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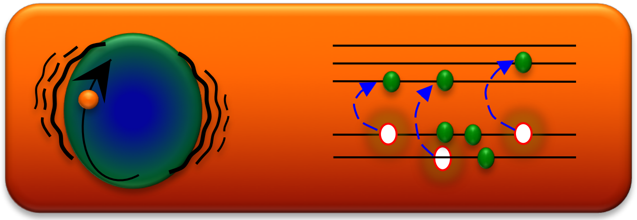
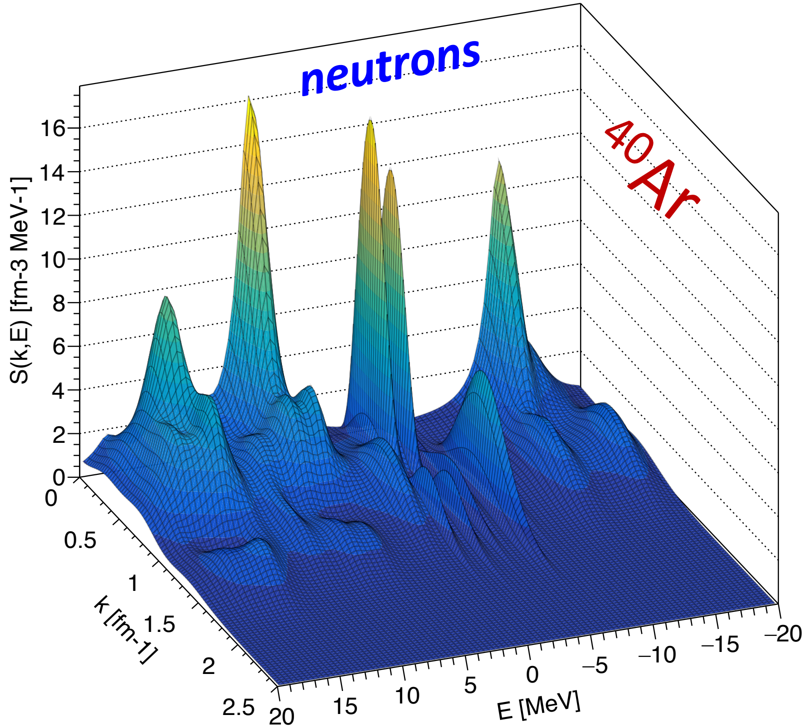
Neutrino interactions with nuclei and star matter

Carlo Barbieri — University of Surrey

8 November 2019

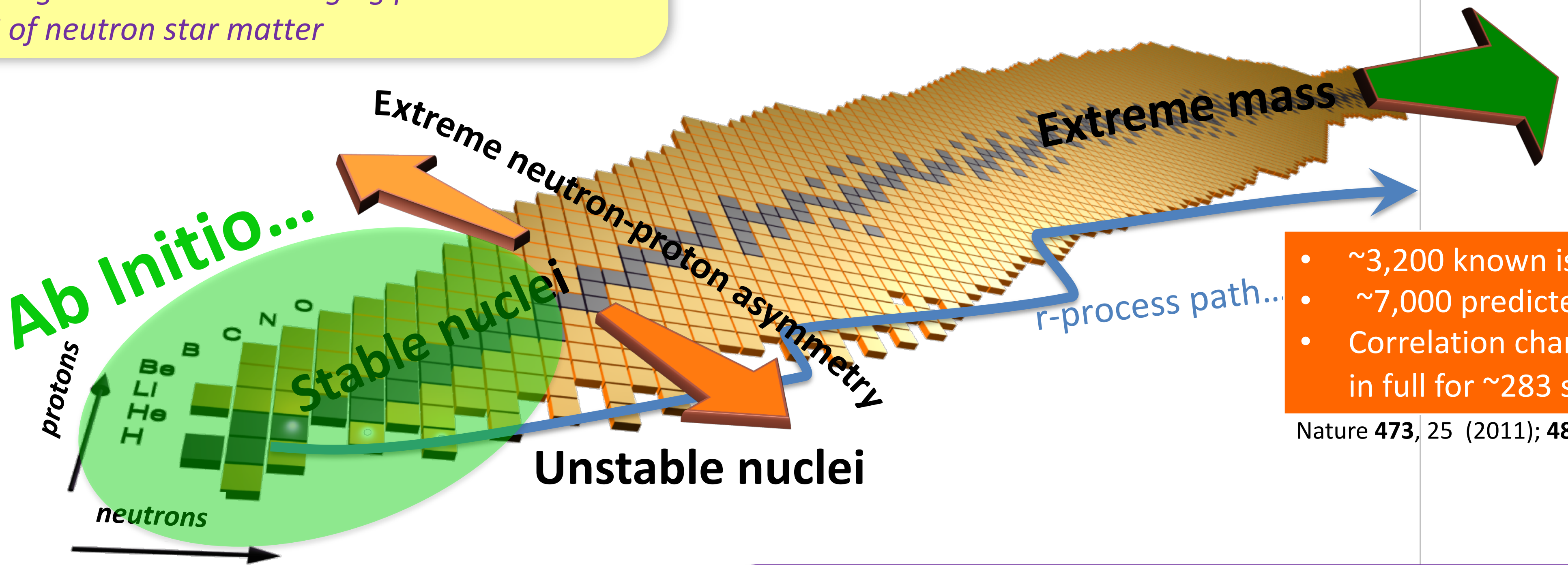




Current Status of low-energy nuclear physics

Composite system of interacting fermions
Binding and limits of stability
Coexistence of individual and collective behaviors
Self-organization and emerging phenomena
EOS of neutron star matter

Experimental programs
RIKEN, FAIR, FRIB, ISAC…



- ~3,200 known isotopes
- ~7,000 predicted to exist
- Correlation characterised in full for ~283 stable

Nature **473**, 25 (2011); **486**, 509 (2012)

I) Understanding the nuclear force
QCD-derived; 3-nucleon forces (3NFs)
First principle (ab-initio) predictions

II) Nuclear correlations
Fully known for stable isotopes
[C. Barbieri and W. H. Dickhoff, Prog. Part. Nucl. Phys ***52****, 377 (2004)]*
Neutron-rich nuclei; Shell evolution (far from stability)

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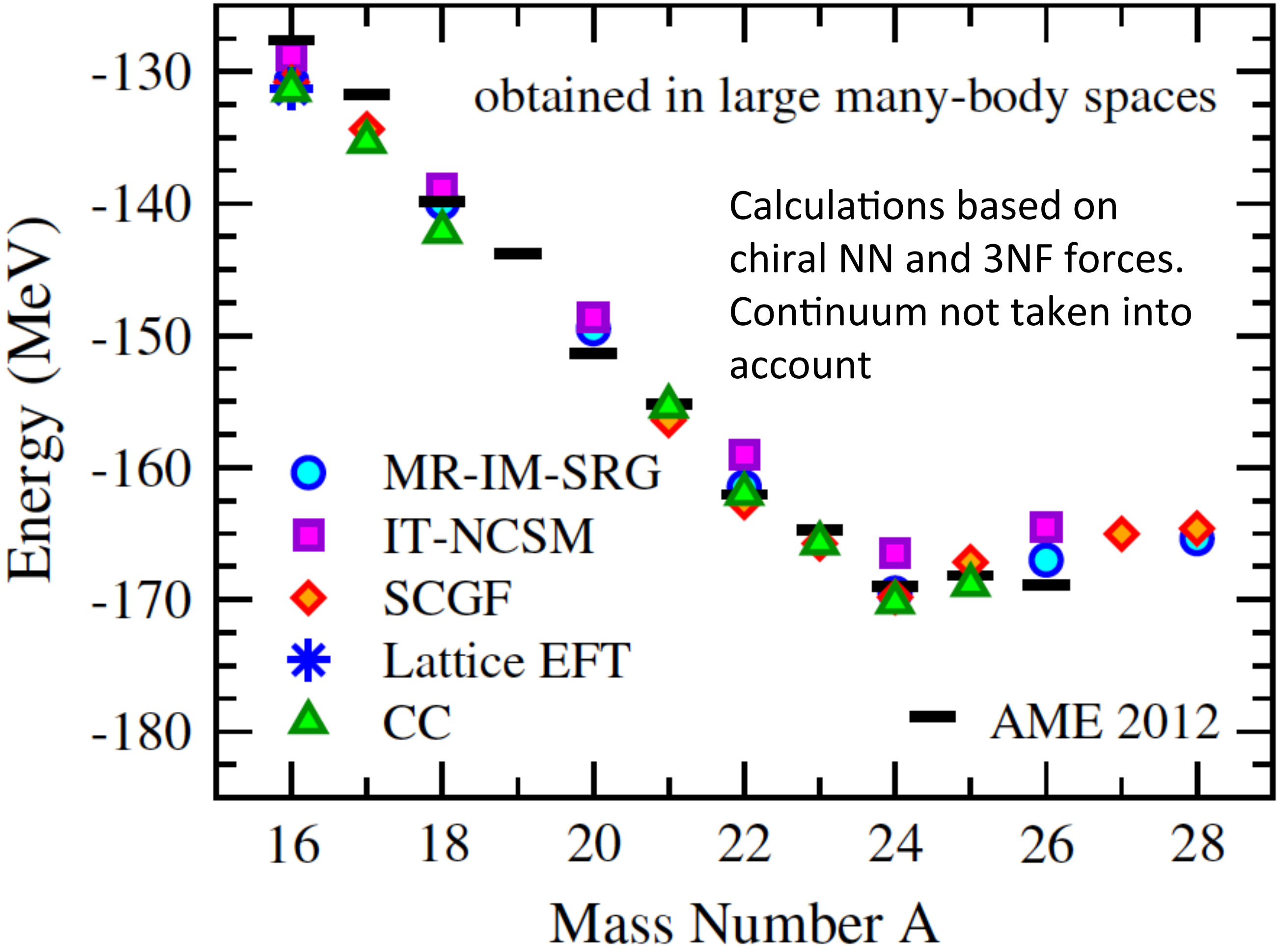
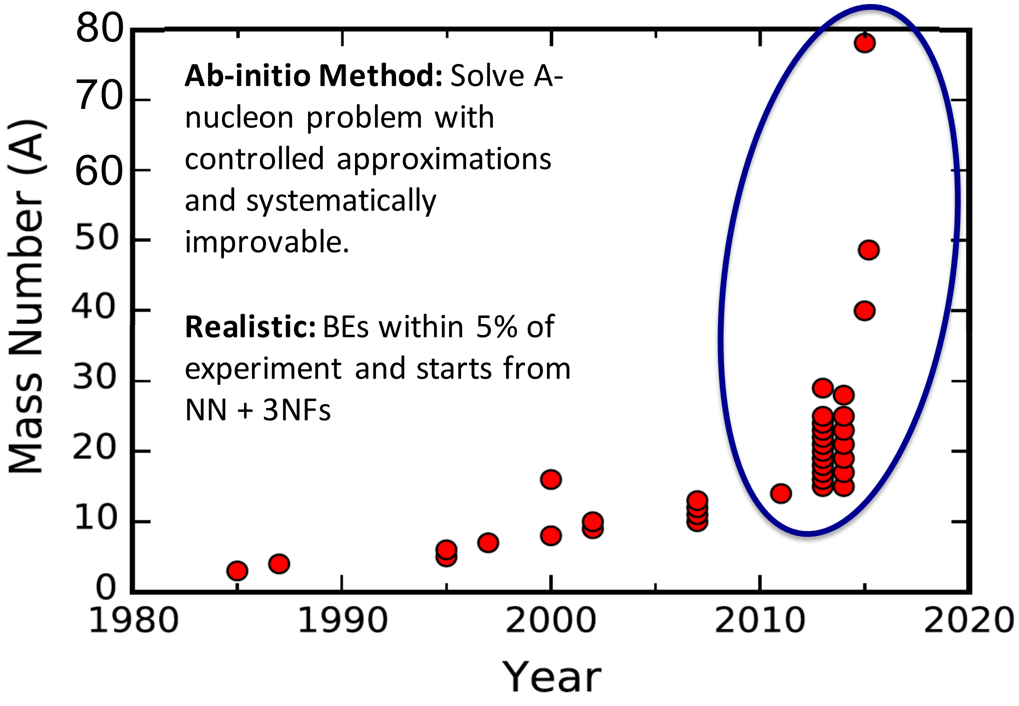
Benchmark of ab-initio methods for oxygen isotopic chain

