# Neutrino interactions in core-collapse supernovae

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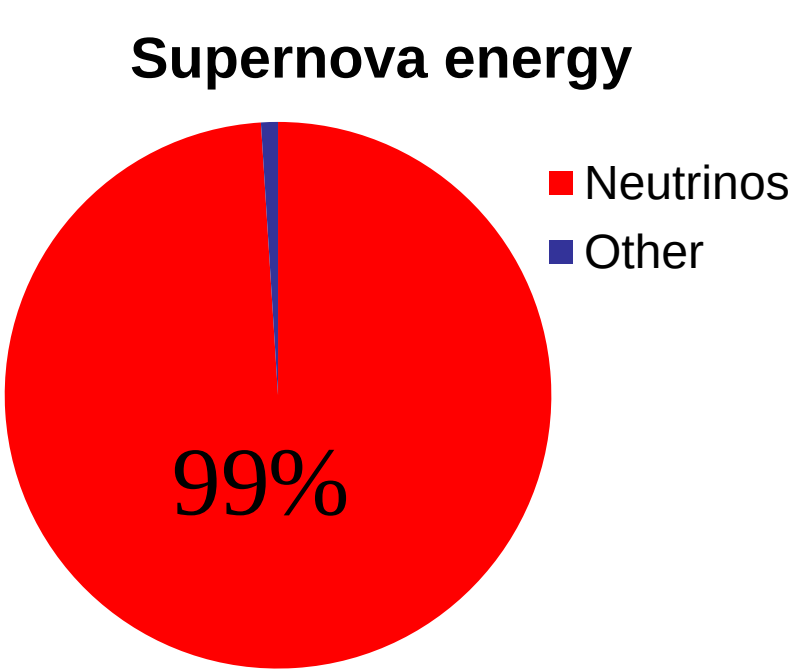
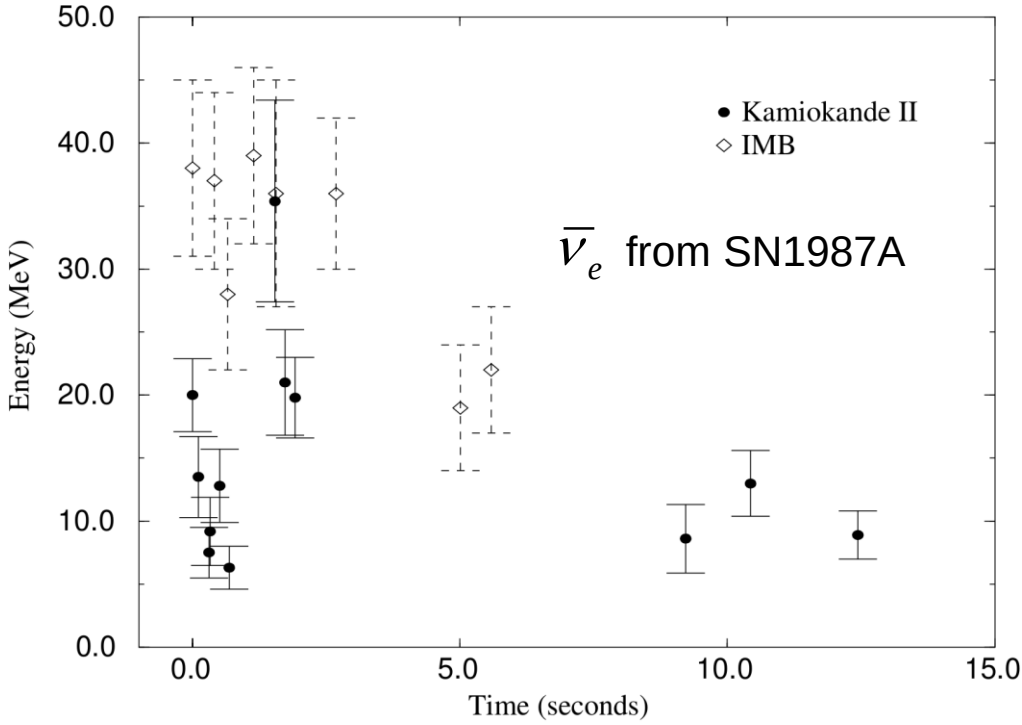
# Neutrinos in Supernovae

Core collapse supernovae release huge amount of energy.




