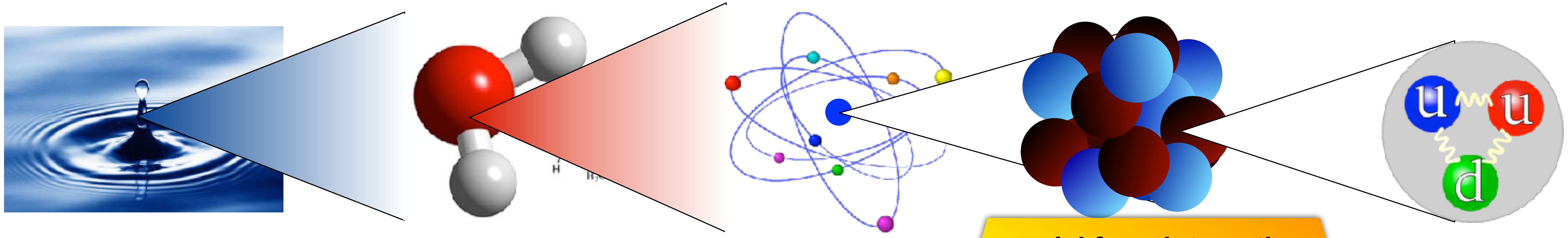
Computing the heart of matter

Sonia Bacca, KPH & MITP

GSI, May 9th, 2023

The constituents of matter



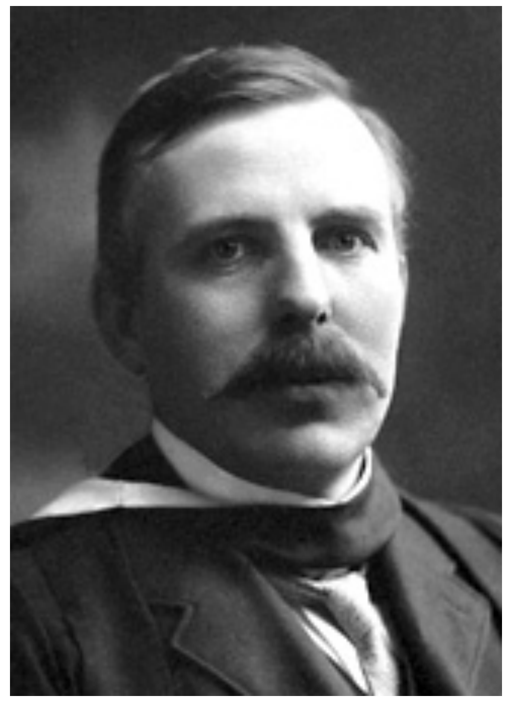
nuclei from interacting protons and neutrons

Probe wave length $\lambda = \frac{h}{p}$

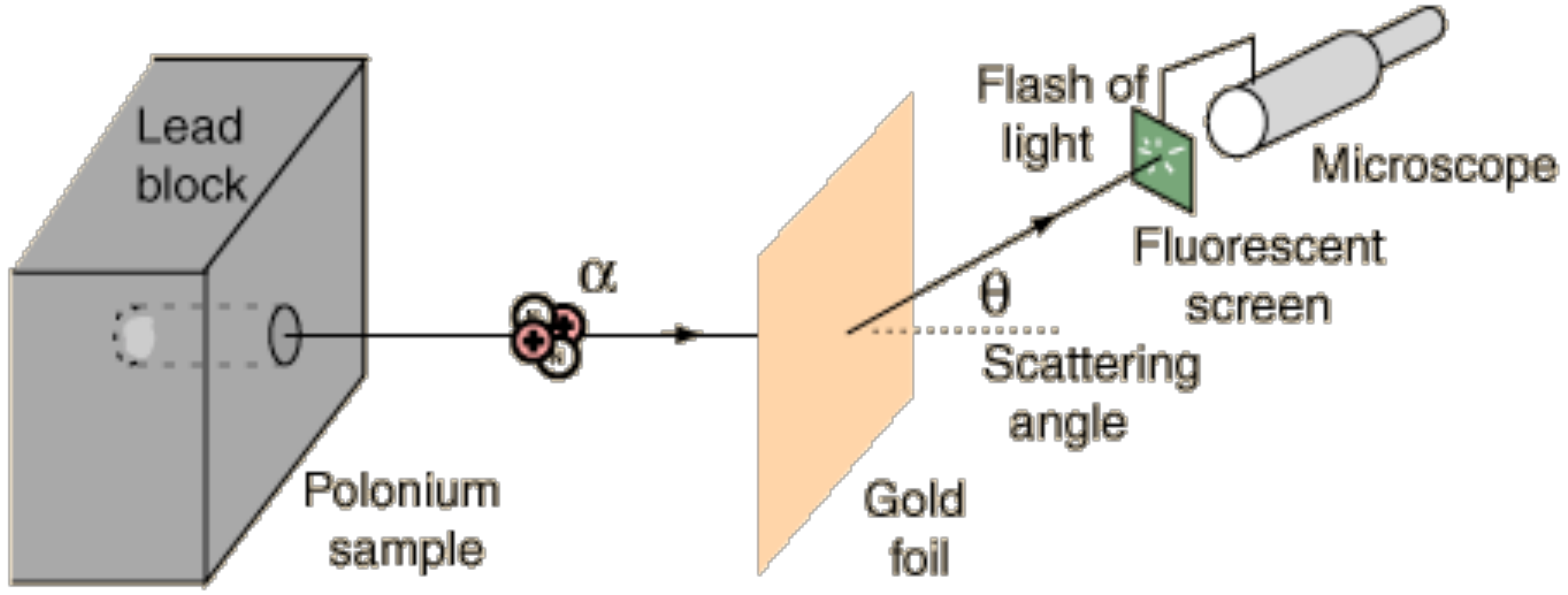
10^{-15} m ≤ length ≤ 10^{-14} m

eV ≤ energy ≤ 100 MeV

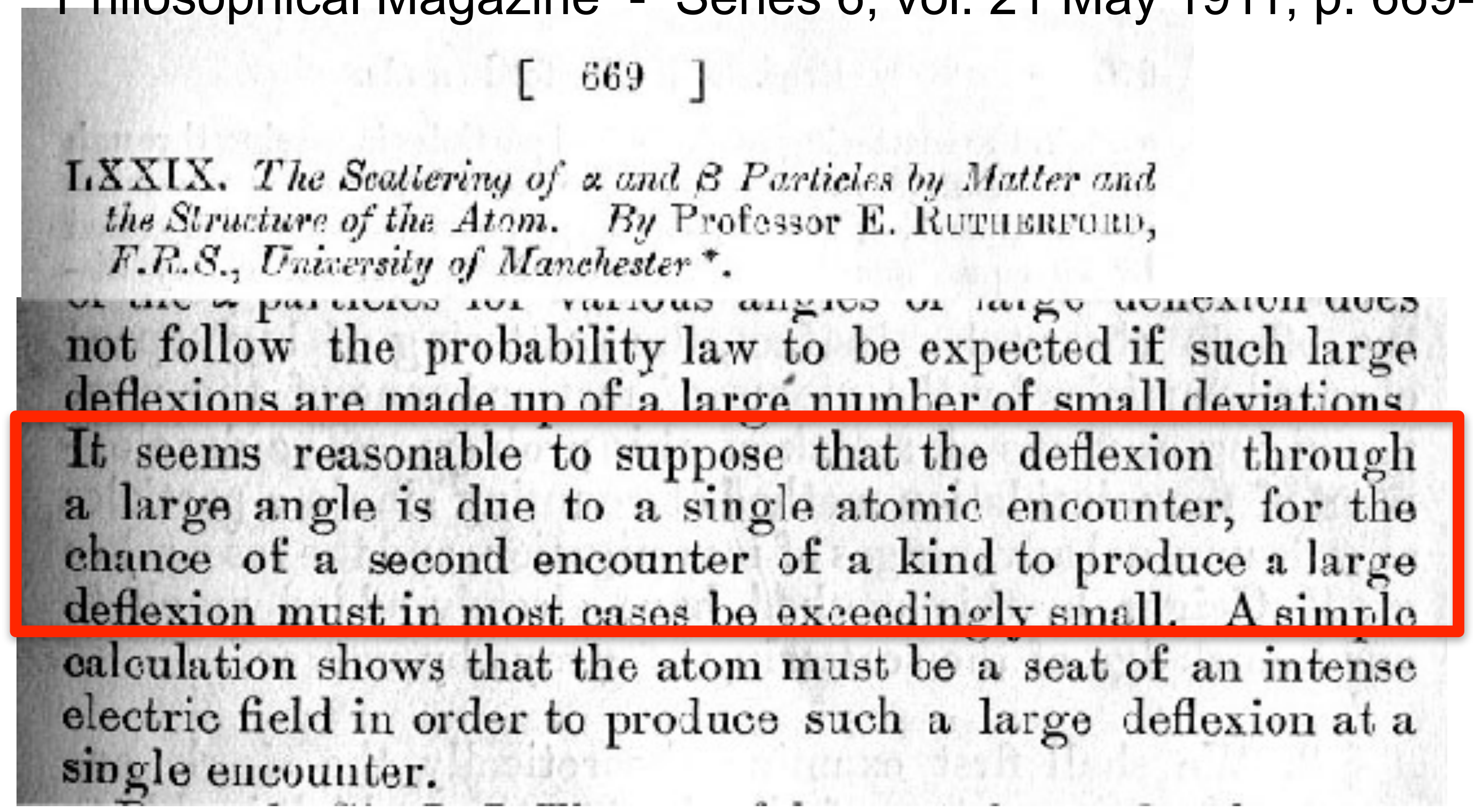
115 years from the discovery of the nucleus



Ernest Rutherford,
Nobel prize in 1908



Philosophical Magazine - Series 6, vol. 21 May 1911, p. 669-688

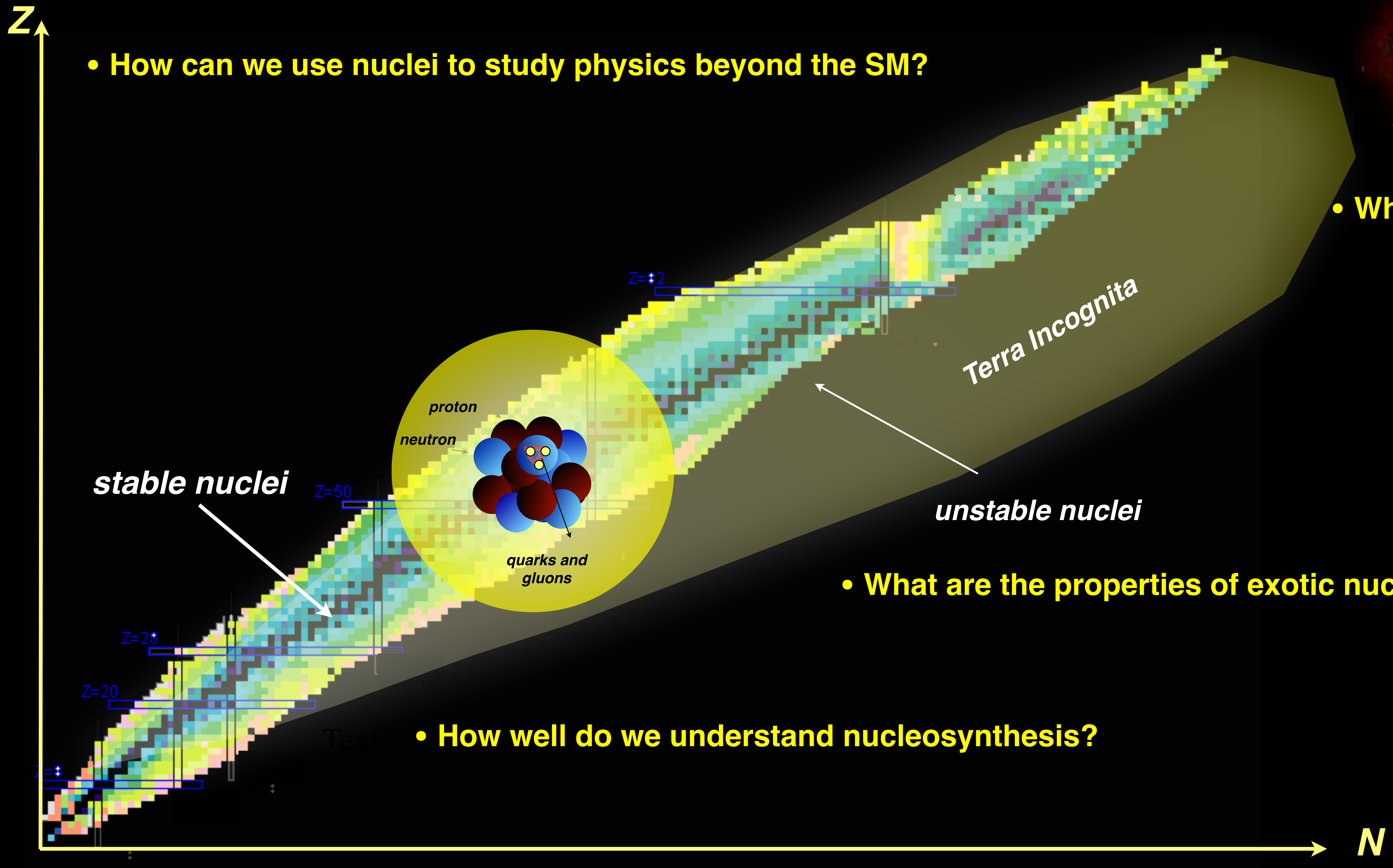


[669]

LXXIX. *The Scattering of α and β Particles by Matter and the Structure of the Atom. By* Professor E. Rutherford, *F.R.S., University of Manchester*.*

of the α particles for various angles of large deflexion does not follow the probability law to be expected if such large deflexions are made up of a large number of small deviations. It seems reasonable to suppose that the deflexion through a large angle is due to a single atomic encounter, for the chance of a second encounter of a kind to produce a large deflexion must in most cases be exceedingly small. A simple calculation shows that the atom must be a seat of an intense electric field in order to produce such a large deflexion at a single encounter.

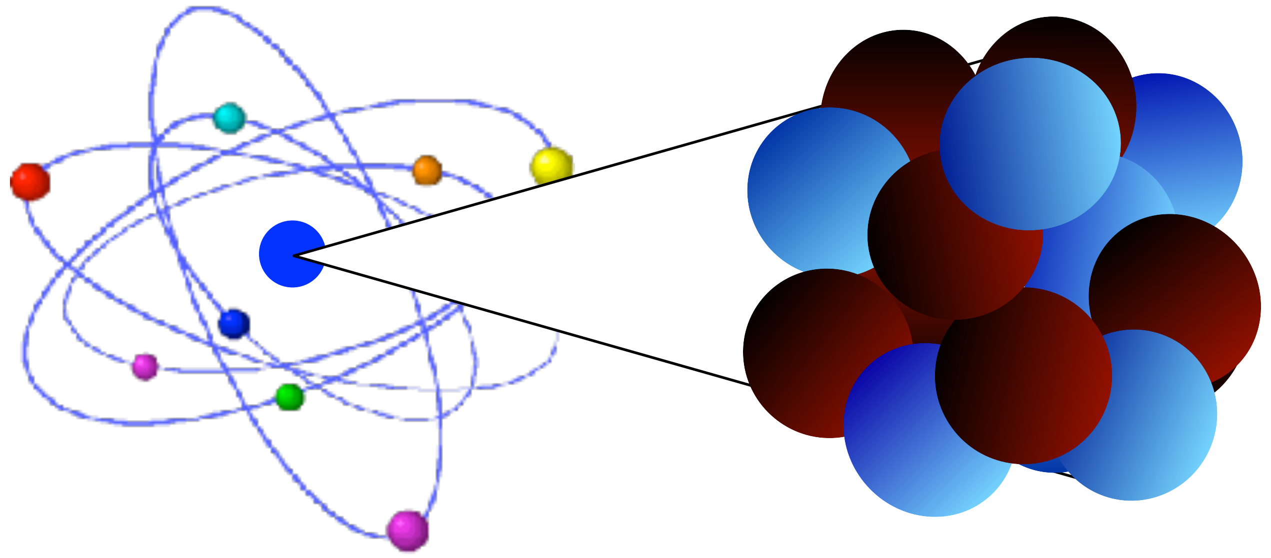
The chart of nuclides



- How can we use nuclei to study physics beyond the SM?
- What are neutron stars?
- What are the properties of exotic nuclei?
- How well do we understand nucleosynthesis?

Computing the heart of matter

The theory perspective



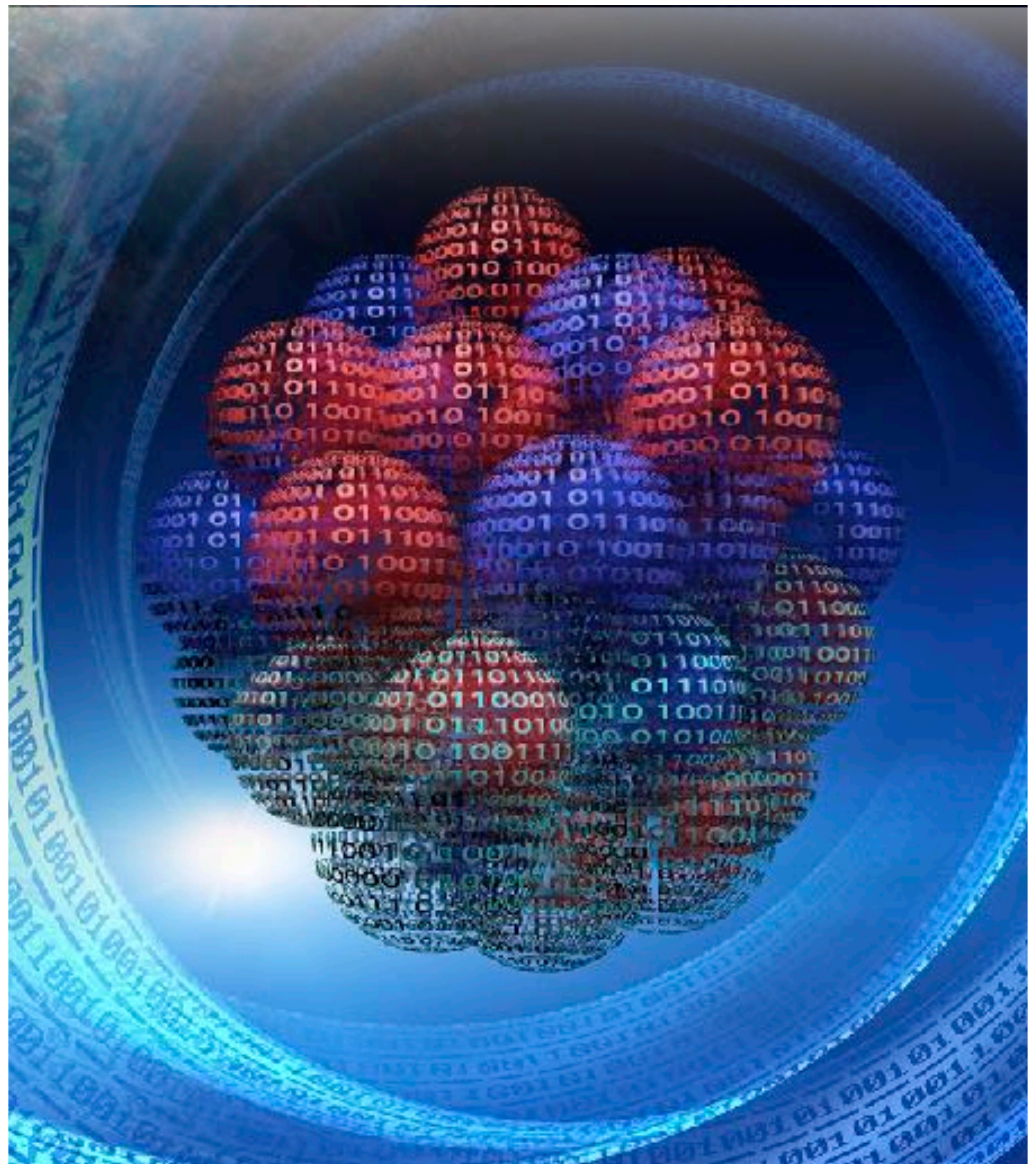
- Start from neutrons and protons
- Solve the quantum mechanics of A interacting nucleons

