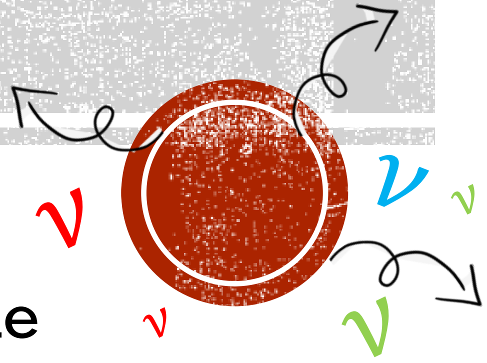
UNCERTAINTY QUANTIFICATION FOR NEUTRINO OPACITIES IN CORE-COLLAPSE SUPERNOVAE AND NEUTRON STAR MERGERS



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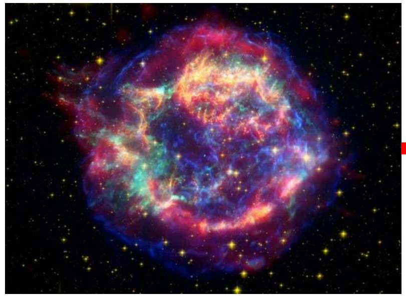
Collaborators: A. W. Steiner, Jerome Margueron

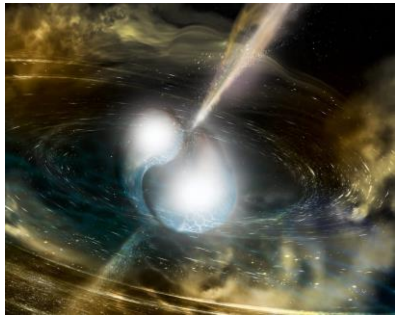
Theory Seminar, TD Lee Institute, 12/23/2022

Neutrinos in Massive stars

Neutron Star (NS)



Core-collapse Supernovae (CCSNe)



Binary Neutron star mergers (BNS)

NS Cooling

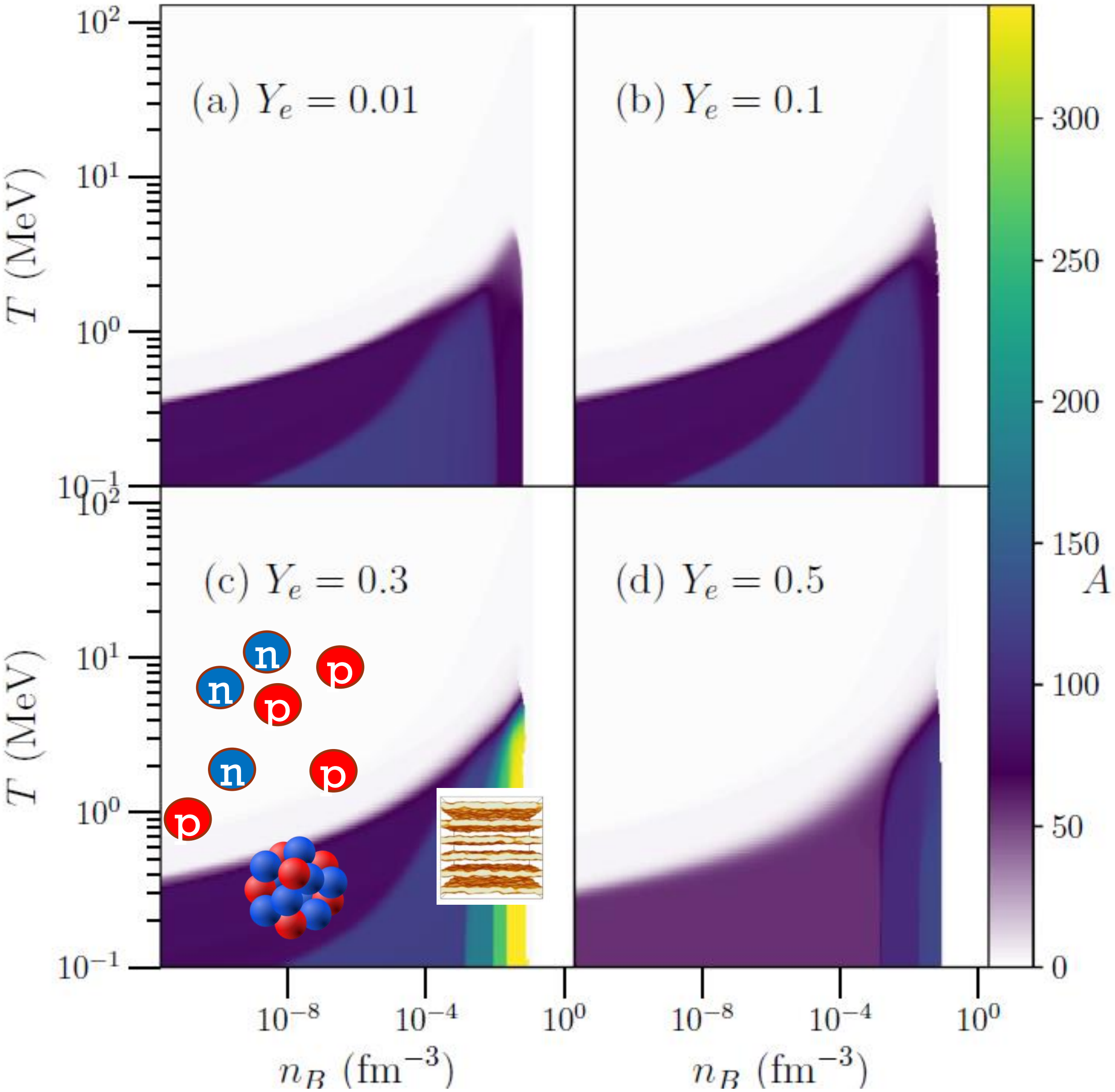
Explosion Mechanism

Nucleosynthesis

ν

Neutrino-dense matter interactions

X. Du *et al.* (2021)



Structures of dense matter are very different, depending on (n, T, Ye)!

