Neutrino Opacity with Supernova Matter using chiral effective field theory potential

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Guo & Martinez-Pinedo, ApJ 887 (2019) 58
Guo, Martinez-Pinedo, & Wu, PRC 110 (2024) 015504
Fischer, Guo, Langanke, Martinez-Pinedo, Qian, & Wu, "neutrinos and nucleosynthesis of elements", PPNP 137 (2024) 104107

Outline

Introduction to neutrino-driven supernova explosion

Supernova neutrino opacity calculations (χEFT potential)

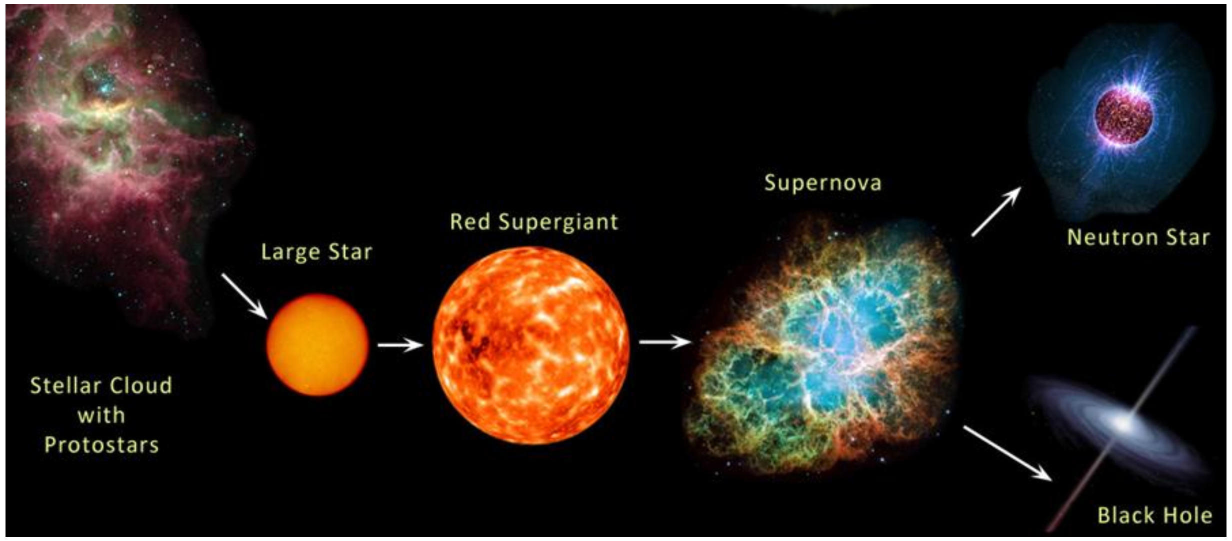
neutrino-nucleon reaction at mean field level

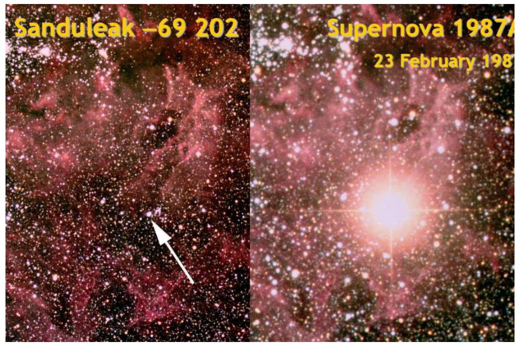
neutrino nucleon-nucleon bremsstrahlung

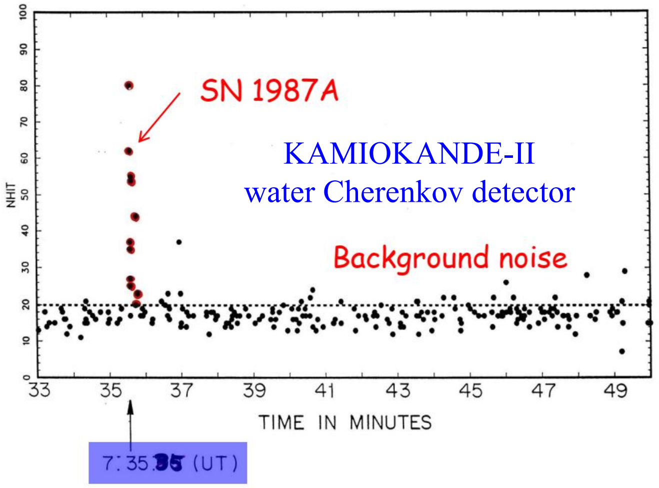
neutrino-nucleon considering nucleon-nucleon correlation effects

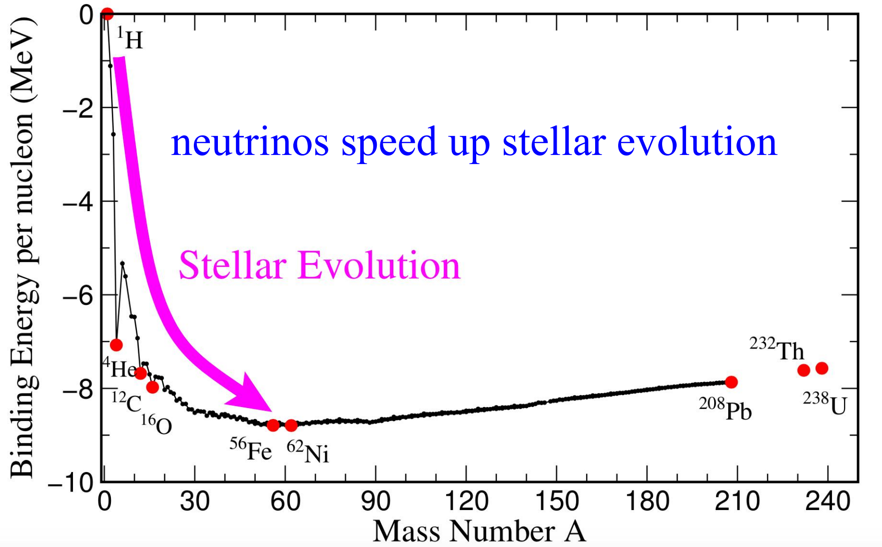
Summary

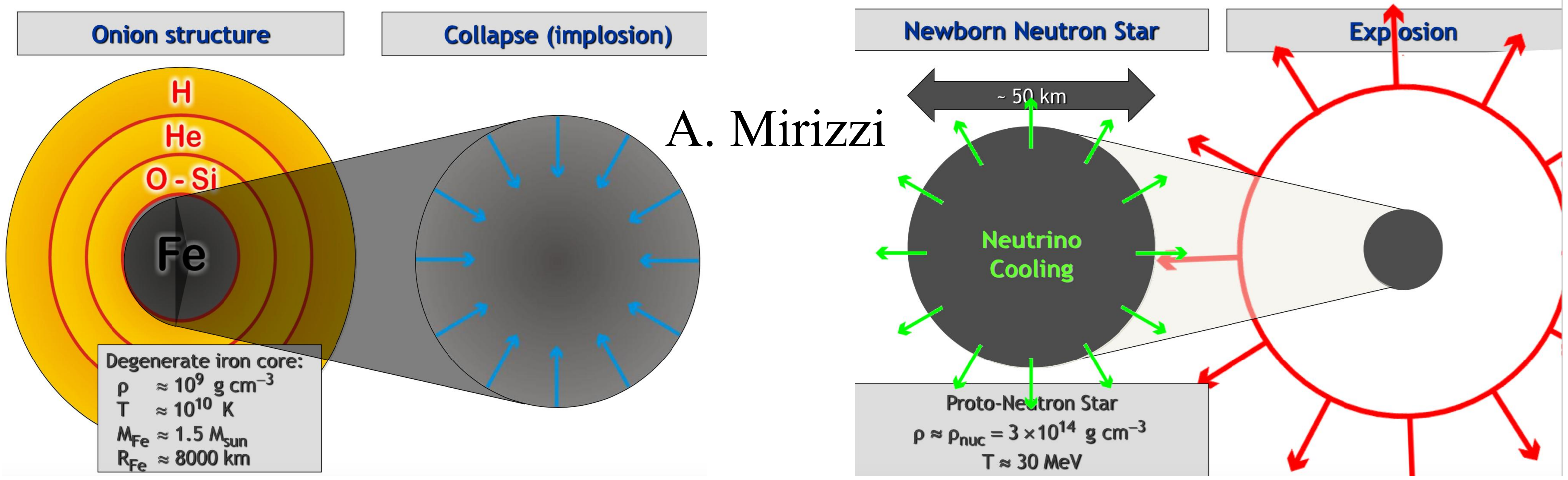
nuclear & neutrino reactions driving evolution and core-collapse explosion of massive stars



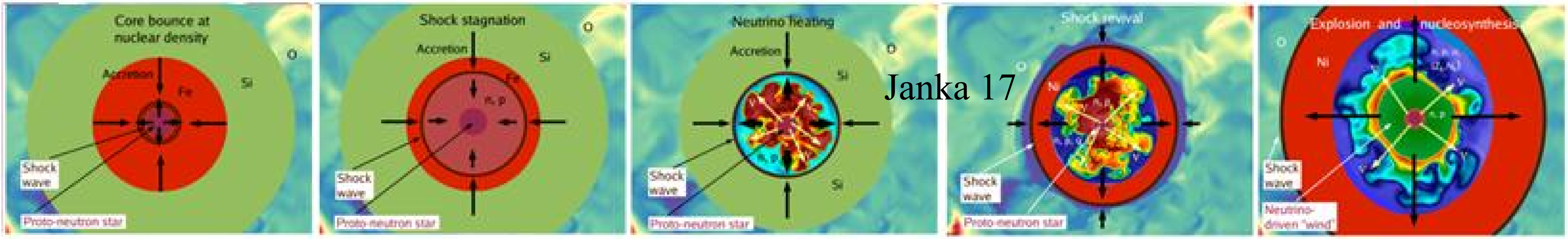








A. Mirizzi



Janka 17

core-collapse & bounce shock

shock stagnation

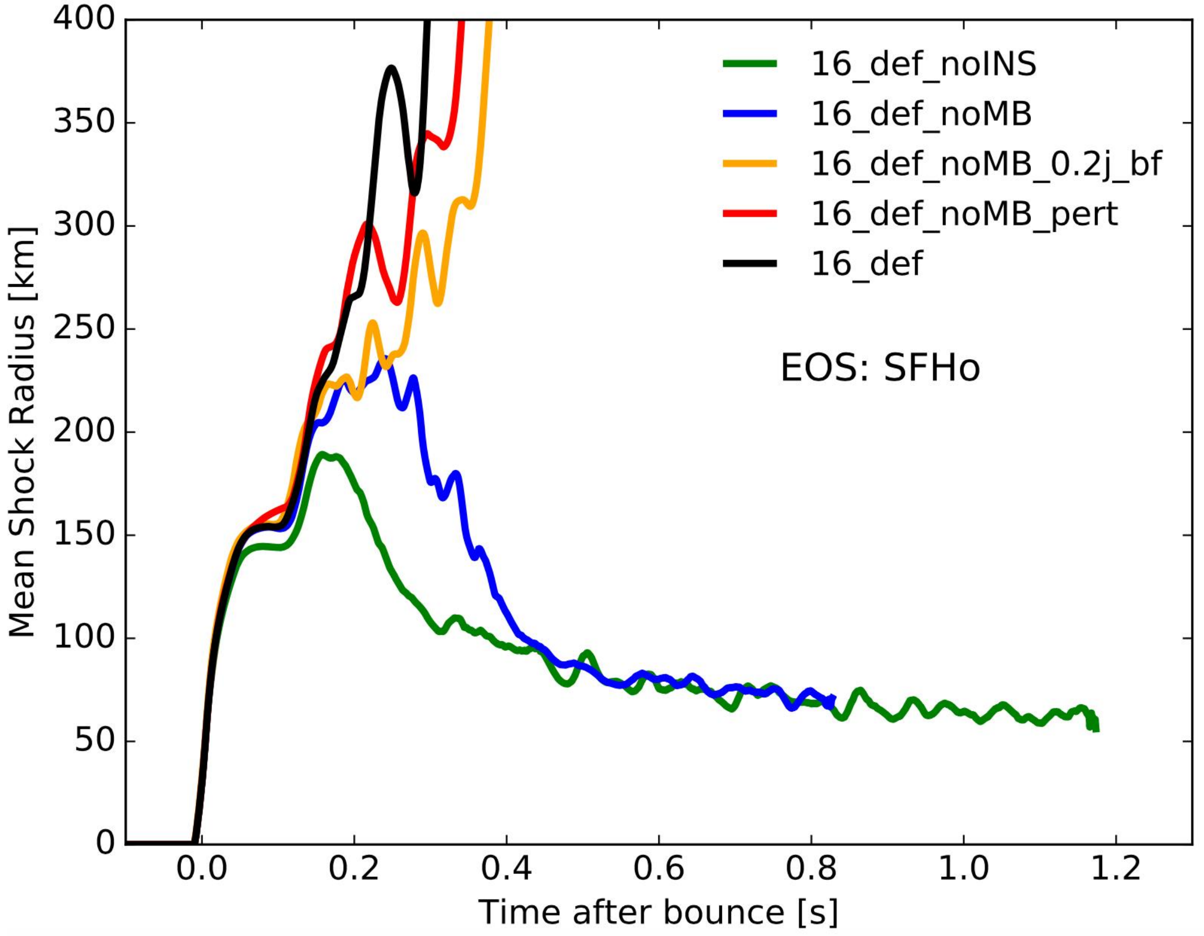
$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