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

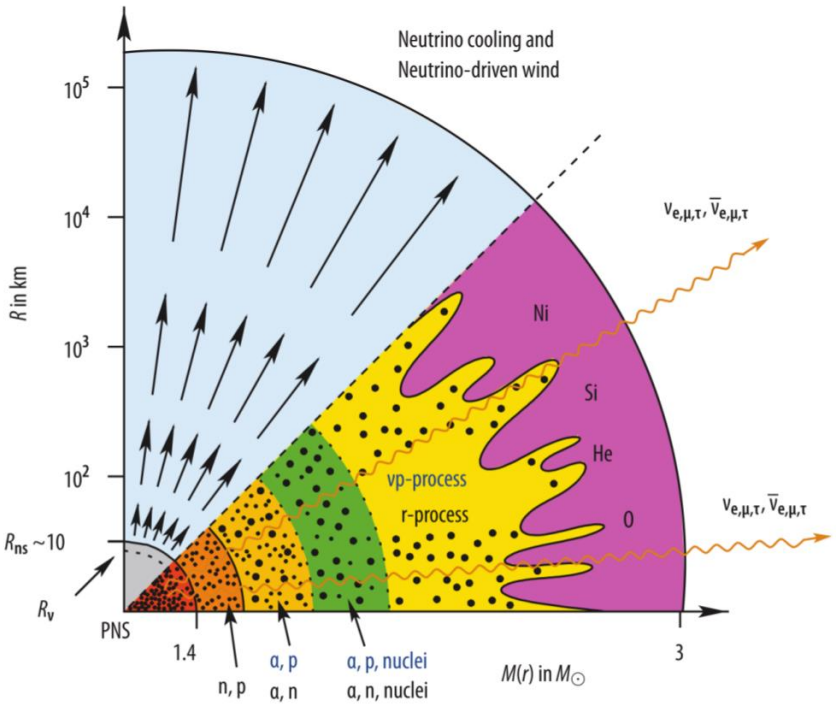
# Neutrino-Interactions: Two Regimes

## Interior of the neutron star:

Neutrino spectra formation

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

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




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

$$\Downarrow$$

$$Y_e$$

## Neutrino Driven Wind Ejecta:

Neutrino absorption ejects matter

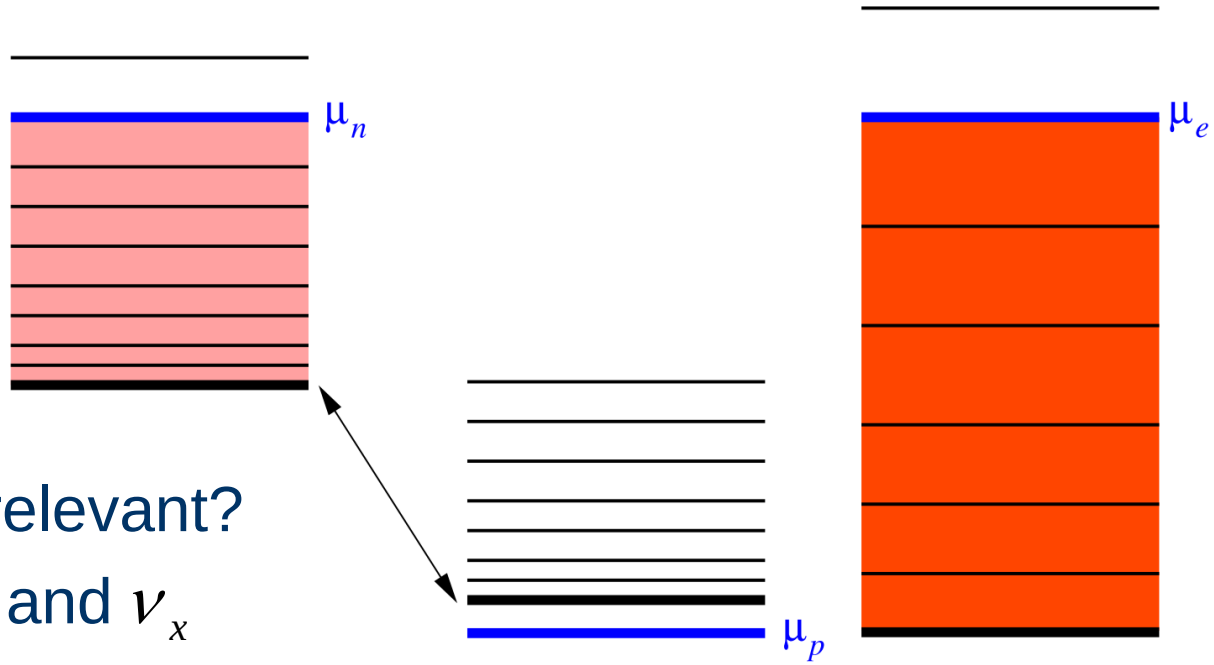
Spectrum determines composition

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

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

# Uncertainties in Neutrino Physics - I

## What is the correct Equation of state?




Which reactions are relevant?

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

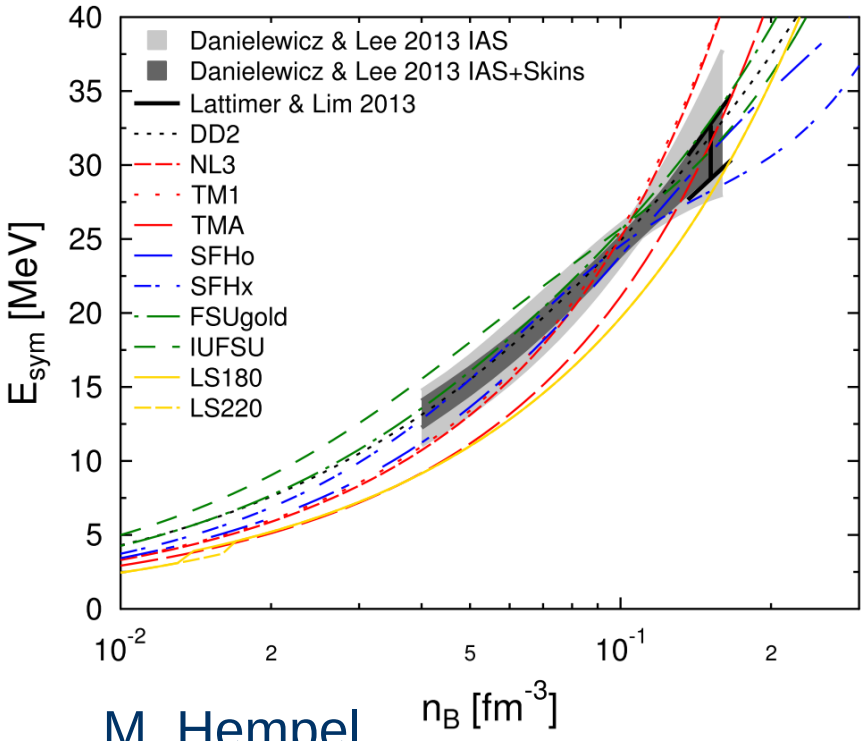
How to compute neutrino interactions?

-inelasticity, relativity, medium effects, weak magnetism …

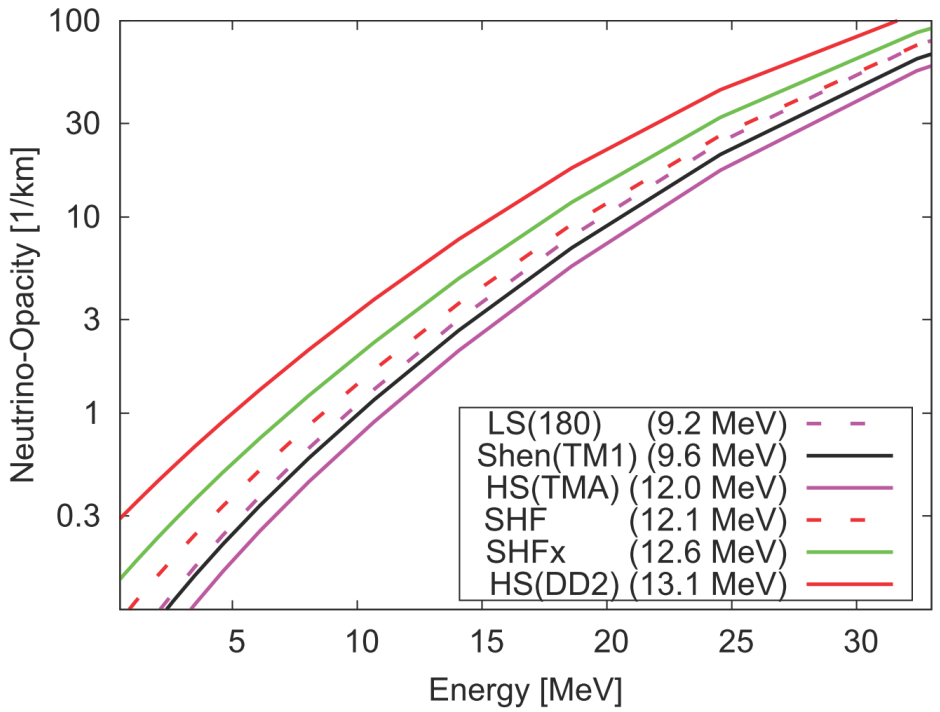
# High density Equation of State

- Key quantity: energy difference between neutrons and protons -> symmetry energy
- Significant constraints from theory, experiments, astronomy:

- chiral EFT, IAS, neutron skin, multifragmentation, NS-masses




M. Hempel

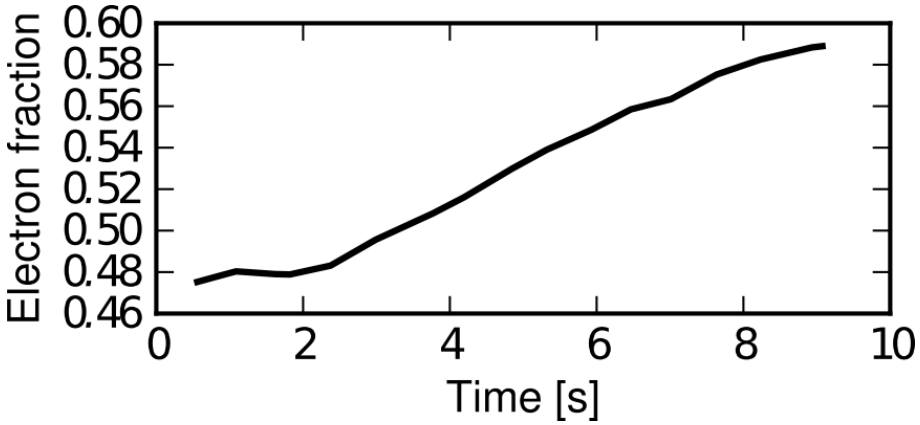


# Nucleosynthesis in Neutrino Driven Wind

Production of heavy elements depends on ($Y_e$,$S$,$v_{Exp}$)

$$Y_e = \frac{r_{\nu_e,n}}{r_{\nu_e,n} + r_{\bar{\nu}_e,p}}$$

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

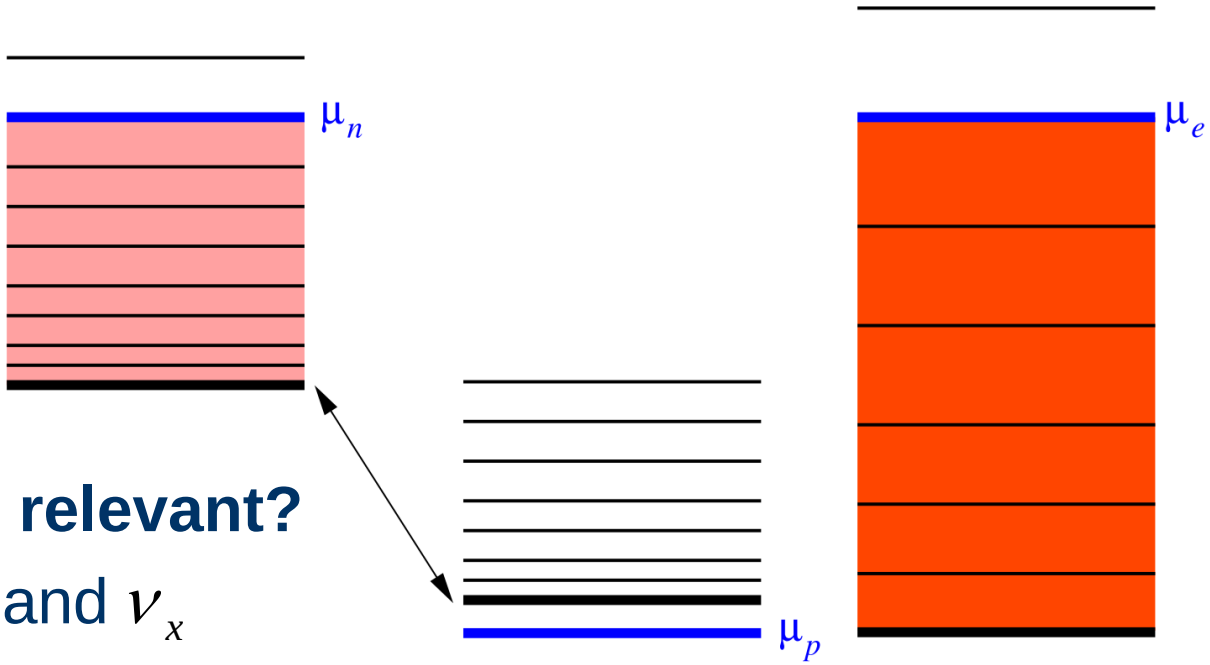



- Long term simulations indicate proton rich late NDW
- $Y_e \leq 0.5$ possible during first seconds
- No full r-process, but weak r-process?

**A more detailed picture requires (among other things) sufficiently precise neutrino rates**

# Uncertainties in Neutrino Physics - II

What is the correct Equation of state?




**Which reactions are relevant?**

- Not obvious for $\bar{\nu}_e$ and $\nu_x$
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How to compute neutrino interactions?

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# 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

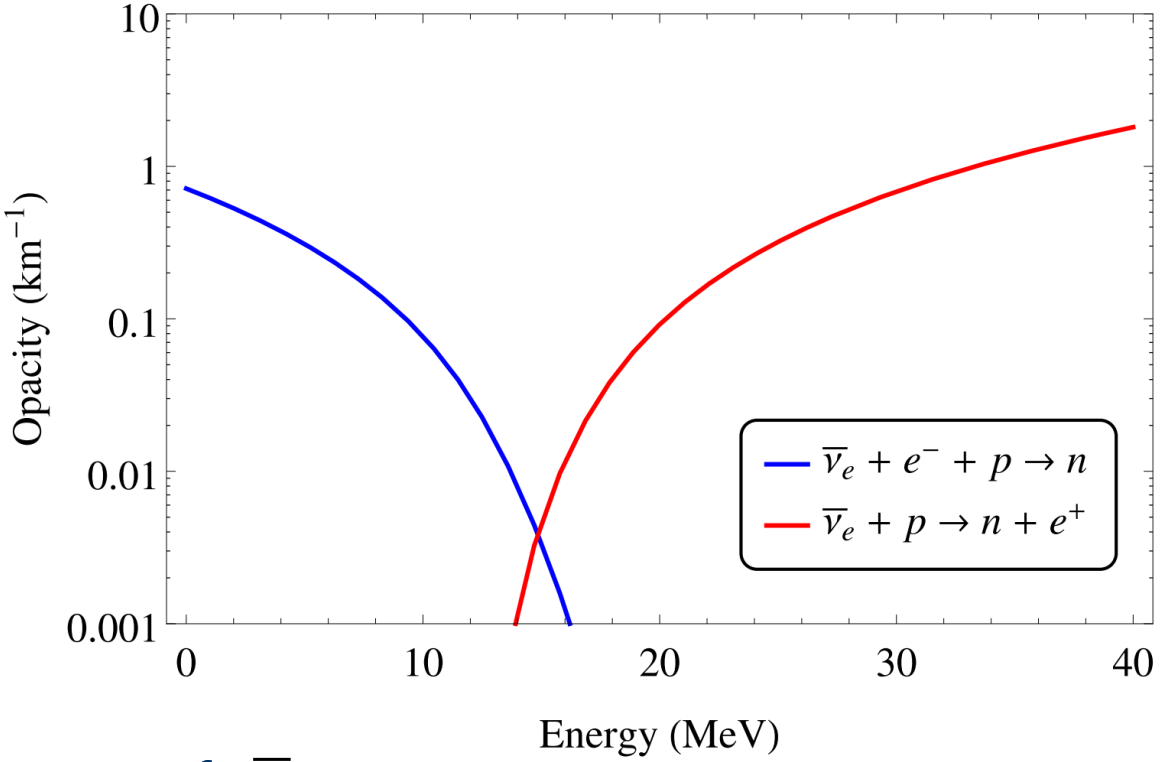
- Inverse Neutron Decay
- Charged-current muonic reactions

# Neutron decay at high density

- Low energy $\bar{\nu}_e$ cannot be absorbed on protons or produced from positron capture for large Un-Up

