Explosion Mechanism of Core-Collapse Supernovae : How to blow up massive stars ?

Kei Kotake

(Fukuoka University)

NIC XIV School @ Niigata University
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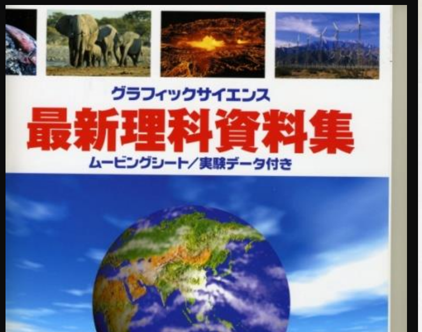
Bottom line



The supernova theory must address the following issues :

- How are "heavy elements" formed ?
- How are compact objects like neutron stars and black holes formed ? (final frontier of stellar evolution theory)
- Promising sources of neutrinos and gravitational waves.

✓ The explosion mechanism is still a topic of debate over 50+ years.

✓ The only means : the *direct* information of the supernova engine,
→ the observations of neutrinos and gravitational waves (GWs).

✓ To check "CCSN theory" with observations: Compare outcomes from first-principle simulations
(multi-D hydrodynamics simulations with Boltzmann neutrino transport)
with multi-messenger observations → The final goal.

Outline

1st part; Today

✓ The Standard Supernova Theory
- what is missing in it !?

✓ **Current Multi-D Supernova Paradigm**
- status of radiation-hydrodynamics simulations

2nd ;Tomorrow

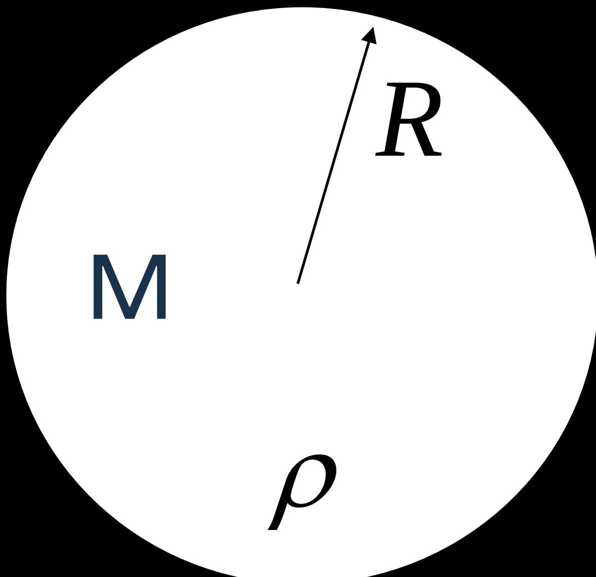
✓ **Multi-messenger signatures**
- Gravitational Waves and Neutrino Signals

✓ **Summary with some perspectives**

Step0 : Stellar evolution: *order-of-magnitude* *estimate* (1/2)

Stellar evolution is primarily determined by the initial stellar mass !

Uniform gas sphere



Mass cons.

$$\rho \sim \frac{M}{4\pi/3R^3}$$

Hydro equilibrium

$$\frac{dP(r)}{dr} = -\rho\frac{GM(r)}{r^2}$$

$$P \sim r \frac{M}{\frac{4\pi r^3}{3}} \frac{GM}{r^2} \sim \frac{GM^2}{r^4}$$

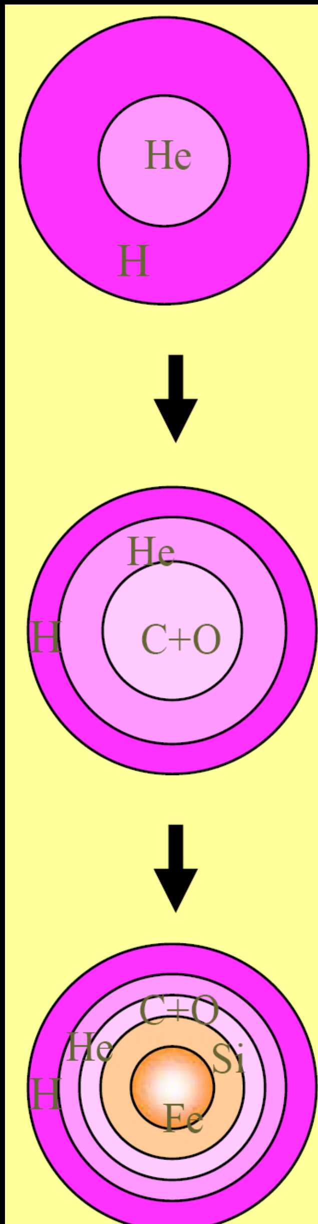
EOS

$$P \sim \rho T$$

Eliminating P and R…

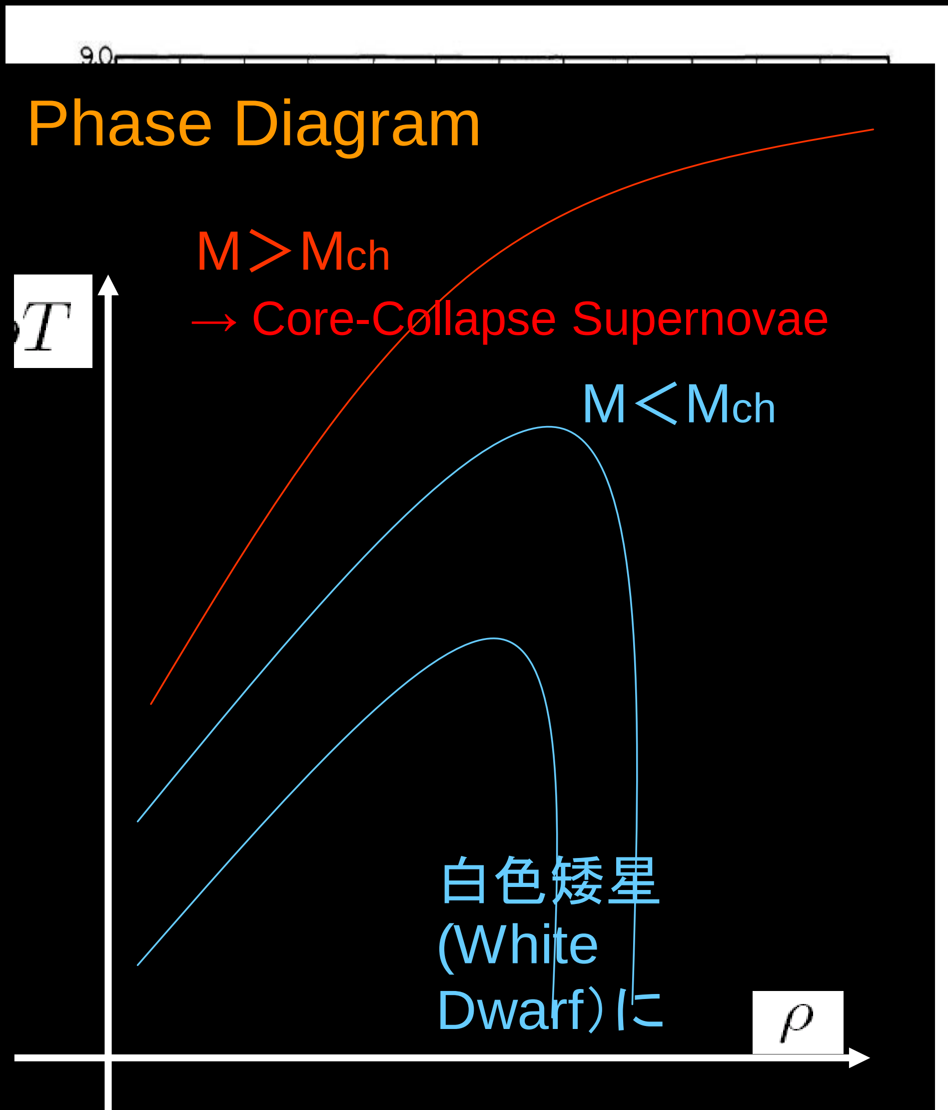
$$\log T \sim \frac{1}{3}\log\rho + \frac{2}{3}\log M + Const$$

If "M" is constant, $T \propto \rho^{1/3}$



Step0 : Stellar evolution: *order-of-magnitude estimate* (2/2)

Phase Diagram



Degenerate pressure (electron)

$$P \sim \frac{\rho Y_e T}{m_p} + K_\gamma Y_e^\gamma \rho^\gamma$$

Ye: electron fraction
(= 0.5 for Helium 4)

Using the equilibrium condition: P~GM^2/ R^4

$$T \sim \frac{m_p}{Y_e k}\left(G M^{2/3} \rho^{1/3} - K_\gamma Y_e^\gamma \rho^{\gamma-1}\right)$$

(adiabatic index ; γ＝4/3 for degenerate e)

$$M > \left(\frac{K_{4/3}}{G}\right)^{3/2} Y_e^2$$ then $$\frac{\partial T}{\partial \rho} > 0$$

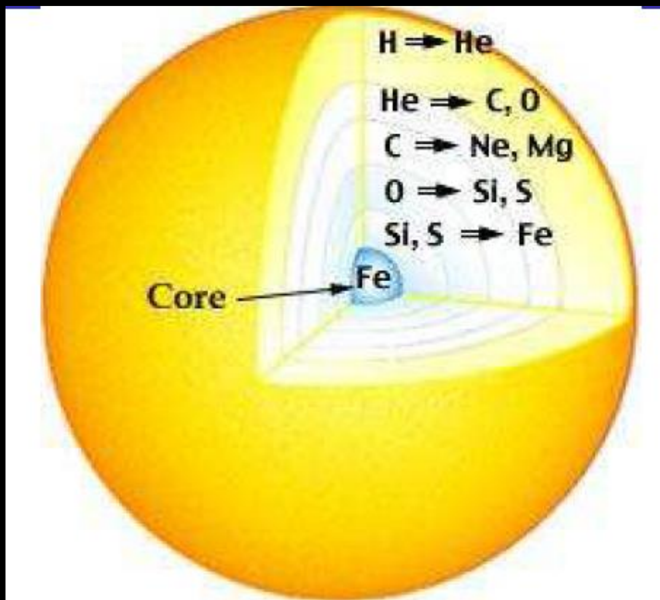
$$= M_{\text{Chandrasekar}} \sim 1.4 M_\odot$$

(Chandrasekhar mass)

