



Spectral imprints of nuclear many-body correlations: Constraining theory toward the spectroscopic accuracy frontier

Elena Litvinova



Western Michigan University



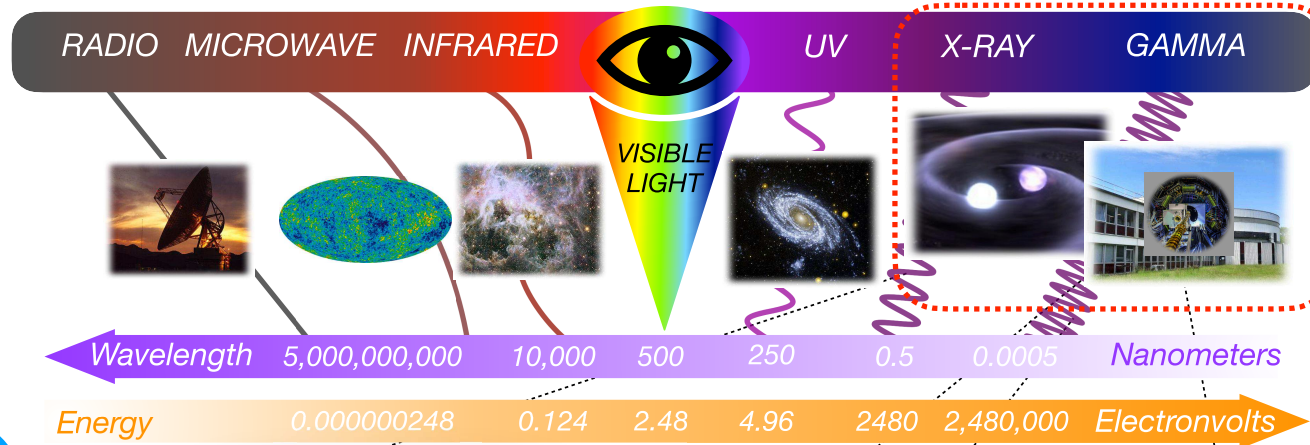
ESNT Workshop: Many-body correlations, phase transitions, and clustering: how to identify and quantify them?
September 7-11, 2026, Saclay, France



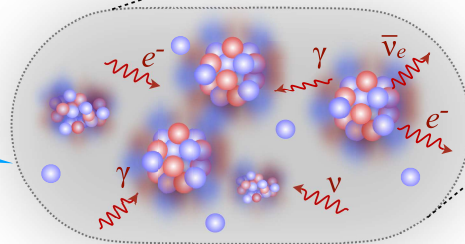
Preface: The strongly coupled many-body problem and nuclear structure

- Nuclear structure theory has strived for decades to achieve *accurate computation of nuclear spectra*, but *spectroscopic accuracy remains a challenge* even for the most advanced many-body models
- Such accuracy is necessary to assess and guide solutions to the strongly-coupled many-body problem generally, and for nuclear structure applications (experiment, astrophysics, new physics searches etc.)
- We address this problem by developing the *relativistic nuclear field theory (RNFT)* in the universal model-independent Quantum Field Theory framework, quantifying fermionic correlation functions (FCFs)
- The theory (i) is transferable across energy scales, (ii) is capable of identifying the bottlenecks of existing nuclear structure approaches, and (iii) *opens the door to spectroscopic accuracy* via systematic treatment of complex correlations encoded in FCFs
- It enables a *systematically improvable (parameter-free) many-body theory* with an optimal balance of fundamentality, feasibility, and accuracy
- *Nuclear spectra* studied at major facilities worldwide help benchmark the numerical implementations and justify extrapolations to exotic systems and astrophysical conditions
- *Outline: Introduction, Formalism, Selected examples and Open Problems*

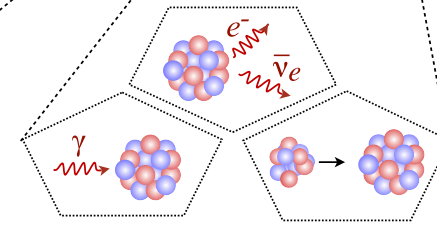
Nuclear Structure and Multimessenger Astrophysics



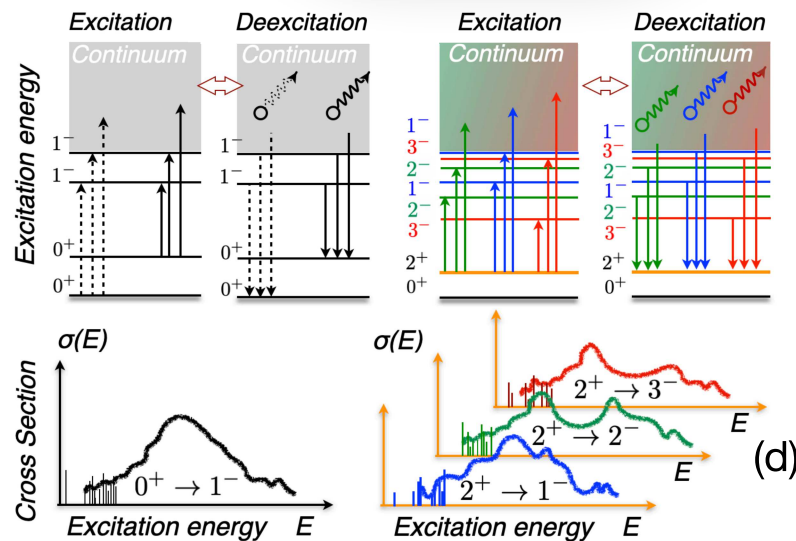
Stellar environments:
Statistical ($T > 0$)
vs direct
transitions between
nuclear excited states



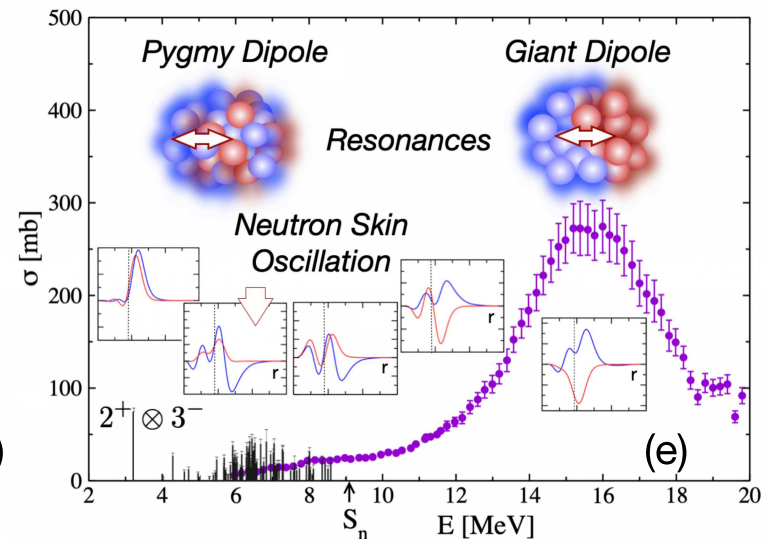
(b)



