Ginsburg`s list of unsoved problems in physics

Vladimir S. Melezhik

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AYSS-2022, Dubna, 28 October 2022

What problems of physics and astrophysics seem now to be especially important and interesting ?

Ginzburg V L Usp. Fiz. Nauk 103 87 (1971) [Sov. Phys. Usp. 14 21 (1971)] 17
Ginzburg V L Physics and Astrophysics. A Selection of Key Problems
(New York: Pergamon Press, 1985)

Ginzburg V L O Fizike i Astrofizike (On Physics and Astrophysics) 24
(Moscow: Byuro Kvantum, 1995).

Ginzburg V L Usp. Fiz. Nauk 169 419 (1999) [Sov. Phys. Usp. 42 353 (1999)] 30

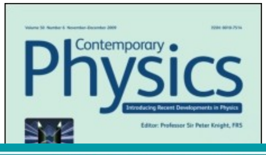
Ginzburg V L Nobel lecture (2003)

Science

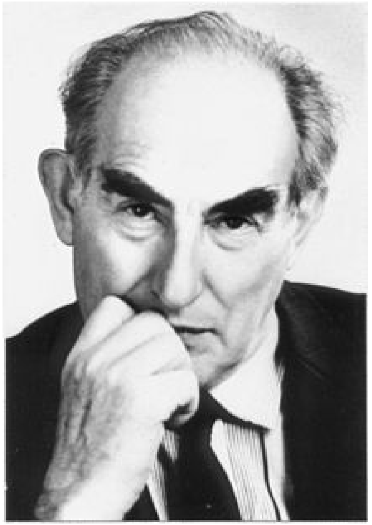
nature

PHYSICS TODAY

physicsworld



Reviews of Modern Physics



1916-2009

2003 Nobel Prize in Physics with A Abrikosov and A Leggett "for pioneering contributions to the theory of superconductors and superfluids".

`Landau`s-minimum':

`physics-minimum'

Ginsburg`s seminar in FIAN (1960-2000)

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1. Controlled nuclear fusion.
2. High-temperature superconductivity.
3. New matherials (Metallic hydrogen, exotic water etc.) .
4. Metallic exiton (electron-hole) liquid in semiconductors.
5. Second-order phase transitions (critical phenomena).
6. Superheavy elements (far transurans).
7. Mass spectrum (third spectroscopy).
8. Fundamental length (quantized space etc.).
9. Particle interaction at high and superhigh energies.

Ginzburg V L Nobel lecture (2003)

1. Controlled nuclear fusion.
2. High-temperature and room-temperature superconductivity.
3. Metallic hydrogen. Other exotic substances.
4. Two-dimensional electron liquid (anomalous Hall effect and some other effects).
5. Some questions of solid-state physics (heterostructures in semiconductors, metal-dielectric transitions, charge and spin density waves, mesoscopics).
6. Second-order and related phase transitions. Some examples of such transitions. Cooling (in particular, laser cooling) to superlow temperatures. Bose ± Einstein condensation in gases.
7. Surface physics. Clusters.
8. Liquid crystals. Ferroelectrics.
9. Fullerenes. Nanotubes.
10. The behavior of matter in superstrong magnetic fields.
11. Nonlinear physics. Turbulence. Solitons. Chaos. Strange attractors.
12. Rasers, grasers, superhigh-power lasers.
13. Superheavy elements. Exotic nuclei.
14. Mass spectrum. Quarks and gluons. Quantum chromodynamics. Quark-gluon plasma.
15. Unified theory of weak and electromagnetic interac-tions.W- and Z_0-bosons. Leptons.
16. Standard model. Grand unification. Superunification. Proton decay. Neutrino mass. Magnetic monopoles.
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10. Nonconservation of CP-invariance.

11. Experimental verification of the general theory of relativity.
12. Gravitational waves and their detection.
13. The cosmological problem. Inflation. About singularities in the general theory of relativity and cosmology .
14. Neutron stars and pulsars.

15. Quasars and galactic nuclei.

16. The origin of superhigh cosmic rays and gamma- and rentgen-bursts.
17. Neutrino astronomy.

Ginzburg V L Nobel lecture (2003)

18. Nonconservation of CP-invariance.
19. Nonlinear phenomena in vacuum and in superstrong magnetic fields. Phase transitions in vacuum.
20. Strings. M-theory.
21. Experimental verification of the general theory of relativity.
22. Gravitational waves and their detection.
23. The cosmological problem. Inflation. L-term. Relationship between cosmology and high-energy physics.
24. Neutron stars and pulsars. Supernova stars.
25. Black holes. Cosmic strings (?).
26. Quasars and galactic nuclei. Formation of galaxies.
27. The problem of dark matter (hidden mass) and its detection.
28. The origin of superhigh-energy cosmic rays.
29. Gamma-bursts. Hypernovae.
30. Neutrino physics and astronomy. Neutrino oscillations.

Three more «great» problems. An attampt to predict the future.

Ginzburg V L Usp. Fiz. Nauk 169 419 (1999) [Sov. Phys. Usp. 42 353 (1999)]

Ginzburg V L Nobel lecture (2003)

First, I mean the increase of entropy, time irreversibility and the `time arrow'.

L Landau: `The question of the physical grounds of the law of monotonic increase of entropy thus remains open'.
The discovery (1964) of CP-parity nonconservation (and, therefore, T-parity non-conservation, i.e., time irreversibility) is clearly related to this subject, but all this is not yet sufficiently investigated and realized.

Second is the problem of interpretation and comprehension of quantum mechanics.

The current interest in the fundamentals of quantum mechanics is partially due to new experiments, mainly in the field of optics.

Third is the question of the relationship between physics and biology and, specifically, the problem of reductionism.

The last `great' problem to be discussed here concerns the relationship between physics and biology.

Three more «great» problems. An attampt to predict the future.

Ginzburg V L Usp. Fiz. Nauk 169 419 (1999) [Sov. Phys. Usp. 42 353 (1999)]

Ginzburg V L Nobel lecture (2003)

Some experimental reactor (but, of course, with a positive energy output) will in any case be constructed in a couple of decades. Laser thermonuclear fusion will also be realized because such an installation is possible and needed for military purposes. Of course, physical experiments will also be carried out on it.

The problem of high-temperature superconductivity has been investigated since 1964 and I had thought of it as quite realistic all the time before the discovery of HTSC in 1986 ± 1987. But at that time there was no real prediction of the possibility of HTSC. It The present-day situation with room-temperature superconductivity (RTSC) is the same.

The static pressures of nearly three million atmospheres now attained to obtain the metallic phase turned out to be insufficient. It is unknown (at least to me) how the pressure can be heightened appreciably ifnew materials stronger than diamond are not discovered. To obtain a `piece' of metallic hydrogen and to use it do not seem to be realistic.

In respect of all the other problems (4 ± 13) it is clear that they will be intensively investigated and many interesting things will be clarified.

In the field of microphysics (elementary particle physics) an obvious recession (in the number of discoveries, etc.) has been observed within the last two decades compared to the previous period. This is perhaps largely due to the want of accelerators of a new generation.

New telescopes ...

Since the nature of dark matter is absolutely unclear, the solution of this problem may now be thought of as the most important in astronomy if we do not touch upon the principal question of cosmology (the region near the classical singularity, i.e., the quantum region; our Universe as part of a branched and apparently infinite system). This is a truly enigmatic problem, and success can only be hoped for. But I shall not be surprised if it is solved soon.

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Controlled nuclear fusion

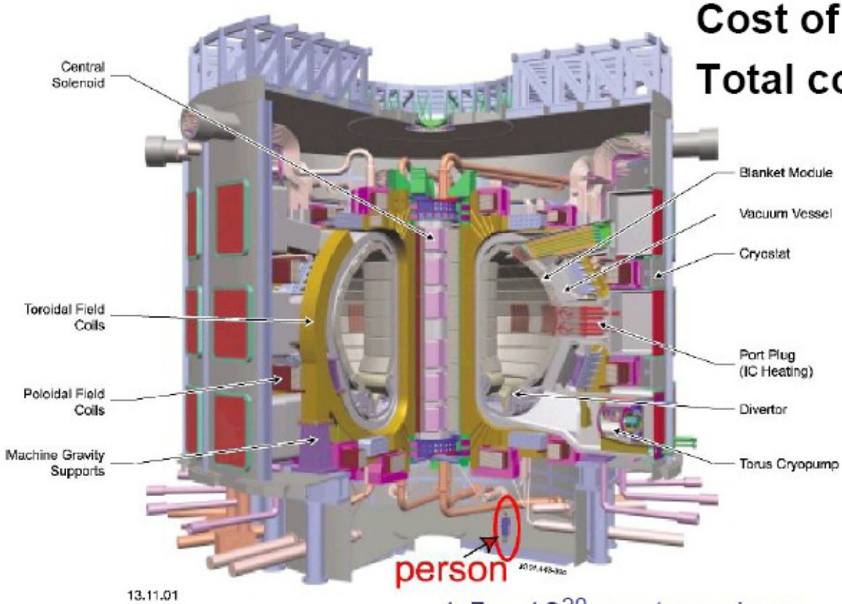
Ginzburg V L Usp. Fiz. Nauk 169 419 (1999) [Sov. Phys. Usp. 42 353 (1999)]

$$d + t \rightarrow He + n + 17.6\,\text{MeV}$$

Internetional Termonuclear Experimental Reactor (ITER)

Cost of the project ~$5B

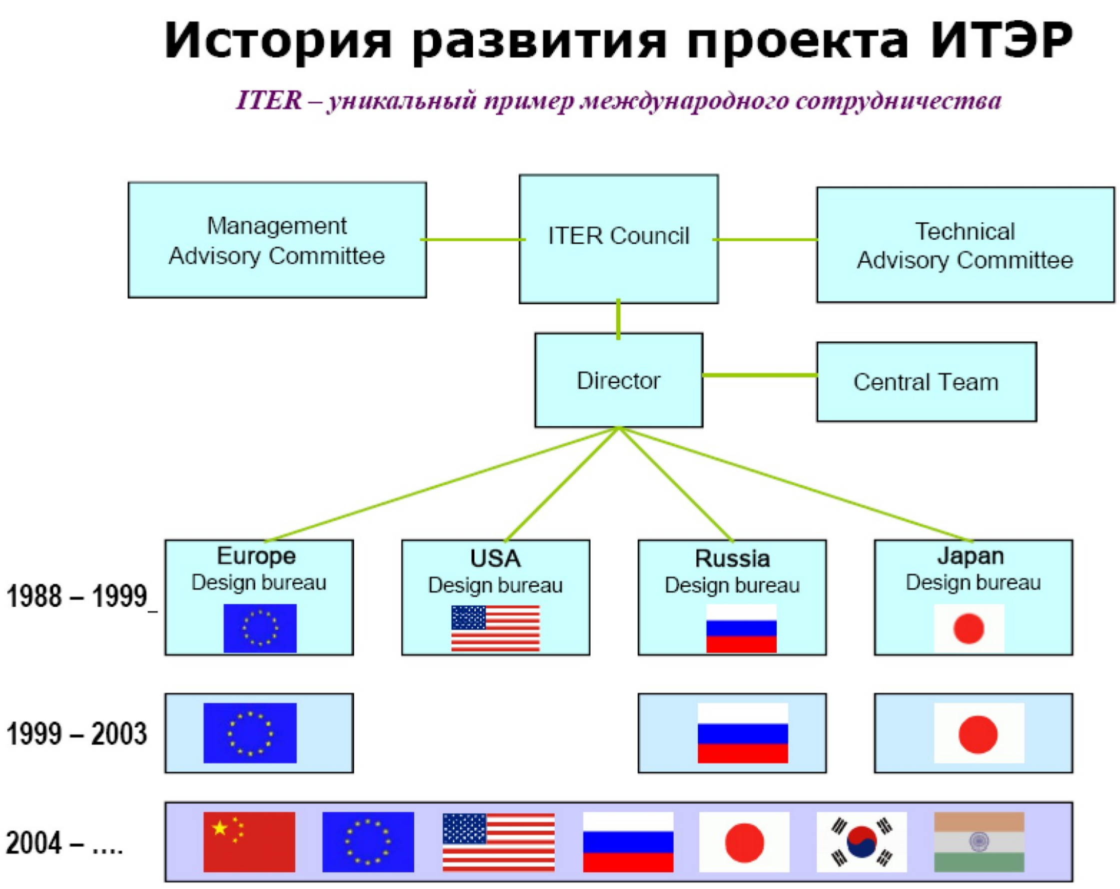
Total cost ~$10B (end 2036)



