TOWARDS A SELF-CONSISTENT DESCRIPTION OF ν INTERACTIONS IN MERGERS:

CHALLENGES & ACHIEVEMENTS

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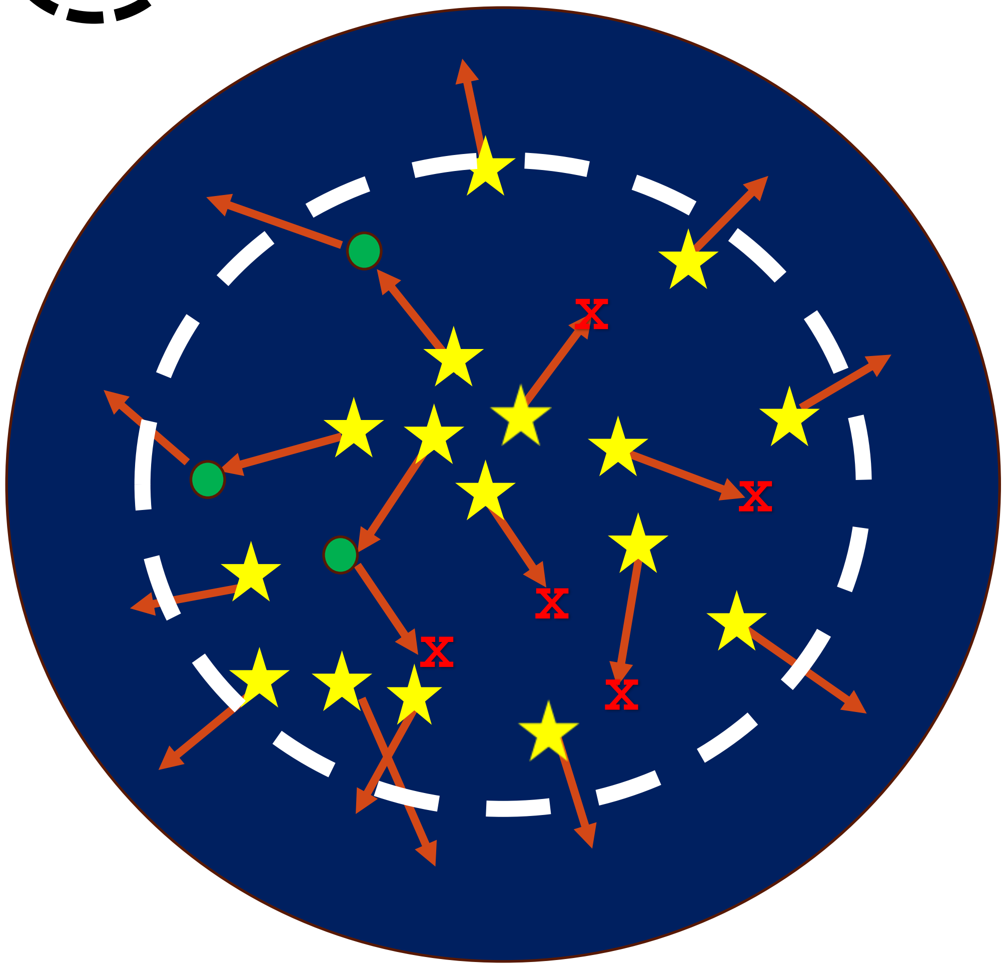
Neutrinos in compact stars

: neutrino sphere

: neutrino flavor oscillation



: neutrino emission

: neutrino scattering

: neutrino absorption

υ are emitted from:
(1) Electron capture
(2) Pair process
(3) URCA ?
(4) …

υ are scattered by:
(1) Electrons
(2) Nucleons
(3) Nuclei
(4) Quarks?
(5) …

υ are absorbed by:
(1) Electrons
(2) Nucleons
(3) Nuclei
(4) …

1. Neutrino sphere location
2. neutrino oscillation
3. neutrino spectra

1. The speed of reaching equilibrium
2. Ye distribution
3. Bulk viscosity and so on…

The emission, scattering, and absorption rates depend on component, thermal properties, and interactions of dense matter

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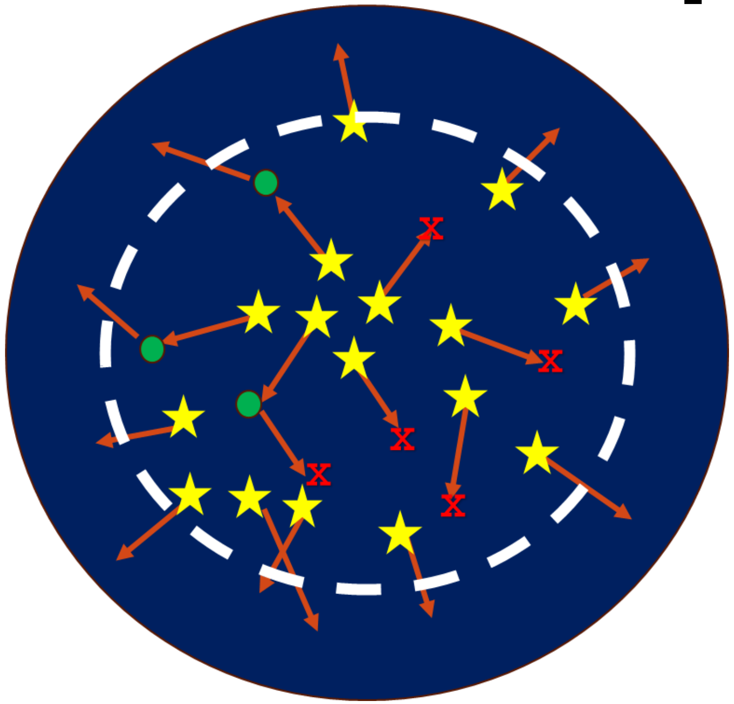
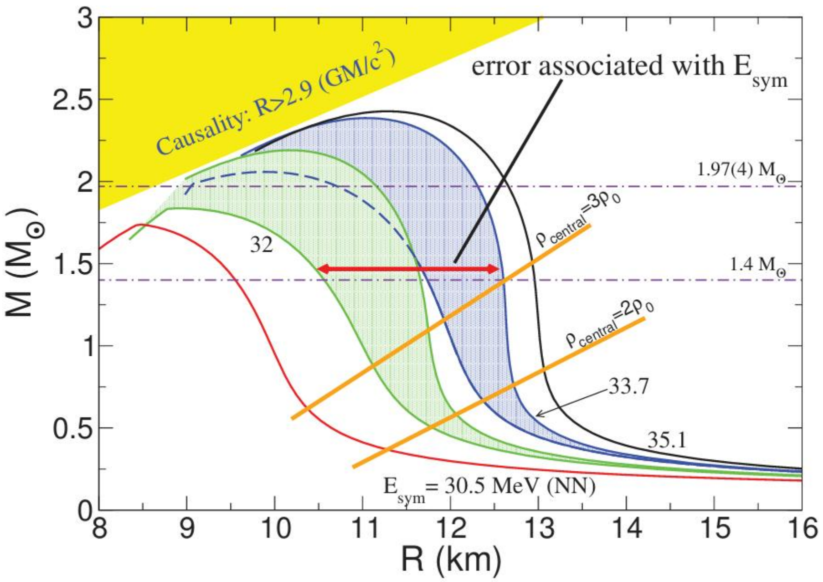
Goals (Dreams?): Self-consistent nuclear models describing both macroscopic compact star properties and microscopic neutrino interactions inside the stars