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

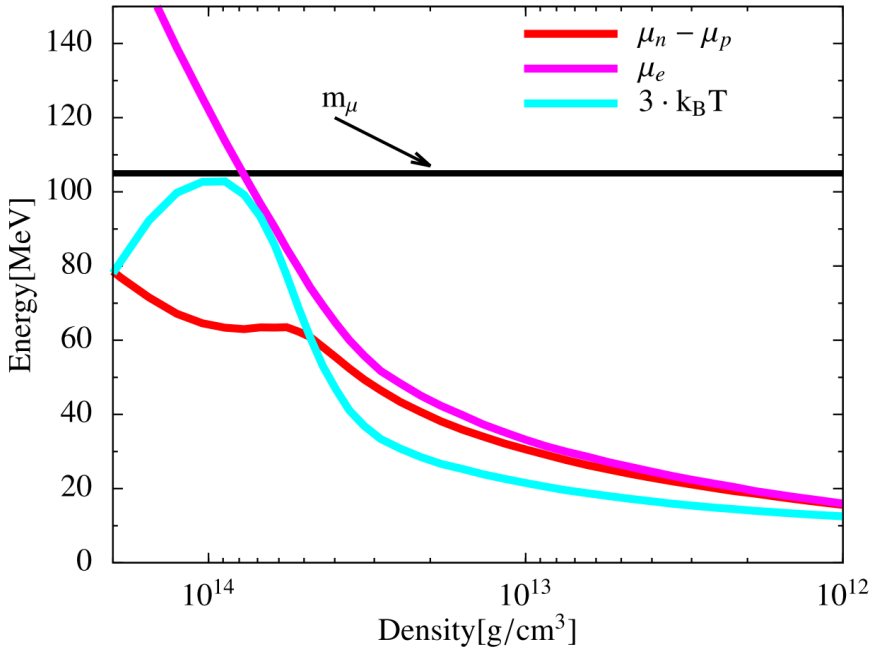
$$n \rightleftarrows \bar{\nu}_e + p + e^-$$




- Decreasing average energy of $\bar{\nu}_e$
- Spectral change will affect nucleosynthesis yields

# Charged-current interactions for muon neutrinos

- For all $\nu_x$: neutral-current interaction (almost) the same
- Charged-current reaction for $\nu_\mu$ must overcome Q-value of $m_\mu$




$$\nu_\mu + n \rightleftarrows p + \mu^-$$

$$\nu_\mu + e^- \rightleftarrows \nu_e + \mu^-$$

$$\nu_\mu + e^- + \bar{\nu}_e \rightleftarrows \mu^-$$

$$\bar{\nu}_e + e^- \rightleftarrows \bar{\nu}_\mu + \mu^-$$

- Charged-current reaction for $\nu_\mu$ significant at high densities
- Spectral differences between $\nu_\mu$ and $\bar{\nu}_\mu$

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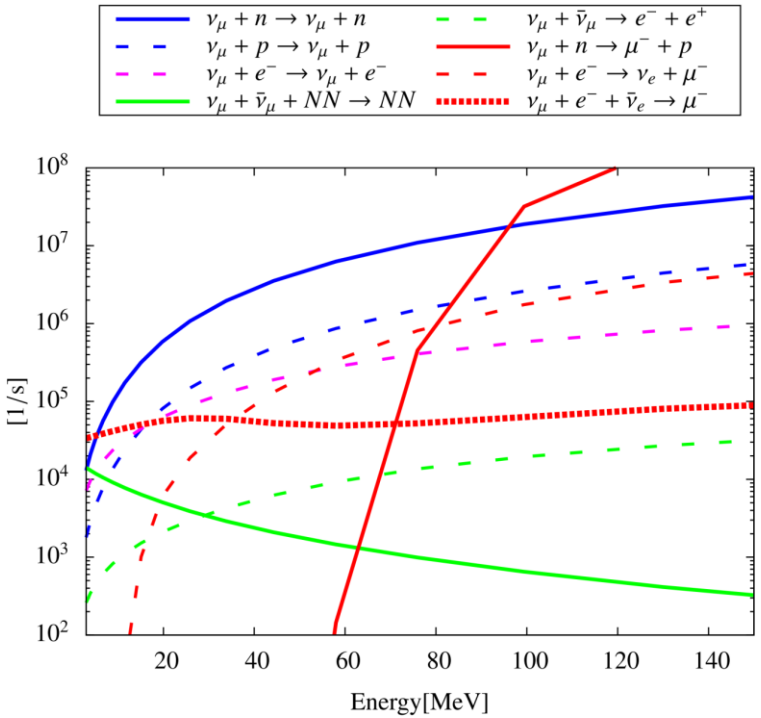


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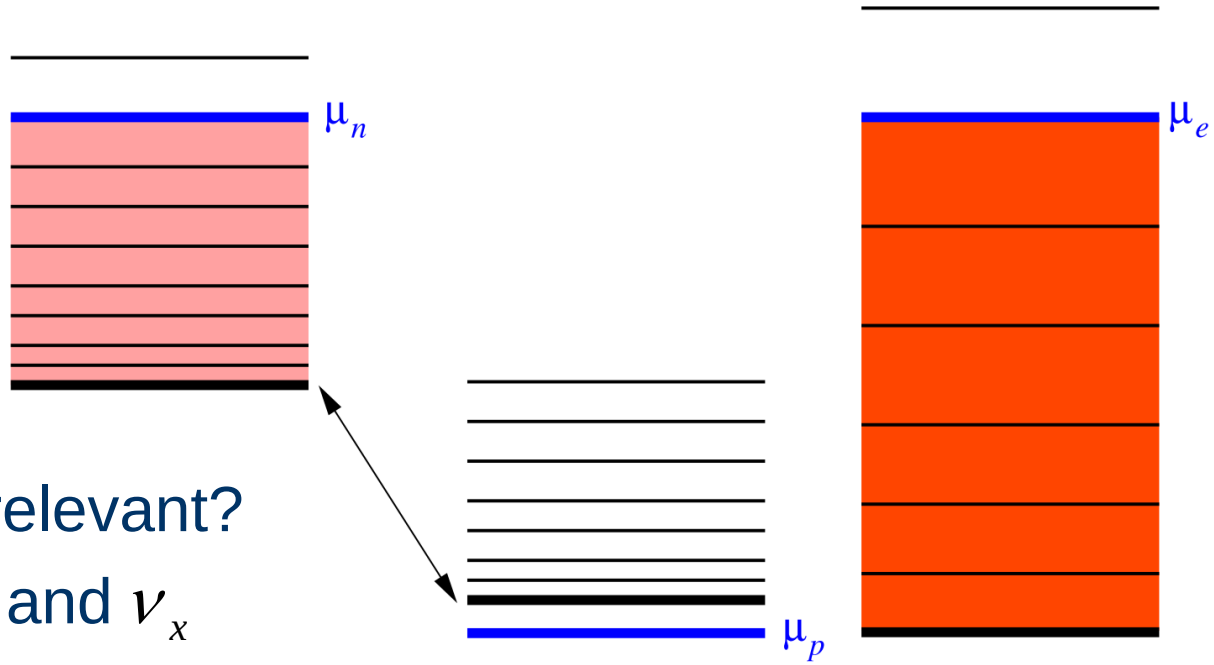
# Uncertainties in Neutrino Physics - III

What is the correct Equation of state?