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

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

CC

$$\frac{n}{p} \approx \frac{L_{\bar{\nu}_e}\langle E_{\bar{\nu}_e}\rangle}{L_{\nu_e}\langle E_{\nu_e}\rangle}$$

Neutron to Proton Ratio

$$\nu_i + p \rightarrow \nu_i + p$$

$$\nu_i + n \rightarrow \nu_i + n$$

NC

$$R_\upsilon$$

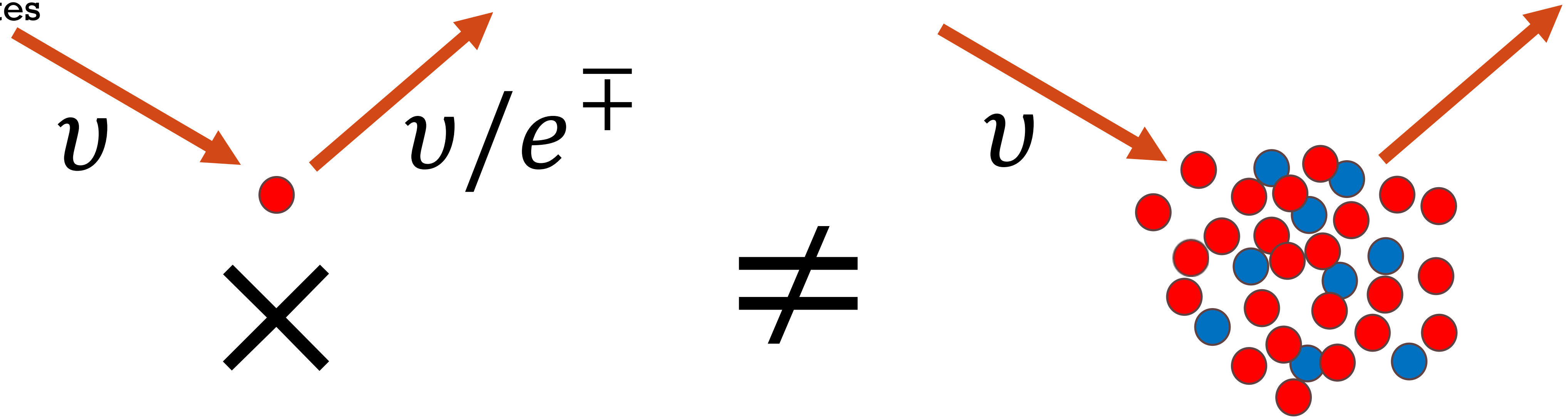
Neutrino Sphere Radius

We focus on neutrino-nucleon interactions today!

Neutrino-dense matter interactions

(We focus on neutrino-nucleon interactions today)

Free-space neutrino-nucleon interaction rates



Density

Because of "in-medium" corrections

An illustration of "in-medium effect"

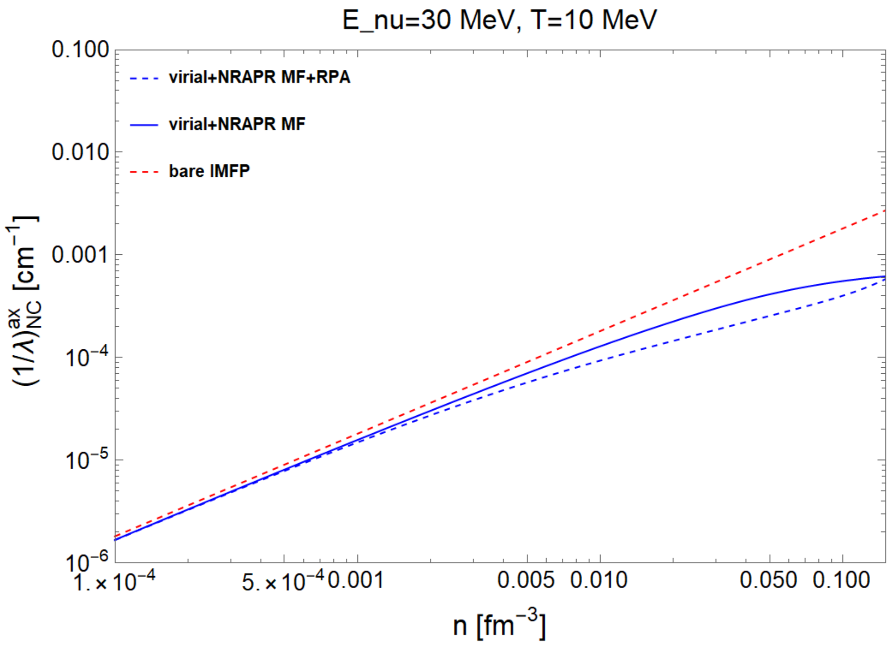
$\mathrm{S}(q_0, \mathrm{q})$ at mean field level:

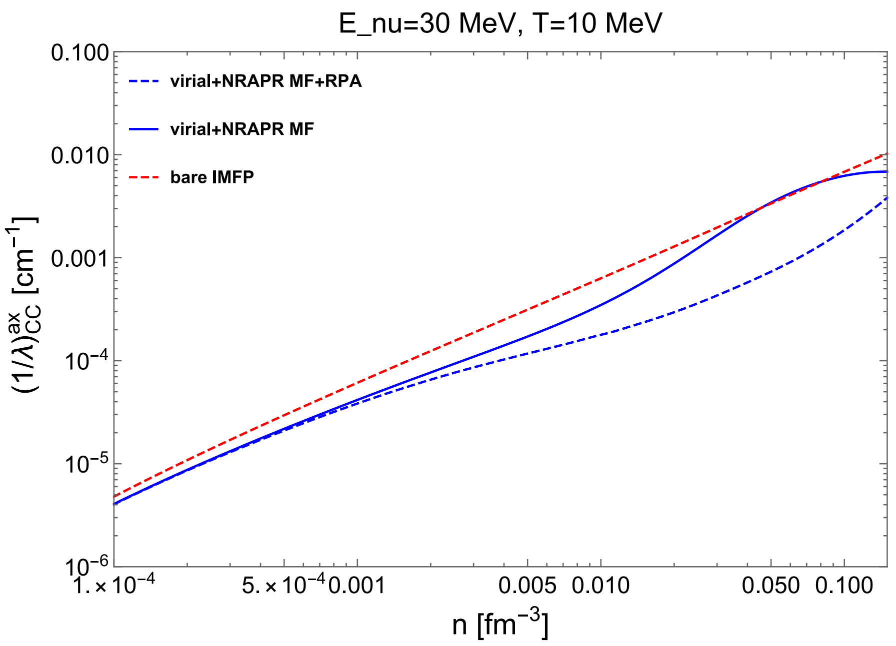
$$S_0(q_0, q) = \frac{2\,\mathrm{Im}\Pi_0}{1 - \exp[(-q_0 - \mu^\tau + \mu^{\tau'})/T]}$$

