Beta-decay strengths of neutron-rich nuclei relevant for astrophysics

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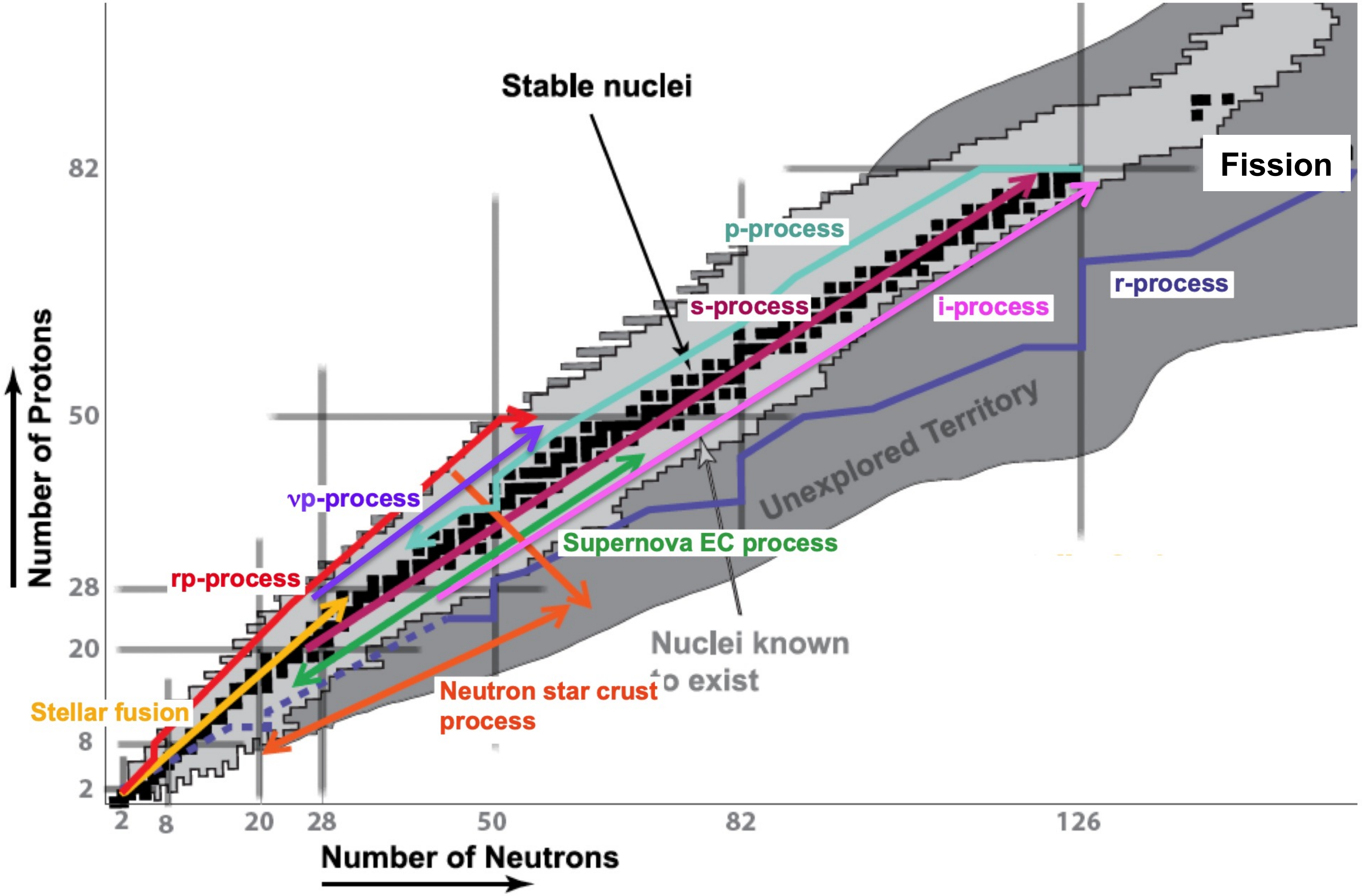
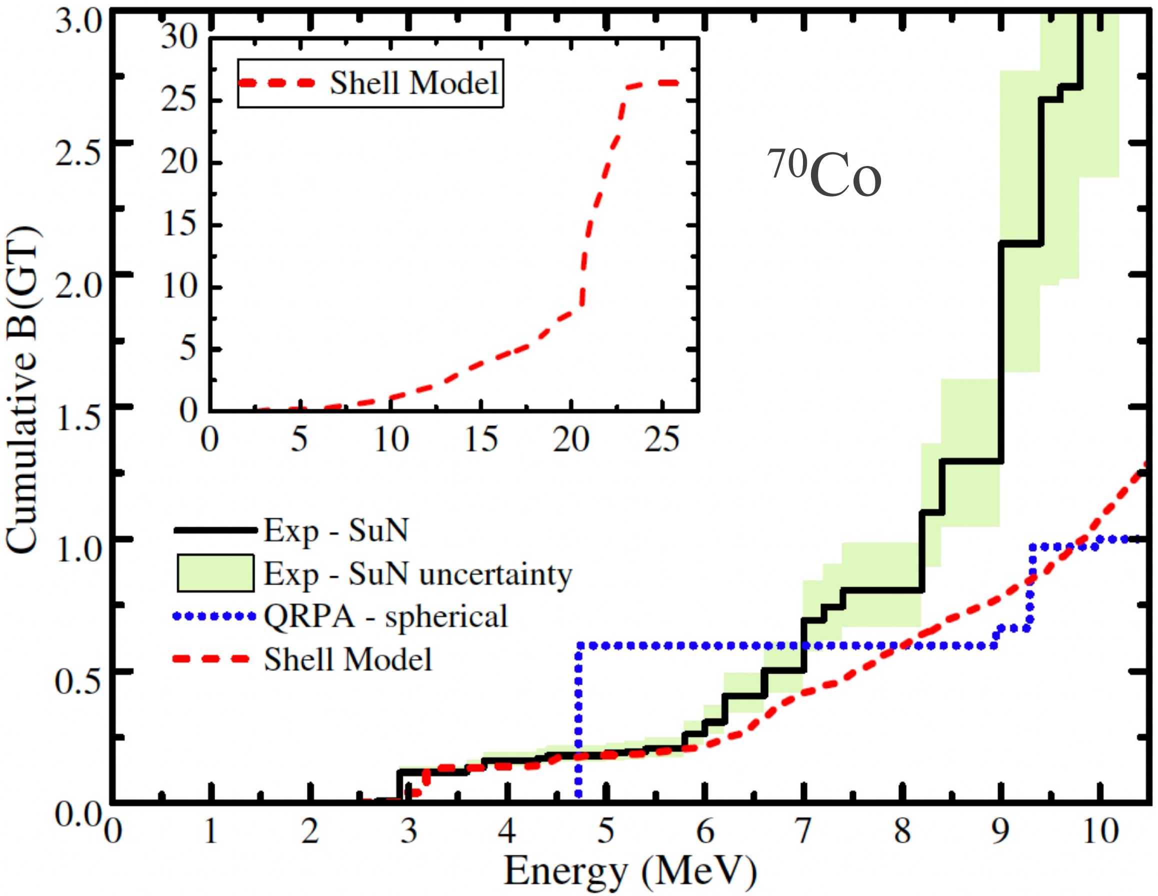
Our understanding of nucleosynthesis relies on nuclear structure properties



Hendrik Schatz, *J. Phys. G: Nucl. Part. Phys.* **43** 064001 (2016)

What are experimental data telling us?

