Expected neutrino signal
from
massive star explosions

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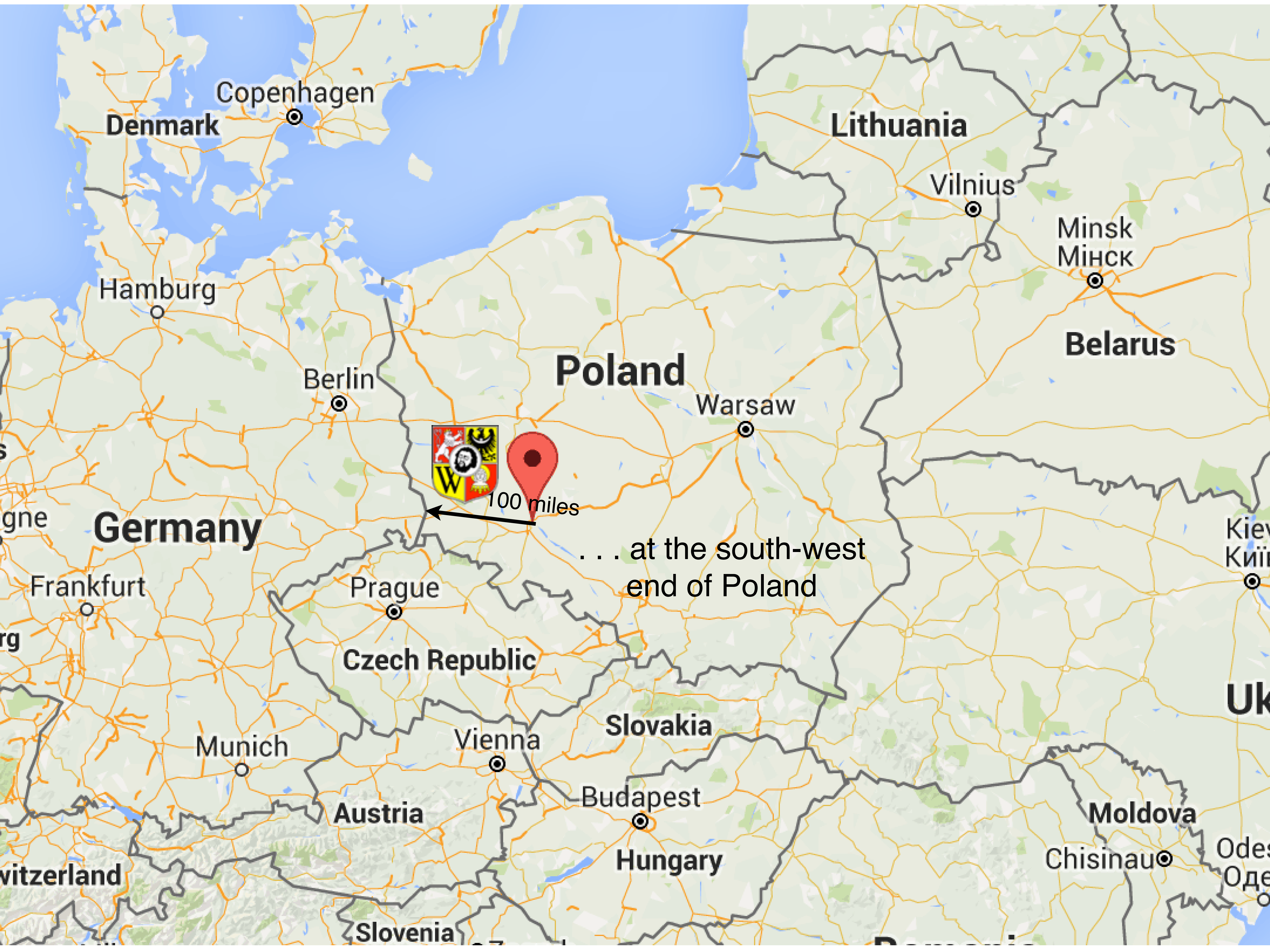
Uniwersytet Wrocławski
NARODOWE CENTRUM NAUKI
NAVI
compstar

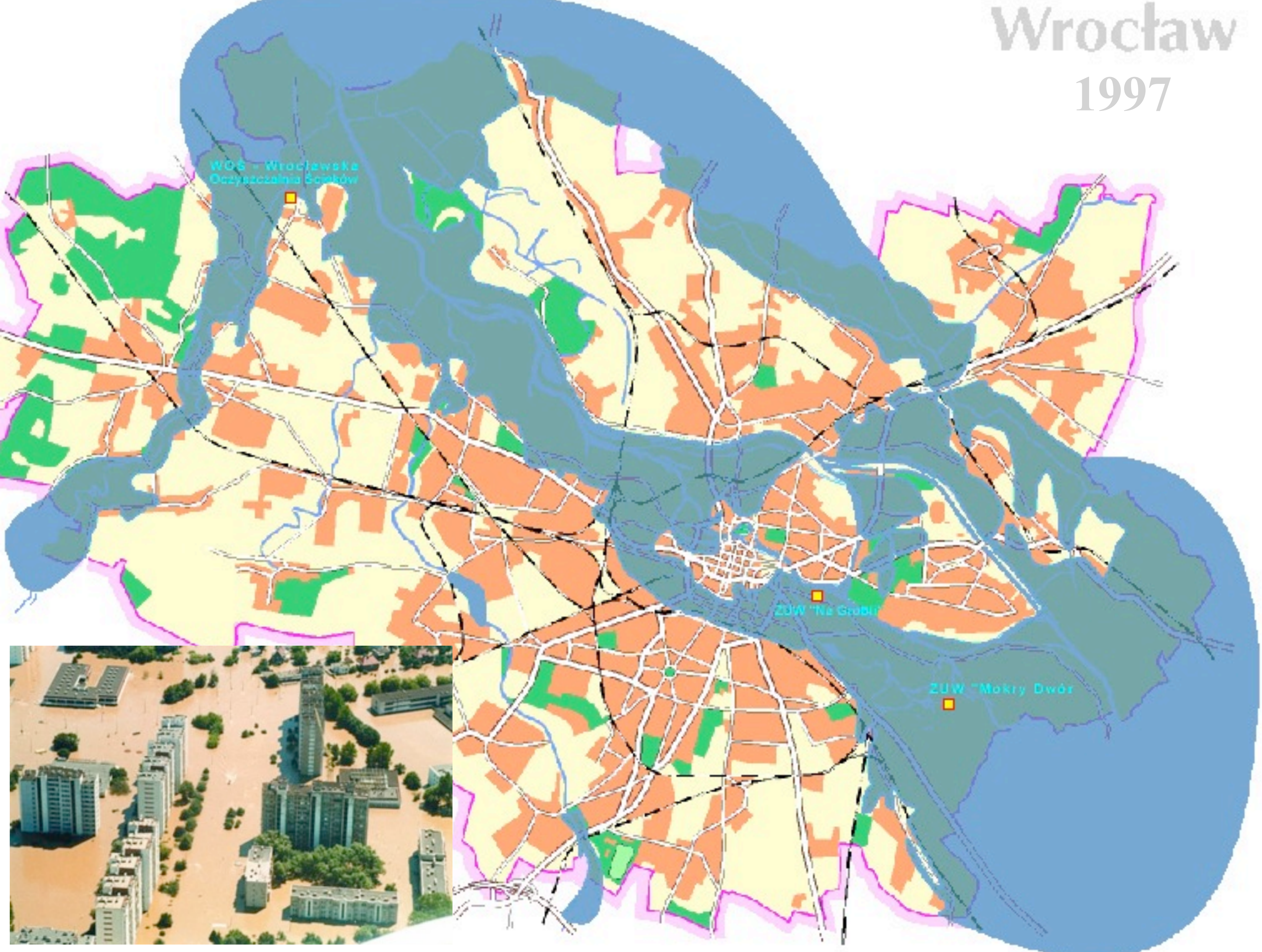
Wrocław: 3rd largest city in Poland, located in the heart of Europe



Copenhagen
Denmark
Lithuania
Vilnius
Minsk
Минск
Hamburg
Belarus
Berlin
Poland
Warsaw
100 miles
Germany
. . . at the south-west
end of Poland
Frankfurt
Prague
Czech Republic
Slovakia
Munich
Vienna
Budapest
Austria
Moldova
Hungary
Chisinau
Slovenia


~600 000 people
living here.
6 Universities in town
Wrocław
PSIE POLE
FABRYCZNA
KRZYKI
Oder
Uraz
Pęgów
E261
Dobroszyce
Boguszyce
S8
S8
Olesnica
Brzezina
Mrozów
Psary
98
Długołęka
Kiełczów
Samotwór
A8
Nadolice
Wielkie
98
Oder
Radwanice
Bielany
Wrocławskie
Siechnice
94
E40
Park
obrazowy
Dolina
ystrzycy
35
Jelcz-Laskowice
8
Żórawina
Marcinkowice
Kobierzyce
Stanowice
Bystrzyca
pwr
Uniwersytet
Ekonomiczny
we Wrocławiu
UMW

Wrocław 1997



7 Nobel Prize winners:

1. Theodor Mommsen (1817-1903)
   1902 (literature)
2. Phillip Lénàrd (1862-1947)
   1905 (physics)
3. Eduard Buchner (1860-1917)
   1907 (chemistry)
4. Paul Ehrlich (1854-1915)
   1908 (medicine)
5. Gerhart Hauptmann (1862-1946)
   1912 (literature)
6. Fritz Haber (1868-1934)
   1918 (chemistry)
7. Max Born (1882-1970)
   1954 (physics)

Expected neutrino signal
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Contents:

- Supernova neutrinos
- Some insights into neutrino-matter interactions
- Summary

Supernova ν observations

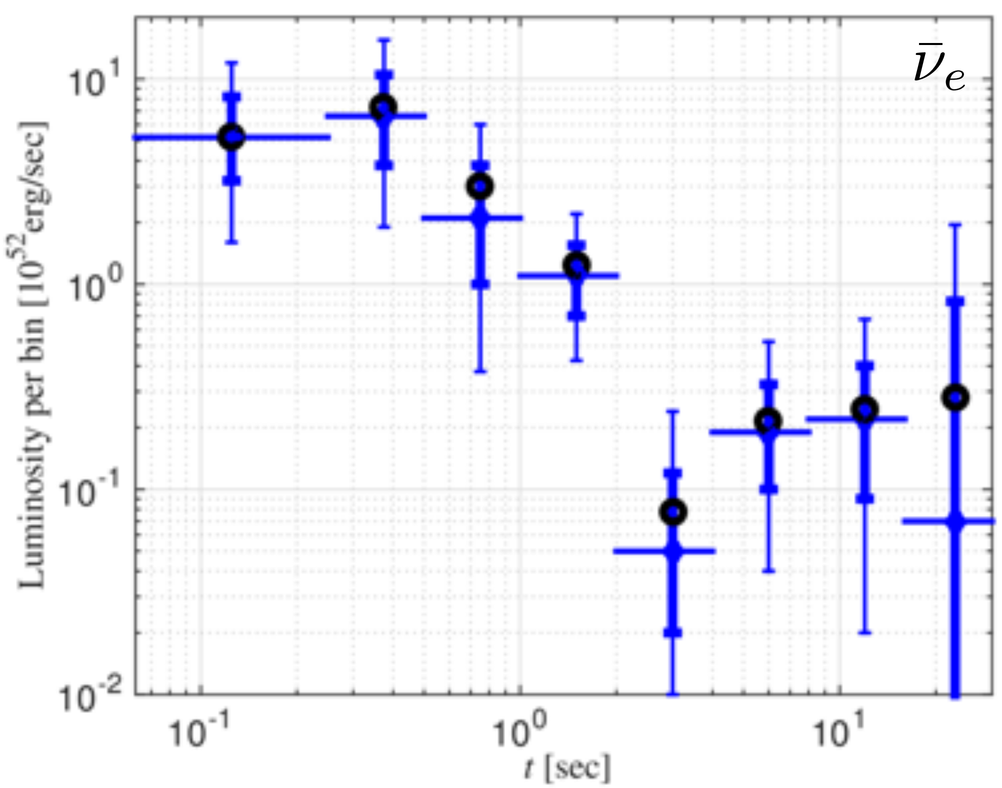
Key object of a core-collapse supernova is the hot & lepton-rich protoneutron star (PNS)

PNSs develop (**deleptonize & cool**) via the emission of neutrinos of all flavors for about 10–30 s

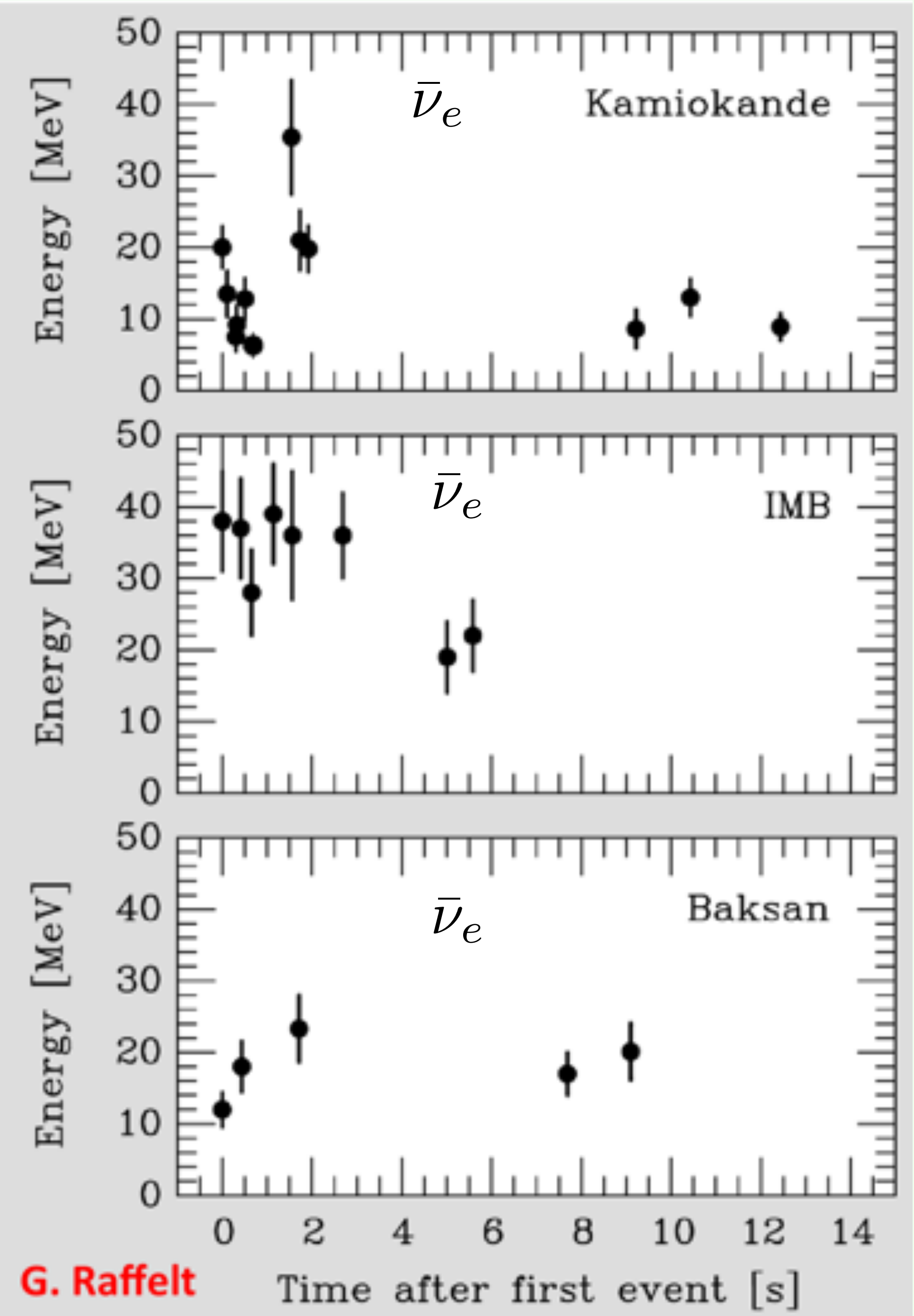
Some insights from SN1987A:

$E_{expl} \sim 10^{51}$ erg , $E_{\nu} \sim 3 \times 10^{53}$ erg

All current supernova models (that include "accurate" **neutrino transport**) are in agreement with SN1987A



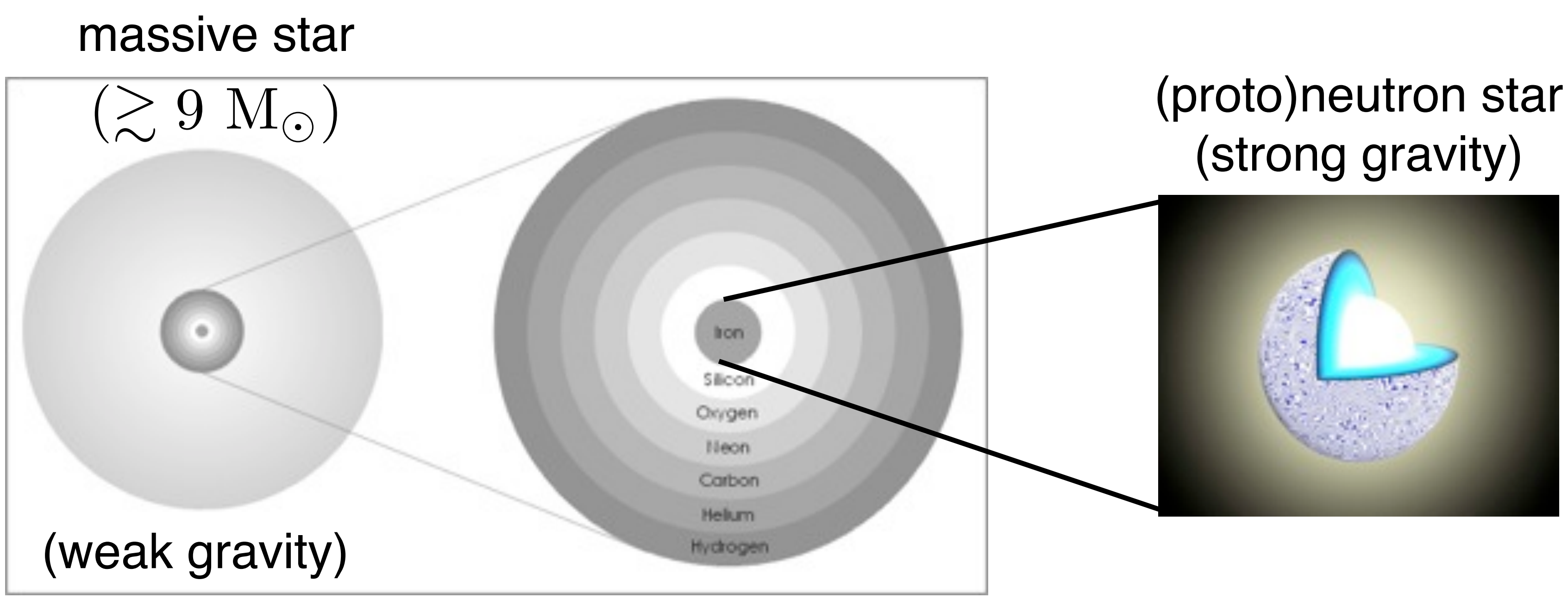
Blum & Kushnir (2016) ApJ (likely-hood analysis)



SN1987A (Feb. 23rd, 1987)

Core-collapse supernova neutrinos

General picture



$$\triangle E_G \simeq 3-6\times 10^{53}\ \mathrm{erg} \longrightarrow (\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau})$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{R}{2} g_{\mu\nu} = 8\kappa T_{\mu\nu} \qquad \text{(Einstein equation)}$$

$$ds^2 = -\alpha(t,a)^2 dt^2 + \left(\frac{r'(t,a)}{\Gamma(t,a)}\right)^2 da^2 + r(t,a)^2 d\Omega$$

$$\begin{array}{rclcl} & & \text{matter} & & \text{microphysics} \\ \hline T^{tt} & = & \rho(1+e & + & J) \\ T^{ta} = T^{at} & = & & & \rho H \\ T^{aa} & = & p & + & \rho K \\ T^{\theta\theta} = T^{\phi\phi} & = & p & + & \frac{1}{2}\rho(J-K) \end{array}$$

Core-collapse supernova converts iron-core of massive star into proto-neutron star (PNS)

Binding energy gain available in form of neutrinos of all flavors

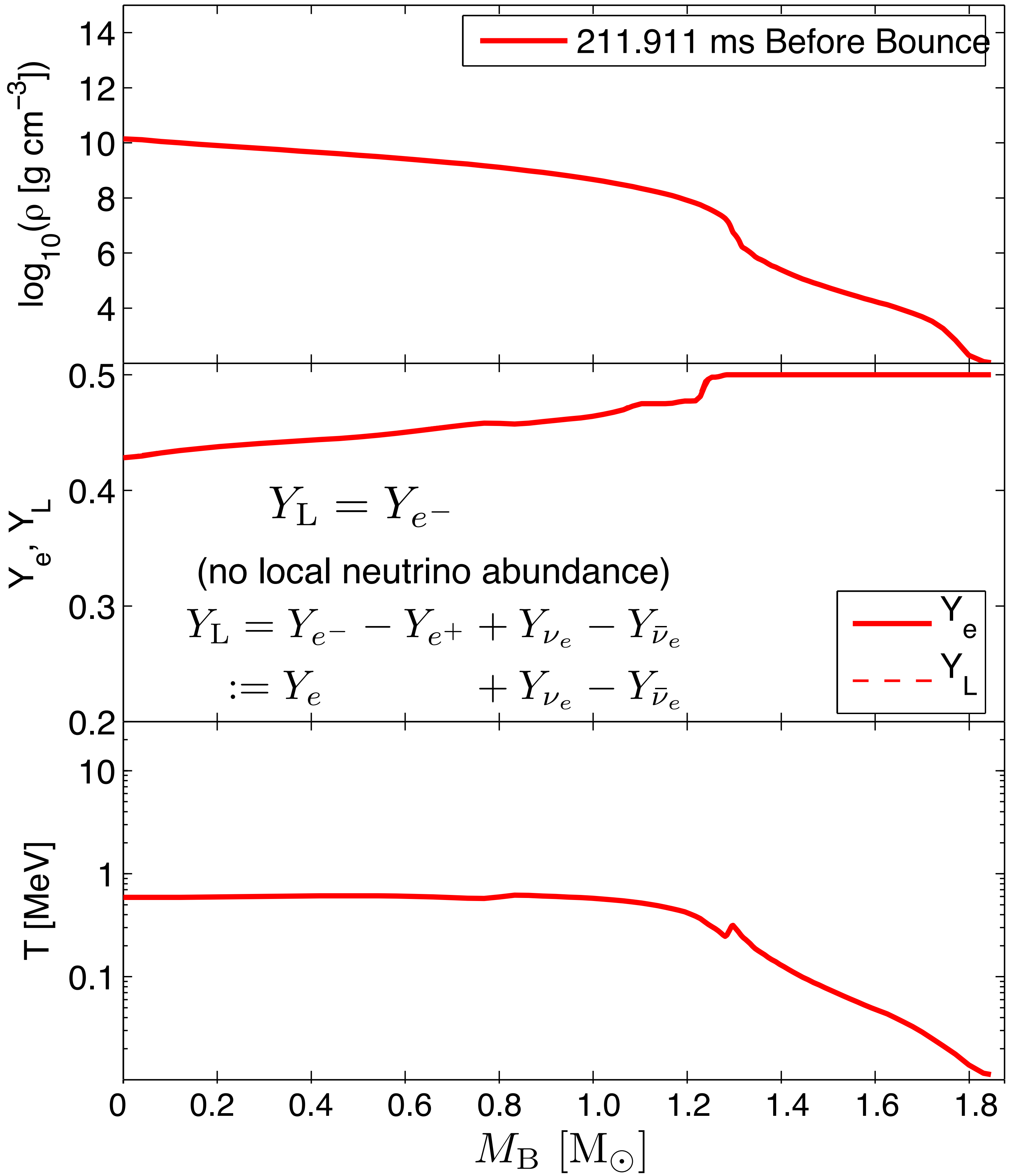
Strong gravity of PNS requires general relativity

Supernova "problem":

ejection of the stellar mantle

Misner & Sharp (1964) PhyRev.136, 571
Lindquist (1966) AnnPhys.37, 487

Stellar core collapse



Implosion of the stellar core due to pressure loss; triggered from e^- captures on protons bound in nuclei

$(Y_e = n_p/n_{\mathrm{B}})$

$(Y_e > 0.5$: neutron defficient $)$

$(Y_e < 0.5$: neutron excess $)$

$$M_{\mathrm{core}} > M_{\mathrm{Ch}} \simeq 1.44 \left(\frac{Y_e}{0.5}\right)^2 \mathrm{M_\odot}$$

$$e^- + {}^{56}\mathrm{Mn} \longrightarrow {}^{56}\mathrm{Fe} + \nu_{\mathrm{e}}$$

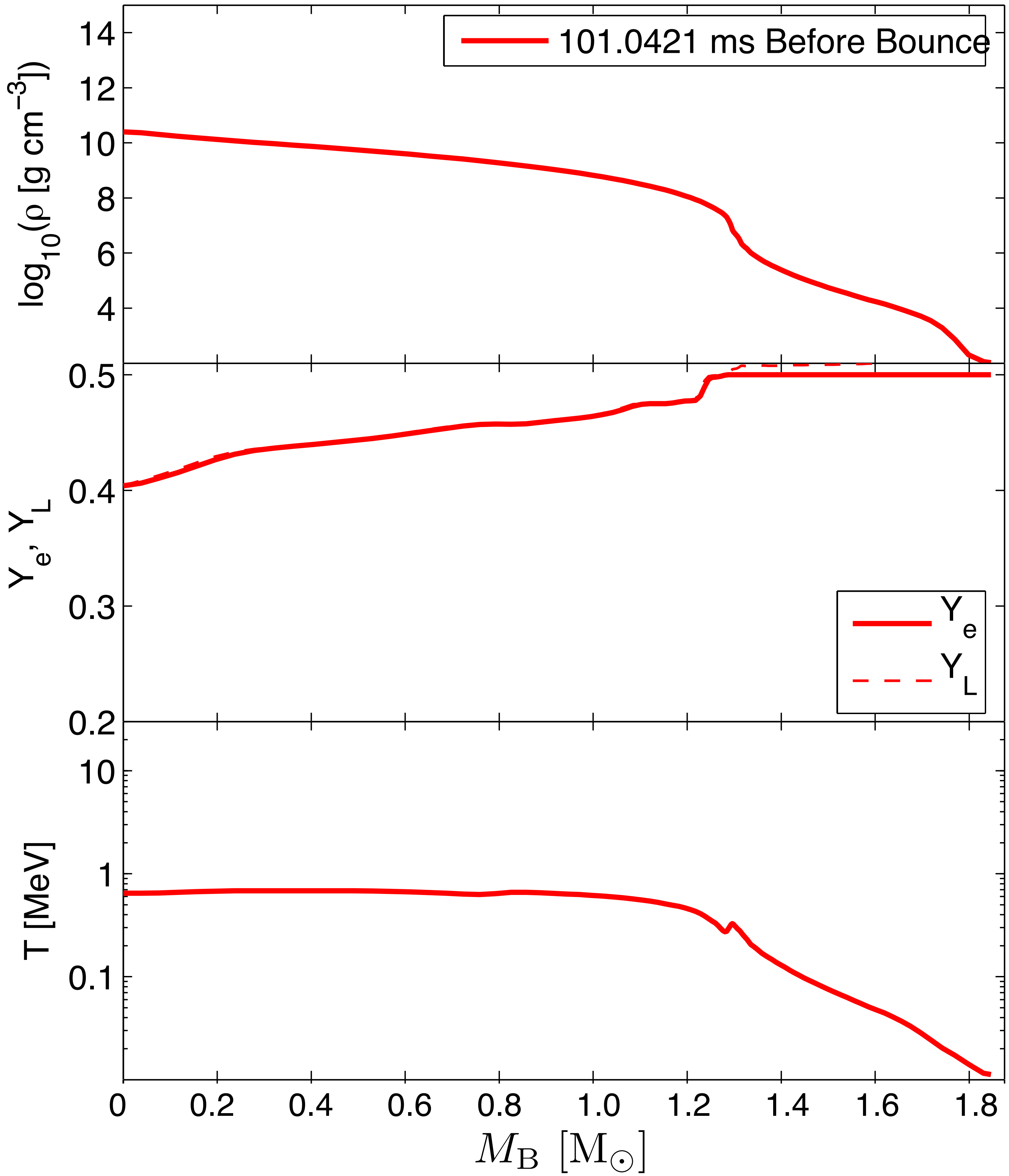
$$e^- + {}^{56}\mathrm{Fe} \longrightarrow {}^{56}\mathrm{Co} + \nu_{\mathrm{e}}$$

$$e^- + {}^{56}\mathrm{Co} \longrightarrow {}^{56}\mathrm{Ni} + \nu_{\mathrm{e}}$$

