UNIVERSITY OF PISA
DEPARTMENT OF PHYSICS «ENRICO FERMI»

Squeezing Forty Orders of (Length) Magnitude in Four Squared Meters

Maria Luisa Chiofalo

QUANTUM MANY-PARTICLES SYSTEMS WITH BROKEN SYMMETRIES:
A unifying idea via 2 concepts

CONSERVED QUANTITIES

- Number of particles
- Momentum/current (angular too)
- Energy
- ………..

+

BROKEN SYMMETRIES

- Liquid to Crystal
- Normal to Super Fluidity
- Para to Ferro Magnetism
- ………..

Appear:
- New Hydodynamic modes
- New elastic constants
- Defects

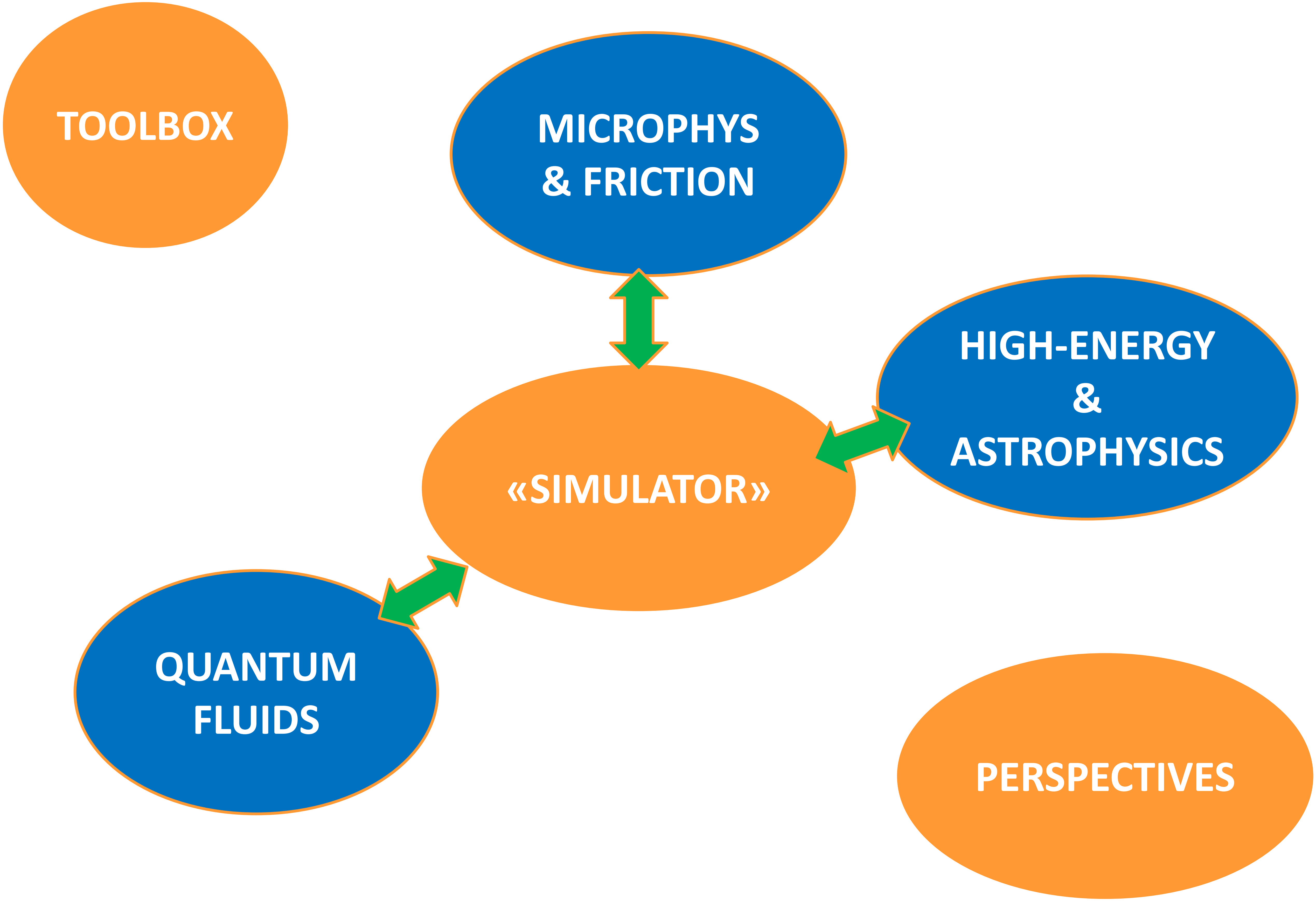
Reduced symmetry

Classical — λ_{dB} ~ sistem size → Quantum

Temperature

Interactions

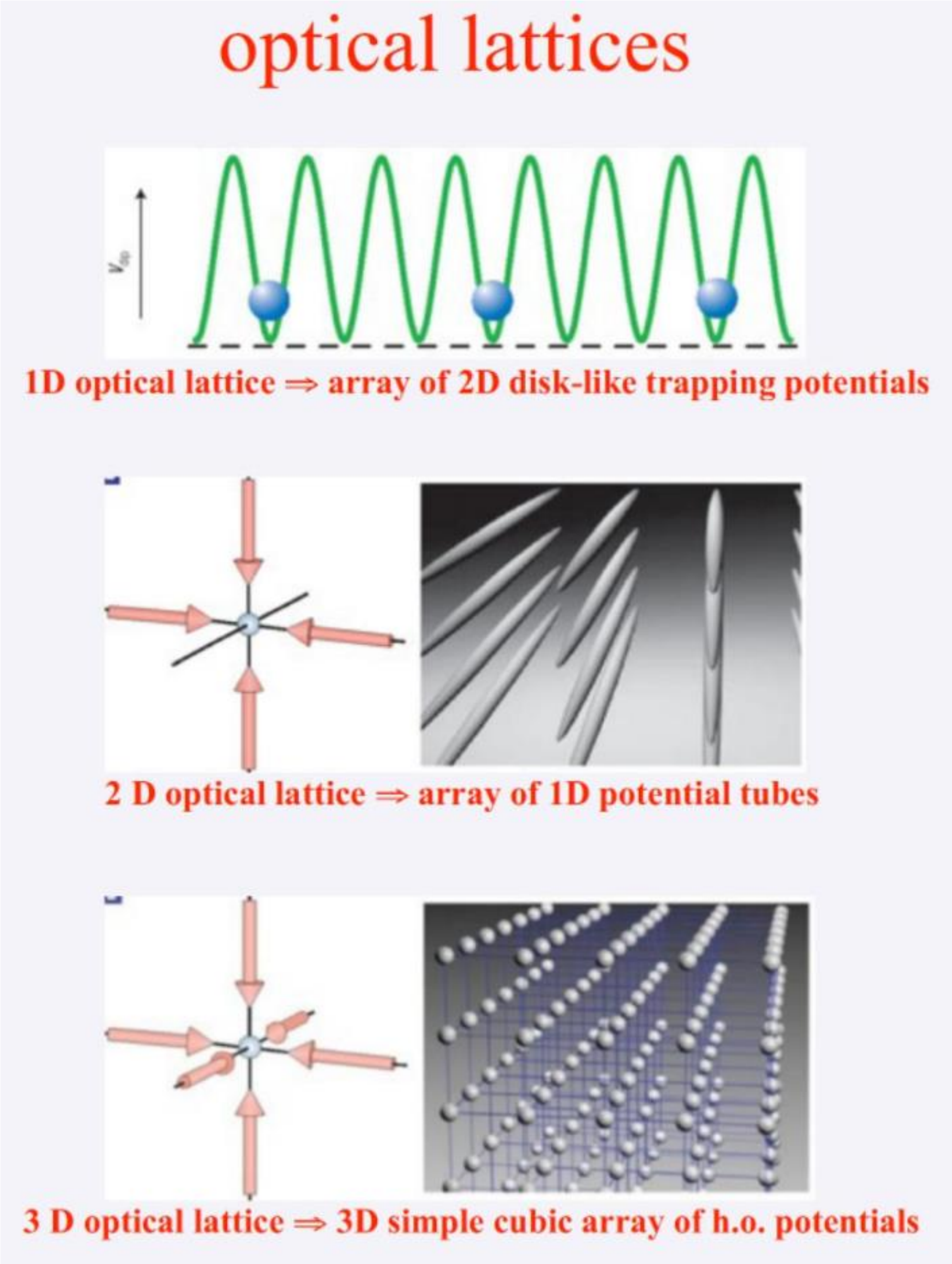
Dimensionality

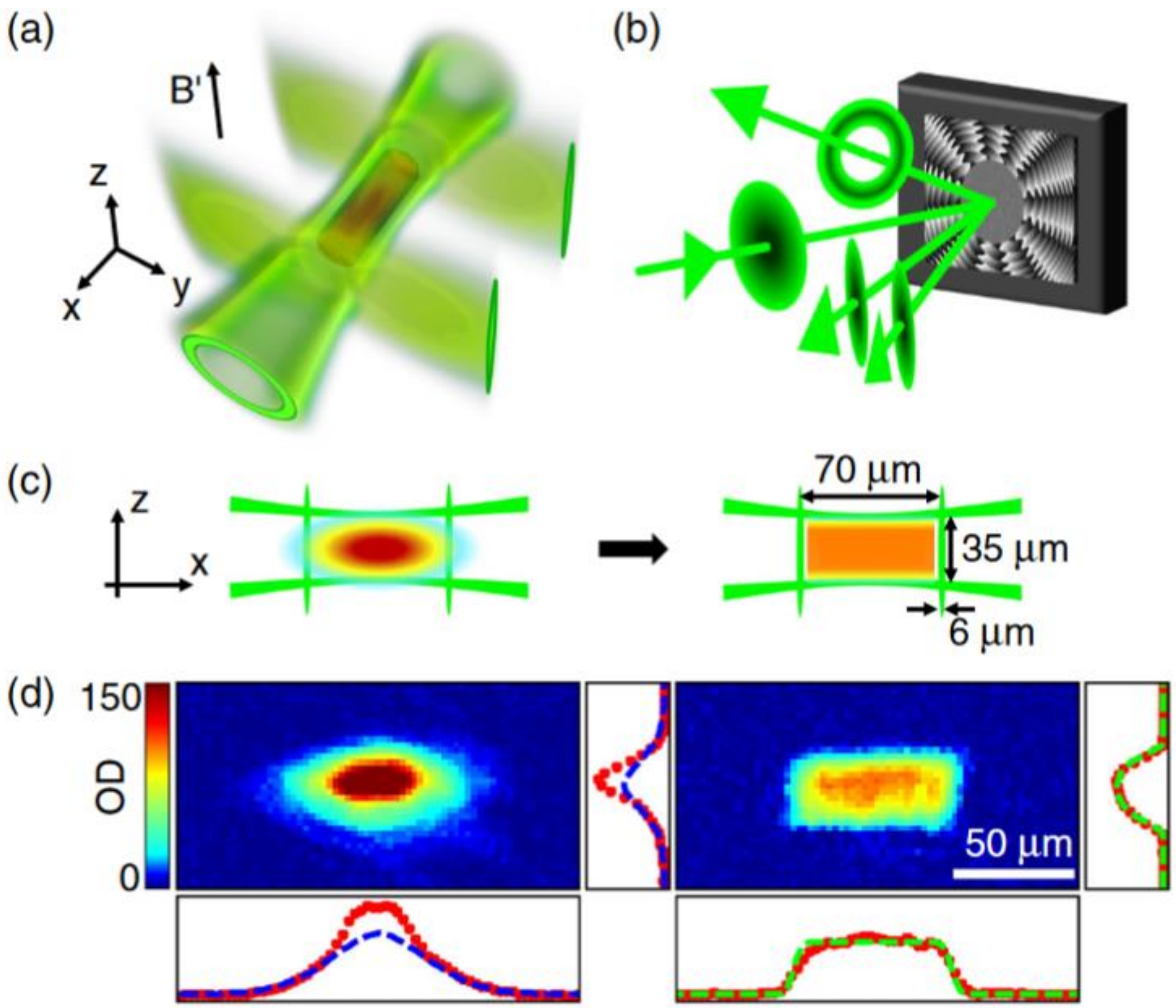

TOOLBOX
MICROPHYS
& FRICTION
HIGH-ENERGY
&
ASTROPHYSICS
«SIMULATOR»
QUANTUM
FLUIDS
PERSPECTIVES

TOOLBOX

THE TOOL-MARY POPPINS BAG

TOOL-MP BAG: GEOMETRY

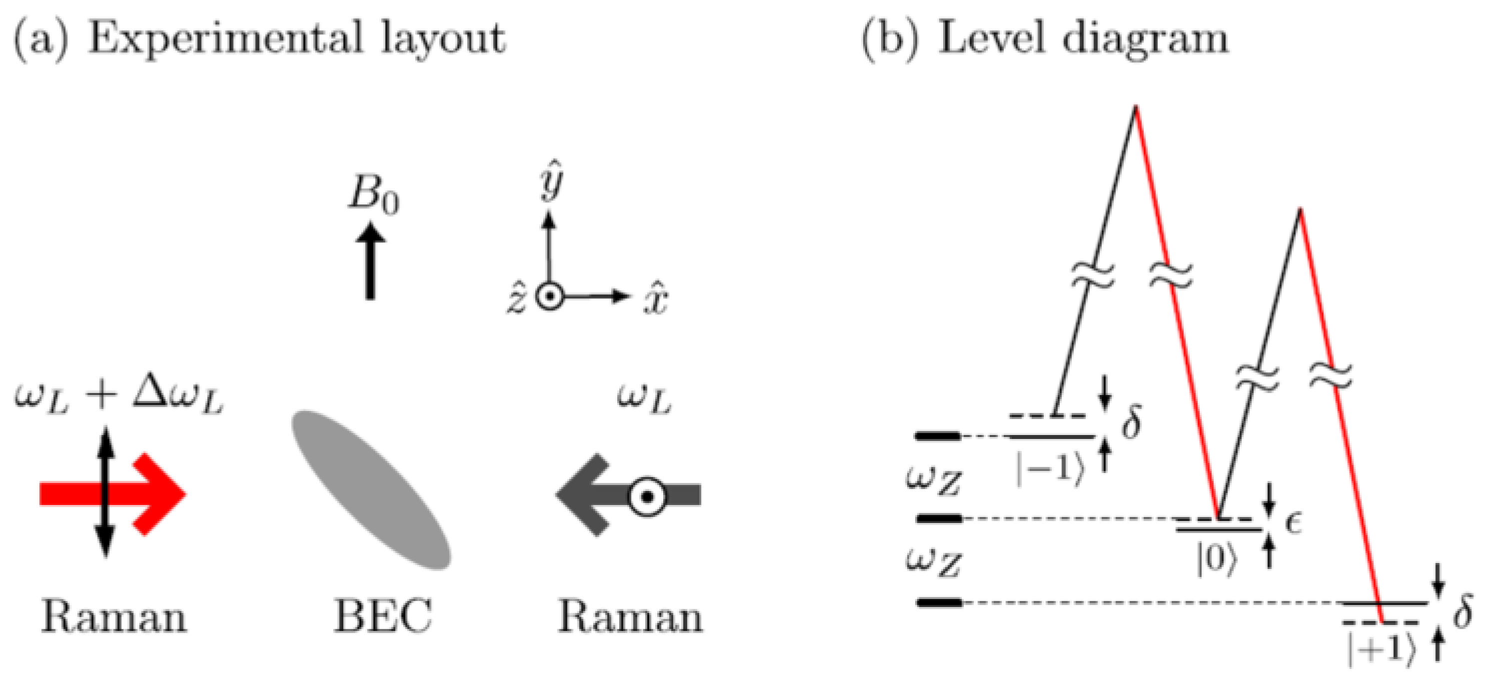




Bloch (review,1995)

Hadzibabic (PRL, 2013)

TOOL-MP BAG: SYNTHETIC GAUGE FIELDS

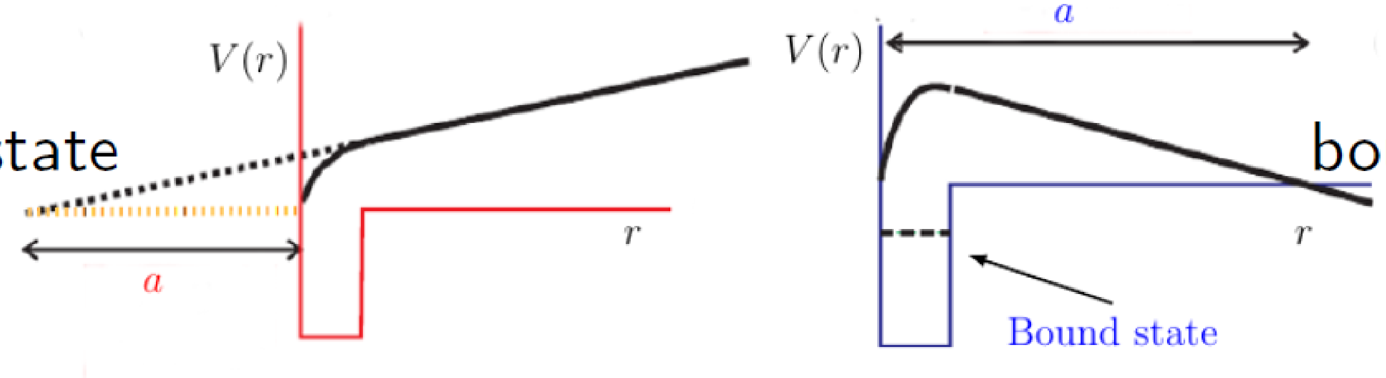


Y.-J. Lin et al. (2009)

USEFUL e.g. TO PRODUCE COUPLING BETWEEN EXTERNAL (ORBITAL) AND INTERNAL (SPIN) DEGREES OF FREEDOM: SPIN-ORBIT COUPLING

Scattering length a for an attractive potential

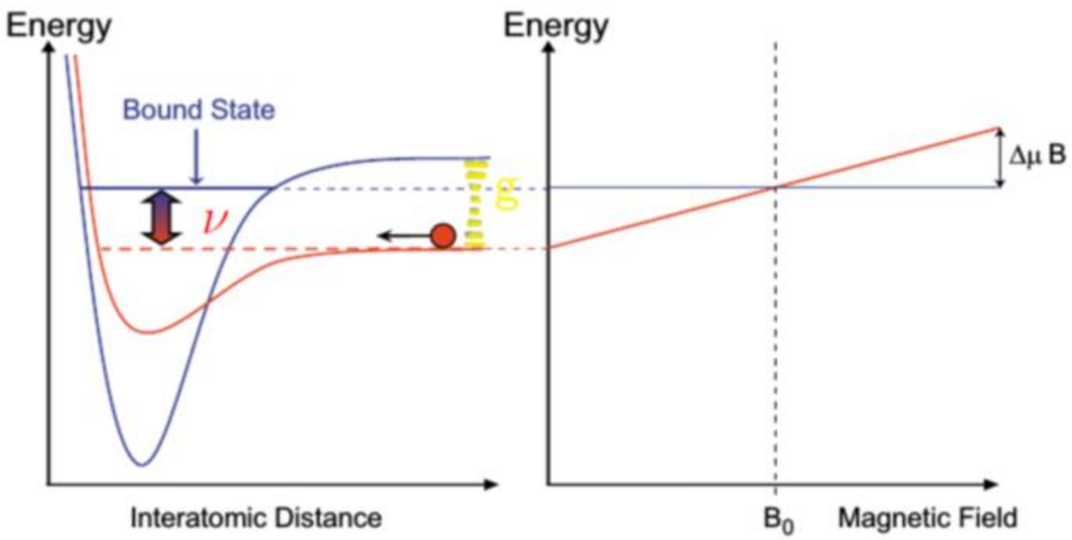
$a < 0$
no bound state



$a > 0$
bound state

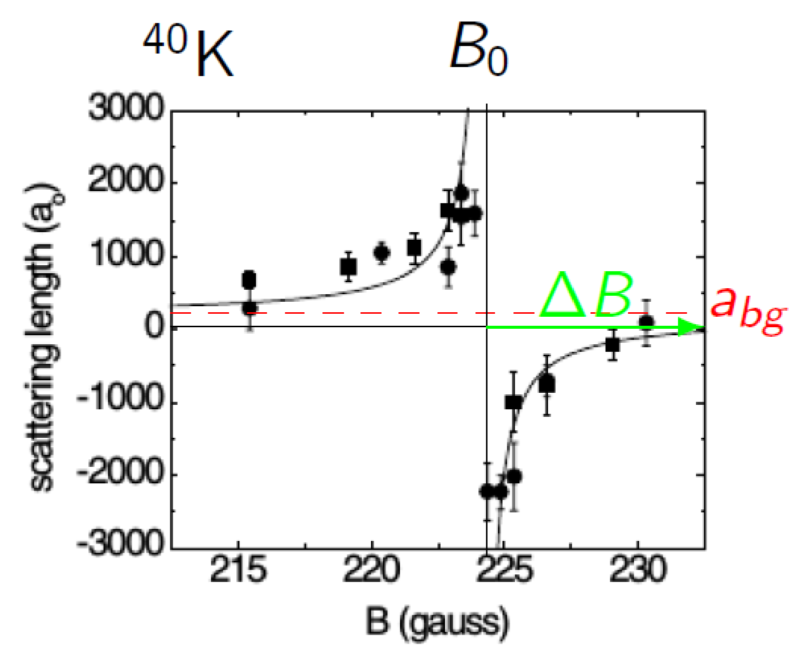
Control the strength of interactions

2 channels ⇔ different spin (hyperfine) states of 2-body scattering



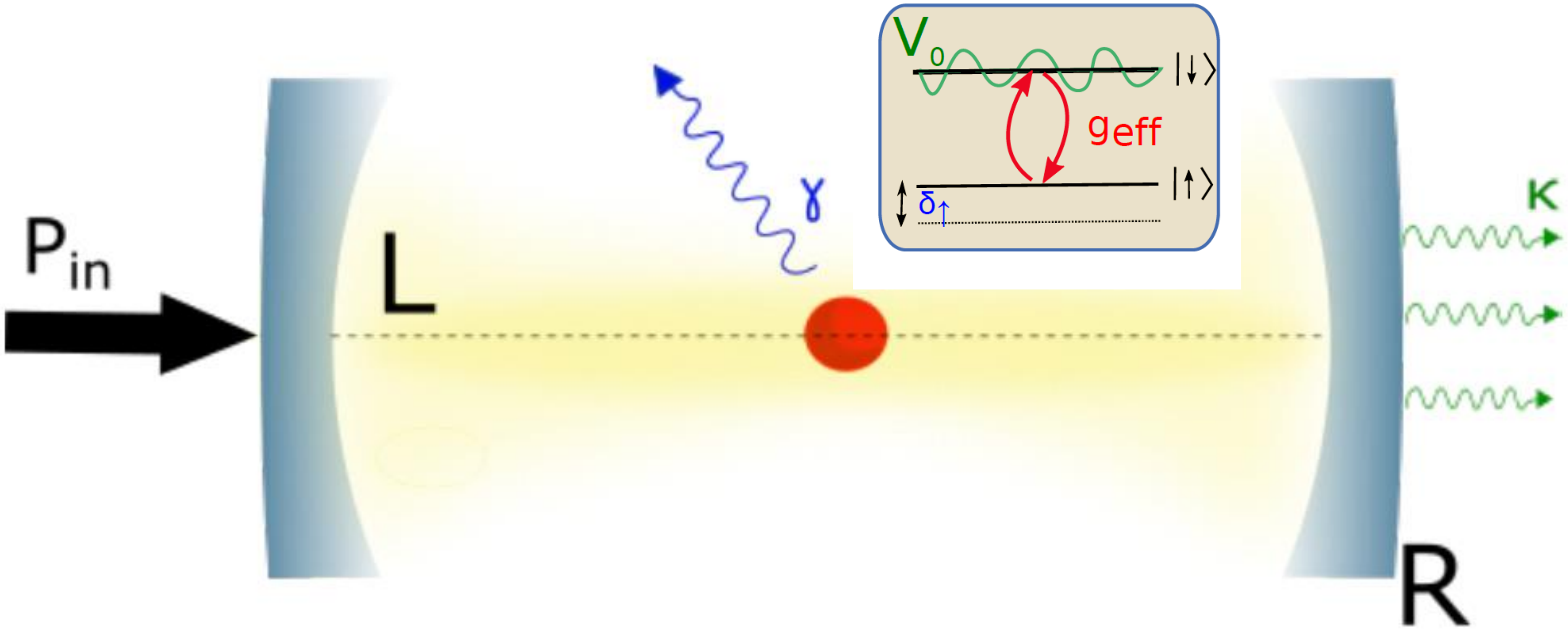
Dependence of a on the magnetic field

Regal et al., 2003



a

TOOL-MP BAG: INTERNAL INTERACTIONS (OPTICAL CAVITY)

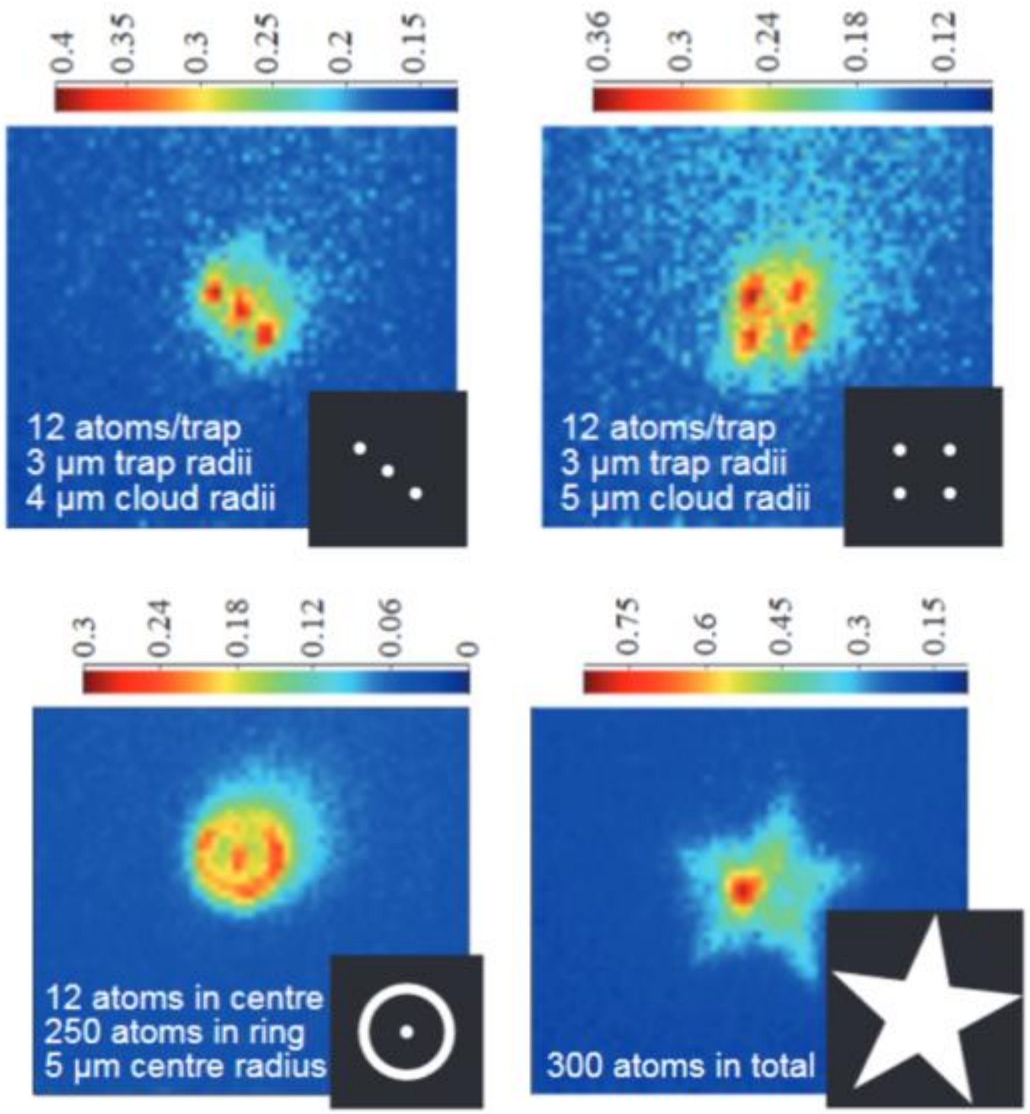


KEY-CONCEPTS:

- **ENHANCE ATOM-LIGHT INTERACTION BY MULTIPLE PHOTON TRIPS**
- **EFFECTIVE INTERACTION TUNABLE IN STRENGTH**
- **COUPLING TO MANY MODES TUNES THE RANGE OF EFFECTIVE INTERACTION [B. Lev group]**

