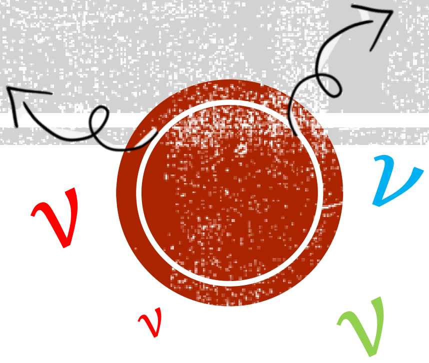
LARGE-SCALE TABULATED NEUTRINO OPACITY TABLE

For future CCSNe/BNS simulations



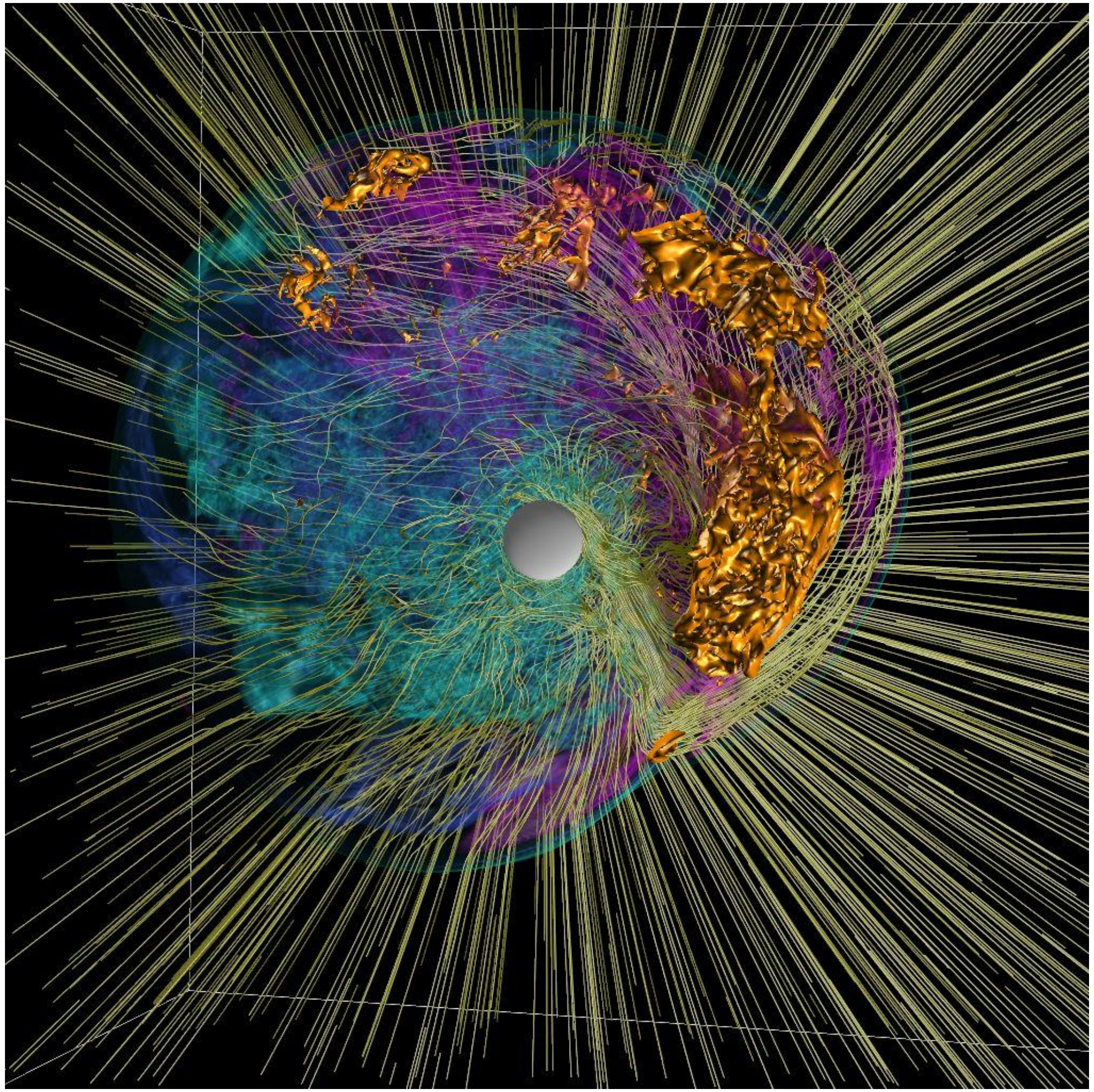
Zidu Lin

University of Tennessee, Knoxville

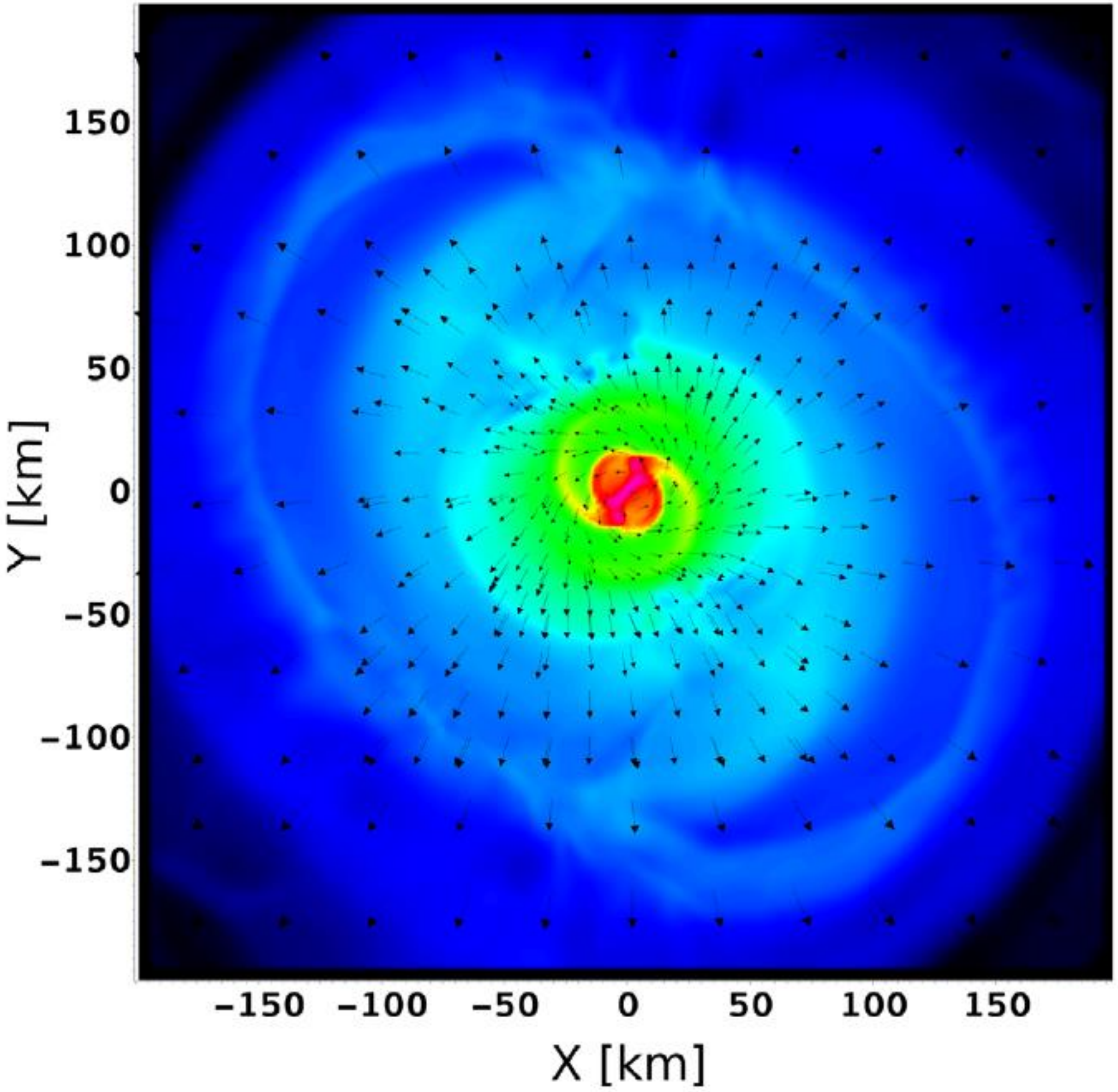
Seminar at Institute for Nuclear Physics, UW, 7/27/2023

Collaborators: A. W. Steiner (UTK), J. Margueron (IP2I), G. Colo (INFN), Y. Ma (MSU), D. Lee (MSU)

ORNL website

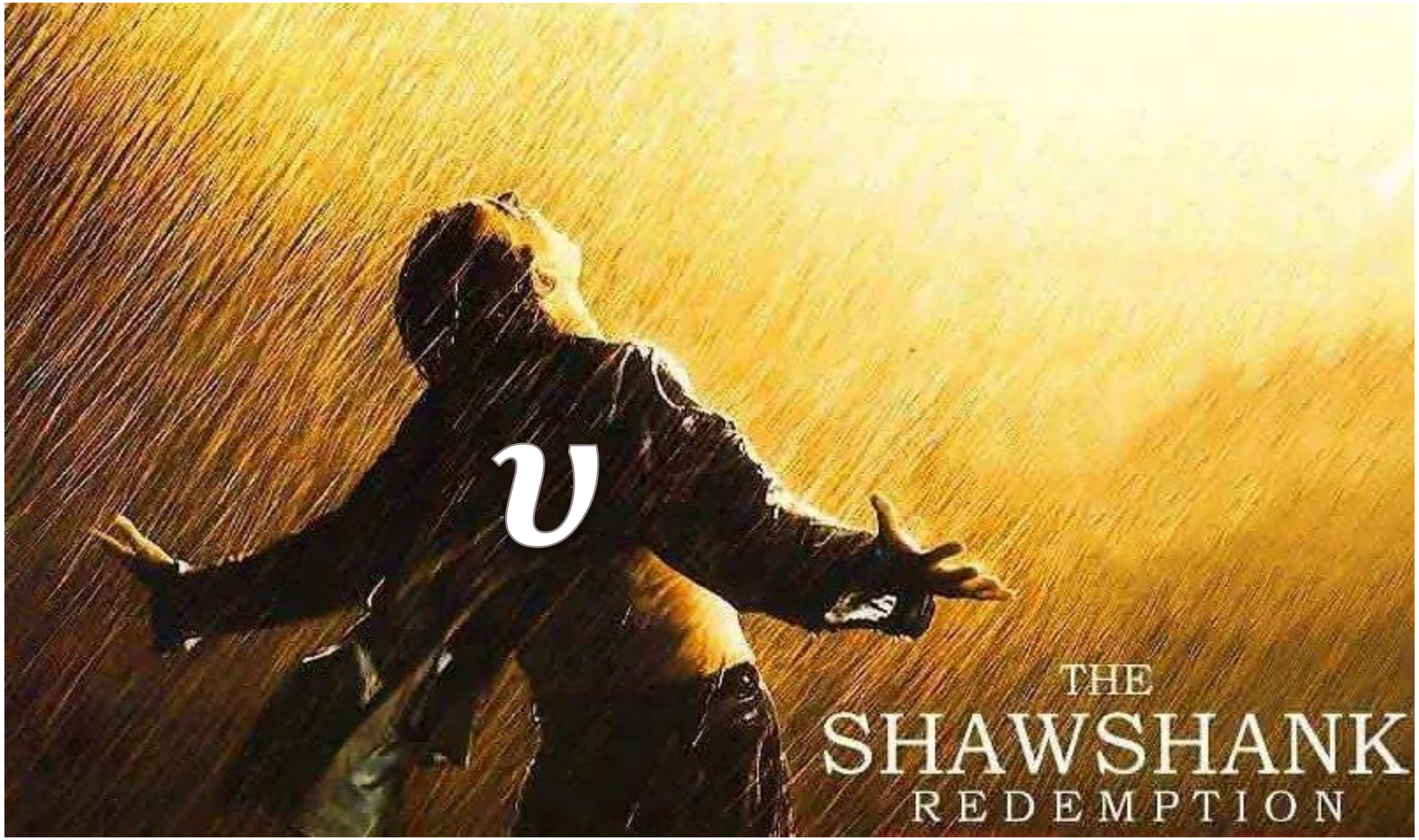


T. Vincent, F. Foucart, M. Duez *et al.*



CCSNe

BNS



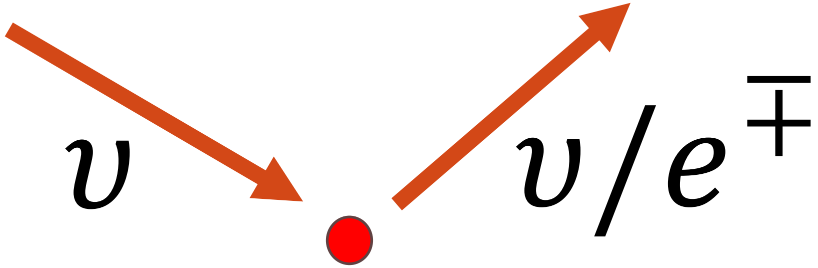
Question to Mr. υ :

Before you escape, what have you done ?

