

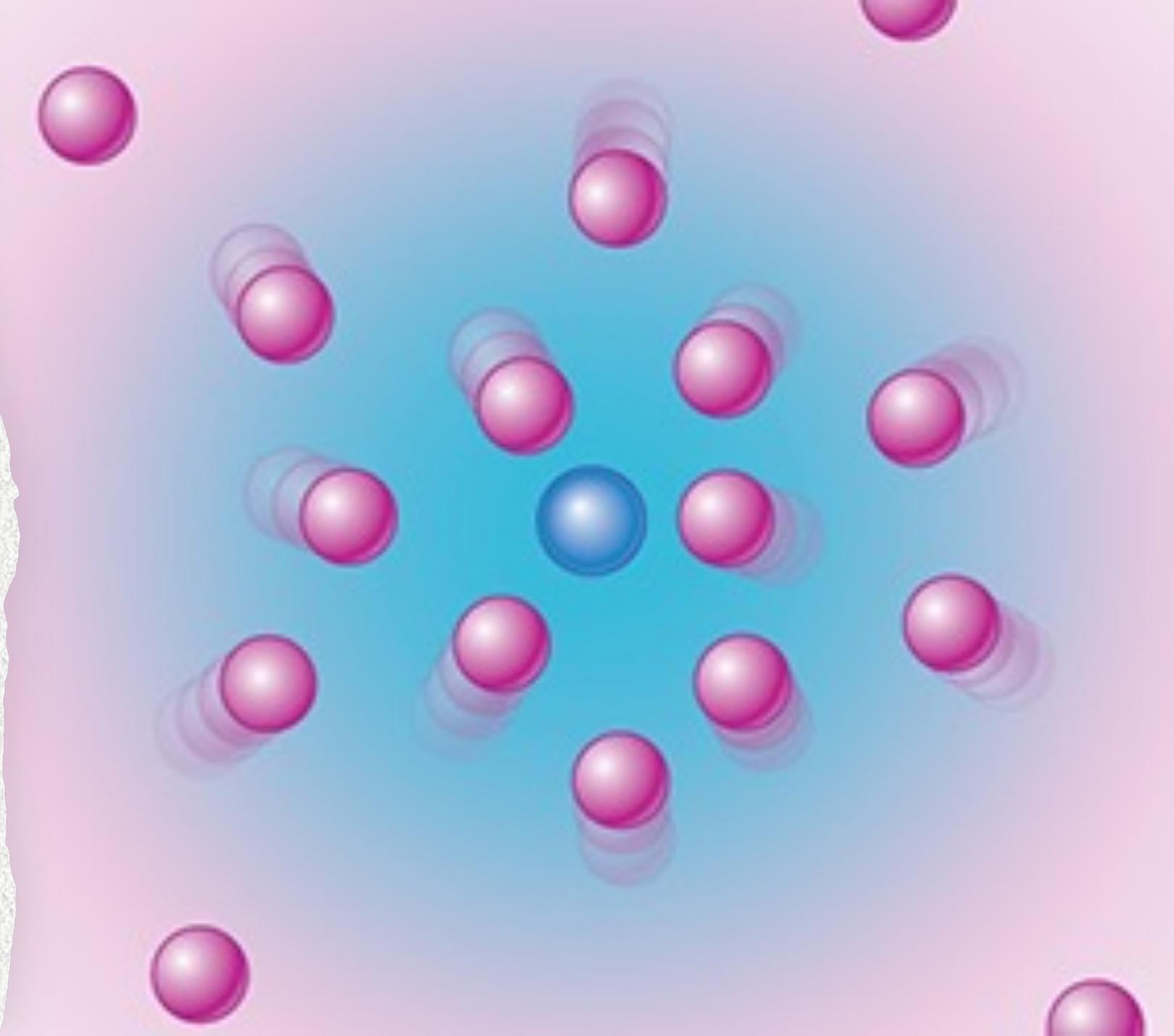
Fermi polaron in low- density spin-polarized neutron matter

