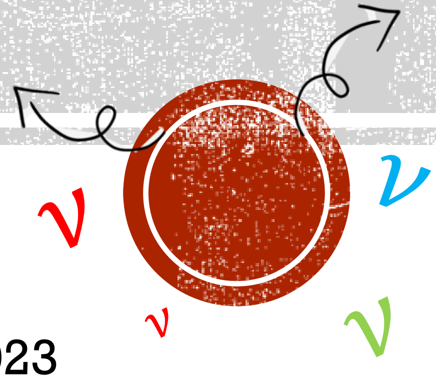
UNCERTAINTIES & CONSTRAINTS FOR ν OPACITIES IN CCSNE AND BNS MERGERS



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Seminar at Institute for Nuclear Physics, UW, 3/30/2023

Collaborators: A. W. Steiner, J. Margueron, G. Colo, Y. Ma, D. Lee

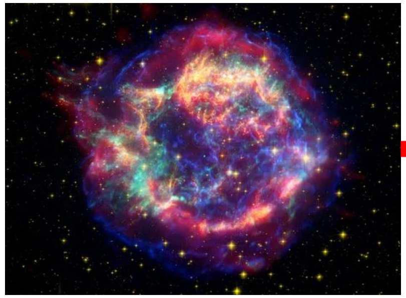
A. HOW DO NEUTRINOS INTERACT WITH DENSE MATTER IN COMPACT OBJECTS?

1. Why neutrino interactions are important in compact objects?
2. Why neutrino interactions are complicated?
3. Description of υ opacities using RPA
4. Uncertainties of υ opacities
5. Constraints for υ opacities

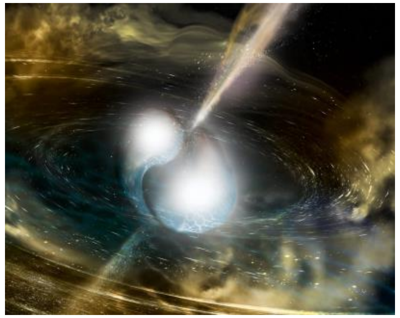
WHY ν INTERACTIONS ARE IMPORTANT?

Neutron Star (NS)

Core-collapse Supernovae (CCSNe)



Binary Neutron star mergers (BNS)



NS Cooling

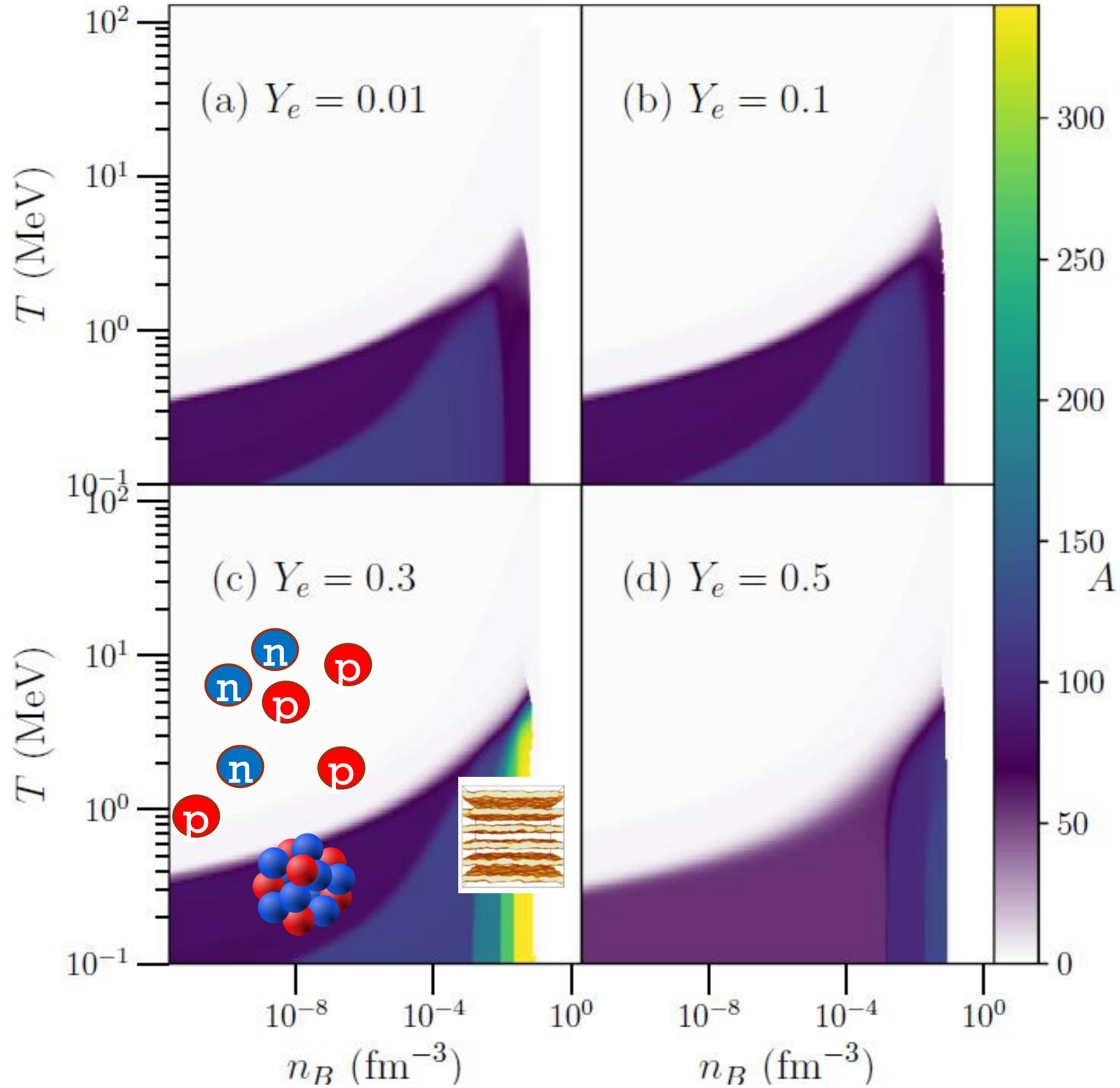
Explosion Mechanism

Nucleosynthesis

ν

WHY υ-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

$$R_\upsilon$$

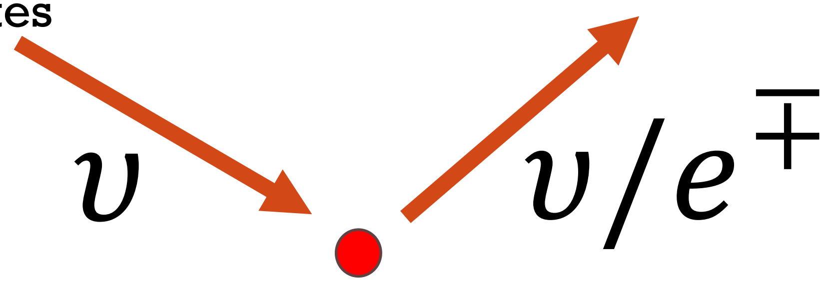
Neutrino Sphere Radius

We focus on neutrino-nucleon interactions today!

WHY NEUTRINO INTERACTIONS ARE COMPLICATED?

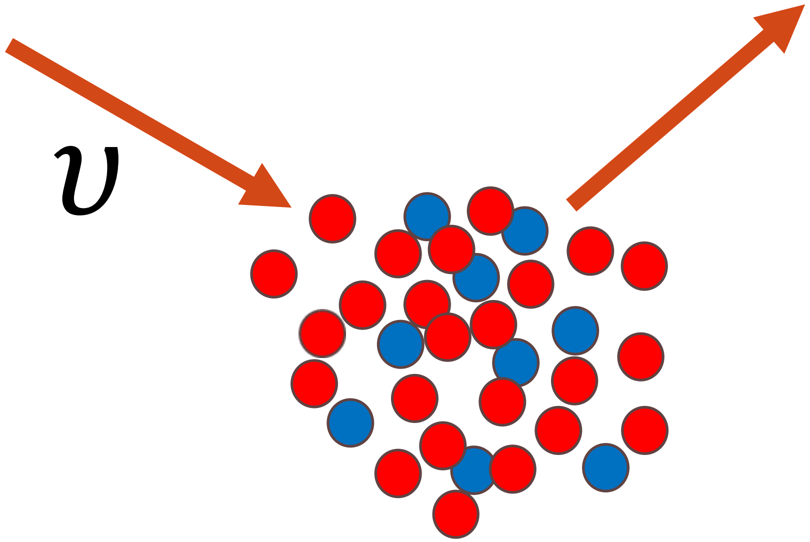
(We focus on neutrino-nucleon interactions today)

Free-space neutrino-nucleon interaction rates



$\times$ Density

$\neq$



Because of "in-medium" corrections

An illustration of "in-medium effect"

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

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

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

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

At MF level, such a correction mainly result from conservation laws & Pauli Blocking

DESCRIPTION OF ν OPACITIES USING RPA

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

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:

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

Mean Field(MF)

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

Random phase approximation (RPA)

Input from EoS

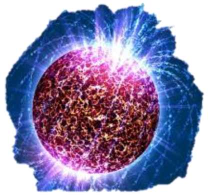
MF Input: U_P U_N μ_P μ_N M_P^* M_N^*

RPA Input: Landau-Migdal Parameters

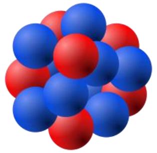
FROM NUCLEON-NUCLEON TO υ-NUCLEON

PARTIAL WAVE ANALYSIS OF N-N SCATTERING [Nijmegen]