J. Phys.: Conf. Ser. 665 012063 S Gandolfi and A W Steiner



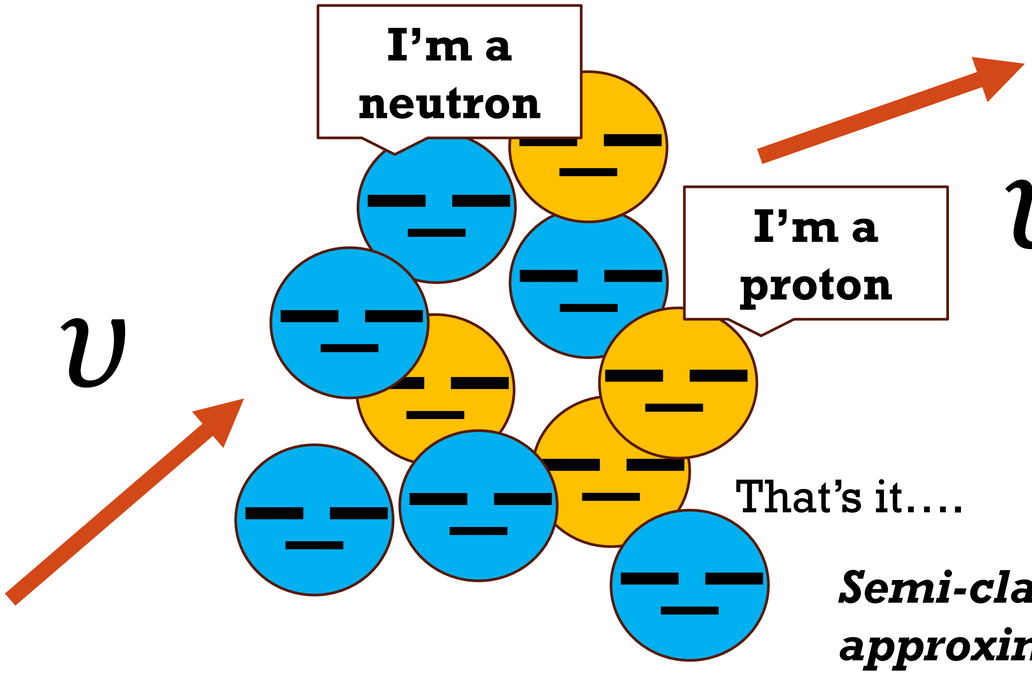
Nuclear models

Microscopic neutrino reactions

Macroscopic compact star properties

Self-consistency?

What does it mean?
How challenging it could be?



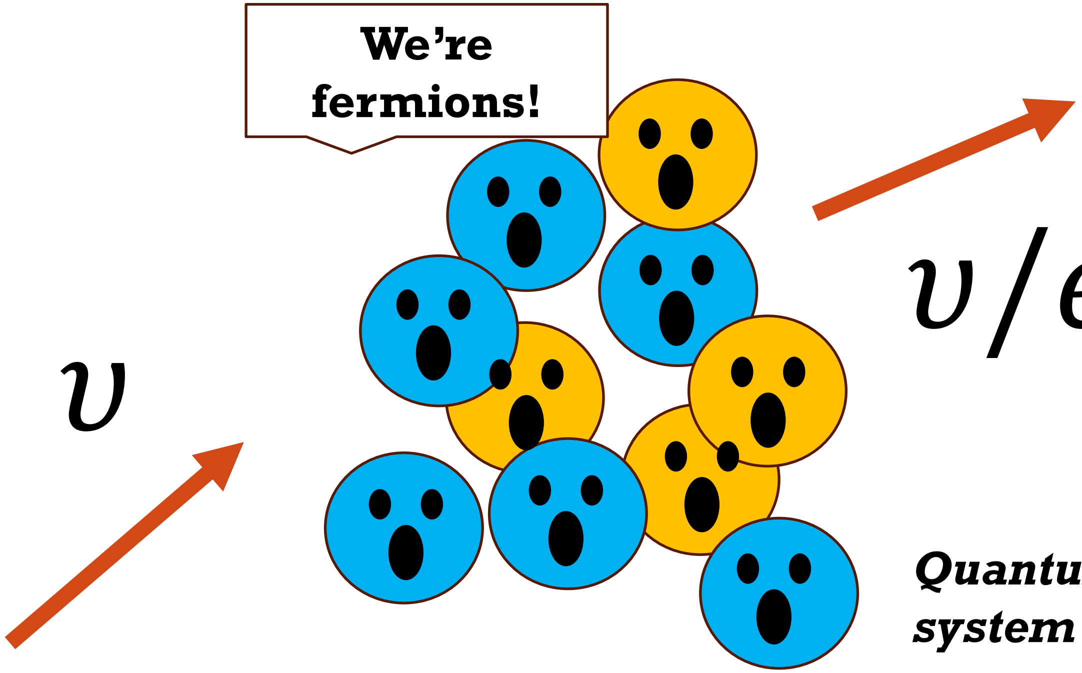
υ $\quad$ $\upsilon/e^{\mp}$

That's it….

Semi-classical approximation

$$\lambda^{-1} = \sigma_0^{n/p} \times n_{n/p}$$

Self-consistency: Y_e, ✔ density ✔



υ $\quad$ $\upsilon/e^{\mp}$

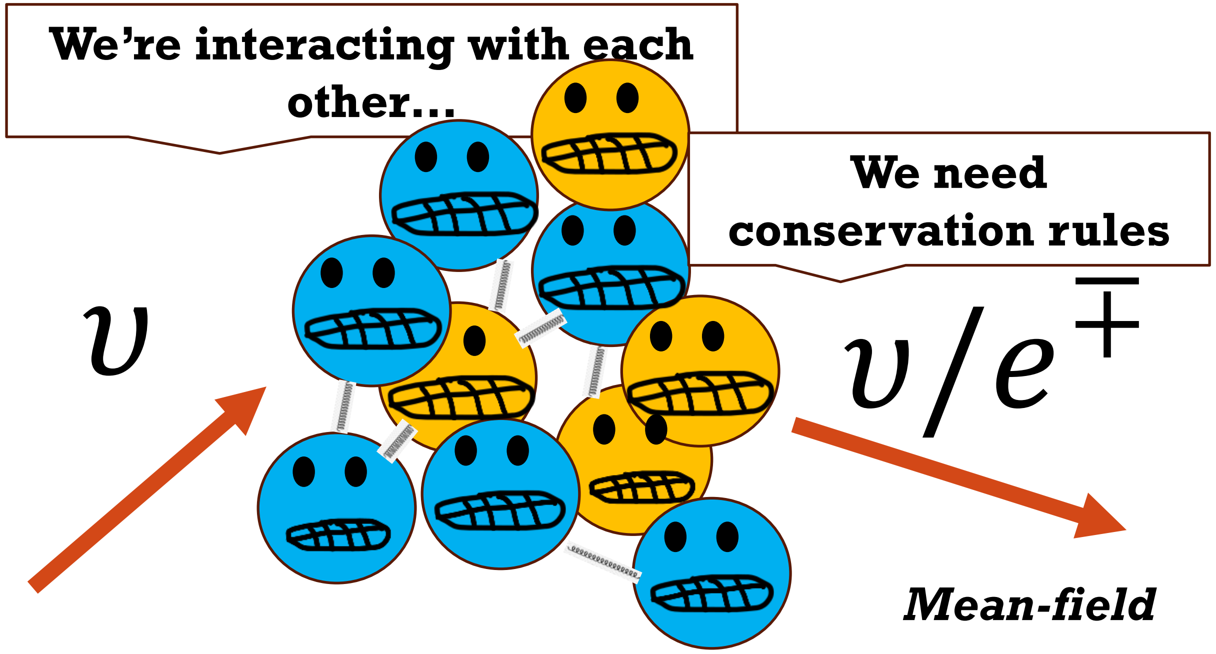
Quantum system

$$\eta = 2\int \frac{d^3 p_{n/p}}{(2\pi)^3} f_{n/p}(1 - f_{p/n})$$

$$\lambda^{-1} = \sigma_0 \times \eta$$

Stephen W. Bruenn , ApjS, 58:771-8411(1985)
(most nuLib data is based on this version)