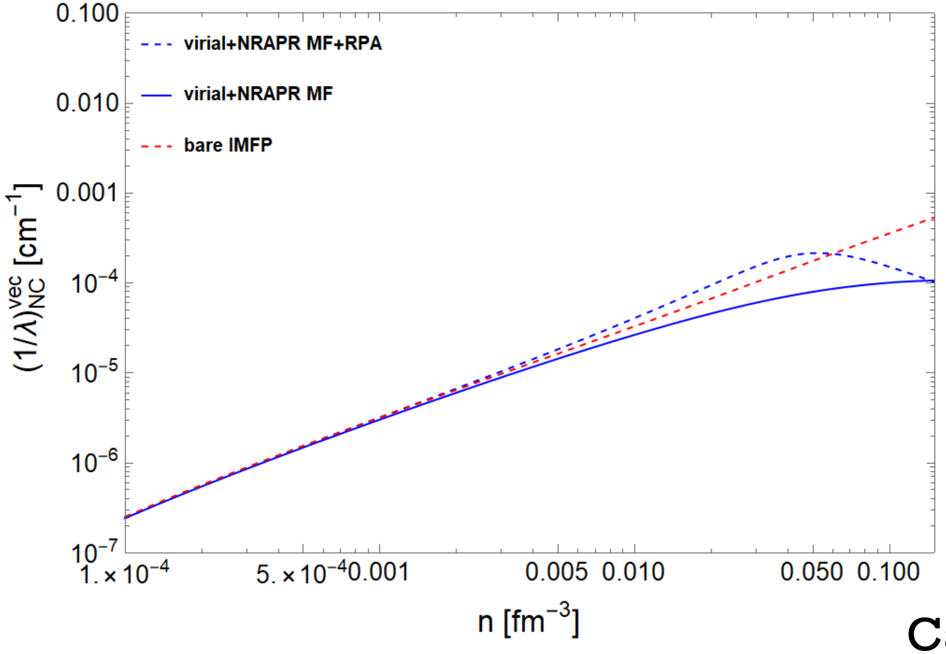
$$= \frac{1}{2\pi^2} \int d^3k\, \underline{\delta(\epsilon^\tau - \epsilon^{\tau'} - q_0)}\, \underline{f^\tau(\vec{k}) \times}$$

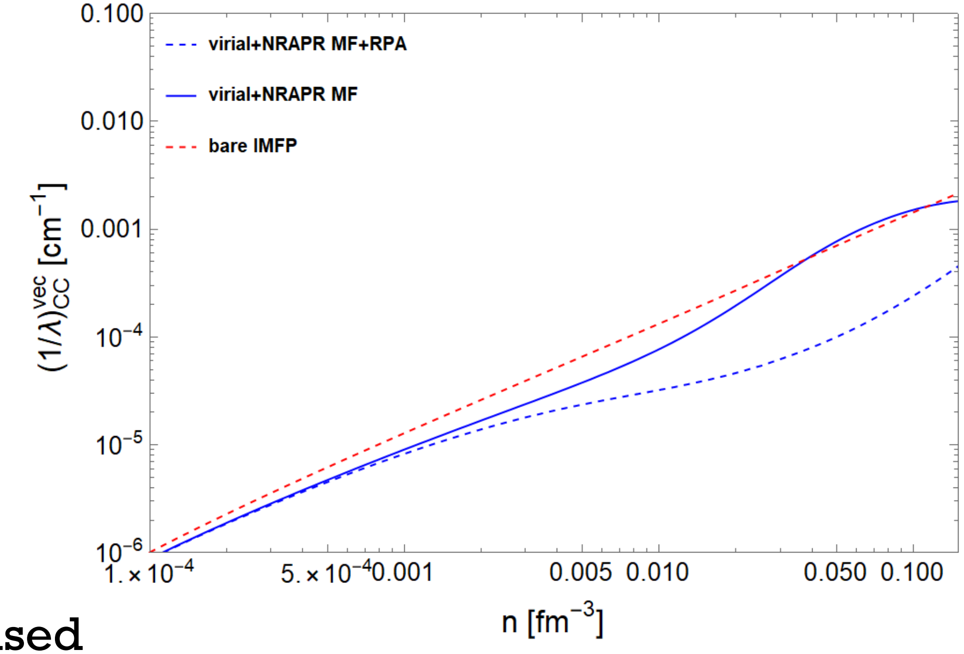
$$\underline{[1 - f^{\tau'}(\vec{k} + \vec{q})]}\,.$$

At MF level, such a correction mainly result from energy conservation & Pauli principles









Scattering

Calculations based on Z. Lin *et al.* (2022)

Absorption

THEORETICAL FRAMEWORK OF OUR NEUTRINO CODE

$$\frac{d^2\sigma}{dwd\Omega} = \cdots L_{\mu\nu}\Lambda^{\mu\nu}$$

Non-Relativistic limit

$$L_{\mu\nu}\Lambda^{\mu\nu} \approx (1+\cos\theta)W_V + (3-\cos\theta)W_A$$

$$W_V = V^2 S_V(q,w) \qquad W_A = A^2\, S_A(q,w)$$

In MF level, $S_v = S_A$

Neutral Current (NC):

$$V = C_V^n = \frac{1}{2};$$
$$A = C_A = -\frac{1.26}{2}$$

Charged Current (CC):

$$V = g_V = 1;$$
$$A = g_A = 1.26$$

Linear Response Theory:

$$S(q_0,\mathrm{q}) = \frac{1}{1-\exp[-\left(q_0 + \frac{\mu_2-\mu_4}{T}\right)]} Im[\Pi_{V/A}]$$

Mean Field(MF)

$$Im[\Pi_{V/A}] = Im[\frac{\Pi^{MF}}{1 - v_{V/A}\Pi^{MF}}]$$

Random phase approximation (RPA)

Input from EoS

MF Input: U_P U_N μ_P μ_N M_P^* M_N^*

RPA Input: Landau Liquid Parameters

EoS consistent with our neutrino code

PARTIAL WAVE ANALYSIS OF N-N SCATTERING [Nijmegen]

Constraints

Virial EoS

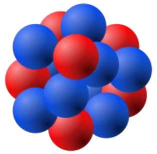
C. J. Horowitz and A. Schwenk (2006)

$$EoS_{general} = g * EoS_{virial} + (1 - g) * EoS_{Sk}$$

g is a transition function where g≈1 at very low densities and g≈0 at very high densities

X. Du *et al.* (2021)

Lab observables of nucleus properties [Phys. Rev. Lett. 114, 122501 (2015) (UNEDF),…]



Constraints

Skyrme EoS

A. W. Steiner *et al.* (2005)

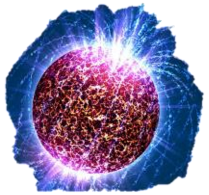
X. Du *et al.* (2019)

As density increases…

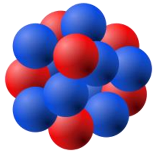
The Main idea of our neutrino code:

PARTIAL WAVE ANALYSIS OF N-N SCATTERING [Nijmegen]