Astronomical observations



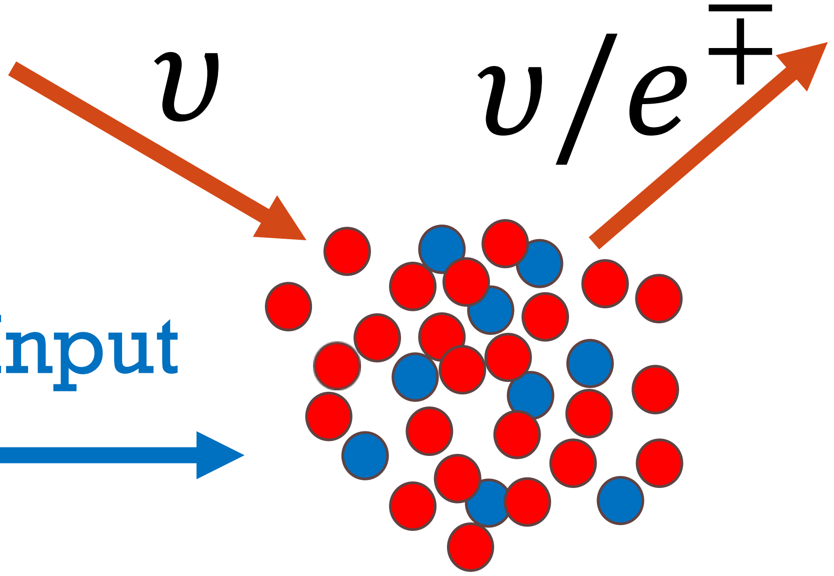
Lab observables of nucleus properties



Constrain

EoS

Provides Input



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

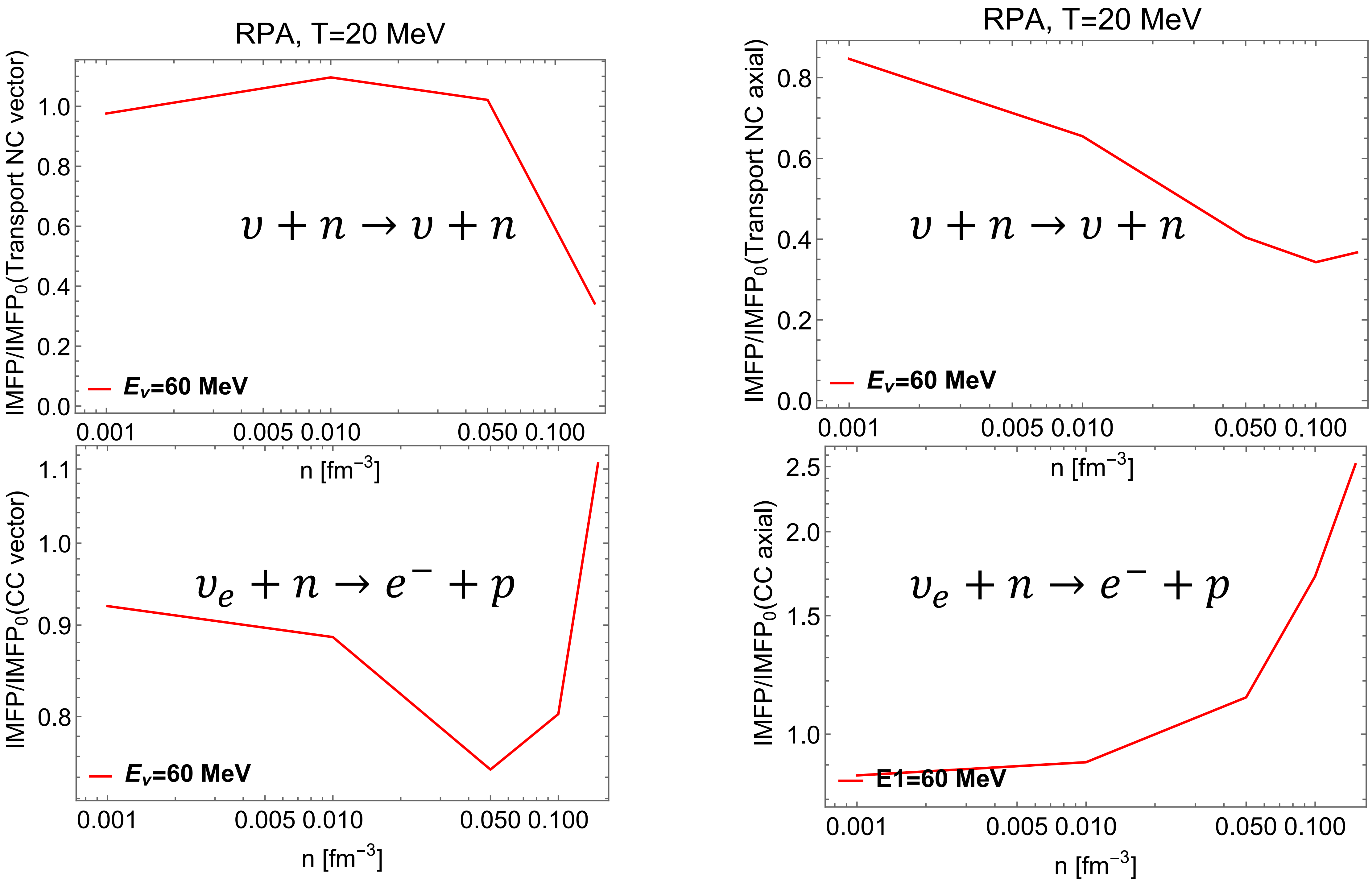
An Example
(υ opacities from RPA consistent with NRAPR EoS)

MANY-BODY EFFECTS BASED ON EXACT DYNAMIC RPA STRUCTURE FACTORS

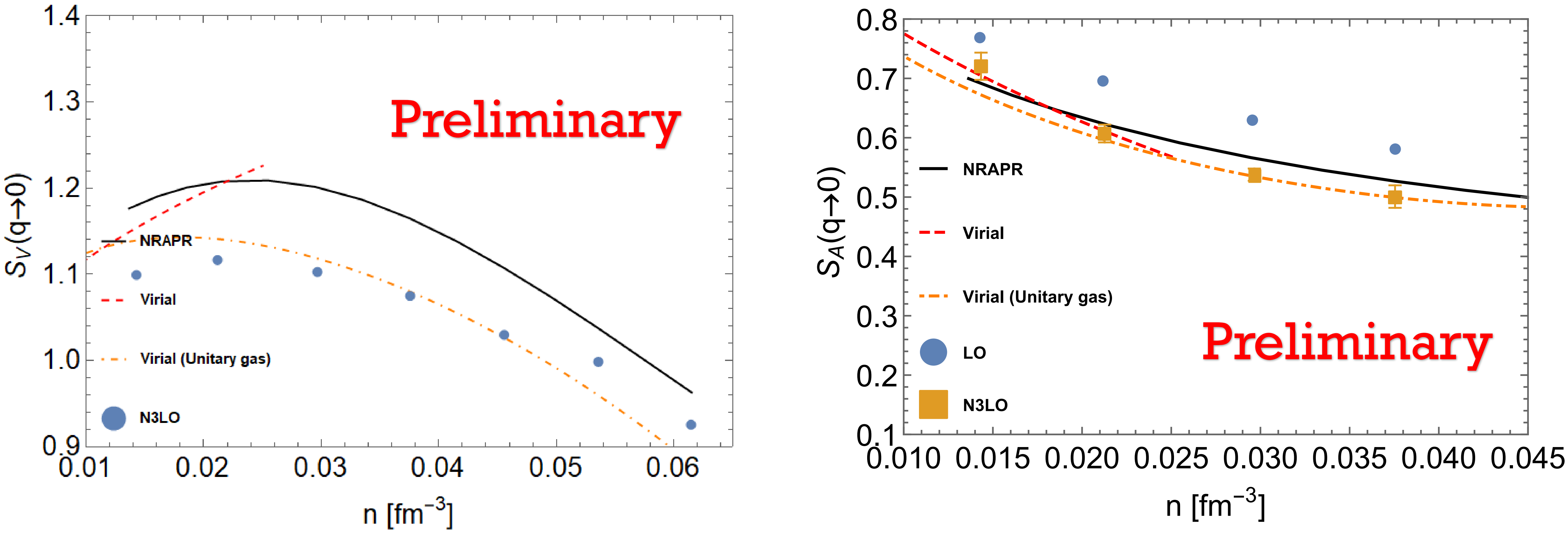
$$IMFP = \int \frac{\partial^2 \sigma}{\partial \Omega \partial q_0} * \underline{S(q_0, q)} d\Omega dq_0$$

$$Transport\ IMFP = \int \frac{\partial^2 \sigma}{\partial \Omega \partial q_0} * (1 - cos\theta) * \underline{S(q_0, q)} d\Omega dq_0$$

Many-body correction is just a weighting factor….


RPA, T=20 MeV
IMFP/IMFP$_0$(Transport NC vector)
$\upsilon + n \rightarrow \upsilon + n$
E_ν=60 MeV
n [fm^{-3}]
RPA, T=20 MeV
IMFP/IMFP$_0$(Transport NC axial)
$\upsilon + n \rightarrow \upsilon + n$
E_ν=60 MeV
n [fm^{-3}]
IMFP/IMFP$_0$(CC vector)
$\upsilon_e + n \rightarrow e^- + p$
E_ν=60 MeV
n [fm^{-3}]
IMFP/IMFP$_0$(CC axial)
$\upsilon_e + n \rightarrow e^- + p$
E1=60 MeV
n [fm^{-3}]

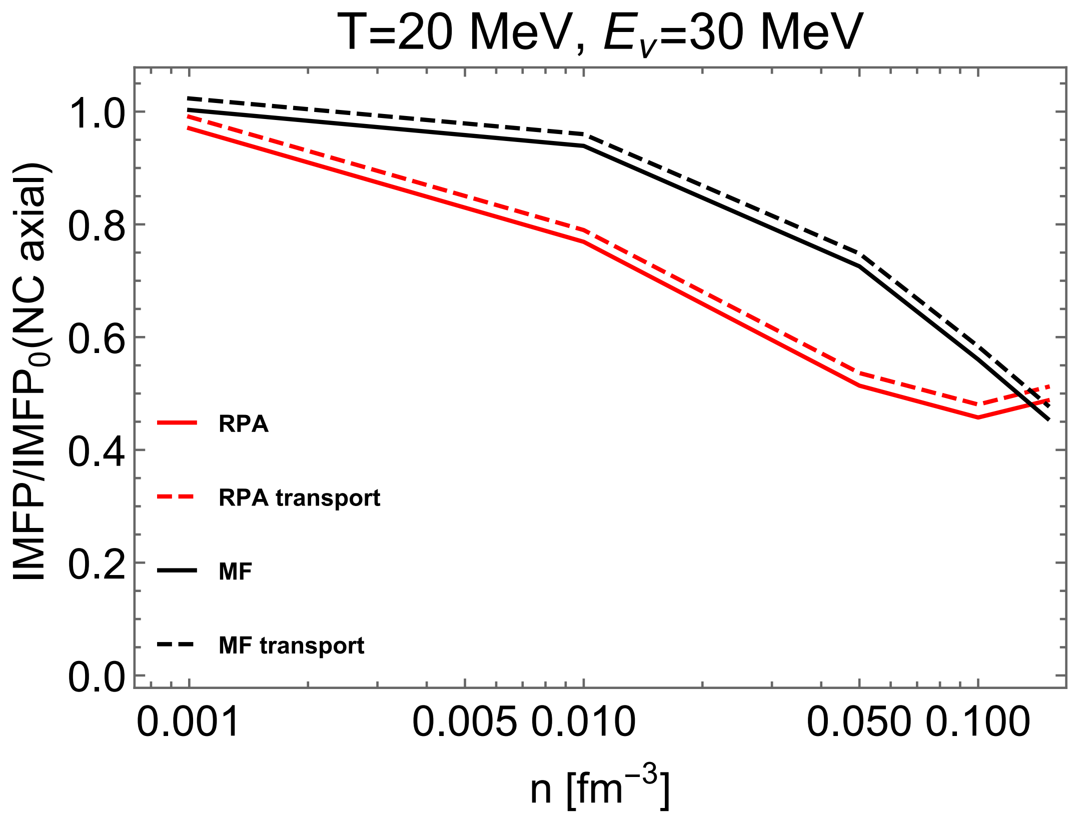
CHECK: RPA VS AB-INITIAL LATTICE EFT IN NC



