TRIUMF

Canada's national laboratory for particle and nuclear physics
Laboratoire national canadien pour la recherche en physique nucléaire
et en physique des particules

# Dipole Strength from Coupled Cluster Theory

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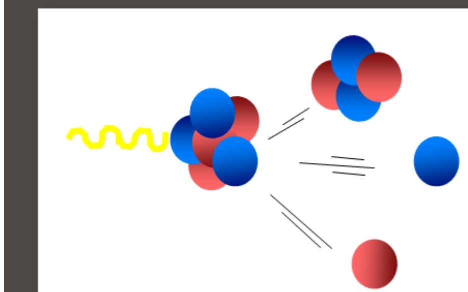
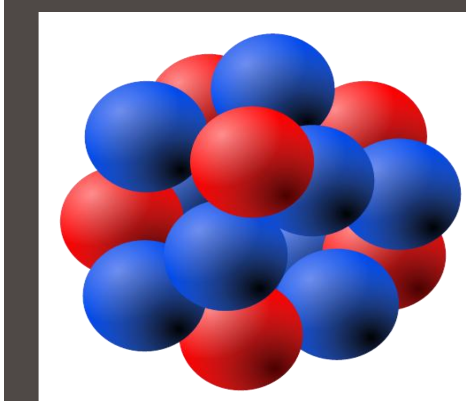
**Collaborators:**
**S. Bacca, N. Barnea, G. Hagen, G. Orlandini, T. Papenbrock**

**February 19th , 2015**

a place of mind
THE UNIVERSITY OF BRITISH COLUMBIA



*Nuclear Reactions*



$^{16,22}O,\ ^{40,48}Ca$

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# Electromagnetic (EM) Reactions

Small coupling constant $\alpha \ll 1$ → Perturbative treatment

"*With the electro-magnetic probe, we can immediately relate the cross section to the transition matrix element of the current operator, thus to the structure of the target itself* "

[De Forest-Walecka, Ann. Phys. 1966]

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[De Forest-Walecka, Ann. Phys. 1966]

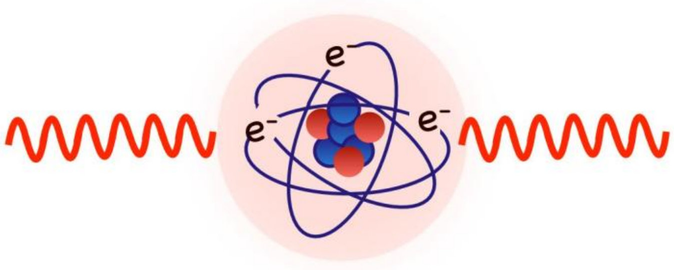
Probing the nuclear structure...

→ Photo-absorption reactions

→ Coulomb excitation reactions

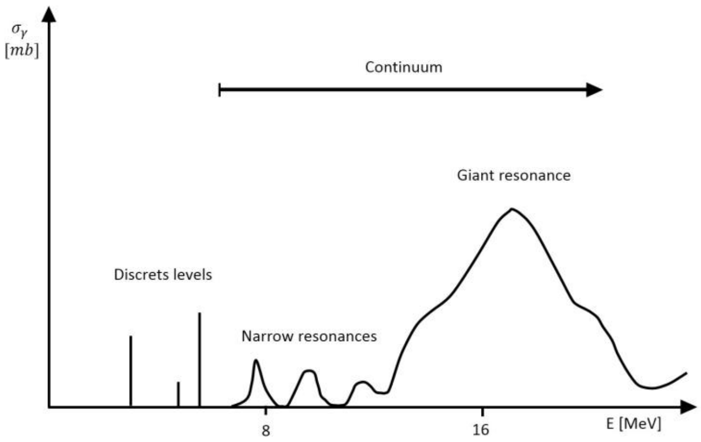
# EM Reactions: Photo-absorption

Interaction of a (real, low-energy) photon with a nucleus.



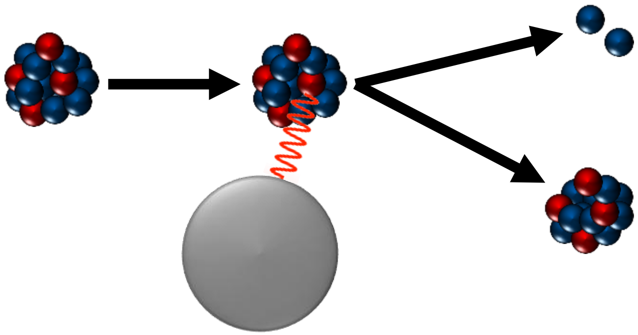

## Giant Dipole Resonance (GDR)

- Observed across all the periodic table
- The peak is localized between 10-30MeV, the position changes with the mass number