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**How to compute neutrino interactions?**

-inelasticity, relativity, medium effects, weak magnetism …

# Mean Free Path for Neutrino Absorption

Elastic Approximation

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

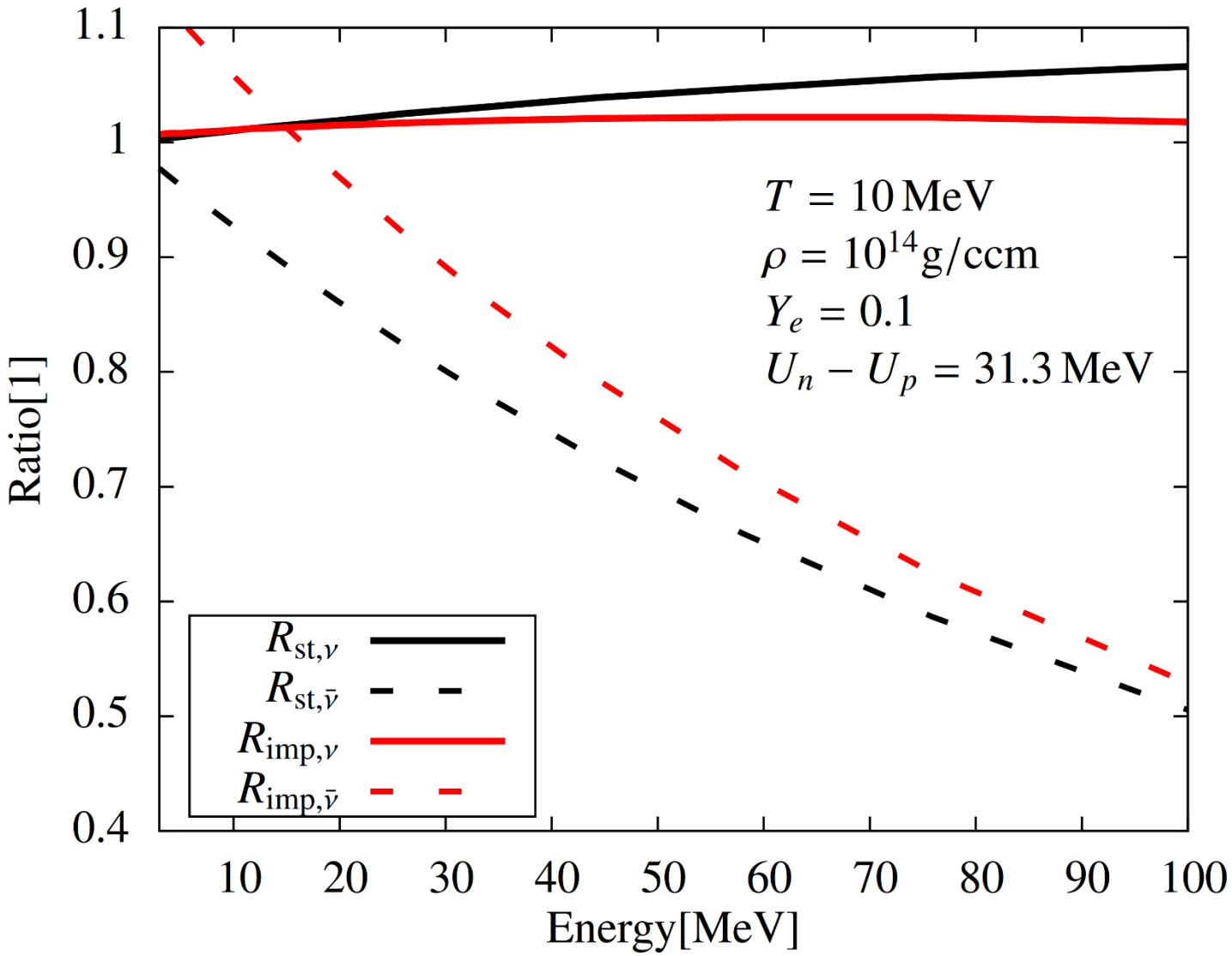
**Nucleons as quasi-free fermions – Hartree response**

- **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 $\lambda(E_\nu)$

# (Improved) Correction Factors at High Densities



# 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

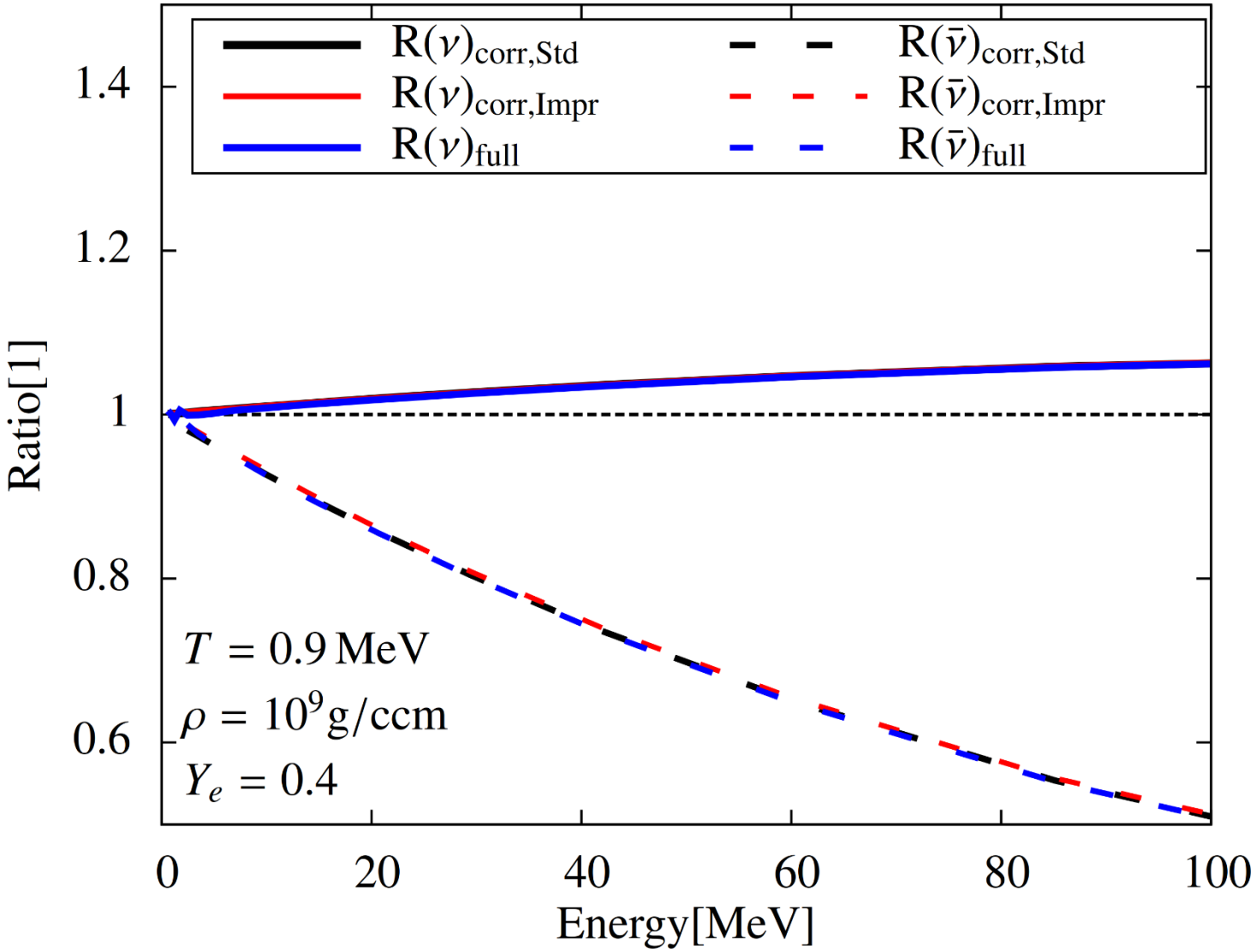
$$E_{n,p} = \sqrt{\mathbf{p}^2 + m^{*2}_{n,p}} + U_{n,p}$$