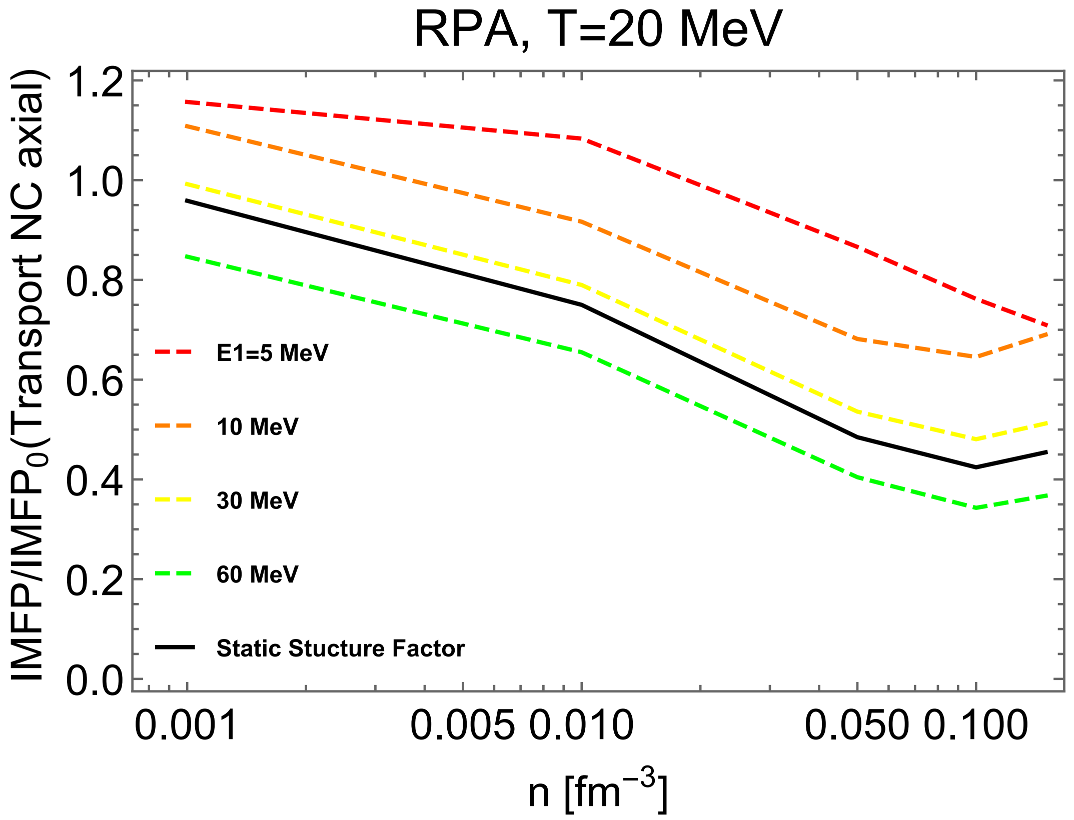
Lattice results from Y. Ma and D. Lee

Static Structure Factor

MANY-BODY EFFECTS BASED ON EXACT DYNAMIC RPA STRUCTURE FACTORS

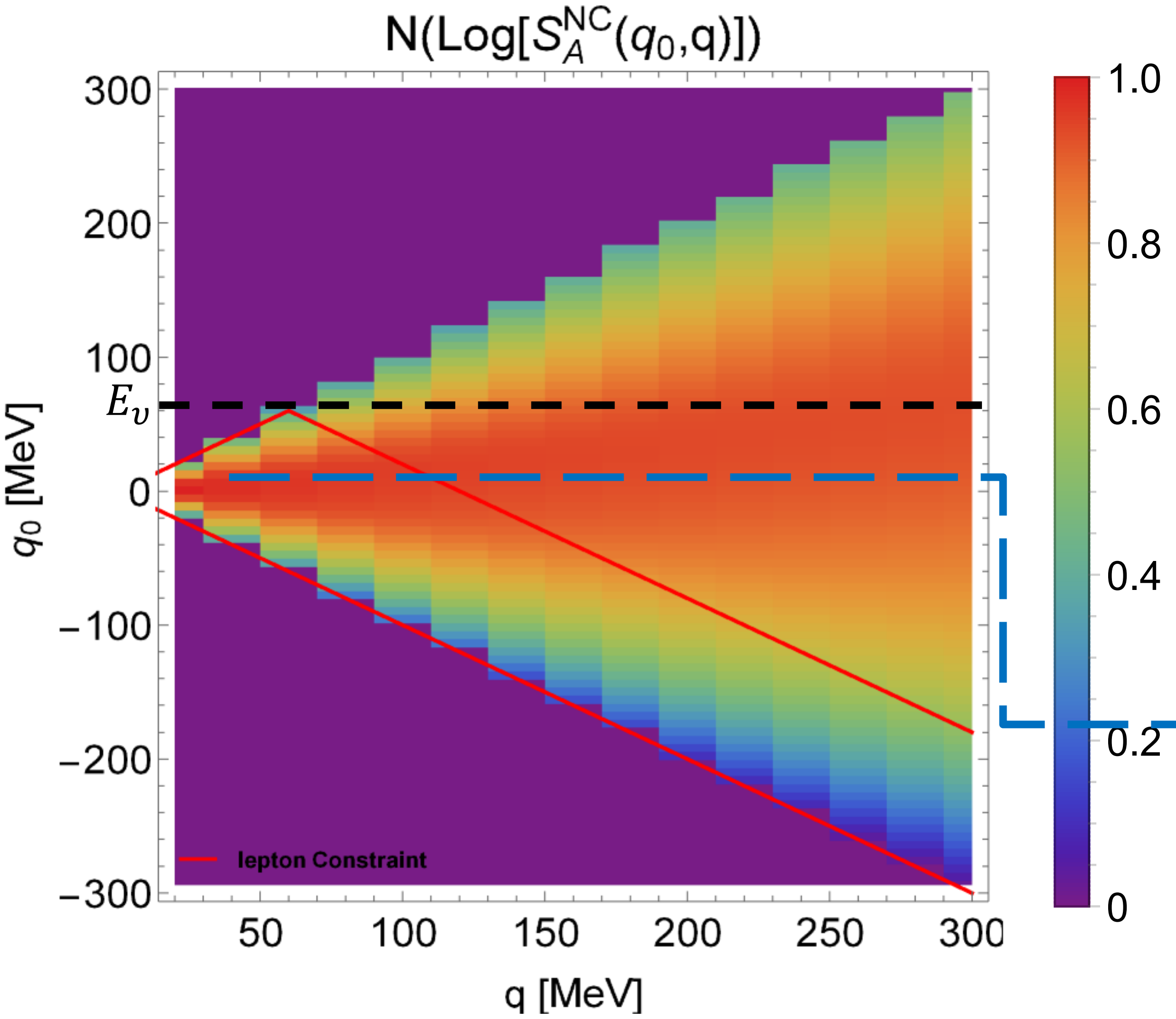


Many-body effects on IMFP
≠Many-body effects on Transport IMFP



Many-body effects for different E_υs
Are different

DYNAMIC S(Q0,Q)+ KINEMATIC CONSTRAINT



Lepton Constraints:

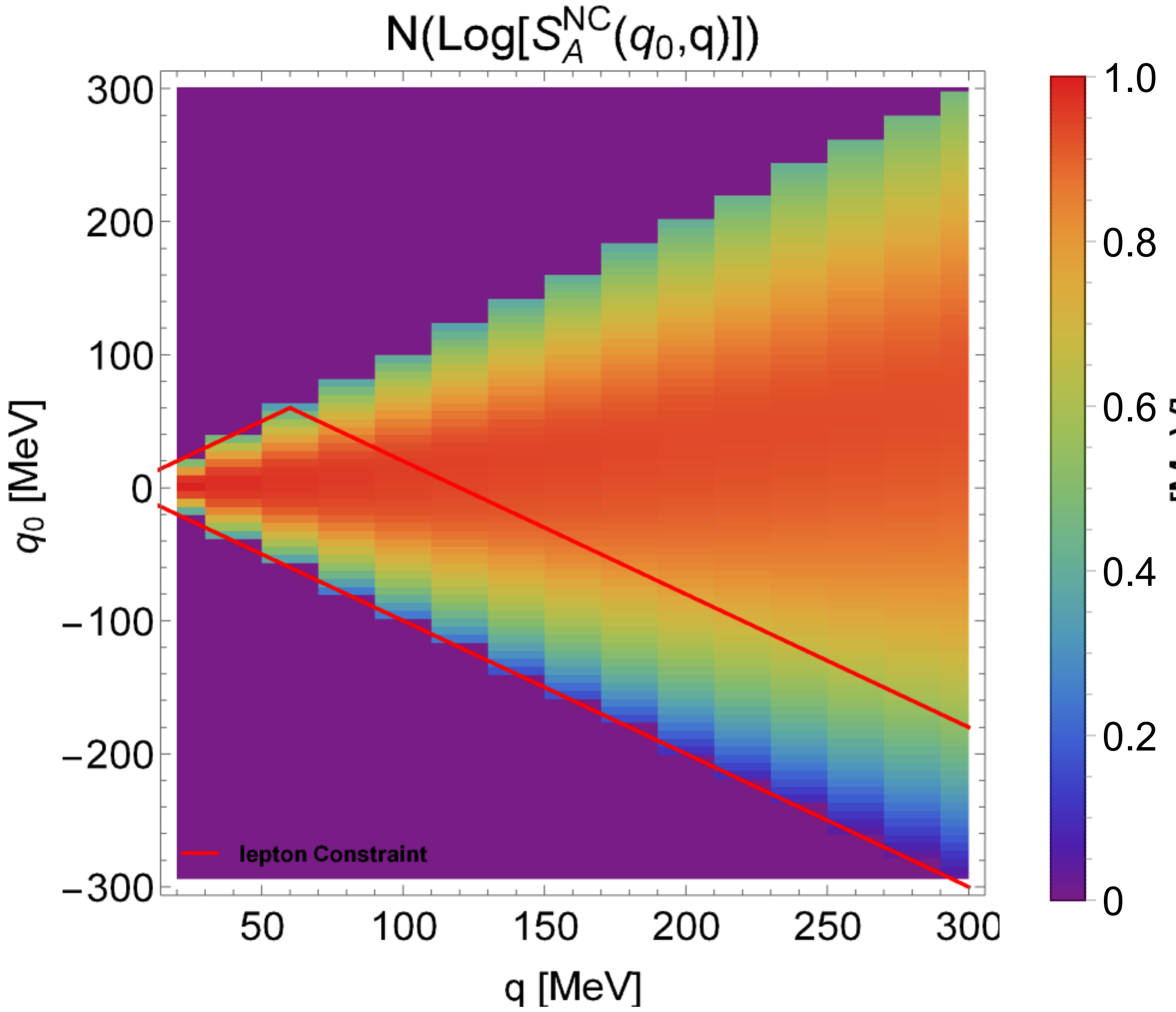
$$E_\upsilon(\vec{P}_\upsilon) - E_{\upsilon'/e}(\vec{P}_{\upsilon'/e}) = q_0$$

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

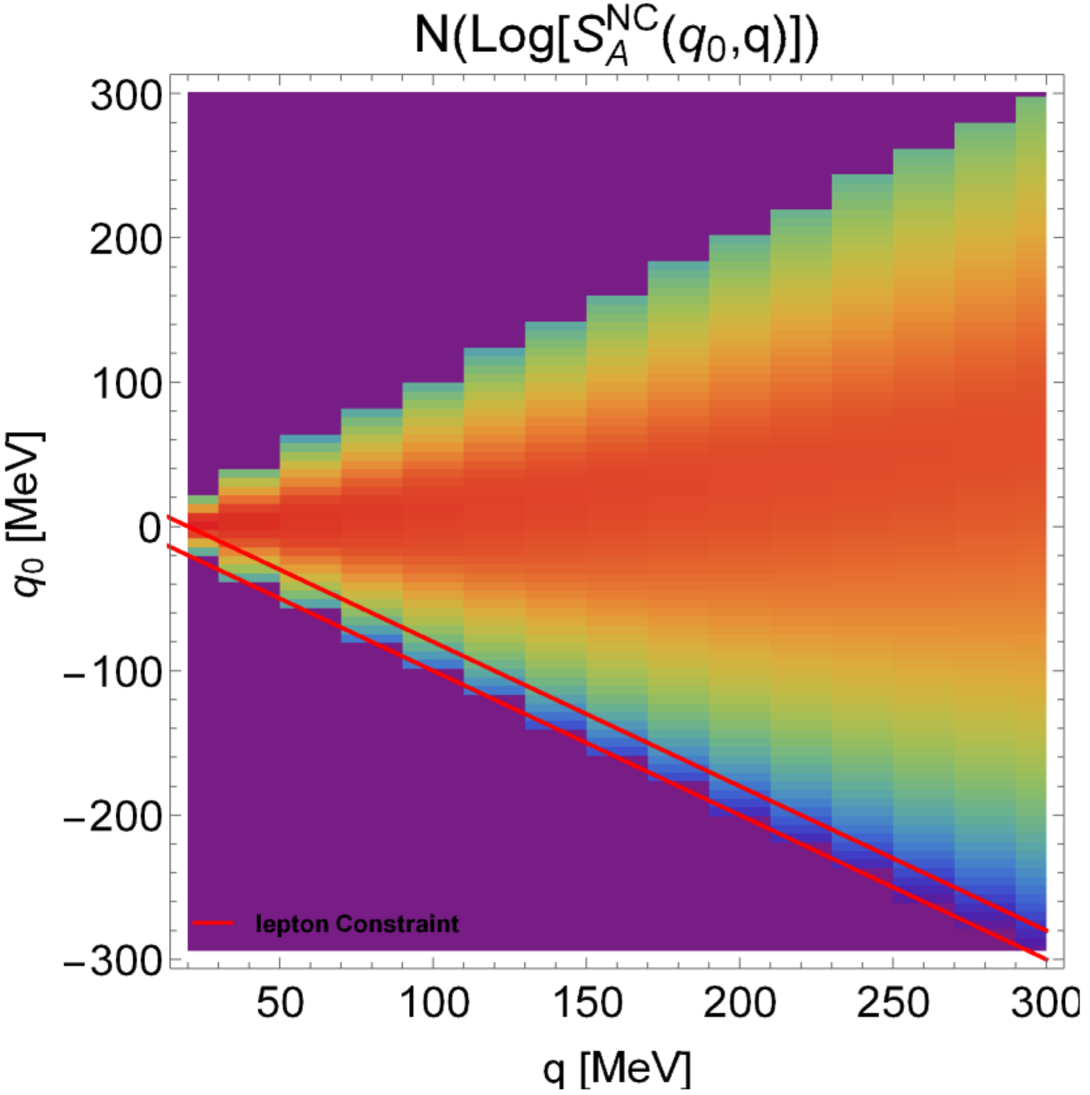
Put the corresponding Pixel (weighting factor) here!

