New States of Quantum Matter

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Recent Progress in Many-Body Theories 14

Barcelona

17 July 2007v

New states of quantum matter created in the past decade

From:

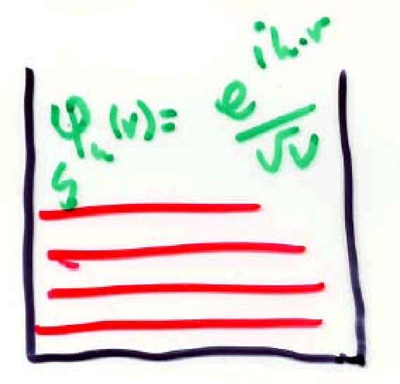
Trapped cold atomic systems:
Bose-condensed and BCS fermion superfluid states
T ~ nanokelvin (traps are the coldest places in the universe!)

To:

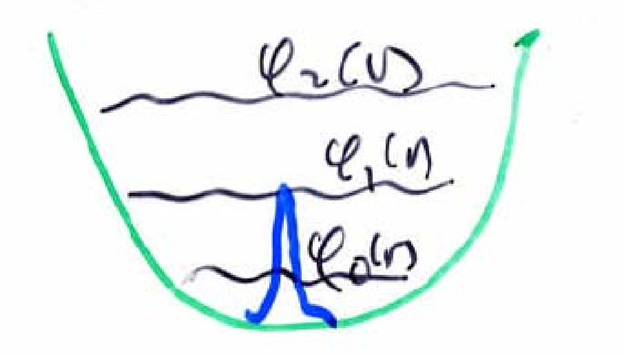
Deconfined quark-gluon plasmas
made in ultrarelativistic heavy ion collisions
T ~ 10^2 MeV ~ 10^{12} K (temperature of early universe at ~1μ sec)

Separated by ~21 decades in characteristic energy scales, yet have intriguing overlaps.

Cold atoms: trapped bosons and fermions



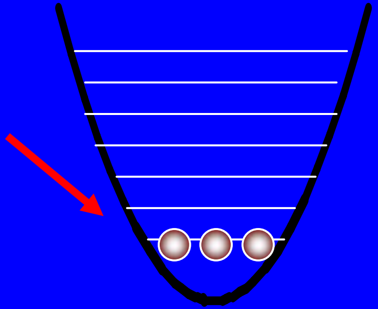
Box

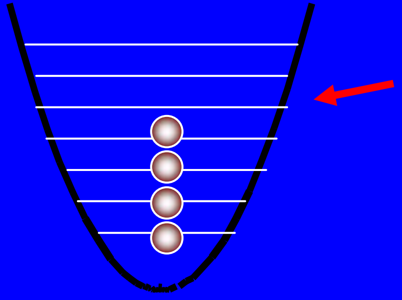


Potential well (trap)

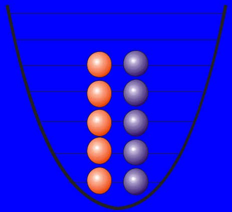
Statistics:

Bose condensate: macroscopic occupation of single mode (generally lowest)





Degenerate Fermi gas



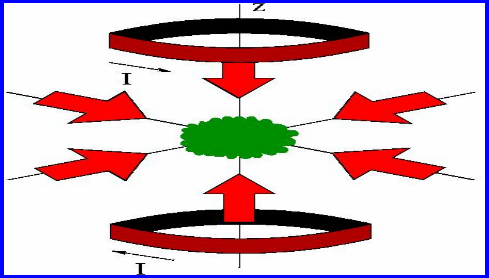
=> BCS pairing

Trapped atomic experiments in a nutshell

Warm atomic vapor

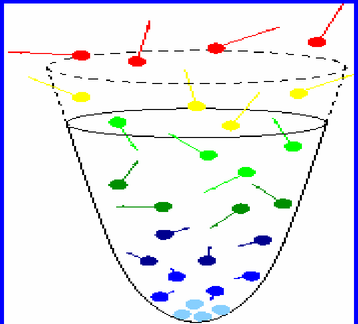
$T=300K$, $n\sim 3\times 10^6/cm^3$

Magneto-optical trap



Laser cool to $T \sim 50\mu K$
$n\sim 10^{11}/cm^3$

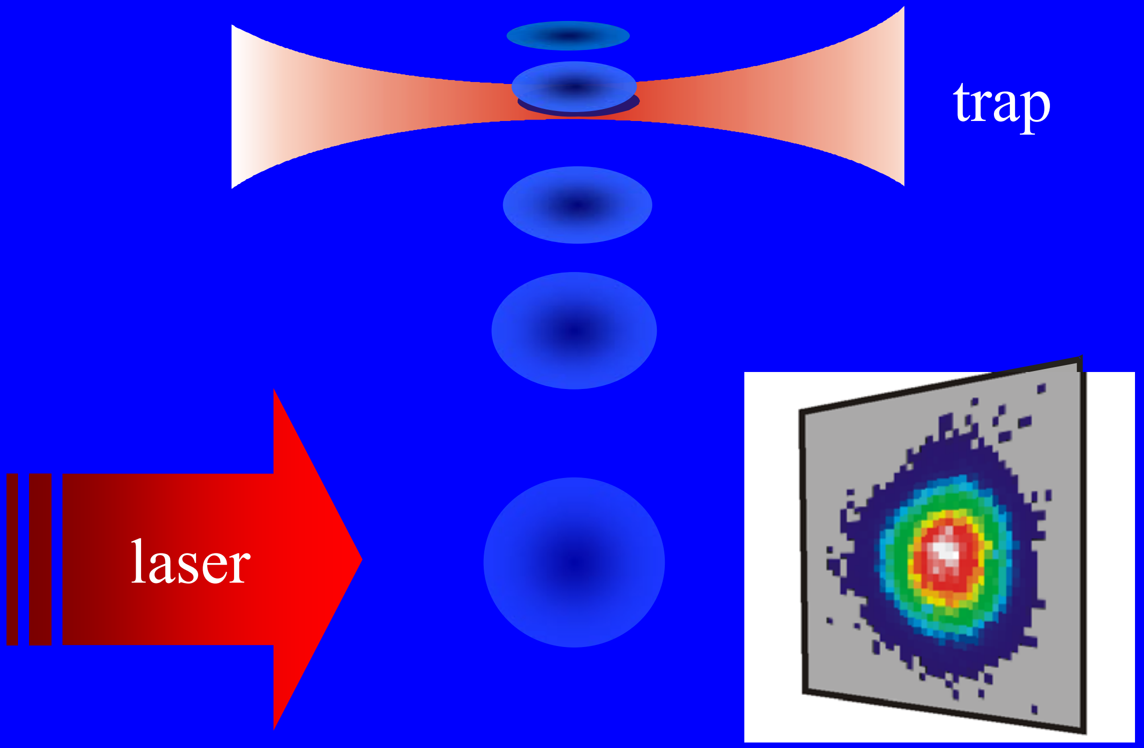
Evaporatively cool in magnetic (or optical) trap



Bosons condense,
Fermions BCS-pair
$T\sim 1\text{-}10^3$ nK
$n\sim 10^{14\text{-}15}/cm^3$
$N \sim 10^5\text{-}10^8$