Astronomical observations



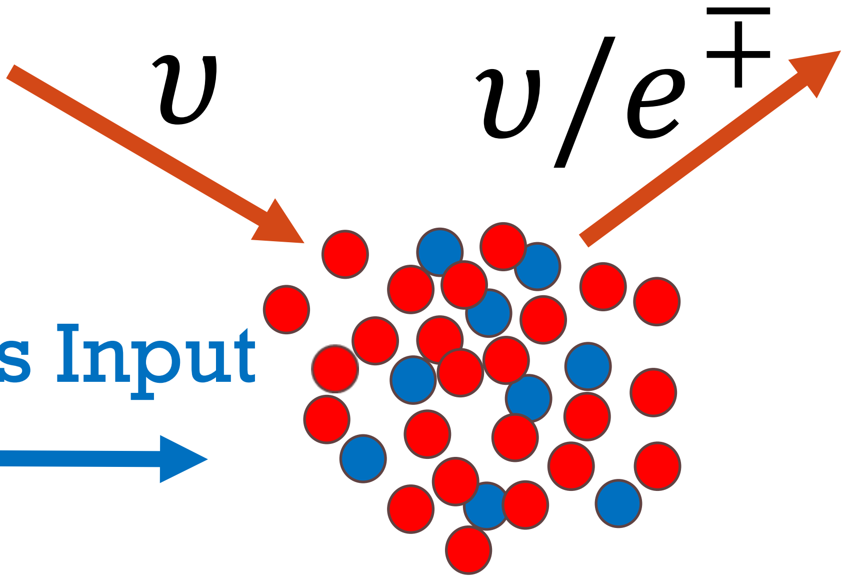
Lab observables of nucleus properties



Constrain

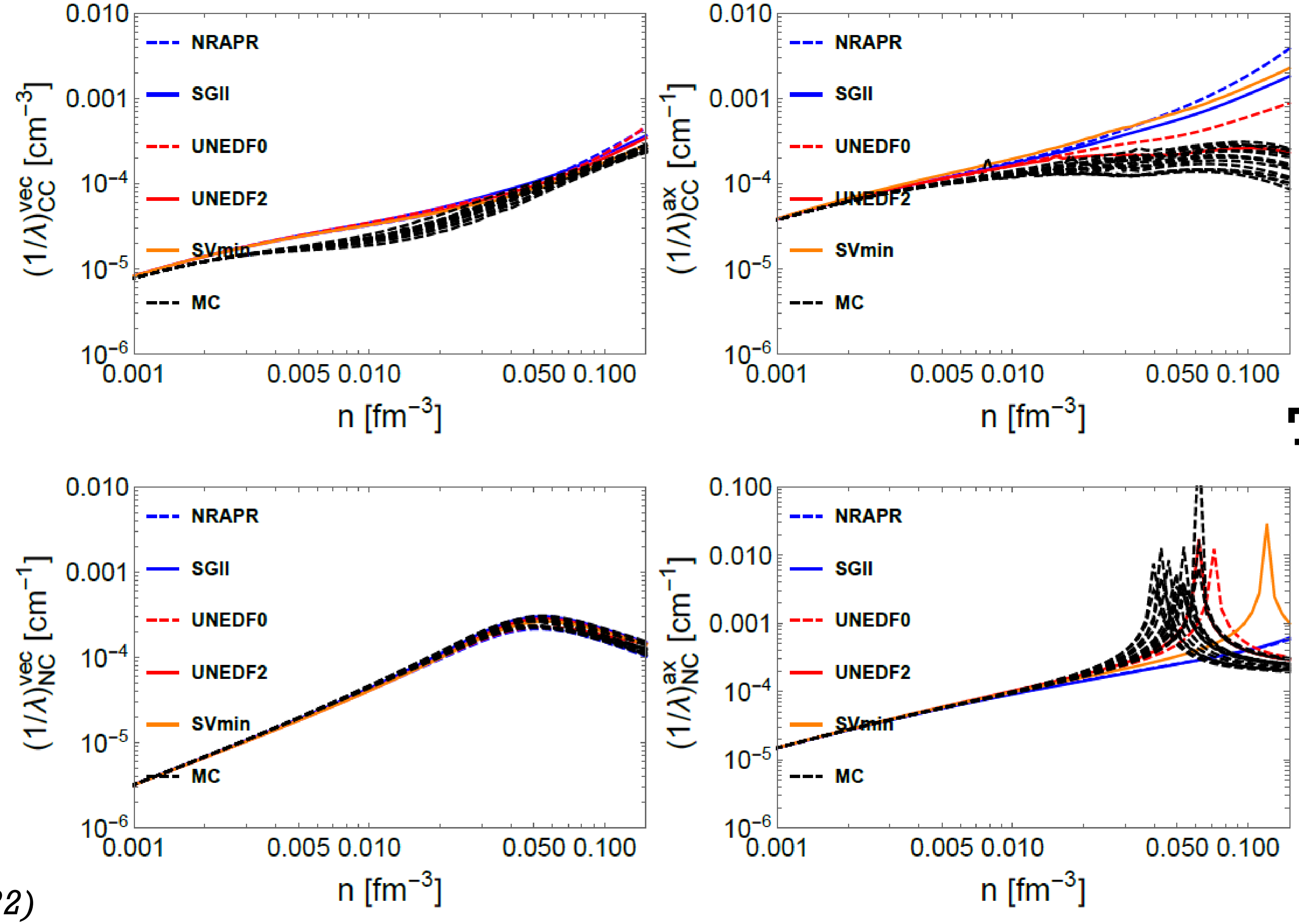
EoS

Provides Input



EoS serve as a *bridge* connecting the ***astronomical observations/nuclear experimental measurements*** with ***neutrino-dense matter interactions***