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

DYNAMIC S(Q0,Q)+ KINEMATIC CONSTRAINT

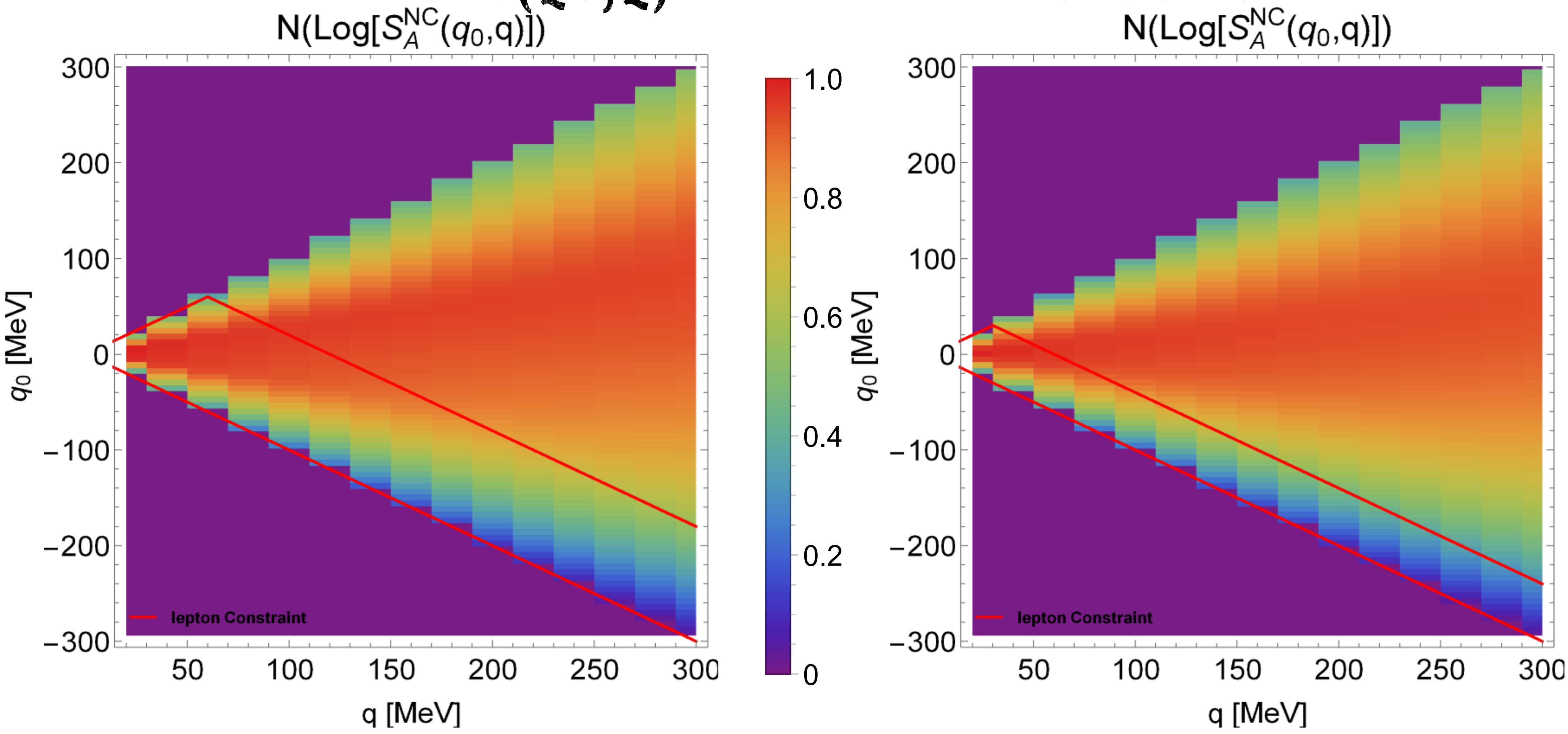


$\mathrm{n}=10^{-2}fm^{-3}$; $E_{\upsilon} = 60$ MeV



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

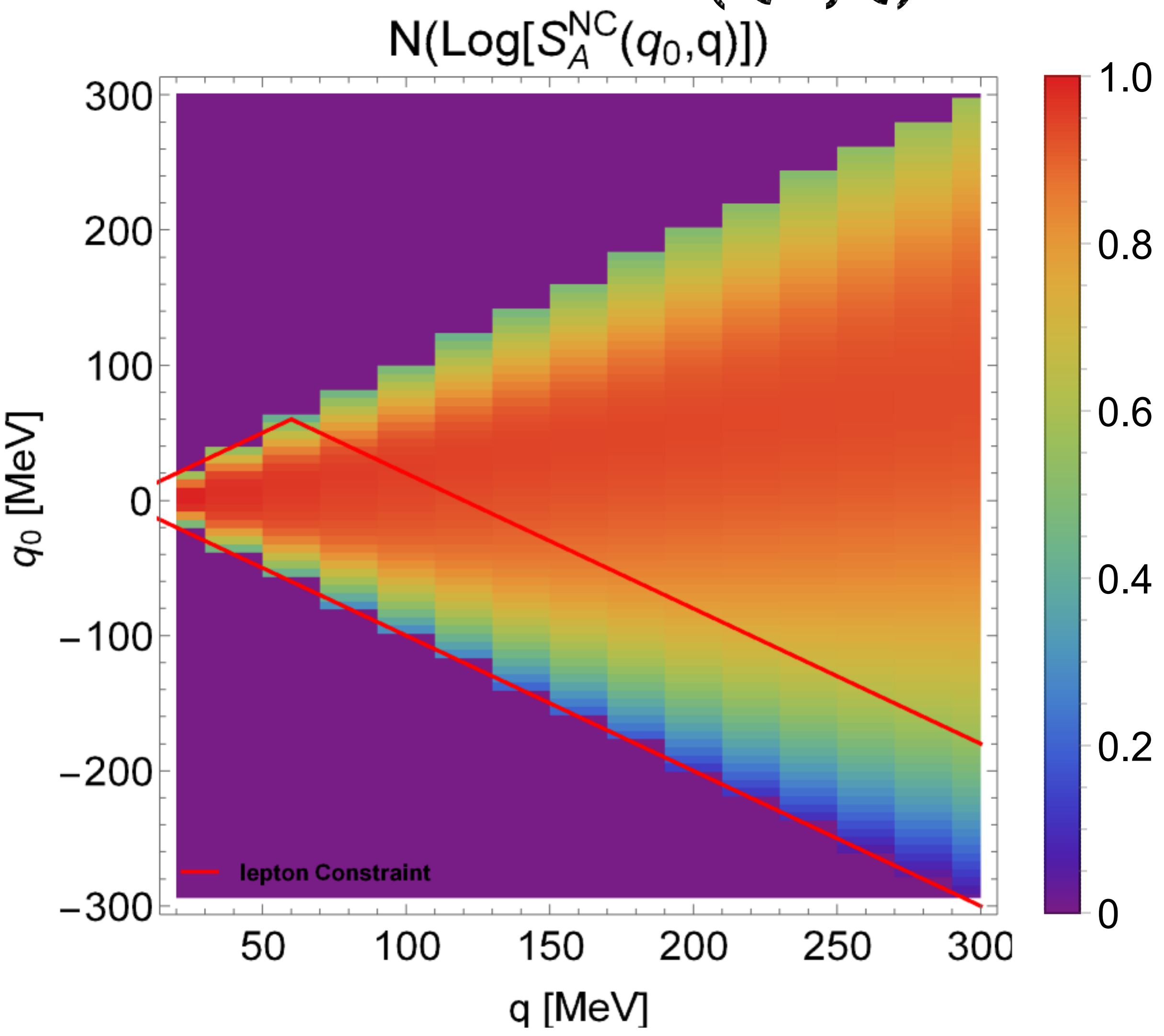
DYNAMIC S(Q0,Q)+ KINEMATIC CONSTRAINT

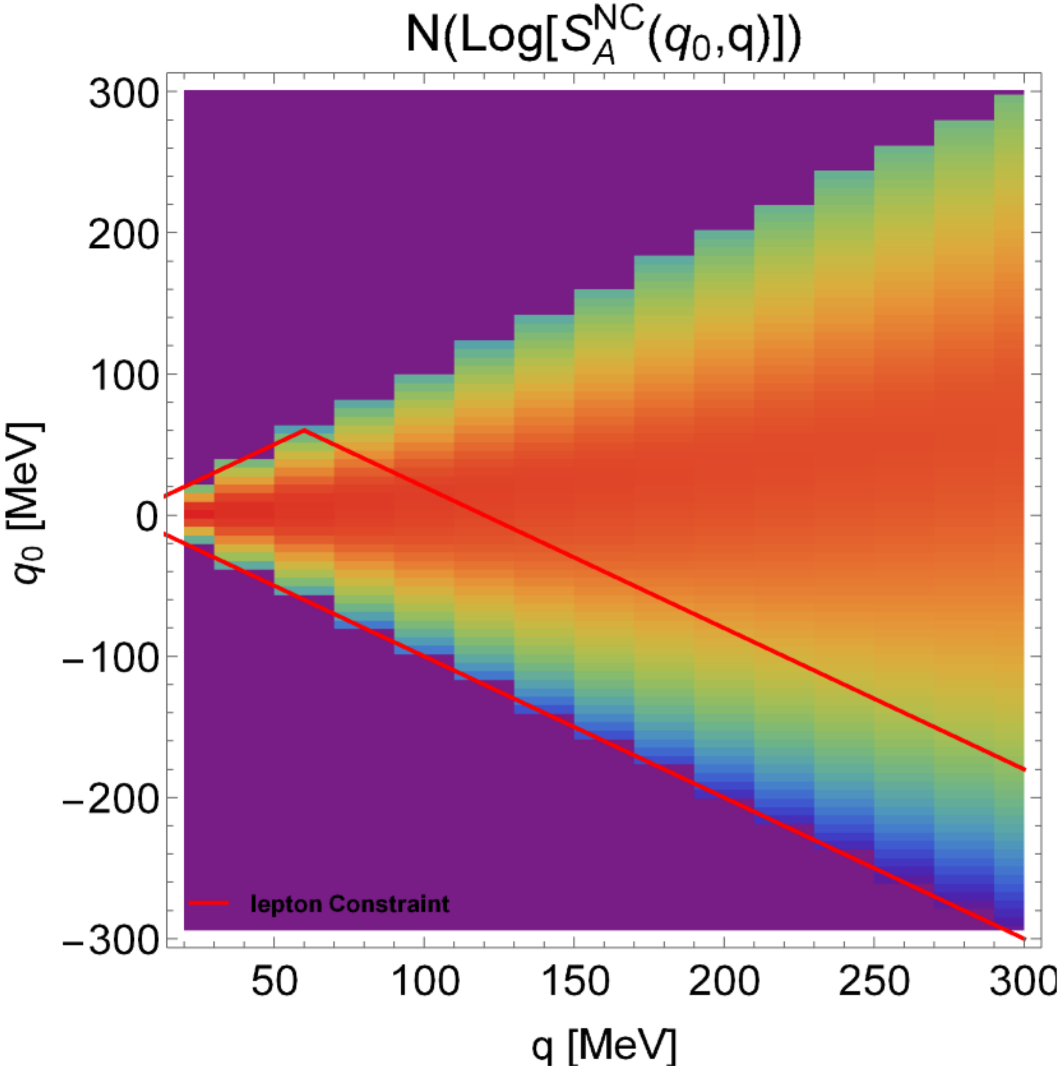


n=0.05 fm^{-3}; $E_{\upsilon} = 60$ MeV

n=$10^{-2} fm^{-3}$; $E_{\upsilon} = 30$ MeV

DYNAMIC S(Q0,Q)+ KINEMATIC CONSTRAINT

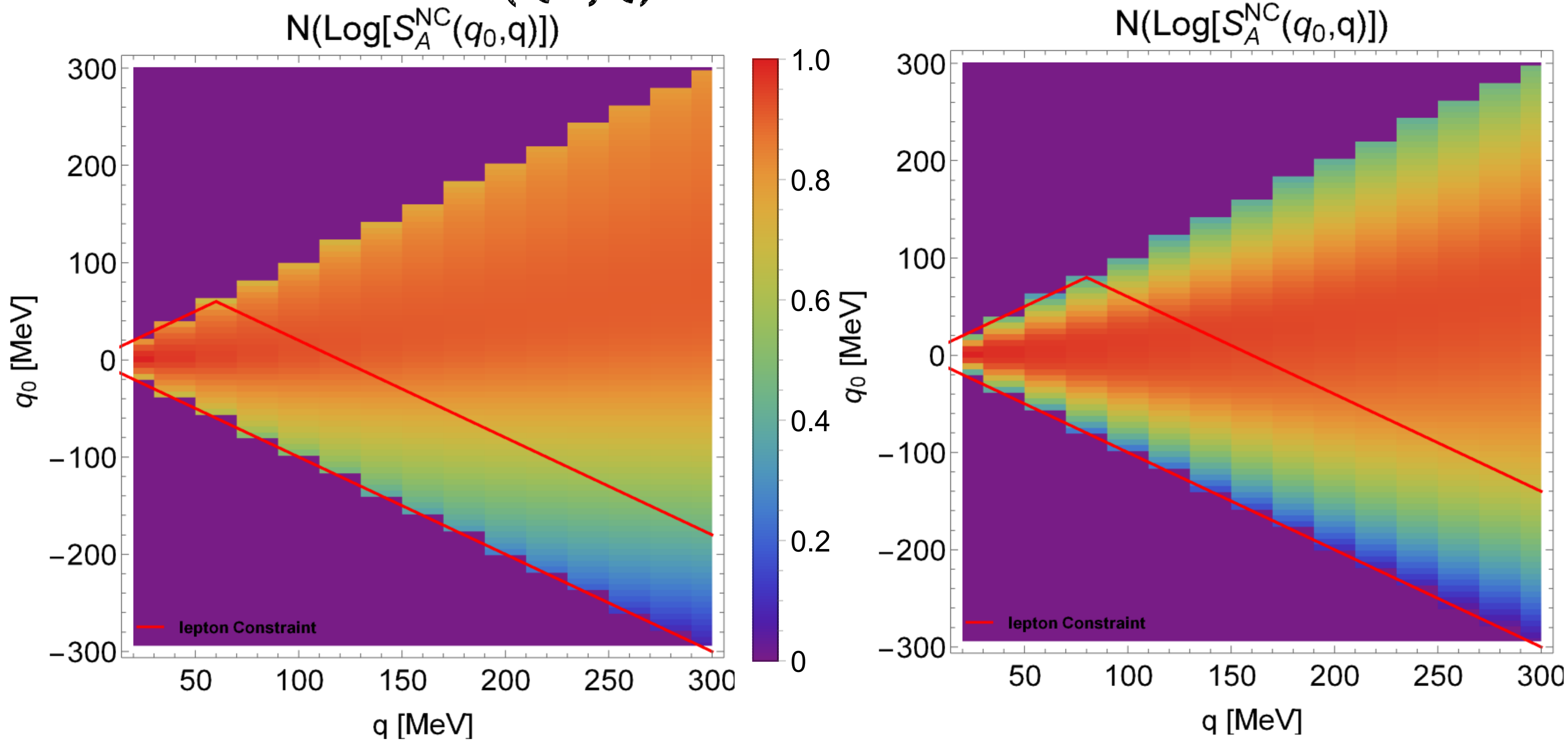




n=0.15 fm^{-3}; $E_\upsilon = 60$ MeV