Experiment, and then measure :

To probe system, release from trap, let expand and then image with laser:



Long-Lived Alkali Atoms

BOSONS (Spin, lifetime)
(Z-N=odd-even nuclei)

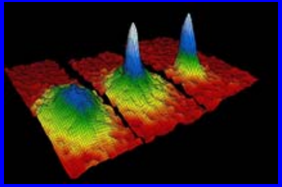
FERMIONS
(Z-N=odd-odd nuclei)

^{7}Li	3/2-		^{6}Li	1+	
^{23}Na	3/2-		^{22}Na	3+	2.6y
^{39}K	3/2+		^{40}K	4-	$1.3\text{x}10^{9}$y
^{41}K	3/2+				
^{85}Rb	5/2-		^{86}Rb	2-	18.6d
^{87}Rb	3/2-	$4.75\text{x}10^{10}$y			
^{131}Cs	5/2+	9.7d	^{132}Cs	2+	6.5d
^{133}Cs	7/2+				
^{135}Cs	7/2+	$2.3\text{x}10^{6}$y	^{134}Cs	4+	2.06y
^{209}Fr	9/2-	50.0s	^{208}Fr	7+	59.1s

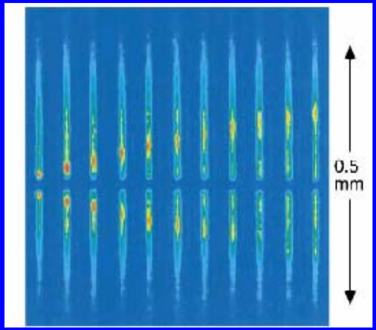
Early days of ultracold trapped atomic gases

$\geq$ 1995 = first Bose condensation of ^{87}Rb, ^{23}Na and ^{7}Li

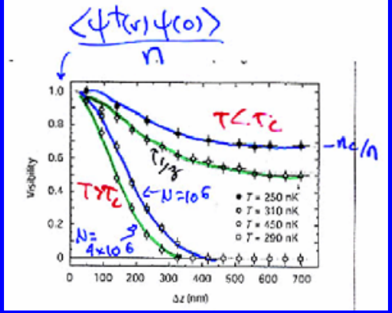
*Structure of condensate.



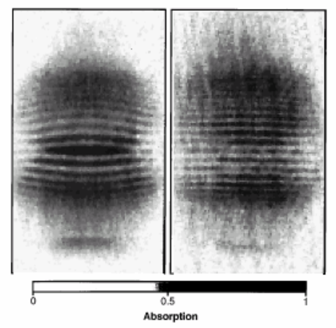
*Elementary modes: breathing, quadrupole, short wave sound, …



*1, 2 and 3 body correlations => evidence for BEC rather than simply condensation in space.



*Interference of condensates.



Primarily described in terms of mean field theory – Gross-Pitaevskii eq.

$$i\hbar\partial\, \psi(r,t)\, /\partial\, t = [-\hbar^2\nabla^2/2m + V(r) + g|\psi(r,t)|^2]\psi(r,t)$$

Recent directions in ultracold atomic systems, I

Strongly correlated systems

* Rapidly rotating bosons: how do many-particle Bose systems carry extreme amounts of angular momentum?

•Trapping and cooling clouds of fermionic atoms

Degenerate Fermi gases and molecular states
BCS pairing => new superfluid
Crossover from BEC of molecules to BCS paired state

* Physics in the strong interaction limit:

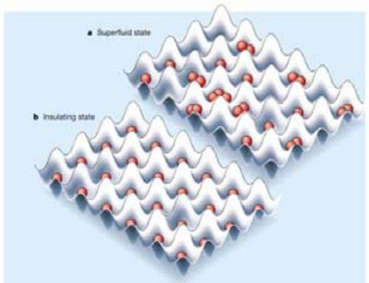
scale-free regime where $r_0 \ll n^{-1/3} \lesssim a$

r_0 = range of interatomic potential ~ few Å
n = particle density
a = s-wave scattering length

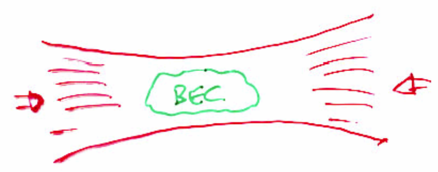
Realize through atomic Feshbach resonances

Recent directions in ultracold atomic systems, II

Novel systems



*Physics in optical lattices: Mott transition from superfluid to insulating states;
low dimensional systems; 2D superfluids



* Spinor gases: trapped by laser fields.
  Physics of spin degrees of freedom
  Fragmented condensates