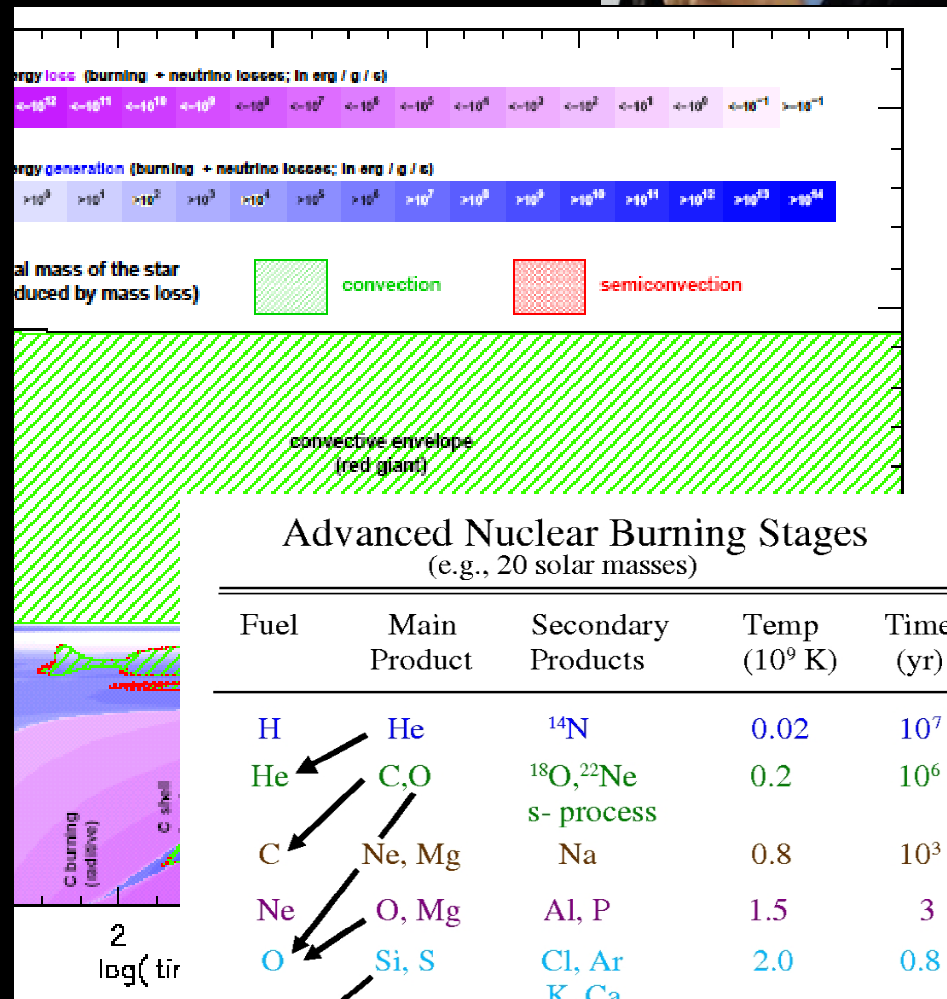
S.Chandra
-sekhar

$$M_{Ch} = 5.76 Y_e^2 M_\odot = 1.44 \left(\frac{Y_e}{0.5}\right)^2 M_\odot$$

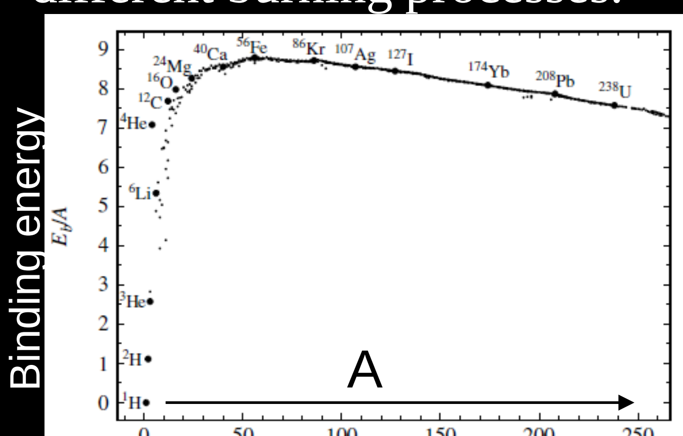
Presupernova star evolution



Kippenharn Diagram



- ✓ Star has an onion like structure.
- ✓ Iron is the final product of the different burning processes.

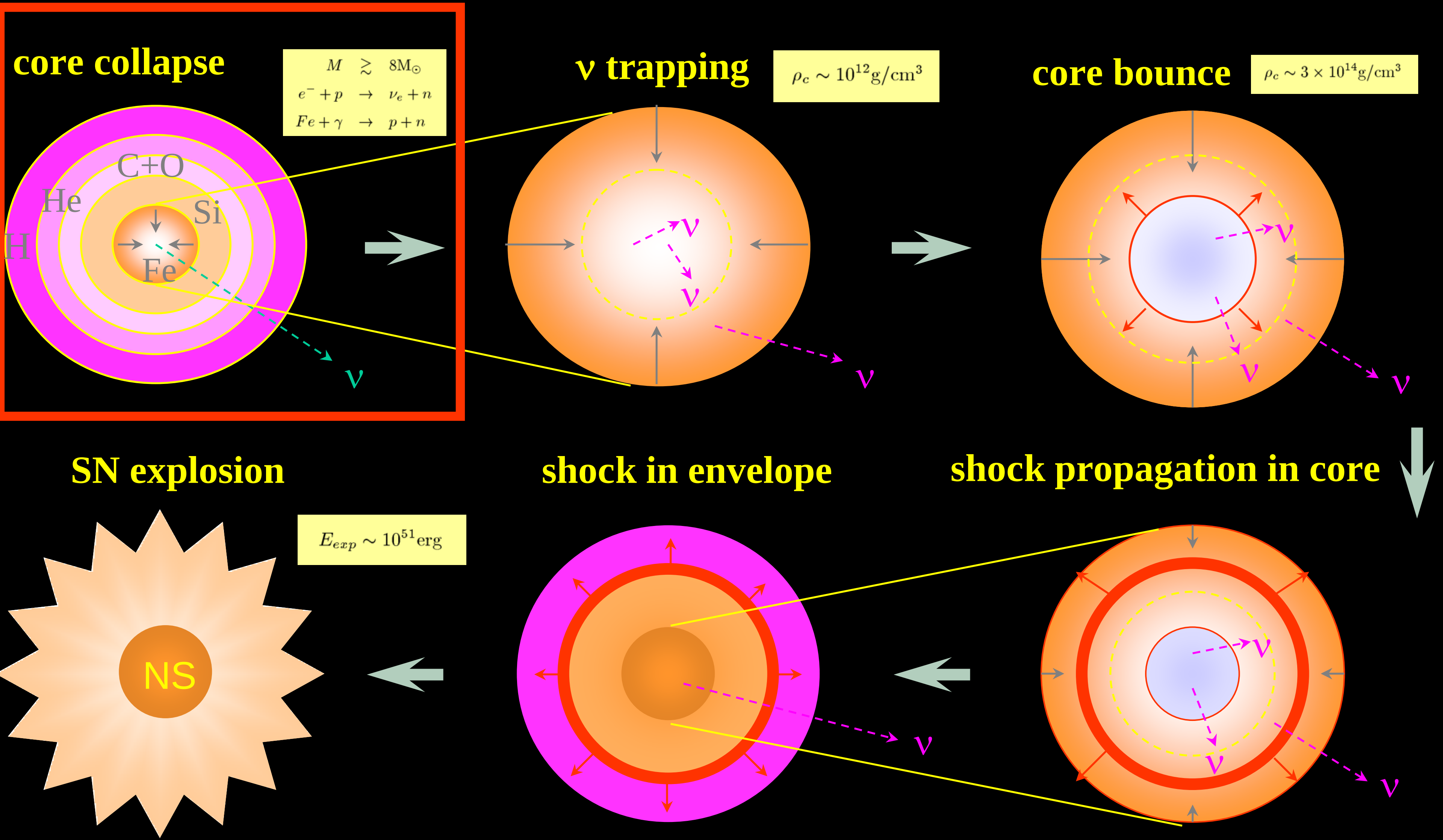


Advanced Nuclear Burning Stages
(e.g., 20 solar masses)

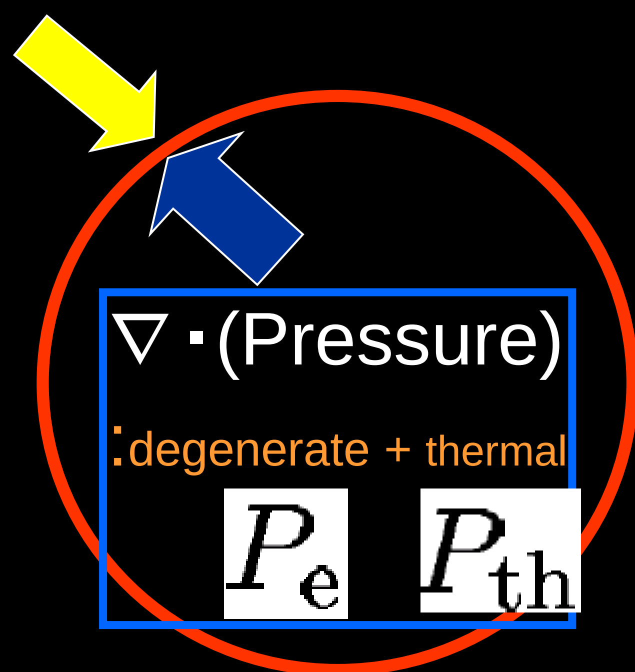
Fuel	Main Product	Secondary Products	Temp (10^9 K)	Time (yr)
H	He	^{14}N	0.02	10^7
He	C,O	^{18}O,^{22}Ne s- process	0.2	10^6
C	Ne, Mg	Na	0.8	10^3
Ne	O, Mg	Al, P	1.5	3
O	Si, S	Cl, Ar K, Ca	2.0	0.8
Si	Fe	Ti, V, Cr Mn, Co, Ni	3.5	1 week

Typical evolution timescale (Woosley&Heger 2002)

Standard scenario of core-collapse SNe



Step 1 Onset of gravitational-collapse



Iron core

$$R_{core} \sim 1000\mathrm{km}$$

$$M_{core} \sim 1.4 M_{\odot}$$

$$\rho_{center} \sim 3 \times 10^9 \mathrm{g/cm^3}$$

T ~ 1 MeV

E_F ~ 10 MeV

1. Electron capture

$$^{56}\mathrm{Fe} + e^- \rightarrow {}^{56}\mathrm{Mn} + \nu_e$$

$$m_{\mathrm{Mn}} - m_{\mathrm{Fe}} = 5.5\mathrm{MeV}$$

Fermi energy of electrons:

$$\mu_e \sim (3\pi^2 n_e)^{1/3}\hbar c = 11.1\mathrm{MeV}(\rho Y_e/10^9 \mathrm{g\ cm^{-3}})^{1/3}$$

∴ density ↗ → μ_e ↗

→ Electron capture ↗ → P_e ↘

2. Photodissociation of Fe nuclei

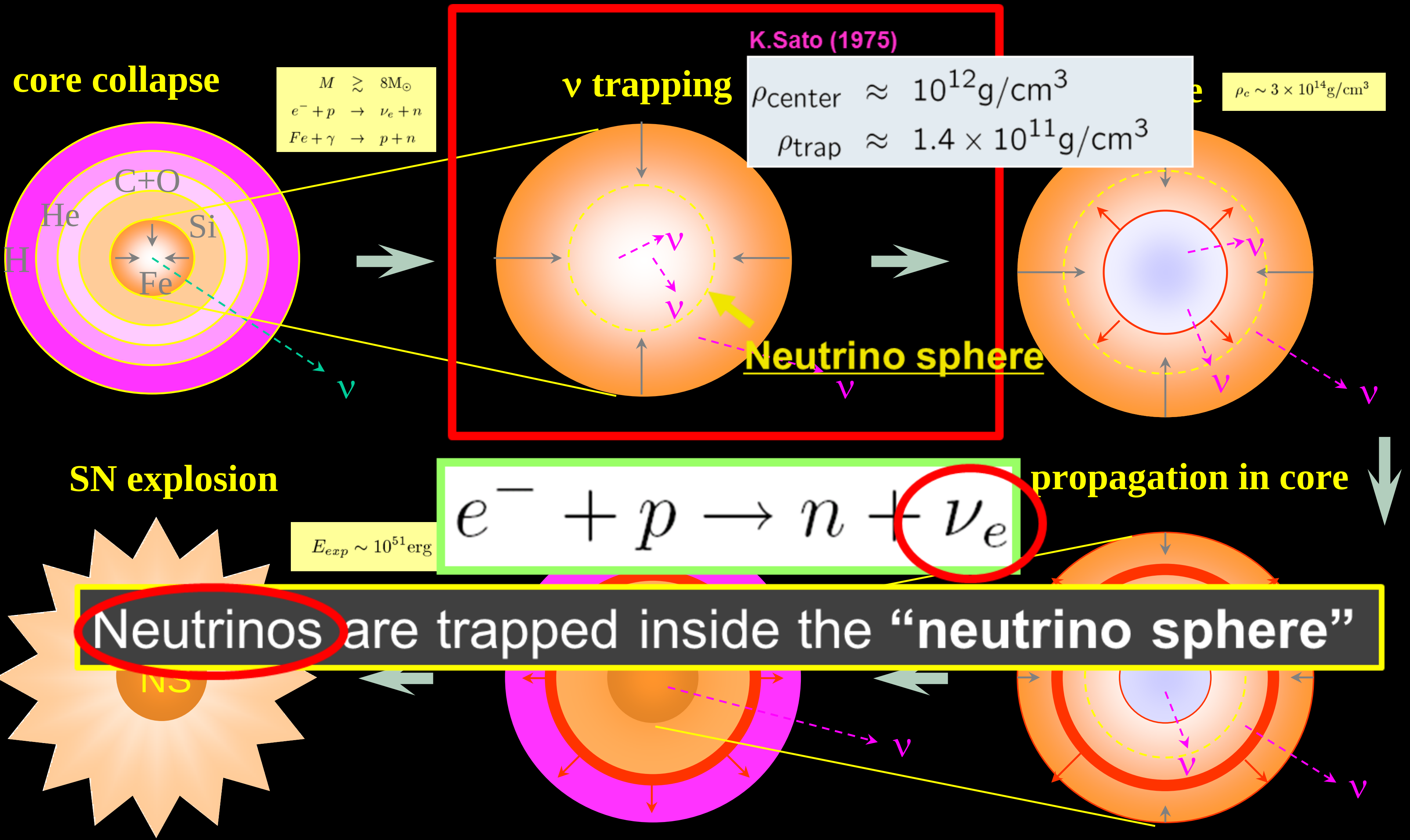
$$^{56}\mathrm{Fe} + \gamma \rightarrow 13\,{}^4\mathrm{He} + 4\mathrm{n} \boxed{- 124.4\mathrm{MeV}}$$

endothermic

→ P_{th} ↘

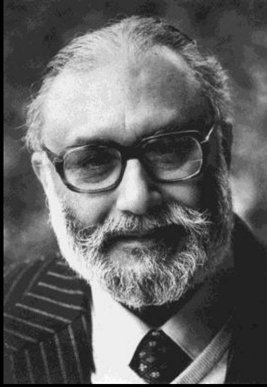
<u>(1, 2) initiate the onset of g- collapse</u>