1.5 x 10^{20} neutrons/sec

R (m)	6.2
a (m)	2
V_P (m^3)	850
I_P (MA)	15(17)
B_t (T)	5.3
δ,κ	0.5, 1.85
P_{aux} (MW)	40-90
P_α (MW)	80+
Q (P_{fus}/P_{in})	10
β_T, β_P	2.5%, 0.7

Controlled nuclear fusion

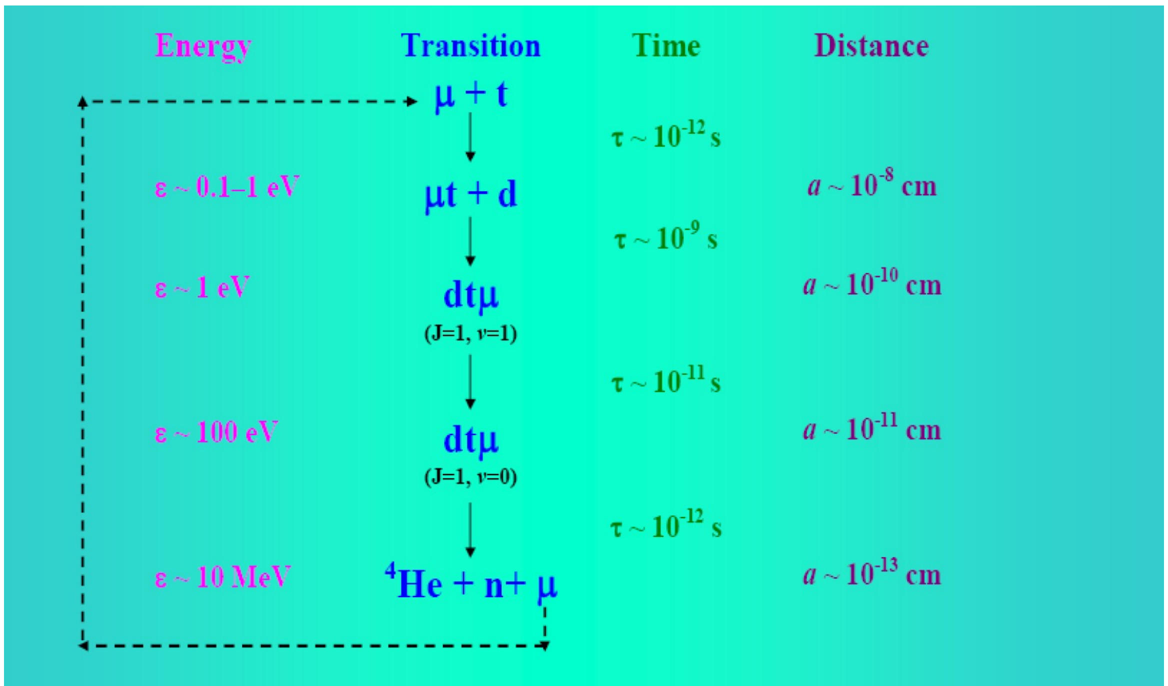


Controlled nuclear fusion

Controlled nuclear fusion: µCF (muon catalyzed fusion)

Ginzburg V L Usp. Fiz. Nauk 169 419 (1999) [Sov. Phys. Usp. 42 353 (1999)]

muon catalysis is very elegant (and should, I think, be elucidated in a course of general physics), but seems to be an unrealistic energy source, at least when not combined with uranium fission, etc.



In µCF-cycle nuclei approach each other during 10^{-9} s to the distance ~10^{11}cm (what is equivalent to temperature 10^8 K in hot fusion) and fusion takes place without heating and any macroscopic fields.

Dubna:
resonant mechanist of ddµ and dtµ formation

S Gersgtein, L. Ponomarev
V Dzhelepov, V. Zinov et al

τµ~10(-6)s

Controlled nuclear fusion: μCF

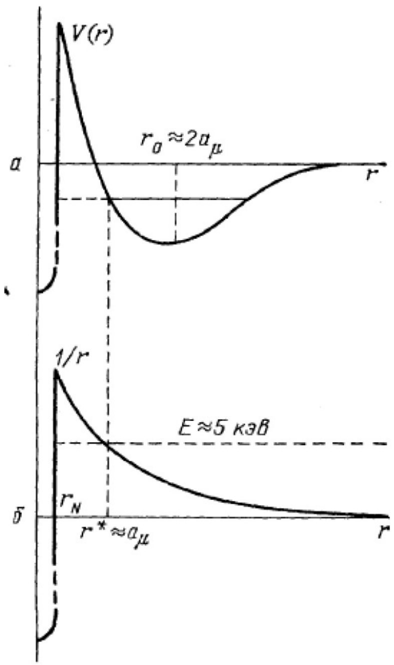
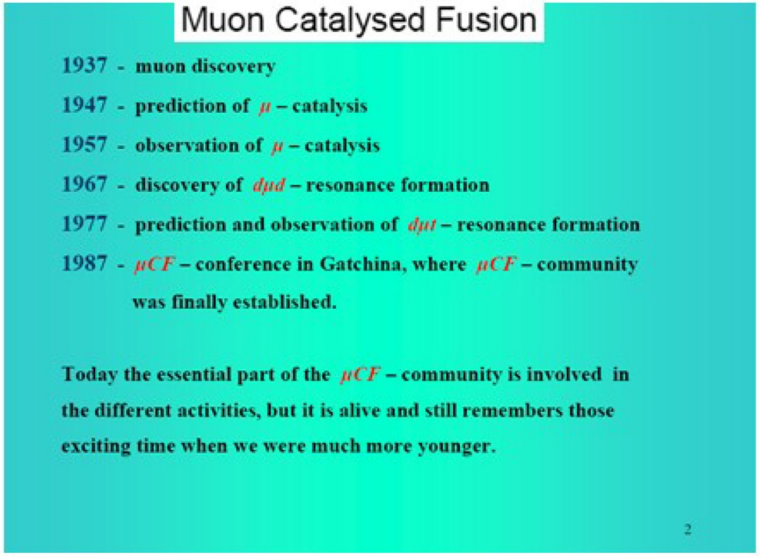
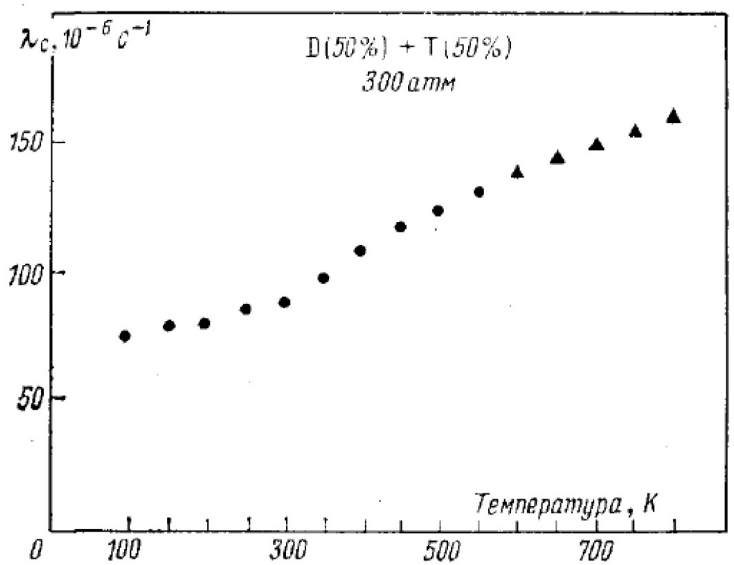


Рис. 1. Схема преодоления кулоновского барьера при синтезе ядер в мезомолекуле (а) и при столкновении ядер (б). r^* — точка остановки



Controlled nuclear fusion: μCF



Температурная зависимость скорости d — μ — t-синтеза

temperature is increases 2 times (from 0.04eV to 0.08eV)
at that output of neutrons in 2.5 times from reaction

$t + d \rightarrow He + n + 17.6$ MeV

Controlled nuclear fusion: μCF

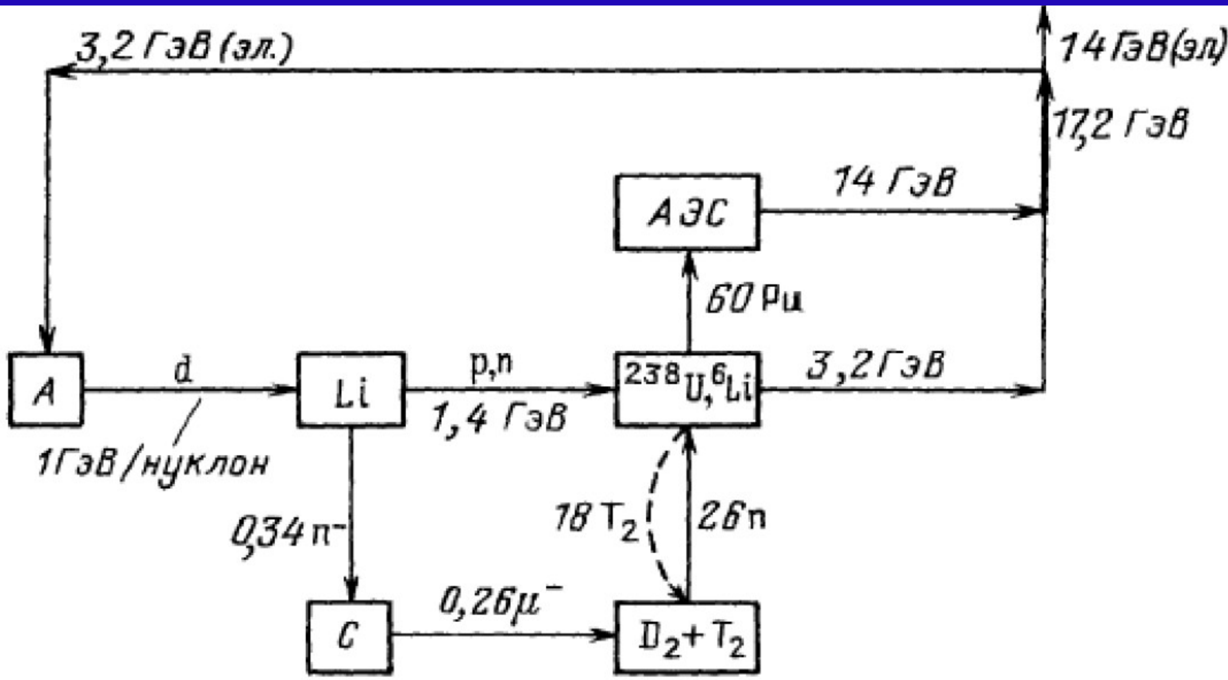


Рис. 5. Концептуальная схема мюонно-каталитического гибридного реактора (МКГР). *А* — ускоритель; Li — мишень для производства π^-; *С* — конвертер, в котором происходит распад $\pi^- \rightarrow \mu^-$; D_2+T_2 — синтезатор, ^{238}U, ^{6}Li — бланкет, *АЭС* — атомная электростанция

Yu V Petrov, Gatchina

Controlled nuclear fusion: μCF

L Ponomarev, S Gershtein, J D Jackson, Yu Petrov

μCF

D Blokhincev, L Ponomarev, S Vinitskii

V Zinov, A Yukhimchuk

μCF


International RIKEN Conference
Muon Catalyzed Fusion and Related Exotic Atoms
April 22-26, 2001 Shimoda, Japan
RIKEN
RIKEN

Muon Catalyzed Fusion
An Investigation of Reactor Design

Richard Spencer Kelly

September 2018

Supervised by Professor Steven Rose

Submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy of Imperial College London

Department of Physics
Imperial College London
Prince Consort Road
London SW7 2BZ

µCF

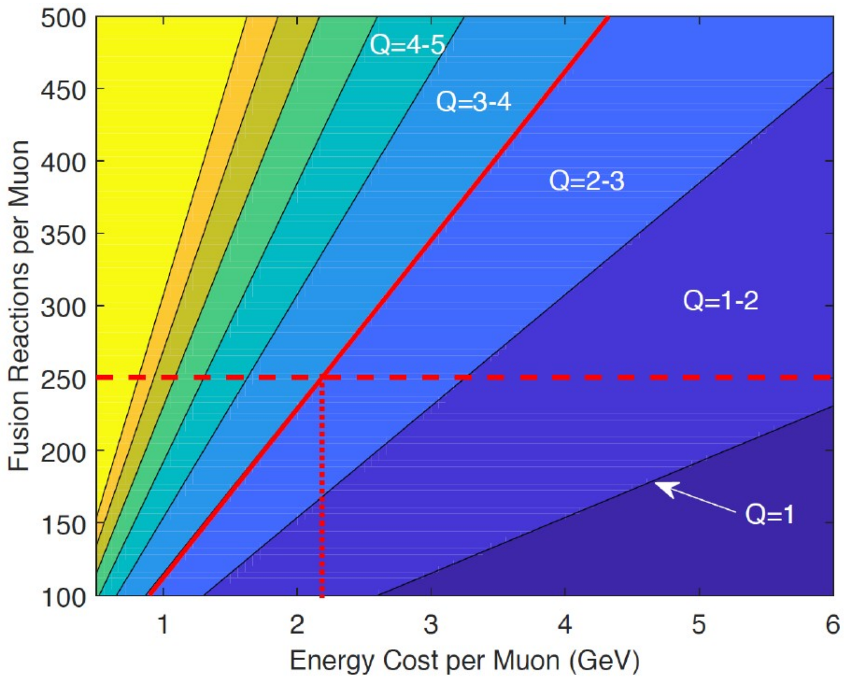


Figure 7.2: Energy production analysis. Assuming that commercial viability occurs at Q=3 (solid red line) then if we can achieve 250 fusion reactions per muon (dashed red line) then we will need to get the cost of producing one muon down to just over 2 GeV (dotted red line).

