

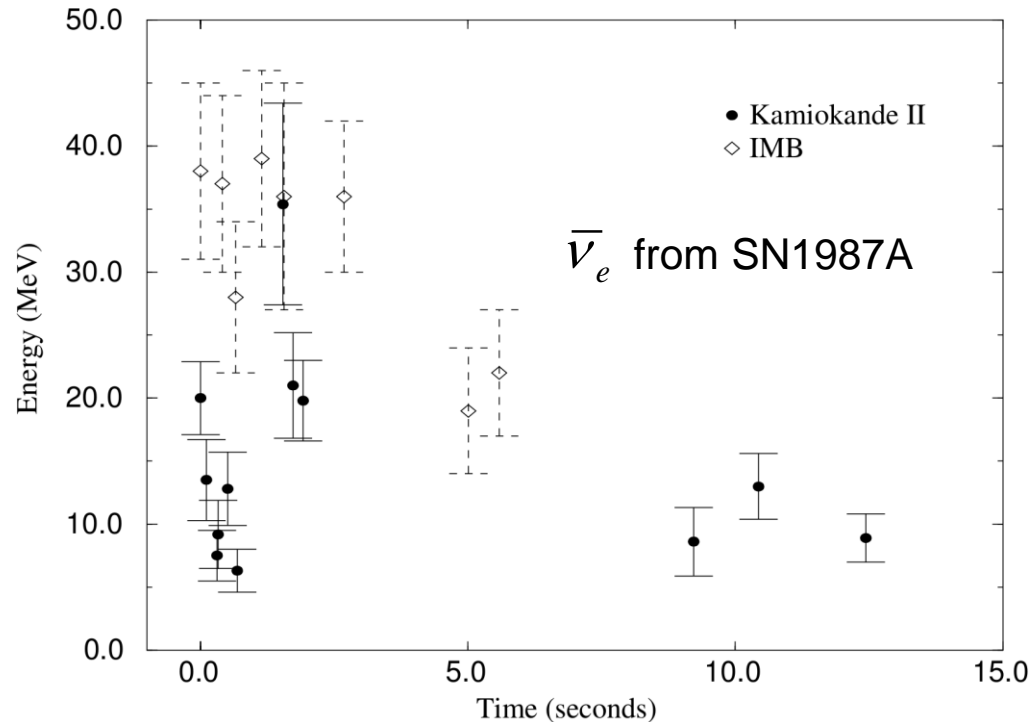
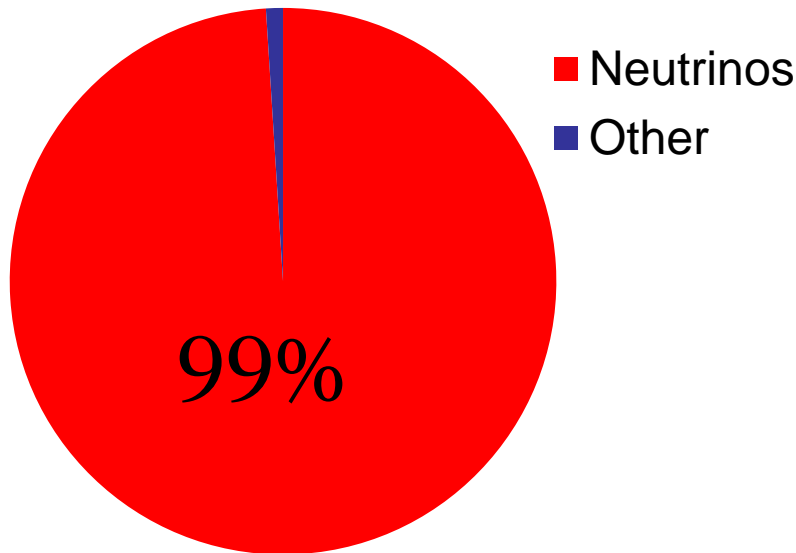
Neutrino-nucleon interactions in supernova matter

Annual NewCompStar Conference 2016
Istanbul – April 28th 2016
Andreas Lohs (Univ. Basel)

Neutrinos in Supernovae

Core collapse supernovae release huge amount of energy.

Supernova energy

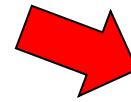
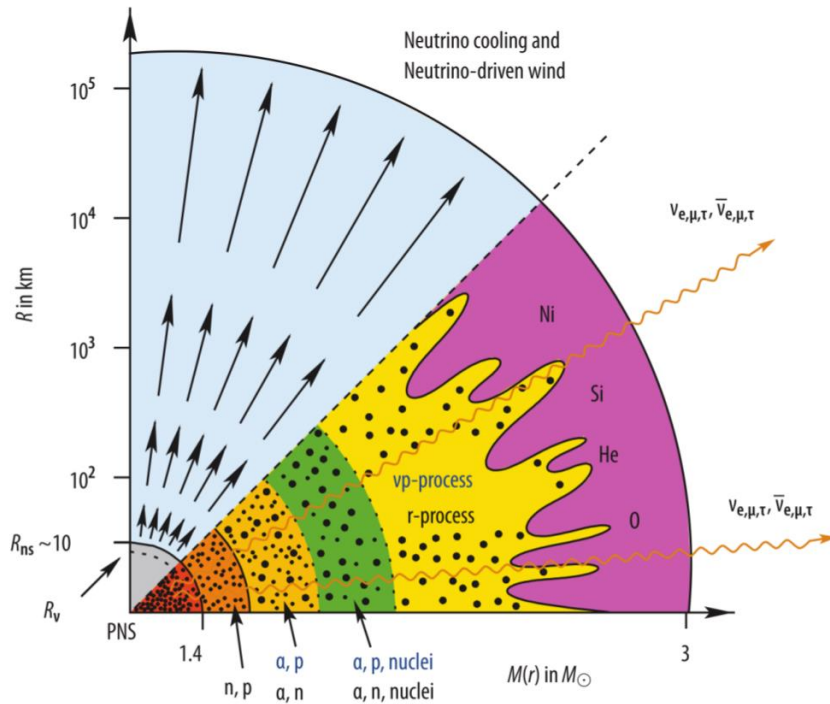
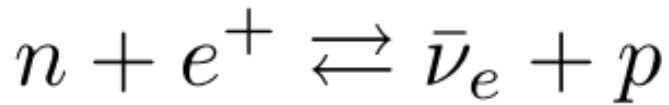
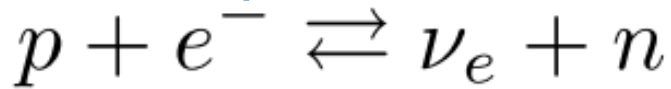


Neutrino spectra and interactions with matter are major determinants of explosion dynamics and nucleosynthesis.