A. Spyrou et al, PRL 117, 142701 (2016).



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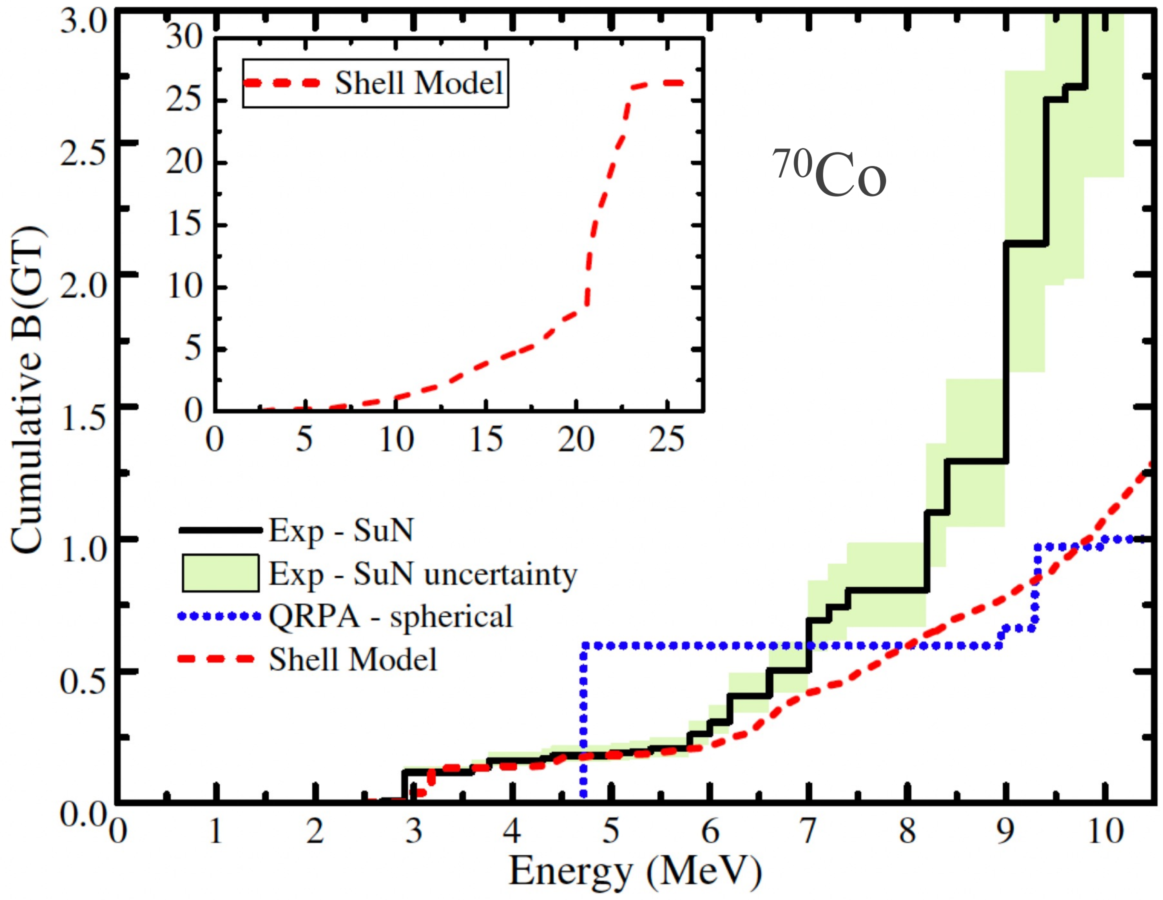
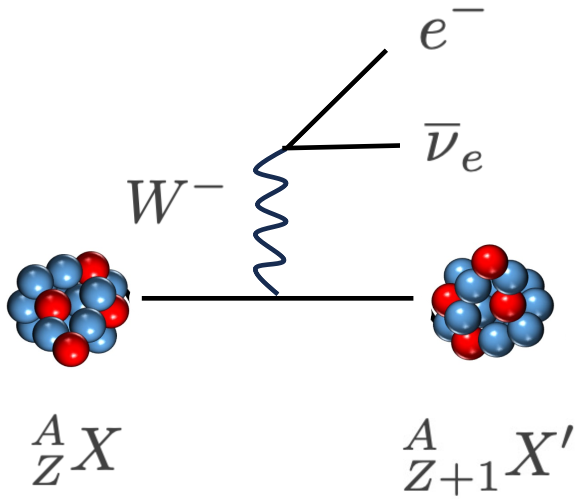


New experiments planned for ^{76,80}Ni

Gamow-Teller response functions

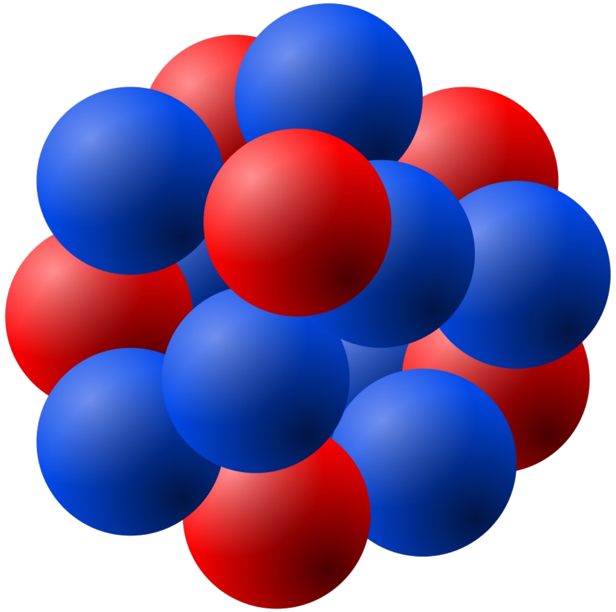
$$R(\omega) = \sum\!\!\!\!\!\!\int_f |\langle \Psi_f|\hat{\Theta}|\Psi_0\rangle|^2 \delta(E_f - E_0 - \omega)$$



$$\hat{\Theta} = \sigma\tau^{\pm}$$

Gamow-Teller operator

Ab initio nuclear theory



- ❑ Building blocks: protons and neutrons.
- ❑ Solve quantum many-body problem

$$H\left|\psi\right\rangle = E\left|\psi\right\rangle$$
$$H = T + V_{NN} + V_{3N}$$

with controlled approximations.

- ❑ 2 ingredients: nuclear interactions from chiral effective field theory and many-body solver.

Coupled-cluster theory

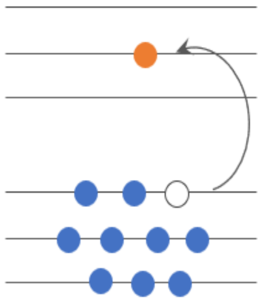
- Starting point: Hartree-Fock reference state $|\Phi_0\rangle$
- Add correlations via:

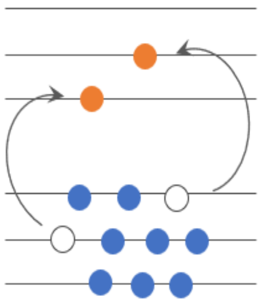
$$|\Psi_0\rangle = e^{T}|\Phi_0\rangle$$

with

$$T = \sum t_i^a a_a^\dagger a_i + \sum t_{ij}^{ab} a_a^\dagger a_b^\dagger a_j a_i + \ldots$$

singles and doubles (CCSD)