$\ldots\ldots$

Stellar core collapse

Hempel & TF et al.,(2012) ApJ 748, 27

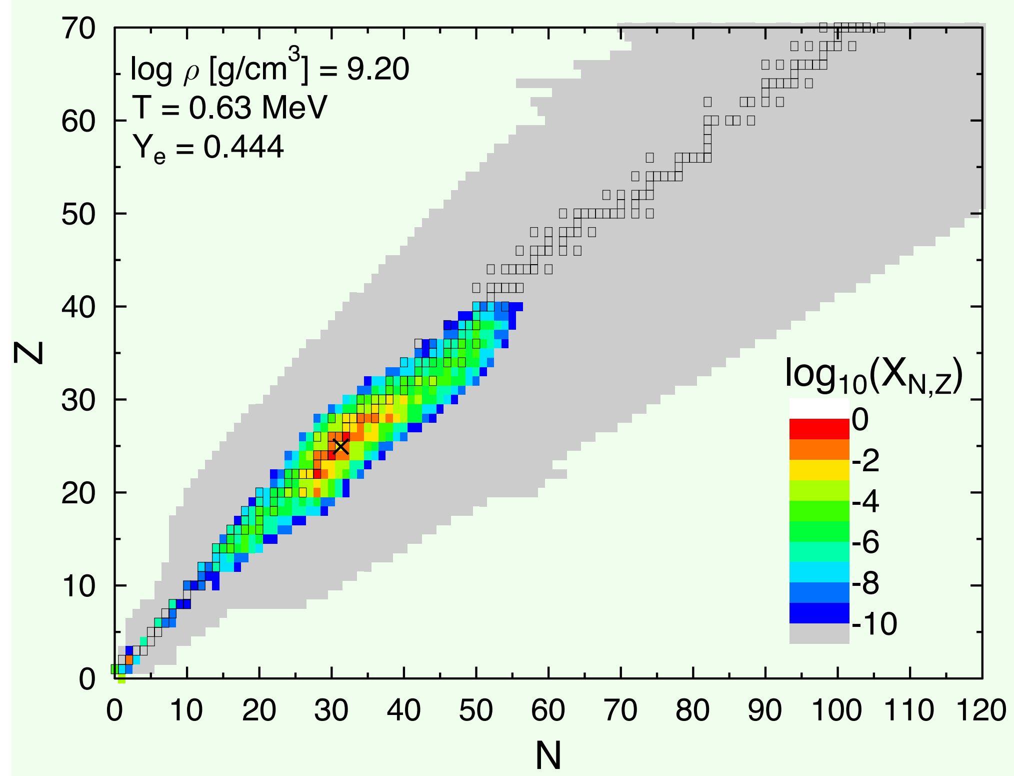


Implosion of the stellar core due to pressure loss; triggered from e^- captures on protons bound in nuclei

$$e^- + \langle A, Z\rangle \longrightarrow \langle A, Z-1\rangle + \nu_e$$

(Juodagalvis et al. (2010), NPA 848, 454)

Stellar core deleptonizes: Y_L drops



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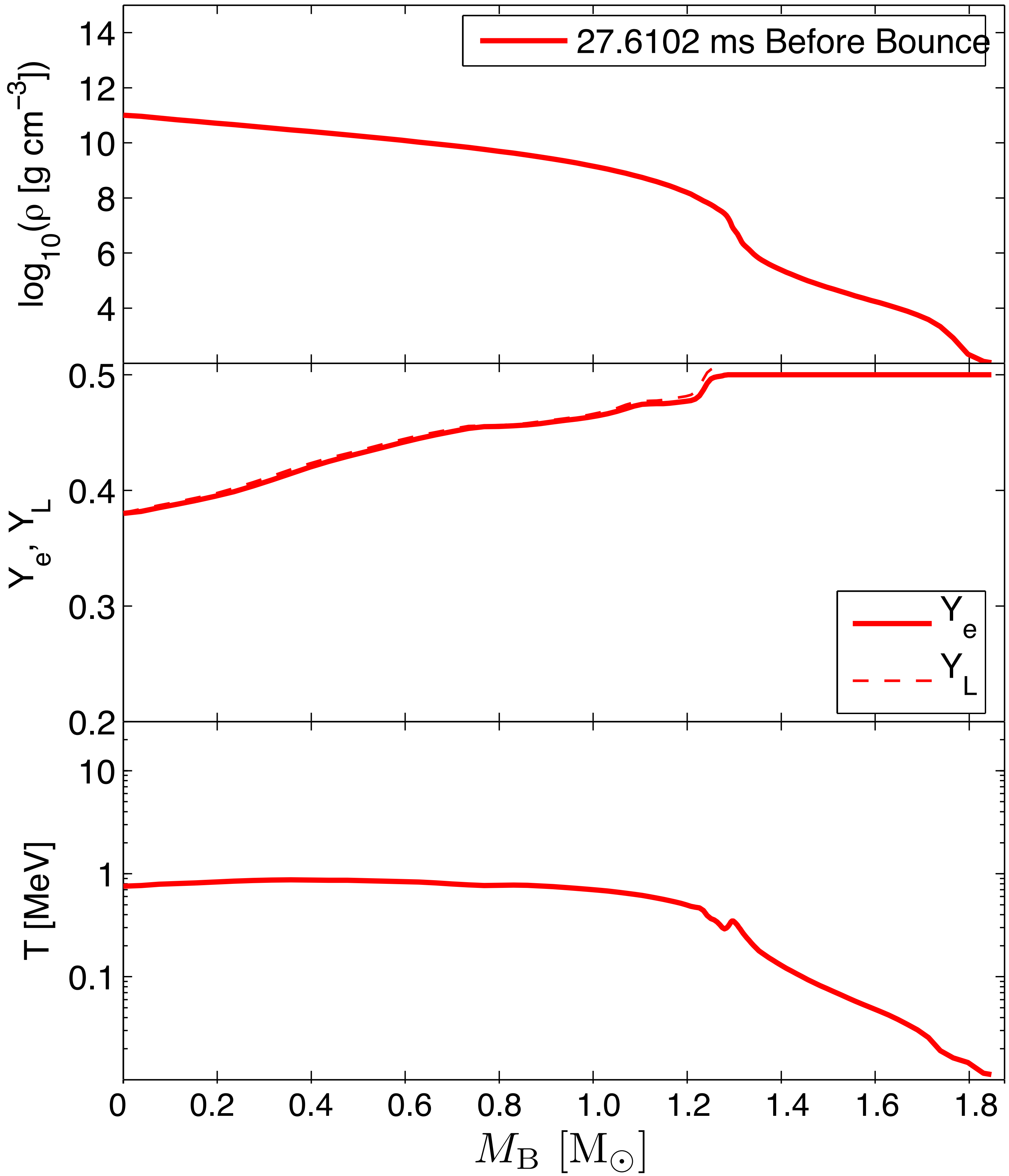
Hempel & TF et al.,(2012) ApJ 748, 27



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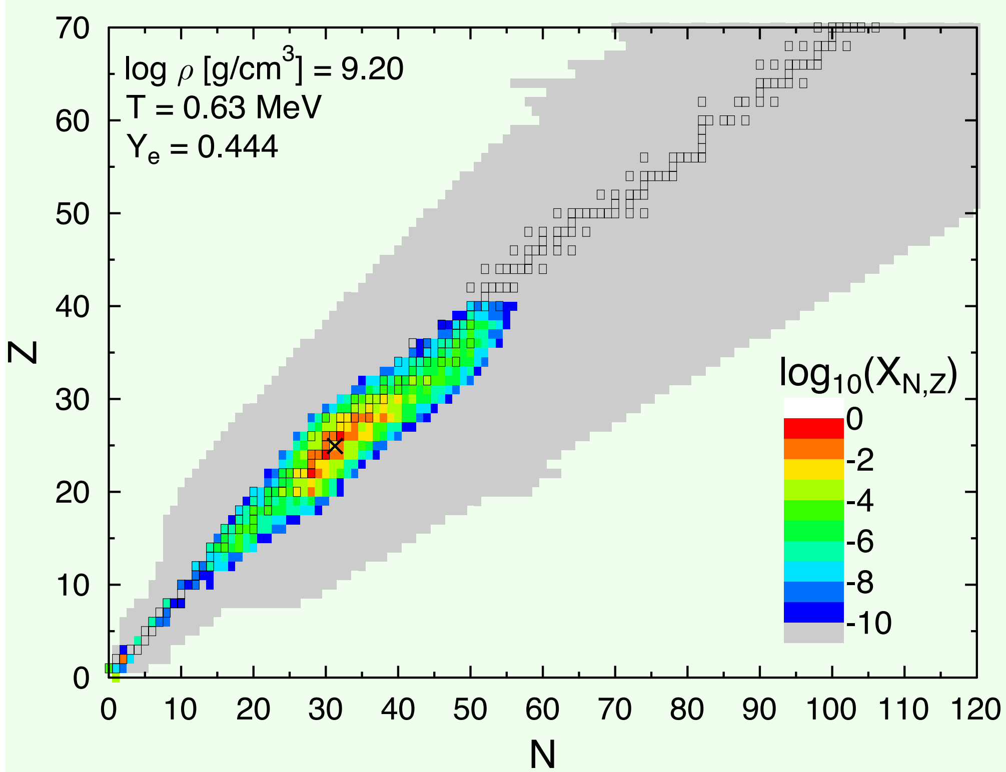
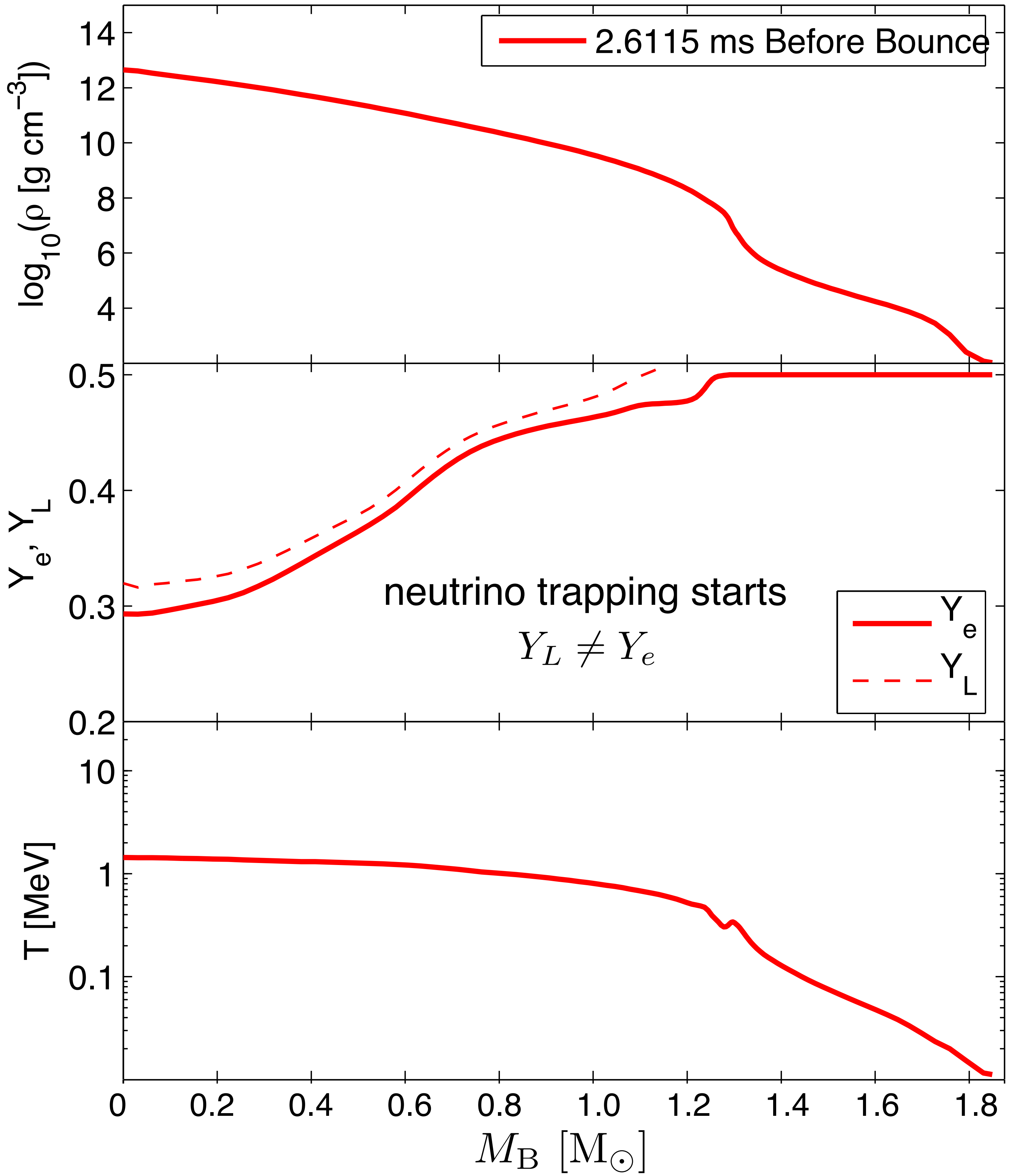


Stellar core collapse



Hempel & TF et al.,(2012) ApJ 748, 27

Implosion of the stellar core due to pressure loss; triggered from e⁻ captures on protons bound in nuclei

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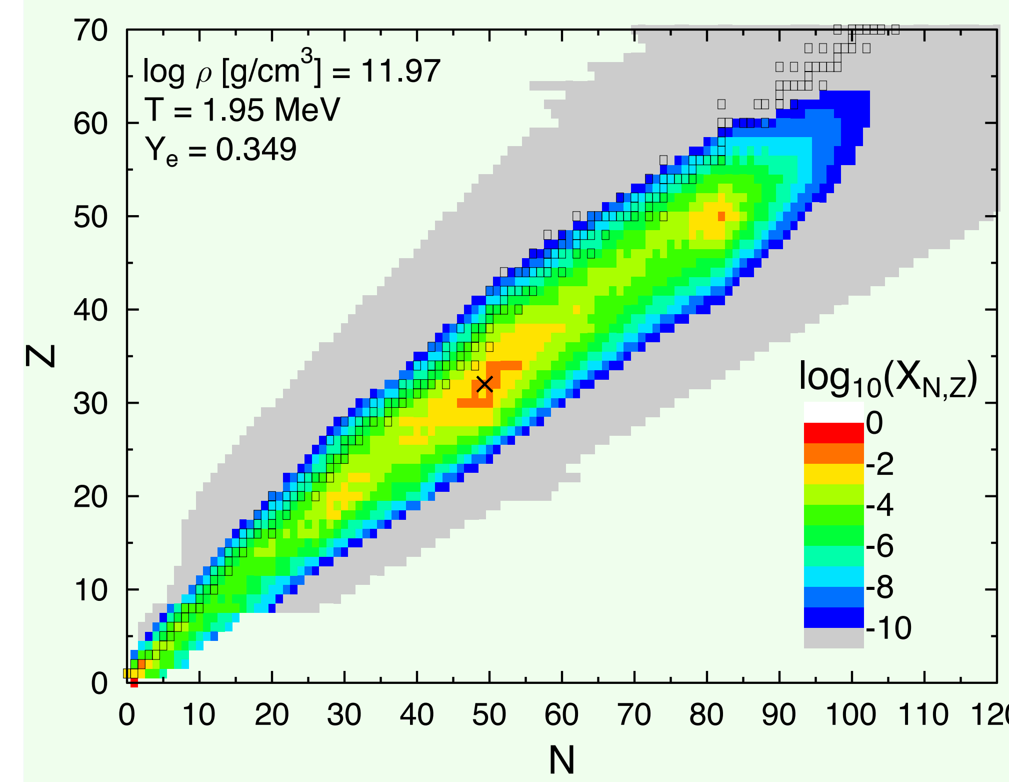
(Juodagalvis et al. (2010), NPA 848, 454)

Stellar core deleptonizes:

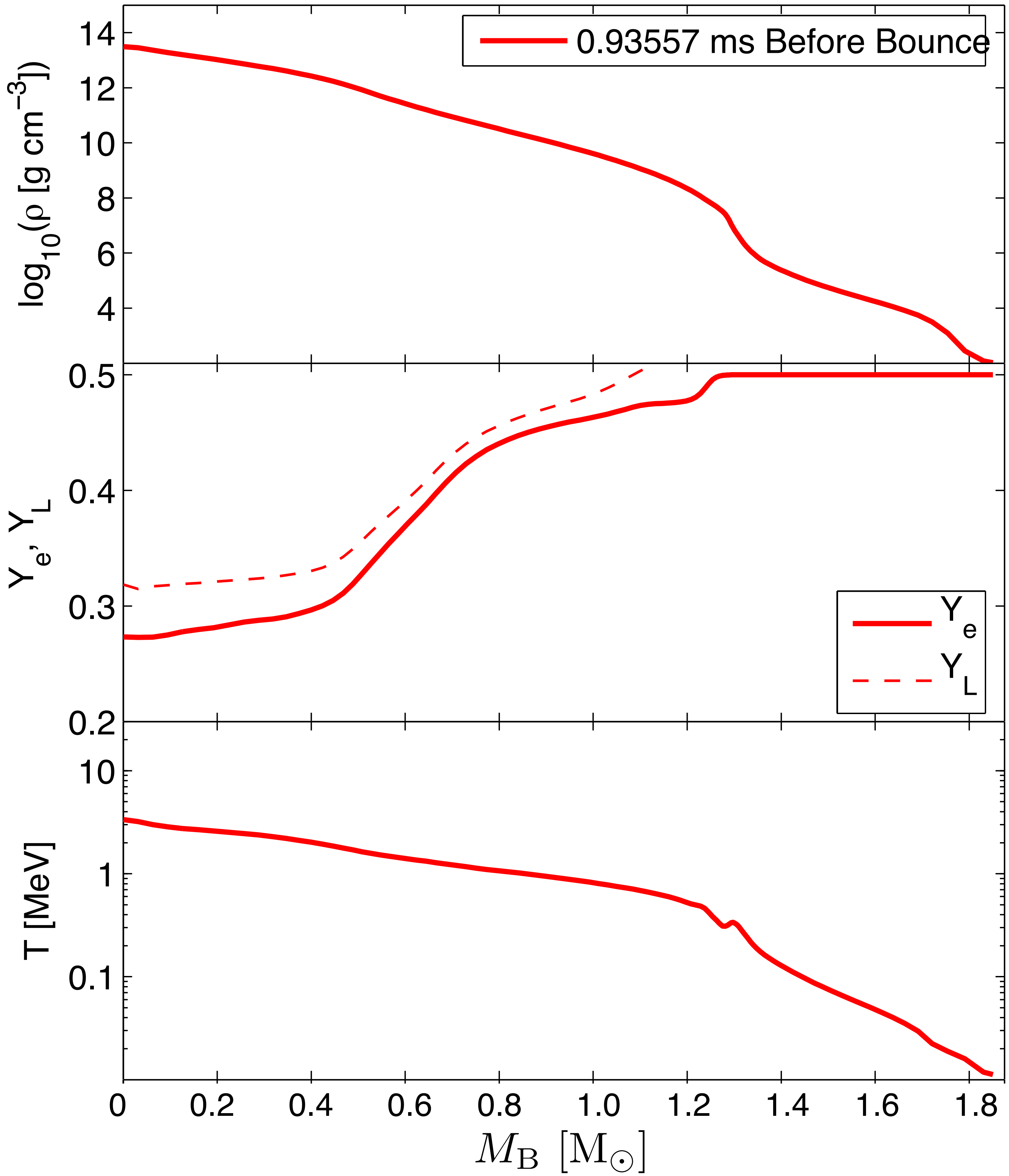
Y_L drops no more!

Nuclear composition: heavy & neutron rich nuclei



Stellar core collapse

Hempel & TF et al.,(2012) ApJ 748, 27



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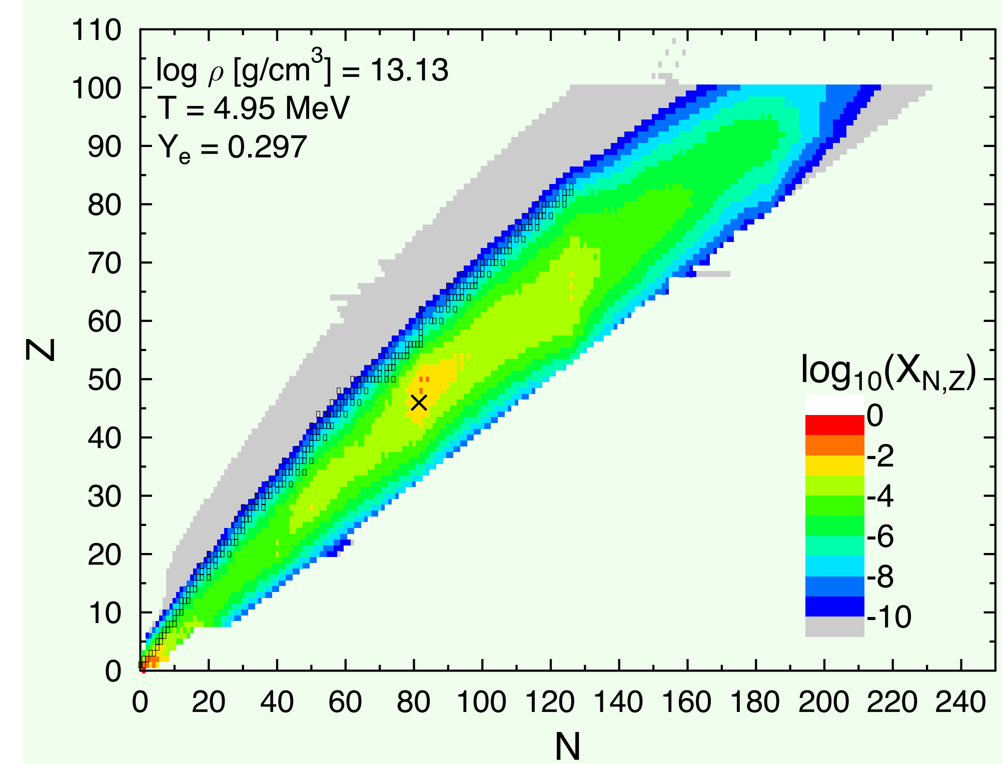
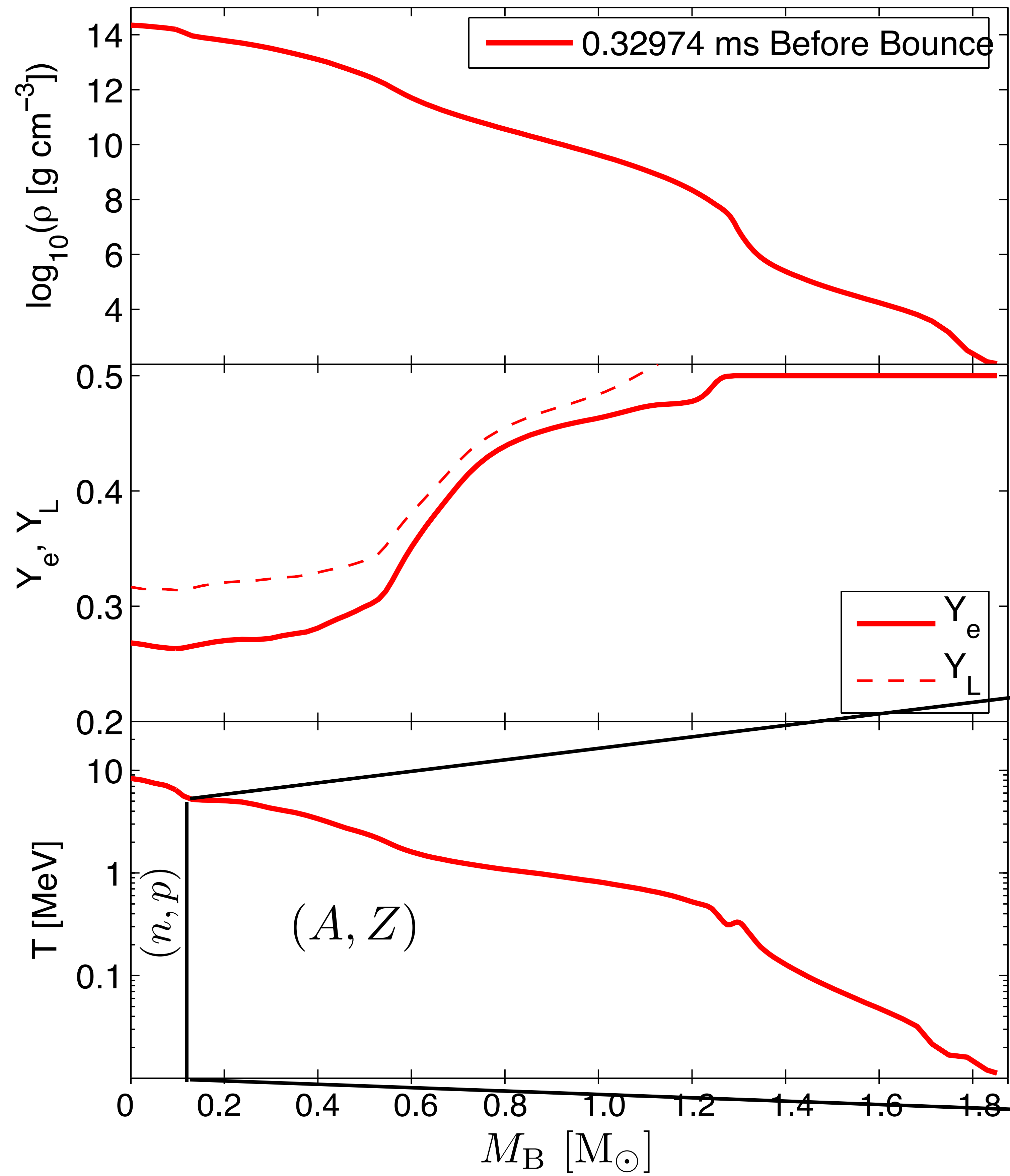