Neutrino-Interactions: Two Regimes

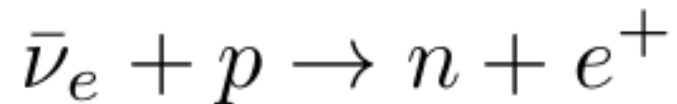
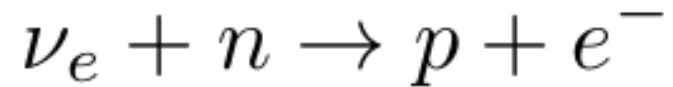
Interior of neutron star:

Neutrino spectra formation

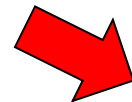


Surface of neutron star:

Neutrino absorption heats matter
Ejection of Neutrino Driven Wind



Spectrum determines composition



$$\langle E_{\bar{\nu}_e} \rangle - \langle E_{\nu_e} \rangle \Rightarrow Y_e$$

Neutrino Reactions in PNS matter

$\nu_e + n \rightarrow e^- + p$
$\bar{\nu}_e + p \rightarrow e^+ + n$
$\nu/\bar{\nu} + N \rightarrow \nu/\bar{\nu} + N$
$\nu/\bar{\nu} + e^\pm \rightarrow \nu/\bar{\nu} + e^\pm$
$\nu + \bar{\nu} + NN \rightarrow NN$
$\nu + \bar{\nu} \rightarrow e^- + e^+$

Standard Reaction set:

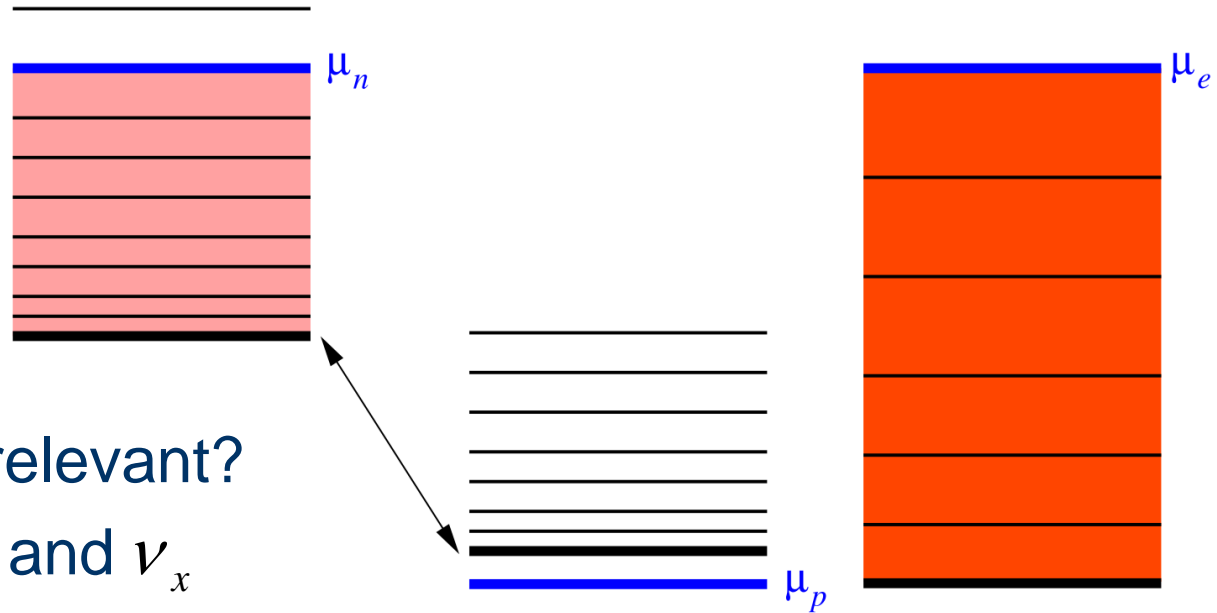
- Absorption on neutrons
- Absorption on protons
- (Elastic) Scattering on nucleons
- (Inelastic) Scattering on electrons
- Inverse Bremsstrahlung
- Pair annihilation

New reactions, previously considered negligible

- Inverse neutron decay
- Charged-current muonic reactions

Uncertainties in Neutrino Physics - I

What is the correct Equation of state?



Which reactions are relevant?

- Not obvious for $\bar{\nu}_e$ and ν_x
- Answer may vary for different SNe

How to compute neutrino interactions?

-inelasticity, relativity, medium effects, weak magnetism

...

Neutrino-Nucleon Microphysics: Explosions in 3D

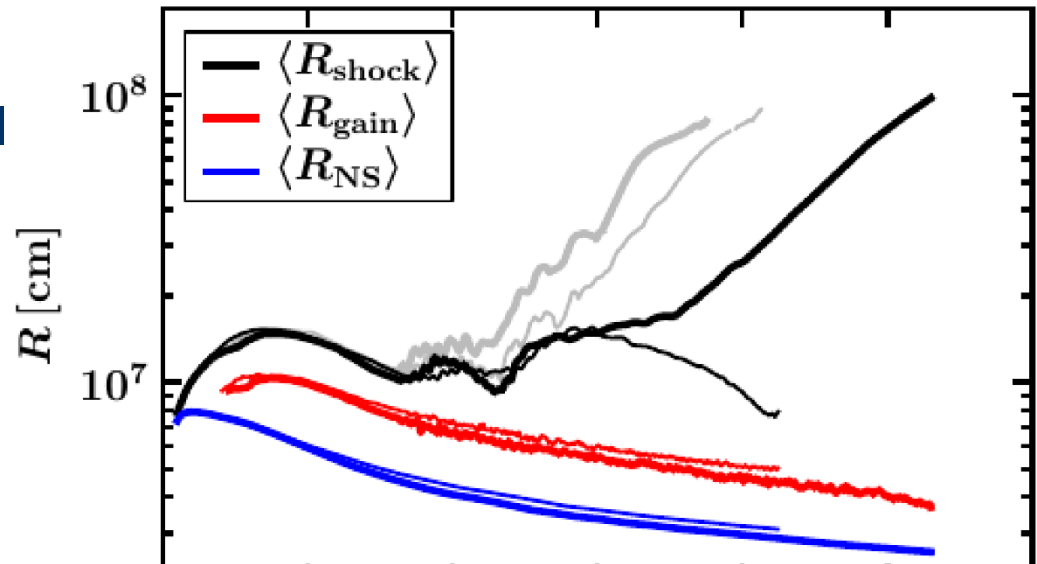
NEUTRINO-DRIVEN EXPLOSION OF A 20 SOLAR-MASS STAR IN THREE DIMENSIONS
ENABLED BY STRANGE-QUARK CONTRIBUTIONS TO NEUTRINO-NUCLEON SCATTERING

