Nuclear Physics Uncertainties in Core-Collapse Supernovae

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We have to improve

nuclear excitations (level densities) and

electron captures (strength distributions)

for nuclei with (N,Z)≈(50,30)

(SF PRC 98.065802('18), SF+ PRC 95.025809 ('17b)).

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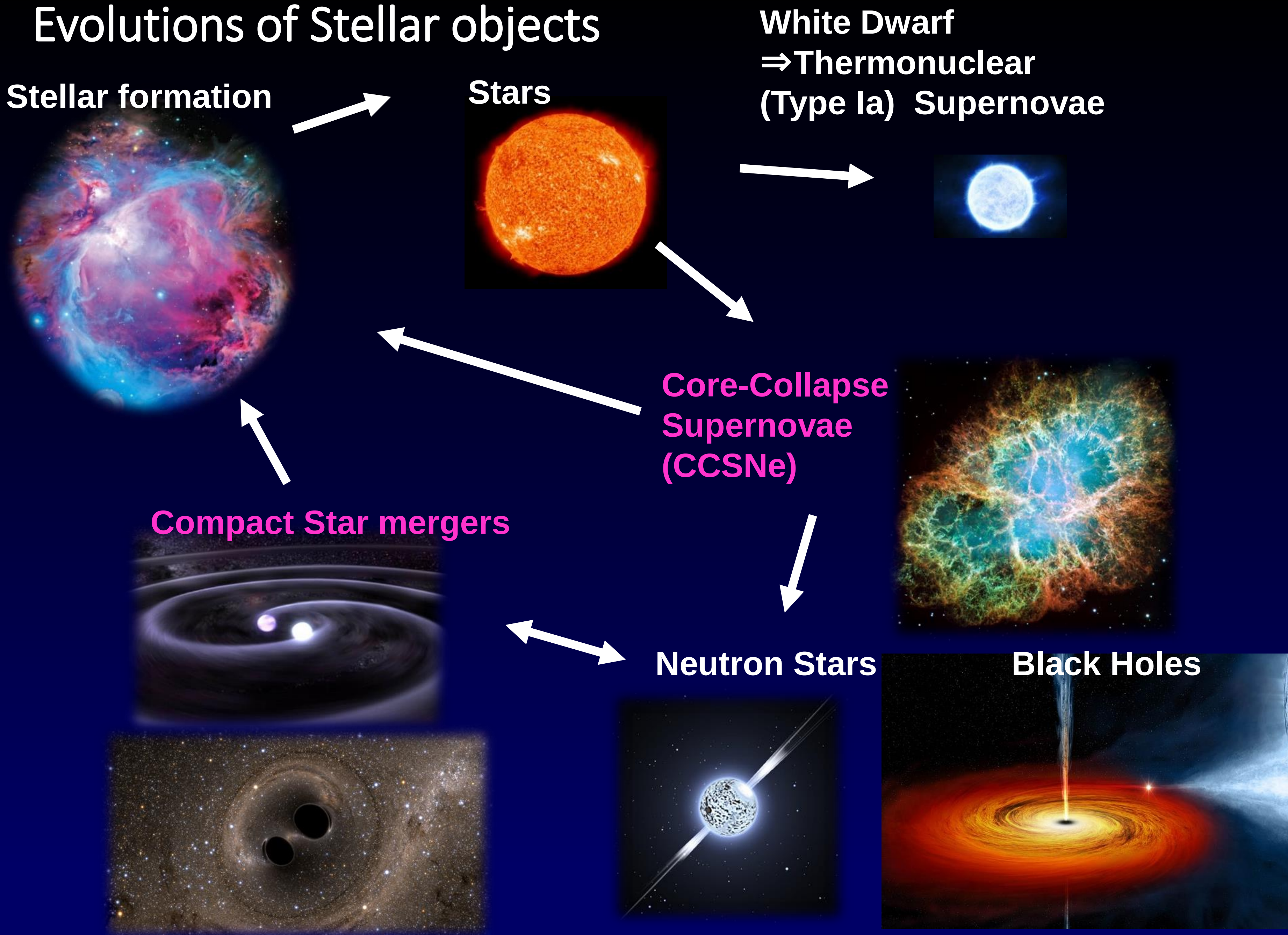
iTHEMS