$$H|\Psi\rangle = E|\Psi\rangle$$

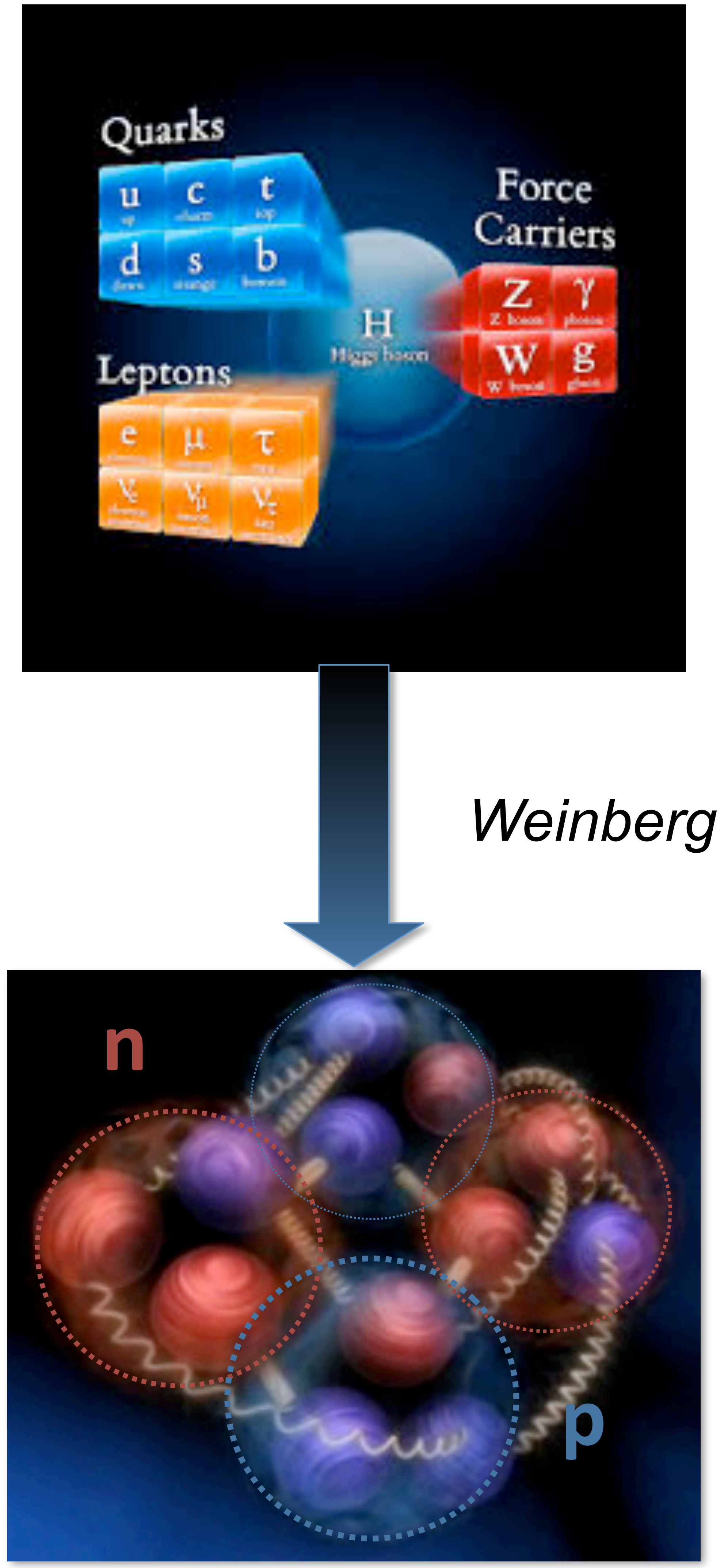
$$H = T + V_{NN}(\Lambda) + V_{3N}(\Lambda) + \ldots$$

- Find numerically exact solutions or controlled approximations

Credits: ORNL, LeJean Hardin and Andy Sproles



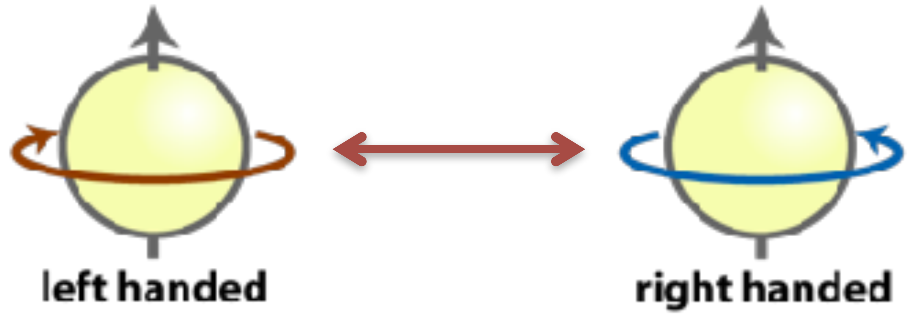
Chiral effective field theory



Quark/gluon (high energy) dynamics

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \bar{q}_L i \gamma_\mu D^\mu q_L + \bar{q}_R i \gamma_\mu D^\mu q_R - \bar{q} \mathcal{M} q$$

In the limit of $\mathcal{M} \to 0$ the QCD Lagrangian is invariant under chiral symmetry



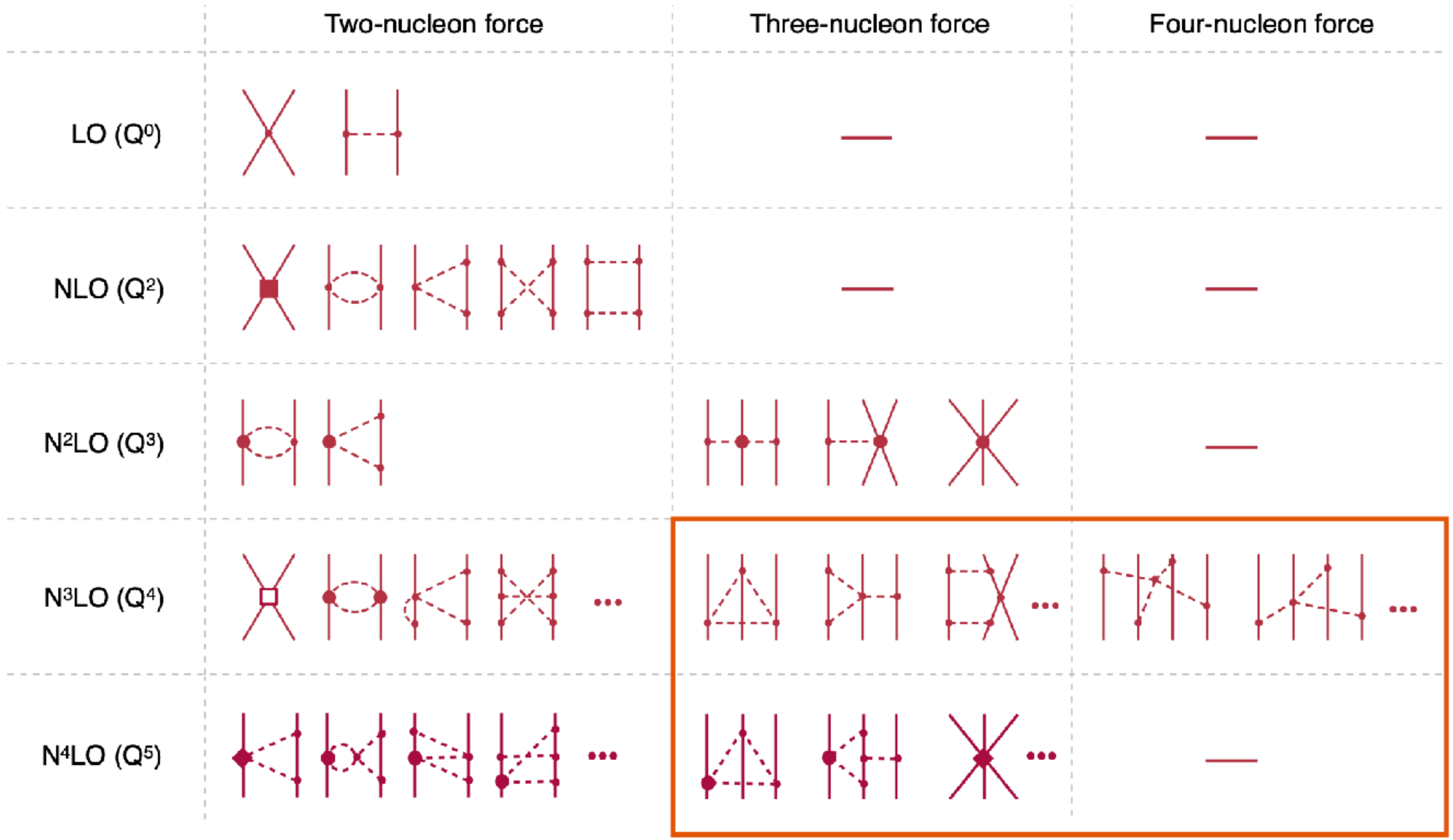
Chiral symmetry is explicit and spontaneous broken

Nucleon/pion (low energy) dynamics

$$\mathcal{L}_{eff} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

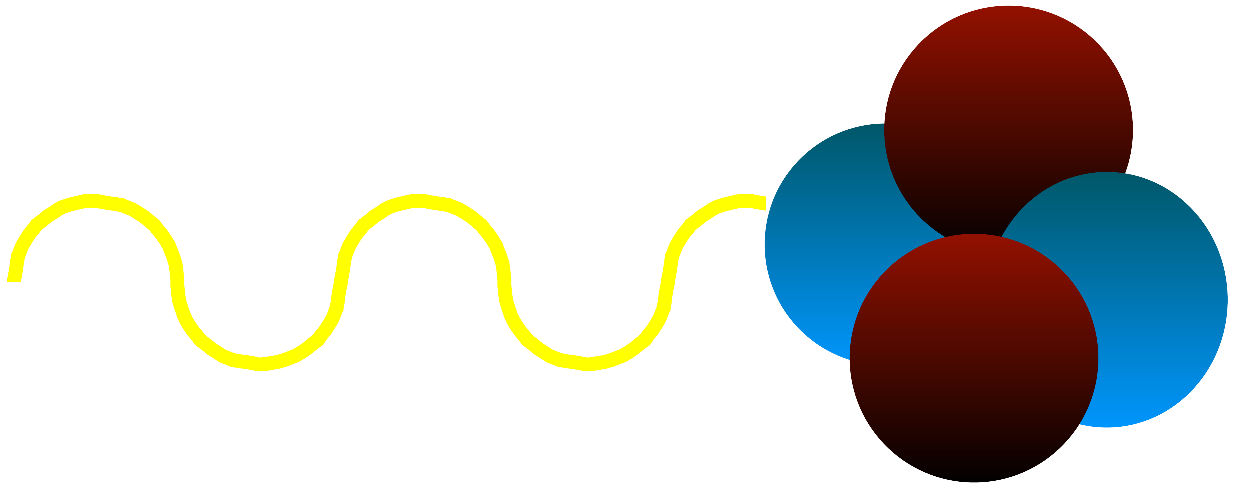
Compatible with explicit and spontaneous **chiral symmetry breaking**

Chiral effective field theory



Credits: E.Epelbaum

Coupling to the electroweak field



Cross Section $$\sigma_{ew} \sim R(\omega) = \sum_f \left| \left\langle \psi_f \middle| \Theta \middle| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Electroweak operator

Also admits order-by-order expansion
in chiral EFT

One first example

Big Bang Nucleosynthesis

How it all started

- BBN is responsible for the synthesis of the light nuclei which took place within a few minutes after the Big Bang (time zero)
- The first nucleus formed is deuterium D via $\mathrm{n\,p} \rightarrow \mathrm{D}\,\gamma$
- BBN leads to the formation of D, ^{3}H, ^{3}He, ^{4}He, ^{6}Li and ^{7}Li

Credits: Focus.it

Big Bang Nucleosynthesis

Bayesian analysis for uncertainty quantification

- Express observable as

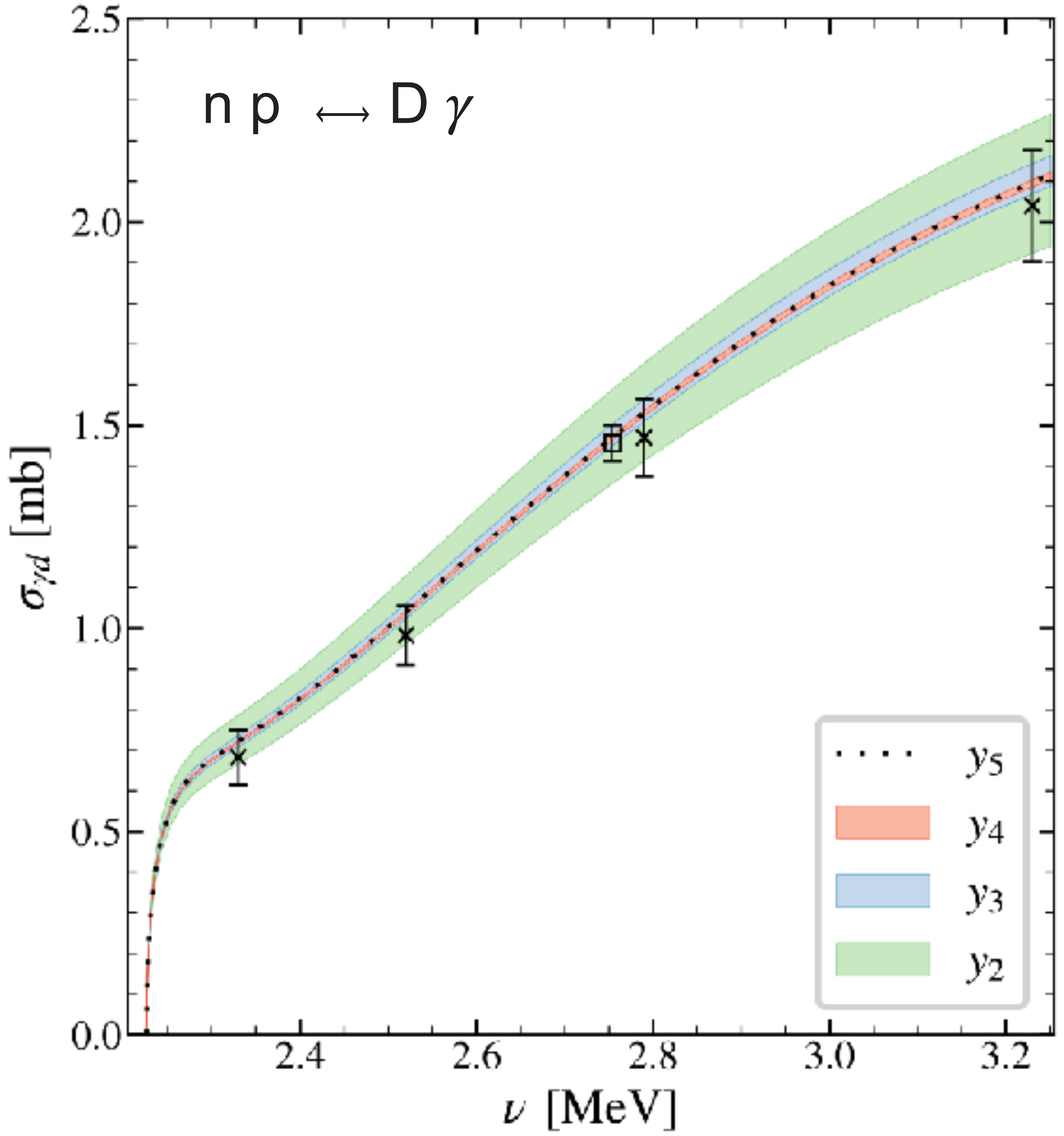
$$y(\nu) = y_{ref}(\nu) \sum_{n=0}^{\infty} c_n(\nu)(Q/\Lambda)^n$$

$$\delta y_k(\nu) = y_{\rm ref}(\nu) \sum_{n=k+1}^{\infty} c_n(\nu)\,(Q/\Lambda)^n$$

- Calibrate a Gaussian process emulator using physics-based info on $c_n(\nu)$ as “prior”

- Calculate “Bayesian posterior” for $c_{n>k}(\nu)$, obtaining statistically interpretable truncation error, amounting to 0.2% at the highest order.

B. Acharya and SB, Phys. Lett. B 827, 137011 (2022)

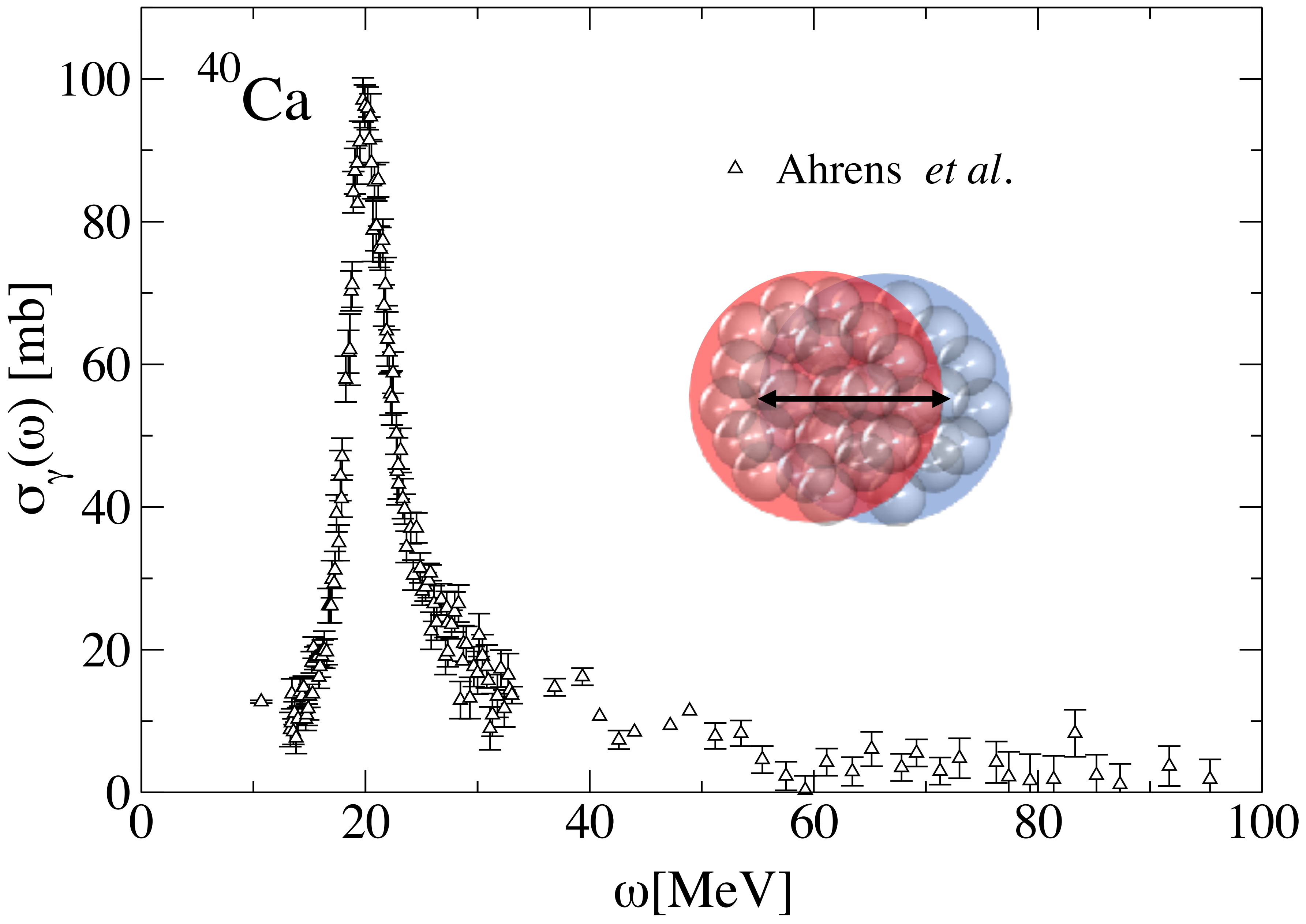


What about reactions with heavier nuclei?