First success of chital-EFT interactions on oxygen isotopes….



Hebeler, Holt, Menendez, Schwenk, Ann. Rev. Nucl. Part. Sci. in press (2015)



Picture from G. Hagen at al., Nature (2016)

…mostly g.s. energies and radii so far!

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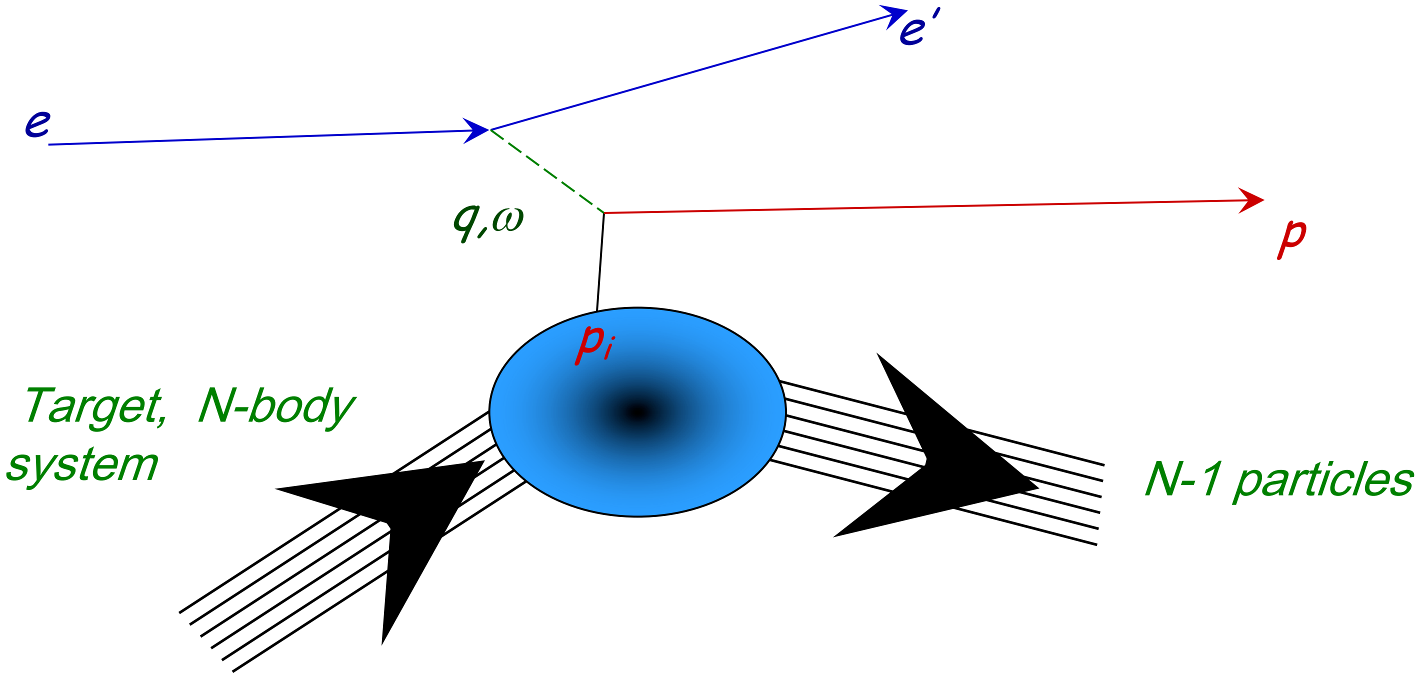
Spectroscopy via knock out reactions-basic idea

Use a probe (ANY probe) to eject the particle we are interested to:



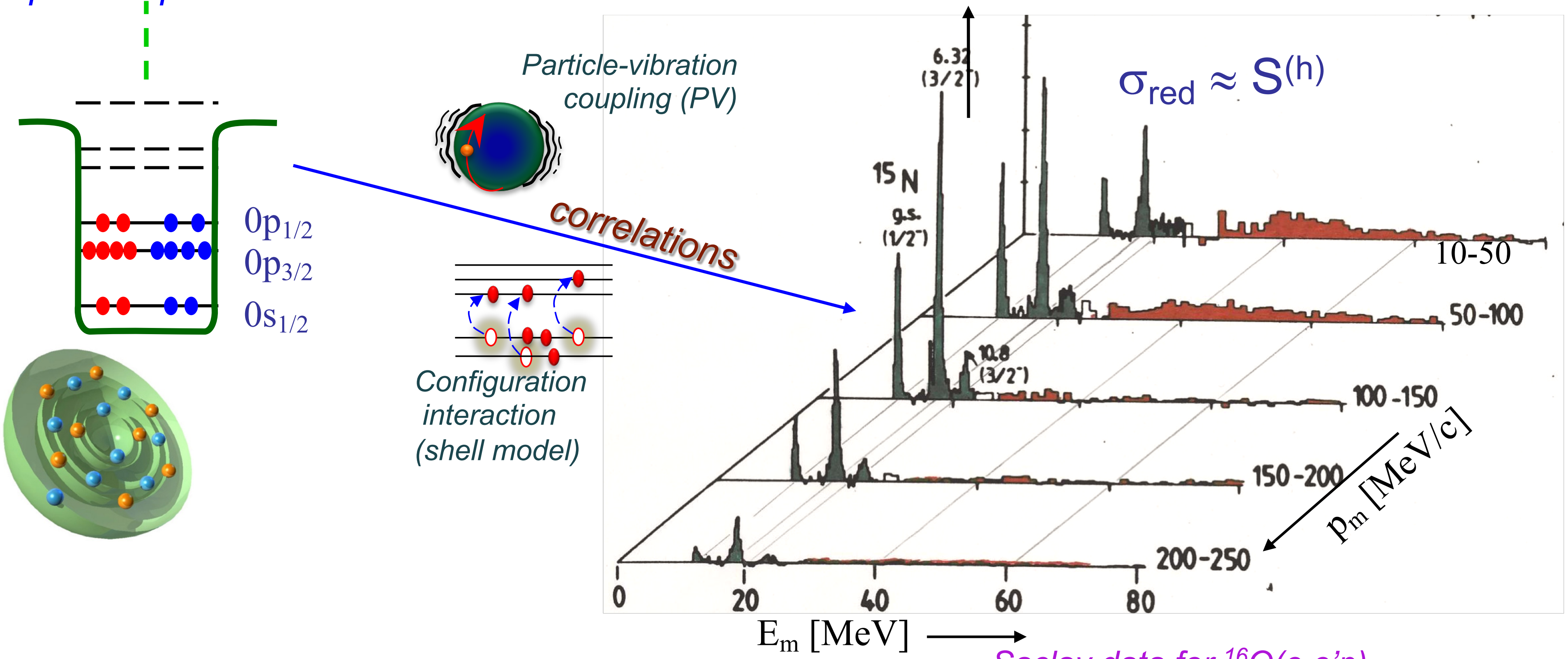
In plane wave impulse approximation (PWIA):

$$\frac{d\sigma_{(e,e'p)}}{dE_{e'}\, d\Omega_{e'}\, d\Omega_p} = \sigma_{e\,p} \times S^h(p_m, E_m)$$