(*The only way to figure it out is to* ***understand υ-matter*** *interactions…*)

ν-MATTER INTERACTIONS:

Free-space neutrino-nucleon interaction rates per volume:

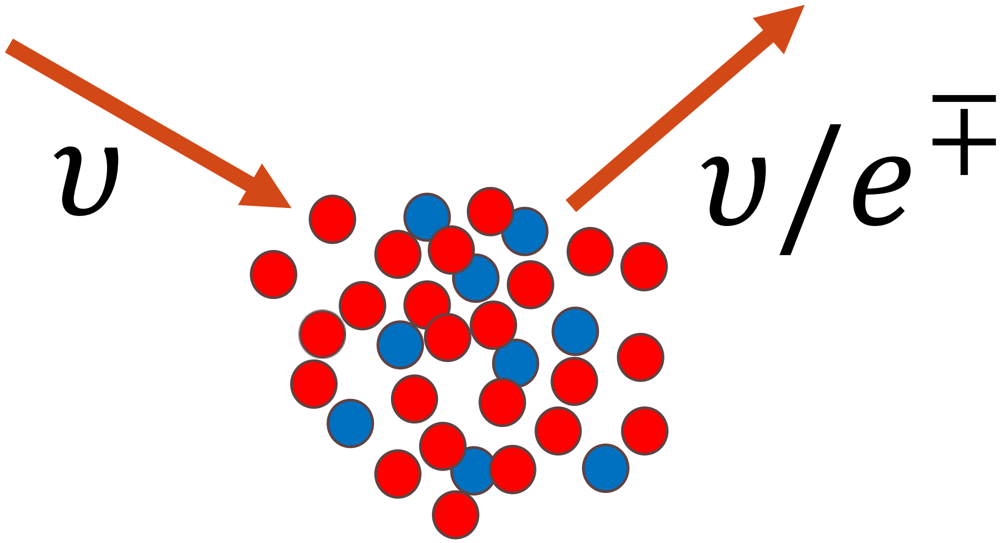


$\times$

Density

$\neq$

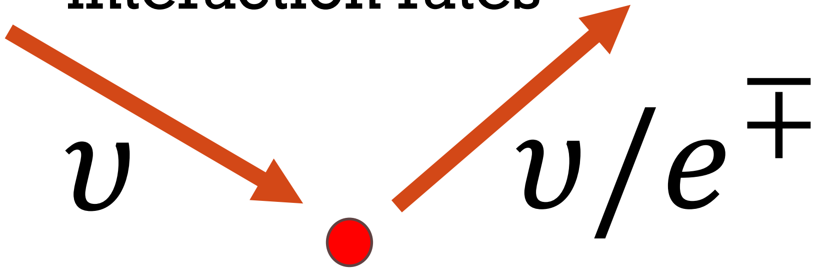
neutrino-nucleon interaction rates in many-body system per volume:



Because of "in-medium" corrections

HAVE WE UNDERSTOOD ν-MATTER INTERACTIONS?

Free-space neutrino-nucleon
interaction rates

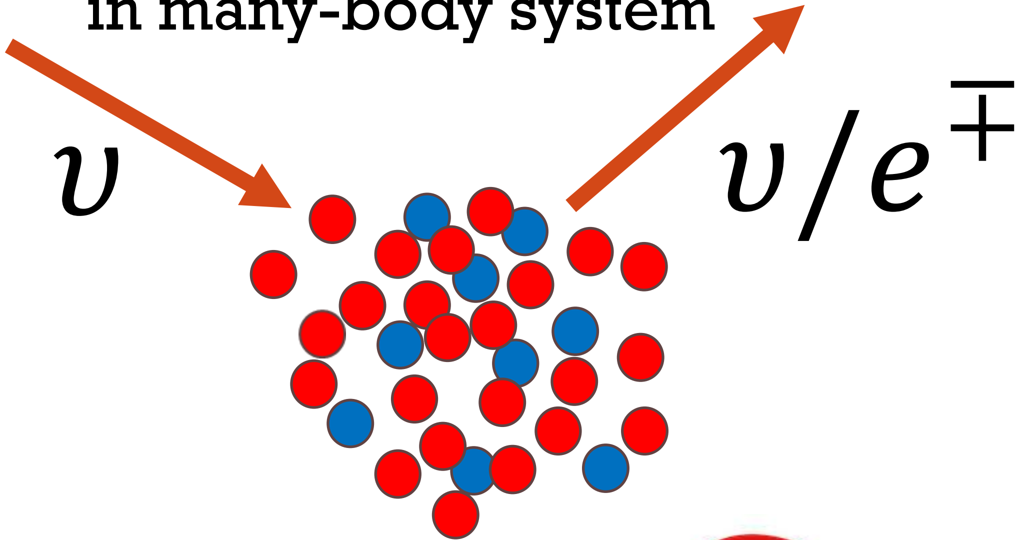


$\times$

Density

$\neq$

neutrino-nucleon interaction rates
in many-body system



We need to understand how nucleons
Propagate in many-body system…

A COMMON EXPRESSION OF υ-NUCLEON INTERACTIONS

$$\frac{1}{V}\frac{d^2\sigma}{d\cos\theta\, d\omega} = \frac{G_F^2}{4\pi^2}(E_\nu - \omega)^2$$

$$\times \left[c_V^2(1+\cos\theta)\underline{S_\rho(q,\omega)} + c_A^2(3-\cos\theta)\underline{S_\sigma(q,\omega)}\right]$$

Nucleon interactions → **Many-body theories** → $S_{\rho/\sigma}$(q,w)

HOW WELL DO WE UNDERSTAND MANY-BODY EFFECTS?

σ_{Nuc} *with* σ_{MB} *induce* $\sigma_{S(q,w)}$

Nucleon interactions → **Many-body theories** → $S_{v/\sigma}$(q,w)

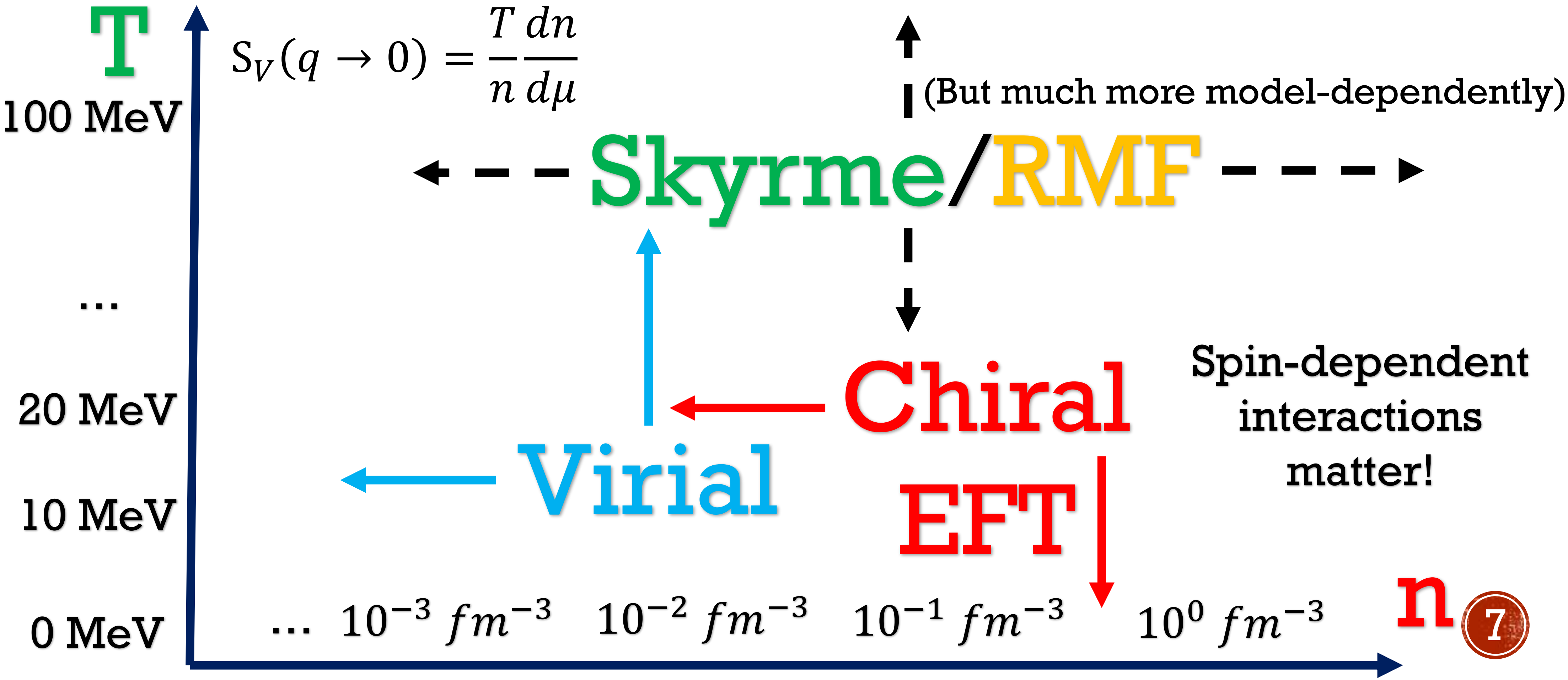
Virial EoS (this talk)
Skyrme EoS (this talk)
RMF EoS
Chiral EFT EoS
(see Ermal's talk)
…

Mean Field (MF) (this talk)
Random Phase Approximation (RPA)
+ MF (this talk)
RPA(+Vertex Corrections)+MF
(see Ermal's talk)
Ab initio Lattice Calculation (this talk)
…

HOW WELL DO WE UNDERSTAND MANY-BODY EFFECTS?

It depends on what n, Ye and T we are talking about…

Warning: This is a plot illustrating Qualitative Features. Don't trust anything quantitatively here!



$$S_V(q \to 0) = \frac{T}{n}\frac{dn}{d\mu}$$

(But much more model-dependently)

Skyrme/RMF

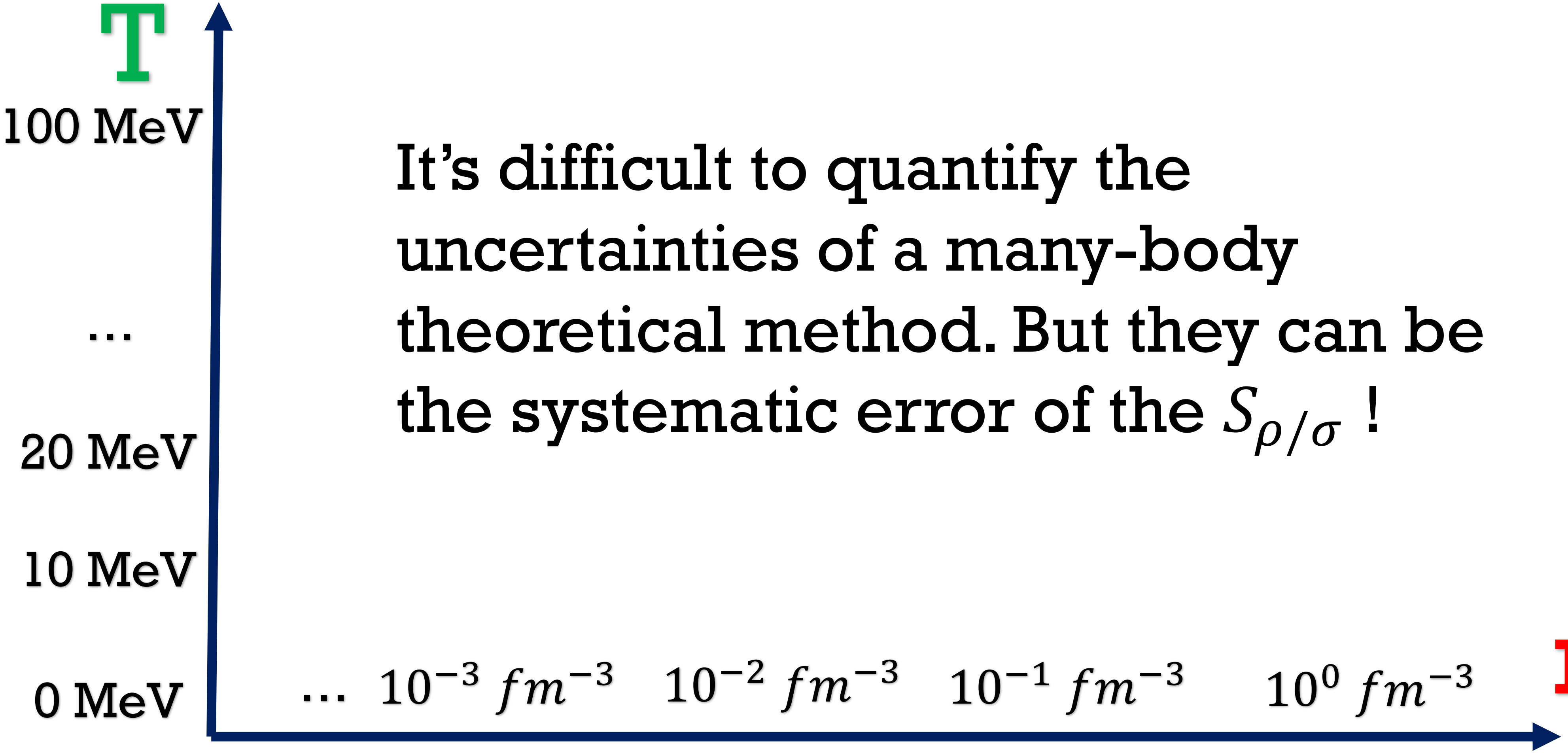
Chiral EFT

Virial

Spin-dependent interactions matter!