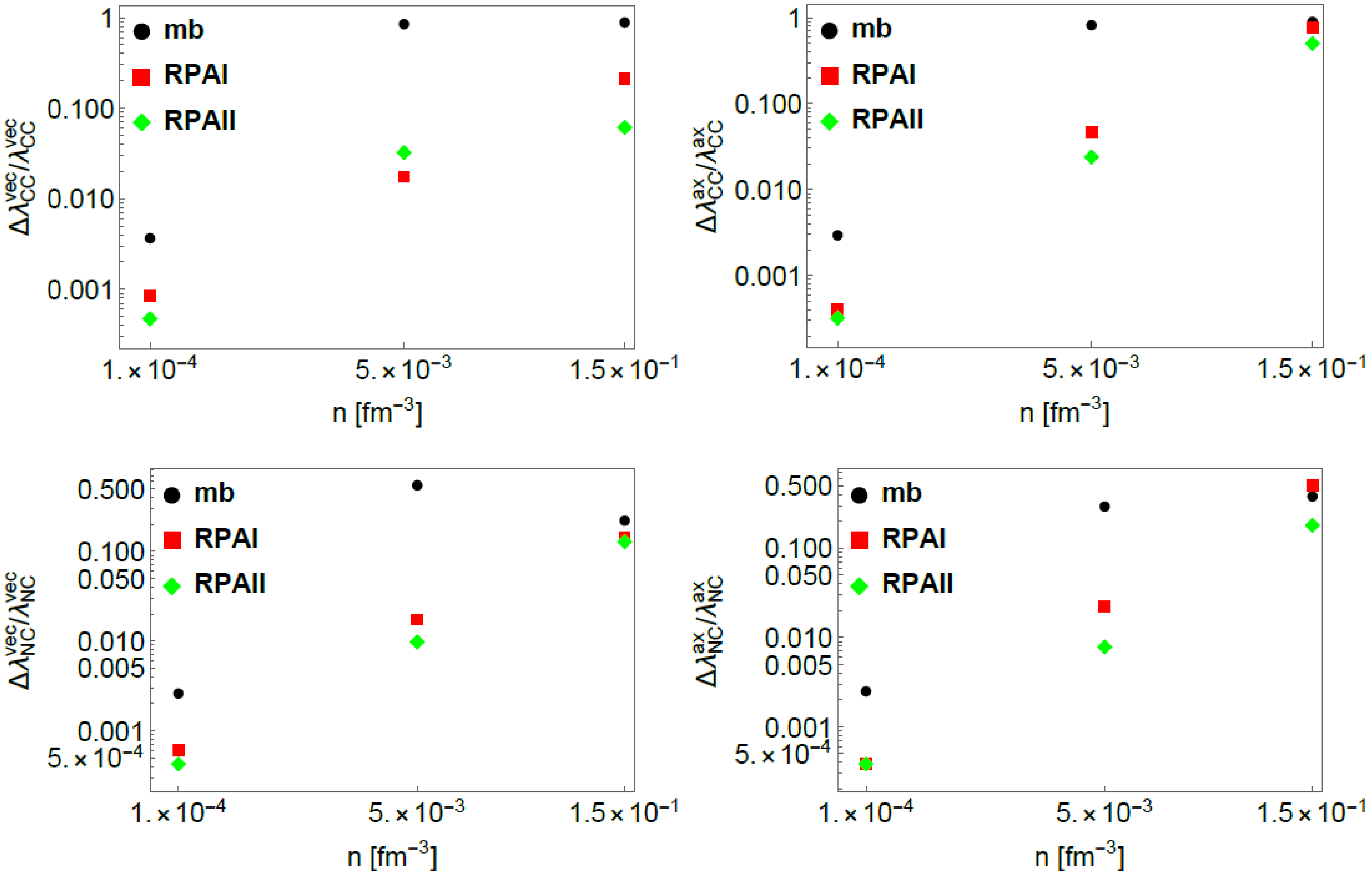
Main Results: 1) the inverse mean free path (IMFP)



T=10 MeV

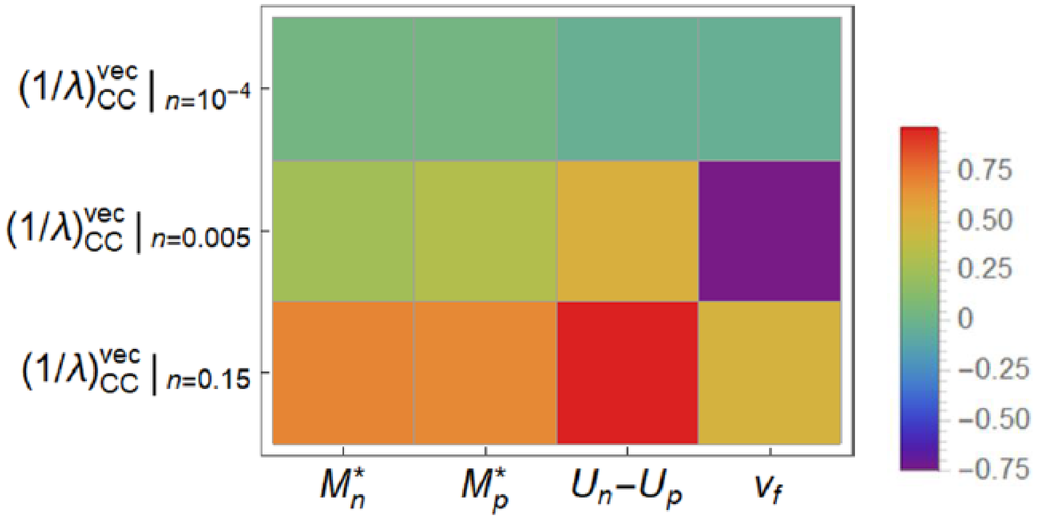
Z. Lin et al. (2022)

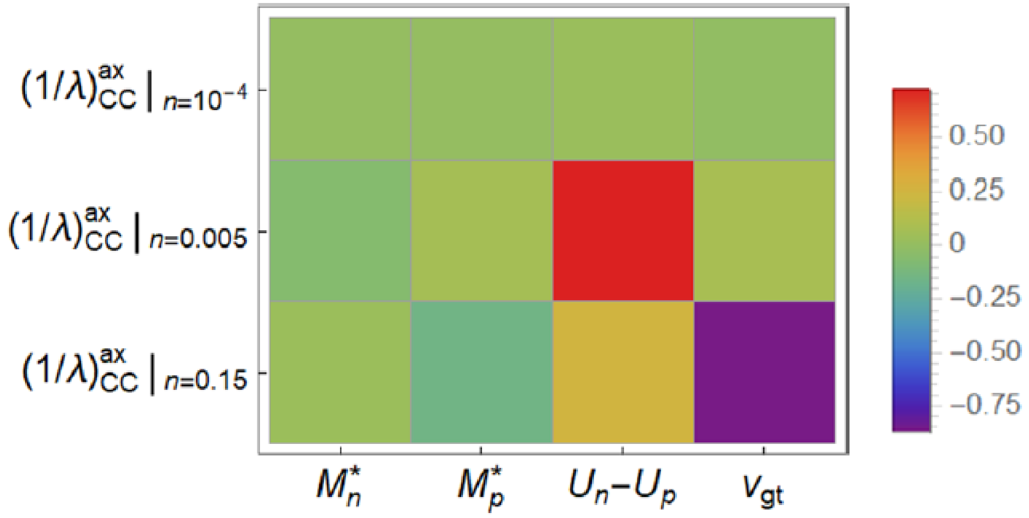
Main Results: 2) Relative uncertainty of IMFP