Around core bounce

Hempel & TF et al.,(2012) ApJ 748, 27



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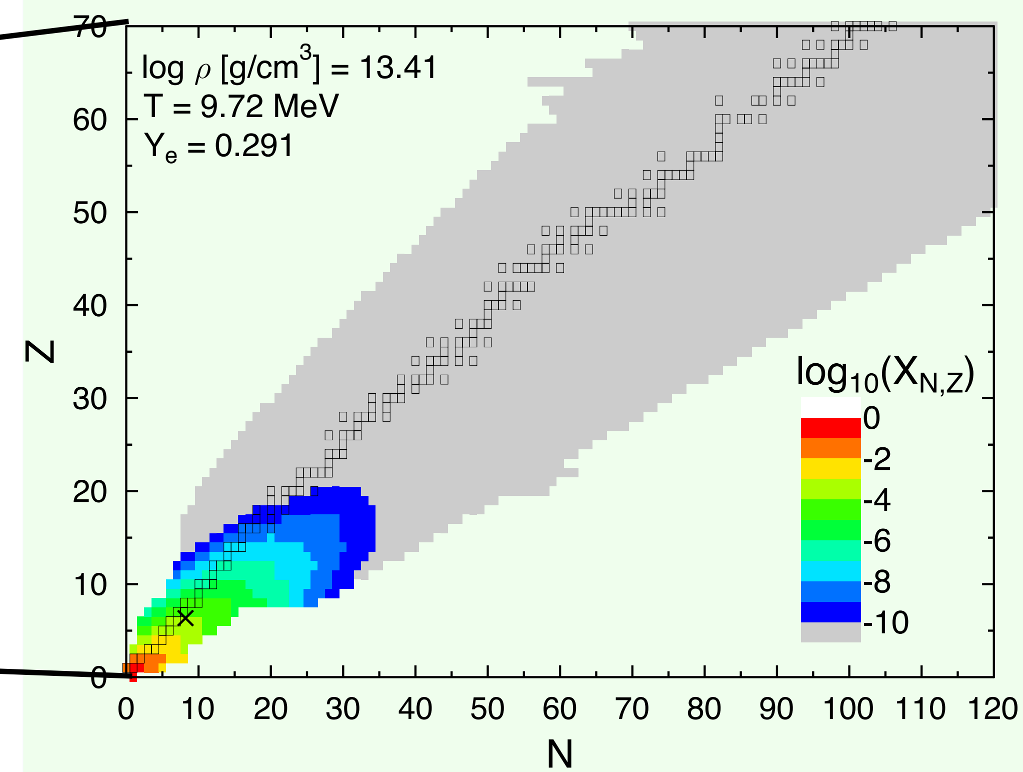
(Juodagalvis et al. (2010), NPA 848, 454)

Stellar core deleptonizes:

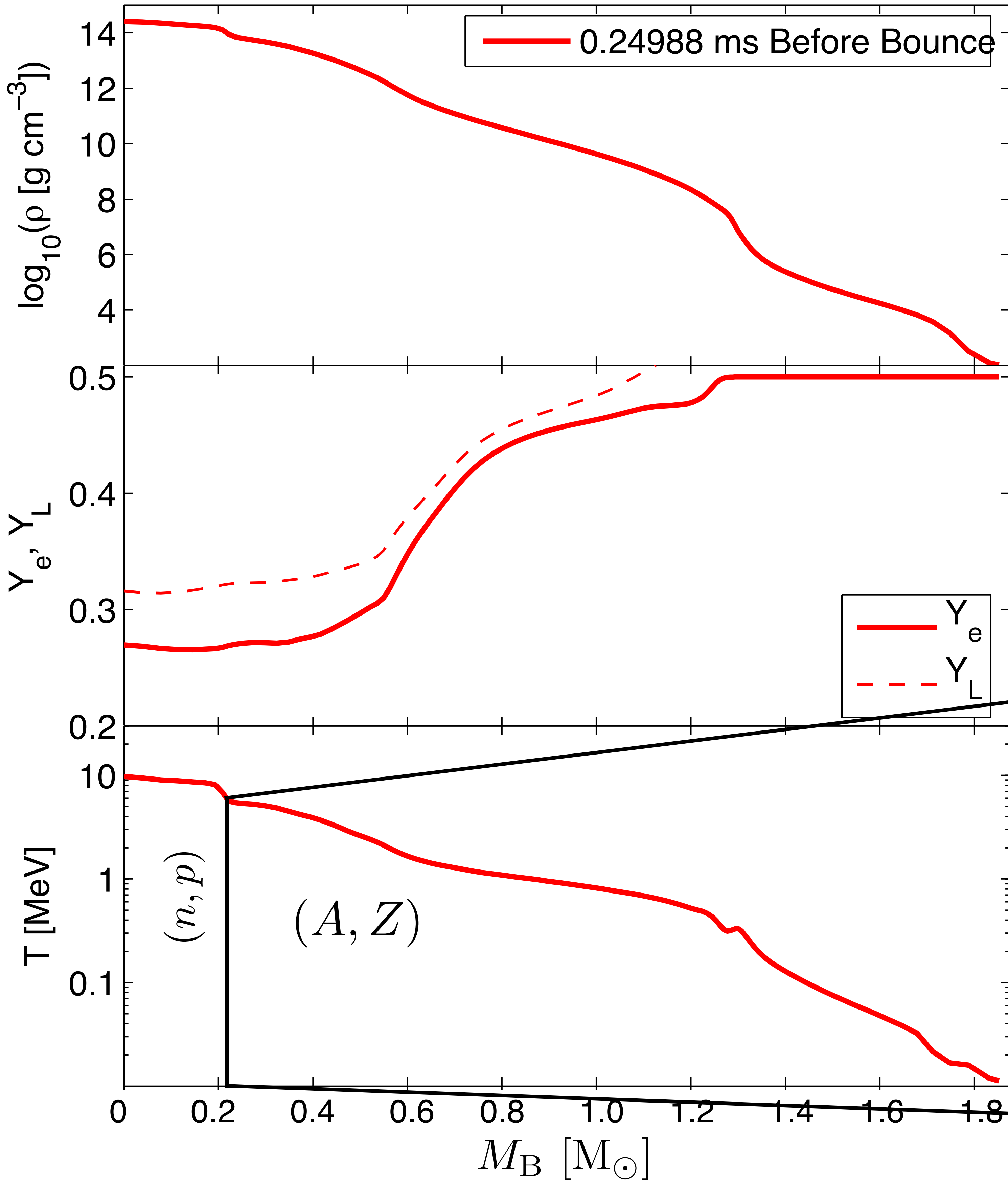
Y_L drops no more!

Nuclear composition:
dissociated matter



Around core bounce

Hempel & TF et al.,(2012) ApJ 748, 27



Implosion of the stellar core due to pressure loss; triggered from e^- captures on protons bound in nuclei

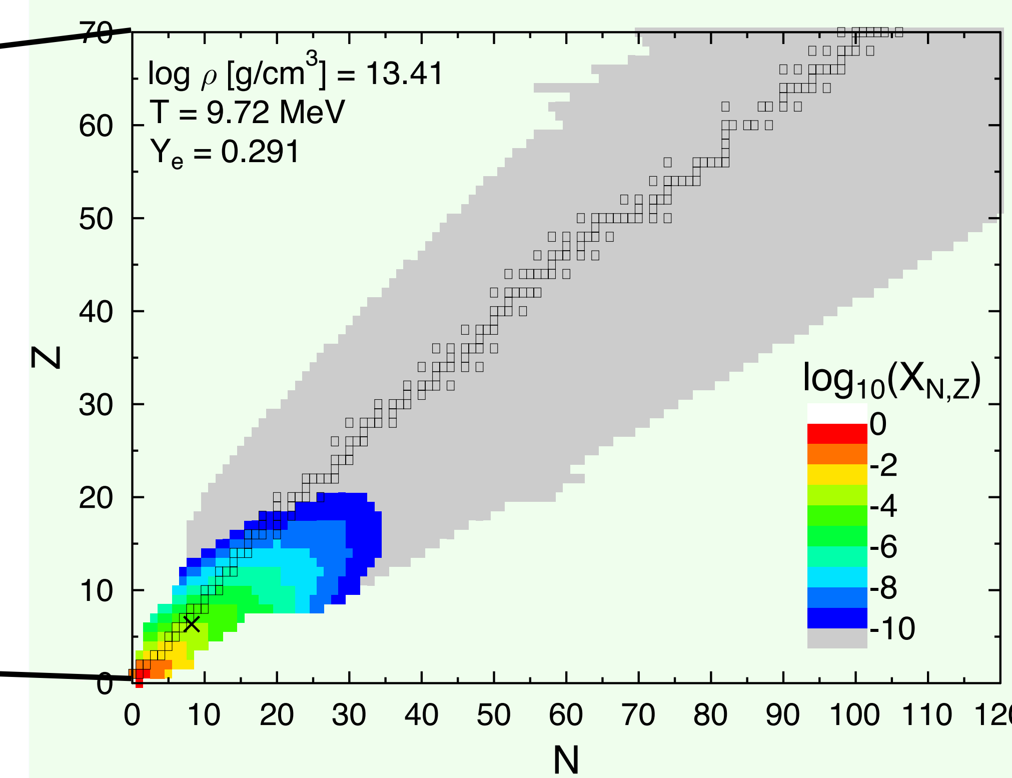
$$e^- + \langle A, Z\rangle \longrightarrow \langle A, Z-1\rangle + \nu_e$$

(Juodagalvis et al. (2010), NPA 848, 454)

Stellar core deleptonizes:

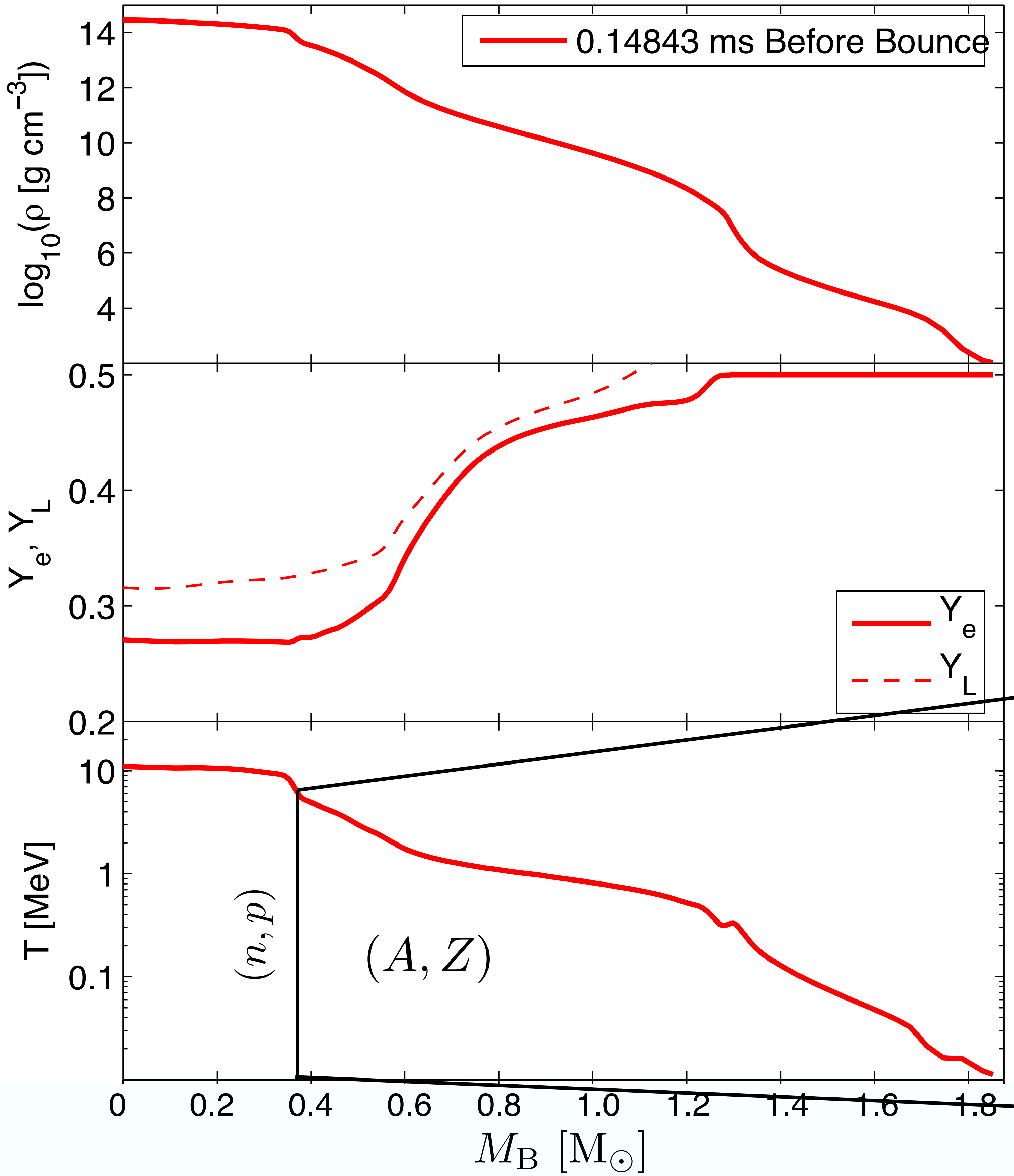
***Y_L* drops no more!**

Nuclear composition:
dissociated matter



Around core bounce

Hempel & TF et al.,(2012) ApJ 748, 27



Implosion of the stellar core due to pressure loss; triggered from e^- captures on protons bound in nuclei

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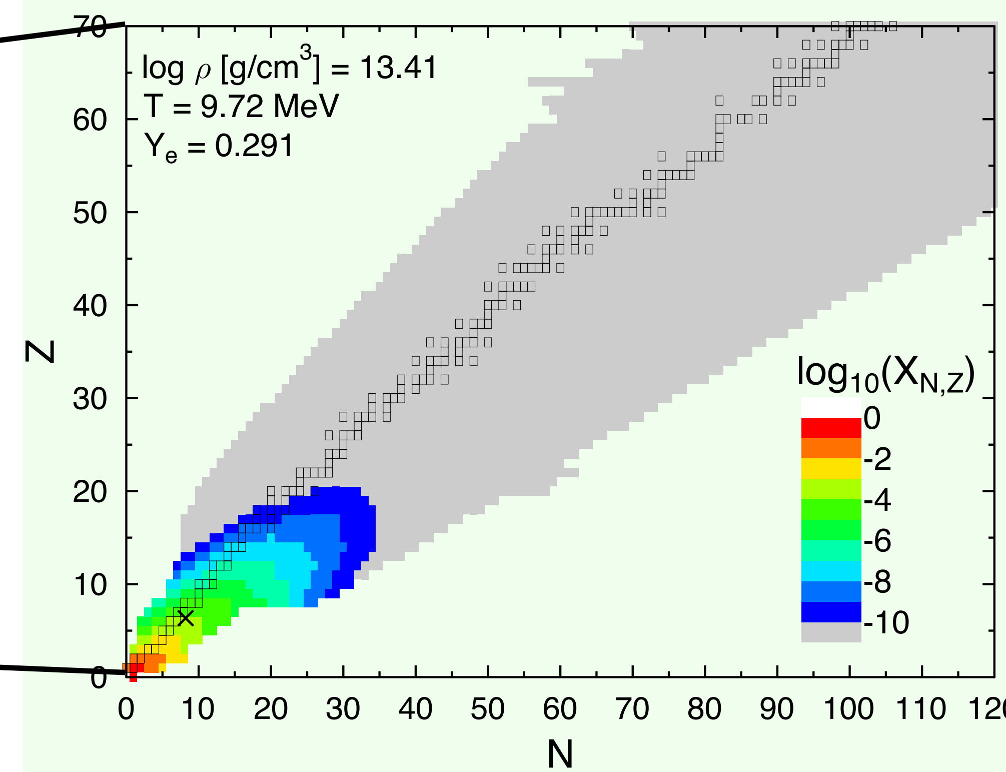
(Juodagalvis et al. (2010), NPA 848, 454)

Stellar core deleptonizes:

Y_L **drops no more!**

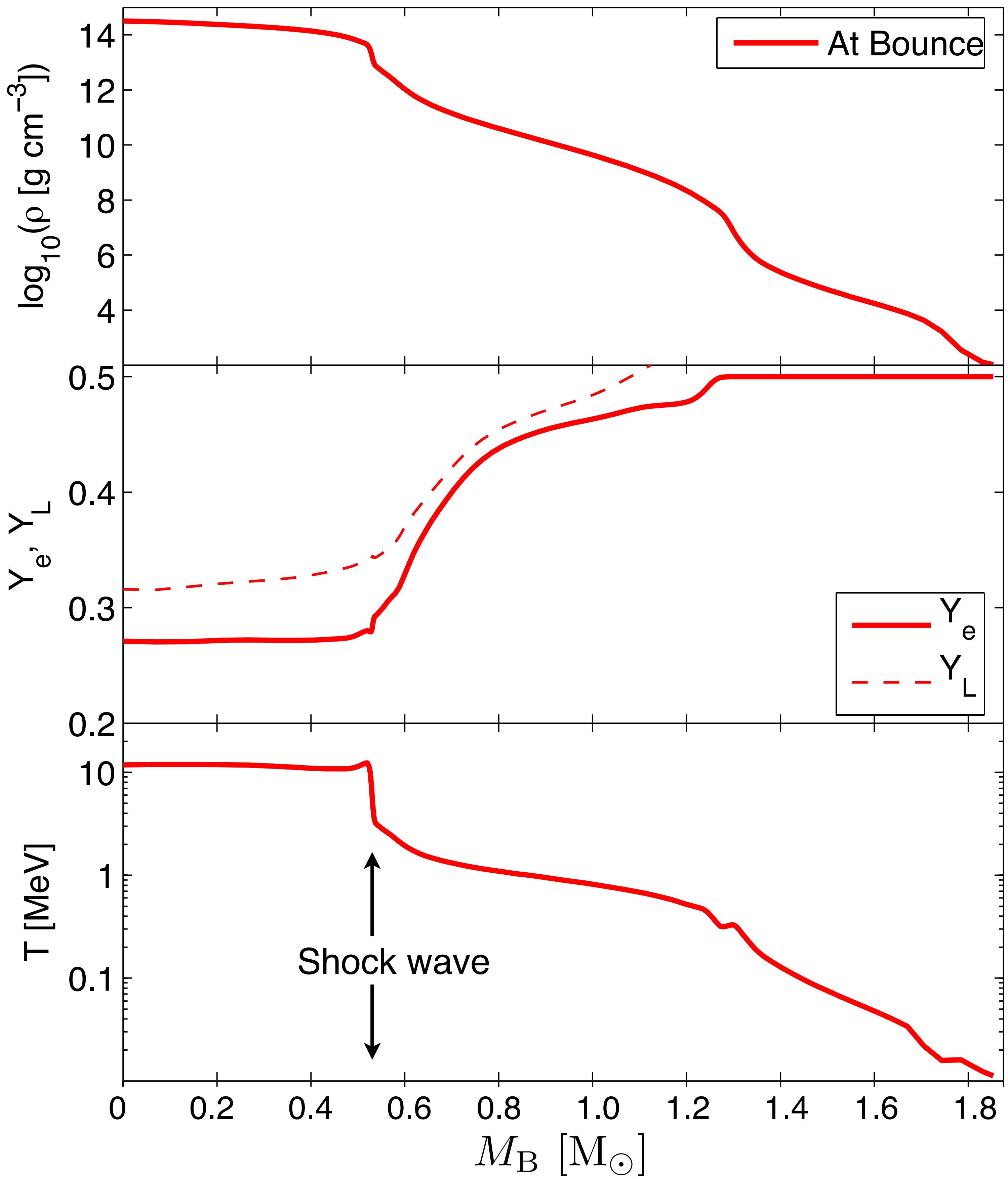
Nuclear composition:

dissociated matter



Core bounce

Hempel & TF et al.,(2012) ApJ 748, 27



Implosion of the stellar core due to pressure loss; triggered from e^- captures on protons bound in nuclei

$$e^- + \langle A, Z \rangle \longrightarrow \langle A, Z-1 \rangle + \nu_e$$

(Juodagalvis et al. (2010), NPA 848, 454)

Stellar core deleptonizes:

Y_L drops no more!

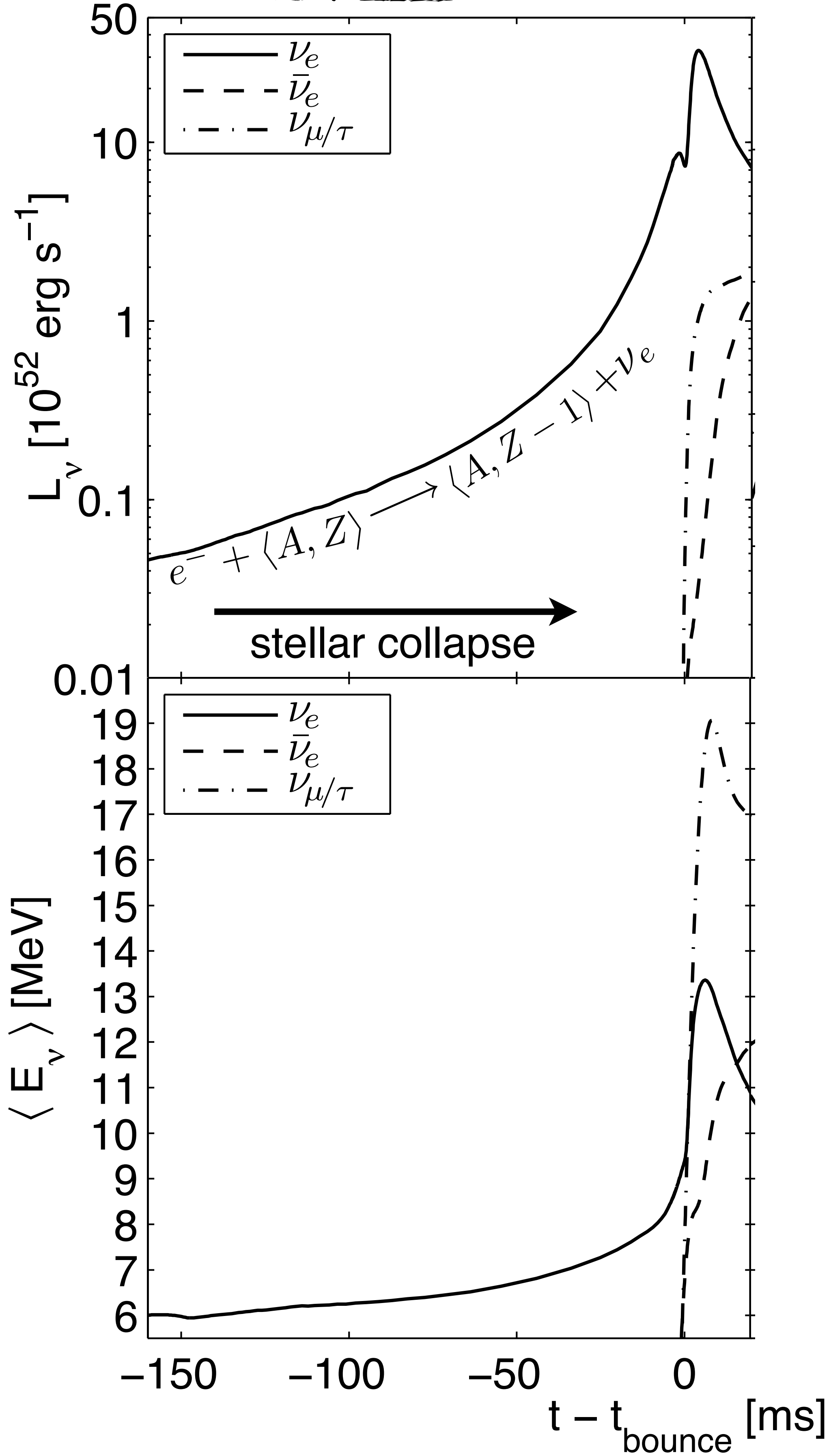
Nucleon self energies; relate to the vector interactions via the chemical potentials:

$$\mu_N = \mu_N^0 + U_N$$

and the nuclear symmetry energy via the parabolic expansion:

$$\mu_n(T, Y_e, \rho) - \mu_p(T, Y_e, \rho) = 4(1 - 2Y_e)\, S_B^F(T, \rho)$$

Neutrino signal – infall phase



Nuclear e⁻ captures neutronize stellar core

$$e^- + \langle A, Z\rangle \quad \longrightarrow \quad \langle A, Z-1\rangle + \nu_e$$

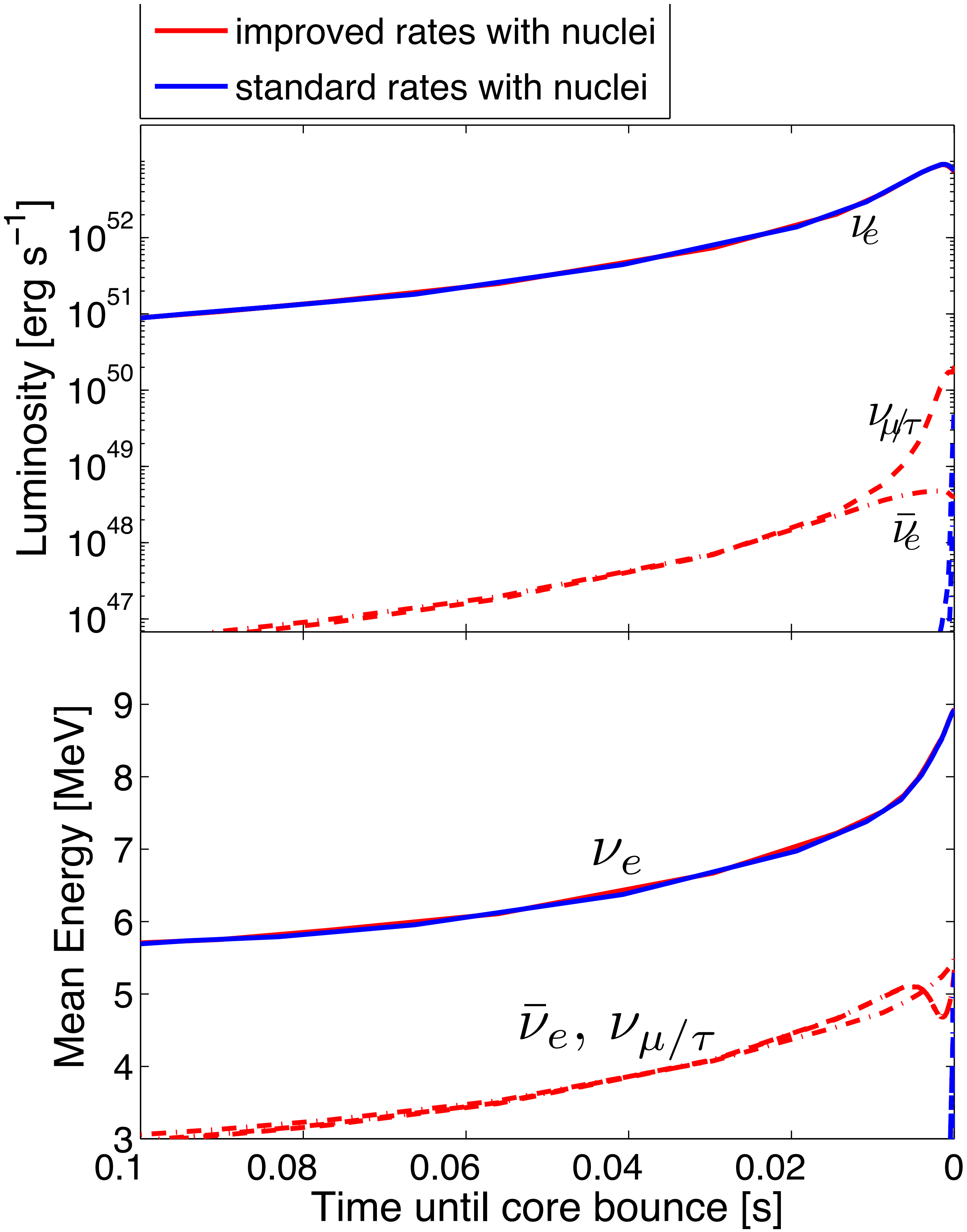
(Juodagalvis et al. (2010), NPA 848, 454)