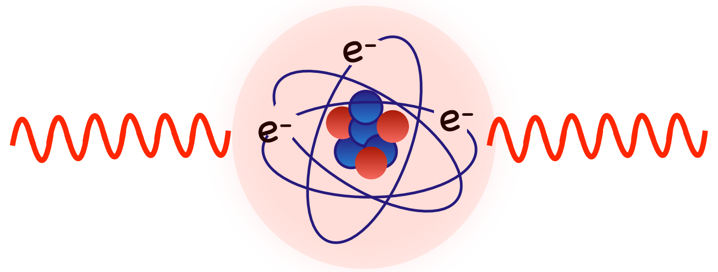
Experimental motivation

Stable Nuclei

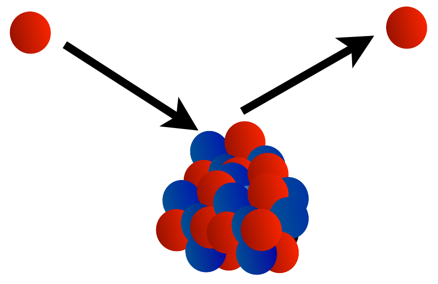
Giant dipole resonances



Photoabsorption experiments

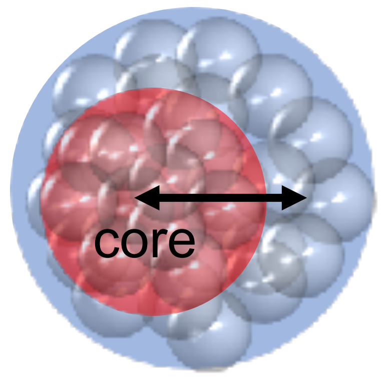


(p,p') experiments

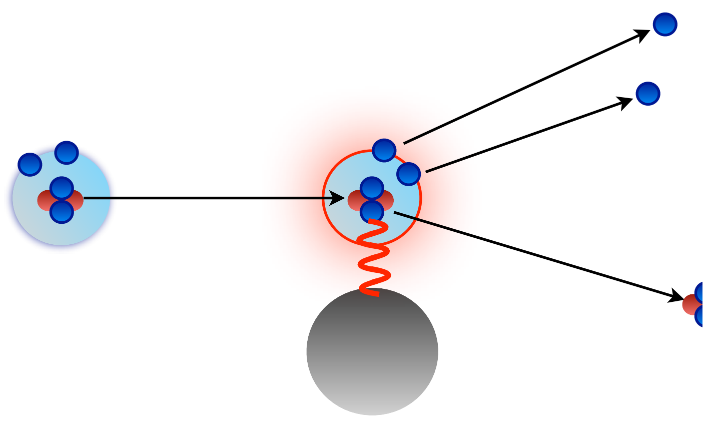


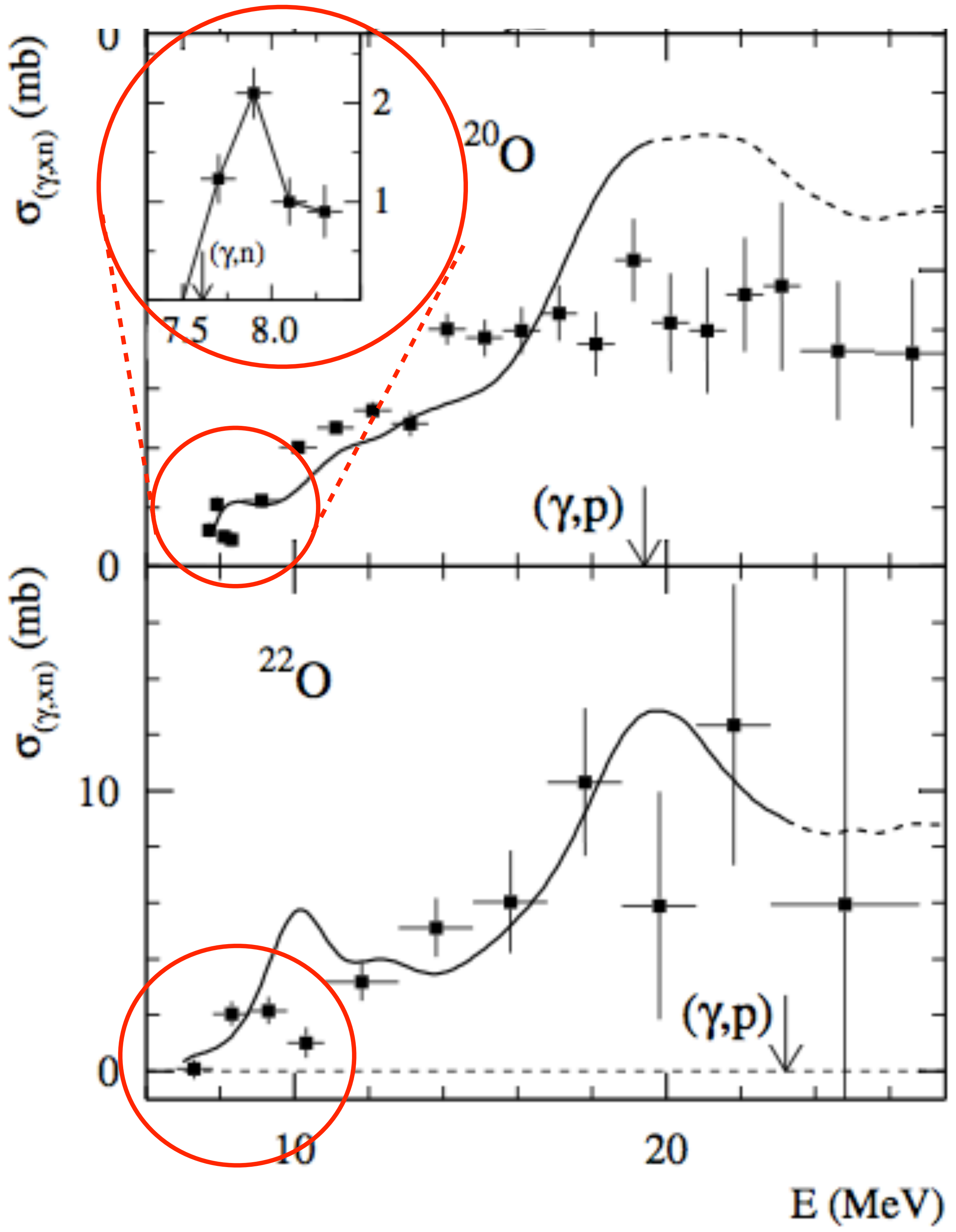
Unstable Nuclei

Pigmy dipole resonances



Coulex experiment



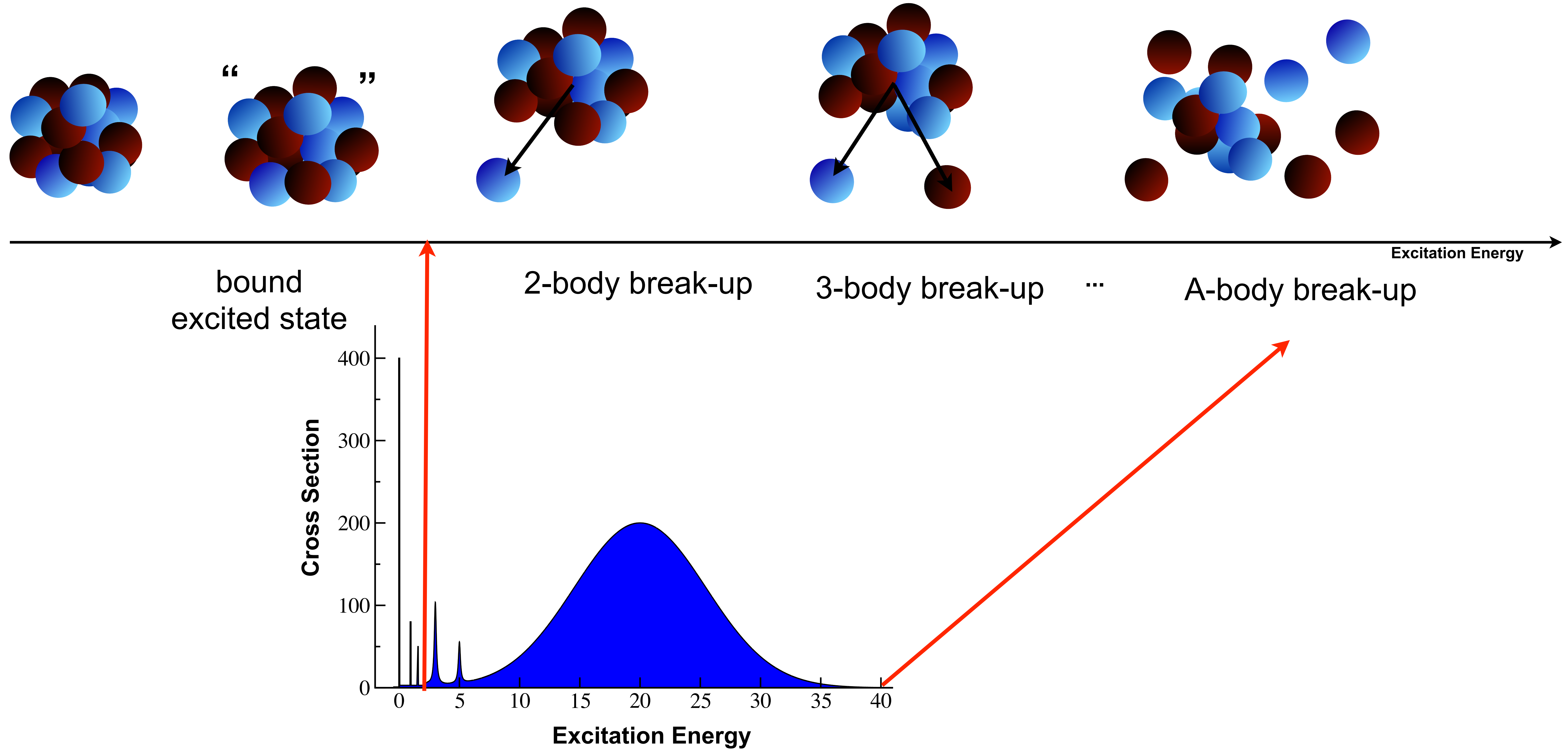


Do we see the emergence of collective motions from first principle calculations?

The continuum problem

$$R(\omega) = \cancel{\sum_f} \left| \left\langle \psi_f \middle| \Theta \middle| \psi_0 \right\rangle \right|^2 \delta(E_f - E_0 - \omega)$$

Depending on E_f, many channels may be involved



bound
excited state

2-body break-up

3-body break-up

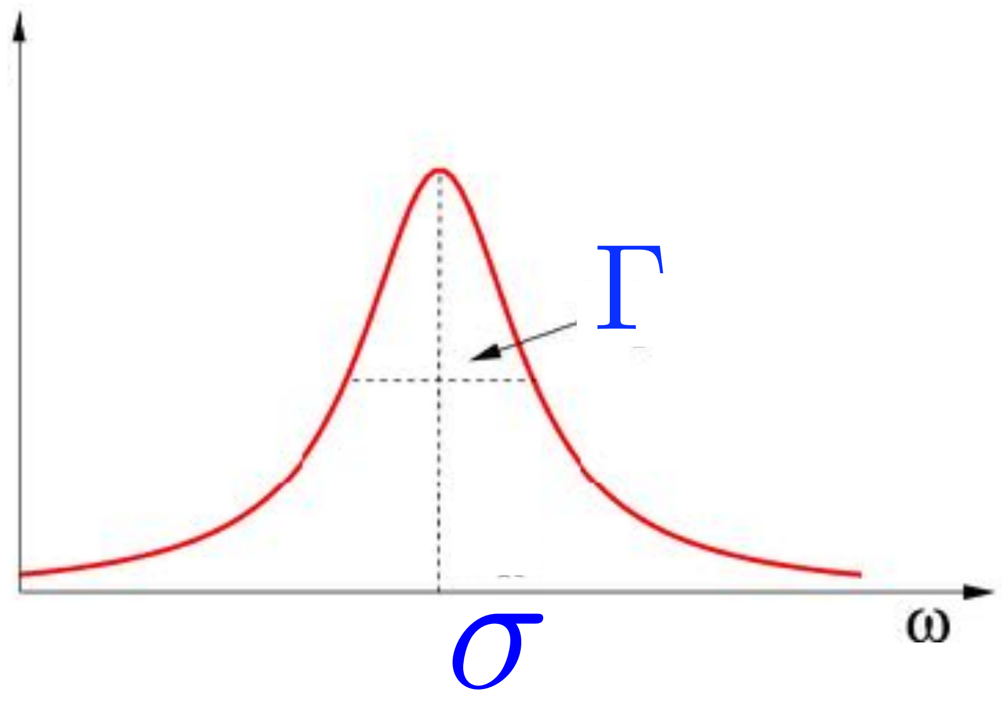
A-body break-up

The Lorentz Integral Transforms

inversion

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

Efros, *et al.*, JPG.: Nucl.Part.Phys. **34** (2007) R459



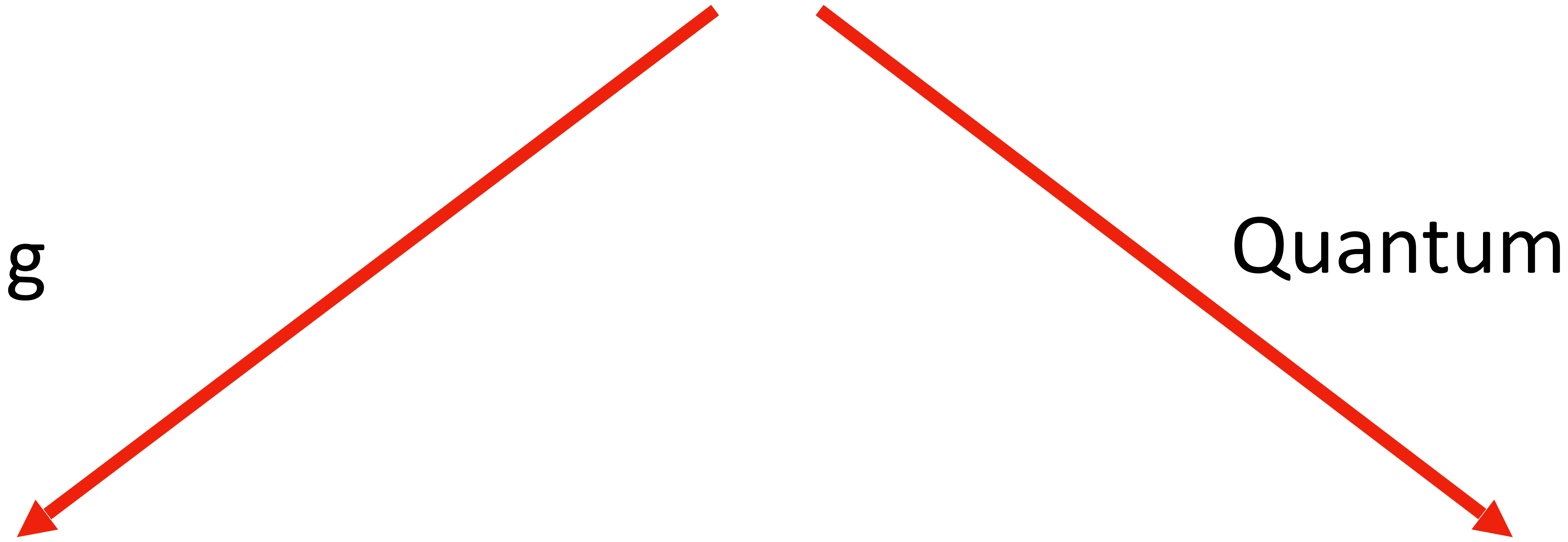
$$\Rightarrow \quad \boxed{(H - E_0 - \sigma + i\Gamma)\,|\,\tilde{\psi}\rangle = \Theta\,|\,\psi_0\rangle}$$

Reduce the continuum problem to a bound-state-like equation

Solving the quantum many-body problem

An exponentially hard problem to solve

$$H|\Psi\rangle = E|\Psi\rangle$$

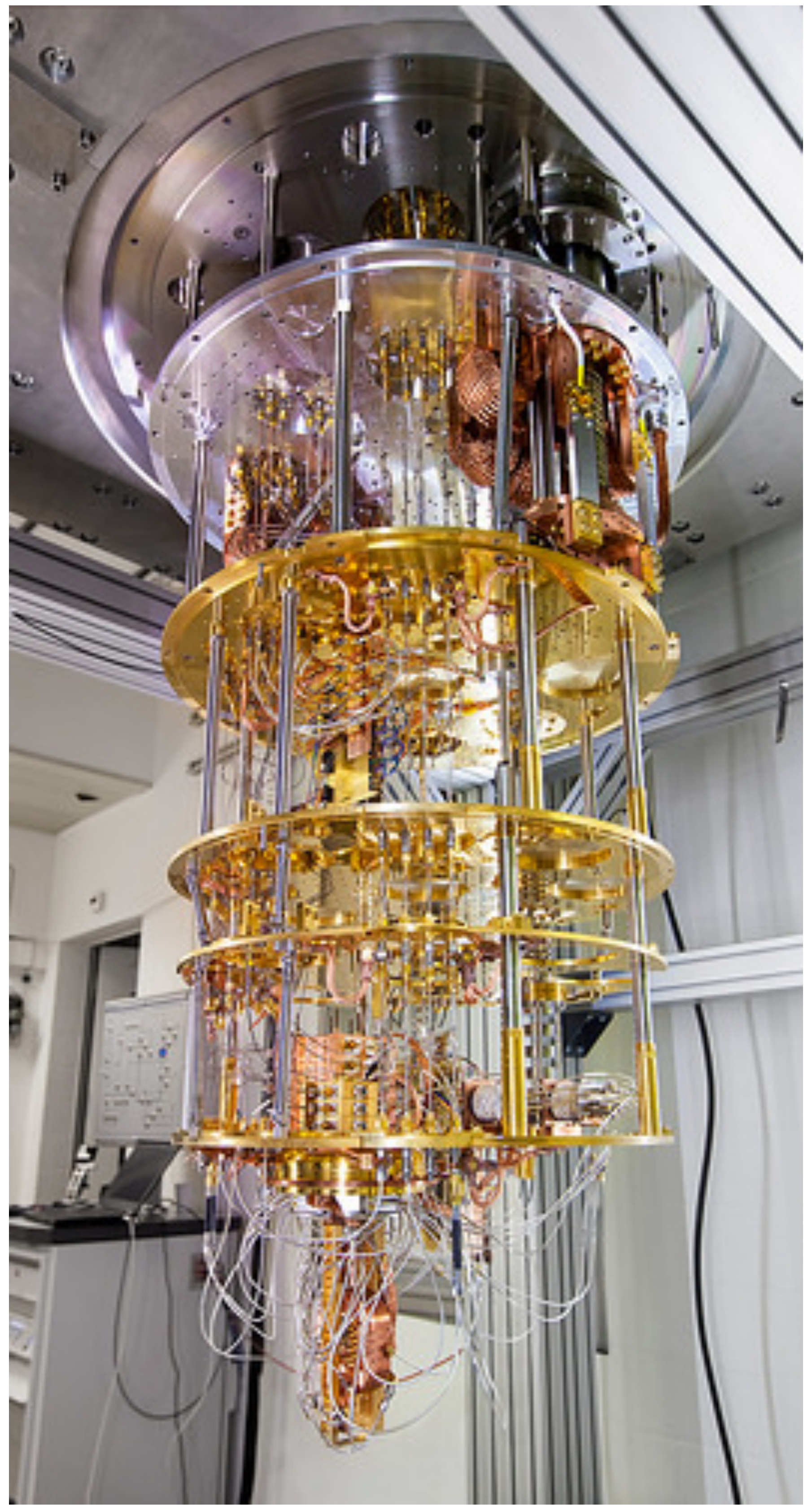


Polynomial scaling

Quantum computing

Systematically improvable approaches with controlled approximations: coupled-cluster theory, IMSRG, SCGF,…