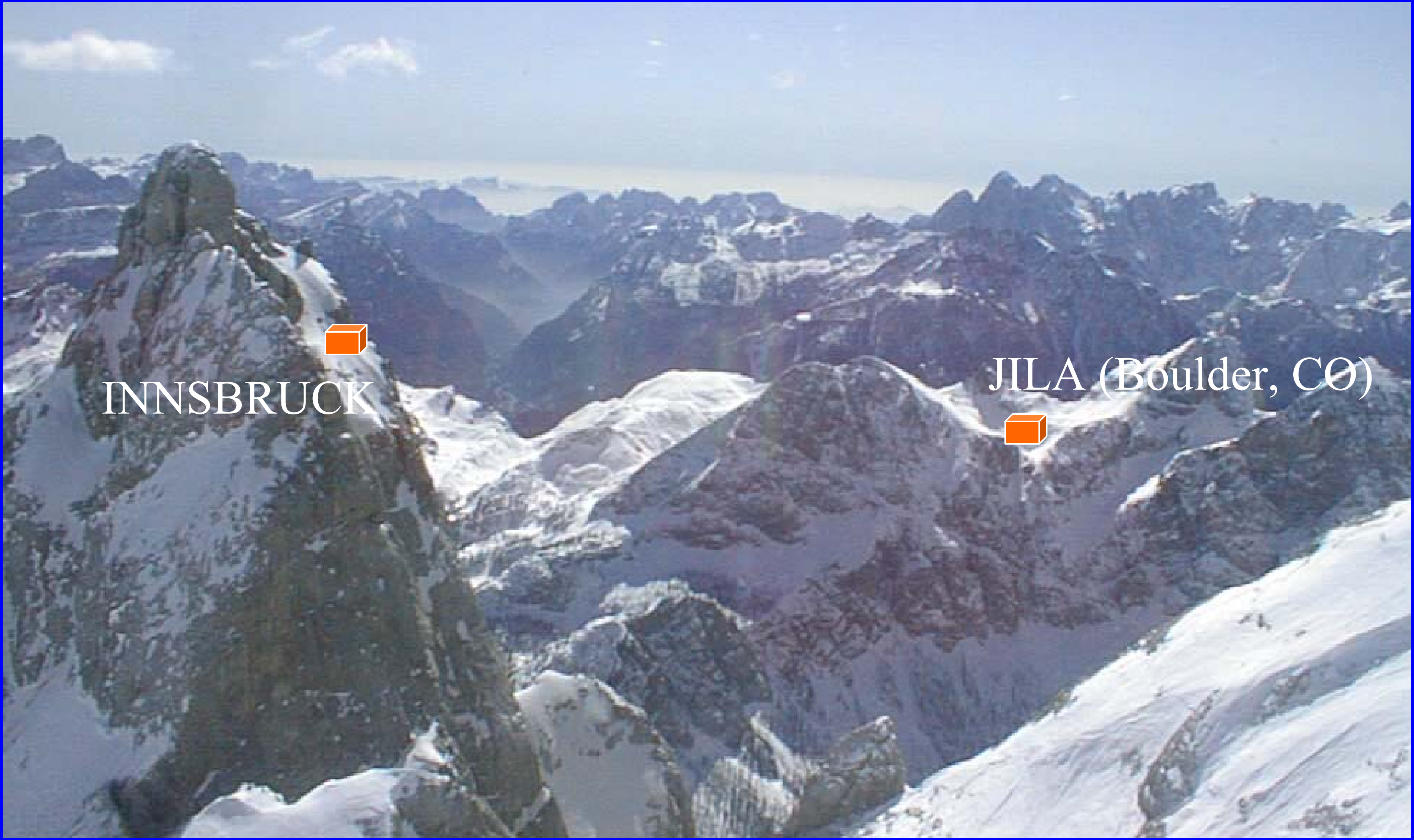
* Mixtures of bosons and fermions

* Ultracold molecules:
  coherent mixtures of atoms and molecules,
  e.g., ^{87}Rb atoms and ^{87}Rb$_2$ molecules;
  heteronuclear molecules: ^{6}Li+^{23}Na, ^{40}K+^{87}Rb

Future applications:

- Trapped ions for quantum computing
- Slow light
- Atom lithography
- Matter lasers

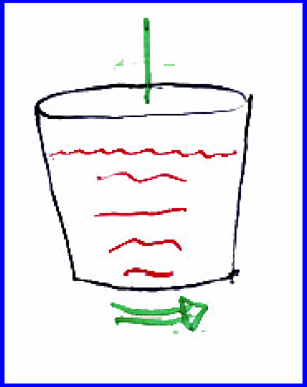
Laboratories for ultracold physics appropriately situated



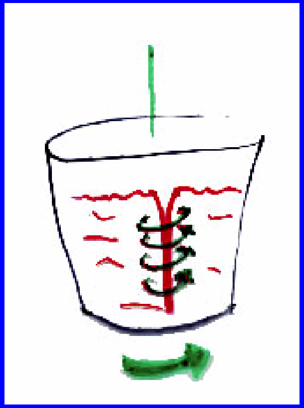
Vortices in trapped atomic clouds

Illinois, every spring

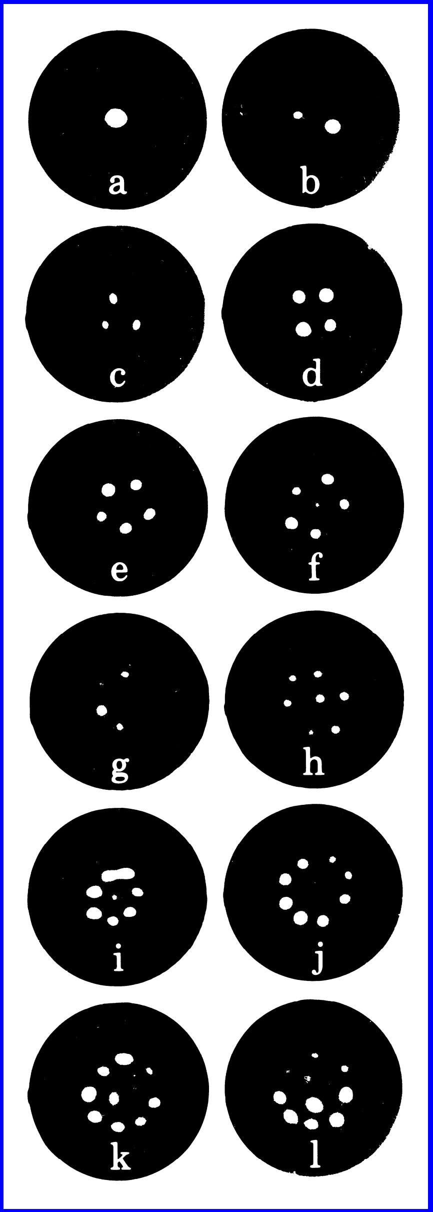
Vortices in superfluids



Spin container of superfluid (e.g., helium) slowly.
Liquid remains at rest



Spin fast enough.
Form vortex in center of liquid!



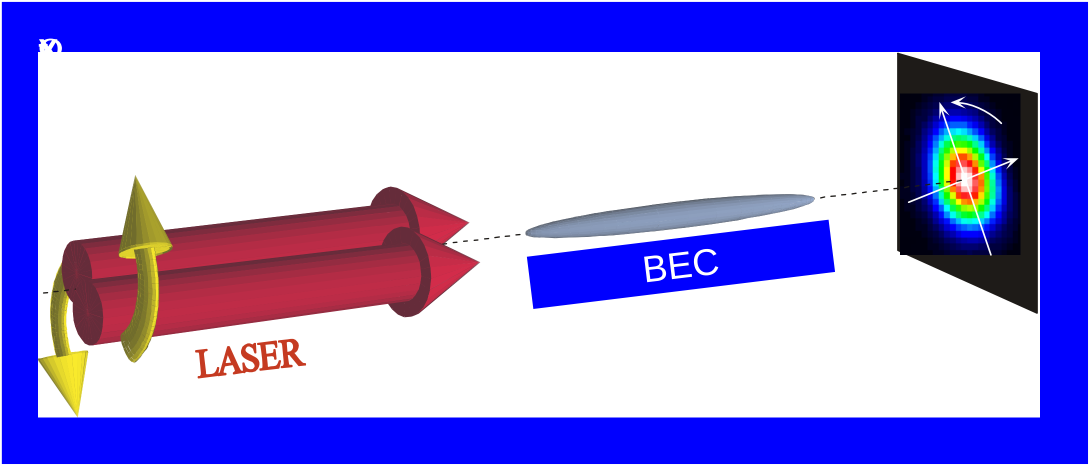
Superfluid ^{4}He viewed along rotation axis. Imaged by trapping electrons in cores

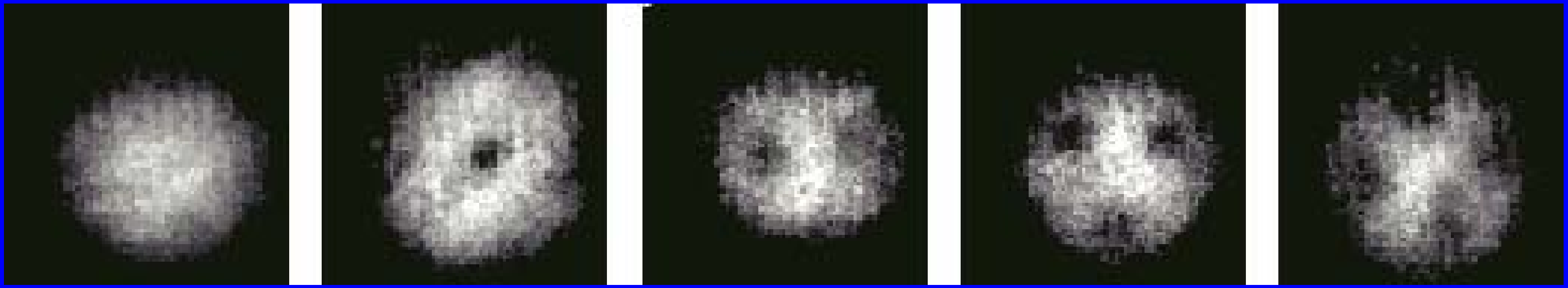
Yarmchuk, Gordon, & Packard, PRL43, 214 (1979)