Standard scenario of core-collapse SNe



(Weinberg)

Step 2 Neutrino Trapping (1)



(Salam)

Neutrino → **Weak interacting particle**

(Neutral-rino: neutral-particle, light mass (<eV))

$$\sigma \sim 10^{-38}\mathrm{cm}^2 \quad (\text{at 1GeV}) \ll \sigma_T \sim 10^{-25}\mathrm{cm}^2$$

Short note: In the core, typical energy scale is O(10 MeV). μ,τ barely exist! The neutrinos are produced only by NC interactions.
They are collectively called as ν_x

Representative Neutrino reactions in the

Neutrino emission/absorption	Scattering with (N: nucleon (A、Z): Nuclei)	
$p + e^- \rightleftarrows n + \nu_e$ $n + e^+ \rightleftarrows p + \bar{\nu}_e$	$\nu + N \rightleftarrows \nu + N$	$e^+ + e^- \rightleftarrows \nu + \bar{\nu}$
$(A, Z) + e^- \rightleftarrows (A, Z-1) + \nu_e$	$\boxed{\nu + (A, Z) \rightleftarrows \nu + (A, Z)}$ $\nu + e^\pm \rightleftarrows \nu + e^\pm$	

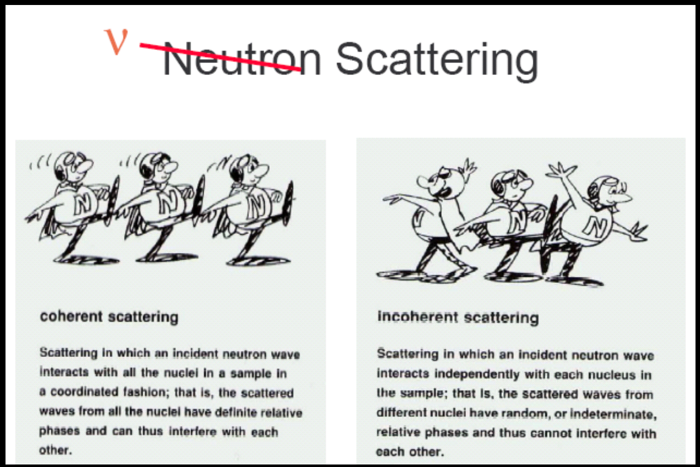
Mass energy			
0.000511 GeV	e	Electron
0.1066 GeV	μ	Muon
1.777 GeV	τ	Tau

Step 2 Neutrino Trapping (2)

Why Neutrino scattering on Nuclei is most important ?

$$\nu_e + (Z,A) \xrightarrow[Z]{} \nu_e + (Z,A)$$

Scattered neutrino



Compton wavelength of neutrino

$$\lambda \approx 20\,\mathrm{fm}\left(\frac{E_\nu}{10\,\mathrm{MeV}}\right)^{-1}$$ (fm=10^{-15} m)

$$\sigma_A = \frac{1}{16}\sigma_0\left(\frac{E_\nu}{m_e c^2}\right)^2 A^2\left[1-\frac{Z}{A}+(4\sin^2\theta_w-1)\frac{Z}{A}\right]^2$$

$$\sigma(\nu_e N \to \nu_e N) = 3\times 10^{-40}\left(\frac{E}{10\mathrm{MeV}}\right)^2\left(\frac{A}{56}\right)^2 \mathrm{cm}^2$$

nuclei

nucleon (p or n)

$$\sigma_\mathrm{n} \sim \sigma_0\left(\frac{E_\nu}{m_e c^2}\right)^2$$

Incident neutrino

$$\sigma_0 = 4G_\mathrm{F}^2(m_e c^2)^2/(\pi(\hbar c)^4) = 1.705\times 10^{-44}\,\mathrm{cm}^2$$

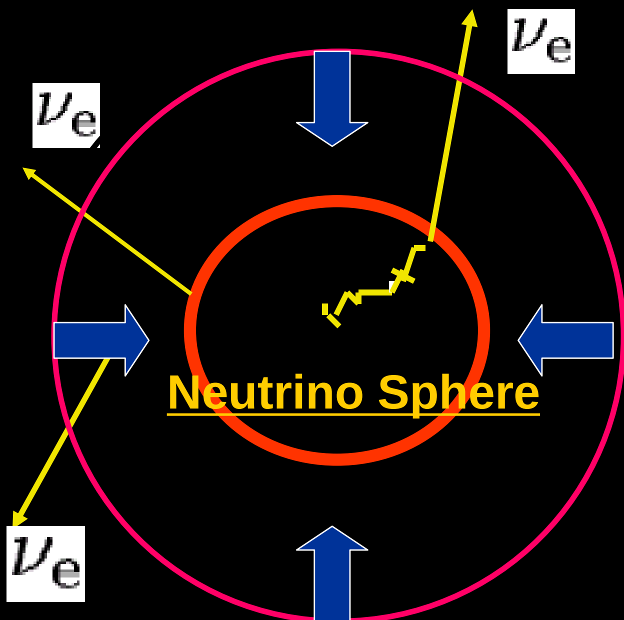
$$r_\mathrm{Nucleus} \sim 1.2A^{1/3} \sim 5\ \mathrm{fm}\left(\frac{A}{56}\right)^{1/3}$$

✓ For $\lambda\nu > R_{nuc}$, quantum interference occurs !
(Freedman (1974), Langanke & Kolbe (1992))

✓ The cross section of coherent scattering is proportion to A^2, thus important !

The condition of “Neutrino trapping”(1/3)

K. Sato (1975)



To judge whether neutrinos can be trapped or not in the iron core,
Compare the two timescales !

Free-fall timescale $\tau_{\rm ff}$

Diffusion timescale due to coherent neutrino-A scattering $\tau_{\rm diff}$

$$\begin{cases} \rho \dfrac{\partial^2 r}{\partial t^2} = -\dfrac{G M_r \rho}{r^2} \\ \rho \sim \dfrac{M}{4\pi/3R^3} \end{cases}$$

$$N_{\rm R} = \left(\frac{R}{\lambda}\right)^2$$

Number of scattering (random walk)

$$N_{\rm R}\frac{\lambda}{c} = \frac{R^2}{c\lambda}$$

Diffusion timescale

$$t_{\rm diff} = \frac{3R^2}{c\lambda}$$

$$t_{\rm diff} \leq t_{\rm dyn}$$

$$R_{\rm core} = \left(\frac{3M}{4\pi\rho}\right)^{1/3}$$

Mean free-path by the coherent scattering

$$\lambda_\nu = \frac{1}{\sigma n_A} \approx 10^7 {\rm cm} \left(\frac{\rho}{3\times 10^{10} {\rm gcm^{-3}}}\right)^{-1} \left(\frac{E_\nu}{12.6{\rm MeV}}\right)^{-2} \left(\frac{A}{56}\right)^{-1} \left(\frac{Y_e}{26/56}\right)^{-\frac{2}{3}}$$

Average neutrino energy

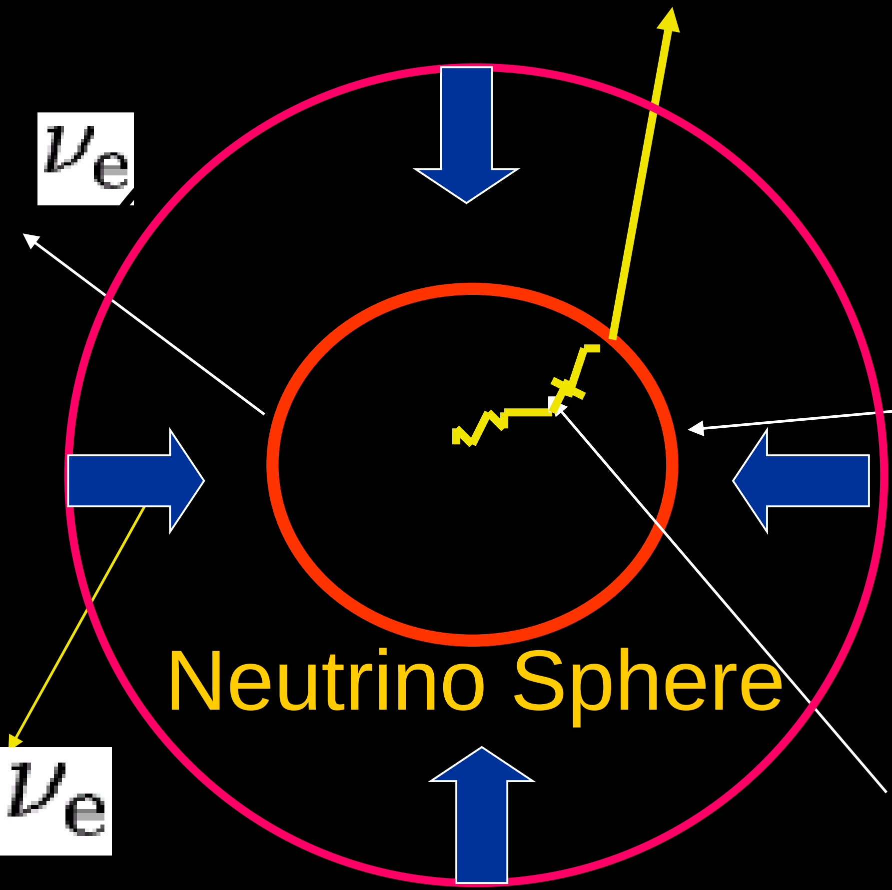
$$E_\nu \approx \frac{5}{6}\mu_e = \frac{5}{6}\left(3\pi^2 \frac{\rho Y_e}{m_p}\right)^{\frac{1}{3}} \hbar c \approx 12.6{\rm MeV} \left(\frac{\rho}{3\times 10^{10} {\rm g\ cm^{-3}}}\right)^{\frac{1}{3}} \left(\frac{Y_e}{26/56}\right)^{\frac{1}{3}}$$

$$\tau_{\rm ff} \sim \frac{1}{\sqrt{G\rho}} = 4\times 10^{-3}\ {\rm s}\left(\frac{\rho}{1\times 10^{12}\ {\rm g\ cm^{-3}}}\right)^{-1/2} = \tau_{\rm diff} \sim 8\times 10^{-2}{\rm s}\left(\frac{\rho}{1\times 10^{12}\ {\rm g\ cm^{-3}}}\right)$$

$$\rho \sim \rho_{\rm trap} \sim 1.4\times 10^{11}\ {\rm g\ cm^{-3}}$$

→“Neutrino trapping density”, the isodensity sphere is called neutrino sphere(s).