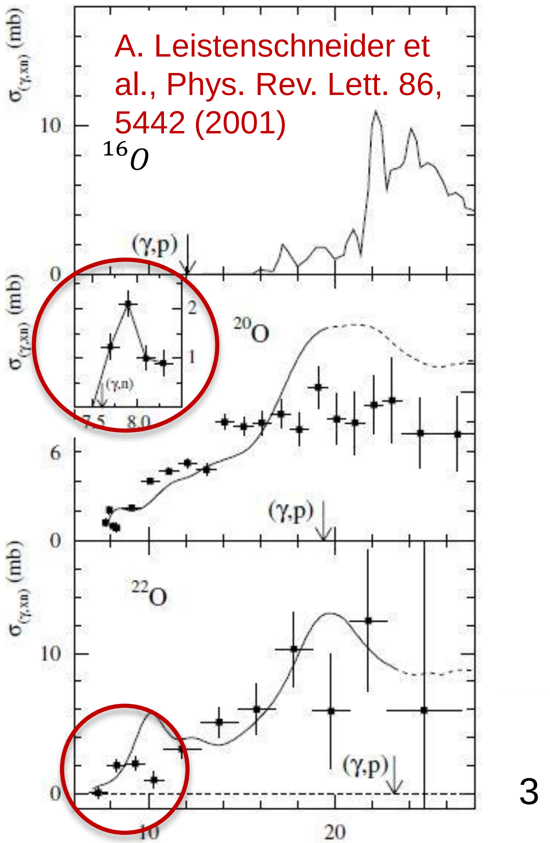
# EM Reactions: Coulomb excitation

Inelastic scattering between two charged particles (exchange of a virtual photon).



## Pigmy Dipole Resonance (PDR)

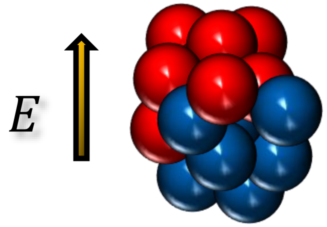
- Unstable nuclei can be used as projectiles
- Neutron-rich nuclei show fragmented low-lying strength (soft modes)



# Electric Dipole Polarizability

It is obtained from the dipole strength $R(\omega)$ as
an inverse weighted sum-rule

- So far no *ab-initio* description for medium mass nuclei
- Correlated with radii
- Used to constrain EOS in neutron stars




$$D = \alpha_D E$$

$$\alpha_E = 2\alpha \int \frac{R(\omega)}{\omega} d\omega$$

Extremely interesting in neutron-rich nuclei: the soft modes at low energy enhance the electric dipole polarizability

# Theoretical Approach

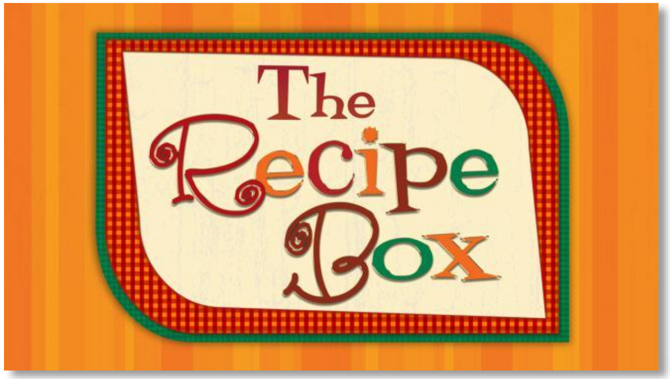
Current situation on the theoretical description:

- **Non-ab-initio**: via macroscopic models or mean field based methods
- **Ab-initio**: described via exact computations for light nuclei using the LIT+EIHH method (up to $A = 7$)

$\rightarrow$ need of a new approach for larger nuclei

What ingredients and tools do we need?

- **Continuum problem** $\rightarrow$ LIT
- **Many-body technique** $\rightarrow$ CC
- **Nuclear interactions** $\rightarrow$ $\chi$EFT



# LIT Method

## The response function $R(\omega)$ is the key quantity

$$\sigma_\gamma(\omega) = 4\pi^2 \alpha \omega R(\omega)$$

$$\alpha_D = 2\int d\omega \frac{R(\omega)}{\omega}$$

$$R(\omega) = \sum\!\!\!\!\!\!\int_f |\langle f|\hat{\theta}|i\rangle|^2 \delta(E_f - E_i - \omega)$$

- Final states problem is tackled with the Lorentz Integral Transform (LIT) method

$$L(\omega_0, \Gamma) = \frac{\Gamma}{\pi}\int d\omega \frac{R(\omega)}{(\omega_0 - \omega)^2 + \Gamma^2}$$

where $(H - E_i + \sigma)|\tilde{\psi}\rangle = \theta|i\rangle$ and $\sigma = -\omega_0 - i\Gamma$

$$L(\sigma) = \frac{\Gamma}{\pi}\langle i|\theta^+(H - E_i + \sigma^*)^{-1}(H - E_i + \sigma)^{-1}\theta|i\rangle = \langle\tilde{\psi}|\tilde{\psi}\rangle < \infty$$

- The exact final state interaction is included in the continuum rigorously!

