Research Activity of Luca Salasnich

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General overview: some numbers

- MSc in Physics at the University of **Padova** in 1991.
- PhD in Physics at the University of **Firenze** in 1995.

My first scientific paper was published in 1992. From that year to now:

Papers in ISI-indexed Journals	Papers in Edited Volumes
206 (47 single-authored)	17 (6 single-authored)

According to ISI Web of Science, and also Scopus, up to now my publications got about 4000 citations, with h-index $h = 34$.

General overview: some numbers

I published papers in several areas of physics (atomic physics, many-body theory, statistical mechanics, quantum field theory, nonlinear phenomena) and in many high-impact-factor scientific journals. Among them:
– 1 in Physics Reports
– 4 papers in Physical Review Letters
– 85 in Physical Review A
– 1 in Physical Review B
– 3 in Physical Review C
– 1 in Physical Review D
– 6 in Physical Review E
– 4 in Scientific Reports
– 5 in New Journal of Physics

- Invited talks: about 50 at international conferences.
- Organized international conferences: 9.
- Funded research projects: about 400 kEuro as principal investigator and about 1.6 MEuro as investigator.
- Supervisor: 8 postdocs, 3 PhD students, 15 MSc students, 34 BSc students.

Quantum chaos (1992-2005)

My Msc and PhD theses were devoted to the investigation of quantum chaos in many-body systems.
Quantum chaos is the study of quantum properties of systems which are classically chaotic. In other words, it is the analysis of the quantum-classical correspondence in systems which display an order-to-chaos crossover by changing some parameter.

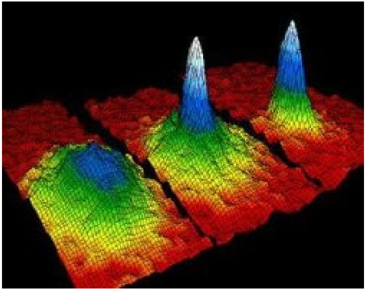
I worked on this topic also as a postdoc at the Univ. of **Madrid** (1 year) and at the Univ. of **Maribor** (6 months).

The main result of this reseach activity is a paper[1] where we found that the power spectrum of energy level fluctuations follows a power law $1/f^{\alpha}$ with $\alpha = 1$ for a fully chaotic system and $\alpha = 2$ for a fully regular system.

[1] J.M.G. Gomez, A. Relano, J. Retamosa, E. Faleiro, LS, M. Robnik, Phys. Rev. Lett. **94**, 084101 (2005).

BEC with ultracold atoms (1997-2019)

In 1997 I started a postdoc at the Istituto Nazionale per la Fisica della Materia (INFM), research unit at the University of **Milano**, on the topic of Bose-Einstein condensation (BEC) in ultracold atoms.



In 1995 the BEC was experimentally achieved[2] for the first time cooling alkali-metal atoms at ultra-low temperatures (100 nK).

[2] M. H. Anderson et al., Science **269**, 198 (1995).

BEC with ultracold atoms (1997-2019)

A pure BEC is very well described by the Gross-Pitaevskii equation[3] (GPE)

$$i\hbar \frac{\partial}{\partial t}\psi(\mathbf{r},t) = \left[-\frac{\hbar^2}{2m}\nabla^2 + U(\mathbf{r}) + (N-1)g|\psi(\mathbf{r},t)|^2 \right] \psi(\mathbf{r},t) \ , \qquad (1)$$

where m is the mass of each boson, $U(\mathbf{r})$ is the external trapping potential, $g = \int V(\mathbf{r}) d^3\mathbf{r}$ is the strength of the inter-atomic potential $V(\mathbf{r}-\mathbf{r}')$, N is the total number of bosons in the BEC, and $\psi(\mathbf{r},t)$ is the wavefunction of the Bose condensate.
In many experiments with BECs there is quasi-1D external confinement

$$U(\mathbf{r}) = \frac{1}{2} m\omega_{\perp}^2 (x^2 + y^2) + V(z) \qquad (2)$$

due to the very strong transverse harmonic confinement of frequency $\omega_{\perp}$. Here $V(z)$ is a generic confinement along the axial direction.

[3] E. P. Gross, Nuovo Cim. **20**, 454 (1961); L.P. Pitaevskii, Sov. Phys. JEPT **13**, 451 (1961).