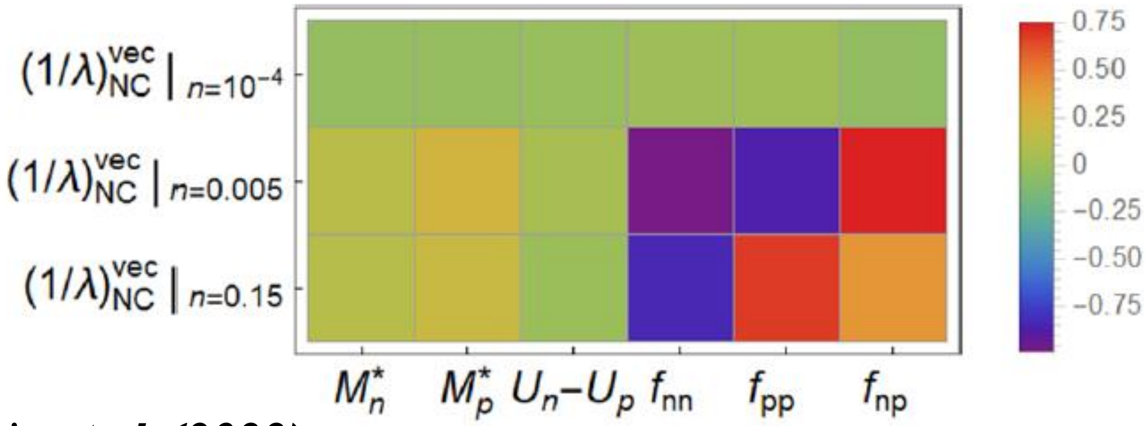


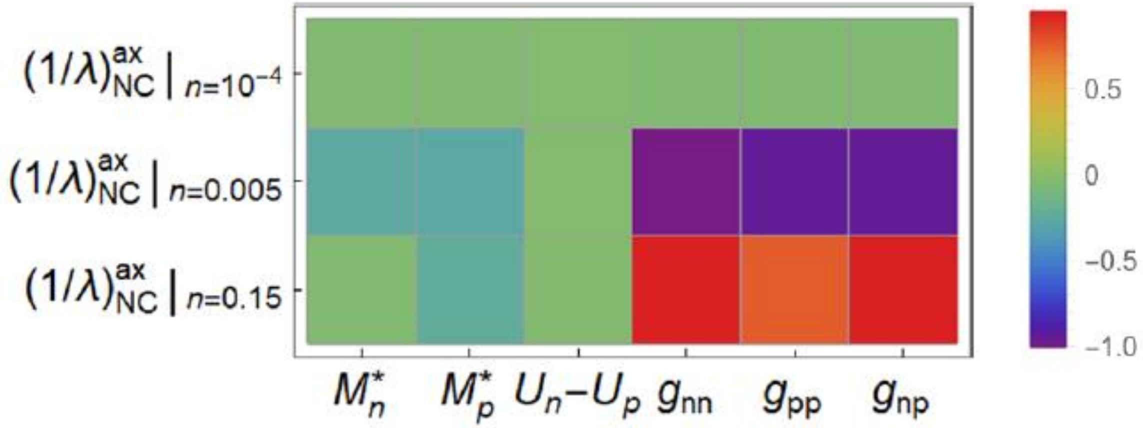
Z. Lin et al. (2022)

Main Results: 3) Correlations between IMFPs and EoSs



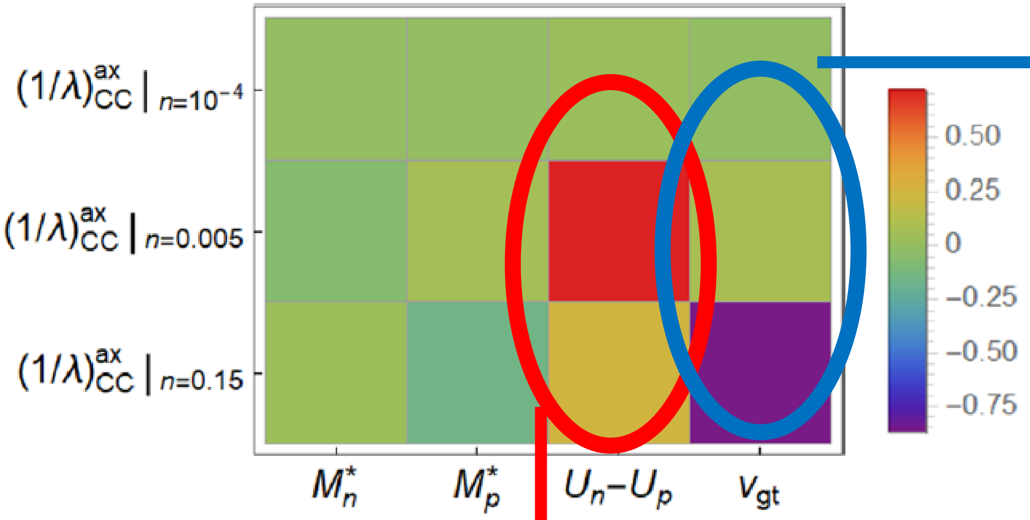






Z. Lin et al. (2022)

Discussion: 1) How does EoS have an influence on IMFP?



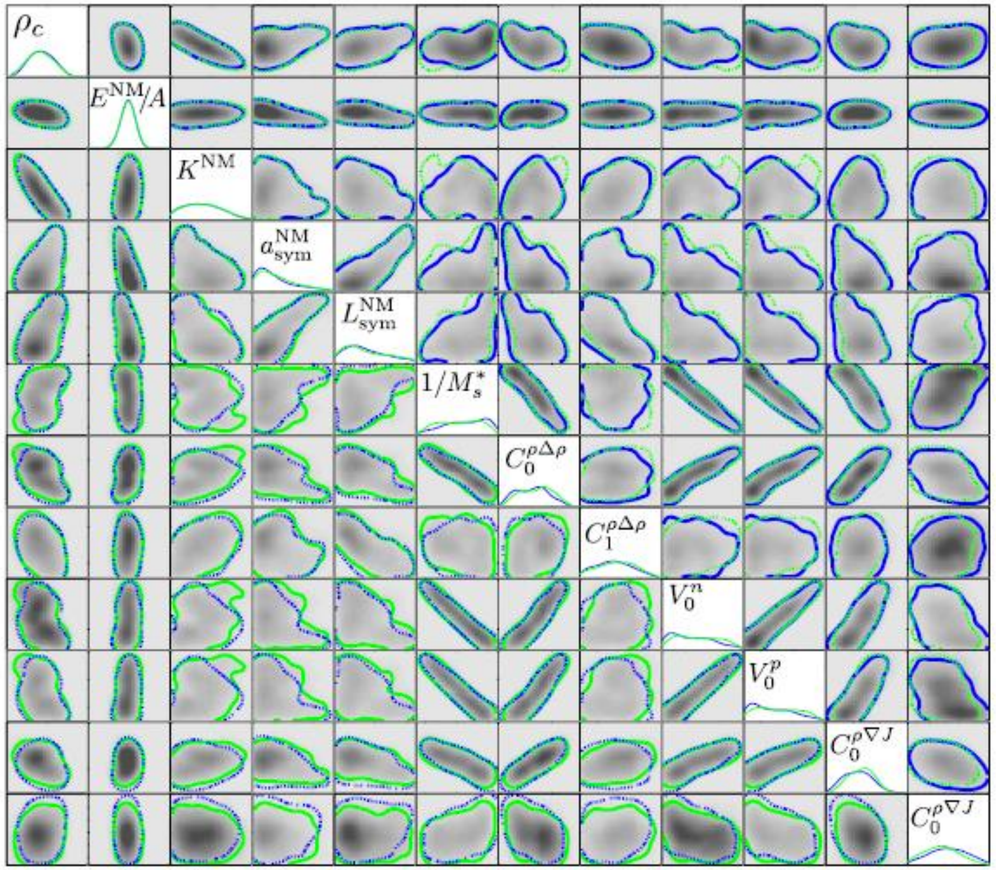
Relating to the ***residual interactions*** between nucleons