HOW WELL DO WE UNDERSTAND MANY-BODY EFFECTS?

It depends on what n, Ye and T we are talking about…



It's difficult to quantify the uncertainties of a many-body theoretical method. But they can be the systematic error of the $S_{\rho/\sigma}$!

OUR PHILOSOPHY OF MAKING v − MATTER OPACITY TALBE

1. Use EoSs that are valid in a wide range of n, Ye and T and are constrained by observational/experimental measurements (for uncertainty quantification)
2. Use basic many-body theories that are valid in a wide range of n, Ye and T and are computationally affordable.

Nucleon interactions → Many-body theories → $S_{v/\sigma}$(q,w)

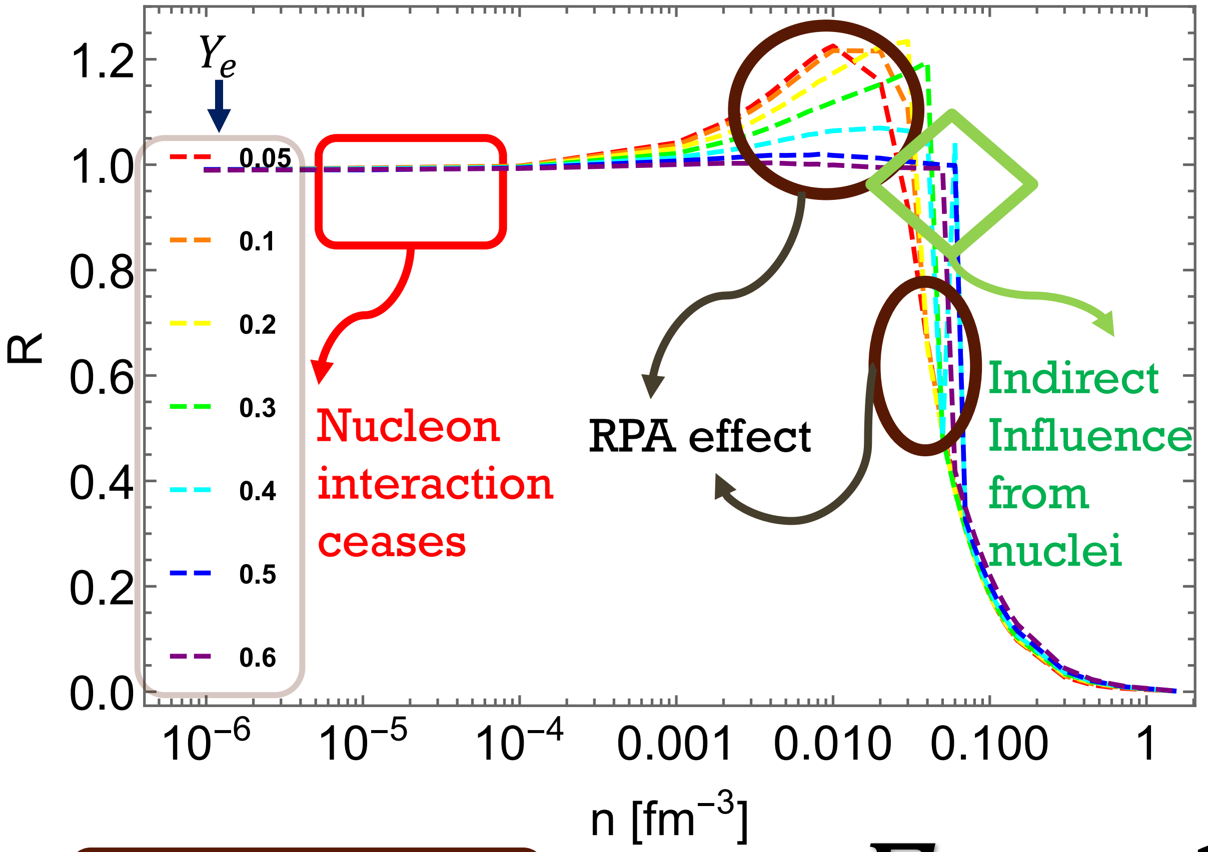
Virial+Skyrme

MF/MF+RPA

scattering/absorption rates for both $v/\bar{v}$ on nucleons

NON-TRIVIAL FEATURES IN
v − MATTER OPACITY TALBE

NC Vec (tran) 5 MeV

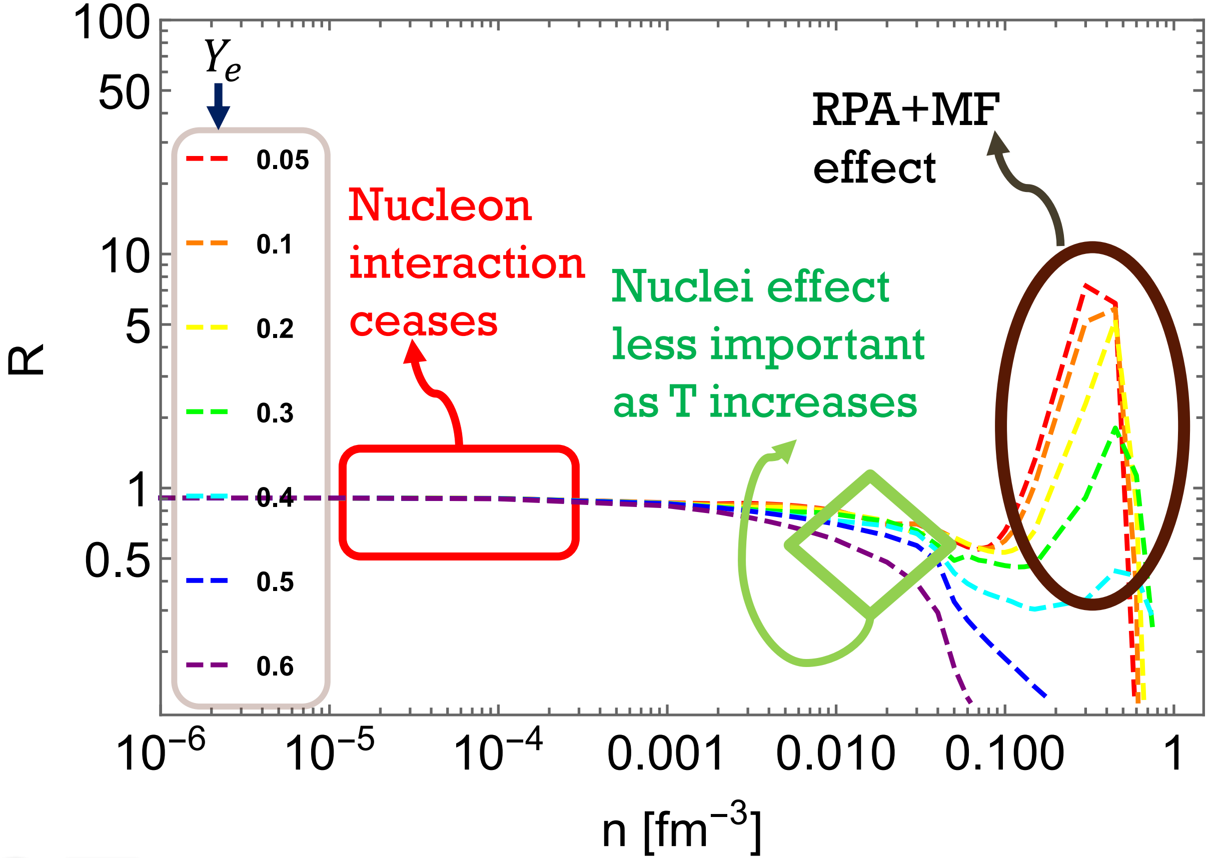


Nucleon interaction ceases

RPA effect

Indirect Influence from nuclei

CC Vec (10 MeV)



Nucleon interaction ceases

Nuclei effect less important as T increases

RPA+MF effect

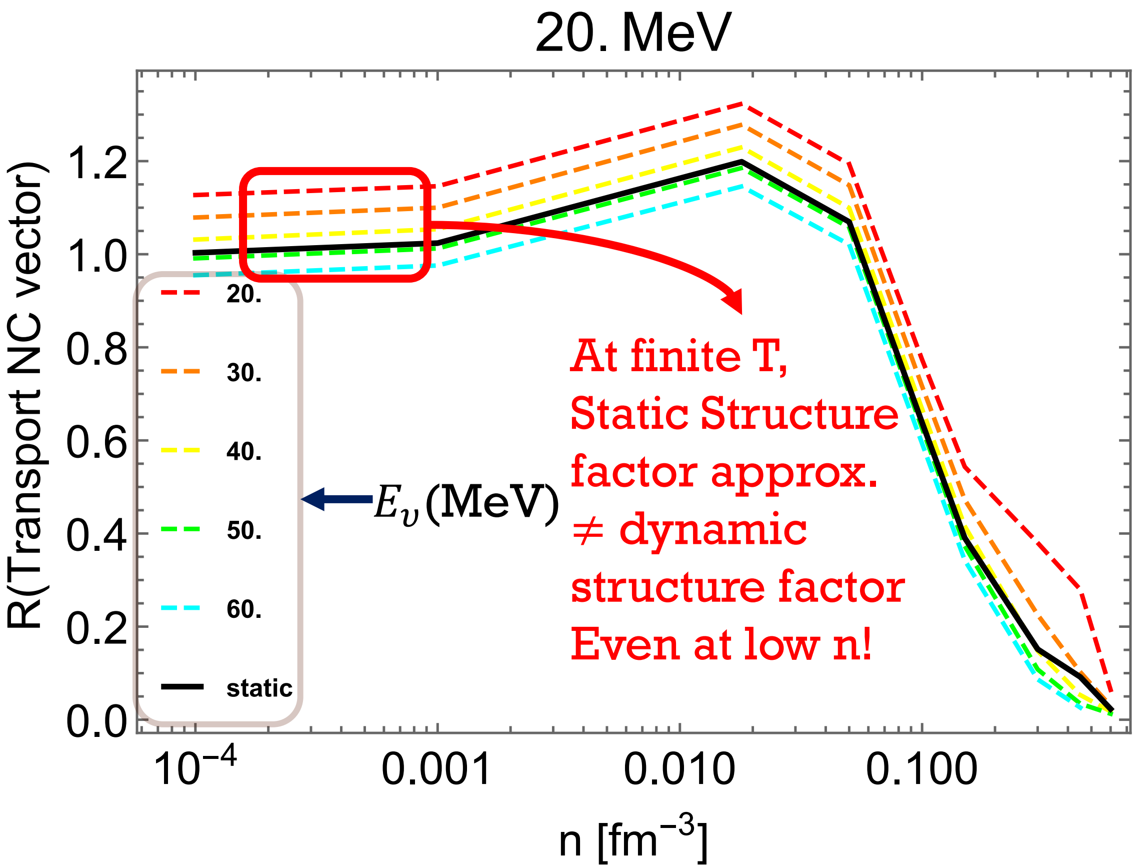
Preliminary

$$E_v = 3T$$

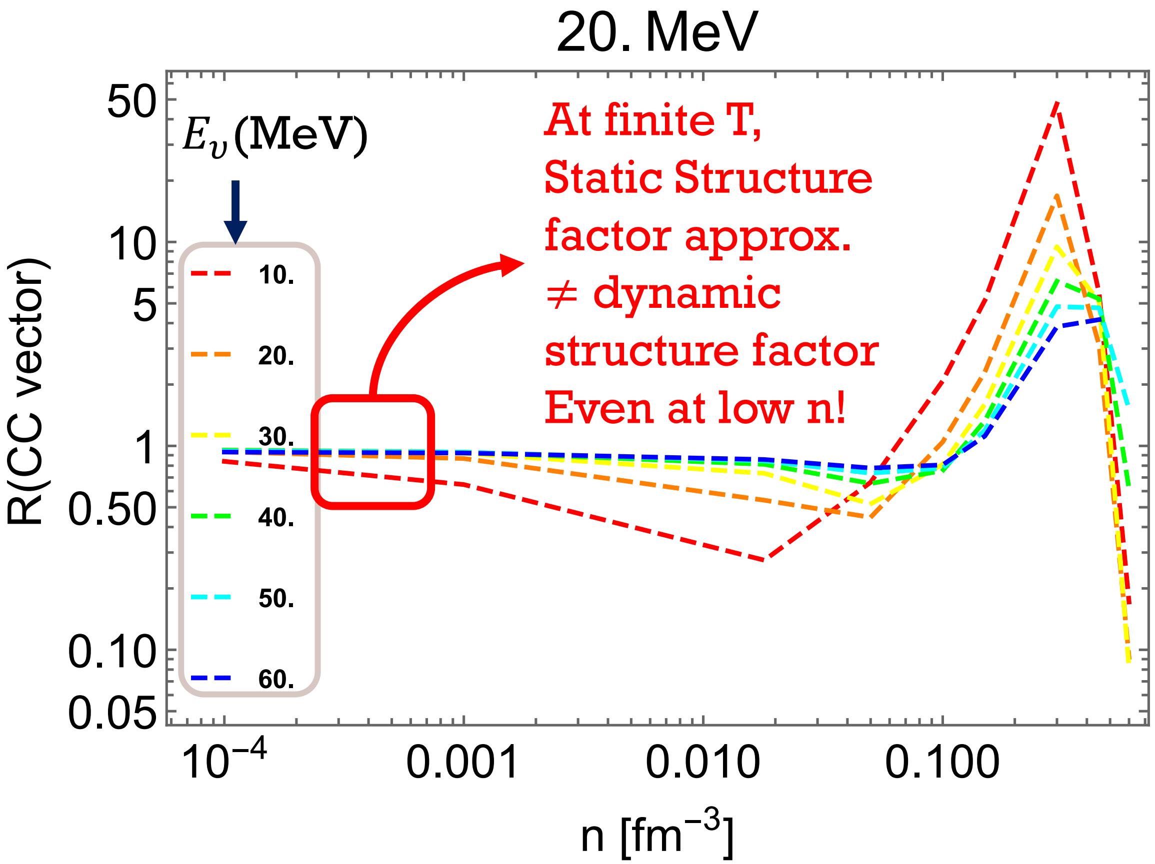
Inverse mean free path (IMFP)≡ σ/V

$$R = IMPF_{with\_MB}/IMPF_{without\_MB}$$

NON-TRIVIAL FEATURES IN
ν − MATTER OPACITY TALBE



At finite T,
Static Structure
factor approx.
≠ dynamic
structure factor
Even at low n!