(c)



(d)



(e)

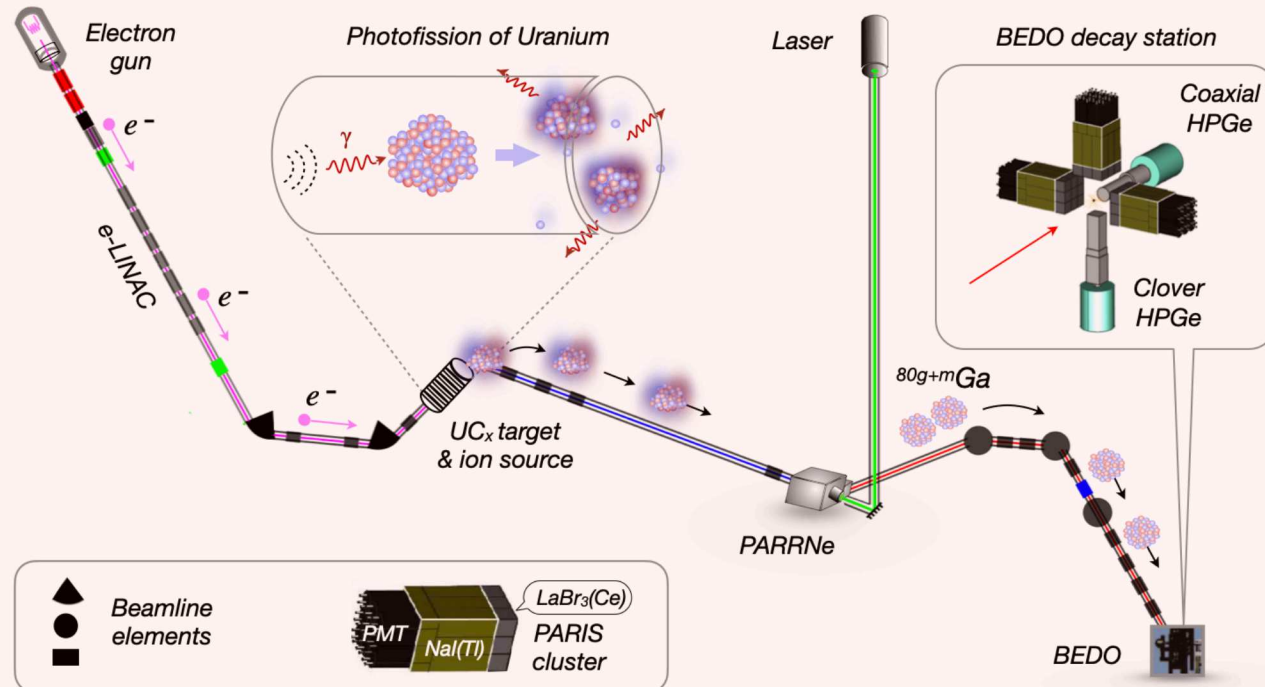
β -Decay of ^{80m}Ga to ^{80}Ge : A Primer on r -Process Waiting-Point Phenomenology

First evidence for the $J > 1$ components of the
pygmy dipole resonance in neutron-rich nuclei

R. Li^{1,2*}, E. Litvinova^{3,4}, M. N. Harakeh⁵, D. Verney¹, I. Matea¹,
L. Al Ayoubi^{1,6}, H. Al Falou⁷, P. Bednarczyk⁸, G. Benzoni⁹,
V. Bozkurt¹⁰, A. Bracco^{9,11}, M. Ciemala⁸, F. C. L. Crespi^{9,11},
I. Deloncle¹, S. Ebata¹², A. Gottardo¹³, K. Hadyńska-Klęk¹⁴,
N. Jovancevic^{1,15}, A. Kankainen⁶, M. Kmiecik⁸, A. Maj⁸,
T. Martínez¹⁶, V. Nanal¹⁷, O. Stezowski¹⁸

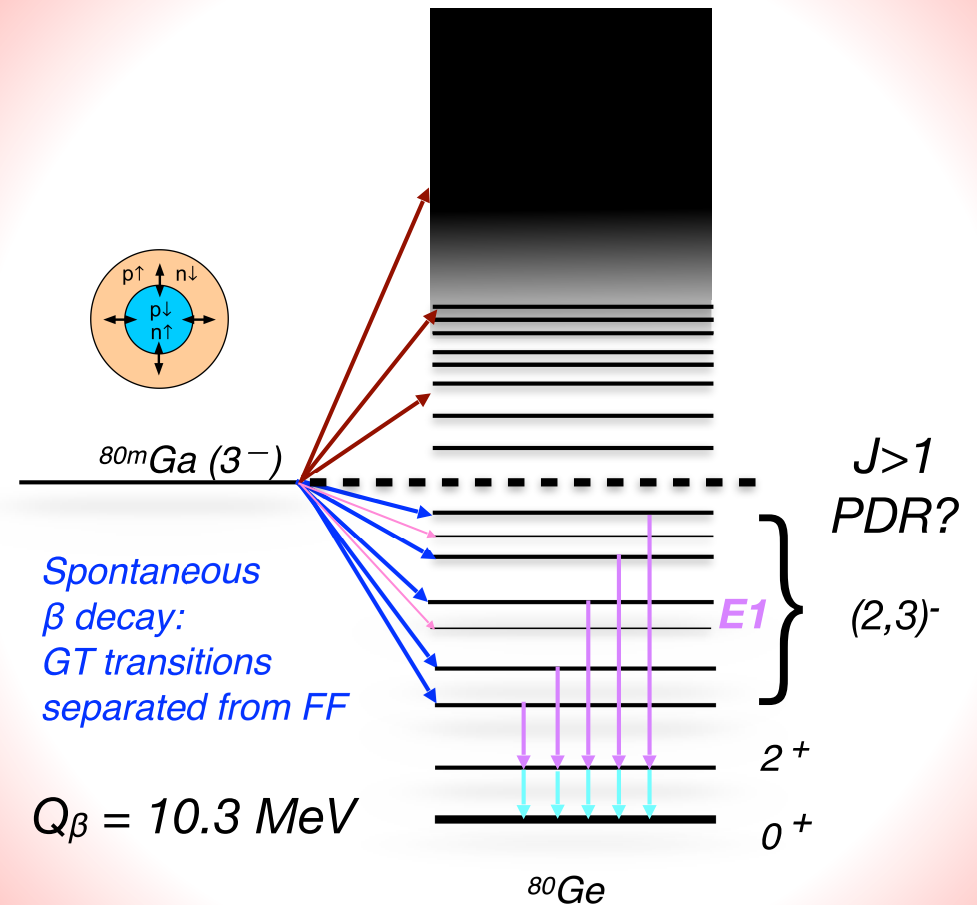
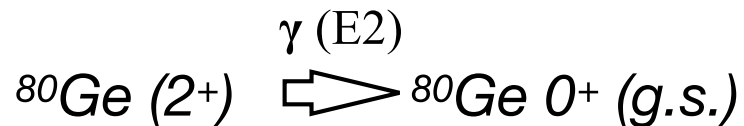
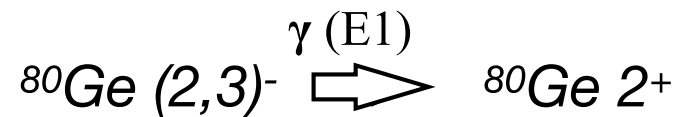
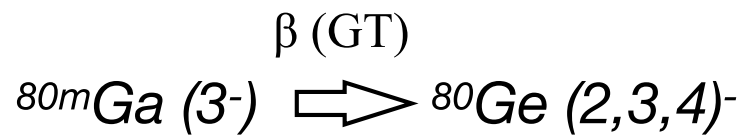
arXiv:2510.27125