Elastic scattering: ν trapping

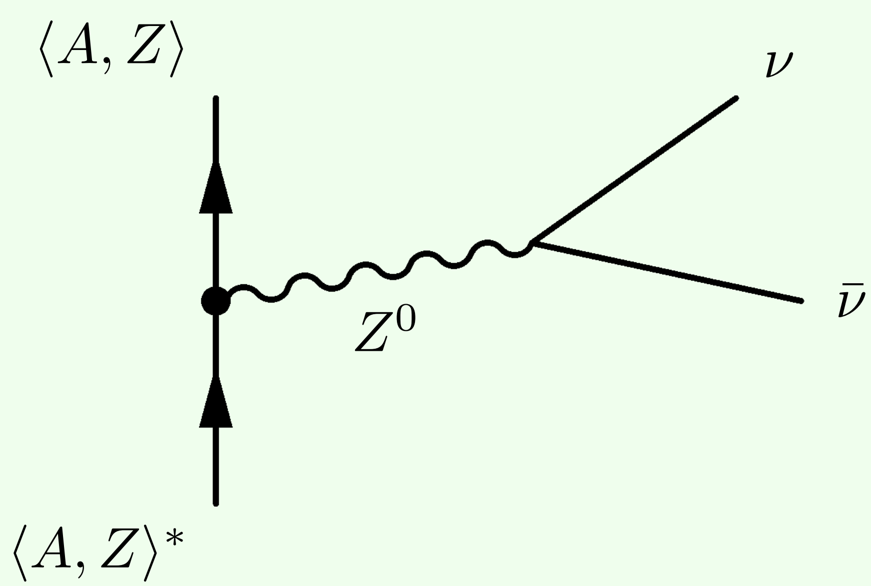
$$\nu_e + \langle A, Z\rangle \quad \longrightarrow \quad \langle A, Z\rangle + \nu_e$$

Neutrino signal – infall phase

Fuller & Meyer (1991) ApJ 376, 701
TF. et al. (2013), PRC 88, 065804



$$\nu_e + \langle A,Z\rangle \longrightarrow \langle A,Z\rangle + \nu_e$$
$$e^- + \langle A,Z\rangle \longrightarrow \langle A,Z-1\rangle + \nu_e$$
$$\langle A,Z\rangle^* \longrightarrow \langle A,Z\rangle + \nu + \bar{\nu}$$

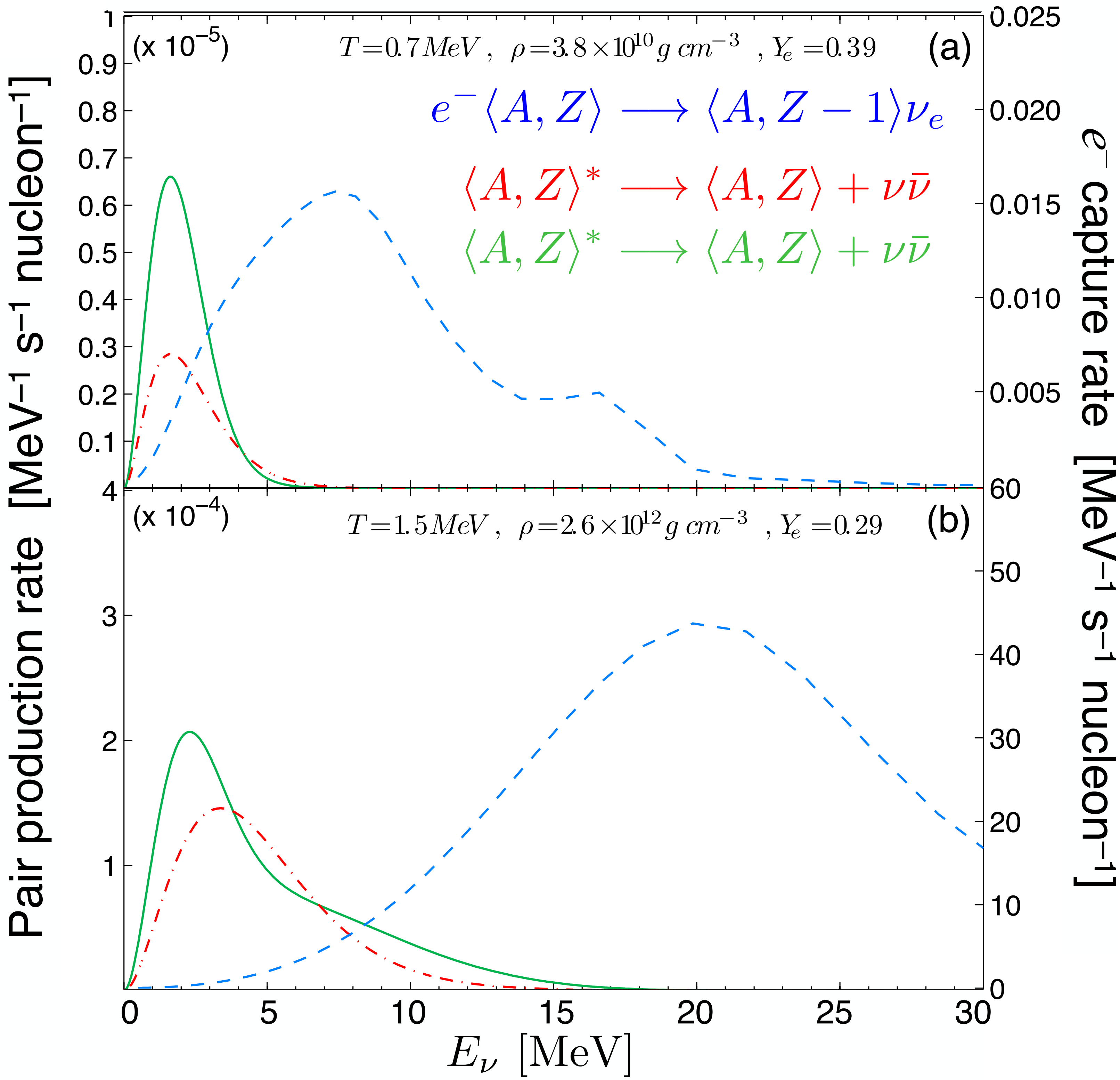


Significant increase of anti–ν_e and heavy-lepton neutrino luminosities during core collapse

(low-energies ~ 3–5 MeV)

Neutrino signal – infall phase

Fuller & Meyer (1991) ApJ 376, 701
TF. et al. (2013), PRC 88, 065804



$$\nu_e + \langle A,Z\rangle \longrightarrow \langle A,Z\rangle + \nu_e$$
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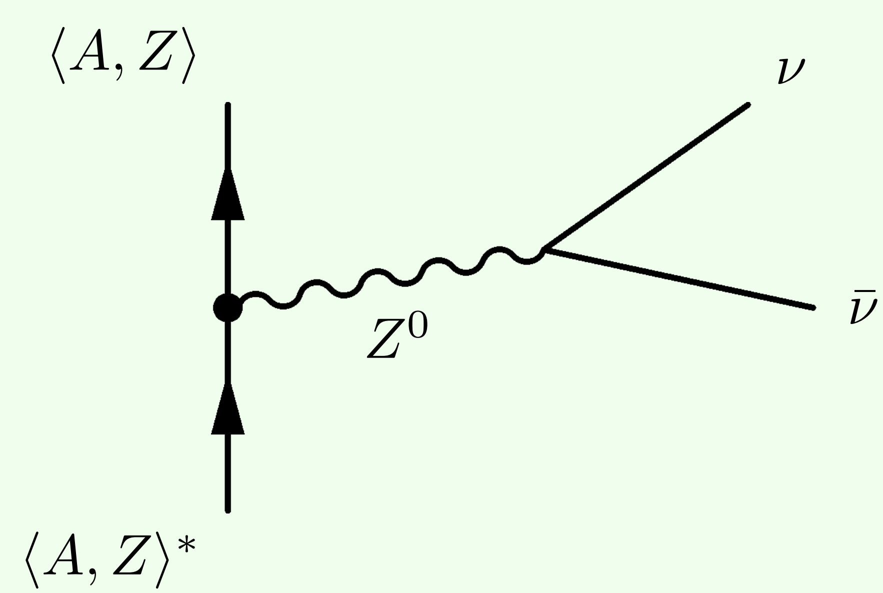
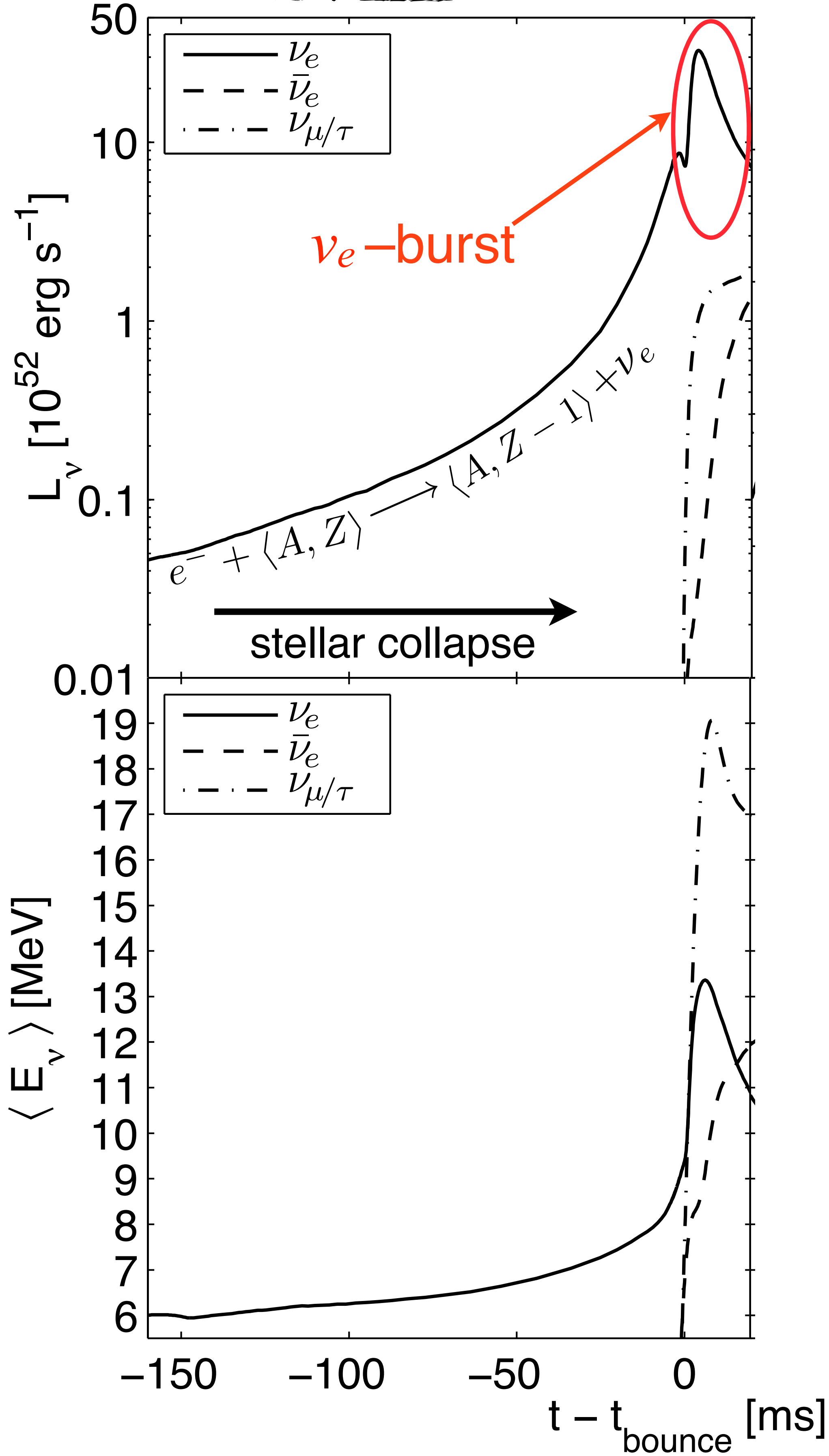


Nuclear e^- capture rate significantly exceeds nuclear (de)excitation rate!

Neutrino signal – bounce



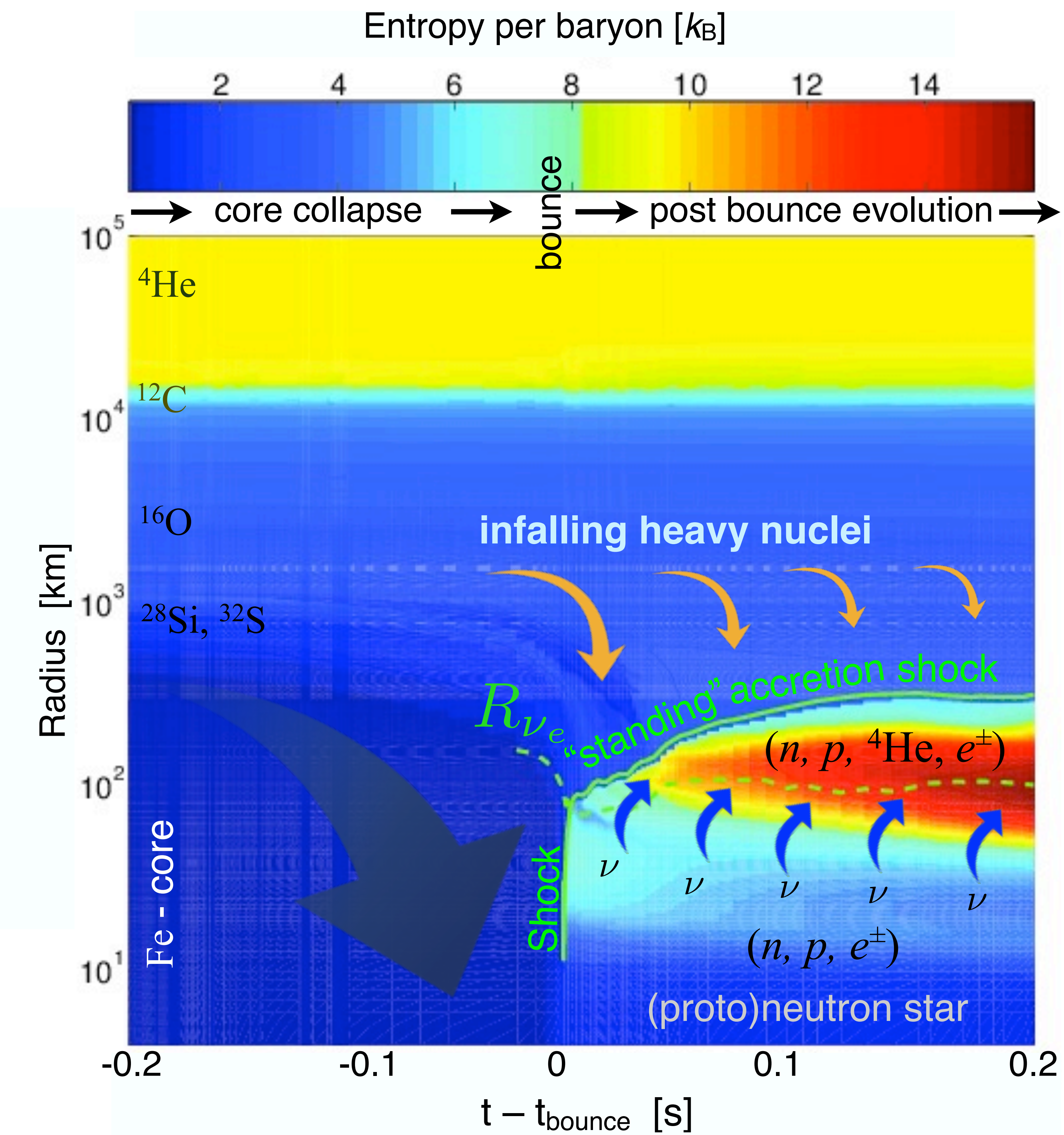
Supernova shock propagation across the sphere of last inelastic scattering (ν-sphere)

ν_e–deleptonization burst is generic feature

charged current reactions

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

Supernova evolution in a nutshell



Collapse halts above saturation density where the core bounces back with the **formation of shock wave**

Rapid shock acceleration to large radii of about 100–200 km

Still gravitationally unstable outer layers of the stellar core

Shock stalling due to energy losses

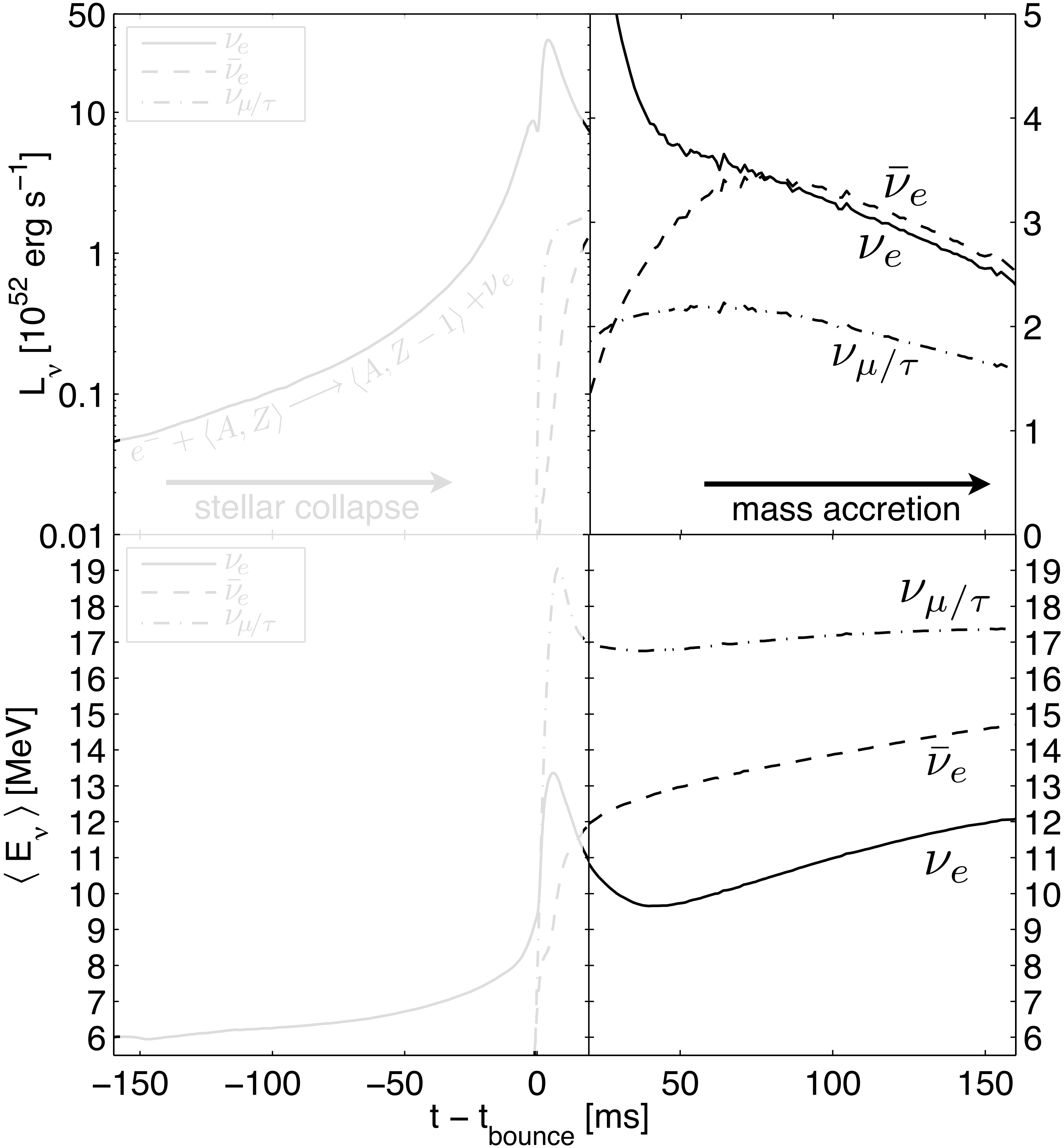
Later evolution determined from energy-balance due to:

(a) ram pressure from mass accretion; infalling material ahead of shock

(b) energy liberation (transport) deposition behind accretion shock

No prompt explosions

Neutrino signal – post-bounce



charged current reactions

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

pair processes

$$e^- + e^+ \leftrightarrows \nu + \bar{\nu}$$
$$N + N \leftrightarrows N + N + \nu + \bar{\nu}$$
$$\nu_e + \bar{\nu}_e \leftrightarrows \nu_{\mu/\tau} + \bar{\nu}_{\mu/\tau}$$

elastic scattering

$$\nu + N \leftrightarrows \nu' + N$$

inelastic scattering

$$\nu + e^\pm \leftrightarrows \nu' + e^\pm$$

Neutrino-energy hierarchy reflects strength of coupling to matter

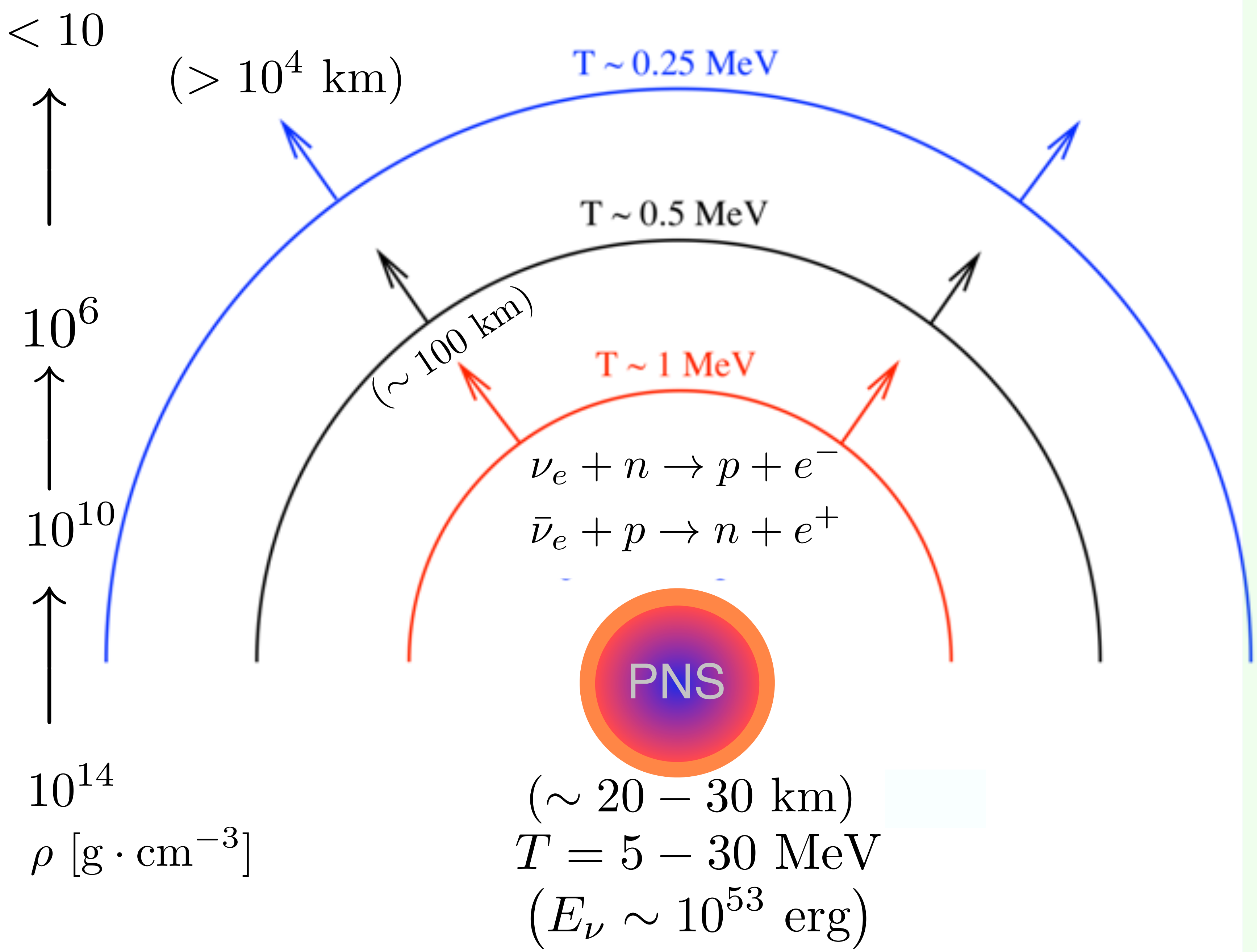
PNS deleptonization

Beyond supernova explosion onset – once the stellar mantle is ejected . . .

The supernova story continues for more than 10 seconds!