Relating to the ***symmetry energy*** of EoS

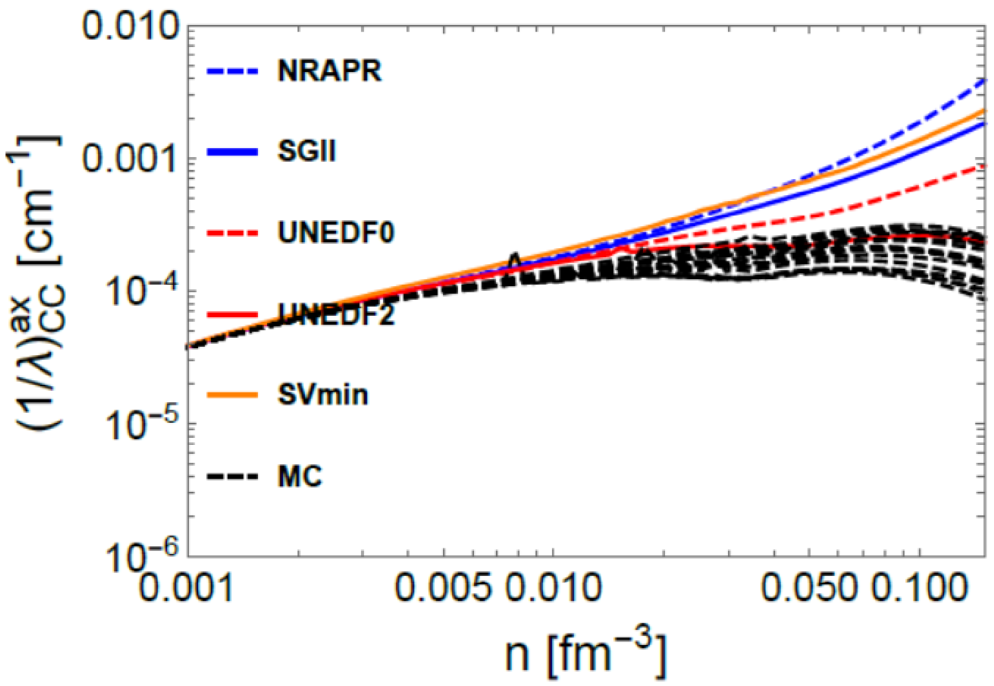
We need to understand ***density-dependent*** symmetry energies and nucleon residual interactions to describe neutrino-nucleon interactions in massive stars!

Discussion: 2) Current understanding of IMFPs?

J. D. McDonnel *et al.* 2015

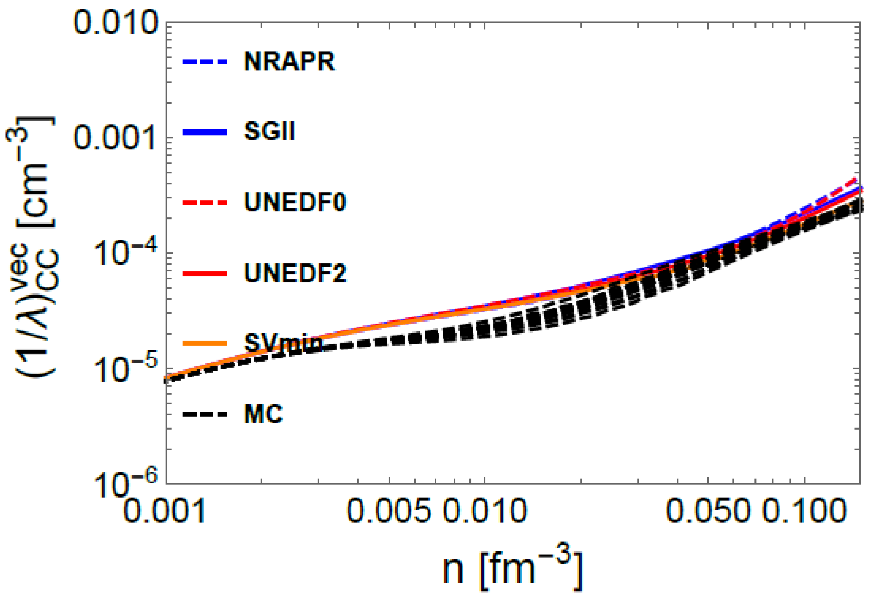


PDF of Skyrme EoS parameters constrained by a lot of nuclei properties

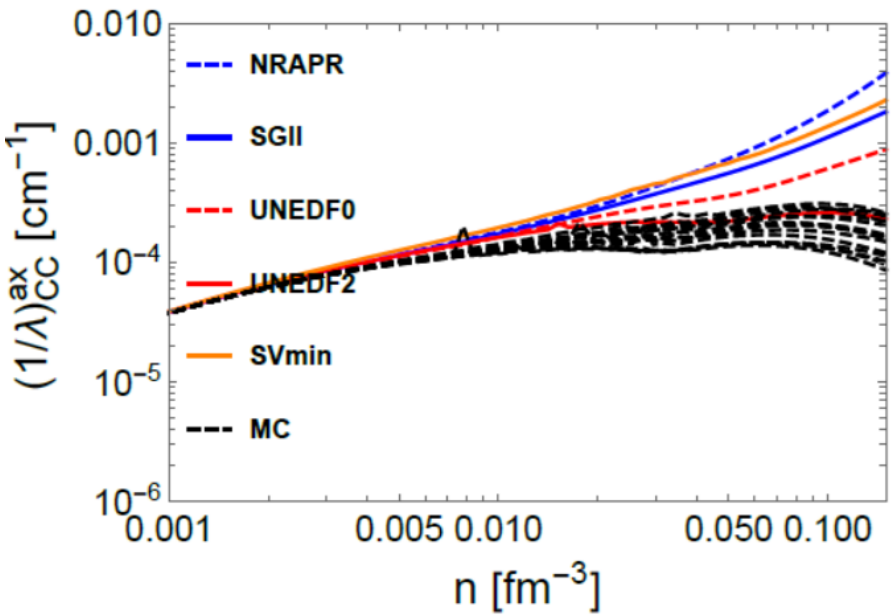


PDF of IMFPs

Discussion: 2) Current understanding of IMFPs?