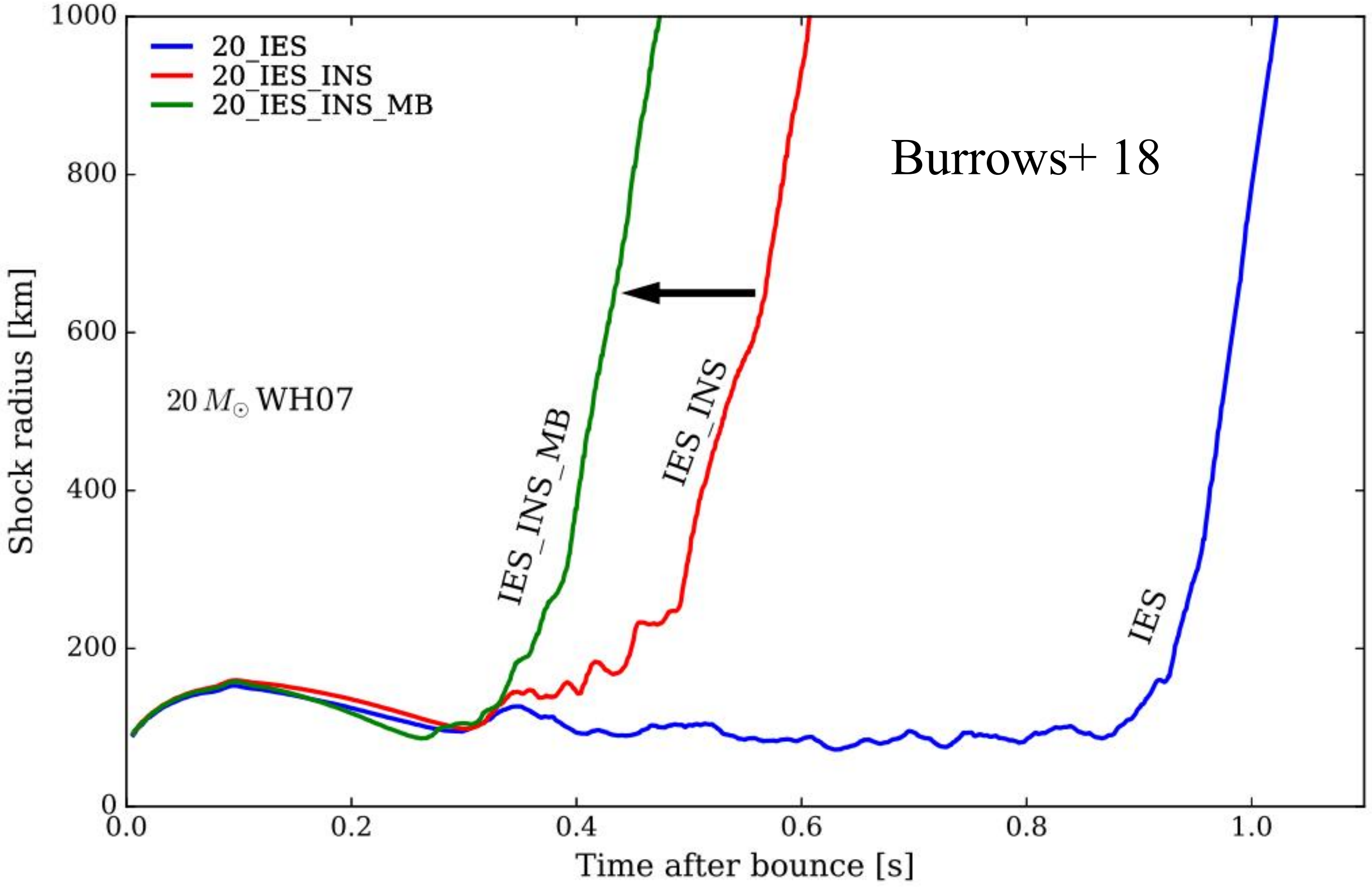
neutrino heating

shock revival

explosion

stellar explosion or not is very sensitive to neutrino



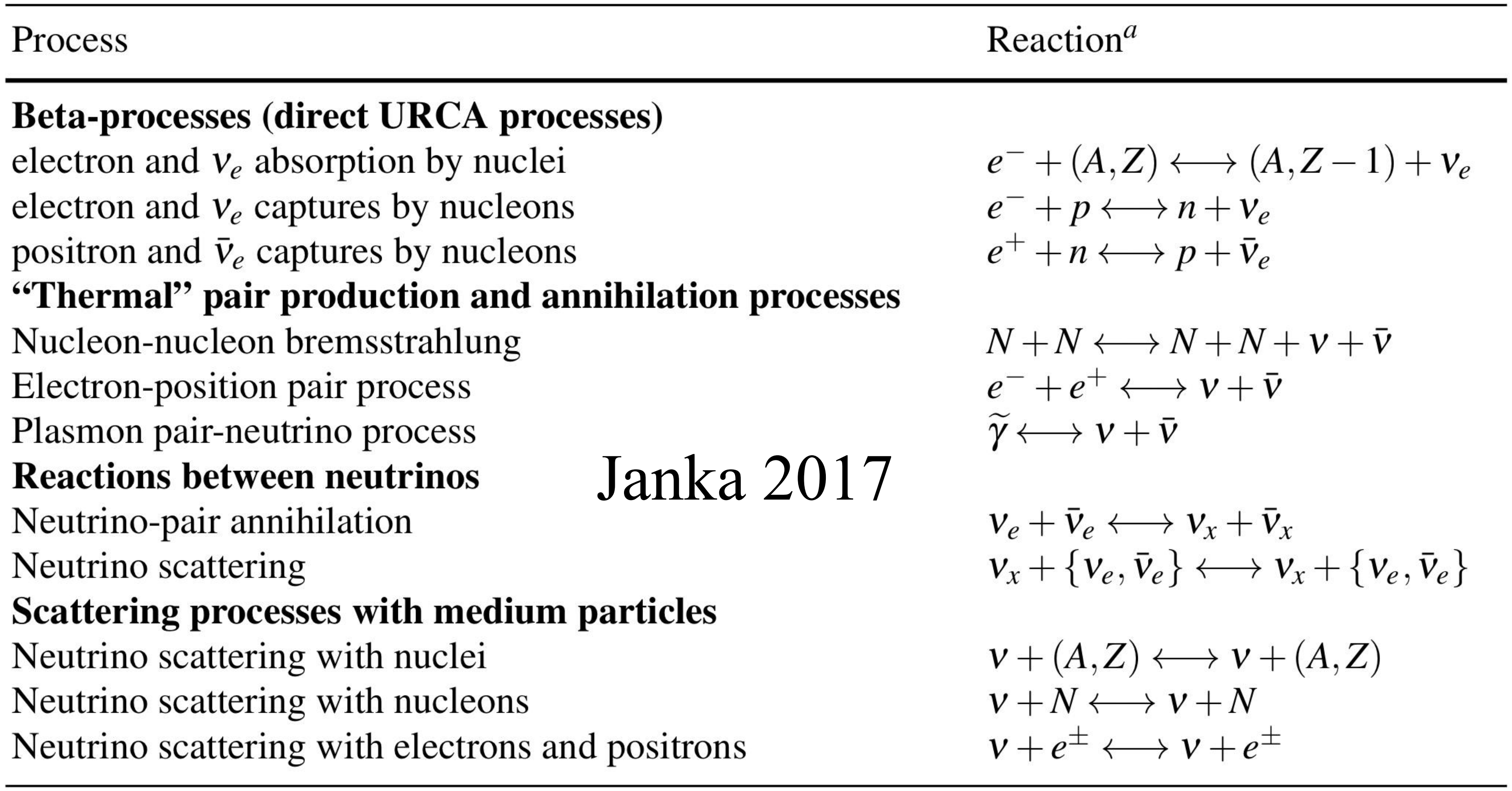


- Neutrino signals from core-collapse supernova (CCSN)
- Nucleosynthesis depends sensitively on the proton fraction Y_p

Accurate description of neutrino rates is highly demanded !!!

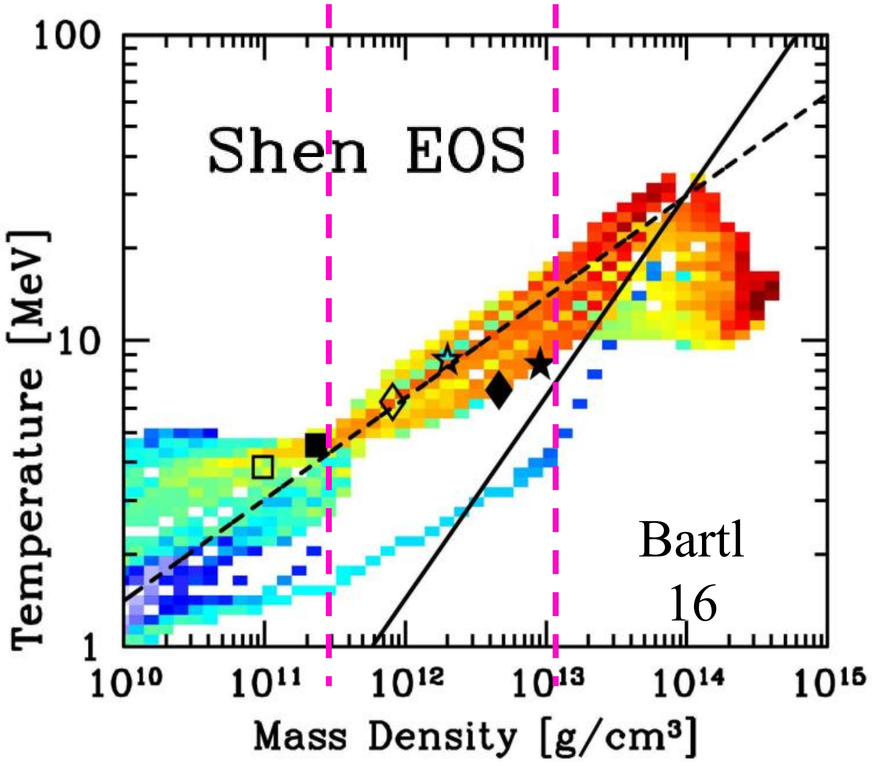
The nuclear Equation of State (EoS) matters too

Complicated Neutrinos Processes in CCSN



Process	Reaction[a]
Beta-processes (direct URCA processes)	
electron and ν_e absorption by nuclei	$e^- + (A,Z) \longleftrightarrow (A,Z-1) + \nu_e$
electron and ν_e captures by nucleons	$e^- + p \longleftrightarrow n + \nu_e$
positron and $\bar{\nu}_e$ captures by nucleons	$e^+ + n \longleftrightarrow p + \bar{\nu}_e$
“Thermal” pair production and annihilation processes	
Nucleon-nucleon bremsstrahlung	$N + N \longleftrightarrow N + N + \nu + \bar{\nu}$
Electron-position pair process	$e^- + e^+ \longleftrightarrow \nu + \bar{\nu}$
Plasmon pair-neutrino process	$\widetilde{\gamma} \longleftrightarrow \nu + \bar{\nu}$
Reactions between neutrinos	
Neutrino-pair annihilation	$\nu_e + \bar{\nu}_e \longleftrightarrow \nu_x + \bar{\nu}_x$
Neutrino scattering	$\nu_x + \{\nu_e, \bar{\nu}_e\} \longleftrightarrow \nu_x + \{\nu_e, \bar{\nu}_e\}$
Scattering processes with medium particles	
Neutrino scattering with nuclei	$\nu + (A,Z) \longleftrightarrow \nu + (A,Z)$
Neutrino scattering with nucleons	$\nu + N \longleftrightarrow \nu + N$
Neutrino scattering with electrons and positrons	$\nu + e^{\pm} \longleftrightarrow \nu + e^{\pm}$

Janka 2017



Bartl 16

neutrinosphere (below ϱ_0)

EoS (above ϱ_0)

Neutrino-nucleon rates are largely affected by the nuclear medium effects: mean field effects, nucleon correlation beyond mean field

hard to accurately compute

towards accurate description of neutrino-nucleon rates in CCSNe

- Neutrino-nucleon scattering or absorption rates at **mean field level**

$$\nu + N \rightarrow \nu + N; \quad \nu + N \rightarrow l^{-} + N$$

- Neutrino pair process from **nucleon-nucleon bremsstrahlung**

$$N + N \rightarrow N + N + \nu + \bar{\nu}; \quad N + N + \nu + \bar{\nu} \rightarrow N + N$$

- Neutrino-nucleon scattering rates taking into **nucleon-nucleon correlation**

$$\nu + N \rightarrow \nu + N$$

neutrino-nucleon reactions at mean field level

Each nucleon feels **an averaged potential** from all the other nucleons and nucleon in medium can be viewed as quasiparticles with modified energy-momentum relation as

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

depending on EoS

Reaction rate $\nu(K_1) + N(P_2) \to \nu(K_3) + N(P_4)$ or $\nu(K_1) + N(P_2) \to l(K_3) + N(P_4)$ from **Fermi's golden rule**:

$$\frac{d^2\Gamma}{d\omega d\cos\theta_{13}} = \frac{(1-f_3)k_3}{8\pi^2 E_1} \int \frac{d^3\boldsymbol{p}_2}{(2\pi)^3} \int \frac{d^3\boldsymbol{p}_4}{(2\pi)^3} \frac{|\mathcal{M}|^2}{4E_2^* E_4^*} \longrightarrow \text{amplitude squared}$$

$$\times (2\pi)^4 \delta^{(4)}(K_1 + P_2 - K_3 - P_4) f_2 (1 - f_4)$$

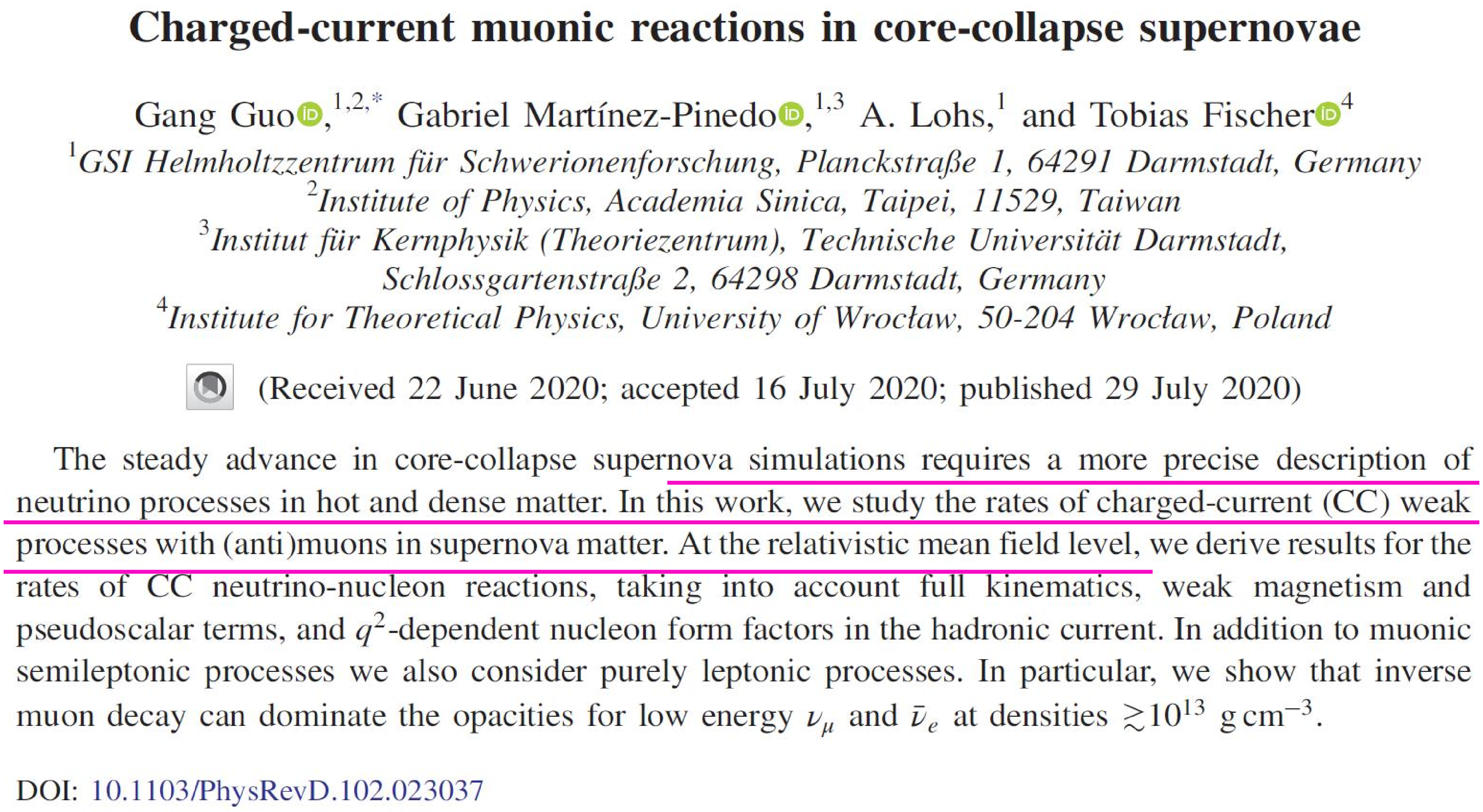
Hadronic current:

$$\bar{\psi}_4 \left\{ \underline{\gamma^\mu [G_V(q^2) - G_A(q^2)\gamma^5]} + \underline{\frac{iF_2(q^2)}{2M_N} \sigma^{\mu\nu} q_\nu^*} - \underline{\frac{G_P(q^2)}{M_N} \gamma^5 q^{*\mu}} \right\} \psi_2$$

Kinematics:

non-relativistic kinematics, elastic approximation, neglect final-state blocking, assume initial nucleons at rest, etc.

‘full’ treatments of neutrino–nucleon rates at **mean field level** are now available



Charged-current muonic reactions in core-collapse supernovae

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The steady advance in core-collapse supernova simulations requires a more precise description of neutrino processes in hot and dense matter. In this work, we study the rates of charged-current (CC) weak processes with (anti)muons in supernova matter. At the relativistic mean field level, we derive results for the rates of CC neutrino-nucleon reactions, taking into account full kinematics, weak magnetism and pseudoscalar terms, and q^2-dependent nucleon form factors in the hadronic current. In addition to muonic semileptonic processes we also consider purely leptonic processes. In particular, we show that inverse muon decay can dominate the opacities for low energy ν_μ and $\bar{\nu}_e$ at densities $\gtrsim 10^{13}$ g cm^{-3}.