This sentiment that the field of muon catalyzed fusion is worth pursuing was the view of Leonid Ponomarev in 1998 when he said: "The social interest in the μCF-phenomenon is determined by hopes to use it for the nuclear energy and nuclear fuel production. This way is open: there are no physics restrictions to use μCF in nuclear energetics but the real perspectives of the μCF practical use are determined not only by physics but also by the economic and technological concurrence of different approaches as well as by the social interest which is very low today".[3]

[3]Leonid I. Ponomarev in "Review of the μCF Theory after EXAT-98"

Ultracold atoms, quantum simulations, quantum computer ...

1997 Nobel prize in physics
S. Chu, C. Cohen Tannoudji, W. Phillips
Laser manipulation of atoms

2001 Nobel prize in physics
E. Cornell, W. Ketterle, C. Wieman
Bose-Einstein Condensation
In atomic gases

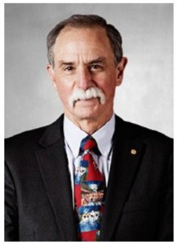


2005 Nobel prize in physics
J. Hall, T. Haensch, R. Glauber
Laser precision spectroscopy and
optical frequency comb



2012 Nobel prize in physics
S. Haroche, D.J. Wineland

Ground-breaking experimental methods
that enable measuring and manipulation of
individual quantum systems

Quantum simulations

- Quantum simulations: why cold atoms ?
- Solid state physics: modeling matter phase-transitions
- Simulations with degenerate quantum gases
- High energy physics: modeling quark-gluon plasma, string theory, …

- Cosmology: unstable quantum vacuum
- Outlook, goals and opportunities

Quantum simulations: why cold atoms ?

R.Feynman's vision: a quantum simulator
to study the quantum dynamics of another system

R. Feynman, Int. J. Theor. Phys. 21, 467 (1982)

Y. Manin, Computable and Uncomputable (Sovetskoye Radio Press, Moscow) (in Russian) 1980.

development of physics of ultracold atoms has opened unique possibility for realisation of R. Feynman's idea:

to use simple quantum systems with desiered properties
(amenable quantitative description and modeling)
to describe more complex systems and phenomena

Quantum simulations: why cold atoms ?

Quantum simulation with fully controlled systems

control over: particle number

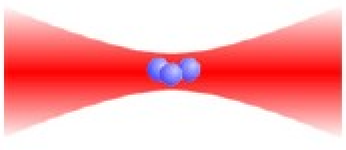
quantum state

interaction

Quantum simulations: why cold atoms ?

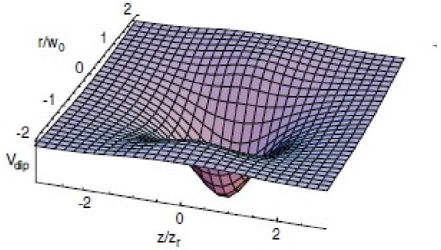
control over: particle number

the focus of a laser beam

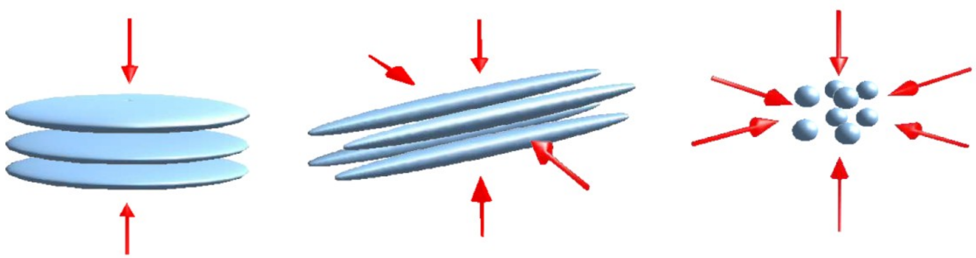


$$d = \alpha(\omega)E.$$

Optical dipole trap



$$V_{dip} = -\frac{1}{2}\langle \mathrm{dE} \rangle = -\frac{1}{2\epsilon_0 c}\mathrm{Re}(\alpha)I$$

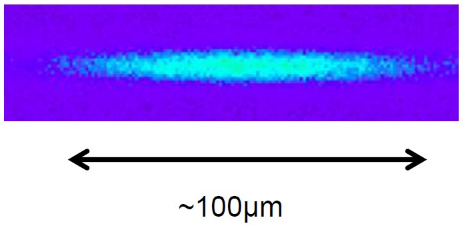


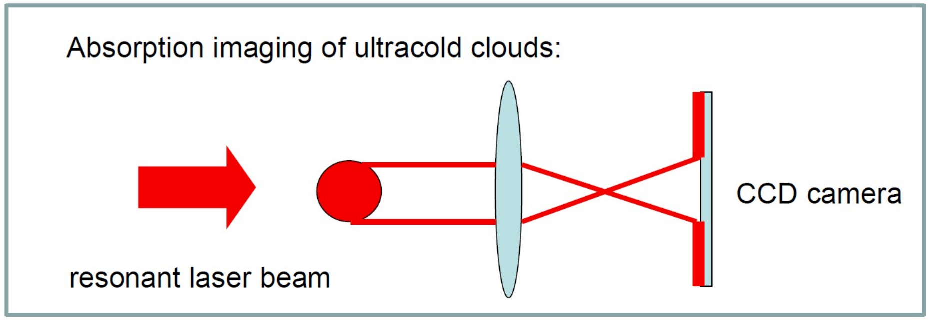
Lattices formed by applying orthogonal standing waves in one, two, and three directions.

Quantum simulations: why cold atoms ?

control over: particle number

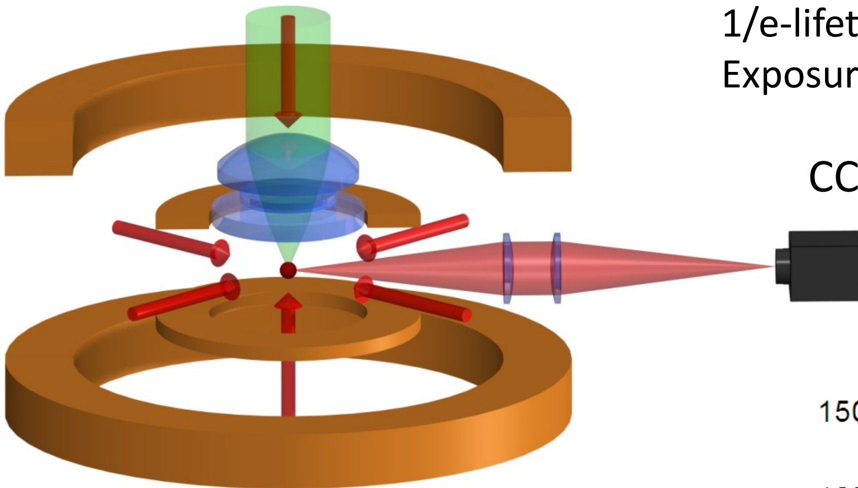
About 50000 atoms @ 250nK, T_F~1μK



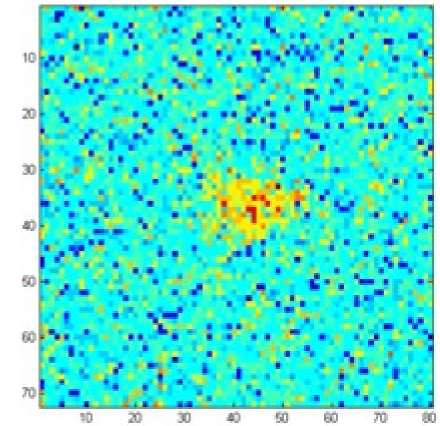


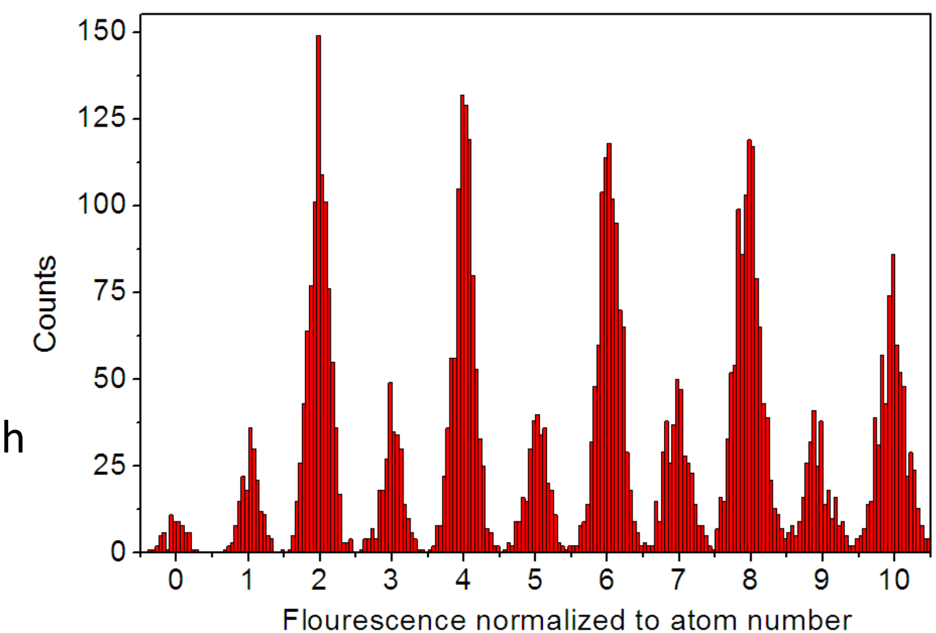
Quantum simulations: why cold atoms ?