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

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

- No correlations, but always better than elastic approximation

# Comparing Approximations and Exact Opacities



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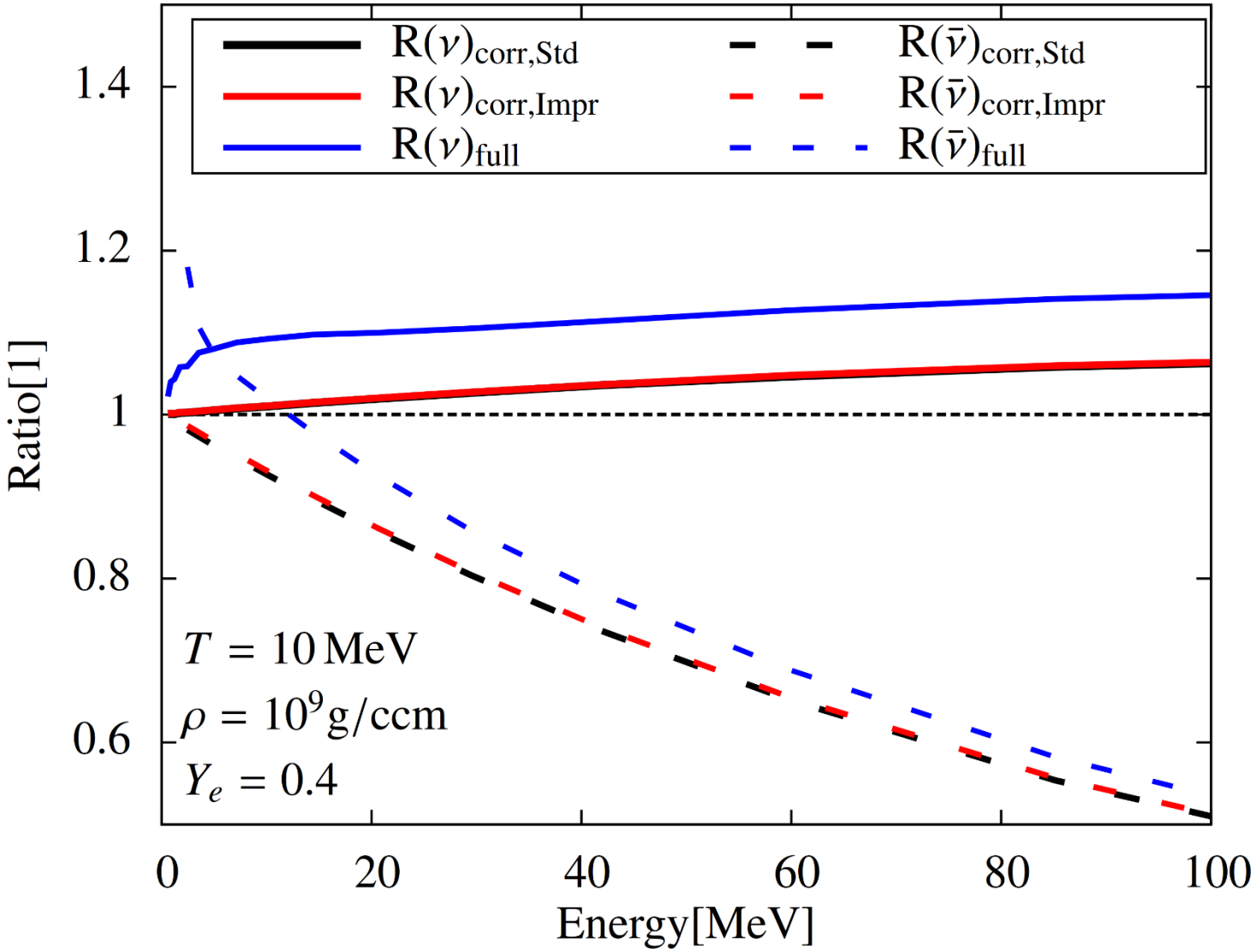
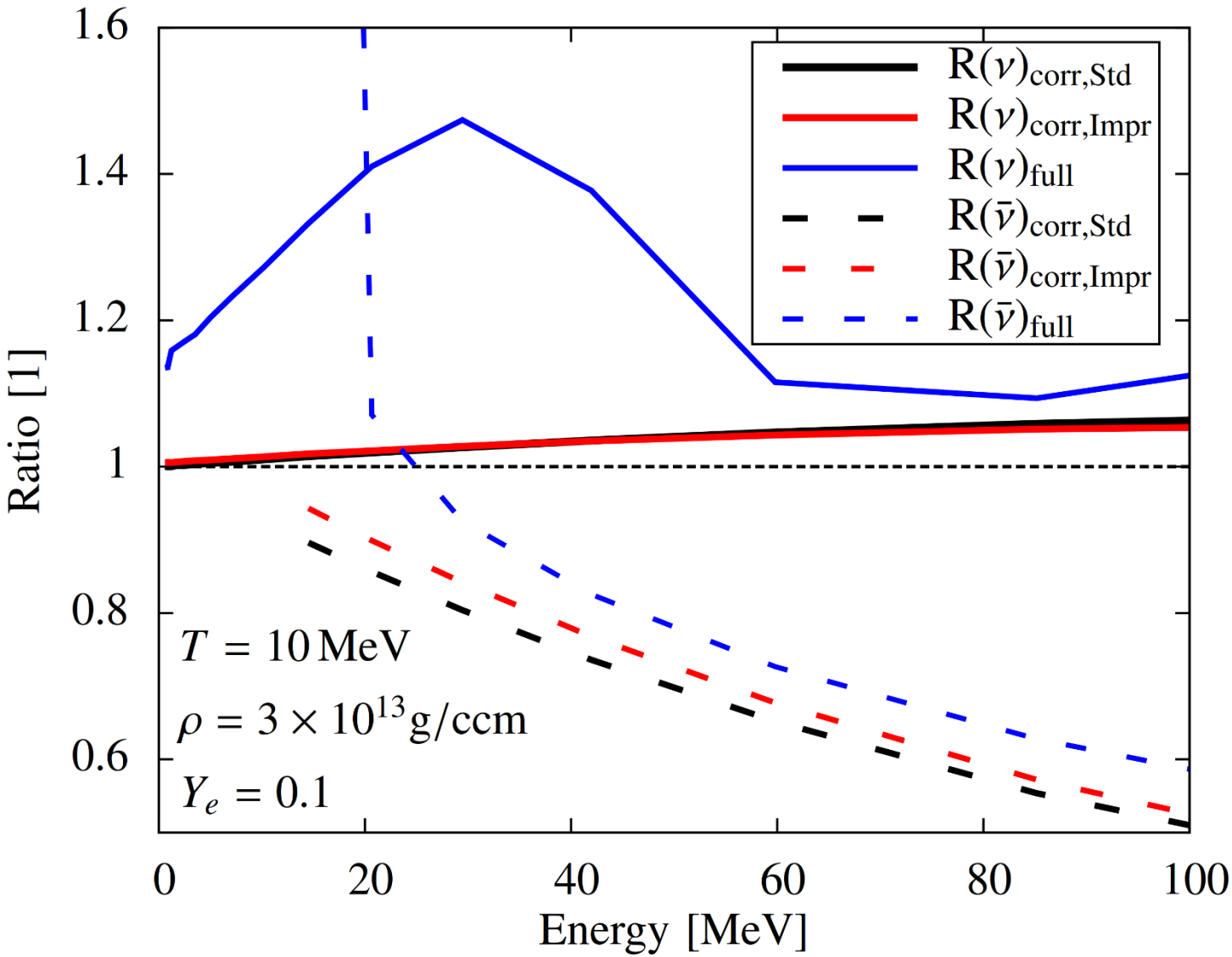


