Software for Nuclear Dynamics

Algorithms for HPC and Quantum Computing:

Case Studies:

- **Lepton-Nucleus (Linear Response):**
  - **Quantum Few- and Many-Body and**
  - **Classical/Semi-classical**
- **Dense Neutrino Environments (SN & NS Mergers)**
  - **Mean-Field/ Many-Body/ Random Matrix**

J. Carlson, LANL June 20, 2024

Nuclear Dynamics

- Substantial Progress to date on
  - Low-Energy Scattering and Reactions (R-matrix, …)
    Similar to Ground State Methods - Implementing Boundary Conditions
  - Few Degrees of Freedom
  - Inclusive Quasi-Elastic Scattering (Linear Response)
    High momentum transfer (compared to Fermi momentum) and
    Energy ↔ Short distances and times (high momenta)
- Leaves a great deal of important physics:
  - Strong Interactions, Moderate energies,
  - Beyond linear response, lower momenta and longer times
  - thermalization/equilibration
  - quantum vs. (semi) classical

Inclusive Lepton Nucleus Scattering:

2 Point function:

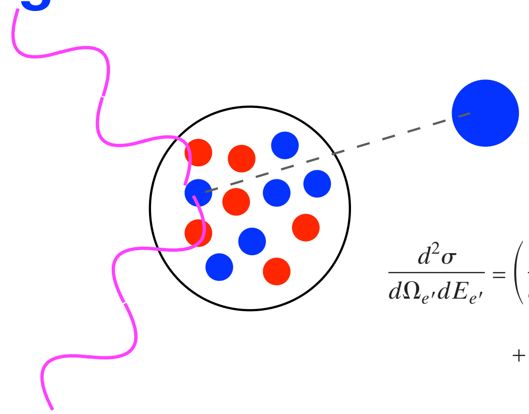
<0| J(q) exp [-iHt] J(q) | 0>

Full quantum treatment:

[Nuclear Scale * q / (2π)]^{3A}

~ [(10 fm) 3 fm^{-1} / (2π)]^{3A}

~ 5 $^{(3A)}$ = 5 ^{120}



$$\frac{d^2\sigma}{d\Omega_{e'}dE_{e'}} = \left(\frac{d\sigma}{d\Omega_{e'}}\right)_M \left[\frac{Q^4}{|\mathbf{q}|^4} R_L(|\mathbf{q}|,\omega) + \left(\frac{1}{2}\frac{Q^2}{|\mathbf{q}|^2} + \tan^2\frac{\theta}{2}\right) R_T(|\mathbf{q}|,\omega)\right]$$

Early use case for Quantum Computing advantage!

- At moderate to high momentum transfer: short distances / Times
  - Spectral Function (single or two-particle removal)
  - Short-time approximation (w/ NN scattering dynamics)