control over: particle number



1/e-lifetime: 250s
Exposure time 0.5s



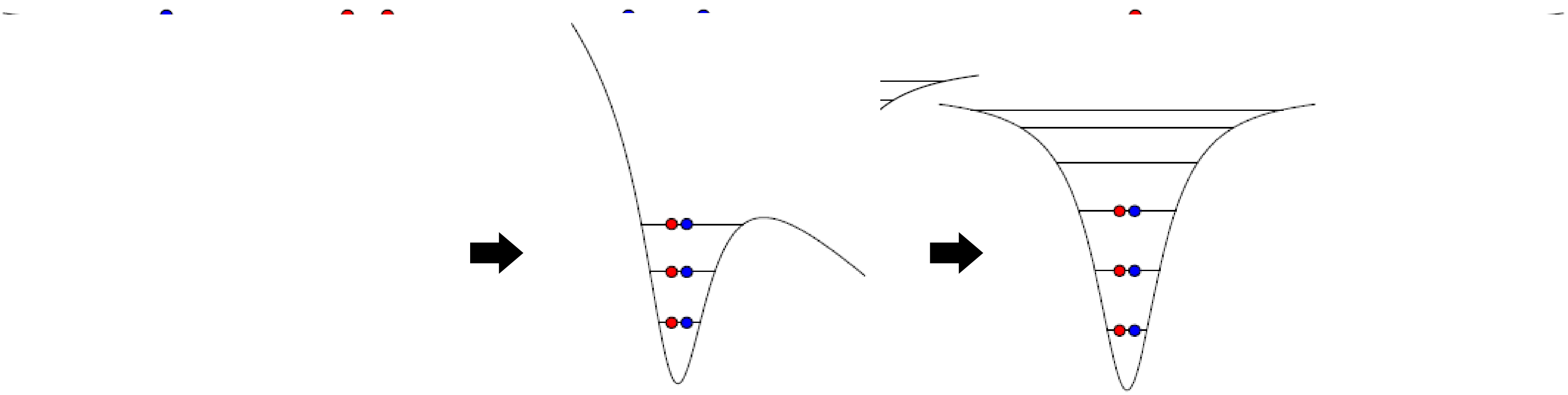


distance between 2 neighbouring atom peaks: ~ 6σ
1-10 atoms can be distiguished with high fidelity > 99%

Quantum simulations: why cold atoms ?

control over: particle number

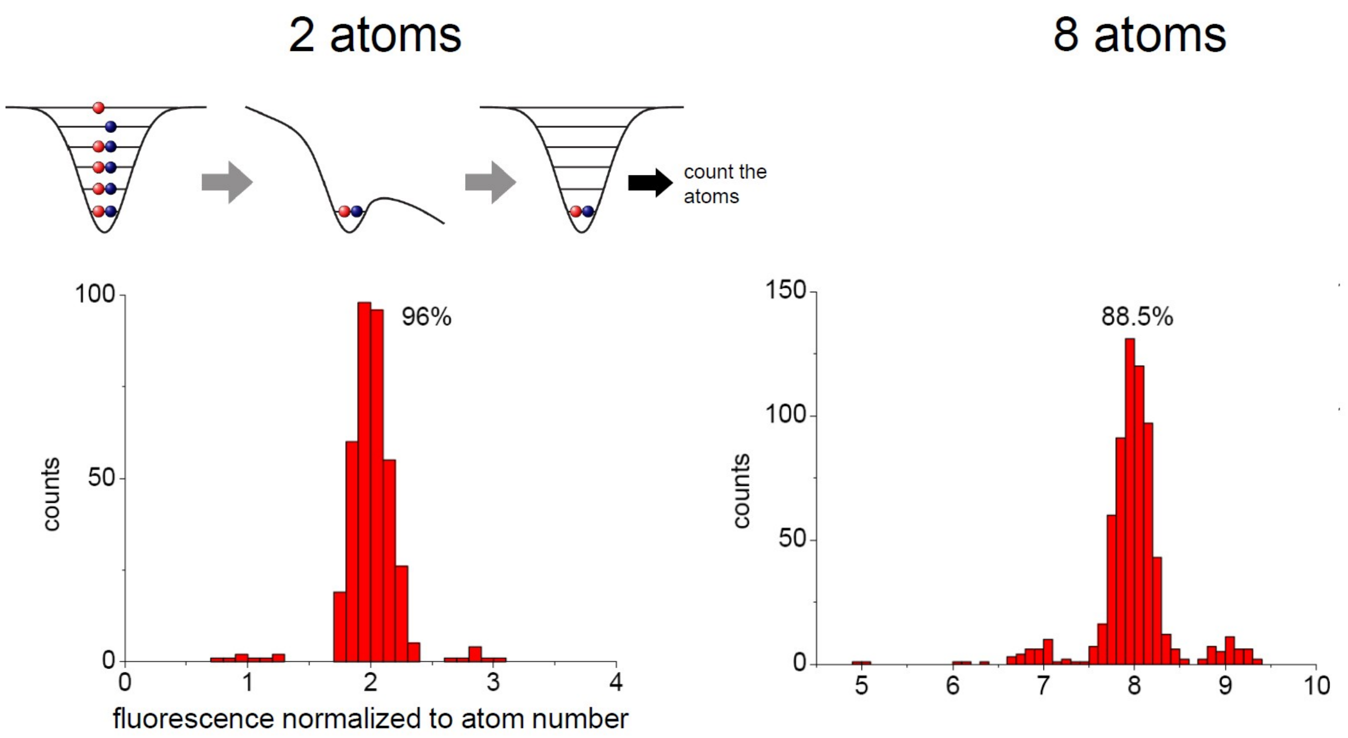
- 2-component mixture in reservoir T=250nK
- superimpose microtrap
- switch off reservoir



+ magnetic field gradient in axial direction

Quantum simulations: why cold atoms ?

control over: particle number with high fidelity

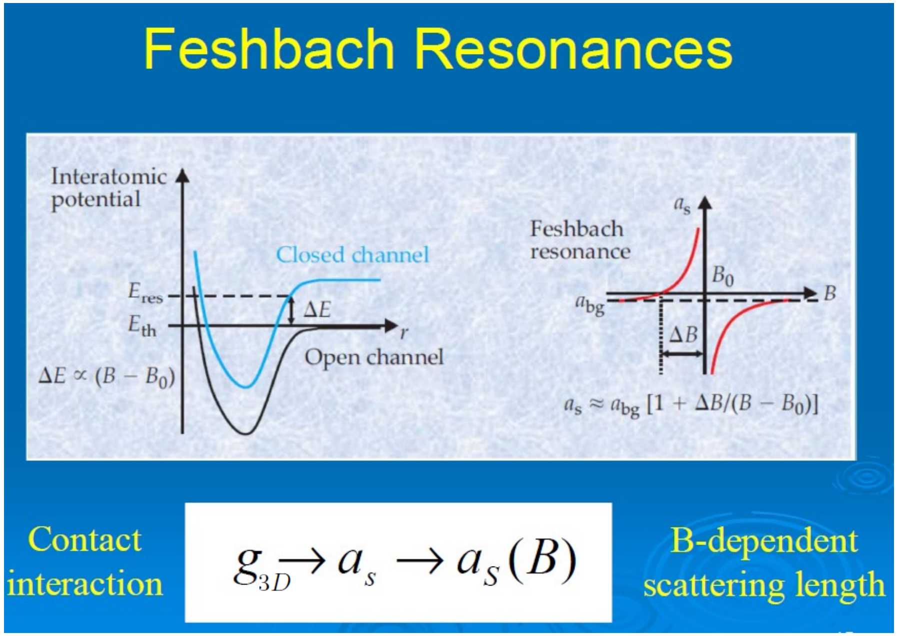


lifetime in ground state ~ 60s

F. Serwane et al., Science **332,** 336 (2011)

Quantum simulations: why cold atoms ?

control over: interaction



$$V(r)$$

$$V(r) = g_{3D}\delta(r)$$

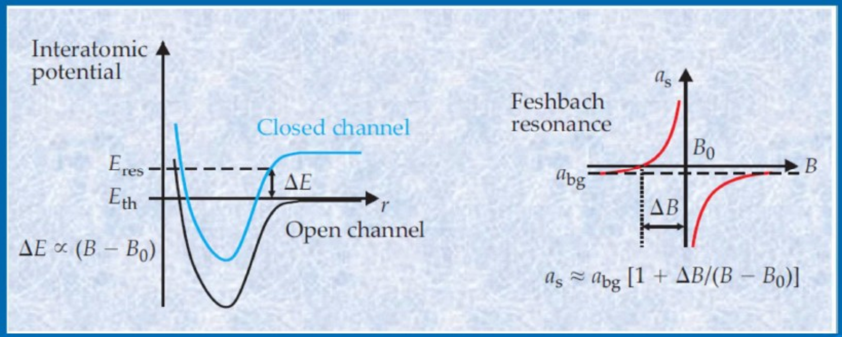
$$g_{3D} = \frac{2\pi\hbar^2}{\mu} a_S(B)$$

Quantum simulations: why cold atoms ?

control over: interaction

$V(r)$

Feshbach Resonances



Contact interaction

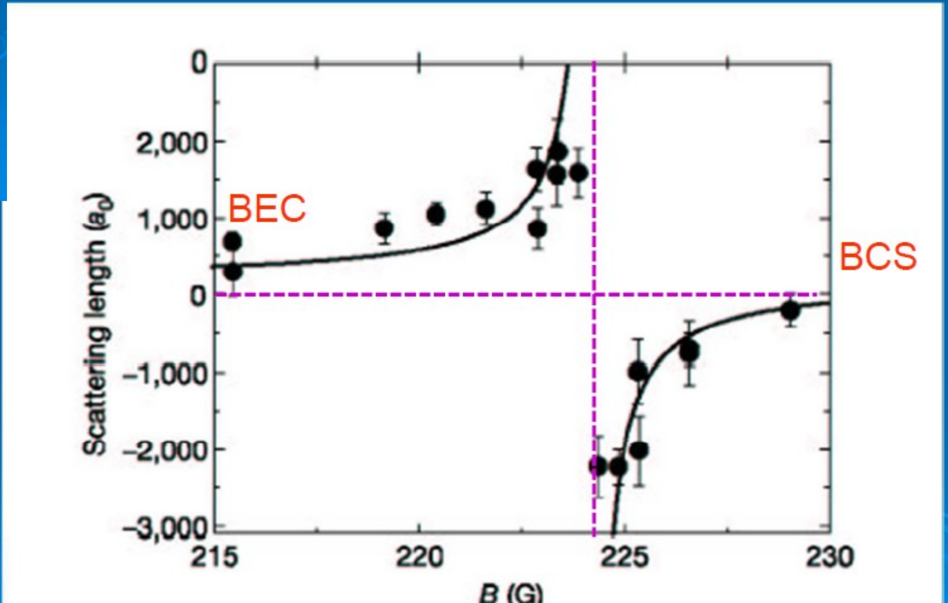
$$g_{3D} \to a_s \to a_S(B)$$

B-dependent scattering length

$$V(r) = g_{3D}\delta(r)$$

$$g_{3D} = \frac{2\pi\hbar^2}{\mu} a_S(B)$$

S-wave scattering length (^{40}K)

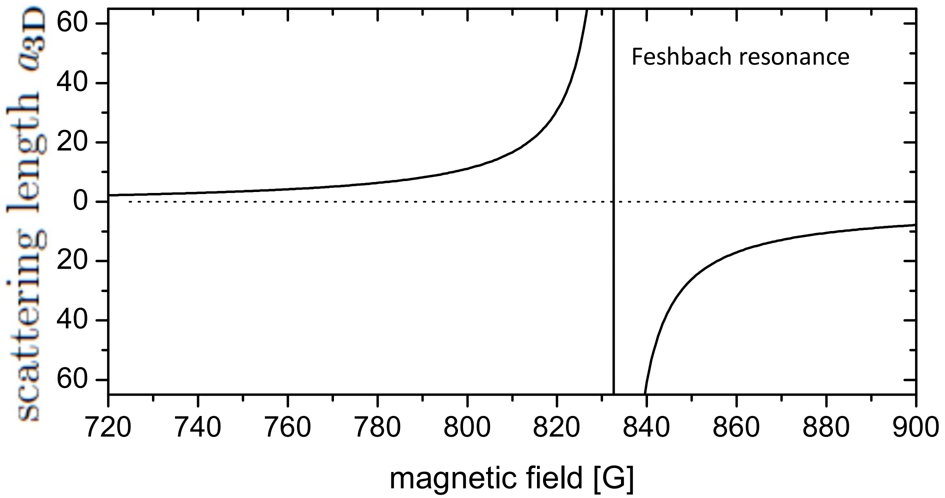


Regal et. al., PRL 90, 230404 (2003)

Quantum simulations: why cold atoms ?

control over: interaction

3D



single-channel pseudopotential

$$V(r) = g_{3D}\delta(r)$$

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Quantum simulations: why cold atoms ?