Concept of correlations

independent particle picture

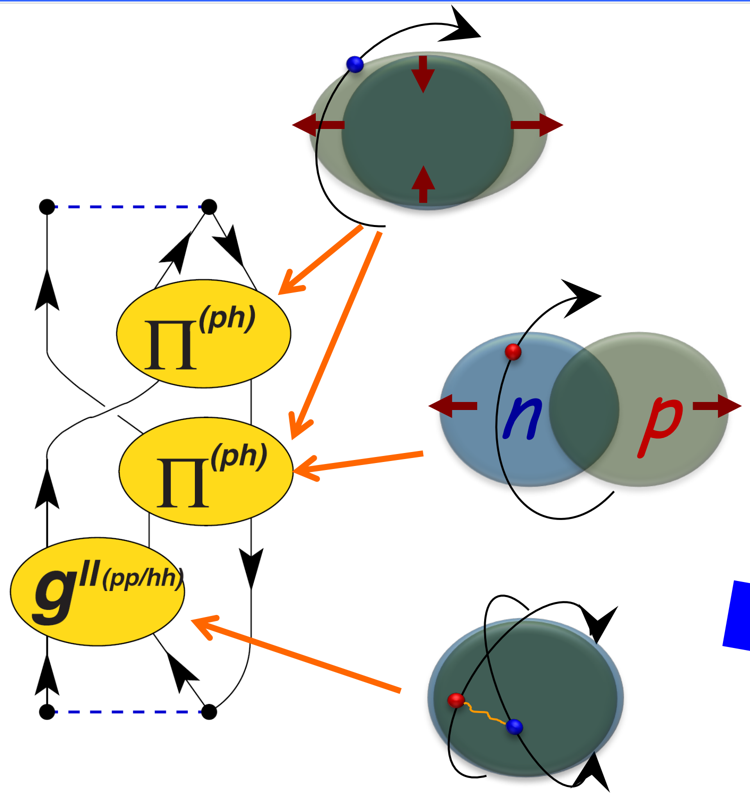
Spectral function: distribution of momentum (p_m) and energies (E_m)



Saclay data for ^{16}O(e,e'p)
[Mougey et al., Nucl. Phys. A335, 35 (1980)]

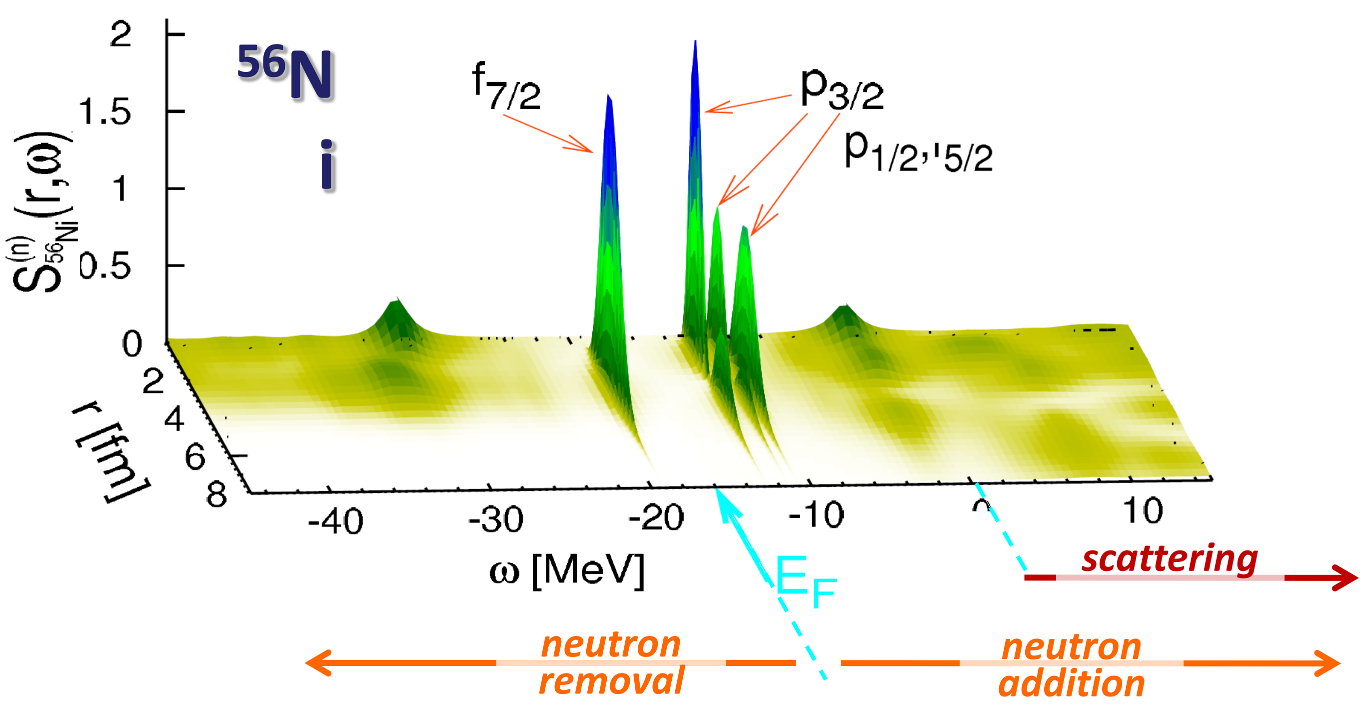
Understood for a few stable closed shells:
*[CB and W. H. Dickhoff, Prog. Part. Nucl. Phys **52**, 377 (2004)]*

One-nucleon spectral function from SCGF



$$S^{p,h}(r,\omega) = \mp\frac{1}{\pi}\,\mathrm{Im}\,g(r=r';\omega)$$

Distribution of particle and hole neutron states in ^{56}Ni



W. Dickhoff, CB, Prog. Part. Nucl. Phys. 53, 377 (2004); CB, M.Hjorth-Jensen, Pys. Rev. C**79**, 064313 (2009)

Electron and neutrino

scattering off nuclei

N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018)

N. Rocco, CB, O. Benhar, A. De Pace, A. Lovato, Phys. Rev. C**99**, 025502 (2019)

CB, N. Rocco, V. Somà, arXiv:1907.01122

Lepton-nucleon cross section

$$\left(\frac{d\sigma}{dT' d\cos\theta'}\right)_{\nu/\bar{\nu}} = \frac{G^2}{2\pi}\frac{k'}{2E_\nu}\left[\hat{L}_{CC}R_{CC} + 2\hat{L}_{CL}R_{CL} + \hat{L}_{LL}R_{LL} + \hat{L}_T R_T \pm 2\hat{L}_{T'}R_{T'}\right] ,$$

Nuclear structure is in the hadronic tensor:

$$R_{CC} = W^{00}$$
$$R_{CL} = -\frac{1}{2}(W^{03} + W^{30})$$
$$R_{LL} = W^{33}$$
$$R_T = W^{11} + W^{22}$$
$$R_{T'} = -\frac{i}{2}(W^{12} - W^{21}) ,$$

$$W^{\mu\nu} = \sum_f \langle 0|j^{\mu\,\dagger}|f\rangle\langle f|j^\nu|0\rangle\delta(E_0 + \omega - E_f)$$

Lepton-nucleon cross section

$$\left(\frac{d\sigma}{dT'd\cos\theta'}\right)_{\nu/\bar\nu} = \frac{G^2}{2\pi}\frac{k'}{2E_\nu}\left[\hat L_{CC}R_{CC} + 2\hat L_{CL}R_{CL} + \hat L_{LL}R_{LL} + \hat L_T R_T \pm 2\hat L_{T'}R_{T'}\right],$$

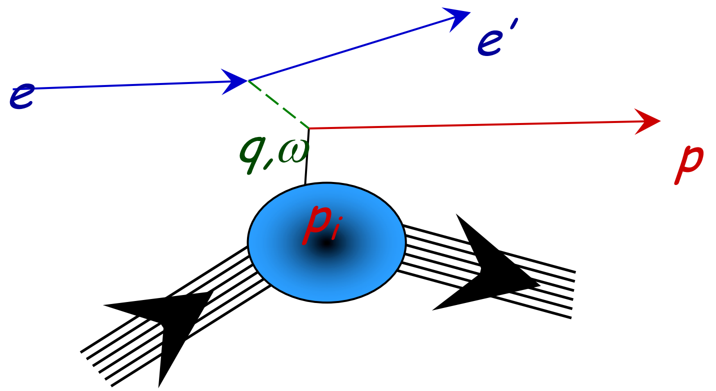
Nuclear structure is in the hadronic tensor:

$$W^{\mu\nu}(\mathbf{q},\omega) = \int \frac{d^3k}{(2\pi)^3} dE\, P_h(\mathbf{k},E) \frac{m^2}{e(\mathbf{k})e(\mathbf{k}+\mathbf{q})} \times \sum_i \langle k|j_i^{\mu\dagger}|k+q\rangle\langle k+q|j_i^\nu|k\rangle \times \delta(\omega + E - e(\mathbf{k}+\mathbf{q})),$$

Two models of the Spectral function

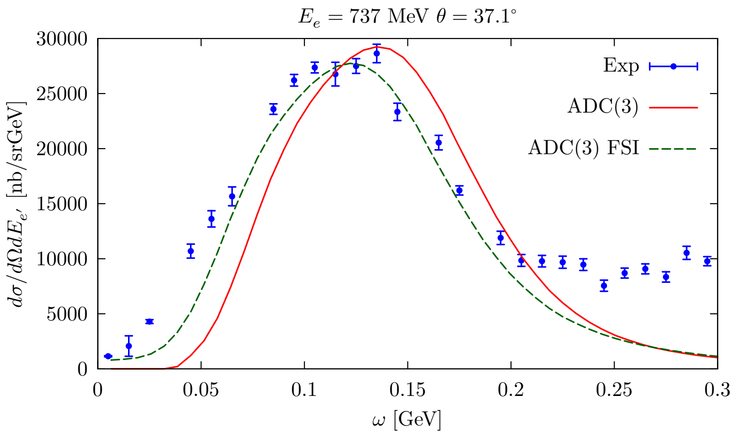
$$P_h(\mathbf{k},E) = \frac{1}{\pi}\sum_{\alpha\beta}\tilde\Phi^*_\beta(\mathbf{k})\tilde\Phi_\alpha(\mathbf{k}) \times \mathrm{Im}\langle\psi_0^A|a_\beta^\dagger \frac{1}{E + (H - E_0^A) - i\epsilon} a_\alpha|\psi_0^A\rangle$$

