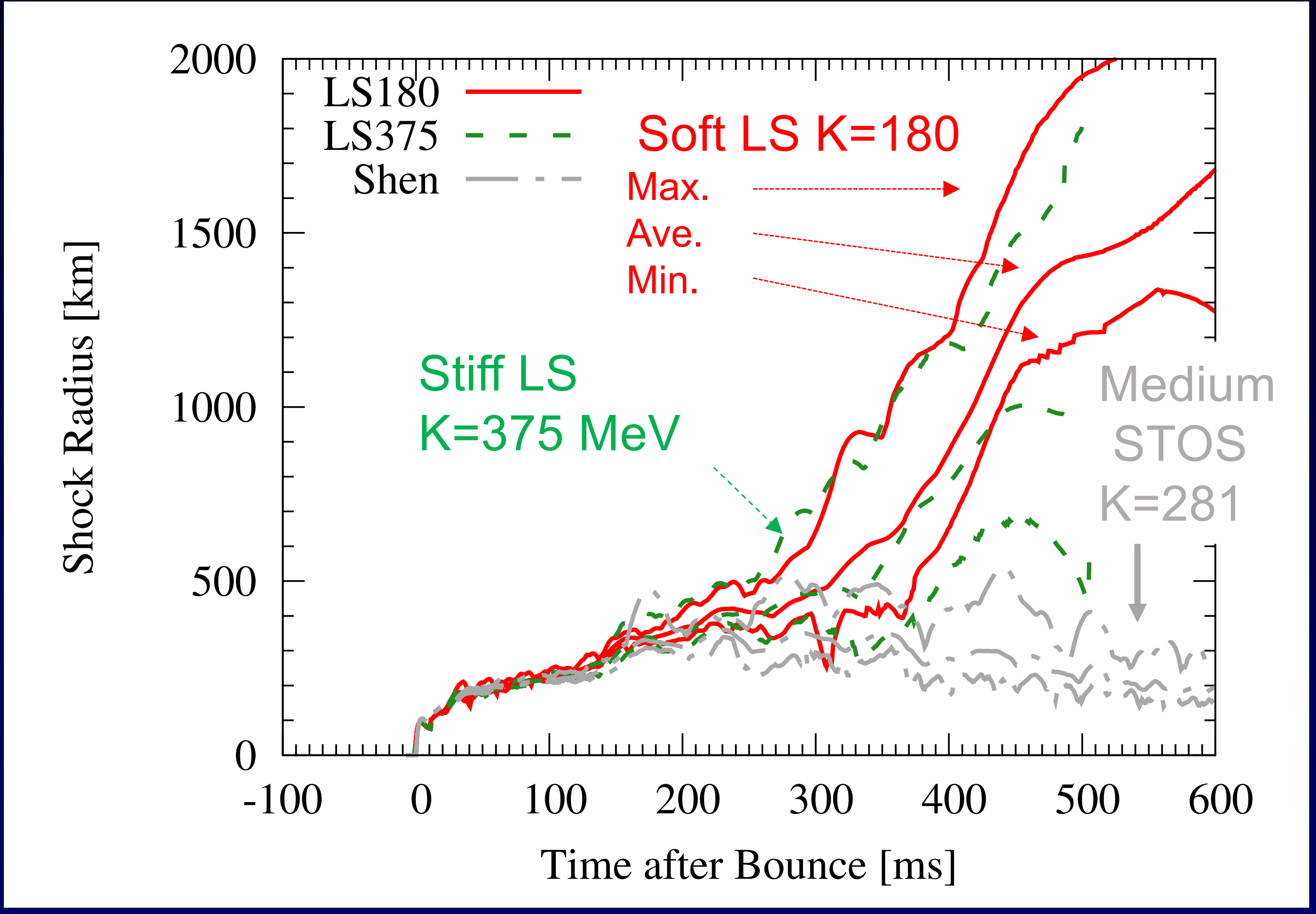
Ex2) Mass fraction of shocked matter



Impact of EOSs on Supernova Simulations

① Soft EOSs give larger shock radii.
(e.g. Sumiyoshi+' 05, Fischer+ '14, Suwa+ '13 …)

② Nuclear model affect the dynamics more than interaction model
(Hempel+' 12, Suwa + '13, Sumiyoshi et al. in prep.)



Suwa + '13

③ Effective mass (Schneider +'19) and/or entropy densities (Boccioli+ '22)
may be key parameters for PNS structure, convection, and dynamics.

Summary

- Core-Collapse Supernovae greatly depends on equation of state (EOS) (interaction model, nuclear model) and weak interaction data.

- The most ambiguous parts in nuclear model in EOS is nuclear excitation model (SF '18)
- Nuclei with (N,Z)≈(50,30) appear at $\rho \sim 10^{11-12}$g/cc.

- Their electron capture rates should be improved.

- Light clusters may affect dynamics and ν emissions after bounce (SF+ '13, Fischer+ '16, Nagakura+ '19)

a review paper (SF & H. Nagakura) in prep.