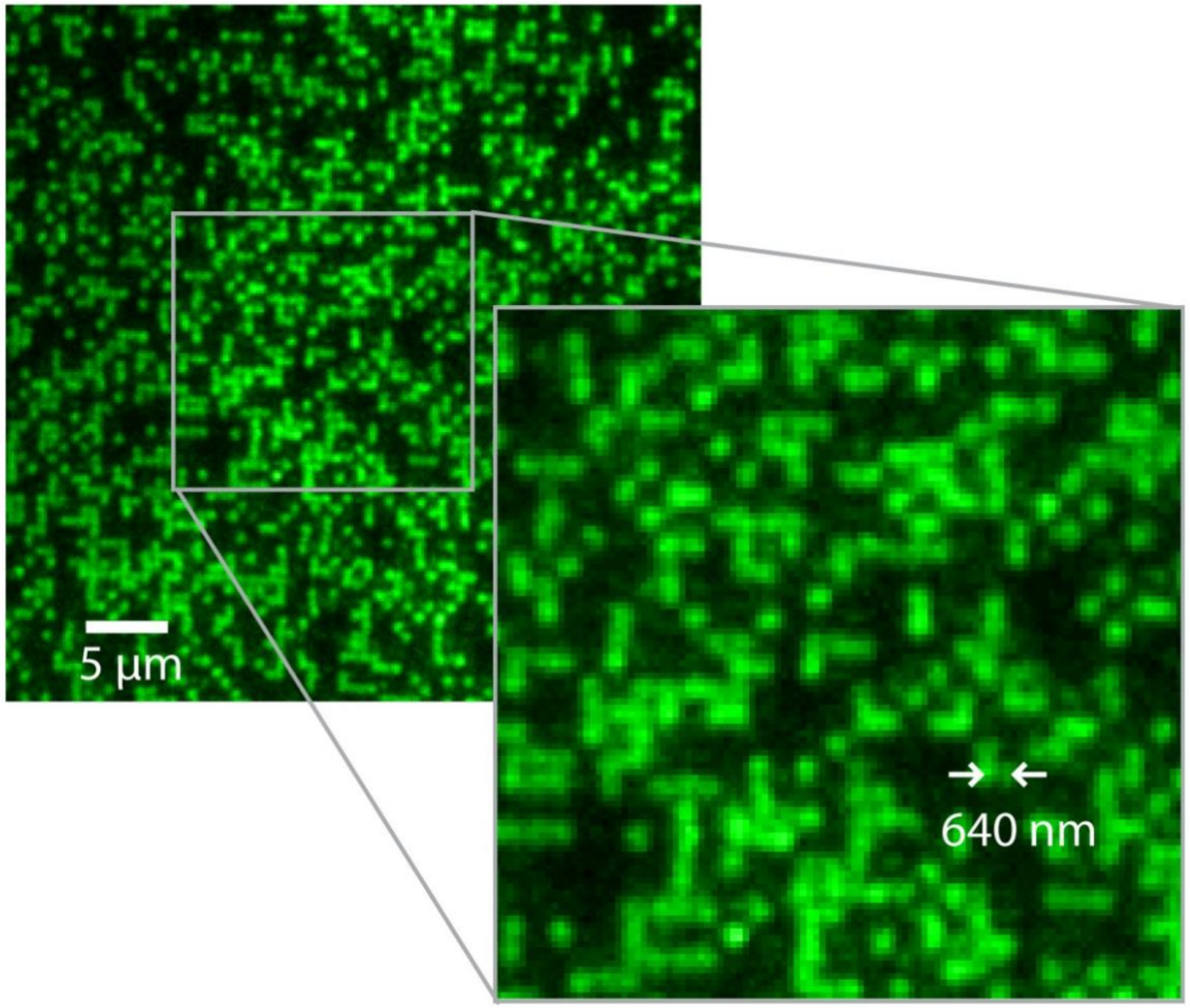
TOOL-MP BAG: ADDRESSING A FEW OR SINGLE ATOMS

Optical tweezers



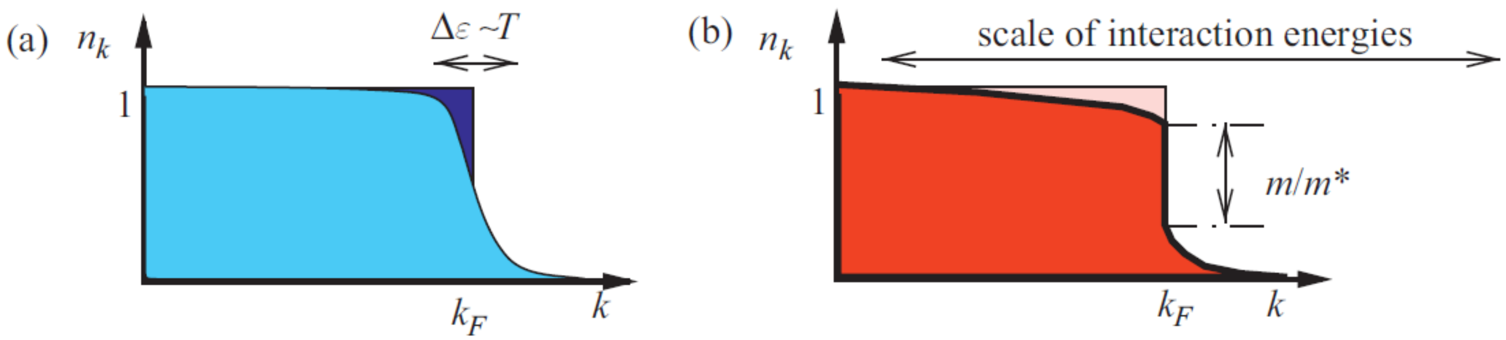
[Muldoon et a., 2012]

Quantum gas microscope



[M. Greiner group]

WHERE THINGS GET INTERESTING: BOOSTING INTERACTIONS



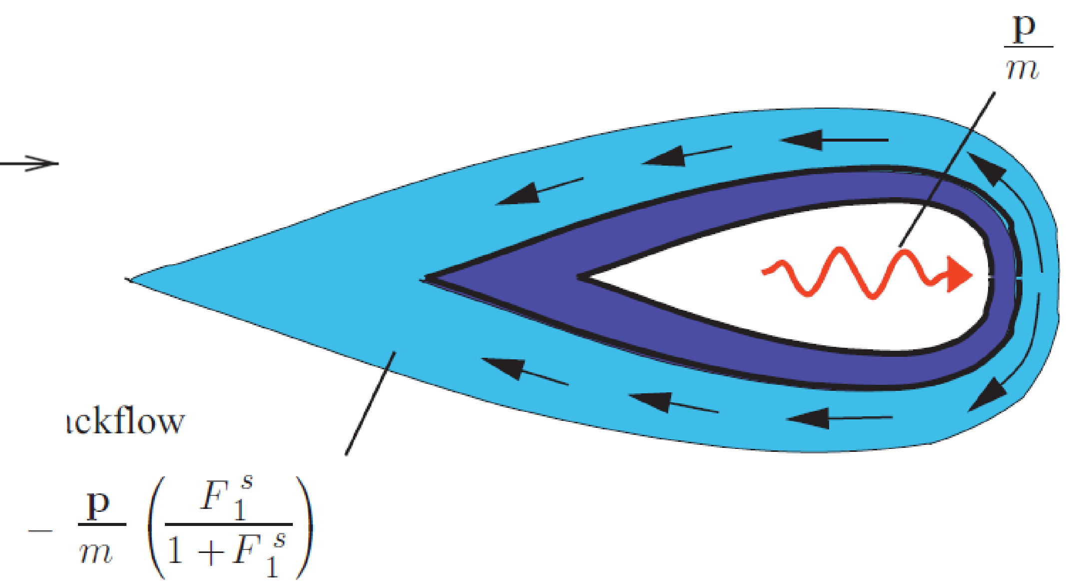


Table 6.1 Key properties of the Fermi liquid.

Property	Non-interacting	Landau Fermi-liquid
Fermi momentum	p_F	Unchanged
Density of particles	$2\frac{V_{FS}}{(2\pi)^3}$	Unchanged
Density of states	$\mathcal{N}(0) = \frac{mp_F}{\pi^2\hbar^3}$	$\mathcal{N}^*(0) = \frac{m^* p_F}{\pi^2\hbar^3}$
Effective mass	m	$m^* = m(1 - F_1^s)^{-1}$
Specific heat coefficient $C_V = \gamma T$	$\gamma = \frac{\pi^2}{3}k_B^2\mathcal{N}(0)$	$\gamma = \frac{\pi^2}{3}k_B^2\mathcal{N}^*(0)$
Spin susceptibility	$\chi_s = \mu_F^2\mathcal{N}(0)$	$\chi_s = \mu_F^2\frac{\mathcal{N}^*(0)}{1+F_0^a}$
Charge susceptibility	$\chi_C = \mathcal{N}(0)$	$\chi_C = \frac{\mathcal{N}^*(0)}{1+F_0^s}$
Collective modes	–	Sound ($\omega\tau << 1$) Zero sound ($\omega\tau >> 1$)

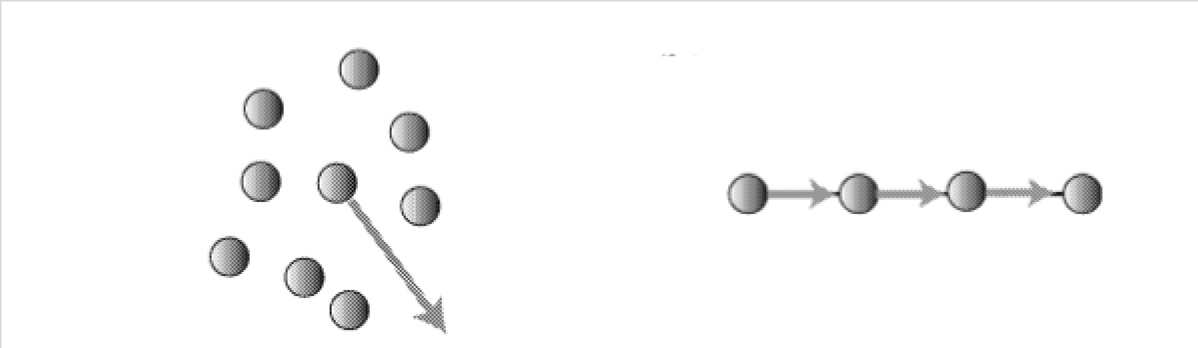
Mott insulator as

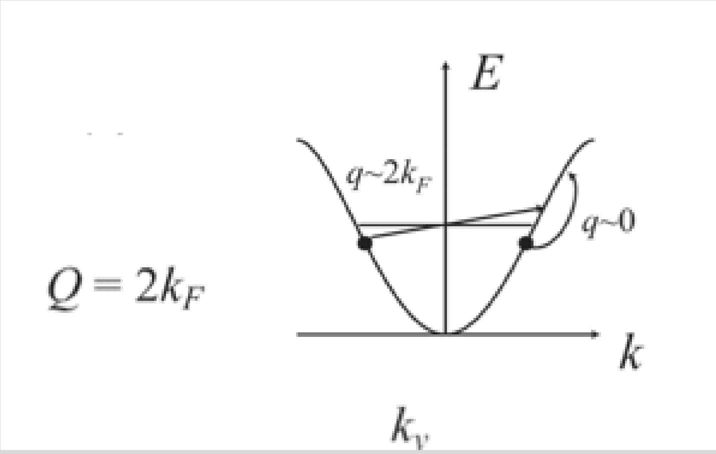
$$F_1^s = 1$$

Stoner ferromagnet as $F_0^a = -1$

P. Coleman, Introduction to Many-Body Physics, Cambridge

WHERE THINGS GET INTERESTING: REDUCED DIM





ALL EXCITATIONS COLLECTIVE
ALWAYS STRONLGY COUPLED **@ LOW-ENERGY**

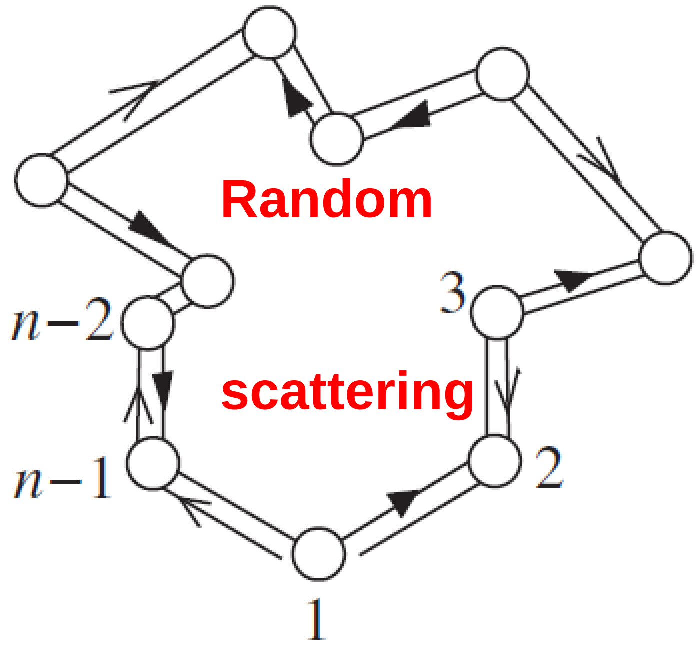
1D: NO FERMI LIQUID

- SPIN AND DENSITY EXCITATIONS SEPARATE AND MAY PROPAGATE WITH DIFFERENT VELOCITIES
- FERMI «SURFACE» NESTING AT ALL TIMES

$$\xi\,(k+2k_F) = -\xi(k)$$

- SPIN AND DENSITY RESPONSE χ EASILY DIVERGE AND INSTABILITIES OCCUR IN SPIN-SPIN AND DENSITY-DENSITY CHANNELS (IN A SENSE SIMILAR TO SUPERFLUIDITY)

WHERE THINGS GET INTERESTING: DISORDER



$$p_{TOT} = p_1 + p_2 + 2\sqrt{p_1 p_2}\cos(\phi_2 - \phi_1)$$

By Time-reversal symmetry $A_{\tilde{P}} = A_P$

Constructive interference

Quantum particle vs. Classical particle

$p_{TOT} = 4p_1$ $p_{TOT} = 2p_1$

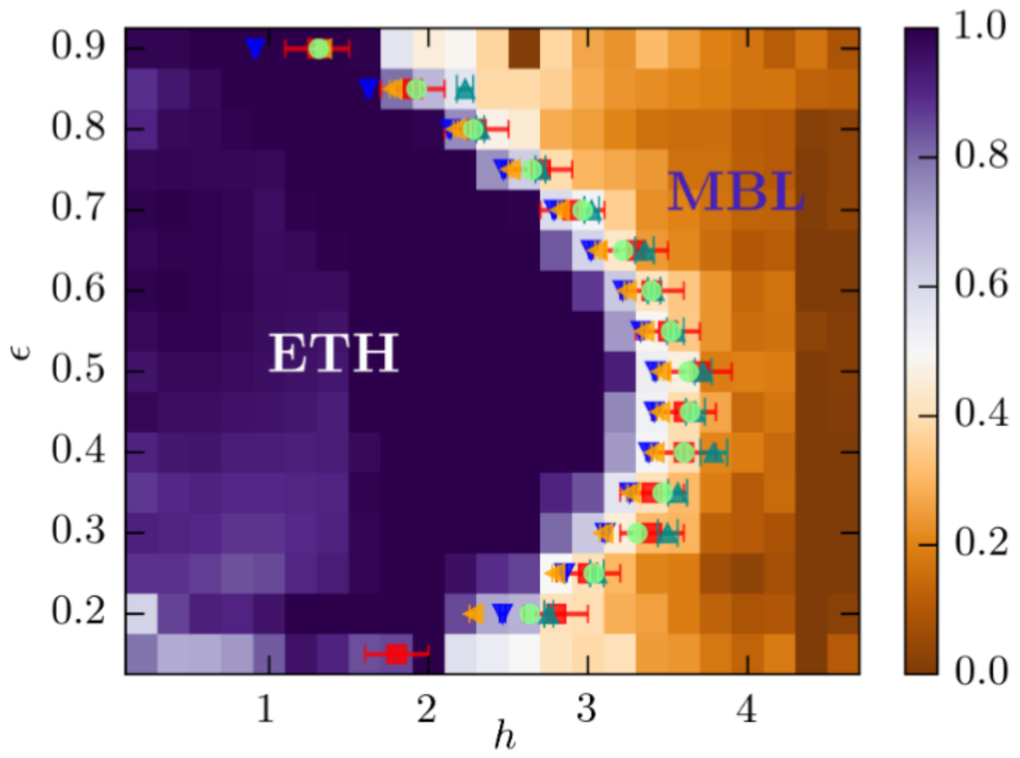
Argument by Altshuler, Aronov, Larkin, Khmelnitskii

Quantum enhancement of probability for localization !!!

2D and 1D: arbitrarily small amounts of disorder lead to (Anderson) localization !

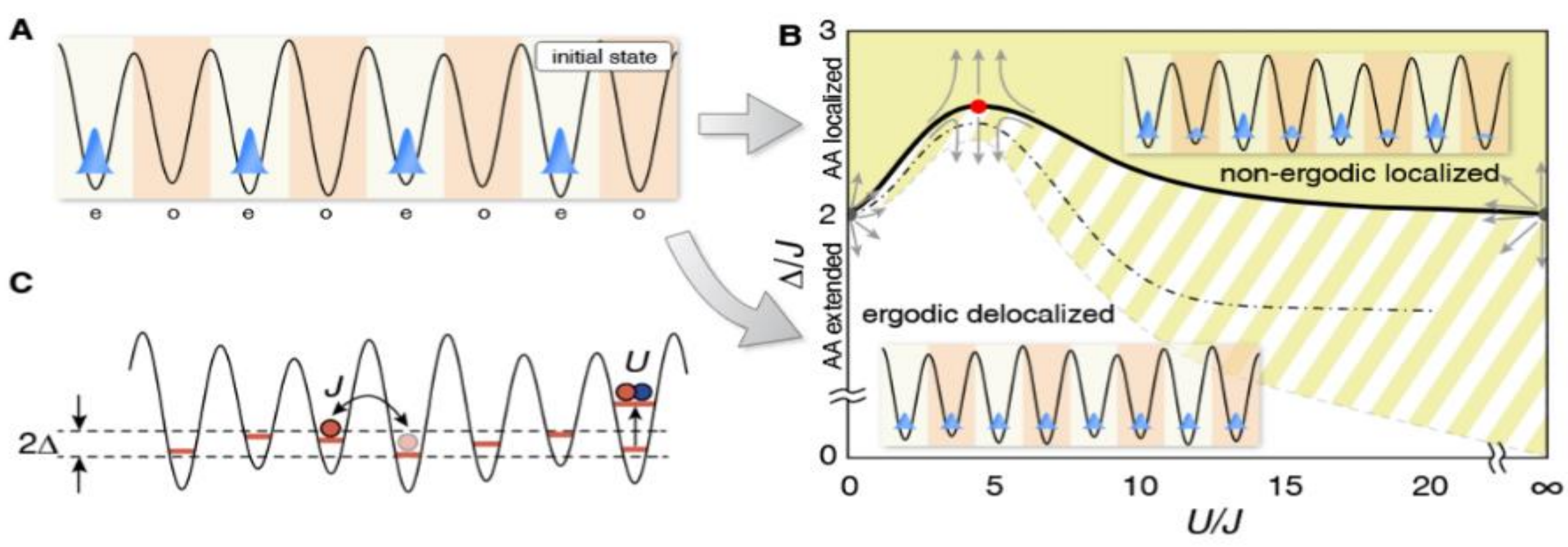
3D : above a critical threshold

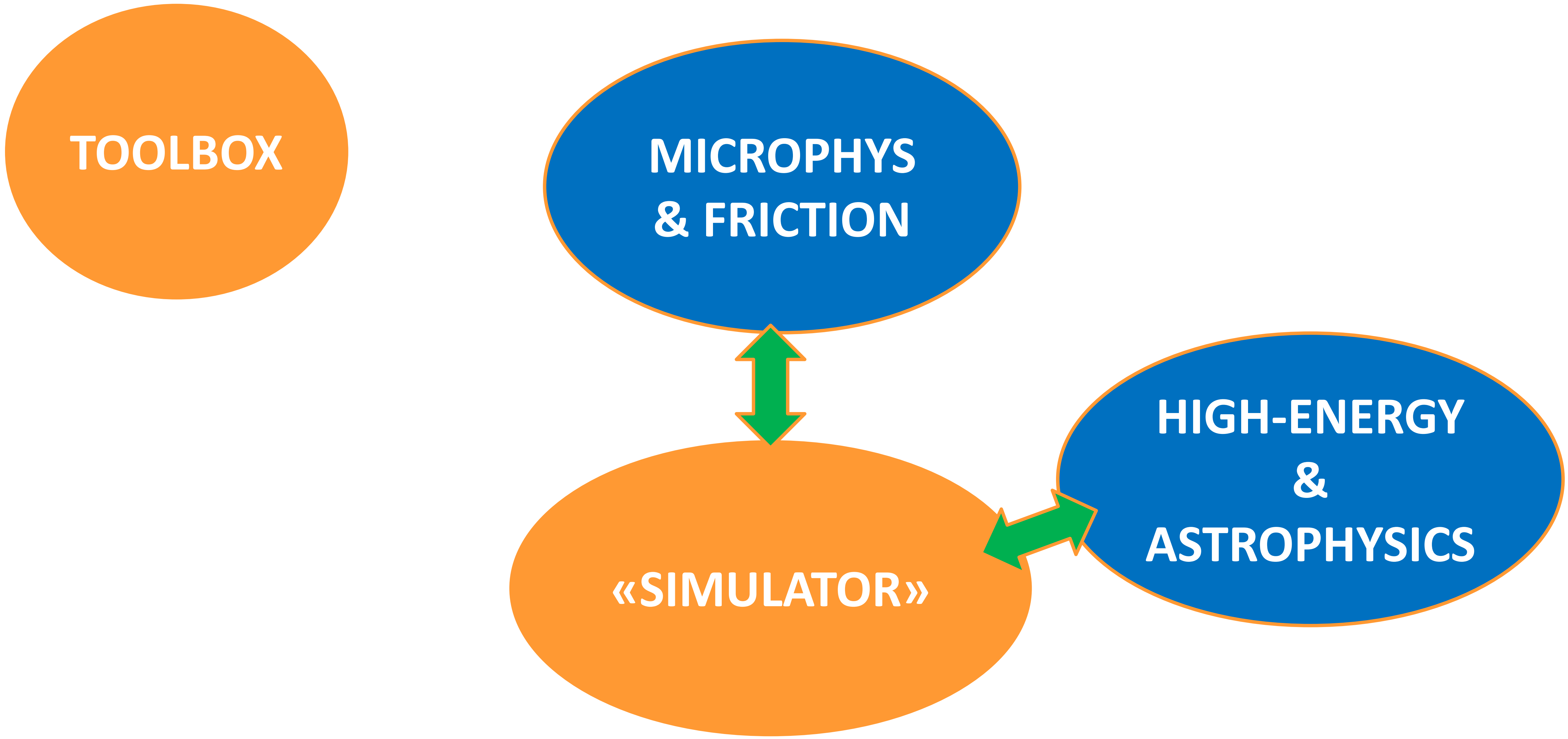
WHERE THINGS GET INTERESTING: DISORDER+INTERACTIONS THERMALIZATION VS. MANY-BODY LOCALIZATION



Numerical analysis [Alet et al.]

[Experiment: M. Schreiber, S. Hodgman, P. Bordia, H. Luschen, M. Fischer, R. Vosk, E. Altman, U. Schneider, I. Bloch, Science 349, 842 (2015)]

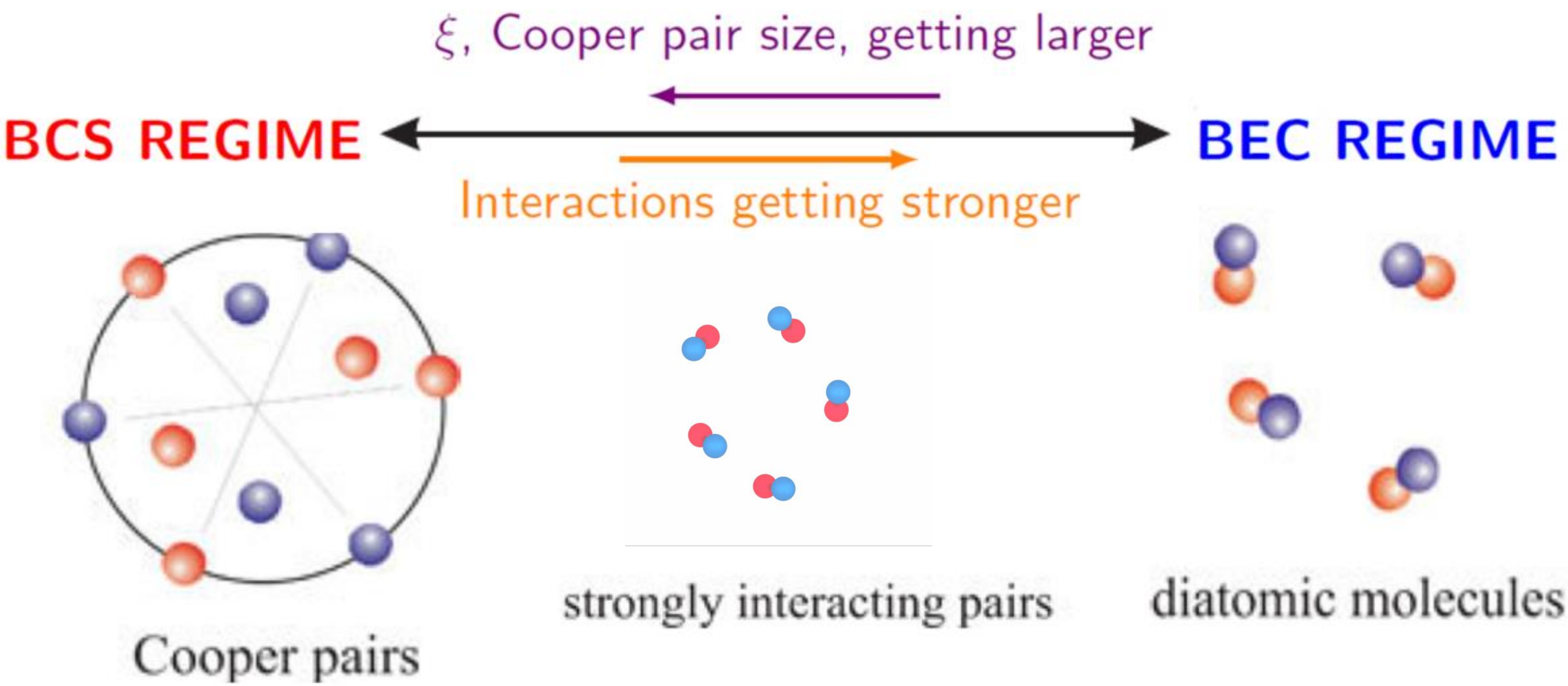




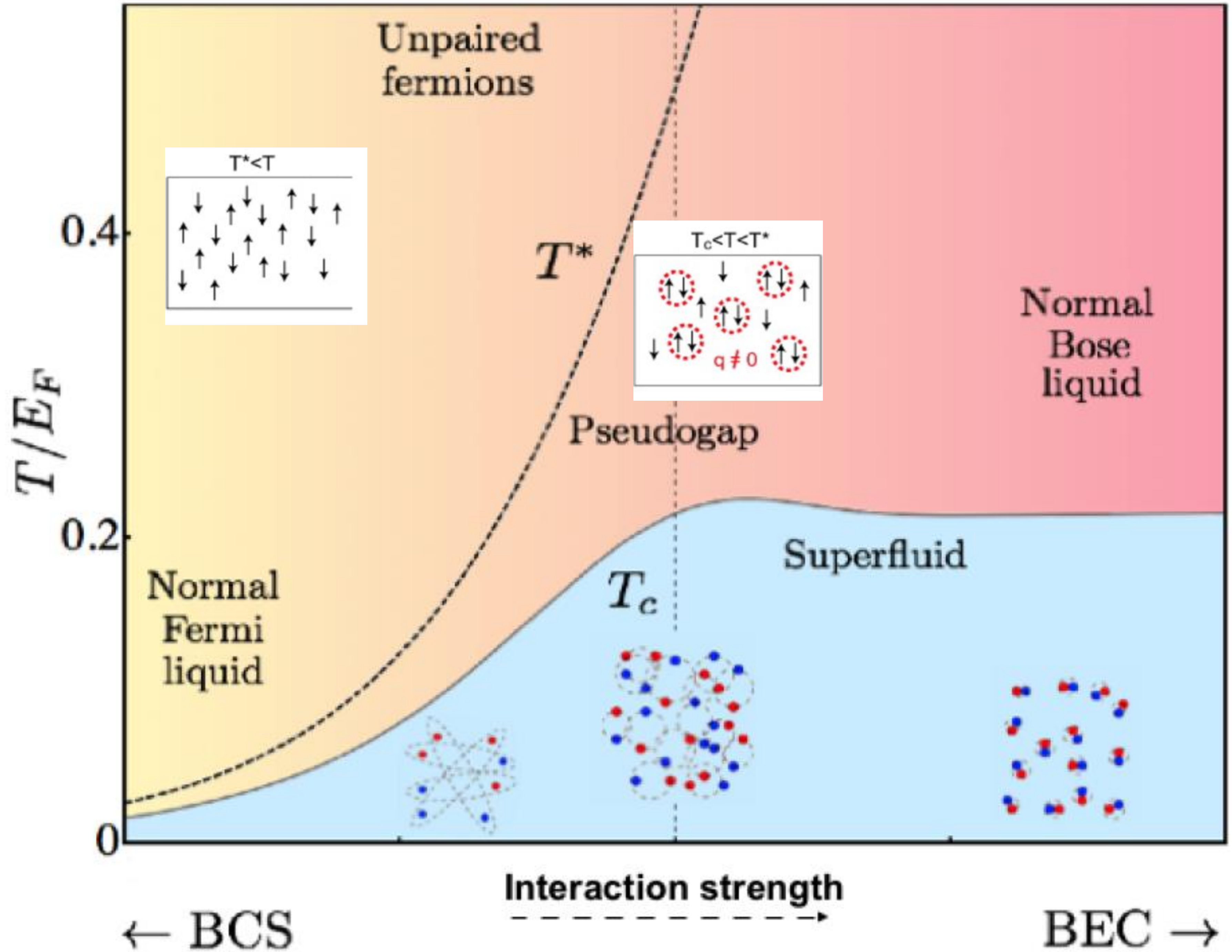
- **Holland M J, Kokkelmans S, Chiofalo M L, Walser R**, PRL 87, 120406 (2001)
- **Musolino S and Chiofalo M**, **EPJ-ST 226**, 2793 (2017)
- **Giambastiani D., Barsanti M. and Chiofalo M.**, EPL 123, 66001(2018).
- **E. Colella, M. Barsanti, R. Citro, D. Rossini, and Chiofalo M.**, PRB **97,** 134502 (2018)
- **Bonetti P. and Chiofalo M.**, *in preparation* (2018)