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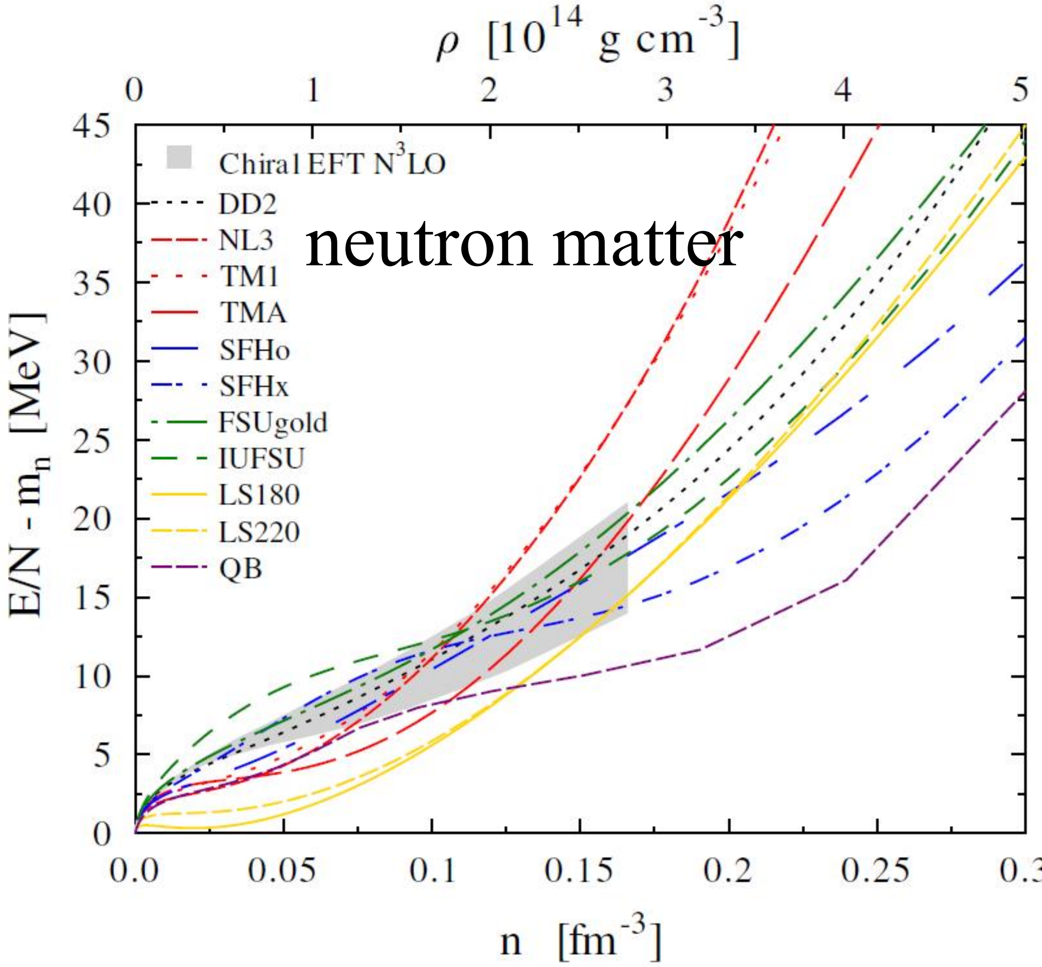
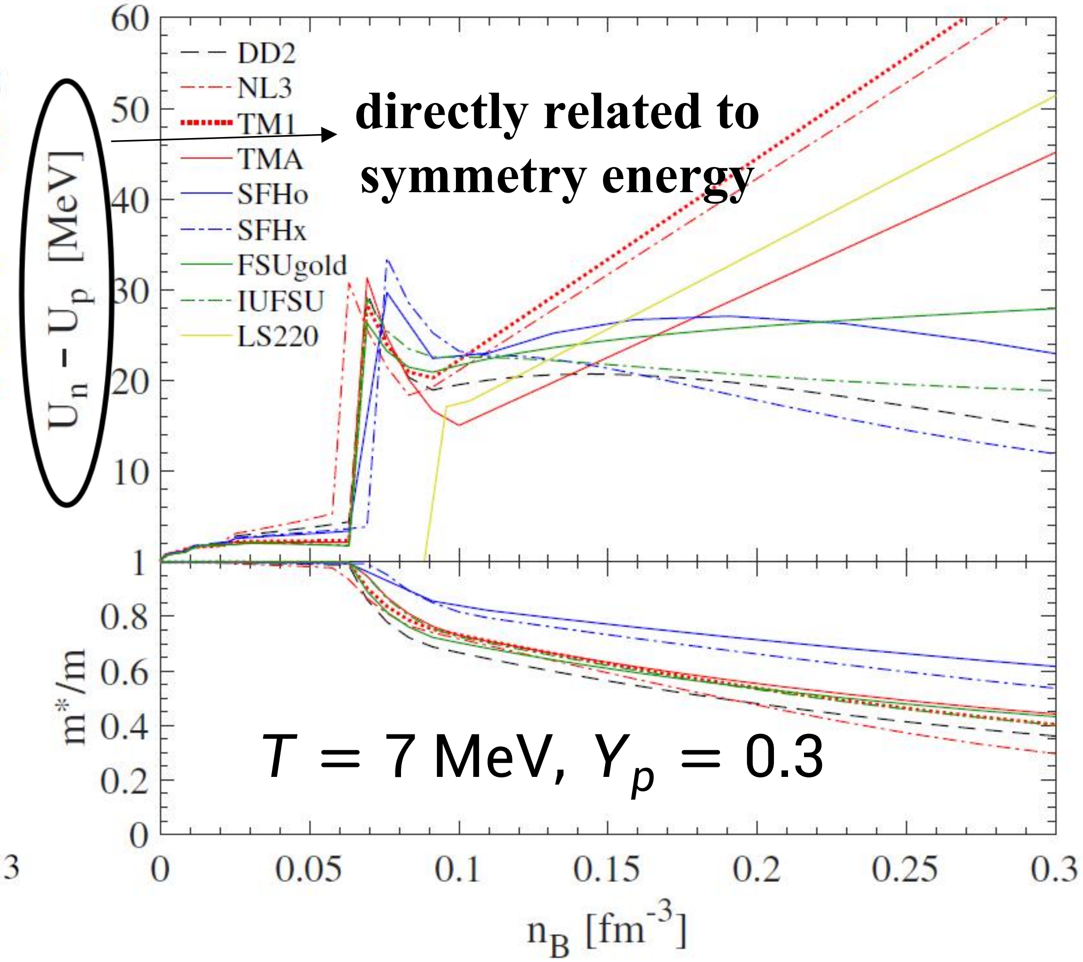
nontrivial dependence of neutrino rates on EoS



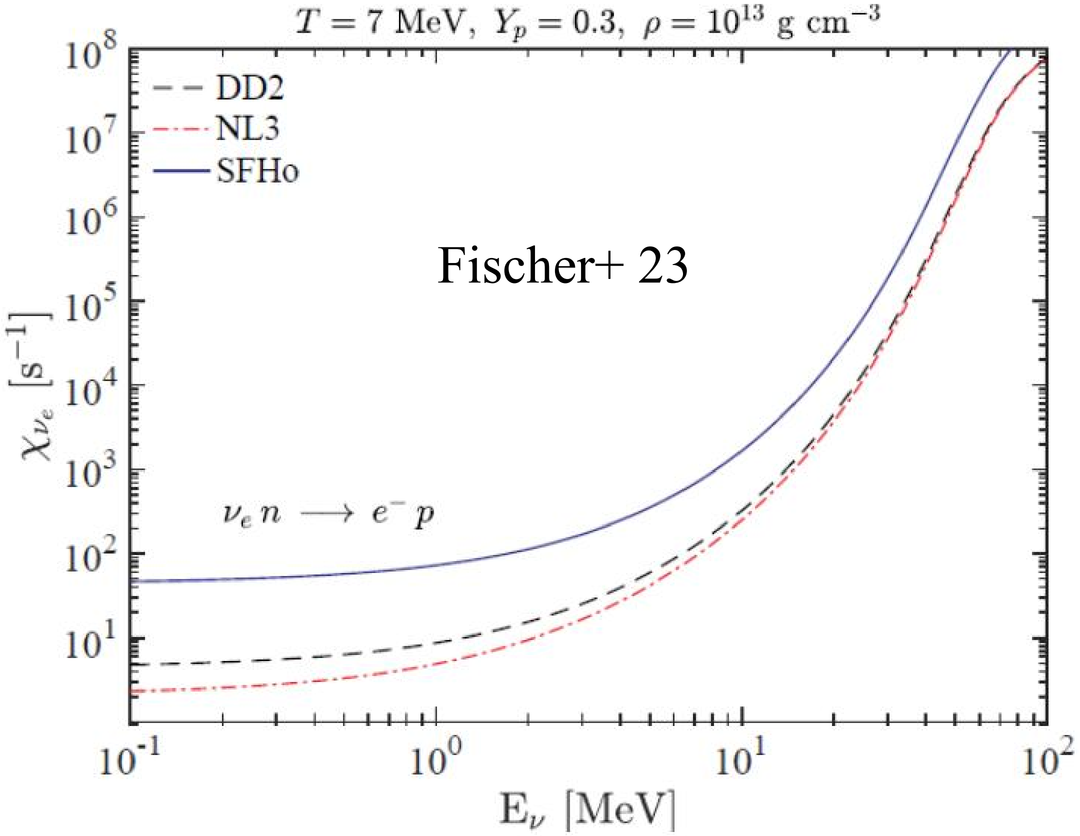


directly related to symmetry energy

$T = 7$ MeV, $Y_p = 0.3$

used EoS are mostly based on relativistic mean field theory

EoS (below ρ_0) taking into account cluster formation using χEFT potential is highly required !!!

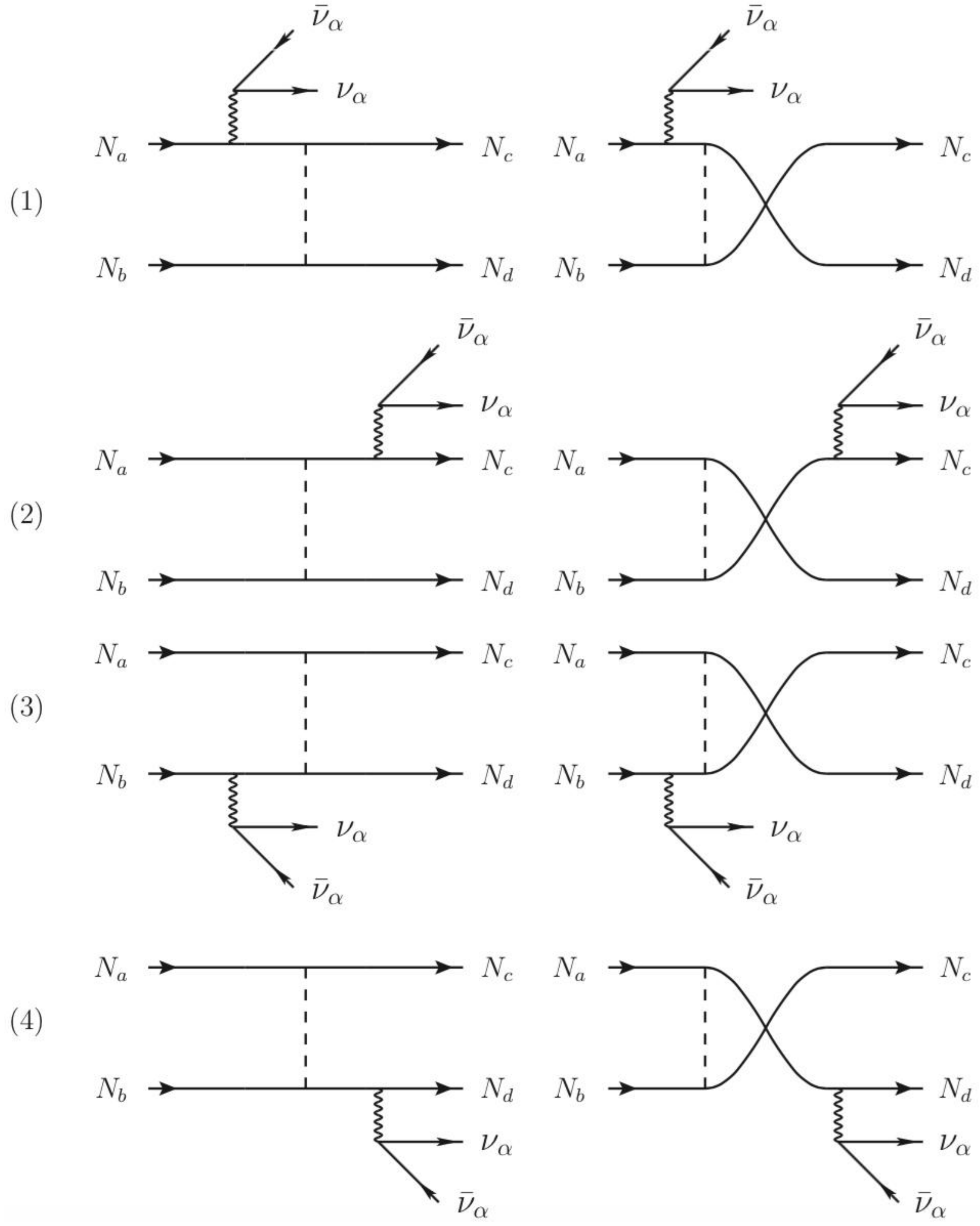


Fischer+ 23

Neutrino pair process from n-n bremsstrahlung

pair emission $N_a + N_b \rightarrow N_c + N_d + \nu_\alpha + \bar{\nu}_\alpha$

pair absorption $N_a + N_b + \nu_\alpha + \bar{\nu}_\alpha \rightarrow N_c + N_d$



direct exchanged

$$\mathcal{M}^{(1)} = \frac{G_F g_A^a}{2\sqrt{2}} \langle cd|V\sigma_i^{(a)}|ab\rangle \frac{l_i}{\omega}$$

$$\mathcal{M}^{(2)} = -\frac{G_F g_A^c}{2\sqrt{2}} \langle cd|\sigma_i^{(c)}V|ab\rangle \frac{l_i}{\omega},$$

$$\mathcal{M}^{(3)} = \frac{G_F g_A^b}{2\sqrt{2}} \langle cd|V\sigma_i^{(b)}|ab\rangle \frac{l_i}{\omega},$$

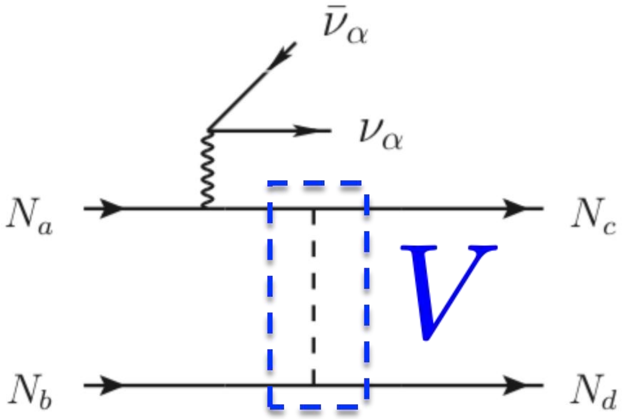
$$\mathcal{M}^{(4)} = -\frac{G_F g_A^d}{2\sqrt{2}} \langle cd|\sigma_i^{(d)}V|ab\rangle \frac{l_i}{\omega},$$

$$\mathcal{M}_{\text{tot}} = \sum_{j=1}^{4} \mathcal{M}^{(j)} = \frac{G_F g_A}{2\sqrt{2}} \langle cd|[V, \sum_{r=1,2} \sigma_i^{(r)}\tau_z^{(r)}]|ab\rangle \frac{l_i}{\omega},$$

$$g_A^p = -g_A^n = g_A \simeq 1.27$$

- only axial-vector term contributes in non-relativistic limit
- ignoring many-body interactions
- what to take for *V* ?