The condition of "Neutrino Trapping"(2/3)



Free escaping region

$$t_{\rm diff} \leq t_{\rm dyn}$$

$$t_{\rm diff} = t_{\rm dyn}$$

Neutrino sphere

Diffusion region

$$t_{\rm diff} \geq t_{\rm dyn}$$

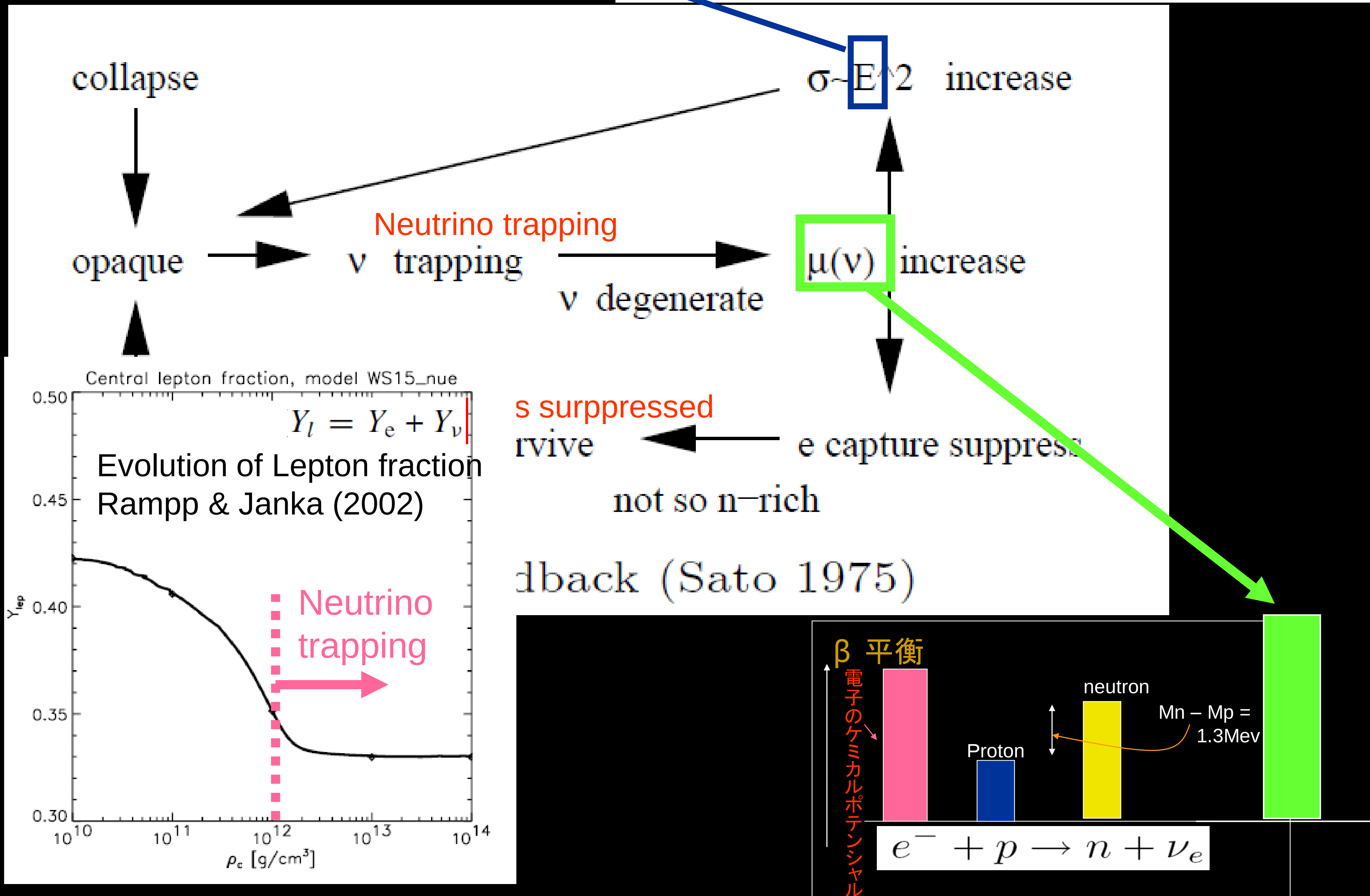
✓ The position of the neutrino sphere is energy-dependent !

$$R_\nu \approx 1.0 \times 10^7 \ {\rm cm} \left(\frac{E_\nu}{10 {\rm MeV}} \right)$$

For lower-energy neutrinos,
the neutrino sphere forms deeper
inside, because they need
a denser environment to be opaque!

Important positive feedback due to Neutrino trapping (3/3)

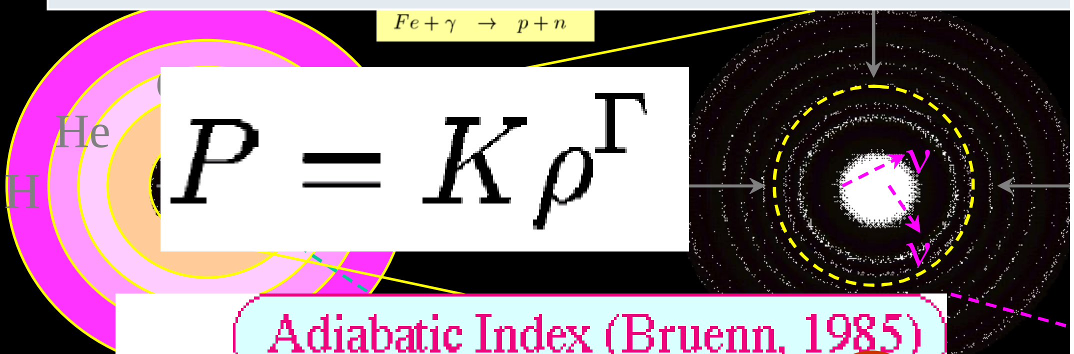
$$E_\nu \approx \frac{5}{6}\mu_e = \frac{5}{6}\left(3\pi^2\frac{\rho Y_e}{m_p}\right)^{\frac{1}{3}}\hbar c \approx 12.6\mathrm{MeV}\left(\frac{\rho}{3\times10^{10}\mathrm{g\ cm^{-3}}}\right)^{\frac{1}{3}}\left(\frac{Y_e}{26/56}\right)^{\frac{1}{3}}$$

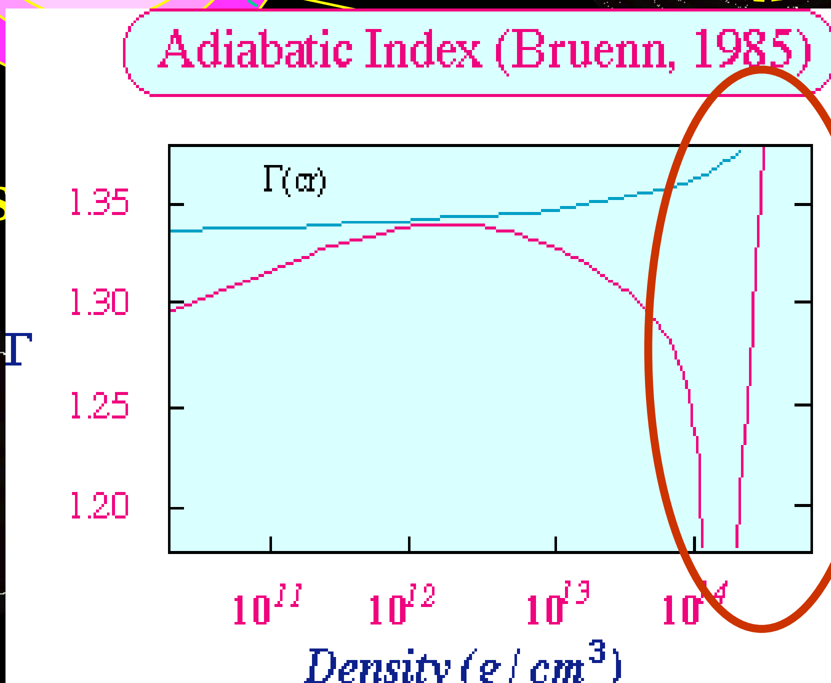


Standard scenario of core-collapse SNe

$$\rho_{\rm center} \approx 3 \times 10^{14} {\rm g/cm}^3$$

$$P = K\rho^{\Gamma}$$





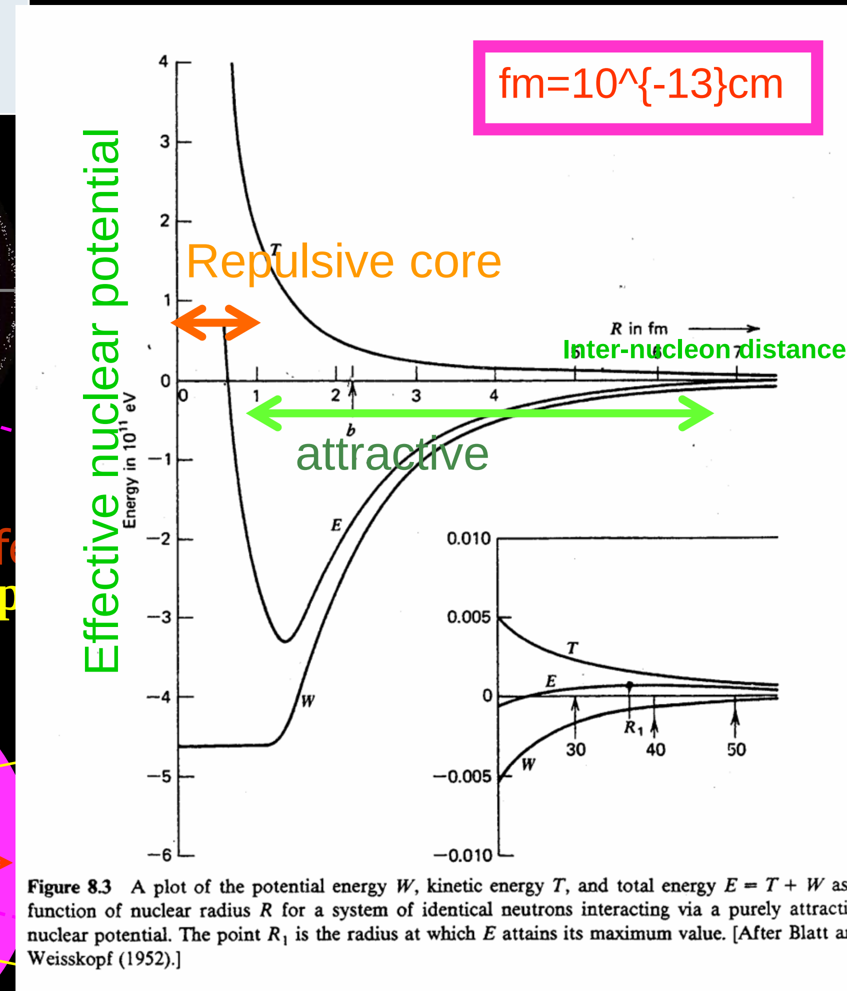
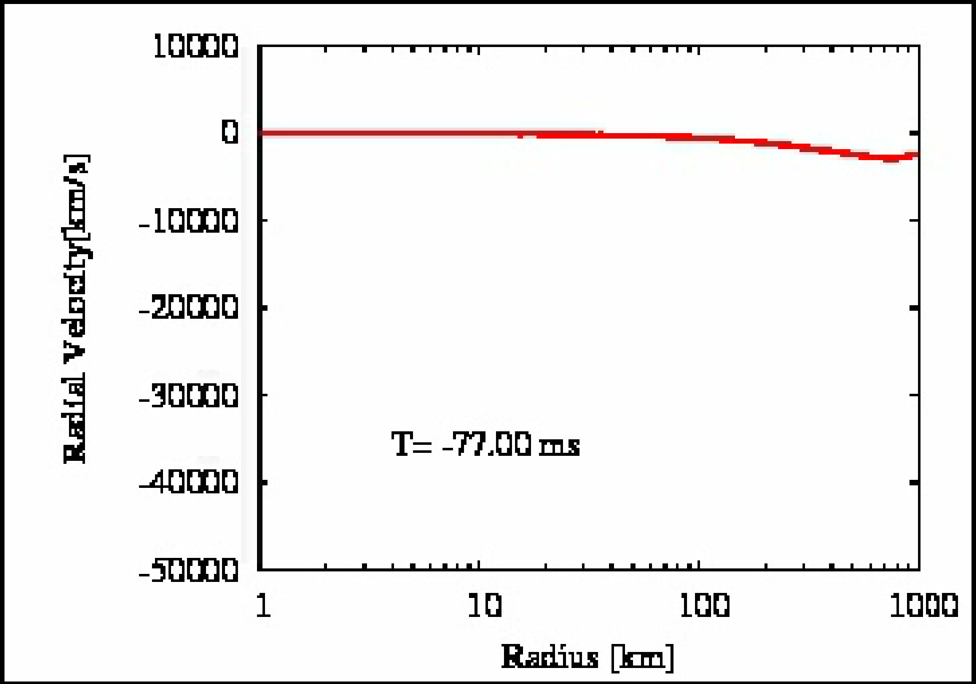


Figure 8.3 A plot of the potential energy W, kinetic energy T, and total energy $E = T + W$ as a function of nuclear radius R for a system of identical neutrons interacting via a purely attractive nuclear potential. The point R_1 is the radius at which E attains its maximum value. [After Blatt and Weisskopf (1952).]