Making vortices in Bose-Einstein condensates

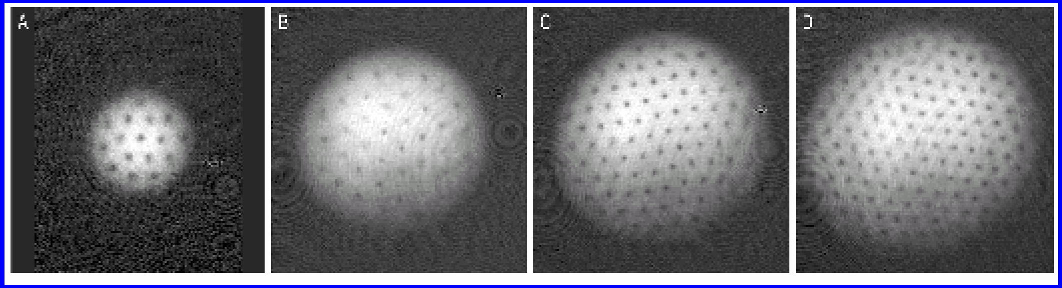
Bose condensed ^{87}Rb *(ENS)*

K. W. Madison, F. Chevy, W. Wohlleben, J. Dalibard 1999

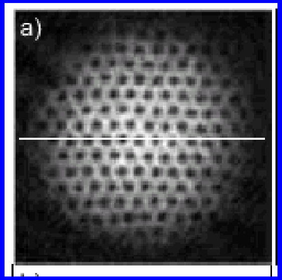




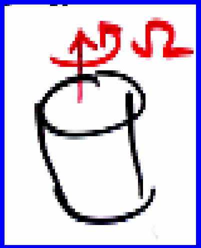
Rapidly rotating superfluid contains triangular lattice of vortices



Abo-Shaeer et al.
(MIT) 2001



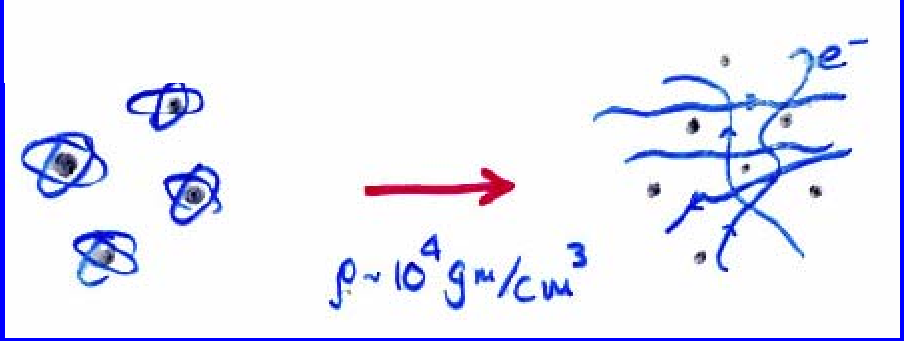
Engels et al.
(JILA) 2002



As Ω grows in harmonic trap, vortex lattice melts, and go through a sequence of new highly correlated states with large angular momentum, $L/N \sim (10^2 - N)\hbar$ not yet reached experimentally.

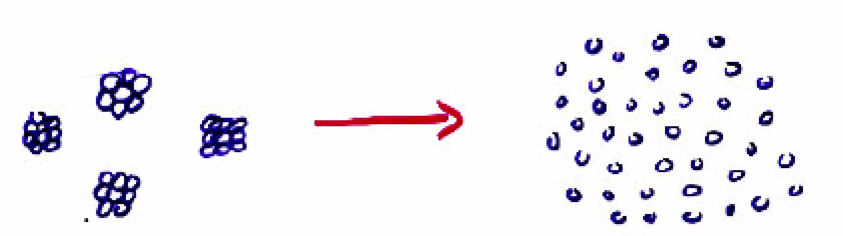
Compress matter to form new states

Atoms



Plasma

Nuclei

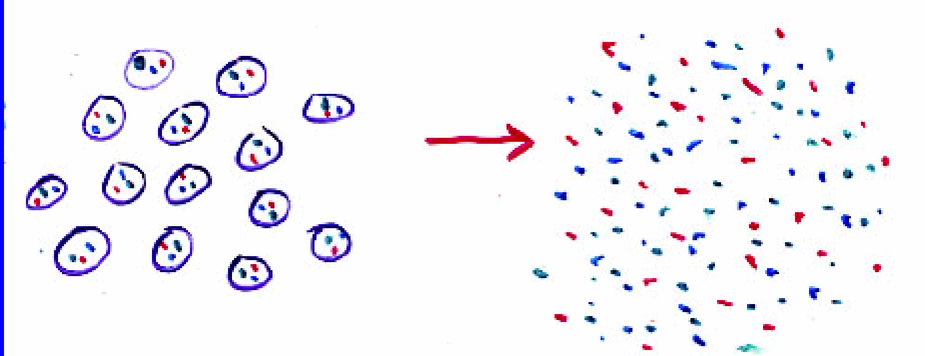


Nuclear matter

$\rho \sim 2.5\text{x}10^{14}\text{gm/cm}^3 = \rho_{nm} = 0.17$ baryons/fm^3

(1 fm = 10^{-13} cm)

Nucleons



Quark matter

Quark degrees of freedom

Quarks = fractionally charged spin-1/2 fermions, baryon no. = 1/3, with internal SU(3) color degree of freedom. { $\bar{3}$ repr. of SU(3)}

Flavor	Charge/|e|	Mass(MeV)
u	2/3	5 *(2.1-3.5)**
d	-1/3	10 *(2.1-3.5)**
s	-1/3	150 *(54-92)**
c	2/3	1300
b	-1/3	4200
t	2/3	175000