control over: interaction

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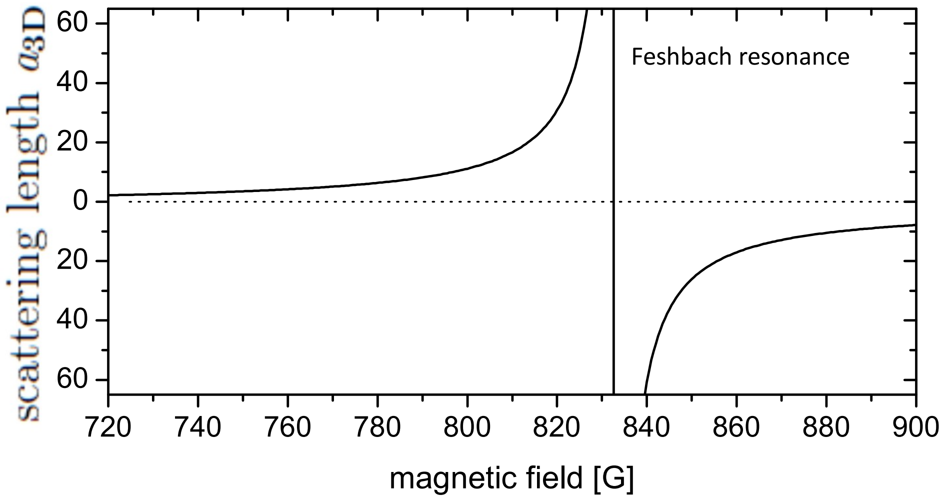

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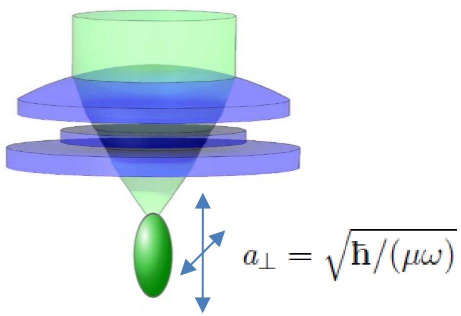
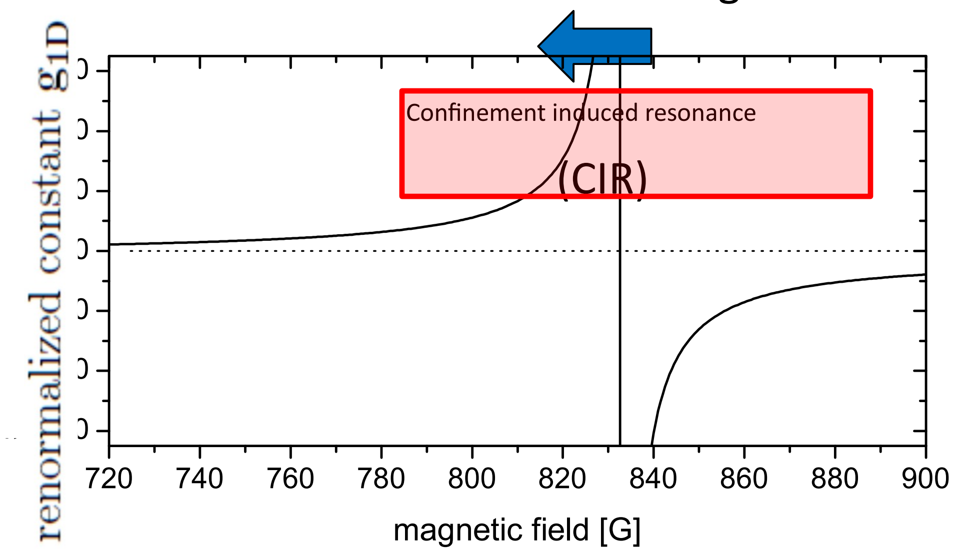


strong confinement

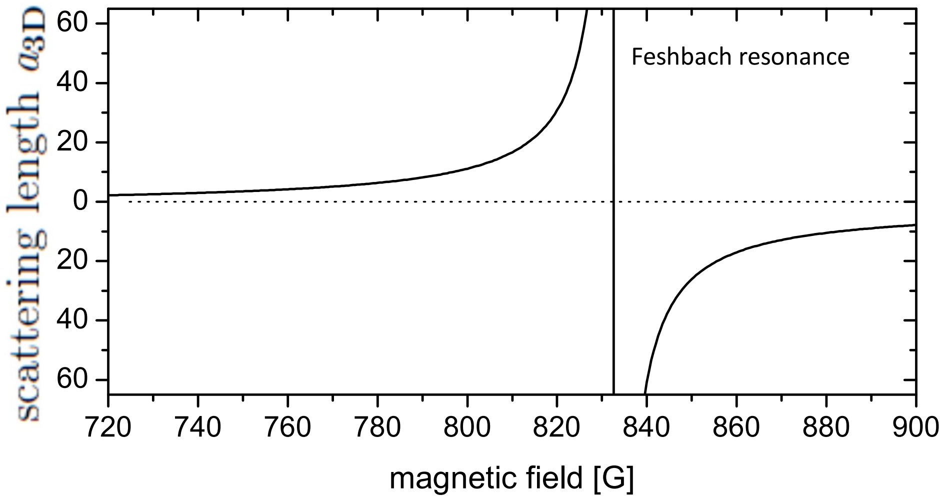
1D



Quantum simulations: why cold atoms ?

control over: interaction

3D



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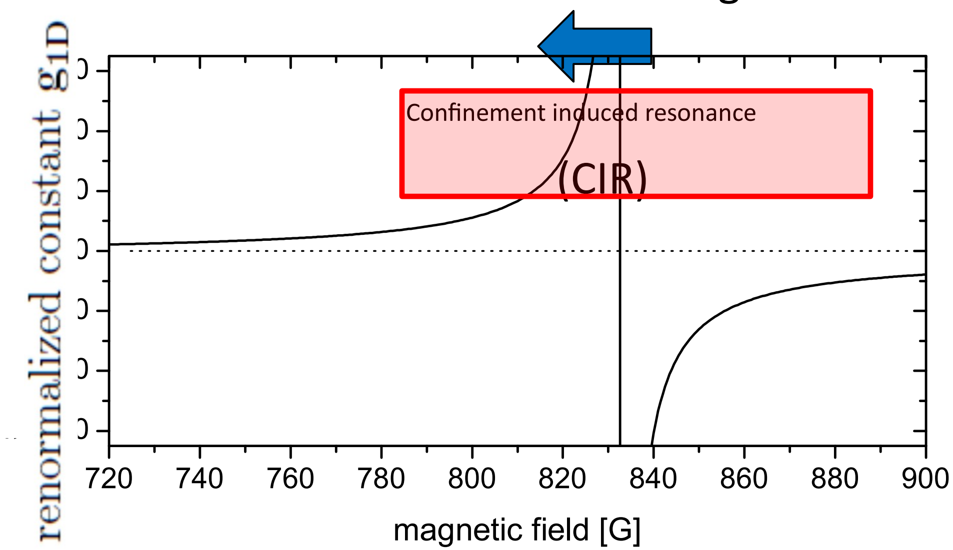
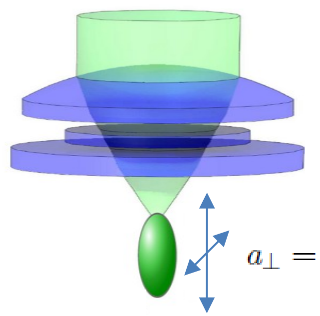
strong confinement

1D





$$a_\perp = \sqrt{\hbar/(\mu\omega)}$$

single-channel pseudopotential with renormalized interaction constant

$$g_{1D} = \frac{2\hbar^2 a_{3D}(B)}{\mu a_\perp} \frac{1}{(a_\perp - C a_{3D}(B))}$$

M. Olshanii, PRL 81, 938 (1998).

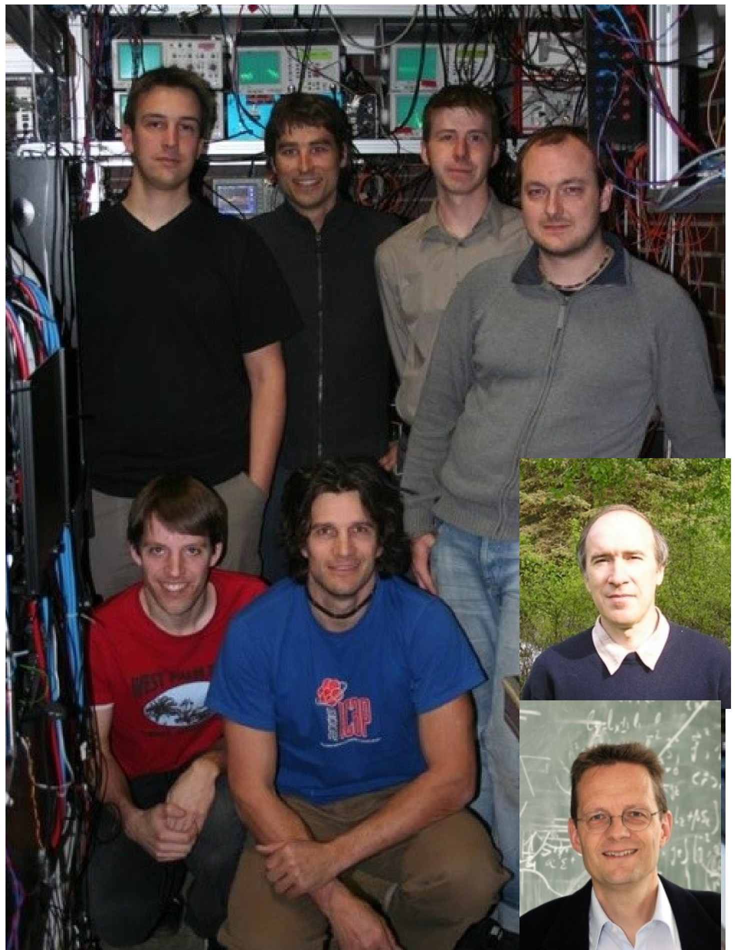
PRL **104,** 153203 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

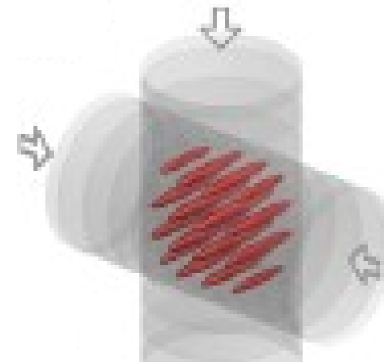
Confinement-Induced Resonances in Low-Dimensional Quantum Systems

Elmar Haller,[1] Manfred J. Mark,[1] Russell Hart,[1] Johann G. Danzl,[1] Lukas Reichsöllner,[1] Vladimir Melezhik,[2] Peter Schmelcher,[3] and Hanns-Christoph Nägerl[1]

[1]*Institut für Experimentalphysik and Zentrum für Quantenphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria*
[2]*Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, Dubna, 141980 Dubna, Russia*
[3]*Zentrum für Optische Quantentechnologien, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
(Received 19 February 2010; published 14 April 2010)

Elmar Haller –> Outstanding Doctoral Thesis in AMO Physics Recipients for 2011

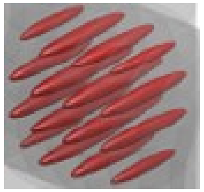


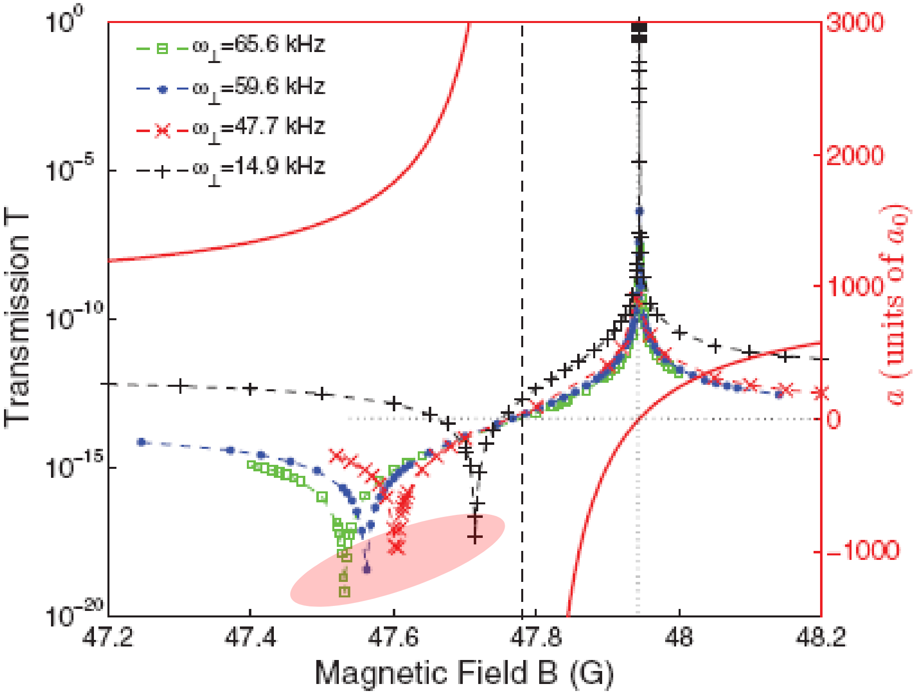


Shifts and widths of Feshbach resonances in atomic waveguides

Sh.Saeidian, V.S. Melezhik ,and P.Schmelcher, Phys.Rev. A86, 062713 (2012)

$$a_\perp = \sqrt{\hbar/(m\omega_\perp)}$$





d-wave FR at 47.8G develops in waveguide as depending on $\omega_\perp$minimums and stable maximum of transmission coefficient T