At finite T,
Static Structure
factor approx.
≠ dynamic
structure factor
Even at low n!

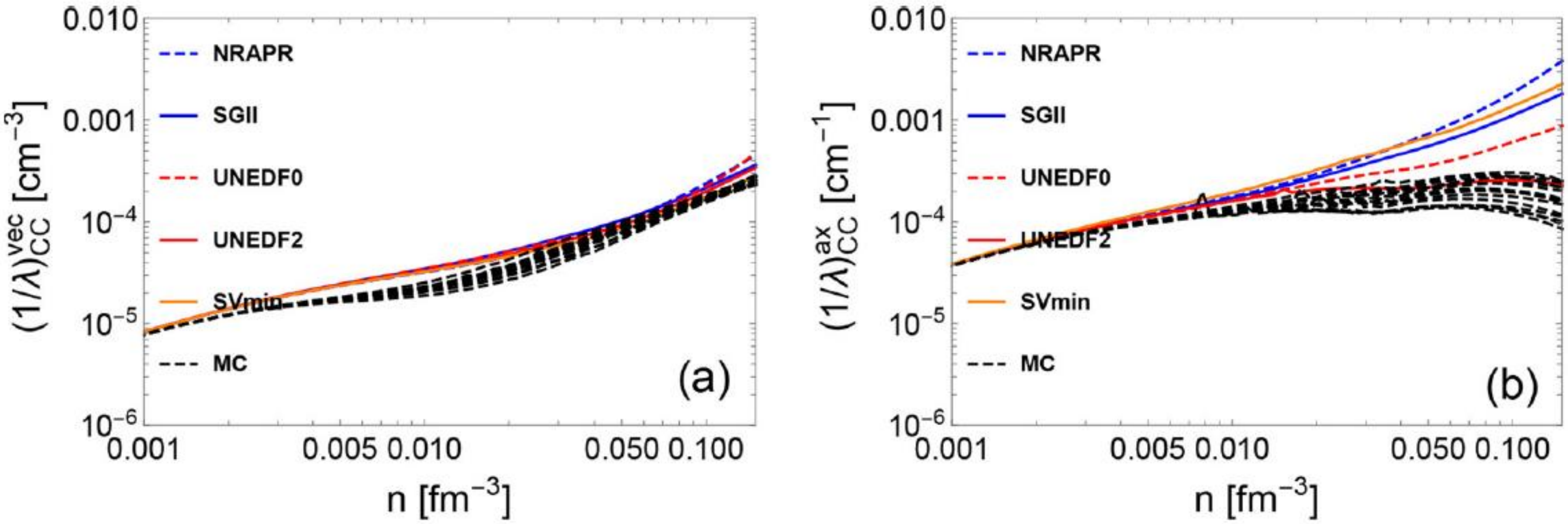
Preliminary

$Y_e \approx 0$

$R = IMPF_{with\_MB}/IMPF_{without\_MB}$

UNCERTAINTIES IN $v -$ MATTER OPACITY TALBE

Uncertainty in Spin (axial) channel is obviously larger!



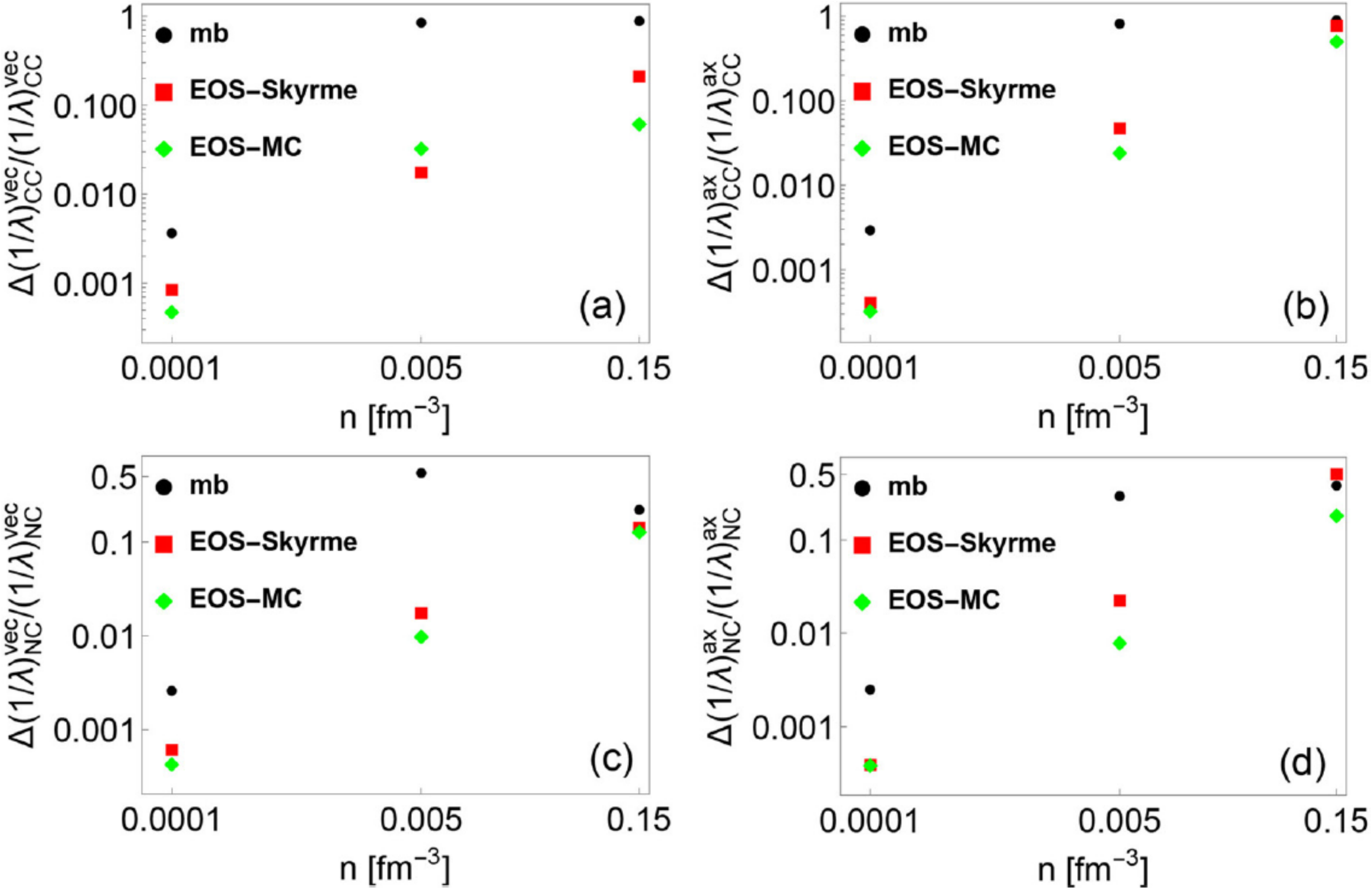
At Beta-equilibrium

E_{v}=3T

Phys. Rev. C **107**, 015804
Z. Lin, A. W. Steiner, J. Margueron

UNCERTAINTIES IN
v – MATTER OPACITY TALBE

Uncertainty in Spin (axial) channel is obviously larger!



At
Beta-
equilibrium

Phys. Rev. C **107**, 015804
Z. Lin, A. W. Steiner, J. Margueron

SEARCHING FOR CONSTRAINTS FOR $\nu -$ MATTER OPACITY TALBE

1. Constraints on density-dependent symmetry energy directly influence CC neutrino opacities with MF corrections
2. Constraints on Landau-Migdal parameters directly influence both CC and NC opacities with RPA corrections
3. Constraints in spin-dependent channel are extremely important for neutrino opacities!

Where to find these constraints?

1. Neutron skin measurements; neutron star radius/mass measurements; heavy ion collision experiments; …

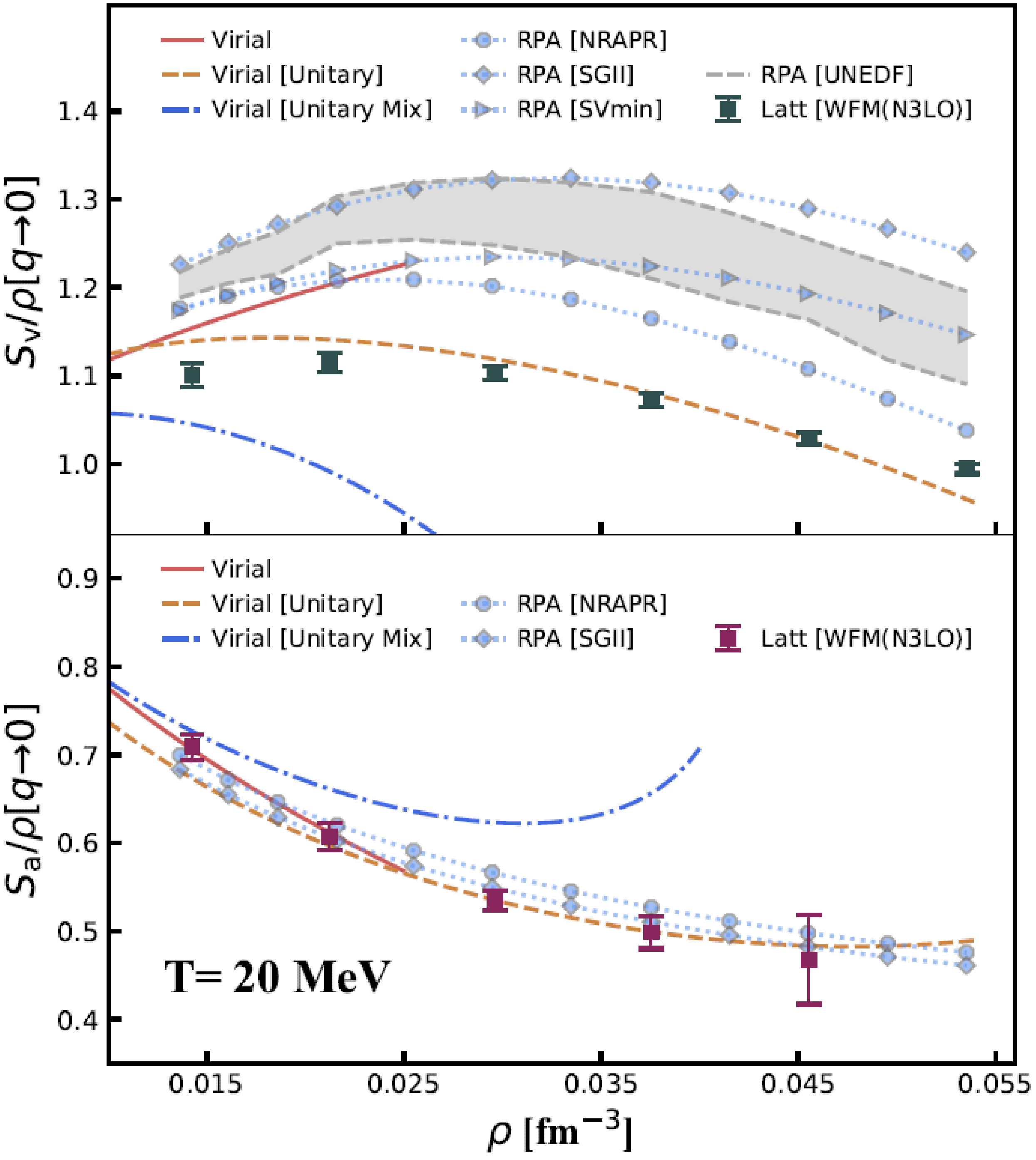
2. Nuclear experiments on finite nuclei excited states that are sensitive to p-h interactions; Ab initial theoretical calculations; …

3. Nuclear experiments on finite nuclei that are sensitive to spin-dependent forces (such as Gamow-Teller resonance); Ab initial theoretical calculations; …

SEARCHING FOR CONSTRAINTS: CLUES FROM AB-INITIO CALCULATIONS

arXiv:2306.04500 [nucl-th]