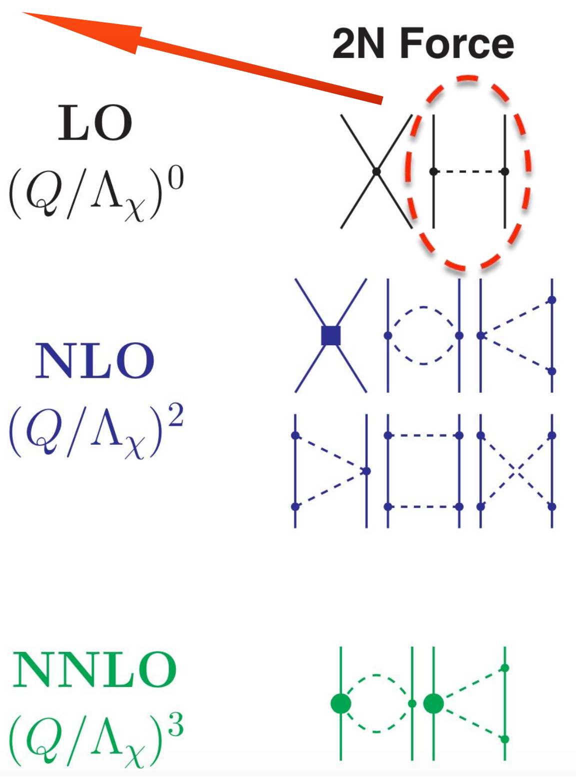
nucleon-nucleon potentials for



V could be (at Born level):

One-Pion Exchange (OPE) potential (Hannestad & Raffelt 1998)

$$V_{\rm OPE}(\vec{p}\,',\vec{p}\,) = -\frac{g_A^2}{4f_\pi^2}\vec{\tau}_1\cdot\vec{\tau}_2\frac{\vec{\sigma}_1\cdot\vec{q}\,\vec{\sigma}_2\cdot\vec{q}}{q^2+m_\pi^2}$$



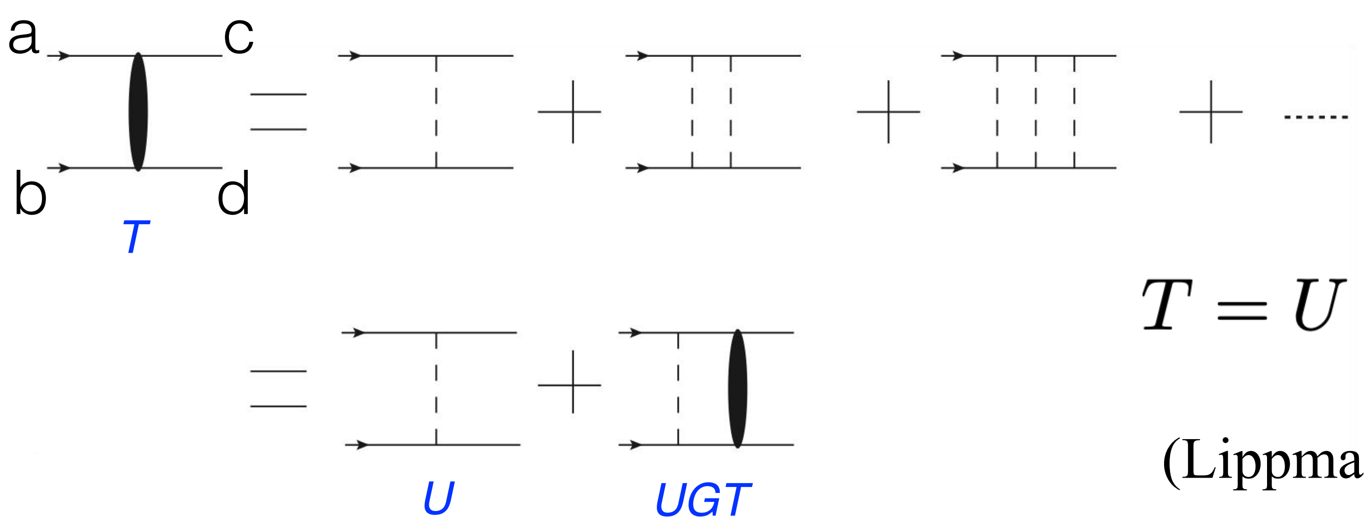
D. R. Entem *et al.* 2017

Chiral effective field theory potential

✦hamiltonian built from spontaneously broken chiral symmetry;

✦an expansion in terms of Q/Λ_χ, coefficients fitted to scattering data, reach desired accuracy

T-matrix formalism

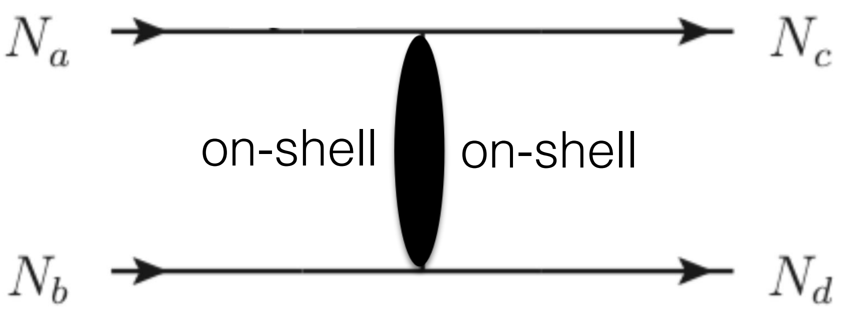


$$T = U + U\frac{1}{E - H_0 + i\epsilon}T$$

(Lippmann-Schwinger Equation)

scattering amplitude is proportional to the T-matrix

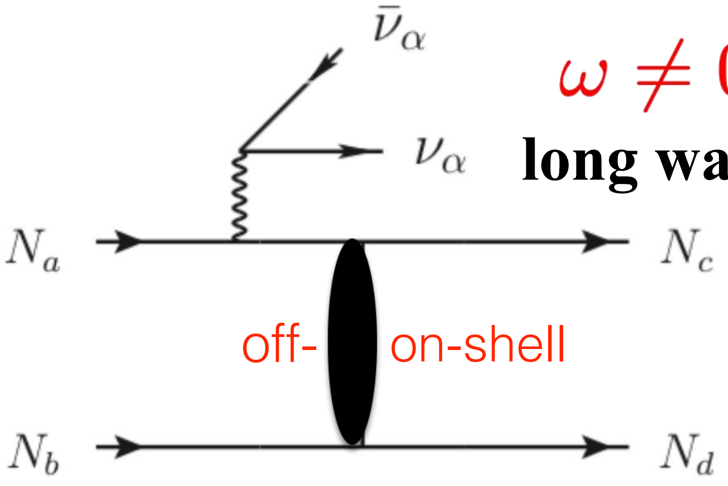
nucleon-nucleon scattering



$$E = k^2/m_N = k'^2/m_N$$

on-shell T-matrix (by Bartl+14)

nucleon-nucleon bremsstrahlung



$\omega \neq 0, q \to 0$

long wavelength limit

$$\frac{k^2}{m_N} - \omega = E = \frac{k'^2}{m_N}$$

half-off-shell T-matrix (by Guo+19)

T-matrix elements in partial wave basis

$$\mathcal{T}_{LL'}^{JST}(k',k;E) = U_{LL'}^{JST}(k',k) + \sum_{L''}\int \frac{k''^2 dk''}{(2\pi)^3} U_{LL''}^{JST}(k',k'') \frac{1}{E - \frac{k''^2}{m_N} + i\varepsilon} \mathcal{T}_{LL''}^{JST}(k'',k;E),$$

discretization of k, then

$$A_{ij}T_{jk} = U_{ik} \xrightarrow{\text{matrix inversion}} T = A^{-1}U$$

Bethe-Goldstone equation (in-medium version of LS)

$$\mathcal{T}_{LL'}^{JST}(k',k;K,\Omega) = V_{LL'}^{JST}(k',k) + \sum_{L''}\int \frac{k''^2 dk''}{(2\pi)^3} V_{LL''}^{JST}(k',k'')\bar{g}_{II}(K,\Omega,k'')\mathcal{T}_{L''L}^{JST}(k'',k;K,\Omega)$$

in-medium T-matrix

$$\bar{g}_{II}(K,\Omega,k) = \left\langle \frac{1 - f(\varepsilon(k_1)) - f(\varepsilon(k_2))}{\Omega - \varepsilon(k_1) - \varepsilon(k_2) + i\eta} \right\rangle_\theta$$

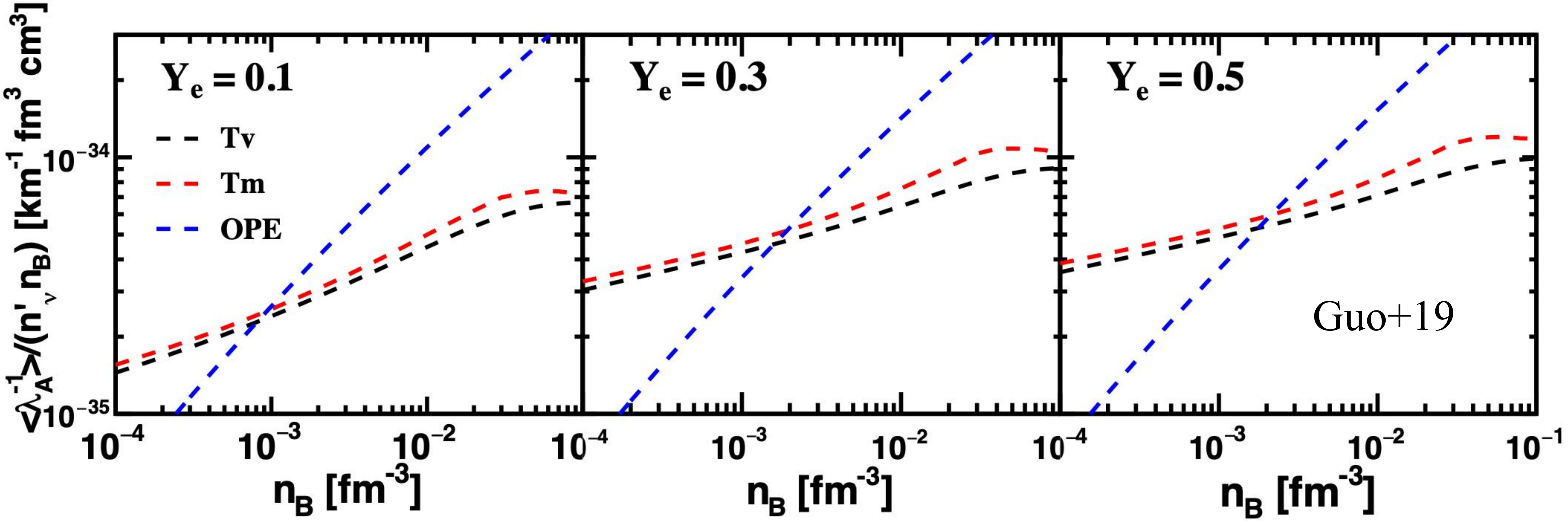
Including the blocking for the intermediate two-nucleon states

Take U to be the chiral potential of D. R. Entem et al. 2017, N4LO

half-off-shell vacuum/in-medium T-matrix is computed

OPE at Born level, vacuum/in-medium *T*-matrix from chiral potential

Born level is not enough



For *T*-matrix studies:

- ✦ enhanced rates at low density due to resonant nuclear force at low energy (**Bartl *et al.* 2014**)
- ✦ suppressed rates at high density due to repulsive short-range forces & non-perturbative effects
- ✦ medium effects on *T*-matrix (in-medium *T*-matrix) enhance rates by ~10%; RPA correlation effect is typically minor

- Neutrino-nucleon scattering or absorption rates at mean field level

$$\nu + N \to \nu + N; \quad \nu + N \to l + N$$

- Neutrino pair process from nucleon-nucleon bremsstrahlung

$$N + N \to N + N + \nu + \bar{\nu}; \quad N + N + \nu + \bar{\nu} \to N + N$$

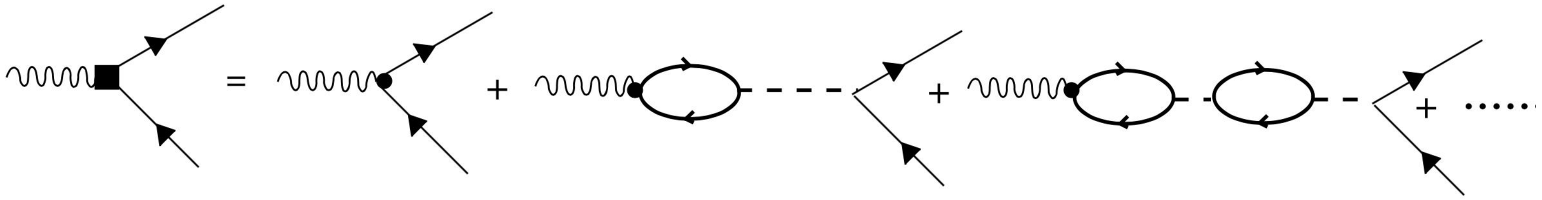
- **Neutrino-nucleon scattering rates considering nucleon-nucleon correlation**

$$\nu + N \to \nu + N$$

one of the keys to robust supernova explosion in simulation

Non-perturbative problem, no perfect way, approx. needed:

- Random Phase Approx. (RPA) (e.g., Burrows & Sawyer 98, 99)



- Virial expansion at low density (Horowitz+06, 17; Bedaque+18)
- Lattice Formulation (Alexandru et al. 20, 21; Ma et al. 24 with N3LO)
- Molecular dynamics simulation (Horowitz et al. 04, Li et al. 17)

neutrino-nucleon scattering rates from EoS calculations

Neutrino response (used to calculate the neutrino-nucleon scattering rate) is exactly given by the derivative

$$S_v(q=0) = \frac{z}{n}\left(\frac{\partial n}{\partial z}\right)_T = \frac{1+4b_n z}{1+2b_n z}$$

$z = e^{\mu/T}$: the fugacity parameter
b_n: 2nd virial coeffients

virial expansion at low densities (z < 0.5)

Horowitz et al. 06, 17; Lin et al 17

Limitations:

- Virial calculation of EoS only works at low density regions

- From the thermodynamic derivatives, one can only obtain the so-called **static neutrino response** in the **long wavelength limit** (i.e., neutrino-nucleon scattering with zero momentum & energy transfer). See also Bedaque+18

Brueckner-Hartree-Fock calculation of EoS

$$
\begin{aligned}
G^{JSS_z}_{ll'}(k',k;P,\Omega) =& V^{JS}_{ll'}(k',k) + \sum_{l''} \frac{k''^2 dk''}{(2\pi)^3} V^{JS}_{ll''}(k',k'') \\
& \times \bar{g}^{S_z}_{II}(P,\Omega,k'') G^{JSS_z}_{l''l'}(k'',k),
\end{aligned}
$$

G-matrix calculated based on chiral EFT potential

Neutron self-energy
(**pure neutron matter**)

$$
\begin{aligned}
\Sigma_\sigma(p,\varepsilon_\sigma(p)) =& \frac{1}{2\pi} \sum_{\sigma'=-\frac{1}{2}}^{\frac{1}{2}} \int \frac{d^3p'}{(2\pi)^3} \sum_{JlI'SS_z}^{S+l \text{ is even}} \left(C^{SS_z}_{\frac{1}{2}\sigma\frac{1}{2}\sigma'} \right)^2 \\
& \times \sum_{Lm} (-1)^m C^{J(m+S_z)}_{lmSS_z} C^{J(m+S_z)}_{l'mSS_z} C^{L0}_{lml'(-m)} C^{L0}_{l0l'0} [ll'] P_L(\hat{\boldsymbol{k}}) \\
& \times f_{\sigma'}(p') G^{JSS_z}_{ll'}(k,k;P,\Omega = \varepsilon_\sigma(p) + \varepsilon_{\sigma'}(p')),
\end{aligned}
$$