Isaac Vidaña, INFN Catania



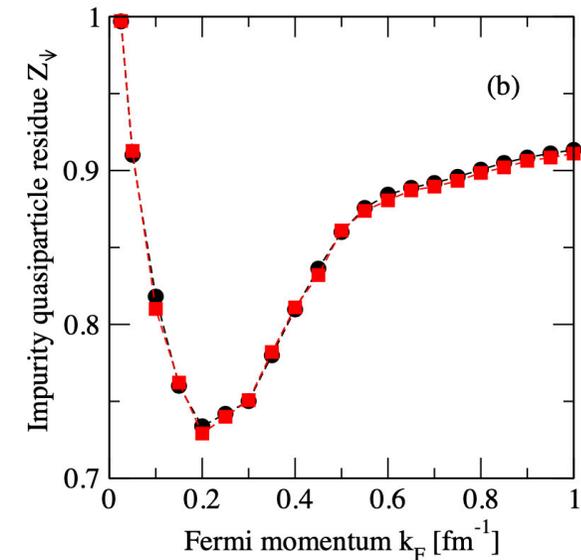
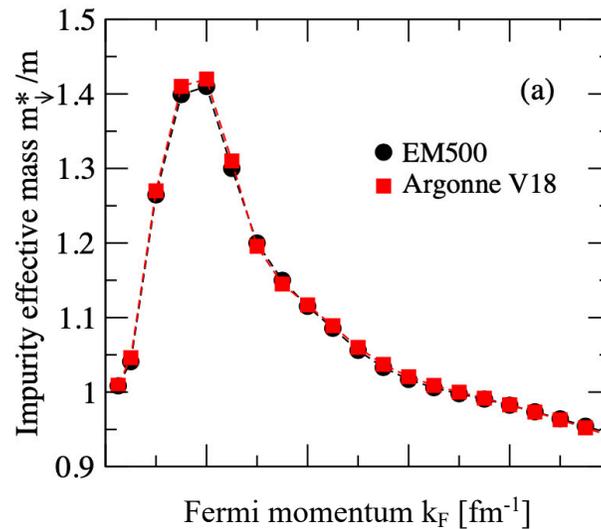
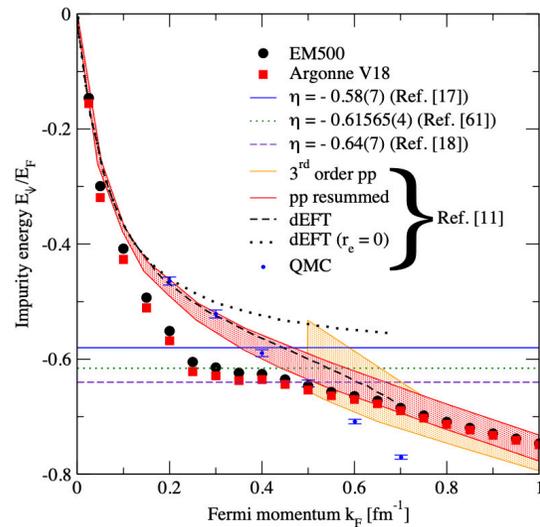
Low-energy nuclear theory: From
few nucleons to the stars

November 13th – 14th 2025 IJCLab
Orsay, (France)



This work in few words

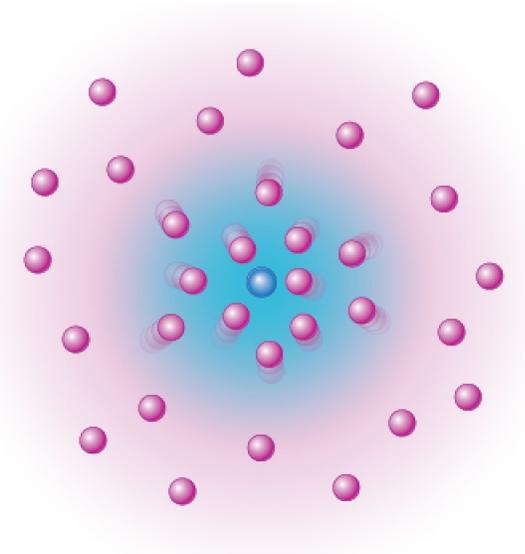
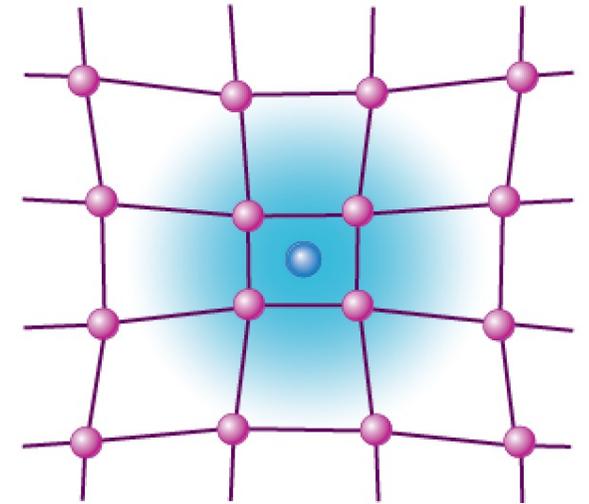
We show that a **spin-down neutron impurity** immersed in a **low-density free Fermi gas of spin-up neutrons** with Fermi momentum in the range $0.25 \leq k_F \leq 0.45 \text{ fm}^{-1}$ exhibit properties (**energy E_{\downarrow}** , **effective mass m_{\downarrow}^*** and **quasiparticle residue Z_{\downarrow}**) very similar to those of an **attractive Fermi polaron in the unitary limit**



The Polaron Concept

Polaron: quasiparticle arising from the dressing of an impurity strongly coupled to an environment or a bath

- Introduced by **Landau (1933) & Pekar (1946)** to describe **conduction electrons** in a **dielectric crystal**
- Further elaborated by **Fröhlich (1954) & Feynman (1955)** who considered the ionic crystal or polar semiconductor as a phonon bath.
 - ✓ Fröhlich formulated a microscopic model (*Fröhlich polaron model*) where an electron interacts with the **polar optical modes** of an **ionic crystal**, effectively treating the lattice as a **phonon bath** that mediates electron–phonon coupling
 - ✓ Feynman introduced a powerful **path-integral variational method** to describe the **Fröhlich polaron**, providing an accurate, nonperturbative treatment of the electron–phonon interaction across all coupling strengths
- Since these initial studies of the electron-phonon polaron, **the polaron concept has been widely extended to diverse fields** from condensed matter to nuclear physics and even general relativity.