Mildly independent from details of the supernova explosion mechanism

Can be modeled in spherical symmetry



low-mass outflow:
"ν-driven wind"
(mass ejection from PNS surface)

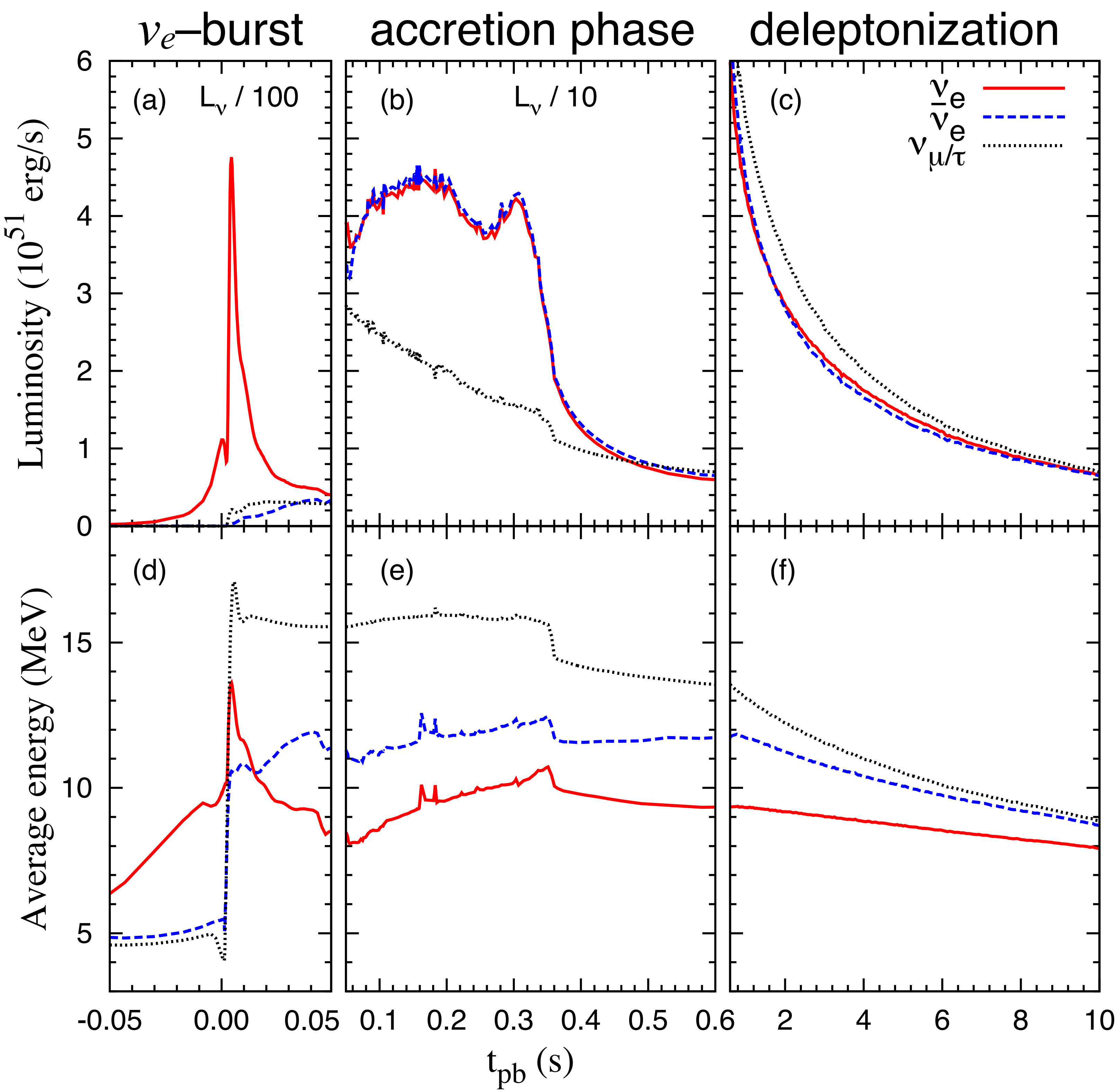
↑

neutrino heating at PNS surface

PNS deleptonization
(neutrino diffusion)

Pons et al., (1999) ApJ 513, 780

Neutrino signal



Fischer et al.,(2010) A&A 517, A80

Hüdepohl et al.,(2010) PRL 104, 251101

Martinez-Pinedo & TF et al.,(2012) PRL 109, 251104

Roberts et al.,(2012) PRC 86, 065803

Martinez-Pinedo & TF et al.,(2014) JPG 41, 044008

TF et al.,(2016) PRD (submitted)

Wu et al.,(2015) PRD 89, 061303

Neutrino detection

Supernova-simulation results for two neutrino detectors; 10 kpc

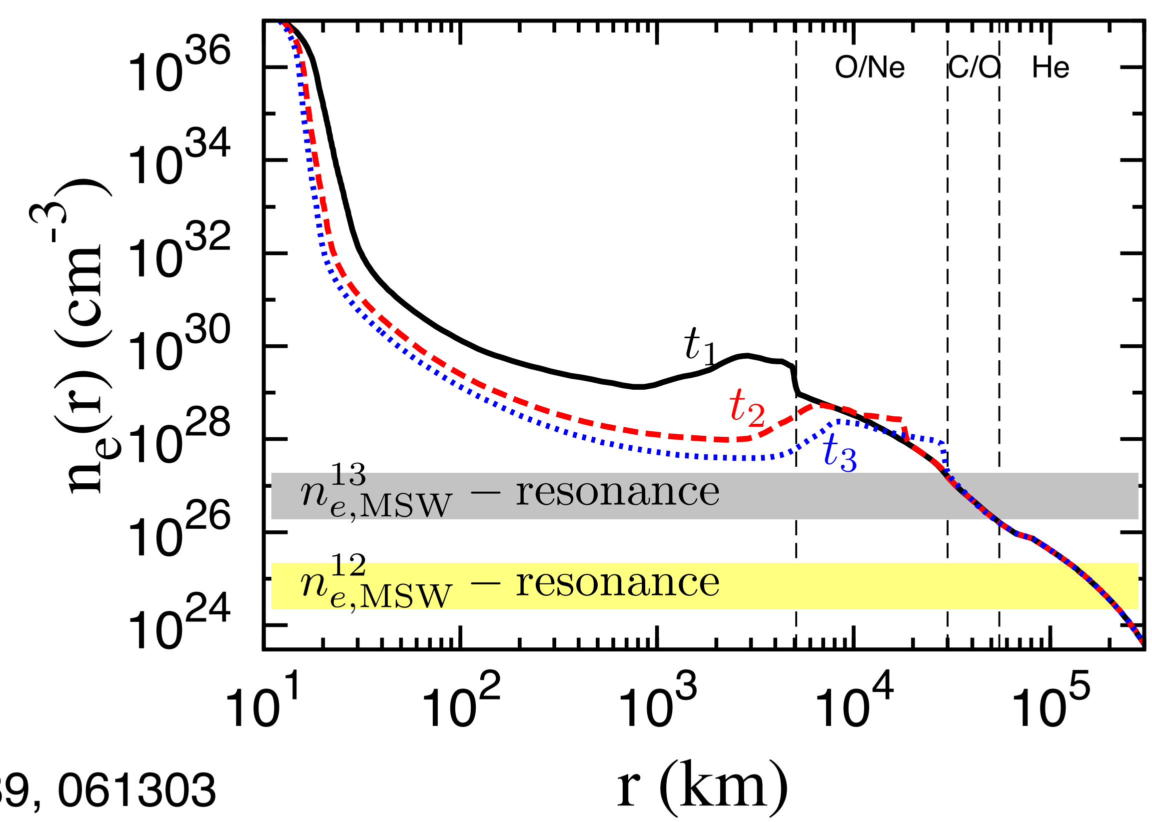
LArTPC
(fictive 34 kton liquid argon time projection chamber)

$$\nu_e + {}^{40}\mathrm{Ar} \longrightarrow {}^{40}\mathrm{K}^* + e^-$$
$$\bar{\nu}_e + {}^{40}\mathrm{Ar} \longrightarrow {}^{40}\mathrm{Cl}^* + e^+$$
$$\nu_\alpha + e^- \longrightarrow \nu_\alpha + e^-$$

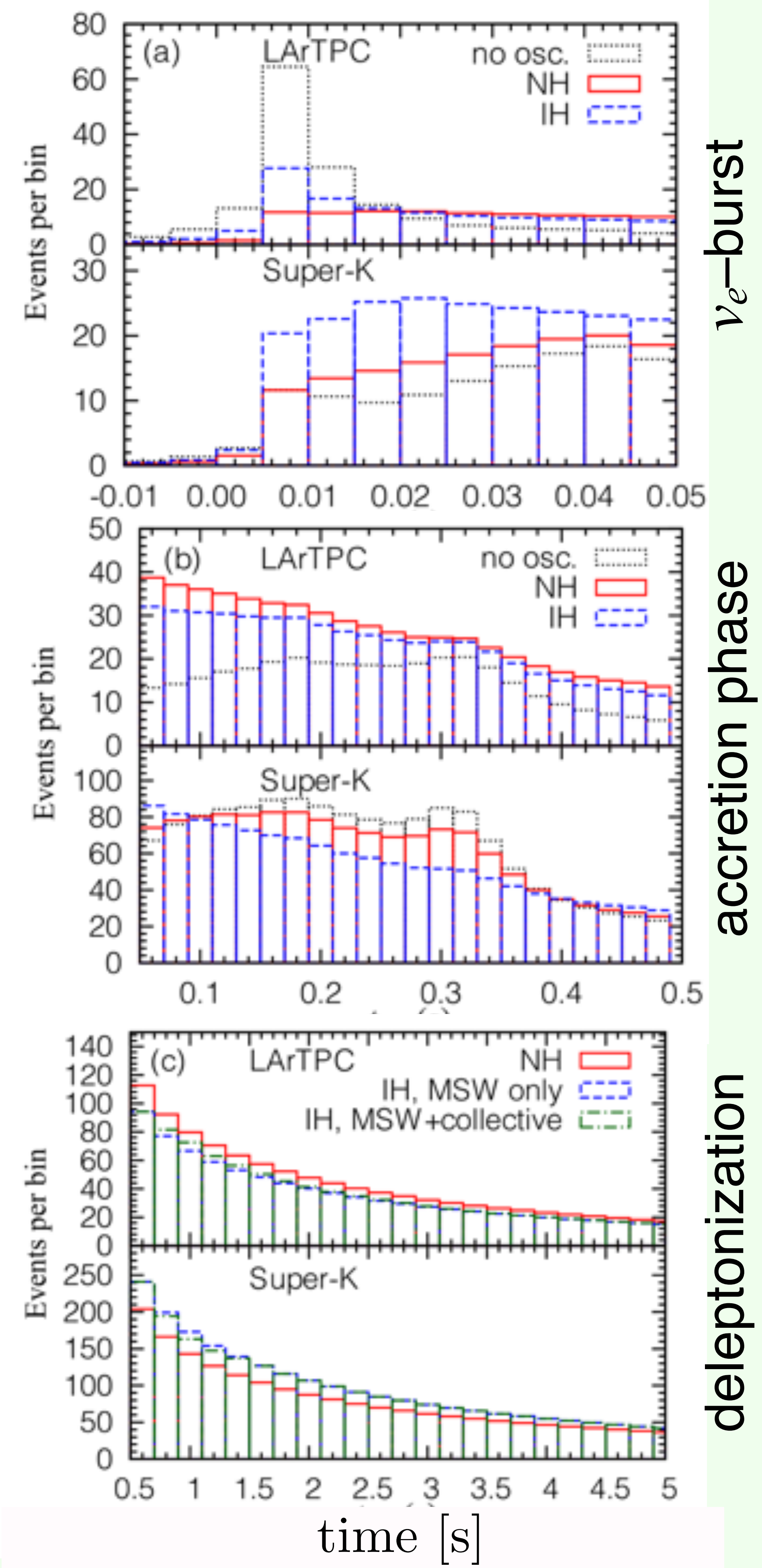
Super-K
(50 kton ultra-pure water)

$$\bar{\nu}_e + p \longrightarrow n + e^+$$
$$\nu_e + {}^{16}\mathrm{O} \longrightarrow {}^{16}\mathrm{F}^* + e^-$$
$$\bar{\nu}_e + {}^{16}\mathrm{O} \longrightarrow {}^{16}\mathrm{N}^* + e^+$$
$$\nu_\alpha + {}^{16}\mathrm{O} \longrightarrow {}^{16}\mathrm{O} + \nu_\alpha$$
$$\nu_\alpha + e^- \longrightarrow \nu_\alpha + e^-$$

Full (3-flavor, multi-angle, multi-energy, time-dependent) consideration of neutrino oscillations for NH/IH; matter (MSW) effects and collective oscillations (multiple-spectral flips)



Wu et al.,(2015) PRD 89, 061303



Some insights into the neutrino opacity

Neutrino opacity and EoS

Reddy et al.,(1998) PRD 58, 013009

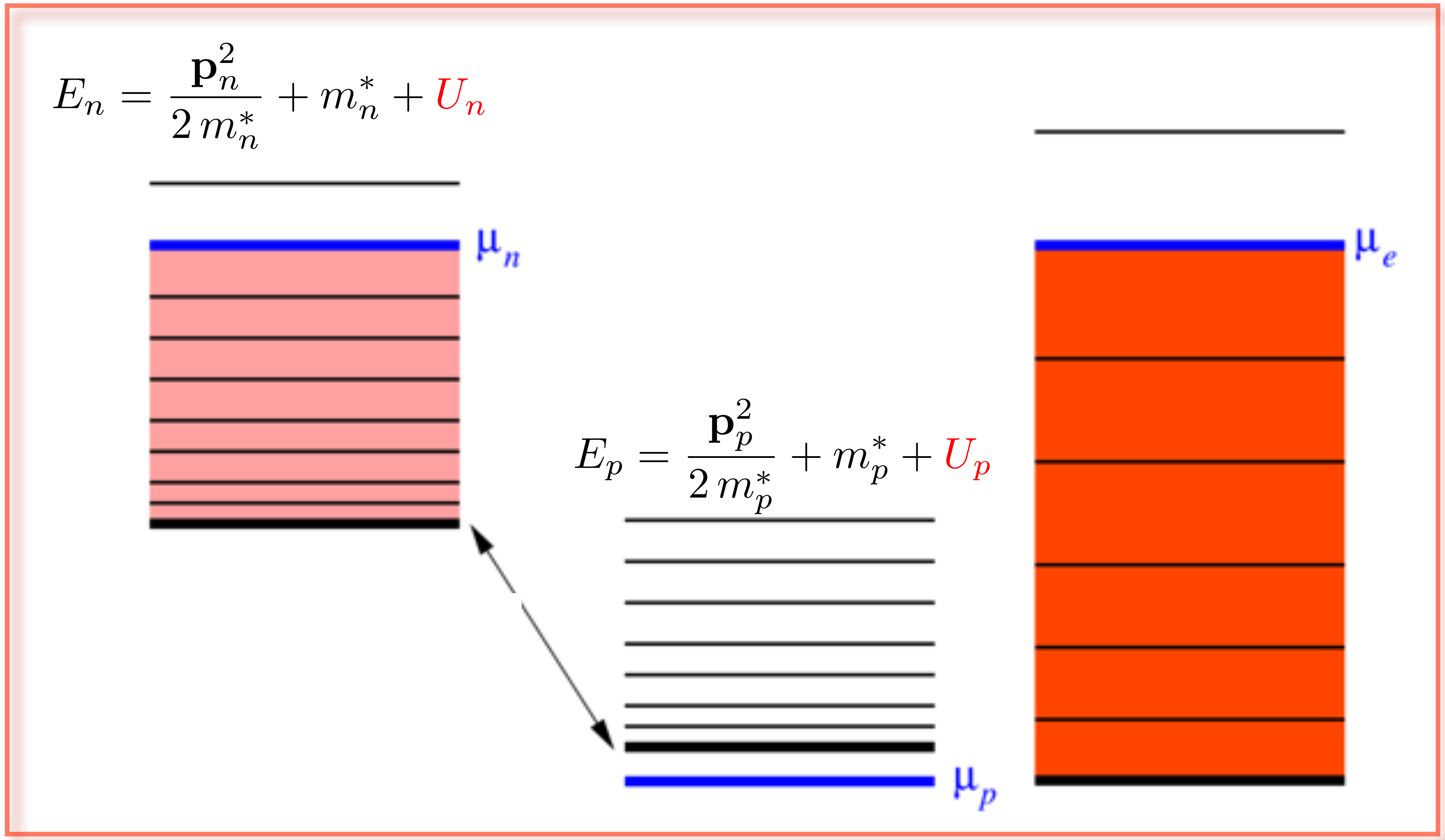
$$\nu_e + n \longrightarrow e^- + p$$

Here: $S_V = S_A \equiv S(q_0, q)$
(density and spin response functions)

$$1/\lambda(E_{\nu_e}) = \frac{G_F^2 V_{ud}^2}{\pi\hbar c}(g_V^2 + 3g_A^2)\int \frac{d^3p_e}{(2\pi\hbar c)^3}(1 - F_e(E_e))\, S(q_0, q)$$

$$q_0 = E_\nu - E_e\ , \qquad q = \mathbf{p}_\nu - \mathbf{p}_e$$

$$S(q_0, q) = 4\pi \int \frac{d^3p_n}{(2\pi\hbar c)^3}\delta(q_0 + E_n - E_p) f_n(E_n)(1 - f_p(E_p))$$



Charged-current absorption; nucleons are not free gas

Lowest order medium modification of the weak rate; depends on the EoS (symmetry energy):

$$U_n - U_p \propto S^F(T, \rho)$$

Martinez-Pinedo & TF et al.,(2012) PRL 109, 251104

Roberts et al.,(2012) PRC 86, 065803

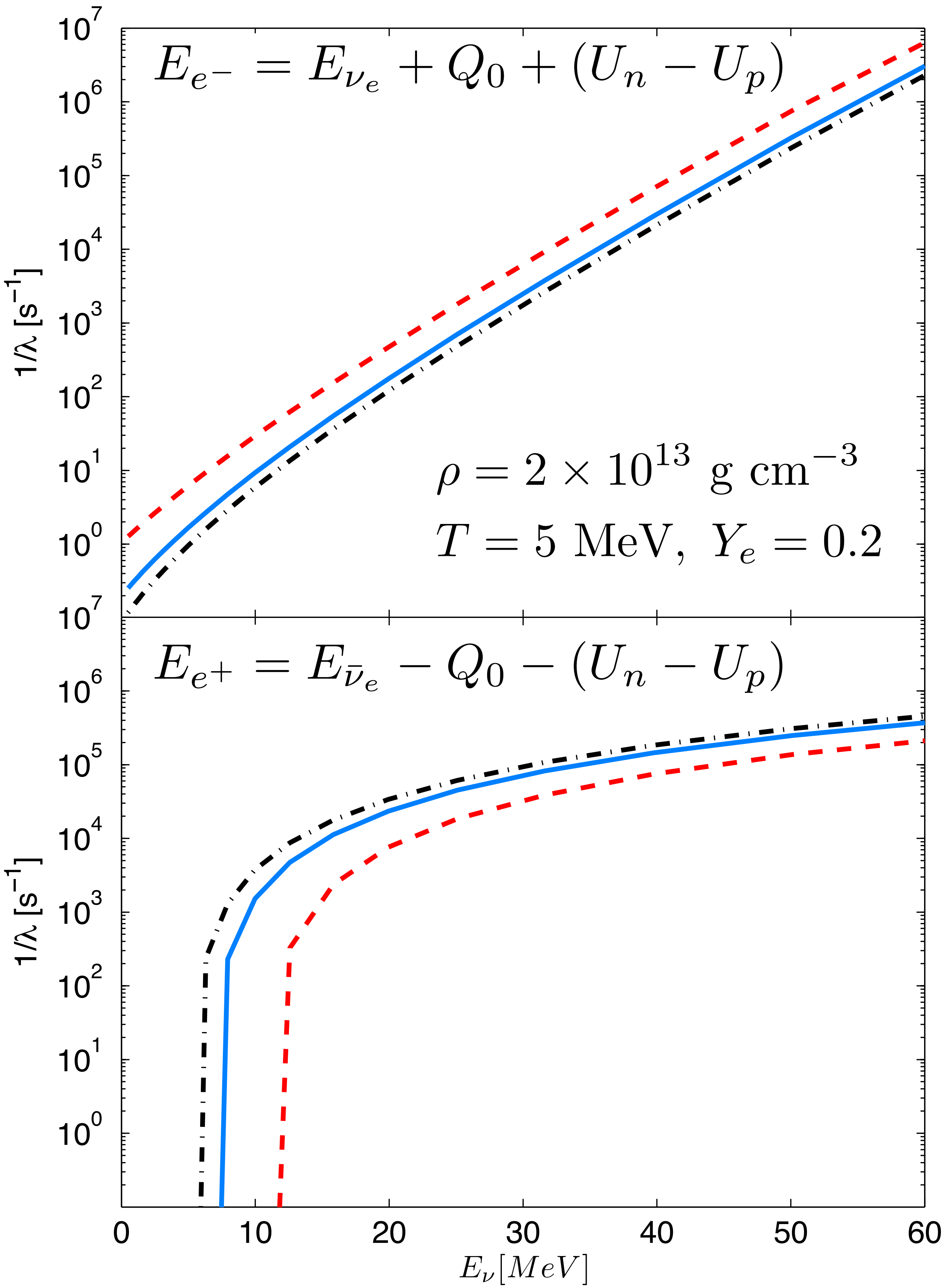
Horowitz et al.,(2012) PRC 86, 065806

Opacity & symmetry energy

TF et al.,(work in progress)

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

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

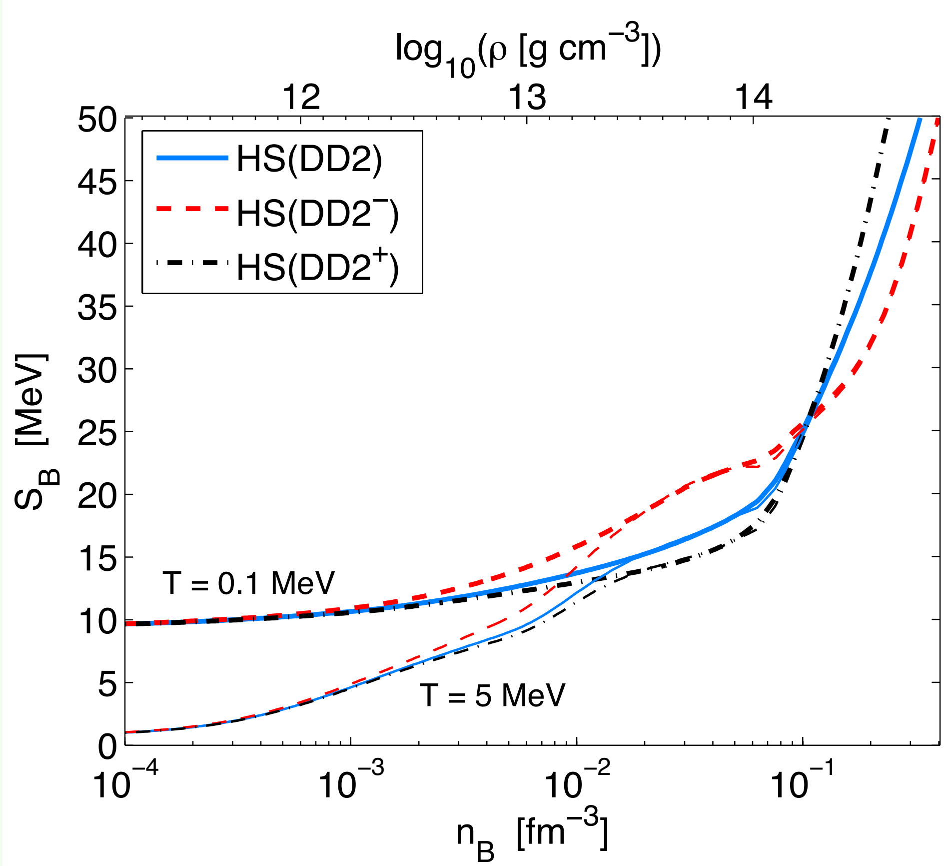


Ref. symmetry energy: DD2

$\mathrm{DD2}^- \; : \; U_n - U_p = 9.4$ MeV

$\mathrm{DD2} \; : \; U_n - U_p = 5.3$ MeV

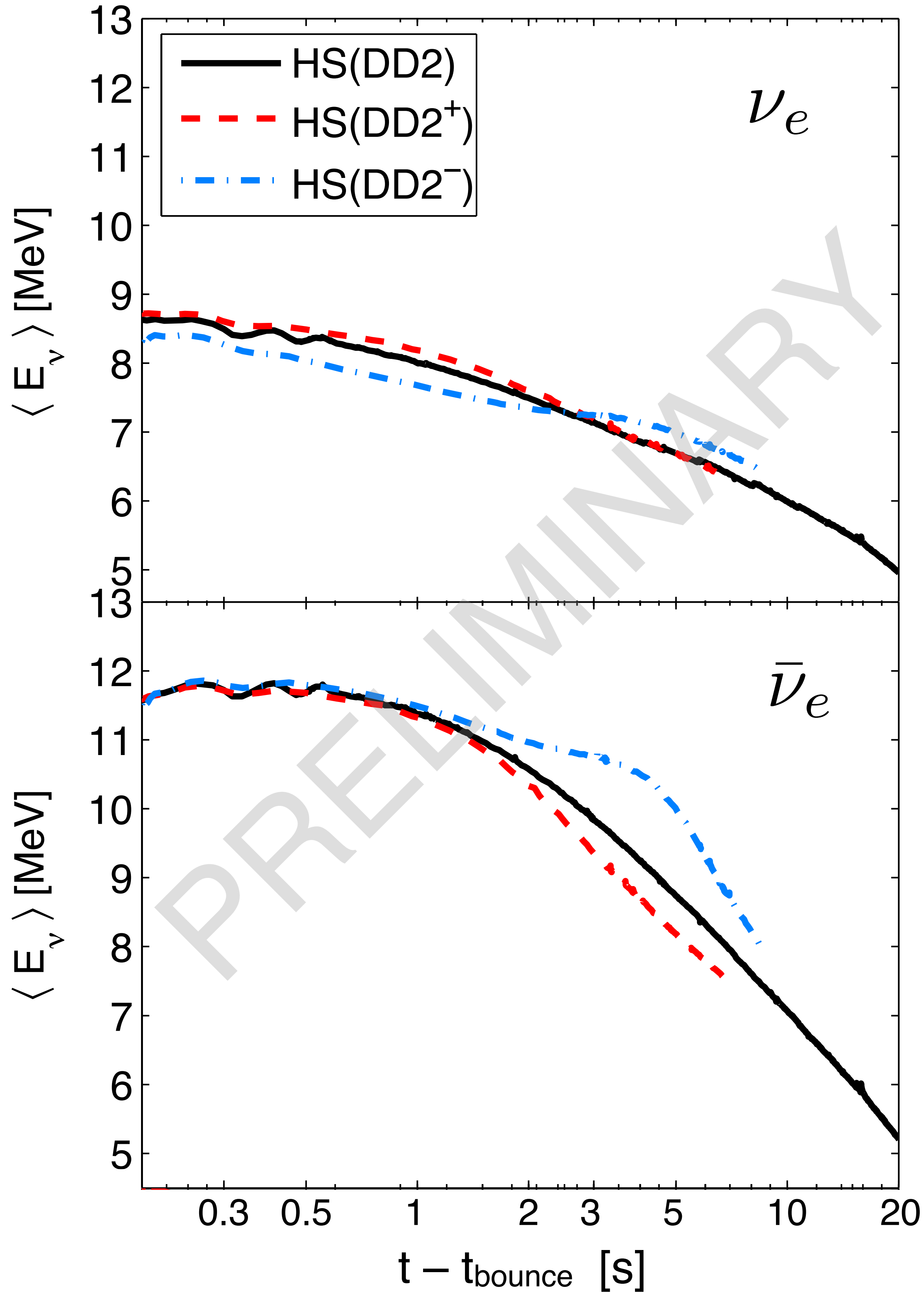
$\mathrm{DD2}^+ \; : \; U_n - U_p = 3.7$ MeV



Large(small) symmetry energy at high density gives small (large) symmetry at low density

Role of symmetry energy

TF et al.,(work in progress)



Nuclear symmetry energy controls the magnitude of spectral differences between neutrinos and anti-neutrinos