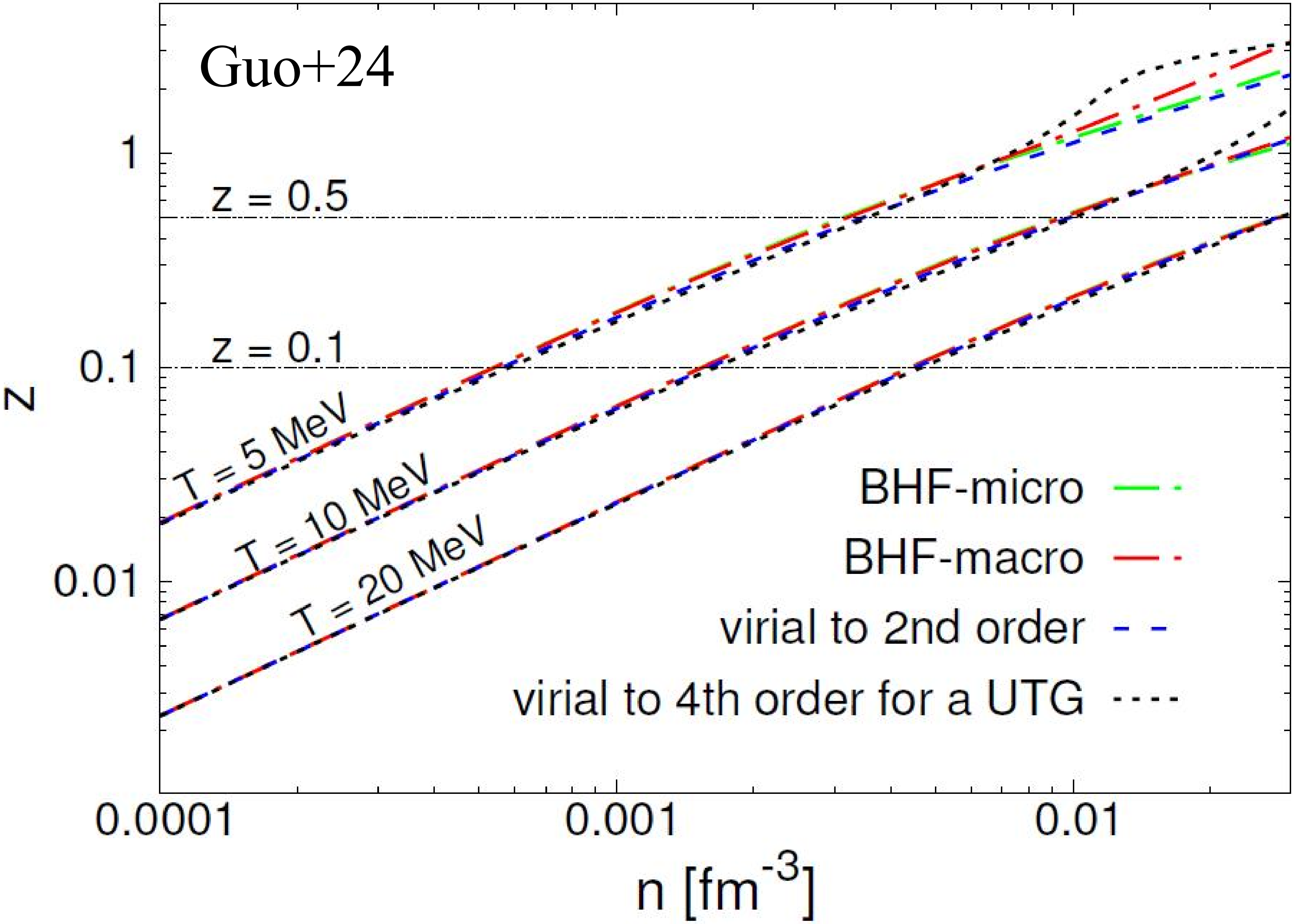
Thermodynamic quantities

$$
\begin{aligned}
f &= \epsilon - Ts, \\
\epsilon &= \sum_\sigma \int \frac{d^3p}{(2\pi)^3} \left[\frac{p^2}{2m_n} + \frac{1}{2}\mathrm{Re}\Sigma_\sigma(p,\varepsilon_\sigma(p)) \right] f_\sigma(p), \\
s &= -\sum_\sigma \int \frac{d^3p}{(2\pi)^3} \Big[f_\sigma(p) \ln \big(f_\sigma(p) \big) \\
& \qquad + \big(1 - f_\sigma(p)\big) \ln \big(1 - f_\sigma(p)\big) \Big].
\end{aligned}
$$

$$
\tilde{\mu} = T \ln(\tilde{z}) = \left(\frac{\partial f}{\partial n} \right)_T,
$$

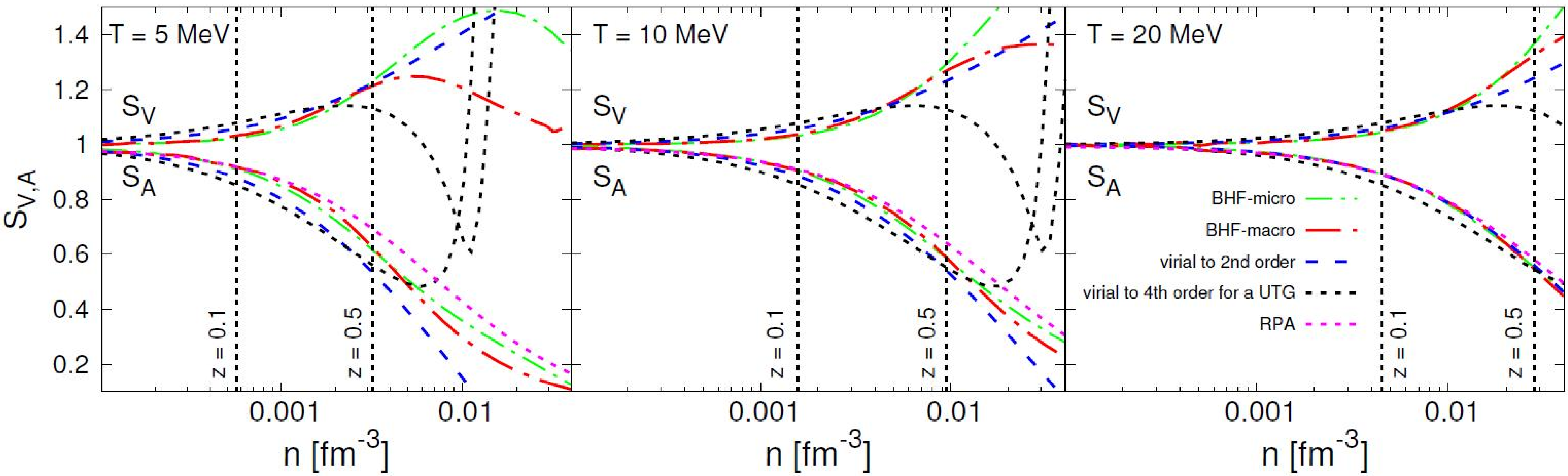
Guo+24

$z = e^{\mu/T}$



BHF reproduces the virial results at low densities

static responses from virial expansion & BHF



Guo+24

S_V: neutrinos couple to nucleon density

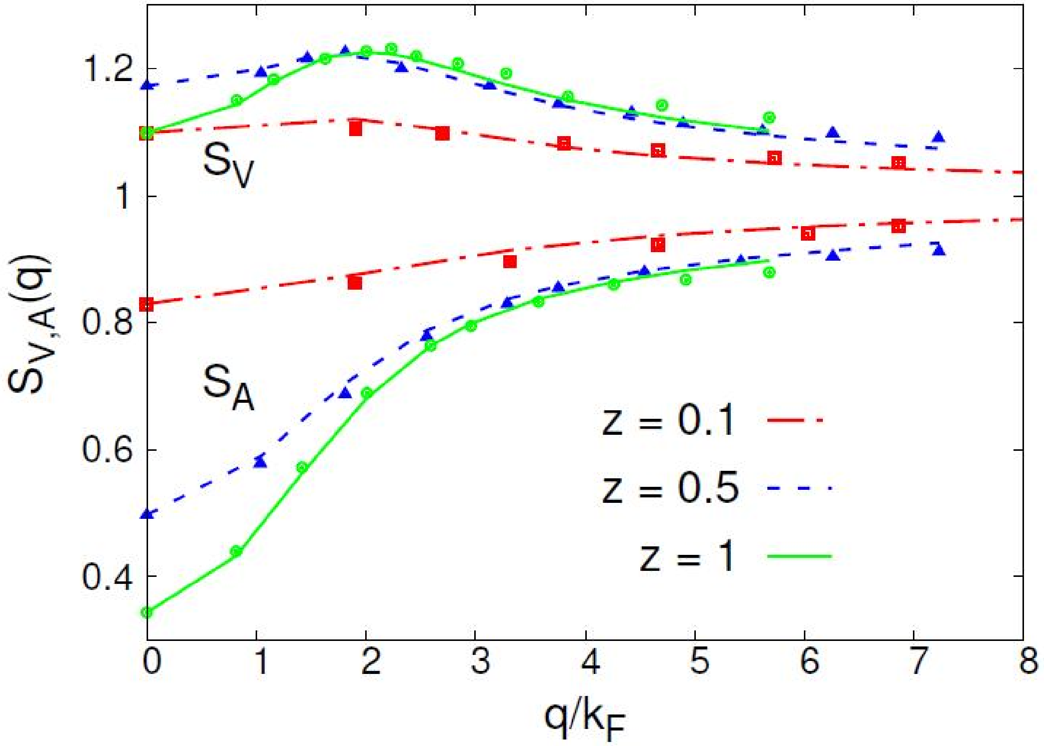
S_A: neutrinos couple to nucleon spin density

Virial results are ill-behaved at high densities ($z \geqslant 0.5$), while the BHF calculations are more reliable

from static responses to dynamic ones

To recover the momentum transfer-dependence

SN neutrinosphere ~ dilute neutron gas ~ a unitary gas



Lattice calculation for a unitary gas at SN conditions (Alexandru+2020)

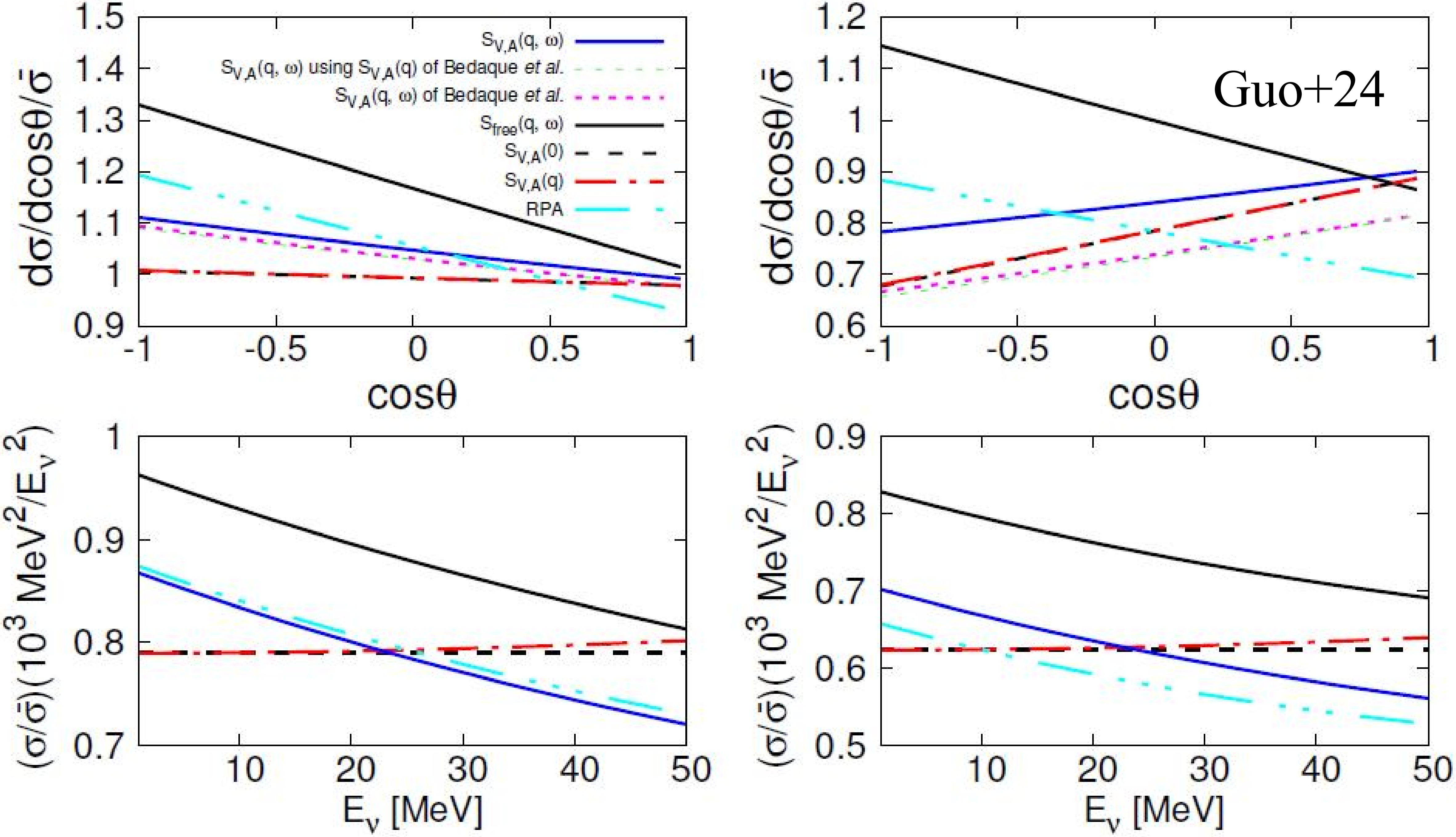
To recover the energy transfer-dependence using sum rules

$$S_{V,A}(q,\omega) = A_{V,A}\ e^{-\frac{(\omega-\omega_q)^2}{4\omega_q T}} + B_{V,A}\ e^{-\frac{(\omega-\frac{1}{2}\omega_q)^2}{2\omega_q T}},$$

$$\int_{-\infty}^{+\infty} d\omega\omega S_{V,A}(q,\omega) = \int_0^{+\infty} d\omega(1+e^{-\omega/T})\omega S_{V,A}(q,\omega) = \frac{q^2}{2m_n},$$

$$\int_{-\infty}^{+\infty} d\omega S_{V,A}(q,\omega) = \int_0^{+\infty} d\omega(1+e^{-\omega/T}) S_{V,A}(q,\omega) = S_{V,A}(q).$$

Neutrino-nucleon rates with static & dynamic responses



Guo+24

Correlation reduces the scattering rates by 10%-15%; Dynamic response enhances/suppresses the rates for low/high-energy neutrinos.

Summary

- Full weak interaction terms of nucleons at **mean field level** and relativistic kinematics (Robert+17; Fischer+20; Guo+20)

$$j^\mu = \bar{\psi}_4 \left\{ \gamma^\mu [G_V(q^2) - G_A(q^2)\gamma^5] + \frac{iF_2(q^2)}{2M_N} \sigma^{\mu\nu} q^*_\nu - \frac{G_P(q^2)}{M_N} \gamma^5 q^{*\mu} \right\} \psi_2$$

EoS of nuclear matter considering light cluster at subsaturation densities based on χEFT potential is highly desired !!!