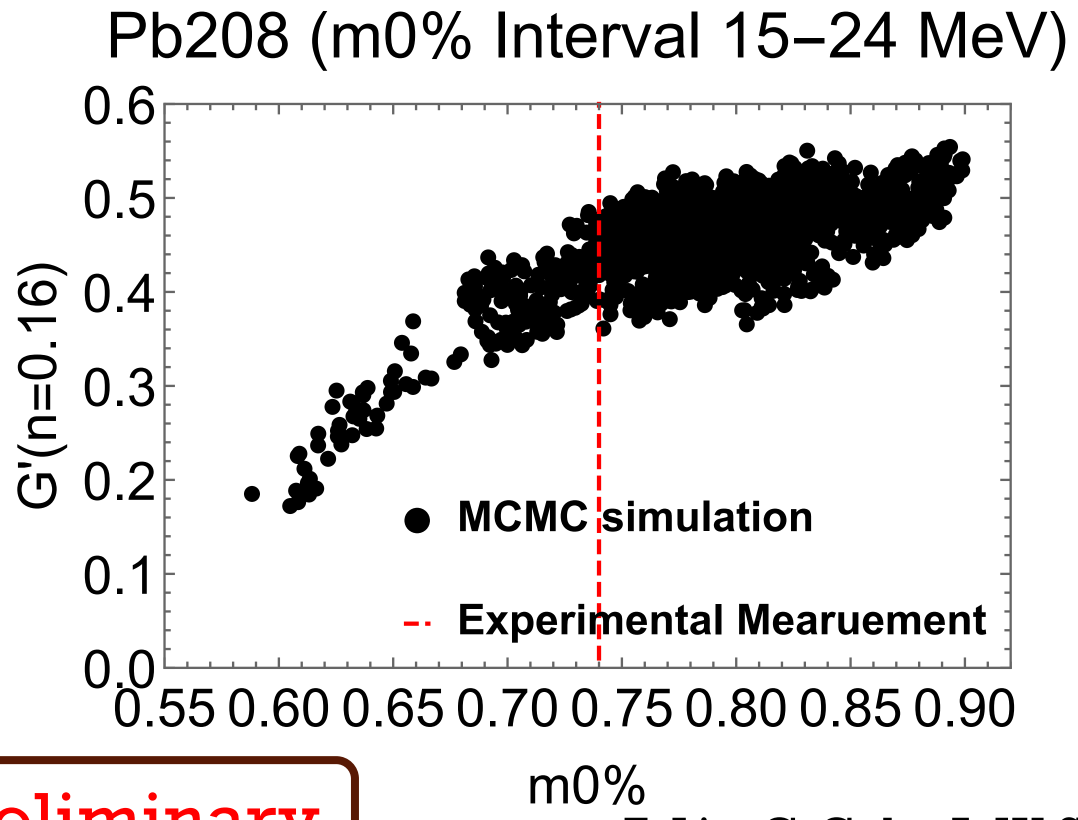
Y. Ma, Z. Lin, B. Lu, *et al.*

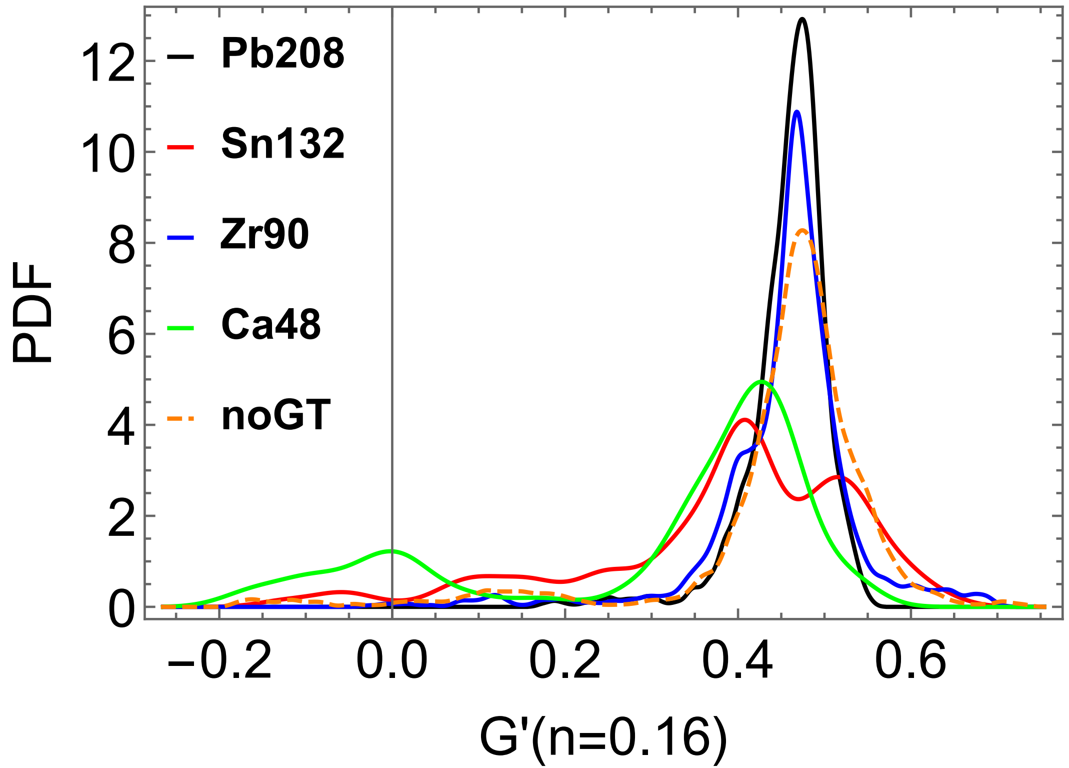


SEARCHING FOR CONSTRAINTS: CLUES FROM GAMOW TELLER EXP

Note: m0% is the percentage of total Gamow-Teller strength exhausted by the Gamow-Teller resonance peak

Note: strength of G' directly influence CC neutrino opacities in the axial current channel





Preliminary

Z. Lin, G. Colo, A. W. Steiner, *et al. (in preparation)*

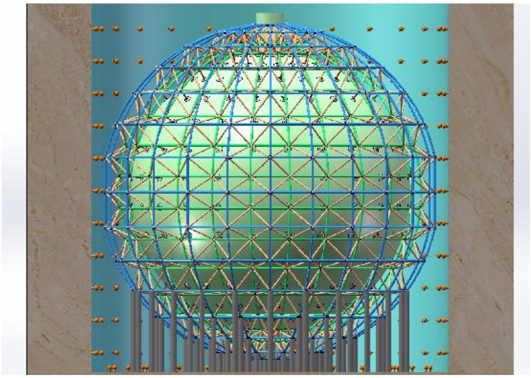
CONCLUSION

1. Many-body corrections exhibit various non-trivial features in both NC and CC neutrino-nucleon reactions, and at very different densities, temperatures, proton fractions
2. It's difficult to find an analytical expression that accurately describe all the many-body effects in a wide range of n, T, Ye. Thus, a large-scale tabulated neutrino opacity table is needed.
3. Constraints on neutrino opacities may come from many different nuclear experiments, astronomical observations and ab-initio calculations
4. Constraints from experimentally measurable quantities on neutrino opacities shed light on the uncertainty quantification of neutrino-matter many-body corrections.

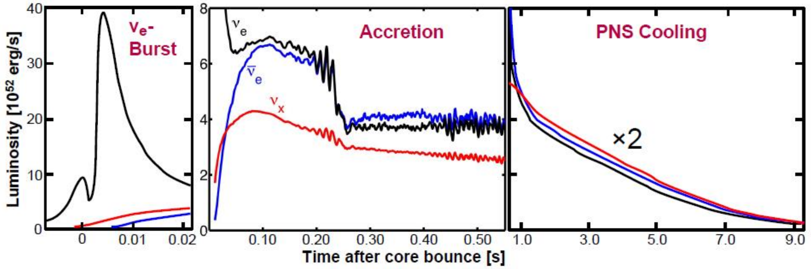
not the End yet ….

What's the most promising Constraint for neutrino-matter Interactions?

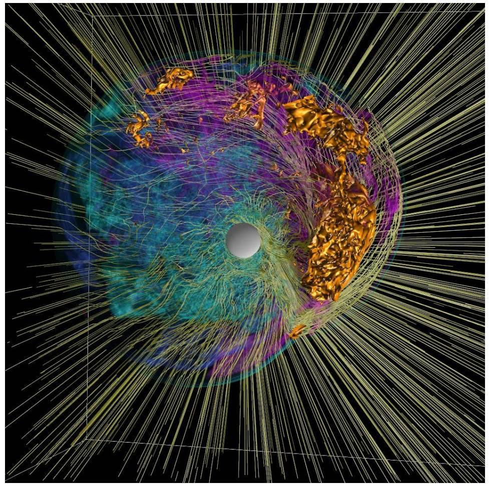
The next galactic CCSN!



Detector events features

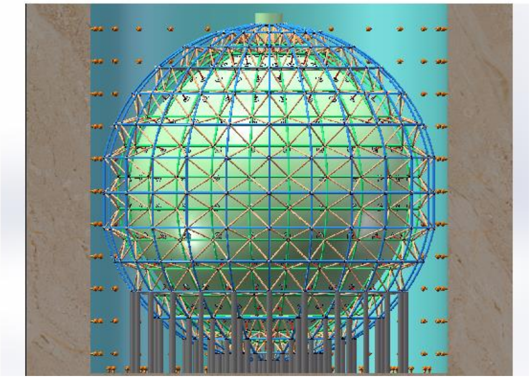


Neutrino flux properties



Simulations

But what we are facing is, actually, a **reverse** problem….



How well can we reconstruct neutrino flux properties?

How many neutrino flux properties are **model-independently** correlating with neutrino reactions in a REAL CCSN?

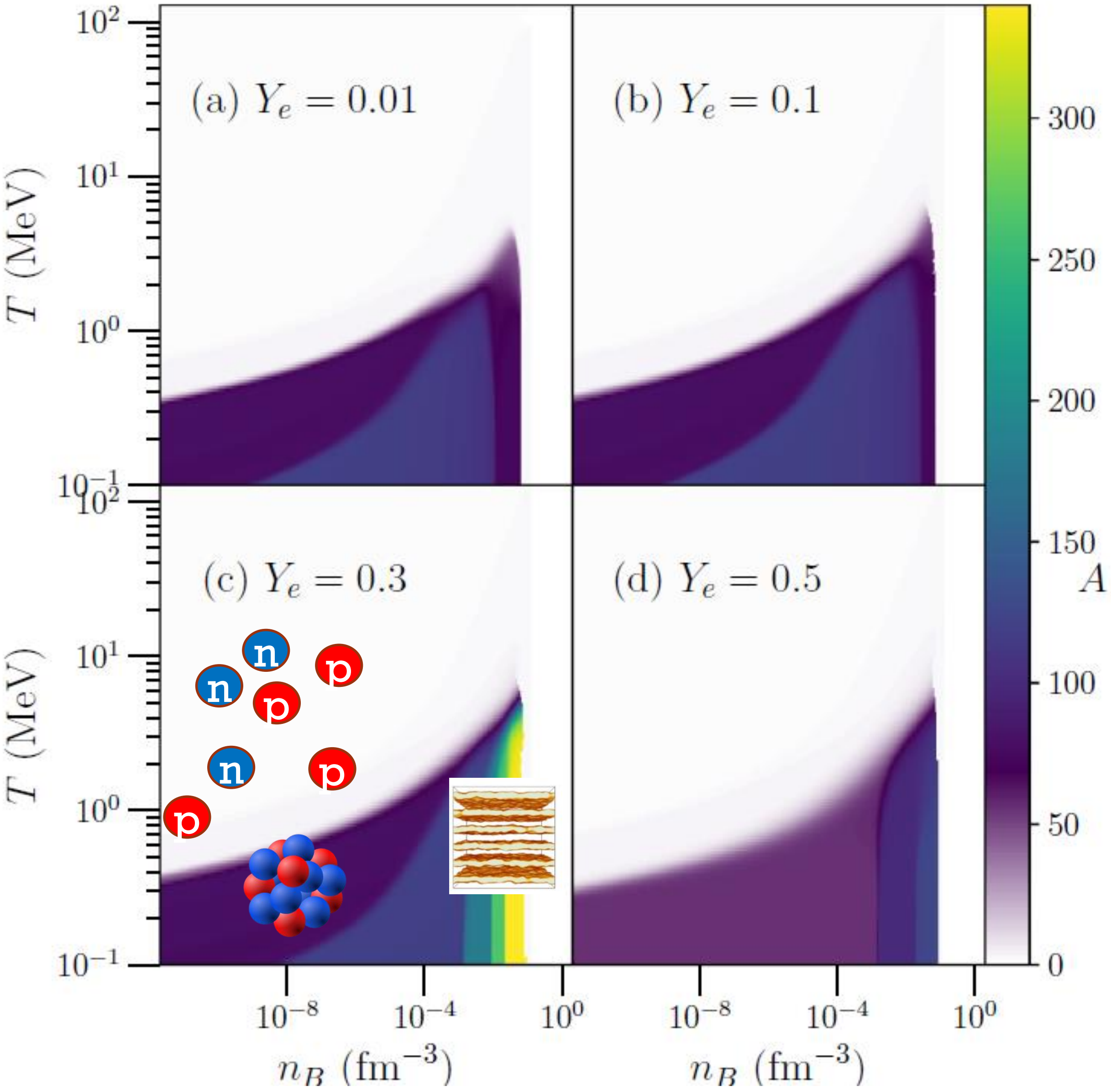
Stay tuned …

Thank you!

Backup

WHY ν-NUCLEON INTERACTIONS ARE IMPORTANT?

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!