Gravitational Wave Physics and Astronomy Genesis

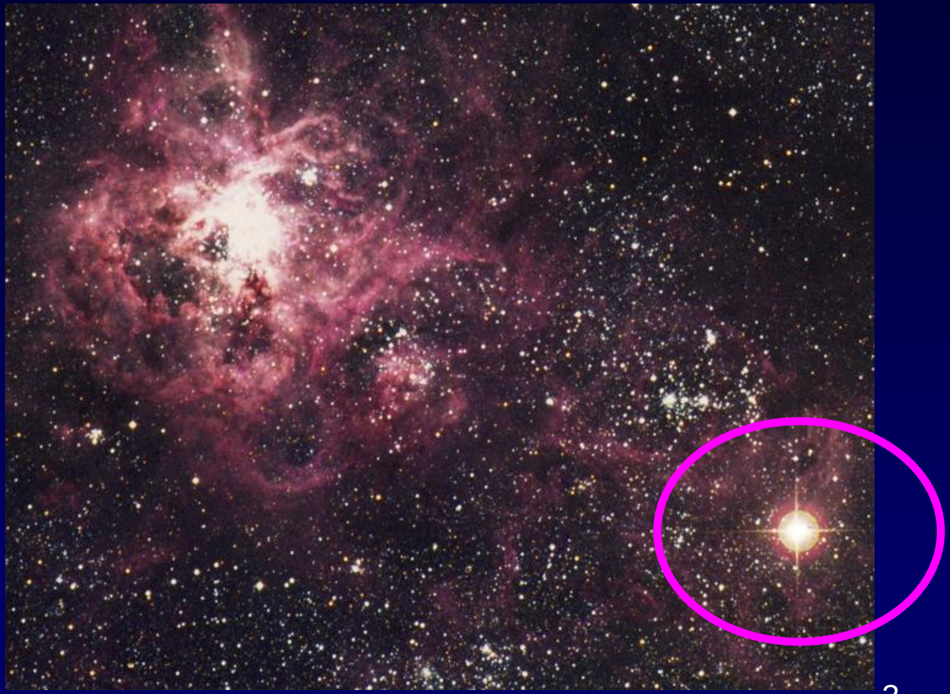
Evolutions of Stellar objects



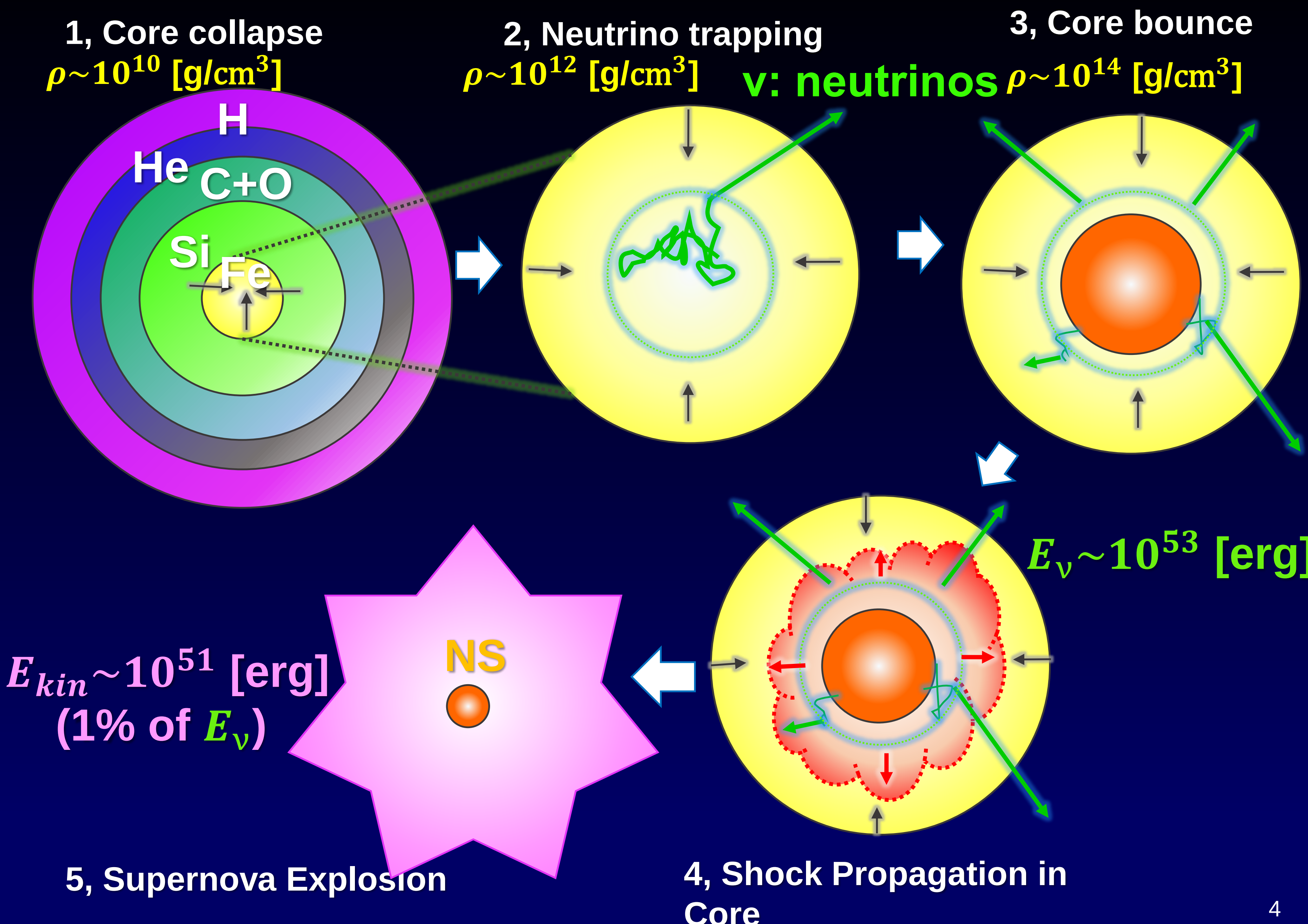
Core-Collapse Supernovae

- 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

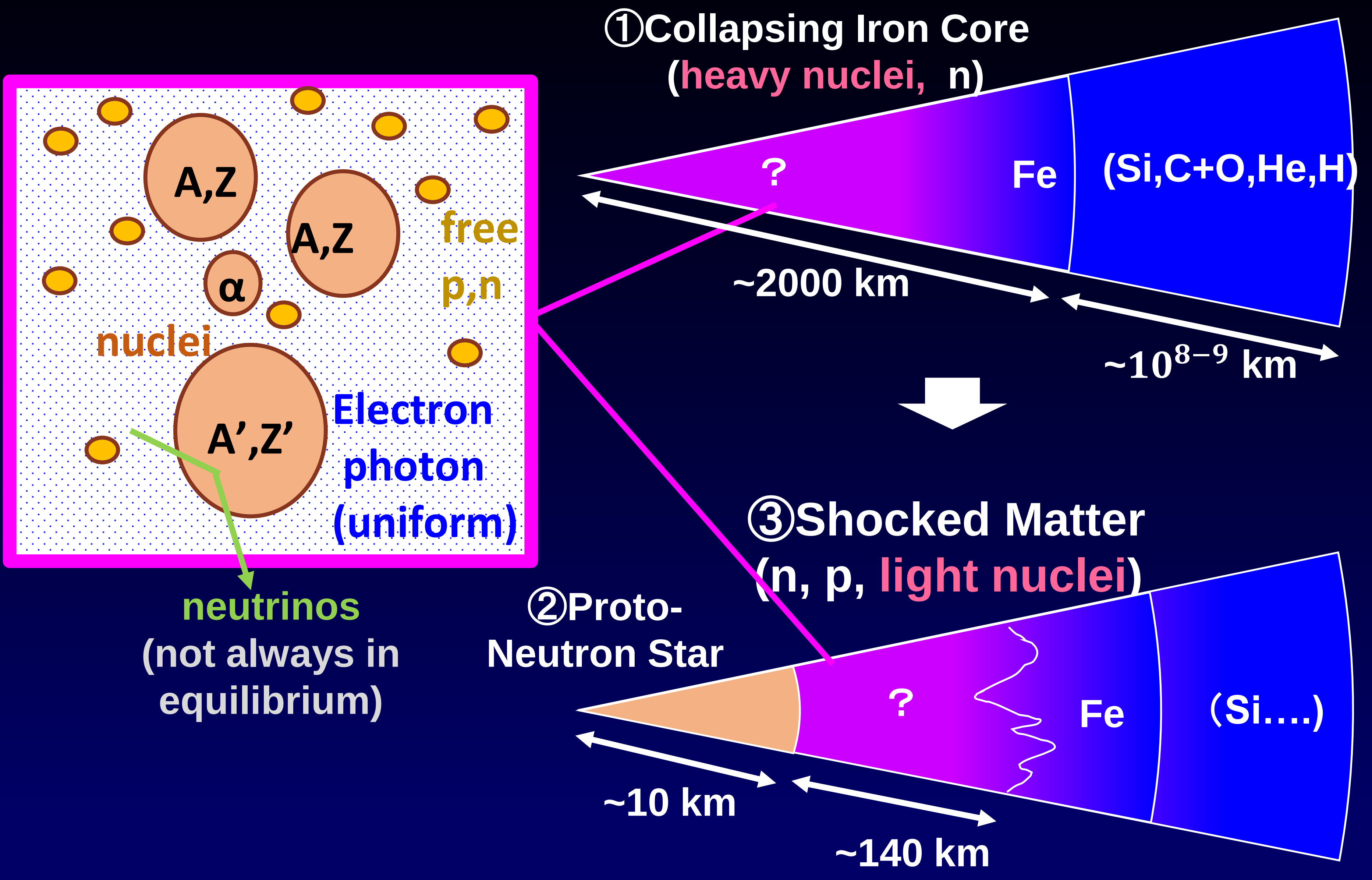
SN 1987A