BCS-BEC CROSSOVER

Eagles '69, Leggett '80, Noziéres and Schmitt-Rink '85



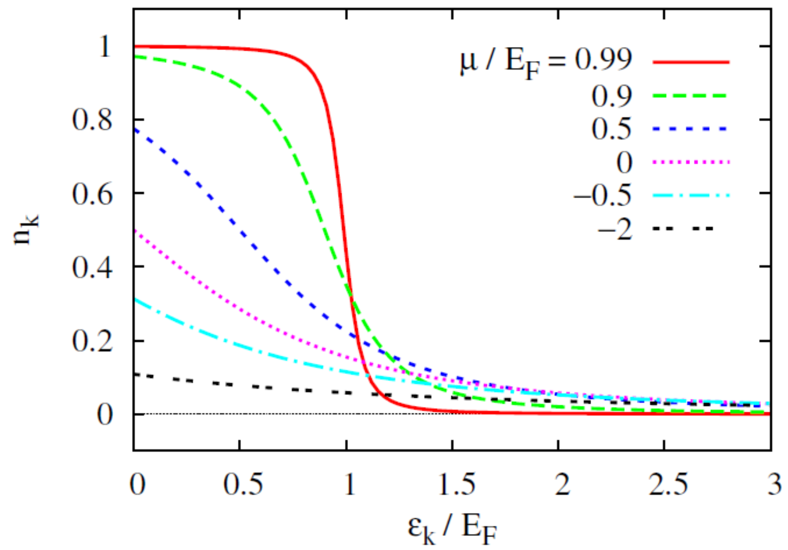
BCS-BEC CROSSOVER IN HTSC

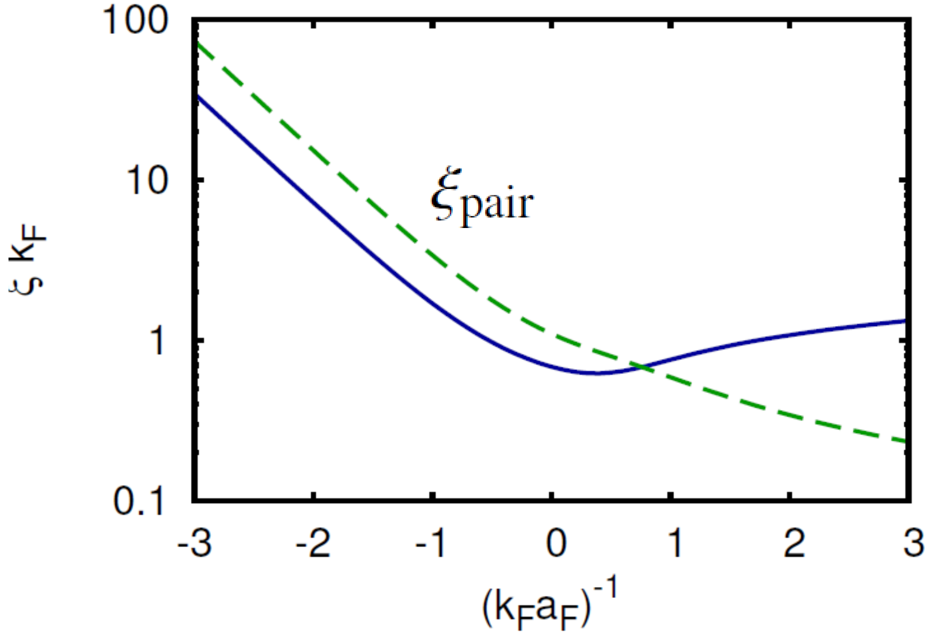


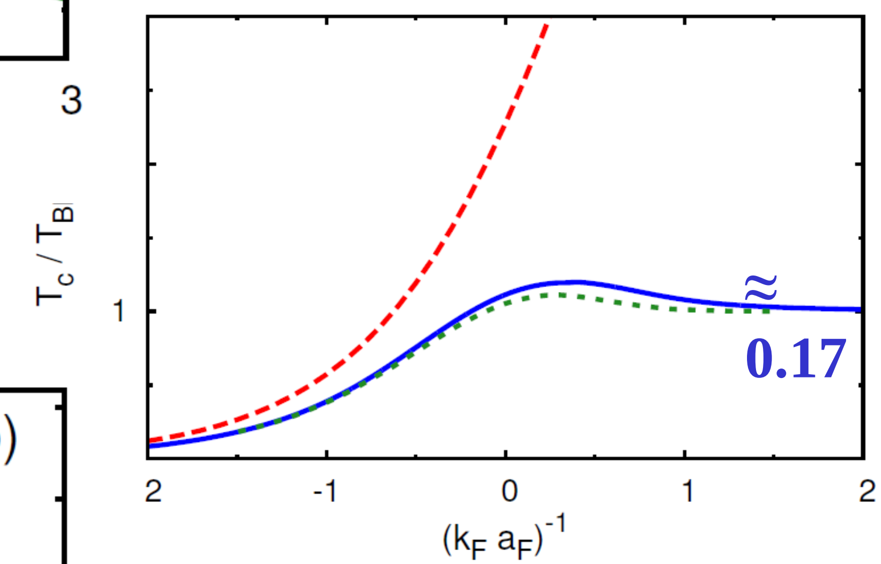
O. DeWolfe et al. (2016)

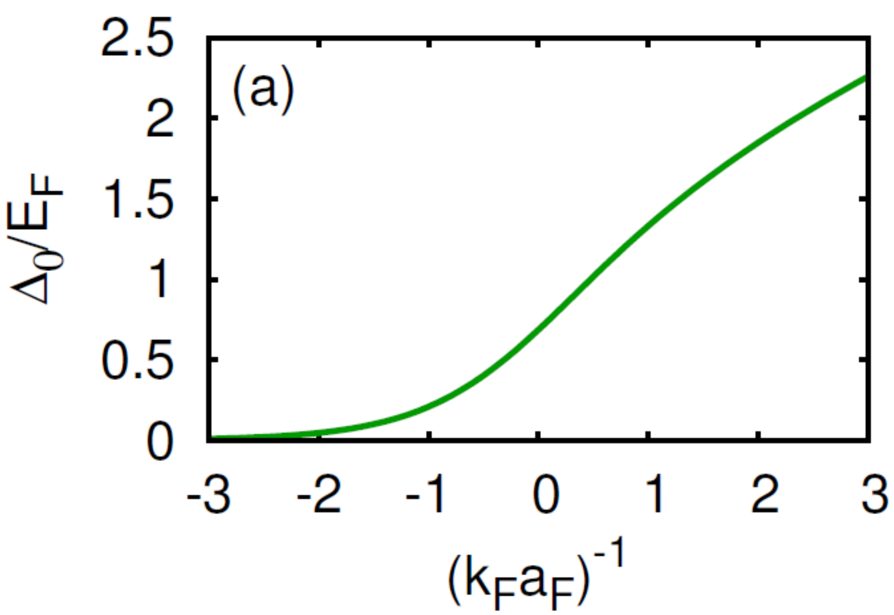
BCS-BEC CROSSOVER @UNITARITY

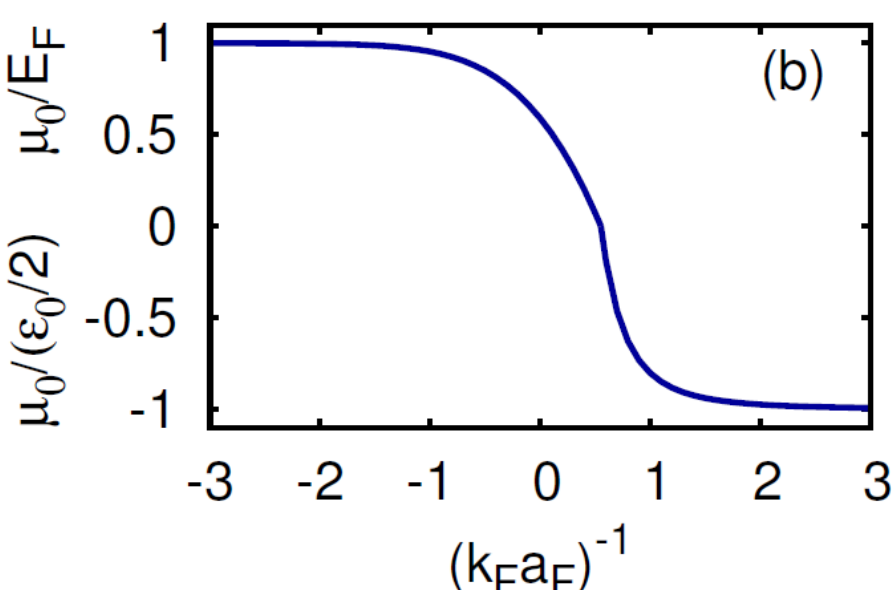
Strinati et al., RPP (2018)







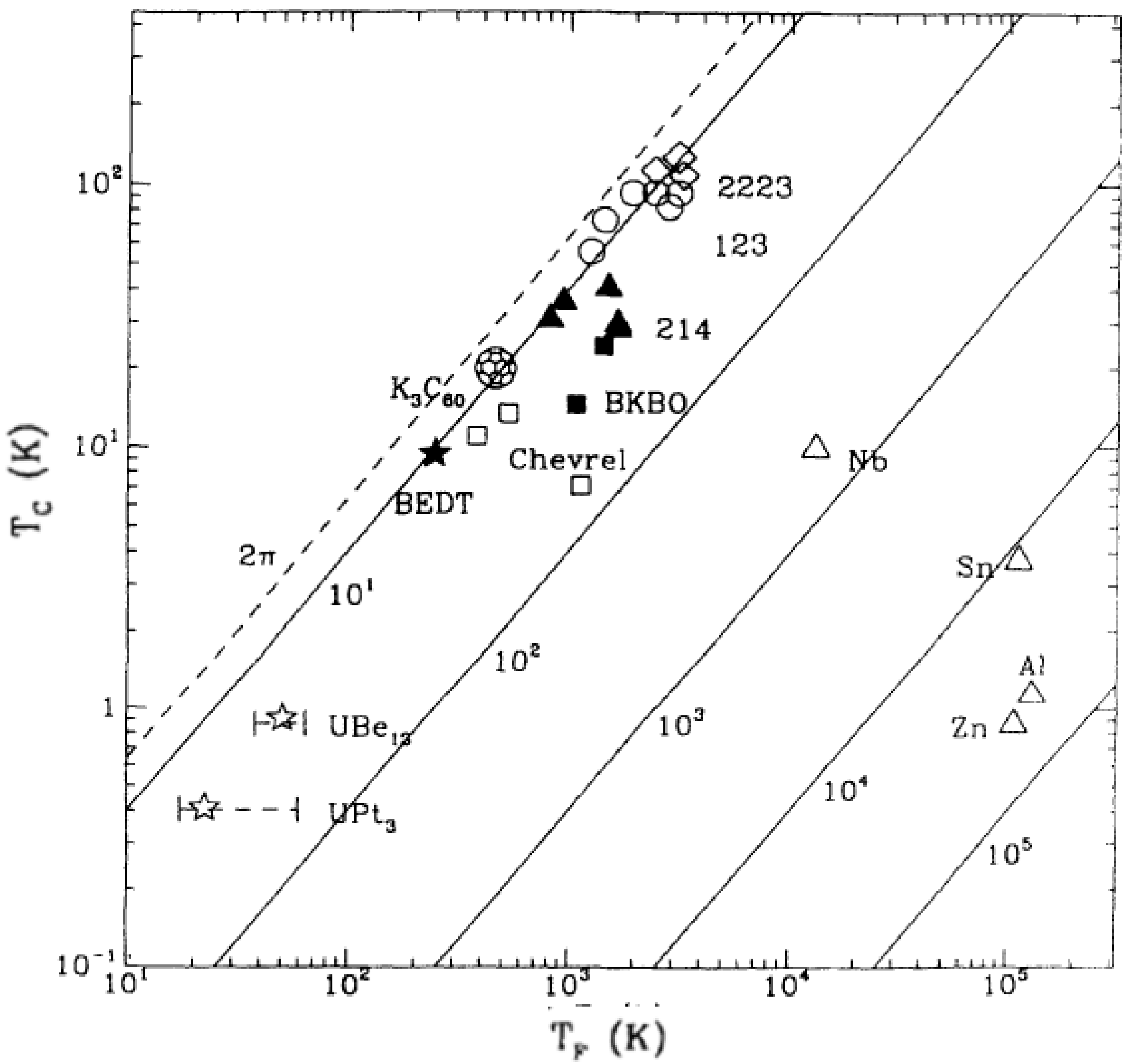




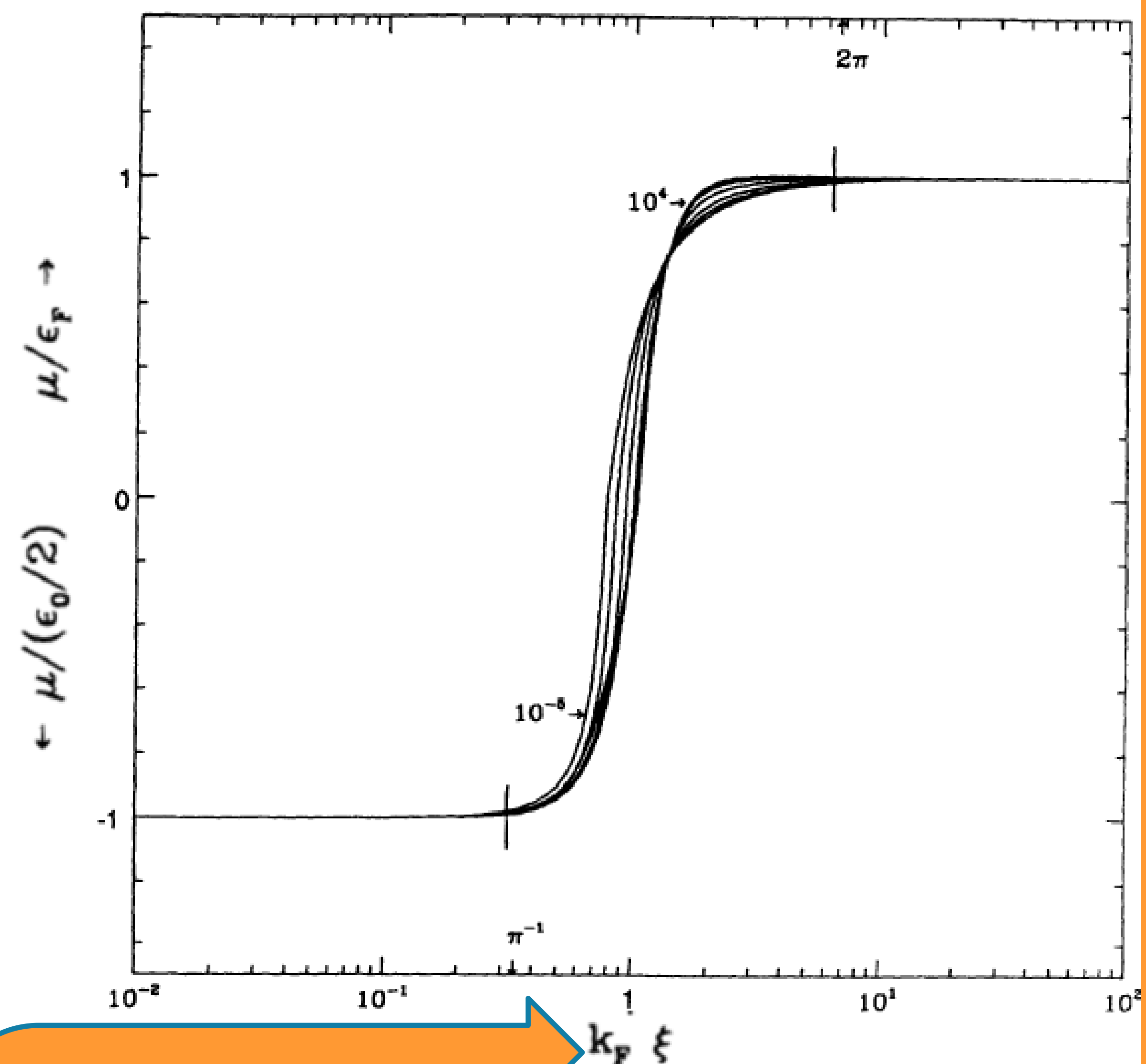
$\mu_0/E_F \approx 0.37$ @ unitarity

BCS-BEC CROSSOVER IN HTSC: UNIVERSALITY

Y. J. Uemura et al. (1991)



F. Pistolesi et al. (1994)

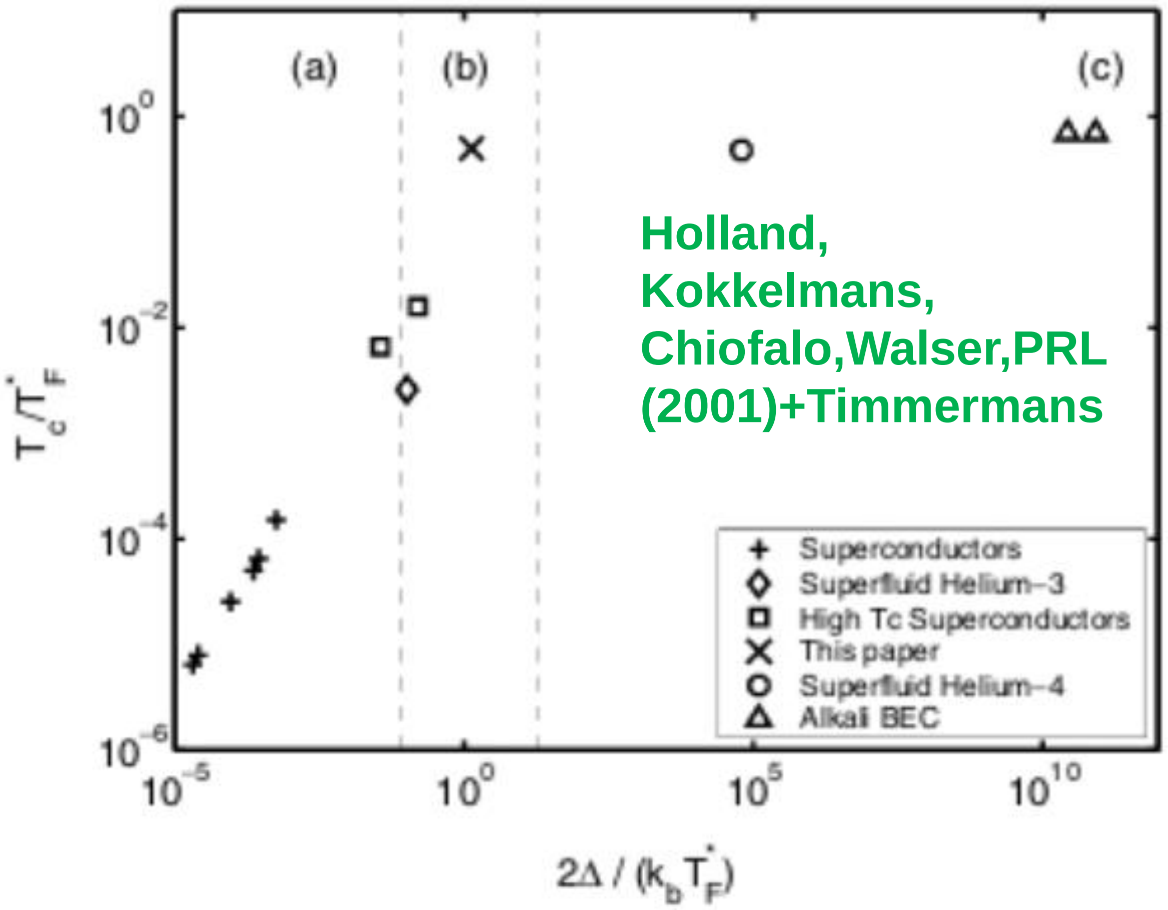


Description in terms of pair correlation length (pair size)

HOW MUCH DOES UNIVERSALITY PERSIST

INDEPENDENTLY OF MICROSCOPIC DETAILS?

BCS-BEC CROSSOVER IN QUANTUM GASES

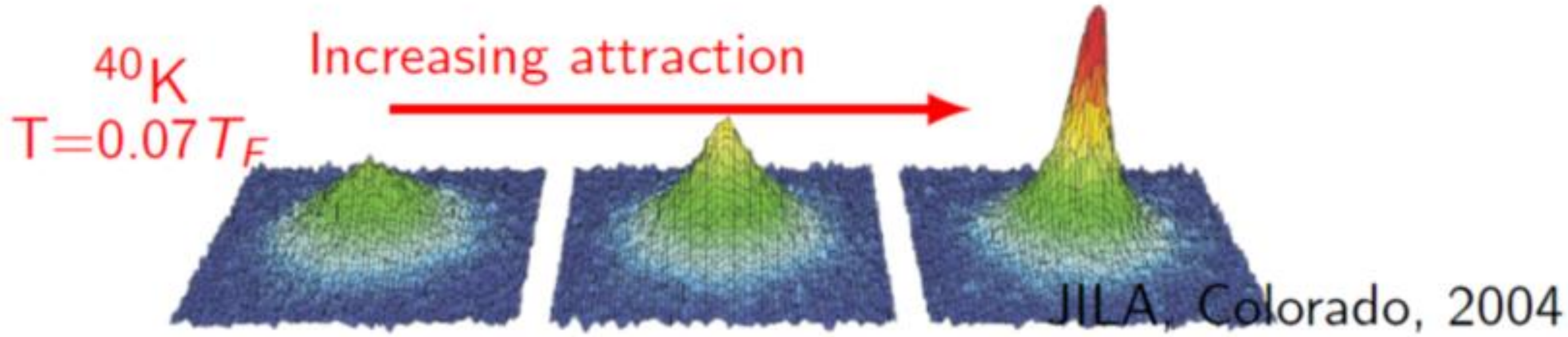


Holland, Kokkelmans, Chiofalo,Walser,PRL (2001)+Timmermans

PREDICTION

OBSERVATION

^{40}K at JILA, ^{6}Li at MIT



Markus Greiner, Cindy Regal and Debbie Jin, Nature 426 (2003)

Zwierlein, Stan, Schunck, Raupach, Gupta, Hadzibabic, and Ketterle, PRL 91 (2003)

EVOLUTION OF THE BCS-BEC CROSSOVER ☺

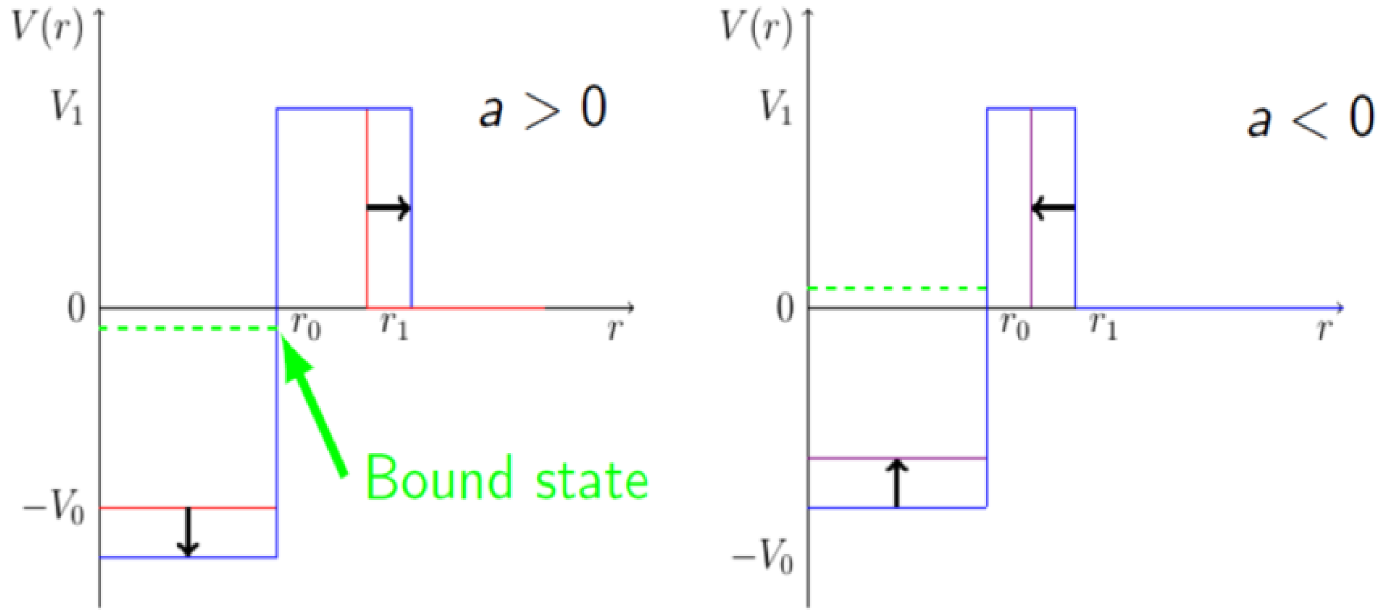
- COND-MAT AND HTSC: PHENOMENOLOGICAL MODEL TO GAIN INSIGHT ON MICROSCOPIC MECHANISMS

- ULTRACOLD QUANTUM GASES: PARADIGM TO BE EXPLORED UNDER CONROLLABLE MICROSCOPIC MECHANISMS

TWO EXAMPLES

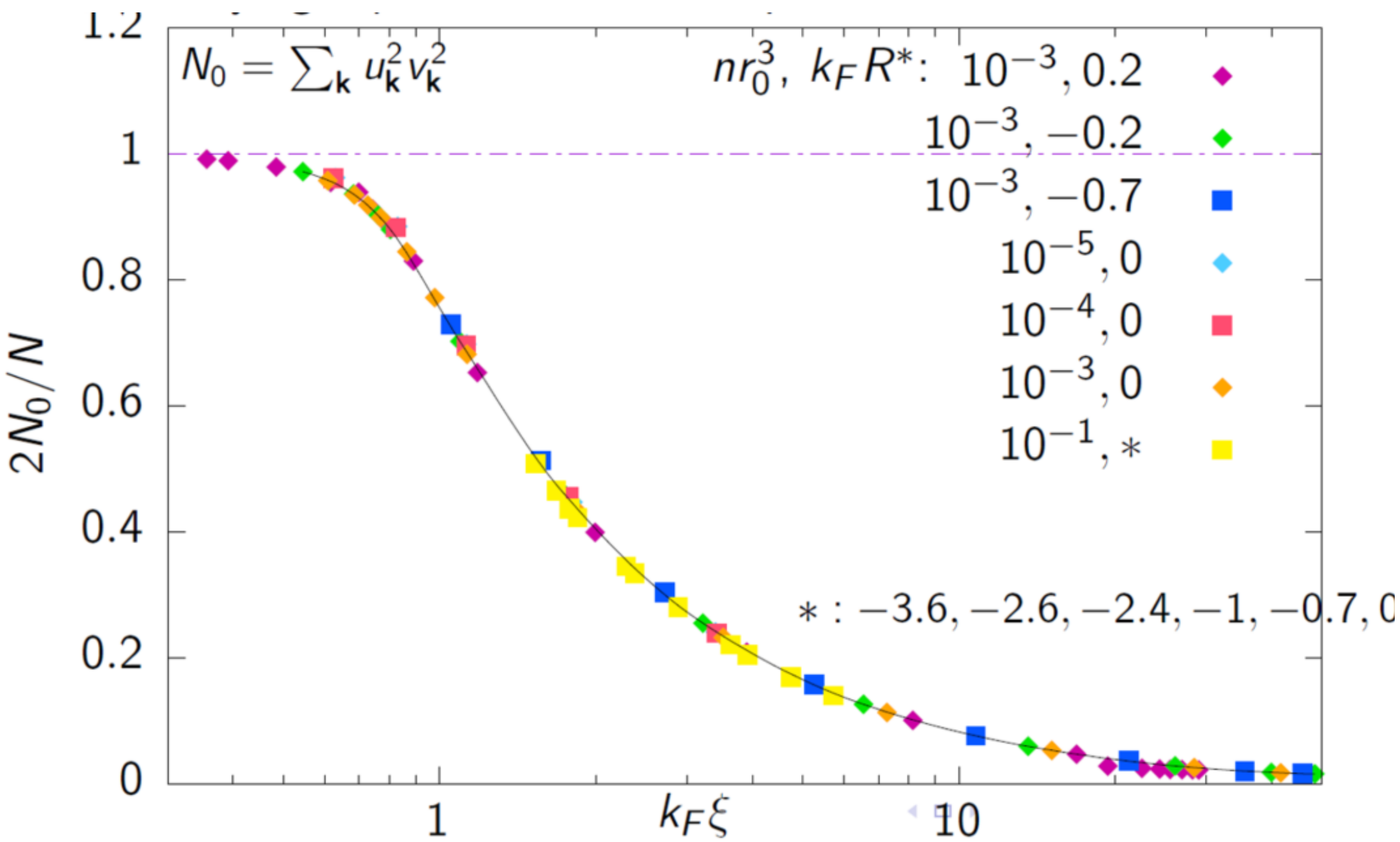
- Shape resonance [Musolino &MLC, EPJ-ST 2017]
- Variable range interaction + SOC [Giambastiani& MLC, EPL 2018]