ALTO Facility @ IJCLab



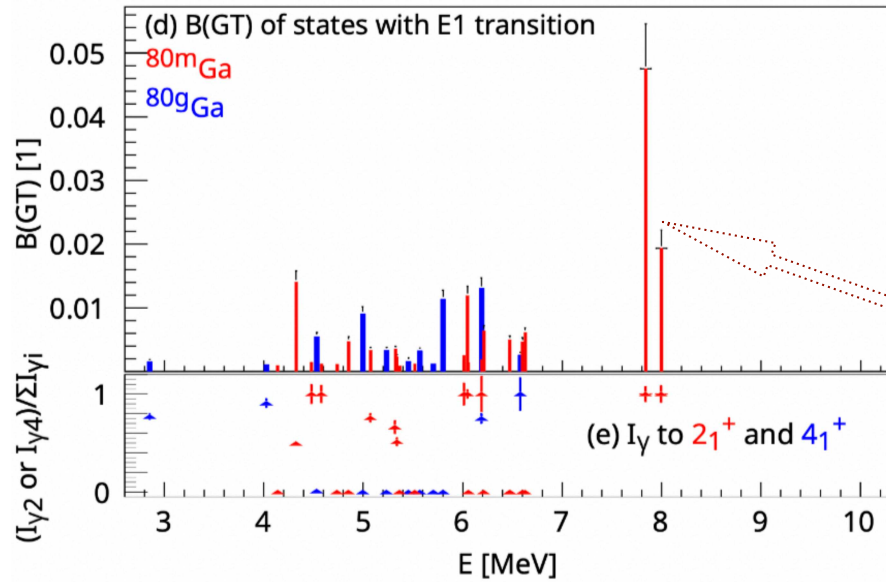
β -Decay of ^{80m}Ga to ^{80}Ge : A Primer on r -Process Waiting-Point Phenomenology

Measured at ALTO / PARIS as

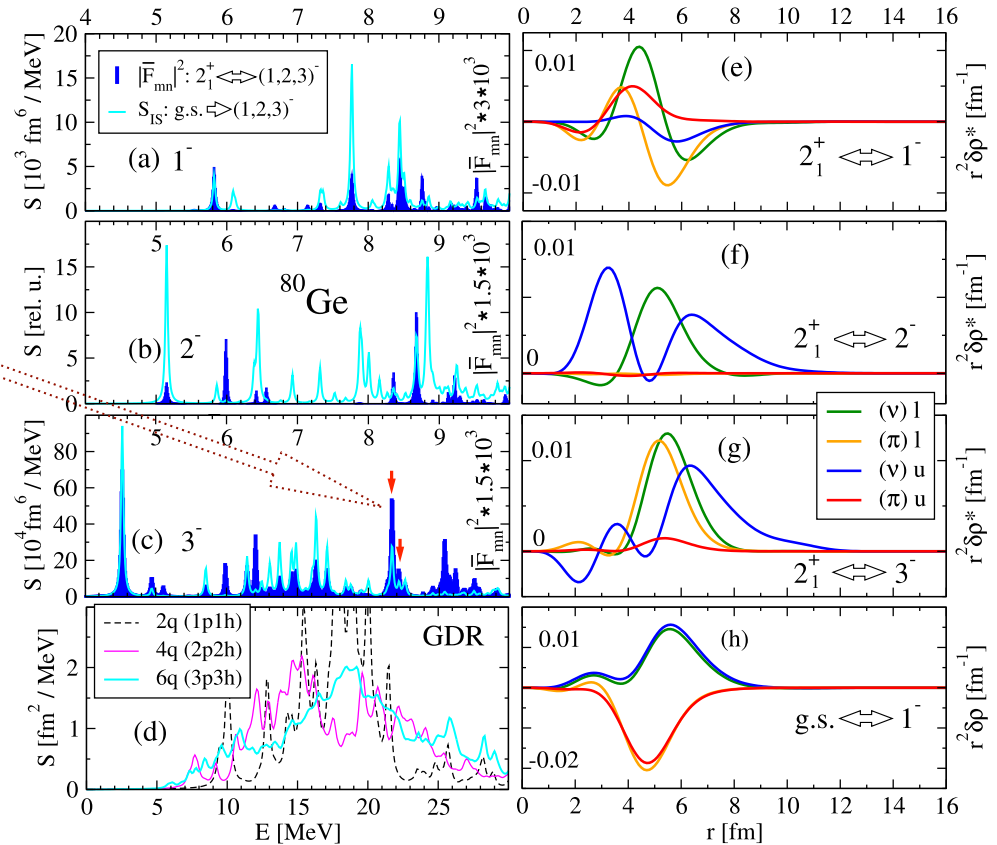


Explicit transitions between excited states in REOM³ : Dipole transitions $2_1^+ \leftrightarrow (1,2,3)^-$ in ^{80}Ge