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

DYNAMIC S(Q0,Q)+ KINEMATIC CONSTRAINT

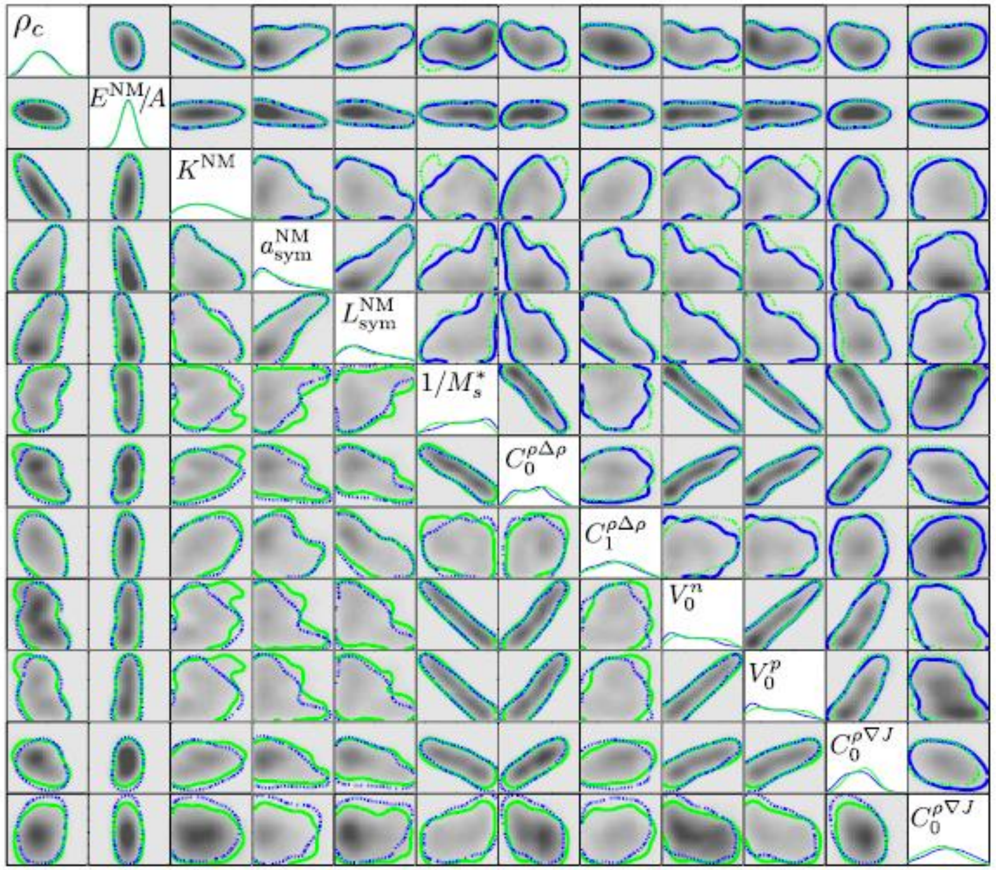


n=0.45 fm^{-3}; $E_\upsilon = 60$ MeV

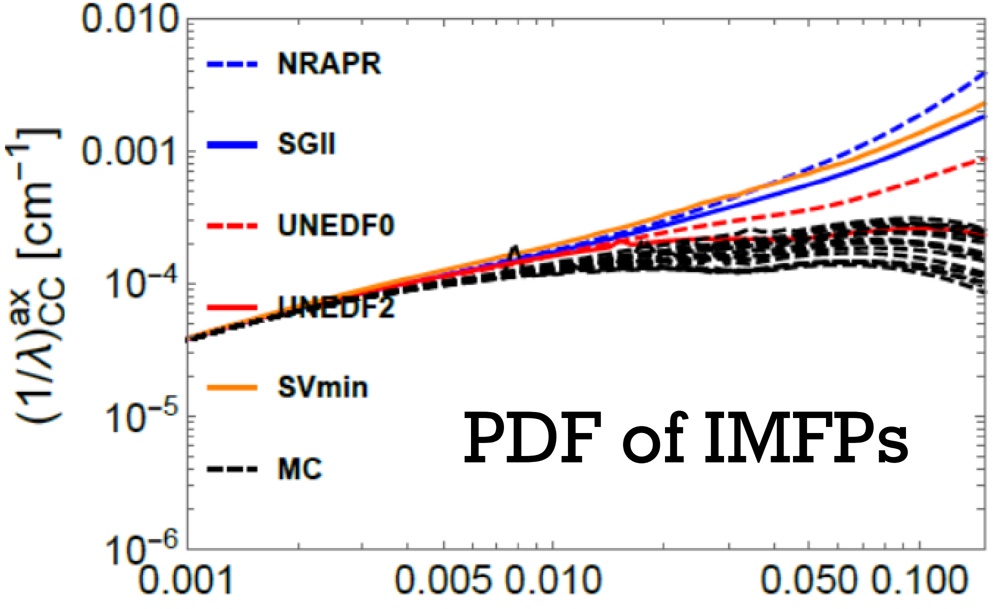
n=$10^{-2} fm^{-3}$; $E_\upsilon = 80$ MeV

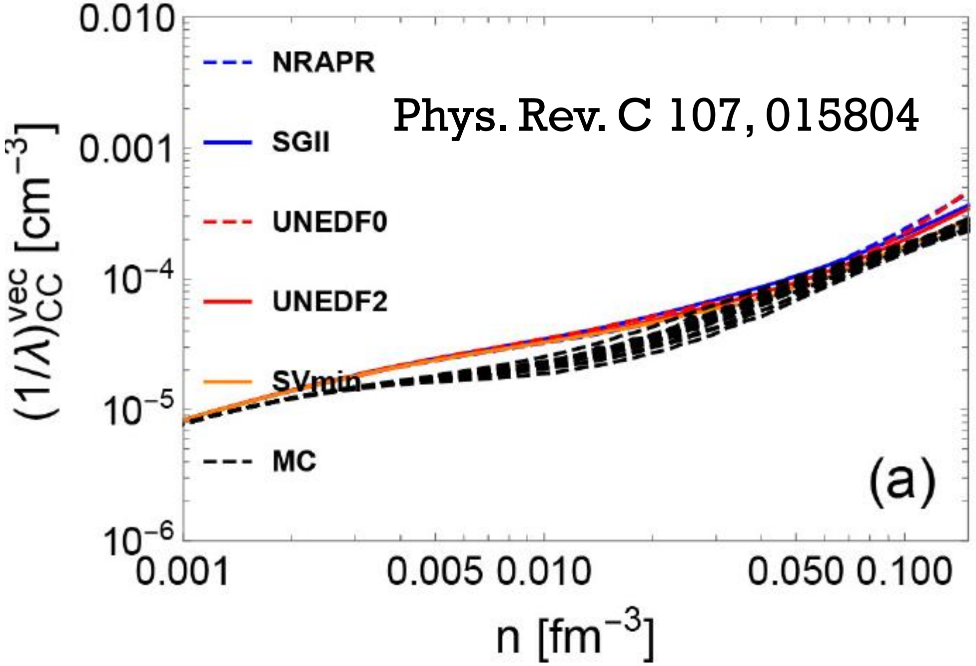
UNCERTAINTIES OF ν OPACITIES

J. D. McDonnel *et al.* 2015



PDF of Skyrme parameters constrained by nuclei properties (UNEDF)



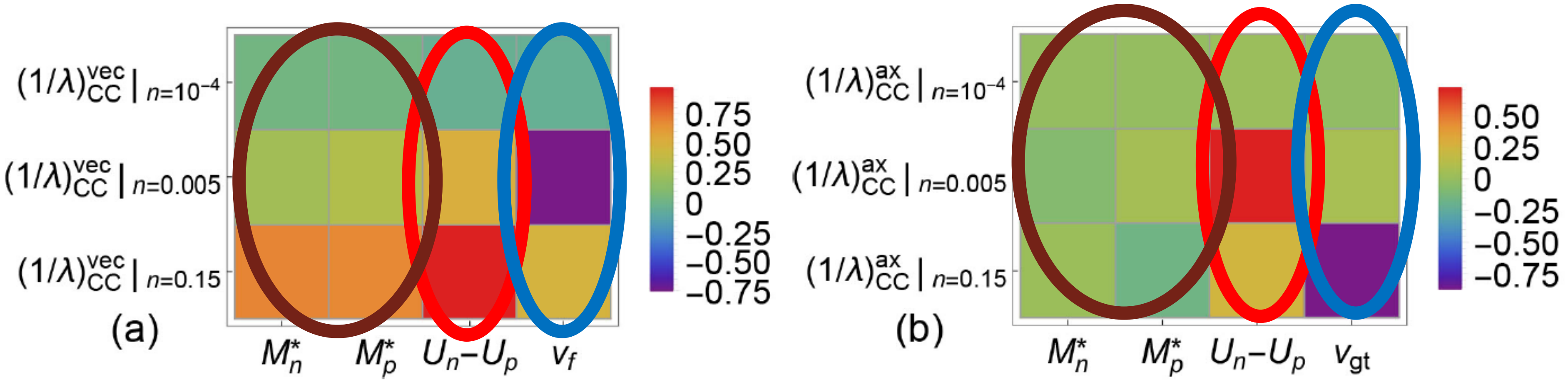


Phys. Rev. C 107, 015804

CORRELATIONS BETWEEN υ OPACITIES & EOS

CC:

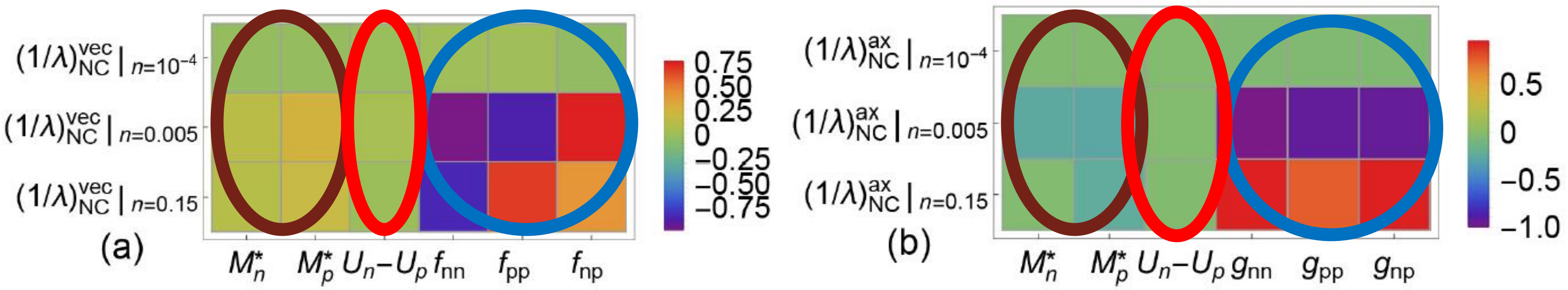
Phys. Rev. C 107, 015804



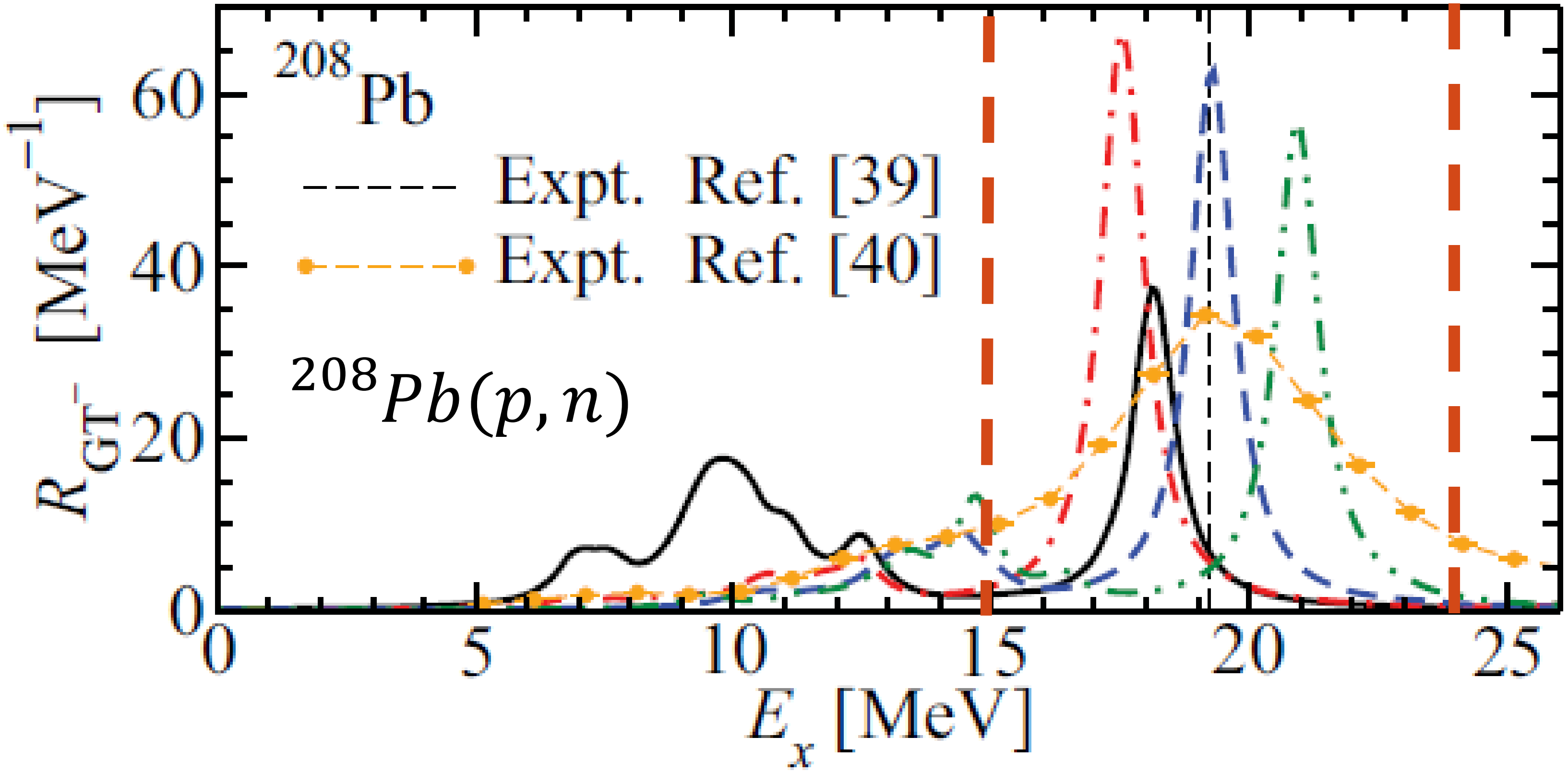
Note that V_{gt}=2G' at symmetric nuclear matter (SNM)

M^* ΔU Landau Migdal Parameters

NC:



CONSTRAINTS FOR G' FROM GTR

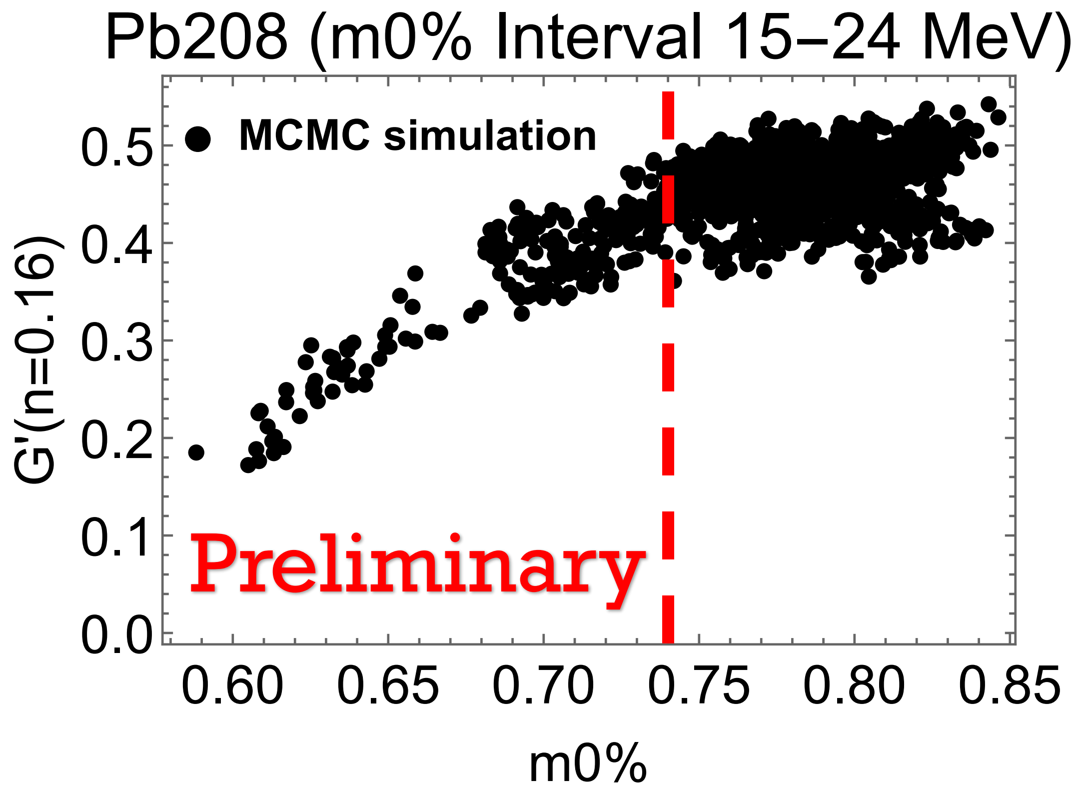


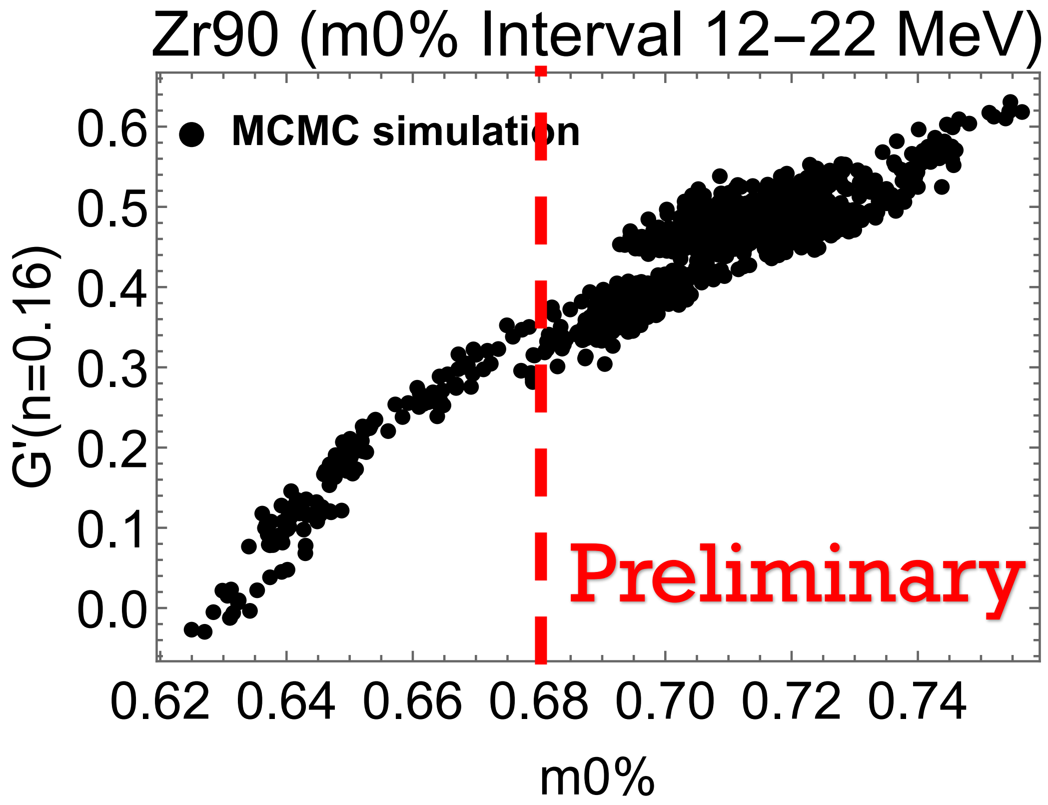
Note that V_{gt}=2G' at symmetric nuclear matter (SNM)

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

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

AN MCMC CONSTRAINING G'