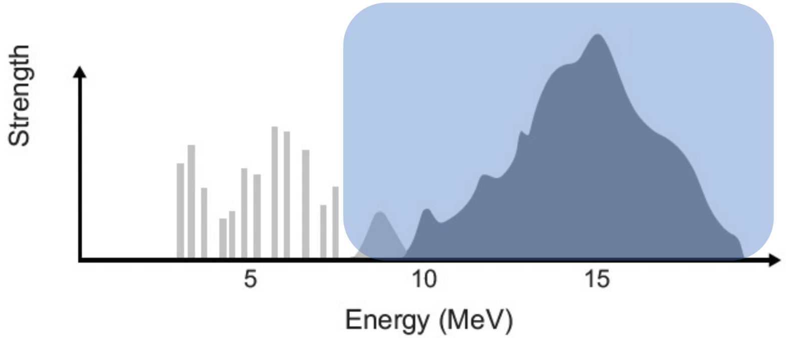




G. Hagen, T. Papenbrock, M. Hjorth-Jensen, D. J. Dean, RPP 77, 096302 (2014).

From bound states to the continuum

$R(\omega)$

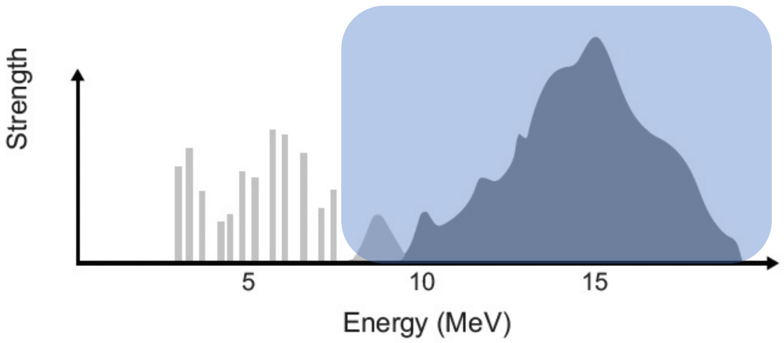


Continuum problem

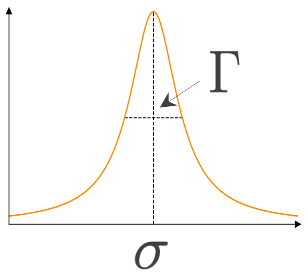
S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock, PRL **111**, 122502 (2013).

From bound states to the response

$R(\omega)$



Continuum problem



Lorentz Integral Transform (LIT)

$$L(\sigma,\Gamma) = \frac{\Gamma}{\pi}\int d\omega \, \frac{R(\omega)}{(\omega-\sigma)^2+\Gamma^2}$$

can be obtained by solving a
bound-state like problem

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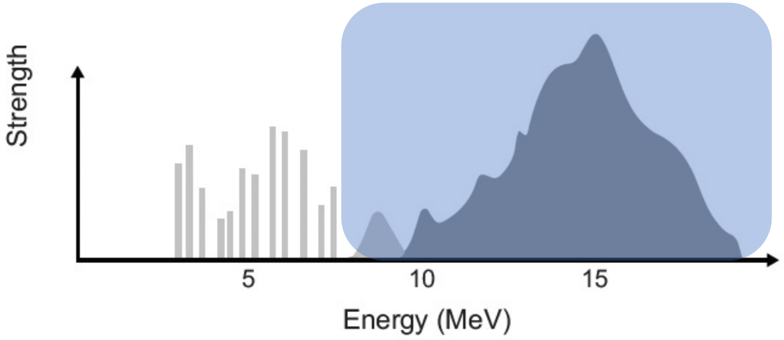

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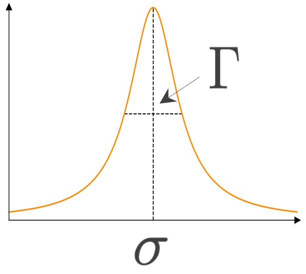


Lorentz Integral Transform (LIT)

$$L(\sigma, \Gamma) = \frac{\Gamma}{\pi} \int d\omega \, \frac{R(\omega)}{(\omega - \sigma)^2 + \Gamma^2}$$

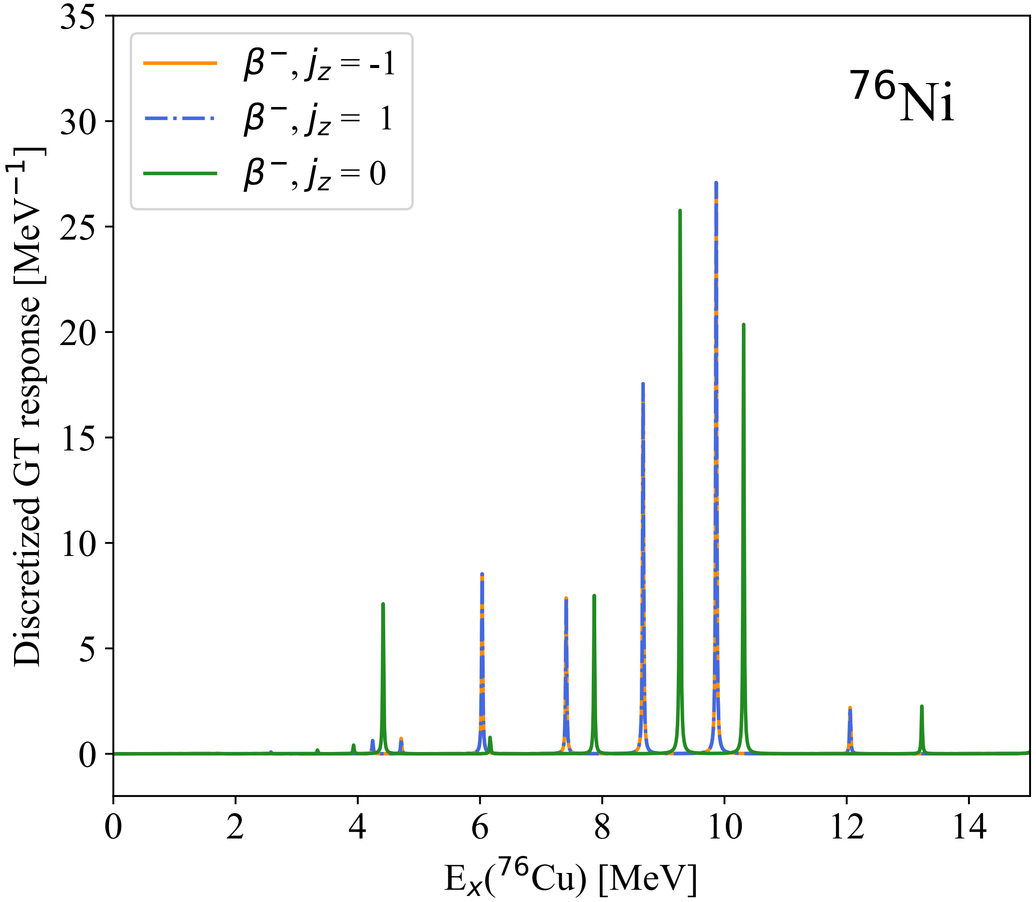
can be obtained by solving a bound-state like problem