Core-Collapse Supernovae

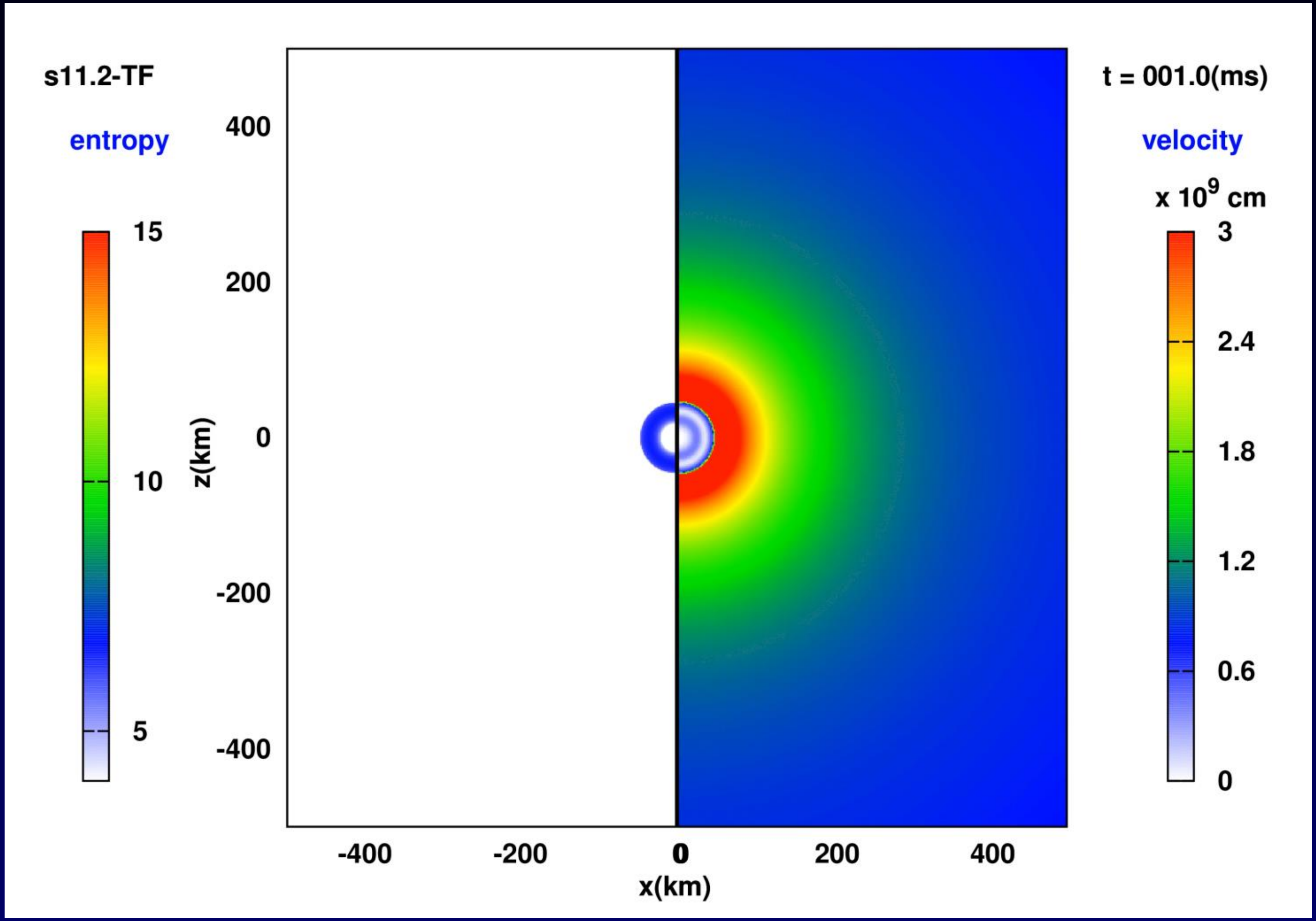


Supernova matter in Core-Collapse Supernovae



Supernova Simulations

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

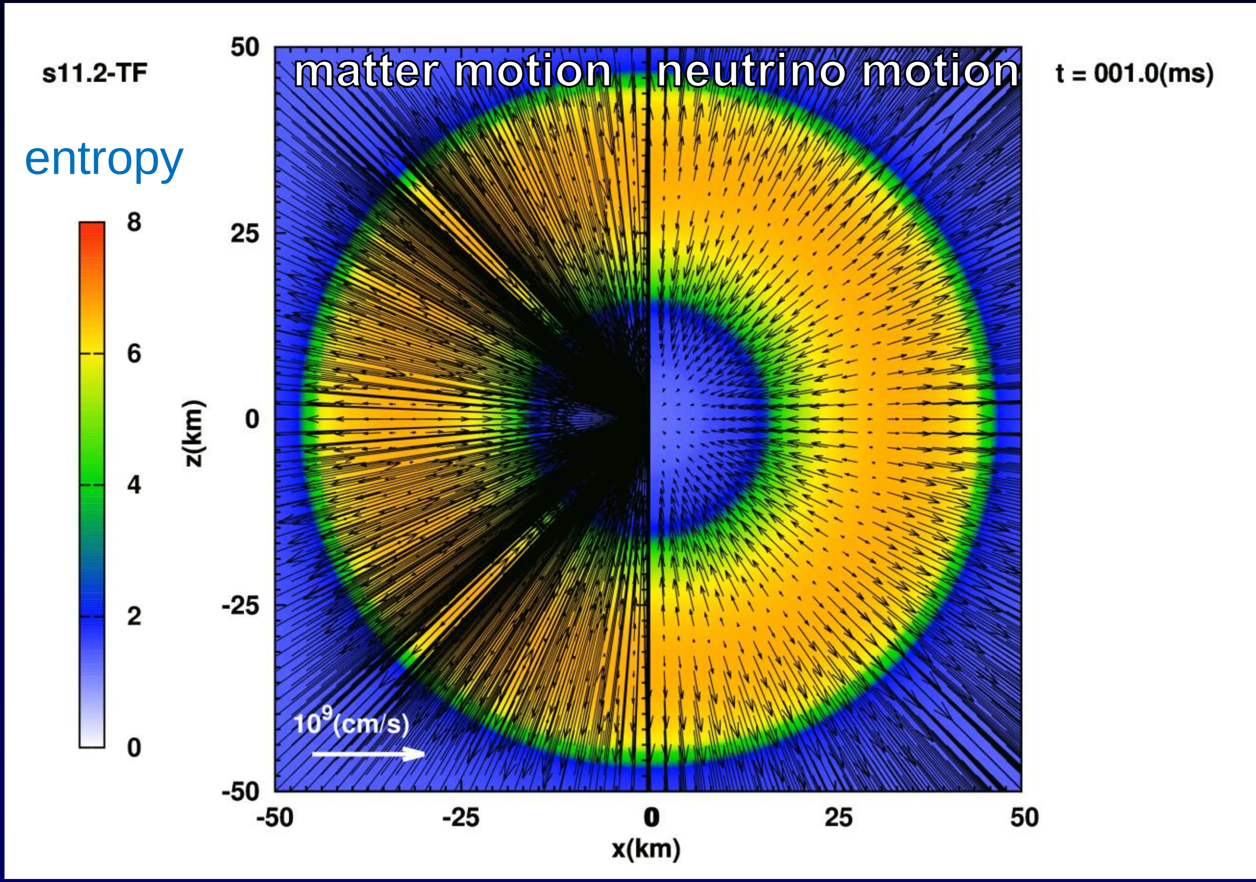


2D (axisymmetric) simulation（Nagakura+） at Supercomputer K