DESCRIPTION OF ν OPACITIES USING RPA

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

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:

$$S(q_0,\mathrm{q}) = \frac{2}{1-\exp[-\left(q_0 + \frac{\mu_2-\mu_4}{T}\right)]} Im[\Pi_{V/A}]$$

Mean Field(MF)

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

Random phase approximation (RPA)

Input from EoS

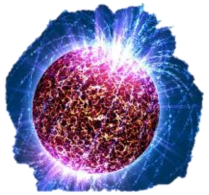
MF Input: U_P U_N μ_P μ_N M_P^* M_N^*

RPA Input: Landau-Migdal Parameters

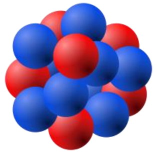
FROM NUCLEON-NUCLEON TO υ-NUCLEON

PARTIAL WAVE ANALYSIS OF N-N SCATTERING [Nijmegen]

Astronomical observations



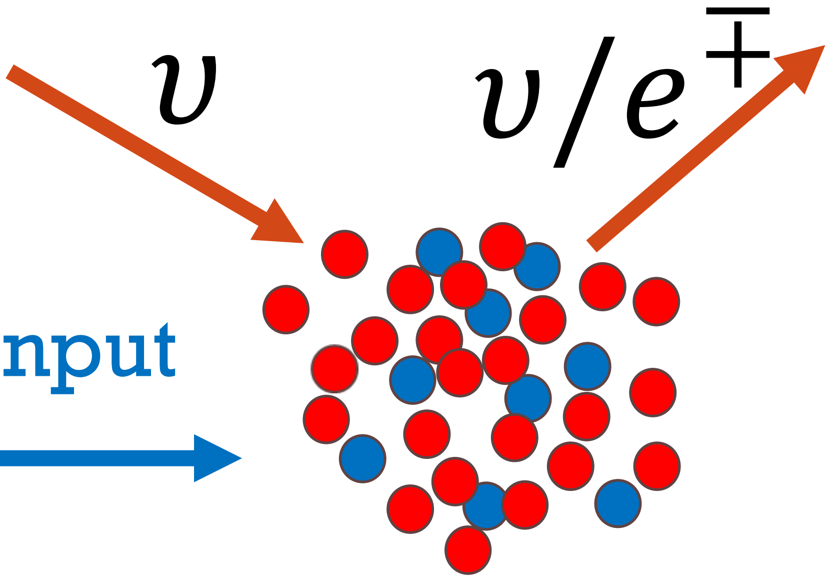
Lab observables of nucleus properties



Constrain

EoS

Provides Input



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

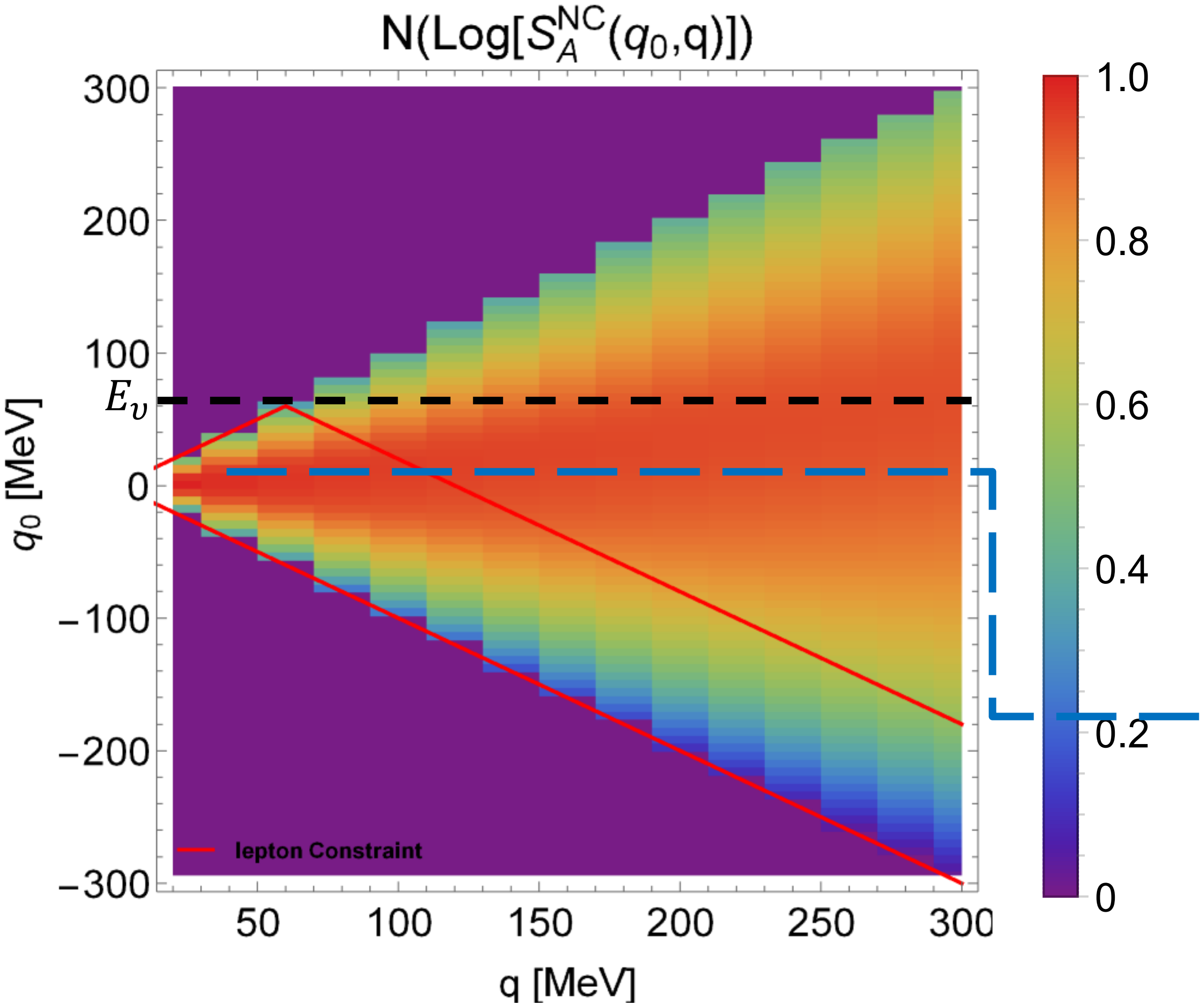
MANY-BODY EFFECTS BASED ON EXACT DYNAMIC RPA STRUCTURE FACTORS

$$IMFP = \int \frac{\partial^2 \sigma_0}{\partial \Omega \partial q_0} * \underline{S(q_0, q)} d\Omega d q_0$$

$$Transport\ IMFP = \int \frac{\partial^2 \sigma_0}{\partial \Omega \partial q_0} * (1 - cos\theta) * \underline{S(q_0, q)} d\Omega d q_0$$

Many-body correction is just a weighting factor….

DYNAMIC S(Q0,Q)+ KINEMATIC CONSTRAINT



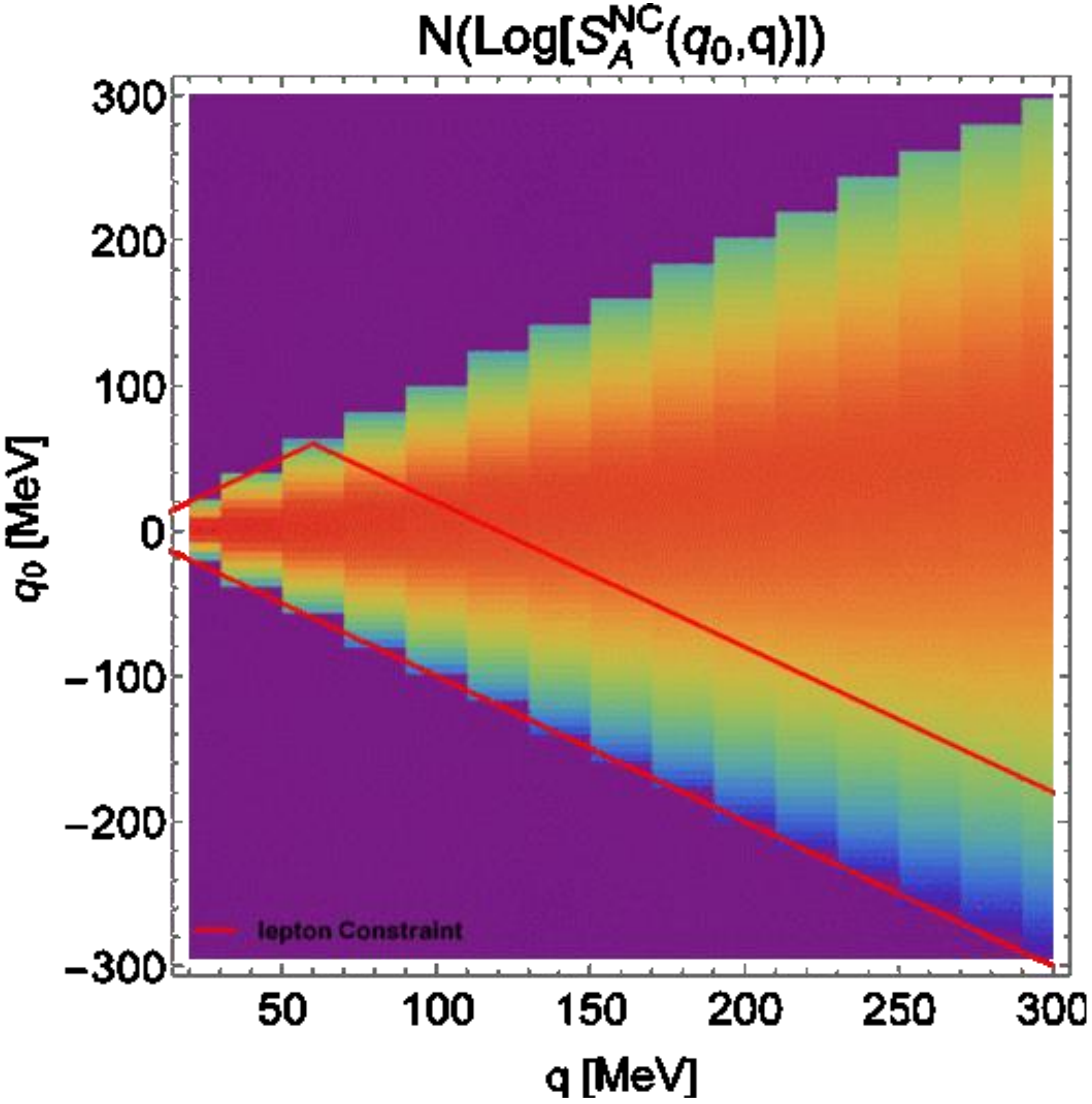
$n=10^{-2} fm^{-3}$; $E_\upsilon = 60$ MeV

Lepton Constraints:

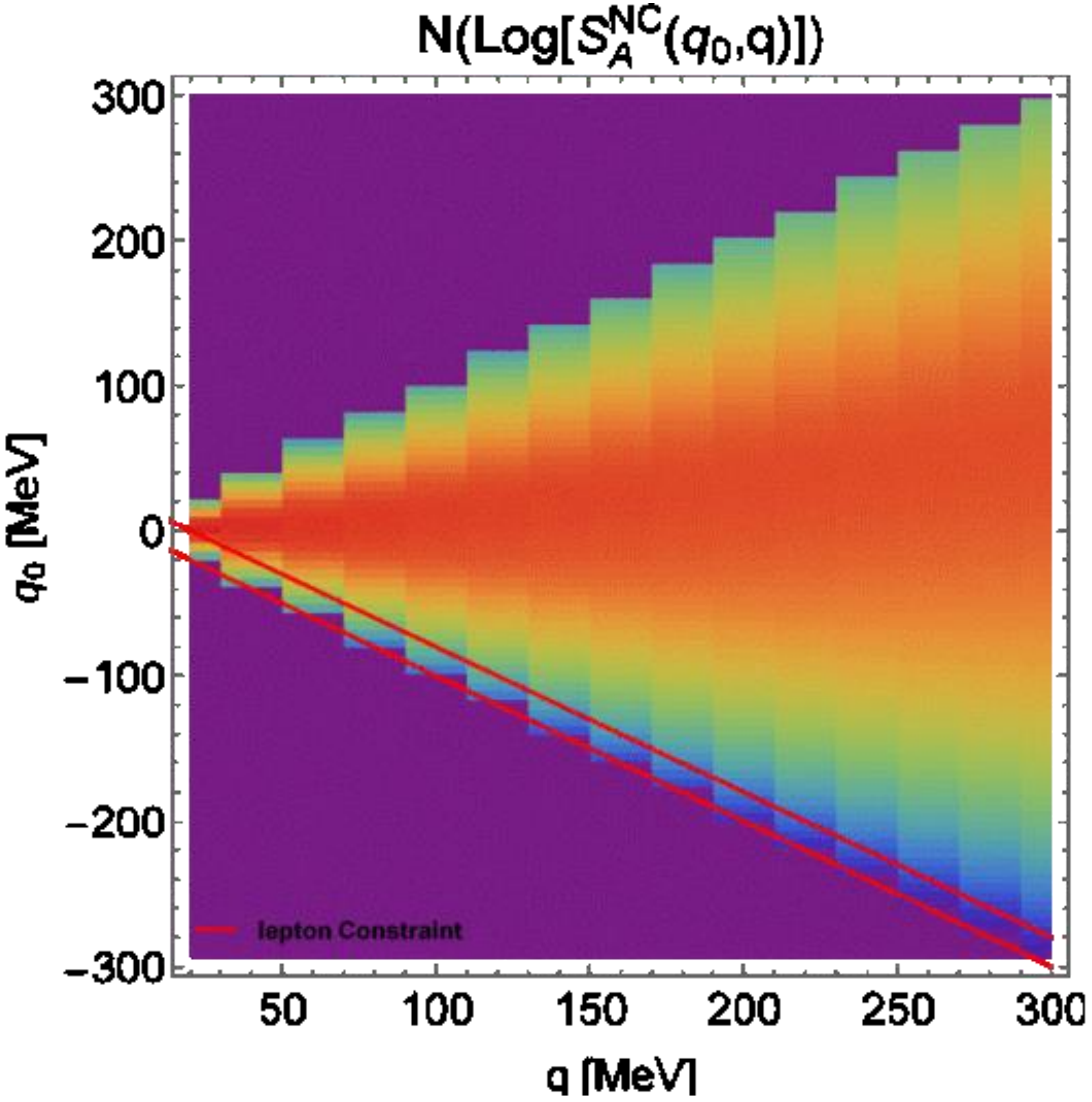
$$E_\upsilon(\vec{P}_\upsilon) - E_{\upsilon'/e}(\vec{P}_{\upsilon'/e}) = q_0$$

$$IMFP = \int \frac{\partial^2 \sigma_0}{\partial\Omega \partial q_0} * 🟥 \, d\Omega dq_0$$

Put the corresponding Pixel (weighting factor) here!