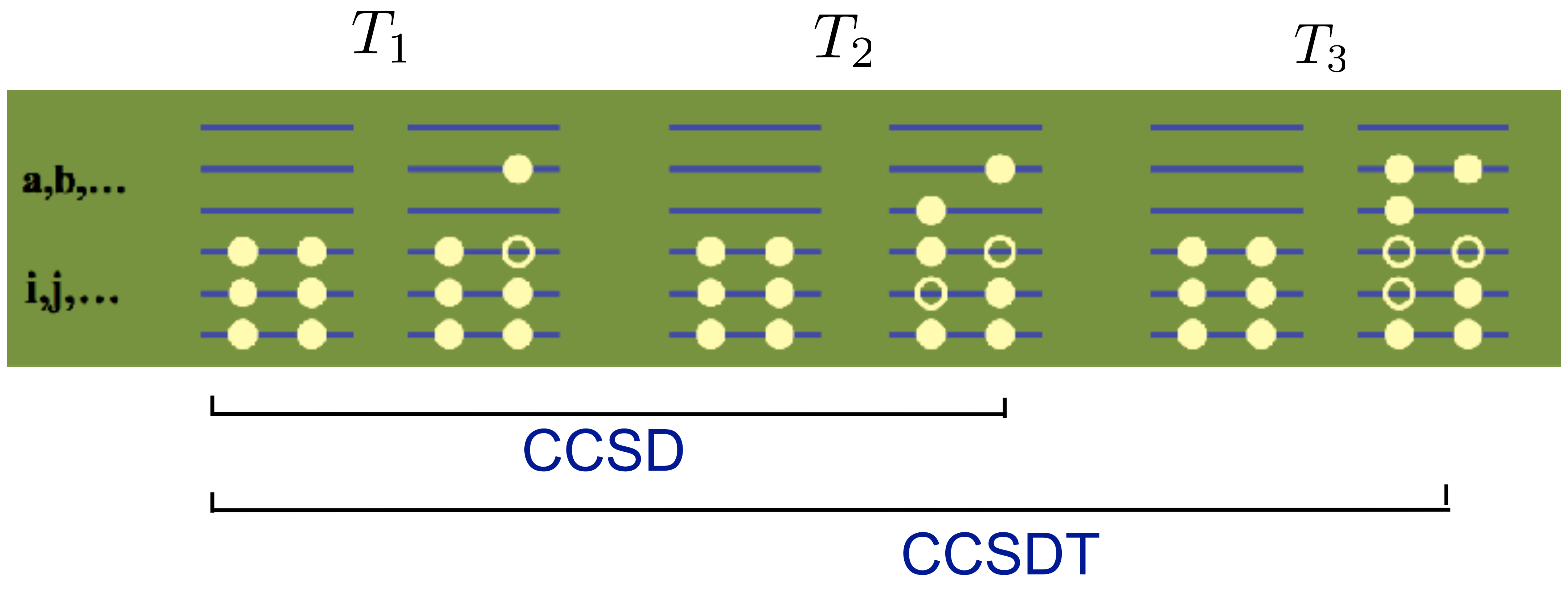
IBM Q Experience



Coupled-cluster theory

$$|\psi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle = e^{T}|\phi_0(\vec{r}_1, \vec{r}_2, ..., \vec{r}_A)\rangle \qquad T = \sum T_{(A)}$$

cluster expansion

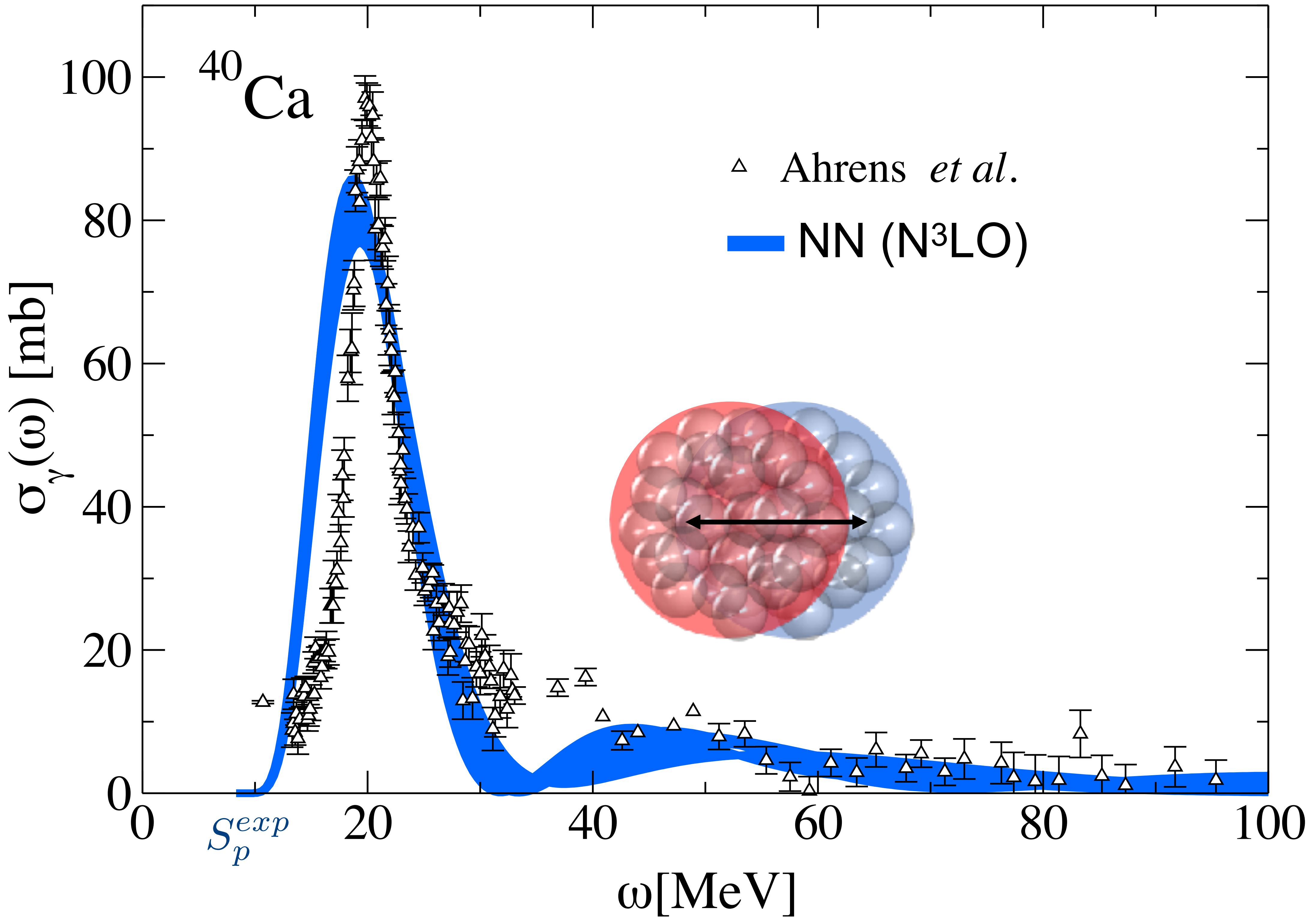


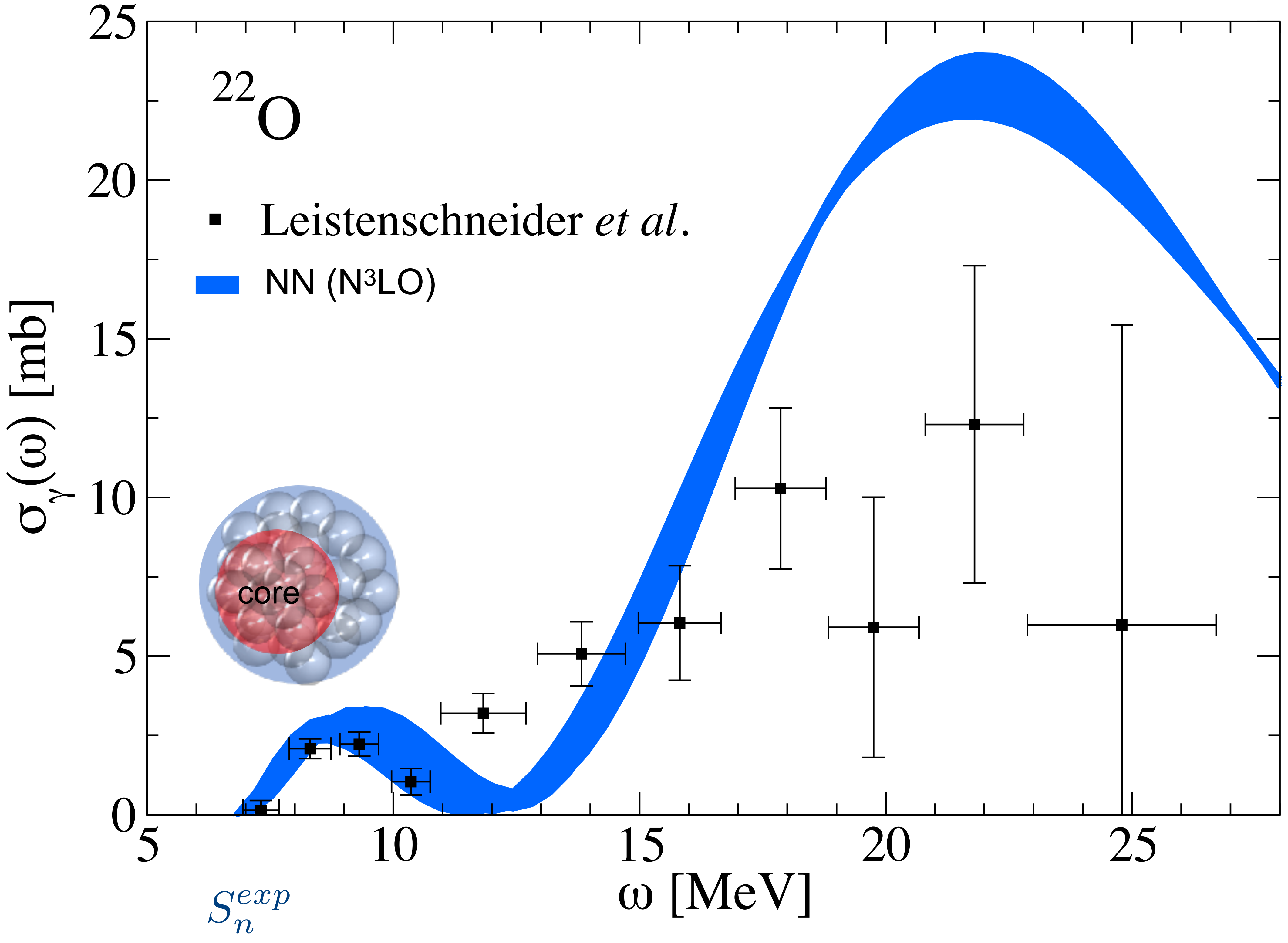
SB et al., Phys. Rev. Lett. 111, 122502 (2013)

$$\boxed{(\bar{H} - E_0 - \sigma + i\Gamma)|\tilde{\Psi}_R\rangle = \bar{\Theta}|\Phi_0\rangle} \longrightarrow \begin{cases} \bar{H} = e^{-T} H e^{T} \\ \bar{\Theta} = e^{-T} \Theta e^{T} \\ |\tilde{\Psi}_R\rangle = \hat{R}|\Phi_0\rangle \end{cases}$$

Medium-mass nuclei

SB et al., PRC 90, 064619 (2014)

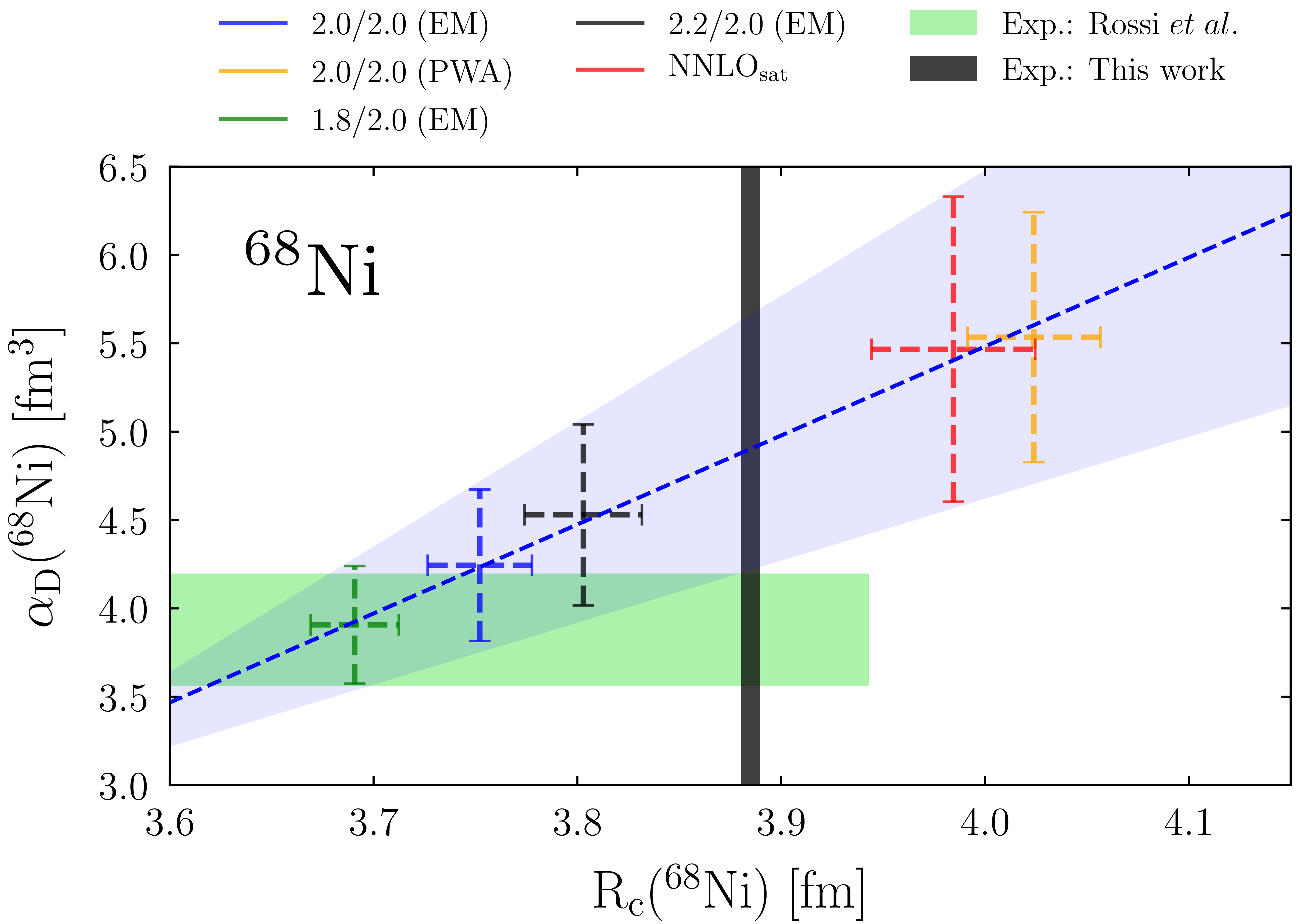




Exotic Nuclei

$$\boxed{\alpha_D = 2\alpha \int_{\omega_{ex}}^{\infty} d\omega \frac{R(\omega)}{\omega}}$$

S.Kaufmann, J. Simonis, SB et al., PRL 104 (2020) 132505

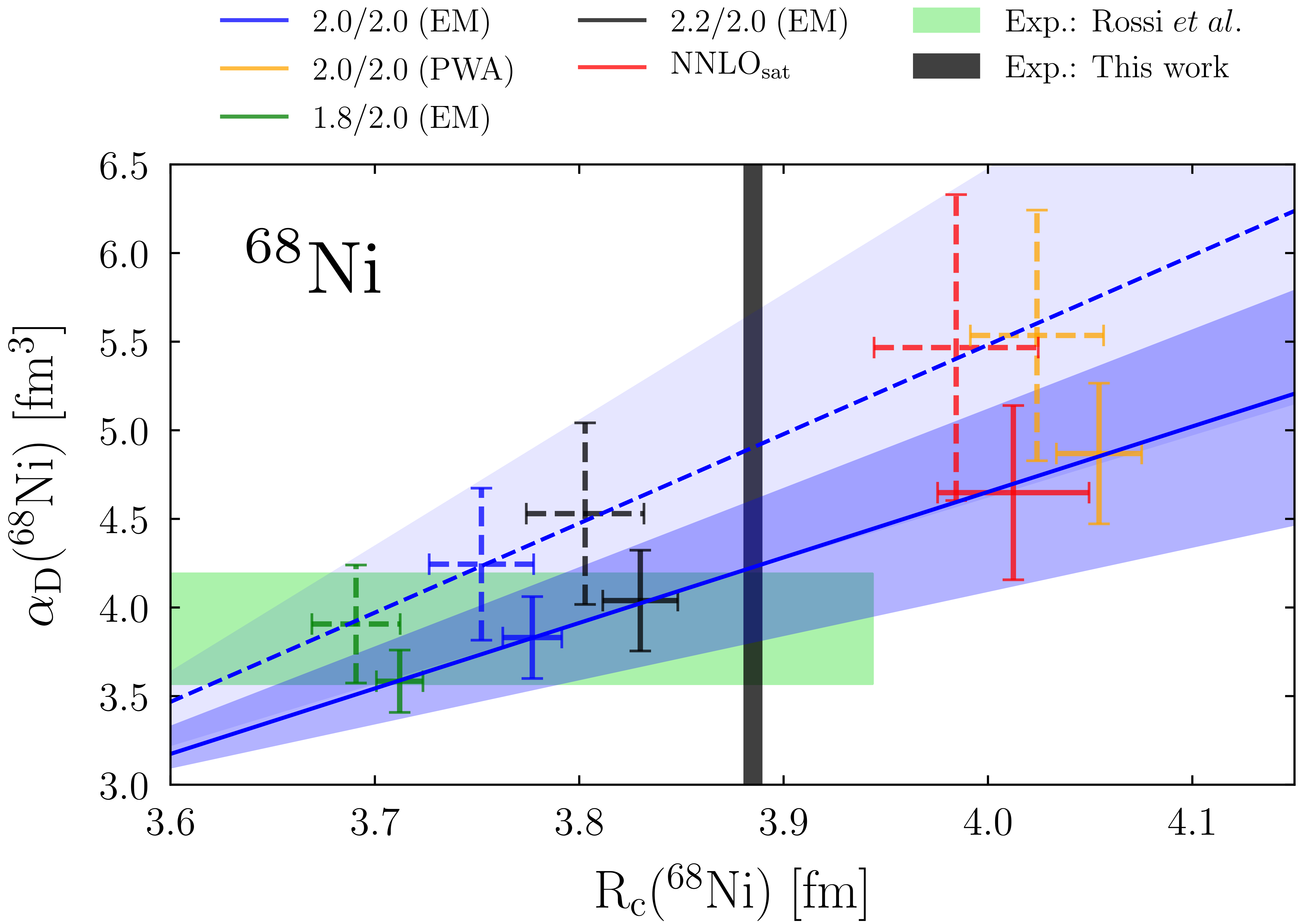


CCSD

Exotic Nuclei

$$\boxed{\alpha_D = 2\alpha \int_{\omega_{ex}}^{\infty} d\omega \frac{R(\omega)}{\omega}}$$