based on Togashi-Furusawa EOS (SF+17d)

Inputs of Supernova Simulations

①Equation of State ⇒ Stiffness, Nuclear compositions(Which nuclei appear)
②Weak interaction rates ⇒ Neutrino emissions, absorptions, and scattering

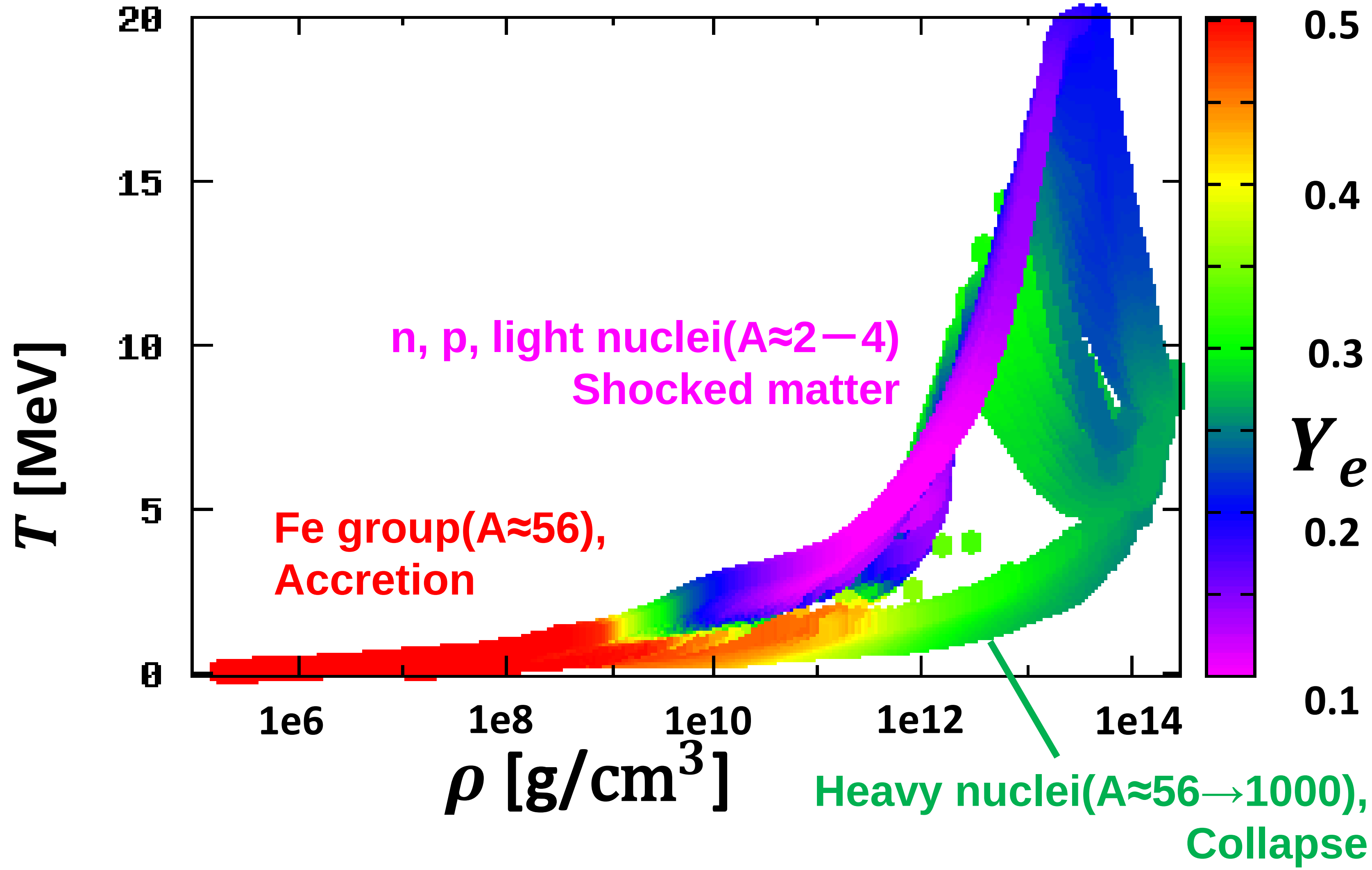
Ex. $(N, Z) + e^- \leftrightarrow (N+1, Z-1) + \nu_e$