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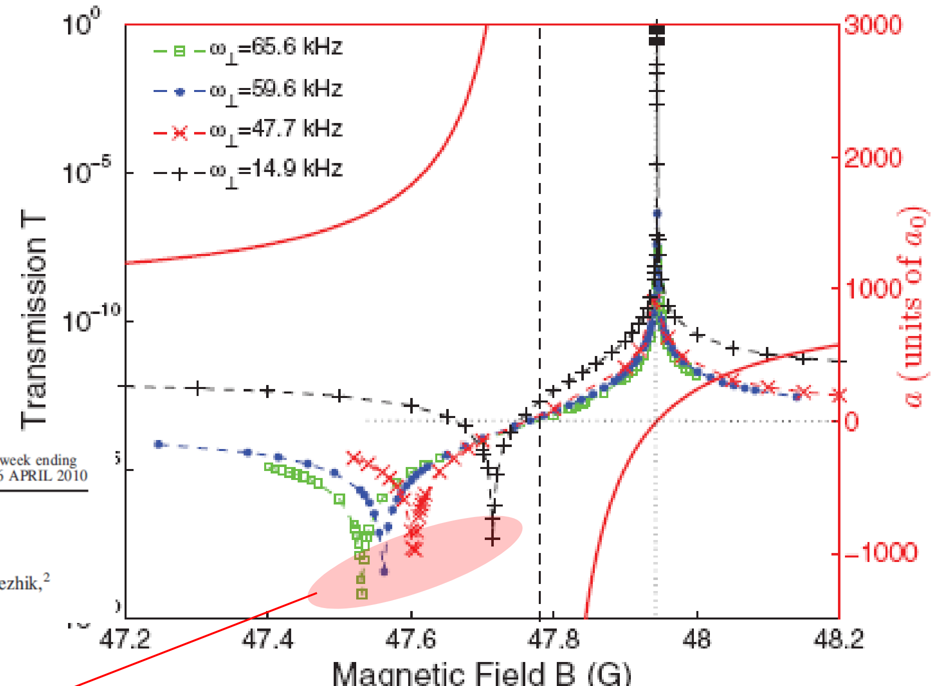

PRL 104, 153203 (2010) PHYSICAL REVIEW LETTERS week ending 16 APRIL 2010

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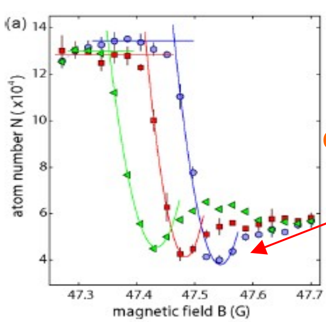

experiment

Shifts and widths of Feshbach resonances in atomic waveguides

Sh.Saeidian, V.S. Melezhik ,and P.Schmelcher, Phys.Rev. A86, 062713 (2012)

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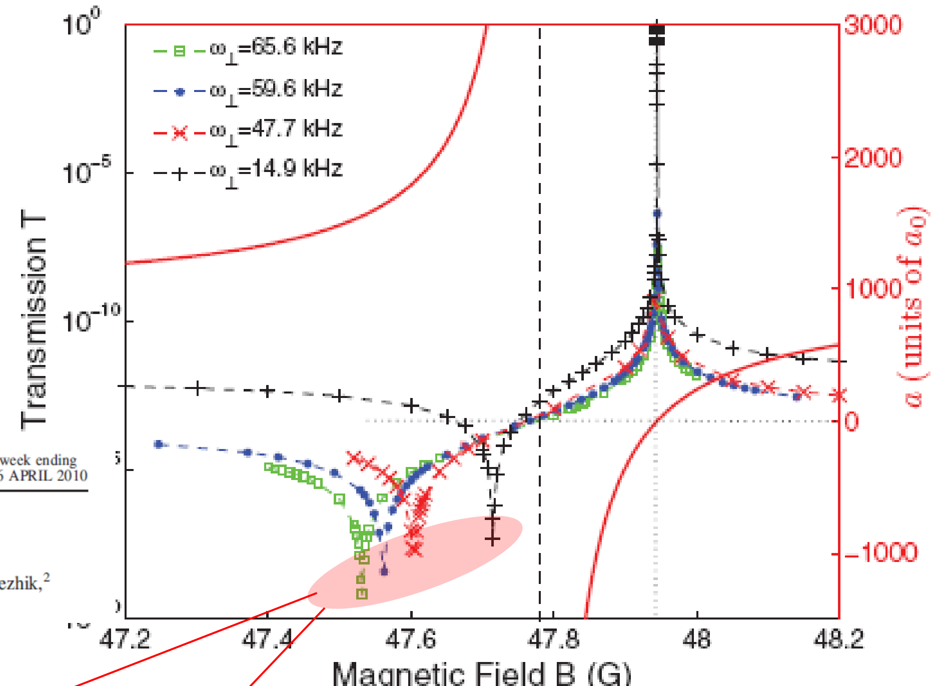

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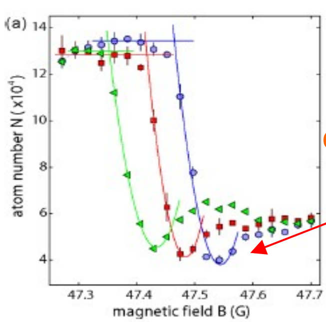
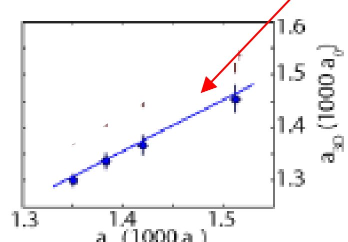


experiment

theory



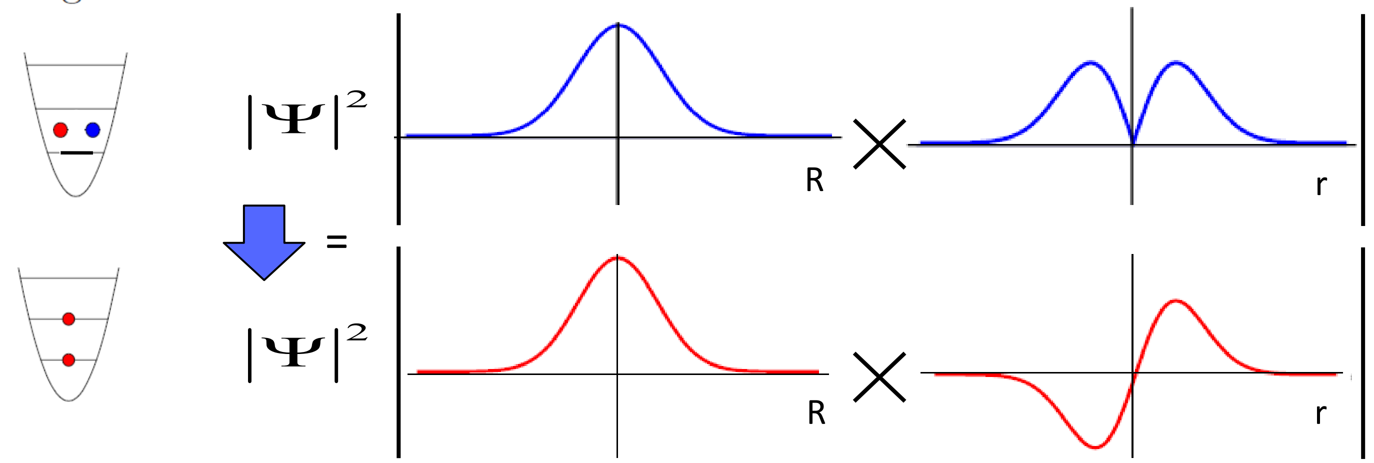
Olshanii formula works for s,d,and g FRs

$$a = 0.68 a_{\perp}$$

Quantum simulations: why cold atoms ?

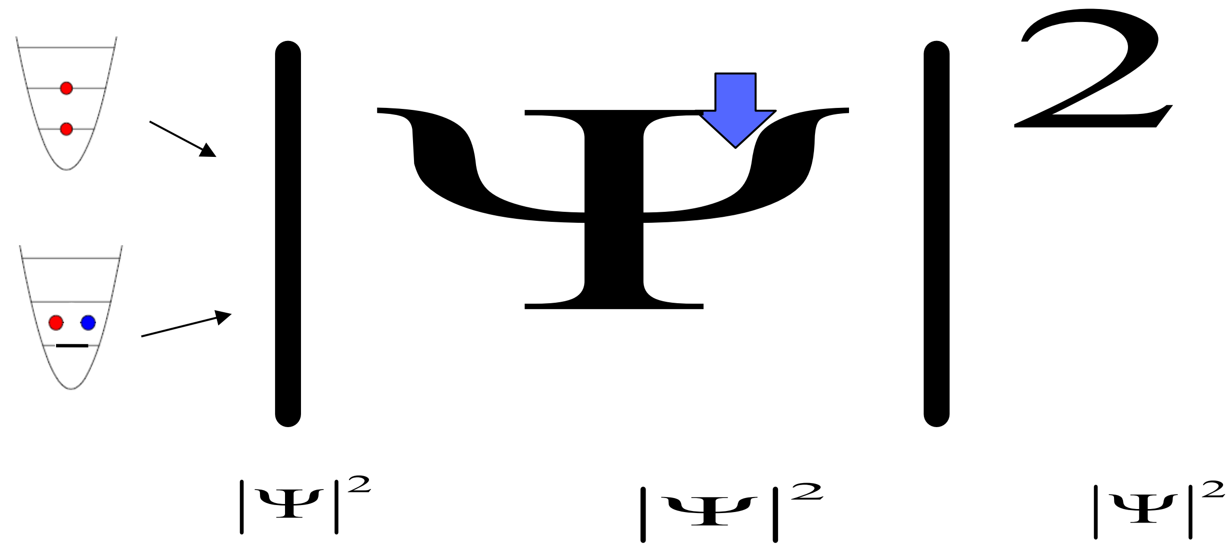
control over: quantum state

distinguishable fermions behave as identical ones at $g_{1D} \rightarrow \pm\infty$



M.D. Girardeau, PRA 82, 011607(R) (2010)

in 1D: same ⟷ same energy



analytic solution for energy:

T. Busch et al., Found Phys Vol.28, No.4 549-559 (1998)

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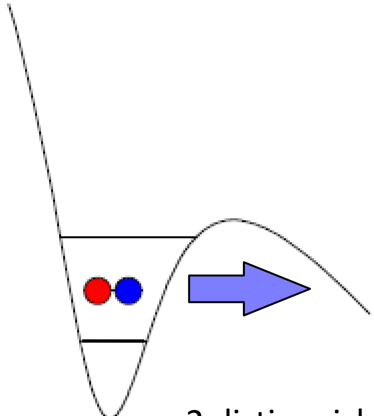
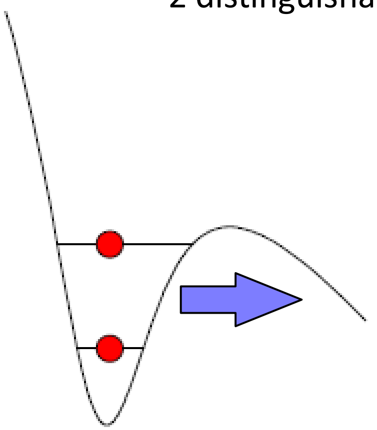