Experimental Realization of the Polaron

Polarons has been experimentally realized & observed in **crystals, molecules, cold atoms & 2D materials**, probed through **optical, spectroscopic & transport** methods — revealing universal features of the quasiparticles regardless of the medium & interactions

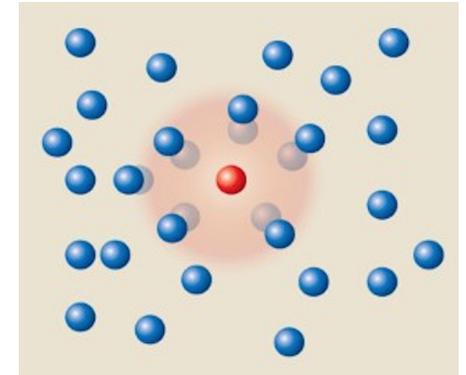
Period	System	Observation
1950s-1960s	Polar/Ionic crystals (e.g. TiO_2 , alkali halides)	First indirect evidence of polarons through optical absorption & transport anomalies confirming the Fröhlich model
1970s-1980s	Organic & Molecular Crystals	Discovery of small polaron hopping in conducting polymers & organic crystals via conductivity and optical spectra
1990s-2000s	Transition Metal-Oxides (e.g. manganite cuprates)	Direct structural and spectroscopic detection of small and self-trapped polarons using extended X-ray absorption, electron paramagnetic resonance & photoemission
2010s	Ultracold atoms	Realization of Fermi & Bose polarons in quantum gases with tunable coupling, observed via radio frequency spectroscopy and quench dynamics
2015 - Present	2D semiconductors (TMD Monolayers)	Observation of exciton-polarons in doped MoSe_2 and WSe_2 through distinct optical branches in photoluminescence spectra

Fermi & Bose Polarons

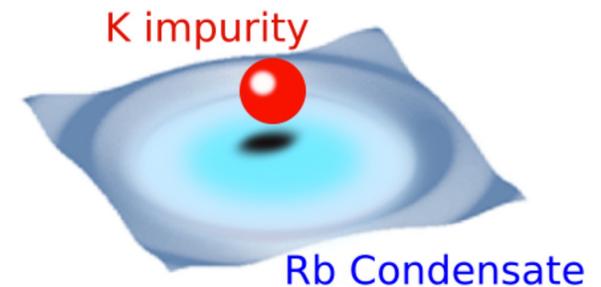
The properties of the polaron depend strongly on the **quantum statistics** of the bath in which it is immersed

Feature	Fermi Polaron	Bose Polaron
Medium	Fermi gas	Bose-Einstein condensate
Dressing mechanism	Impurity interacts with particle-hole excitations of the Fermi sea	Impurity interacts with phonon-like (Bogoliubov) excitations of the condensate
Energy shift	Attractive/repulsive branches	Attractive/repulsive branches
Observations	Radio Frequency in ultracold Fermi gases (e.g., ^6Li , ^{40}K)	Impurities in BEC condensates (e.g. Rb-K mixtures)

Fermi Polaron



Bose Polaron



Universal Polaron Features

Despite the differences between **Fermi** and **Bose polarons**, and between their **solid-state** and **ultracold atomic** realizations, there are several **universal features** that all polarons share

- **Dressed quasiparticle**

A polaron is always a dressed impurity.
The dressing leads to:

- ✓ Renormalized energy (binding shift)
- ✓ Effective mass $m^* > m$
- ✓ Quasiparticle residue $Z < 1$

- **Universality near unitarity**

Close to the unitarity limit all properties depend only on the dimensionless coupling parameter, not on microscopic details. Fermions ($1/k_F a$). Bosons ($n^{1/3} a$)

- **Universal low-energy structure**

The polaron dispersion relation & spectral function have the same form across systems

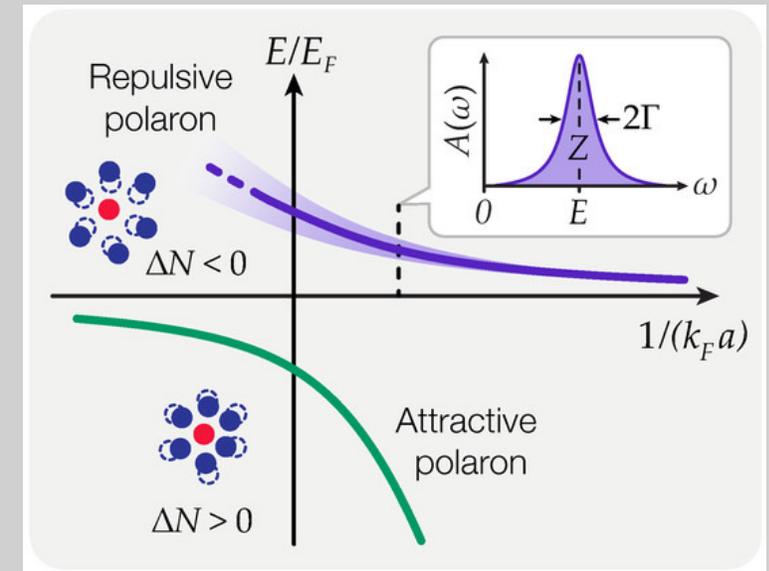
$$E(k) = E_p + \frac{\hbar^2 k^2}{2m^*}, \quad A(k, \omega) = Z\delta(\omega - E(k)) + A_{cont}$$