TOBIAS MELSON^{1,2}, HANS-THOMAS JANKA¹, ROBERT BOLLIG^{1,2}, FLORIAN HANKE^{1,2}, ANDREAS MAREK³, AND BERNHARD MÜLLER⁴

[ApJ 808 (2015) no.2]

Strange contribution to neutral
weak axial coupling

$$c_A = \frac{1}{2} (\pm g_a - g_A^S)$$
$$\rightarrow g_A^S = -0.2$$



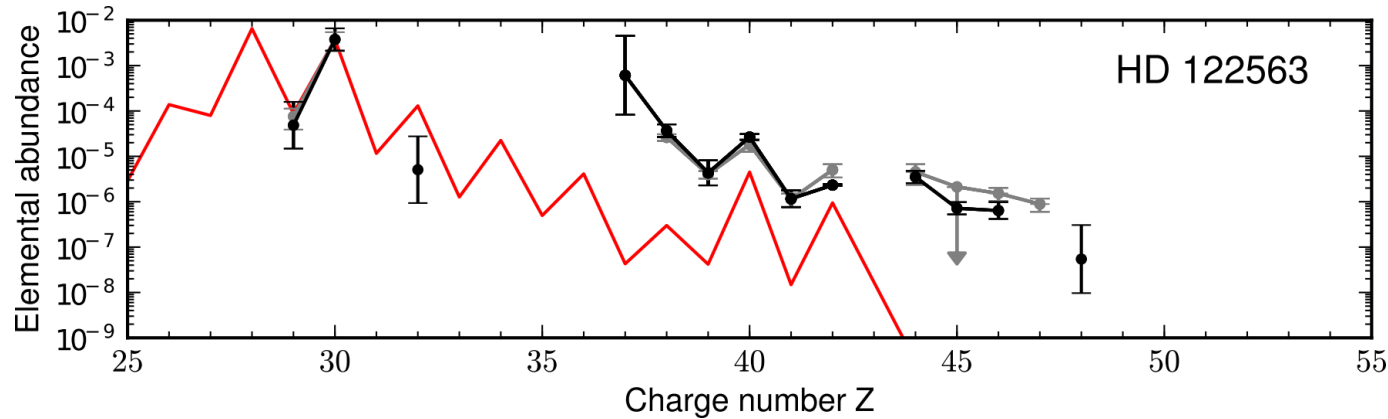
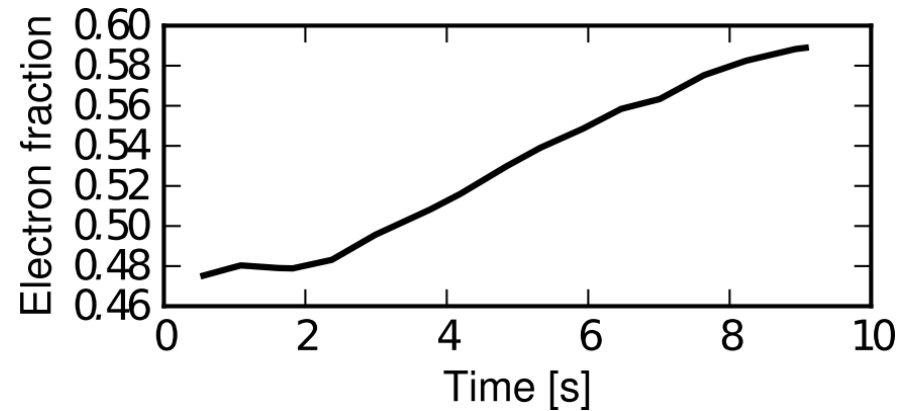
„...the outcome of multi-dimensional core-collapse simulations that marginally explode or fail can sensitively depend on effects on the 10% level in the neutral-current neutrino-nucleon interactions.“

Neutrino-Nucleon Microphysics: Weak r-Process

Nucleon potential differences
at high densities strongly

affect charged-current rates

- NDW initially neutron rich
- Allows for weak r-process



[Martinez-Pinedo,Fischer,AL,Huther, PRL 109 (2012) 251104]

[Martinez-Pinedo,Fischer,Huther, JPhG 41 (2014) 044088]

[Roberts,Reddy,Shen, PRC 86 ('12) 065083]

[Horowitz,Shen,O'Connor,Ott, PRC 86 ('12) 065806]

Mean Free Path for Neutrino Absorption (CC)

Elastic Approximation

- Lowest order expression for nonrelativistic nucleons
- Analytic formula for $\lambda(E_\nu)$
- Can be corrected to include recoil, weak magnetism, ...

Inelastic Opacities – full „relativistic Hartree response“

- **Relativistic kinematics, „full“ matrix element**
- **Mostly 2-D numerical integrals to obtain $\lambda(E_\nu)$**

Structure function from RPA / Linear response theory

- Fully consistent with RMF-EOS, correlations (can be) included
- Requires 3-D numerical integrals to obtain $\lambda(E_\nu)$

Computing „Exact“ Neutrino Opacities in CCSN

Hartree approximation for nucleon response:

- nucleon-nucleon interaction described by RMF-potentials and effective masses
- nucleons are quasi-free particles with modified energy

$$E_{n,p} = \sqrt{\mathbf{p}^2 + m_{n,p}^{*2}} + U_{n,p}$$

- relativistic kinematics, „full“ matrix element, weak magnetism included

$$\lambda(E_\nu)^{-1} \sim \int d^3 p_e [1 - f_e(E_e)] \int d^3 p_n \int d^3 p_p \frac{\langle |M|^2 \rangle}{16 E_\nu E_n E_e E_p} f_n(E_n) [1 - f_p(E_p)] \delta^4$$