- **Neutrino-nucleon bremsstrahlung** revisited with **full T-matrix using χEFT potential** (Guo & Martinez-Pinedo 19); **3-body force, mean field effects**

- Many progresses on **nucleon correlation effects**, especially the ab initio studies using **χEFT potential**

Guo et al. 24: neutrino rates from BHF caculation of EoS with **χEFT potential (N4LO)**

Duan & Urban 23: **the 1st mean field (HF level) + RPA study using χEFT potential (N3LO-414)**

Ma et al. 24: the **1st** ab initio lattice calculations in hot neutron matter using **χEFT potential (N3LO-414)**

Thanks

backup

Adopt typical conditions in SN

$$T_{SN}(\rho) = 3\ \mathrm{MeV}\ \left(\frac{\rho}{10^{11}\ \mathrm{g\ cm^{-3}}}\right)^{1/3}$$

$$\rho : 1.7 \times 10^{11-14}\ \mathrm{g/cm^3}$$

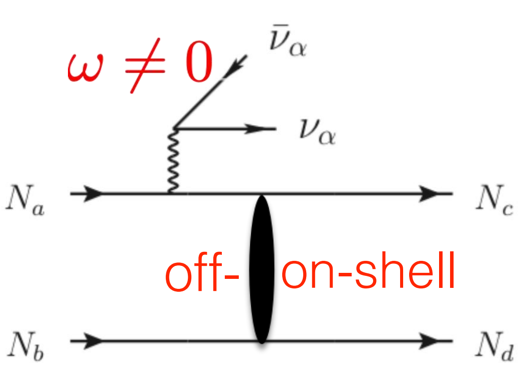
$$n_B : 10^{-4} - 10^{-1}\ \mathrm{fm^{-3}}$$

$$Y_e = \frac{n_p}{n_B} = \frac{n_p}{n_n + n_p} < 0.5$$

Opacity due to pair absorption $N + N + \nu + \bar{\nu} \rightarrow N + N$

$$\frac{\langle \lambda_A^{-1} \rangle}{n'_\nu} \equiv \frac{1}{n'_\nu} \frac{\int \lambda_A^{-1}(E_\nu) f(E_\nu) E_\nu^2 dE_\nu}{\int f(E_\nu) E_\nu^2 dE_\nu}$$

using effective on-shell T-matrix is not enough

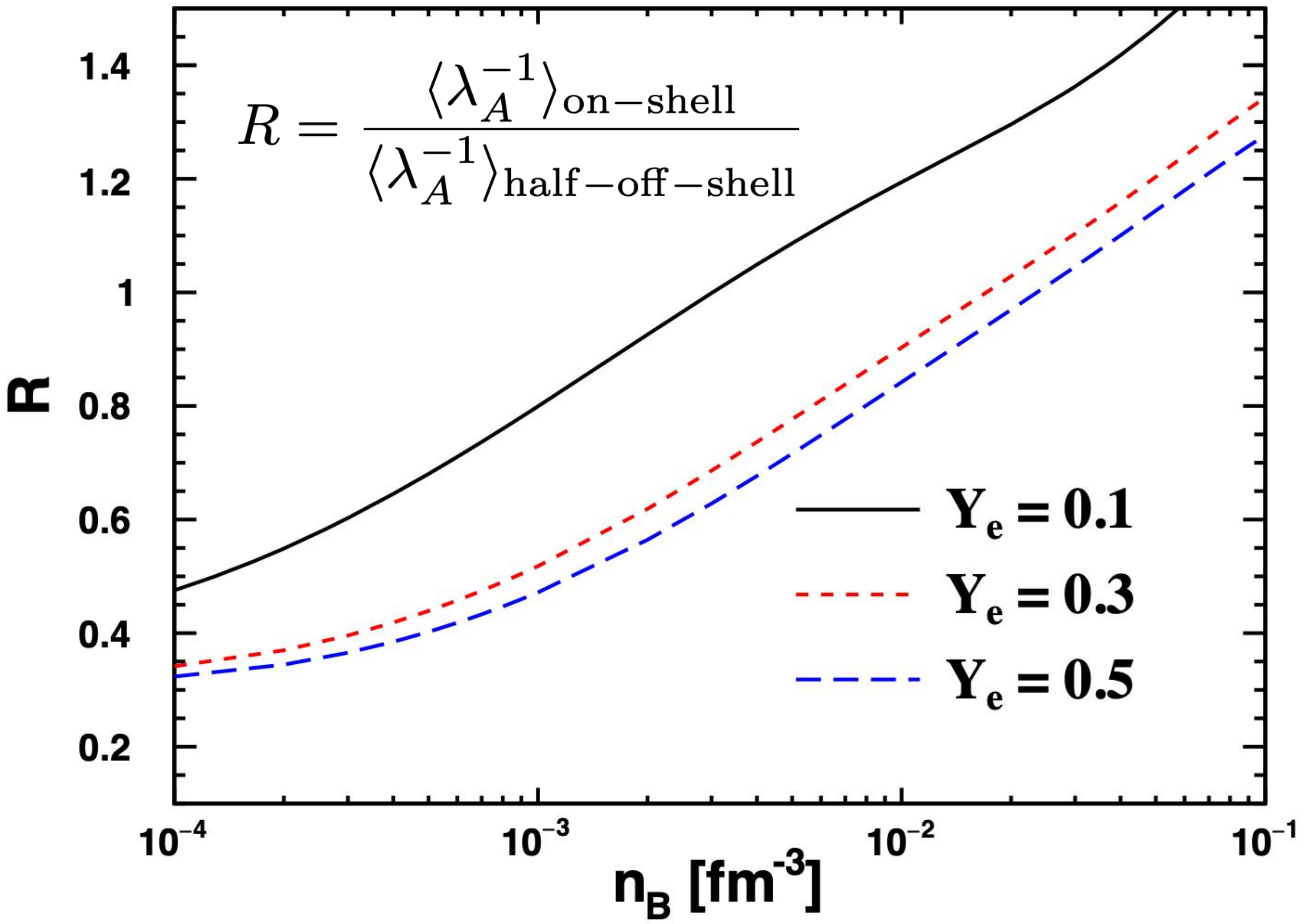


$$\langle k_f|\mathcal{T}|k_i\rangle \longrightarrow \langle \bar{k}|\mathcal{T}|\bar{k}\rangle, \quad \bar{k} = \sqrt{\frac{1}{2}(k_i^2 + k_f^2)}$$

half-off-shell ‘on-shell’

Bartl *et al.* 2014

(can be simply extracted from NN scattering data)



virial expansion at low densities

SN neutrinosphere: T ~ 5-10 MeV; density~1E12-1E13 g/cm^3

neutron rich (with proton fraction < 10%)

SN neutrinosphere ~ dilute neutron gas ~ a unitary gas

(with a very large scattering length &
small interaction range)

virial expansion of the EoS for the dilute neutron gas

$$P = \frac{2T}{\lambda^3}\left(z + z^2 b_n + z^3 b_n^{(3)} + \mathcal{O}(z^4)\right)$$

$$n = \frac{2}{\lambda^3}\left(z + 2z^2 b_n + 3z^3 b_n^{(3)} + \mathcal{O}(z^4)\right)$$

$z = e^{\mu/T}$: the fugacity parameter, with μ the nucleon chemical potential;

b_n: the 2nd virial coefficients, related to neutron scattering phase shifts.

virial results are reliable & model-independent

Complicated Neutrinos Processes in CCSNe

Collapse phase:

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

$$e^- + (A,Z) \longrightarrow \nu_e + (A,Z-1)\,,$$

$$\nu + A \rightleftarrows \nu + A \text{ (trapping)} \quad \gtrsim 10^{12}\ \mathrm{g/cm^3}$$

Bounce shock & neutrino burst: $e^- + p \longleftrightarrow n + \nu_e$

Accretion phase & neutrino heating:

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

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

Cooling phase:

$$N + N \to N + N + \nu + \bar{\nu}$$

$$e^- + e^+ \to \nu + \bar{\nu}$$

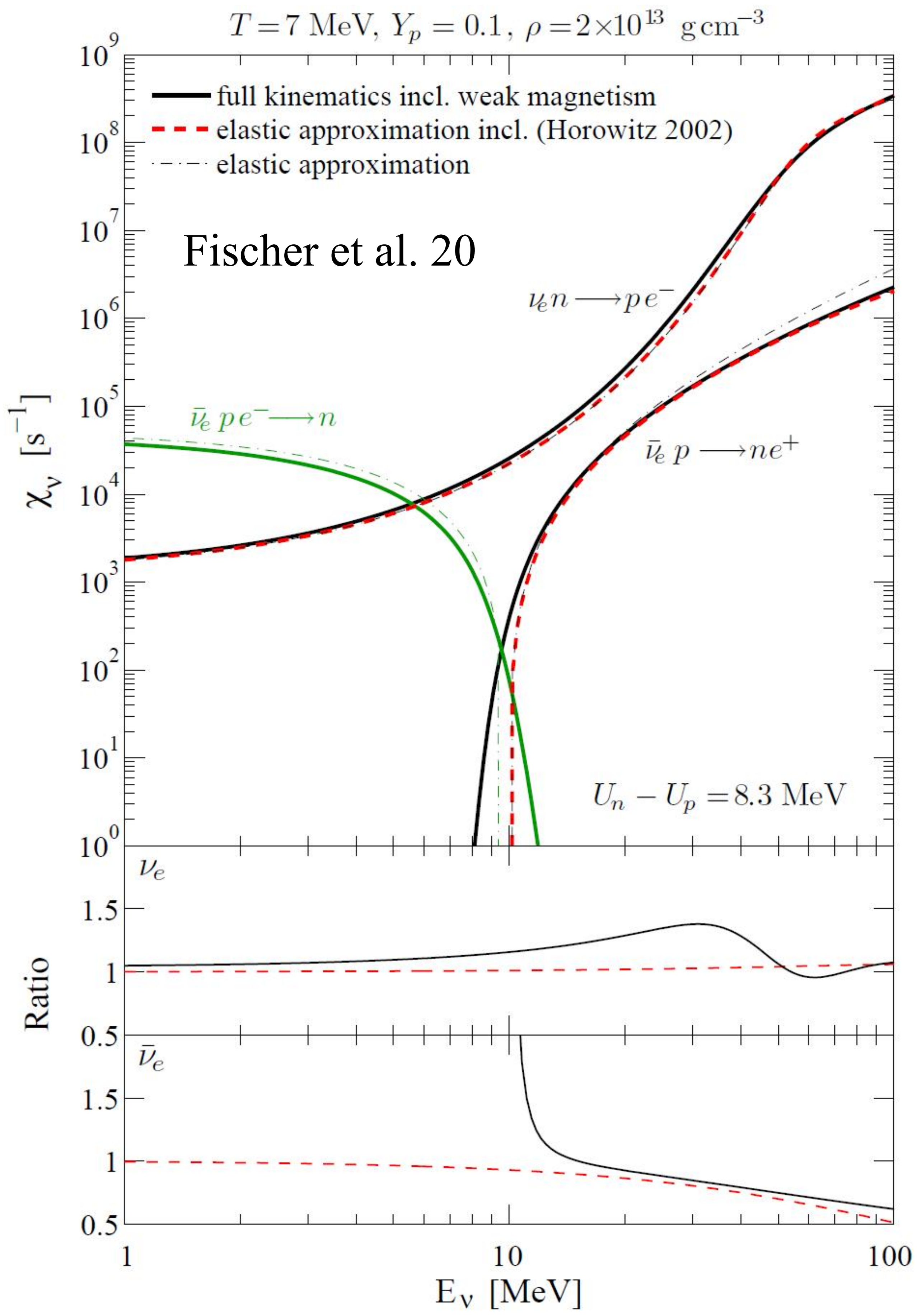
$$\gamma^* \to \nu + \bar{\nu}$$

Neutrino pair-production

High-Dimension Detailed Neutrino Transport is Required

very time-consuming!

charged-current opacities for $\nu_e(\bar{\nu}_e)$

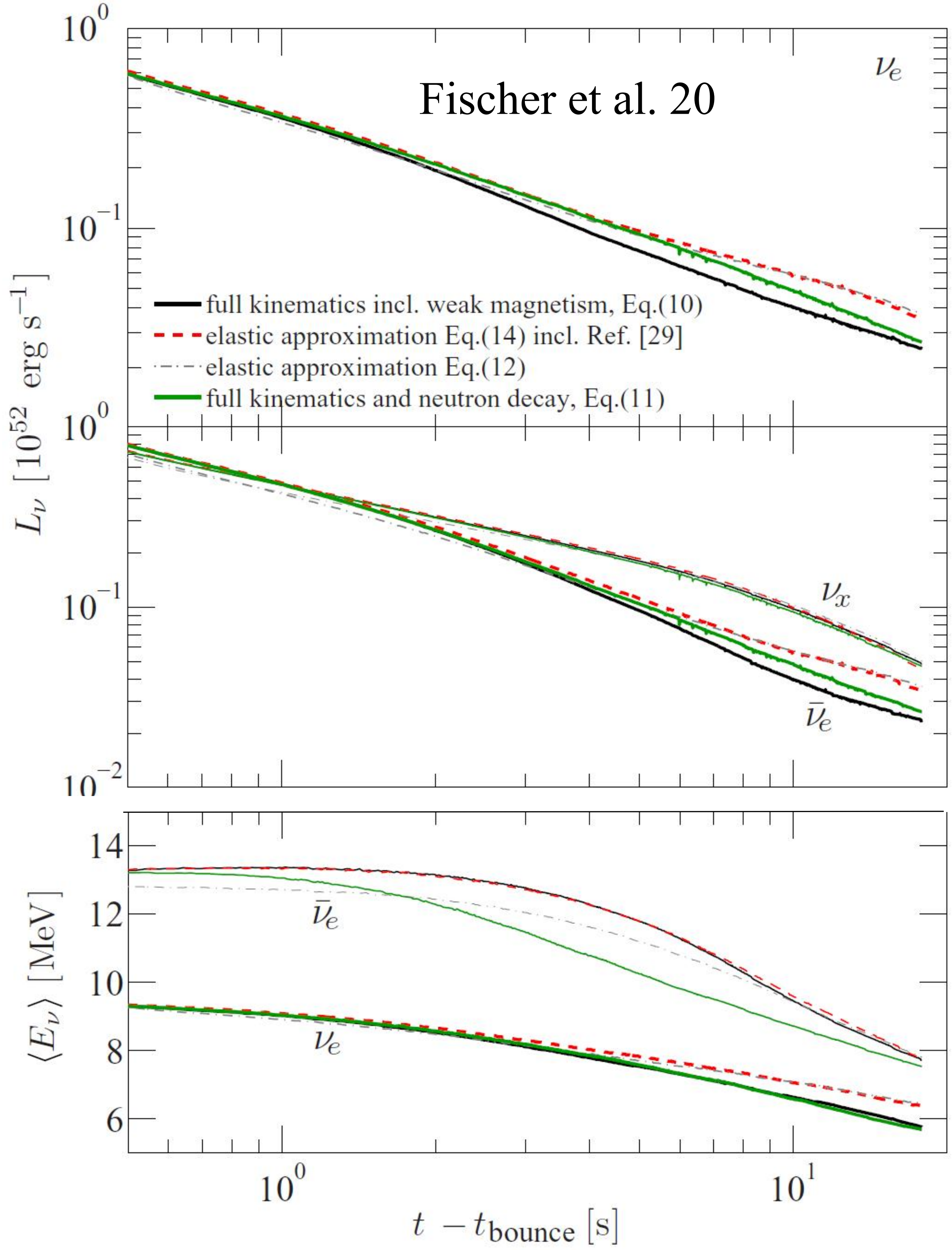


Fischer et al. 20

weak magnetism + full kinematics enhances opacities for $\nu_e/\bar{\nu}_e$ at low & intermediate energies

inverse neutron decay contributes significantly to $\bar{\nu}_e$ opacity at low energies

effects of CC ν_e rates on SN neutrino signals


Fischer et al. 20

larger opacity
↓
lower luminosity

larger (inelastic) opacity
↓
decouple at lower density region with lower temperatures