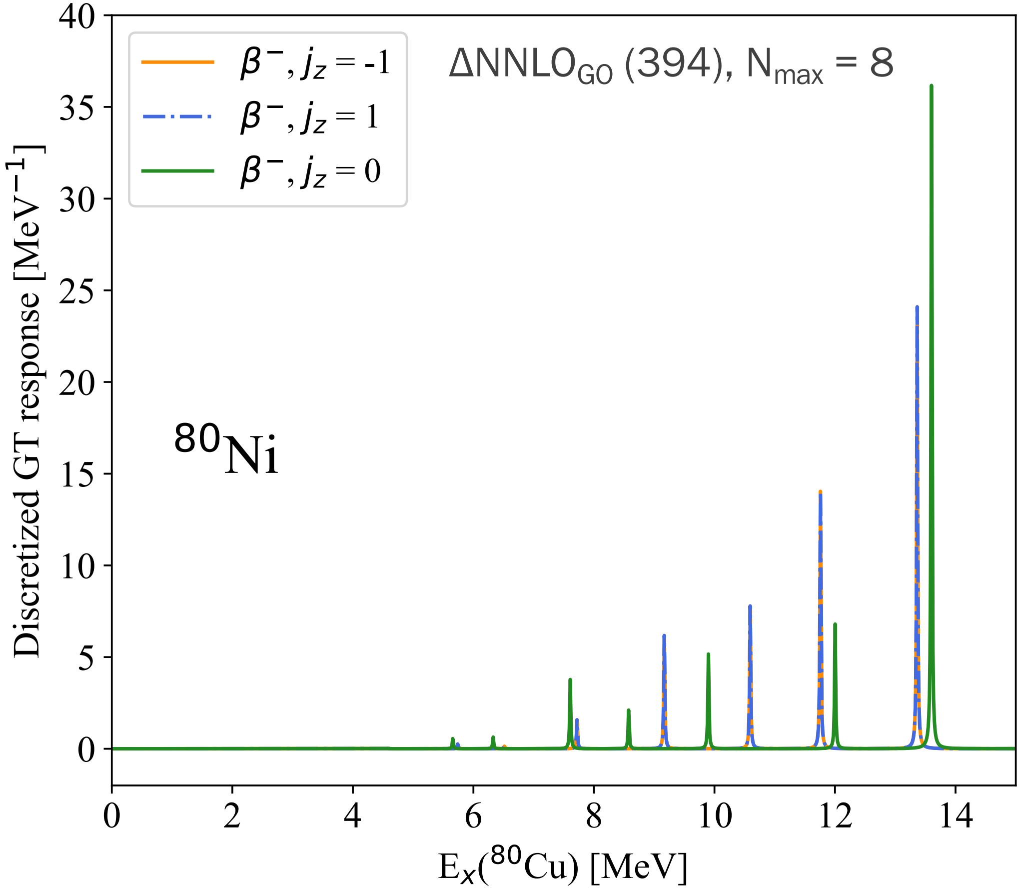
- ❑ For closed-shell nuclei, we start from a spherical reference.
- ❑ For open-shell nuclei, as in the case of ^{76,80}Ni, we can break rotational invariance and use an axially-symmetric reference state.

S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock, PRL **111**, 122502 (2013).

Gamow-Teller response in ^{76,80}Ni

GT: J^{π} = 1+, but angular momentum not conserved → look at results with different j_z



