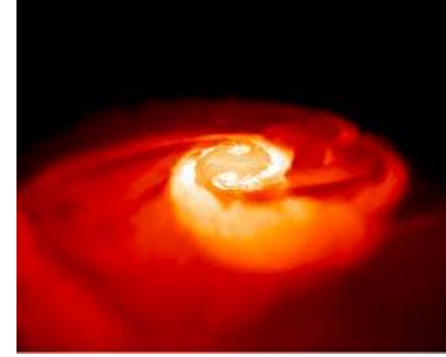
Nuclear Astrophysics Virtual Institute NAVI

experimental nuclear physics

theoretical nuclear physics

astrophysical modeling

astronomical observation



Improving Microphysics of Neutrino-Nucleon Interactions in Supernovae

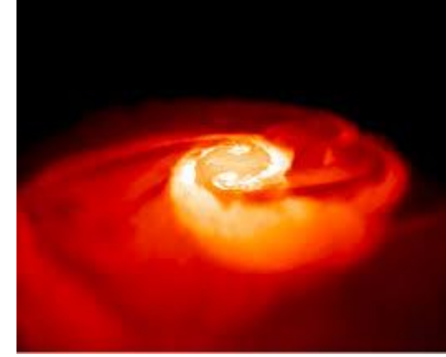
MICRA 2015 – August 21– Stochkolm

Andreas Lohs (Univ. Basel)

Universität Basel

GSI

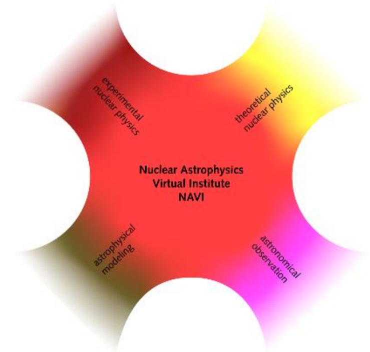
TECHNISCHE UNIVERSITÄT DARMSTADT

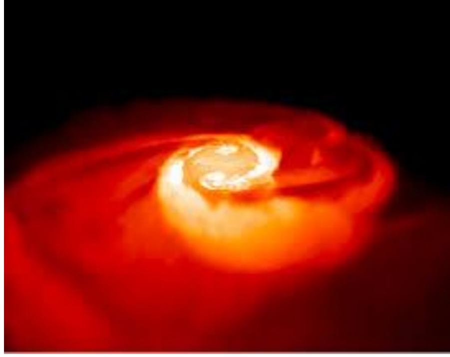


(Almost) Improving Microphysics of Neutrino-Nucleon Interactions in Supernovae

MICRA 2015 – August 21– Stochkolm

Andreas Lohs (Univ. Basel)



Improving Microphysics of Neutrino-Nucleon Interactions in Supernovae (in Medium)

MICRA 2015 – August 21– Stochkolm

Andreas Lohs (Univ. Basel)