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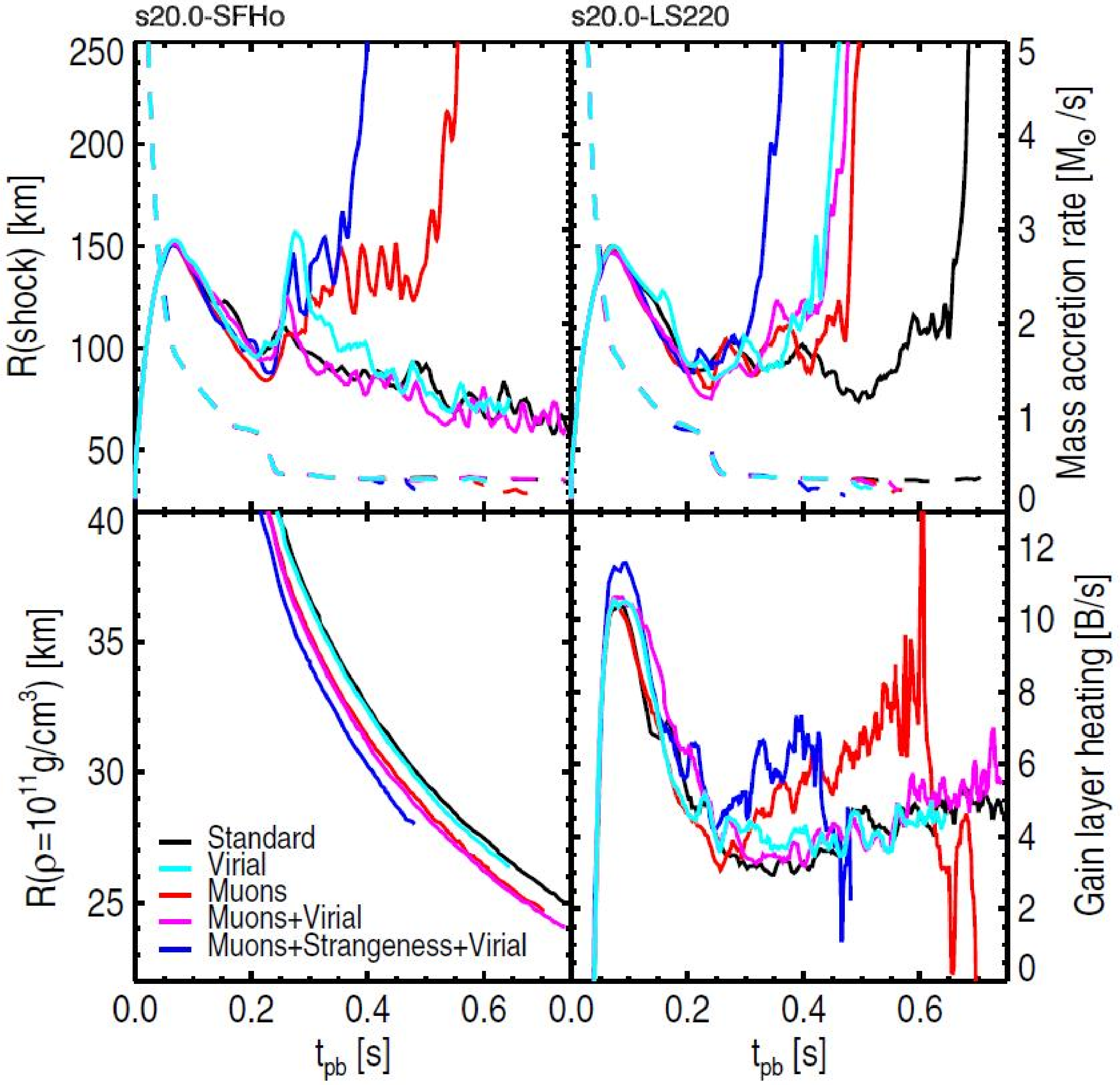
inclusion of inverse neutron decay

- larger $\bar{\nu}_e$ opacity → lower E_ν;
- less spectral difference between ν_e and $\bar{\nu}_e$ → higher $Y_e \sim 0.5$ & lower neutron abundance
  → lower scattering opacity on neutron
  → higher luminosity for both ν_e and $\bar{\nu}_e$

muons facilitates supernova explosion



Bollig et al. 17

large muon rest mass, CC for muonic rates were previously ignored

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

creation of μ^- and μ^+ softens the EoS by conversion of thermal and degeneracy energy of e^- into rest-mass energy of $\mu^\pm$

↓

neutrino luminosities and average energy increase

↓

enhanced neutrino heating & easier explosion

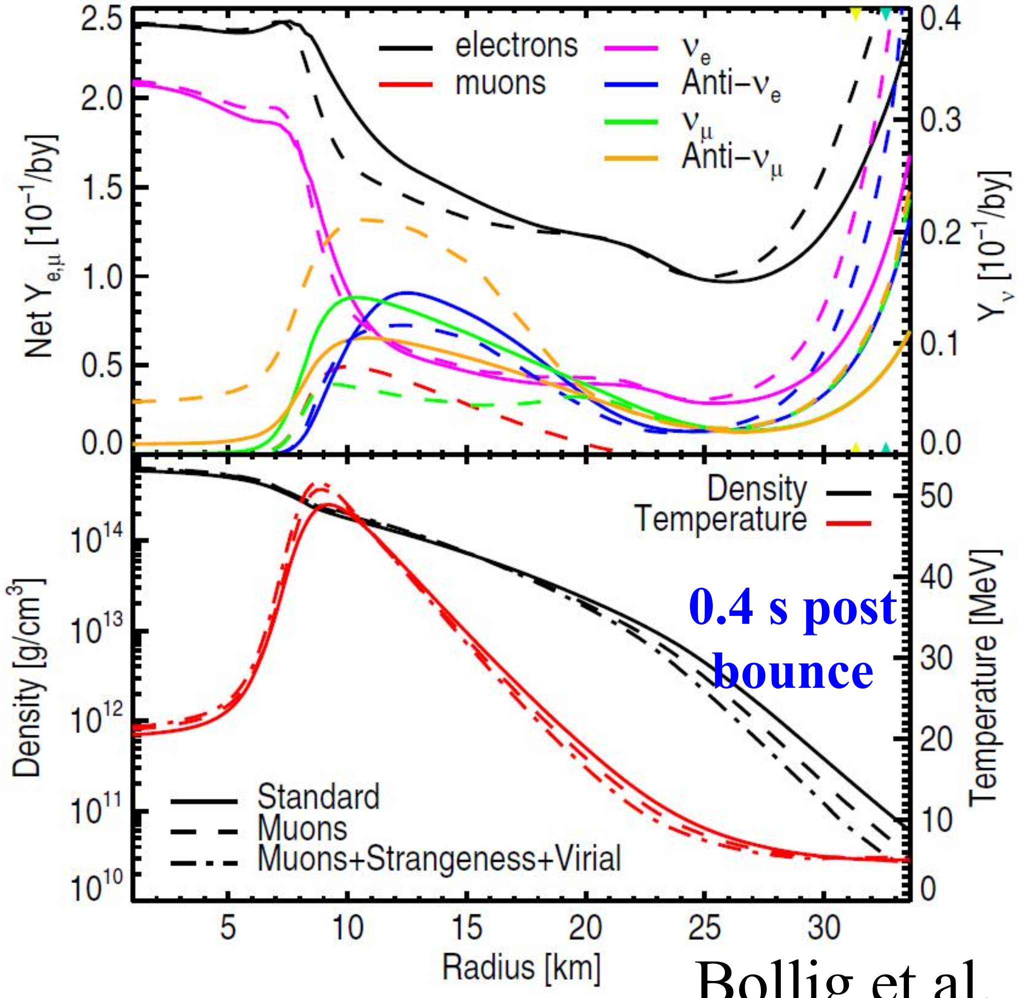
muonization and neutrino rates

muon-neutrinos are pair produced around core bounce

$\nu_\mu + n \rightarrow \mu^- + p$ (faster)

$\bar{\nu}_\mu + p \rightarrow \mu^+ + n$ (slower)

$\bar{\nu}_\mu$ escape more easily with lower opacities, which also aids muonization (an excess of μ^- over μ^+)



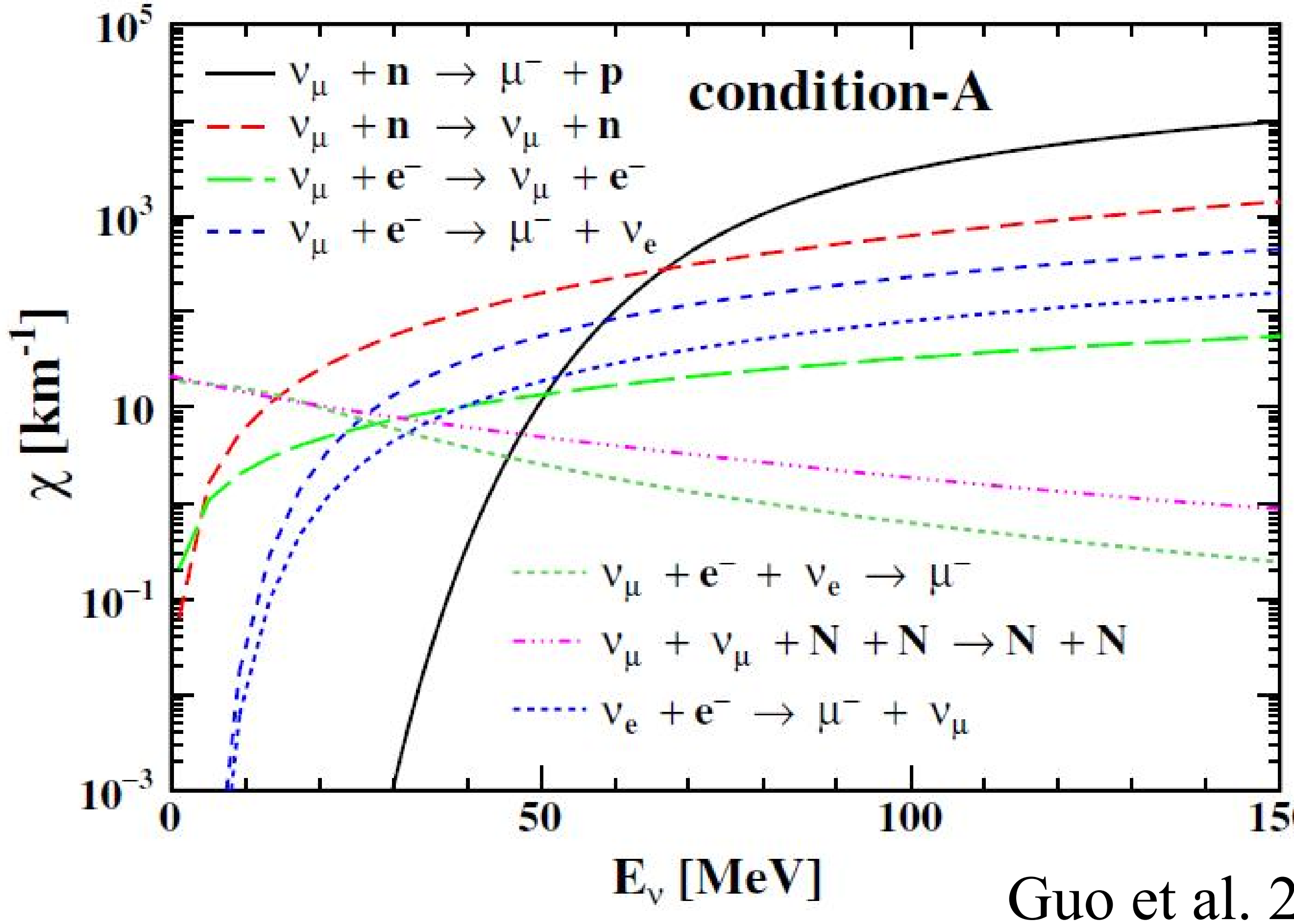
0.4 s post bounce

Bollig et al. 17

reactions involving muons

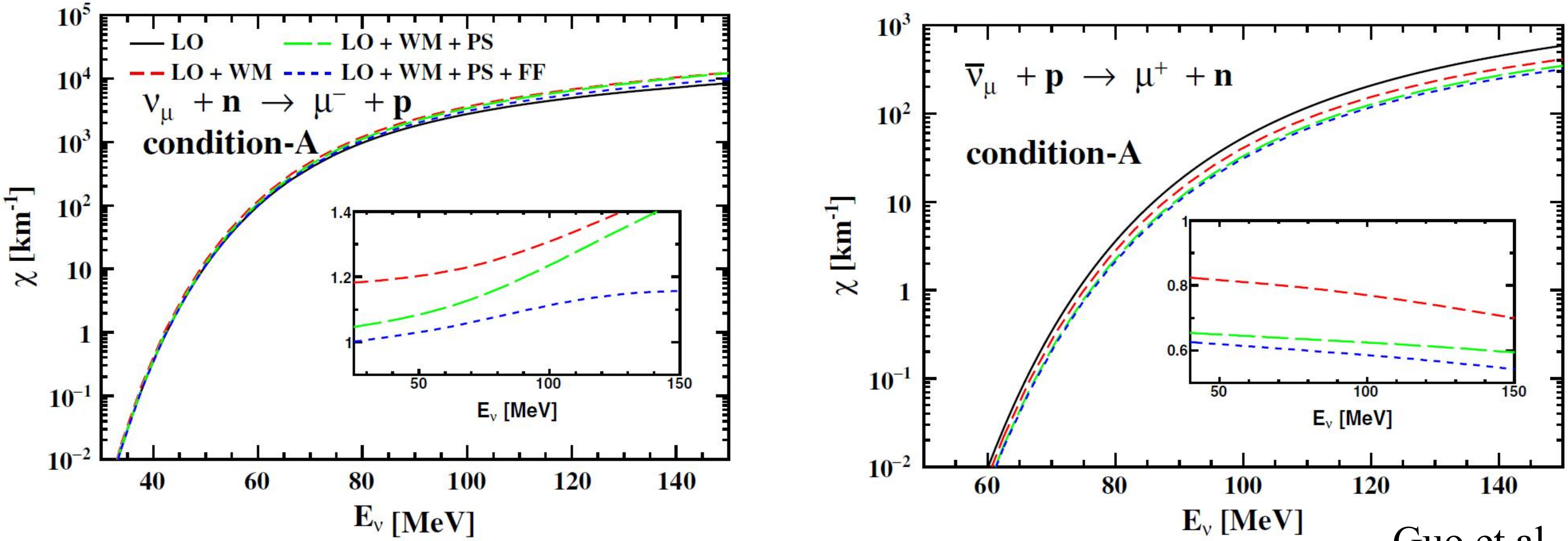
$\nu + \mu^- \rightleftarrows \nu' + \mu^{-\prime}$	$\nu + \mu^+ \rightleftarrows \nu' + \mu^{+\prime}$
$\nu_\mu + e^- \rightleftarrows \nu_e + \mu^-$	$\bar{\nu}_\mu + e^+ \rightleftarrows \bar{\nu}_e + \mu^+$
$\nu_\mu + \bar{\nu}_e + e^- \rightleftarrows \mu^-$	$\bar{\nu}_\mu + \nu_e + e^+ \rightleftarrows \mu^+$
$\bar{\nu}_e + e^- \rightleftarrows \bar{\nu}_\mu + \mu^-$	$\nu_e + e^+ \rightleftarrows \nu_\mu + \mu^+$
$\nu_\mu + n \rightleftarrows p + \mu^-$	$\bar{\nu}_\mu + p \rightleftarrows n + \mu^+$