BEC with ultracold atoms (1997-2019)

In my most cited paper[4], we proposed a dimensional reduction of the GPE from 3D to 1D setting

$$\psi(\mathbf{r},t) = \frac{1}{\pi^{1/2}\sigma(z,t)} \; e^{-(x^2+y^2)/(2\sigma(z,t)^2)} \; f(z,t) \qquad (3)$$

where $f(z,t)$ is the generic axial wavefuction and $\sigma(z,t)$ is the space-time dependent width of the transverse Gaussian wavefuction. In this way, from the 3D GP action we obtained the so-called 1D nonpolynomial Schrödinger equation (NPSE) for the axial wavefunction

$$i\hbar \frac{\partial}{\partial t} f = \left[-\frac{\hbar^2}{2m}\partial_z^2 + V + \frac{\hbar^2}{2m\sigma^2} + \frac{1}{2} m\omega_\perp^2 \sigma^2 + \frac{(N-1)g}{2\pi\sigma^2}|f|^2 \right] f \; , \qquad (4)$$

where

$$\sigma(z,t) = a_\perp \left(1 + \frac{(N-1)g}{2\pi a_\perp^2} |f(z,t)|^2 \right)^{1/4} \qquad (5)$$

with $a_\perp = \sqrt{\hbar/(m\omega_\perp)}$ characteristic length of transverse confinement.

[4] LS, A. Parola, L. Reatto, Phys. Rev. A **65**, 043614 (2002).

BEC with ultracold atoms (1997-2019)

In the weak-coupling regime $(N-1)g|f|^2/(2\pi a_\perp^2) \ll 1$ one finds $\sigma \simeq a_\perp$ and the 1D NPSE becomes the familiar 1D GPE with a simple renormalization of the interaction strength

$$g_{1D} = \frac{g}{2\pi a_\perp^2} \; . \qquad (6)$$

Far from the weak-coupling regime, the 1D NPSE is a reliable generalization of the 1D GPE which takes into account of the transverse dynamics.

The 1D NPSE (and also the 2D NPSE) is now used in many papers. It also adopted by several experimental groups to compare with their observational data.

In a highly-cited paper[5] we used the 1D NPSE to analyze and explain the experimentally observed formation of a train of bright solitons[6] in the case of attractive interaction strength $(g < 0)$.

[5] LS, A. Parola, L. Reatto, Phys. Rev. Lett. **91**, 080405 (2003).

[6] K.E. Strecker et al, Nature **417**, 150 (2002).

BEC with ultracold atoms (1997-2019)

In another highly-cited paper[7] we obtained analytical formulas for bright solitons ($g < 0$) and dark solitons ($g < 0$) of the 1D NPSE in the absence of axial confinement, i.e. with $V(z) = 0$.
These analytical results generalize the seminal ones derived by Shabat and Zakharov[8] with the 1D cubic nonlinear Schrödinger equation (i.e. the 1D GPE).

Quite remarkably, both bright solitons and dark solitons have been observed with atomic BECs, and the transverse effects predicted by the 1D NPSE have been found in these experiments.

In another highly-cited paper[9], I derived and studied a system of NPSEs for a two coupled BECs loaded in a cigar-shaped trap.

[7] LS, A. Parola, L. Reatto, Phys. Rev. A **66**, 043603 (2002).
[8] A. Shabat and V Zakharov, Sov. Phys. JETP **34**, 62 (1972).
[9] LS and B.A. Malomed, Phys. Rev. **74**, 053610 (2006).

BEC with ultracold atoms (1997-2019)

In the last years, one of my main research interest is the investigation of beyond-mean-field effects in the thermodynamics of atomic BECs, by adopting the elegant formalism of functional integration, where the partition function is given by

$$\mathcal{Z} = \int \mathcal{D}[\psi, \psi^*] \ \exp\left\{ -\frac{S[\psi, \psi^*]}{\hbar} \right\} , \tag{7}$$

with $\psi(\mathbf{r}, \tau)$ the bosonic field and $S[\psi, \psi^*]$ its Eucidean action functional.

Recently, by using functional integration and dimensional regularization[10] in a single-authored PRL paper[11] I obtained analytically the nonuniversal equation of state of a 2D Bose gas as a function of temperature, density and interaction parameters (scattering length and effective range).