Self-consistency: Y_e, ✔ density, ✔ μ_n, ✔ μ_p, ✔ μ_e, ✔ T ✔



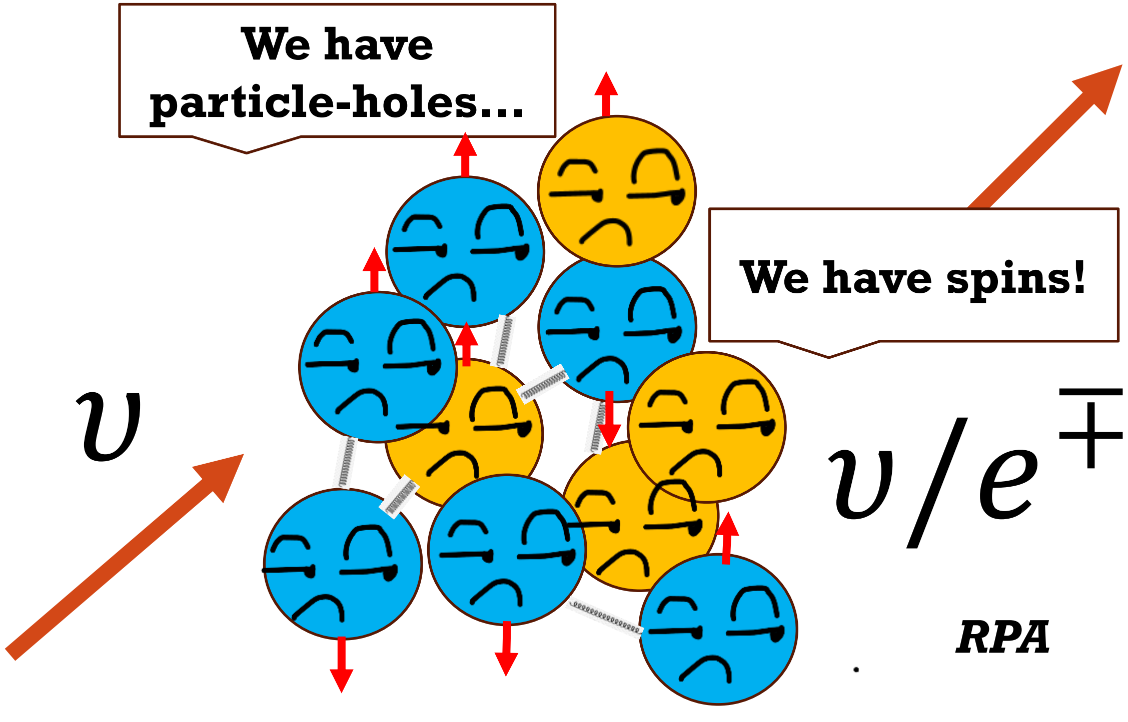
$$\lambda^{-1} = \sigma_0 \int dq\, dq_0 S(q, q_0) \ldots$$

$$S(q_0, q) = \frac{1}{2\pi^2} \int d^3p_2\, \delta(q_0 + E_2 - E_4) f_2(E_2)(1 - f_4(E_4))$$

$$E_i(p_i) = \frac{p_i^2}{2M_i^*} + U_i\,, \quad i = n, p$$

S. Reddy, et al., PRD **58**, 013009 (1997)

Self-consistency: …, $+U_n, U_p, M_n^*, M_p^*$ ✔ ✔ ✔ ✔



S. Reddy et al., PRC 59, 2888(1999)
A. Burrows et al,, PRC 58, 554 (1998)
C. J. Horowitz et al. Phys. Rev. C 95, 025801(2017)

$$S(q, q_0)$$

$S_V(q, q_0)$ — Spin-independent

$S_A(q, q_0)$ — Spin-dependent

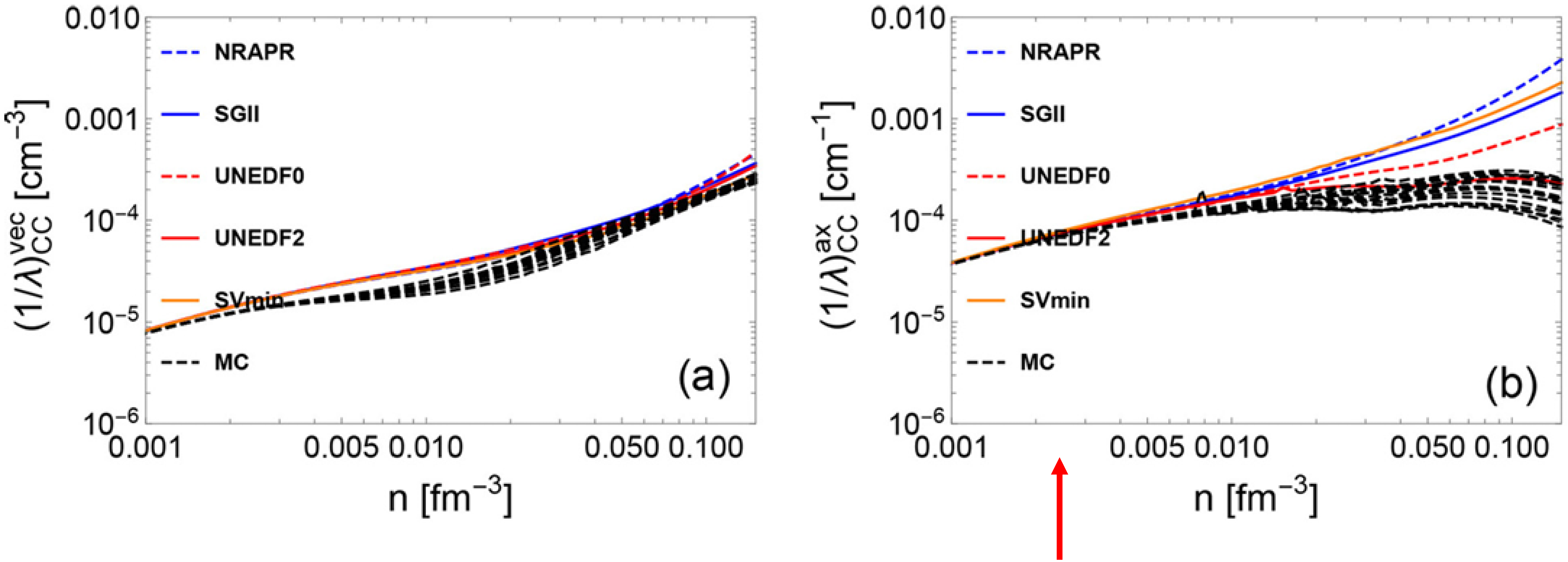
$$S\,(q_0, q) = \frac{2\,\mathrm{Im}\Pi}{1 - \exp[(-q_0 - \mu^\tau + \mu^{\tau'})/T]}$$

$$\Pi^\alpha_{\mathrm{RPA}} = \frac{\Pi_0}{1 - V^\alpha_{ph}\Pi_0}$$

Self-consistency: …, $+V^\alpha_{ph}$ ✔

Do we have enough information to perform self-consistent calculations?

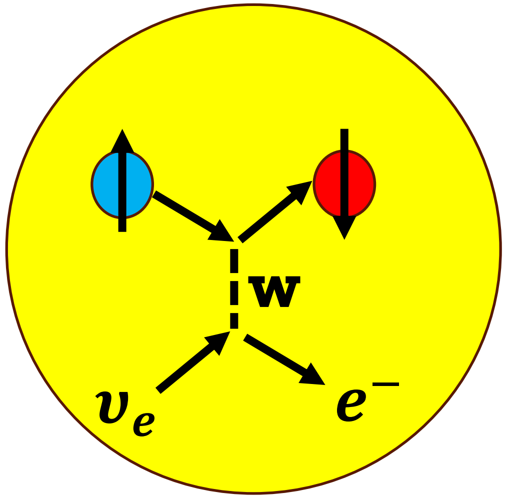
Zidu Lin, Andrew W. Steiner, and Jérôme Margueron, Phys. Rev. C **107**, 015804



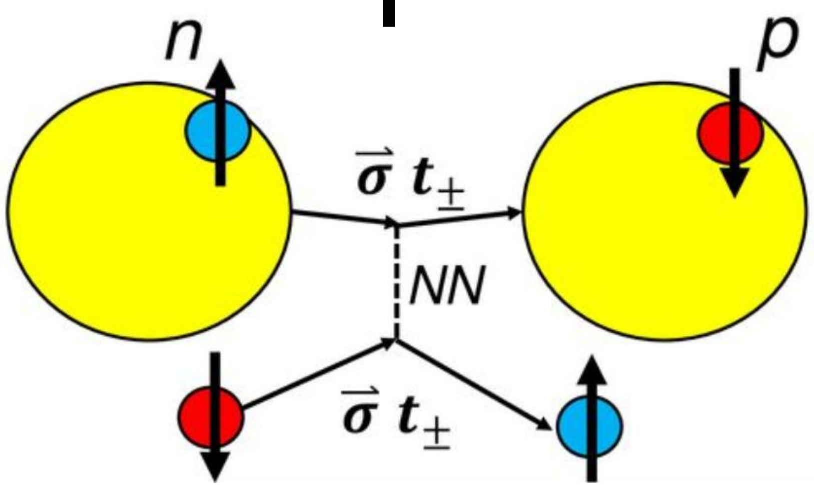
Our ignorance of spin-dependent nucleon-nucleon interactions results in larger uncertainties of axial current neutrino-nucleon reaction rates.