Universität Basel

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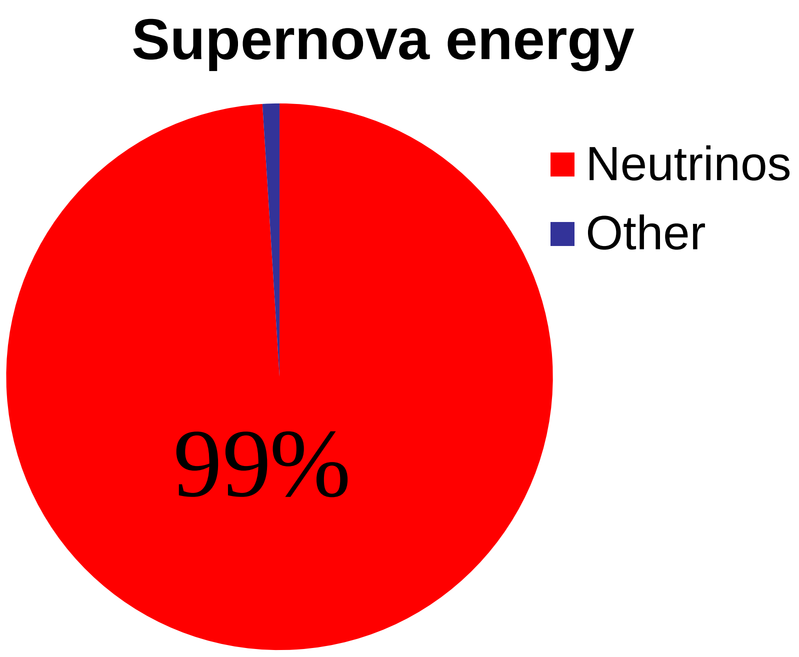
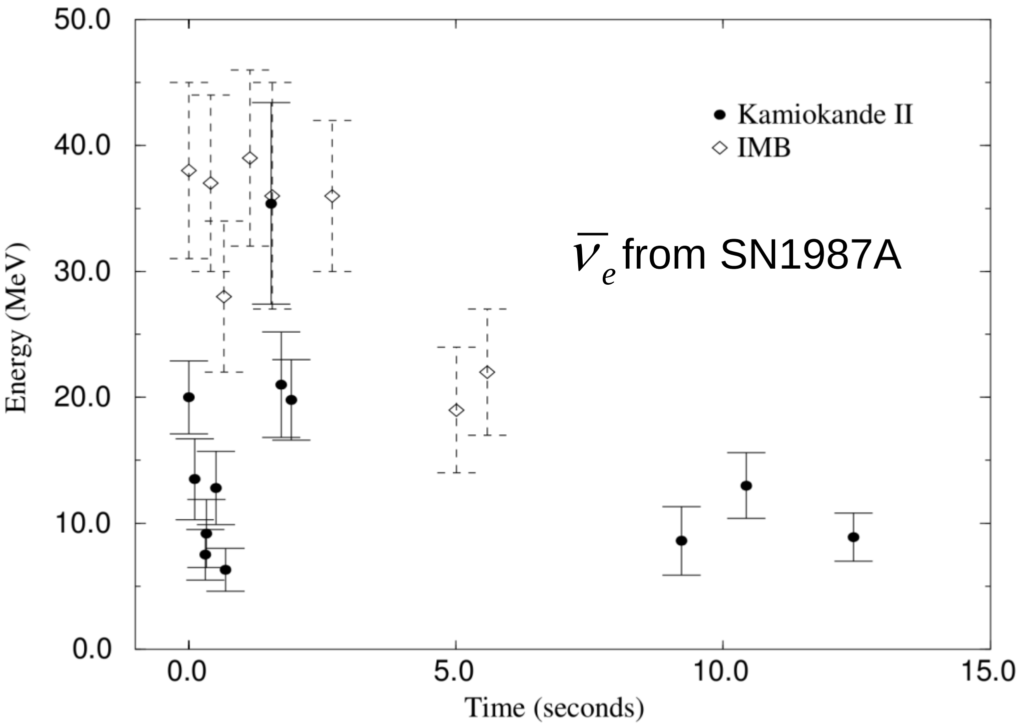
Neutrinos in Supernovae

Core collapse supernovae release huge amount of energy

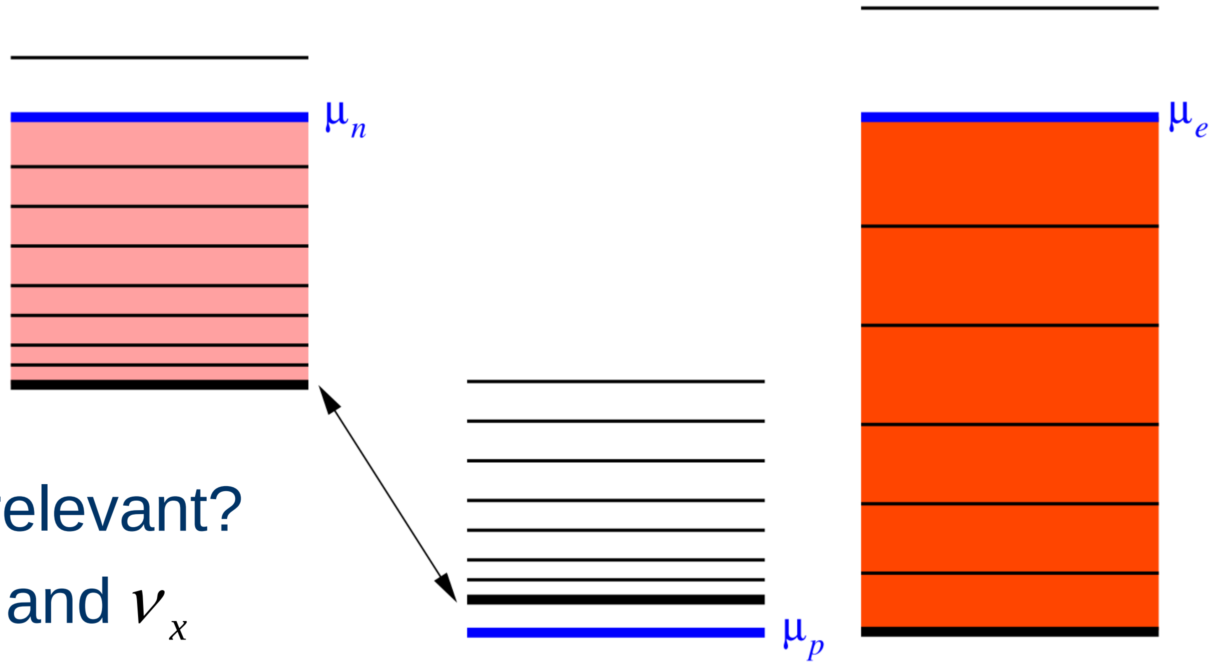




As neutrinos affect many aspects of Sne, what are main questions of neutrino transport?