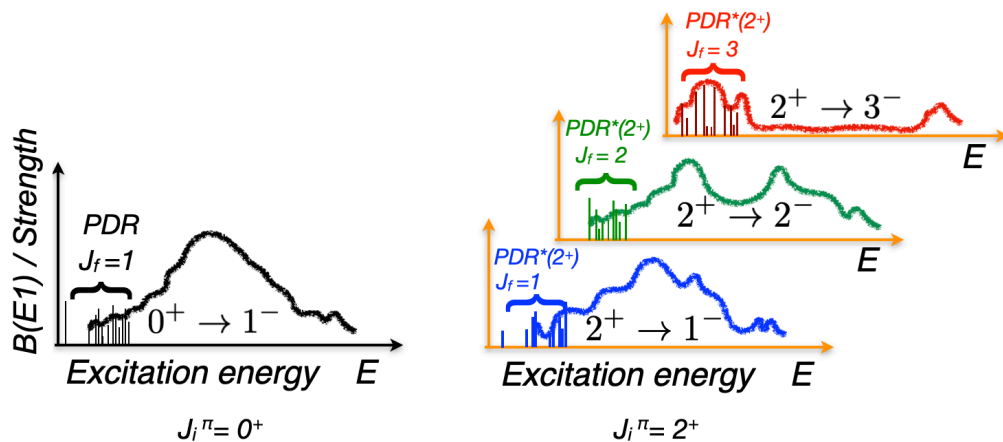
Measured $B(\text{GT})$



Calculated $B(E1)$ & $B(\text{GT})$ [not shown]



PDR vs $PDR^*(2_1^+)$



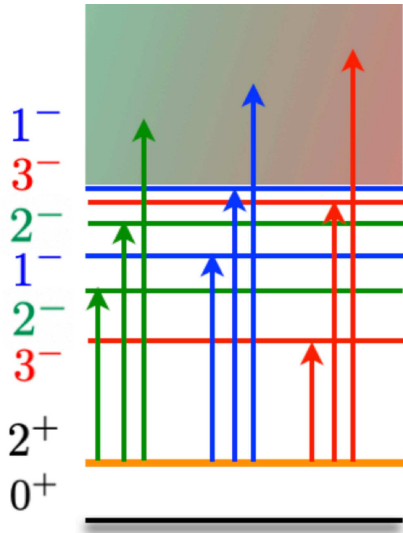
$$\mathcal{X}_{jk}^n = \langle 0 | \alpha_k \alpha_j | n \rangle \quad \mathcal{Y}_{jk}^n = \langle 0 | \alpha_j^\dagger \alpha_k^\dagger | n \rangle$$

$$\mathcal{F}_{mn} = \langle m | \mathcal{F} | n \rangle = f_{ij} (\mathcal{X}_{ik}^{m*} \mathcal{X}_{jk}^n + \mathcal{Y}_{jk}^{m*} \mathcal{Y}_{ik}^n)$$

Leading order; recoupling via 6j-symbols

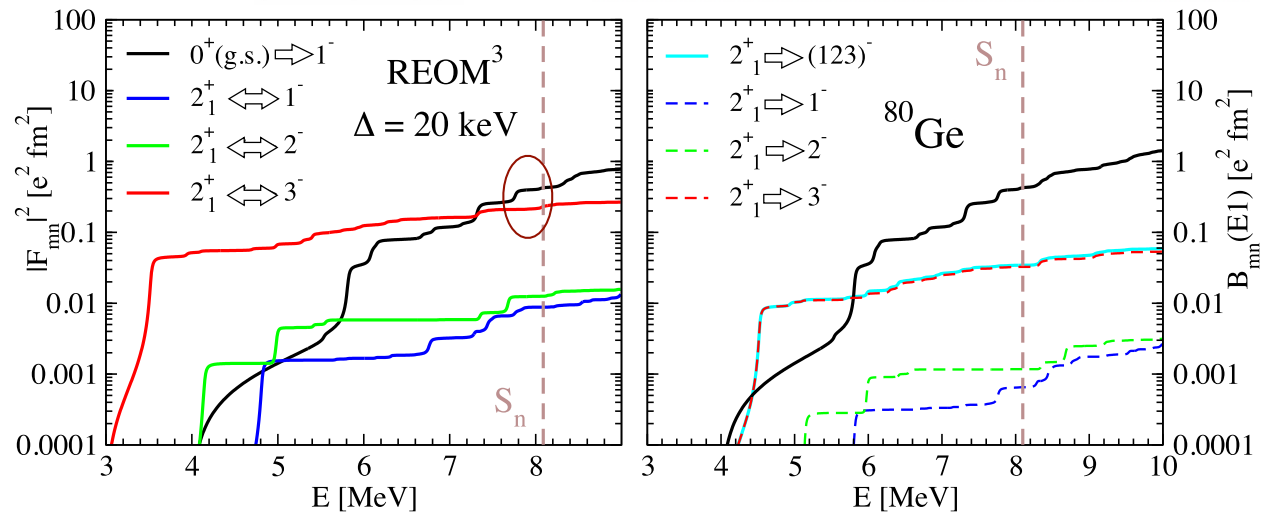
(1,2,3)- strength in ^{80}Ge : quantifying $PDR^*(2_1^+)$

$PDR^*(2_1^+)$



$$|\bar{F}_{mn}(E1)|^2$$

$$B_{mn}(E1) = |\bar{F}_{mn}(E1)|^2 / (2J_m + 1)$$

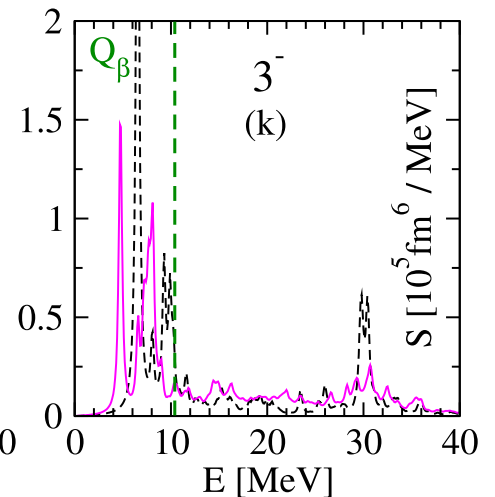
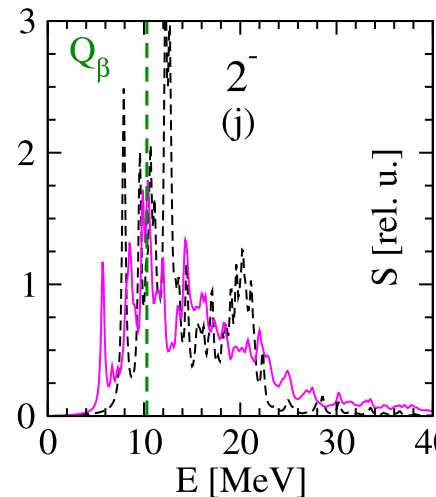
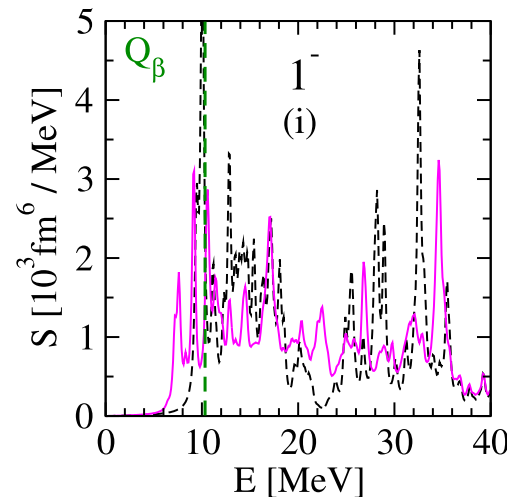