2 distinguishable fermions



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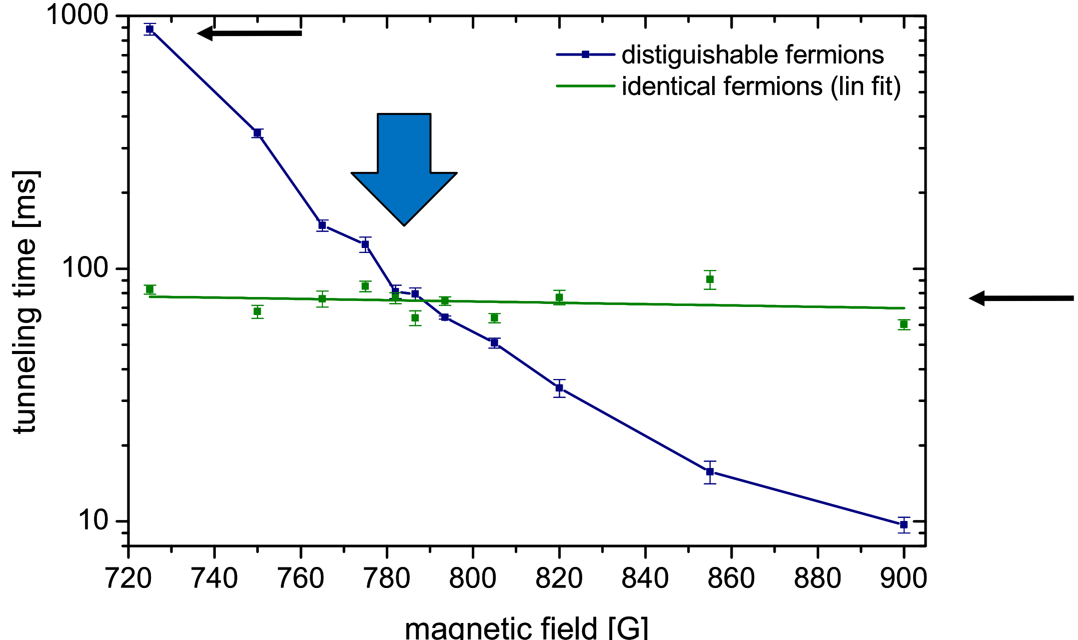
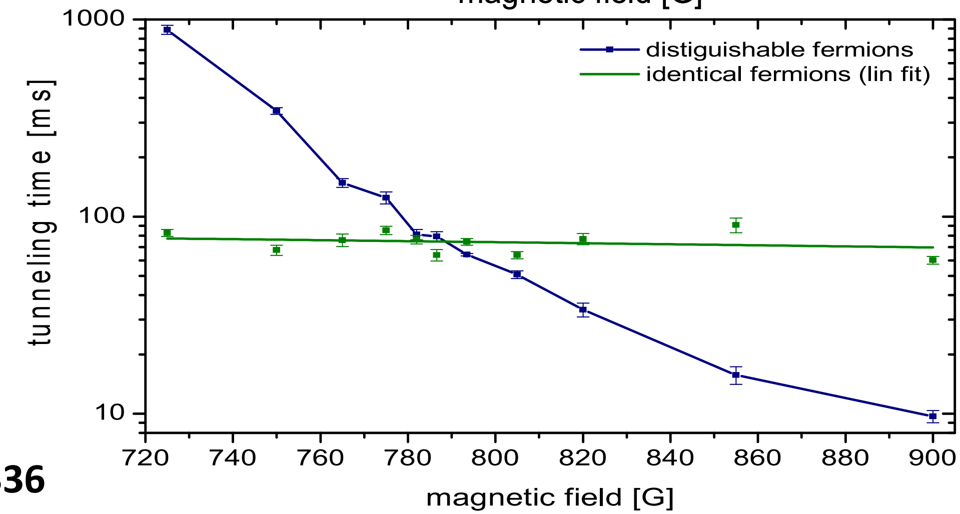
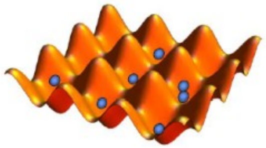




F.Serwane et al. Science 332(2011)336

Solid state physics: modeling phase-transitions

The ultra-cold atom simulator



Atoms ↔ Electrons

Optical lattice ↔ Ionic Crystal

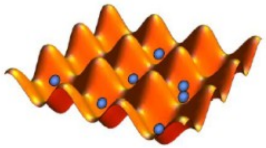
Optical Lattices	Solid state crystals
• Fully controllable, no defects, no vibrations	• Very complex condensed matter environment
• Lattice spacing micrometers	• Lattice spacing Angstroms
• Trapped atom mass ~ 10-100 amu	• Electron mass 1/1900 amu
• Temperature : T~1 nK	• Temperature : T~ 100 K

Solid state physics: modeling phase-transitions

Bose-Hubbard Hamiltonian

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

The ultra-cold atom simulator



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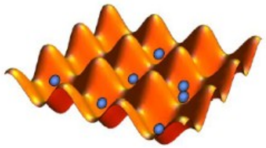
Tunnelmatrix element/Hopping element

$$J = -\int d^3x\, w(\mathbf{x}-\mathbf{x}_i)\left(-\frac{\hbar^2}{2m}\Delta + V_{lat}(\mathbf{x})\right) w(\mathbf{x}-\mathbf{x}_j)$$

Onsite interaction matrix element

$$U = \frac{4\pi\hbar^2 a}{m}\int d^3x\, |w(\mathbf{x})|^4$$

The ultra-cold atom simulator



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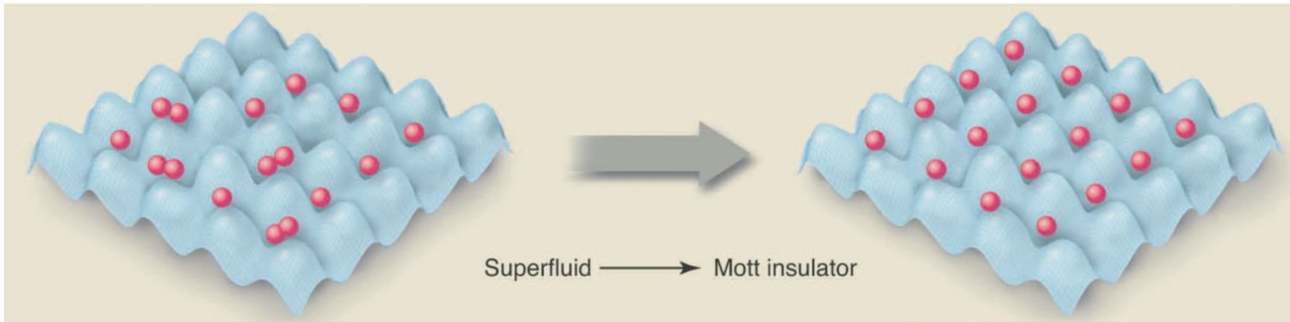
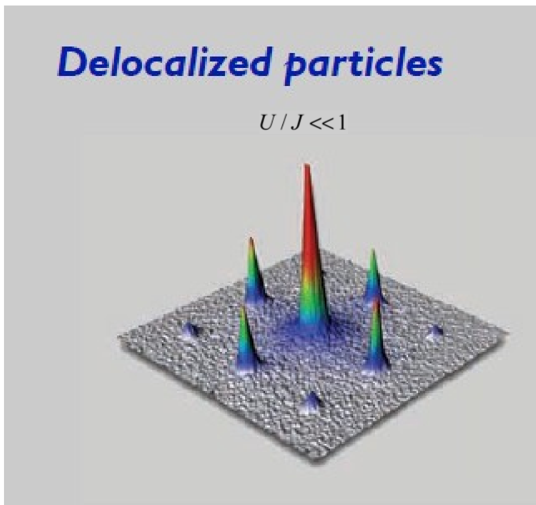
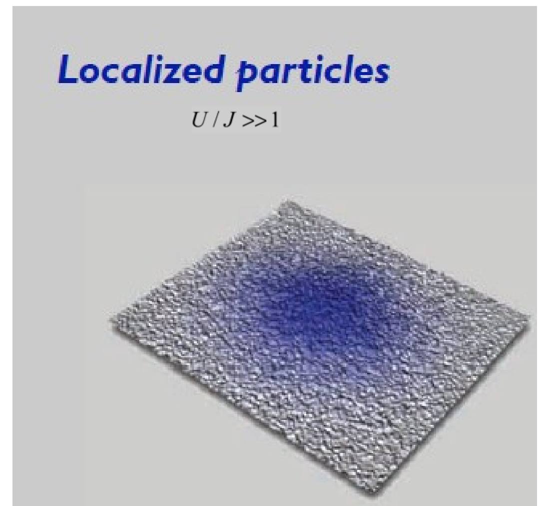






Phase coherence

$$H = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{n}_i + \frac{1}{2} U \sum_i \hat{n}_i (\hat{n}_i - 1)$$

Greiner, M., O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, 2002, Nature (London) **415**, 39.

Simulations with degenerate quantum gases

Gross-Pitaevski equation

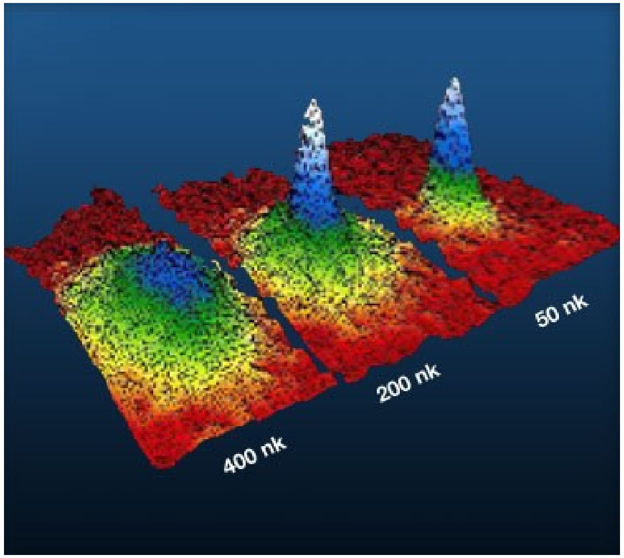
$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2\mu}\Delta\psi + U(\vec{r})\psi + g|\psi|^2\psi$$

kinetic energy — confining potential — interaction energy

Tunability of g and V

Bose-Einstein condensation

degenarate quantum gases

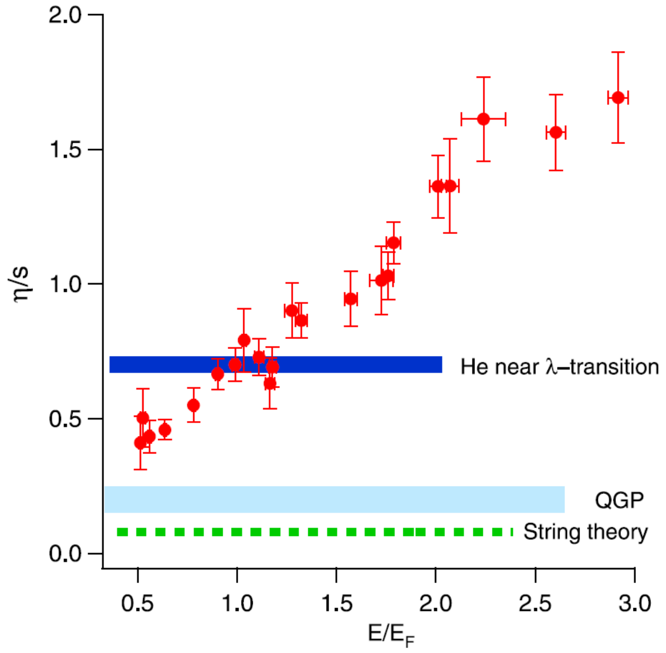


Modeling quark-gluon plasma, string theory

Optically-trapped, strongly-interacting atomic Fermi gases provide a unique possibility for modeling nonperturbative many-body systems and theories. Particularly → quark-gluon plasma, string theory

a highly-degenerate Fermi gas of spin-1/2 ^{6}Li atoms.