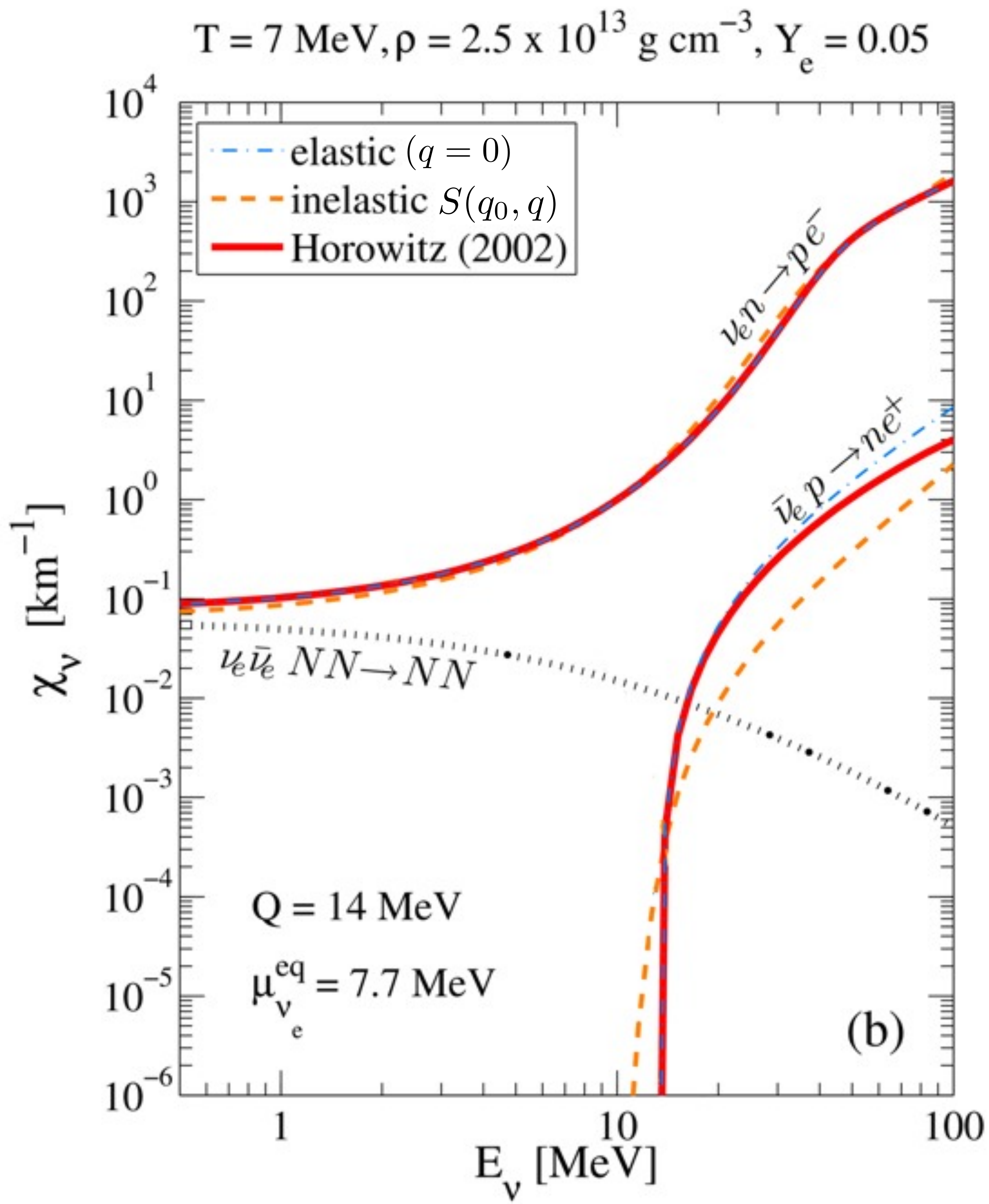
Large(small) symmetry energy at low density gives large(small) spectral differences

Relevance for nucleosynthesis:

$$\langle \varepsilon_{\bar{\nu}_e} \rangle - \langle \varepsilon_{\nu_e} \rangle \begin{cases} \gtrsim 5 \text{ MeV} & (Y_e < 0.5) \text{ neutron rich} \\ < 5 \text{ MeV} & (Y_e > 0.5) \text{ proton rich} \end{cases}$$

Qian et al.,(1996) ApJ 471, 331

Recoil and weak magnetism



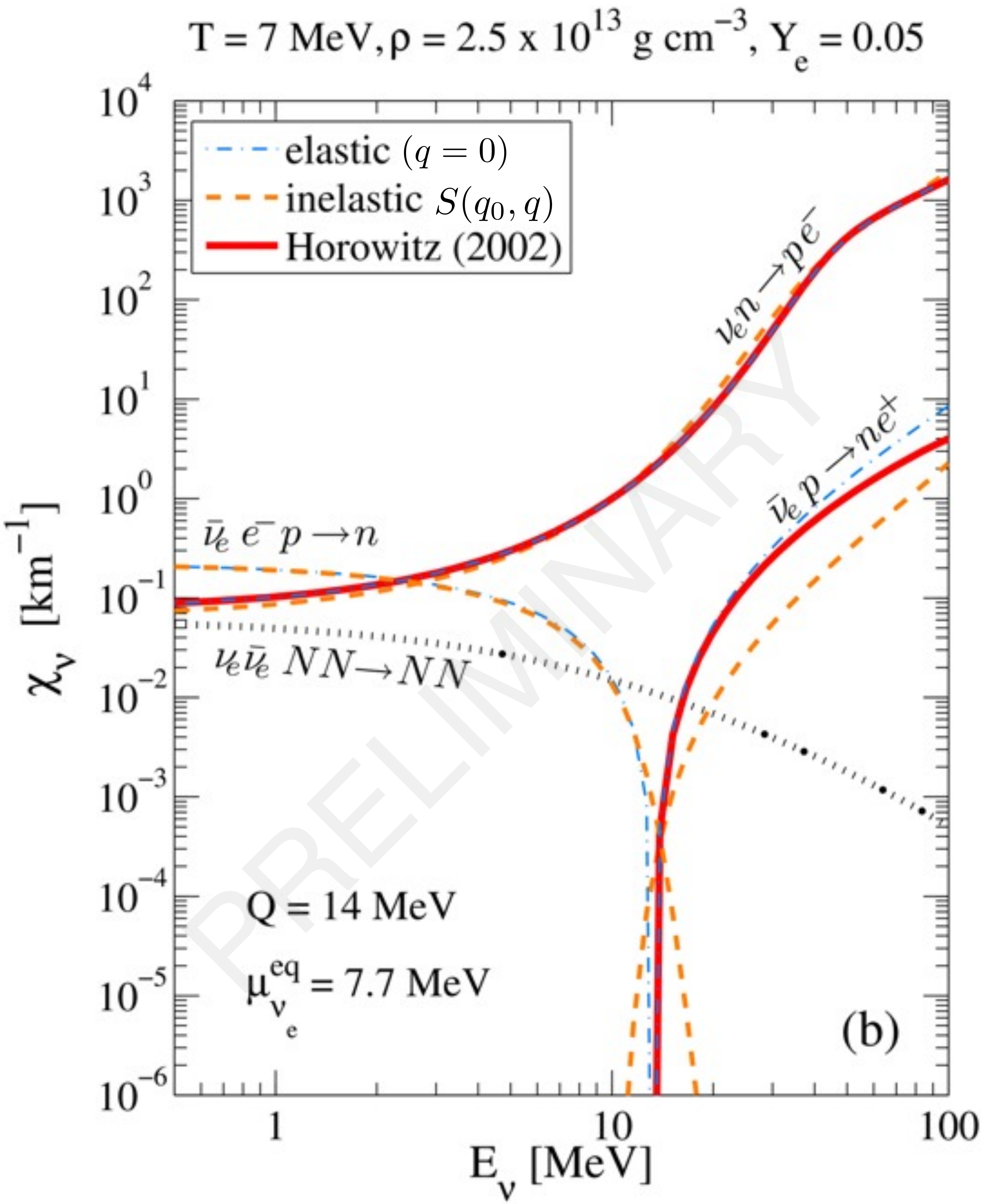
Inelastic contributions generally reduce the rates

Parity violation of the nucleon weak magnetic moment coupling to its axial current; generally increasing differences between ν and anti-ν

Main source ν_μ and anti-ν_μ spectral differences in supernova simulations

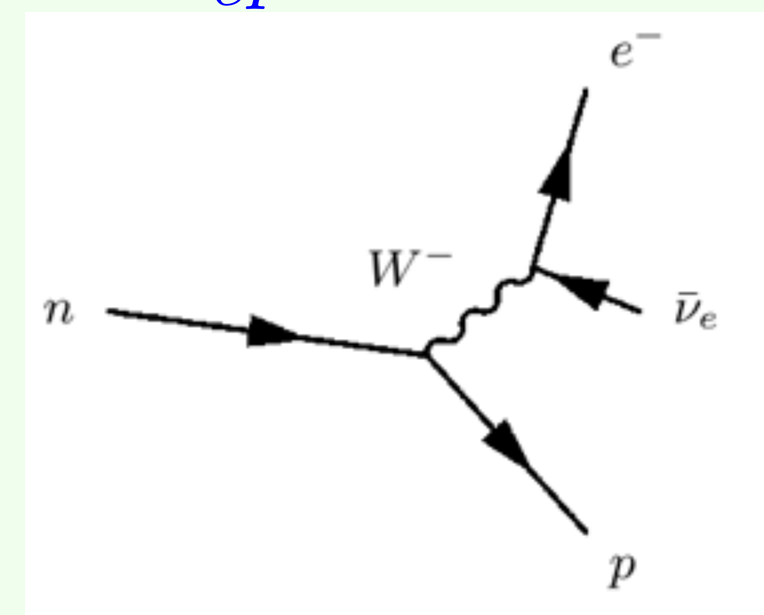
Inverse neutron decay

TF et al.,(in preparation)



Source of opacity at low energy

$$\bar{\nu}_e p e^- \longrightarrow n$$



Same matrix element as anti-ν_e absorption on protons; no e^- blocking

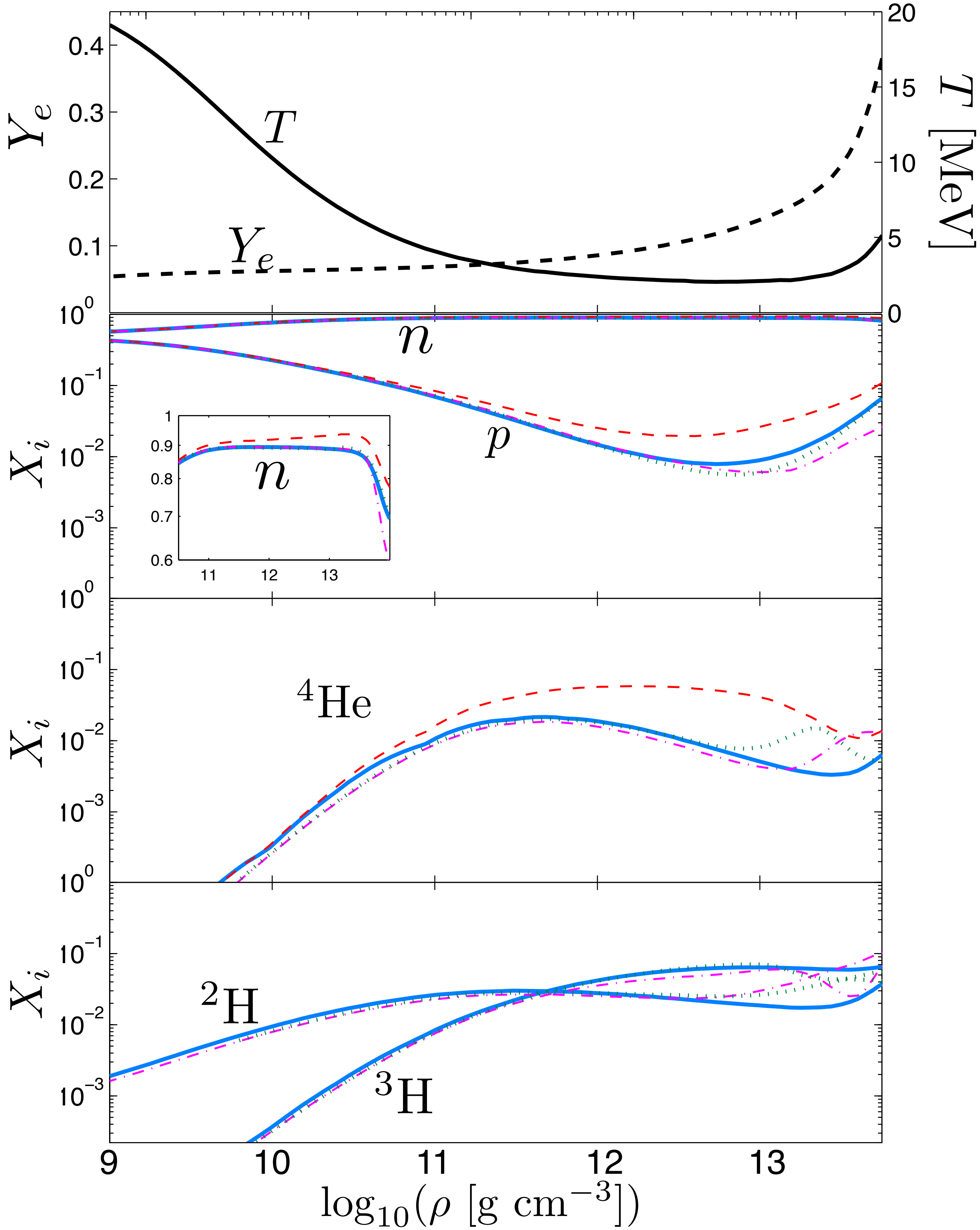
Following replacements for opacity:

$$(1 - f_e(E_e)) \longrightarrow f_e(E_e))$$

$$E_e = -E_{\bar{\nu}_e} + (m_n - m_p) + (U_n - U_p)$$

Presence of light clusters ?

TF et al., (work on progress)



Impact on the EoS:

NSE w. "all" clusters

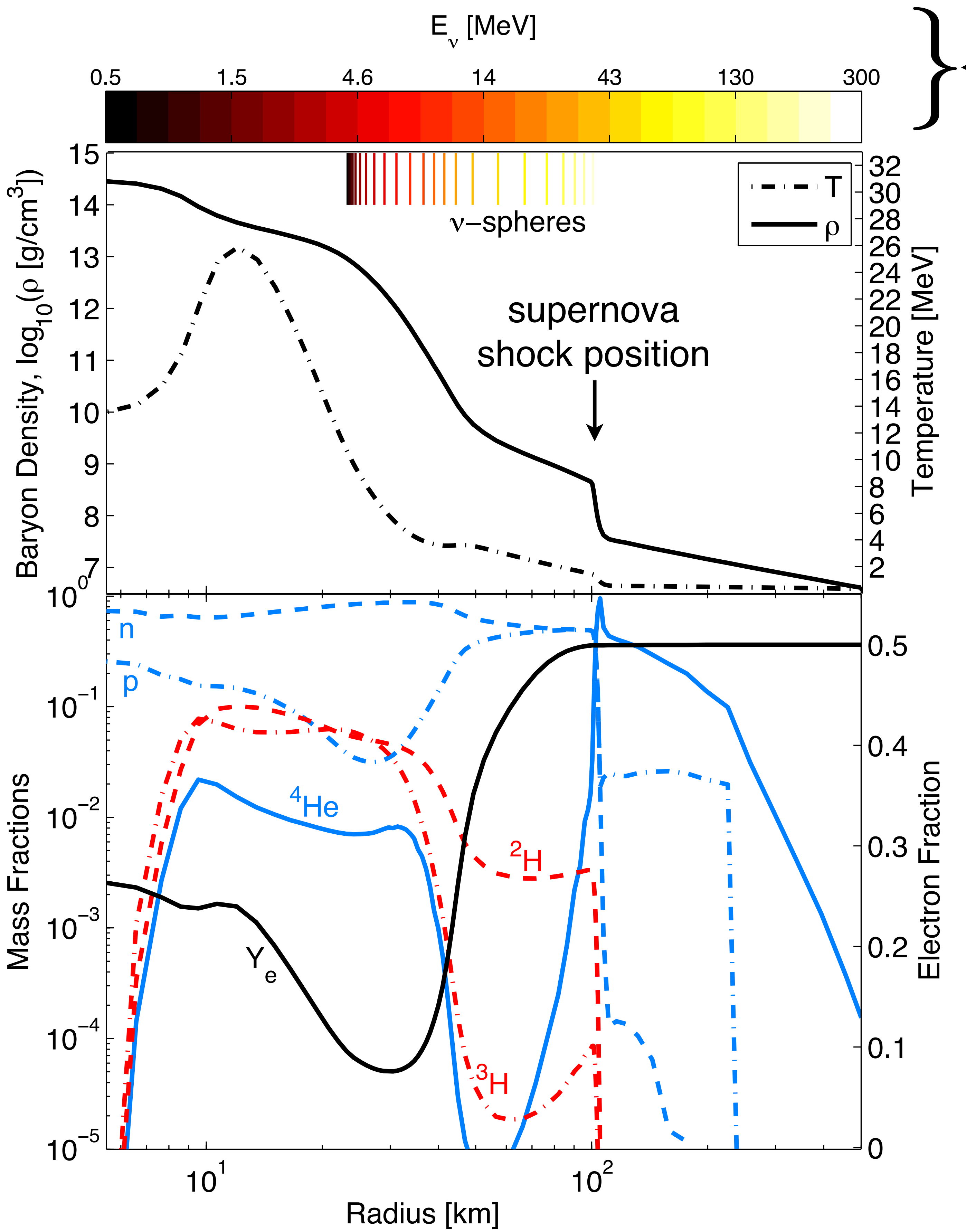
NSE w. {n, p, ^{4}He, (A,Z)}

gRDF

QS

Presence of light clusters ?

Sumiyoshi & Röpke (2008) PRC 77, 055804
Arcones et al.,(2008) PRC 77, 055804
Hempel & TF et al.,(2012) ApJ 748, 70



Neutrino decoupling is a spectral phenomenon

ν–decoupling at low densities **prior to explosion onset**:

$$\rho(R_\nu) \simeq 10^{11} - 10^{12} \text{ g cm}^{-3}$$

Neutrino spectra/luminosities are powered by mass accretion; charged current processes with free nucleons ("standard" weak processes)

What about light clusters:

- ^{2}H, ^{3}H as abundant as p

No impact on SN dynamics; No impact on neutrino signal !!!

Impact from light clusters ?

Sumiyoshi & Röpke (2008) PRC 77, 055804
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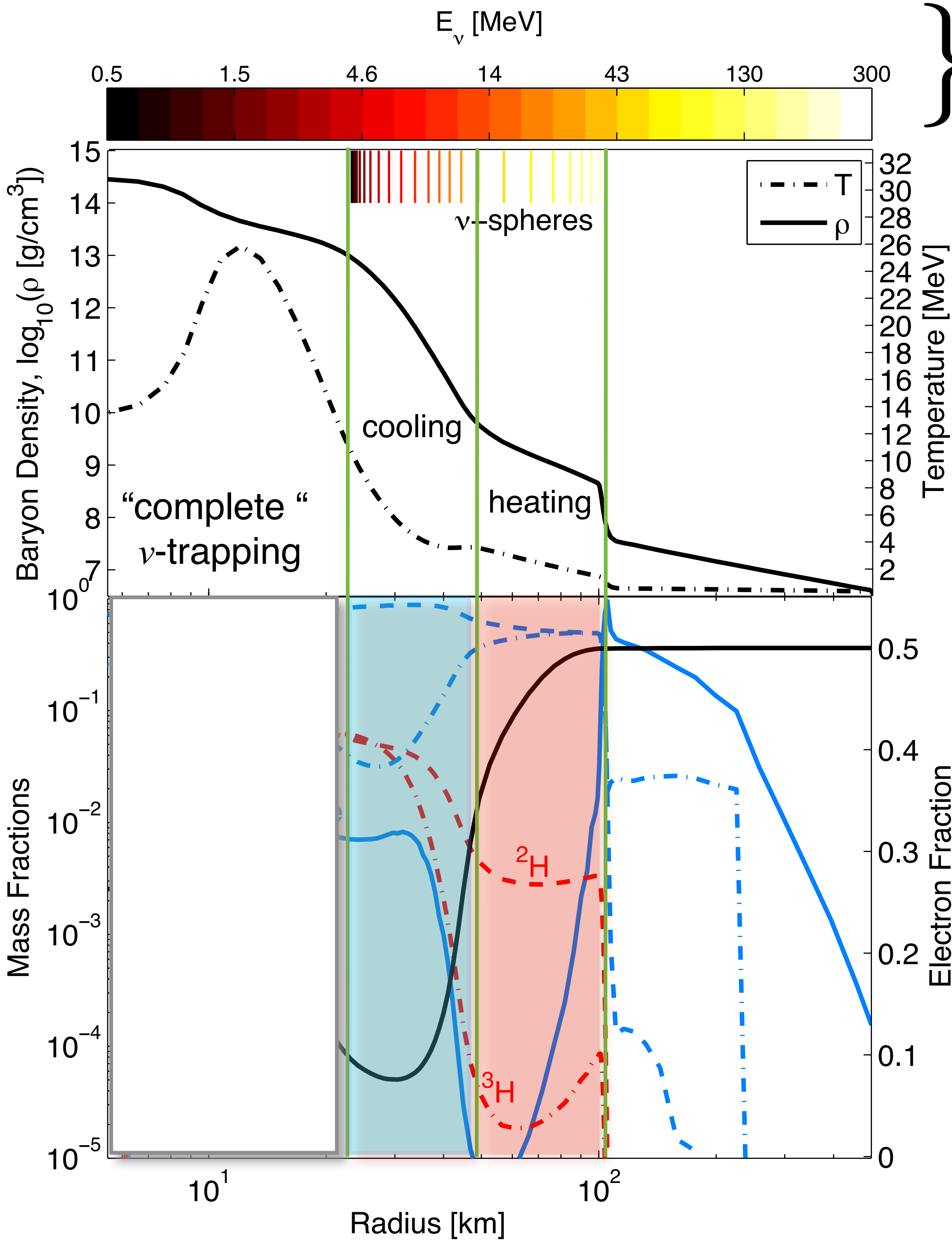

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Furusawa et al.,(2013) ApJ 774, 13

ν's and light clusters ?

Table 1:

	Weak process
1	$\nu_e\, {}^2\mathrm{H} \rightleftarrows p\, p\, e^-$
2	$\bar{\nu}_e\, {}^2\mathrm{H} \rightleftarrows n\, n\, e^+$
3	$\nu_e\, n\, n \rightleftarrows {}^2\mathrm{H}\, e^-$
4	$\bar{\nu}_e\, p\, p \rightleftarrows {}^2\mathrm{H}\, e^+$
5	$\bar{\nu}_e\, e^-\, {}^2\mathrm{H} \rightleftarrows n\, n$
6	$\nu_e\, e^+\, {}^2\mathrm{H} \rightleftarrows p\, p$
7	$\nu_e\, {}^3\mathrm{H} \rightleftarrows n\, p\, p\, e^-$
8	$\bar{\nu}_e\, {}^3\mathrm{H} \rightleftarrows n\, n\, n\, e^+$
9	$\nu_e\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{He}\, e^-$
10	$\bar{\nu}_e\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{H}\, e^+$
11	$\nu\, {}^2\mathrm{H} \rightleftarrows p\, n\, \nu$
12	$\nu\, {}^2\mathrm{H} \rightleftarrows {}^2\mathrm{H}\, \nu$
13	$\nu\, {}^3\mathrm{H} \rightleftarrows {}^3\mathrm{H}\, \nu$
14	$\nu\, {}^3\mathrm{He} \rightleftarrows {}^3\mathrm{He}\, \nu$

charged-current absorption (1–10)

scattering (11–14)

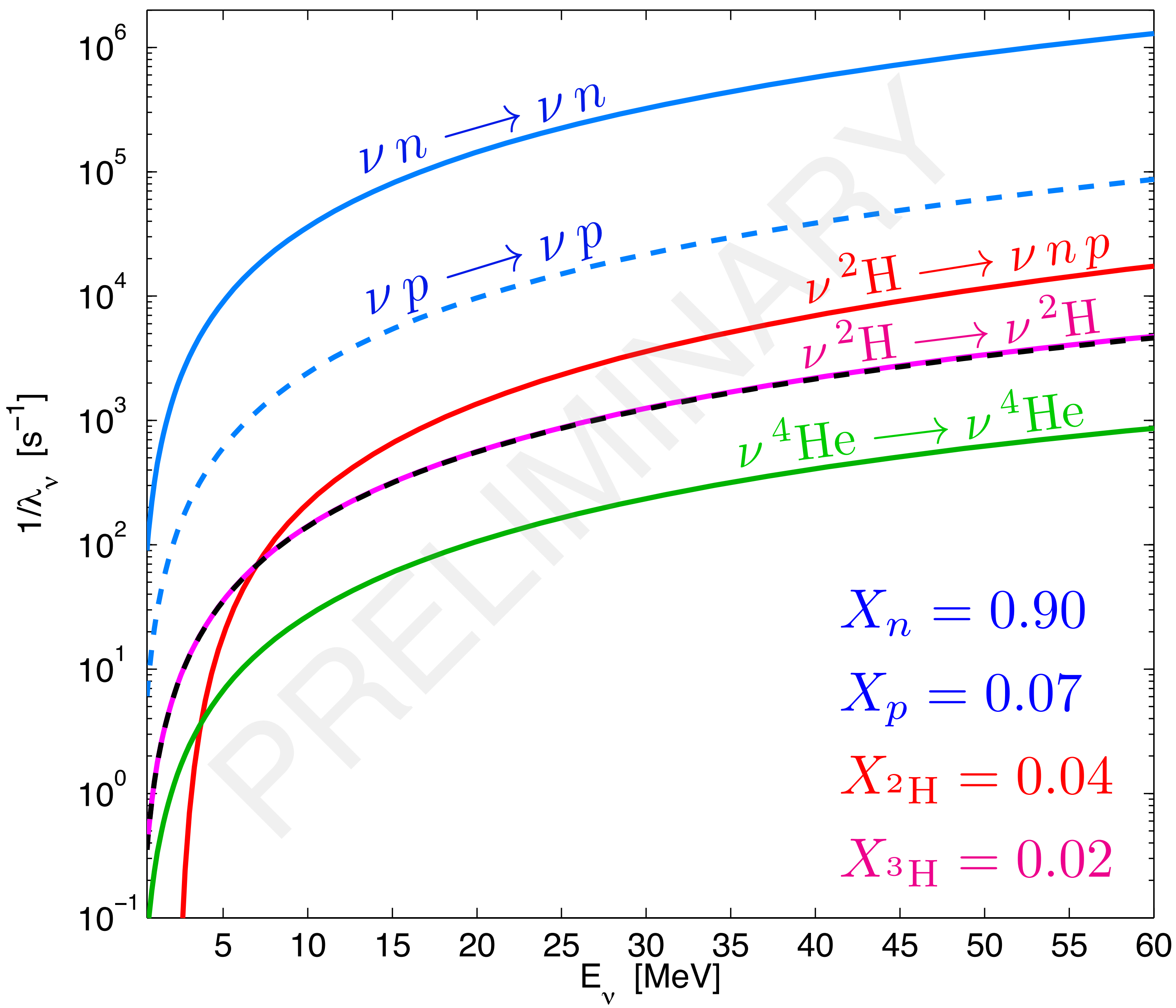
$$\left(\nu = \{\nu_e, \bar{\nu}_e, \nu_{\mu/\tau}, \bar{\nu}_{\mu/\tau}\}\right)$$

Nasu et al.,(2015) ApJ 801, 12

NC rates with light clusters

TF et al.,(2016) EPJConf. 109, 06002

$$(T = 5\ \mathrm{MeV},\ \rho = 5 \times 10^{11}\ \mathrm{g\ cm^{-3}},\ Y_e = 0.1)$$



Scattering on neutrons (and protons) dominates neutral current opacity, at any conditions!