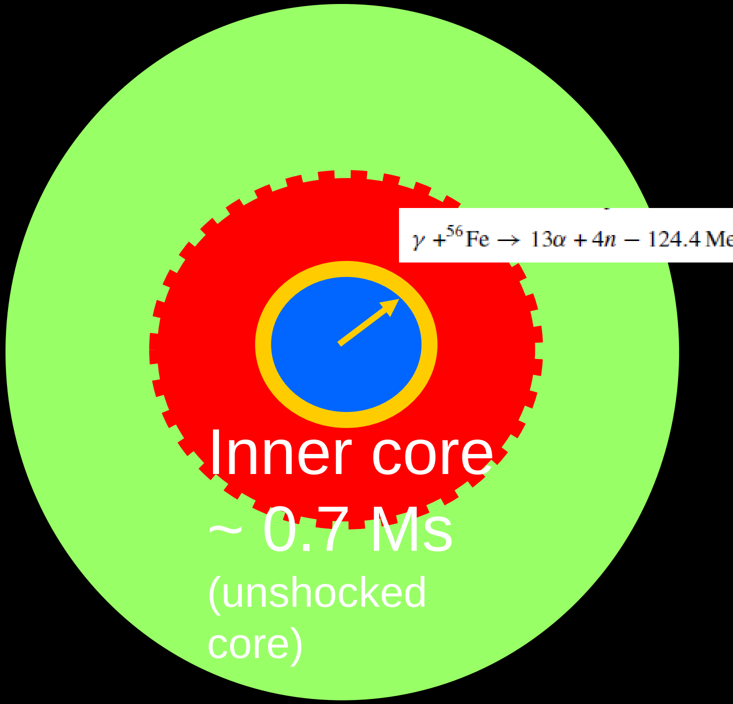
(Shapiro & Teukolsky 1983,p204)

Dynamics near bounce

Evolution of Radial velocity versus stellar radius
based on radiation-transport simulations



Iron core = 1.4 Ms



✓The initial shock position is given ~ $M_{\rm ic} \sim 0.7 M_\odot \left(\frac{Y_e}{0.34}\right)^2$ $Y_e = \frac{n_e}{n_b}$

Mass outside the inner core

$$E_{\rm loss} \sim 10^{50} {\rm erg}/{\rm M}_\odot \left(\frac{\Delta M}{0.1 M_\odot}\right)^{-1}$$

✓ The kinetic energy of the shock gets small due to the photo-dissociation $^{56}\mathrm{Fe} + \gamma \rightarrow 13\,^4\mathrm{He} + 4\mathrm{n} - 124.4\mathrm{MeV}$

✓ Larger Ye leads to more massive inner core ⇒ Good for explosions. to accurately determine electron cap. rates is crucial!! (eg., Balasi et al. PrPNP 2015)

Some remarks on Nuclear Equation of State (EOS)

$$\cancel{P = K\rho^{\Gamma}}$$

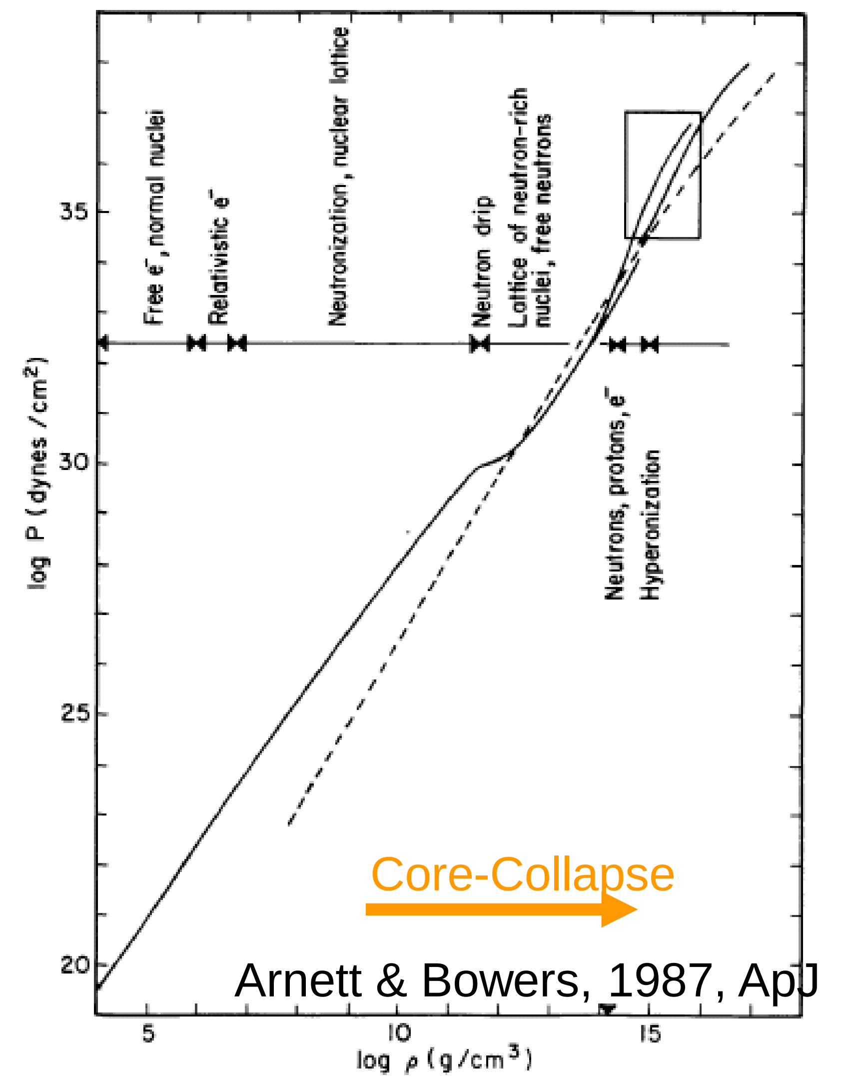
Never simple !

✓ EOS depends on three variables

- EOS data table (~60MB) covers
  - Density: $10^5 \sim 10^{15}$ g/cm^3
  - Proton fraction: $0 \sim 0.56$
  - Temperature: $0 \sim 100$ MeV

✓ SN EOS should cover the wide range (10 orders-of-mag. in ρ); rich nuclear physics

(see lectures by Profs. Takeuchi and Paar)



Arnett & Bowers, 1987, ApJ

FIG. 3.—Representative equations of state for cold neutron stars based on nonrelativistic calculations. For comparison the equation of state for a free gas of neutrons is shown (– – –). The region contained in the rectangular region (*upper right corner*) is shown enlarged in Fig. 4.

Some remarks on Nuclear Equation of State (EOS)

TABLE 1B

EQUATIONS OF STATE

Model	Interactions	
A.	Reid soft core—adapted to nuclear matter	Variational pı
B.	Same as A; arbitrary reduction for hyperon-hyperon attraction	Same as A
C.	Modified Reid soft core; noninteger *n* in equation (3.1)	Constrained v
D.	Same as C; more nearly realistic adaptation to hyperon matter	Same
E.	Reid soft core; modified hyperon interactions based on quark theory	Reaction mati
F.	Thomas Fermi model	Brueckner *G*-ı
G.	Modified Reid soft core. Localization via nonrelativistic harmonic oscillators.	*T*-matrix; incl
H.	None	Fermi statistic
I.	Levinger-Simmons velocity-dependent V_α	Hartree-Fock potential
L.	Nuclear attraction due to scalar exchange	Mean field ap method
M.	Nuclear attraction due to pion exchange tensor interactions	Constrained v
N.	Relativistic mean field scalar plus vector exchange fitted to nuclear matter	Mean field ap
O.	Nonperturbative, phenomenological approximation to relativistic meson exchange	Relativistic fiı

Tens of Nuclear EOSs ?

Which one is correct ?!

ar)

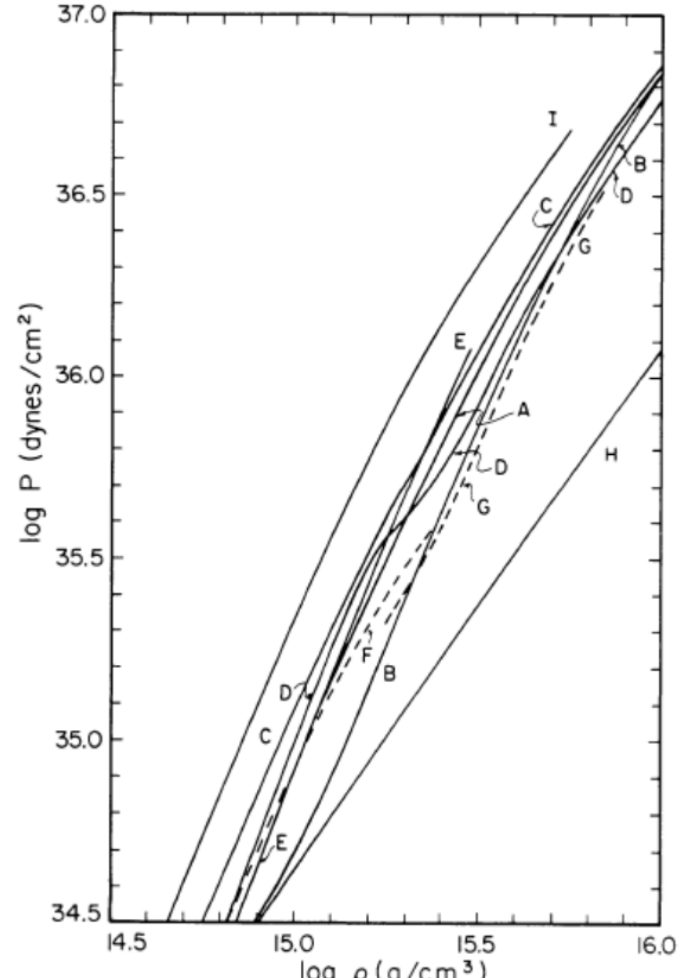
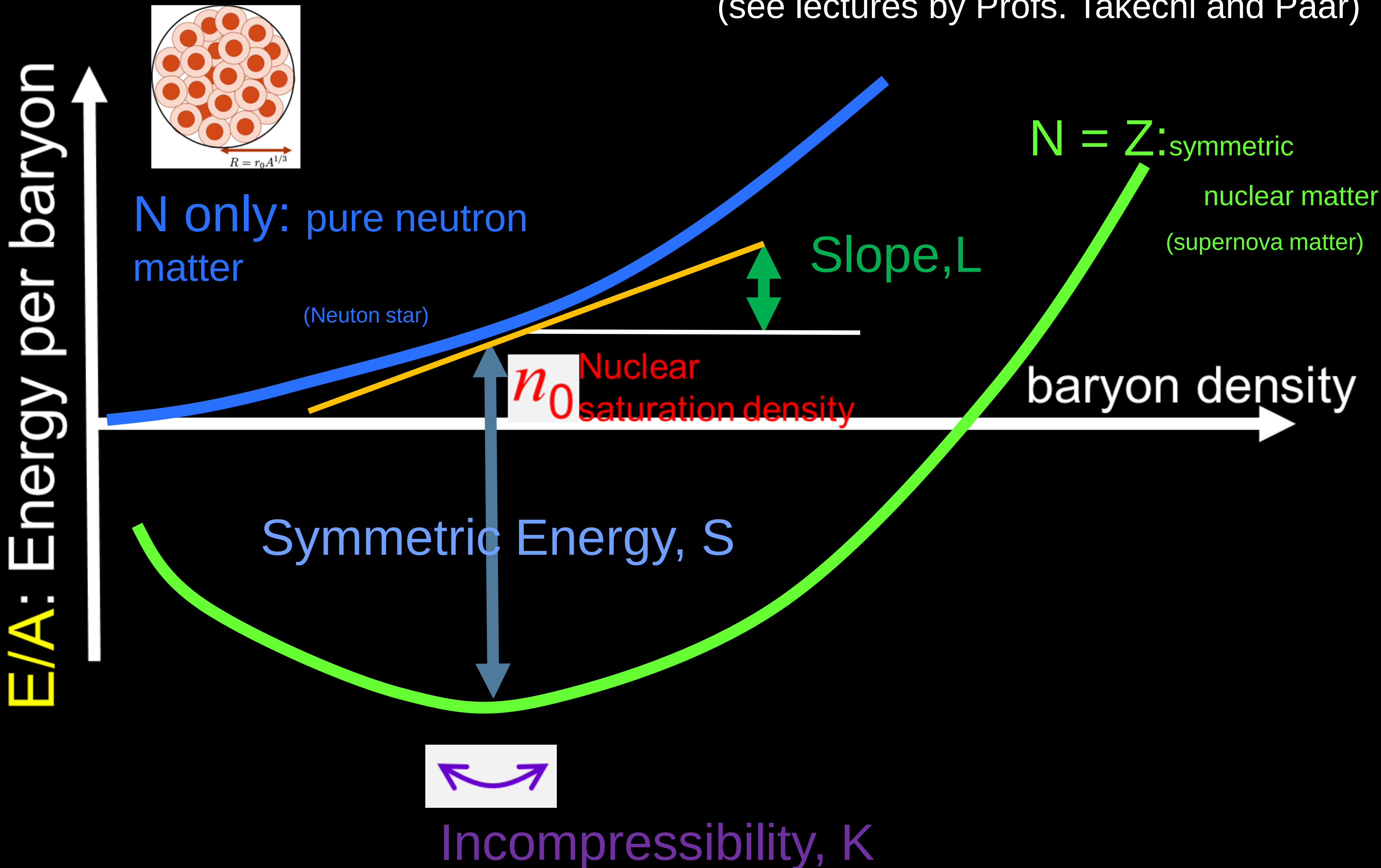