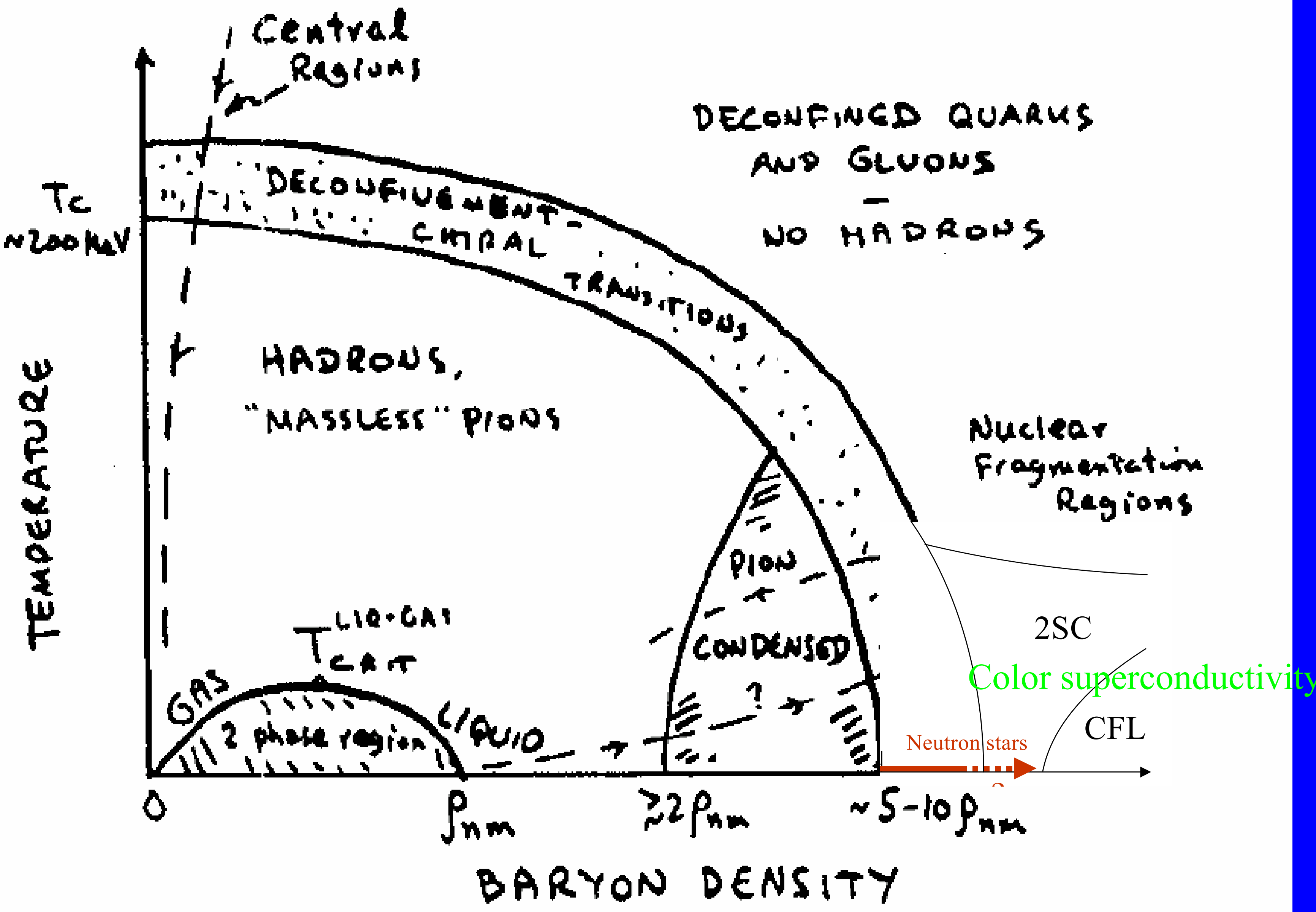
**Lattice gauge theory calculations, Gough et al., PRL 79, 1622 (1997)*

Hadrons are composed of quarks:
proton = u + u + d
neutron = u + d + d
$\pi^+ = u + \bar{d}$, etc.

Form of baryons in the early universe at t < 1μ sec (T > 100 MeV).

Possible basic degrees of freedom in deep interiors of neutron stars.

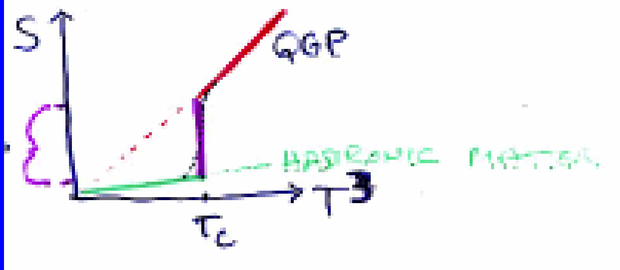
PHASE DIAGRAM OF NUCLEAR MATTER



Quark-gluon plasma state

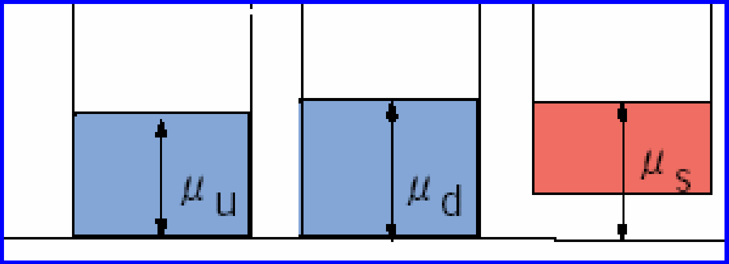
Degrees of freedom are deconfined quarks and gluons

Many more degrees of freedom than hadronic matter (color, spin, particle-antiparticle, & flavor); much larger entropy at given temperature.



<= Large latent heat
(or sharp rise at least)

At low temperatures form Fermi seas of degenerate u,d, and s quarks:
(e.g., in neutron stars?)



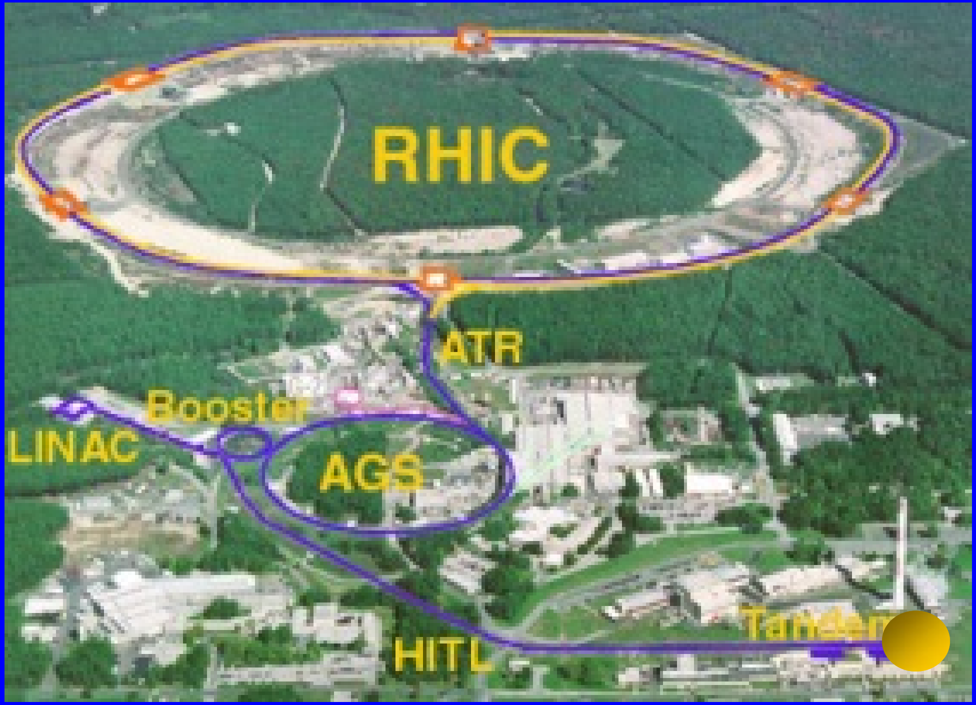
核子重如牛
對撞生新態

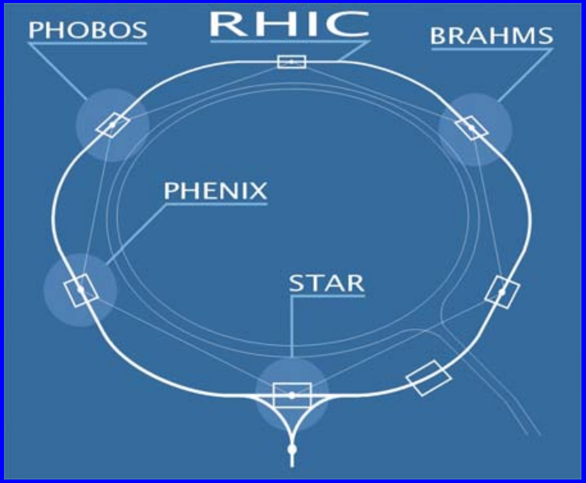
Nuclei as heavy as bulls
Through collision
Generate new states of matter