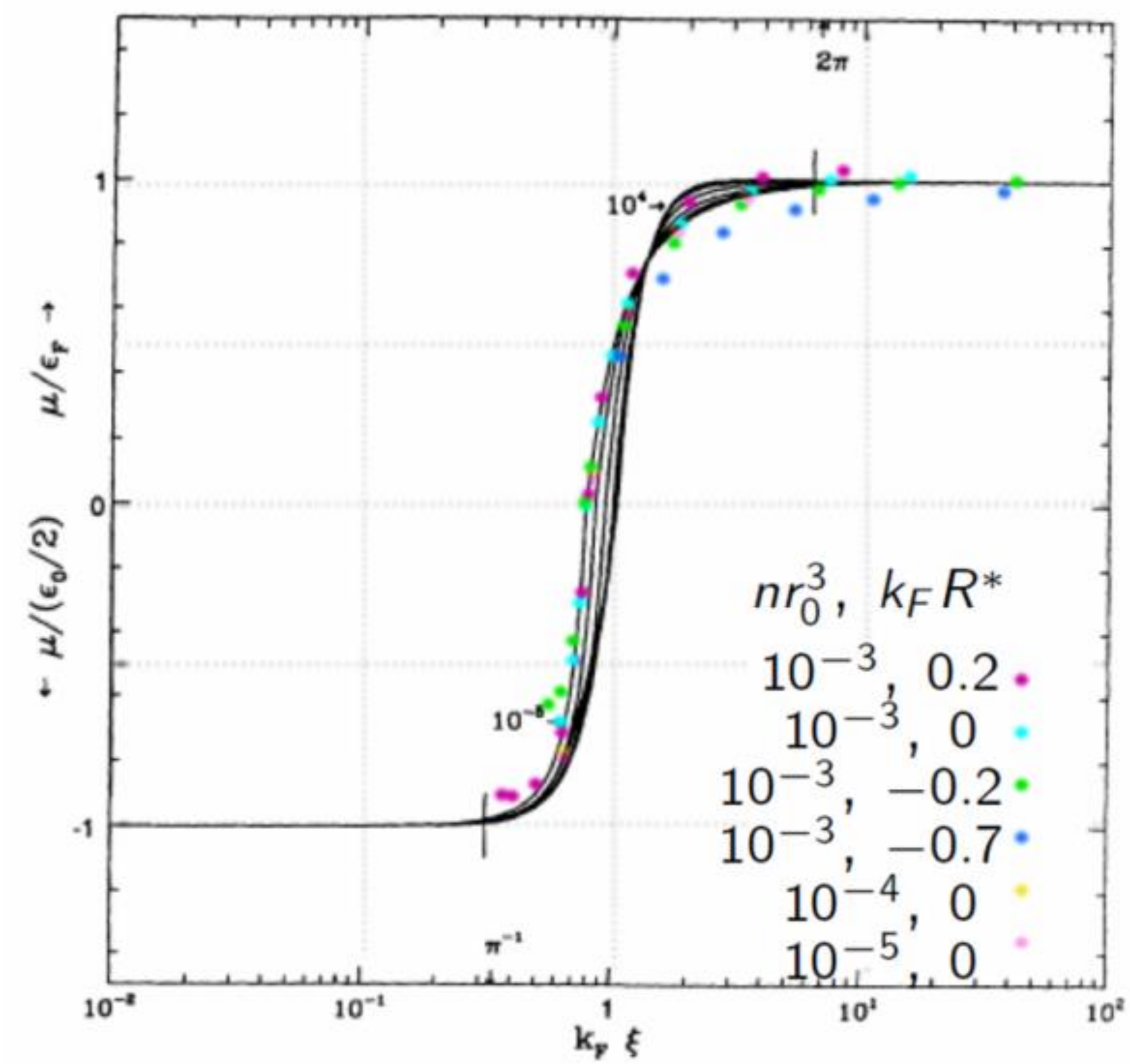
CROSSOVER WITH SHAPE RESONANCE



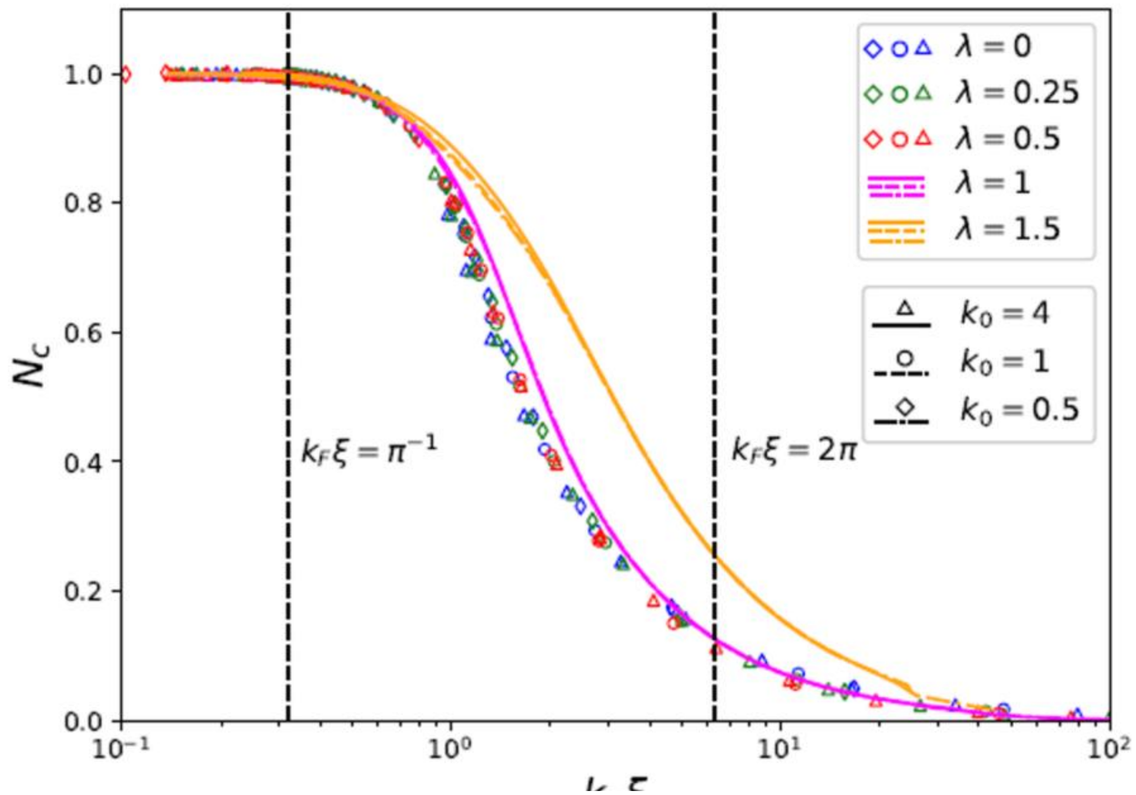
3 Parameters in the theory

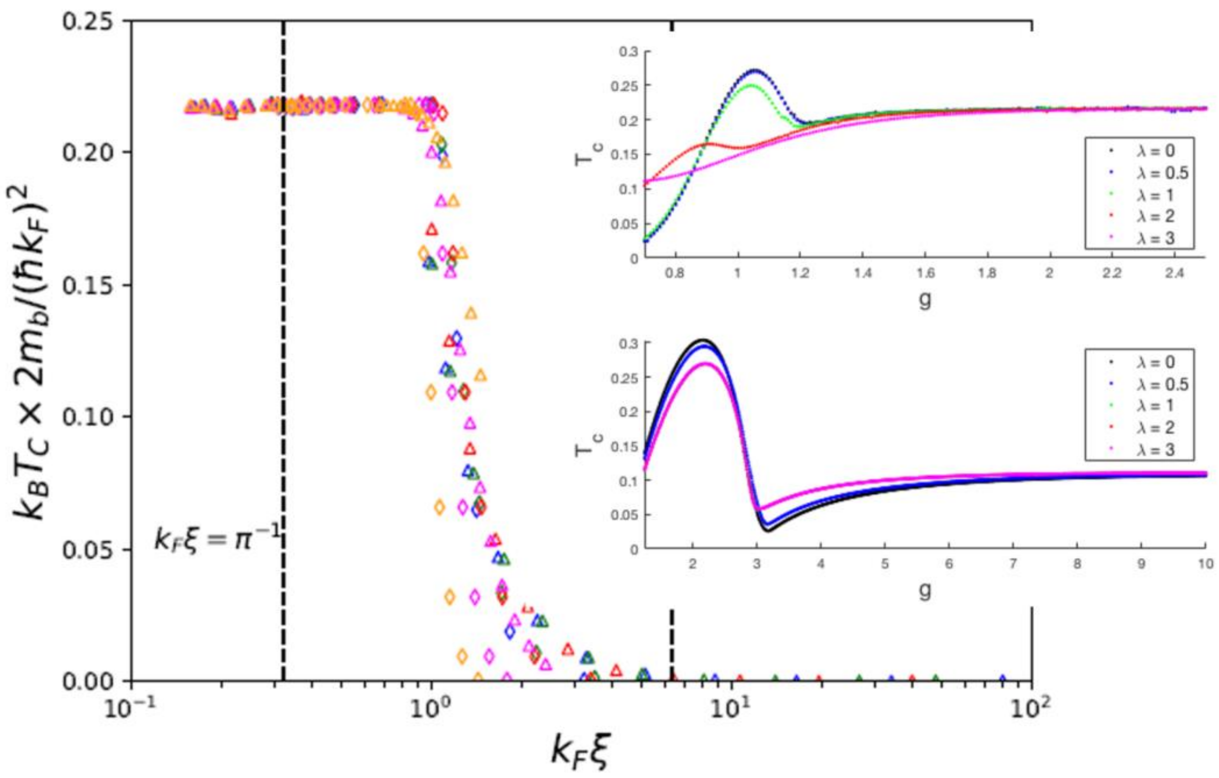
$$((k_F a)^{-1}, k_F R^*, nr_0^3) \Longrightarrow k_F \xi$$



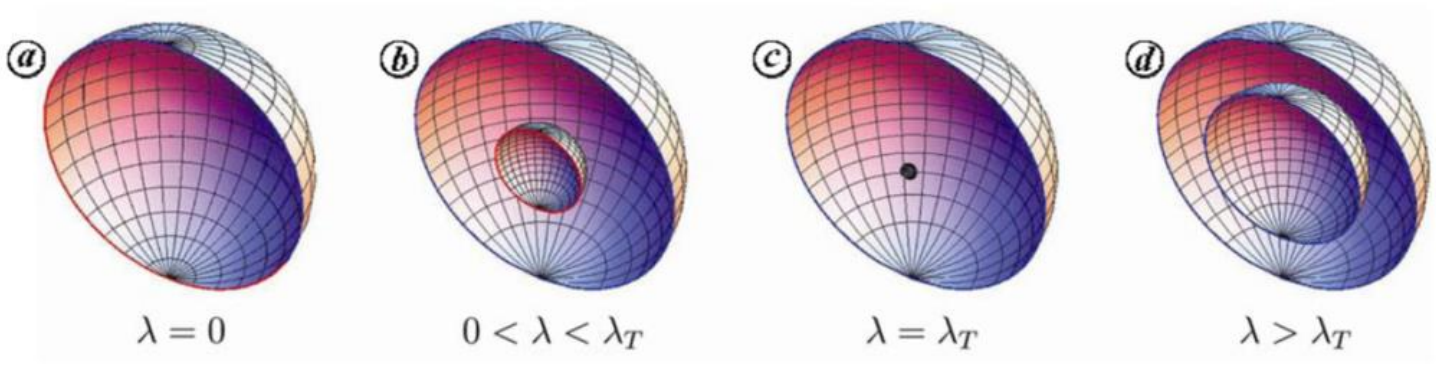


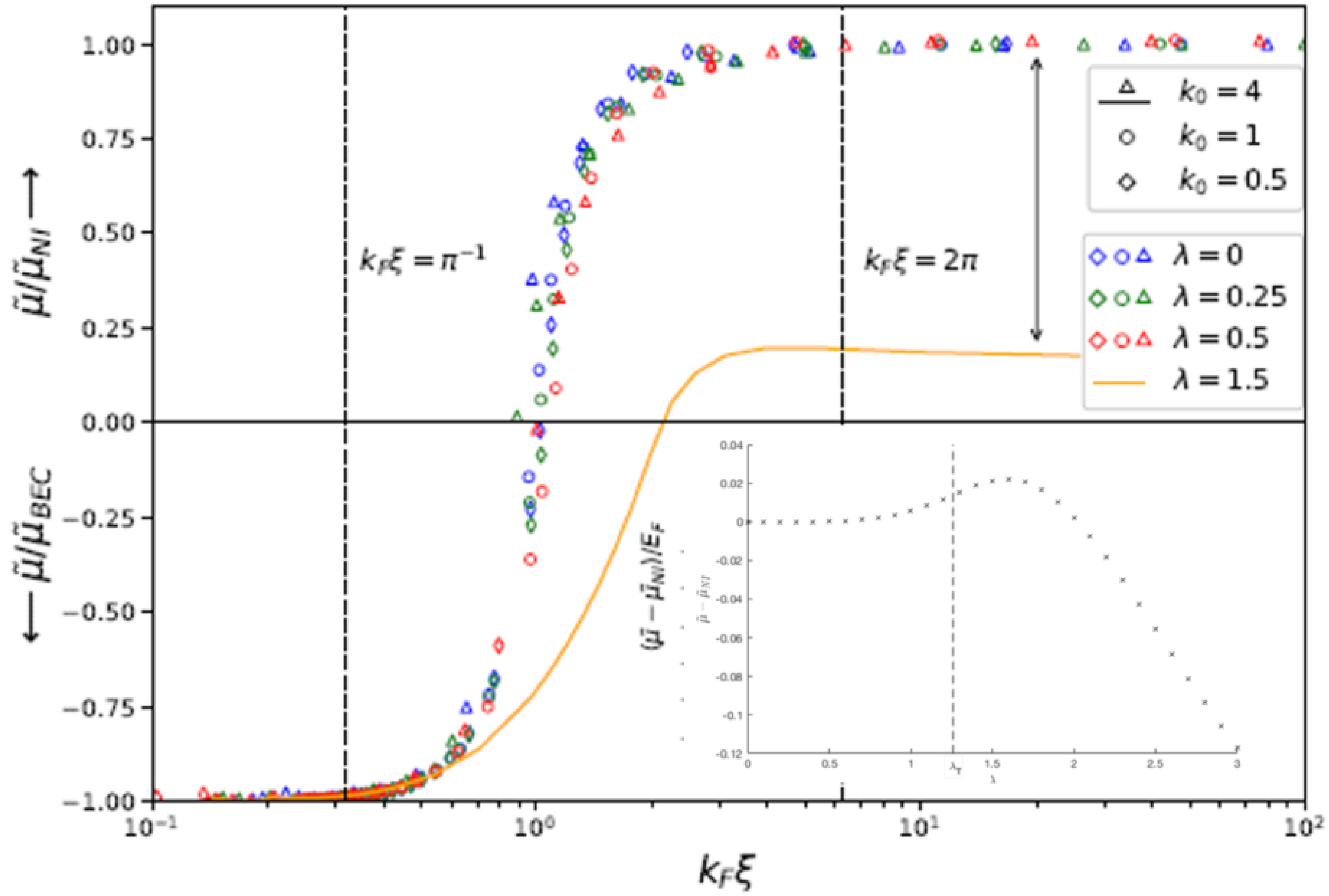
CROSSOVER WITH SPIN-ORBIT COUPLING





3 Parameters in the theory: **$(k_0, g, \lambda) \rightarrow k_F\xi$**





QUARK-GLUON PLASMA vs. QUANTUM GASES

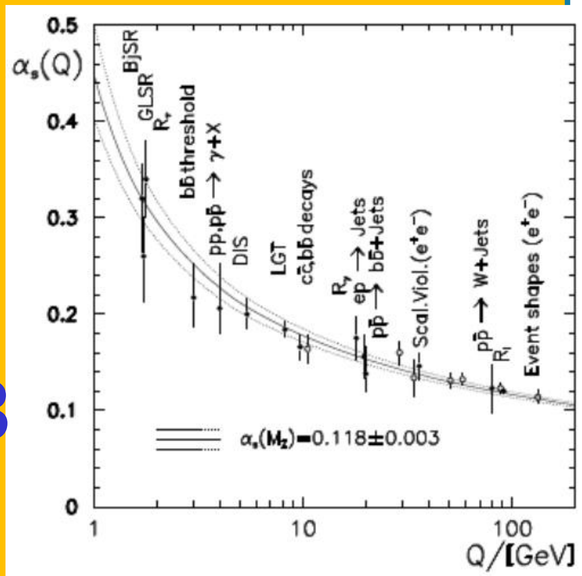
Quark-Gluon Plasma

- $T \sim 10^2$ MeV $\sim 10^{12}$ K
  (T@1 μs after Big Bang)
- Many $\sim 10^4$ - $\sim 10^7$ degrees of freedom
- Always strong interacting:
  even at GUT $\sim 10^{15}$ GeV

$$\alpha_s(p) = \frac{g_s^2}{4\pi}$$ $g_s \sim 1/2$

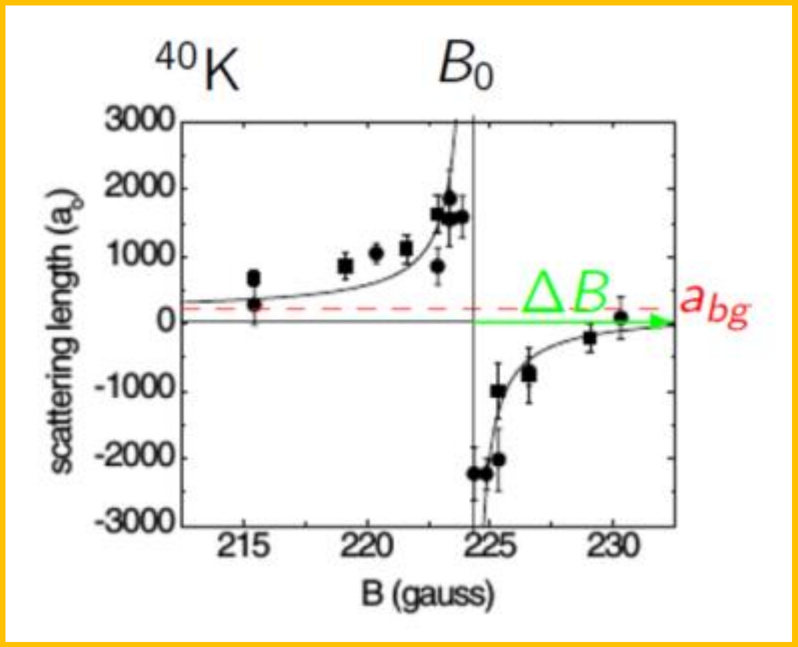
Notice that

$$\alpha = \frac{e^2}{4\pi} = \frac{1}{137}$$ $e \sim 1/3$



Ultracold Quantum Gases

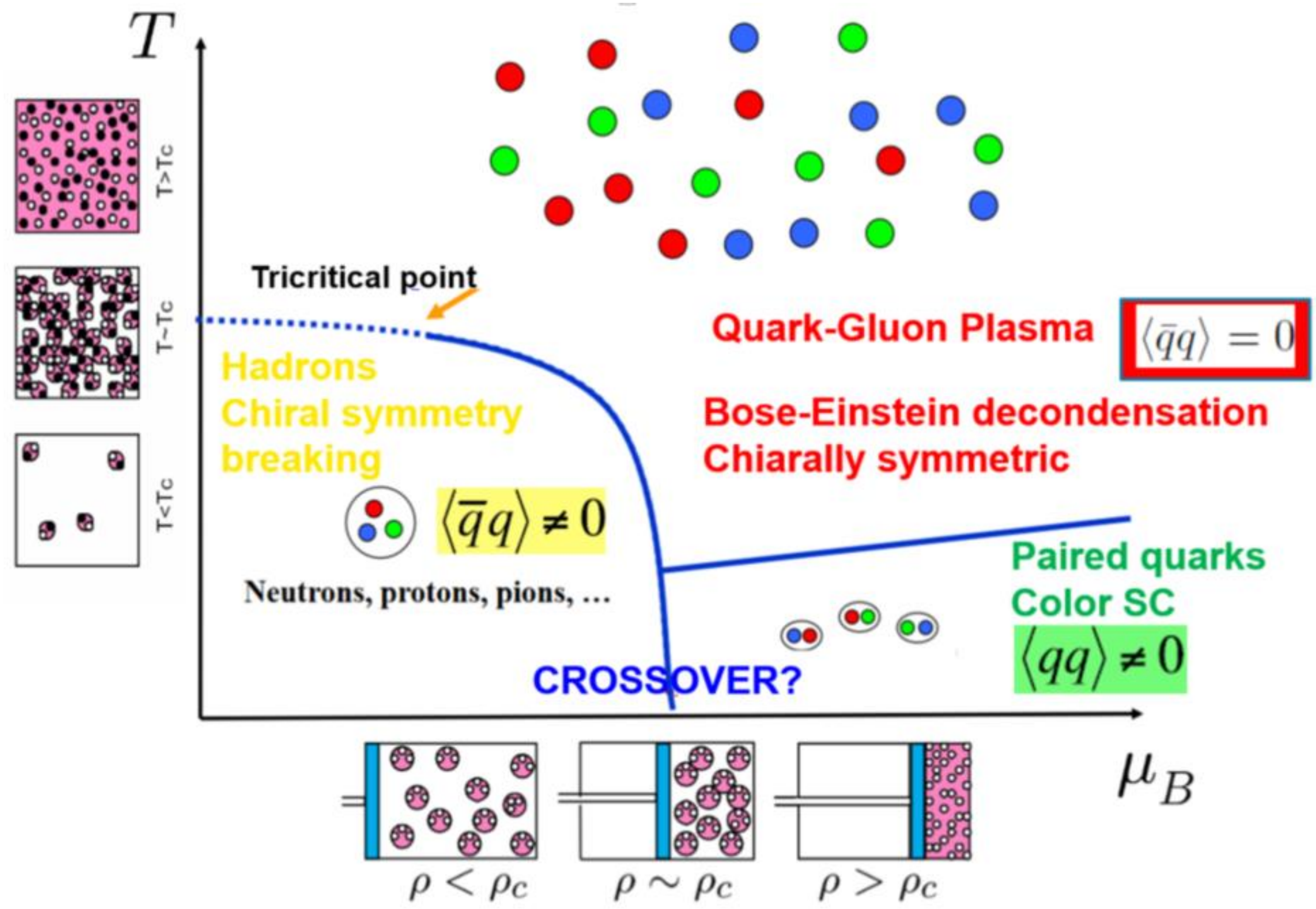
- $T \sim 10^{-6}$ to $\sim 10^{-9}$ K
  (coldest in Universe)
- Many $\sim 10^4$ - $\sim 10^7$ d.o.f.
- Interaction strength at will



G. Baym in BCS:50 Years, World scientific (2011)

PHASE DIAGRAM OF QUARK-GLUON PLASMA

Fukushima&Hatsuda., RPP (2011)



G. Baym, BCs: 50 yrs (2011)

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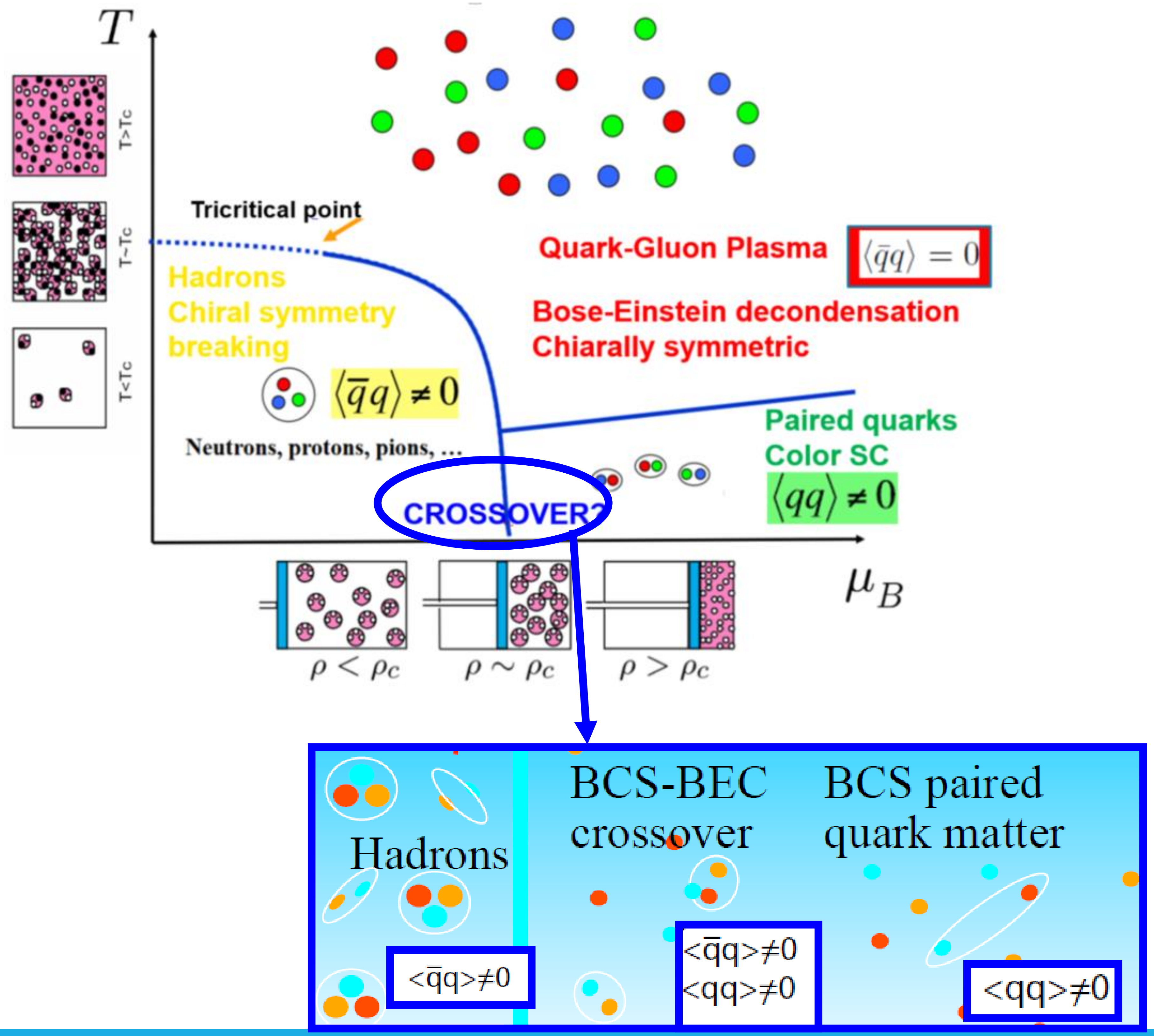