Motions of neutrinos and matter around Proto-Neutron Star

（Nagakura+） Togashi-Furusawa EOS (SF+17d)

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



Nuclear Statistical Equilibrium (NSE, 核統計平衡)

- $\tau_{\text{nuclear reaction}}$ (strong and ele.mag.) $\ll \tau_{\text{dynamics}}$
- All nuclear components in chemical equilibrium @T>~0.4 MeV

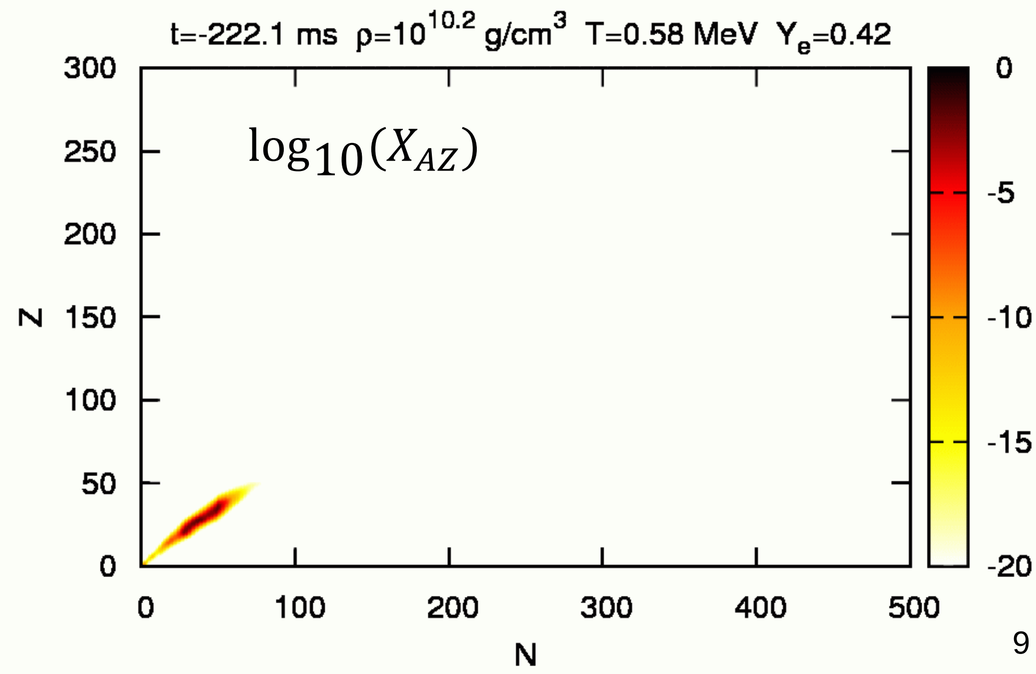
$$(A, Z) \leftrightarrow (A-1, Z) + n$$

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

- **Free energy minimization** ⇒ $\mu_{AZ} = Z\,\mu_p + (A-Z)\,\mu_n$

Ex1) Central mass fraction of stellar core collapse

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



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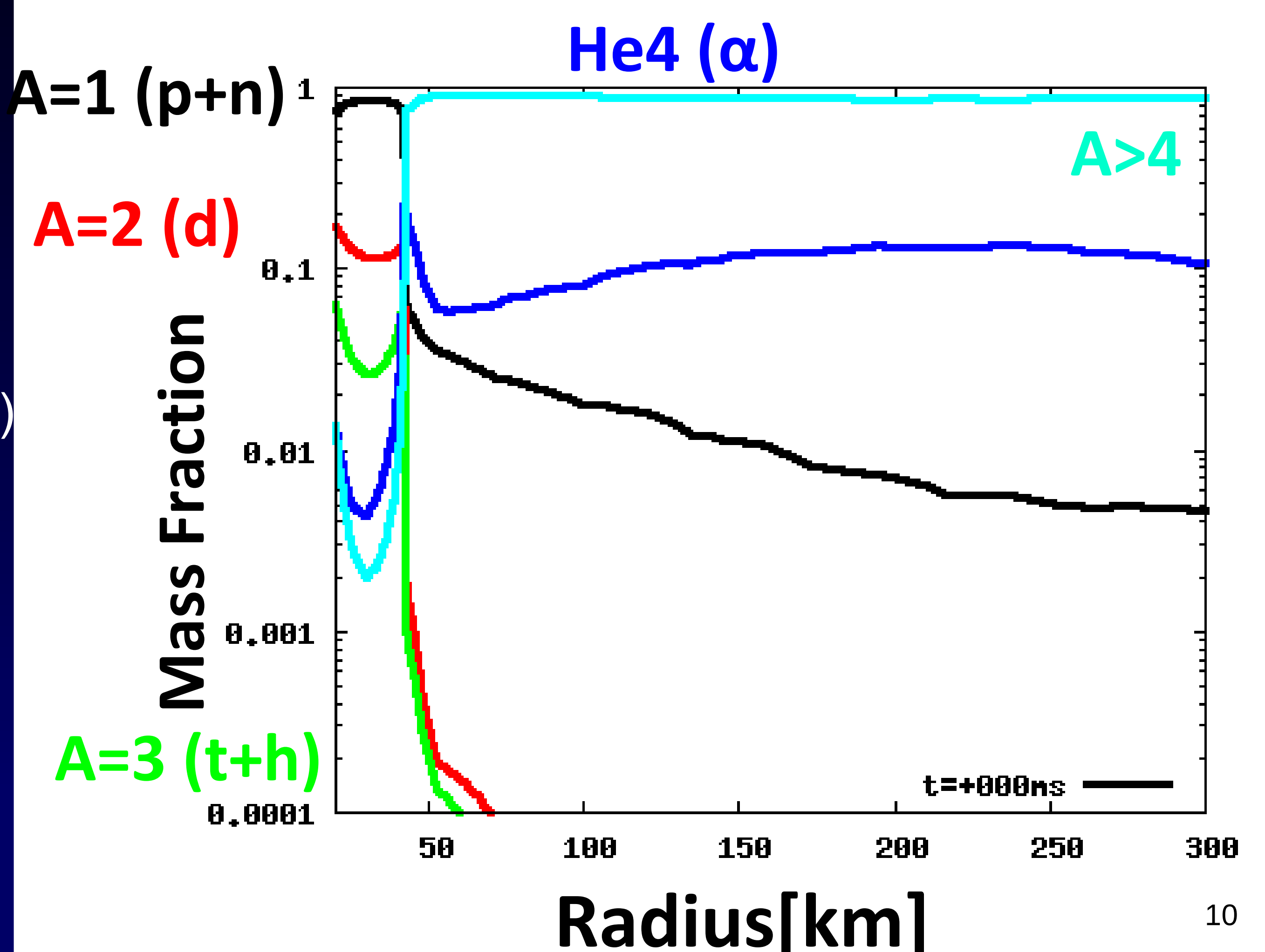
- **Free energy minimization ⇒ NSE** $\mu_{AZ} = Z\,\mu_p + (A-Z)\,\mu_n$