T.D. Lee

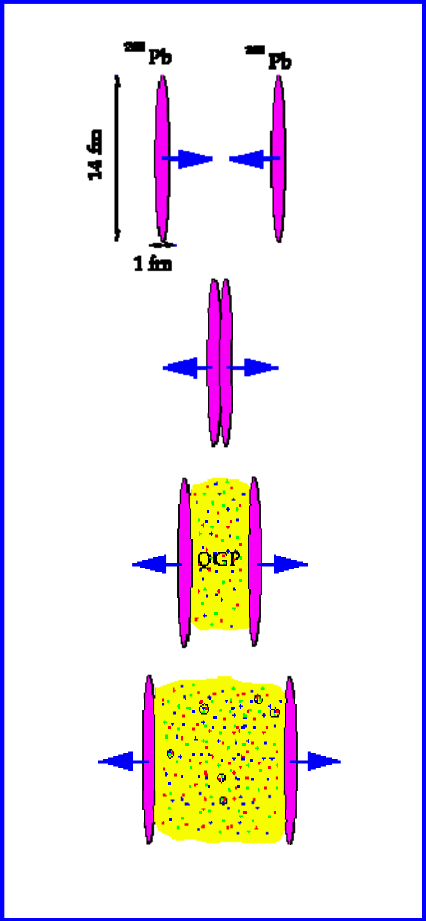
Creating high energy density matter in the lab

Relativistic Heavy Ion Collider (Brookhaven) since 2000. Colliding beams 100 GeV/A
Large Hadron Collider (CERN) in 2008. 2700 GeV/A

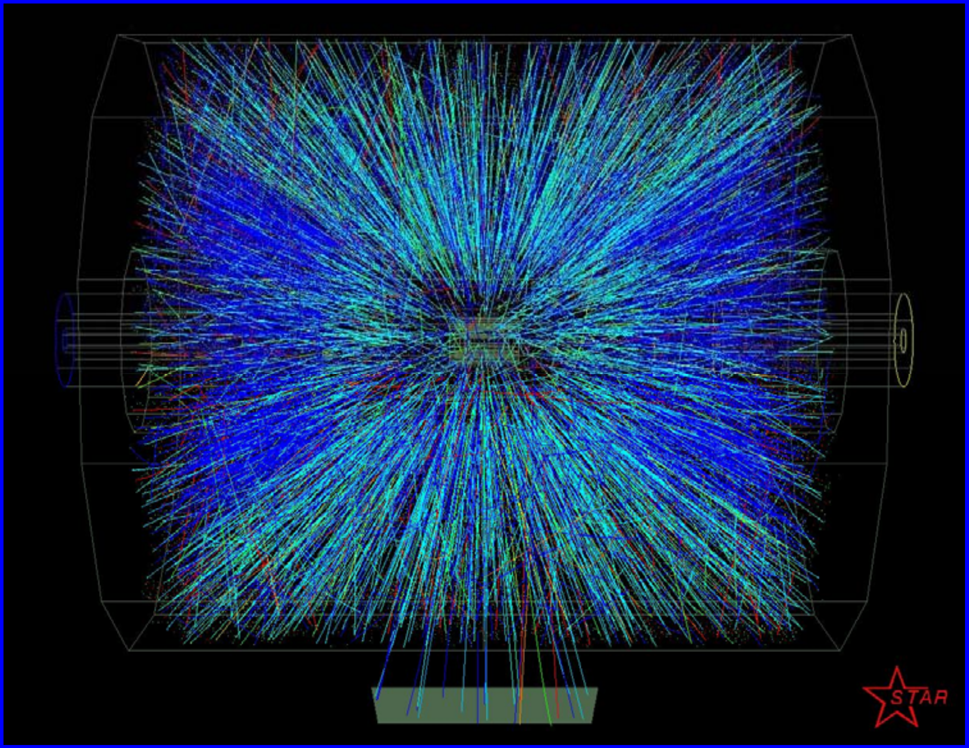




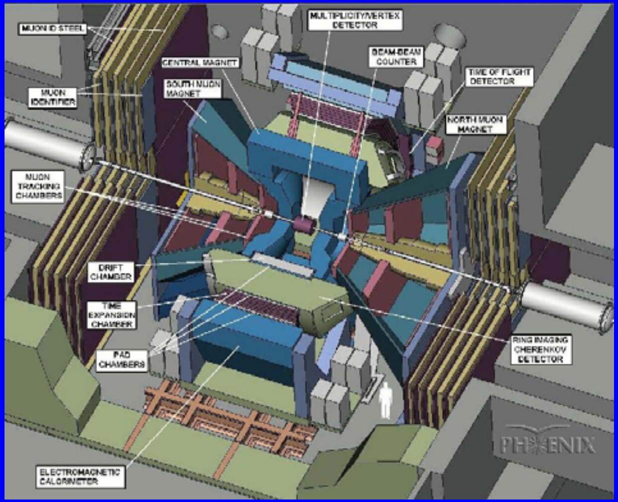
100 GeV per nucleon
Au(197 × 100) + Au(197 × 100)



Schematic collision:
Two Lorentz contracted nuclei collide, pass through each other, leaving highly excited state of vacuum in between.