# Comparing Approximations and Exact Opacities



# Limit of Approximations for Neutrino Opacities

- 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 precision at 10% level, „exact“ opacity generally favourable over elastic approximation
- When interested in correlations, inelastic but approximated opacity + corrections can be suitable

# $q^2$-Dependence of Weak Hadronic Couplings

Effective couplings of nucleons depend on momentum transfer

$$q^2 = 2E_\nu E_e \left(v_e \cos\theta - 1\right) + m_e^2$$

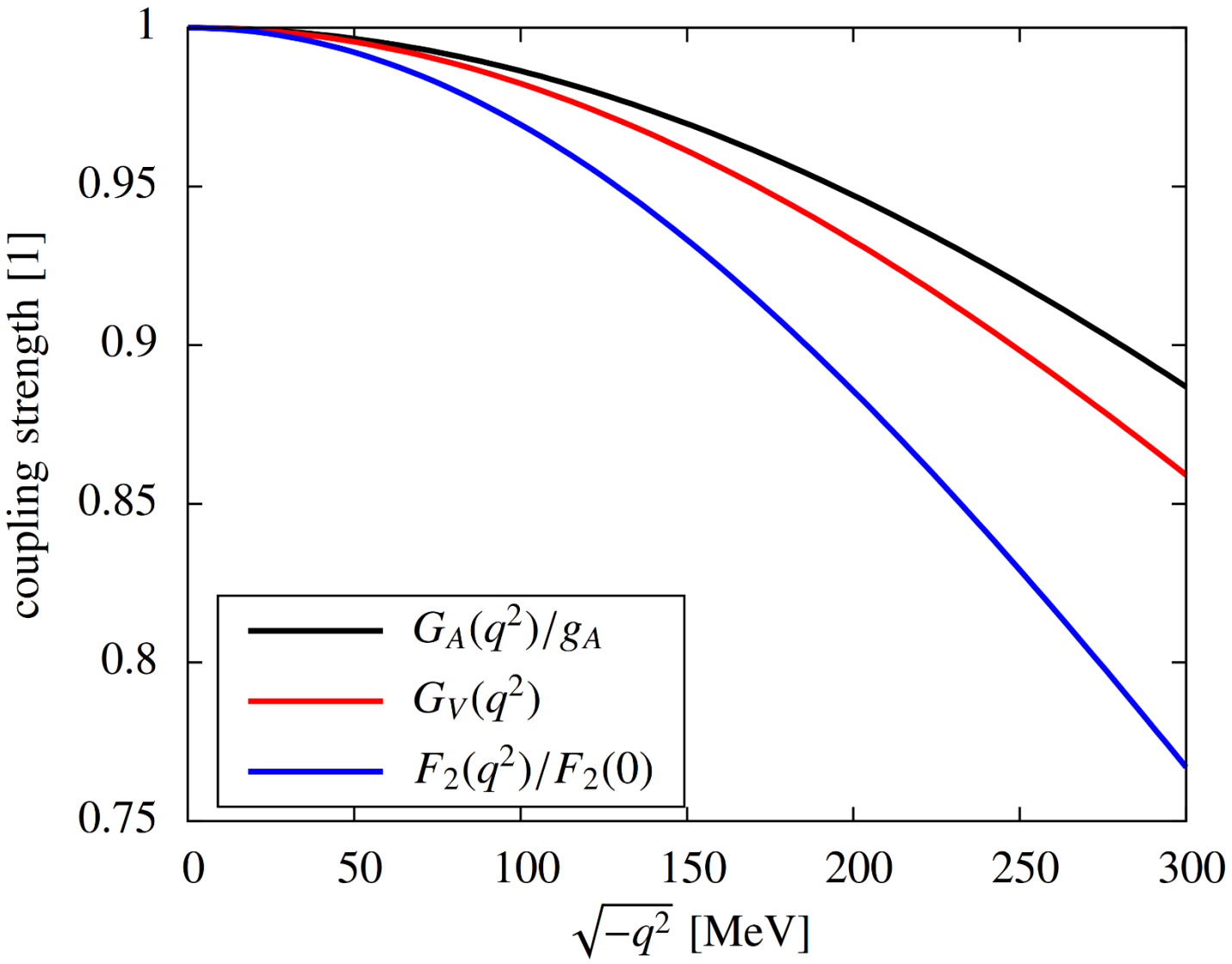
Neutrino transport in *CCSN* usually neglects $q^2$-dependence