S.Kaufmann, J. Simonis, SB et al., PRL 104 (2020) 132505

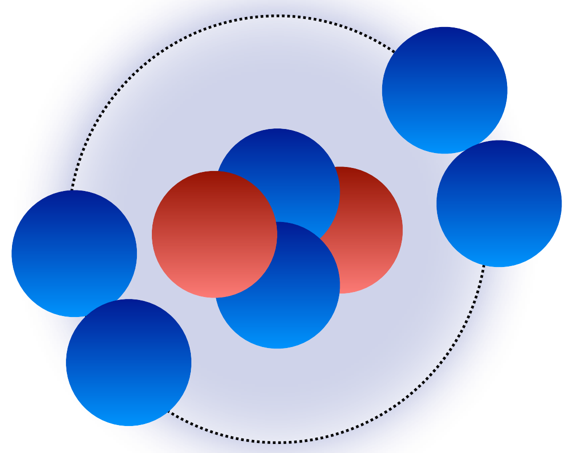


CCSD

CCSD-T1

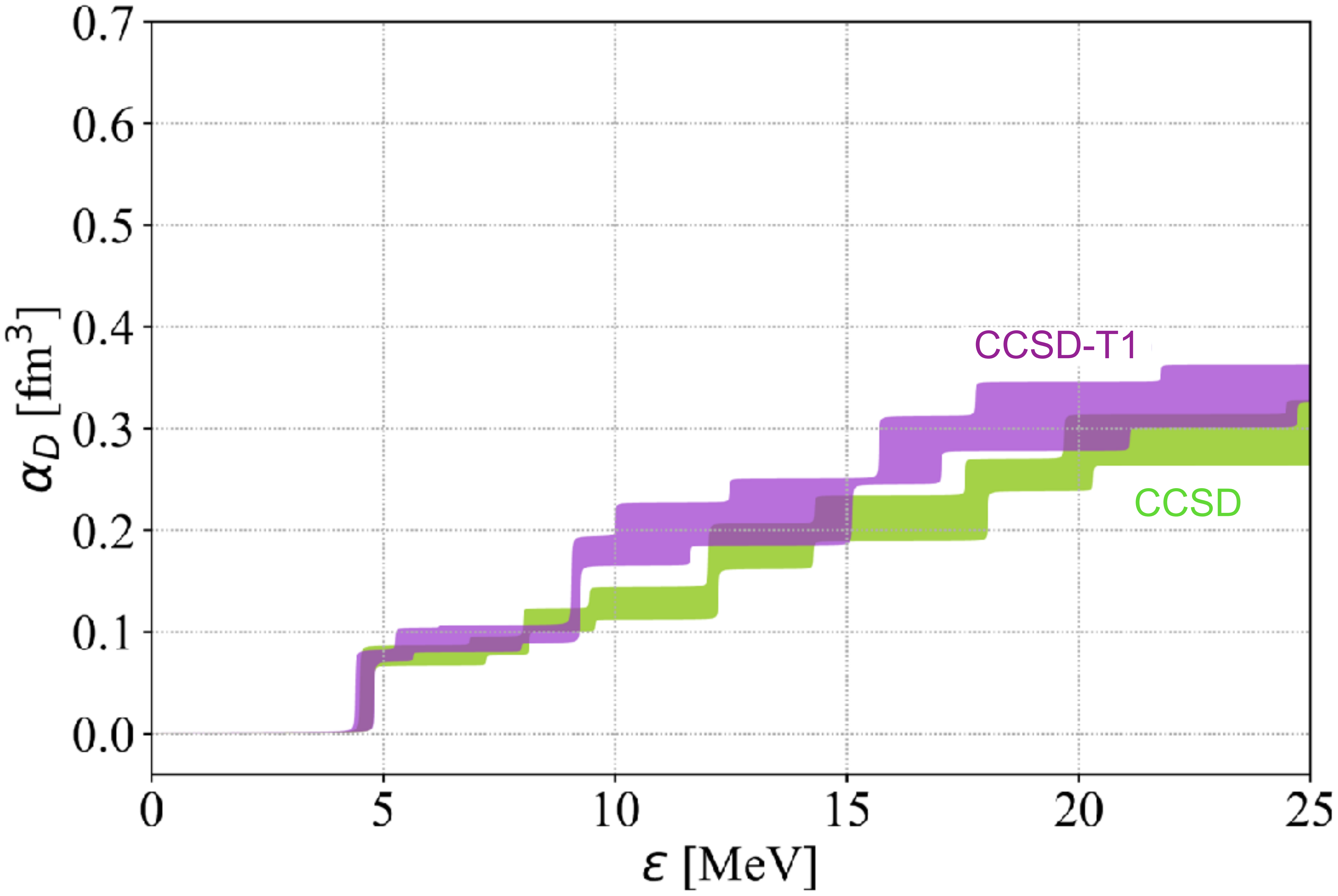
Most Exotic Nucleus N/Z=3

$^{8}\mathrm{He}$



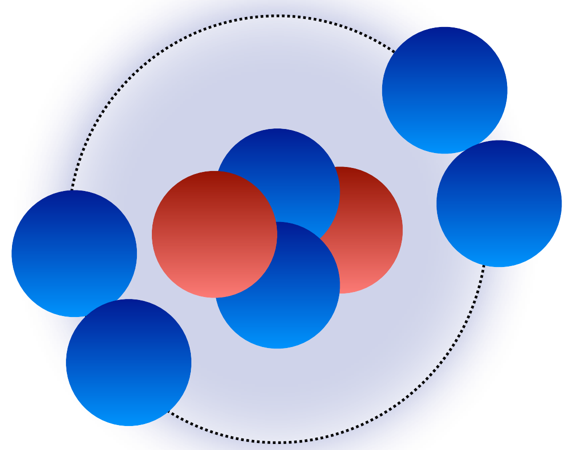
Halo nucleus

F. Bonaiti, SB, G.Hagen, PRC 105, 034313 (2022)



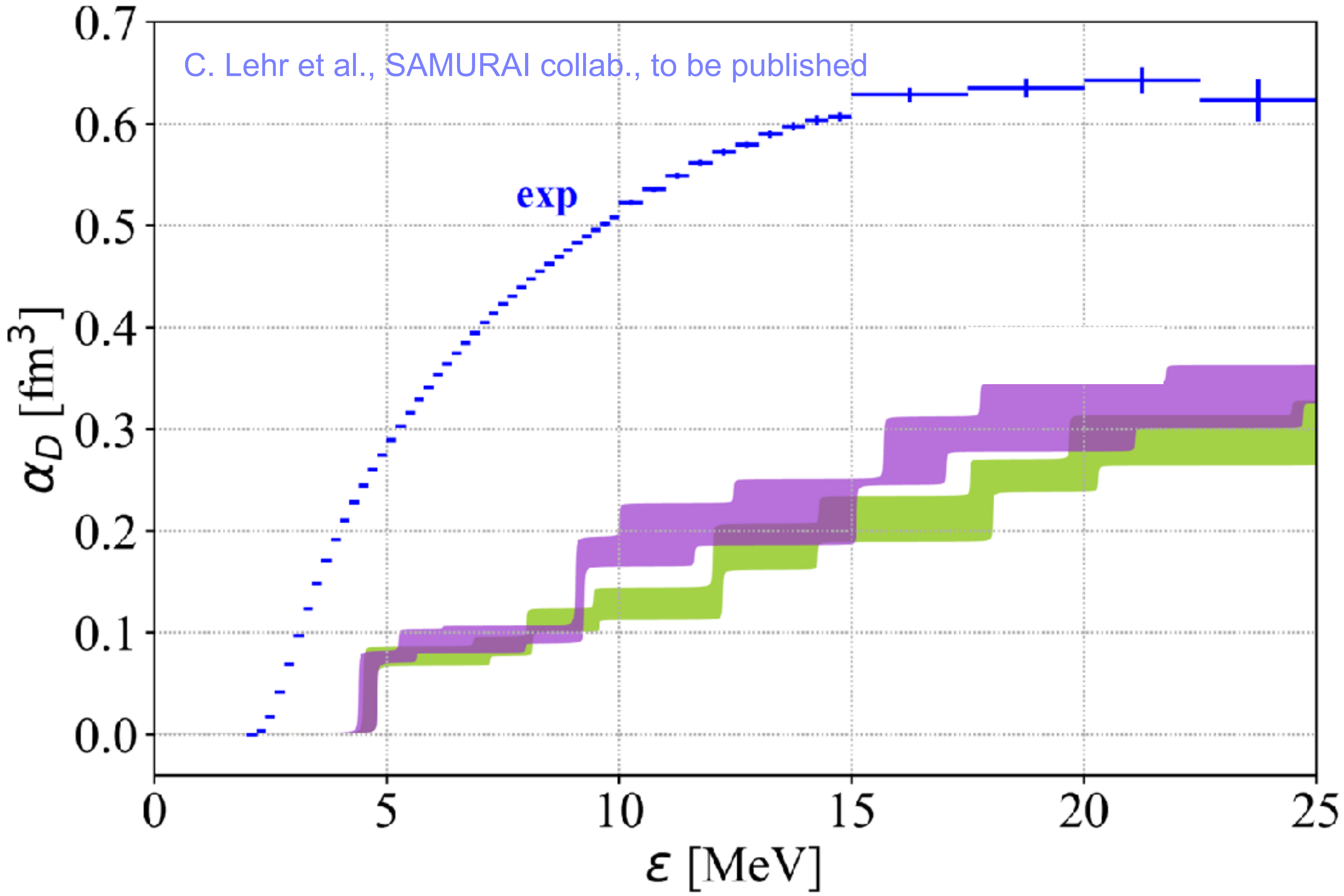
Most Exotic Nucleus N/Z=3

$^{8}\mathrm{He}$



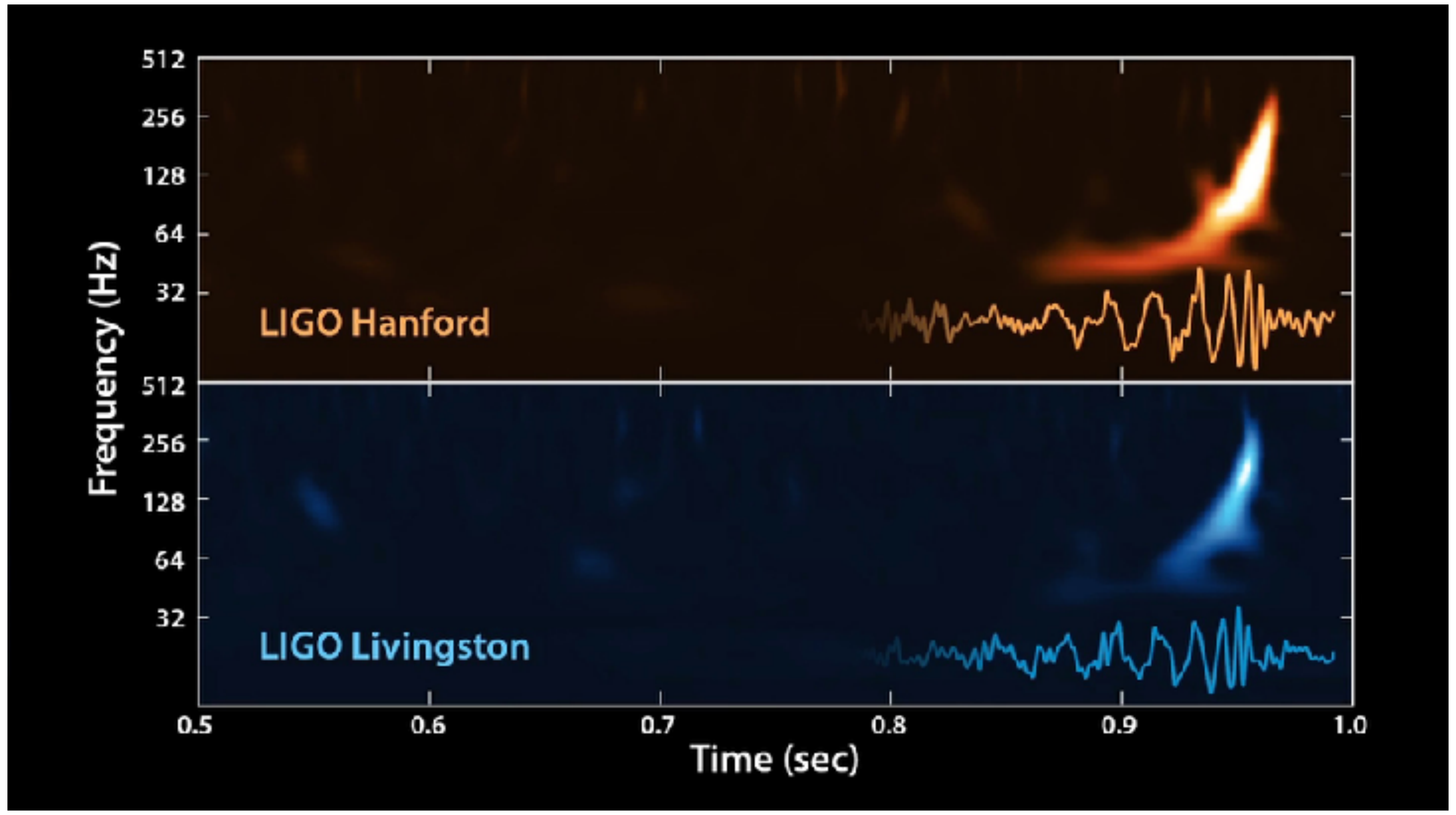
Halo nucleus

F. Bonaiti, SB, G.Hagen, PRC 105, 034313 (2022)



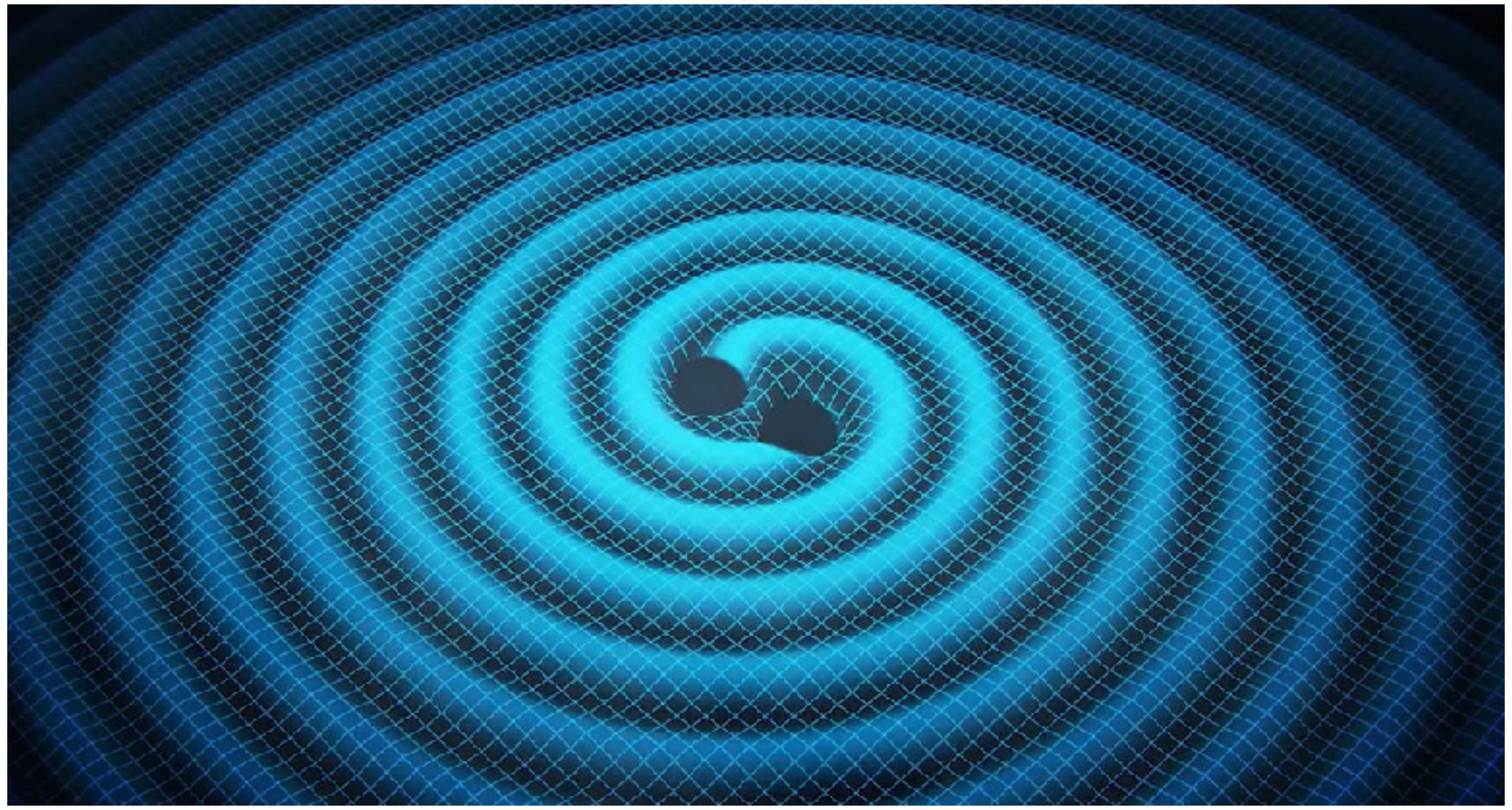
Neutron Stars

Gravitational Waves



Credits: LIGO

Sept 14,2015, **Binary Black Hole Mergers**
Abbott et al., PRL **116**, 061102 (2016)



Credits: R-Hurt/Caltech-JPL

Aug 17,2017, **Binary Neutron Star Mergers GW170817**
Abbott et al., PRL **119**, 161101 (2017)

In the era of multi-messenger astronomy, GW from neutron star mergers will constraints the nuclear EOS

Neutron Stars

The nuclear equation of state

$$E(\rho,\delta) = E(\rho,0) + S(\rho)\delta^2 + \mathcal{O}(\delta^4)$$

$$S(\rho) = S_0 + \frac{L}{3\rho_0}(\rho-\rho_0) + \frac{K_{sym}}{18\rho_0^2}(\rho-\rho_0)^2 + \dots$$

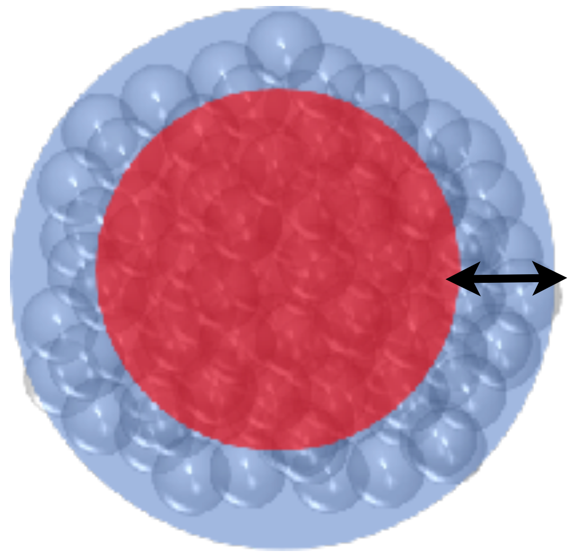
$$\rho = \rho_n + \rho_p, \quad \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

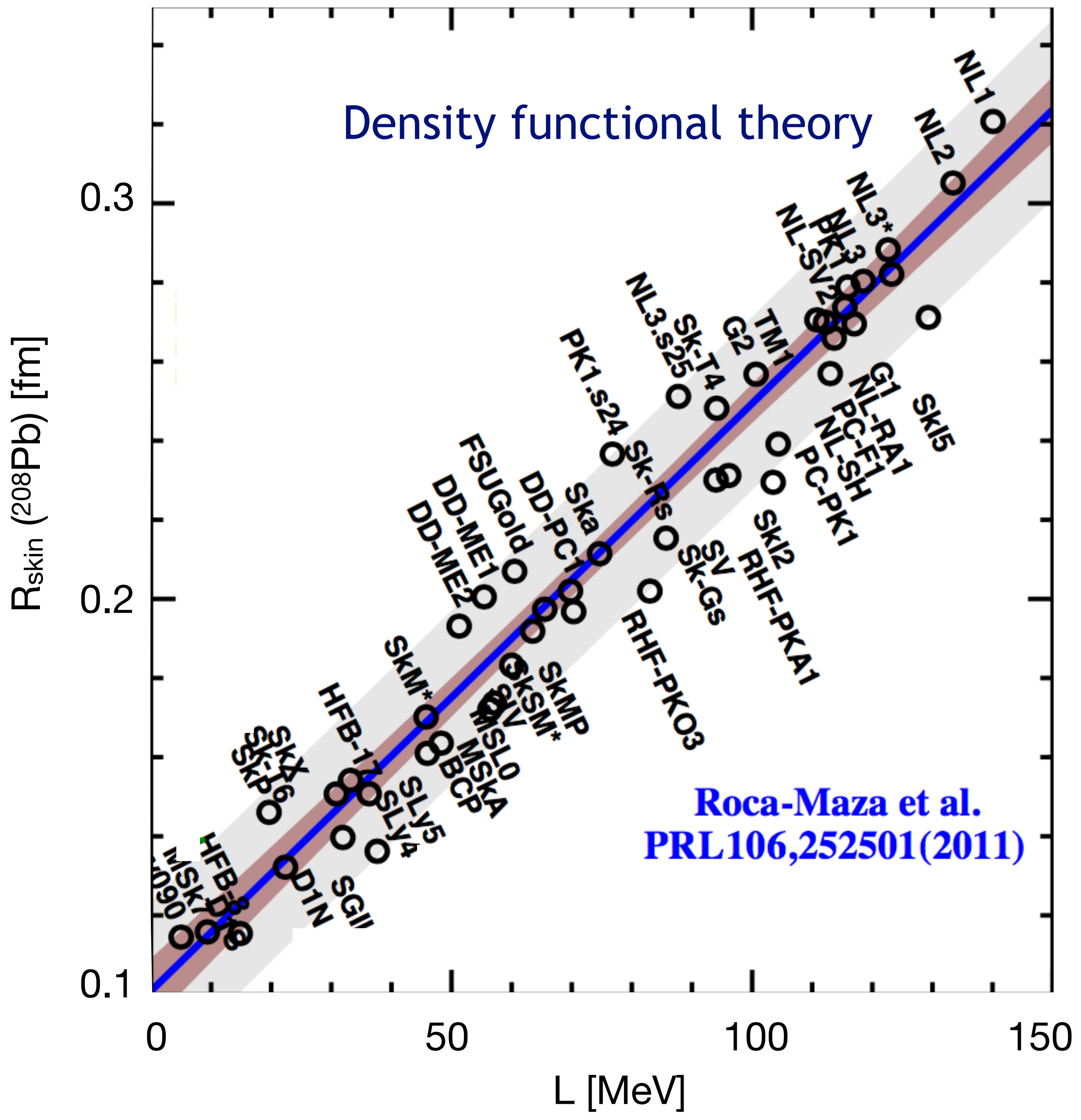
S_0 and L, K_{symm} are property of the nuclear EOS