The total $|\bar{F}_{mn}(E1)|^2$ below S_n are comparable within theoretical uncertainty

IS E1

SD M2

IS E3



*Octupole dominance
below $Q_\beta = 10.3$ MeV:*

*The high-energy
Giant Octupole Resonance
(GOR) is nearly absent,
Major 3- strength is below Q_β*



*Many-body correlations and phase transitions:
how to identify and quantify them?*

Exact “ab initio” (EOM) for the two-fermion correlation function with an unspecified NN interaction

$$H = \sum_{12} \bar{\psi}_1 (-i\gamma \cdot \nabla + M)_{12} \psi_2 + \frac{1}{4} \sum_{1234} \bar{\psi}_1 \bar{\psi}_2 \tilde{v}_{1234} \psi_4 \psi_3 + \dots = T + V^{(2)} + \dots$$

Bare
(Relativistic)
Hamiltonian

Particle-hole correlator
two-time propagator,
(response function):

$$R_{12,1'2'}(t - t') = -i \langle T(\bar{\psi}_1 \psi_2)(t) (\bar{\psi}_{2'} \psi_{1'})(t') \rangle$$

In-medium scattering amplitude
spectra of excitations, decays, ...

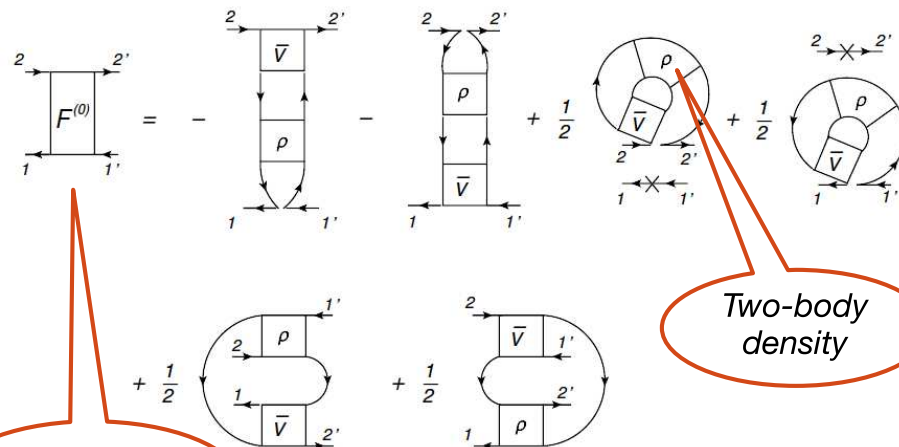
EOM: Bethe-Salpeter-(Dyson) Eq. ()**

$$R(\omega) = R^{(0)}(\omega) + R^{(0)}(\omega) F(\omega) R(\omega)$$

Irreducible kernel (exact): in-medium “interaction”

$$F(t - t') = F^{(0)} \delta(t - t') + F^{(r)}(t - t')$$

Instantaneous term (“bosonic” mean field):
Short-range correlations

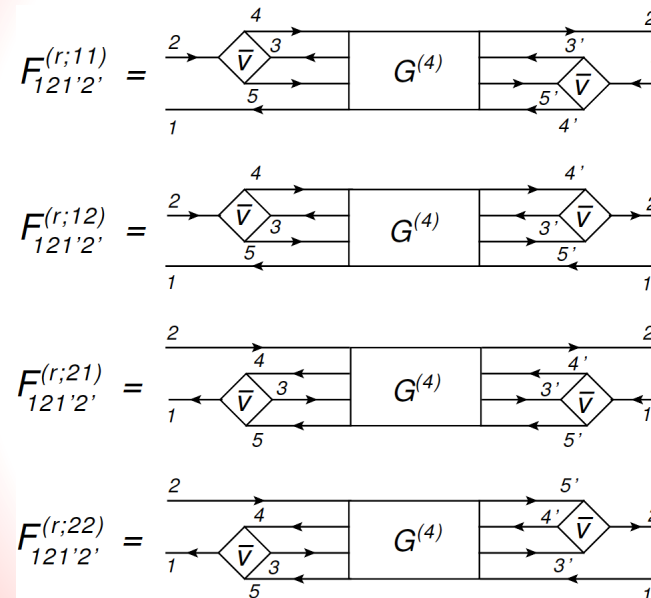


~ “Effective Interaction”

$$\rho_{12,1'2'} = \delta_{22'} \rho_{11'} - i \lim_{t' \rightarrow t+0} R_{2'1,21'}(t - t')$$

contains the full solution of (**) **including the dynamical term!**

t-dependent (dynamical) term:
Long-range correlations:
Couples to higher-rank FCFs



Symmetric form:

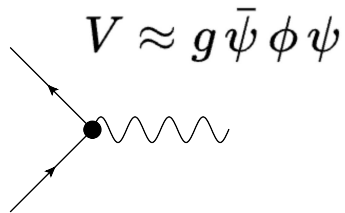
P. Schuck,
J. Dukelsky,
S. Adachi, et al.

Non-Symmetric form: see

J. Schwinger,
F. Dyson,
et al.

Language remarks: “ab initio”

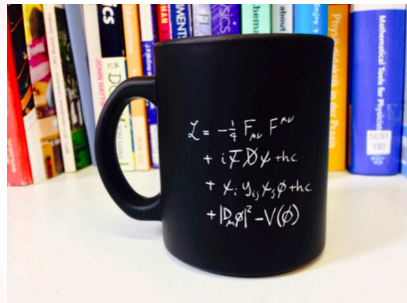
- *Ab initio* = “from the beginning” (lat.), in science and engineering “from first principles”
- **First-principle theory** does not (yet) exist:
Even the Standard Model (SM) is an effective theory:



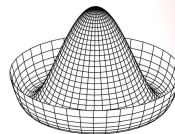
~20 parameters:
masses, coupling constants,
etc.