Ex2) Mass fraction of shocked matter

Light cluster physics
(deuteron weak rates,
pairing at high T & ρ…)
should be improved.
(SF+13b)



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

Soft $R_{1.4}<12.5$ km, $R_{1.4}=12.5\text{-}13.5$ 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, 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)

Different Inputs for NSE EOS
①bulk matter,
②masses, and
③excitations

Systematical study of nuclear physics inputs for NSE EOS
(SF, PRC '18b)

free energy density

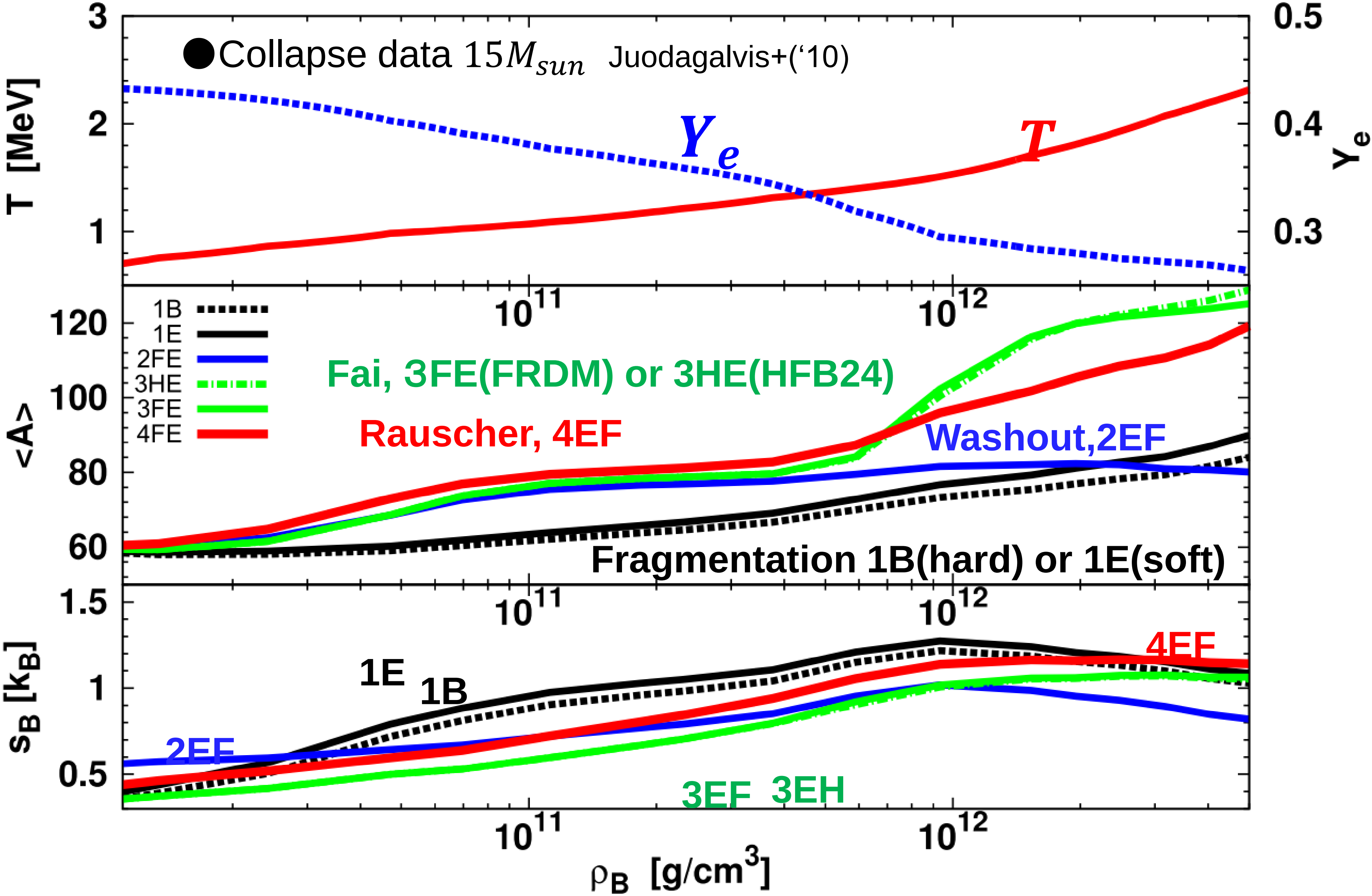
$$f = f_{n,p} + \sum_{AZ} n_{AZ}(E^{kin}_{AZ} + M_{AZ})$$

Individual number density

$$n_{AZ} = \kappa g_{AZ} \left(\frac{M_{AZ}T}{2\pi\hbar^2}\right)^{3/2} \exp\left(\frac{\mu_{AZ} - M_{AZ}}{T}\right)$$

Name	g_{AZ} Nuclear Excitations	$f_{n,p}$ $(+M_{AZ})$ Bulk matter	M_{data} Mass data
1B	Fragmentation model (~SMSM)	**B**(Stiff)	No
1E		**E**(Soft) Oyamatsu &Iida('07)	
2EF	Liquid drop model + shell washout (~FYSS)		**F**RDM
3EF	Fai & Randrup (1982) (∼HS)		
3EK			**H**FB24
4EF	Rauscher (2003) (∼SRO)		**F**RDM