  - Requires only few nucleon quantum degrees of freedom

Semi-classical approximation used for exclusive channels

Tests of Accuracy, where is classical quantum transition

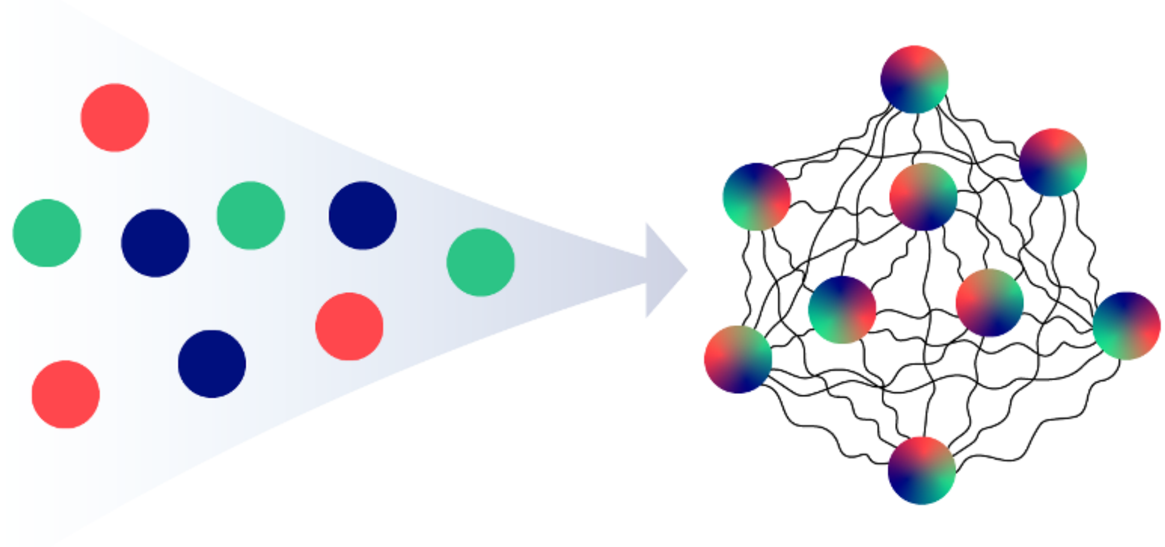
Continuum of difficulty from inclusive high energy

to exclusive modest energy

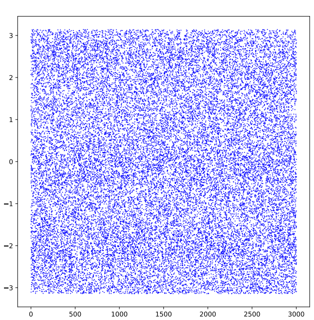
Strongly-Entangled Dense Neutrinos
Rapid equilibration: similar to hard cartons in QCD medium

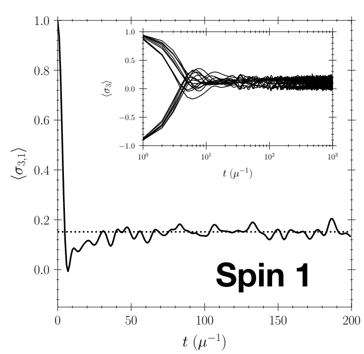
$$H_{\nu-\nu} = \frac{\sqrt{2}G_F\rho_\nu}{N}\sum_{i<j}(1-\hat{k}_i\cdot\hat{k}_j)\ \sigma_i\cdot\sigma_j$$

Initial state: product of single neutrino states
w/ randomness in flavors directions, momenta
Quantum entanglement develops very quickly



Rapid Equilibration:
phases from snapshot at 10 different times





$\nu_e\bar{\nu}_e \leftrightarrow \nu_\mu\bar{\nu}_\mu$ leads to conservation of product of neutrino and anti-neutrino densities
$\rho_e\rho_{\bar{e}} = \rho_\mu\rho_{\bar{\mu}} = \rho_\tau\rho_{\bar{\tau}}$ (2 constraints)

- Equilibration of quantum many-body fast neutrino flavor oscillations
JD Martin, D Neill, A Roggero, H Duan, J Carlson
PRD 108 (12), 1230109 202
- Many-body neutrino flavor entanglement in a simple dynamic model
JD Martin, A Roggero, H Duan, J Carlson arXiv preprint arXiv:2301.07049102023
- Neutrino many-body flavor evolution: the full Hamiltonian
V Cirigliano, S Sen, Y Yamauchi arXiv preprint arXiv:2404.16690

Quantum Dynamics in Nuclear Physics is an Extremely Important Field

Fission and Fusion
Lepton Scattering
Dense Neutrinos
QCD: ….

Rapidly Evolving Algorithms/ Hardware:

Mean field vs. QMB
Quantum vs. (semi)Classical
Number of Degrees of Freedom

New insights/ new software is key!

High Performance Computing
Quantum Computing
New algorithms for new capabilities across fields