<u>Elastic scattering on nuclei:</u>

Coherent scattering on nucleus

$$\sigma^{\text{elastic}} \propto n_{A,Z} E_\nu^2$$

Non-coherent scattering

(neutrino scatters on the nucleons bound in the nucleus)

<u>Inelastic scattering on deuteron:</u>

Nakamura et al.,(2001) PRC 63, 034617

<u>Reminder: scattering on N</u>

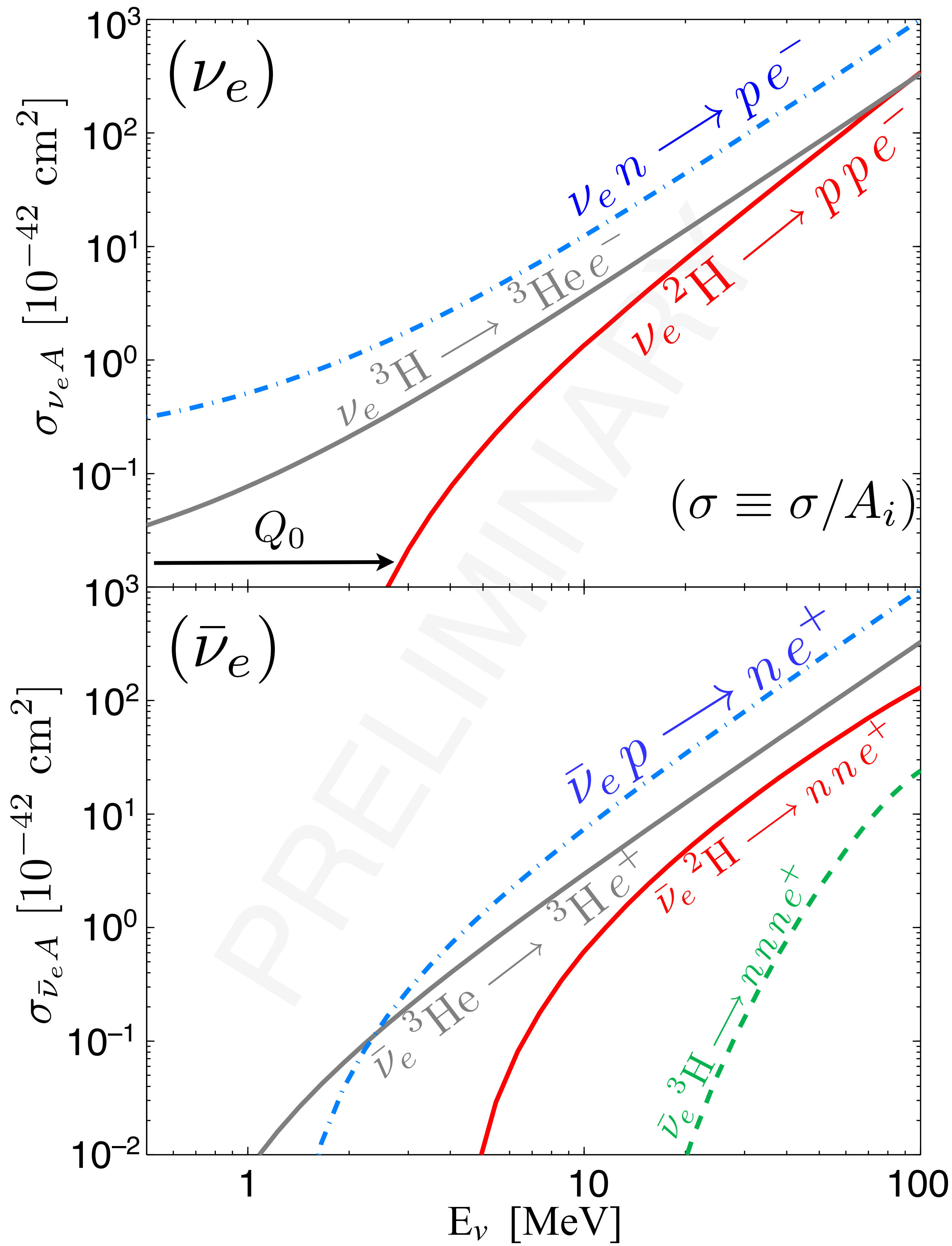
$$\frac{d\sigma}{d\Omega} \propto E_\nu^2 \left(C_V^2 (1 + \cos\vartheta) + C_A^2 (3 - \cos\vartheta)\right)$$

$$\sigma^{\text{elastic}} = \int d\Omega \frac{d\sigma}{d\Omega} (1 - \cos\vartheta)$$

$$= \frac{G_F^2 E_\nu^2}{\pi} \frac{2}{3} \left(C_V^2 + 5 C_A^2\right)$$

CC – vacuum cross sections

TF et al.,(2016) EPJConf. 109, 06002



Arcones et al.,(2008) PRC 78, 015806

Absorption cross sections for ^{2}H:

Nakamura et al.,(2001) PRC63, 034617

Absorption cross sections for N:

$$\sigma_{\nu_e n} = \sigma_0 \; p_{e^-} E_{e^-}$$

$$\sigma_{\bar{\nu}_e p} = \sigma_0 \; p_{e^+} E_{e^+}$$

$$E_{e^\pm} = E_\nu \pm Q_0$$

$$(Q_0 = 1.2935 \text{ MeV})$$

$$\sigma_0 = \frac{G_F^2}{\pi} \frac{V_{ud}^2}{(\hbar c)^4} \left(g_V^2 + 3 g_A^2\right)$$

Absorption cross sections for ^{3}H/^{3}He:

$$\sigma_{\nu_e^3\mathrm{H}} = \sigma_0 \; p_{e^-} E_{e^-}$$

$$\sigma_{\bar{\nu}_e^3\mathrm{He}} = \sigma_0 \; p_{e^+} E_{e^+}$$

$$E_{e^\pm} = E_\nu \pm Q_0$$

$$(Q_0 = 0.529 \text{ MeV})$$

$$\sigma_0 = \frac{G_F^2}{\pi} \frac{V_{ud}^2}{(\hbar c)^4} B(GT)$$

$$(B(GT) = 5.97 \text{ MeV})$$

CC – rates

TF et al.,(2016) EPJConf. 109, 06002

$$\nu_e\, {}^2\mathrm{H} \longrightarrow p\, p\, e^- \;, \qquad \bar{\nu}_e\, {}^2\mathrm{H} \longrightarrow n\, n\, e^+ \;,$$

CC cross sections from: Nakamura et al.,(2001) PRC63, 034617

$$1/\lambda(E_\nu) = \frac{g_{^2\mathrm{H}}}{2} \int \frac{d^3 p_{^2\mathrm{H}}}{(2\pi\hbar c)^3} d\Omega_e dp_e d(\cos\theta) \left(\frac{d\sigma_{\nu\, ^2\mathrm{H}}}{dp_e}(E^*_\nu) \right)$$
$$\times \tilde{f}_{^2\mathrm{H}}(E_{^2\mathrm{H}}) \left(1 - f_e(E_e)\right) \left(1 - f_1(E_1)\right) \left(1 - f_2(E_2)\right)$$

final states incl. Pauli-blocking

number density of targets (Bose/Maxwell)

Momentum integration incl. occupation no./Pauli-blocking of all contributing particles

Vacuum cross sections are modified by nuclear medium

CC – rates

TF et al.,(2016) EPJConf. 109, 06002

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$$\times \tilde{f}_{^2\mathrm{H}}(E_{^2\mathrm{H}}) (1 - f_e(E_e)) (1 - f_1(E_1)) (1 - f_2(E_2))$$

final states incl. Pauli-blocking

number density of targets (Bose/Maxwell)

* **medium-modified vacuum cross sections**!

$$E^*_{\nu_e} = E_{\nu_e} + (m^*_{^2\mathrm{H}} - m_{^2\mathrm{H}}) + U_{^2\mathrm{H}} - 2(m^*_p - m_p) - 2U_p$$

$$E^*_{\bar{\nu}_e} = E_{\bar{\nu}_e} + (m^*_{^2\mathrm{H}} - m_{^2\mathrm{H}}) + U_{^2\mathrm{H}} - 2(m^*_n - m_n) - 2U_n$$

Momentum integration incl. occupation no./Pauli-blocking of all contributing particles

Vacuum cross sections are modified by nuclear medium

Deduction of deuteron mean-filed potential – comparison with (free) non-interacting chemical potential:

$$U_{^2\mathrm{H}} = \mu_{^2\mathrm{H}} - \mu^0_{^2\mathrm{H}}$$

CC – rates

TF et al.,(2016) EPJConf. 109, 06002

$$\nu_e\,{}^2\mathrm{H} \longrightarrow p\,p\,e^- \,, \qquad \bar{\nu}_e\,{}^2\mathrm{H} \longrightarrow n\,n\,e^+ \,,$$

$$1/\lambda(E_\nu) = \frac{g_{^2\mathrm{H}}}{2} \int \frac{d^3 p_{^2\mathrm{H}}}{(2\pi\hbar c)^3} d\Omega_e dp_e d(\cos\theta) \left(\frac{d\sigma_{\nu\,^2\mathrm{H}}}{dp_e}(E^*_\nu) \right) \times \tilde{f}_{^2\mathrm{H}}(E_{^2\mathrm{H}})(1 - f_e(E_e))\,(1 - f_1(E_1))\,(1 - f_2(E_2))$$

$$\begin{cases} E^*_{\nu_e} = E_{\nu_e} + (m^*_{^2\mathrm{H}} - m_{^2\mathrm{H}}) + U_{^2\mathrm{H}} - 2(m^*_p - m_p) - 2U_p \\ E^*_{\bar{\nu}_e} = E_{\bar{\nu}_e} + (m^*_{^2\mathrm{H}} - m_{^2\mathrm{H}}) + U_{^2\mathrm{H}} - 2(m^*_n - m_n) - 2U_n \end{cases}$$

$$\nu_e\,n\,n \longrightarrow {}^2\mathrm{H}\,e^- \,, \qquad \bar{\nu}_e\,p\,p \longrightarrow {}^2\mathrm{H}\,e^+$$

$$1/\lambda(E_{\nu_e}) = \frac{g_{^2\mathrm{H}} g_e}{4} \int \frac{d^3 p_{^2\mathrm{H}}}{(2\pi\hbar c)^3} d(\cos\theta) d\Omega_e dp_e \left(\frac{p_e^2}{p_{\nu_e}^2} \frac{d\sigma_{\bar{\nu}_e\,^2\mathrm{H}}}{d\Omega_e dp_{\nu_e}}(E^*_e) \right) \times \left(1 + \tilde{f}_{^2\mathrm{H}}(E_{^2\mathrm{H}})\right)(1 - f_e(E_e))\,f_1(E_1) f_2(E_2)$$

$$\begin{cases} E^*_{e^-} = E_{e^-} + (m^*_{^2\mathrm{H}} - m_{^2\mathrm{H}}) + 2(m^*_n - m_n) + (U_{^2\mathrm{H}} - 2U_n) \\ E^*_{e^+} = E_{e^+} + (m^*_{^2\mathrm{H}} - m_{^2\mathrm{H}}) + 2(m^*_p - m_p) + (U_{^2\mathrm{H}} - 2U_p) \end{cases}$$

$e^-\,{}^2\mathrm{H}$ has same cross section as anti-ν_e ${}^2\mathrm{H}$ but different phase space

$$\nu_e\,{}^3\mathrm{H} \longrightarrow {}^3\mathrm{He}\,e^- \,, \qquad \bar{\nu}_e\,{}^3\mathrm{He} \longrightarrow {}^3\mathrm{H}\,e^+$$

$$1/\lambda(E_\nu) = n_i \frac{G_F^2 V_{ud}^2}{\pi(\hbar c)^4} p_e E_e\,(1 - f_e(E_e))\,B(GT)$$

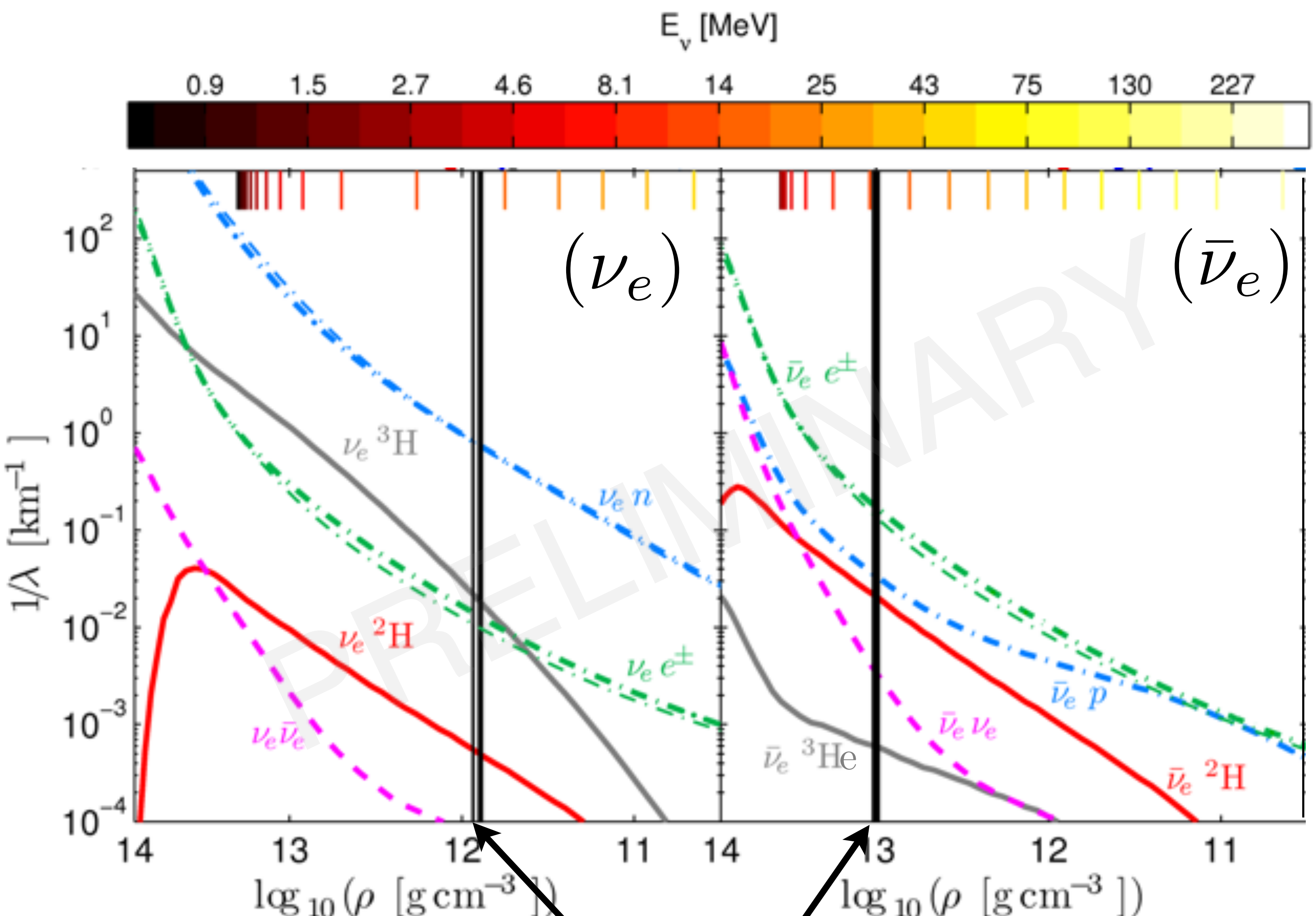
$$\begin{cases} E_{e^-} = E_{\nu_e} + (m_{^3\mathrm{H}} - m_{^3\mathrm{He}}) + (U_{^3\mathrm{H}} - U_{^3\mathrm{He}}) \\ E_{e^+} = E_{\bar{\nu}_e} - (m_{^3\mathrm{H}} - m_{^3\mathrm{He}}) - (U_{^3\mathrm{H}} - U_{^3\mathrm{He}}) \end{cases}$$

Triton mean-filed potential – comparison with (free) non-interacting chemical potential:

$$U_{^3\mathrm{H}} = \mu_{^3\mathrm{H}} - \mu^0_{^3\mathrm{H}}$$

CC – opacity analysis

TF et al.,(2016) EPJConf. 109, 06002



(energy-dependent ν-spheres)

Averaged neutrino spheres of last inelastic scattering

- ν_e dominated by absorption on neutrons (as expected)
- anti-ν_e dominated by scattering on electrons/ positrons:

$$\bar{\nu}_e\,e^{\pm} \longrightarrow \bar{\nu}_e\,e^{\pm}$$

- Situation remains qualitatively at all times

Important: include correct phase space and final-state blocking !

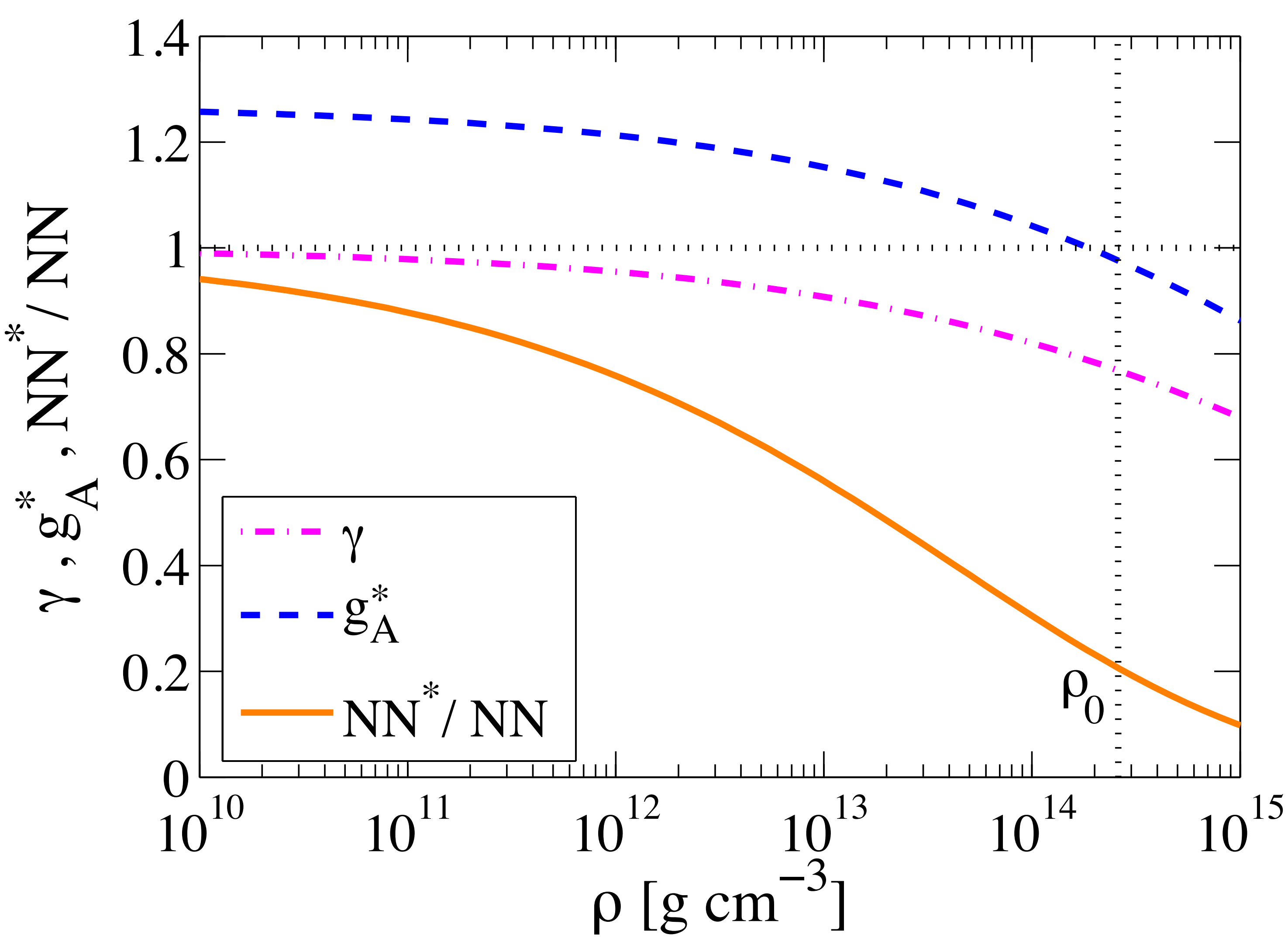
NN–Bremsstrahlung

TF (2016) A&A (submitted)

Hannestad & Raffelt (1998) ApJ 507, 339

$$\mathcal{R}_{\nu\bar{\nu}NN}(-\triangle E, \cos\theta) \propto \langle|\mathcal{M}|^2\rangle\,(3-\cos\theta)$$

$$\langle|\mathcal{M}|^2\rangle \propto G_F^2\, g_A^2 \longrightarrow G_F^2\,(g_A^*)^2\,\gamma^4$$



Bartl et al.,(2014) PRL 113, 081101

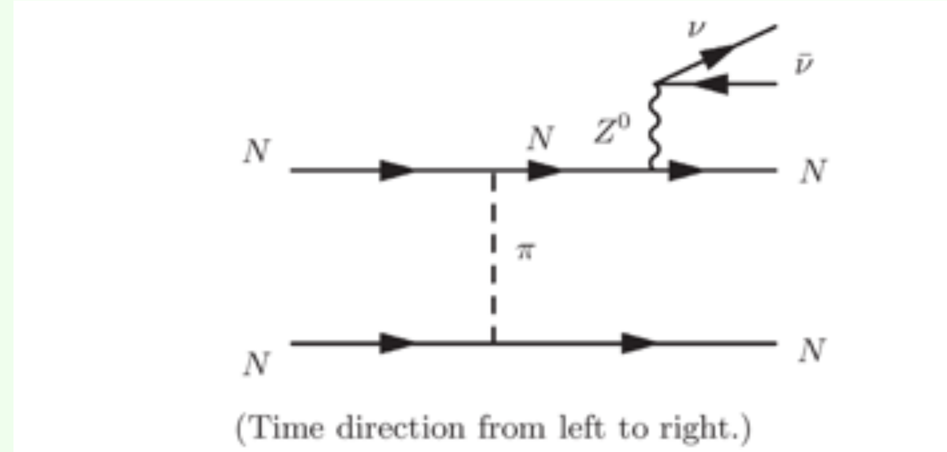
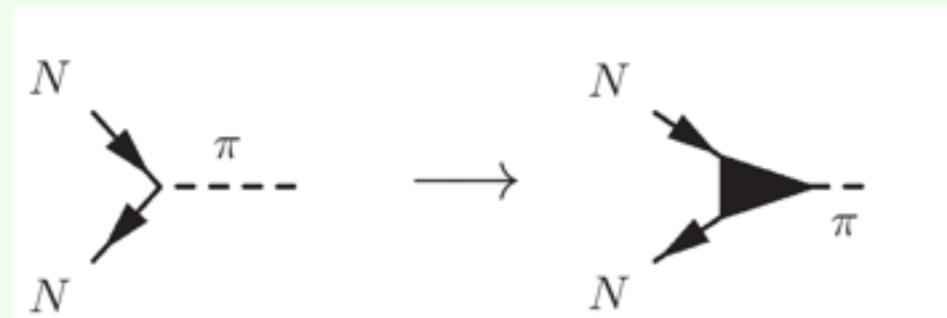


Fig. 1. Neutrino pair-emission from NN–bremsstrahlung within the FOPE approximation.

Leading-order medium modifications at "low" density:



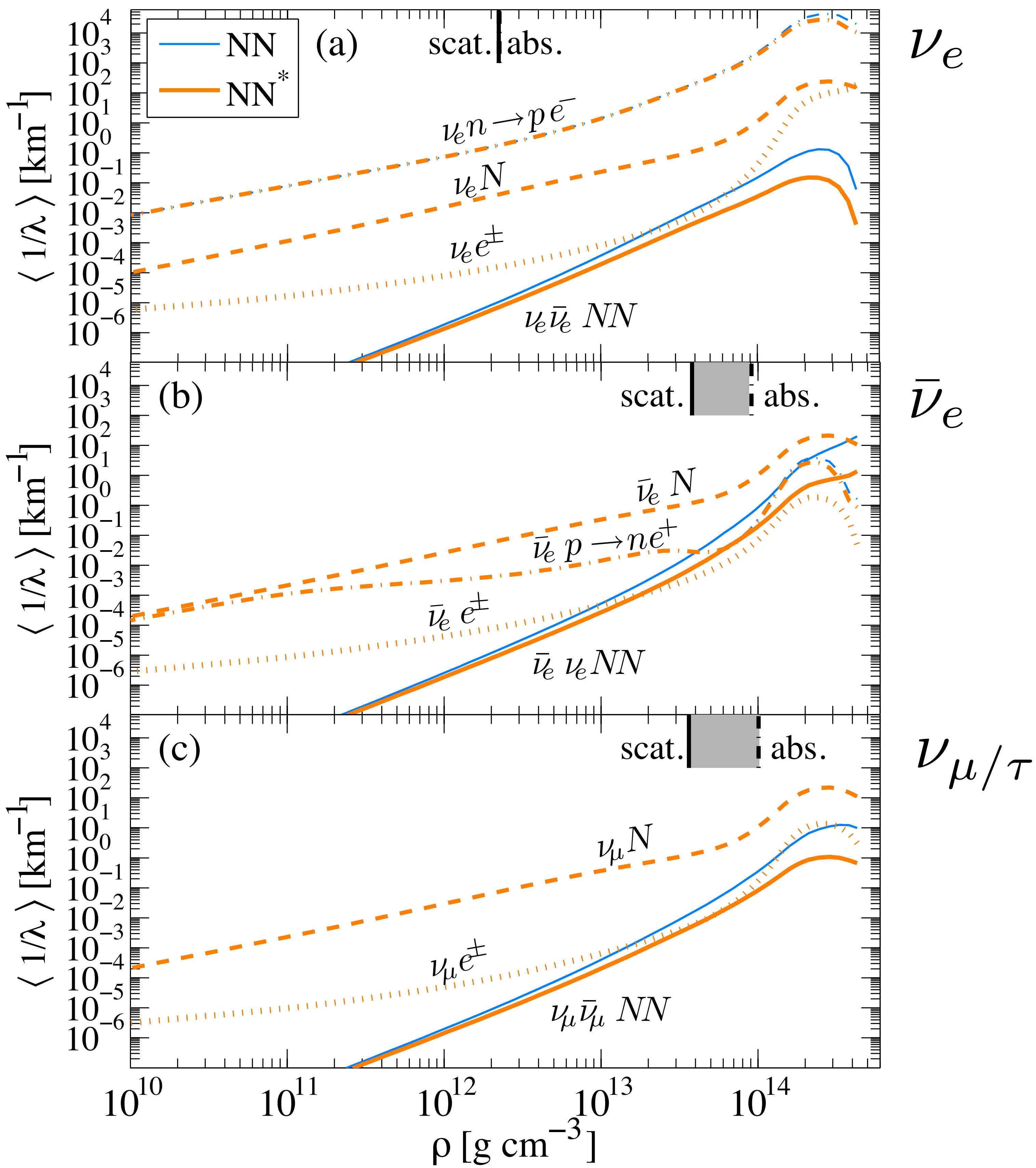
$$\gamma \simeq \left\{1+\frac{1}{3}\left(\frac{m_N^*}{m_N}\right)\left(\frac{p_F(\rho)}{p_F(\rho_0)}\right)\right\}^{-1}$$