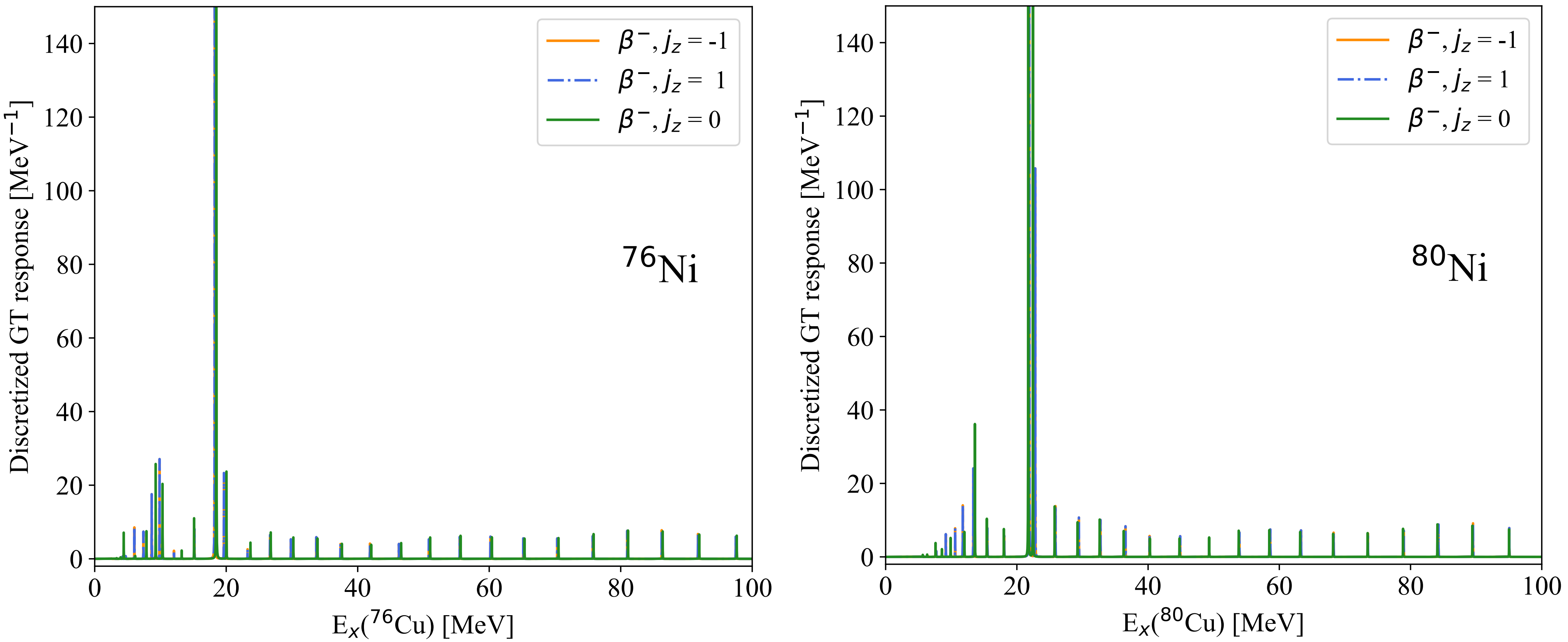


Preliminary

Gamow-Teller response in ^{76,80}Ni

Preliminary

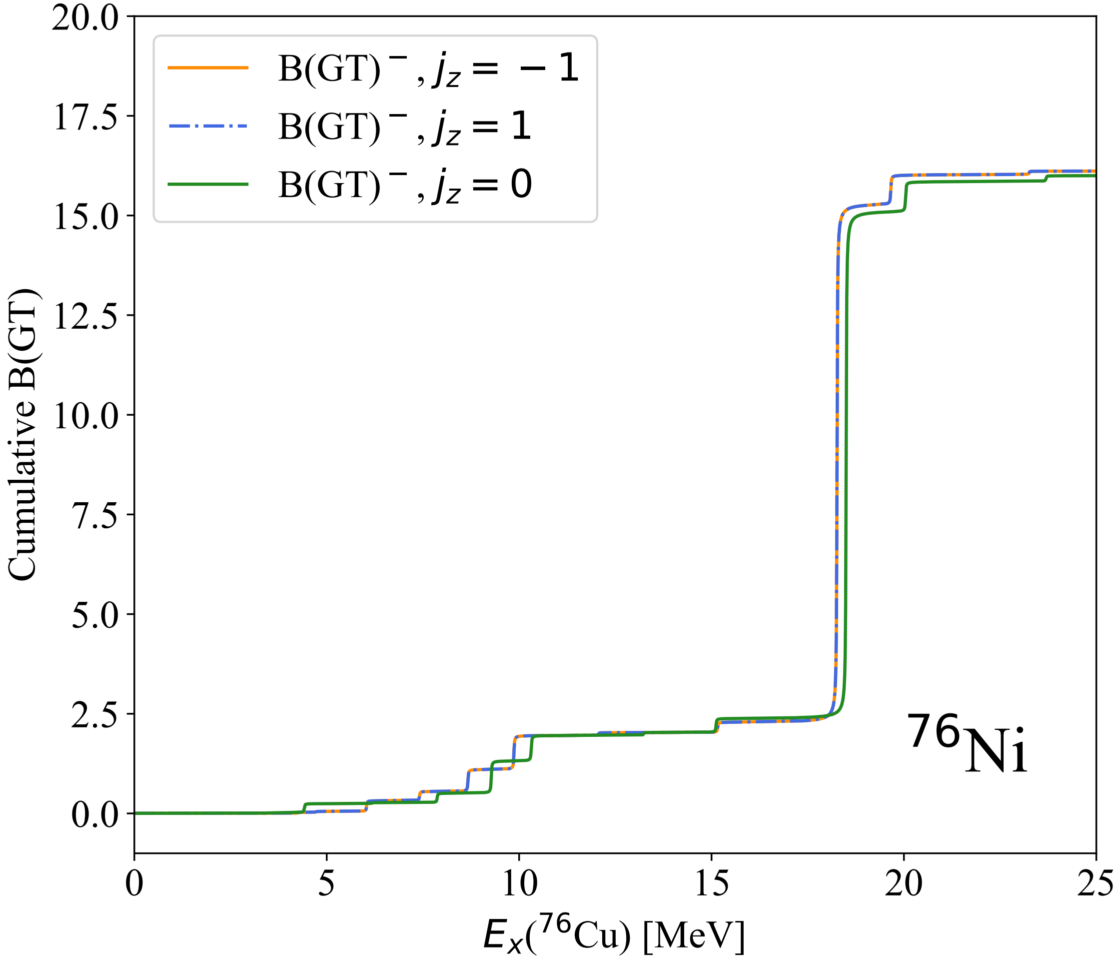
ΔNNLO$_{GO}$ (394), N_{max} = 8

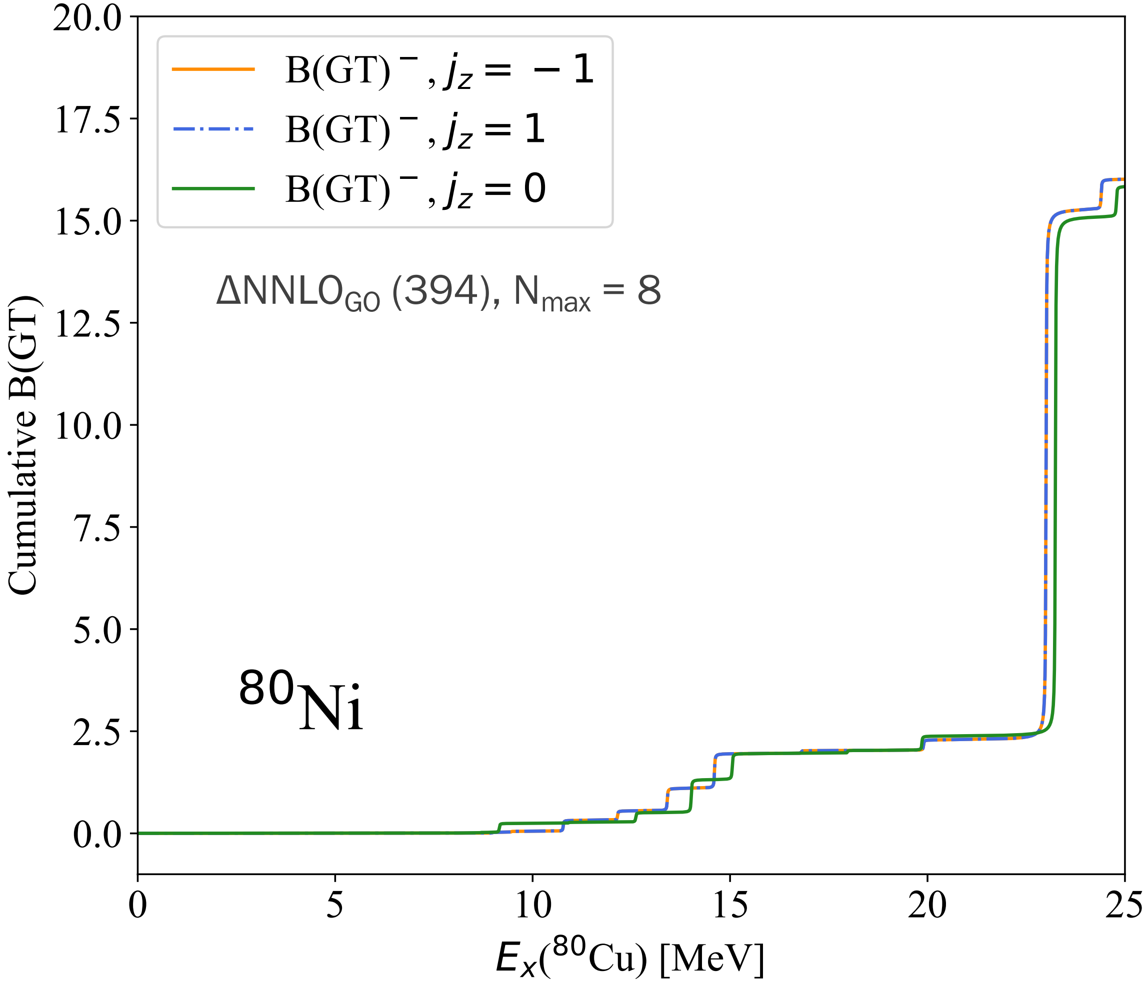


Main takeaway: **breaking rotational symmetry** impacts mostly **low-lying states**, at higher energies results with different j_z coincide.