- **Universal scaling of quasiparticle parameters**

E_p , m^* and Z follow dimensionless, universal curves regardless of the medium & details of the impurity-medium interaction

- **Adiabatic continuity & dual branches**

The attractive and repulsive branches evolve smoothly with interaction strength



Experimental Determination of the (Fermi) Polaron Properties

Experiments with ultracold ${}^6\text{Li}$ or ${}^{40}\text{K}$ gases have directly probed Fermi polarons using **radio-frequency (RF) spectroscopy** & **momentum-resolved spectroscopy**

Property	Experimental Observation	Reference
Energy $E_p = \eta E_F$	Measured via RF peak shift $\eta = -0.58(5)$ $\eta = -0.64(7)$	Shin. Phys. Rev. C 77, 041603 (R), 2008 Schiotzek et al., PRL 102. 230402, 2009
Effective mass m^*	Measured from momentum-resolved spectroscopy & transport $\frac{m^*}{m} = 1.17 \pm 0.1$	Kohstall <i>et al.</i> , Nature 485, 2012
Quasiparticle residue Z	Extracted from the RF spectral weight $Z \approx 0.7$ at weak/moderate interaction Decreases towards 0 at strong interaction	Schiotzek <i>et al.</i> , Nature Phys. 5, 2009 (${}^6\text{Li}$); Scazza <i>et al.</i> , PRC 118, 083602, 2017

Polarons in Nuclear Physics

Several studies have explored the concept of **polarons in nuclear physics**, particularly focusing on neutron matter & its implications for astrophysical environments & nuclear structure. Some of them include:

- **Proton impurity in Neutron Matter**

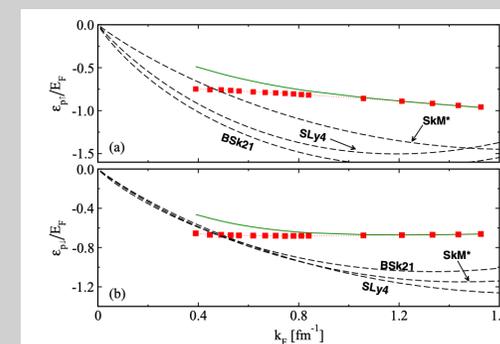
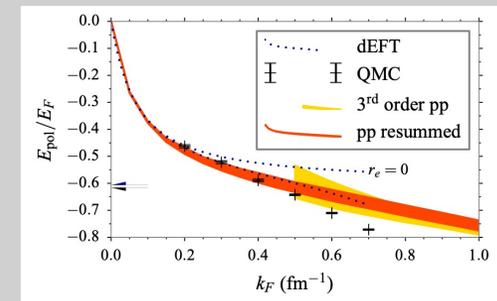
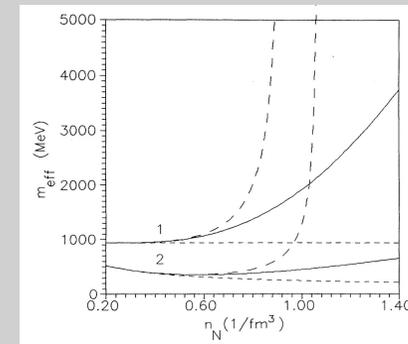
Kutschera & Wójcik, PRC 47, 1077 (1993)

Kutschera & Wójcik investigated the interactions of a proton impurity with density oscillations in neutron matter, employing a Debye approximation. Their findings revealed that the proton's effective mass increases with neutron matter density, exhibiting behavior akin to a polaron in solids

- **Neutron & Proton Polaron as a Constraint on Nuclear Energy Density Functionals**

Forbes *et al.*, PRC 89, 041201(R) (2014); Roggero *et al.*, PRC 92, 054303 (2015)

- ✓ Forbes *et al.* used **QMC & EFT** methods that include finite-range effects to study neutron polaron energy finding the impurity effective mass consistent with the Fermi polaron at unitarity & used the neutron polaron energy to refine the time-odd components of nuclear EDFs
- ✓ Roggero *et al.* used QMC with chiral interactions to show that a **proton impurity in polarized neutron matter behaves as a polaron** & employed their results to impose tight constraints on the time-odd components of Skyrme-type nuclear EDFs

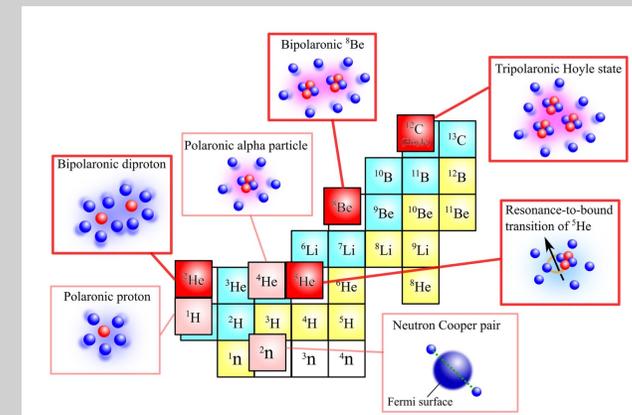


Polarons in Nuclear Physics

- Intersections of Ultracold Atomic Polarons & Nuclear Clusters**

Tajima *et al.*, AAPPS Bull. 34, 9 (2024)