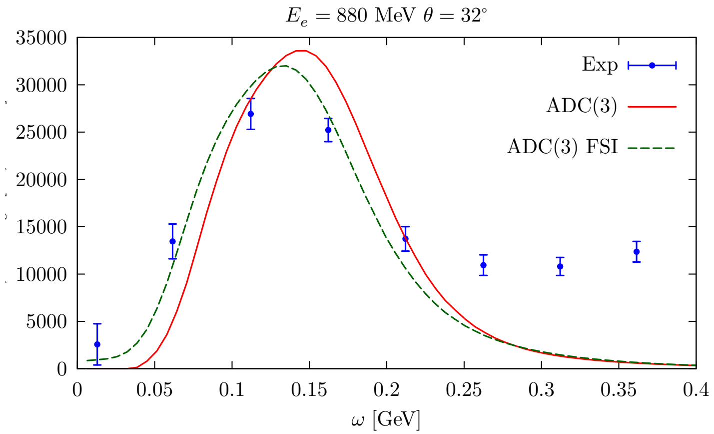
SCGF/ADC(3)
using chiral NNLOsat



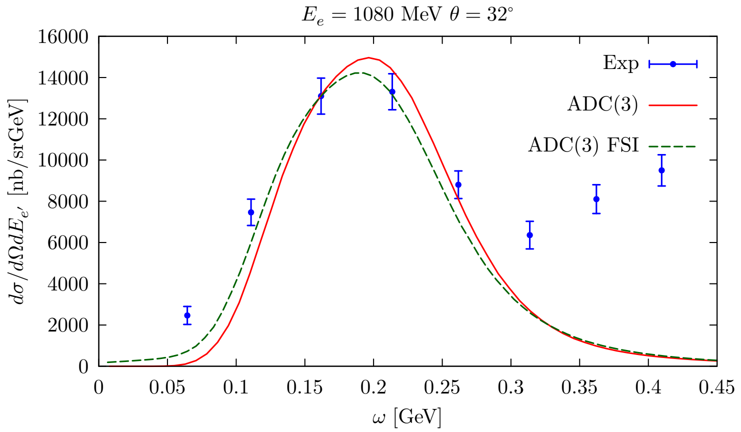
N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

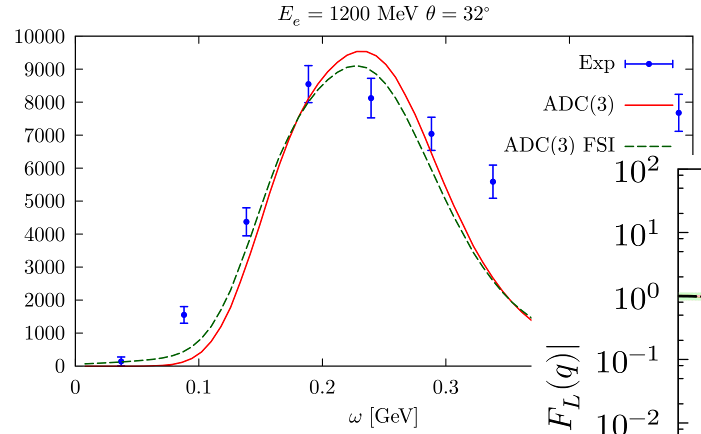
^{16}O-e$^-$ cross sections from the SCGF Spect. Fnct.

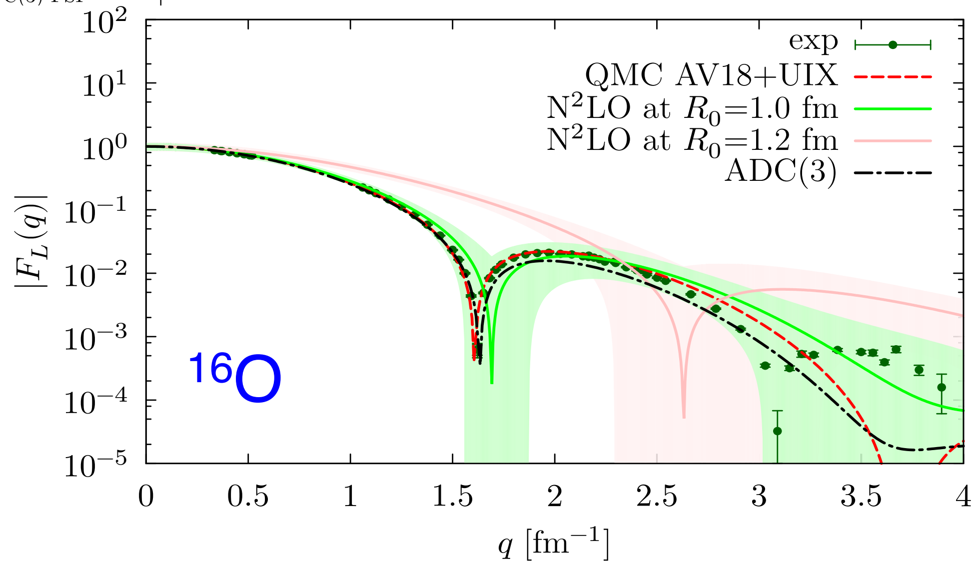




Based on the saturating chiral N2LO-sat nuclear force







N. Rocco, CB, Phys. Rev. C**98**, 025501 (2018).

Lepton-nucleon cross section

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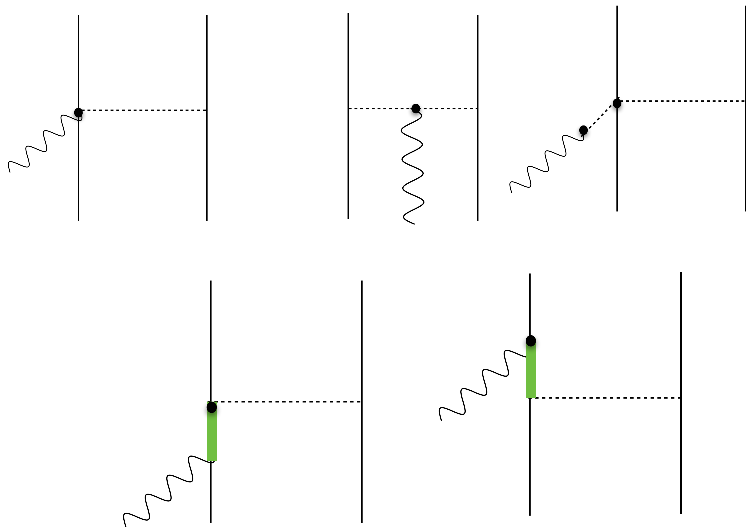
Nuclear structure is in the hadronic tensor:

$$\begin{aligned} W^{\mu\nu}(\mathbf{q},\omega) = &\int \frac{d^3k}{(2\pi)^3} dE\, P_h(\mathbf{k},E) \frac{m^2}{e(\mathbf{k})e(\mathbf{k}+\mathbf{q})} \\ &\times \sum_i \langle k|j_i^{\mu\,\dagger}|k+q\rangle\langle k+q|j_i^\nu|k\rangle \\ &\times \delta(\omega + E - e(\mathbf{k}+\mathbf{q}))\,, \end{aligned}$$