- No p-h-correlations, always better than elastic approximation

Corrections to Opacities in Elastic Approximation

Elastic approximation

- yields analytic opacities,
- highly simplified matrix element and kinematics

$$E_n - E_p \simeq m_n - m_p + U_n - U_p$$

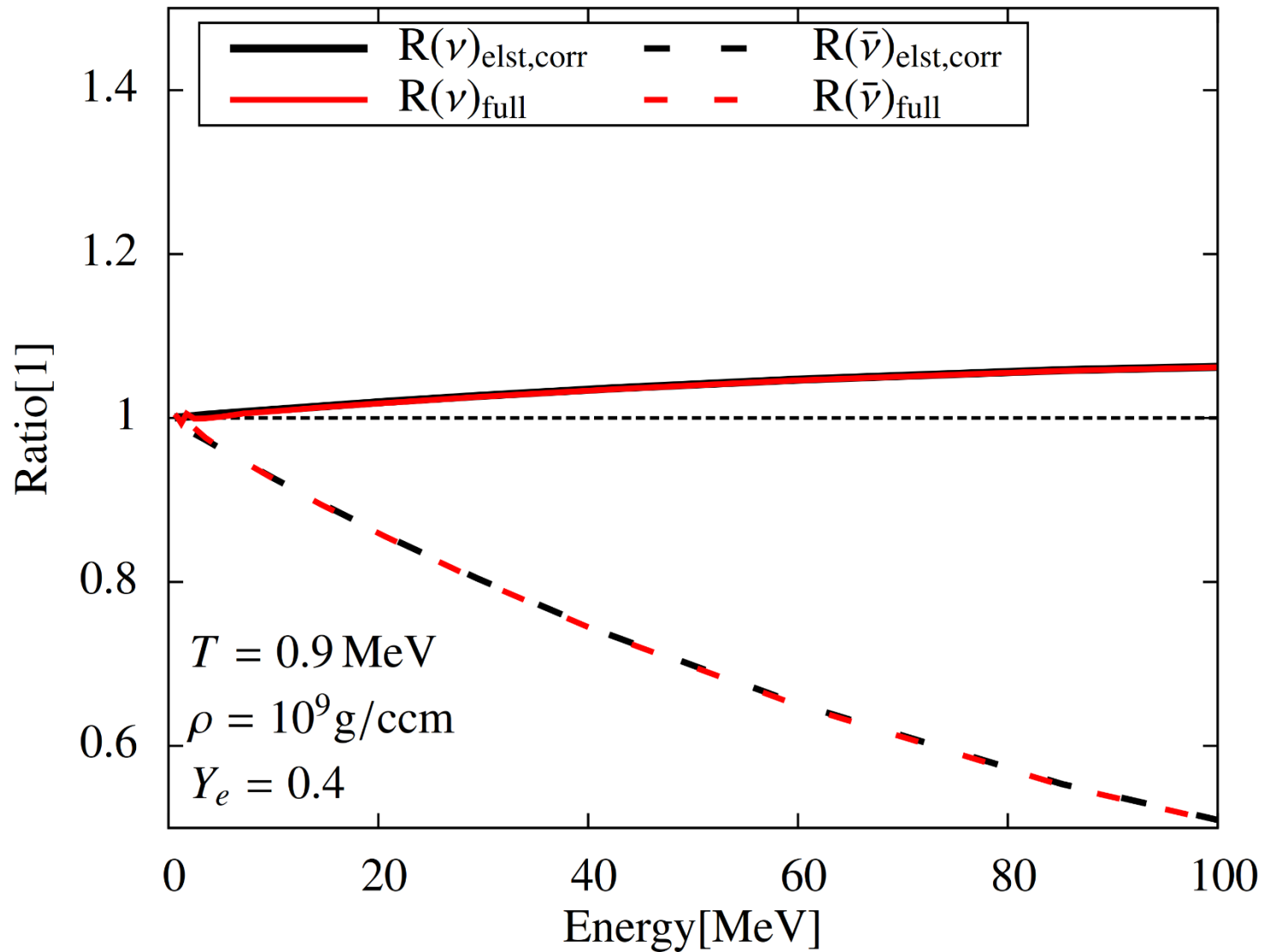
[Horowitz, PRD 65 (2002) 043001] pointed out:

- Kinematics/Recoil can be treated relativistically

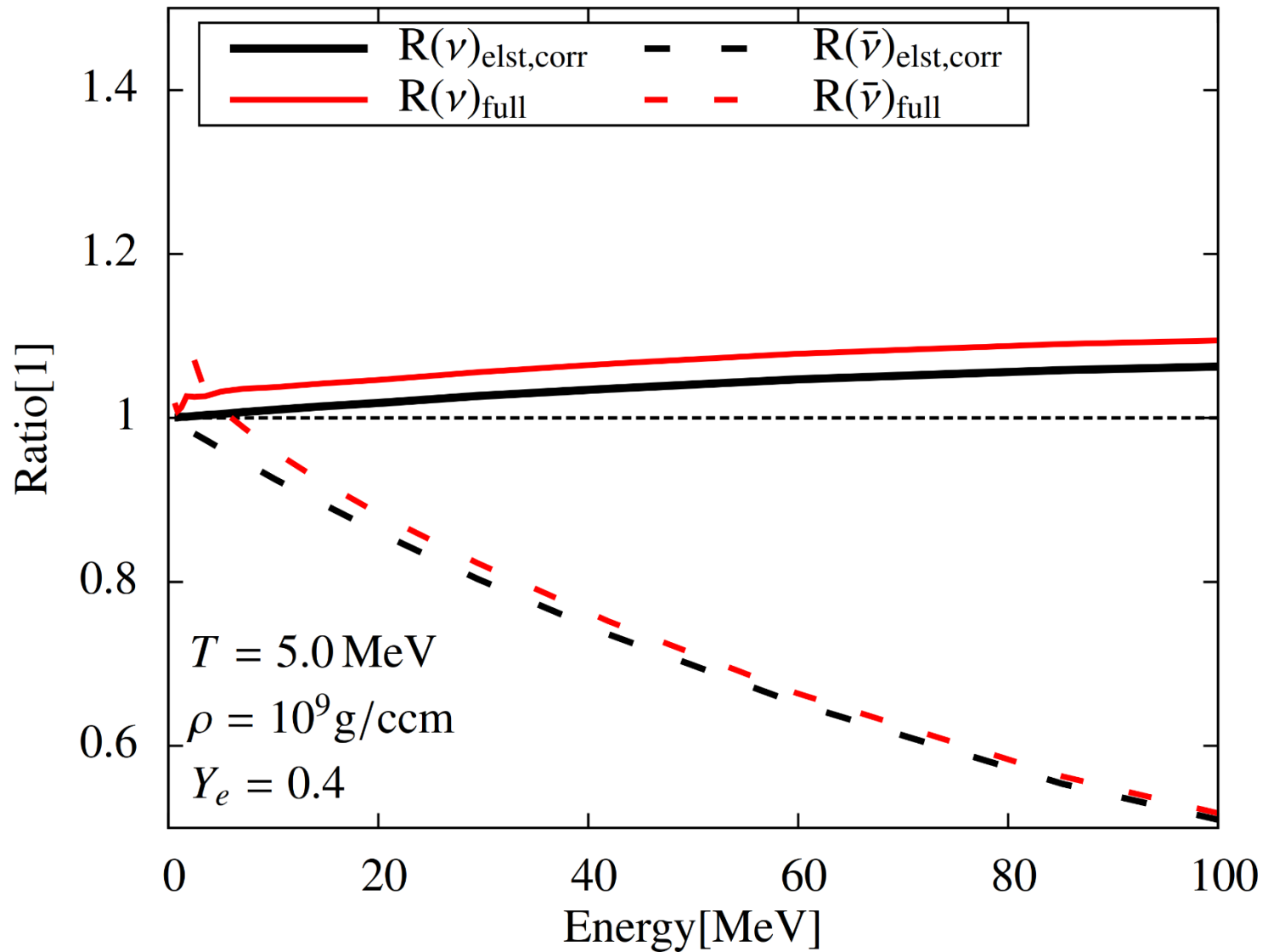
$$E_n = m_n \Rightarrow E_e = \frac{E_\nu}{1 + \frac{E_\nu}{m_n} (1 - x)}$$