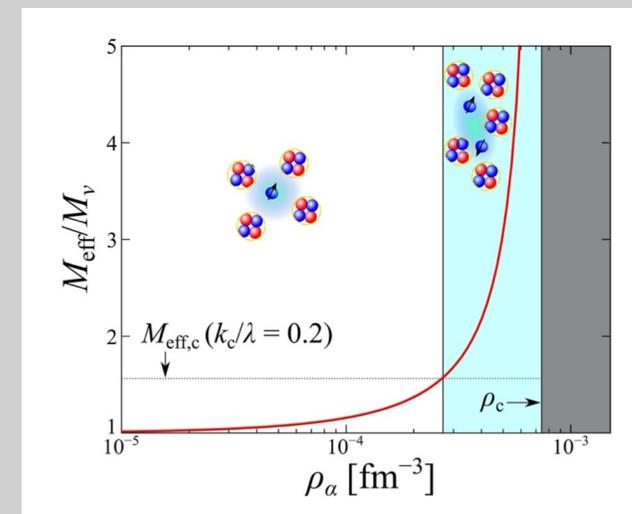
Tajima *et al.* reviewed in-medium properties of **impurities & clusters in dilute neutron matter**, relating them to polarons. They discussed how atomic & nuclear systems are interconnected through polaron physics & suggested that the quasiparticle energy of a single proton in neutron matter is associated with the **symmetry energy**, offering a novel perspective on the nuclear equation of state.



- Neutron polaron in dilute α matter: a p-wave Bose polaron**

Tajima *et al.*, PRC 111, 025802 (2025)

Tajima *et al.* studied how a neutron behaves as a quasiparticle within an α -particle condensate, resembling a **Bose polaron near a p-wave Feshbach resonance**. They showed that the **effective mass of the neutron increases with the density of the condensate** & that two such neutrons, each acting as a heavy polaron, can form a **bound dineutron** in the medium - unlike in vacuum - offering insights into multinucleon clustering & astrophysical many-body systems



Polarons in Nuclear Physics

- **Quasiparticle properties of a single α particle in neutron matter**

Nakano *et al.*, PRC 102, 055802 (2020)

The work models an α particle in a dilute neutron gas as a nuclear analog of a Fermi polaron, using a non-self-consistent ladder approximation for the impurity-gas effective interaction to study its quasiparticle properties like **energy (E_p)**, **effective mass (m^*/m)**, **quasiparticle residue (Z)** & **damping rate (Γ)**

E_p	m^*/m	Z	Γ
$0.467E_F$	1.217	0.650	$0.032E_F$

- **Quark Model & Polarons**

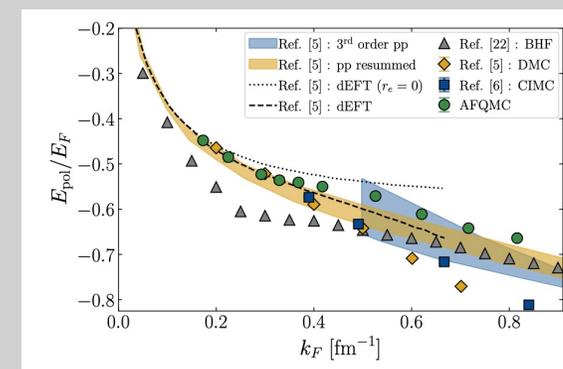
Afonsin & Tulub EPJC 85, 784 (2025)

Afonsin & Tulub propose that **polaron theory** from solid-state physics **can effectively model non-perturbative QCD**. By linking electron–lattice interactions to pion–nucleon dynamics, they reproduced key nucleon properties - such as mass and the pion–nucleon sigma term - and showed that constituent quarks make up about one-third of the nucleon mass, matching lattice QCD results

- **Neutron & Fermi Polarons in the Lattice**

Curry *et al.*, arXiv:2510.0533 (2025)

Very recently, Curry *et al.* have conducted an ab initio study using the auxiliary-field Quantum Monte Carlo method to examine the **properties of a fermionic impurity interacting with a background sea of spin-polarized fermions** finding **good agreement with previous similar studies** (such as the **current one**)



A \downarrow neutron impurity in a low-density \uparrow neutron free Fermi gas

In this work, we study the properties of a **spin-down (\downarrow) neutron impurity** immersed in a low-density free Fermi gas of **spin-up (\uparrow) neutrons**

- **Low-density neutron matter**

- ✓ Density: $n \ll n_o \approx 0.16 \text{ fm}^{-3}$
- ✓ Dominant channel: 1S_0
- ✓ 1S_0 scattering length: $a_{nn} = -18.9(4) \text{ fm}$
- ✓ 1S_0 effective range: $r_e = 2.75(11) \text{ fm}$