GW will provide constraints

But laboratory measurements on finite nuclei are crucial

$^{208}\mathrm{Pb}$

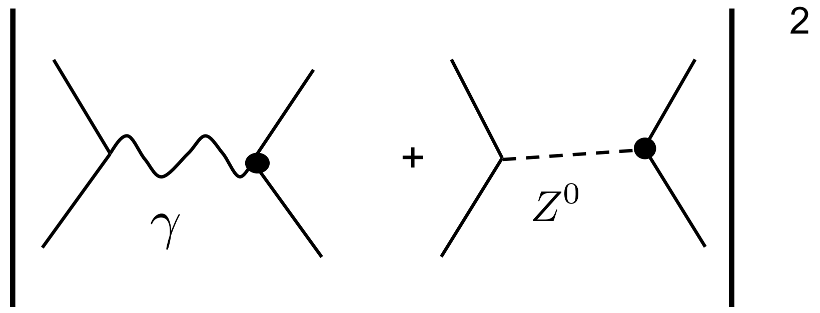




Neutron Stars

In the laboratory

Parity violating electron scattering

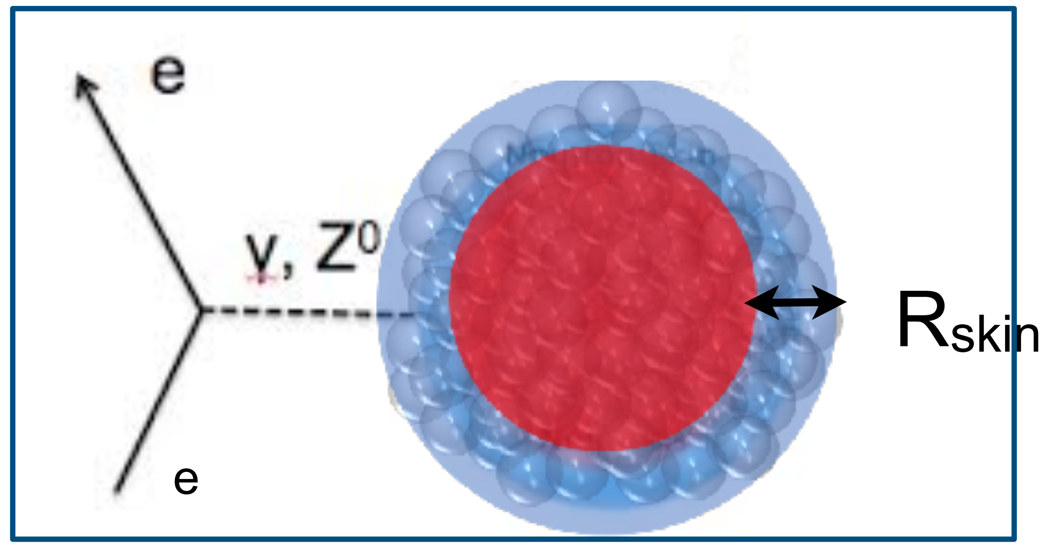


$$= |M_\gamma + M_{Z^0}|^2 \sim |M_\gamma|^2 + 2M_\gamma(M^*_{Z^0}) + \dots$$

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \approx -\frac{G_F q^2}{4\pi\alpha\sqrt{2}} \frac{Q_W F_W(q^2)}{Z F_{ch}(q^2)}$$

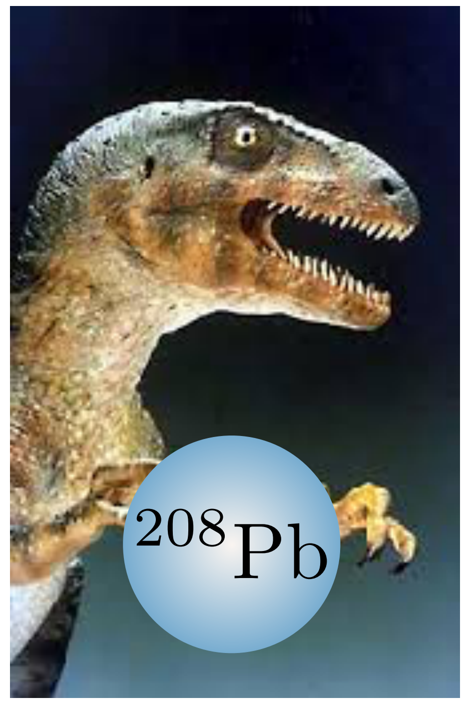
	Proton	**Neutron**
Electric charge	1	0
Weak charge	~0.08	~-1

polarized electron beam



unpolarized target

Pb Radius Experiment



PREX-I $r_{\text{skin}}(^{208}\text{Pb}) = 0.33^{+0.16}_{-0.18}$ fm

PREX-II $r_{\text{skin}}(^{208}\text{Pb}) = 0.283 \pm 0.071$ fm

Ca Radius Experiment

CREX $r_{skin}(^{48}\text{Ca}) = 0.21 \pm 0.026(\text{exp}) \pm 0.024(\text{exp})\text{fm}$

Future: Mainz Radius Experiment @ MESA

MREX

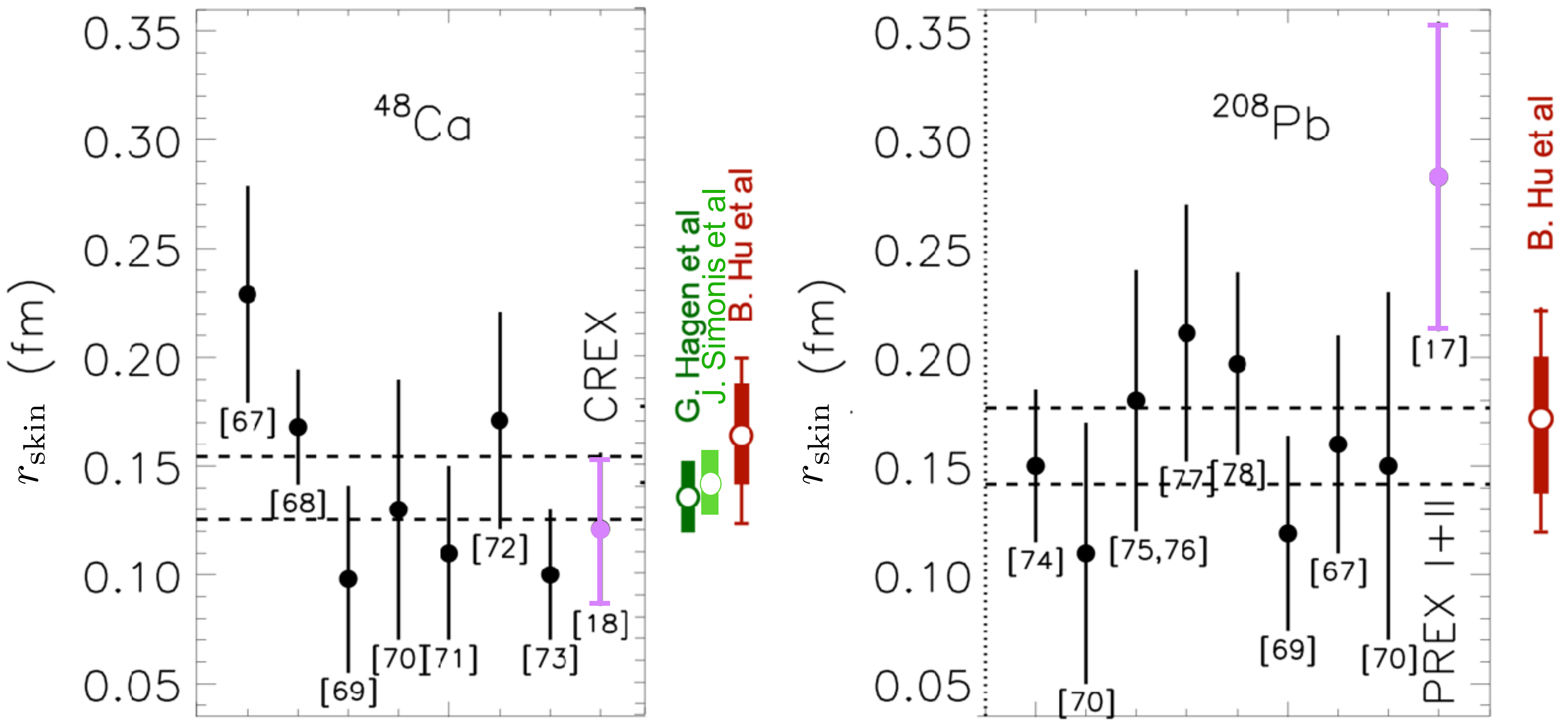
Improve the precision by a factor of two wrt PREX-II

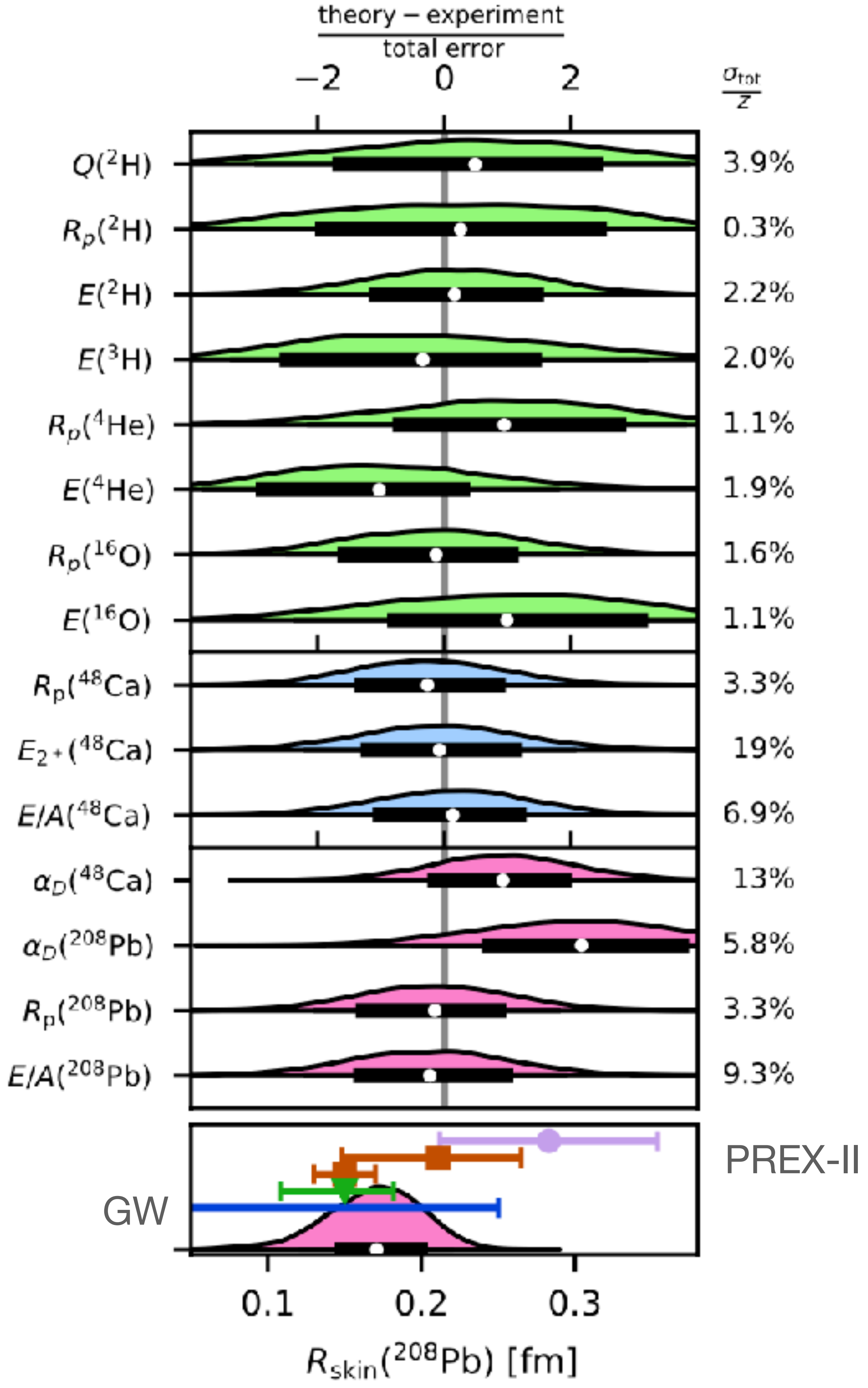
Neutron-skin thickness

Comparison to calculations

B. Hu, W. Jiang et al.,
Nature Phys. **18**, 1196 (2022)

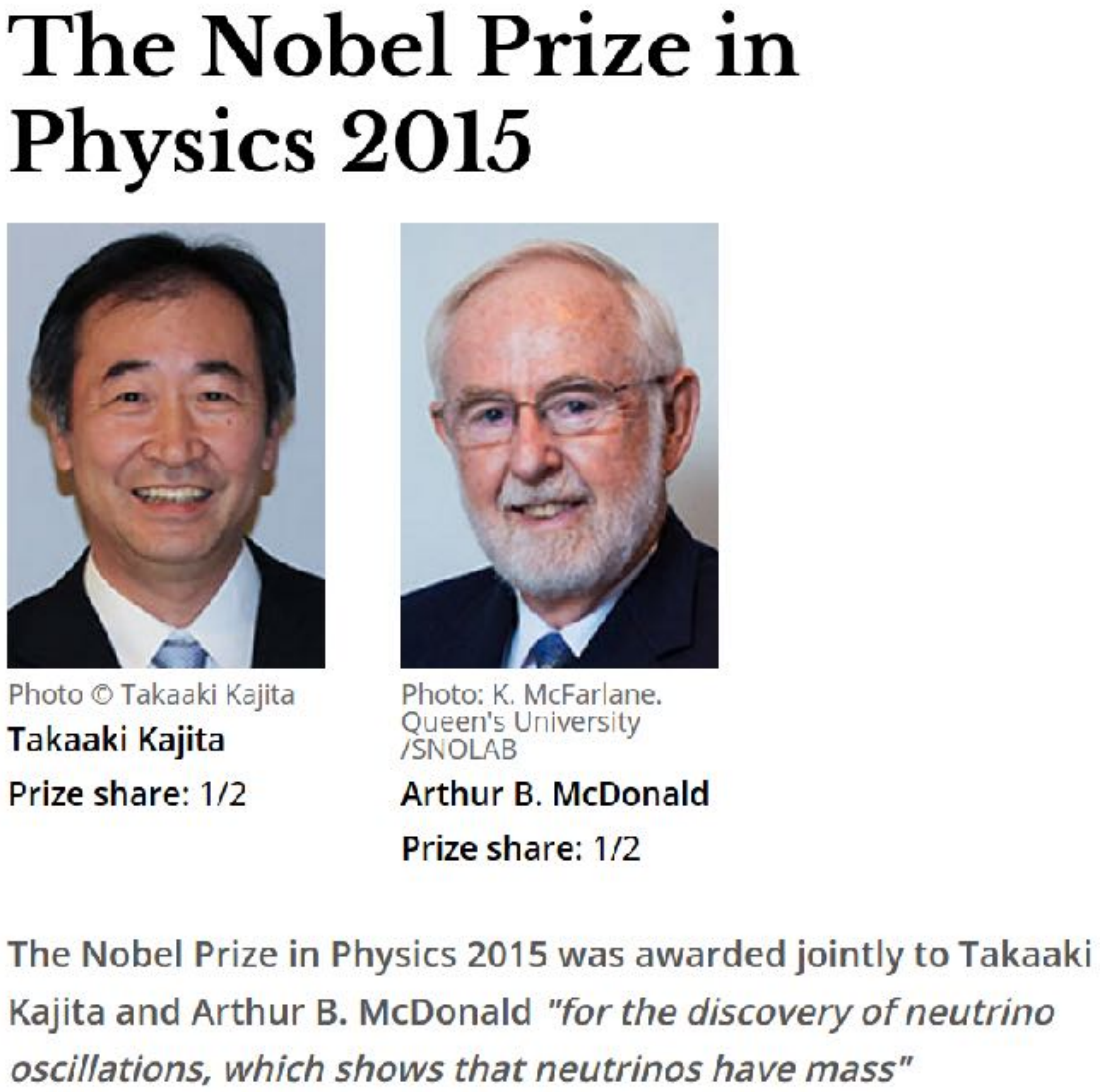
Constraints on Nuclear Symmetry Energy Parameters J. Lattimer. Particles **6**, 30-56 (2023)