Uncertainties in Neutrino Physics

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 …

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

-Relativistic kinematics, „full“ matrix element, no correlations

-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 $\lambda(E_\nu)$

Elastic Approximation for Neutrino Absorption

Mean-free path for (quasi-) free particles:

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

Assume non-relativistic nucleons and elastic collision:

$$E_{n,p} \simeq m_{n,p} \Rightarrow \frac{\left\langle |M|^2 \right\rangle}{16 E_\nu E_n E_e E_p} \simeq G_A^2 (3 - x) + G_V^2 (1 + x)$$

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

Mean-free path reduces to

$$\lambda(E_\nu)^{-1} \sim \left(3G_A^2 + G_V^2\right) \left(E_\nu + \Delta m + \Delta U\right)^2 \left[1 - f_e(E_\nu + \Delta m + \Delta U)\right] \frac{n_n - n_p}{1 - \exp\left[\left(\eta_p - \eta_n\right)/T\right]}$$

Recoil and Weak Magnetism Corrections

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

-“Elastic Approximation“ is more simplified than necessary

-Kinematics/Recoil can be treated relativistically

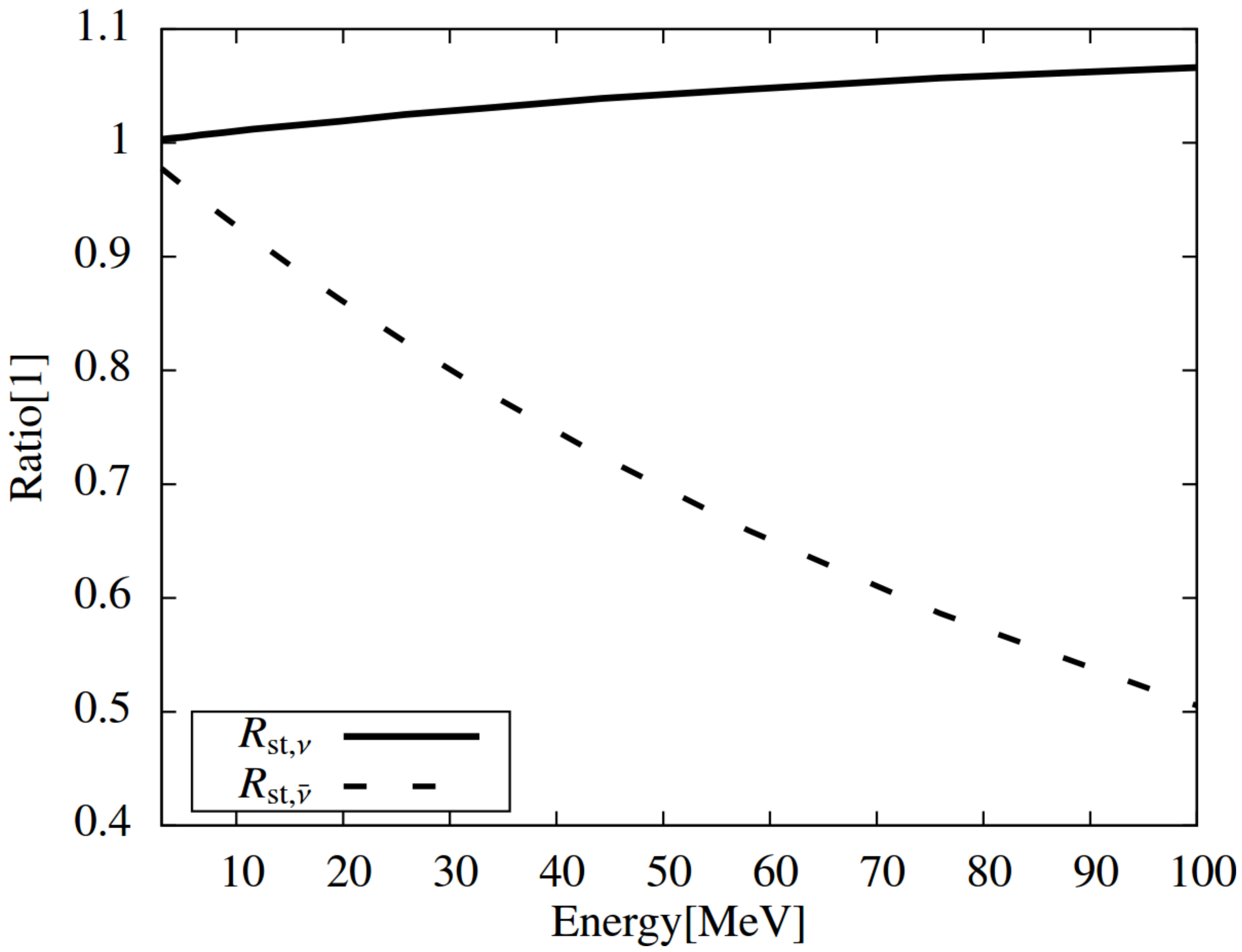
$$E_n = m_n \Rightarrow E_e = \frac{E_\nu}{1 + \frac{E_\nu}{m_n}(1-x)}$$