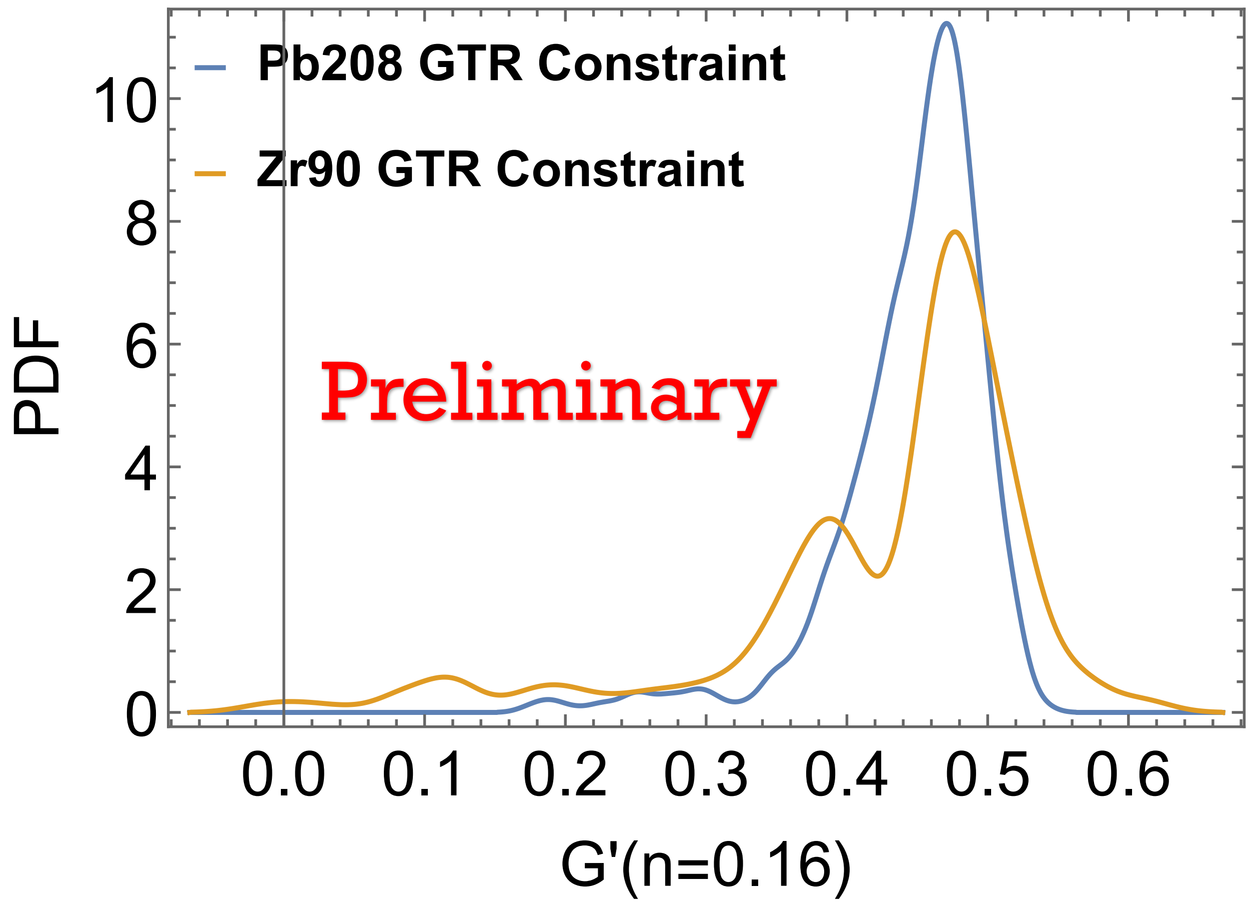




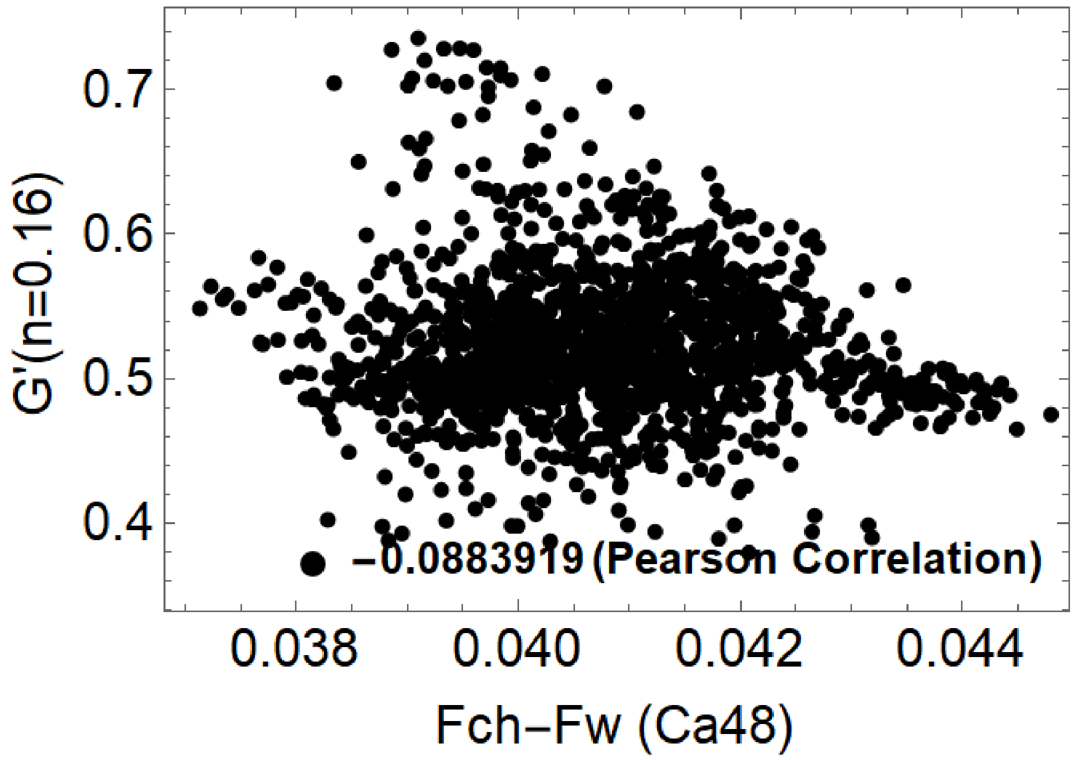
GTR results are from collaboration with G. Colo

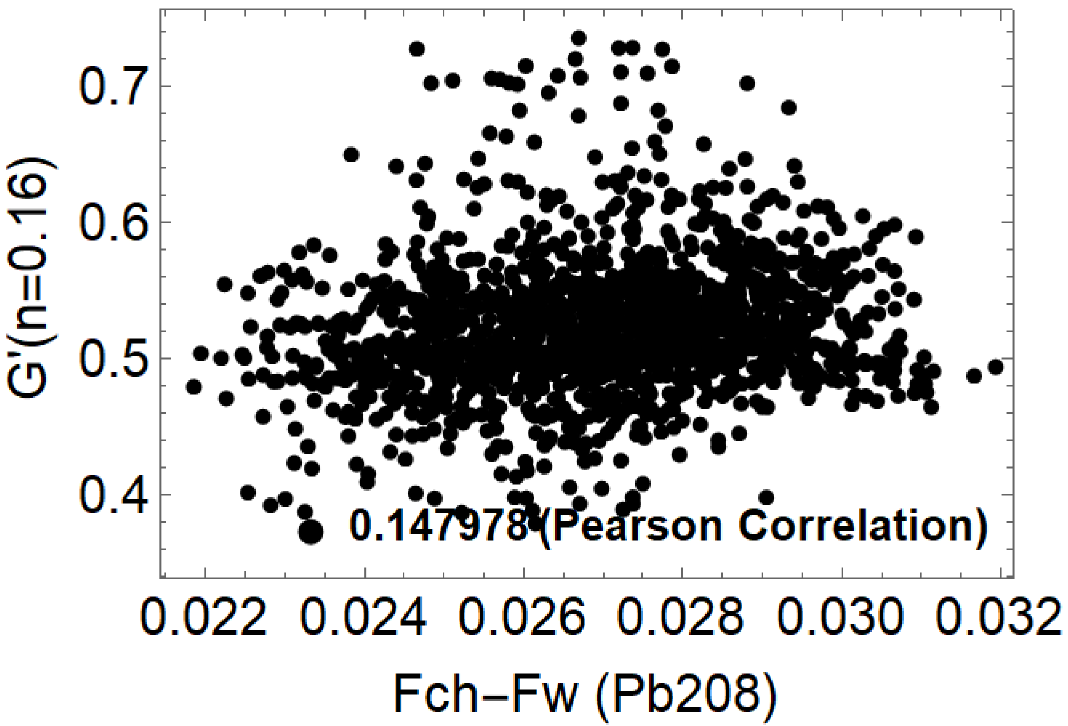
We are also running G' MCMC on Sn132 & Ca48

More are coming…



Information of G' told by different
Nucleus is different...
Finally, we need a Bayesian Inference of G'





Correlations between spin-dependent quantities
and spin-independent ones are weak

The EoSs giving similar M-R of NSs may seem very different to neutrinos

EoS 1　EoS 2　EoS 3　EoS 4

For NSs, there are no difference since they are all gummy bears

For υ s, they are quite different since υ see the color of gummy bears…

It is important for us to construct Nuclear EoSs

that not only reasonably describe spin-independent properties

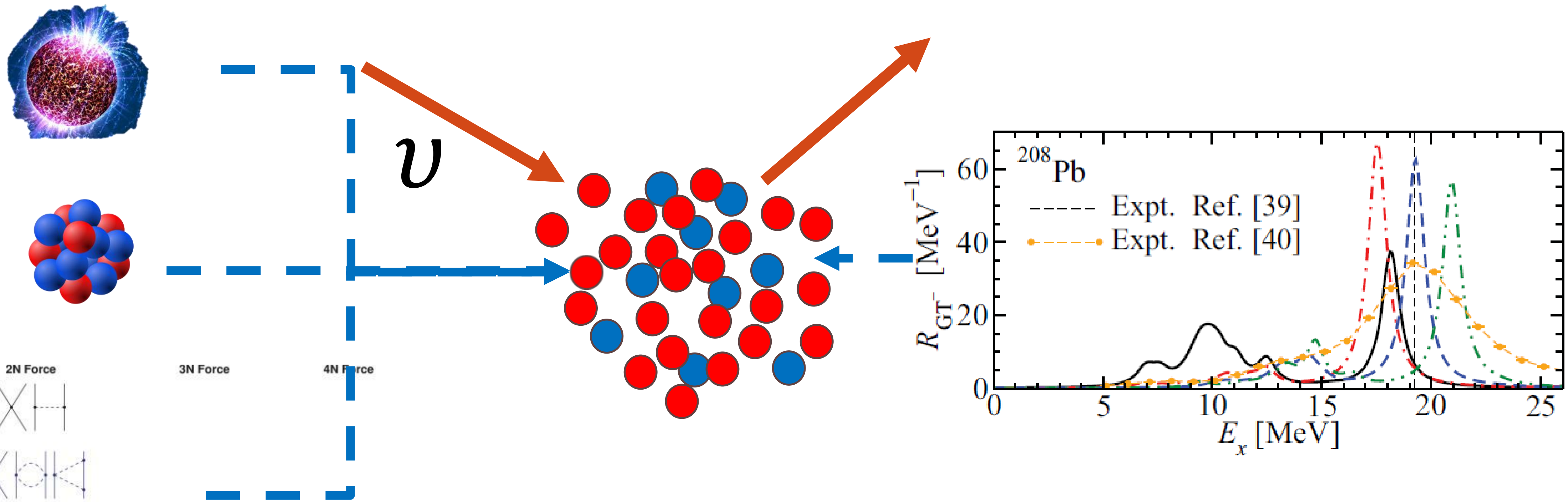
but also spin-dependent properties

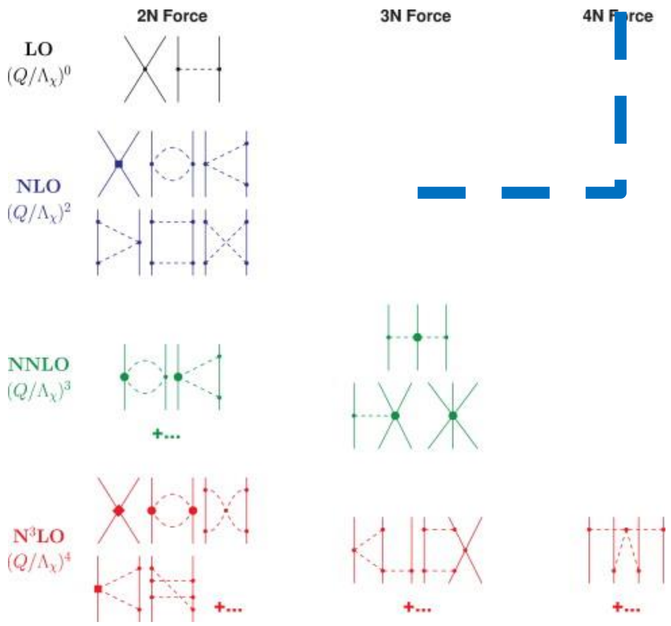
because they determine important things like neutrino opacities/pion condensations/… in NSs

CONCLUSION

1. We compare RPA NC static structure factors with ab-initial calculations at densities around υ sphere. The agreement is good.
2. The effect of many-body corrections on transport crx and on normal crx is different. The many-body corrections are also different for different incoming υ energies
3. We estimated the uncertainties of υ opacities
4. We constrain G' by using Gamow-Teller Resonance experiments in a MCMC simulation
5. Construct new EoSs with better description of spin-dependent quantities may be important for future study of NSs/CCSNe/mergers