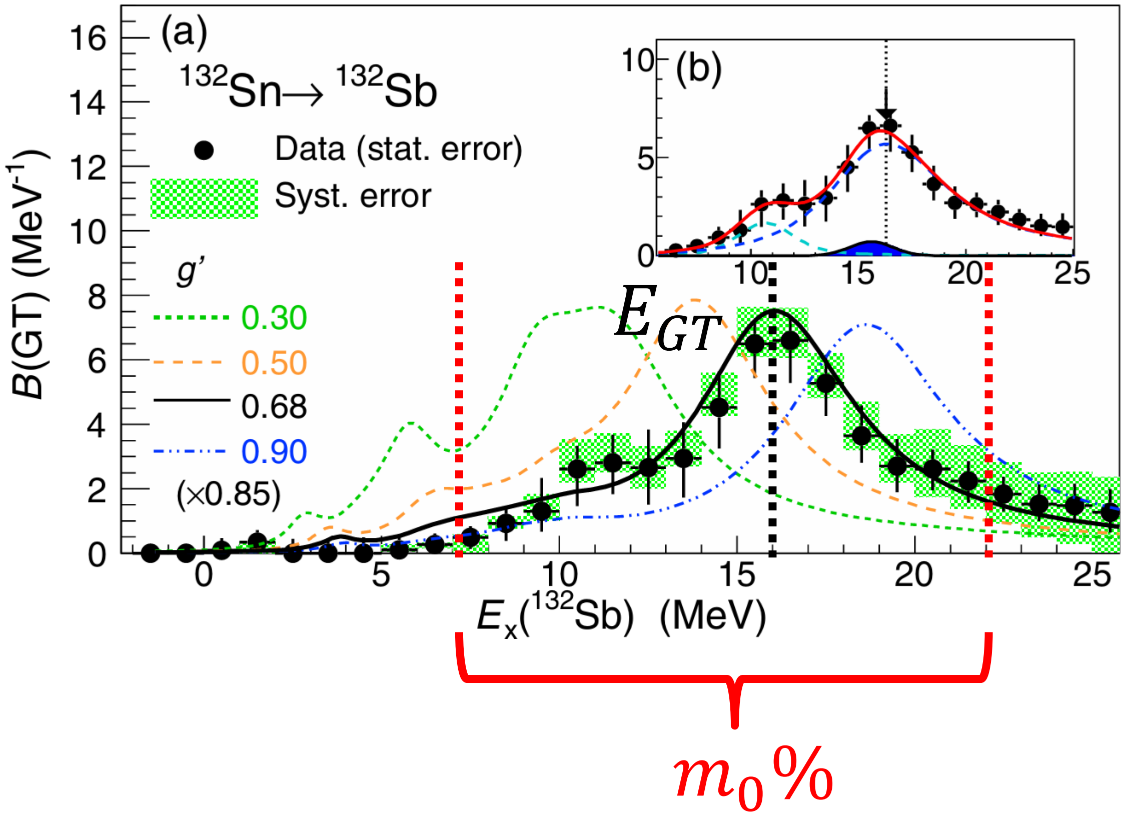
THE GAMOW-TELLER (GT) TRANSITION IN NS AND NUCLEI

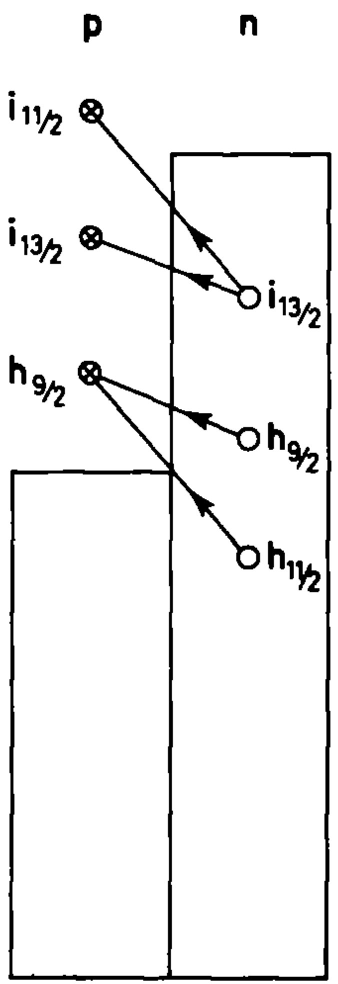
NS:



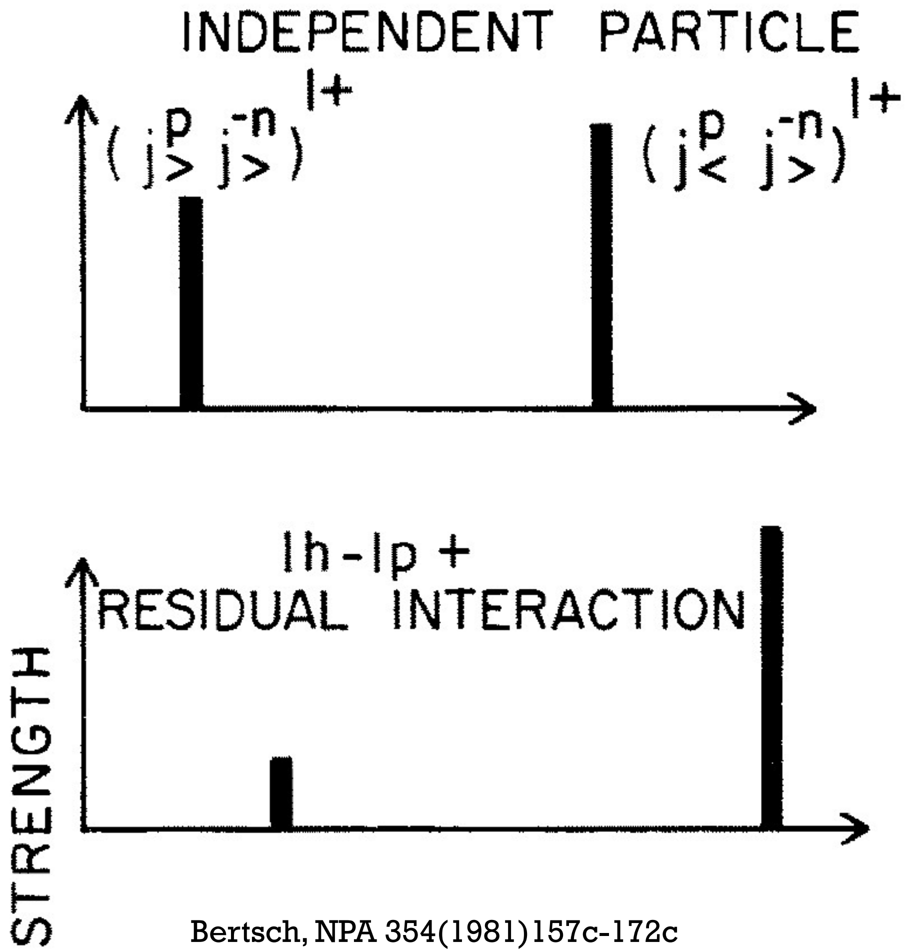
Nuclei:







Brown and Rho, NPA 372(1981)397-417

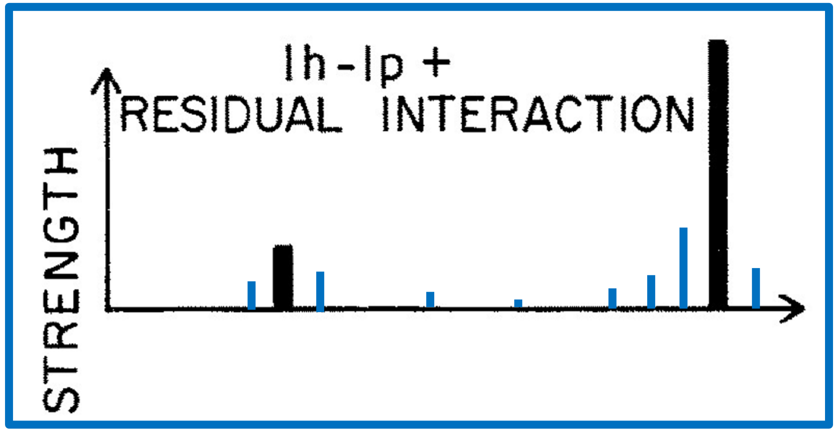


Bertsch, NPA 354(1981)157c-172c

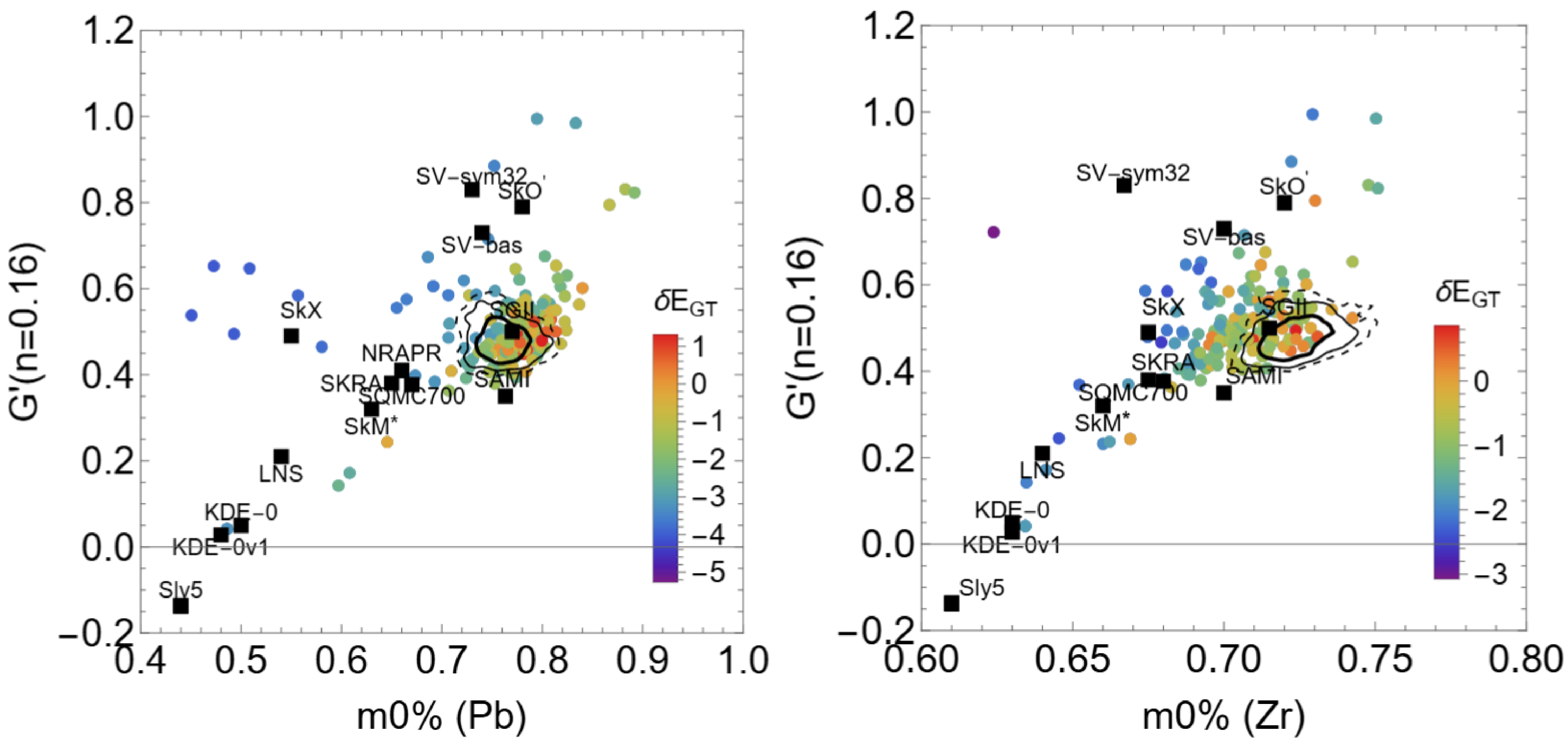
A few Experimental single particle state energy as inputs of the schematic calculation

A self-consistent calculation of single-particle energies and residual p-h interactions

$$\begin{pmatrix} A & B \\ -B^* & -A^* \end{pmatrix} \begin{pmatrix} X^n \\ Y^n \end{pmatrix} = E_n \begin{pmatrix} X^n \\ Y^n \end{pmatrix}$$



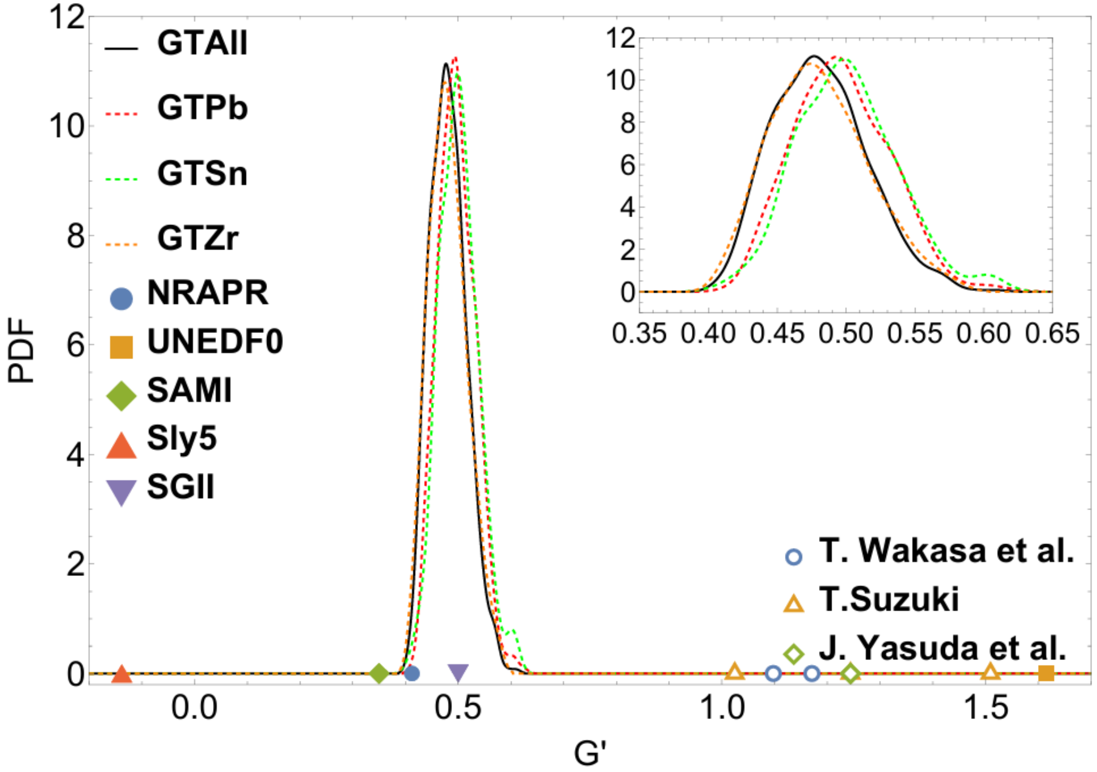
Consider many single-particle states in a self-consistent model (this work)



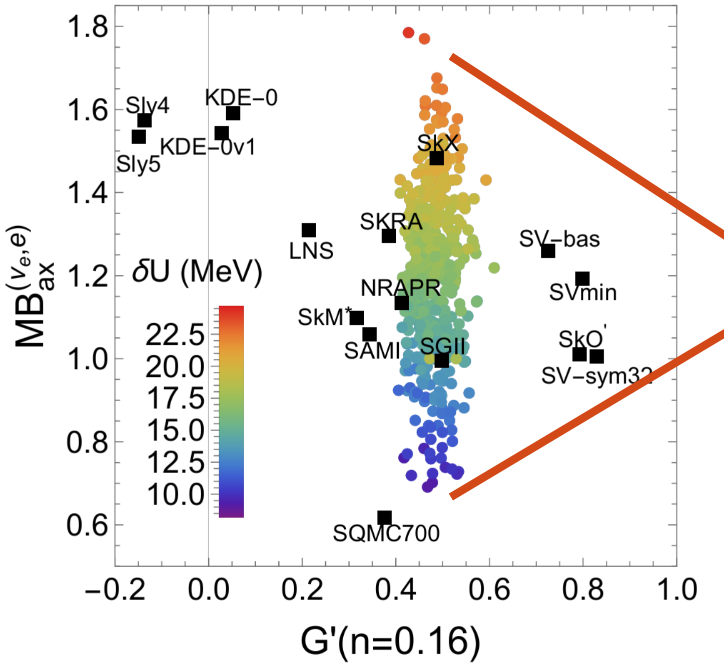
Zidu Lin, Gianluca Colò, A. W. Steiner, Amber Stinson, arXiv:2506.05564

$$\mathrm{MB}_{ax}^{(\nu_e/\bar{\nu}_e, e^-/e^+)} = \frac{\int \frac{1}{V} \frac{d^2\sigma_{ax}^{\pm}}{dcos\theta dE_{e^-/e^+}} dcos\theta dE_{e/e^+}}{\int \frac{1}{V} \frac{d^2\sigma_{0,ax}^{\pm}}{dcos\theta} dcos\theta}$$