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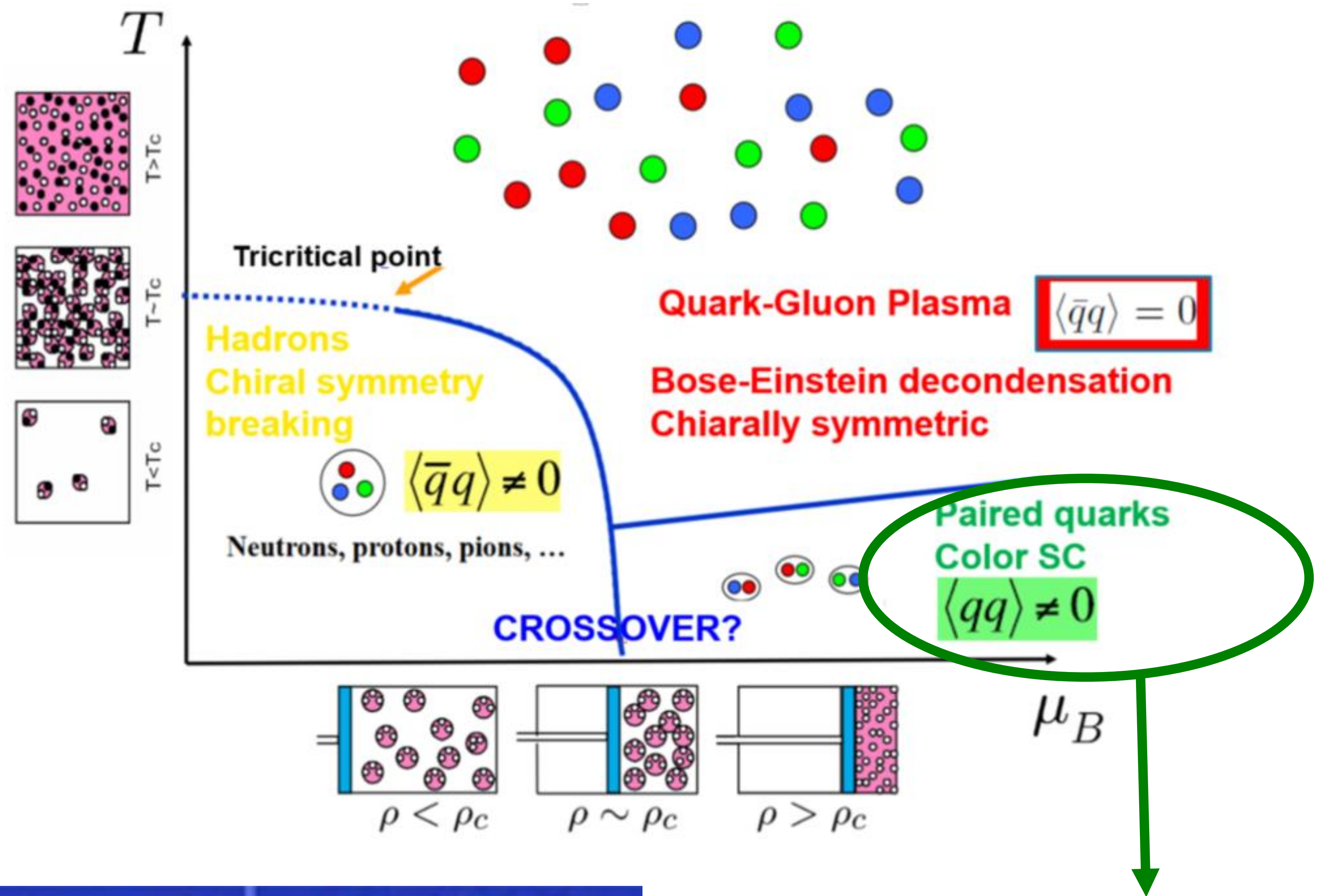


G. Baym, BCs: 50 yrs (2011)

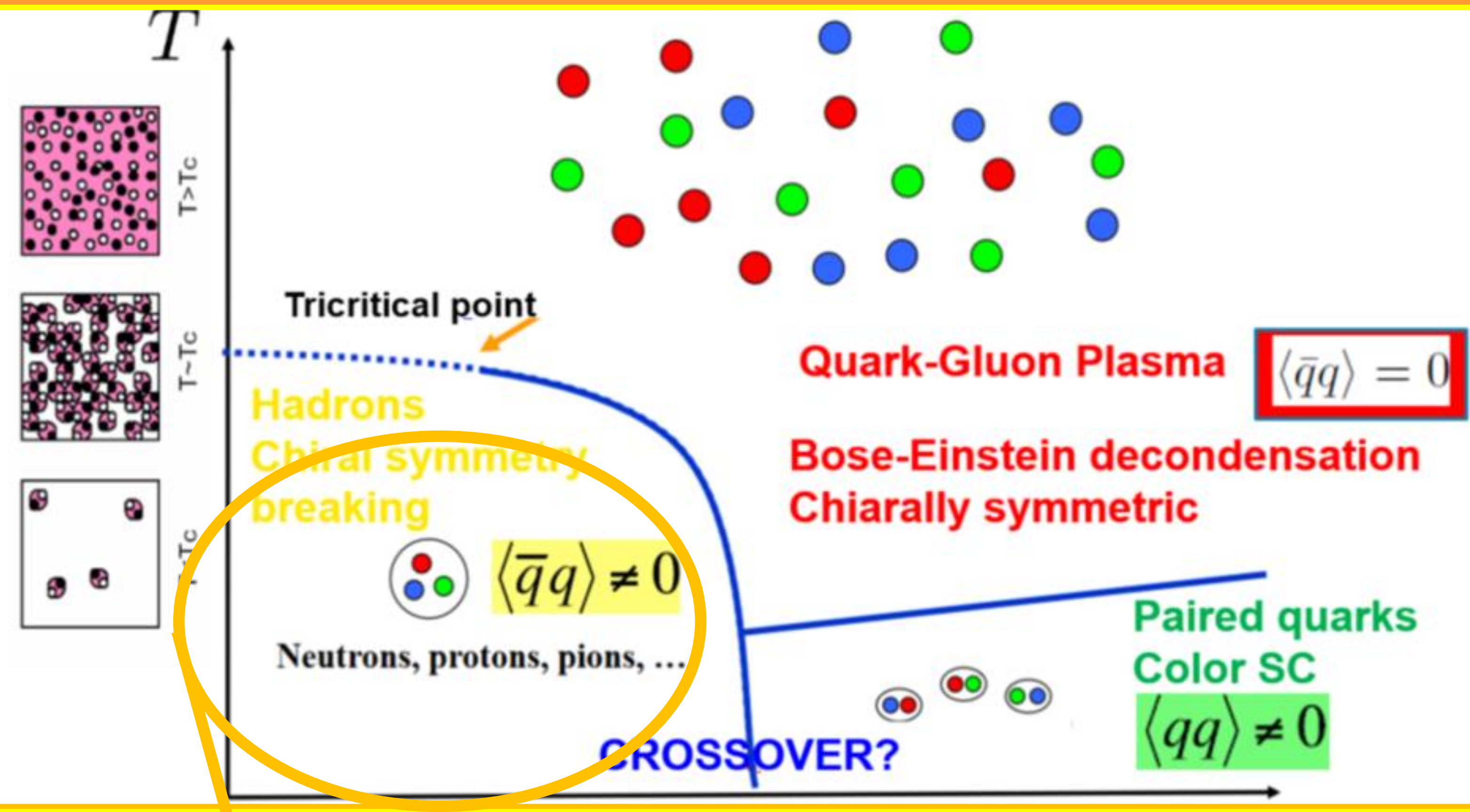
Flavor	Charge/|e|	Mass(MeV)
u	2/3	(2.1-3.5) 5
d	-1/3	(2.1-3.5) 10
s	-1/3	(54-92) 150

- **Color Flavor Locked State ???????**
  18 condensates (u,d,s)x(red,green,blue)
  breaking color+flavor

- **ud pairs antisymmetric in color ??????**

PHASE DIAGRAM OF QUARK-GLUON PLASMA

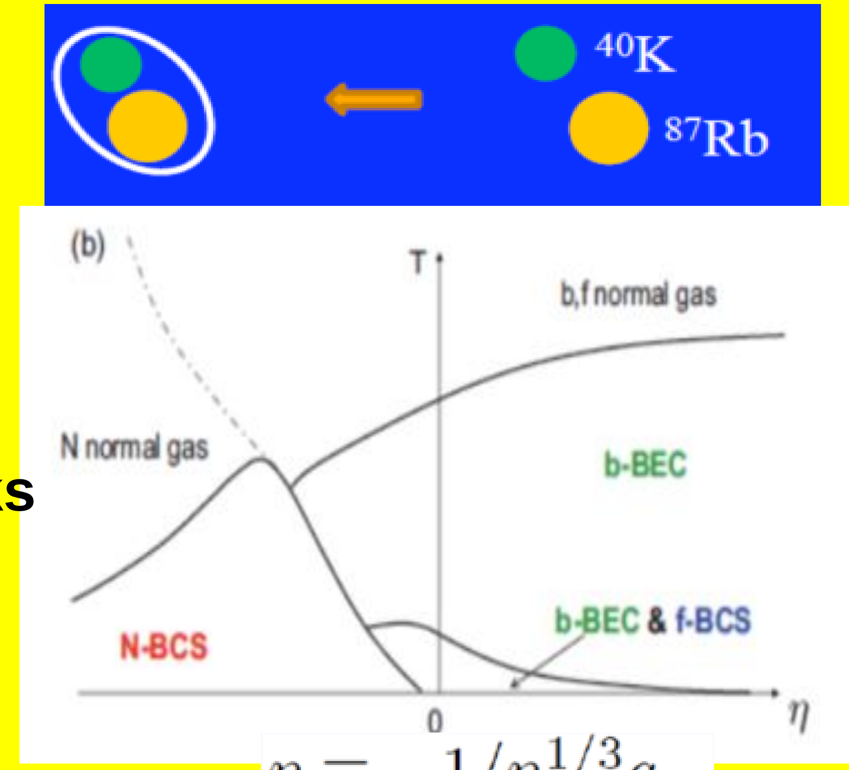
Fukushima&Hatsuda., RPP (2011)



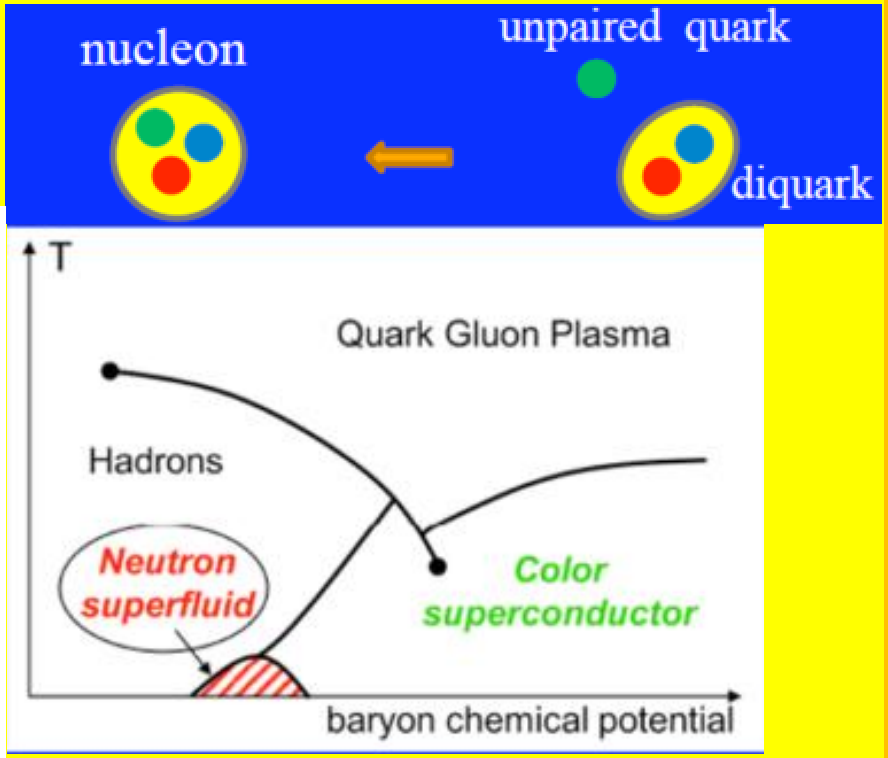
Experiments: Bloch

.....

- **Bosons: diquarks**
- **Fermions: unpaired quarks**
- **B-F molecule: nucleon**

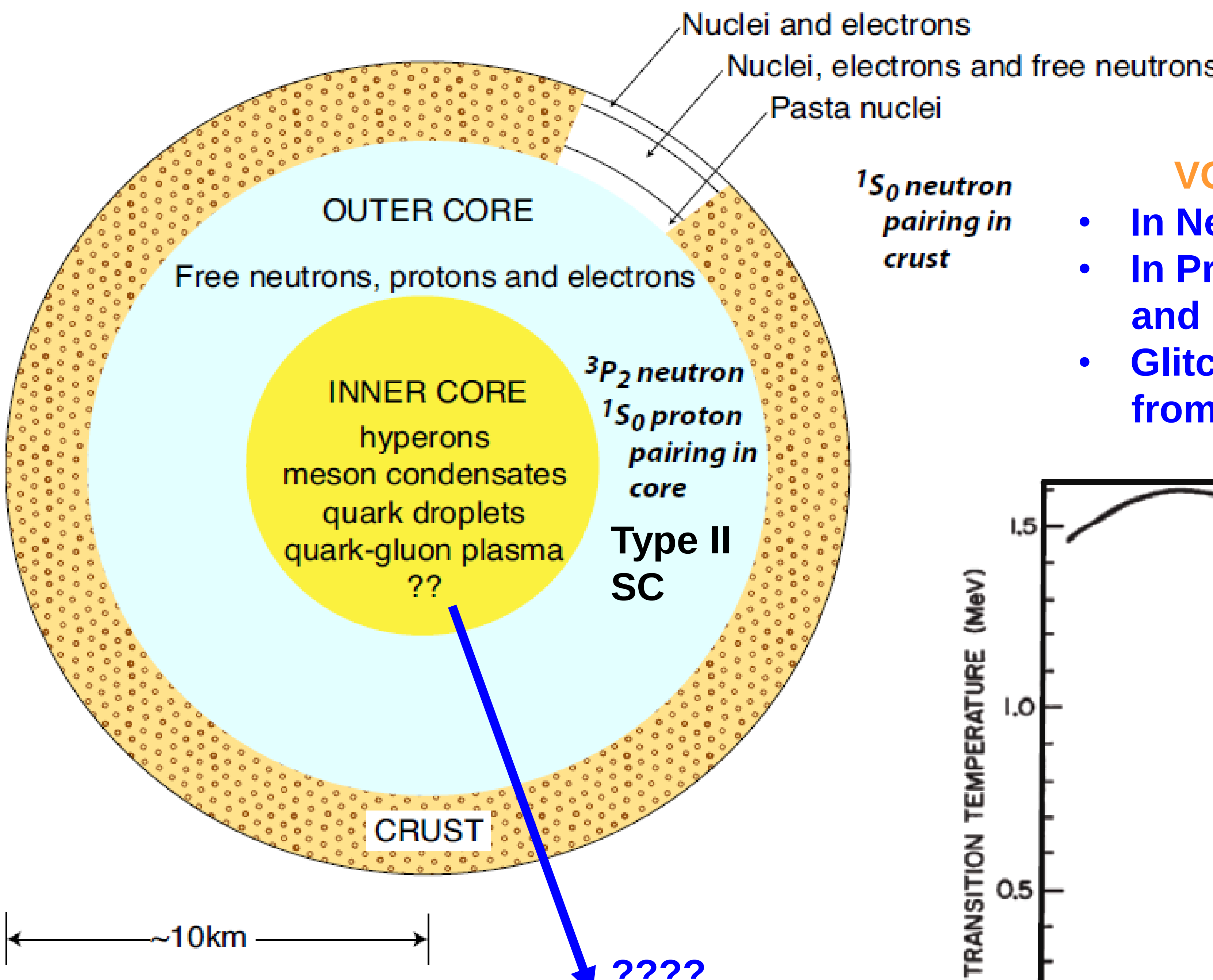


$\eta \equiv -1/n^{1/3}a_{\rm bf}$



G. Baym, BCs: 50 yrs (2011)

NEUTRON STARS

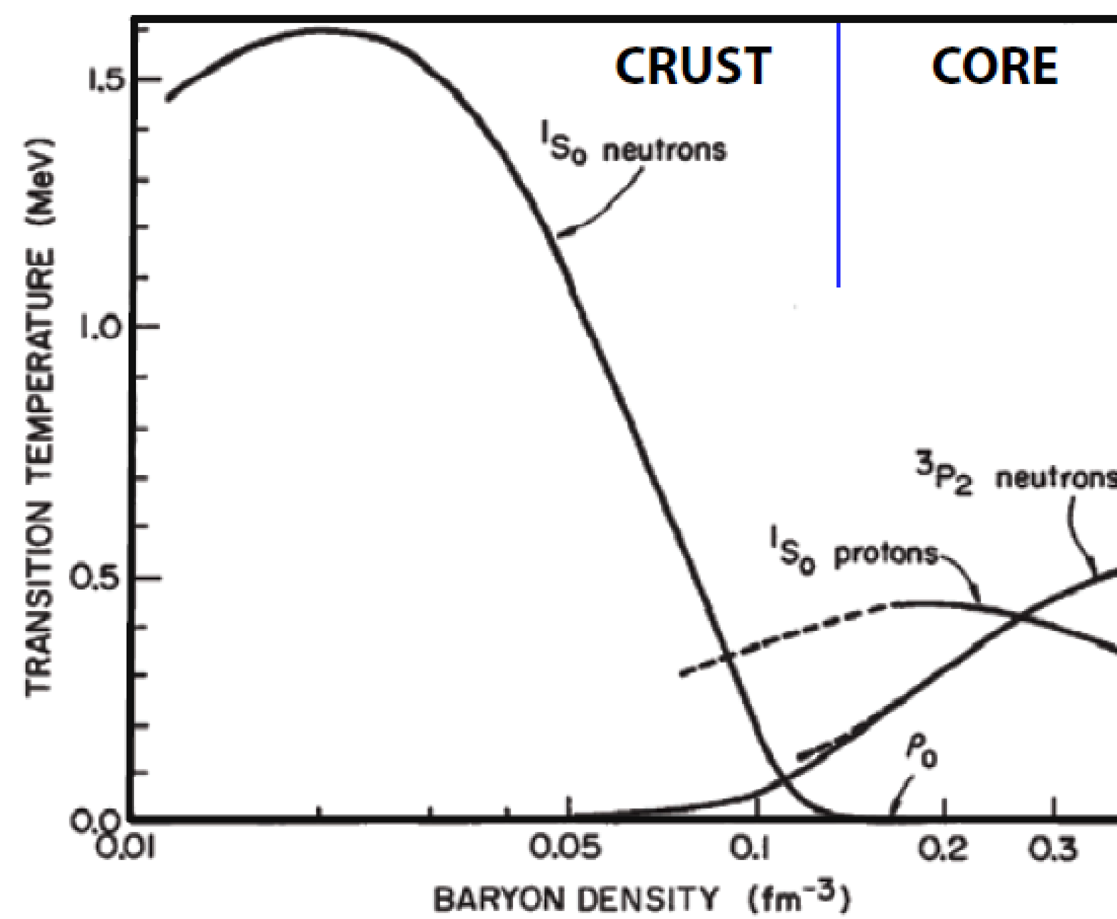


VORTEXES with ~ 10 fm core

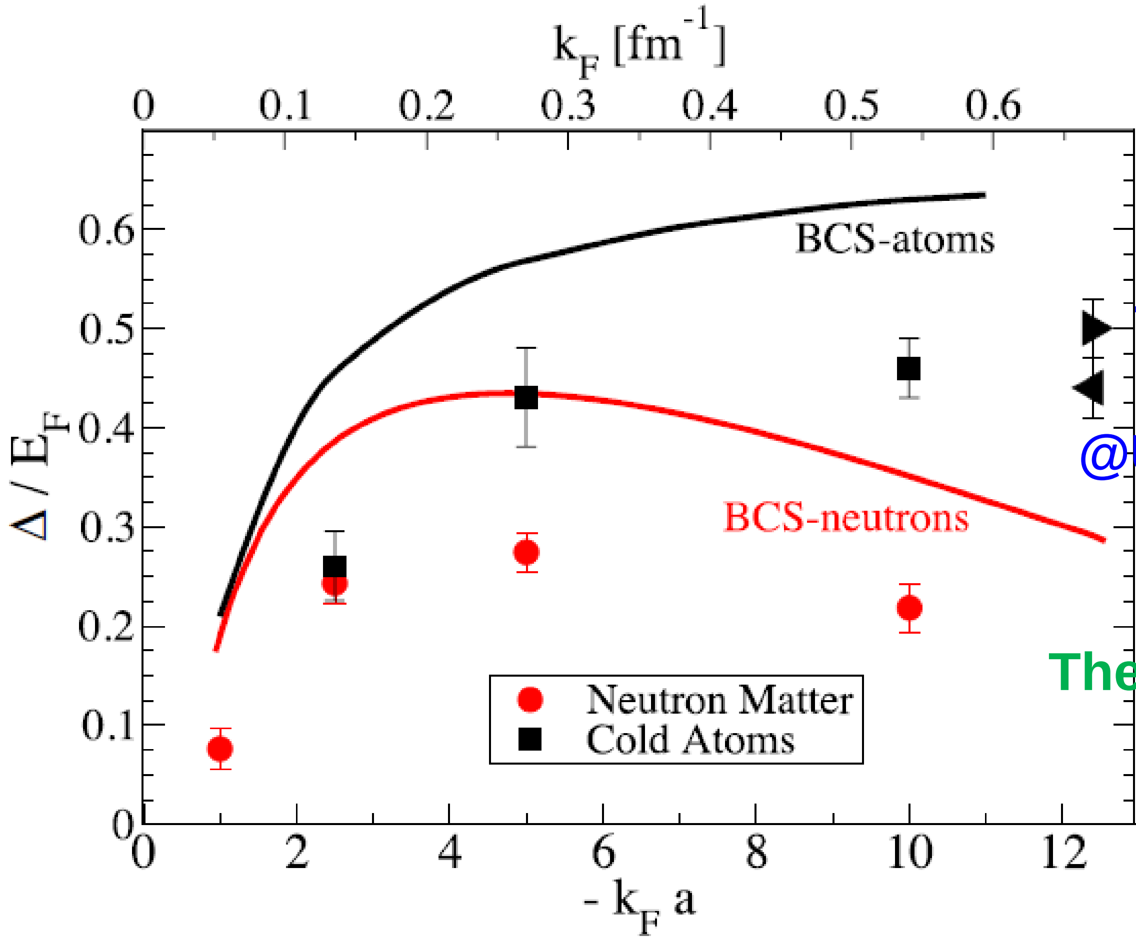
- In Neutron SF are very dilute
- In Proton SF array with sub ^{0}A-pace and Universe-age long diffusion time
- Glitches and (un)pinning of vortexes from SF to crust

????

- Electrons non SC
- Neutrons SF $^3P_2$
- Quarks SC $^1S_0$

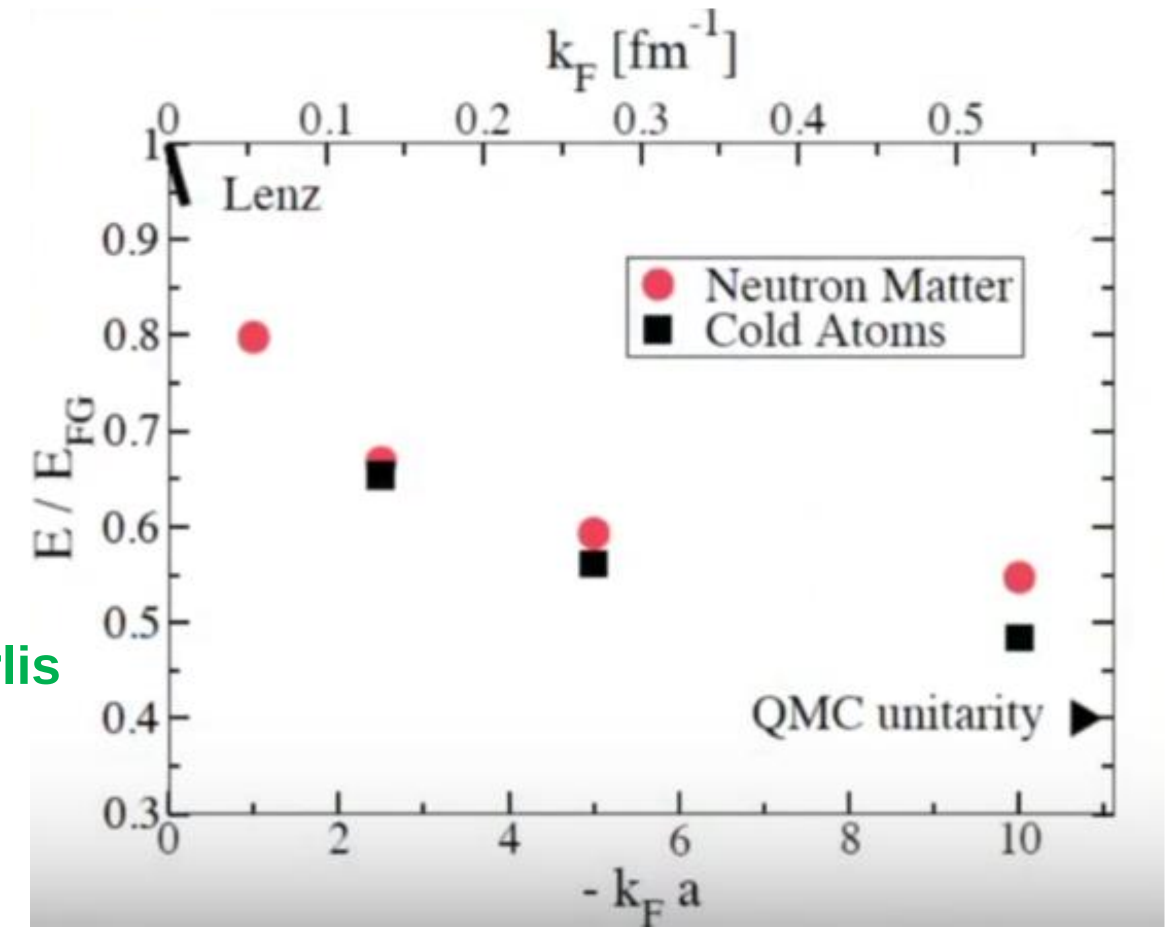


NEUTRON STARS: need to account for interaction range!