η/s = shear viscosity/ entropy density

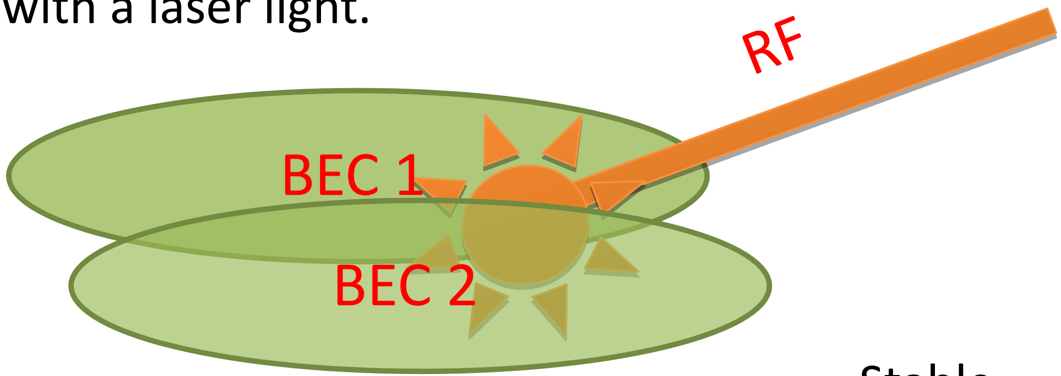


A. Turlapov, J. Kinast, B. Clancy, L. Luo, J. Joseph, J.E. Thomas,

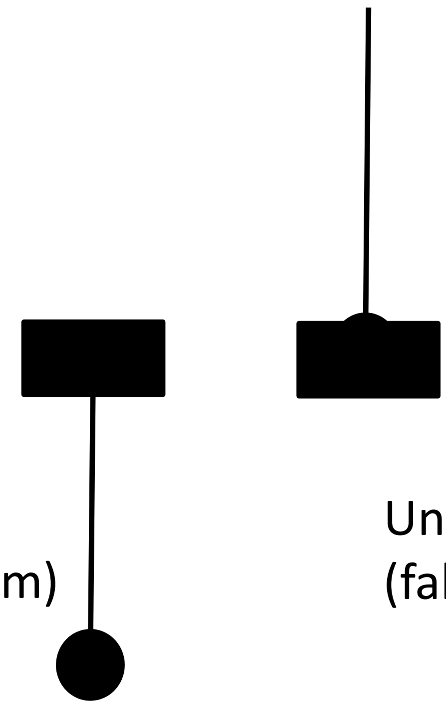
J Low Temp Phys 150 (2008) 567

Modeling unstable quantum vacuum

Take 2 BECs and couple them with a laser light.



$$\phi_1 - \phi_2 \approx \theta$$



Stable (true vacuum)

$\theta = 0$

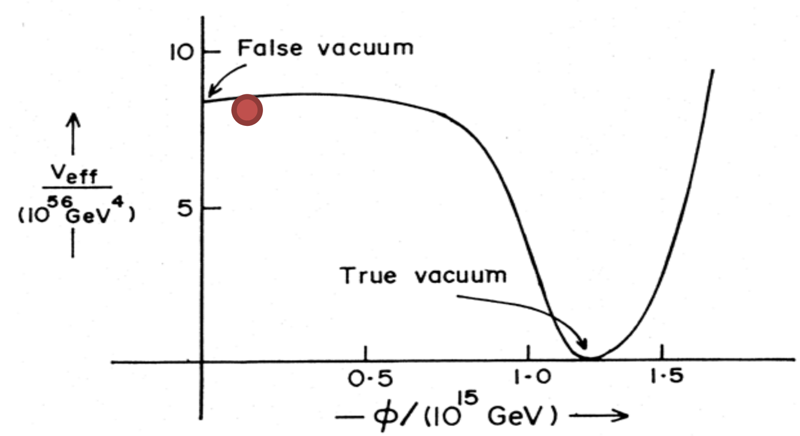
Unstable (false vacuum)

$\theta = \pi$

Their phase difference behaves like a pendulum, which has stable and unstable points.

$$\partial_t^2 \theta - c^2 \nabla^2 \theta = -\partial_\theta V(\theta)$$

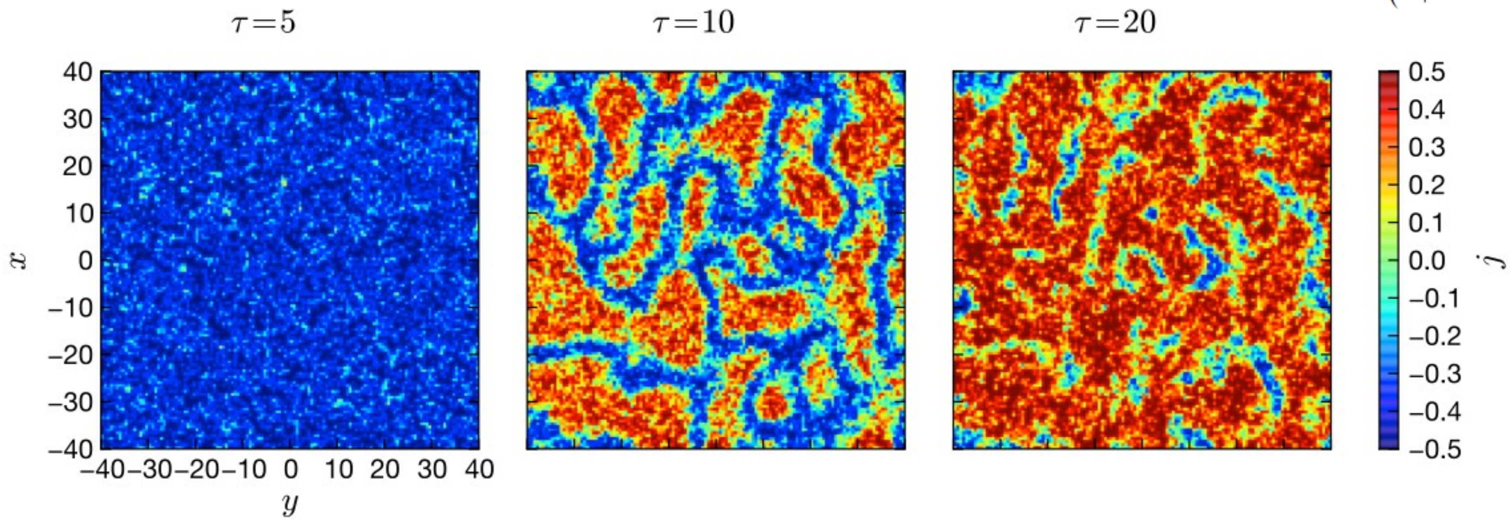
-- relativistic field equation of the early Universe.



Unstable quantum vacuum: BEC simulations

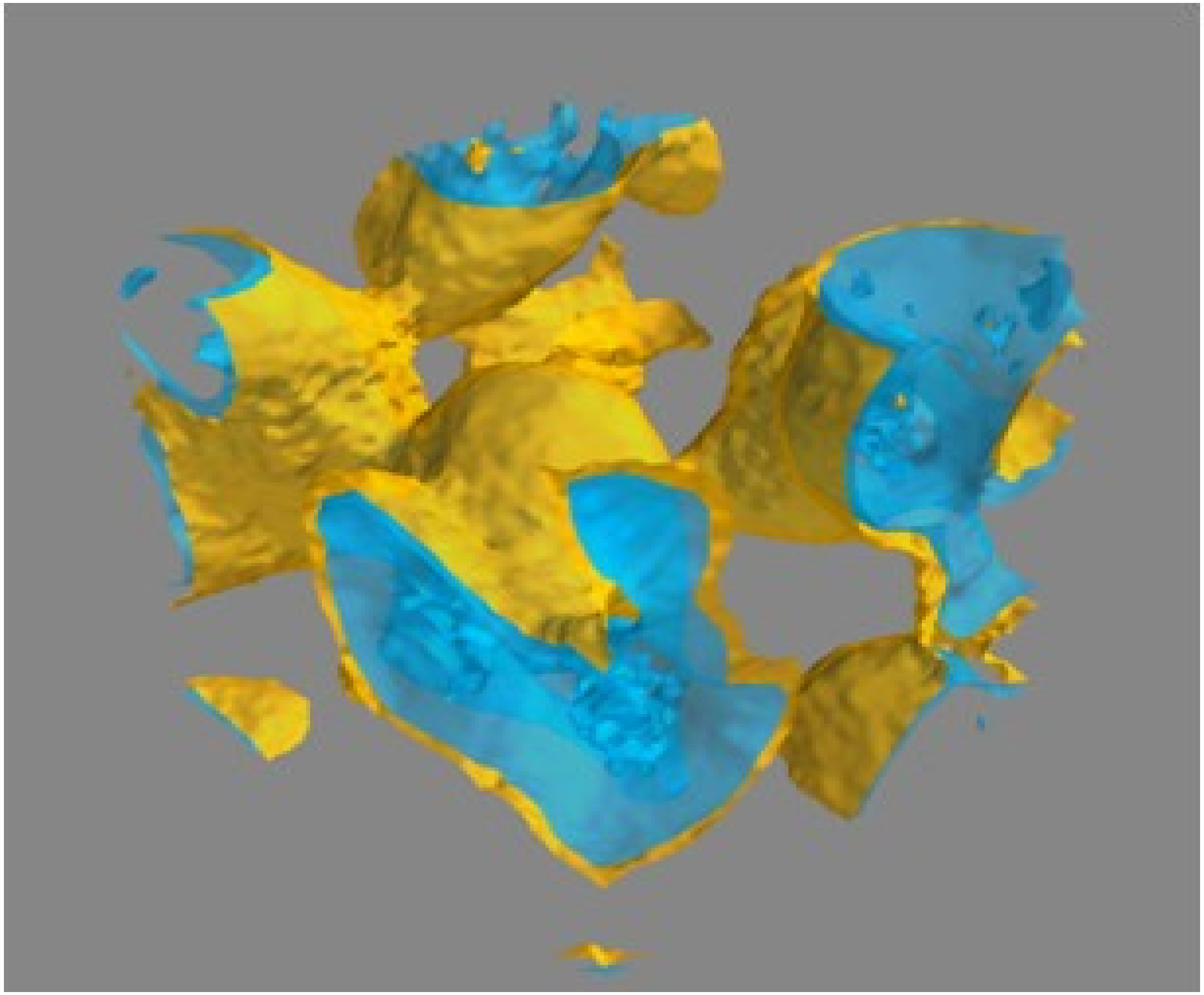
"Bubbles" appear during the transition to true vacuum

$$j = \frac{n_+ - n_-}{2\,(n_+ + n_-)} \approx \frac{1}{2}\cos\phi_a\,.$$



Plot of 3D density evolution.
Opanchuk et. al, Annalen der Physik **525**, 866 (2013).

3D bubbles



Opanchuk et al. Annalen der Physik 525 (2013) 866

Outlook, goals and opportunities

Quantum simulation with fully controlled systems

control over: particle number, quantum states, interaction

Fast-growing field, promising applications in study of many problems

I.M.Georgescu et al. Quantum simulations, Rev.Mod.Phys. 86 (2014) 153
J.I. Cirac and P.Zoller, Goals and opportunities in quantum simulation, Nature Phys. 8 (2012) 264
M.Dalmonte and S.Montangero, Lattice gauge theories simulations…,arXiv:1602.03776

~ few tens experimental groups worldwide

Rb,Cs,K,Sr,Li … Rb_2, Cs_2, RbK …　　1D, 2D, 3D

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recently -> hybrid "atom-ion" systems Li-Yb+, Rb-Ba+ …

10 Crossover from a molecular Bose-Einstein condensate to a degenerate Fermi gas / M. Bartenstein, A. Altmeyer, S. Riedl, S. Jochim, C. Chin, J. Hecker Denschlag, R. Grimm // *Phys. Rev. Lett.* 2004, Mar. Vol. 92, no. 12. P. 120401. 1

11 Mechanical stability of a strongly interacting Fermi gas of atoms / M. E. Gehm, S. L. Hemmer, S. R. Granade, K. M. O'Hara, J. E. Thomas // *Phys. Rev. A*. 2003, Jul. Vol. 68, no. 1. P. 011401(R). 1

12 Evidence for superfluidity in a resonantly interacting Fermi gas / J. Kinast, S. L. Hemmer, M. E. Gehm, A. Turlapov, J. E. Thomas // *Phys. Rev. Lett.* 2004, Apr. Vol. 92, no. 15. P. 150402. 1

in proposed quantum simulators improved controllability and scalability are required.