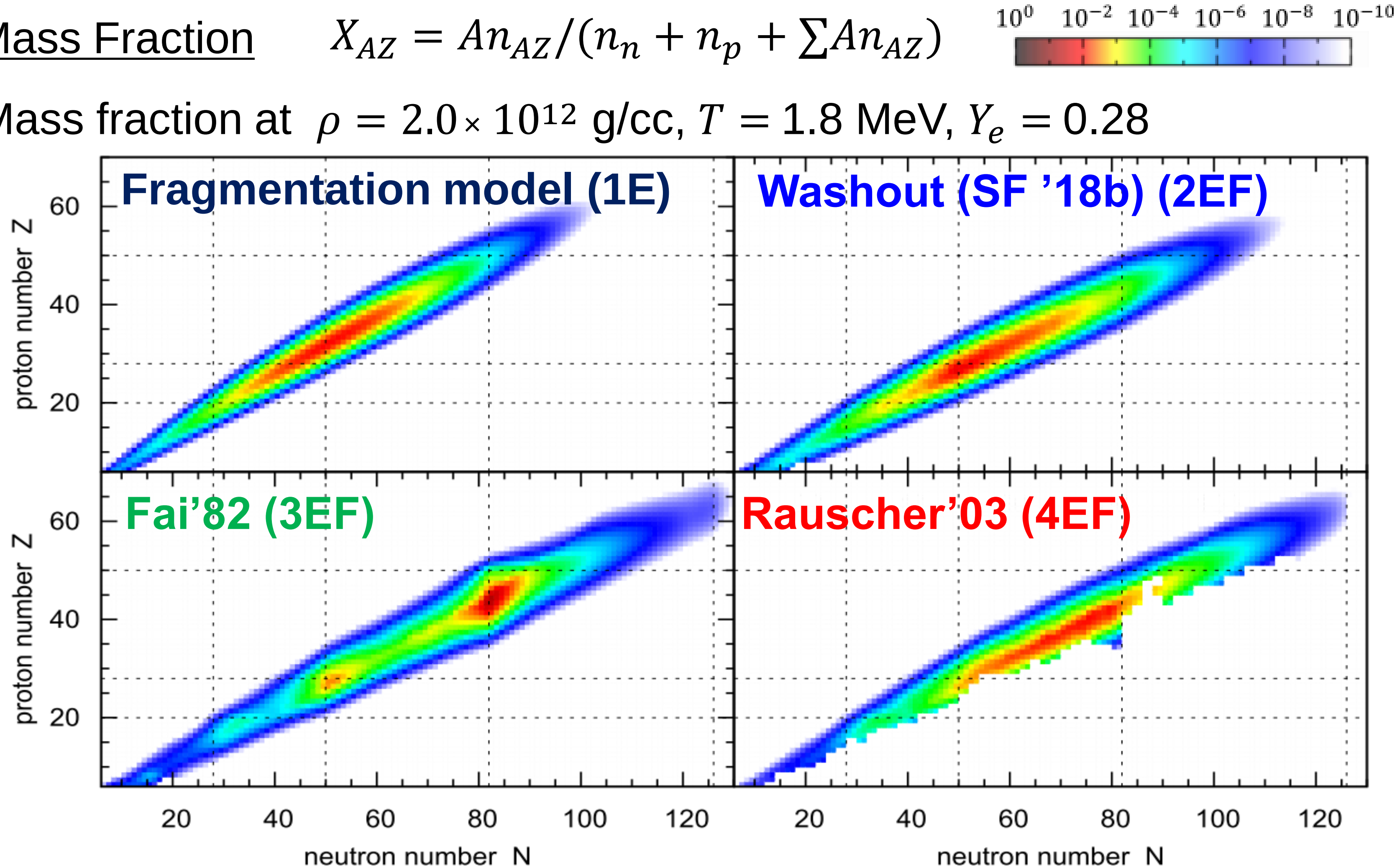
Average nuclear size and entropy are sensitive to excitation models



Nuclei at $\rho \sim 10^{11-12}$g/cc

● Mass Fraction $X_{AZ} = An_{AZ}/(n_n + n_p + \sum An_{AZ})$

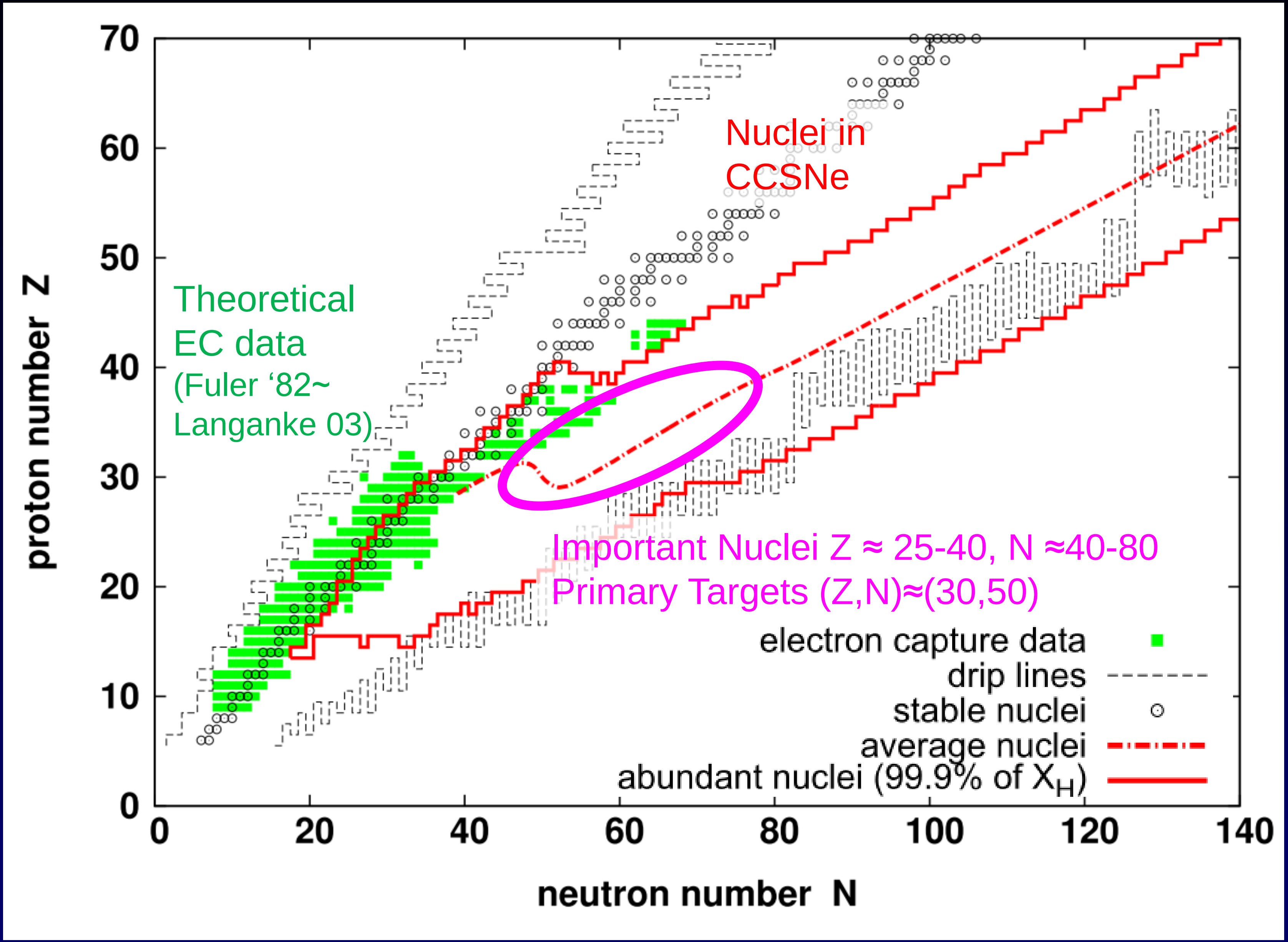
Mass fraction at $\rho = 2.0 \times 10^{12}$ g/cc, $T = 1.8$ MeV, $Y_e = 0.28$