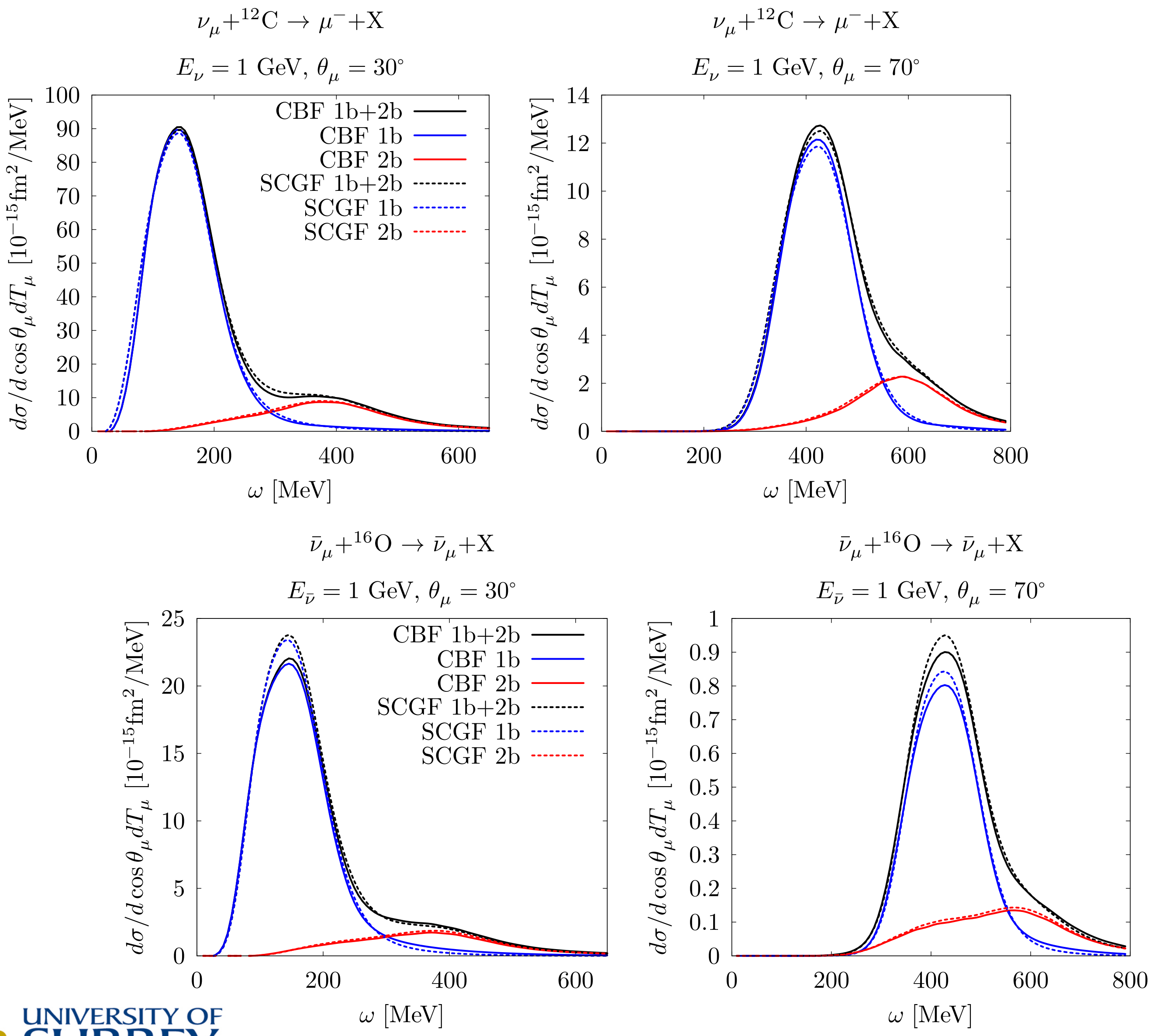
$$\begin{aligned} W^{\mu\nu}_{2b}(\mathbf{q},\omega) = &\frac{V}{2}\int d\tilde{E}\frac{d^3k}{(2\pi)^3} d\tilde{E}'\frac{d^3k'}{(2\pi)^3}\frac{d^3p}{(2\pi)^3} \\ &\times \frac{m^4}{e(\mathbf{k})e(\mathbf{k}')e(\mathbf{p})e(\mathbf{p}')} P_h^{\rm NM}(\mathbf{k},\tilde{E})P_h^{\rm NM}(\mathbf{k}',\tilde{E}') \\ &\times \sum_{ij}\langle k\,k'|j_{ij}^{\mu\,\dagger}|p\,p'\rangle\langle p\,p'|j_{ij}^\nu|k\,k'\rangle \\ &\times \delta(\omega + \tilde{E} + \tilde{E}' - e(\mathbf{p}) - e(\mathbf{p}'))\,. \qquad (41) \end{aligned}$$

- Two-body diagrams contributing to the axial and vector responses



N. Rocco, CB, O. Benhar, A. De Pace, A. Lovato, Phys. Rev. C**99**, 025502 (2019)

Charged-current reaction for 1 GeV neutrinos



One-body current describe quasi elastic peak

Difference between CBF(AV18) and SCGF(NNLOsat) from 1-b terms

Two-body currents fiull up dip region

Missing Delta and meson emission contributions

X-sec. droppin with scattering angle

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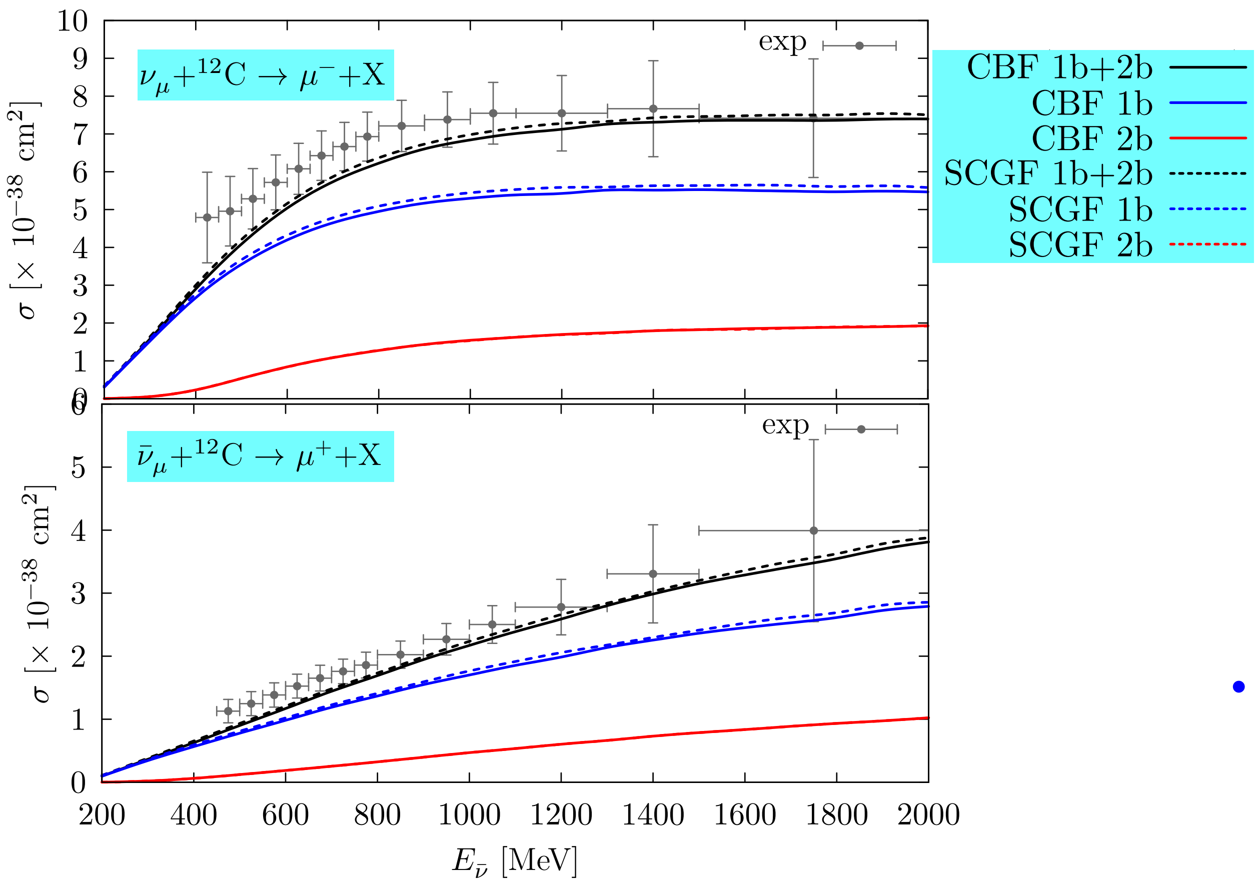
N. Rocco, CB, O. Benhar, A. De Pace, A. Lovato, Phys. Rev. C**99**, 025502 (2019)

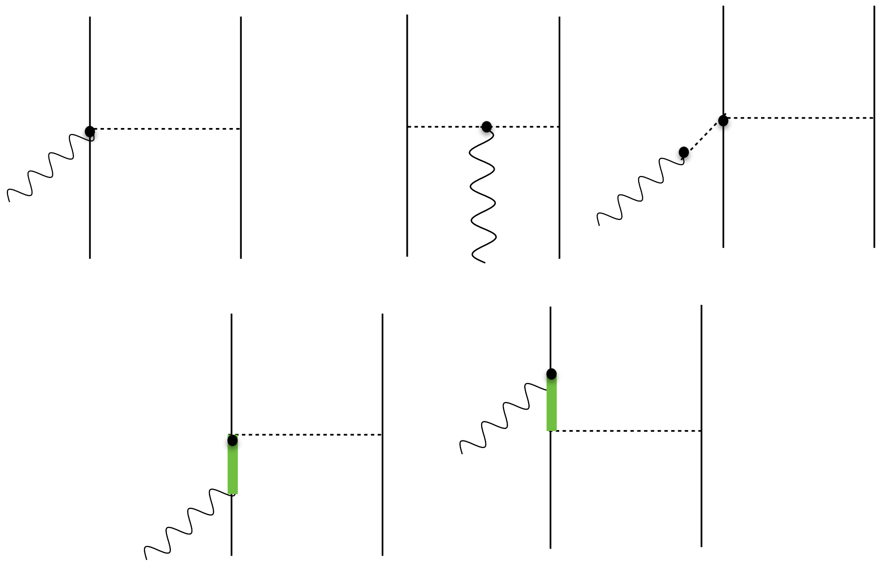
Role of two-body (meson exchange) currents in ν-A

CC0π total cross section: MiniBooNE data



The 2p2h contribution is needed to explain the magnitude of the total cross section

- Two-body diagrams contributing to the axial and vector responses



- Preliminary implementation discards 1b-2b interference:

$$W^{\mu\nu}_{2p2h} = W^{\mu\nu}_{ISC} + W^{\mu\nu}_{MEC} + \cancel{W^{\mu\nu}_{int}}$$

N. Rocco, CB, O. Benhar, A. De Pace , A. Lovato, arXiv:1810.0wxyz (in preparation)

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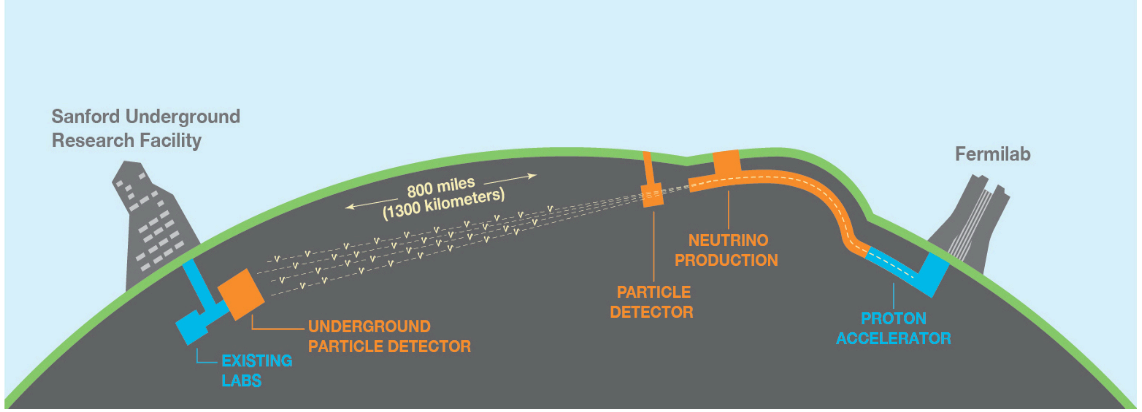
Neutrino Oscillations – next generation experiments