B(GT) in ^{76,80}Ni

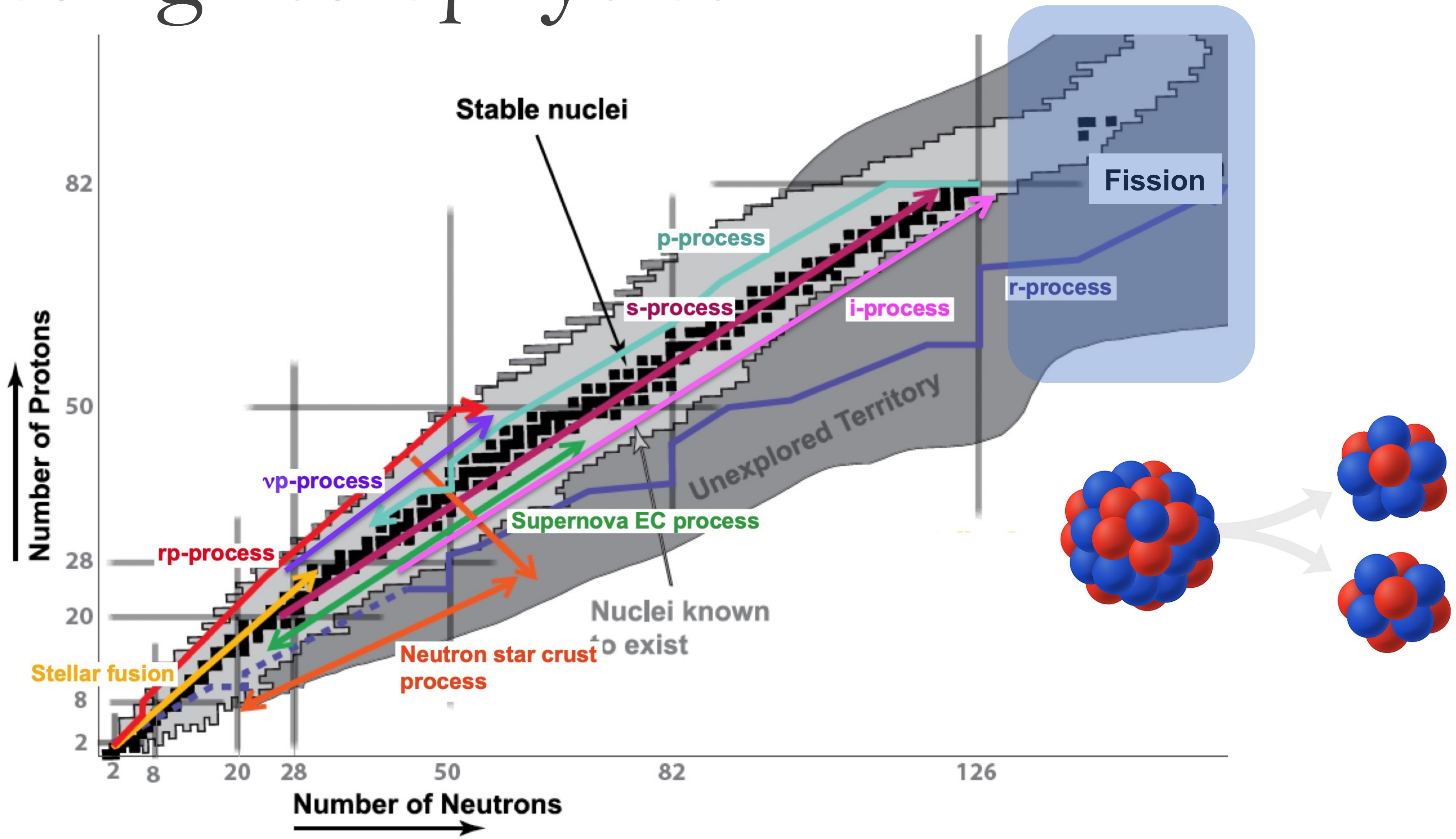
Preliminary





Small variations between different j_z results for B(GT).

There are other nuclear processes impacting astrophysics



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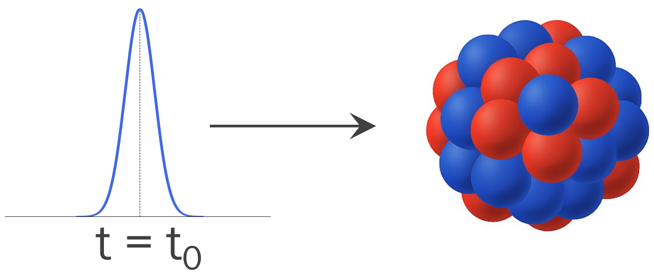
Responses in a time-dependent approach

Goal: solving

$$i\hbar \frac{d}{dt} |\Psi(t)\rangle = \hat{H}(t) |\Psi(t)\rangle$$



with

$$\hat{H}(t) = \hat{H}_0 + \epsilon f(t) \hat{D}$$

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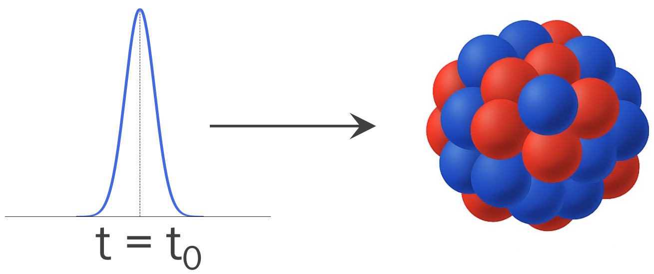


with

$$\hat{H}(t) = \hat{H}_0 + \epsilon f(t) \hat{D}$$

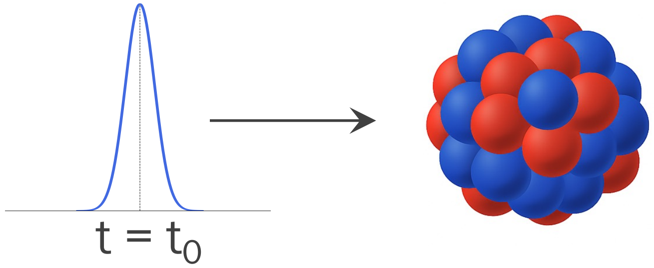
For small ε, first-order time-dependent perturbation theory yields:

$$D(t) = \langle \Psi(t) | \hat{D} | \Psi(t) \rangle$$

Responses in a time-dependent approach

Goal: solving

$$i\hbar\frac{d}{dt}|\Psi(t)\rangle = \hat{H}(t)\,|\Psi(t)\rangle$$



with

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For small ε, first-order time-dependent perturbation theory yields:

$$D(t) = \langle\Psi(t)|\hat{D}|\Psi(t)\rangle \longrightarrow \tilde{D}(\omega)$$

Fourier transform

Responses in a time-dependent approach

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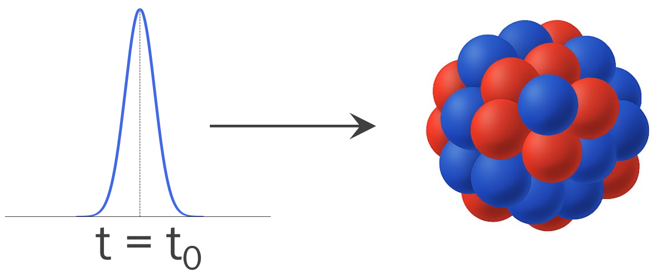
$$i\hbar\frac{d}{dt}\left|\Psi(t)\right\rangle = \hat{H}(t)\left|\Psi(t)\right\rangle$$



with

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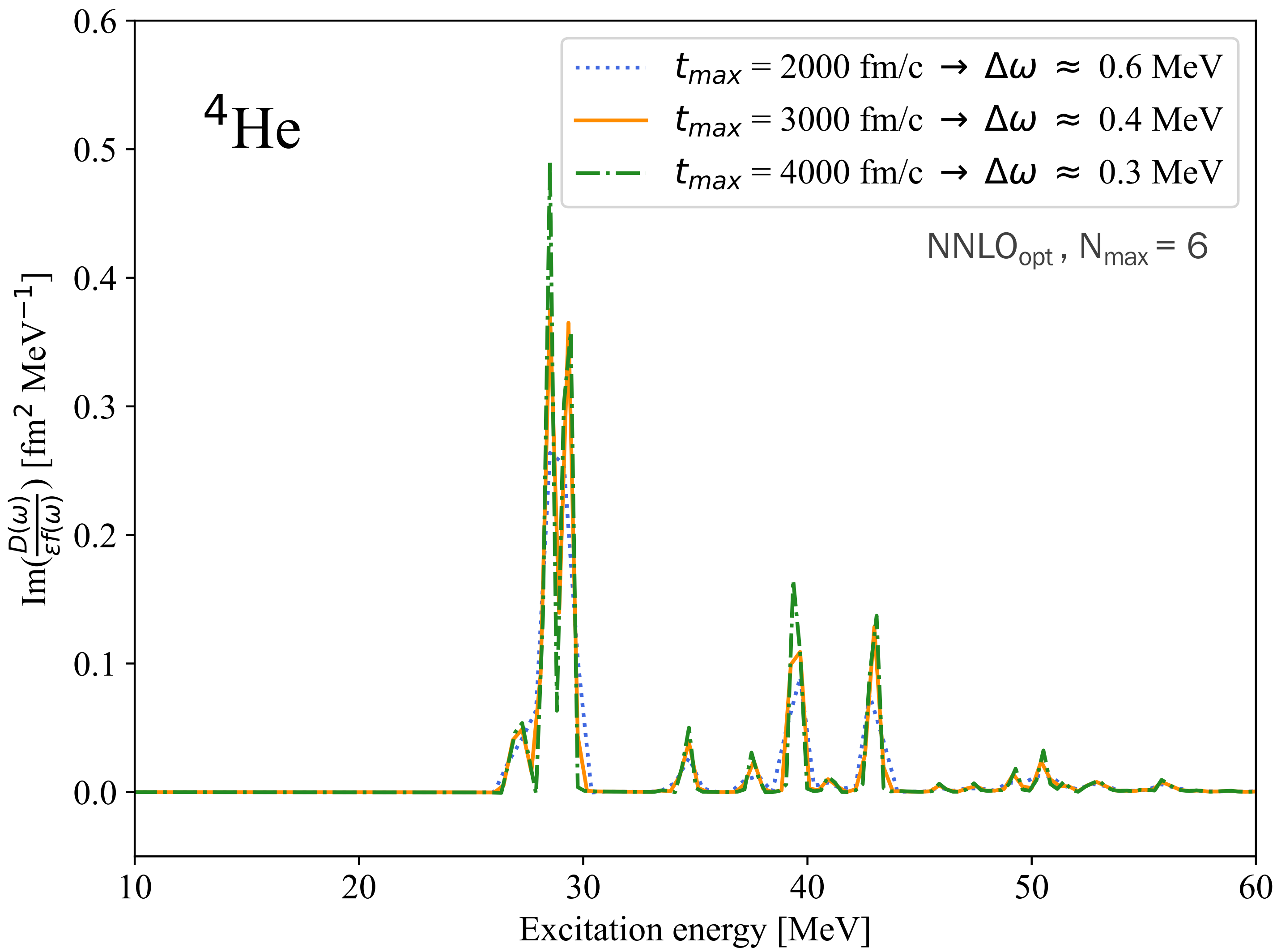
For small ε, first-order time-dependent perturbation theory yields:

$$D(t) = \langle\Psi(t)|\hat{D}|\Psi(t)\rangle \longrightarrow \tilde{D}(\omega) \longrightarrow R(\omega) = \mathrm{Im}\left(\frac{\tilde{D}(\omega)}{\epsilon\tilde{f}(\omega)}\right)$$

Fourier transform

Simulation time and resolution



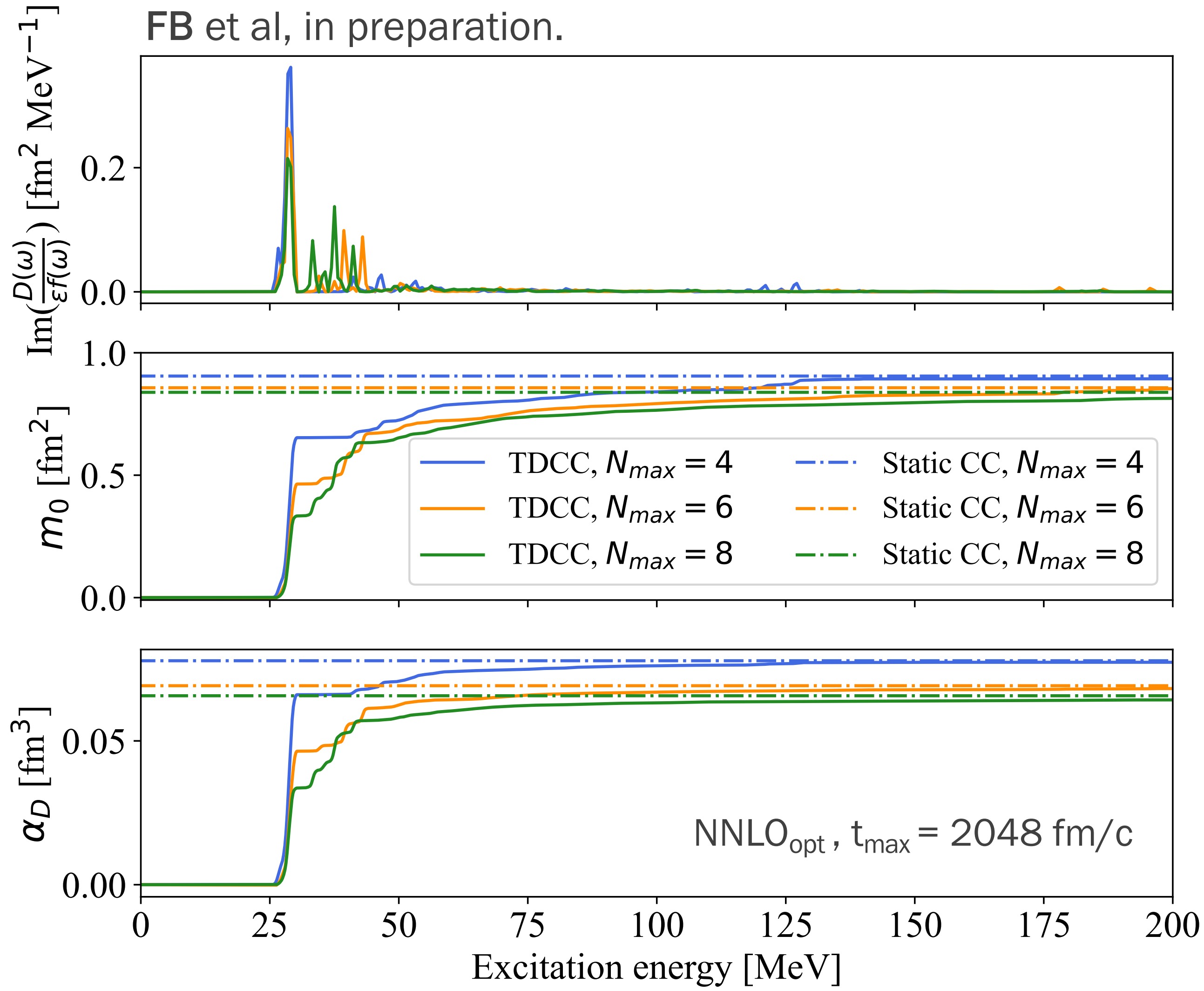
Resolution

$$\Delta\omega = \frac{2\pi\hbar c}{t_{max}}$$

Maximum simulation time

Static CC vs time-dependent CC: ^{4}He

FB et al, in preparation.



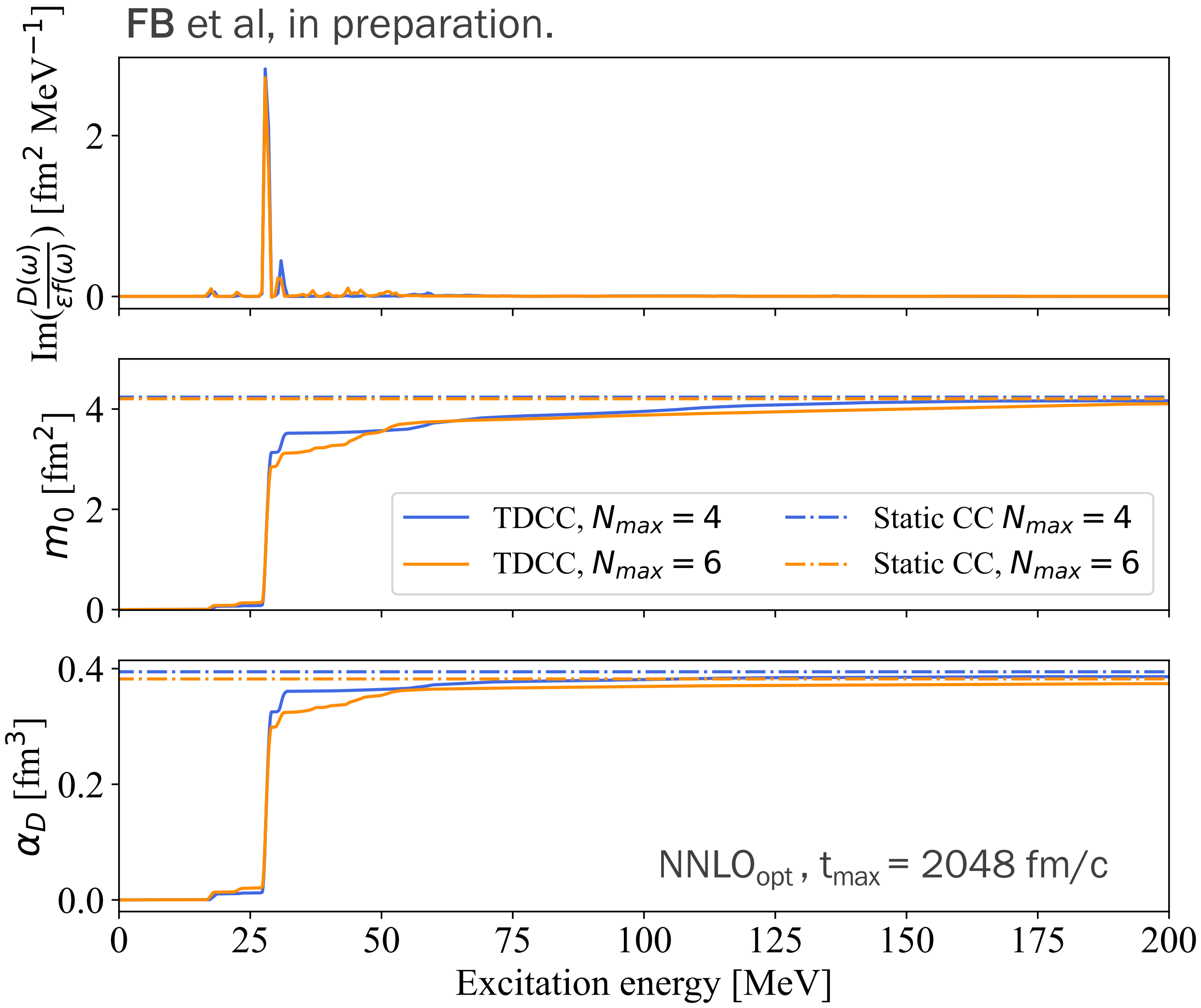
$$R(\omega) = \mathrm{Im}\left(\frac{\tilde{D}(\omega)}{\epsilon \tilde{f}(\omega)}\right)$$