Applications to Neutrino Physics

Neutrino Oscillations



The Nobel Prize in Physics 2015

Photo © Takaaki Kajita

Takaaki Kajita

Prize share: 1/2

Photo: K. McFarlane. Queen's University /SNOLAB

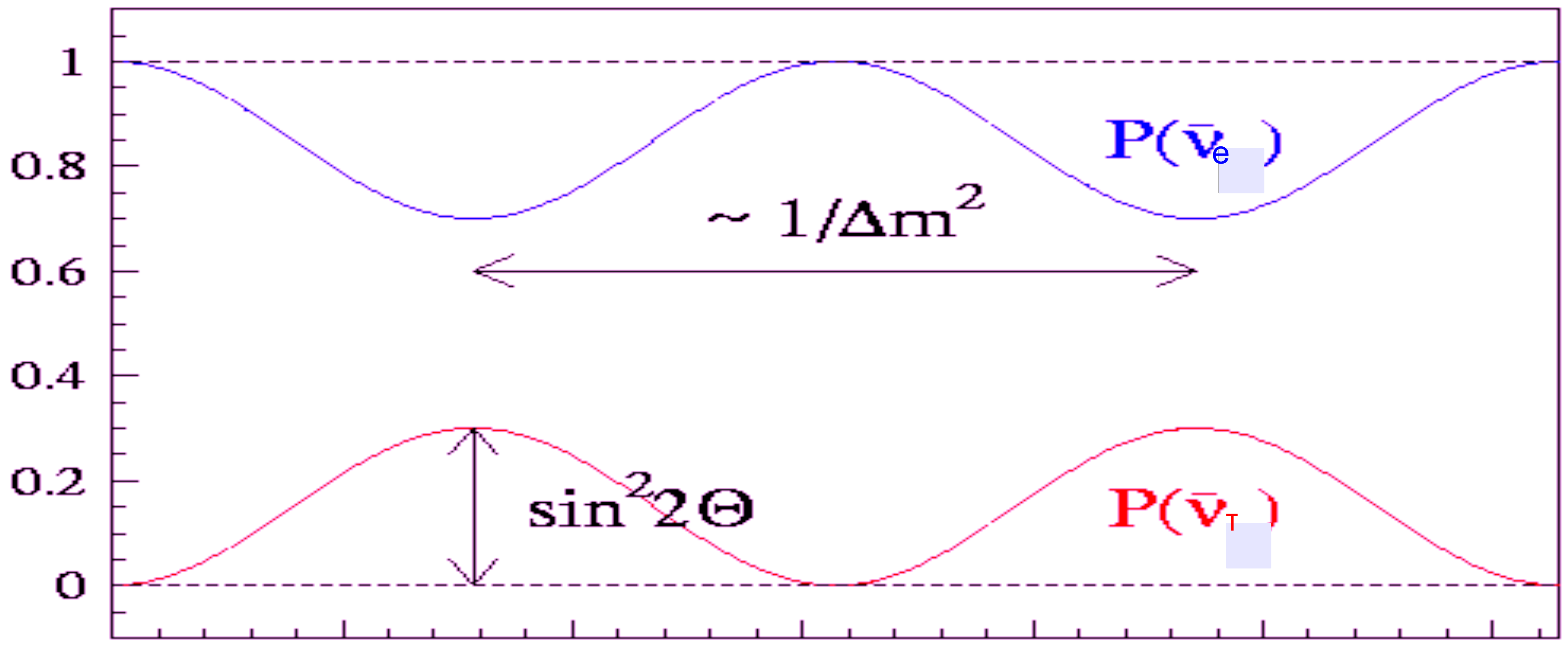
Arthur B. McDonald

Prize share: 1/2

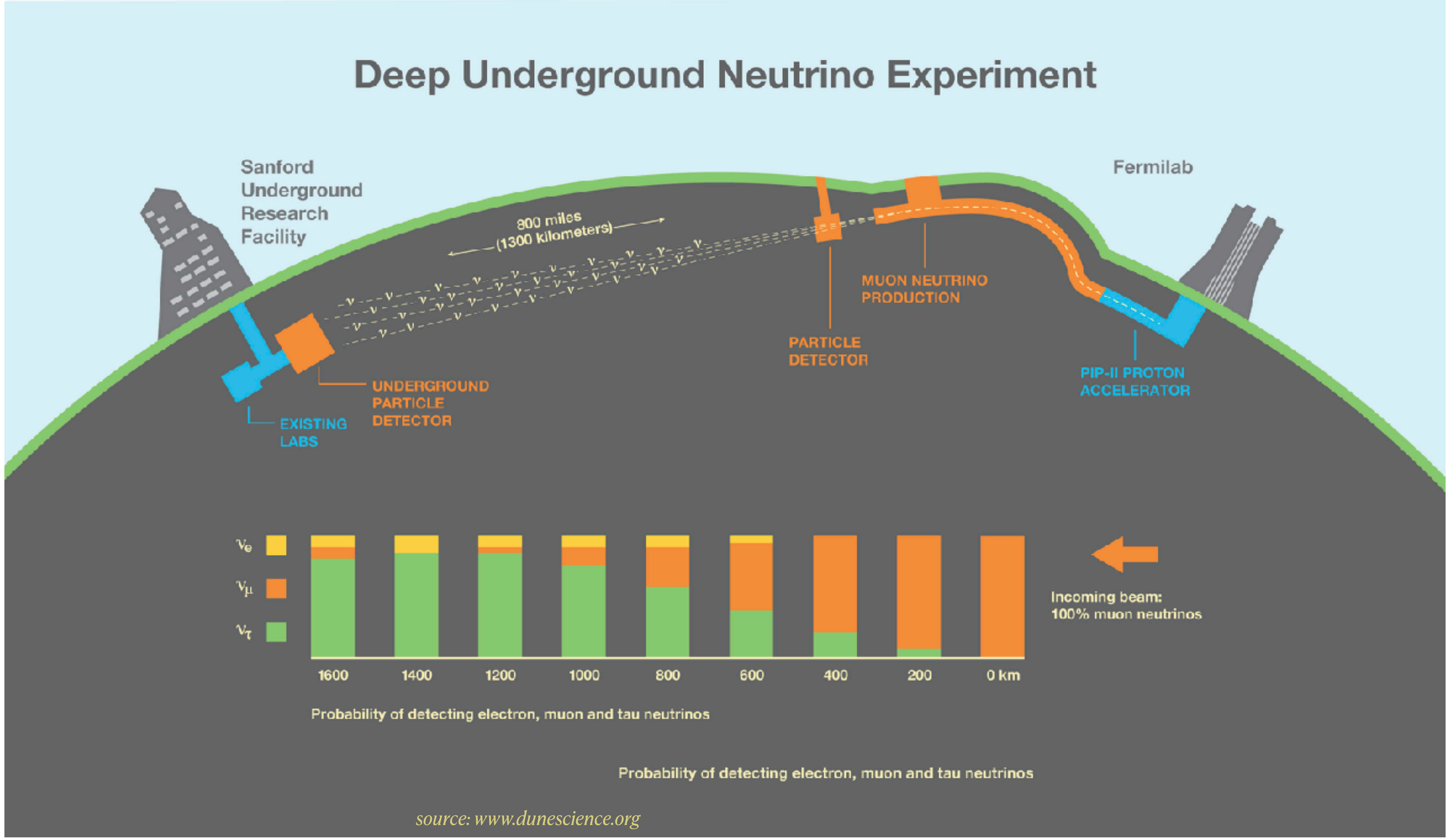
The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald *"for the discovery of neutrino oscillations, which shows that neutrinos have mass"*

oscillations ⇒ small masses ⇒ BSM physics

$$P_{\nu_e \to \nu_\mu} = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{2E_\nu} \right)$$



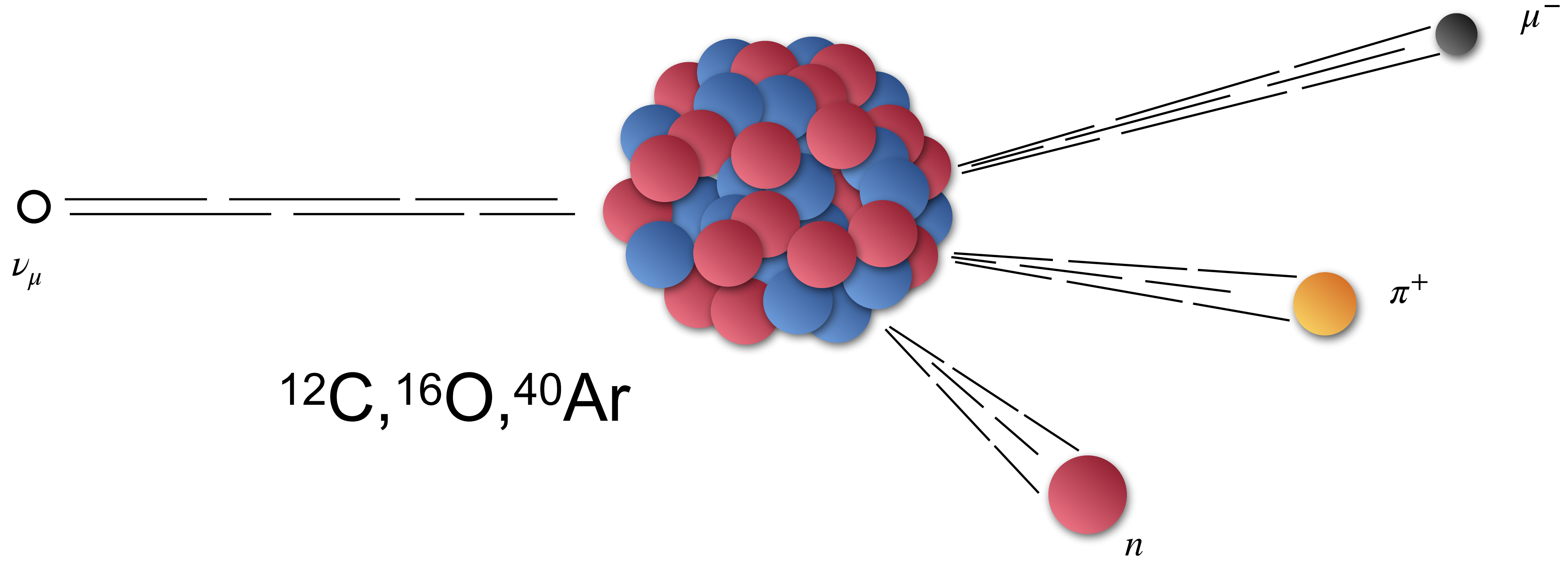
Neutrino Oscillations

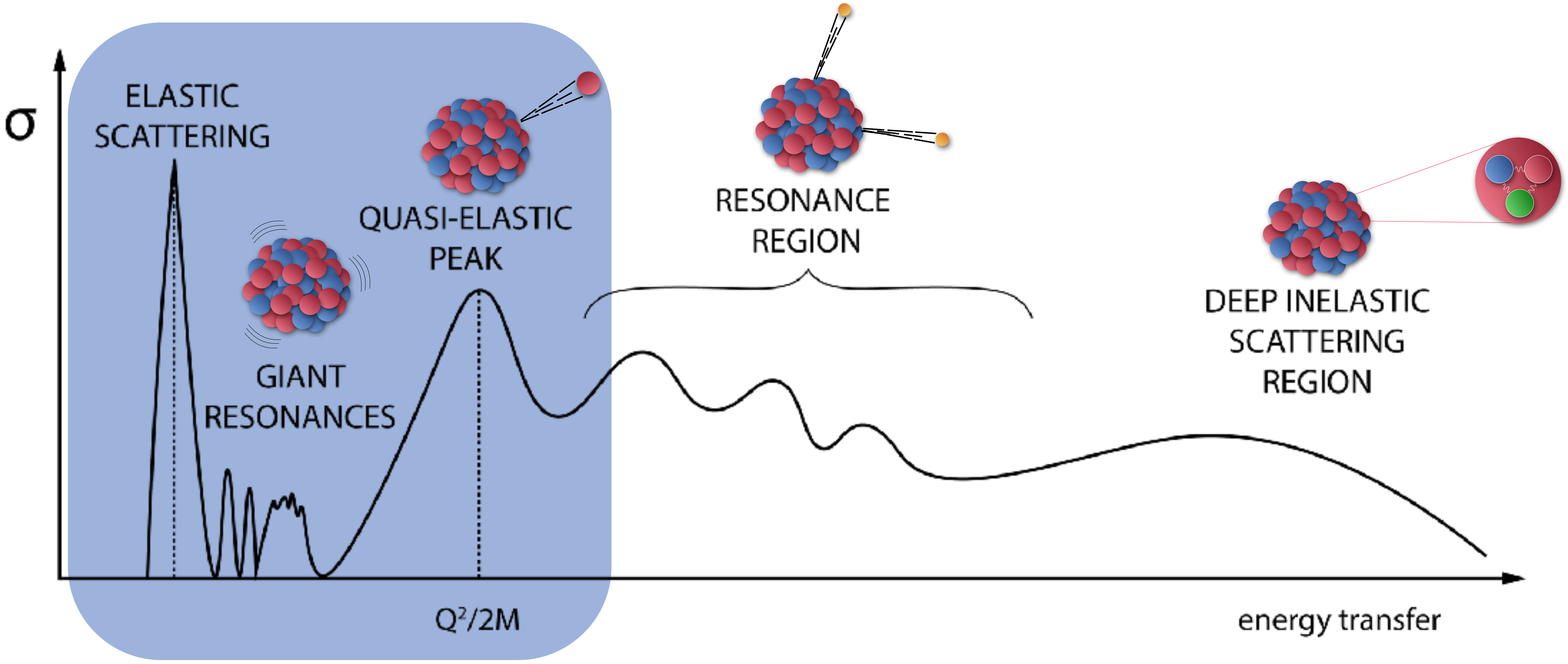


source: www.dunescience.org

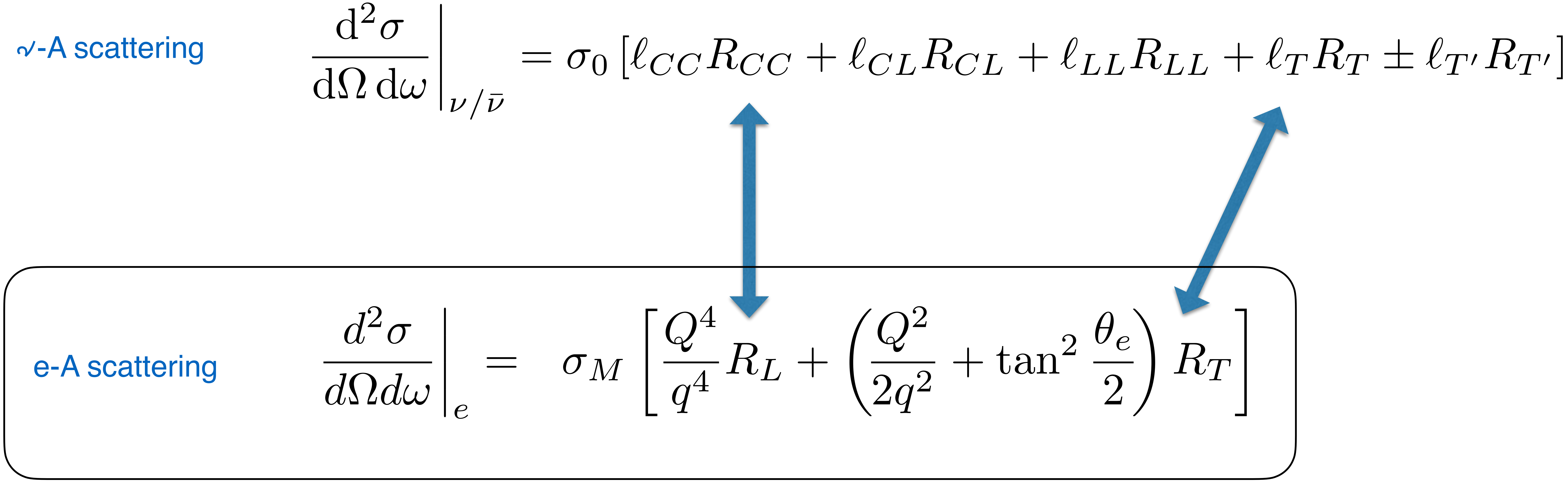
Aims and Challenges

Neutrino energy is reconstructed in each event





Electrons for neutrinos



ν-A scattering

$$\left.\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}\omega}\right|_{\nu/\bar{\nu}} = \sigma_0\left[\ell_{CC}R_{CC}+\ell_{CL}R_{CL}+\ell_{LL}R_{LL}+\ell_{T}R_{T}\pm\ell_{T'}R_{T'}\right]$$

e-A scattering

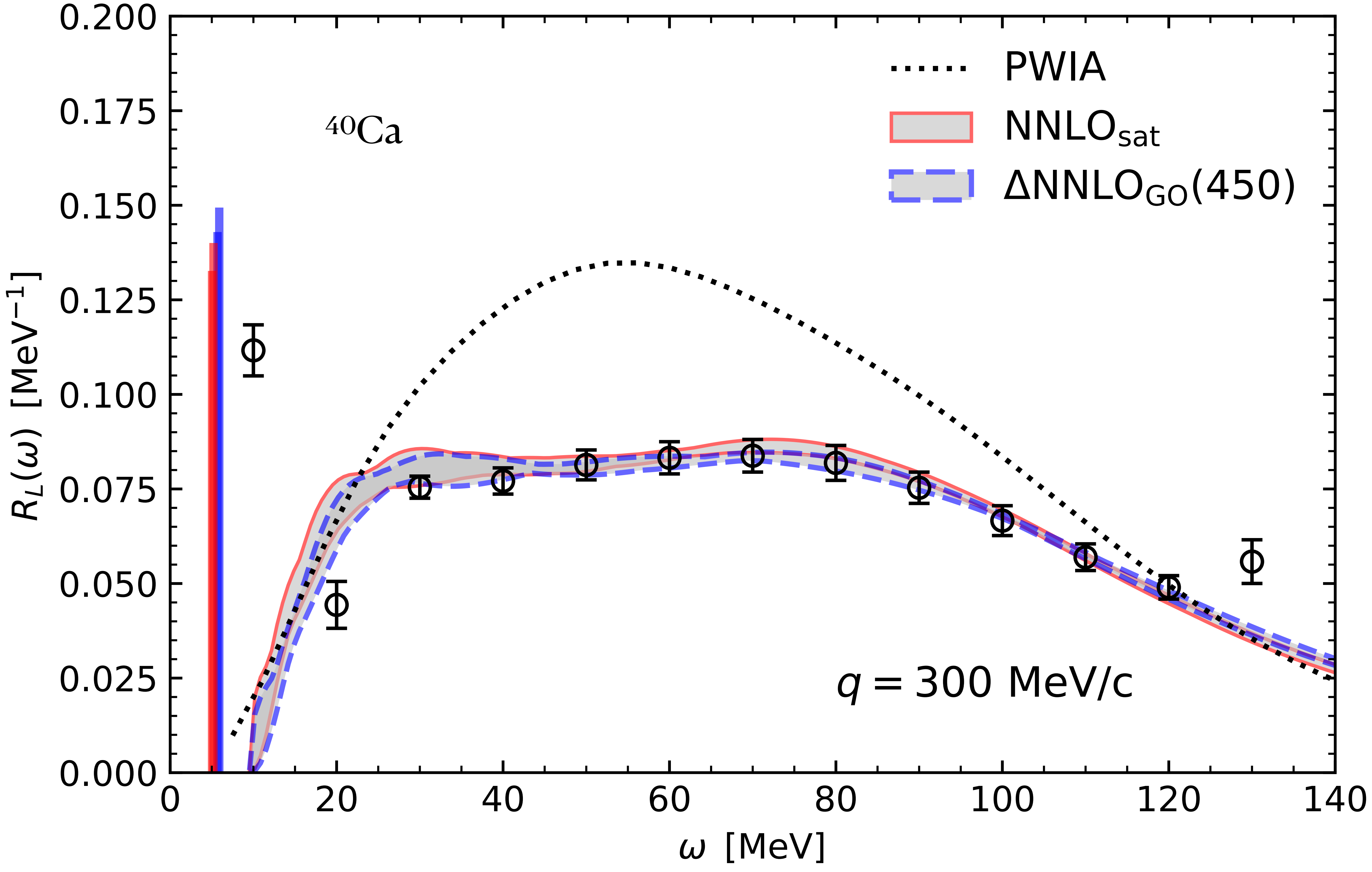
$$\left.\frac{d^2\sigma}{d\Omega d\omega}\right|_{e} = \sigma_M\left[\frac{Q^4}{q^4}R_L+\left(\frac{Q^2}{2q^2}+\tan^2\frac{\theta_e}{2}\right)R_T\right]$$