$$L(\sigma) \xrightarrow{Inversion} R(\omega)$$

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# CC Theory

- Continuum problem → Bound state problem

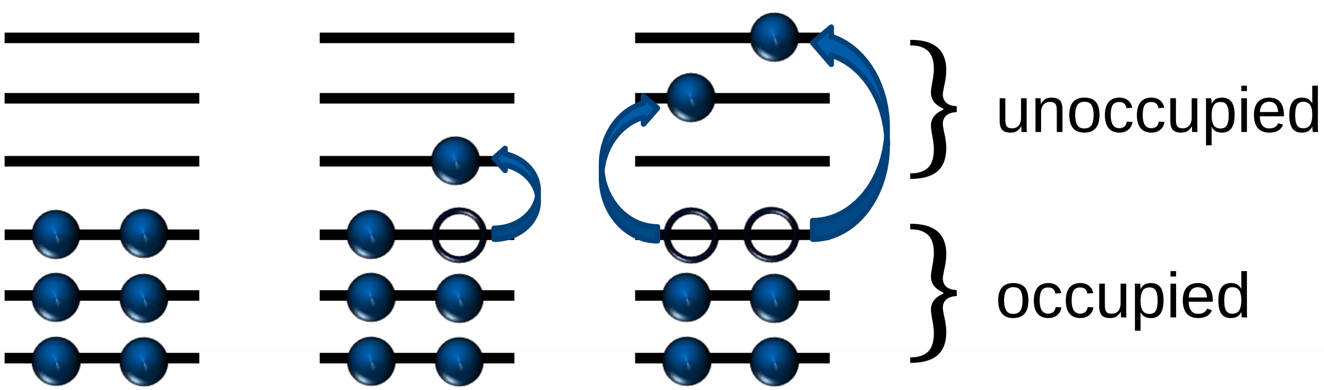
$$L(\sigma) = \frac{\Gamma}{\pi}\langle i|\theta^{+}(H - E_i + \sigma^*)^{-1}(H - E_i + \sigma)^{-1}\theta|i\rangle = \langle\,\tilde{\psi}|\tilde{\psi}\rangle$$

- Computation of the ground state → **Coupled Cluster (CC) theory**

$$|i\rangle = e^{T}|0\rangle$$

$$\mathrm{T} = \sum_{n=1}^{A} T_n$$

$$T_n = \frac{1}{(n!)^2}\sum_{\substack{a_1,a_2,\ldots,a_n\\ i_1,i_2,\ldots,i_n}} t^{a_1 a_2 \ldots, a_n}_{i_1 i_2 \ldots i_n}\{a_1^{+} i_1 a_2^{+} i_2 \ldots a_n^{+} i_n\}$$



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# LIT + CC-EOM

- Similarity transformed operators and LIT-CC equations

$$(H - E_i + \sigma)|\tilde{\psi}\rangle = \theta|i\rangle \quad \xrightarrow{\bar{O} = e^{-T} O e^{T}} \quad \begin{array}{l} (\bar{H} - E_i + \sigma)|\tilde{\psi}_R(\sigma)\rangle = \bar{\theta}|0_R\rangle \\ \langle\tilde{\psi}_L(\sigma^*)|(\bar{H} - E_i + \sigma^*) = \langle 0_L|\bar{\theta} \end{array}$$

- Equation of motion (EOM) Coupled Cluster

$$|\tilde{\psi}_R(\sigma)\rangle = \hat{R}(\sigma)|0_R\rangle = \left(r_0(\sigma) + \sum_{ia} r_i^a(\sigma)\hat{c}_a^\dagger \hat{c}_i + \sum_{ia} r_{ij}^{ab}(\sigma)\hat{c}_a^\dagger \hat{c}_b^\dagger \hat{c}_j \hat{c}_i + \cdots\right)|0_R\rangle$$