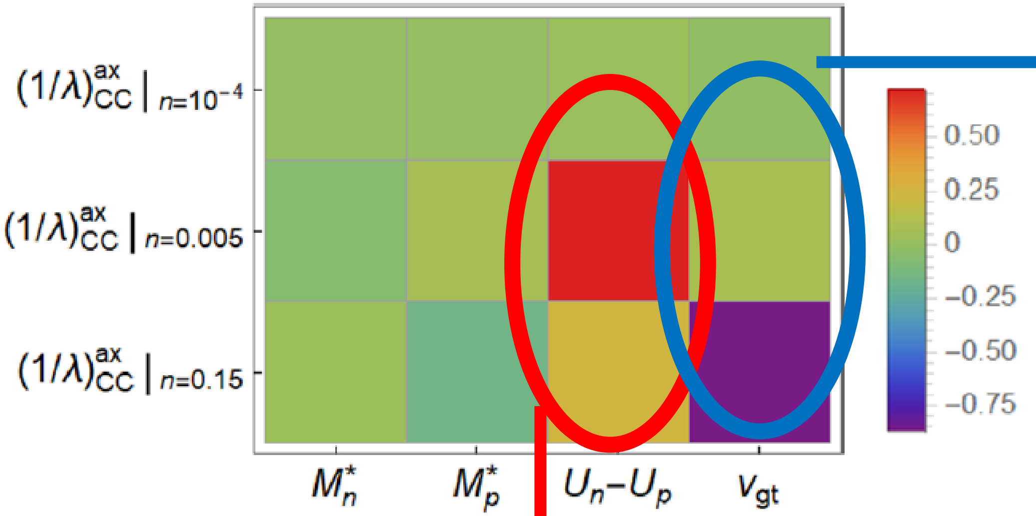
The vector part of IMFPs are relating to ***spin-independent*** properties of EoSs. Uncertainties are not-so-large☺

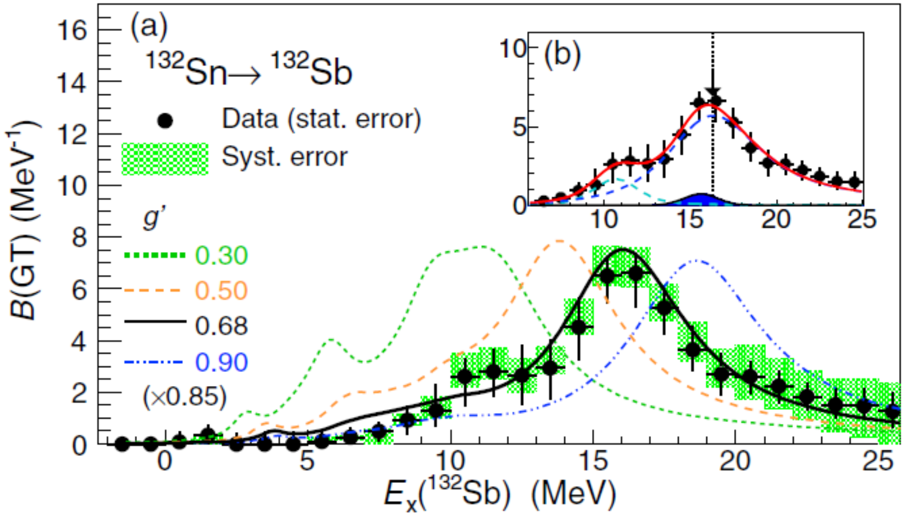


The axial-vector part of IMFPs are relating to ***spin-dependent*** properties of EoSs! They are poorly constrained!

Much Larger uncertainties!

Discussion: 3) How to constrain IMFPs in CCSNe/BNS?

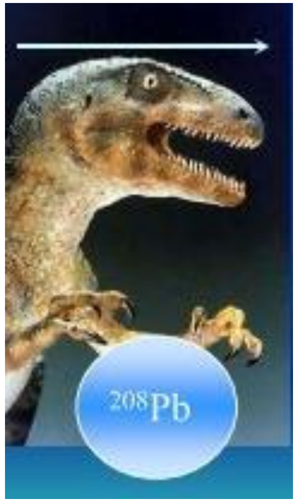


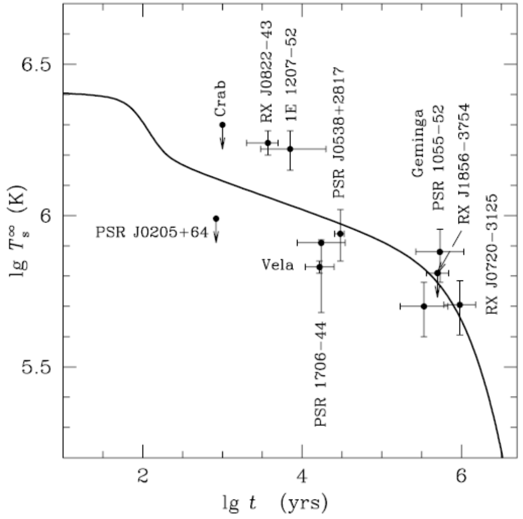


Gamow-Teller Spectrum Measurements (relating to spin-dependent forces!)

J. Yasuda et al. (2018)

Neutron Skin thickness





Neutron Star Cooling

D. G. Yakovlev et al. (2005)

TAKE-HOME MESSAGES

1. Many-body corrections on neutrino-nucleon interactions are dependent on the underlying EoSs
2. Relevant densities for neutrino-nucleon interactions in CCSNe/BNS range from sub-saturation to supra-saturation densities. So, to have a full understanding of neutrino opacities in massive stars, we need information about density-dependent EoS symmetry energies/effective mass/residual interactions!
3. Constraints on traditional EoSs are usually spin-independent. However, spin-isospin properties of the EoSs are very important for neutrino-nucleon interactions!
4. By conducting neutrino opacity calculations consistent with underlying EoSs, experiments/observations that constrain EoSs indirectly constrain the properties of neutrino-nucleon interactions in massive stars!