CC $\nu_\mu(\bar{\nu}_\mu)$-nucleon dominates muonization



Guo et al. 20

accurate calculation of CC muonic rates with nucleons at mean field level

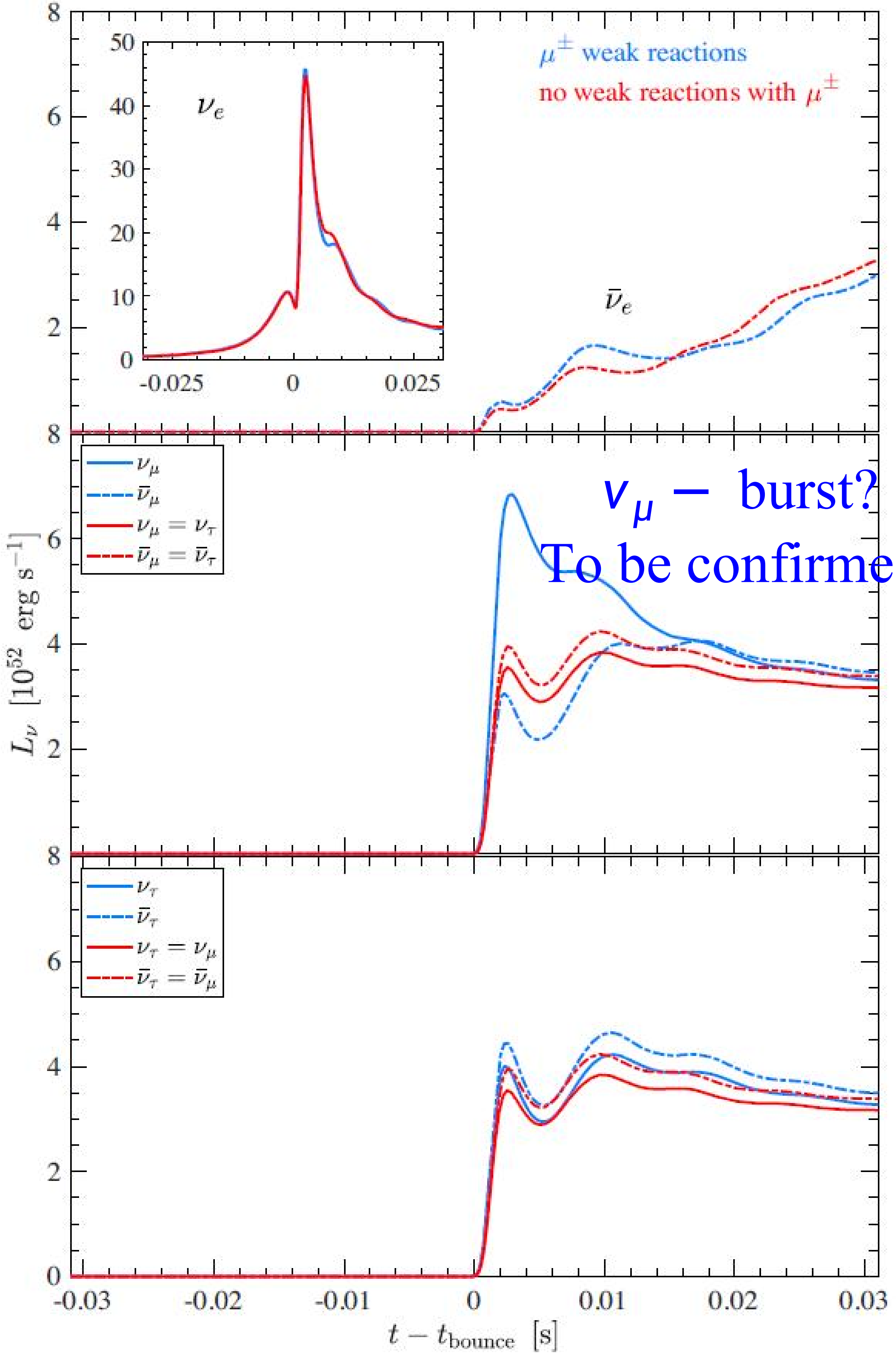


Guo et al. 20

$$\bar{\psi}_4\left\{\gamma^\mu[G_V(q^2)-G_A(q^2)\gamma^5]+\frac{iF_2(q^2)}{2M_N}\sigma^{\mu\nu}q^*_\nu\underline{-\frac{G_P(q^2)}{M_N}\gamma^5 q^{*\mu}}\right\}\psi_2$$

- pseudoscalar term and form factor dependence matter for muonic reaction;
- For ν_μ, the enhancement due to weak magnetism is largely cancelled;
- The rates for $\bar{\nu}_\mu$ are highly suppressed as all corrections reduce the rate;
- The new muonic rates to be tested in simulations.

effects on neutrino signals

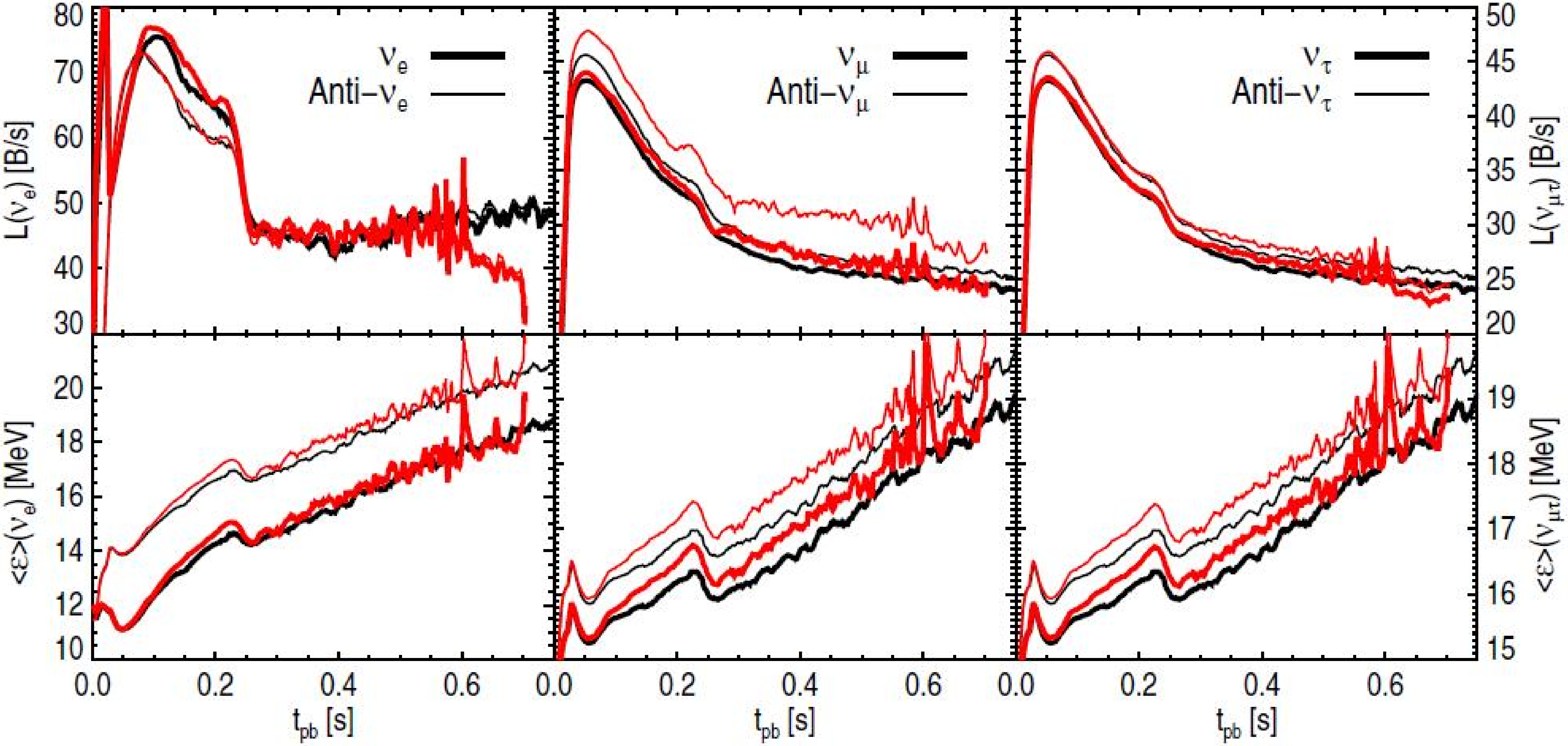


ν_μ − burst?
To be confirmed!

(a) Luminosty

Fischer et al. 20

muons rates on neutrino signals



Bollig+17

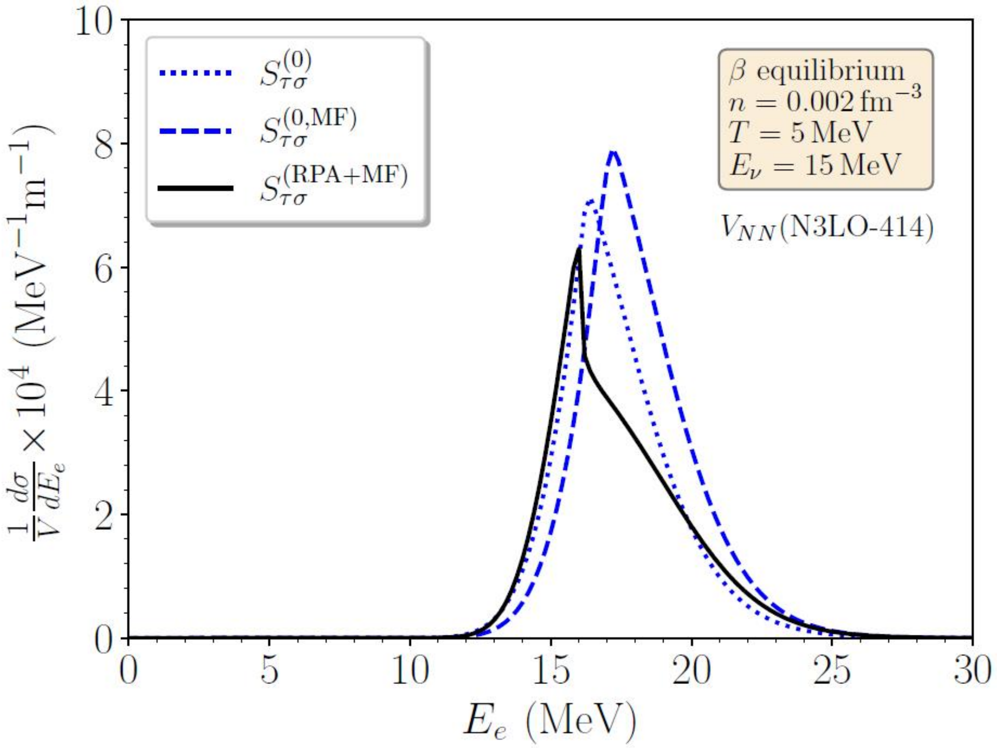
RPA corrections on neutrino opacity

ph interaction in terms of simple Landau parameters (Burrows & Sawyer 98, 99)

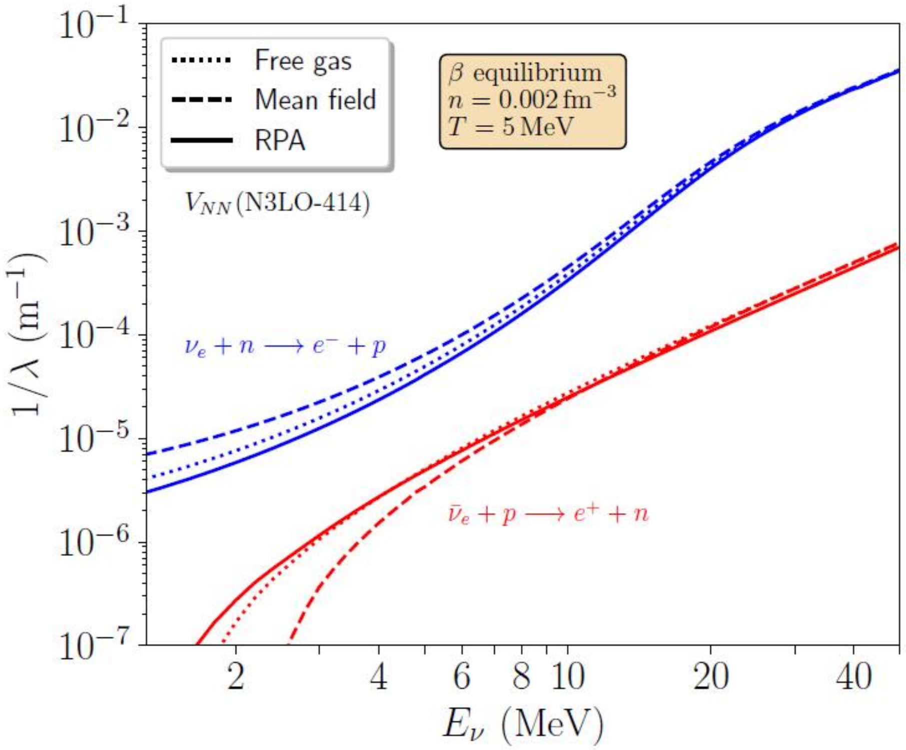
Full ph interaction from Skyrme interactions (Duan & Urban 23)

$$\mathcal{V}^0_{21} = \frac{\delta^2 E_s}{\delta\rho_{2'2}\delta\rho_{11'}},$$

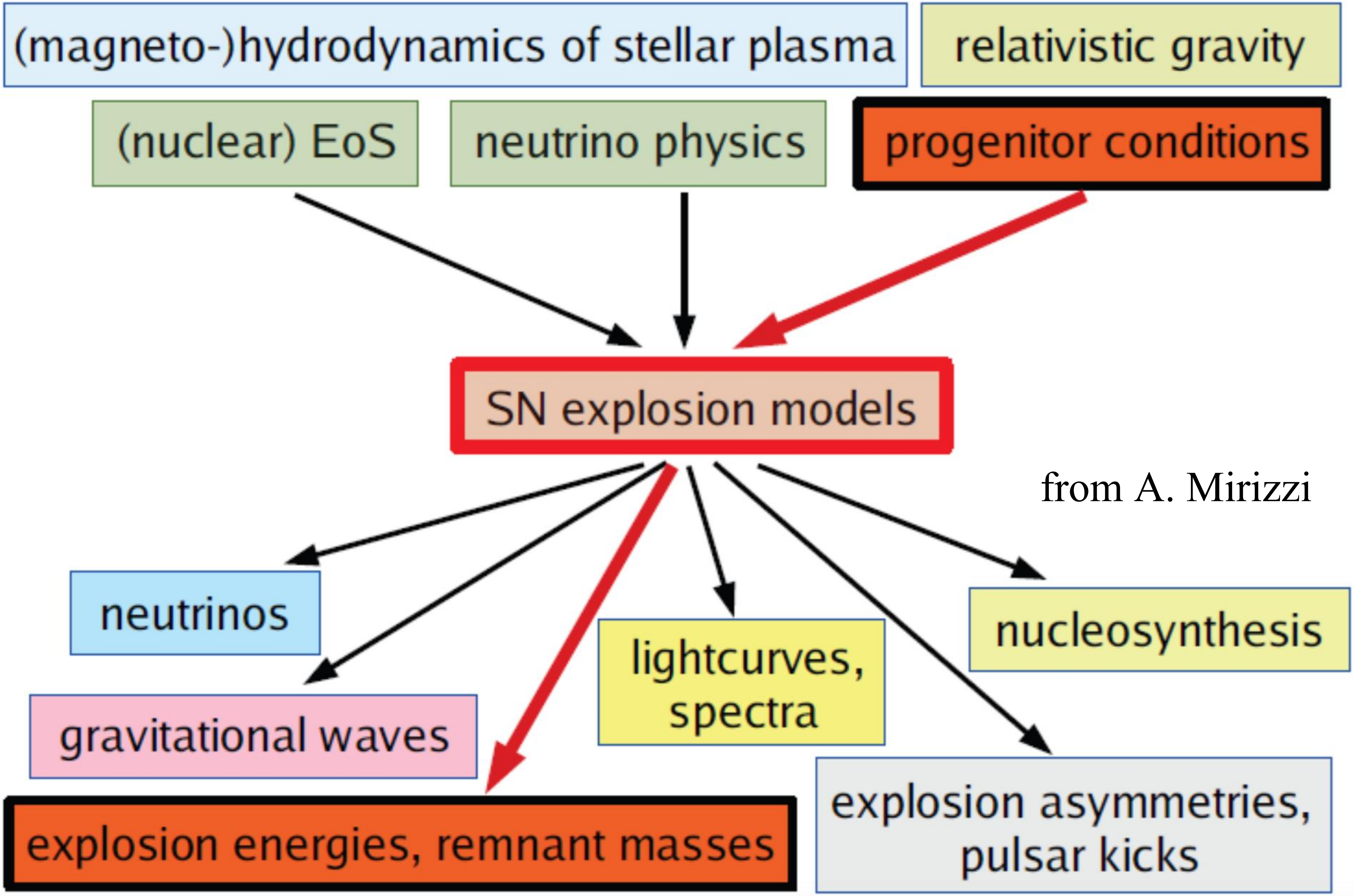
the 1st mean field (HF level) + RPA study using χEFT potential (N3LO-414)



Shin+23



SN project



(magneto-)hydrodynamics of stellar plasma

relativistic gravity

(nuclear) EoS

neutrino physics

progenitor conditions

SN explosion models

from A. Mirizzi

neutrinos

gravitational waves

lightcurves, spectra

nucleosynthesis

explosion asymmetries, pulsar kicks

explosion energies, remnant masses