FIG. 4.—Equations of state used in obtaining the results in Tables 2–8. For comparison we include a free neutron gas (H) and the early work of Cohen, Langer, Rosen, and Cameron (I). Letters denote equation of state referenced in the Introduction.

right corner) is shown enlarged in Fig. 4.

Several key quantities of nuclear EOS

(see lectures by Profs. Takechi and Paar)

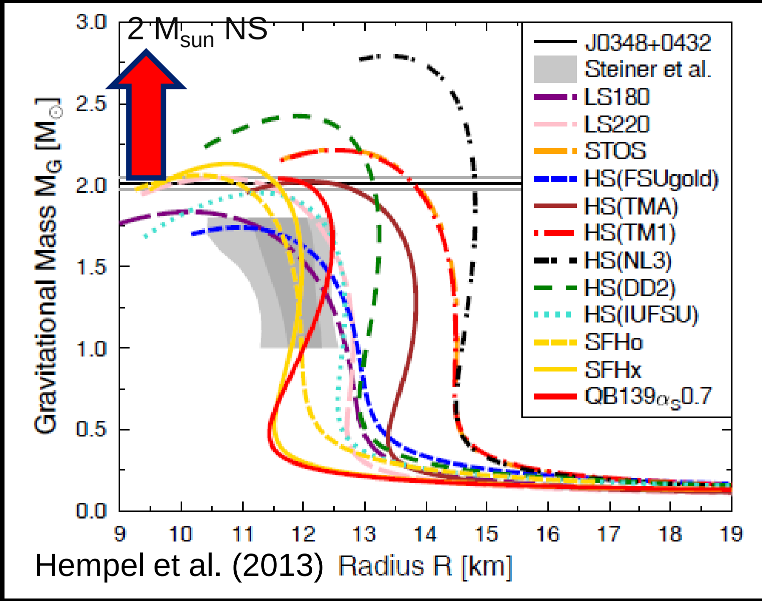


EOS constraints - saturation properties & maximum mass

Fisher et al. (2014)

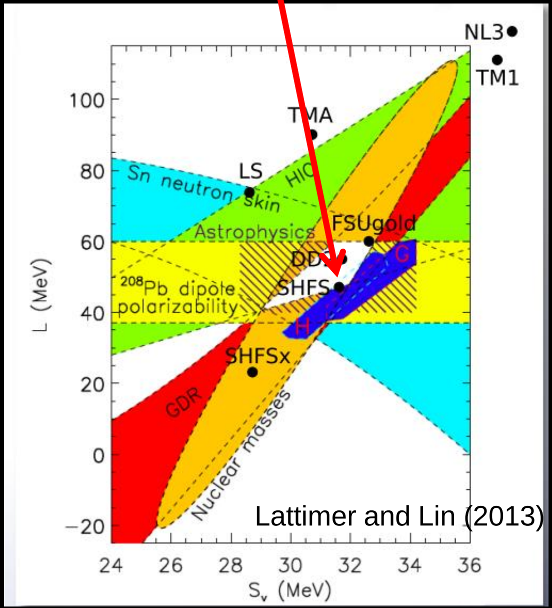
	n_B^0 [fm^{-3}]	E_0 [MeV]	K [MeV]	J [MeV]	L [MeV]	M_{max} [M$_\odot$]
TM1	0.146	-16.31	282	36.95	110.99	2.213
TMA	0.147	-16.03	318	30.66	90.14	2.022
FSUgold	0.148	-16.27	230	32.56	60.44	1.739
NL3	0.148	-16.24	271	37.39	118.50	2.791
DD2	0.149	-16.02	243	31.67	55.04	2.422
SHFS	0.158	-16.19	245	31.57	47.10	2.059
SHFSx	0.160	-16.16	239	28.67	23.18	2.130
LS180	0.155	-16.00	180	28.61	73.82	1.828
LS220	0.155	-16.00	220	28.61	73.82	2.031
Exp.	~ 0.15	~ -16	240 ± 10 [1]	30 - 34 [2]	40 - 110 [2]	$> 1.97 \pm 0.04$ [3]

Mass-Radius Relation for Cold NS with diff. EOSs



Hempel et al. (2013)

Constraints from nuclear experiments



Lattimer and Lin (2013)

EOS constraints - saturation properties & maximum mass

Fisher et al. (2014)

	n_B^0 [fm^{-3}]	E_0 [MeV]	K [MeV]	J [MeV]	L [MeV]	$M_{\max}$ [M$_\odot$]
TM1	0.146	-16.31	282	36.95	110.99	2.213
TMA	0.147	-16.03	318	30.66	90.14	2.022
FSUgold	0.1					1.739
NL3	0.1					2.791
DD2	0.1					2.422
SHFS	0.1					2.059
SHFSx	0.1					2.130
LS180	0.1					1.828
LS220	0.1					2.031
Exp.	$\sim$ (					1.97 ± 0.04 [3]

SHFS and SHFSx interactions

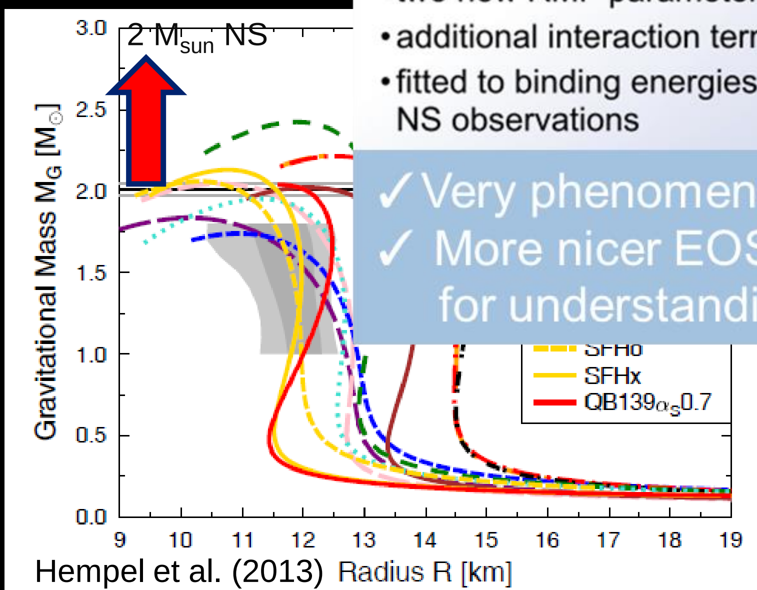
$$\mathcal{L} = \bar\Psi\left[i\partial\!\!\!/ - g_\omega \omega\!\!\!/ - \tfrac{1}{2} g_\rho \vec{\rho\!\!\!/}\cdot\vec\tau - M + g_\sigma\sigma - \tfrac{1}{2} e(1+\tau_3) A\!\!\!/\right]\Psi + \tfrac{1}{2}(\partial_\mu\sigma)^2$$
$$-V(\sigma) - \tfrac{1}{4} f_{\mu\nu} f^{\mu\nu} + \tfrac{1}{2} m_\omega^2 \omega^\mu\omega_\mu - \tfrac{1}{4}\vec B_{\mu\nu}\cdot\vec B^{\mu\nu} + \tfrac{1}{2} m_\rho^2 \vec\rho^\mu\cdot\vec\rho_\mu - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+\frac{\zeta}{24} g_\omega^4 (\omega^\mu\omega_\mu)^2 \boxed{+ \frac{\xi}{24} g_\rho^4 (\vec\rho^\mu\cdot\vec\rho_\mu)^2 + g_\rho^2 f(\sigma,\omega_\mu\omega^\mu)\vec\rho^\mu\cdot\vec\rho_\mu\,,}$$

$$V(\sigma) = \tfrac{1}{2} m_\sigma^2\sigma^2 + \frac{\kappa}{6}(g_\sigma\sigma)^3 + \frac{\lambda}{24}(g_\sigma\sigma)^4 \quad \boxed{f(\sigma,\omega_\mu\omega^\mu) = \sum_{i=1}^{6} a_i\sigma^i + \sum_{j=1}^{3} b_j(\omega_\mu\omega^\mu)^j}$$

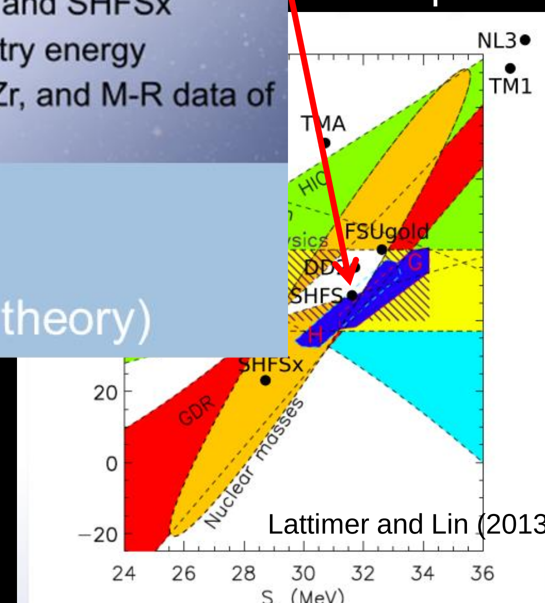
- two new RMF parameterizations & SN EOS tables: SHFS and SHFSx
- additional interaction terms included, more flexibel symmetry energy
- fitted to binding energies and charge radii for ^{208}Pb and ^{90}Zr, and M-R data of NS observations

✓Very phenomenological …
✓ More nicer EOS needed (: central, for understanding the stellar evolution theory)

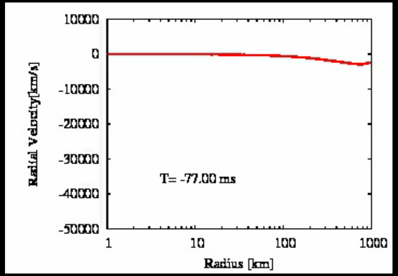
Mass-Radius Relat



clear experiments



Short summary (till shortly after bounce)