Open questions:

- Can the SM be UV-completed and include gravity?
- What are the SM interactions?
- What is the origin of the Higgs potential?
- What is dark matter & energy?
- Neutrino mass?
- ...



Higgs mechanism
of mass generation
(~ mean field)



$$\mathcal{L} = (\partial_\mu \phi)^\dagger (\partial^\mu \phi) - V(\phi),$$

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2.$$

The Standard Model

mass → charge → spin →	~2.3 MeV/c ² 2/3 1/2 u up	~1.275 GeV/c ² 2/3 1/2 c charm	~173.07 GeV/c ² 2/3 1/2 t top	0 0 1 g gluon	~126 GeV/c ² 0 0 H Higgs boson
QUARKS	~4.8 MeV/c ² -1/3 1/2 d down	~95 MeV/c ² -1/3 1/2 s strange	~4.18 GeV/c ² -1/3 1/2 b bottom	0 0 1 γ photon	
	0.511 MeV/c ² -1 1/2 e electron	105.7 MeV/c ² -1 1/2 μ muon	1.777 GeV/c ² -1 1/2 τ tau	91.2 GeV/c ² 0 1 Z Z boson	
	~2.2 eV/c ² 0 1/2 ν_e electron neutrino	~0.17 MeV/c ² 0 1/2 ν_μ muon neutrino	<15.5 MeV/c ² 0 1/2 ν_τ tau neutrino	80.4 GeV/c ² ±1 1 W W boson	
LEPTONS				GAUGE BOSONS	

The Standard Model of physics describes the known particles and forces that operate at the tiny quantum scale. (Wikimedia Commons: Miss J)

“Bare”
Interaction
(aka forces,
potentials):

Ab initio...

$$V(\mathbf{r}_1 - \mathbf{r}_2)$$



- In **Theoretical Physics**: knowing the bare (vacuum) interaction between the two particles quantitatively describing the many-particle system
- Such an *ab initio* theory is known, but consistent implementations for medium-mass and heavy nuclei **are still impossible with the desired accuracy**

Common confusion:

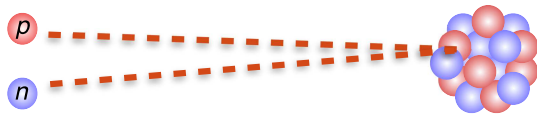
- (i) There is an *ab initio* nuclear theory as opposed to “traditional” nuclear theory
- (ii) There is “the theory” (χ PT potential) and there are “models” (the many-body approaches)
- (iii) Only *ab initio* χ PT can provide quantified uncertainties
- (iv) There are equally good many-body “solvers” which are unimportant attachments to χ PT

Which are wrong

“Bare”
Interaction
(aka forces,
potentials):

$$V(\mathbf{r}_1 - \mathbf{r}_2)$$

Ab initio...



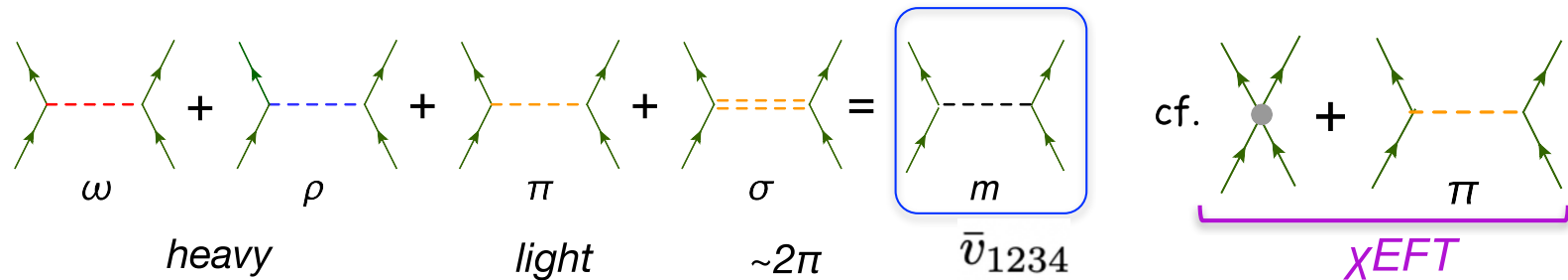
- In **Theoretical Physics**: knowing the bare (vacuum) interaction between two particles, quantitatively describe the many-particle system
- “Ab initio = UV-complete” as opposed to “effective”
- Interactions adjusted to many-particle systems (e.g., finite nuclei) are not *ab initio* but effective

Formulation of the theory and its implementation

- We can formulate an *ab initio* theory, but it has not been implemented accurately (yet). Working with effective interactions, we still need an *ab initio* theory in the theoretical physics sense to constrain concrete implementations, e.g., for maintaining their algebraic structure.
- All “traditional” microscopic many-body models employing effective interactions can be derived *ab initio* and represent various approximations to the static and dynamical kernels of the same formally exact EOMs.
- Paraphrasing Steven Weinberg, saying that “all non-renormalizable theories are as renormalizable as renormalizable theories”, we find that, in the theoretical physics sense, **“traditional” theories are as *ab initio* as *ab initio* theories :)**

Linking the nucleon-nucleon NN(...N) interaction and the many-body theory

Quantum
Hadrodynamics
(QHD)

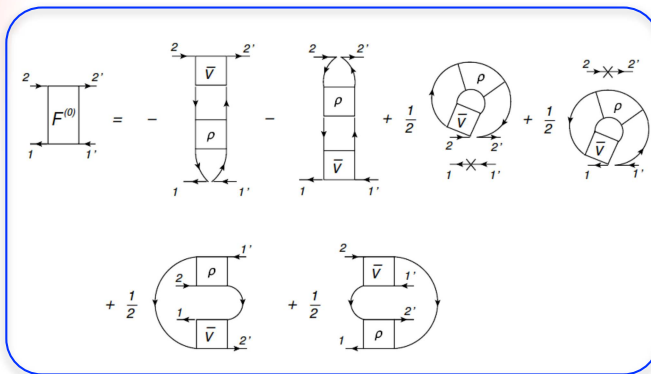


RNFT (this work): non-PT, in-medium
beyond the tree-level

Beyond the leading order:

cf. χEFT : PT for hadrons in the vacuum

E. Epelbaum et al., Front. Phys. 8, 98 (2020)

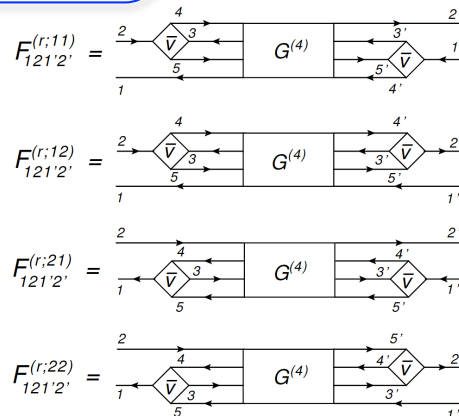


Static

+ Dynamical

New spontaneously
broken symmetries:

The in-medium power counting is associated
with emergent scales of low-energy collective modes
in medium-heavy nuclei



+ Dynamical

Many-body... "solver" (?)