-Include in phase space factor and matrix element

-Gives rise to analytic correction factor for cross-section

$$R = \left\{ G_V^2 \left(1 + 4e + \frac{16}{3}e^2\right) + 3G_A^2\left(1 + \frac{4}{3}e\right)^2 \pm 4G_A\left(G_V + F_2\right)e\left(1 + \frac{4}{3}e\right) + \frac{8}{3}G_V F_2 e^2 + \frac{1}{3}F_2^2 e^2 (5 + 2e) \right\} / \left[(1+2e)^3 \left(G_V^2 + 3G_A^2\right)\right]$$

Correction Factor for Cross-Section



Improvement: Consider Mass and Potential Differences

-Masses and strong interaction potentials of nucleons differ

-At large densities effective masses decrease

$$E_e = \frac{E_\nu + \frac{M_*^2 - m_p^{*2}}{2M_*}}{1 + \frac{E_\nu}{M_*}(1-x)} \qquad M_* = m_n^* + U_n - U_p$$

-Analytic correction factor can still be derived the same way

-In the matrix element, additional terms can be included

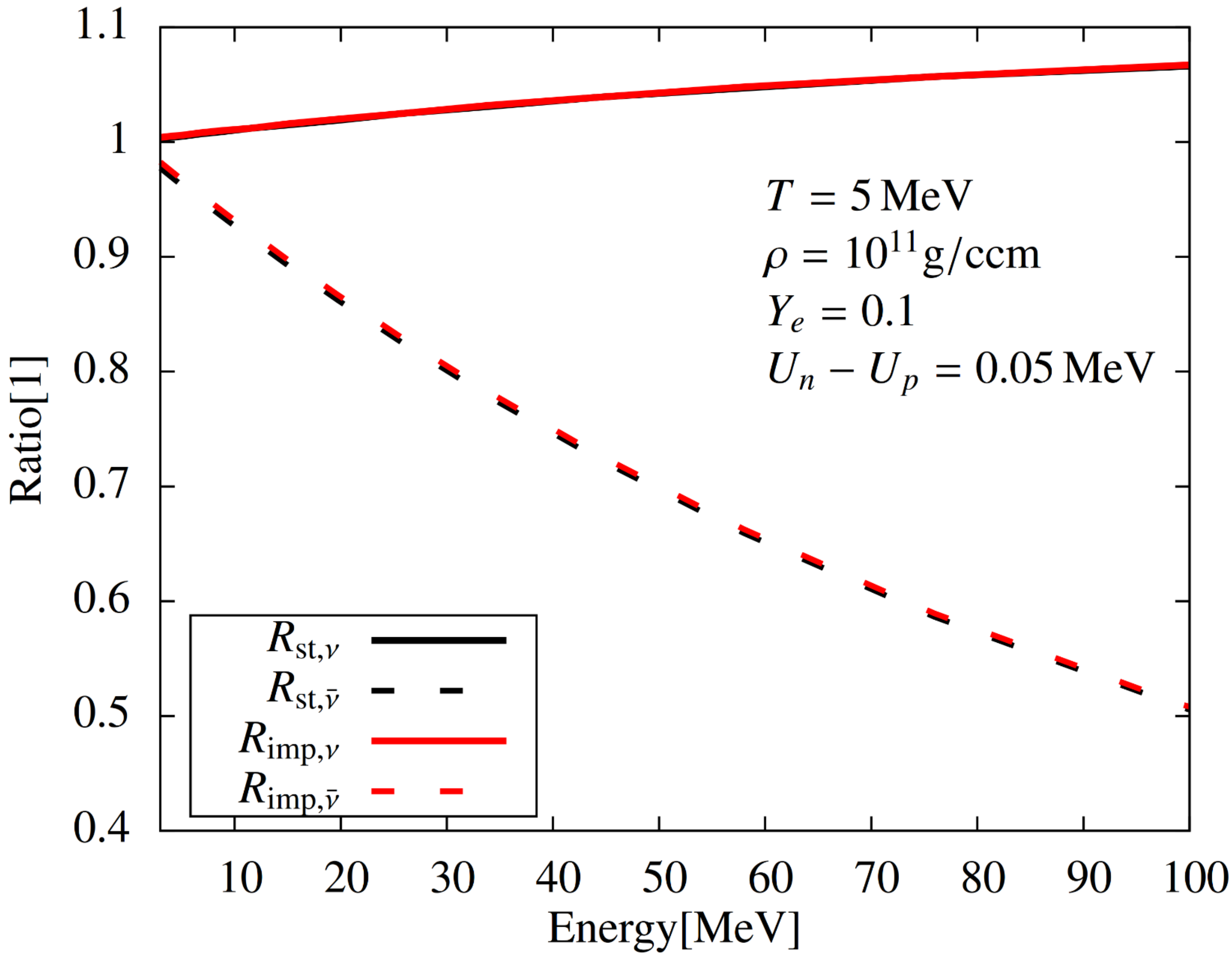
-For neutrino scattering, only difference is exchange of rest mass with effective mass