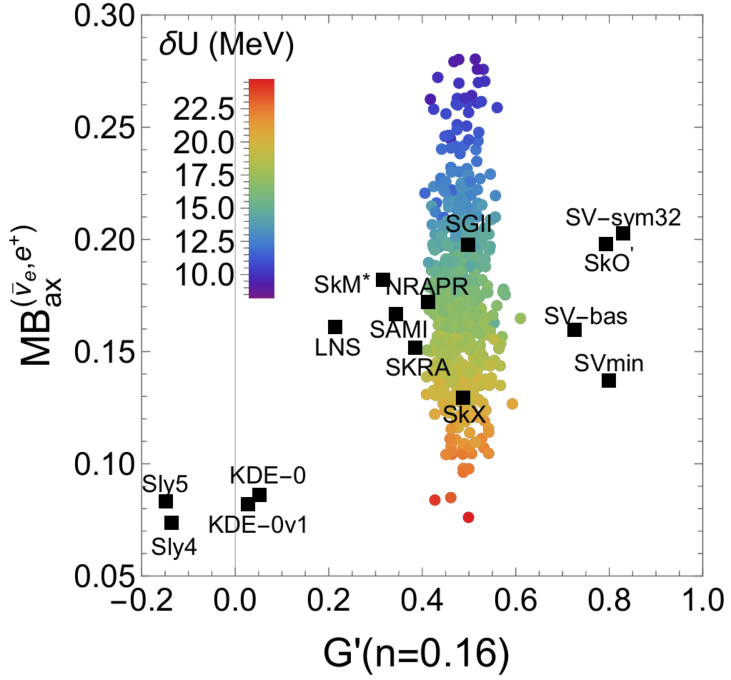
$$\frac{1}{V}\frac{d^2\sigma_{ax}^{\pm}}{dcos\theta dE_{e^-/e^+}} = \frac{G_F^2 g_A^2 p_{e^-/e^+} E_{e^-/e^+}}{4\pi^2} \times (3 - cos\theta) S_A(q_0, q).$$



Zidu Lin, Gianluca Colò, A. W. Steiner, Amber Stinson, arXiv:2506.05564



Uncertainty due to ignorance of symmetry energy at n=0.02 fm^{-3}



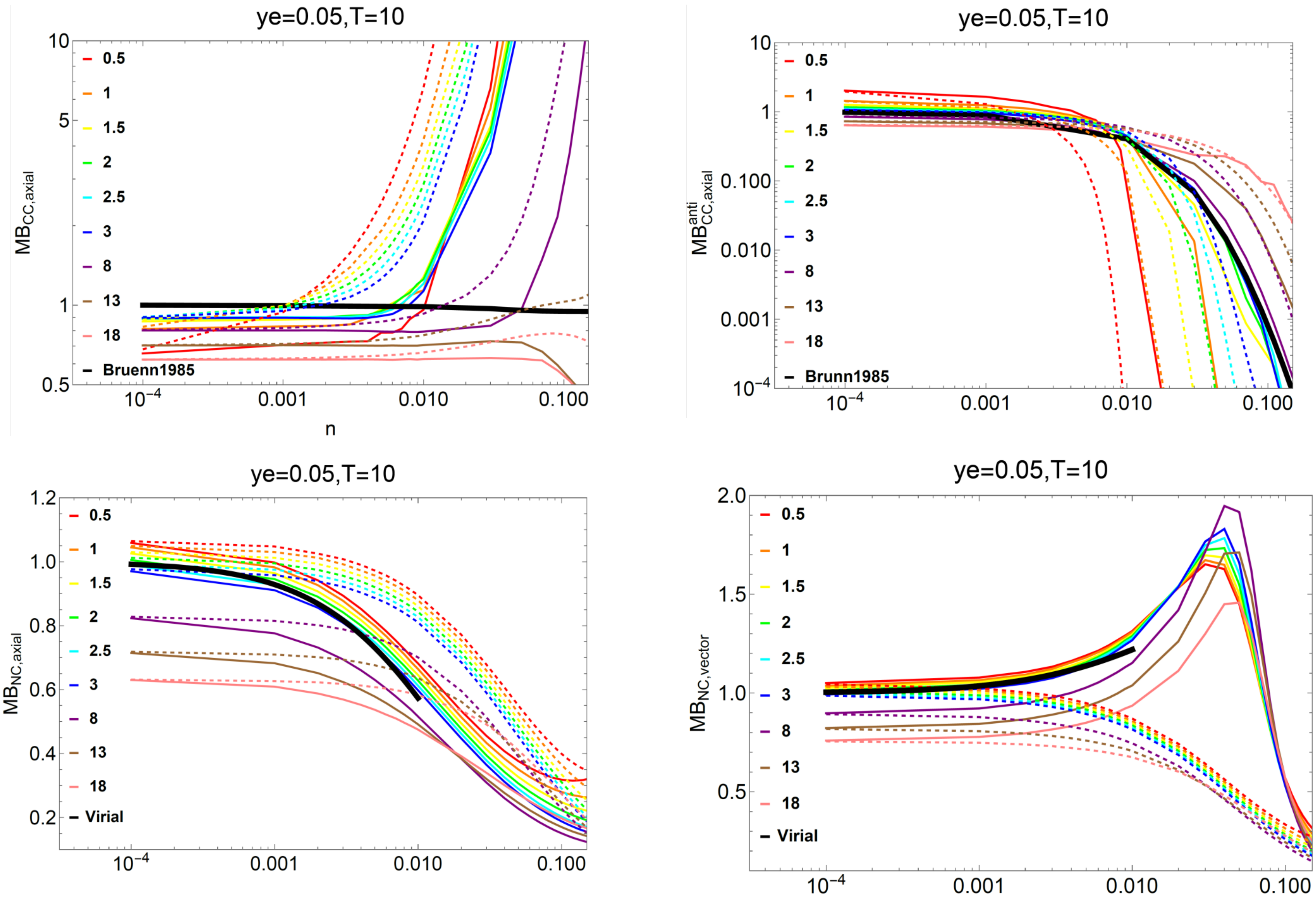
T=10 MeV
Ye=0.05
E_ν=30 MeV

Ground& excited states of finite nuclei

Infinite dense matter properties

		Experiment	nuSkyI	nuSkyII	nuSkyIII
^{208}**Pb**	B/A [MeV]	7.87 [44, 45]	7.73	7.89	7.89
	R_{ch} [fm]	5.50 [44, 45]	5.47	5.44	5.44
	F_{ch} []	0.409 [46]	0.412	0.418	0.417
	ΔF []	0.041±0.013 [46]	0.0241	0.0185	0.0288
	E_{GT} [MeV]	19.2 [47, 48]	20.04	20.05	19.46
	$m_0\%$ []	$74\% \pm 1.48\%$ [47, 48]	75.6%	77.0%	74.8%
^{132}**Sn**	B/A [MeV]	8.355 [44, 45]	8.25	8.36	8.37
	R_{ch} [fm]	4.71 [44, 45]	4.69	4.67	4.67
	E_{GT} [MeV]	13.97 [43]	14.66	14.56	13.97
	$m_0\%$ []	$81\% \pm 16\%$ [43]	79.23%	79.54%	78.72%
^{90}**Zr**	B/A [MeV]	8.71 [44, 45]	8.65	8.74	8.79
	R_{ch} [fm]	4.27 [44, 45]	4.23	4.23	4.22
	E_{GT} [MeV]	15.8 [49]	16.2	16.0	16.15
	$m_0\%$ []	$68\% \pm 1.4\%$ [49]	69.8%	72.8%	70.7%
^{48}**Ca**	B/A [MeV]	8.67 [44, 45]	8.78	8.82	8.86
	R_{ch} [fm]	3.48 [44, 45]	3.46	3.48	3.46
	F_{ch} []	0.158 [50]	0.155	0.154	0.155
	ΔF []	0.0277±0.0055 [50]	0.0423	0.036	0.0422
	E_{GT} [MeV]	10.5 [51]	11.0	10.6	10.8
Landau-Migdal Parameter	G_0' []	0.44 ± 0.09 (this work)	0.35	0.44	0.41
NS	$R_{1.4}$ [km]	$12.71^{+1.14}_{-1.19}$ [52] ; $13.02^{+1.24}_{-1.06}$ [53]	12.12	N/A	12.20
	M_{max} [$M_\odot$]	> 2.0	2.08	N/A	2.05

Zidu Lin, Gianluca Colò, A. W. Steiner, Amber Stinson, arXiv:2506.05564



Colored curves: $\frac{E_\upsilon}{T}$

Solid curves: RPA

Dashed Curves: MF

Z. Lin, S. Rath, P. Hammond, F. Foucart , A. W. Steiner, In preparation

To understand the influence of **microscopic** nuclear many-body calculations on **macroscopic** numerical simulations.