Beyond light nuclei problematic

- Standard "solvers" are too simplistic
- Bare NN and many-body theory should be linked consistently
- In the correlated nuclear medium, the χEFT power counting becomes irrelevant: new Nambu-Goldstone modes emerge

	Two-nucleon force	Three-nucleon force	Four-nucleon force
LO (Q^0)		—	—
NLO (Q^2)		—	—
N ² LO (Q^3)			—
N ³ LO (Q^4)			
N ⁴ LO (Q^5)			

Dynamical kernels: bridging scales and emergent EFT

• **Quantum many-body problem:** Direct EOM for $G^{(n)}$ generates $G^{(n+2)}$ in the (symmetric) dynamical kernels and further high-rank correlation functions (CFs); $N_{\text{Equations}} \sim N_{\text{Particles}} \& \text{ Coupled}$ 🧐 !!!

• **Non-perturbative solutions:**

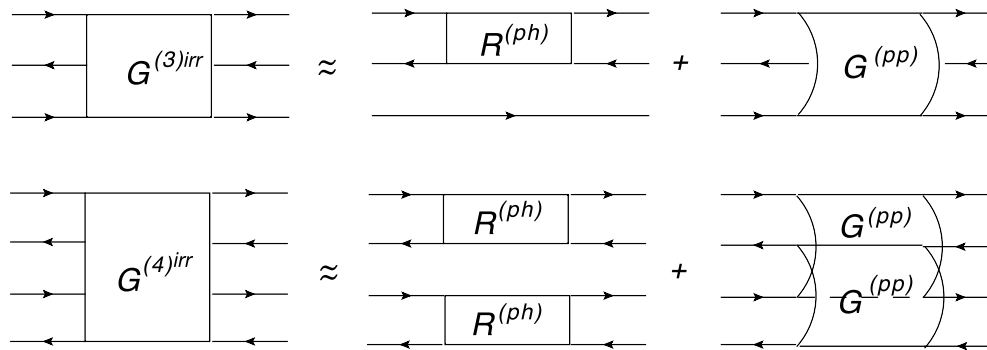
Cluster decomposition
[QFT, S. Weinberg]

Leading at:

$$\begin{aligned} \blacklozenge G^{(3)} &= \boxed{G^{(1)} G^{(1)} G^{(1)}} + \boxed{G^{(2)} G^{(1)}} + \boxed{\Xi^{(3)}} \\ \blacklozenge G^{(4)} &= \boxed{G^{(1)} G^{(1)} G^{(1)} G^{(1)}} + \boxed{G^{(2)} G^{(2)}} + \boxed{G^{(3)} G^{(1)} + \Xi^{(4)}} \end{aligned}$$

weak **intermediate** **strong** coupling
self-consistent GFs phonon coupling Faddeev +
second RPA etc. **this work** **future work**

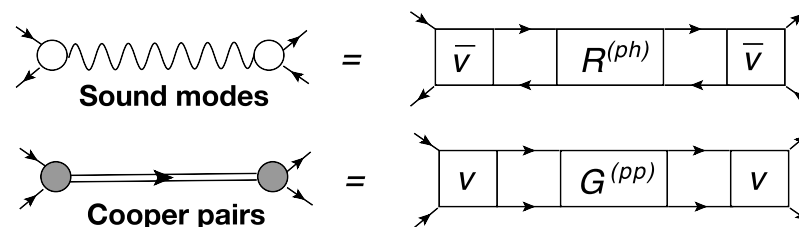
Beyond weak coupling:



- P. C. Martin and J. S. Schwinger, *Phys. Rev.* 115, 1342 (1959).
- N. Vinh Mau, *Trieste Lectures* 1069, 931 (1970)
- P. Danielewicz and P. Schuck, *Nucl. Phys.* A567, 78 (1994)
- ...

Emergence of low-energy Nambu-Goldstone bosons, phonons
[SO(3) symmetry breaking]:

Exact mapping: particle-hole (2q) quasibound states



Emergence of superfluidity [U(1) symmetry breaking]:

Quasiparticle-vibration coupling (qPVC) in nuclei. Cf. NFT

Diquarks in hadrons

Cf. C. Popovici, P. Watson, and H. Reinhardt [PRD83, 025013 (2011)]

Exact mapping to the particle-vibration coupling (PVC)

$$\begin{aligned}
 & \frac{1}{4} \left[\text{Diagram a)} \right] \approx \frac{1}{4} \left[\text{Diagram a)} \right] \\
 & + \text{Diagram b)} + \text{Diagram c)} - \text{Diagram h)} - \text{Diagram i)} - \text{Diagram j)} + \text{Diagram k)} \Big] = \text{Diagram 1)} + \text{Diagram 2)} + \text{Diagram 3)}
 \end{aligned}$$

ph correlator: coupling to normal phonons

$$\begin{aligned}
 & \text{Diagram 1)} = \text{Diagram 2)} \\
 & \text{Diagram 3)} = \text{Diagram 4)}
 \end{aligned}$$

pp correlator: coupling to pairing phonons

Dropping the uncorrelated term: “factor 1/2” problem” (Ring & Schuck, Book)
 “sign problem” (Danielewicz & Schuck, NPA567 (1994) 78)
But: The lowest order is not the leading order in the strong coupling regime!
 => the uncorrelated term can be safely neglected

Model-independent mapping to the PVC:

$$\sum_{242'4'} \bar{v}_{1234} R_{24,2'4'}^{ph}(\omega) \bar{v}_{4'3'2'1'} = \sum_{\nu, \sigma=\pm 1} g_{13}^{\nu(\sigma)} D_{\nu}^{(\sigma)}(\omega) g_{1'3'}^{\nu(\sigma)*}$$