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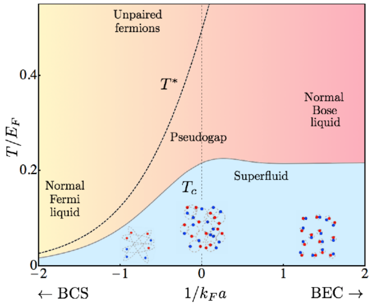
[10] LS and F. Toigo, Phys. Rep. **640**, 1 (2016).

[11] LS, Phys. Rev. Lett. **118**, 130402 (2017).

BCS-BEC crossover (2005-2019)

During the period of my transfer from **Milano** to **Padova** I started the investigation of the BCS-BEC crossover.



In 2004 this crossover was observed[12] with ultracold gases made of two-component fermionic atoms (^{6}Li or ^{40}K), changing with an external magnetic field the scattering length a_F of inter-atomic potential.

[12] C.A. Regal et al, Phys. Rev. Lett. **92**, 040403 (2004); M.W. Zwierlein et al, PRL 92, 120403 (2004).

BCS-BEC crossover (2005-2019)

In a highly-cited paper[13], by using a time-dependent density functional, we predicted the collective modes of oscillations (breathing mode and quadrupole mode) of the Fermi superfluid at unitarity ($a_F = \pm\infty$) under harmonic trapping. These predictions, which involve non-trivial beyond-mean-field effects, were later confirmed by experiments.

In another highly-cited paper[14], we obtained an analytical formula for the condensate density of Cooper pairs in the BCS-BEC crossover

$$n_0 = \int |\langle \hat{\psi}_\uparrow(\mathbf{r})\hat{\psi}_\downarrow(\mathbf{r}')\rangle|^2 \; d^3\mathbf{r} d^3\mathbf{r}' = \frac{m^{3/2}}{8\pi\hbar^3}\Delta_0^{3/2}\sqrt{\frac{\mu}{\Delta_0} + \sqrt{1 + \frac{\mu^2}{\Delta_0^2}}} \quad (8)$$

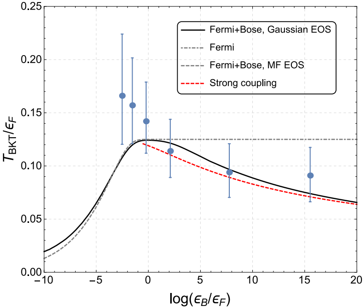
where $\hat{\psi}_\sigma(\mathbf{r})$ is the fermionic field operator, μ is the chemical potential and Δ_0 the energy gap. We found that the condensate fraction n_0/n is exponentially small in the BCS regime but to goes to 1 in the deep BEC regime, as later confirmed by experiments.

[13] N. Manini and LS, Phys. Rev. A **71**, 033625 (2005).

[14] LS, N. Manini, A. Parola, Phys. Rev. A **72**, 023621 (2005).

BCS-BEC crossover (2005-2019)

Recently, the Berezinskii-Kosterlitz-Thouless (BKT) transition from superfluid to normal fluid has been observed with ^{6}Li atoms in quasi-2D confinement[15], across the 2D BCS-BEC crossover.



In the figure there is the critical temperature T_{BKT} vs binding energy ϵ_B of pairs. The **solid black curve** is our beyond-mean-field theory[16] based on functional integration with Gaussian corrections. $\epsilon_F = \hbar^2 \pi n/m$ is the 2D Fermi energy with n the 2D number density.

[15] P. A. Murthy et al., Phys. Rev. Lett. 115, 010401 (2015).
[16] G. Bighin and LS, Phys. Rev. B **93**, 014519 (2016).

Conclusions and open problems

- During the 27 years of my research activity the main topics of study were:
  – many-body systems (statistical physics, density functional, quantum field theory)
  – nonlinear physics (chaos, solitons, quantized vortices)
  – Bose-Einstein condensation with ultracold atoms
  – superfluidity in the BCS-BEC crossover
- I always compared my theoretical results with the available experimental data, trying to be at the edge of the knowledge.
- Presently, I am working on several topics. Among them:
  – Josephson and Rabi dynamics in bosonic and fermionic superfluids;
  – beyond-mean-field effects in coupled BECs and fermionic superfluids;
  – Bose-Einstein condensation on the surface of a sphere.

Acknowledgements

Thank you for your attention!