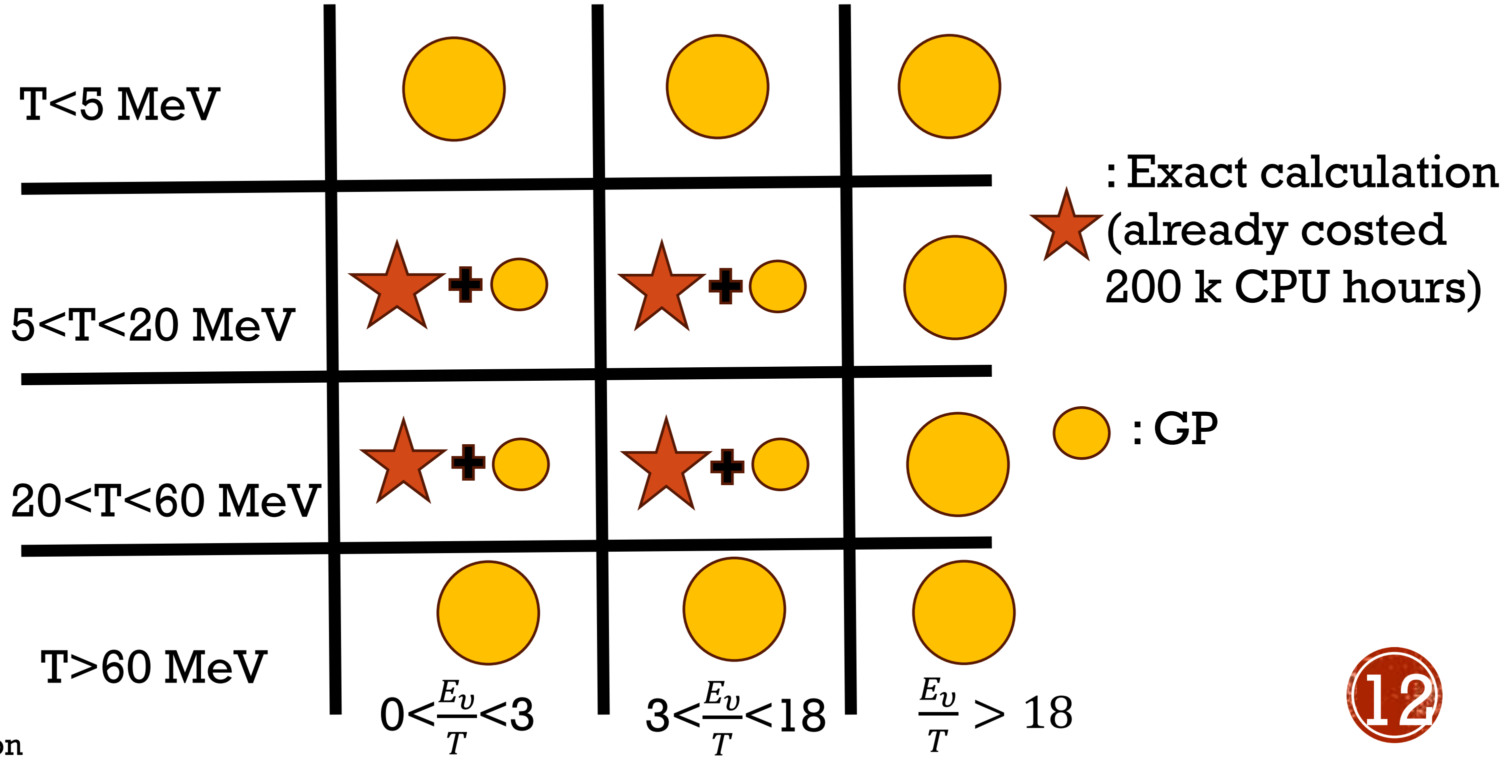
A calculation at representative environment is not enough.

MANY many-body calculations at various conditions are needed

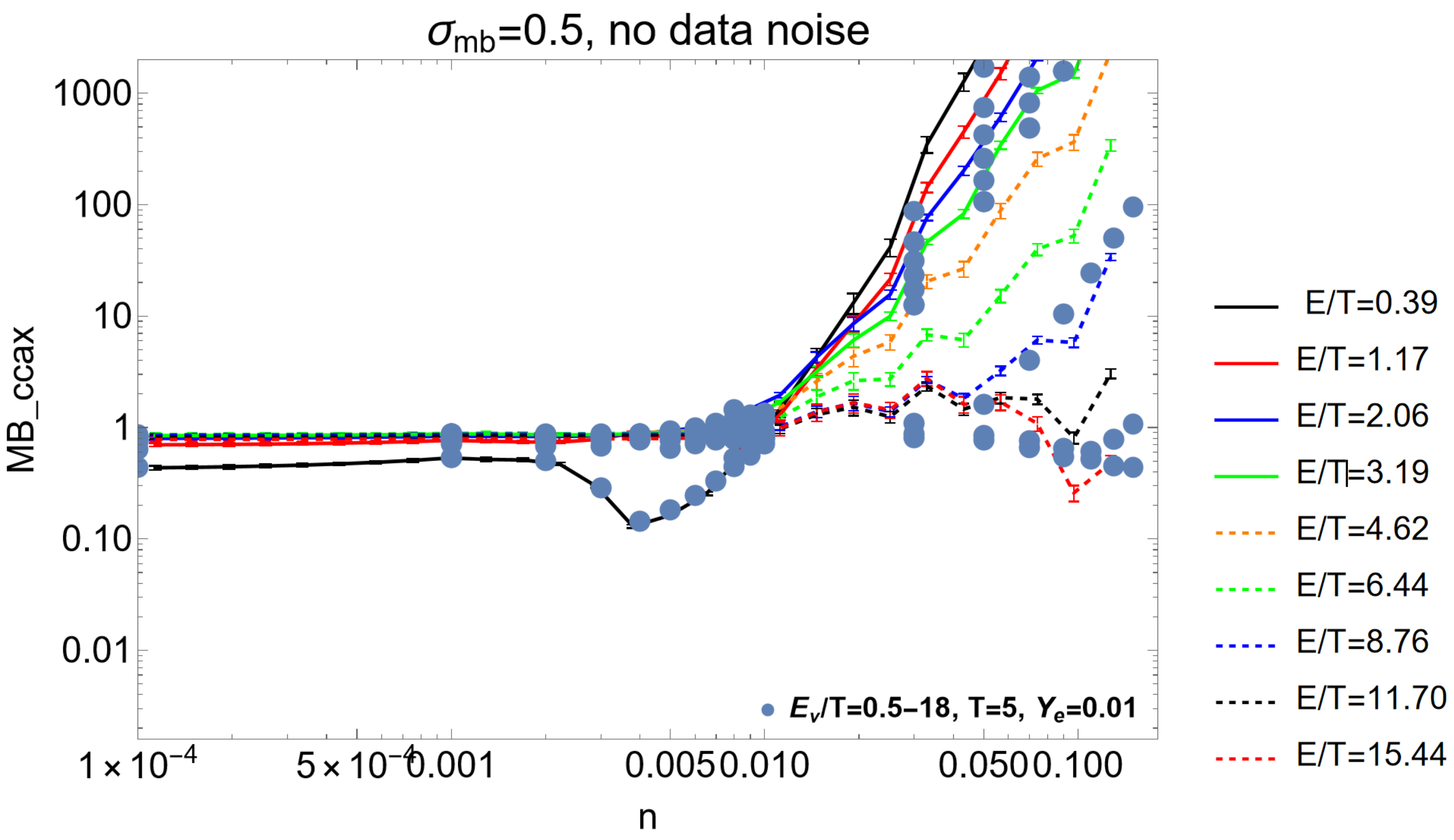
Need for high-fidelity many-body calculations (from nuclear physics side)

Need for high-resolution and wide-spreading grids of υ opacity (from simulation side)

Exact RPA calculations + Gaussian Process (GP)



Z. Lin, S. Rath, P. Hammond, F. Foucart , A. W. Steiner, In preparation



GP:

$\mathrm{Prob}(\vec{F}_{pre}|\vec{F}_D)$

GP gives conditional probability of interpolated (extrapolated) neutrino many-body correction based on the data (with/without uncertainties)

$$\begin{bmatrix}\mathbf{x}\\ \mathbf{y}\end{bmatrix} \sim \mathcal{N}\left(\begin{bmatrix}\boldsymbol{\mu}_x\\ \boldsymbol{\mu}_y\end{bmatrix}, \begin{bmatrix}A & C\\ C^\top & B\end{bmatrix}\right) \quad \mathbf{x}|\mathbf{y} \sim \mathcal{N}(\boldsymbol{\mu}_x + CB^{-1}(\mathbf{y}-\boldsymbol{\mu}_y),\ A - CB^{-1}C^\top)$$