“phonon” vertex:

$$g_{13}^{\nu} = \sum_{24} \bar{v}_{1234} \rho_{42}^{\nu}$$

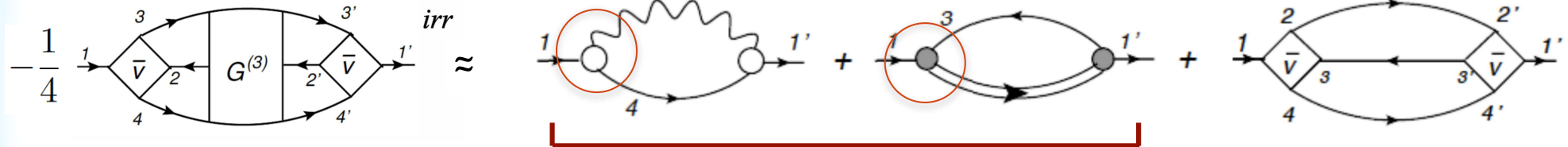
“phonon” propagator:

$$R_{12,1'2'}(\omega) = \sum_{\nu>0} \left[\frac{\rho_{21}^{\nu} \rho_{2'1'}^{\nu*}}{\omega - \omega_{\nu} + i\delta} - \frac{\rho_{12}^{\nu*} \rho_{1'2'}^{\nu}}{\omega + \omega_{\nu} - i\delta} \right]$$

$$D_{\nu}^{(\sigma)}(\omega) = \frac{\sigma}{\omega - \sigma(\omega_{\nu} - i\delta)}$$

Emergence of effective degrees of freedom at intermediate coupling

Dynamical self-energy $\Sigma^{(r)}$:



Can be treated in a unified way (superfluid theory):
qPVC in nuclei, correlations in hadrons / matter / solid state

Emergent phonon vertices and propagators: *calculable from the underlying H* ,
which does not contain phonon degrees of freedom

“Ab-initio”

$$H = \sum_{12} h_{12} \psi_1^\dagger \psi_2 + \frac{1}{4} \sum_{1234} \bar{v}_{1234} \psi_1^\dagger \psi_2^\dagger \psi_4 \psi_3$$

“Effective” qPVC

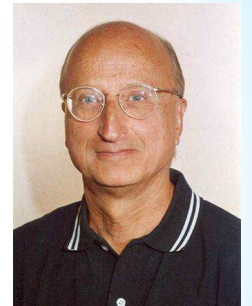
$$H = \sum_{12} \tilde{h}_{12} \psi_1^\dagger \psi_2 + \sum_{\lambda\lambda'} \mathcal{W}_{\lambda\lambda'} Q_\lambda^\dagger Q_{\lambda'} + \sum_{12\lambda} [\Theta_{12}^\lambda \psi_1^\dagger Q_\lambda^\dagger \psi_2 + h.c.]$$

**Quasiparticle-
Phonon Model (QPM)**



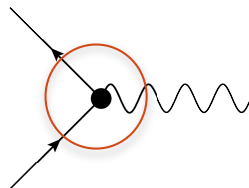
Vadim Soloviev
(1925-1998)

**Nuclear Field
Theory (NFT)**



Ricardo Broglia
(1939-2022)

Cf.: The Standard Model elementary interaction vertices: boson-exchange interaction is the *input*:



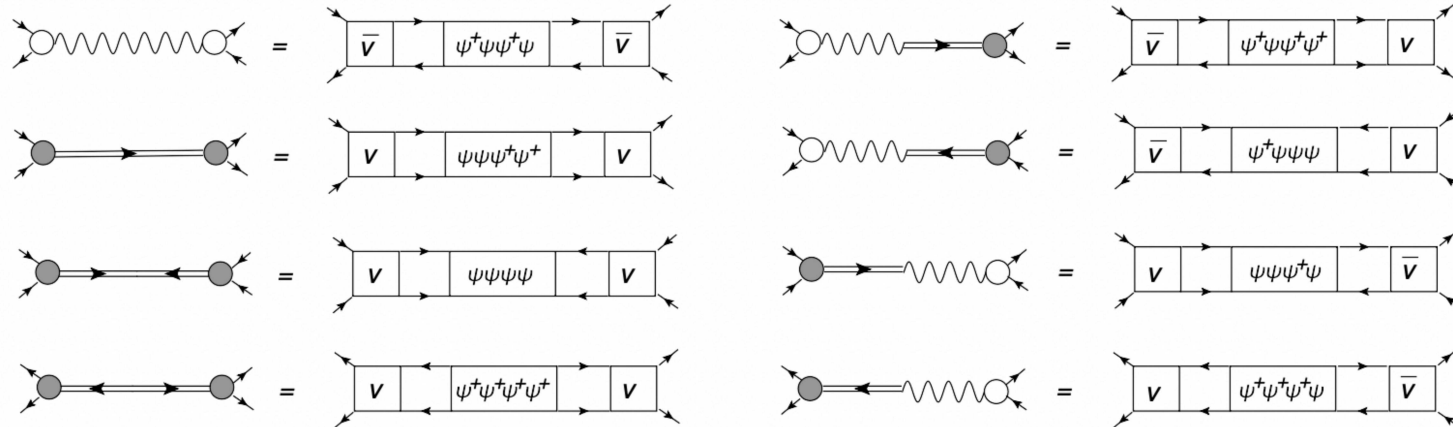
$$\gamma, g, W^\pm, Z^0$$

E.L., P. Schuck, PRC 100, 064320 (2019)
E.L., Y. Zhang, PRC 104, 044303 (2021)

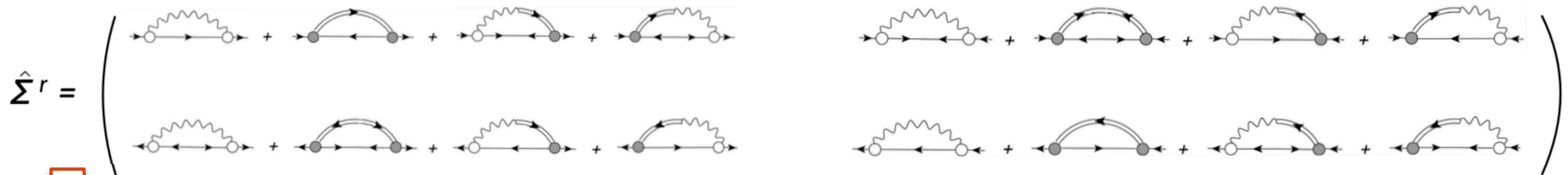
"Ab-initio" qPVC in superfluid systems

Superfluid dynamical kernel: adding particle-number violating contributions

Mapping on the qPVC in the canonical basis



Quasiparticle dynamical self-energy (matrix): normal and pairing phonons are unified



Bogoliubov transformation

**Compact form,
(almost) as simple as
non-superfluid**

Cf.: Quasiparticle static
self-energy (matrix) in HFB

$$\hat{\Sigma}^0 = \begin{pmatrix} \tilde{\Sigma}_{11'} & \Delta_{11'} \\ -\Delta_{11'}^* & -\tilde{\Sigma}_{11'}^T \end{pmatrix}$$