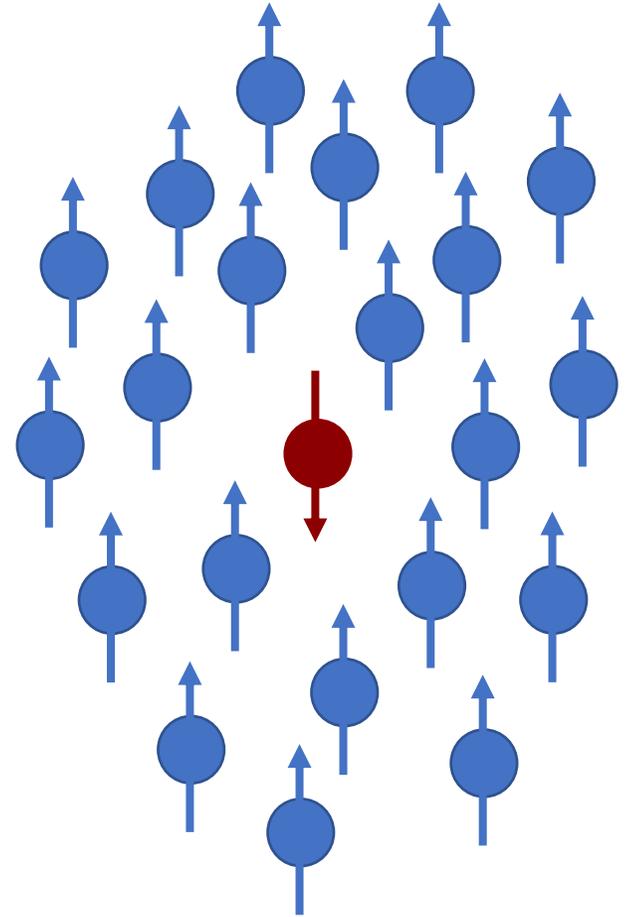
$|a_{nn}| \gg r_e \rightarrow$ **low-density neutron matter is dilute but strongly correlated**

- **Unitary Fermi gas**

- ✓ Ideal system with $|a| \rightarrow \infty, r_e = 0$
- ✓ All properties proportional to the corresponding ones of a free Fermi gas

$$(E = \xi E_F, \quad \xi = 0.37 - 0.4, \quad \Delta/E_F = 0.4 - 0.5)$$

Low-density neutron matter actually **never reaches the unitary limit**, although it shows properties “close” to it in the range $r_e < n^{-1/3} < |a_{nn}|$



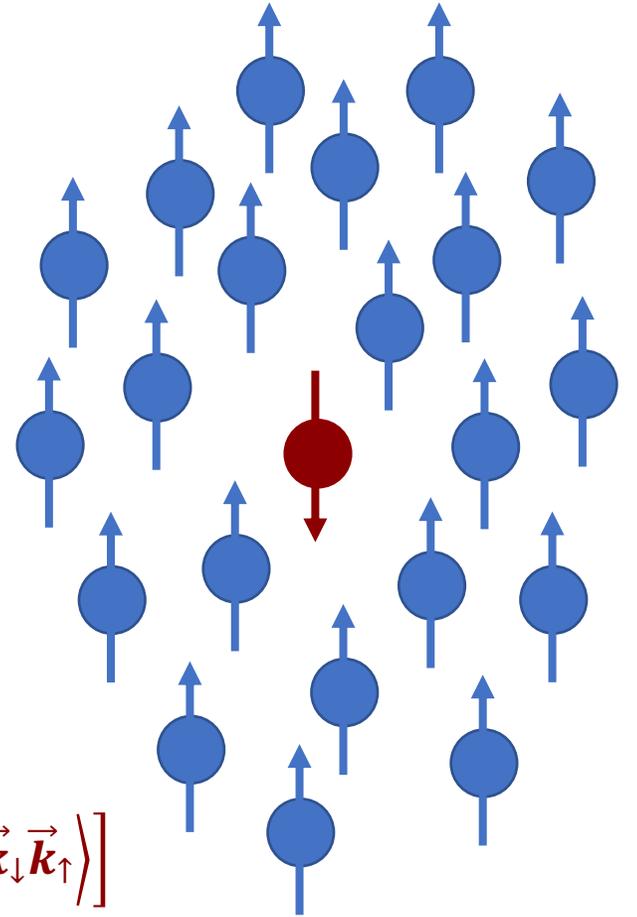
A few words about our calculation

Our calculation starts with the construction of the $\langle \vec{k}_\downarrow \vec{k}_\uparrow | G(\omega) | \vec{k}_\downarrow \vec{k}_\uparrow \rangle$ G-matrix elements describing the **in-medium interaction** of the \downarrow neutron impurity with the \uparrow neutrons of the free Fermi gas

- We solve the **coupled-channel Bethe-Goldstone integral equation** using the EM500 & the Argonne V18 bare interactions between the \downarrow & \uparrow neutrons