Theo
Exp
@Unitarity

Thesis of Gezerlis



$$\frac{E}{N} = \xi(k_{\rm F} r_{\rm e}) \, \frac{3k_{\rm F}^2}{10m}$$

Schwenk&Pethick (2005)

Quantum gases with broad resonances

negligible $k_{\rm F} r_{\rm e}$

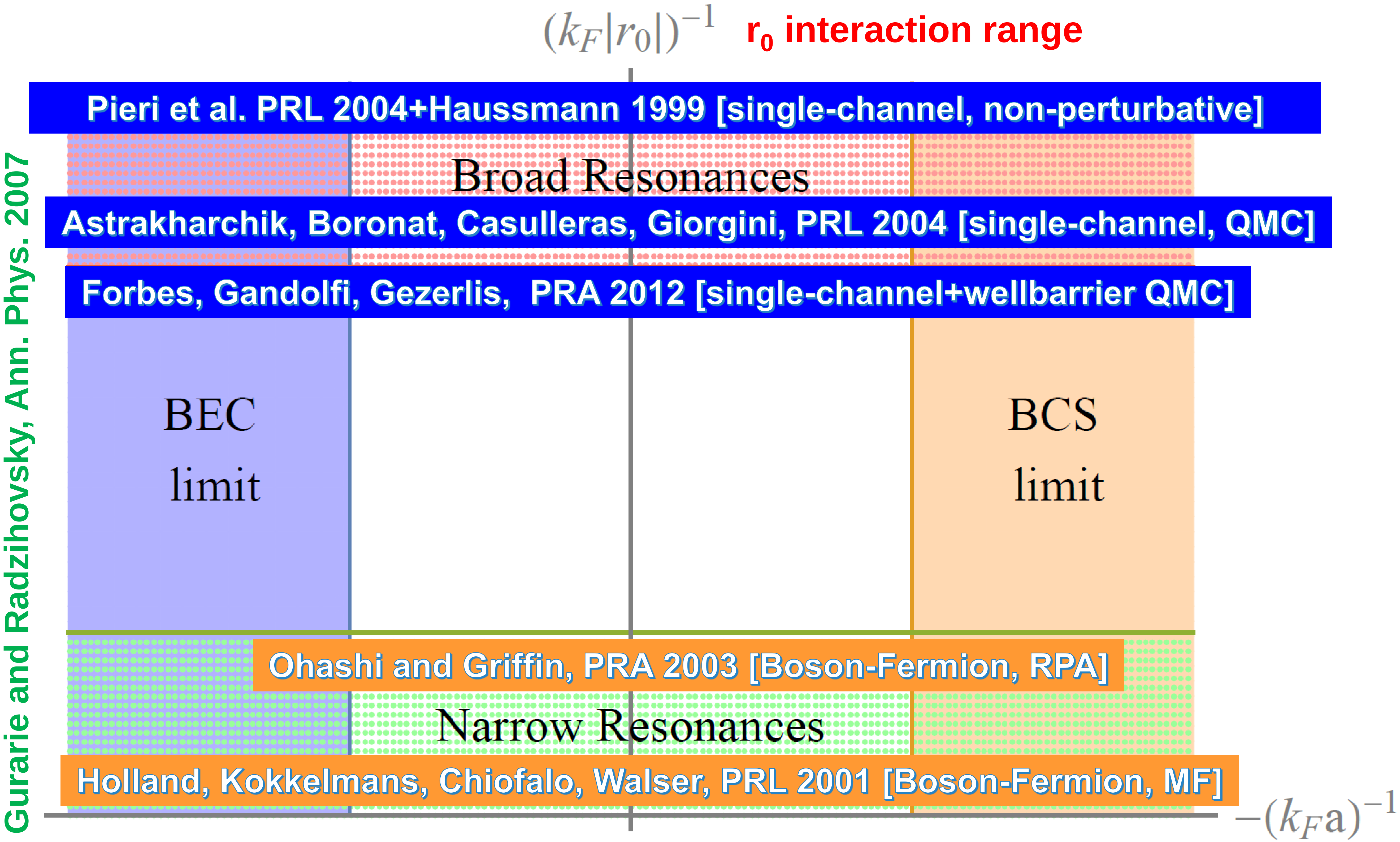
$\xi(k_{\rm F} r_{\rm e}) \rightarrow \xi = 0.44 \pm 0.01$

Neutron Stars

- **Interparticle spacing** $R \approx 1.4\,\text{fm}$
- **Scattering length** $a_{\rm nn} \approx -18.5\,\text{fm}$

large $r_{\rm e}/R \approx 2$

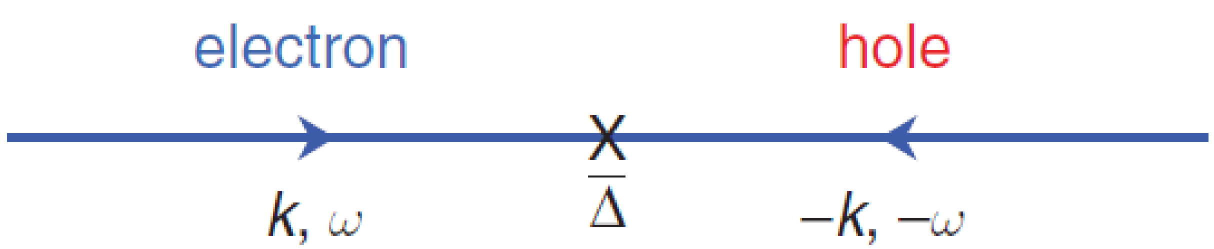
CROSSOVER WITH VARIABLE FANO-FESHBACH RESONANCE WIDTH



BROKEN-SIMMETRY PHASE IN TERMS OF ANDREEV REFLECTION

Andreev reflection in ordinary superconductors

Andreev reflection : $e^- \rightleftharpoons \text{pair}^{2-} + h^+$

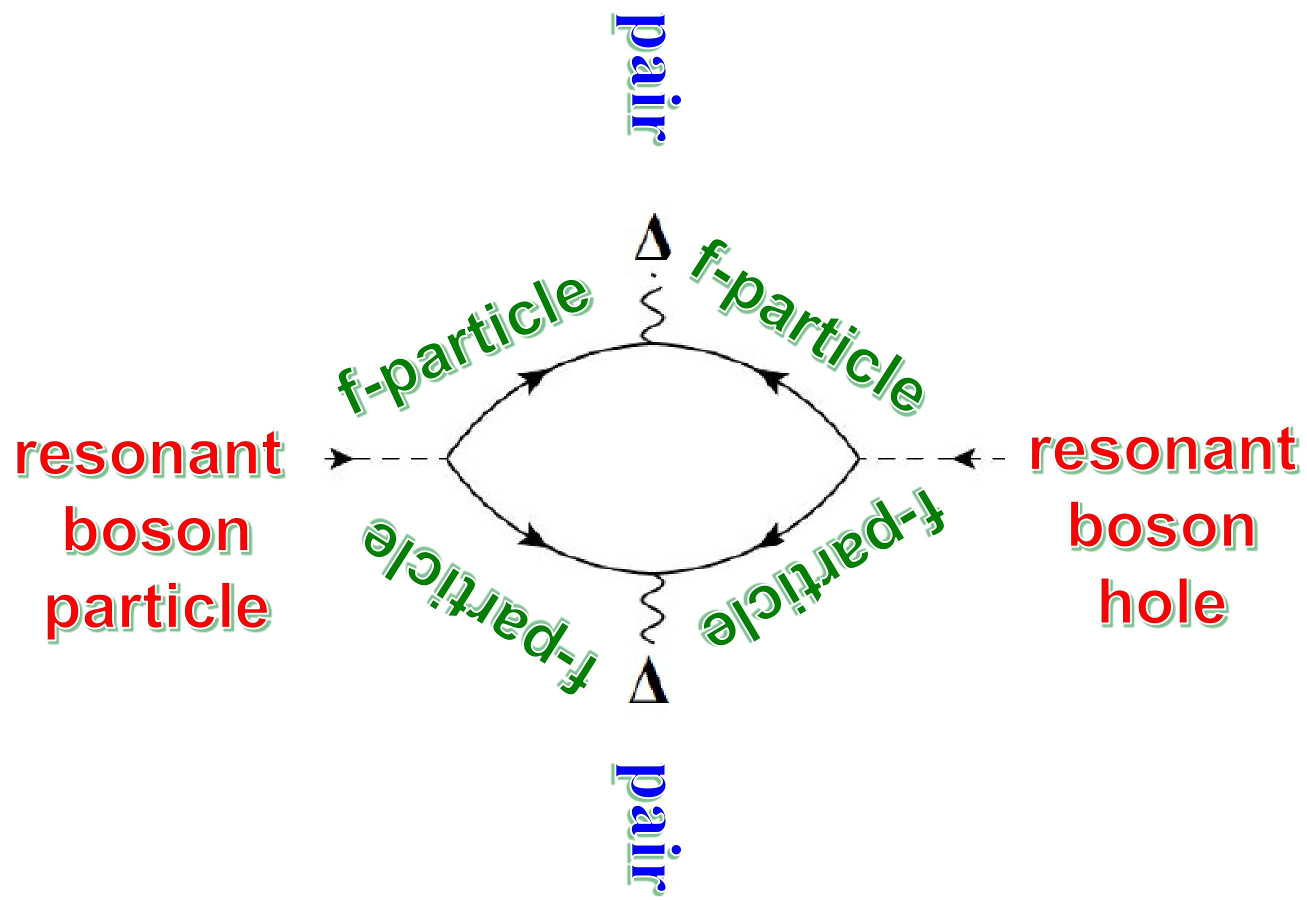


Elastically scatters particles into holes reversing ALL components of velocity

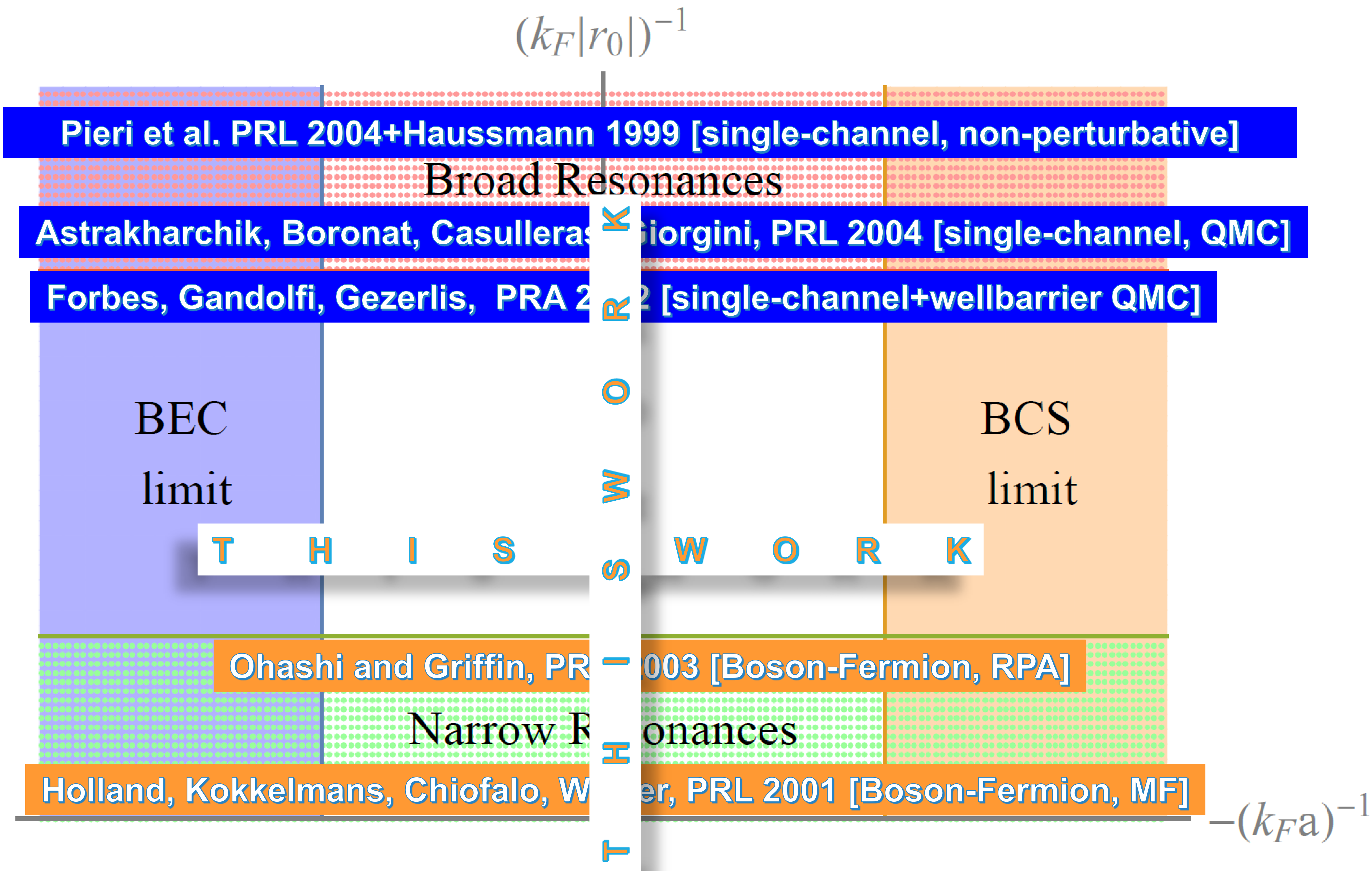
Conserves:

- **Spin**
- **Charge**
- **Momentum**

Andreev reflection In Boson-Fermion Model (<bb> correlations)

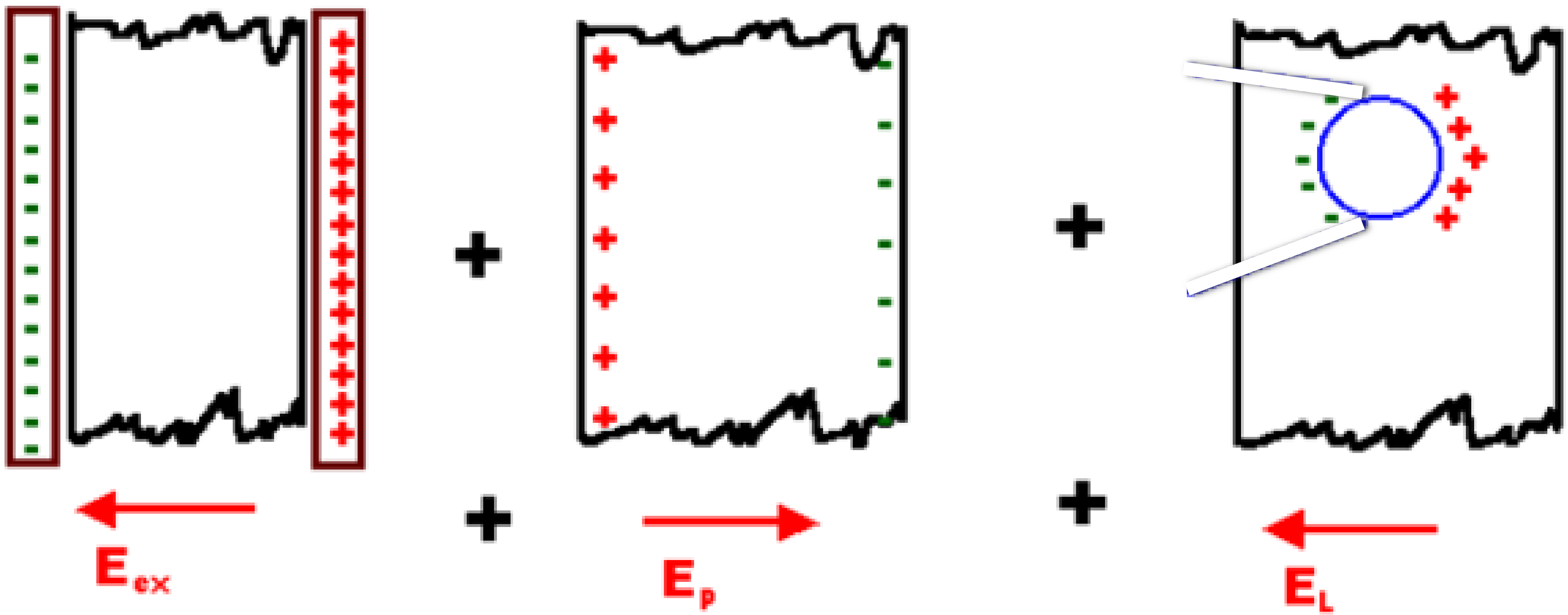


LOCAL-FIELD DIELECTRIC THEORY FOR RESONANCE SUPERFLUIDITY: WHY



Gurarie and Radzinovsky, Ann. Phys. 2007

Lorentz cavity



$$n_{1\sigma}(q,\omega) = \chi_{0\sigma}(q,\omega) V_{eff,\sigma}(q,\omega)$$

$$V_{eff,\sigma}(\vec{q},\omega) = V_{ext,\sigma}(\vec{q},\omega) + \sum_{\sigma'} v_q n_{\sigma'}(\vec{q},\omega) - \sum_{\sigma'} v_q G_{\sigma\sigma'}(q,\omega) n_{\sigma'}(\vec{q},\omega)$$

χ_0 — **Lindhard function**

$$\chi_{\mathrm{RPA}} = \frac{\chi_0(\boldsymbol{q},\omega)}{1 - v_{\boldsymbol{q}} \chi_0(\boldsymbol{q},\omega)}$$

$$\chi(\boldsymbol{q},\omega) = \frac{\chi_0(\boldsymbol{q},\omega)}{1 - v_{\boldsymbol{q}} \left[1 - G(\boldsymbol{q},\omega)\right] \chi_0(\boldsymbol{q},\omega)}$$

BF-STLS THEORY: LINEAR RESPONSE – IDENTIFY VARIABLES

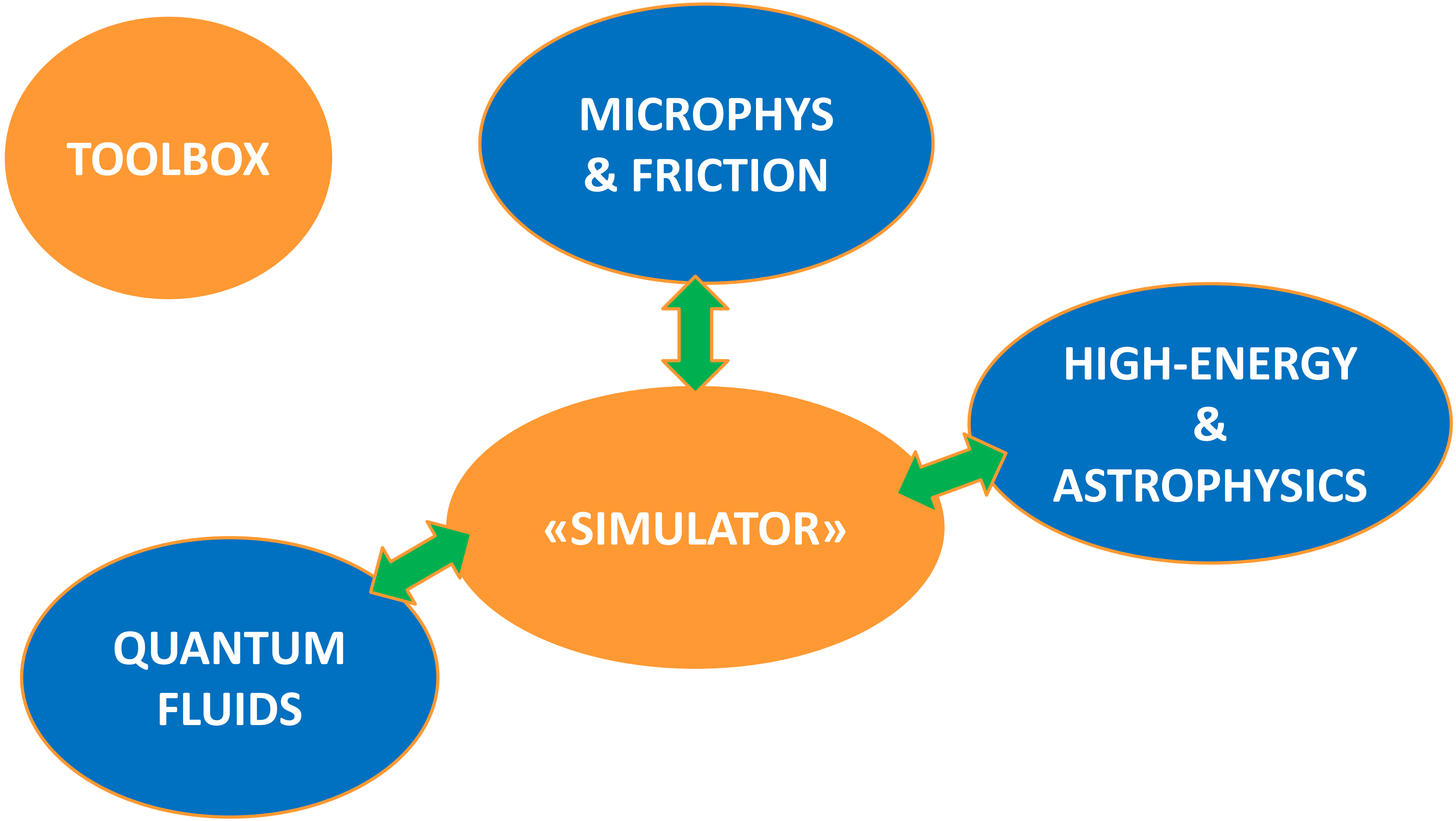
6 kinds of excitations at both $T < T_c$ and $T > T_c$ $\Rightarrow$ we focus on the superfluid state

- gap amplitude fluctuations "Higgs mode" → $\varrho^1_{\mathbf{q}} = \sum_{\mathbf{k}} \left[c_{-\mathbf{k}+\mathbf{q}/2,\downarrow} c_{\mathbf{k}+\mathbf{q}/2,\uparrow} + \text{h.c.} \right]$
- gap phase fluctuations "Goldstone mode" → $\varrho^2_{\mathbf{q}} = i \sum_{\mathbf{k}} \left[c_{-\mathbf{k}+\mathbf{q}/2,\downarrow} c_{\mathbf{k}+\mathbf{q}/2,\uparrow} - \text{h.c.} \right]$
- density fluctuations → $\varrho^3_{\mathbf{q}} = \sum_{\mathbf{k},\sigma} c^\dagger_{\mathbf{k}+\mathbf{q}/2,\sigma} c_{\mathbf{k}-\mathbf{q}/2,\sigma}$
- spin fluctuations → $\varrho^4_{\mathbf{q}} = \sum_{\mathbf{k},\sigma} \text{sgn}(\sigma) c^\dagger_{\mathbf{k}+\mathbf{q}/2,\sigma} c_{\mathbf{k}-\mathbf{q}/2,\sigma}$

+ 2 resonant bosonic fluctuations $\varphi^-_{\mathbf{q}} = b_{-\mathbf{q}}$ and $\varphi^+_{\mathbf{q}} = b^\dagger_{\mathbf{q}}$

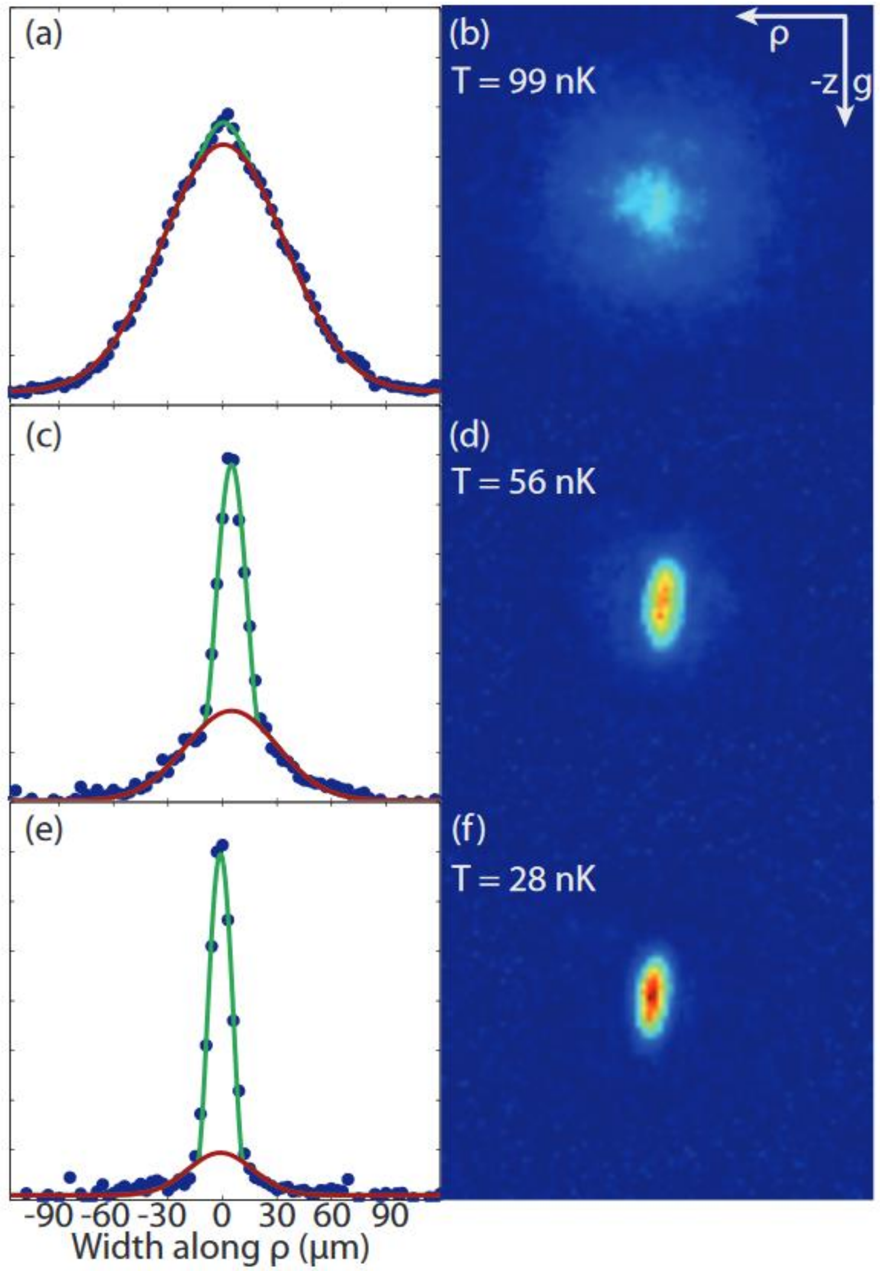
we want the response functions →
we perturb the Hamiltonian with external fields coupling to the excitations

$$\mathcal{H}' = \mathcal{H}_{\text{BF}} + \sum_{i=1}^{4} V^i \varrho^i + \sum_{\alpha=\pm} V_B^{-\alpha} \varphi^\alpha$$

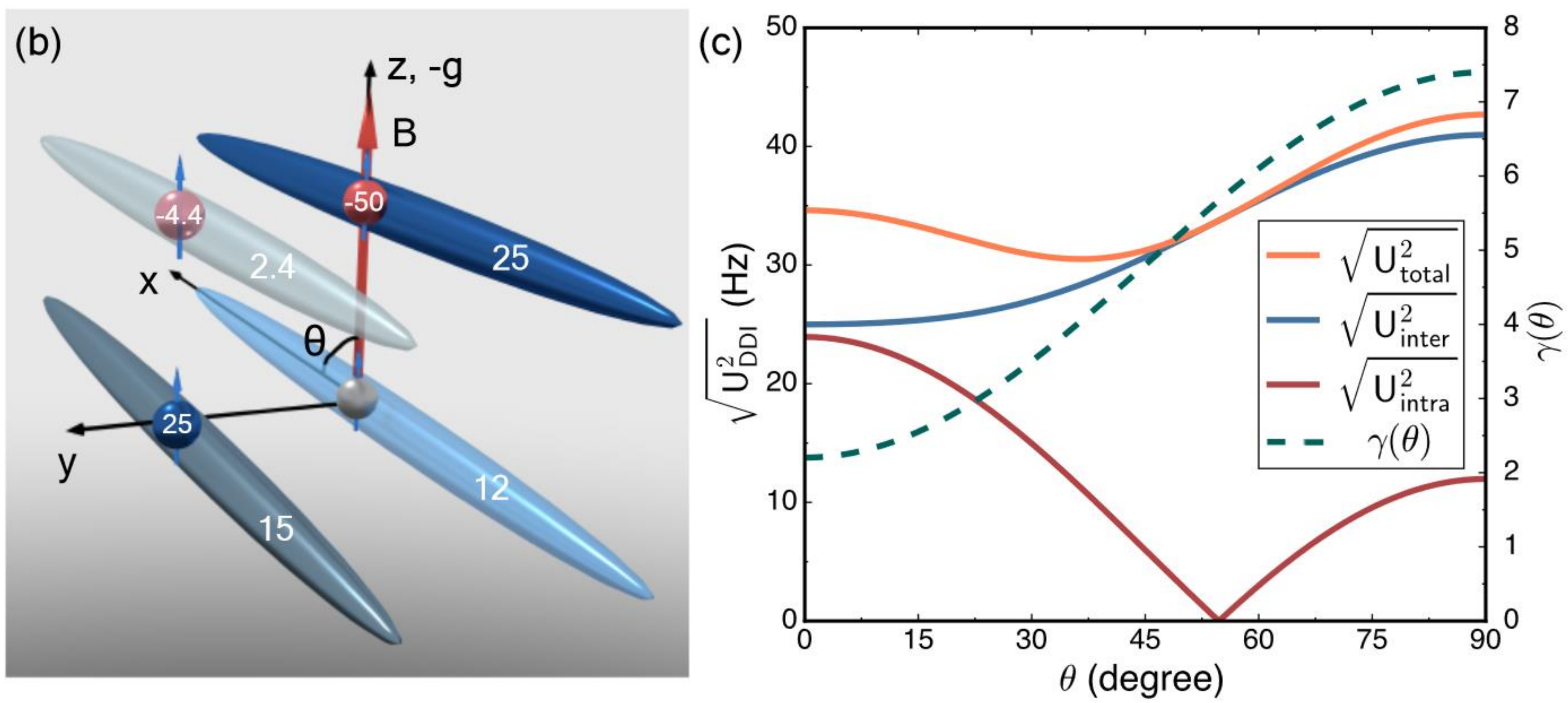


- **Citro R, Orignac E, De Palo S, Chiofalo M**, **PRA 75**, 51602 (2007); **De Palo S, Orignac E, Citro R, Chiofalo M**, **PRB 77**, 212101 (2008); **Citro R, De Palo S, Orignac E, Pedri P, Chiofalo M**, **NJP 10**, 45011 (2008)
- **Di Dio M., De Palo S., Orignac E., Citro R., Chiofalo M**, **PRB 92,** 60506 (2015)
- **Lucchesi L. and Chiofalo M**, **in preparation**

LUTTINGER-LIQUID BEHAVIOR IN 1D DIPOLAR GASES



DYSPROSIUM



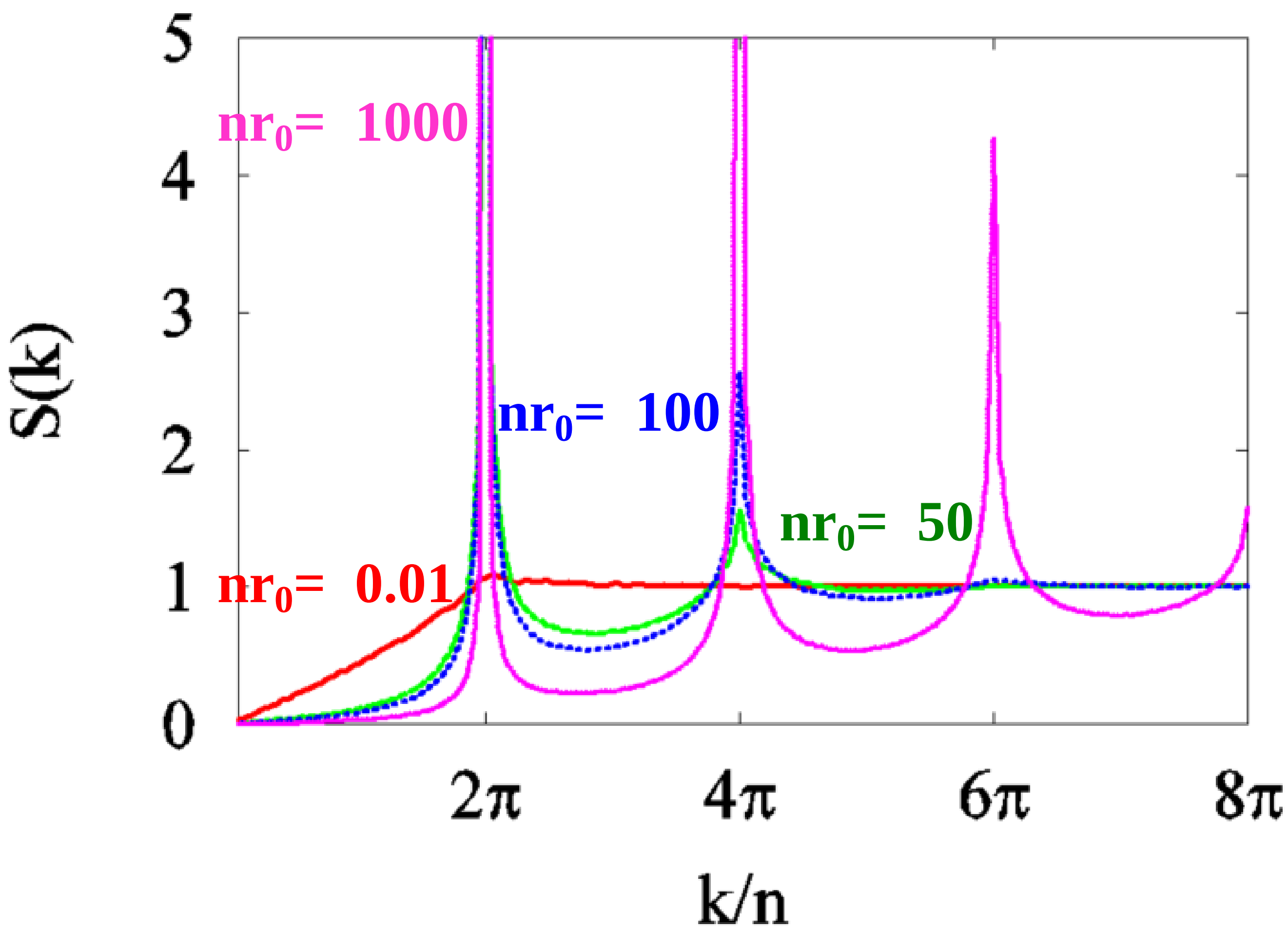
M. Lu, N. Burdick, S. Ho Youn, B. Lev
PRL 107, 190401 (2011)