DUNE experiment will measure long base line neutrino oscillations (mass hierarchy, CP violation in weak interactions, physics beyond SM)

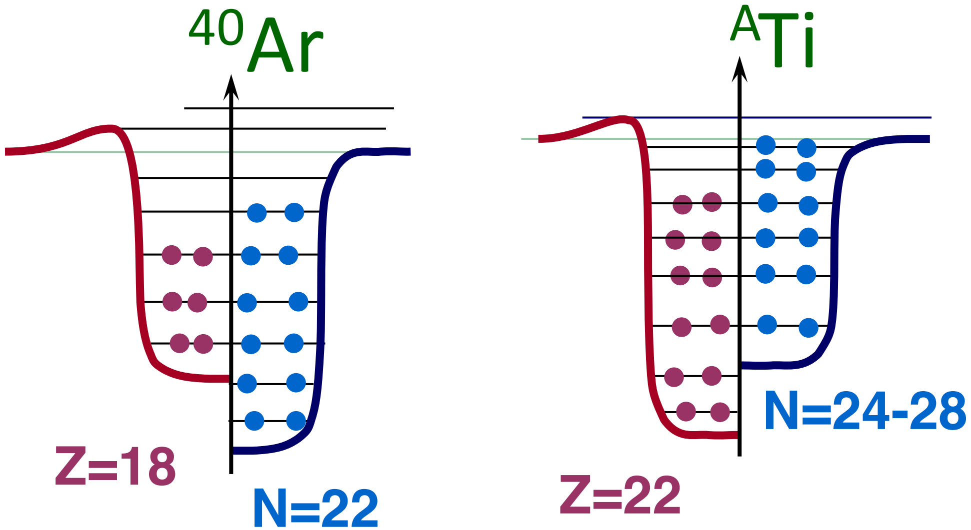


Liquid Argon projection chamber is being used. It will require one order of magnitude (20% → 2%) improvement in theoretical prediction for ν-^{40}Ar cross sections to achieve proper event reconstruction.

➔ **Need good knowledge of ^{40}Ar spectral functions.**

Jlab experiment E12-14-012 (Hall A)

Phys. Rev. C 98, 014617 (2018); arXiv:1810.10575



Proton distribution in Ti similar to neutron in ^{40}Ar ??

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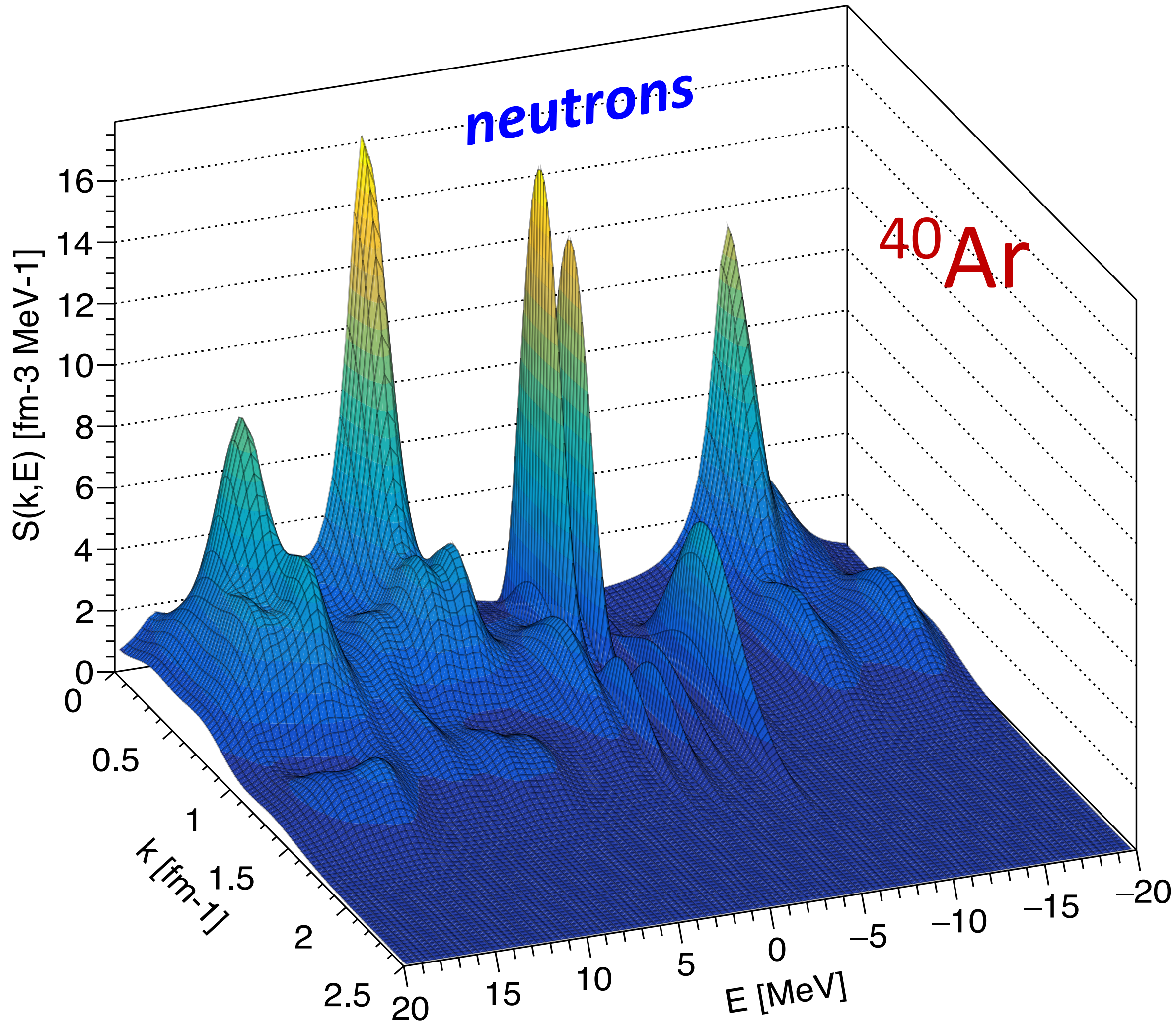
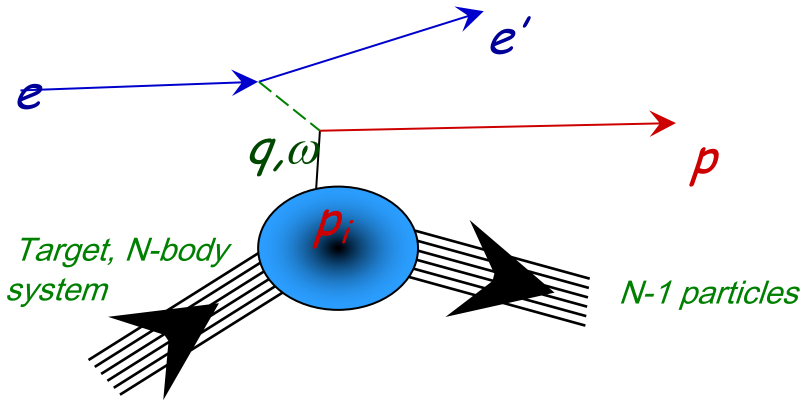
Spectral function for ^{40}Ar



- Experimental datat now available from Jlab:
  H. Dai et al., arXiv:1803.01910/ 1810.10575

- Ab initio simulations based on the ADC(2) truncation of the N2LO-sat Hamiltoninan

➔ Want validation of initial state correlation before they are implementer in neutrino-^{40}Ar simulations