$$G_A\left(q^2\right) = g_A \left(1 - q^2/m_A^2\right)^{-2}$$

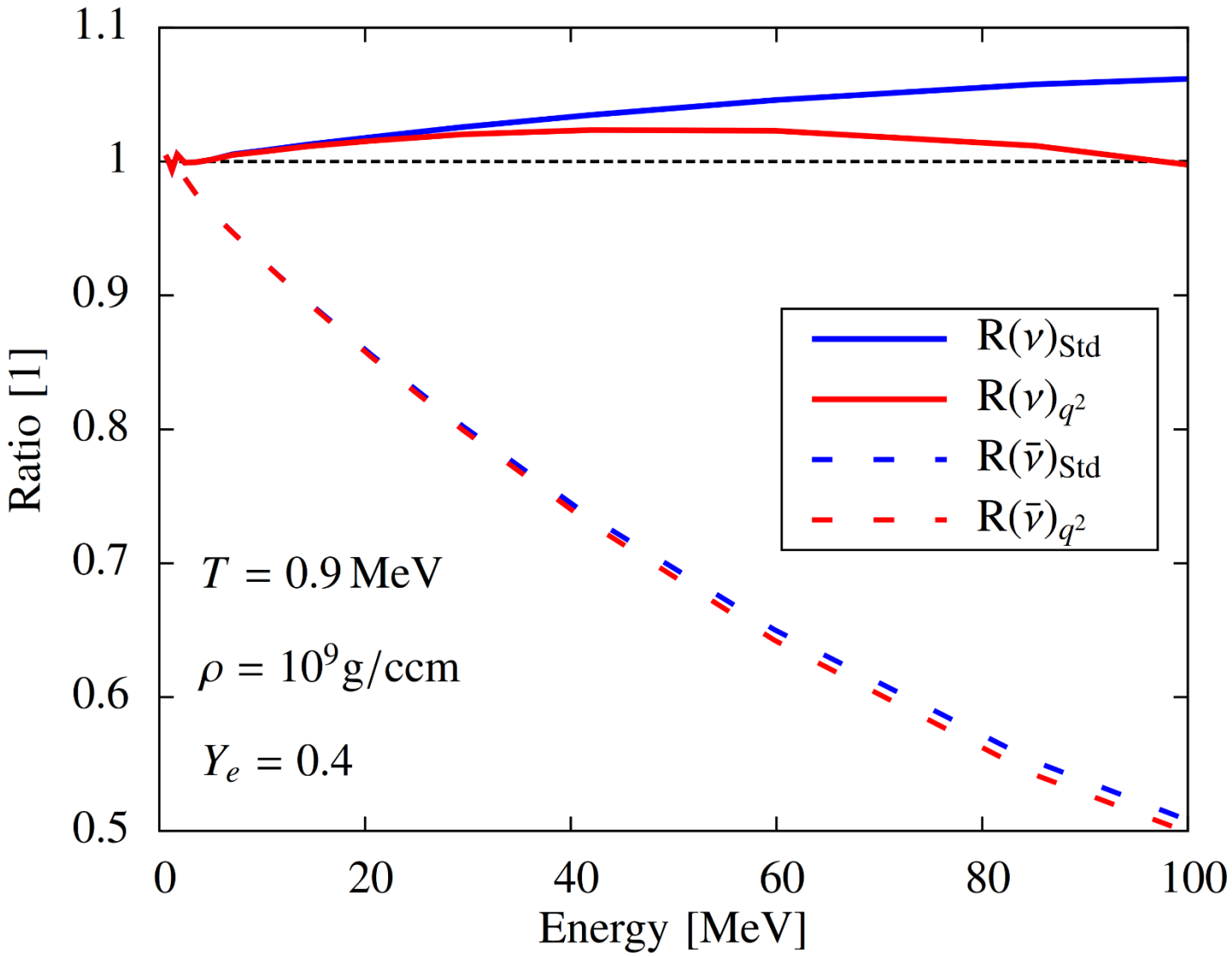
$$G_V\left(q^2\right) = \left[1 - \left(F_2(0) + 1\right) \frac{q^2}{4m_N^2}\right] \left(1 - \frac{q^2}{4m_N^2}\right)^{-1} \left(1 - \frac{q^2}{M_V^2}\right)^{-2}$$

$$F_2\left(q^2\right) = F_2(0) \left(1 - q^2/4m_N^2\right)^{-1} \left(1 - q^2/M_V^2\right)^{-2}$$

# $q^2$-Dependence of Weak Hadronic Couplings



# Opacities with $q^2$-dependent Couplings



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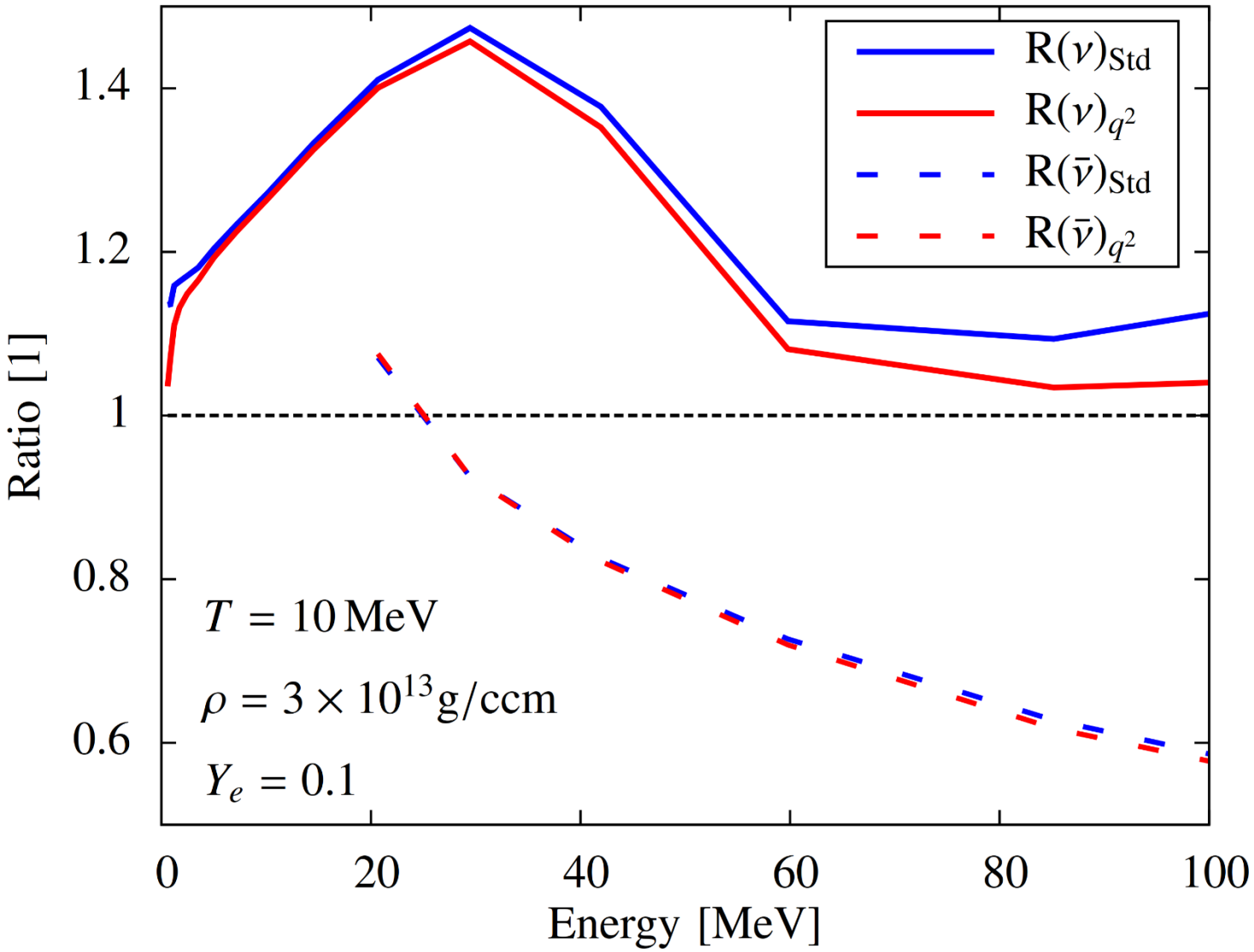

# Summary and Conclusion

**Improved microphysics for neutrino matter interaction**

- Transport and nucleosynthesis consistent with EOS
- Probing nuclear physics at high densities

**Additional neutrino reactions**

- Neutron decay and charged-current muonic reactions

**Precise computation of neutrino rates**

- Extend „correction factors“ to include strong interaction potentials and effective masses
- „Exact“ opacities consider inelasticity, relativity, nuclear EOS, $q^2$-dependence in effective couplings.

- Outlook: Relativistic RPA-opacities with correlations

# Summary and Conclusion

Collaborators:

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**Matthias Hempel** (Univ. Basel, CH)

**Stefan Typel** (TU Darmstadt / GSI)

**Lutz Huther** (TU Darmstadt / GSI)

**THANK YOU FOR YOUR ATTENTION!**