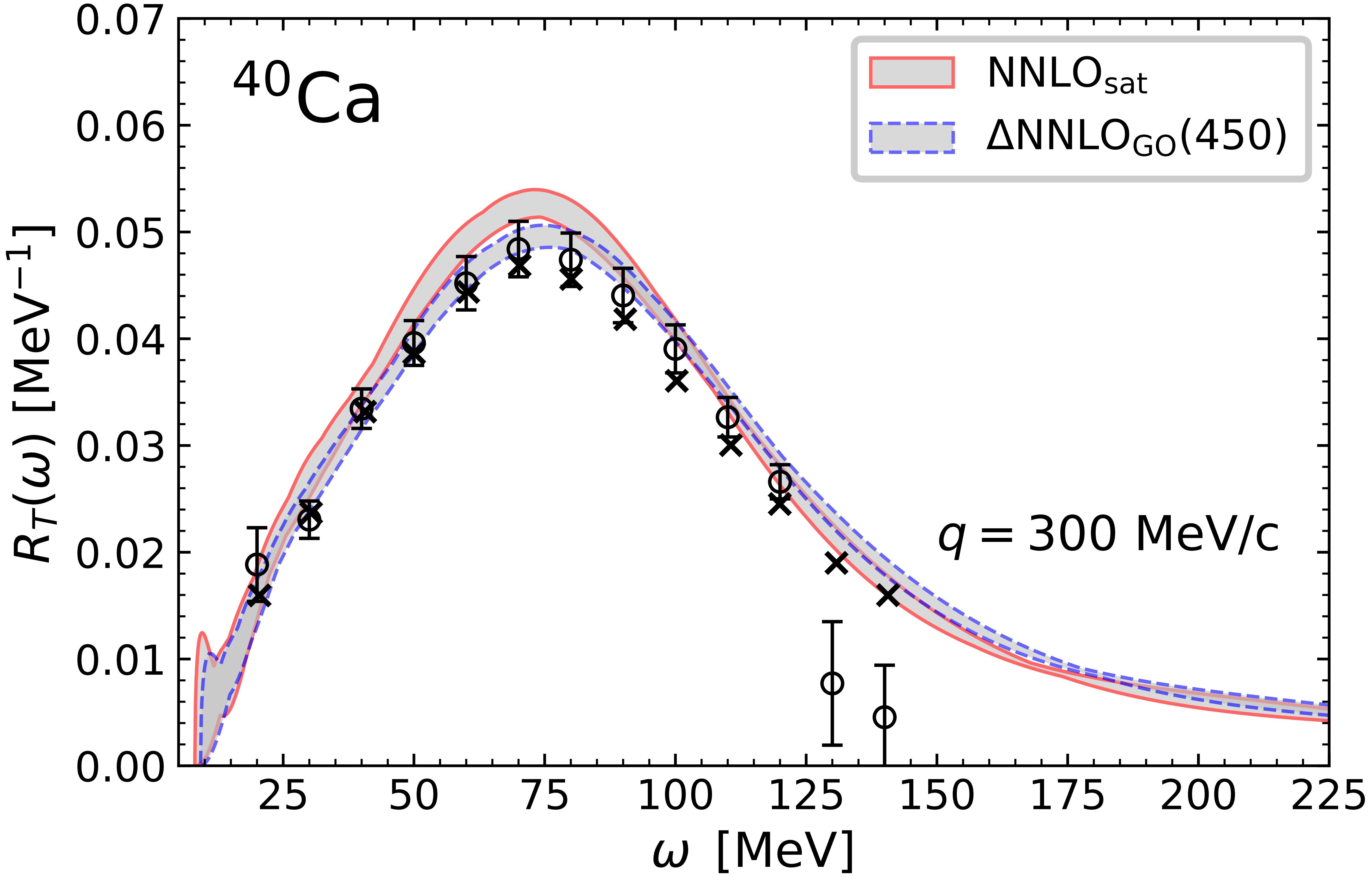
Recent highlights

40Ca(e,e')X with LIT

Sobcyzk, Acharya, SB, Hagen, PRL 127 (2021) 7, 072501

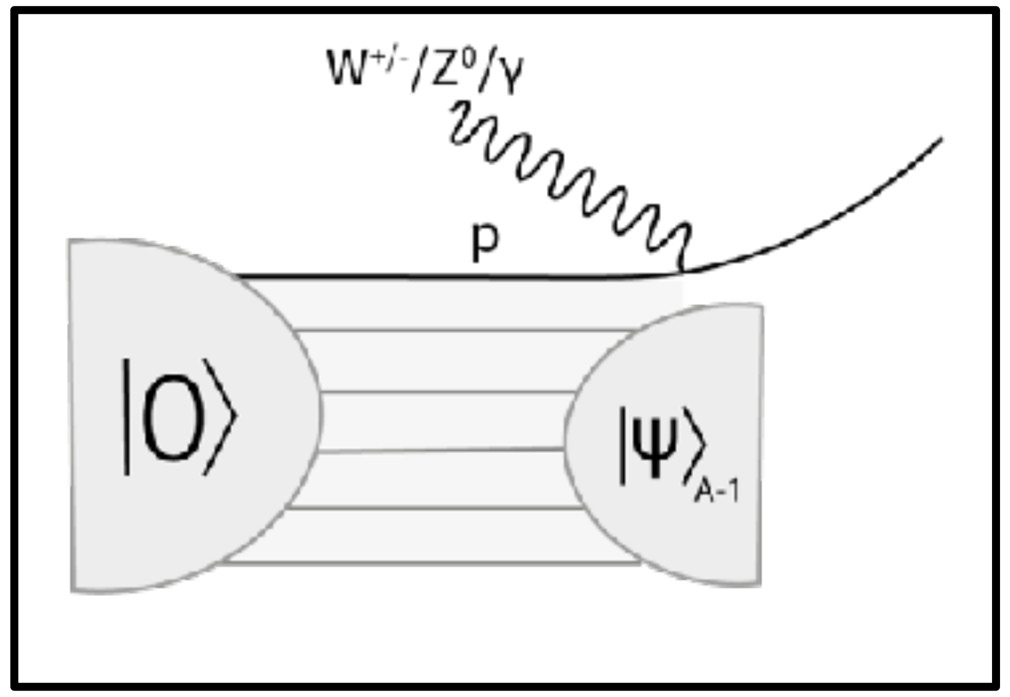
Acharya, Sobczyk, SB, et al., in preparation



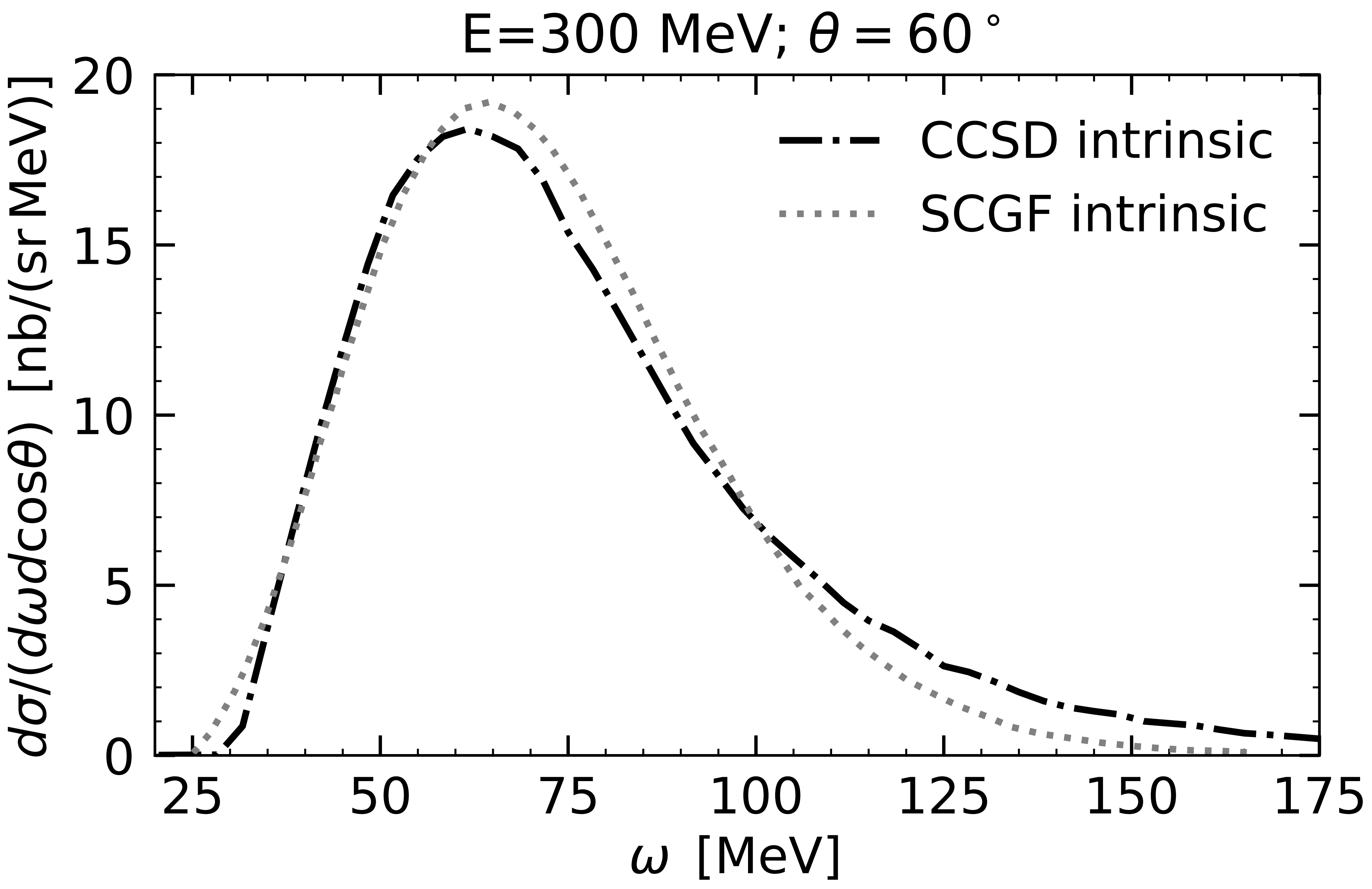


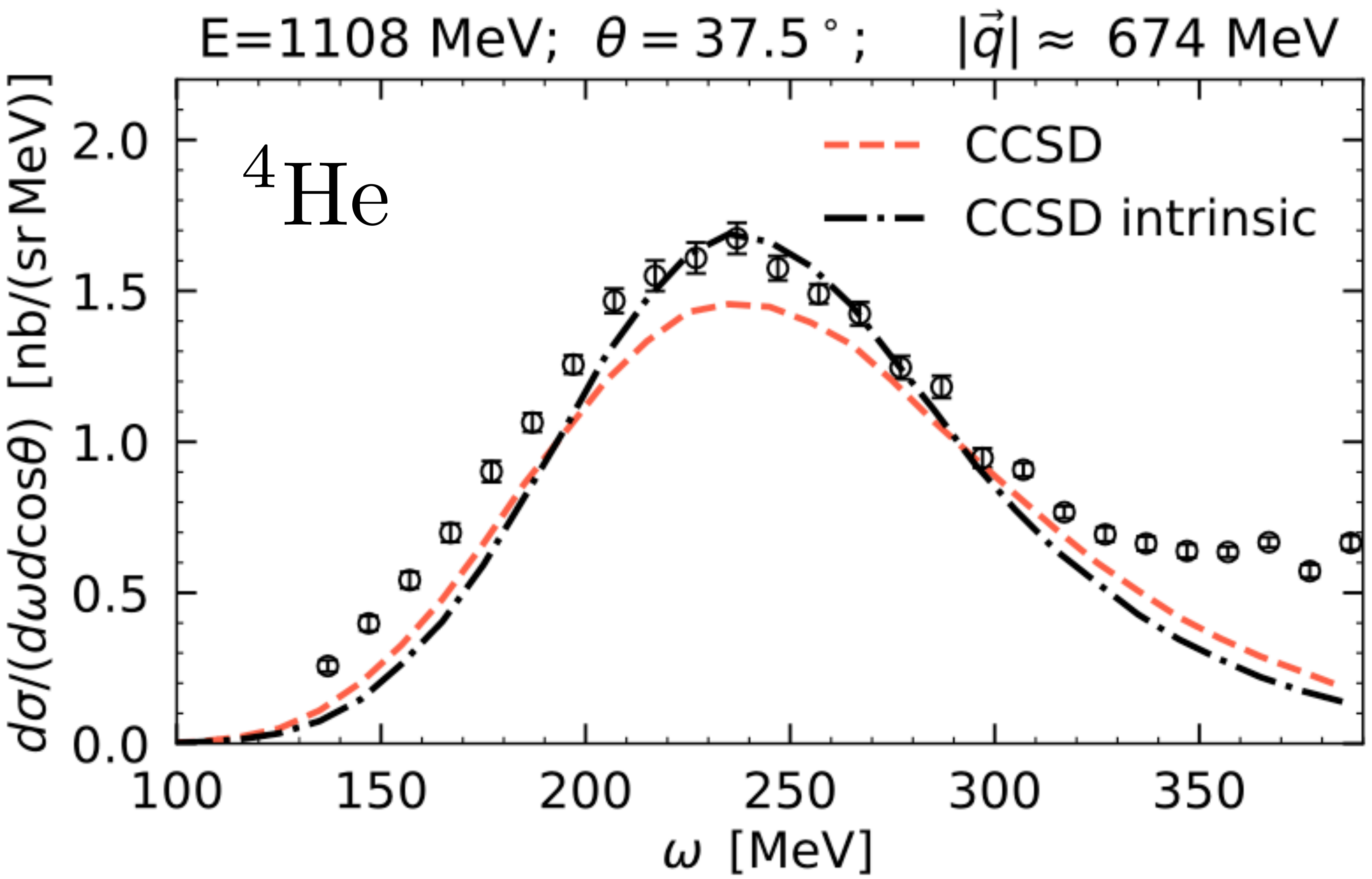
Recent highlights

Spectral function formalism



Sobczyk, SB, Hagen, Papenbrock, PRC 106, 034310 (2022)



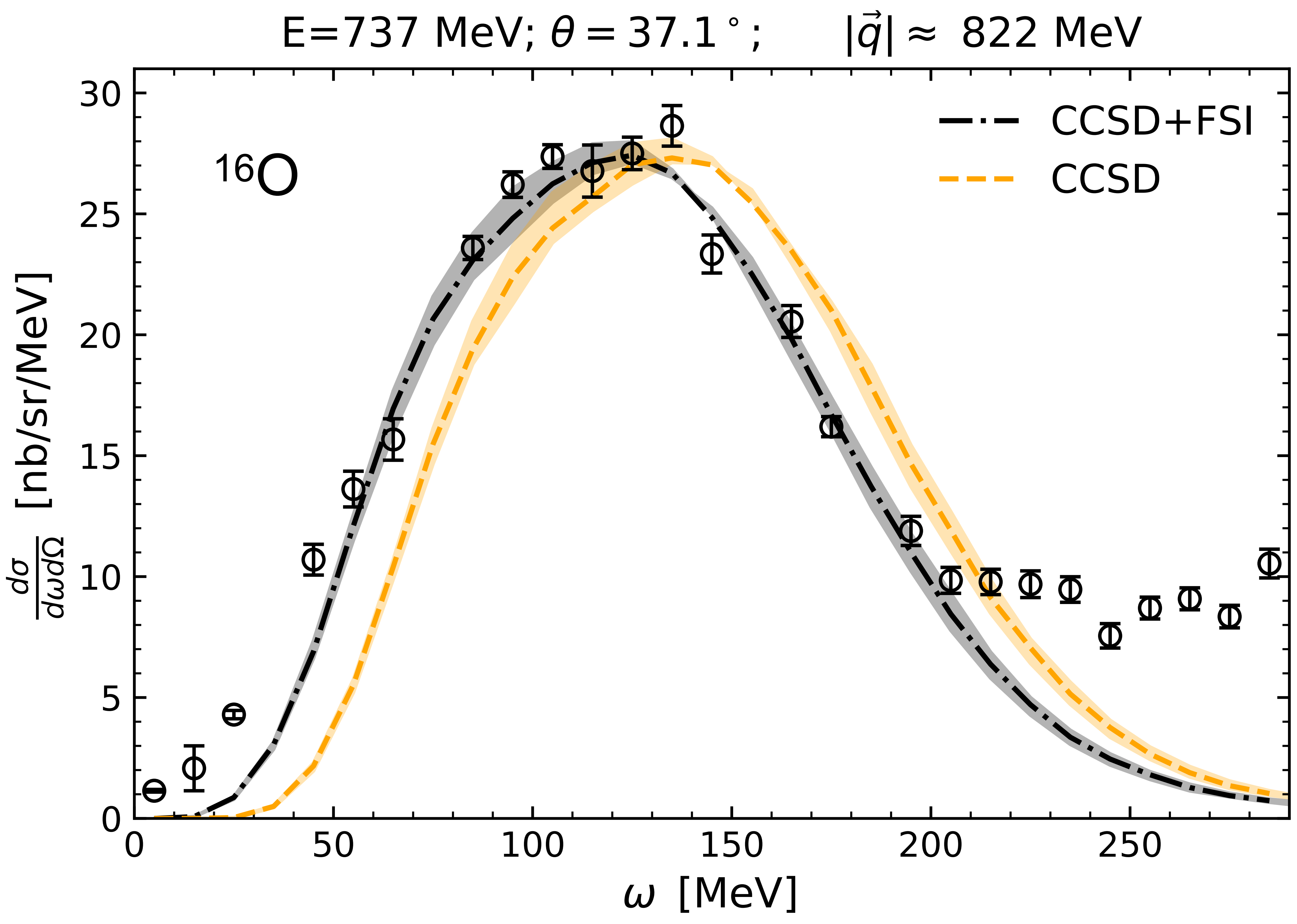


SCGF: Rocco, Barbieri, PRC 98 (2018) 022501

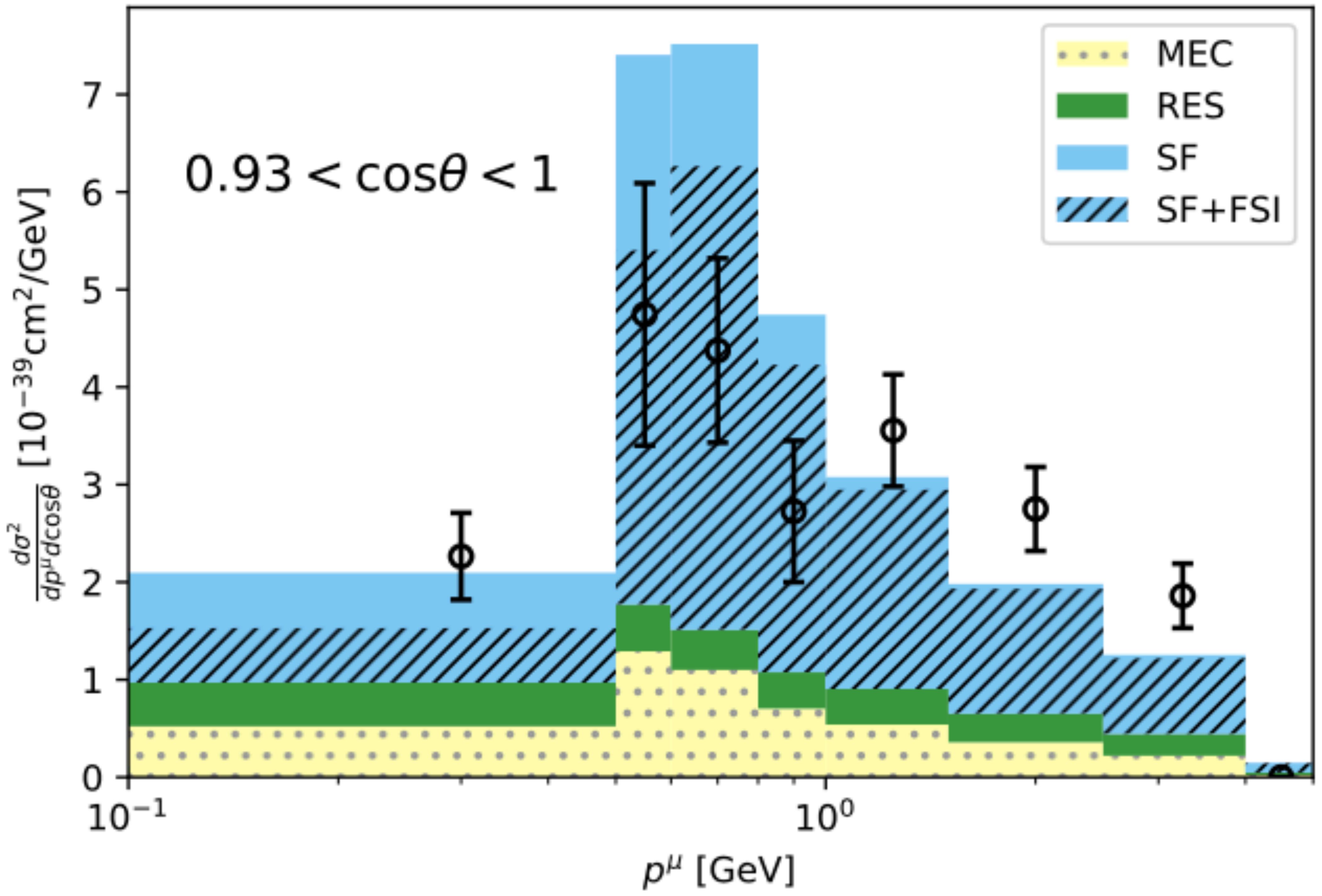
Towards neutrino scattering

Sobczyk and SB, to be submitted (2023)

$$e + {}^{16}\mathrm{O} \rightarrow e' + X$$



$$\nu_\mu + {}^{16}\mathrm{O} \rightarrow \mu^- + X$$



Conclusions and Outlook

- Remarkable progress in ab initio calculations
- Electroweak reactions are fascinating because they allow to connect nuclear physics to other areas of physics
- Stay tuned for future progress!

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B. Acharya, F. Bonaiti, W. Jiang, G. Hagen, T. Papenbrock, A. Schwenk,
J. Simonis, **J.E. Sobczyk,** et al.

Thanks for your attention!