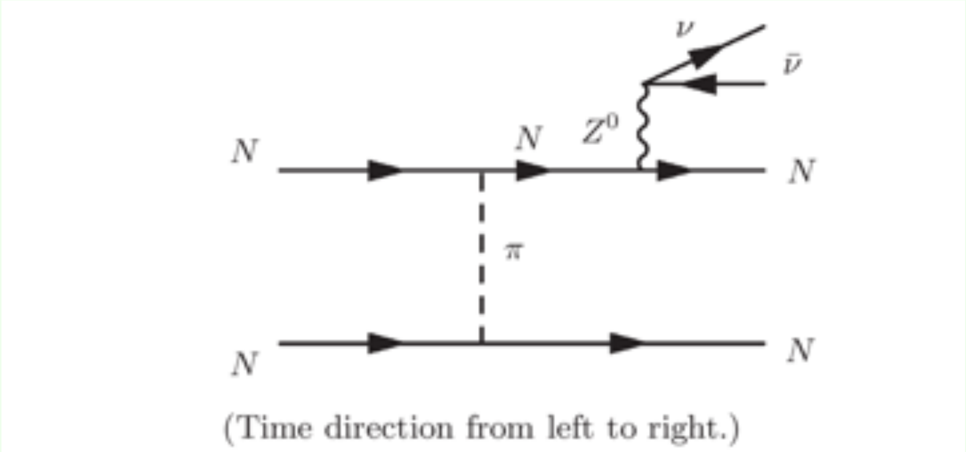
$$m_N^{(*)}\,g_A^{(*)} = f_\pi^{(*)}\,g_{\pi NN}^{(*)}$$

$$\frac{\mathcal{R}^*_{\nu\bar{\nu}NN}}{\mathcal{R}_{\nu\bar{\nu}NN}} \simeq \left(\frac{1}{1+1/3\,(\rho/\rho_0)^{1/3}}\right)^6$$

NN–Bremsstrahlung

TF (2016) A&A (submitted)





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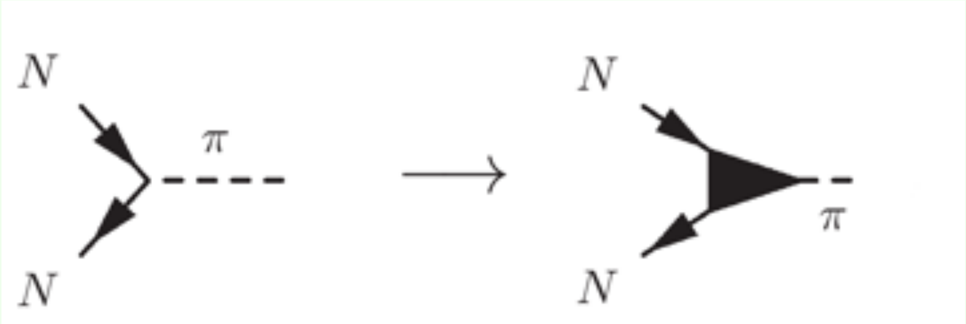

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NN–Bremsstrahlung

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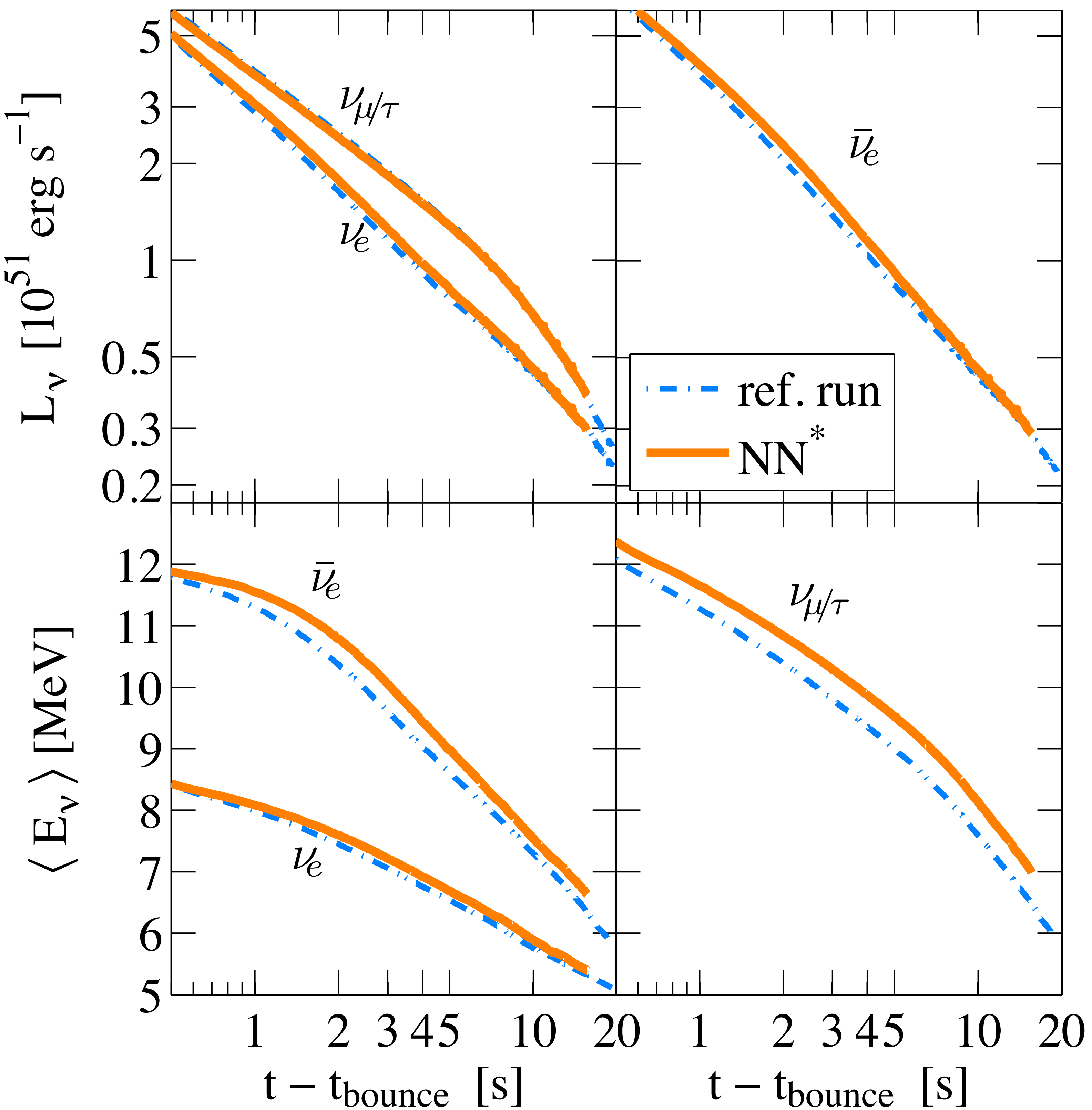
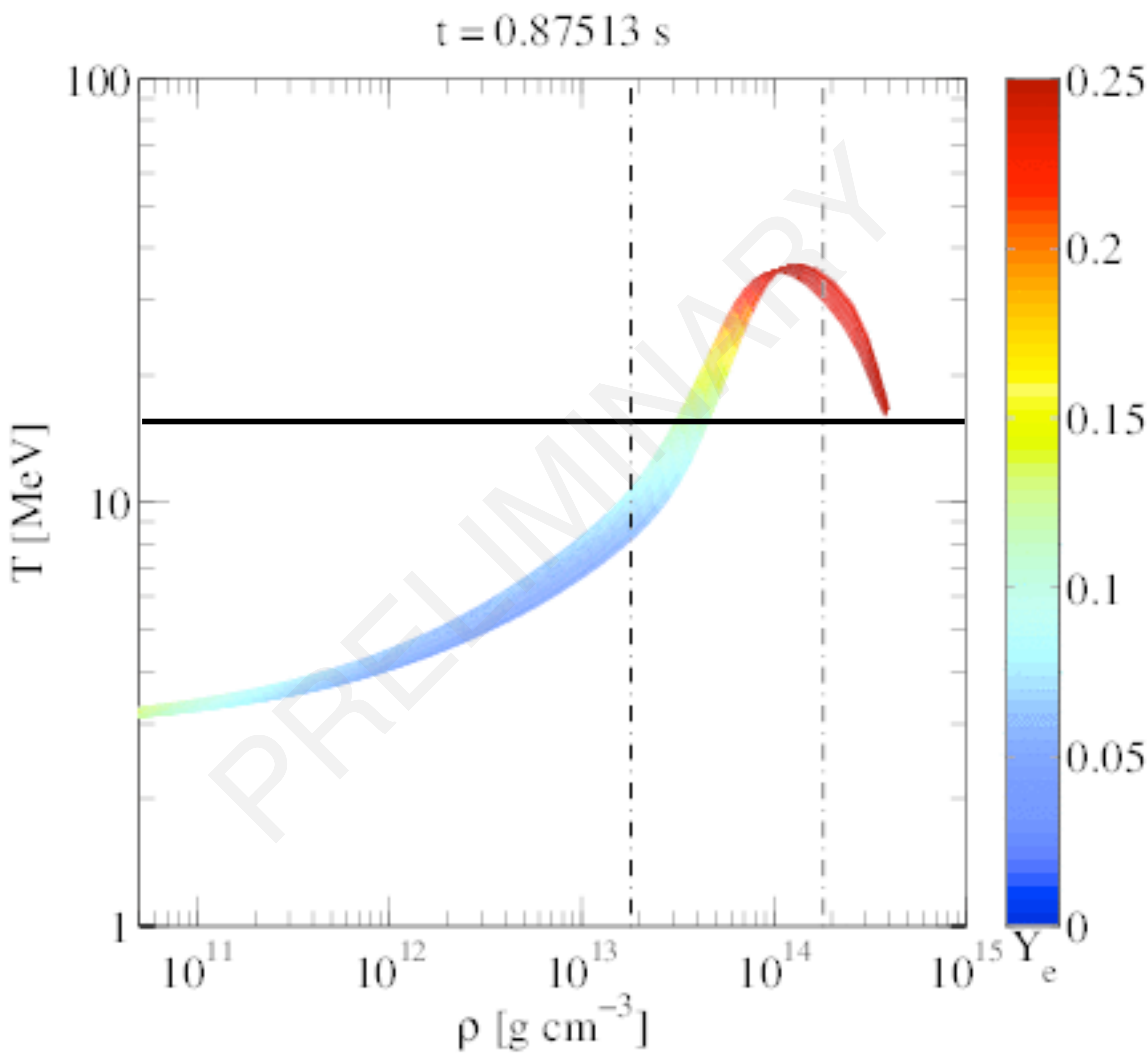
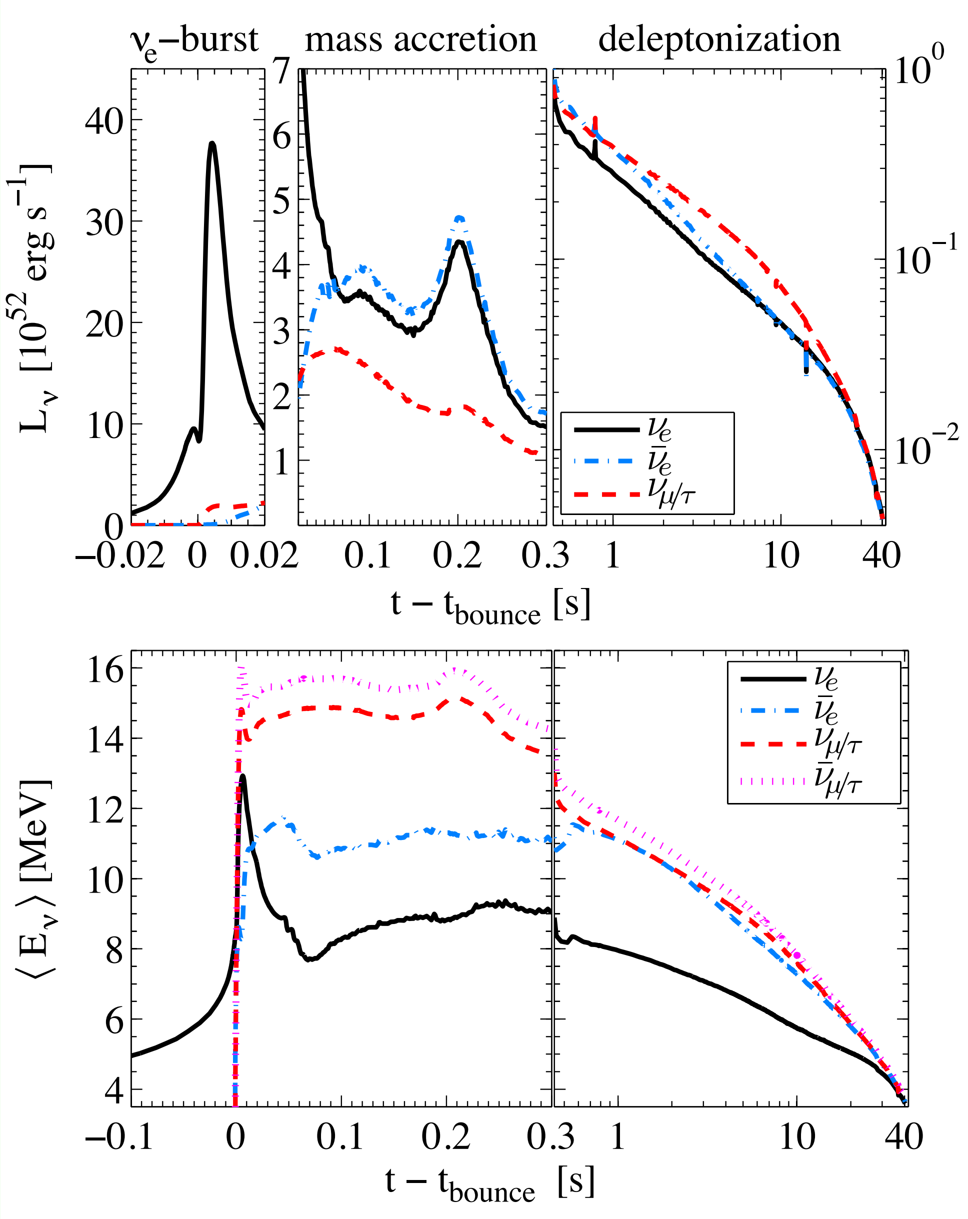


Leading-order medium modifications at "low" density: dressing of the vertex function

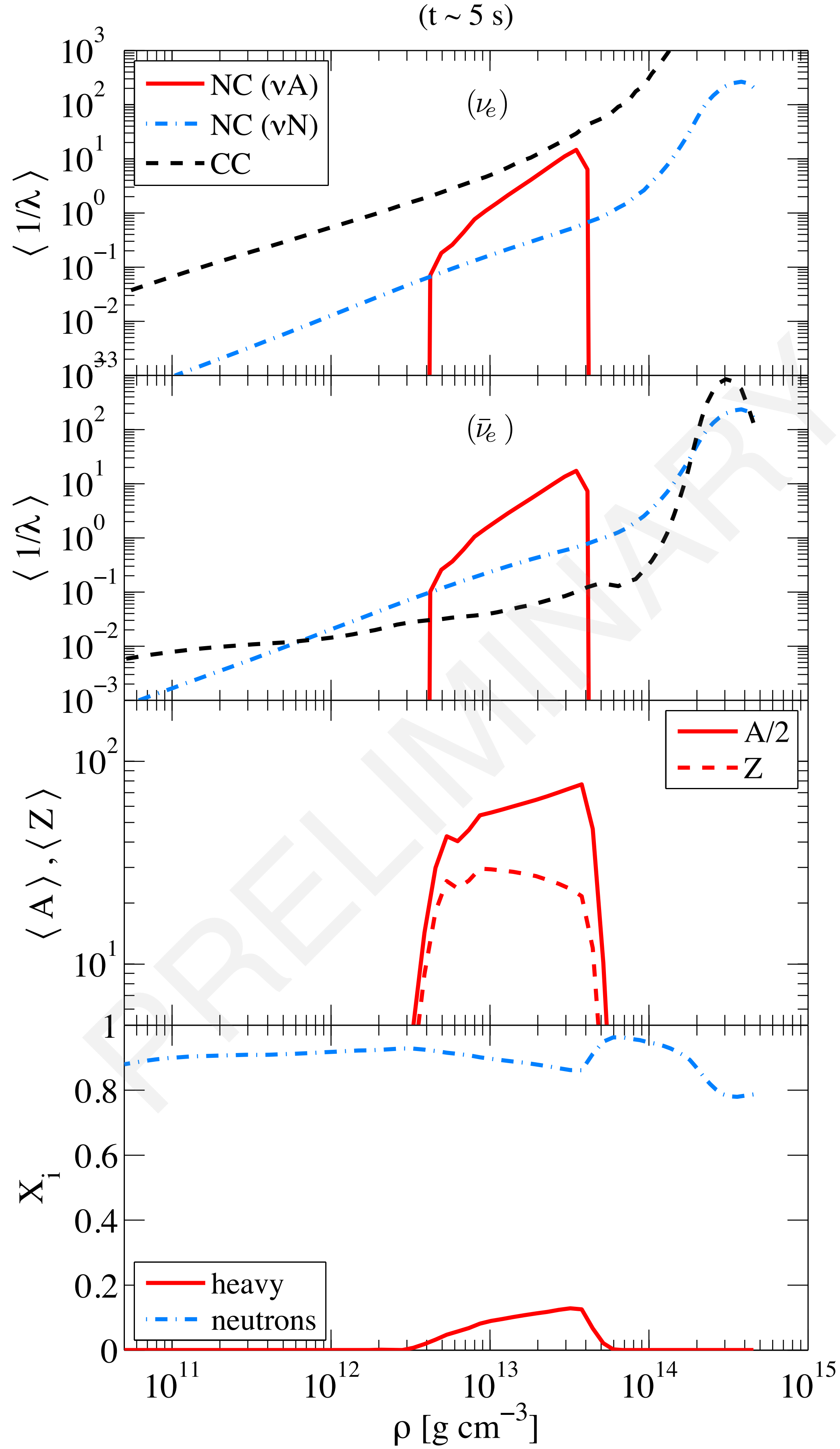
Simulations of PNS deleptonization: ν_μ and anit-ν_e signals are sensitive at such scale

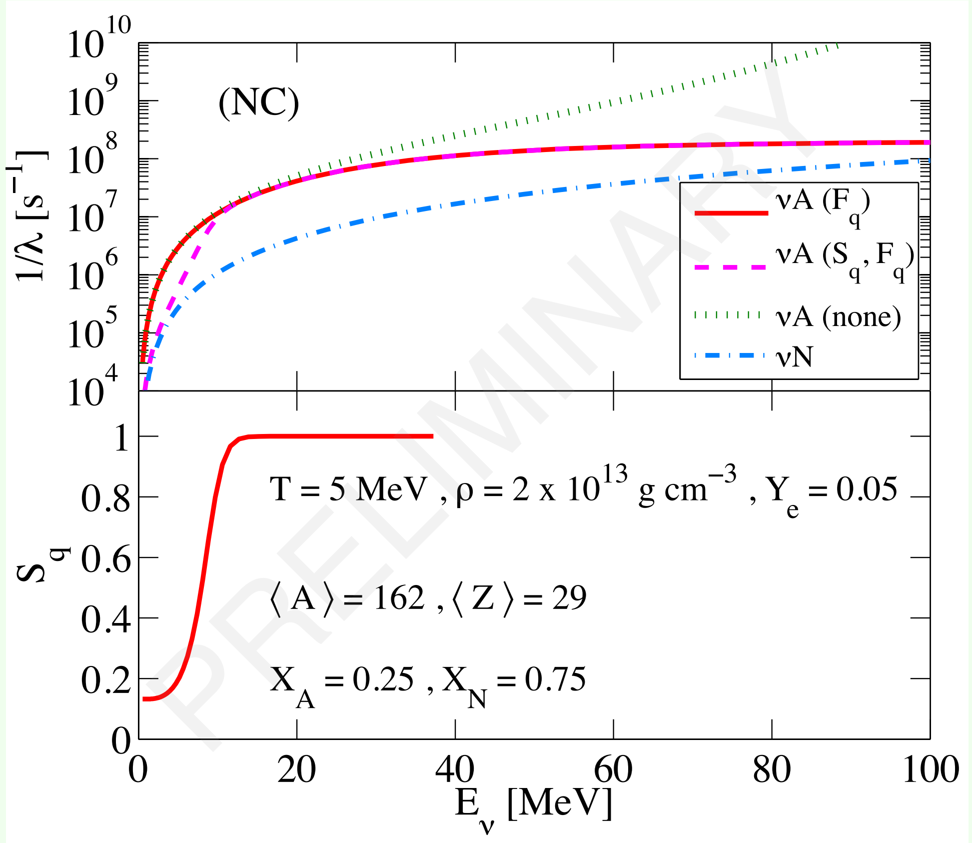
A chance for pasta





“Spherical” pasta ?





Summary

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Neutrino signal from the next Galactic massive star explosion will reveal insights into core “happenings”

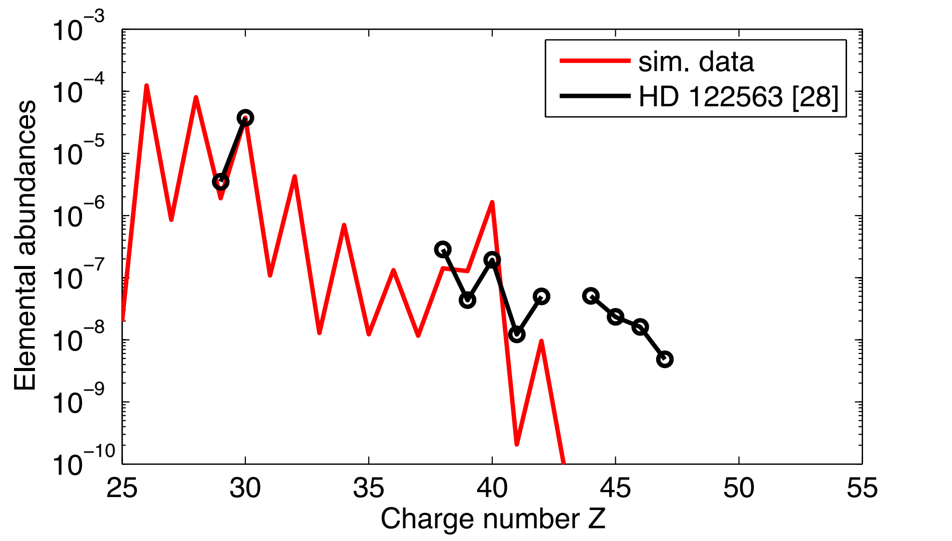
Reliable predictions of the neutrino signal requires“accurate” treatment of neutrino transport incl. “complete” set of weak processes (input physics)

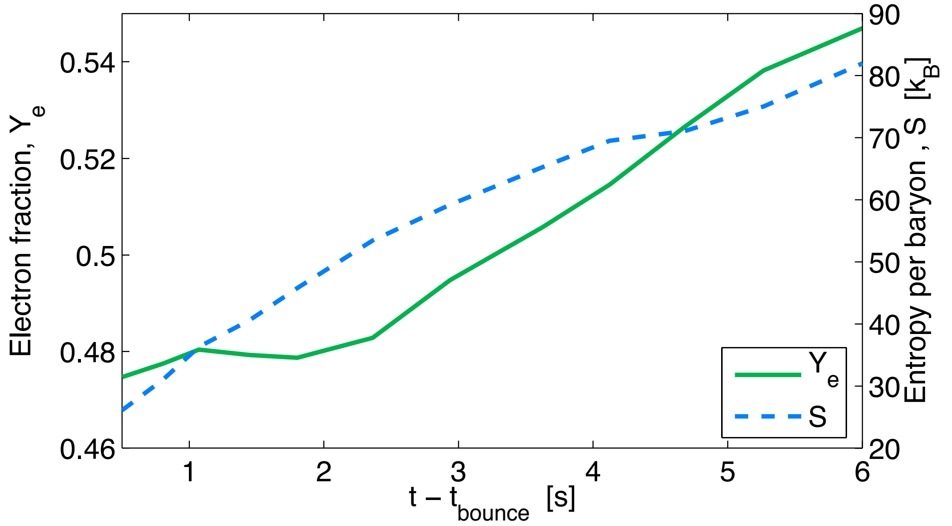
Most neutrinos will be observed from PNS deleptonization for more than 10 seconds

Site for the production of heavy elements (role of the symmetry energy?)

Probing properties of dense matter (e.g. correlations, g_A, light clusters) with the neutrino signal

Neutrino oscillations for detection analysis
(good understanding of supernova matter/stellar envelope)





Consistent with metal-poor star observations (HD 122563)

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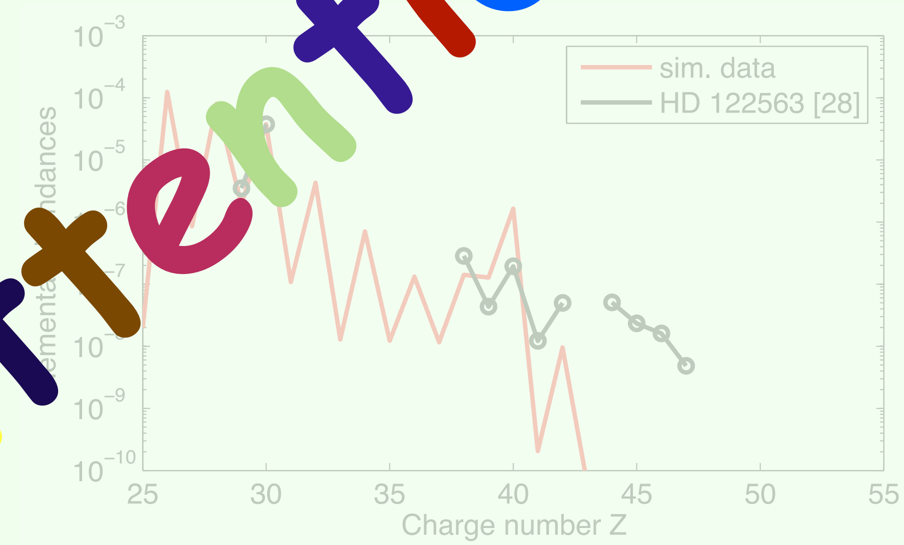

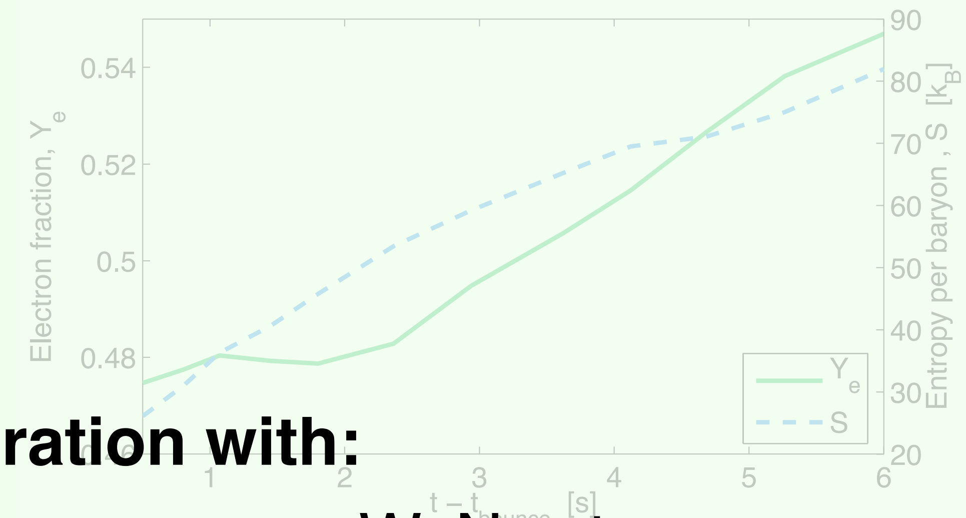

Consistent with metal-poor star observations (HD 122563)

Thanks for your attention

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