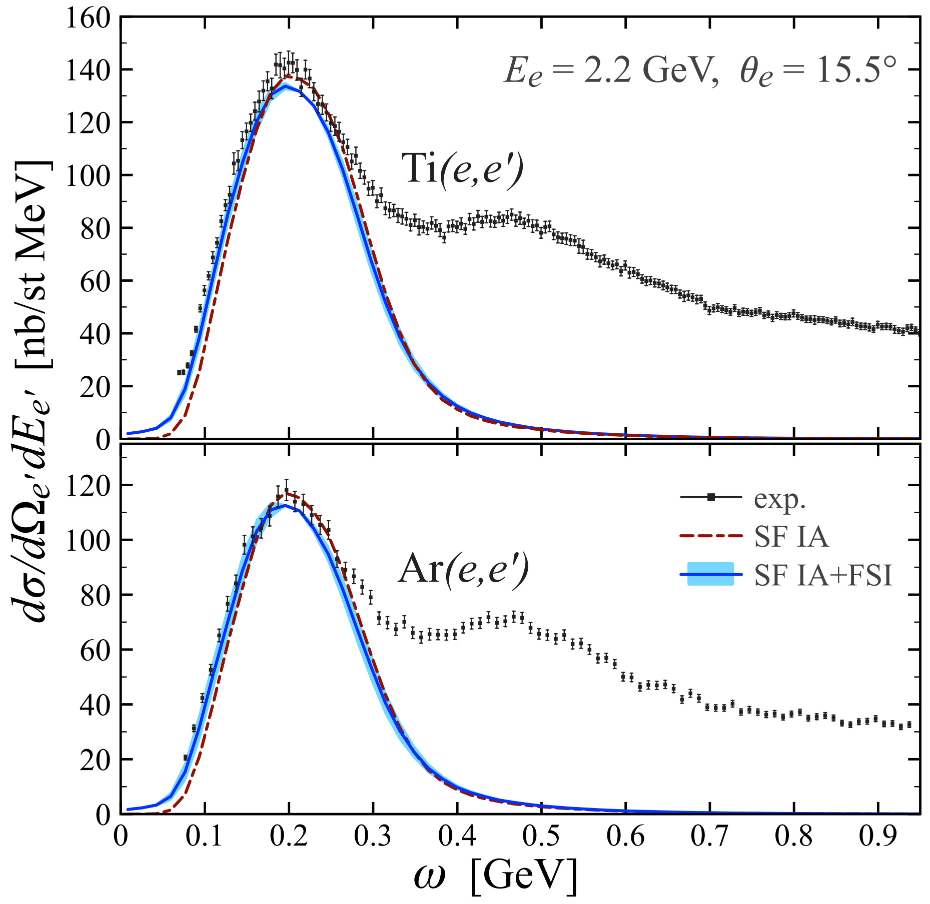


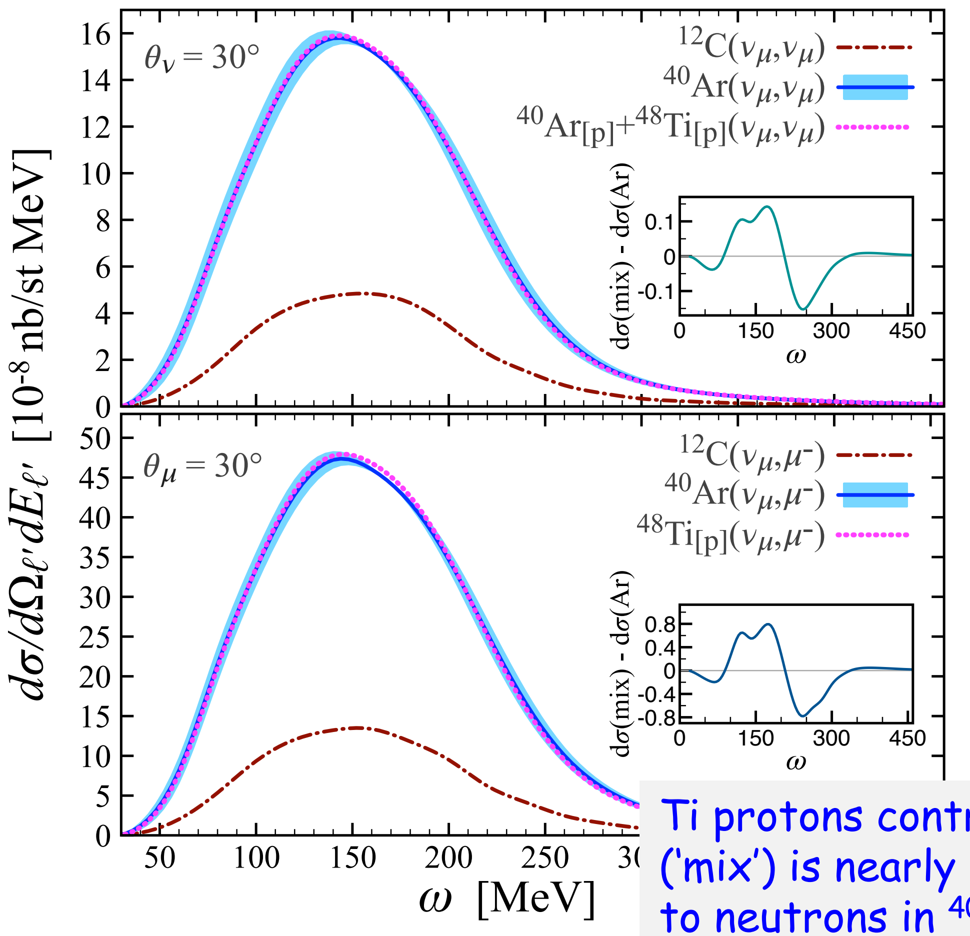
CB, N. Rocco, V. Somà, arXiv:1907.01122

Electron and ν scattering on ^{40}Ar and Ti

Jlab experiment E12-14-012 (Hall A)

[Phys. Rev. C 98, 014617 (2018)]





Ti protons contribution ('mix') is nearly identical to neutrons in ^{40}Ar.

^{40}Ar(e,e′p) and Ti(e,e′p) data being analyzed

CB, N. Rocco, V. Somà, arXiv:1907.01122

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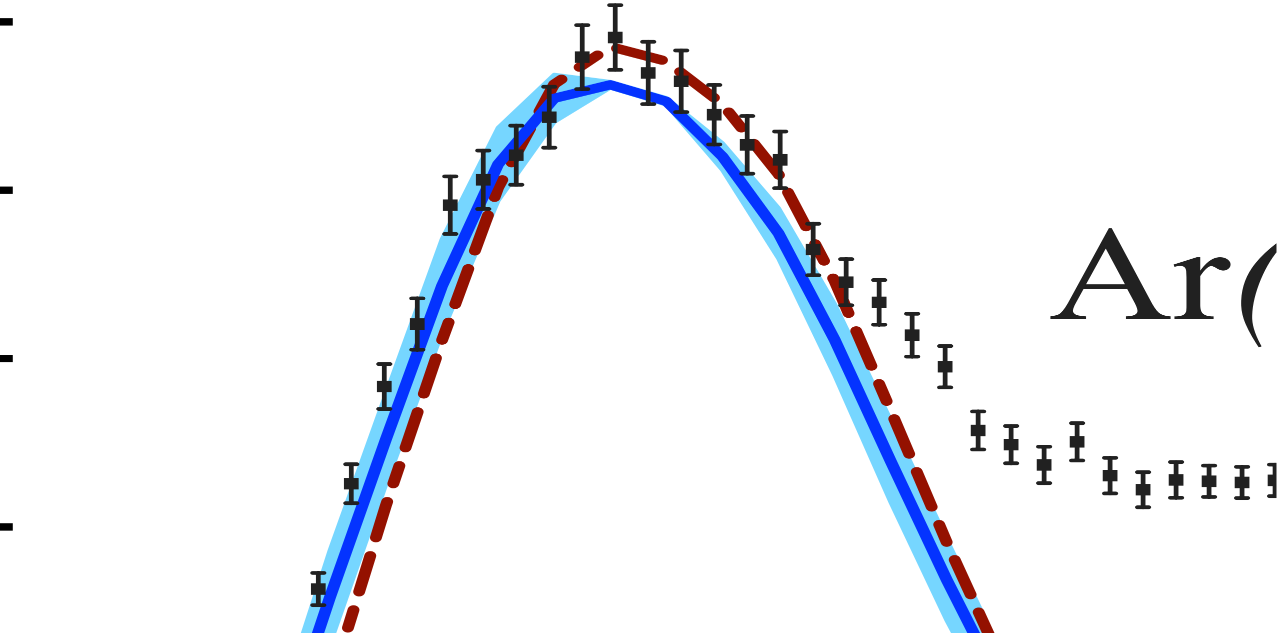

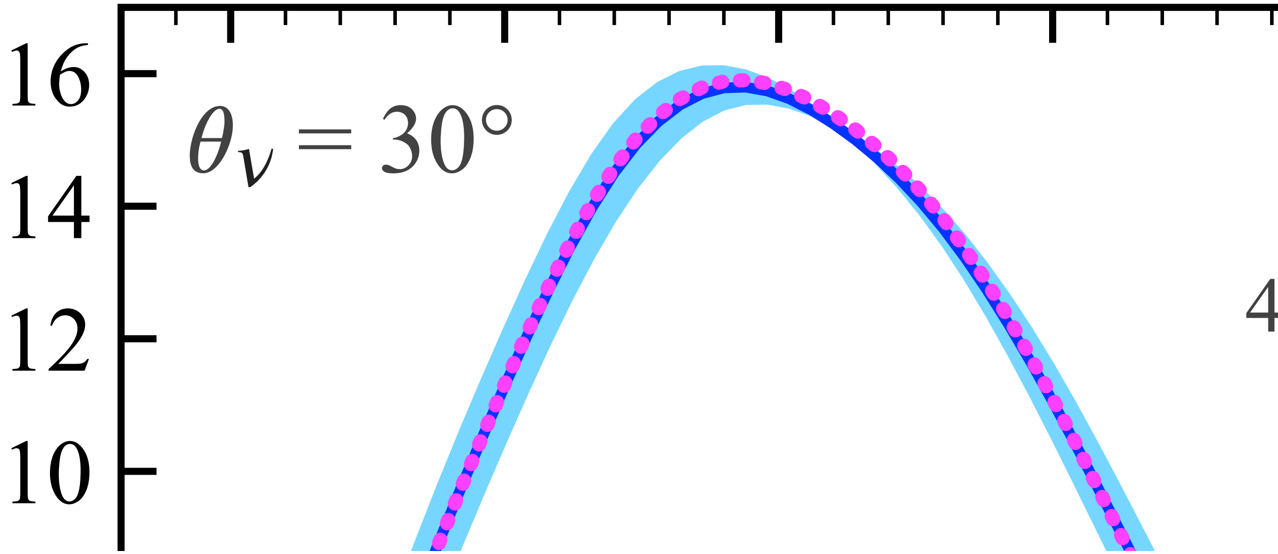

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CB, N. Rocco, V. Somà, arXiv:1907.01122