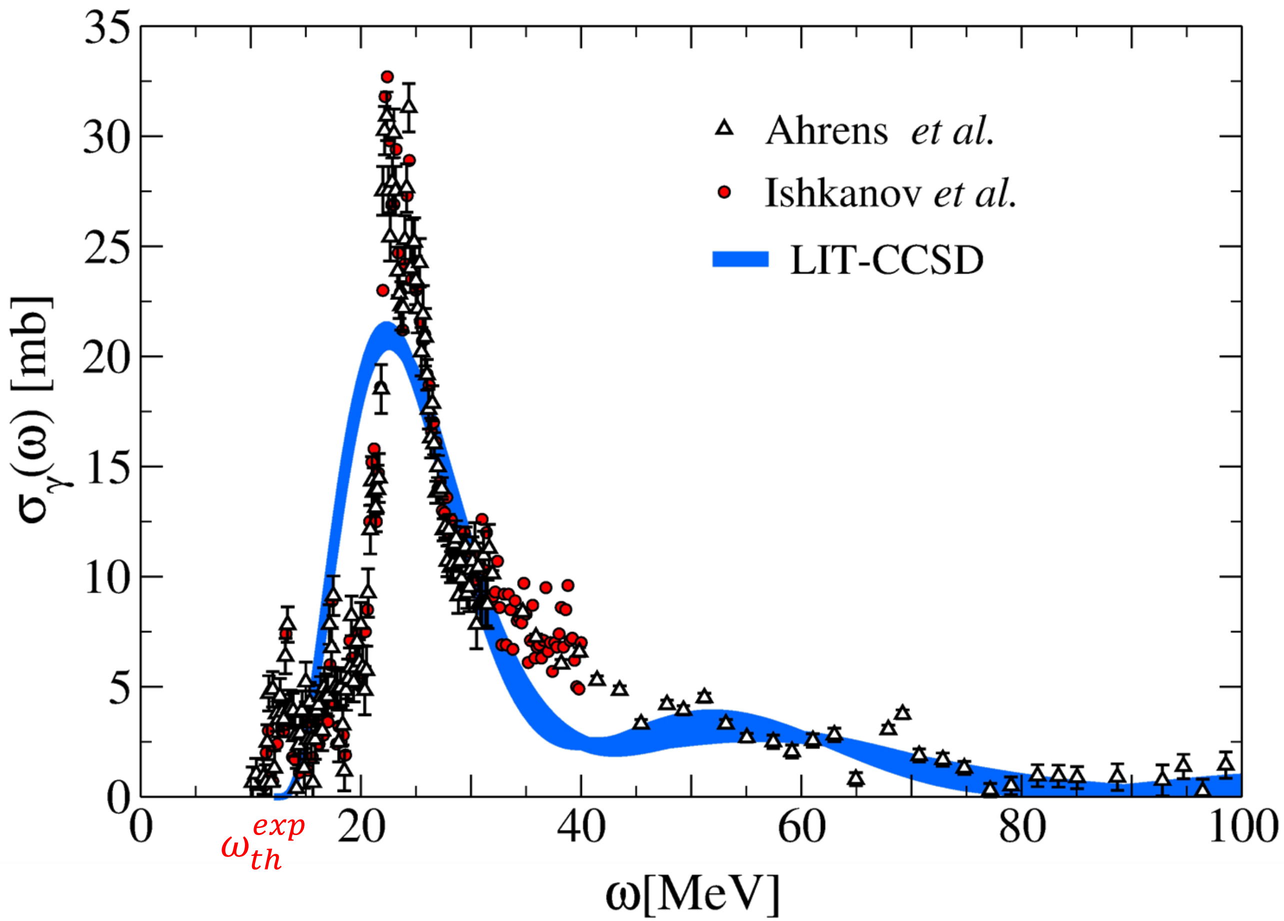
- The LIT becomes

$$L(\sigma) = -\frac{1}{2\pi} Im\left\{\langle 0_L \left|\bar{\theta}^\dagger \left(\hat{R}(\sigma^*) - \hat{R}(\sigma)\right)\right| 0_R\rangle\right\}$$

→ Solved using the Lanczos method

# The Oxygen Isotopes - $^{16}O$

S. Bacca, N. Barnea, G. Hagen, G. Orlandini and T. Papenbrock,
Phys. Rev. Lett. 111, 122502 (2013)




NN interaction at N3LO (EM) + CCSD

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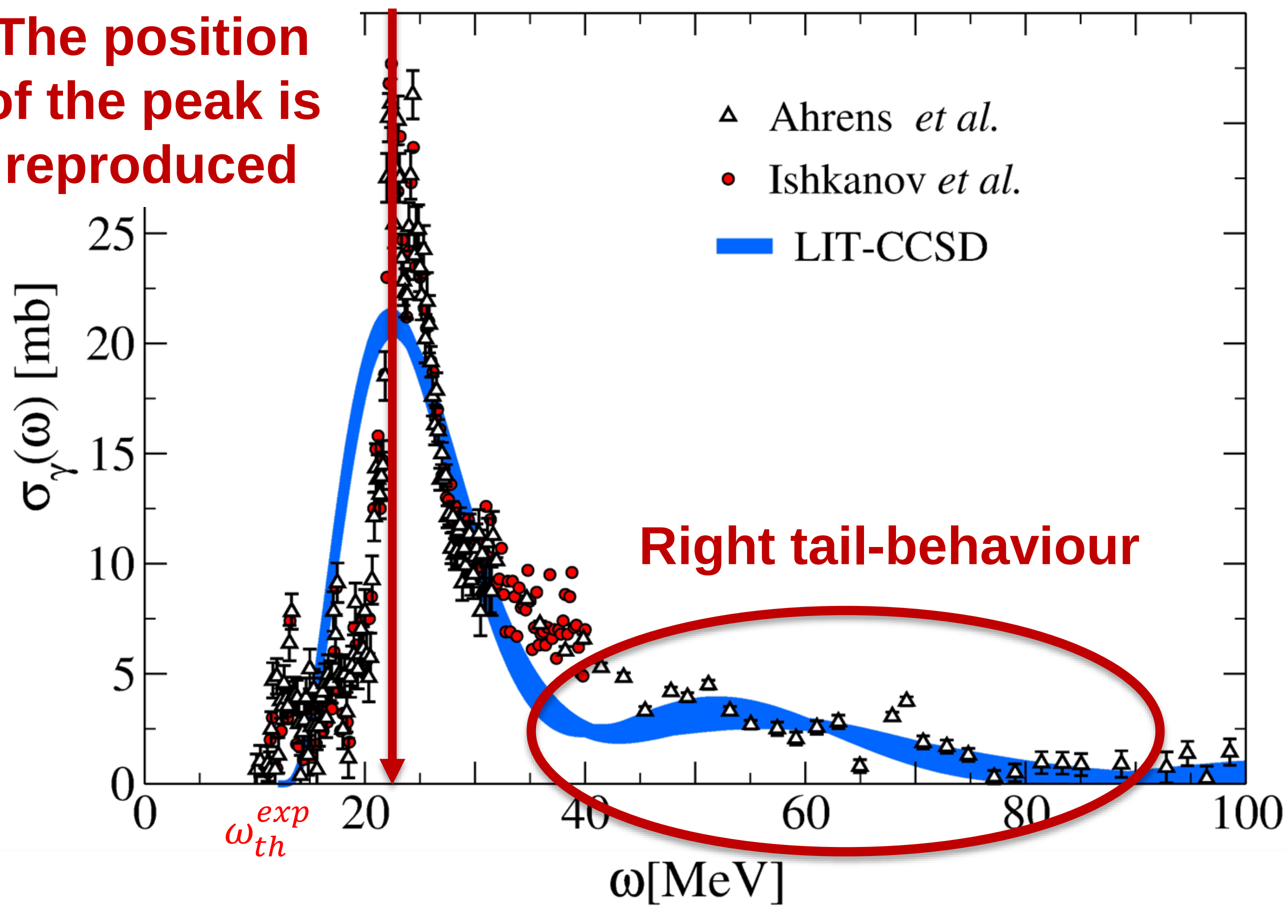
**The position of the peak is reproduced**