Improved Correction Factor

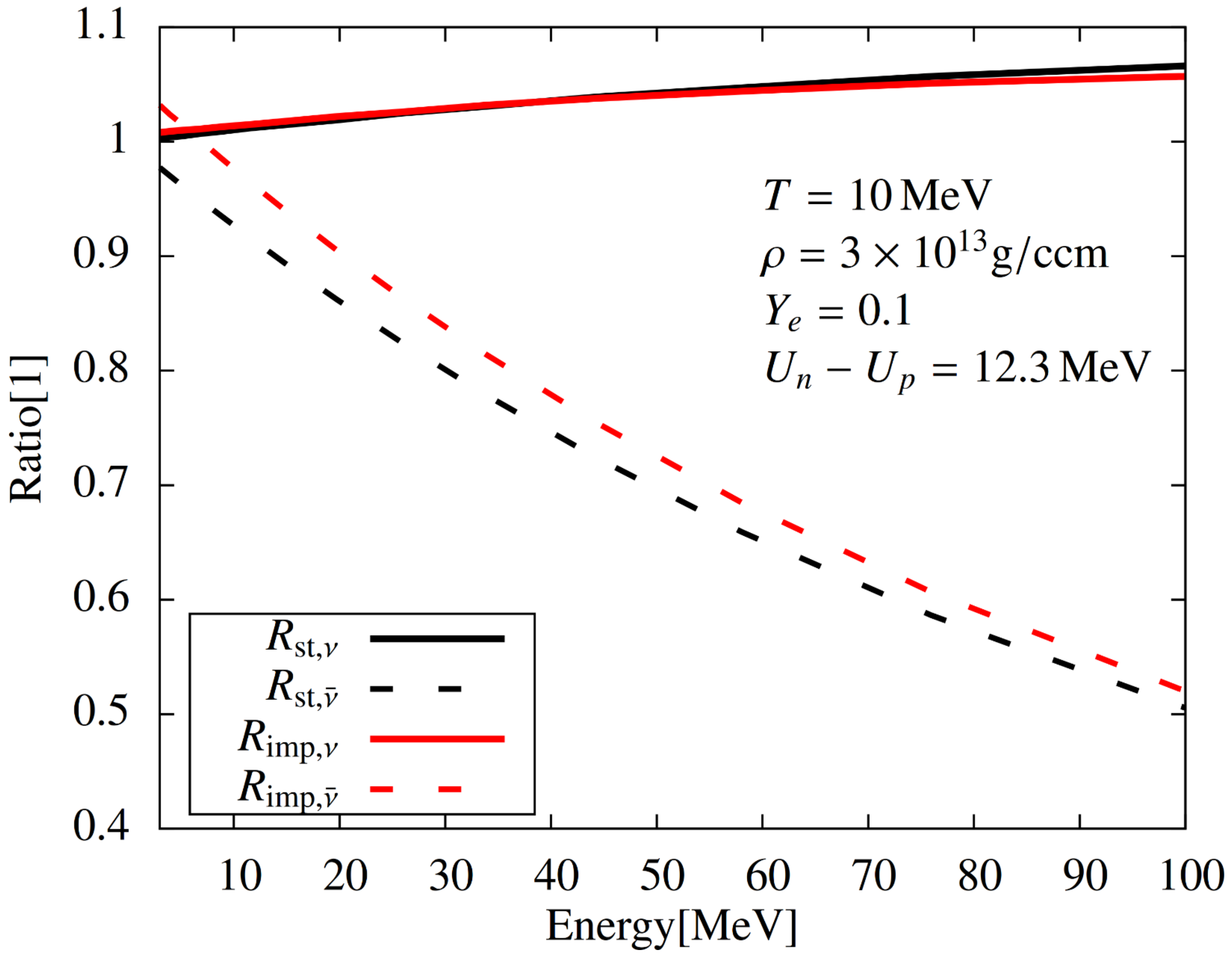
$$R = \Big\{ G_V^2 \left[1 + 4e_* + \frac{16}{3}e_*^2 + \frac{4}{3}e_*\xi + \left(1 + \frac{2}{3}e_*\right)(\xi - q_*) \right]$$
$$+ G_A^2 \left[3 + 8e_* + \frac{16}{3}e_*^2 - \frac{4}{3}e_*\xi - \left(1 + \frac{2}{3}e_*\right)(\xi + q_*) \right]$$
$$\pm G_A \left[G_V + F_2 \frac{M_*}{m_N}\left(1 - \frac{\xi}{2}\right) \right] \left[4e_* + \frac{16}{3}e_*^2 + q_*\left(2 + \frac{4}{3}e_*\right) \right]$$
$$+ G_V F_2 \frac{M_*}{m_N} \left[\left(1 + \frac{q_*}{e_*} - \frac{\xi}{2}\right)\frac{8}{3}e_*^2 + \xi q_* \left(1 + 2e_* + \frac{4}{3}e_*^2\right) \right]$$
$$+ F_2^2 \frac{M_*^2}{m_N^2} \left[\frac{5}{3}e_*^2 + \frac{2}{3}e_*^3 + \left(\frac{1}{2} + e_*\right)\tilde{A} + \left(\frac{1}{2} + \frac{1}{3}e_*\right)\tilde{B} + \frac{2}{3}e_*\tilde{C} \right] \Big\}$$
$$/ \left[(1 + 2e)^3 \left(G_V^2 + 3G_A^2\right) \right]$$