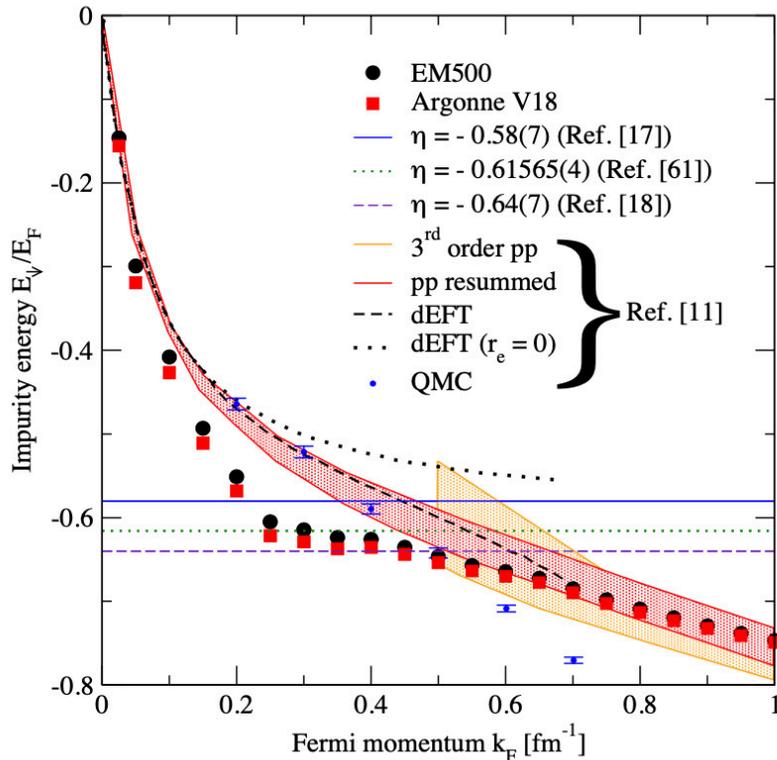
$$\langle \vec{k}_{\sigma_1} \vec{k}_{\sigma_2} | G(\omega) | \vec{k}_{\sigma_3} \vec{k}_{\sigma_4} \rangle = \langle \vec{k}_{\sigma_1} \vec{k}_{\sigma_2} | V | \vec{k}_{\sigma_3} \vec{k}_{\sigma_4} \rangle + \sum_{\sigma_i \sigma_j} \frac{\langle \vec{k}_{\sigma_1} \vec{k}_{\sigma_2} | V | \vec{k}_{\sigma_i} \vec{k}_{\sigma_j} \rangle \langle \vec{k}_{\sigma_i} \vec{k}_{\sigma_j} | Q | \vec{k}_{\sigma_i} \vec{k}_{\sigma_j} \rangle \langle \vec{k}_{\sigma_i} \vec{k}_{\sigma_j} | G(\omega) | \vec{k}_{\sigma_3} \vec{k}_{\sigma_4} \rangle}{\omega - E_{\sigma_i}(\vec{k}_{\sigma_i}) - E_{\sigma_j}(\vec{k}_{\sigma_j}) + i\eta}$$

- ✓ Only the **1S_0 contribution** (dominant at low-densities) is considered
- ✓ Three-nucleon forces (expected to be irrelevant at low-densities) are **neglected**
- ✓ \uparrow neutron energy: $E_\uparrow(\vec{k}_\uparrow) = \frac{\hbar^2 k_\uparrow^2}{2m}$
- ✓ \downarrow neutron energy: $E_\downarrow(\vec{k}_\downarrow) = \frac{\hbar^2 k_\downarrow^2}{2m} + \text{Re} \left[\sum_{|\vec{k}_\uparrow| \leq k_{F\uparrow}} \langle \vec{k}_\downarrow \vec{k}_\uparrow | G(\omega = E_\uparrow(\vec{k}_\uparrow) + E_\downarrow(\vec{k}_\downarrow)) | \vec{k}_\downarrow \vec{k}_\uparrow \rangle \right]$



Energy of the spin-down neutron impurity

Fermi polaron energy E_{pol} : change in the energy of the non-interacting Fermi gas when an impurity of zero momentum is added to it