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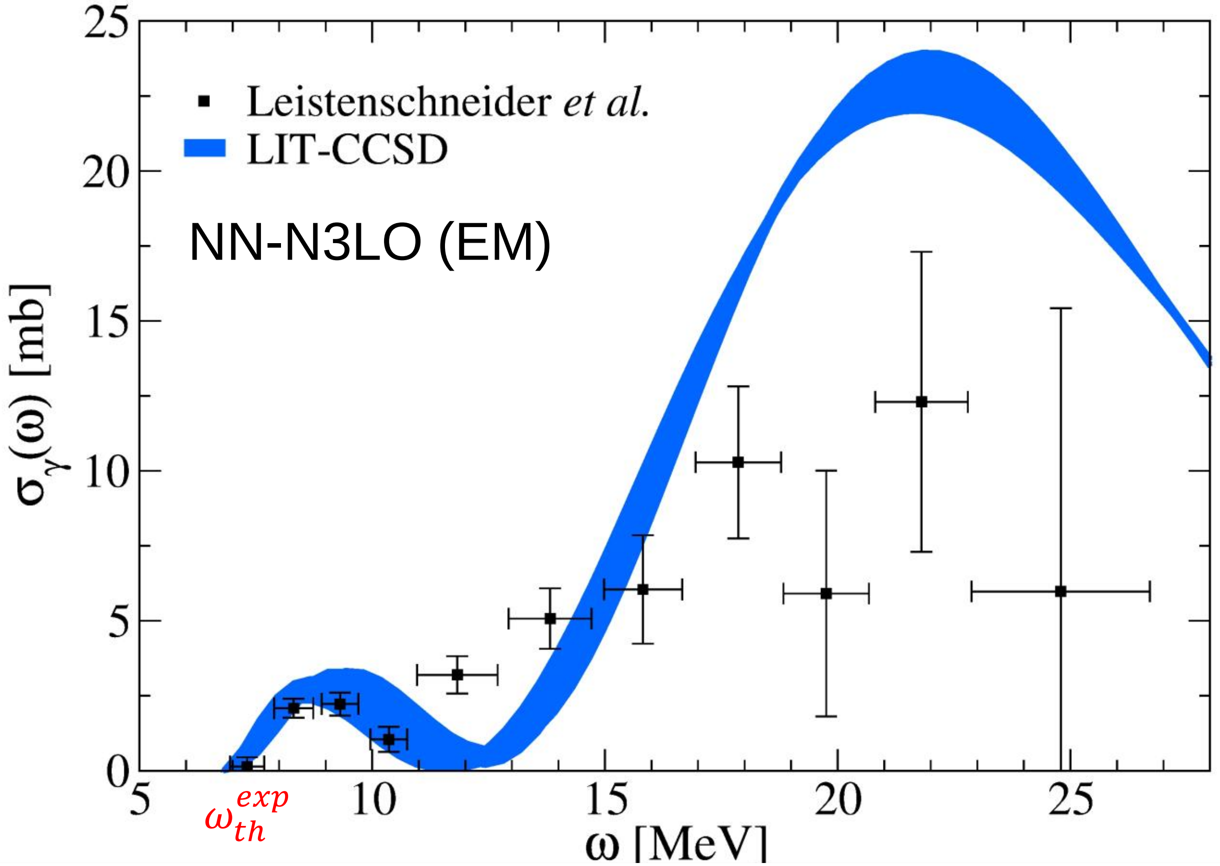