$$\xi = \frac{\Delta m^* + \Delta U}{M_*}, \quad q = \frac{m_n^{*2} - m_p^{*2}}{2M_*^2}, \quad q_* = \frac{M_*^2 - m_p^{*2}}{2M_*^2}$$

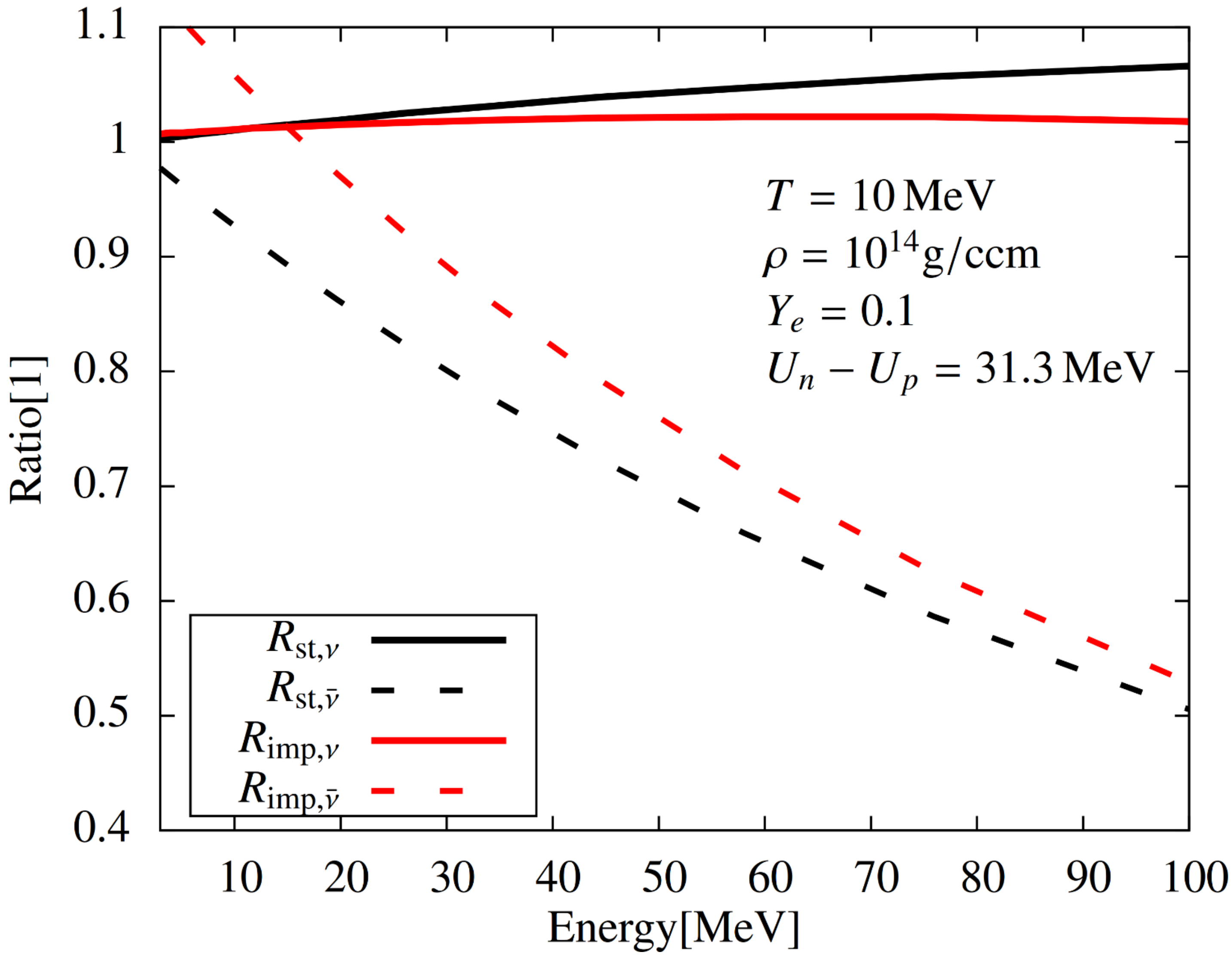
Improved Correction Factor at Low Densities