$$m_0 = \int d\omega R(\omega)$$

$$\alpha_D = 2\alpha \int d\omega\, \omega^{-1} R(\omega)$$

Deviations of less than 1-2% between the two complementary approaches!

Static CC vs time-dependent CC: ^{16}O



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$$m_0 = \int d\omega R(\omega)$$

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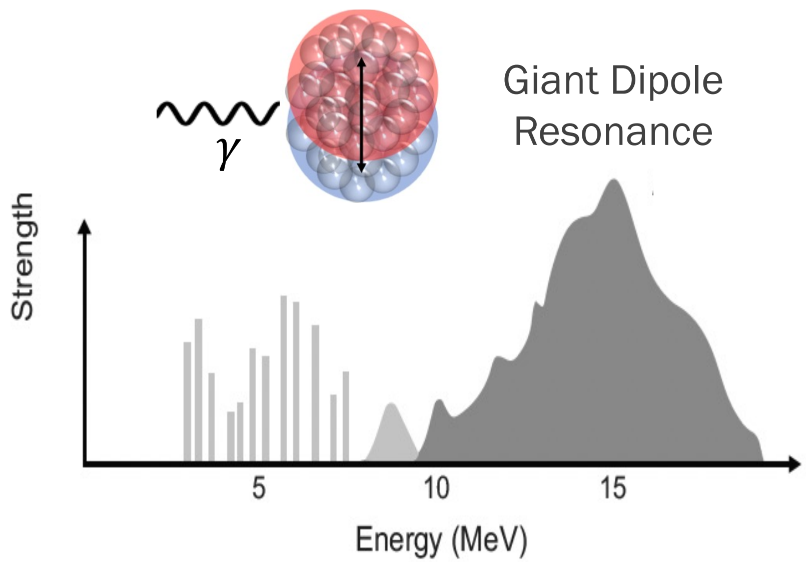
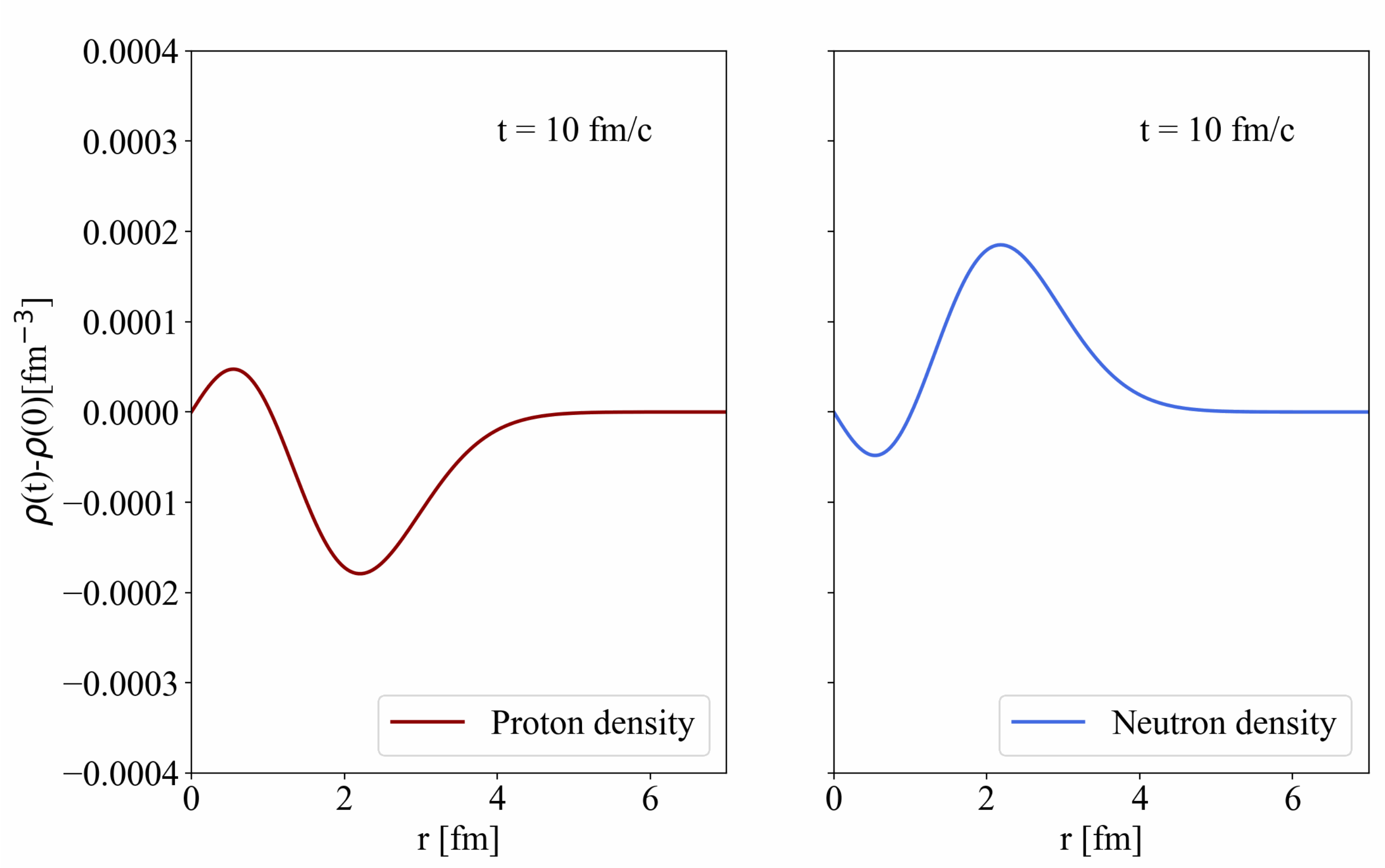
Very good agreement also for ^{16}O!

Collective oscillations in real time

^{16}O





FB et al, in preparation.

Conclusions

- We obtained preliminary results for Gamow-Teller responses in neutron-rich nickel isotopes, and we plan to explore the effect of two-body currents and work on a more accurate estimate of our theoretical uncertainty.

- We can describe nuclear responses in a time-dependent framework and we're working on different strategies to optimize it (natural orbital basis + adapting solver to GPUs + emulators…) for applications to non-linear problems and reactions in the long term.

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