Neutrino transport in dense matter – supernovae and proton-neutron stars

A. Rios, S. Reddy, CB, *work in progress…*

Neutrino propagation in dense matter

Kinematical constraint

$$E_n(|\vec{k}\,|) - E_p(|\vec{k} + \vec{q}\,|) = -\omega$$

Non-interacting

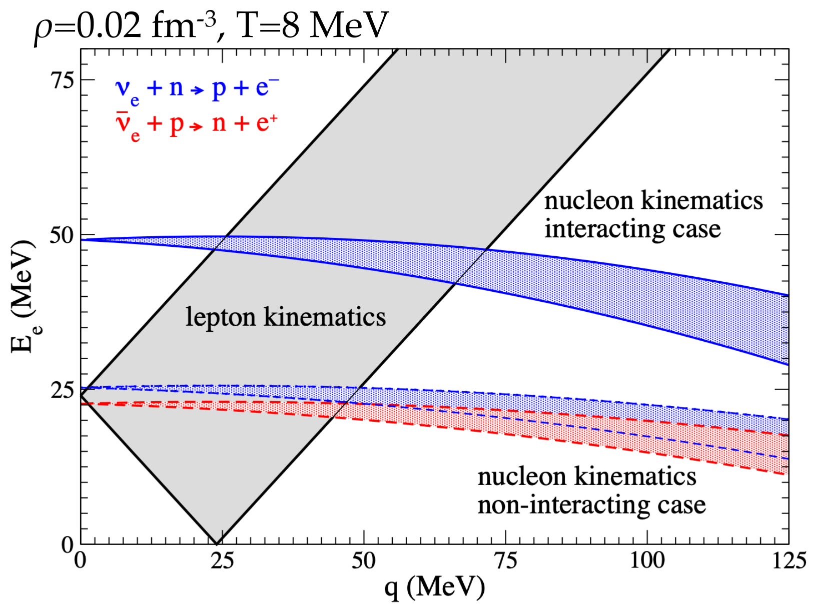
$$E_\tau(|\vec{k}\,|) = M_\tau + \frac{k^2}{2M_\tau}$$

Interacting quasi-particle

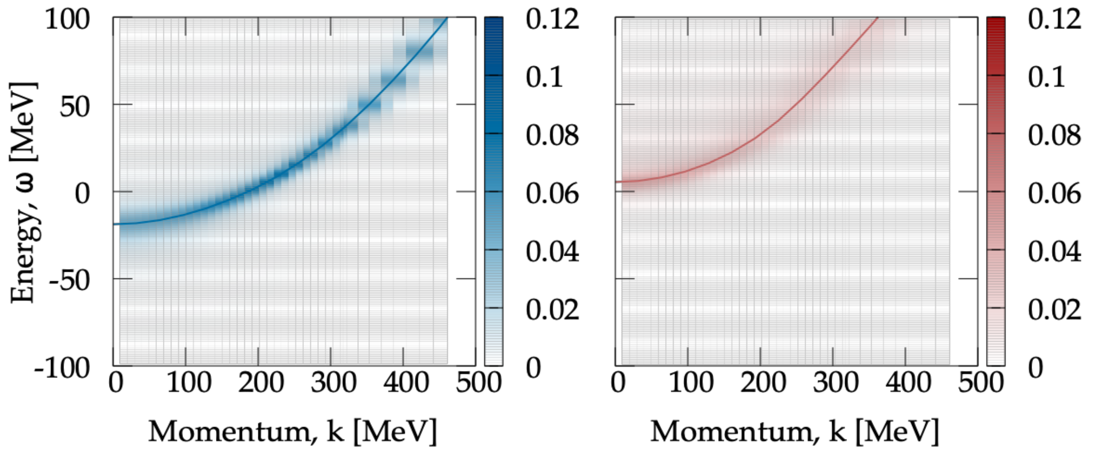
$$E_\tau(|\vec{k}\,|) = M_\tau + \frac{k^2}{2M_\tau} + \Sigma_\tau(k)$$

$$\Sigma_n(k) - \Sigma_p(k) \simeq 30$$

Fragmented strength?



Rrapaj Holt, Bartl, Reddy & Schwenk, *PRC 91 035806 (2015)*



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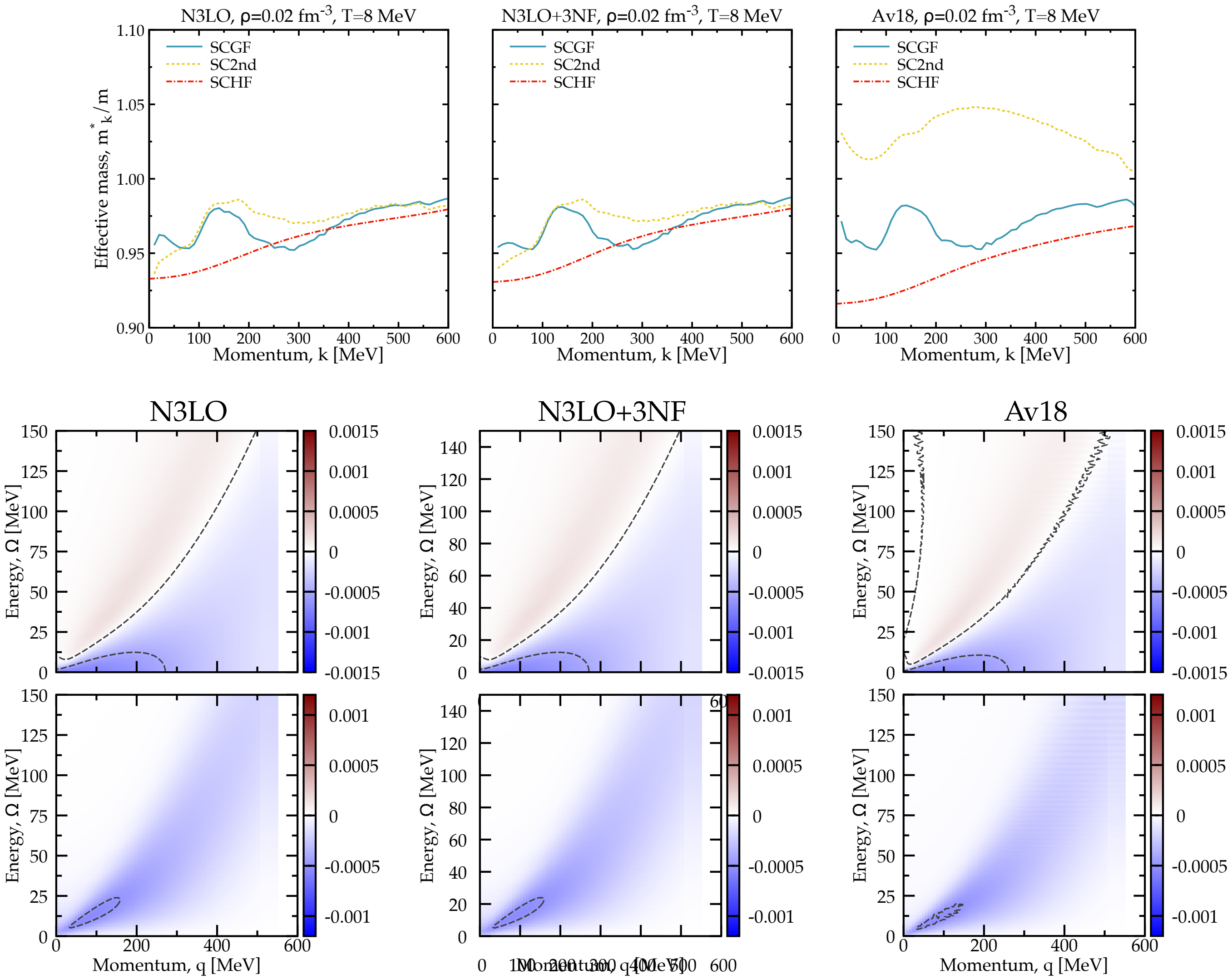
Neutrino propagation in dense matter

Effective masses:

(dependence of the modelling of the nuclear force…)

Response funtions:



Very preliminary computations, by A. Rios

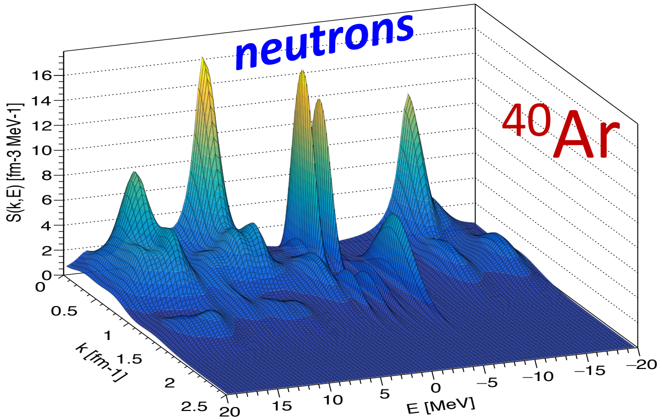
Summary

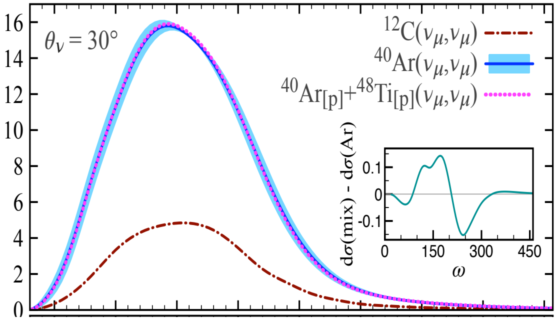
Thank you for your attention!!!

Ab initio computations for nuclear structure

→ *Strong link to underlying QCD thorugh EFT-inspiered Hamiltonians*

→ *Ground state properties up to masses A~100 now with high accuracy; spectral distributions becoming available…*





Applications to electron and neutrino scattering:

→ *Good reproduction of charge/momentum distribution and electron scattering.*

→ *Inclusion of electroweak currents (1b and 2b) underway (by N. Rocco).*

→ *Validation of nuclear structure input from ^{40}Ar and Ti data from Jlab.*

Neutrino propagation in dense matter

UNIVERSITY OF SURREY — A. Rios

V. Somà

A. Lovato, **N. Rocco**

ECT* — **A. Carbone**

INSTITUTE for NUCLEAR THEORY — S. Reddy

SAPIENZA UNIVERSITÀ DI ROMA — O. Benhar