Improved Correction Factor at High Densities



Improved Correction Factor at High Densities

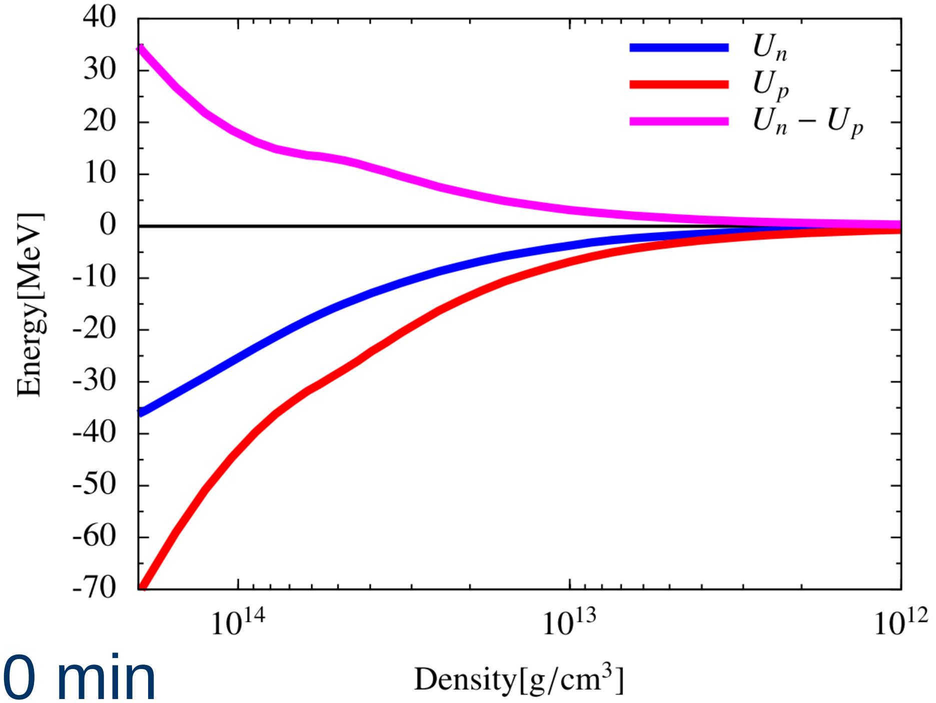


Neutron decay at high density

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

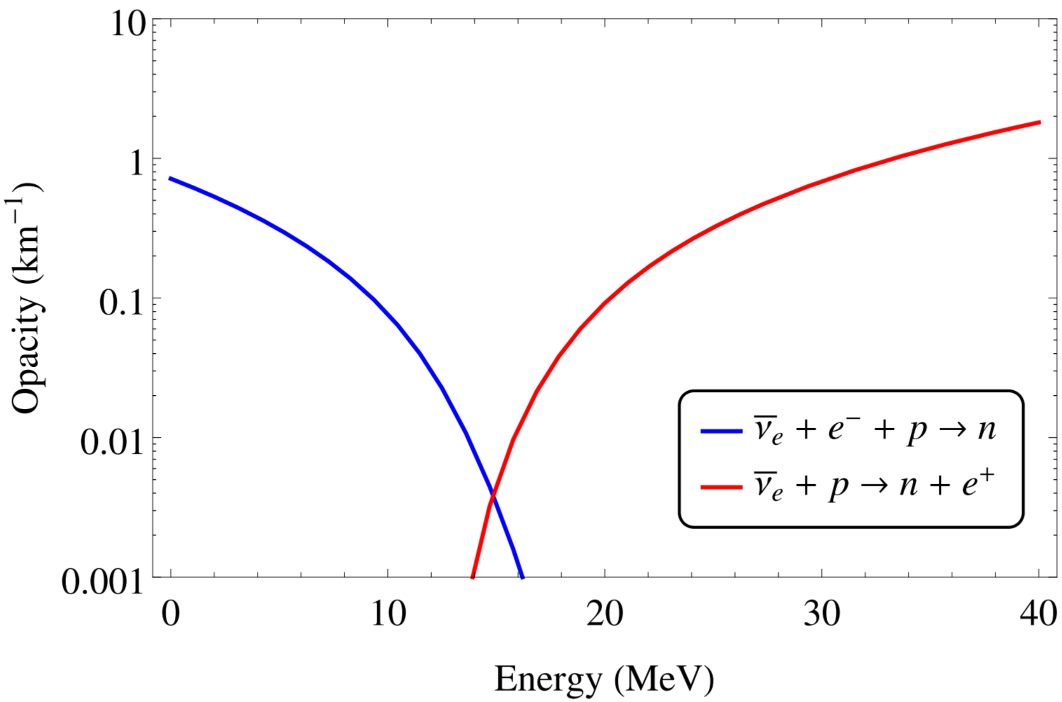
$$n + e^+ \rightleftarrows \bar{\nu}_e + p$$