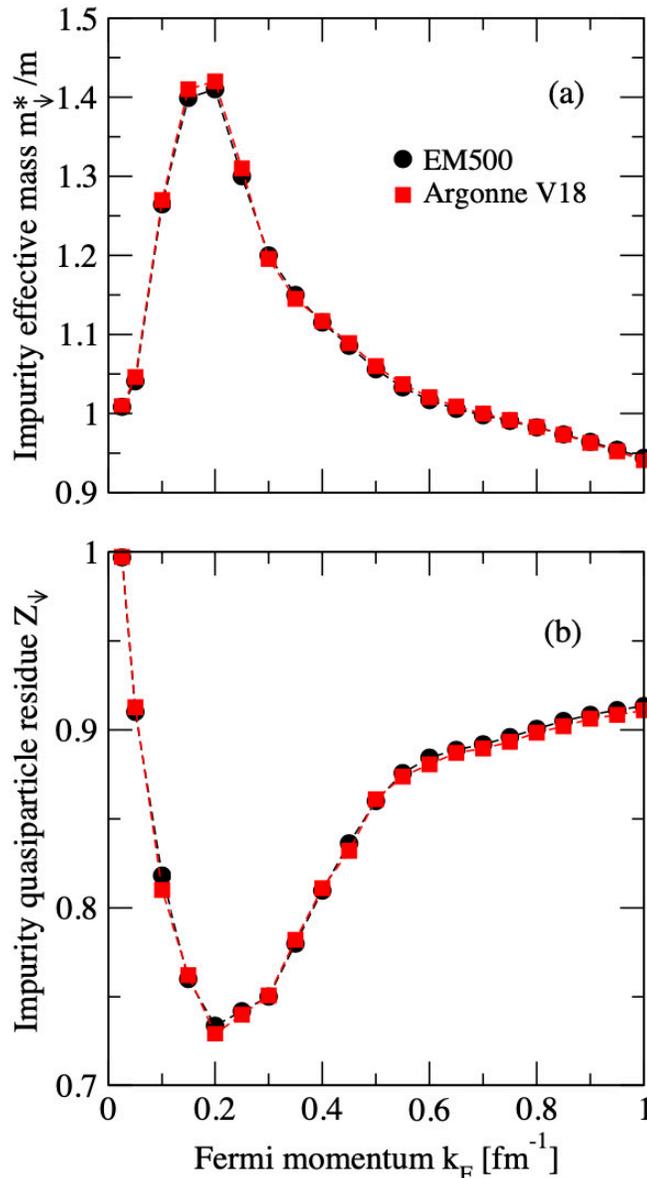


$$E_{pol} \equiv E_{\downarrow}(\vec{0}_{\downarrow}) = \text{Re} \left[\sum_{|\vec{k}_{\uparrow}| \leq k_{F\uparrow}} \langle \vec{0}_{\downarrow} \vec{k}_{\uparrow} | G(\omega = E_{\uparrow}(\vec{k}_{\uparrow}) + E_{\downarrow}(\vec{0}_{\downarrow})) | \vec{0}_{\downarrow} \vec{k}_{\uparrow} \rangle \right]$$

- Almost identical for EM500 & V18 → NN interaction details irrelevant at low densities
- For $0.25 \leq k_F \leq 0.45 \text{ fm}^{-1}$ our results show a plateau around -0.6 , consistent with the proportionality constant η from previous theoretical studies & experiments
- Furthermore, in this Fermi momenta region the condition $r_e < n^{-1/3} < |a_{nn}|$ is fulfilled, and hence low-density neutron matter shows properties “close” to those of a unitary Fermi gas
- Agreement with Forbes *et al.* only at very low or high densities; discrepancies (i.e., no plateau) for $0.1 \leq k_F \leq 0.5 \text{ fm}^{-1}$. Due probably to the missing in our calculation of long-range correlations (i.e., no coupling of impurity with ph excitations)

- Full circles & squares: BHF results with EM500 & V18
- Horizontal lines: QMC results from Van Hocke *et al.* & experiments with spin-polarized ${}^6\text{Li}$ atoms
- Lines & bands: Forbes *et al.* (PRC 89, 041301(R) (2014) results using chiral NN interactions, difermion EFT (with/without effective range), and QMC simulations

Effective mass & quasiparticle residue of the spin-down neutron impurity



- Effective mass: extracted by fitting the BHF polaron energy to $E_{\downarrow}(k) = E_{\downarrow} + \frac{\hbar^2 k^2}{2m_{\downarrow}^*}$
- Quasiparticle residue: measures the importance of correlations. The smaller it is, the more important are the correlations

$$Z_{\downarrow} = \left(1 - \frac{\partial U_{\downarrow}(\vec{k}_{\downarrow} = \vec{0}, \tilde{E}_{\downarrow})}{\partial \tilde{E}_{\downarrow}} \right)_{\tilde{E}_{\downarrow} = U_{\downarrow}(\vec{k}_{\downarrow} = \vec{0})}^{-1}$$

$m_{\downarrow}^*(Z_{\downarrow})$ increases (decreases) initially, reaches a maximum (minimum) at $k_F \sim 0.2$ fm⁻¹ and then it decreases (increases) at higher values of k_F

- Around $k_F \sim 0.2$ fm⁻¹ $n^{-1/3} \sim |a_{nn}| \Rightarrow$ this region establishes a border between a more ($0.1 \leq k_F \leq 0.2$ fm⁻¹) & a less ($k_F \geq 0.2$ fm⁻¹) correlated regime
- Furthermore, for $0.25 \leq k_F \leq 0.45$ fm⁻¹, where low-density neutron matter is “close” to unitarity:

$$\text{EM500: } 1.300m \leq m_{\downarrow}^* \leq 1.085m, 0.741 \leq Z_{\downarrow} \leq 0.836$$

$$\text{V18: } 1.310m \leq m_{\downarrow}^* \leq 1.089m, 0.739 \leq Z_{\downarrow} \leq 0.832$$

Compatible with the result $m_{\downarrow}^* = 1.197m$ of the full-many body analysis of Combescot & Giraud (PRL 101, 050404 (2008)), & that of the diagrammatic Monte Carlo method by Vlietinck *et al.* (PRB 87, 115133 (2013)) who obtained $Z_{\downarrow} = 0.759$

The final message of this talk



- We have analyzed the properties (**energy** E_{\downarrow} , **effective mass** m_{\downarrow}^* and **quasiparticle residue** Z_{\downarrow}) of a spin-down neutron impurity in a low-density free Fermi gas of spin-up neutrons
- Calculations have been done within the BHF approach using the chiral NN force of Entem & Machleidt at $N^3\text{LO}$ with a 500 MeV cut-off and the Argonne V18 potential including only contributions from the 1S_0 partial wave
- Our results show that a **\downarrow neutron impurity in a free Fermi gas of \uparrow neutrons** with Fermi momentum in the range **$0.25 \leq k_F \leq 0.45 \text{ fm}^{-1}$** presents properties very similar to those of an **attractive Fermi polaron in the unitary limit**

- ✧ You for your time & attention
- ✧ The organizers, Pierre, Chlöe, Guillaume, Elias, Bira & Michael, for their kind invitation