- Gives rise to analytic correction factor for cross-section

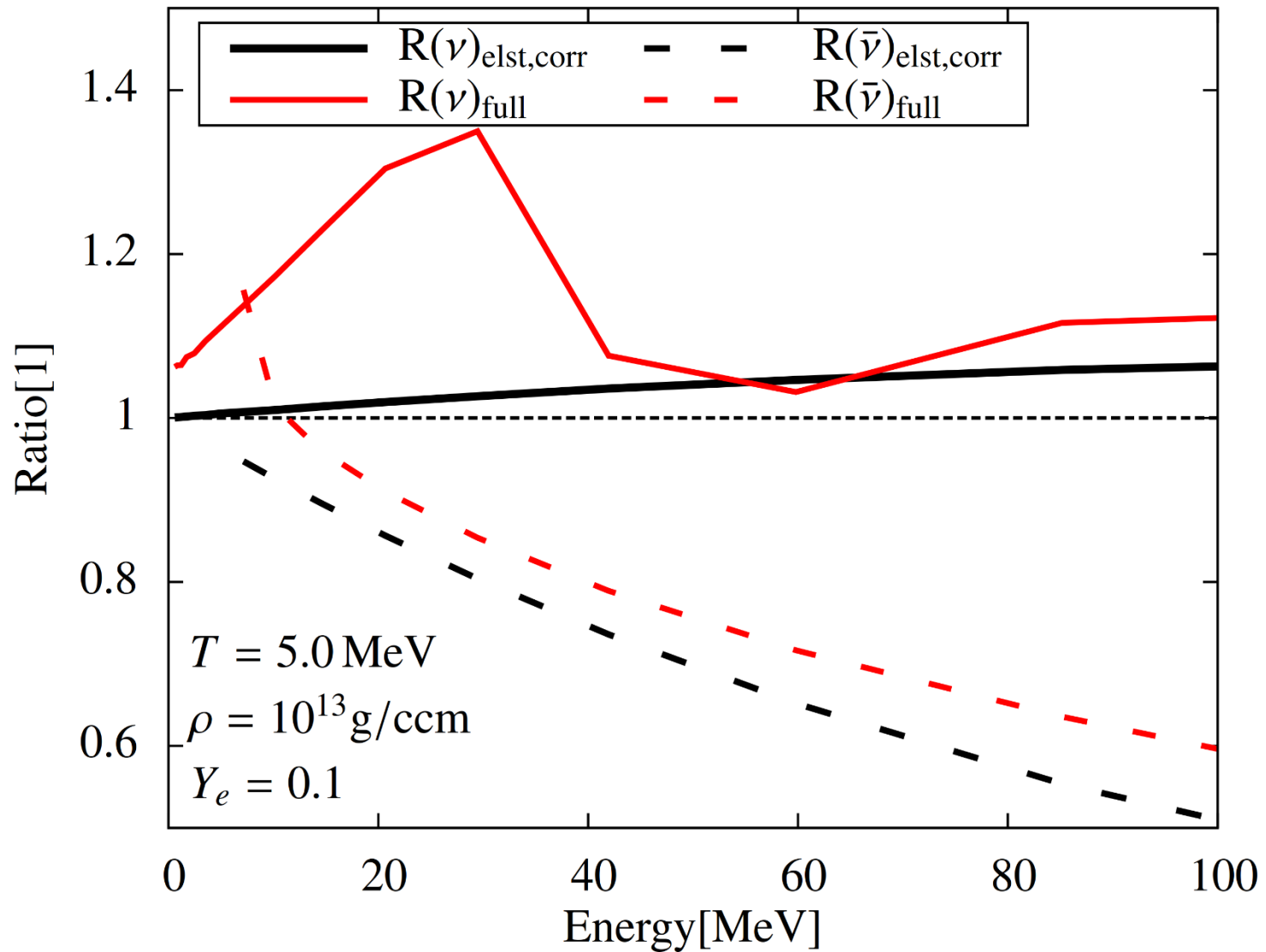
Elastic Approximation at low T and ρ



Elastic Approximation at high T and low ρ



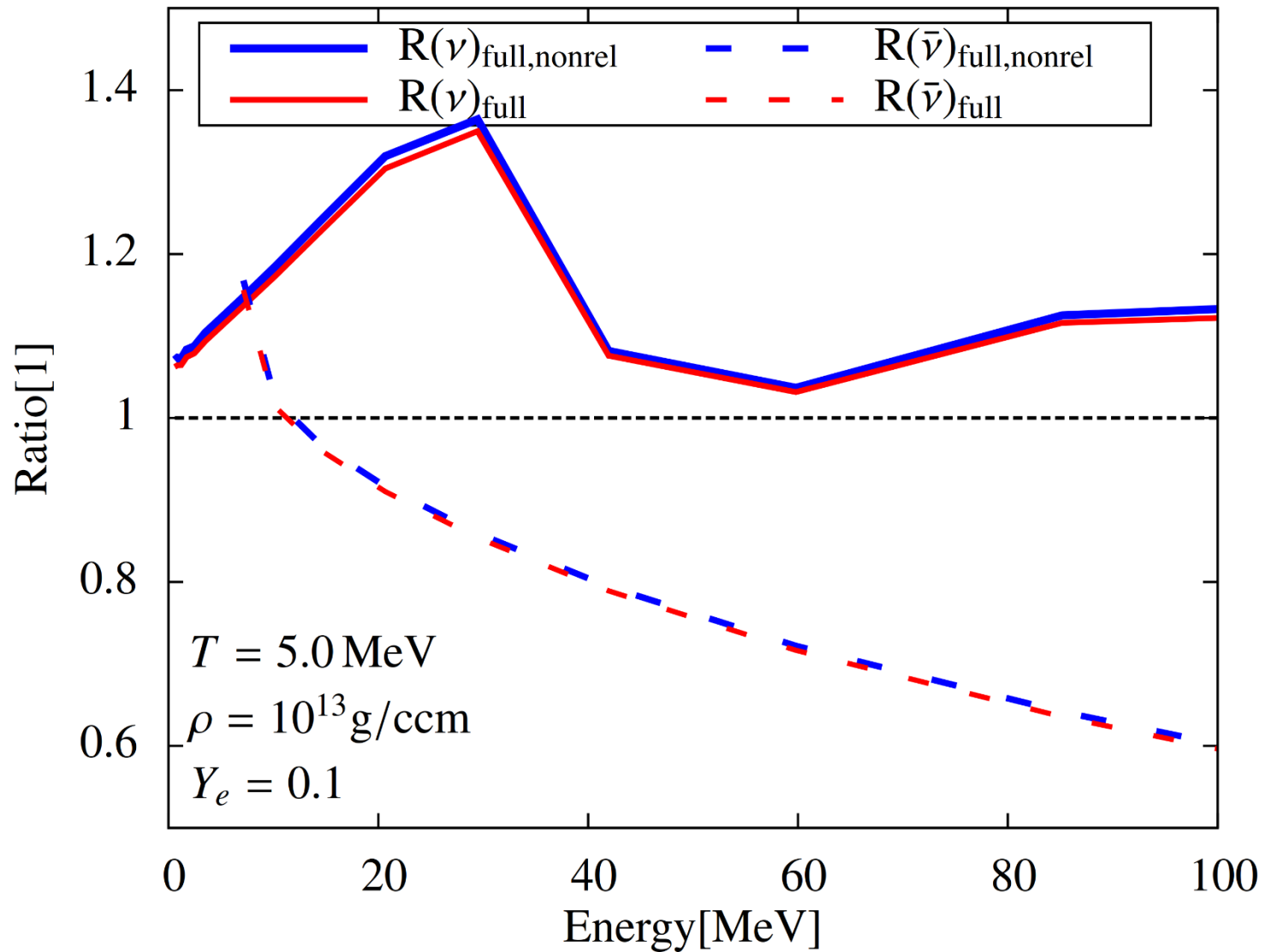
Elastic Approximation at high T and ρ



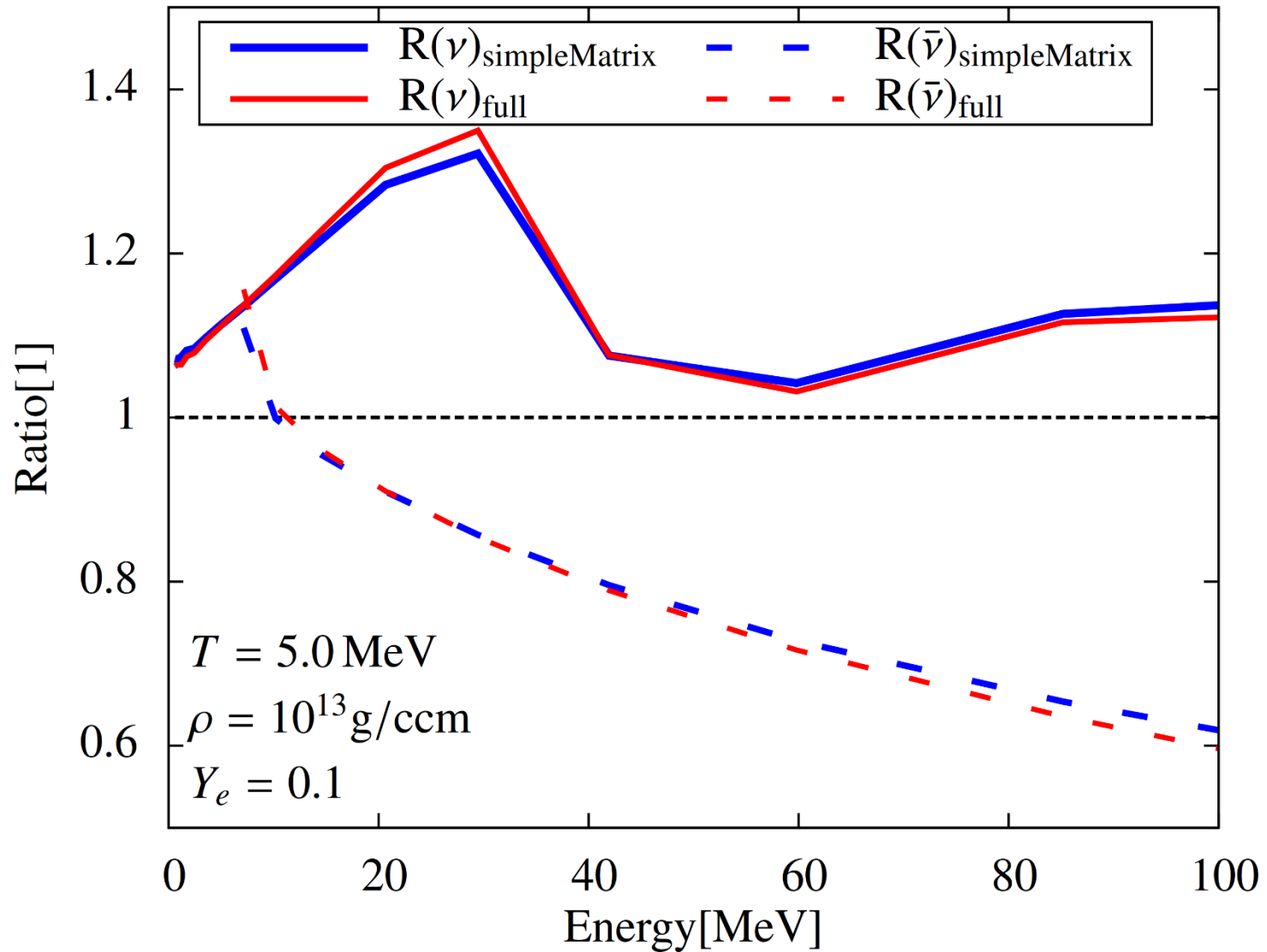
Limits of Elastic Approximation

- Elastic opacities with weak magnetism corrections are indeed very good for low temperatures and densities (NDW?)