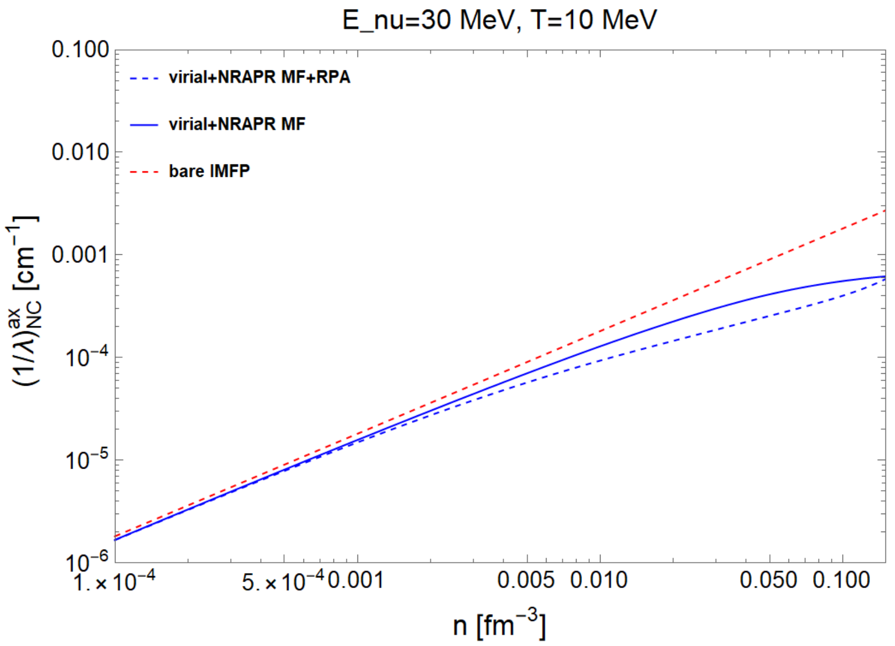
Before we are lucky enough to get a galactic CCSN…

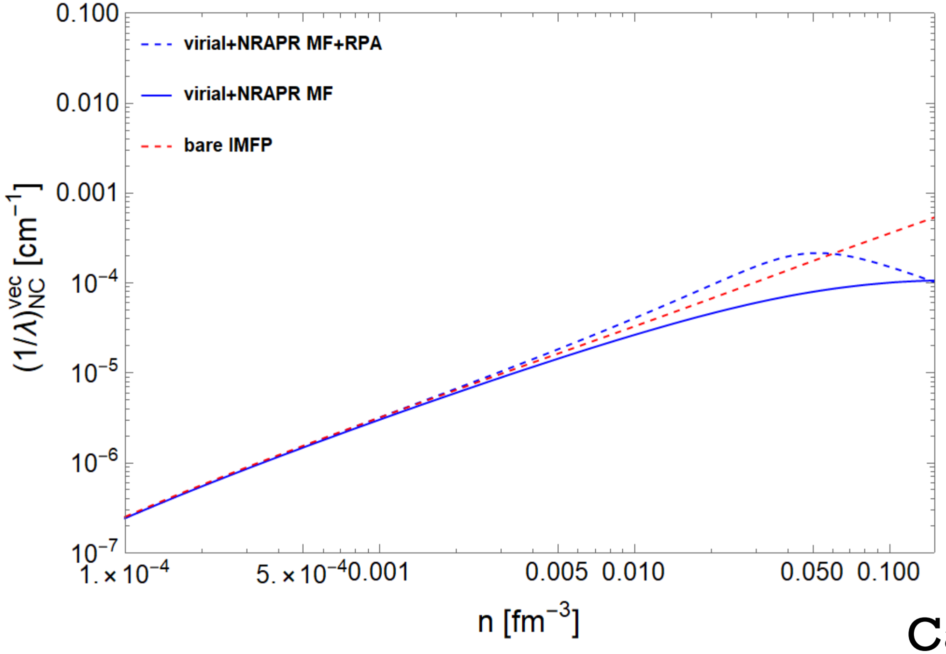




These indirect multi-messengers may be the only constraints we can use for υ-dense matter opacities…

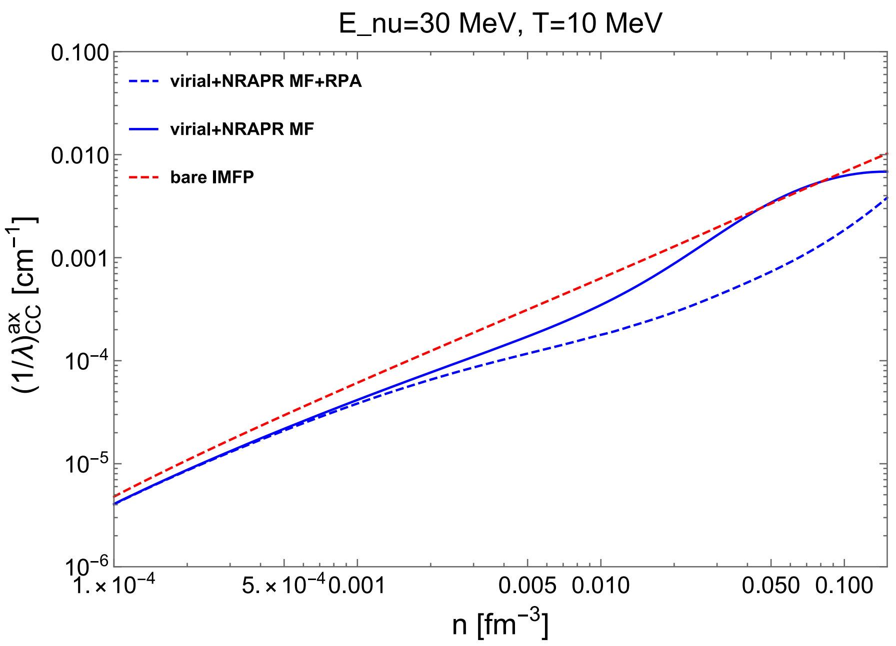
BACKUP SLIDES

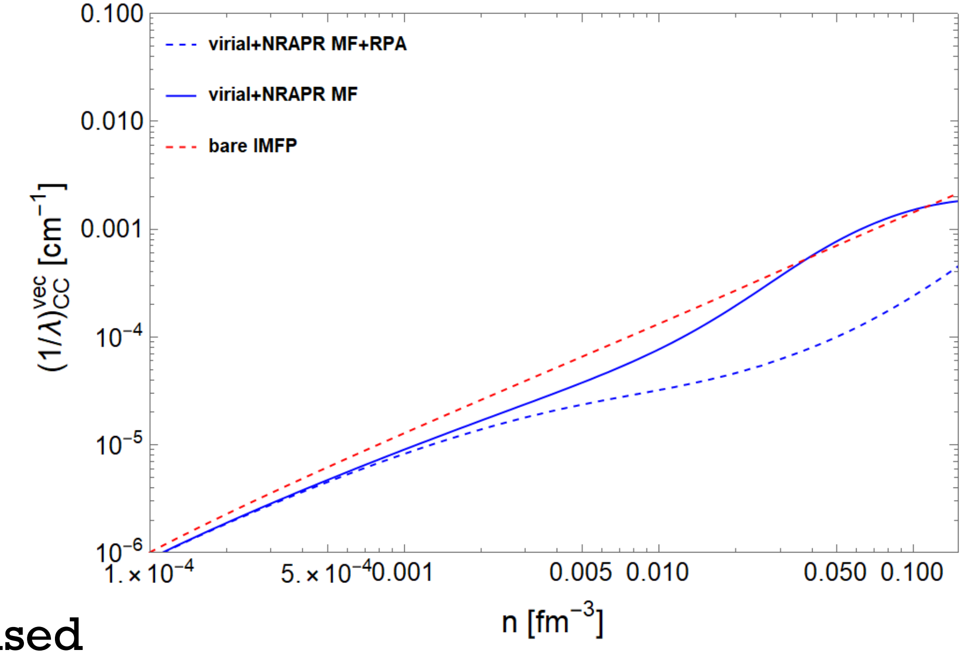




Scattering

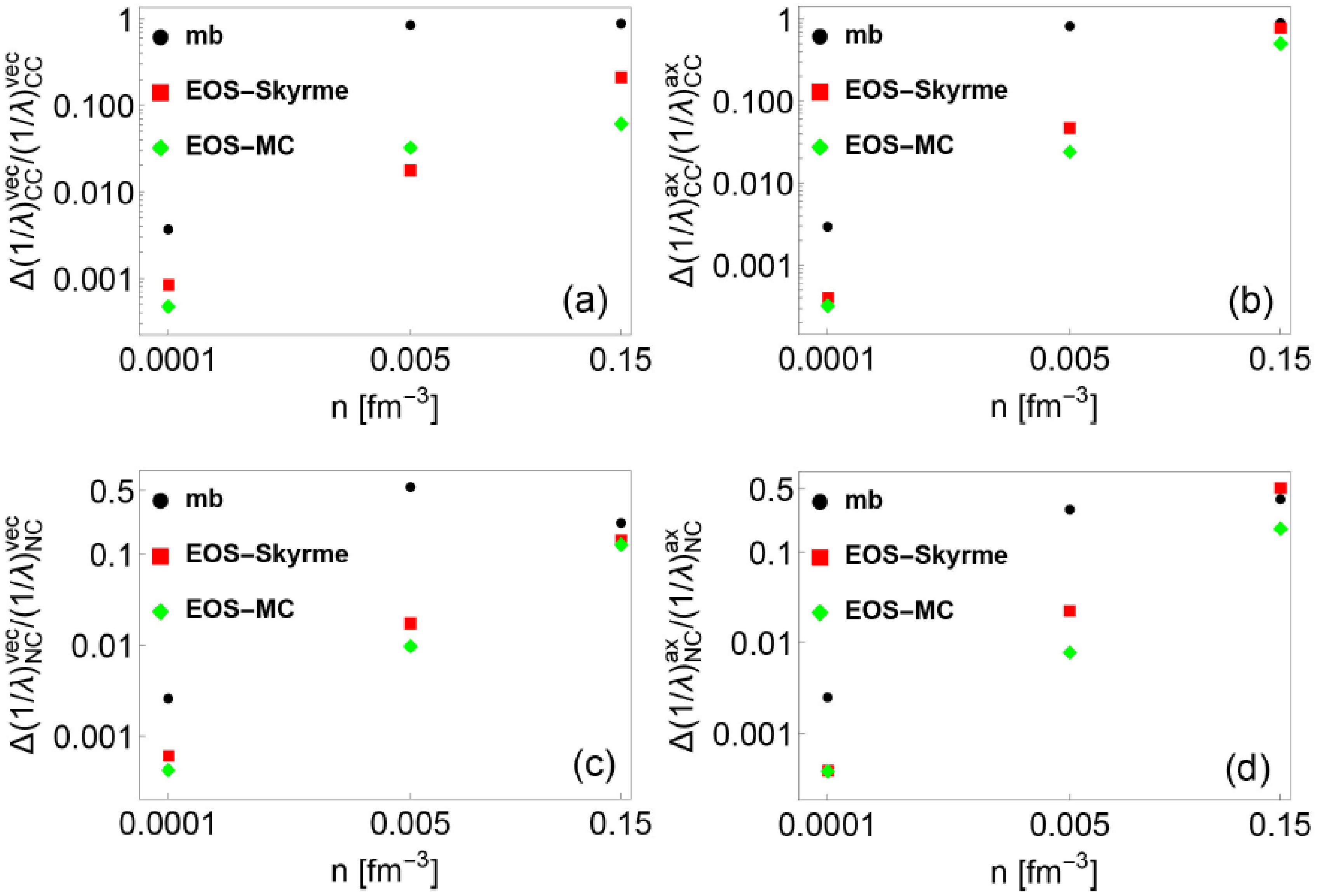
Calculations based on Z. Lin *et al.* (2022)





Absorption

Main Results: 2) Relative uncertainty of IMFP



Z. Lin et al. (2022)

Landau-Migdal Parameters

$$f_0 = \frac{\partial^2 E}{\partial n \partial n},$$

$$f_0' = \frac{\partial^2 E}{\partial n_{3,0} \partial n_{3,0}},$$

$$g_0 = \frac{\partial^2 E}{\partial n_{0,3} \partial n_{0,3}},$$

$$g_0' = \frac{\partial^2 E}{\partial n_{3,3} \partial n_{3,3}},$$

$$f_0 = \frac{1}{2}\left(f_0^{\tau\tau} + f_0^{\tau-\tau}\right), \quad f_0' = \frac{1}{2}\left(f_0^{\tau\tau} - f_0^{\tau-\tau}\right),$$

$$g_0 = \frac{1}{2}\left(g_0^{\tau\tau} + g_0^{\tau-\tau}\right), \quad g_0' = \frac{1}{2}\left(g_0^{\tau\tau} - g_0^{\tau-\tau}\right).$$

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

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

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