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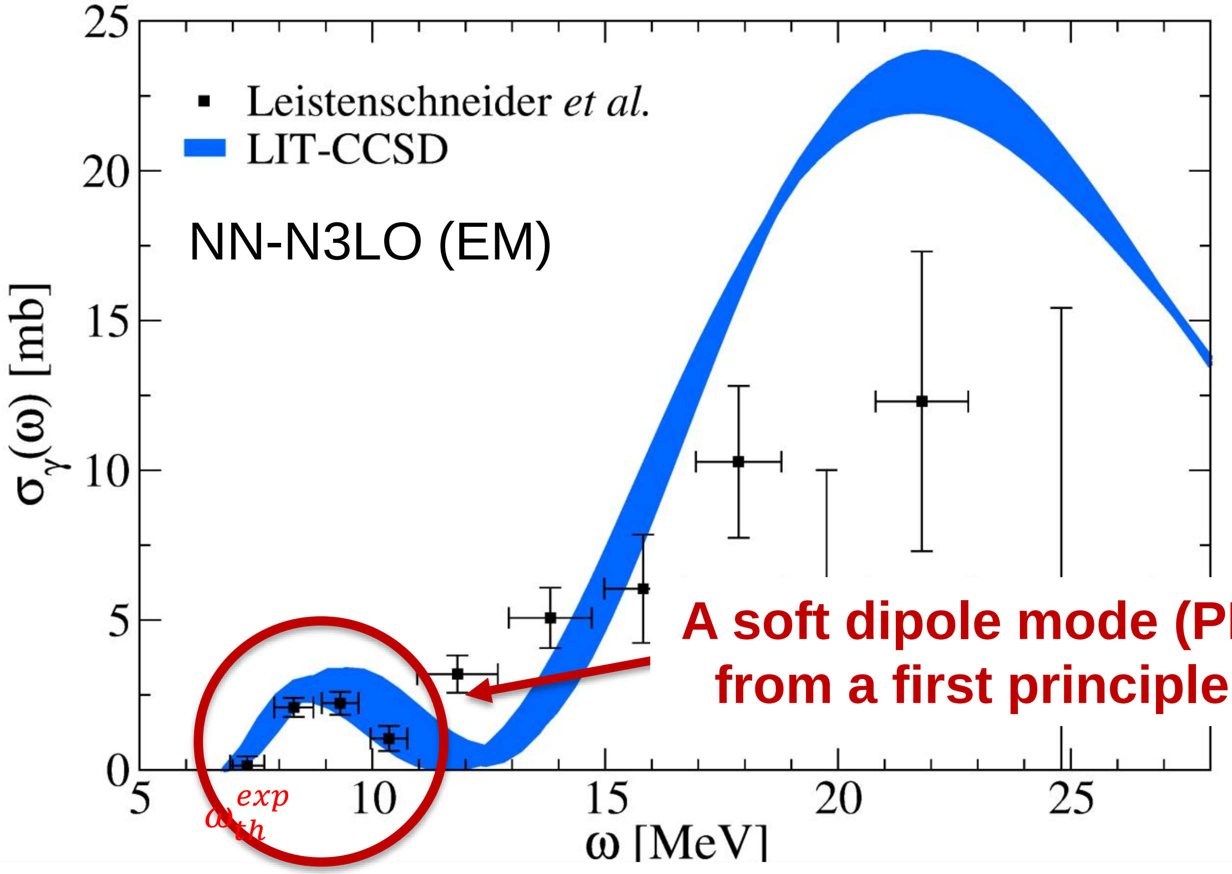
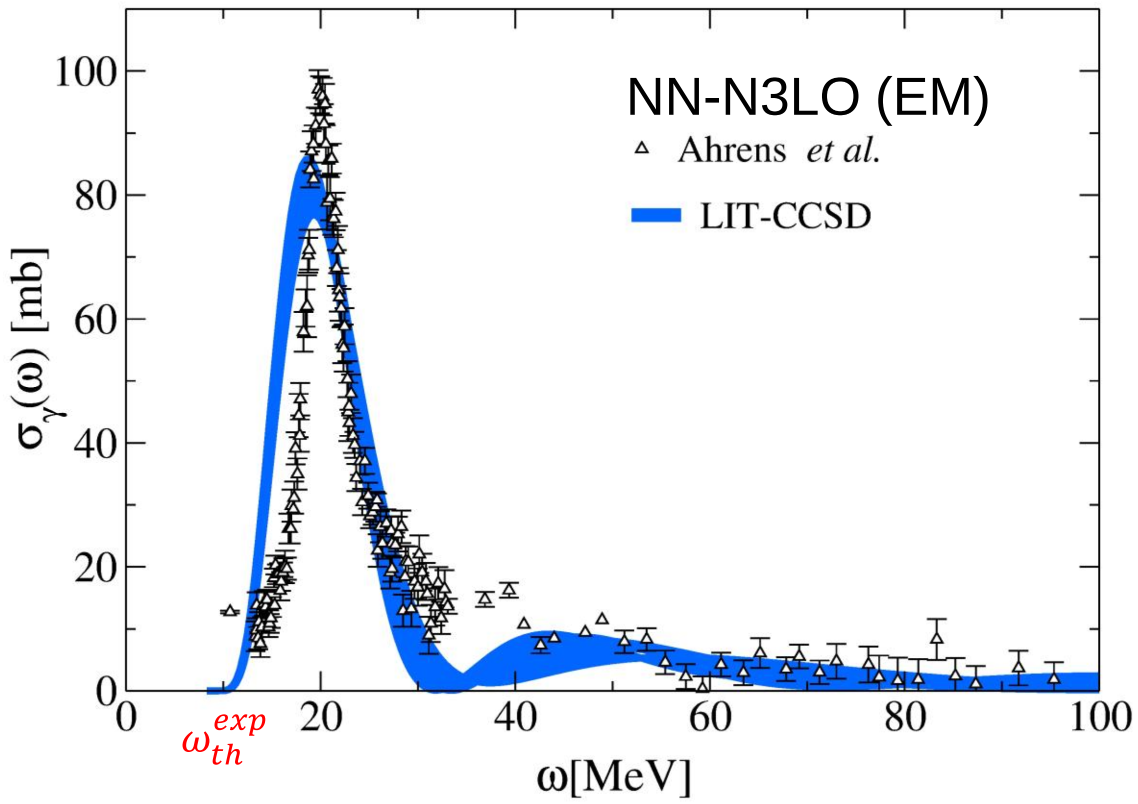