What collisions actually look like in the lab. STAR detector



Two major detectors at RHIC

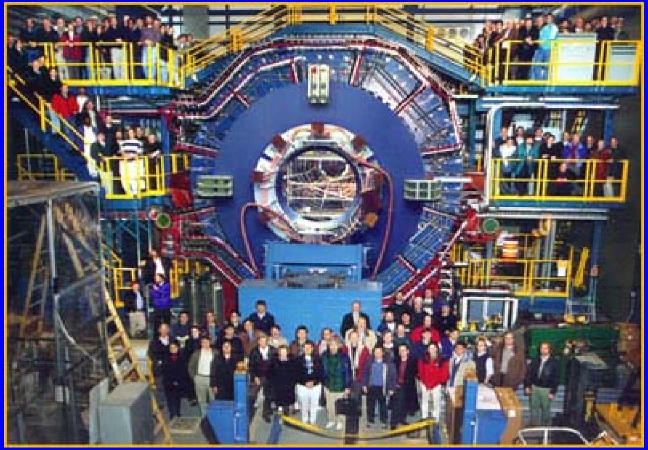
PHENIX

STAR

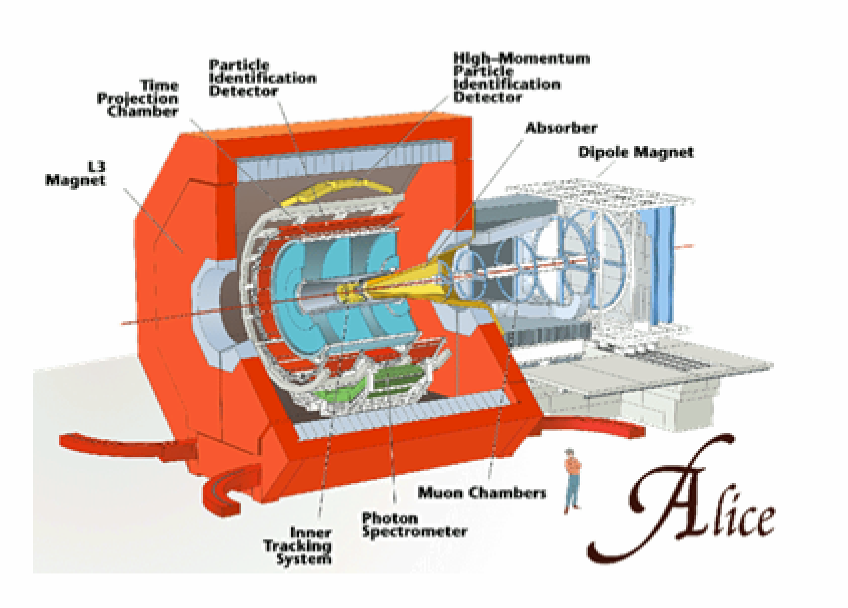
Two smaller detectors

BRAHMS

PHOBOS



ALICE detector at LHC



A few crucial observations at RHIC:

Produce matter with energy densities $\sim$ 5 GeV/fm^3

$\sim$ 10-30 $\times$ energy density of ordinary nuclei $\sim$ 0.15 GeV/fm^3

Certainly produce quark-gluon plasma.

Fast quarks traversing medium lose energy rapidly. “Opaque” medium

Very rapid build-up of pressure in collisions:
Large collective flow, fast thermalization, large interaction cross sections.

Hydrodynamics => small viscosity

Common problems of cold atom physics and RHIC physics:

Small clouds with many degrees of freedom $\sim 10^4 - 10^7$

Strongly interacting systems

Infrared (long wavelength) problems in qcd and condensed bosons.

Recent connections:

Crossover: BEC ⇔ BCS and hadron ⇔ quark-gluon plasma

Viscosity: heavy-ion elliptic flow ⇔ Fermi gases near unitarity

Superfluidity and pairing in unbalanced systems:
trapped fermions ⇔ color superconductivity

Ultracold ionized atomic plasma physics

Strong interactions

In quark-gluon plasma,

$$\alpha_s(p) = \frac{g_s^2}{4\pi} = \frac{6\pi}{(33 - 2N_f)\ln(p/\Lambda)}$$

$\Lambda \sim 150$ MeV

Even at GUT scale, 10^{15}GeV, $g_s \sim 1/2$

(cf. electrodynamics: $e^2/4\pi = 1/137 \Rightarrow e \sim 1/3$)

QGP is always strongly interacting

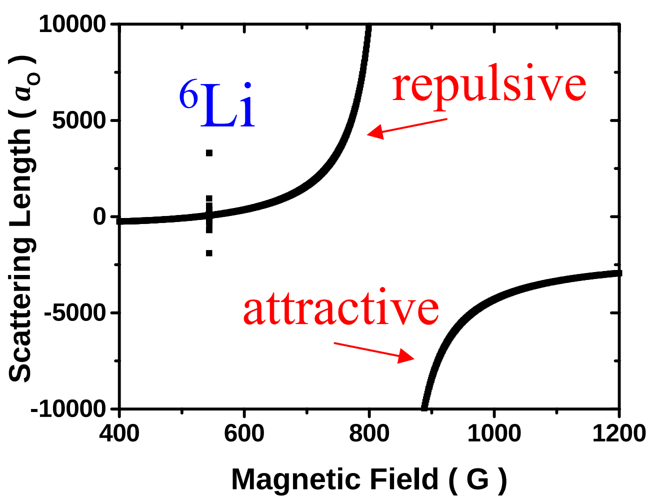
In cold atoms, effective atom-atom interaction is short range and s-wave:

$$V(r_1-r_2) = (4\pi\hbar\, a/m)\, \delta\, (r_1-r_2)$$

a = s-wave atom-atom scattering length.

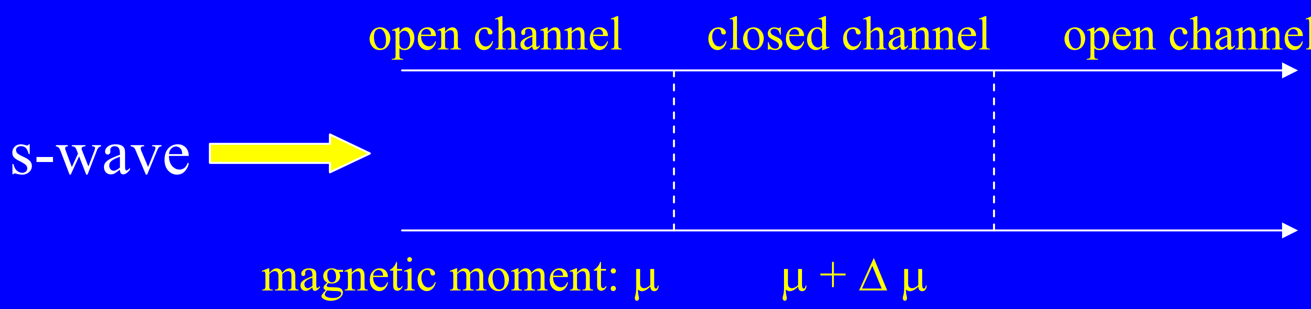
Cross section: $\sigma=8\pi a^2$

Go from weakly repulsive to strongly repulsive to strongly attractive to weakly attractive by dialing external magnetic field through Feshbach resonance .