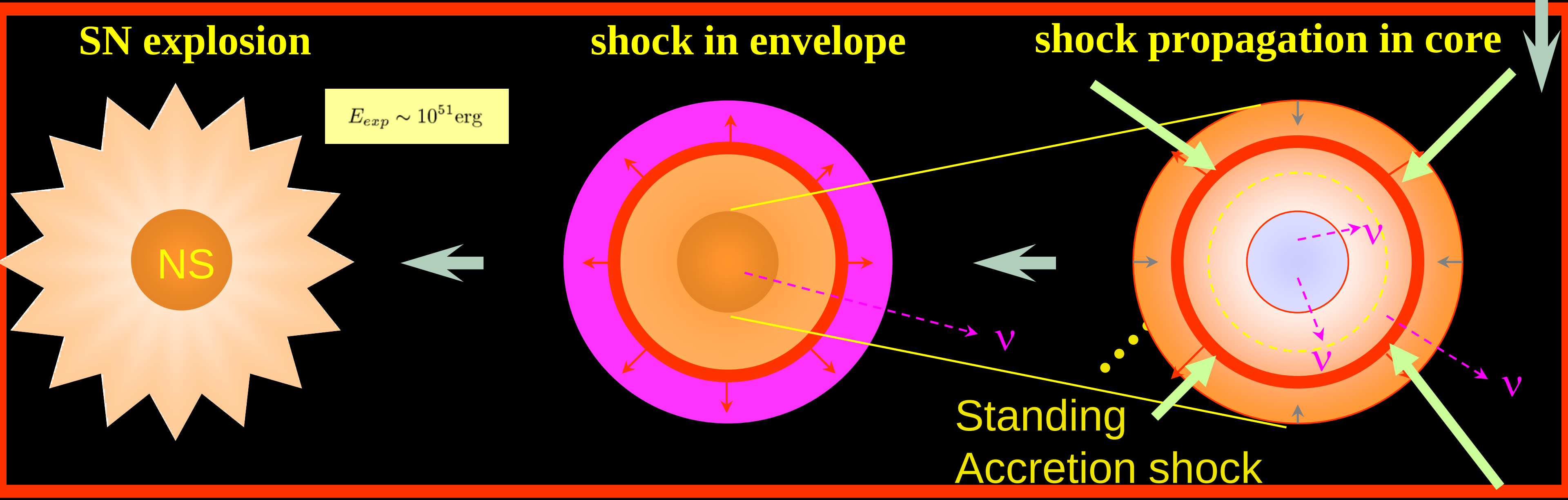


✓ SN simulations over these 20 years show that the bounce shock always stall because the kinetic energy of the shock is lost by the photo-dissociation of iron nuclefi.

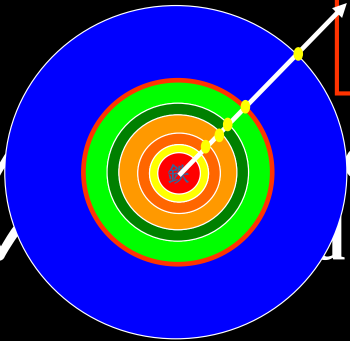
→ Direct "prompt" hydrodynamic explosion fails.

✓ The bounce shock turns into the standing accretion shock.

✓ The supernova problem is how to revive the stalled shock into explosion!

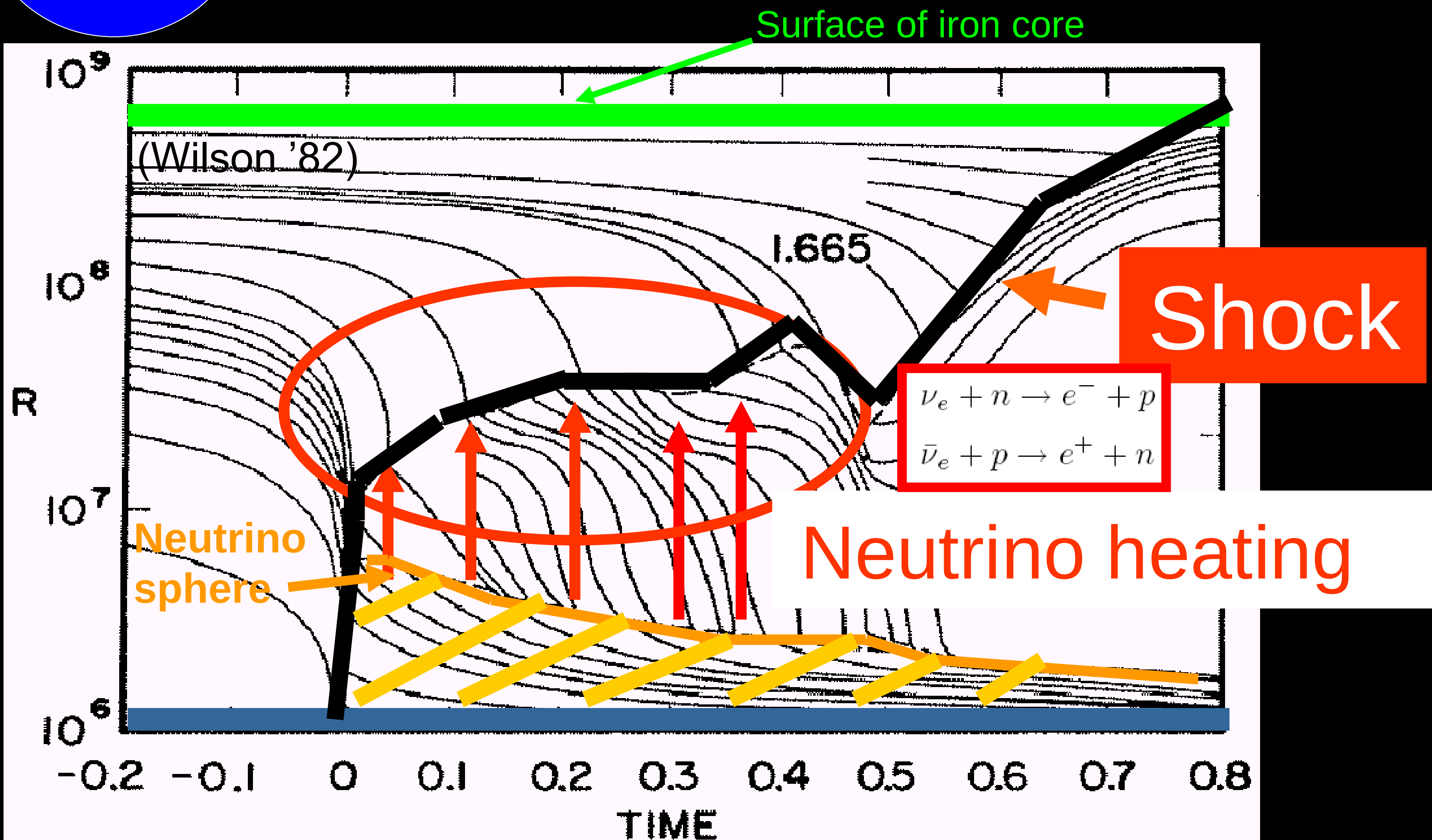


Neutrino-heating mechanism



✓ …d and most promising way to produce SN explosions.

✓ …l in the **1D numerical simulation** by Bethe & Wilson ’85.



How the neutrino mechanism works ? （1/2）

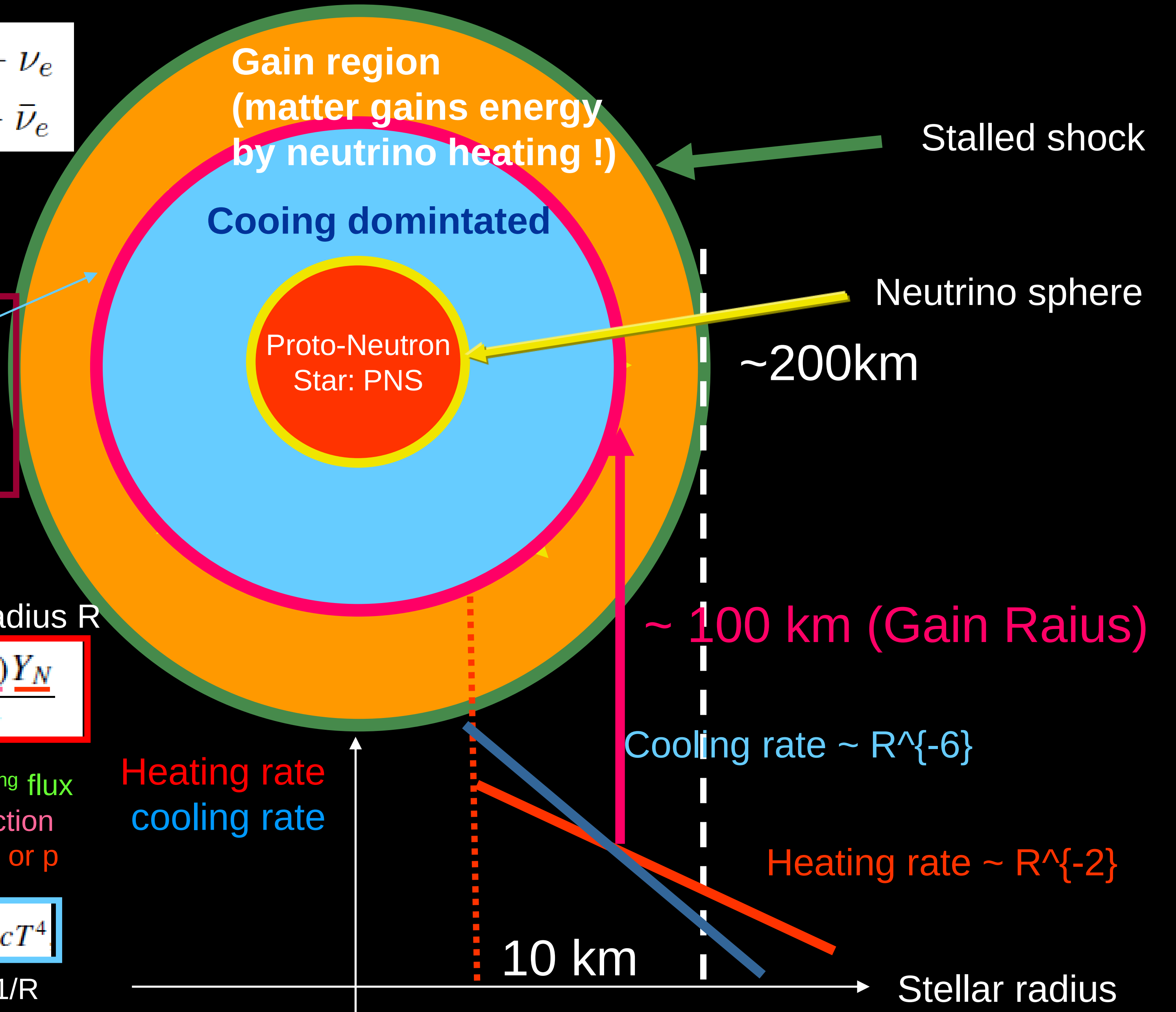
heating

$$p + e^- \rightleftarrows n + \nu_e$$

$$n + e^+ \rightleftarrows p + \bar{\nu}_e$$

cooling

Behind the shock, Fe is disintegrated to He, then to neutron and proton. (n and p most abundant)



Heating rate at radius R

$$Q_\nu^+ \cong \frac{L_\nu \, \sigma(E_\nu) Y_N}{4\pi R^2}$$

(erg/s cm^2) Incoming flux

x cm^2 : cross section

x # fraction of n or p

$$Q_\nu^- = -\sigma(T) a' c T^4$$

with T~1/R

How the neutrino mechanism works ?　(2/2)

$$n + \nu_e \rightarrow e^- + p$$

Heating rate for single neutron at radius "R"

absorbing neutrino (with luminosity L_ν energy E_ν ,)

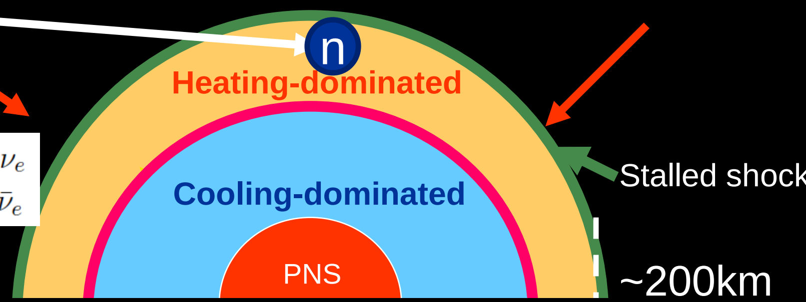
$$Q_\nu^+ \cong \frac{L_\nu \sigma(E_\nu) Y_N}{4\pi R^2}$$