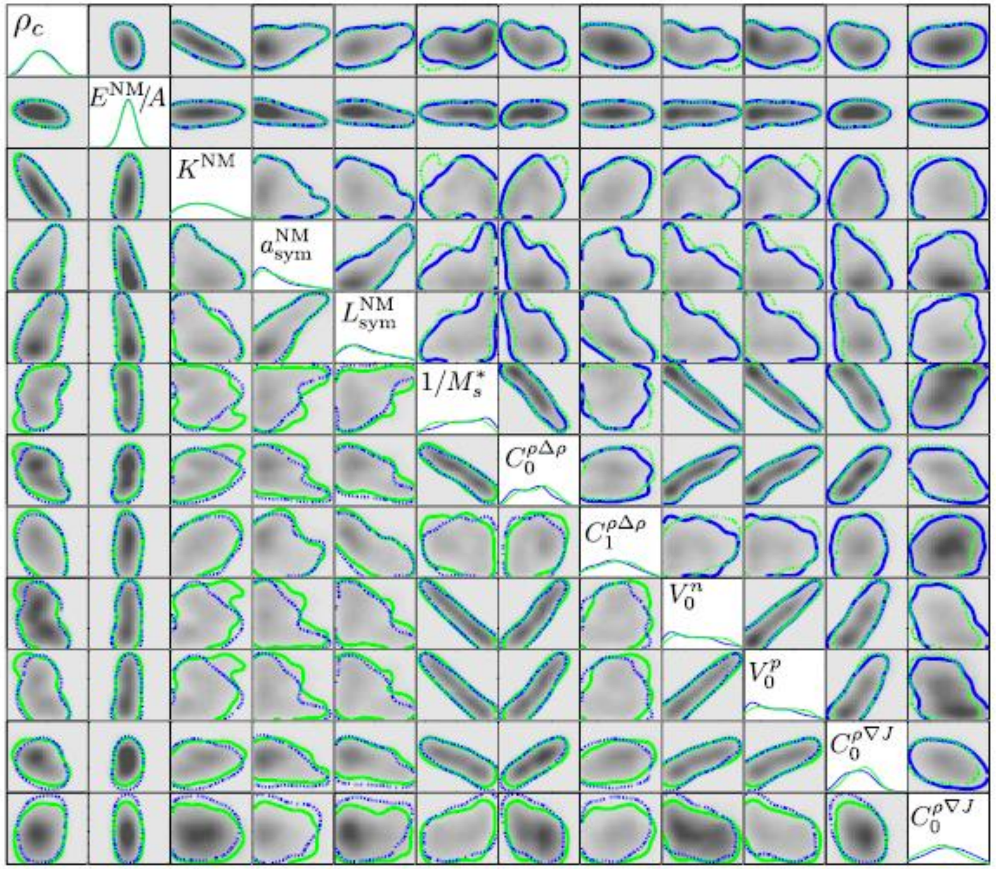
n=0.01−0.45fm^{-3}; $E_v = 60$ MeV



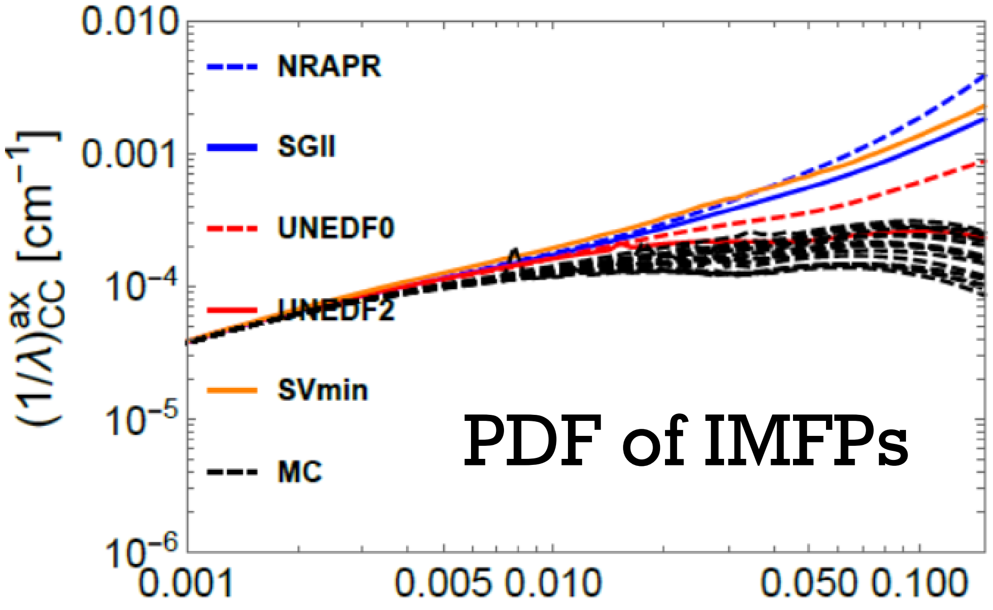
n=$10^{-2}fm^{-3}$; $E_v = 10 - 80$ MeV

UNCERTAINTIES OF υ OPACITIES

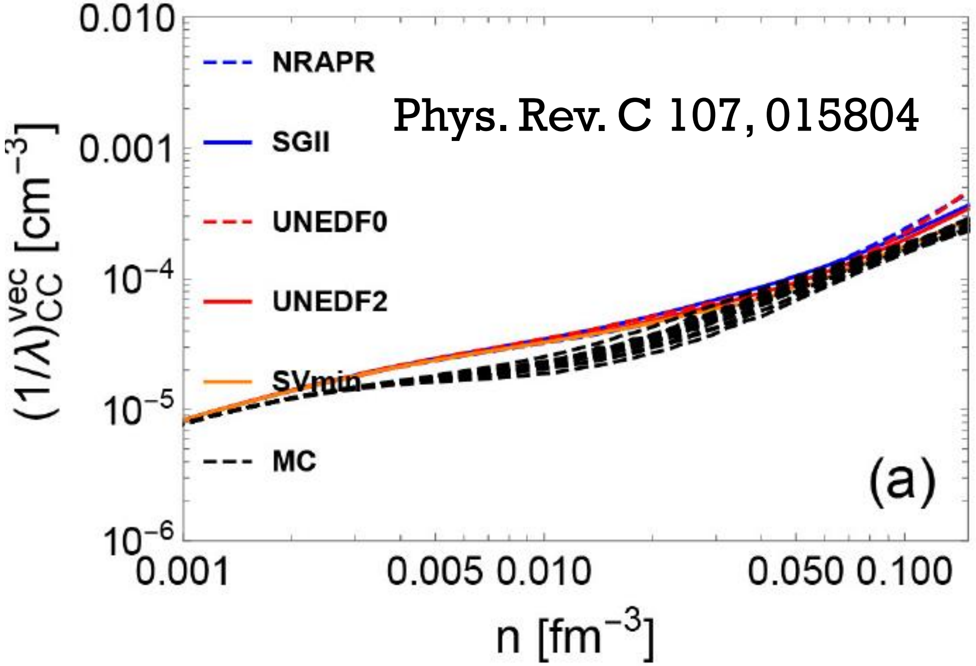
J. D. McDonnel *et al.* 2015



PDF of Skyrme parameters constrained by nuclei properties (UNEDF)

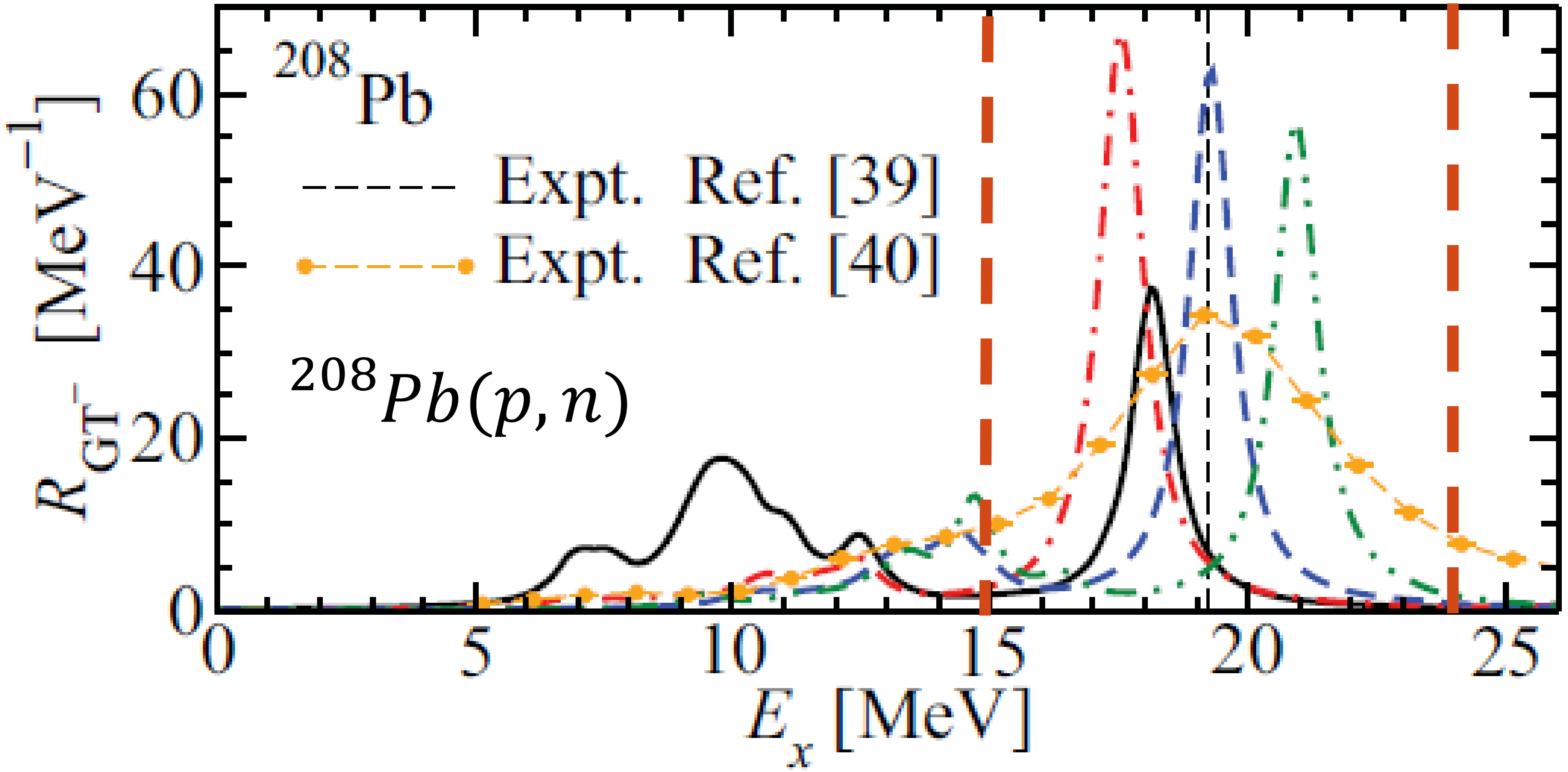


PDF of IMFPs



Phys. Rev. C 107, 015804

CONSTRAINTS FOR G' FROM GTR

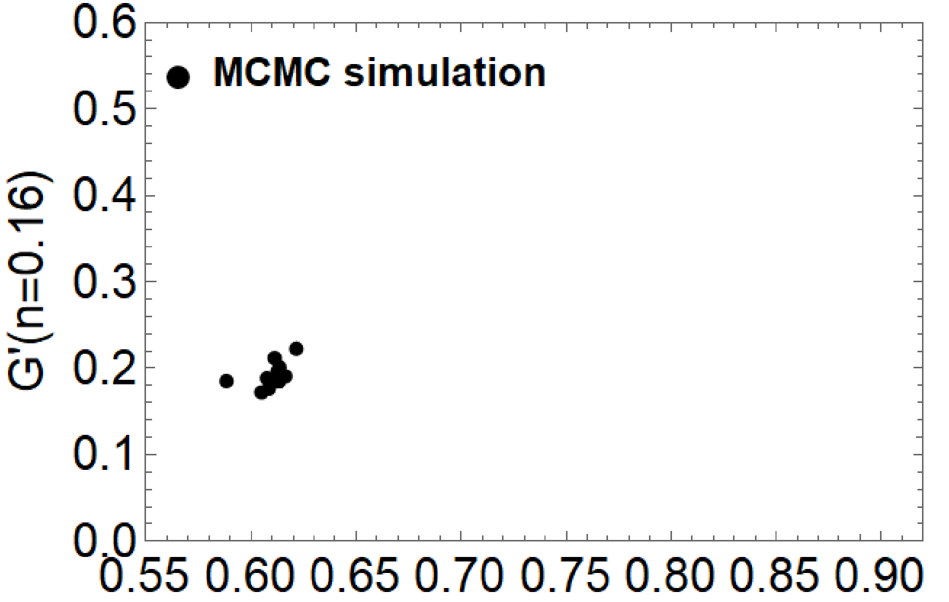


Note that V_{gt}=2G' at symmetric nuclear matter (SNM)