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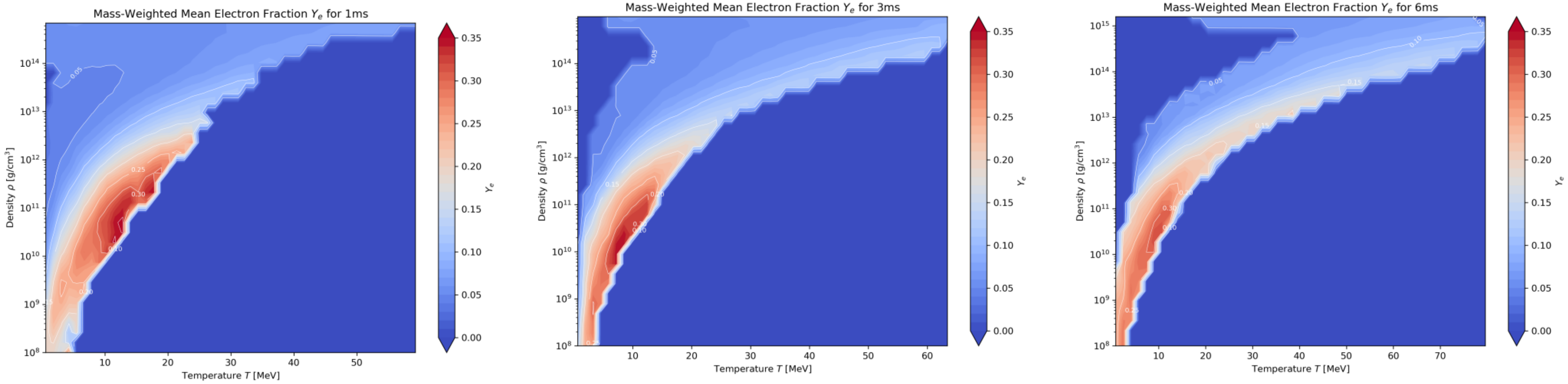
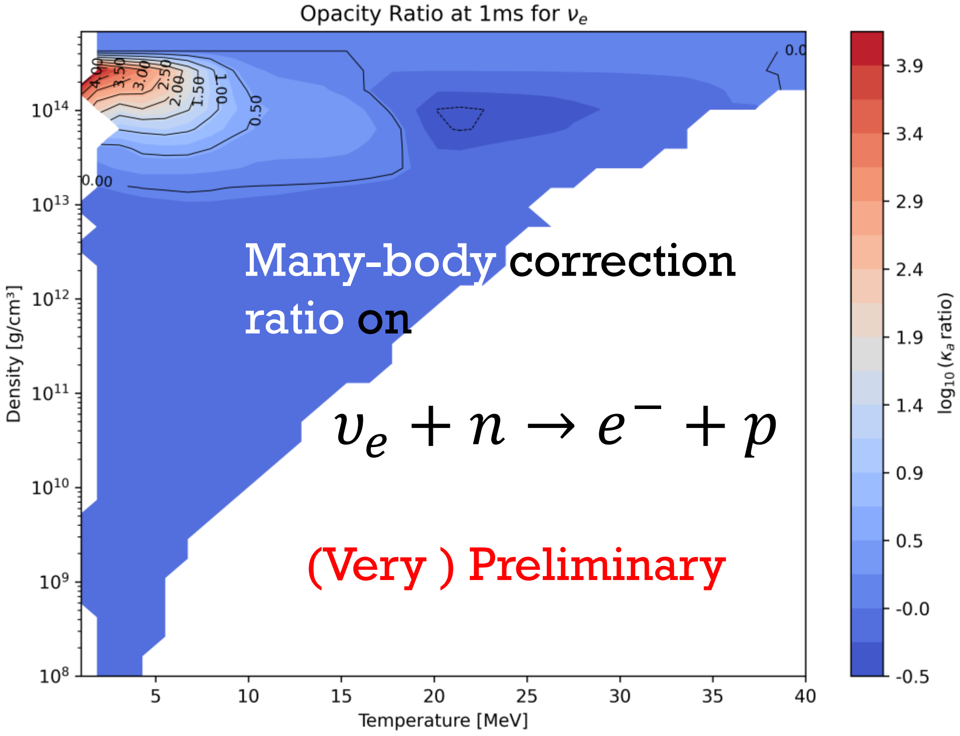
New opacity in BNS mergers



Y_e distribution in the first 6 ms after the merger

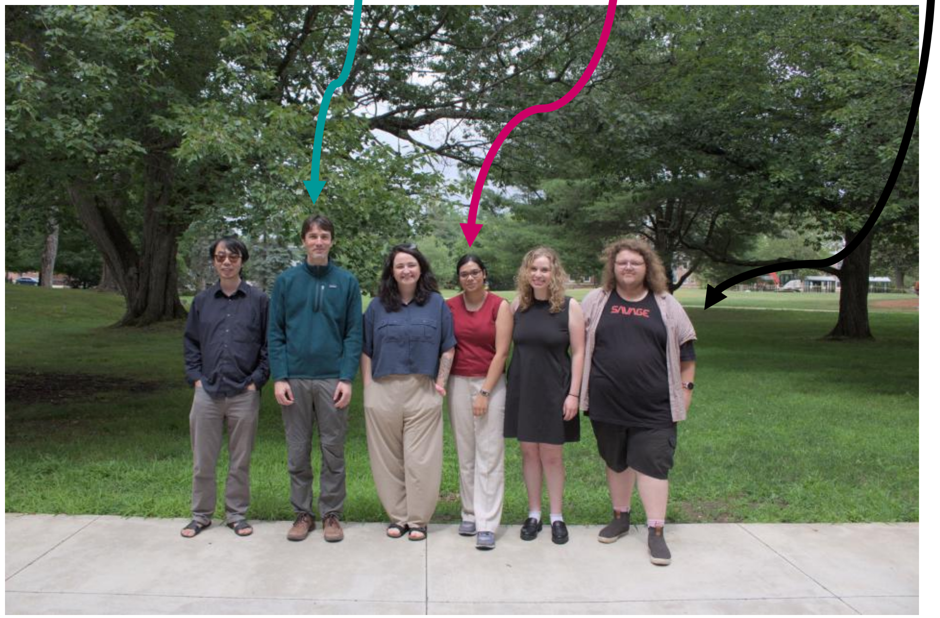


Many-body correction ratio on

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

(Very) Preliminary

Credit to F. Foucart, S. Rath, P. Hammond



Thanks!

Backup

Solving for RPA equations

$$G^{\alpha}_{RPA}(q_0, q, \vec{k}_1) = G_{HF}(q_0, q, \vec{k}_1) + G_{HF}(q_0, q, \vec{k}_1)$$
$$\times \sum_{\alpha'} \int \frac{d^3 k_2}{(2\pi)^3} V_{ph}^{\alpha,\alpha'}(q, \vec{k}_1, \vec{k}_2) \times G^{\alpha'}_{RPA}(q_0, q, \vec{k}_2)$$

$$< G >_{RPA} = (\beta_0 + 2W_2^{\alpha}(\beta_0\beta_3 - \beta_1^2)q^2)$$
$$/\{1 - W_1^{\alpha}\beta_0 + 2q^2 W_2^{\alpha}[-\beta_2 + \beta_3 + W_1^{\alpha}(\beta_1^2 - \beta_0\beta_3)] + q^4 (W_2^{\alpha})^2[-\beta_0\beta_5 + 4(\beta_1\beta_4 - \beta_2\beta_3) + \beta_2^2]$$
$$+ 2q^6 (W_2^{\alpha})^3[-\beta_0\beta_3\beta_5 + \beta_0\beta_4^2 + \beta_1^2\beta_5 - 2\beta_1\beta_2\beta_4 + \beta_2^2\beta_3]\},$$

$$\beta_l = \int \frac{d^3 k}{(2\pi)^3} G_{HF} F_l$$

$$F_{0-5} = \{1, \frac{\vec{k}\cdot\vec{q}}{q^2}, \frac{k^2}{q^2}, \frac{(\vec{k}\cdot\vec{q})^2}{q^4}, \frac{\vec{k}\cdot\vec{q}\,k^2}{q^4}, \frac{k^4}{q^4}\}$$

E. S. Hernandez, J. Navarro, and A. Polls, Nucl. Phys. A 658, 327 (1999).

J. Margueron, J. Navarro, and N. Van Giai, Phys. Rev. C 74, 015805 (2006)