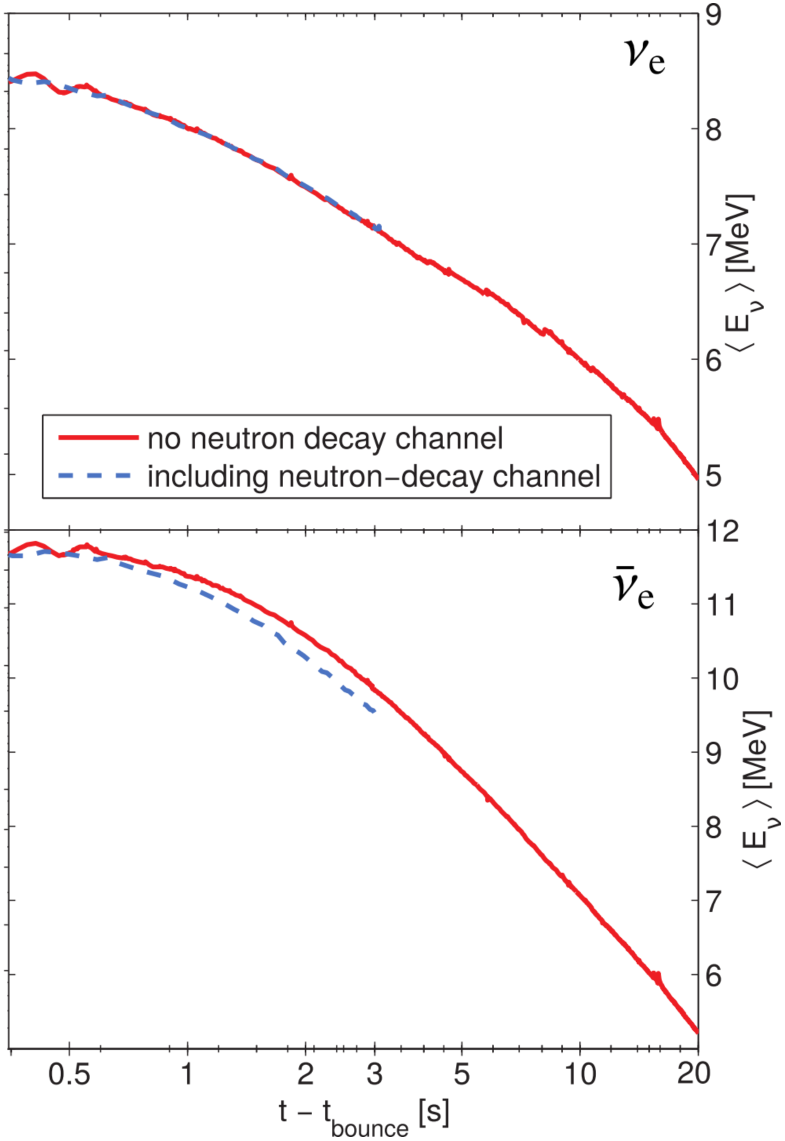
$$n \rightleftarrows \bar{\nu}_e + p + e^-$$



- Neutron lifetime in vacuum ~ 10 min
- Strong interaction increases Q-value for nucleon conversion
  →Decay rate raises

Neutron decay at high density





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

$\to$ Rising Y_e

Elastic Approximation and Corrections for Neutron Decay

Elastic approximation for neutron decay similar to absorption

$$\lambda(E_\nu)^{-1} \sim \left(3G_A^2 + G_V^2\right)(\Delta m + \Delta U - E_\nu)^2 f_e(\Delta m + \Delta U - E_\nu)\frac{n_p - n_n}{1 - \exp\left[\left(\eta_n - \eta_p\right)/T\right]}$$

Kinematic relation for inverse neutron decay, assuming proton at rest

$$E_e = \frac{-E_{\bar{\nu}} + \frac{M_*^2 - M_f^2}{2M_*}}{1 + \frac{E_{\bar{\nu}}}{M_*}(1-x)}$$

Physical meaning only for different nucleon masses and/or potentials

Summary and Conclusion

Correction Factors for neutrino-nucleon interactions

- Can be extended to include strong interaction potentials and effective masses
- Shifts Correction factors at high densities
- Correction factor for neutron decay requires improvement to have physical meaning

Outlook:

- Correction factor for neutron decay
- Include finite lepton masses
- Include momentum dependence of coupling constants