- For temperatures of several MeV, approximation underestimates opacities ($\sim 10\%$)
- At higher densities, additional significant deviations for neutrino energies of several 10 MeV
- Approximation „fails“ at the level of weak magnetism corrections for higher densities/temperatures
 - What is the reason for the failure? (target at rest; inelasticity; relativity)
 - Is there a „cure“?

Nonrelativistic Kinematics at high T and ρ



Simplified Matrixelement at high T and ρ



Elastic vs. Inelastic Opacities

- Neither relativity nor simplified matrix element are the main reason for error in elastic approximation.
- Probably no „*cure*“ since elastic approximation itself seems to be the problem

Alternative approximation:

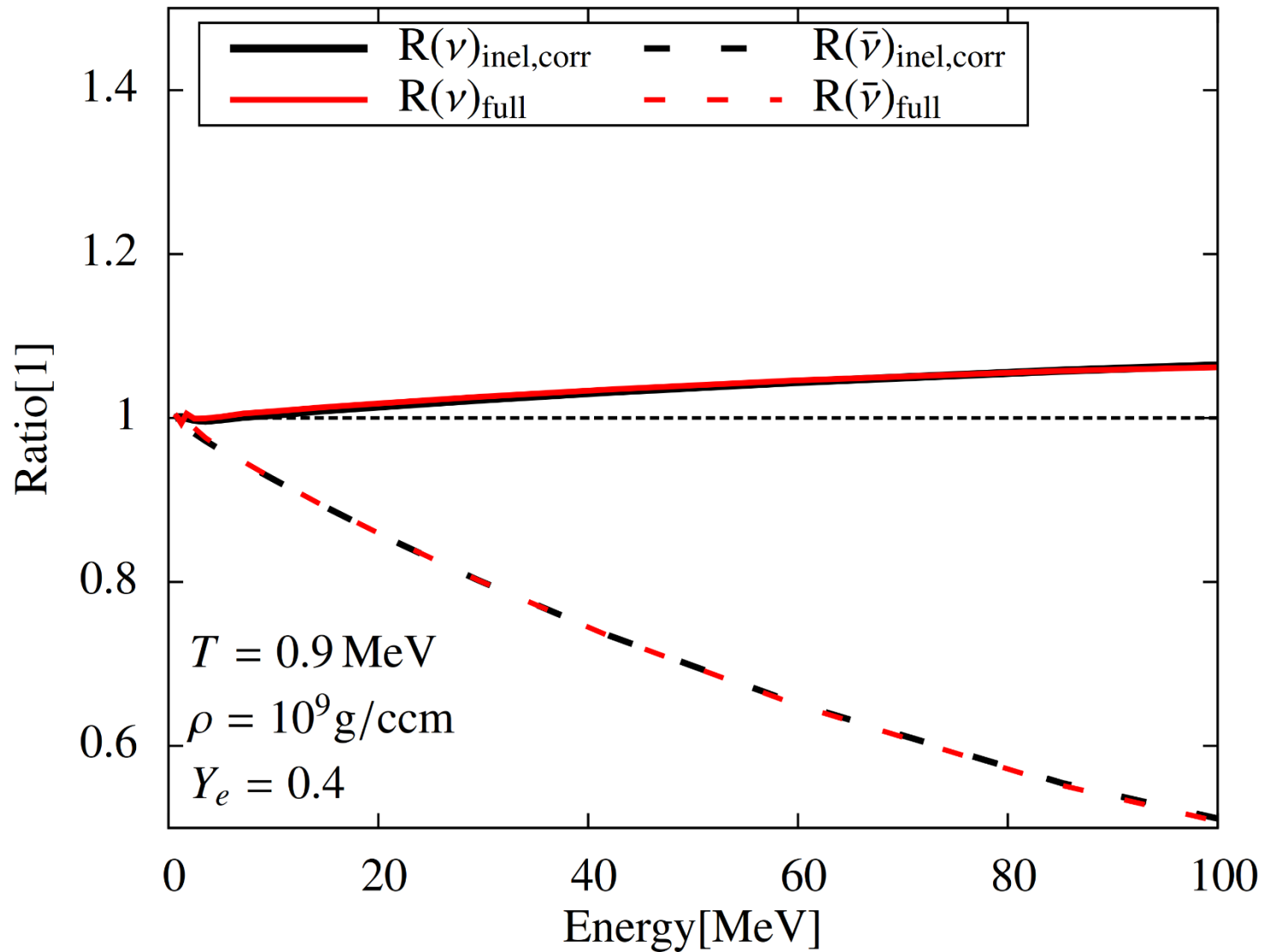
- Inelastic opacities with non-relativistic kinematics and simplified matrix element

[Reddy,Prakash,Lattimer, PRD 58 ('98) 013009]