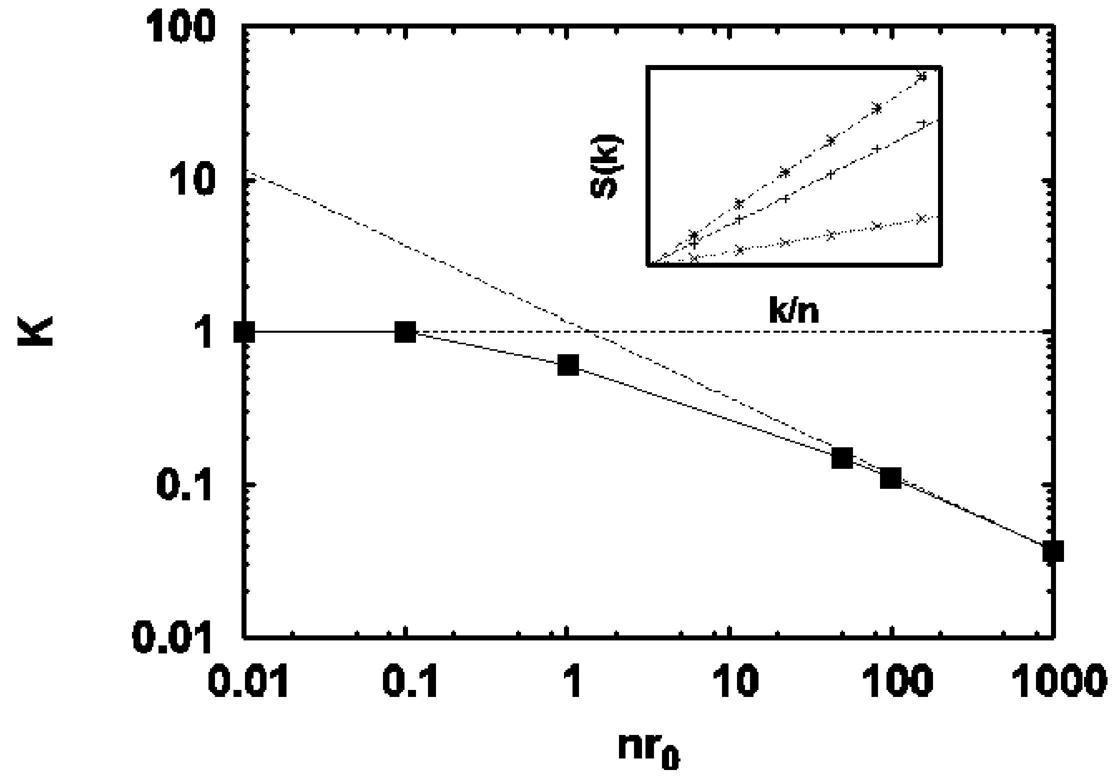
Y. Kao, Kuan-Yu Li, S. Seo, K. Mallayya, M. Rigol, S. Gopalakrishnan, B. Lev
PRX 8, 021030 (2018)

RQMC OF REAL SYSTEM

EFFECTIVE LUTTINGER H

N=40





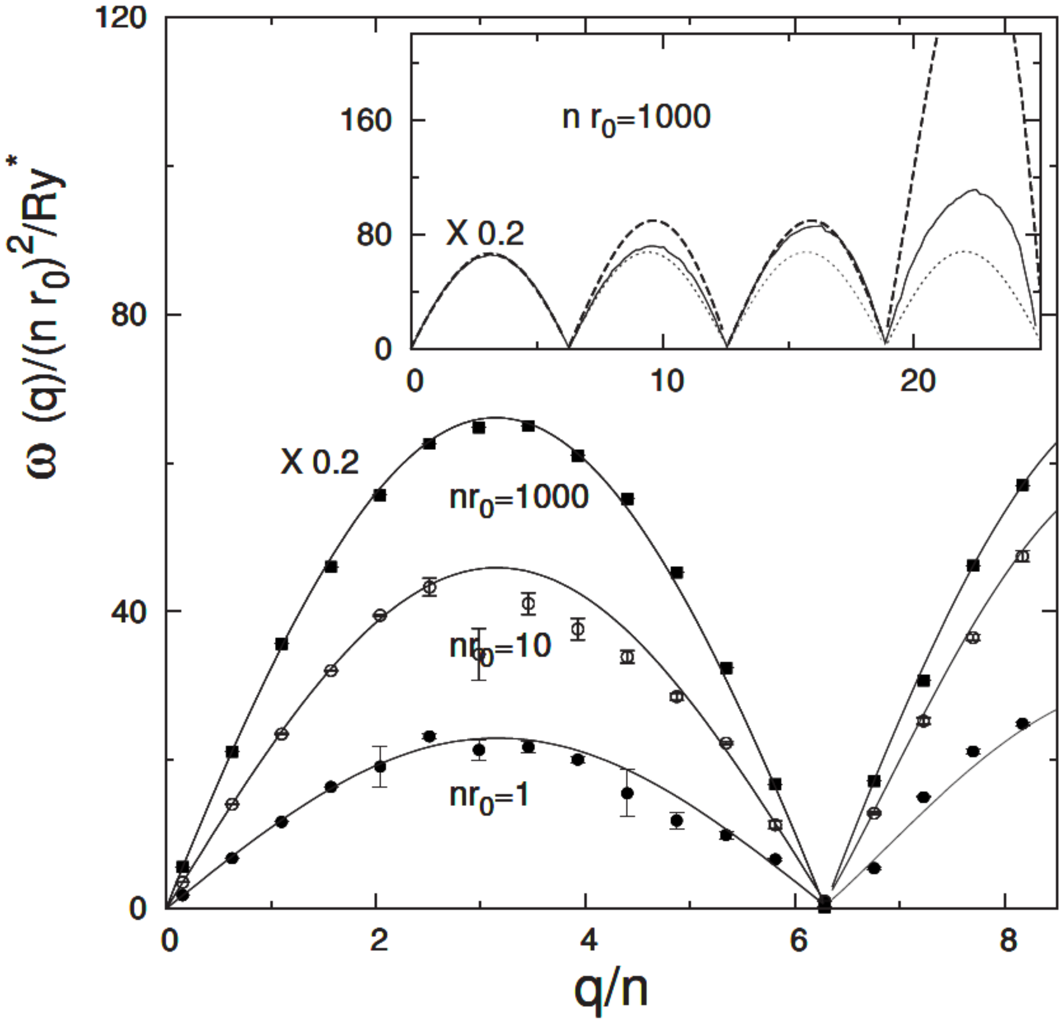
$$H = \hbar \int \frac{dx}{2\pi}\left[uK(\pi\Pi)^2 + \frac{u}{K}(\partial_x \phi)^2\right]$$

$$H = -\frac{1}{r_s^2}\sum_{i=1}^{N}\frac{\partial^2}{\partial x^2} + \frac{1}{r_s^3}\sum_{i<j}^{N}\frac{1}{|x_i - x_j|^3}$$

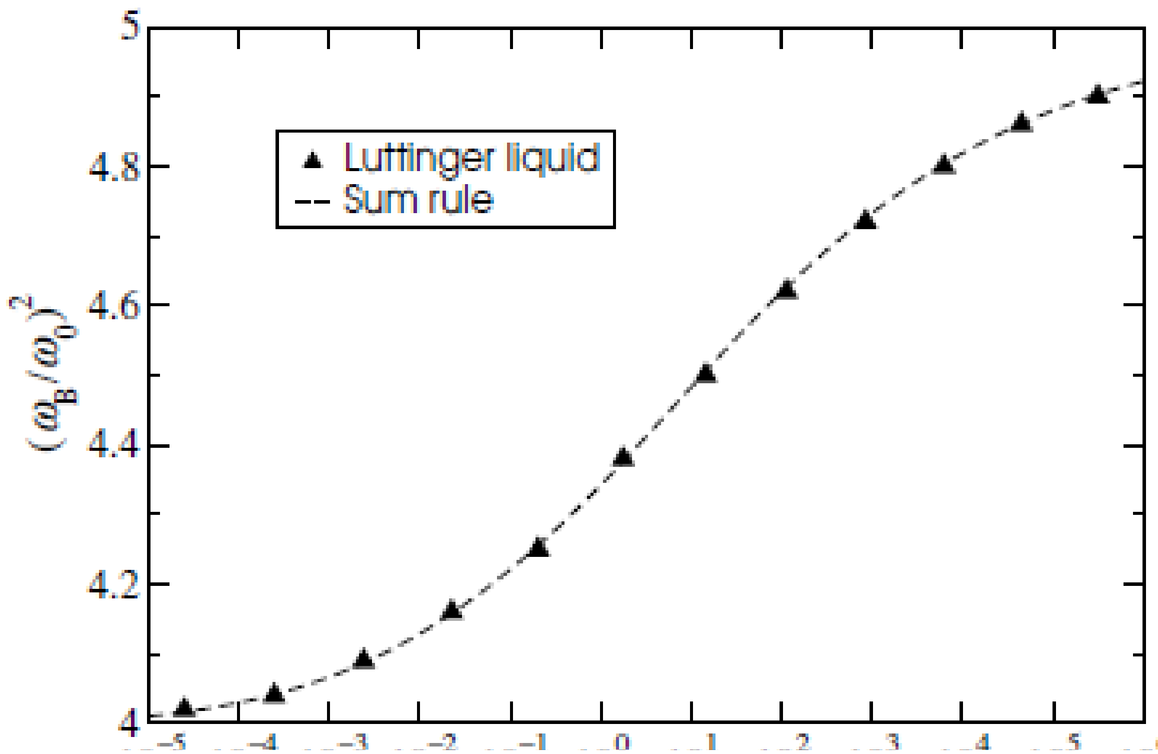
$$C_{dd} = \mu_0 \mu_d^2 \qquad C_{dd} = \frac{d^2}{\varepsilon_0}$$

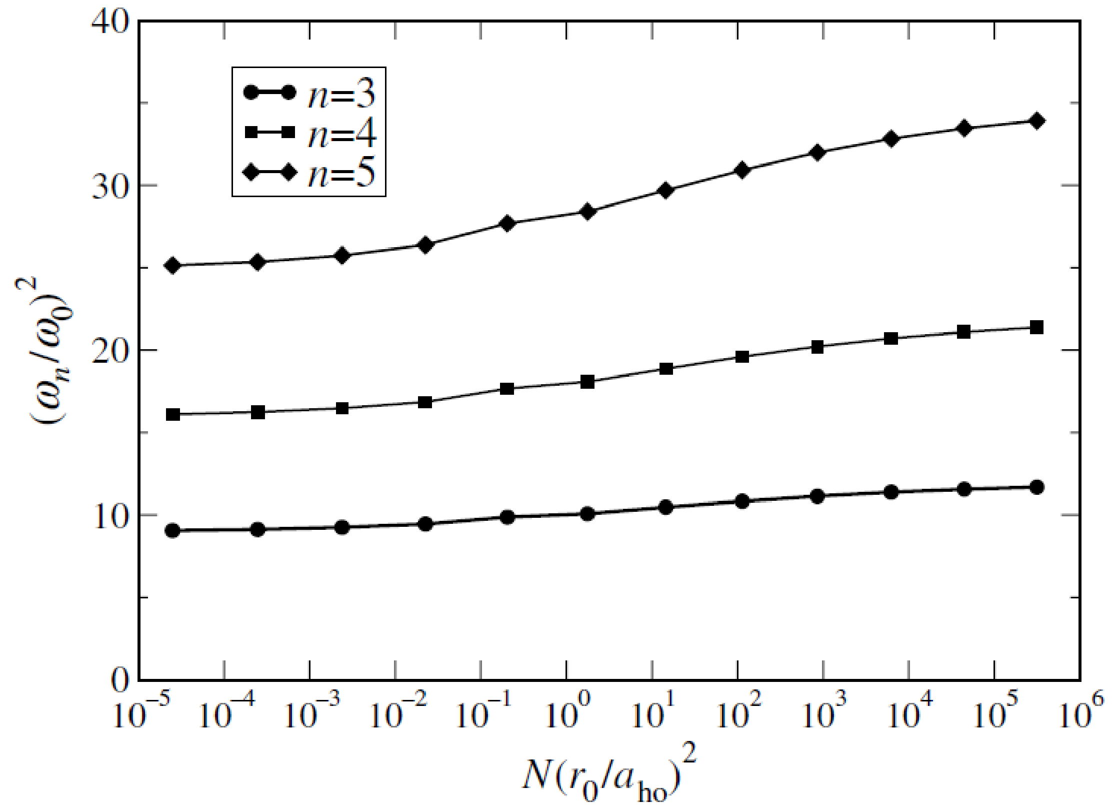
[Citro R, Orignac E, De Palo S, Chiofalo M, **PRA 75**, 51602 (2007)]

EXCITATIONS IN HOMOGENEOUS SYSTEM



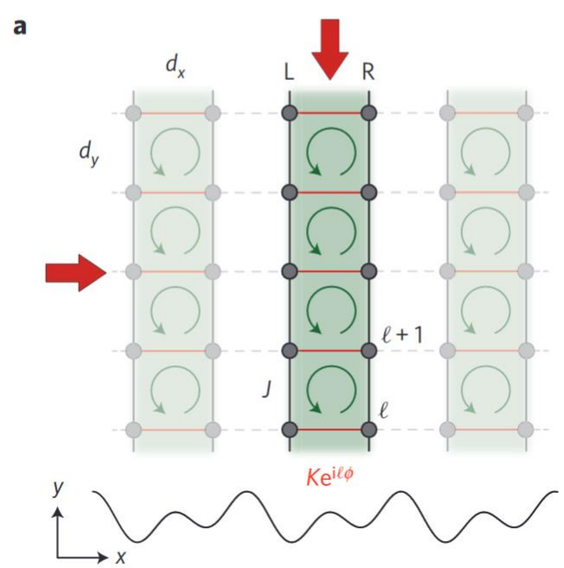
EXCITATIONS IN TRAP

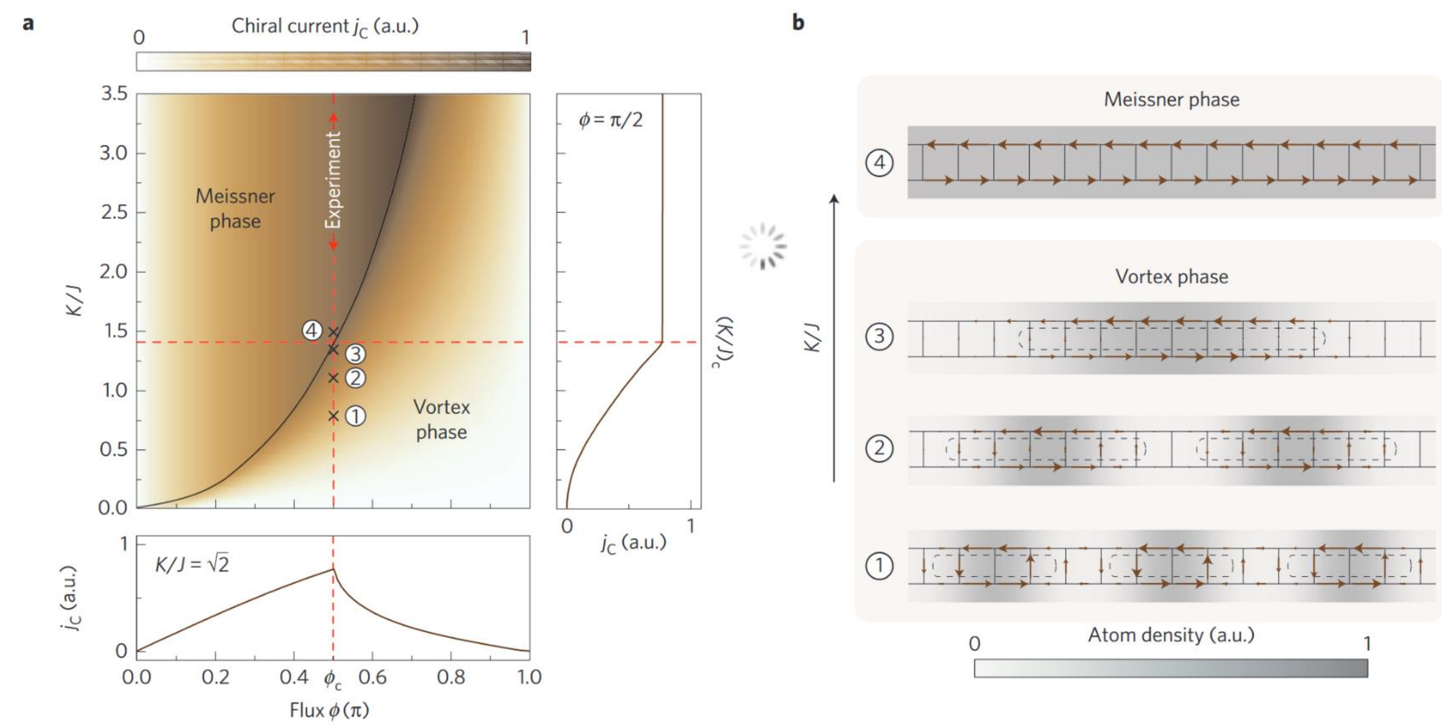




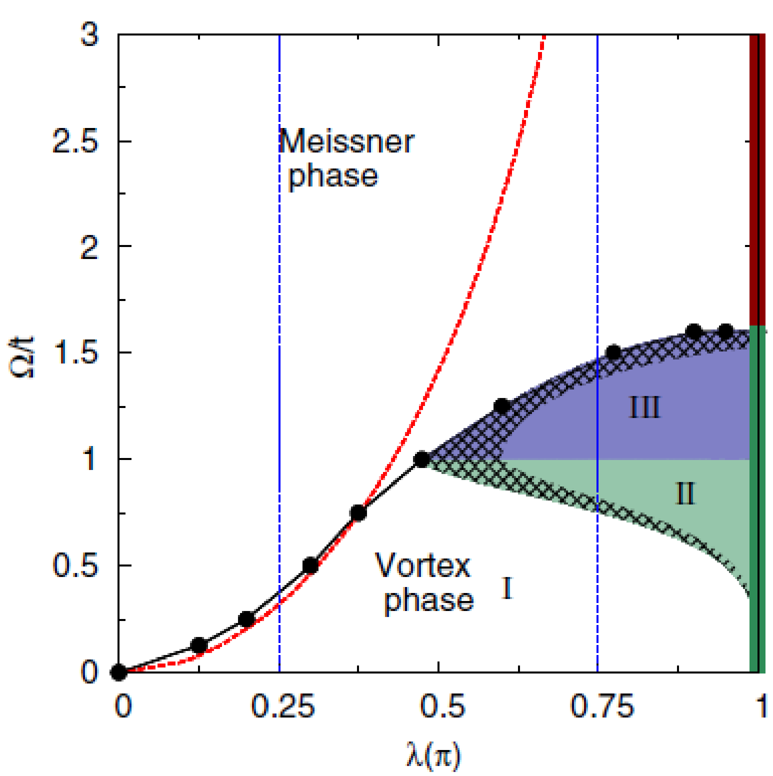
ADDING SPIN IN 1D LADDER: MEISSNER-TO-VORTEX TRANSITION

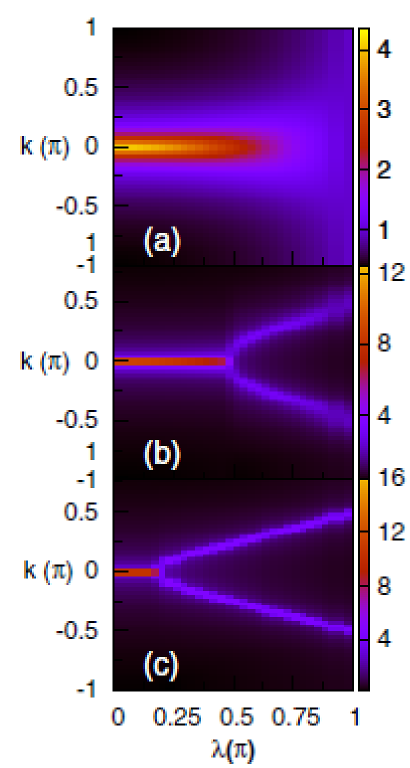
Lab. experiment





Atala et al., Nature (2014)





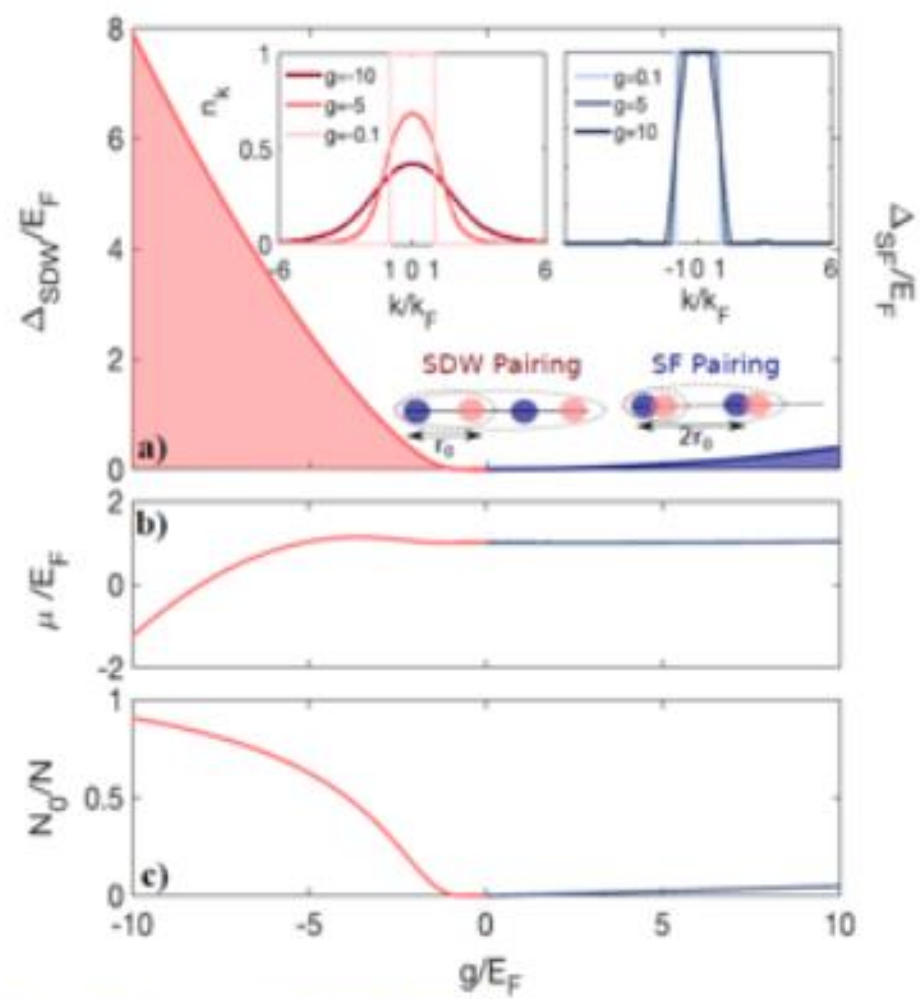
DMRG numerical experiment

$$H_\lambda = -t\sum_{j,\sigma}(b^\dagger_{j,\sigma}e^{i\lambda\sigma}b_{j+1,\sigma} + \text{H.c.})$$

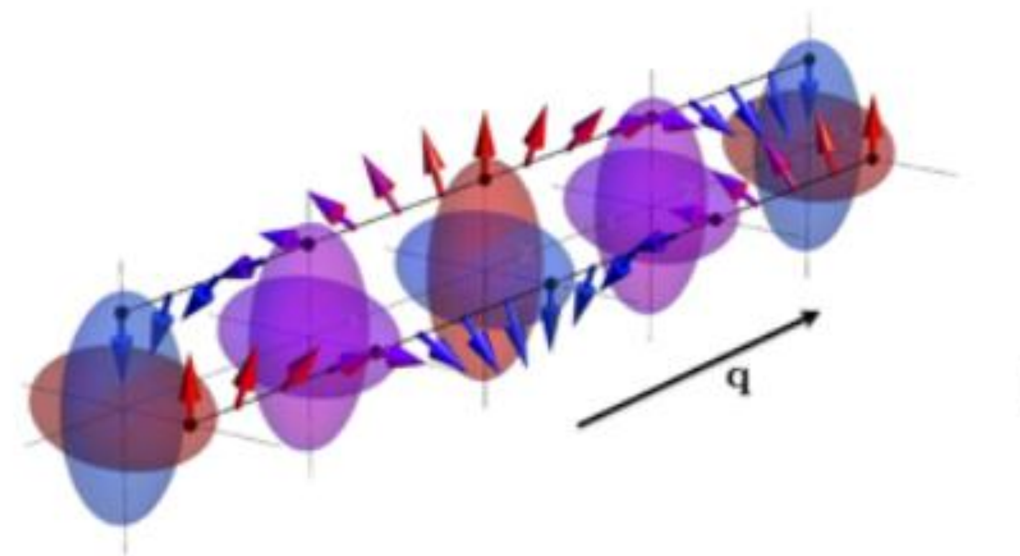
$$+\,\Omega\sum_{j}(b^\dagger_{j,\uparrow}b_{j,\downarrow} + \text{H.c.}),$$

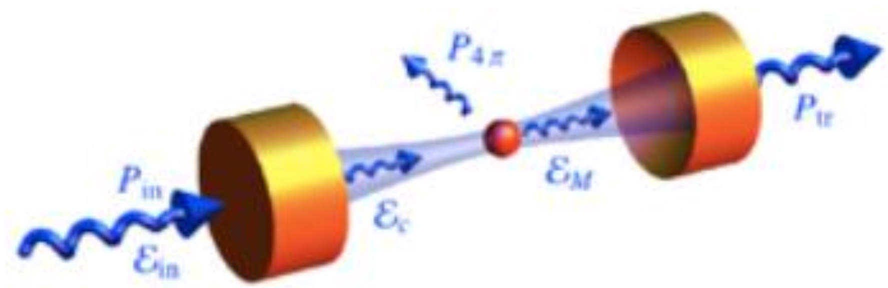
[Di Dio M., De Palo S., Orignac E., Citro R., Chiofalo M, **PRB 92,** 60506 (2015)]

1D SPINFUL FERMI GASES WITH INFINITELY LONG-RANGE INTERACTIONS IN OPTICAL CAVITIES (VIA MF+ED+BOSONIZATION)