(erg/s cm^2) Incoming flux
x cm^2 : cross section
x # fraction of n or p

heating

$$p + e^- \rightleftarrows n + \nu_e$$
$$n + e^+ \rightleftarrows p + \bar{\nu}_e$$

cooling



$$\sigma(E_\nu) \approx 9 \times 10^{-44} (E_\nu / 1\,\mathrm{MeV})^2\ (\mathrm{cm}^2)$$

$$Q_\nu^+ \sim 44.8 \left(\frac{L_\nu}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)\left(\frac{E_\nu}{15\,\mathrm{MeV}}\right)^2\left(\frac{R}{150\,\mathrm{km}}\right)^{-2}\left(\frac{Y_N}{1.0}\right)\left[\frac{\mathrm{MeV}}{\mathrm{s \cdot nucleon}}\right]$$

Neutrino cooling rate

$$Q_\nu^- = -\sigma(T) a' c T^4$$
$$a' = 7/16 \times 1.37 \cdot 10^{26}\,\mathrm{erg\,cm^{-3}\,MeV^4}$$

Net heating rate

$$Q_{\mathrm{tot}} = Q_\nu^+ - Q_\nu^- = Q_\nu^+\left[1 - \left(\frac{2R}{R_\nu}\right)^2\left(\frac{T}{T_\nu}\right)^6\right]$$

using $T = T_s \frac{R_s}{R}$

The gravitational binding energy of single neutron pulled by PNS

$$-\frac{G M_{\mathrm{NS}} m_u}{R} = -13.0\left(\frac{M_{\mathrm{NS}}}{1.4 M_\odot}\right)\left(\frac{R}{150\,\mathrm{km}}\right)^{-1}\quad [\mathrm{MeV/nucleon}].$$

$$R_g = \sqrt{\frac{2R_s^3}{R_\nu}\left(\frac{T_s}{T_\nu}\right)^3}.$$

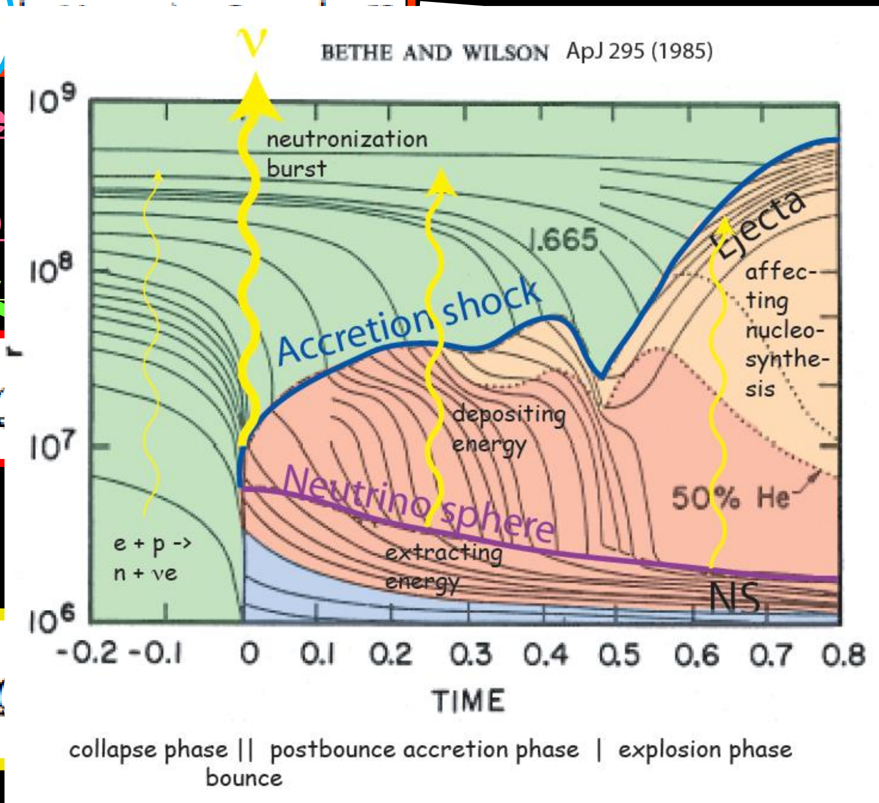
$T_\nu = 4.2\,\mathrm{MeV}$, $T_s = 1.5\,\mathrm{MeV}$,
$R_s = 200\,\mathrm{km}$, $R_\nu = 80\,\mathrm{km}$

$R_g \approx 95\,\mathrm{km}$.

✓If the neutrino heating could last > ~0.25 sec, the absorbed energy exceeds the local grav. binding energy -> inflows turns into outflows !

✓More correctly neutrino cooling occurs, which delays the onset of explosion.

How the neutrino mechan

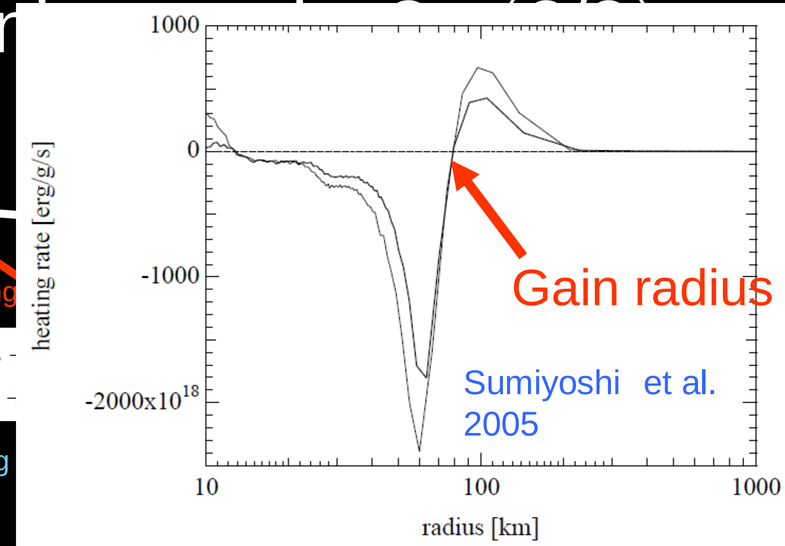


heating

$e^- \rightleftarrows n$

$e^+ \rightleftarrows p$

cooling



$\left[\frac{\text{MeV}}{\text{s} \cdot \text{nucleon}}\right]$

Neutrino cooling rate

$$Q_\nu^- = -\sigma(T) a' c T^4$$

$$a' = 7/16 \times 1.37 \cdot 10^{26}\ \text{erg cm}^{-3}\ \text{MeV}^4$$

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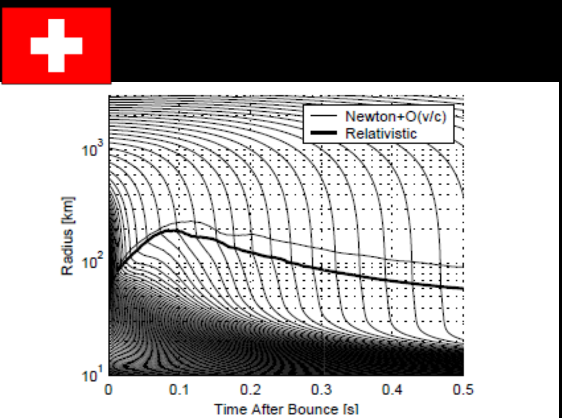
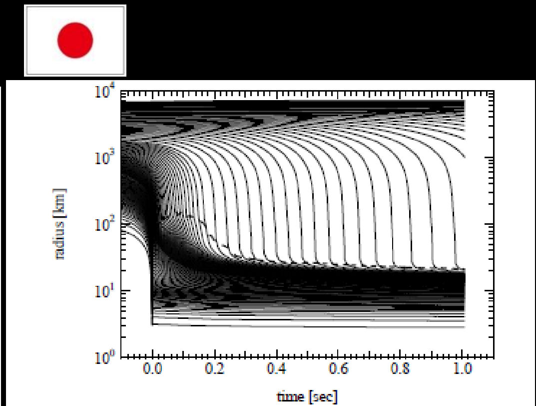
The Wilson's simulation really the final answer?

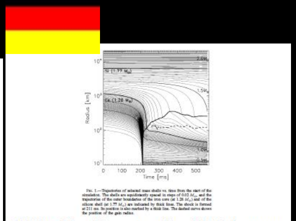
✓ Numerical resolution (low), neutrino physics (simplified set), general relativity (neglected), progenitor model/EOS (very old)



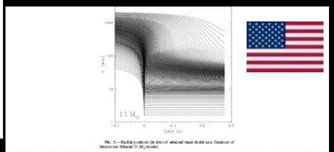
NH 13$M_\odot$, GR Boltzman, LS EOS+Si burning Liebendörfer *et al.*, Phys.Rev. D63 (2001) 103004 (astro-ph/0006418 v2) Fig.6



15$M_\odot$, Shen EOS, Sumiyoshi *et al.*, 2005.



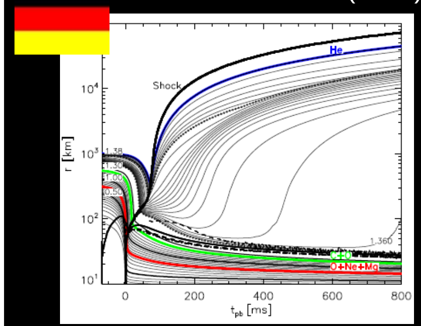
WW 15$M_\odot$, $M_{\rm Fe}$ = 1.28$M_\odot$, NR Boltzmann (tangent-ray method), only ν_e,$\bar{\nu}_e$, without $e^-e^+ \leftrightarrow \nu\bar{\nu}$, LS EOS, Rampp *et al.*, ApJ 539 (2000) L33 Fig.1

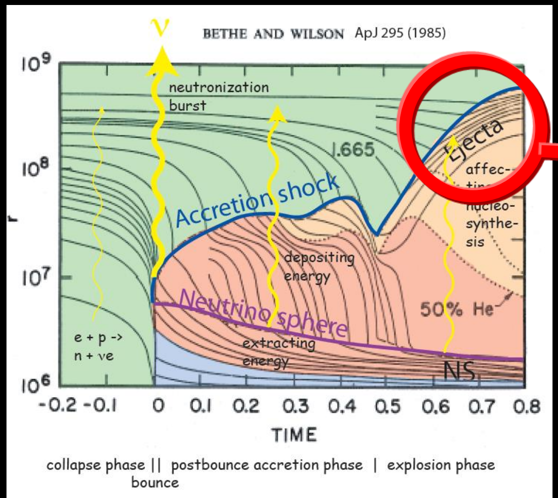


NR 1D Boltzmann ν-transfer, Thompson *et al.*, ApJ 592 (2003) 434 Fig.5

Success: 8 -10M_{sun} ONeMg core star

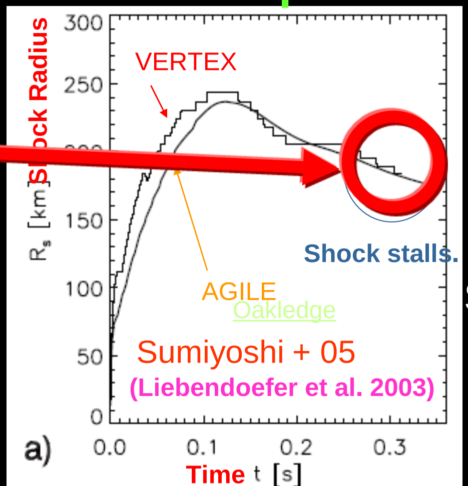
Kitaura et al. AA(2006)





~20 years

Detailed comparison between SN groups



Doing-best simulations, but..

did not explode
In good agreement !

The supernova shock reaches to the stellar surface somehow… with its kinetic E of 10^{51} erg (≡1 Bethe) !

Then, how do massive stars blow up ?!

Summary

✓Assuming spherical symmetry,
the neutrino heating mechanism cannot explain explosions of most massive stars.

✓Many uncertainties: Go to multi-D (2D or 3D) ?, EOS/microphysics is incorrect (needs to be improved)? → Tomorrow