**A soft dipole mode (PDR) emerges from a first principle calculation**

# $^{40}Ca$ - The Response Function

**The presence of a GDR is predicted theoretically from first principles!**

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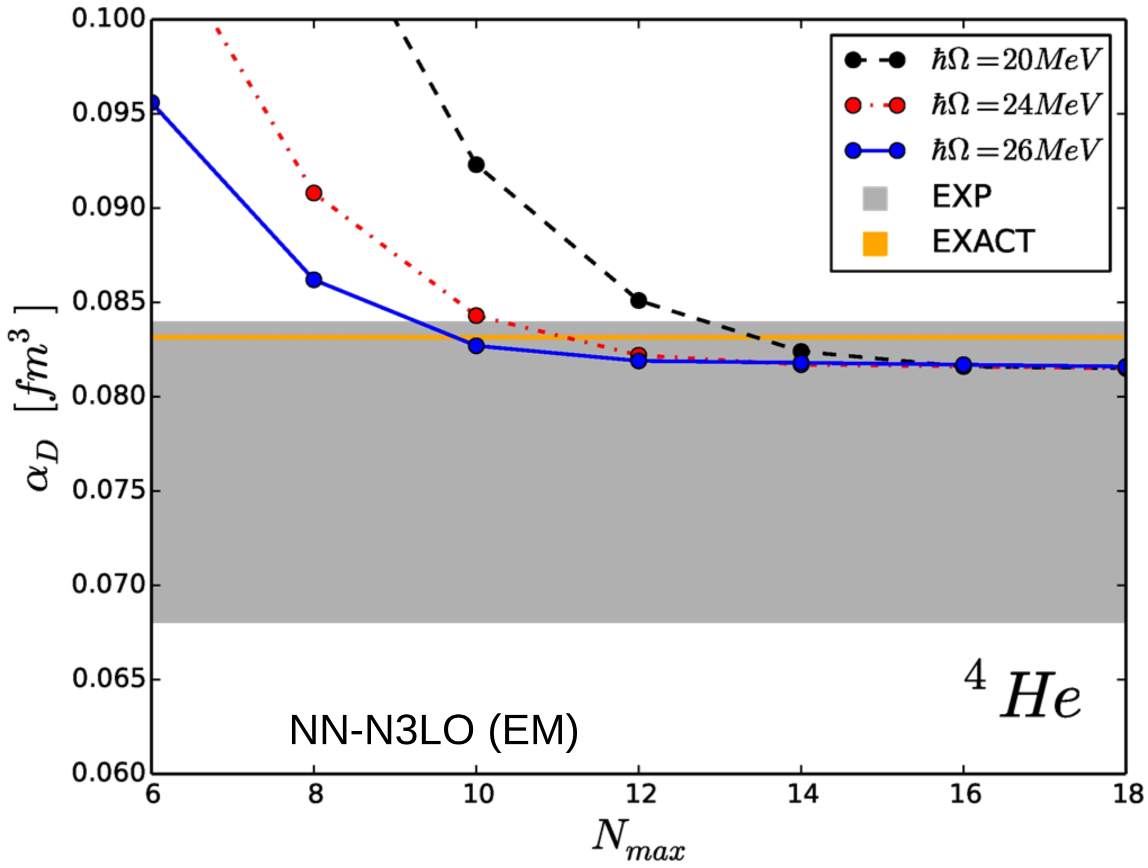
# The Electric Dipole Polarizability

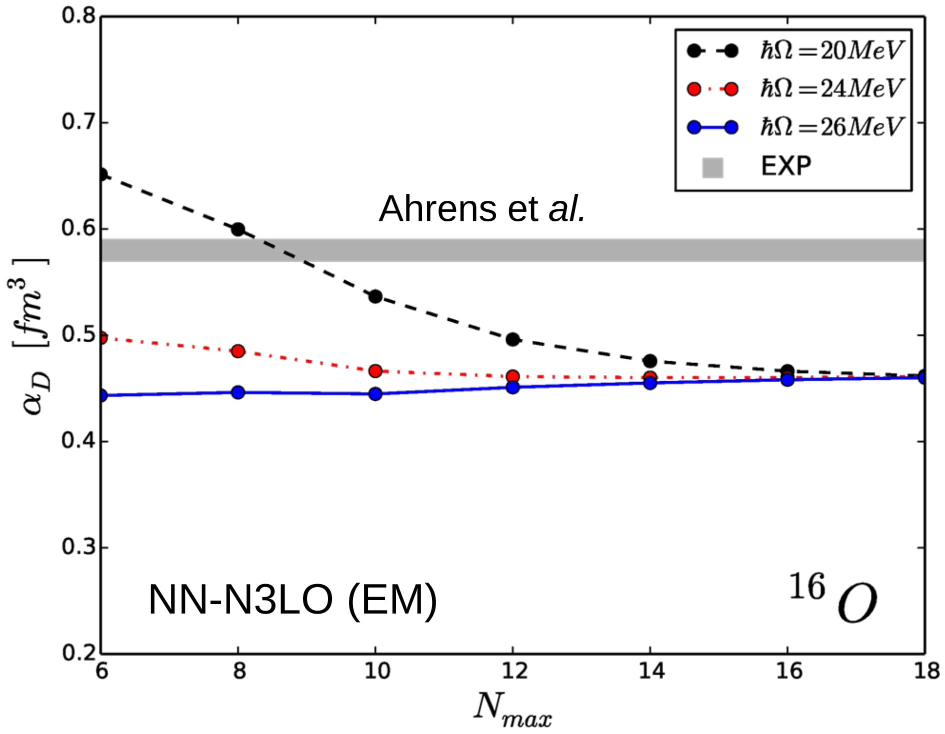
M.M. et *al.*, in preparation (2015)