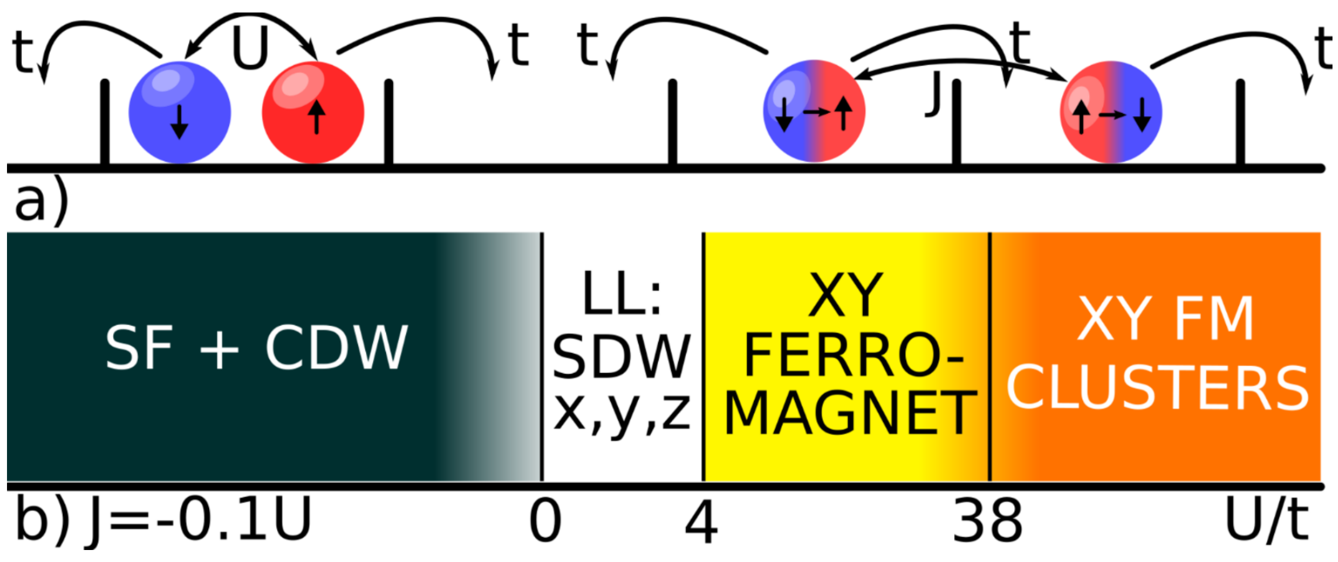
From Colella et al., PRB 2018

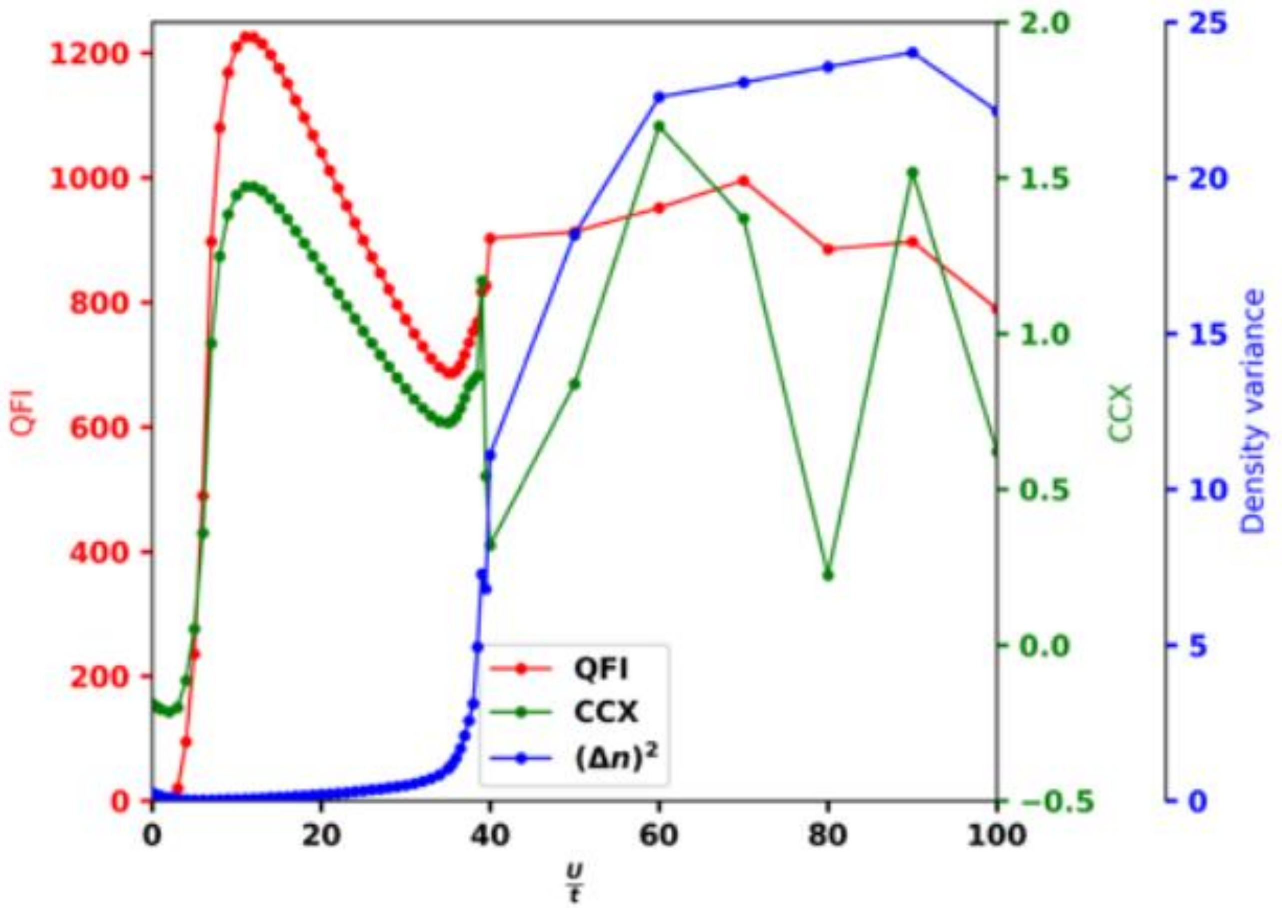


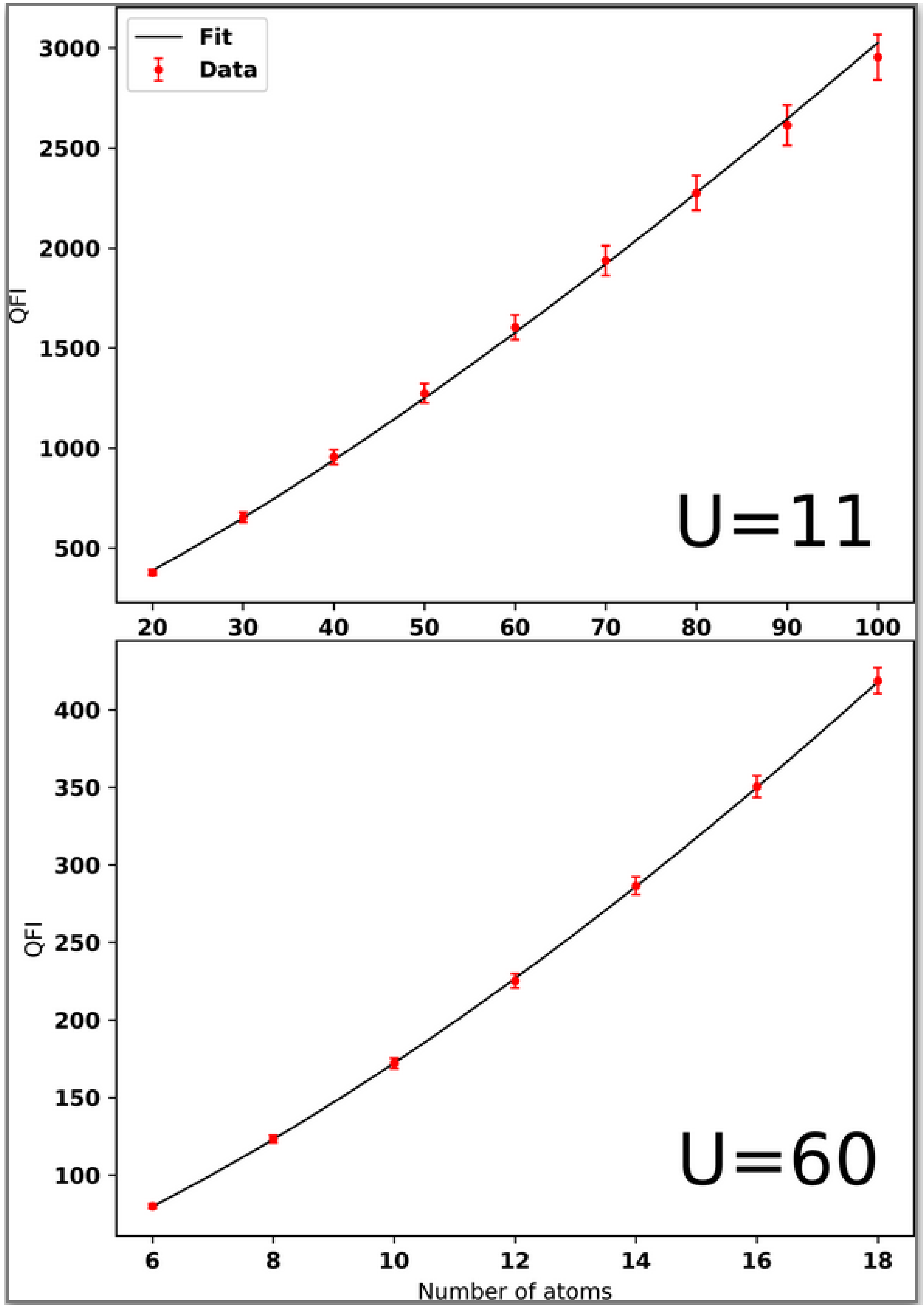


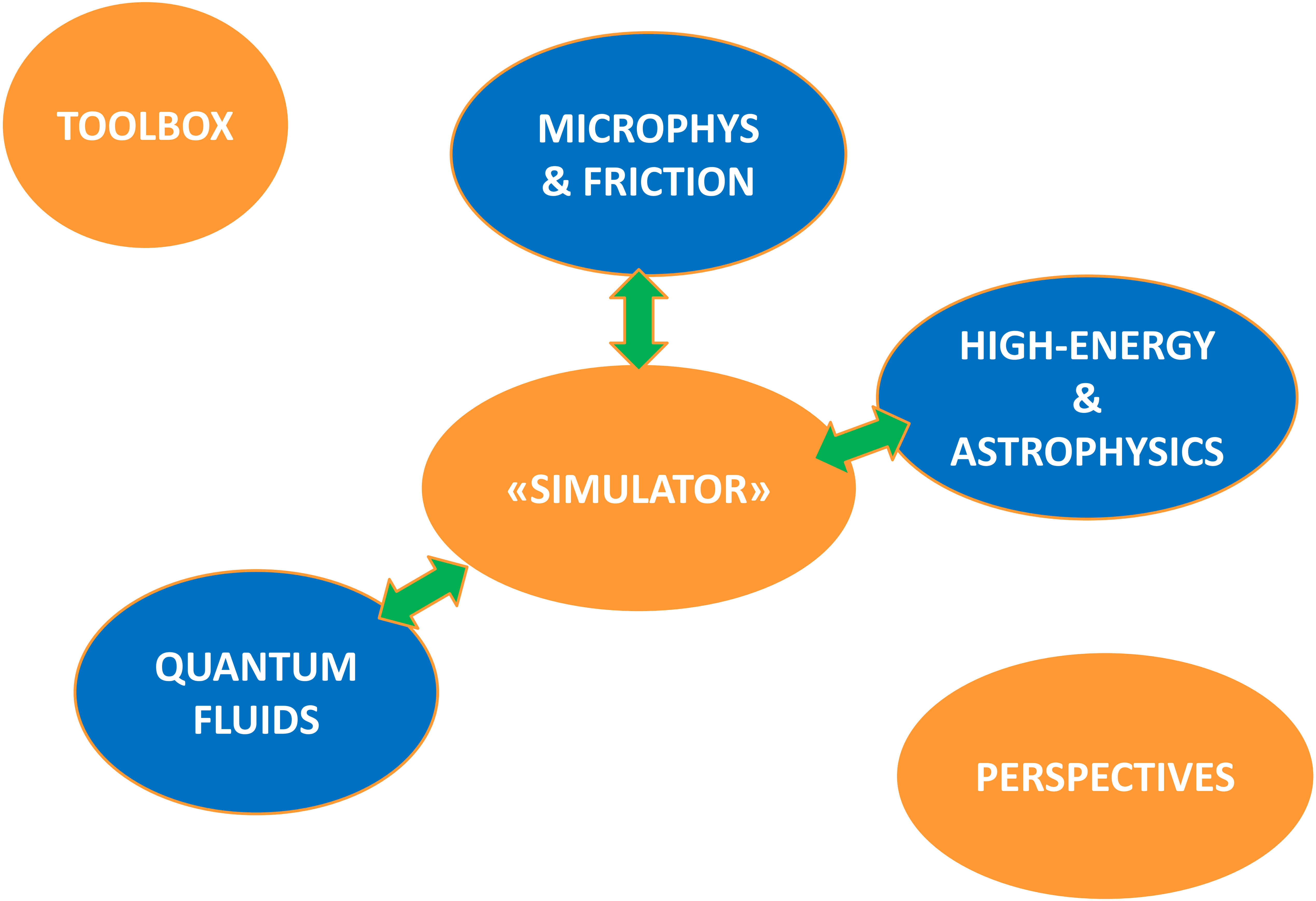
$$V(x,x') = \cos(k_L x)\cos(k_L x')$$

1D SPINFUL FERMI GASES WITH TUNABLE-RANGE INTERACTIONS (VIA DMRG)





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G.E. Volovik

Pages 195-348

Living Rev. Relativity, **14**, (2011), 3
http://www.livingreviews.org/lrr-2011-3
(Update of lrr-2005-12)

LIVING REVIEWS in relativity

Analogue Gravity

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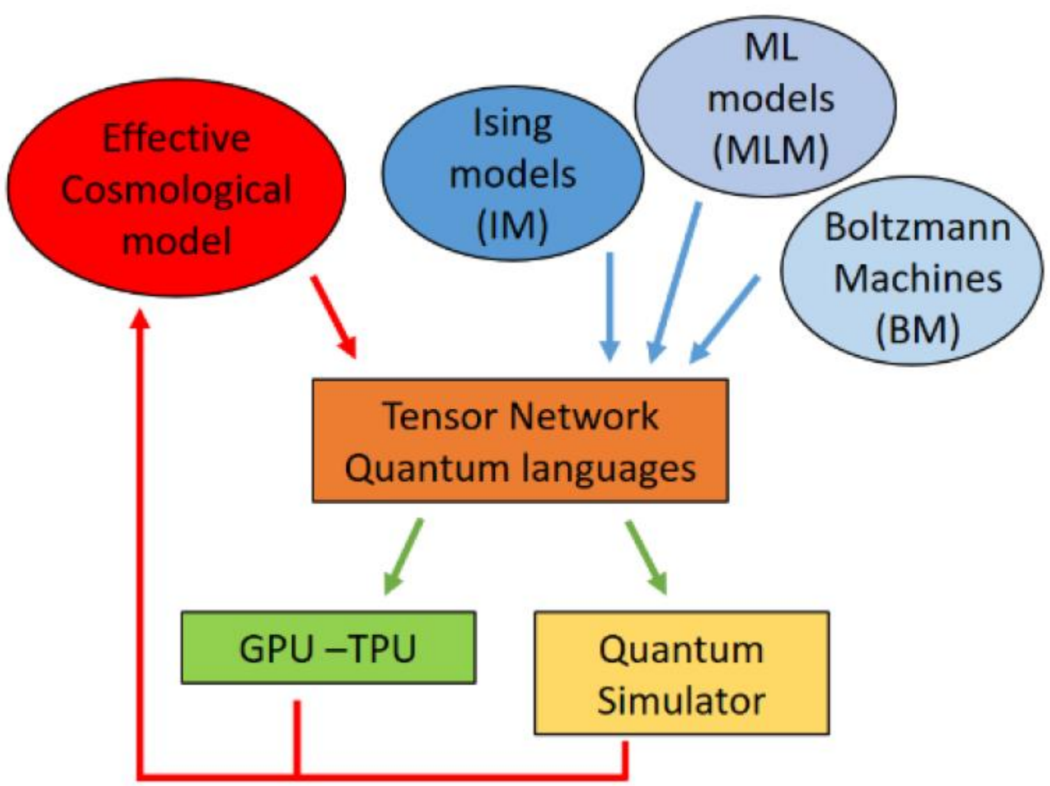
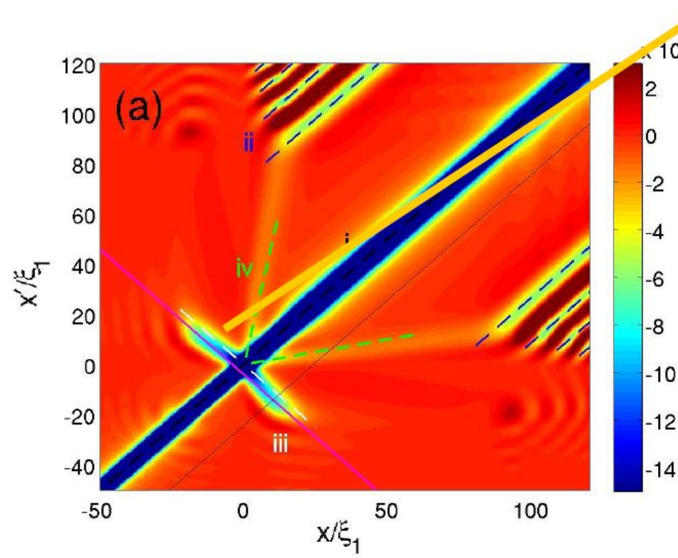


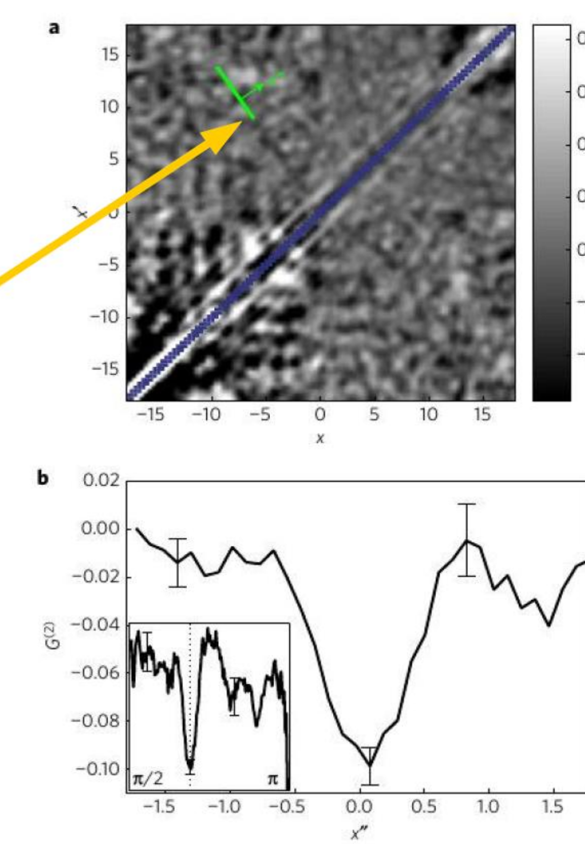
Analog Hawking radiation detected

Analog black hole configuration obtained by sending 1D atomic BEC against optical potential

Experimental evidence of HR based on Balbinot-Fabbri moustache in correlation function of density fluctuations



Theory: IC et al., NJP 2008



Expt: Steinhauer Nat. Phys. '16

Courtesy of Iacopo Carusotto

Quantum simulations of lattice gauge theories using ultracold atoms in optical lattices

Erez Zohar[1], **J Ignacio Cirac**[1] **and Benni Reznik**[2]

[1] Max-Planck-Institut für Quantenoptik, Hans-Kopfermann-Straß e 1, 85748 Garching, Germany
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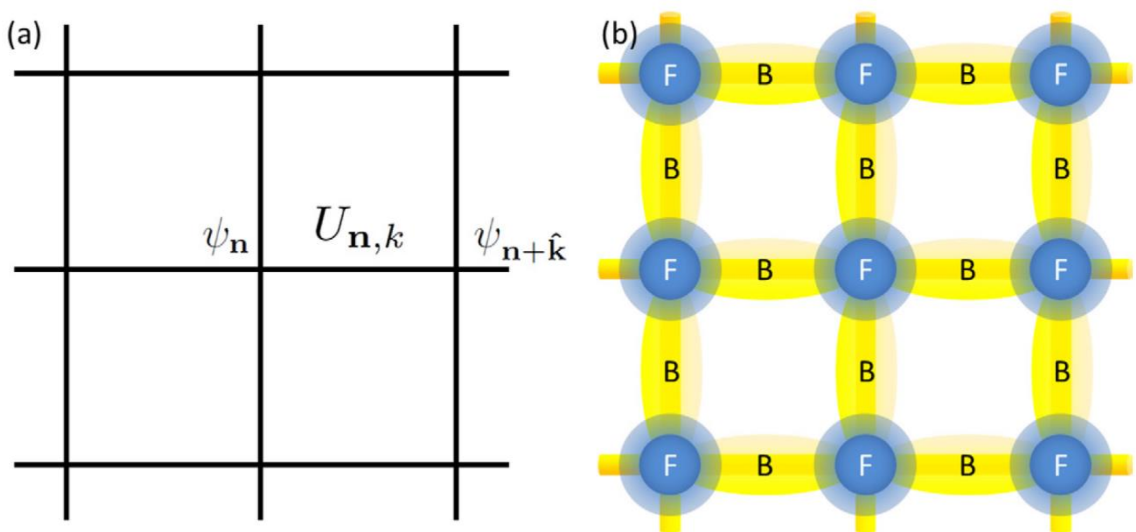
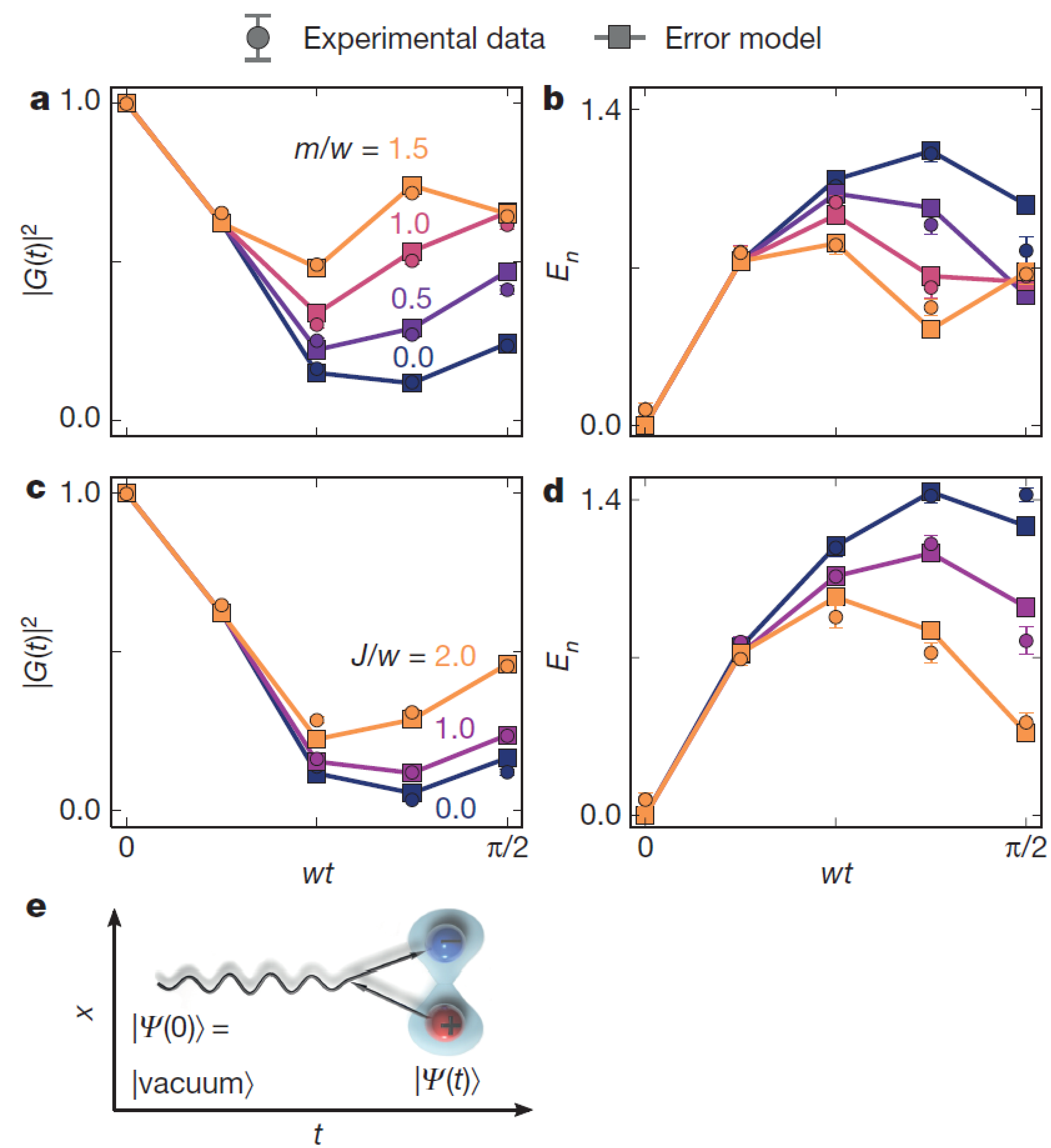


LETTER

doi:10.1038/nature18318

Real-time dynamics of lattice gauge theories with a few-qubit quantum computer

Esteban A. Martinez[1]*, Christine A. Muschik[2,3]*, Philipp Schindler[1], Daniel Nigg[1], Alexander Erhard[1], Markus Heyl[2,4], Philipp Hauke[2,3], Marcello Dalmonte[2,3], Thomas Monz[1], Peter Zoller[2,3] & Rainer Blatt[1,2]



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BCS-BEC CROSSOVER

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Quantum Phases and Many-Body Entanglement of Fermi Gases in Optical Cavities

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Now PhD@Innsbruck

with Helmut Ritsch

In collaboration with

Ben Lev@Stanford, Johnatan Keeling @St. Andrews (Scotland), D. Rossini@UniPI

Also: 1D Dipolar Bose Gases [with R. Citro, S. De Palo, E. Orignac]

Effects of Collision-driven interactions performing Matter-Waves Interferometers

Cosetta Baroni

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Now PhD@IQQT Innsbruck

with Rudi Grimm

In collaboration with

Andrea Trobettoni and

Giacomo Gori@SISSA, Trieste

Quantum effects in the Aubry Transition to Superlubricity

Pietro M.Bonetti

Just MD @Physics Dept.
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MaxPlanck@Stuttgart for PhD

In collaboration with
Vladan Vuletic@MIT and Massimo D'Elia@UniPI

Squeezing of Momentum States for MAGIA-Advanced Atomic Interferometer

Michele Barsanti

Researcher @Dept. of
Engineering

UniPisa

In collaboration with
Guglielmo Tino, Nicola Poli, and Co.@LENS, Firenze, MJHOLLAND &Co.@JILA

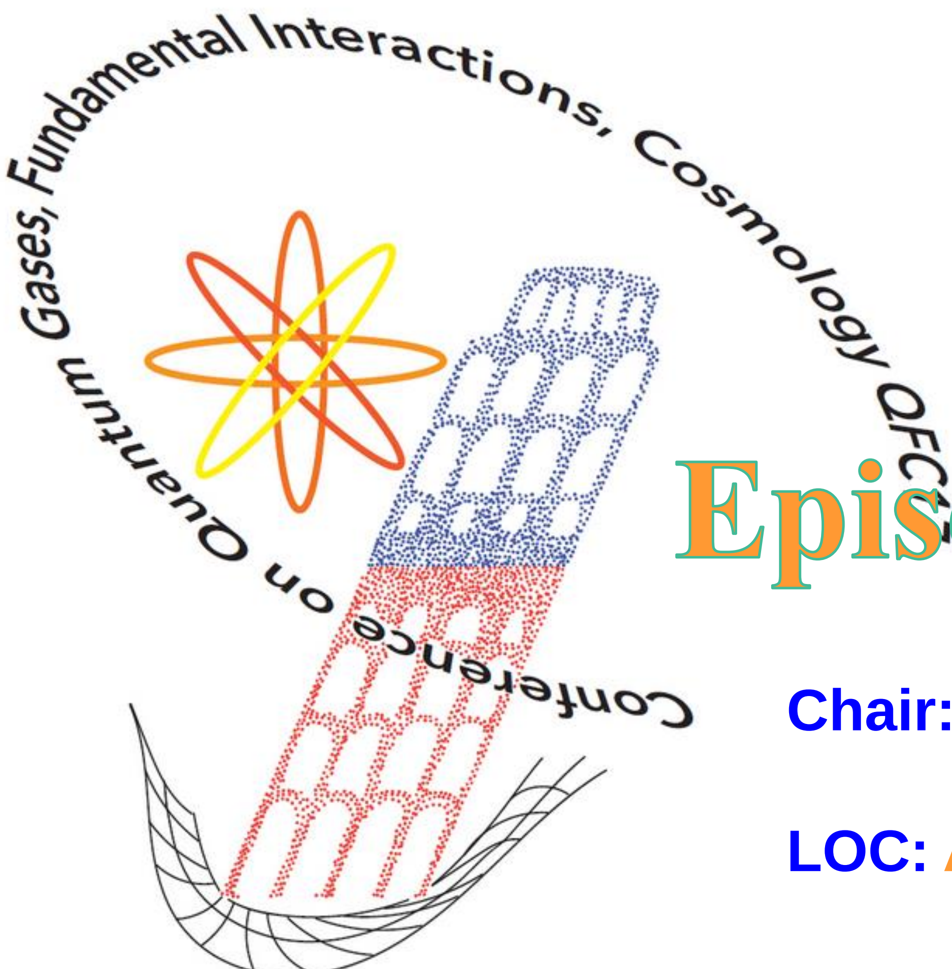
Quantum Gases as Simulators for Cosmological Open Problems

Carla Signorini
Until June 30th, Head of Electrical Department at European Space Agency

In collaboration with

- Andrea Ferrara@Scuola Normale Superiore Pisa
- Physics of the Universe @ Physics Department, UNIPI+INFN

Road under Construction



Episode II: Pisa, October 2019

Chair: M. L. Chiofalo

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THANKS
FOR
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