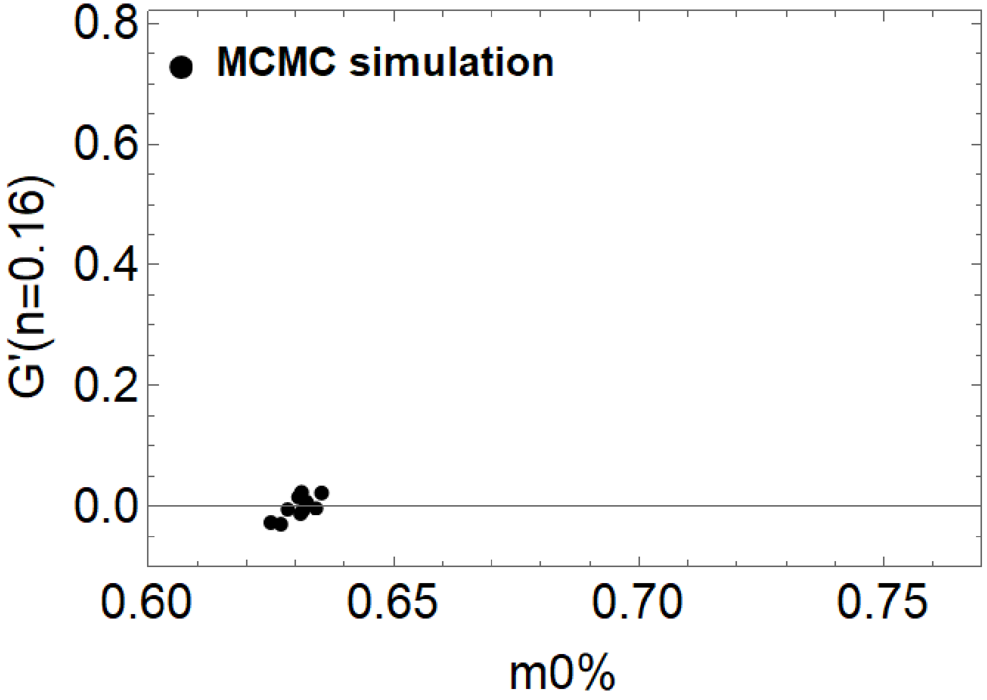
X. Roca-Maza, G. Colo, and H. Sagawa (2012)

The area covered by GTR peak is strongly Correlating with G'

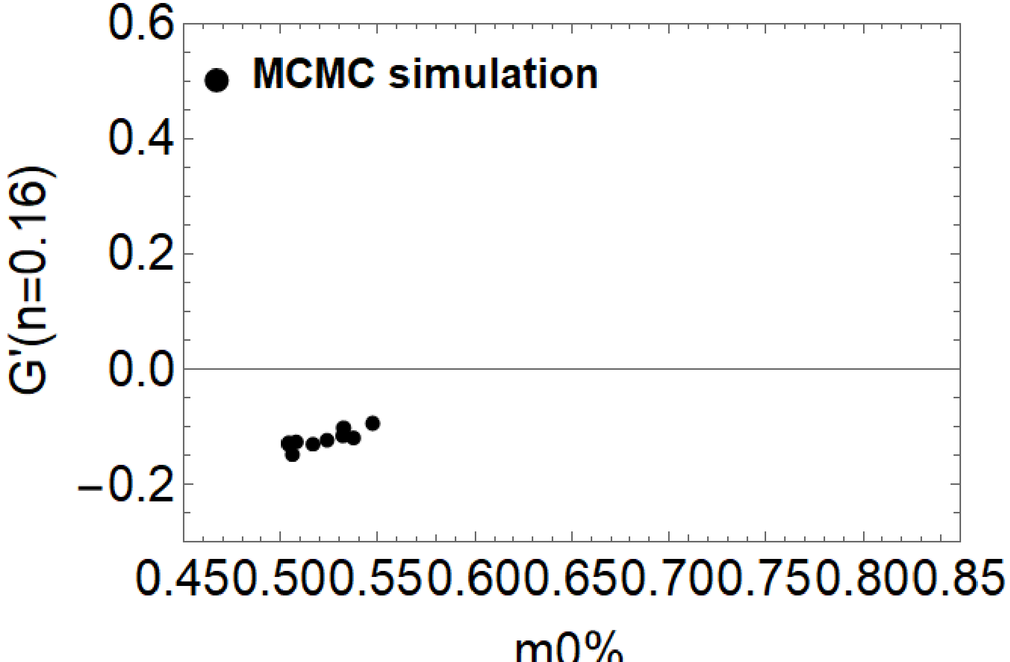
Pb208 (m0% Interval 15–24 MeV)



Zr90 (m0% Interval 12–22 MeV)



9 –24 MeV (Sn132)



We are running MCMC to determine G' using GTR on Pb208, Sn132, Zr90 and Ca48

More are coming…

Landau-Migdal Parameters

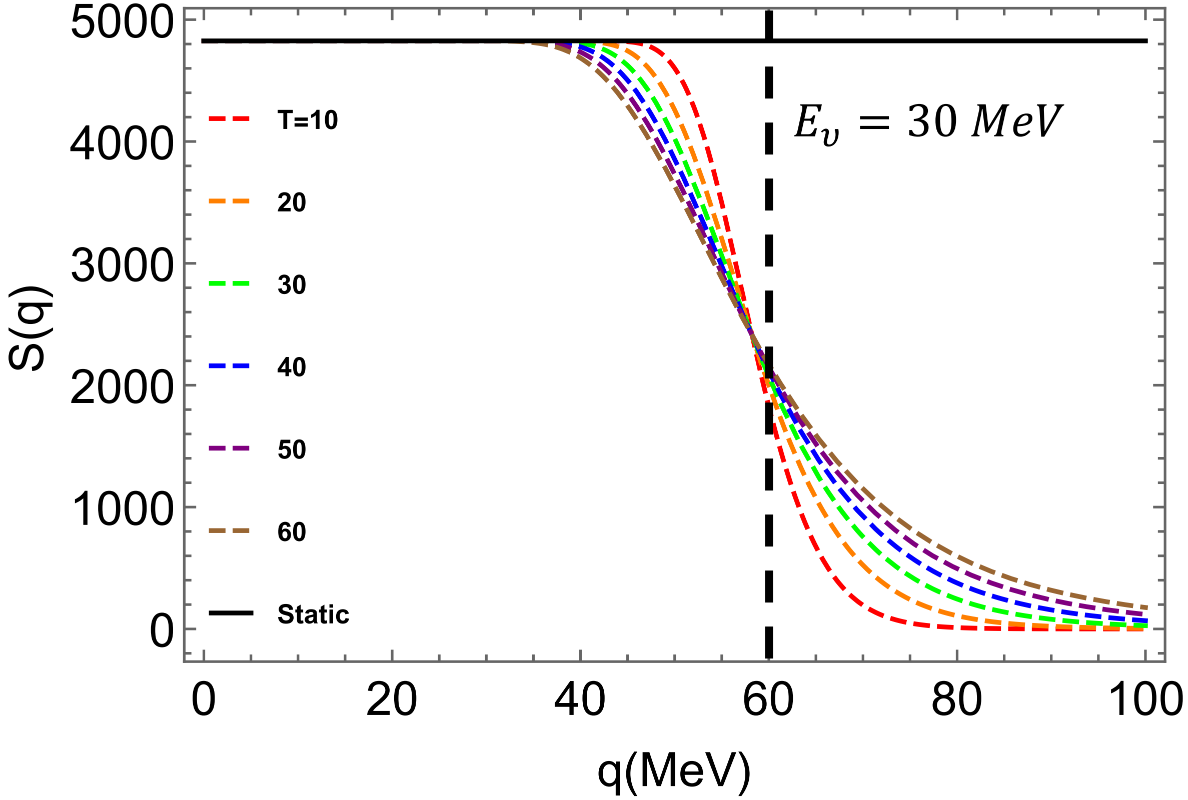
$$\left.\begin{aligned} f_0 &= \frac{\partial^2 E}{\partial n \partial n}, \\ f_0' &= \frac{\partial^2 E}{\partial n_{3,0} \partial n_{3,0}}, \\ g_0 &= \frac{\partial^2 E}{\partial n_{0,3} \partial n_{0,3}}, \\ g_0' &= \frac{\partial^2 E}{\partial n_{3,3} \partial n_{3,3}}, \end{aligned}\right\} \quad \begin{aligned} f_0 &= \tfrac{1}{2}\left(f_0^{\tau\tau} + f_0^{\tau-\tau}\right), \quad f_0' = \tfrac{1}{2}\left(f_0^{\tau\tau} - f_0^{\tau-\tau}\right), \\ g_0 &= \tfrac{1}{2}\left(g_0^{\tau\tau} + g_0^{\tau-\tau}\right), \quad g_0' = \tfrac{1}{2}\left(g_0^{\tau\tau} - g_0^{\tau-\tau}\right). \end{aligned}$$

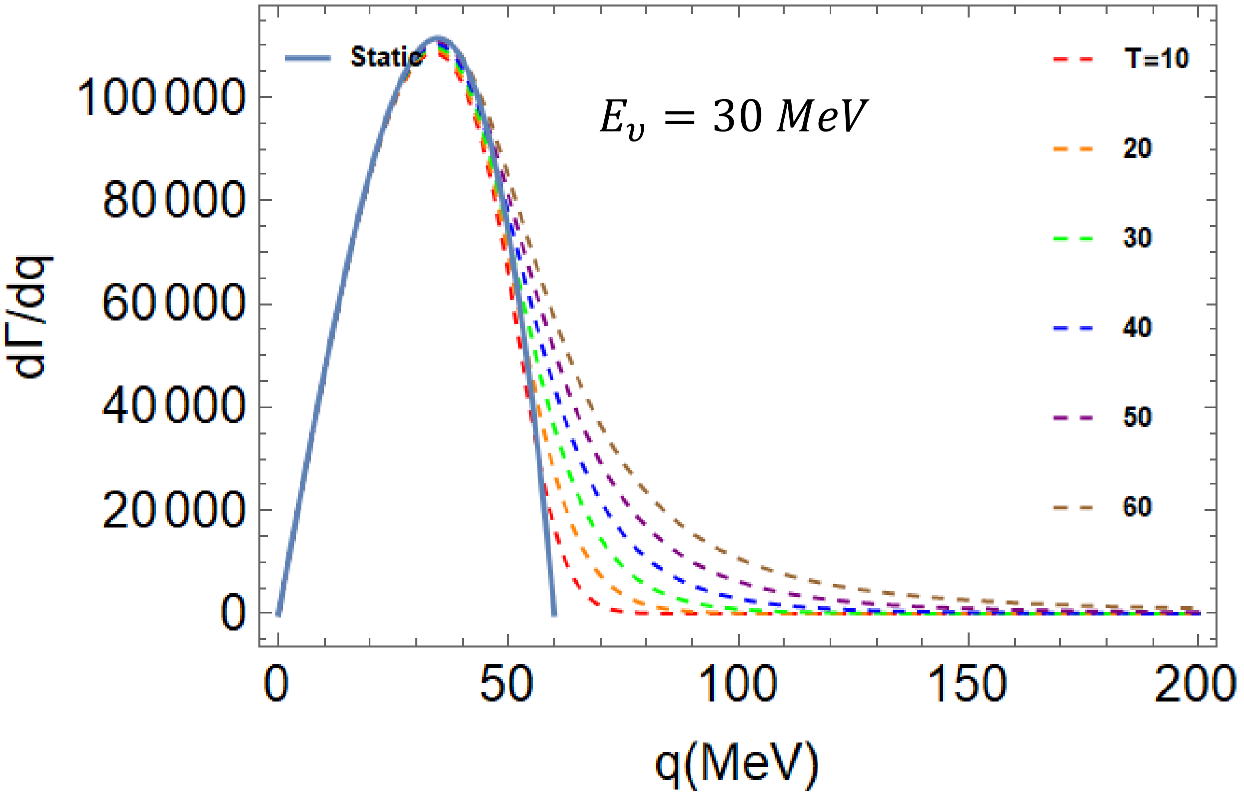
$$n_{3,0} = n_p - n_n$$

$$n_{3,3} = n_{p\uparrow} - n_{p\downarrow} - n_{n\uparrow} + n_{n\downarrow}$$

$$n_{0,3} = n_{p\uparrow} - n_{p\downarrow} + n_{n\uparrow} - n_{n\downarrow}$$

NC non-interacting





Structure Factor

Differential rate