## $^4He$ benchmark with exact LIT+EIHH



# $^{16}O$ - The Electric Dipole Polarizability

M.M. et *al.*, in preparation (2015)




$$\alpha_D = 0.46 fm^3$$

$$\alpha_D^{exp} = 0.585(9) fm^3$$

$$R_{ch} = 2.3 fm$$

$$R_{ch}^{exp} = 2.6991(52)$$

# $^{40}Ca$ - The Electric Dipole Polarizability

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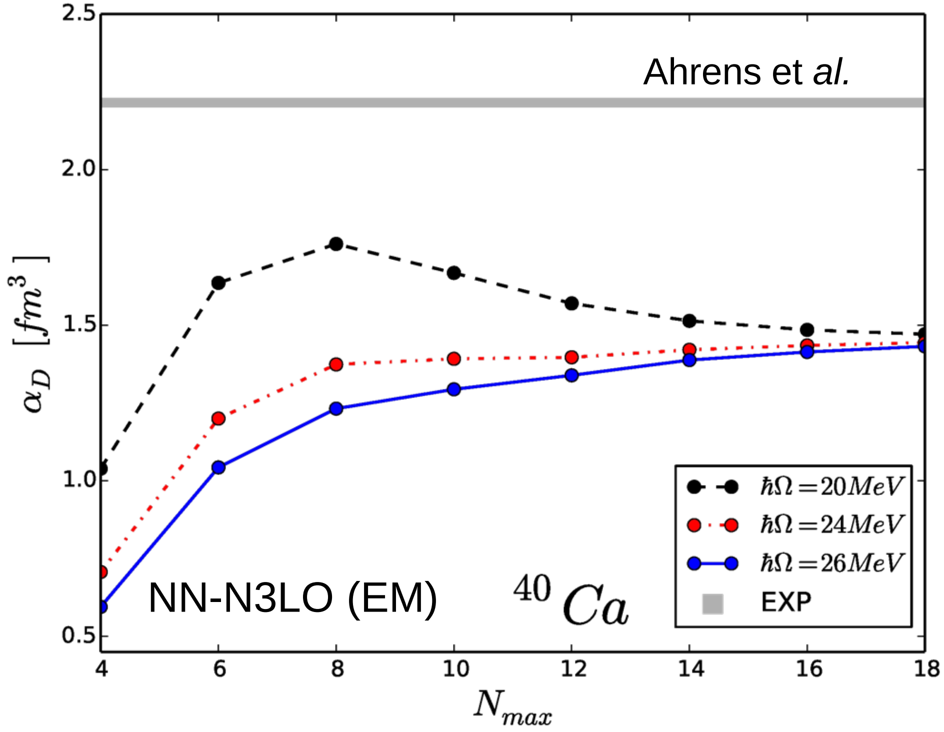


$$\alpha_D = 1.47 fm^3$$

$$\alpha_D^{exp} = 2.23(3) fm^3$$

$$R_{ch} = 3.05 fm$$

$$R_{ch}^{exp} = 3.4776(19)$$

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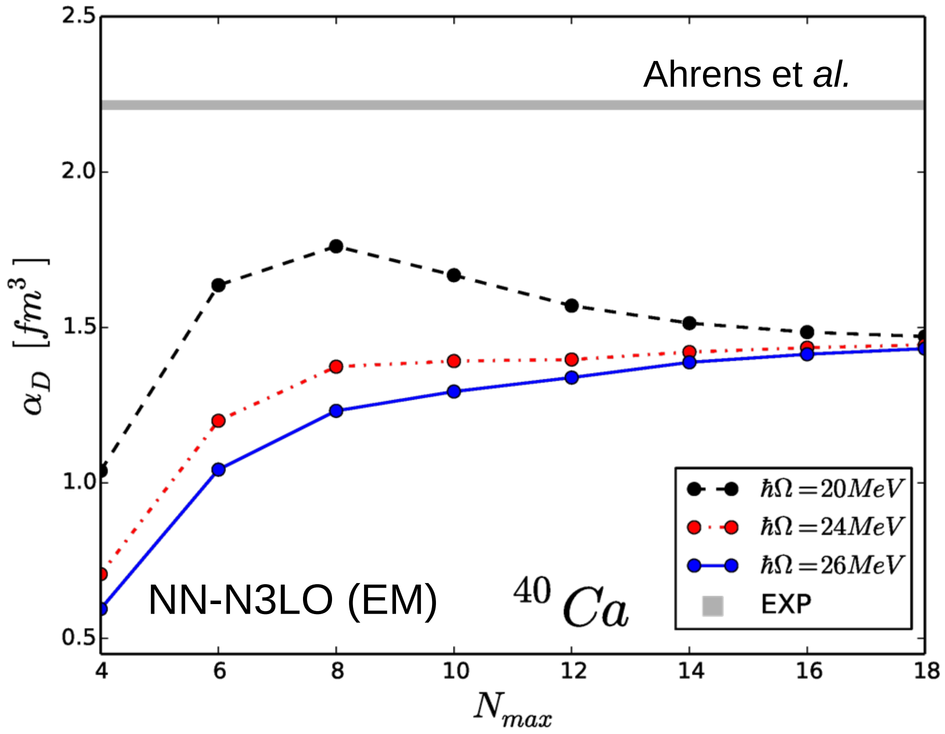


$$\alpha_D = 1.47 fm^3$$

$$\alpha_D^{exp} = 2.23(3) fm^3$$

$$R_{ch} = 3.05 fm$$

$$R_{ch}^{exp} = 3.4776(19)$$

**This chiral Hamiltonian predicts too compact nuclei!**

**As a consequence we have higher dipole excitation energies, smaller radii and polarizabilities!**

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# Summary and Outlook

**TAKE HOME MESSAGE**

- We can calculate the dipole strength from first principles for the first time in the medium-mass region
- We can provide calculations for $^{48}Ca$ (strong experimental interest)

**OUTLOOK**

- Obtain the dipole strength from accurate interaction with 3NF
- Extend the method to other neutron-rich nuclei
- Improve the calculation adding triples

# Thank you!
# Merci