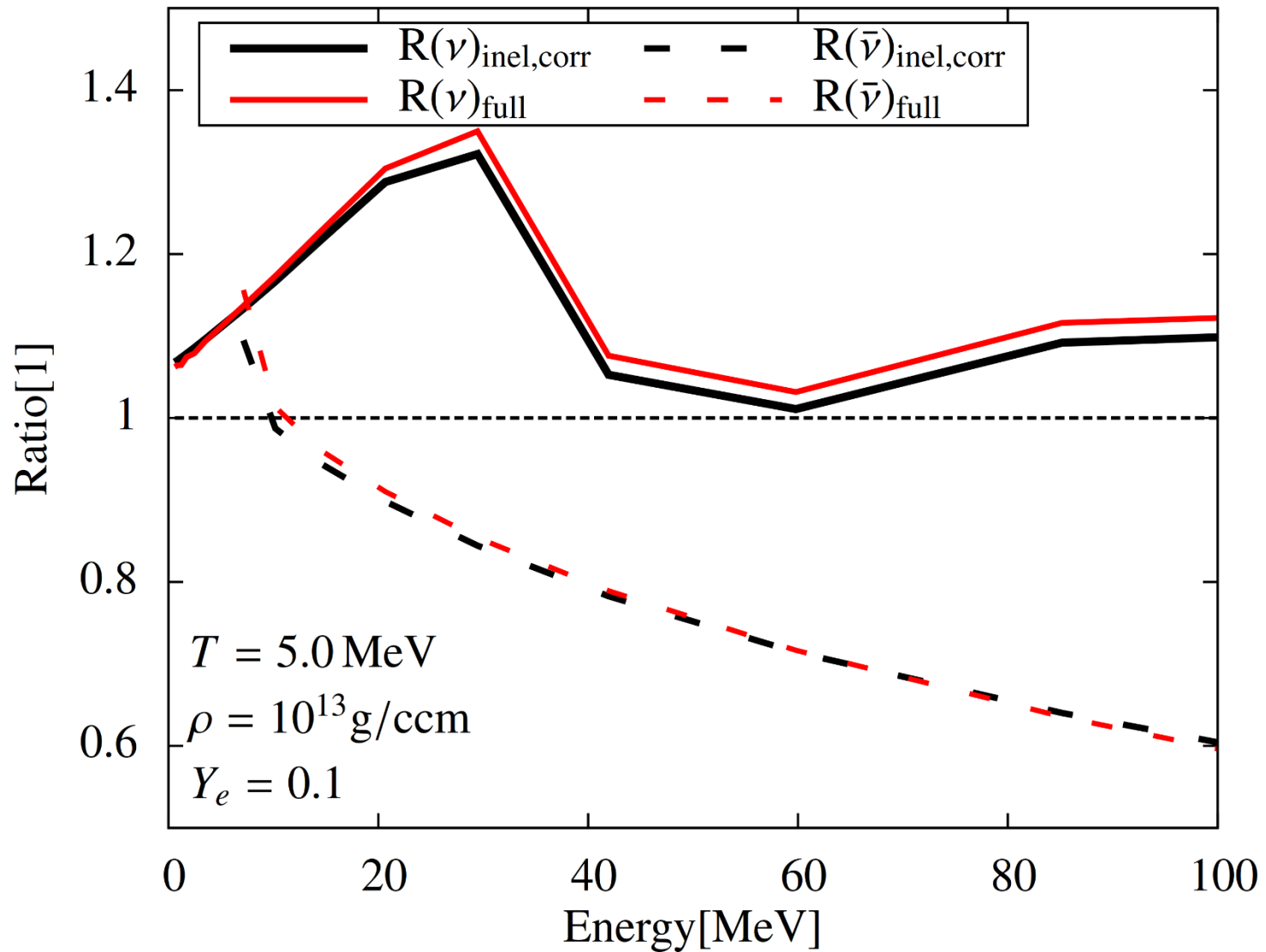
- Apply appropriate correction factor
- Can include p-h-correlations in nonrelativistic RPA

[Burrows,Sawyer, PRC 59 ('99) 510]

Inelastic Opacity at low T and ρ



Inelastic Opacity at high T and ρ



Summary & Conclusion

- For densities up to NDW-conditions and temperatures below several MeV, exact neutrino opacities can be reproduced by elastic approximation + correction factors.
- For higher temperatures or for neutrinosphere densities, the approximation „fails“ at the level of the correction.
- For inelastic opacities, „good“ corrections can be found also at higher densities and temperatures.
- Calculation of simplified, inelastic opacities equally demanding as „exact“ relativistic Hartree response
 - For precision at 10% level, relativistic Hartree response favourable over elastic approximation
 - When interested in p-h-correlations, inelastic but approximated opacity + corrections can be suitable [Buras et al., A&A447 ('06) 1049]

Caveat: (Relativistic) RPA correlations

Formalism for relativistic RPA has already been developed, but not used in any CCSN-simulation

[Horowitz, Wehrberger, PhysLettB266 ('91) 236]

[Reddy, Prakash, Lattimer, Pons, PRC59 ('99) 2888]

[Horowitz, Pérez-Garcia, PRC68 ('03) 025803]



Effect below $n_0/4$ rarely investigated.

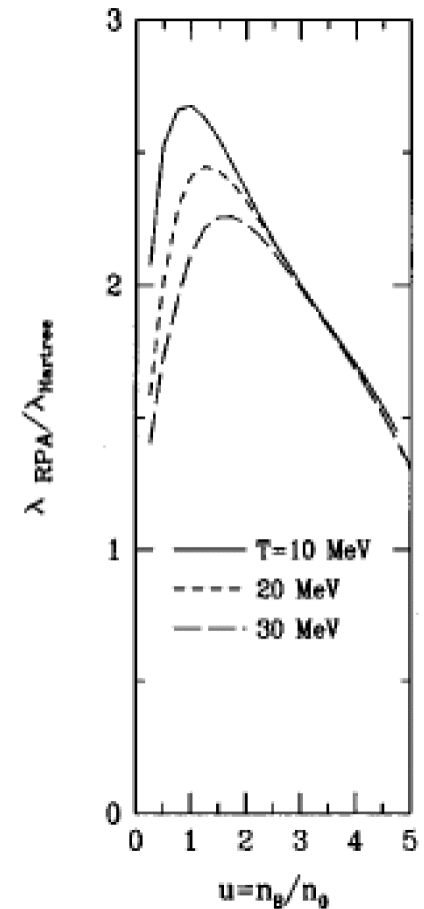
Suppression up to several 10% at 10^{13} g/ccm

ρ (g cm ⁻³)	Y_ν	T (MeV)	Y_e	S_A	S_V
1.40×10^{13}	0.067	15	0.258	0.790	0.840

[Burrows, Sawyer, PRC59 ('99) 510]

Beyond p-h-correlations: multi-particle scattering

[Roberts, Reddy, Shen, PRC86 ('12) 065083]



Summary and Conclusion

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**THANK YOU FOR YOUR
ATTENTION!**