- Nuclei with (N,Z)=(40-80,25-40)
- Sensitive to choice of excitation models
- Nuclei with (N,Z)≈(50,30) are commonly abundant in all models

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

(+ partition function level densities for Equation of State)

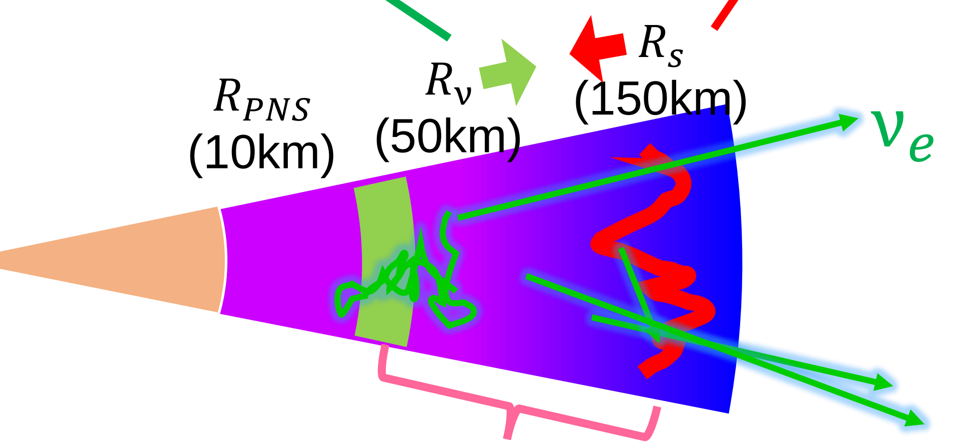


Electron captures on nuclei reduce neutrino bursts
(Sullivan et al.16, see also Hix ’03, Lentz ‘13)

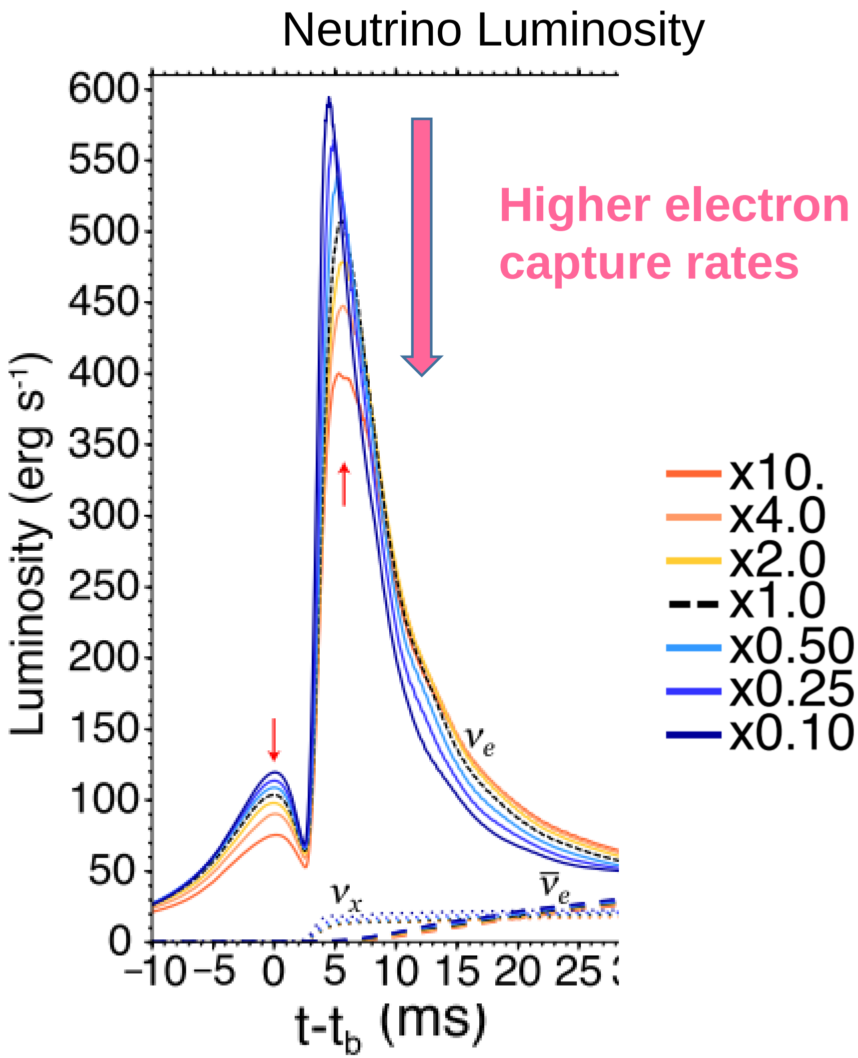
More electron captures on nuclei

⇒ ①fewer leptons
⇒smaller proto NS
⇒**smaller shock radius** R_s

⇒② more neutrino captures
⇒**larger neutrino spheres** R_ν



⇒ **smaller neutrino emissions**



Summary

- Core-Collapse Supernovae greatly depends on weak rates and nuclear statistical equilibrium (NSE).

- NSE EOS requires ① bulk matter calculation,
  ② mass data, and
  ③ nuclear excitation model
  (the most ambiguous part).
- Nuclei with (N,Z)=(40-80,25-40) appear at $\rho \sim 10^{11-12}$g/cc.

- Primary targets are nuclei with (N,Z)≈(50,30)
- We lack in their model or data of
  Electron Captures (β+ strength distribution)
  and nuclear excitations (level density).