Resonance at B= 830 G

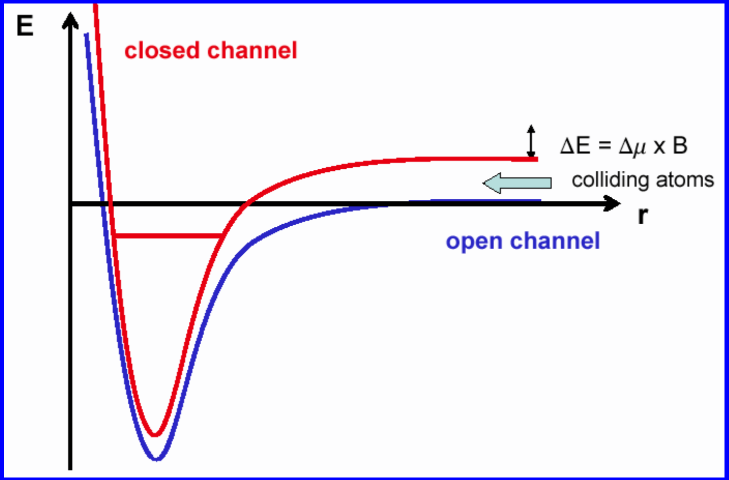
Feshbach resonance in atom-atom scattering



$$\boxed{\text{Scattering amplitude} \propto \frac{|M|^2}{E_c - E_o}}$$

$$E_c\text{-}E_0 \sim \Delta\mu\, B + \ldots$$

Low energy scattering dominated by bound state closest to threshold

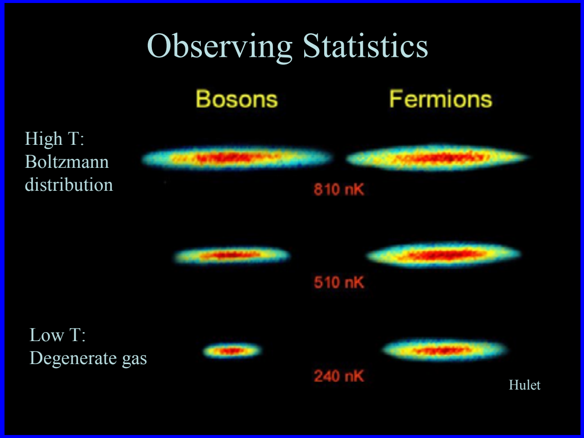


Adjusting magnetic field, B, causes level crossing and resonance, seen as divergence of s-wave scattering length, a:

$$a(B) = a_{bg}\left(1 - \frac{\Delta}{B - B_{Feshbach}}\right)$$

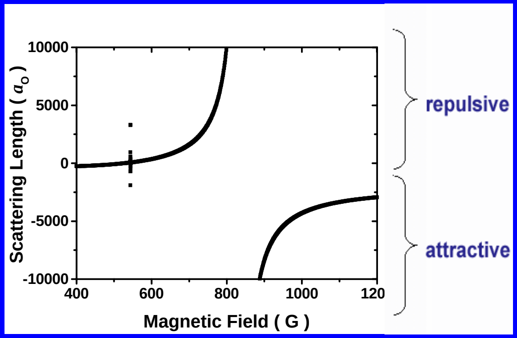
BCS paired fermions: a new superfluid

Produce trapped degenerate Fermi gases: ^{6}Li, ^{40}K



^{7}Li vs. ^{6}Li

Increase attractive interaction with Feshbach resonance



At resonance have "unitary regime": no length scale

Experiments: JILA, MIT, Duke, Innsbruck, ...

Both systems scale-free in strongly coupled regime

$F_{qgp} \sim \text{const}\ n_{exc}^{4/3}$ $E_{\text{cold atoms}} \sim \text{const}\ n^{2/3}/m$

Only length-scale for cold atoms near resonance is density. No microscopic parameters enter equation of state

$$\frac{E}{N} = \frac{3}{5} E_F (1 + \beta)$$

β is universal parameter. No systematic expansion

Fixed Node Green's Function Monte Carlo, Carlson et al. (2003):

β = -0.56 to – 0.58

Diagrammatic. Perali, Pieri & Strinati (2004) β = -0.545

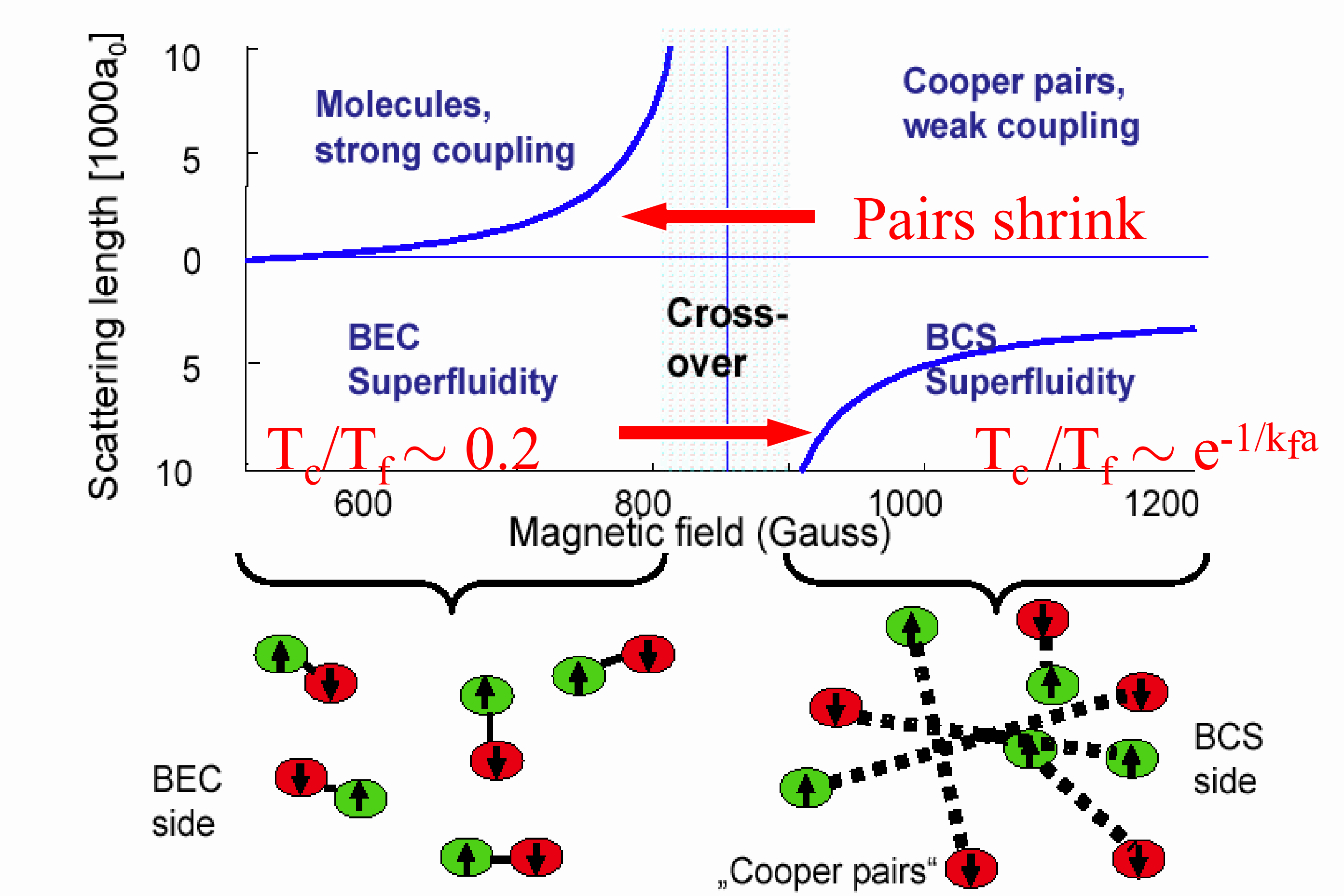
Experiment:

Rice: -0.54(5), Duke: -0.26(7), ENS: -0.3, JILA: -0.4, Innsbruck: 0.68(1)

BEC-BCS crossover in Fermi systems

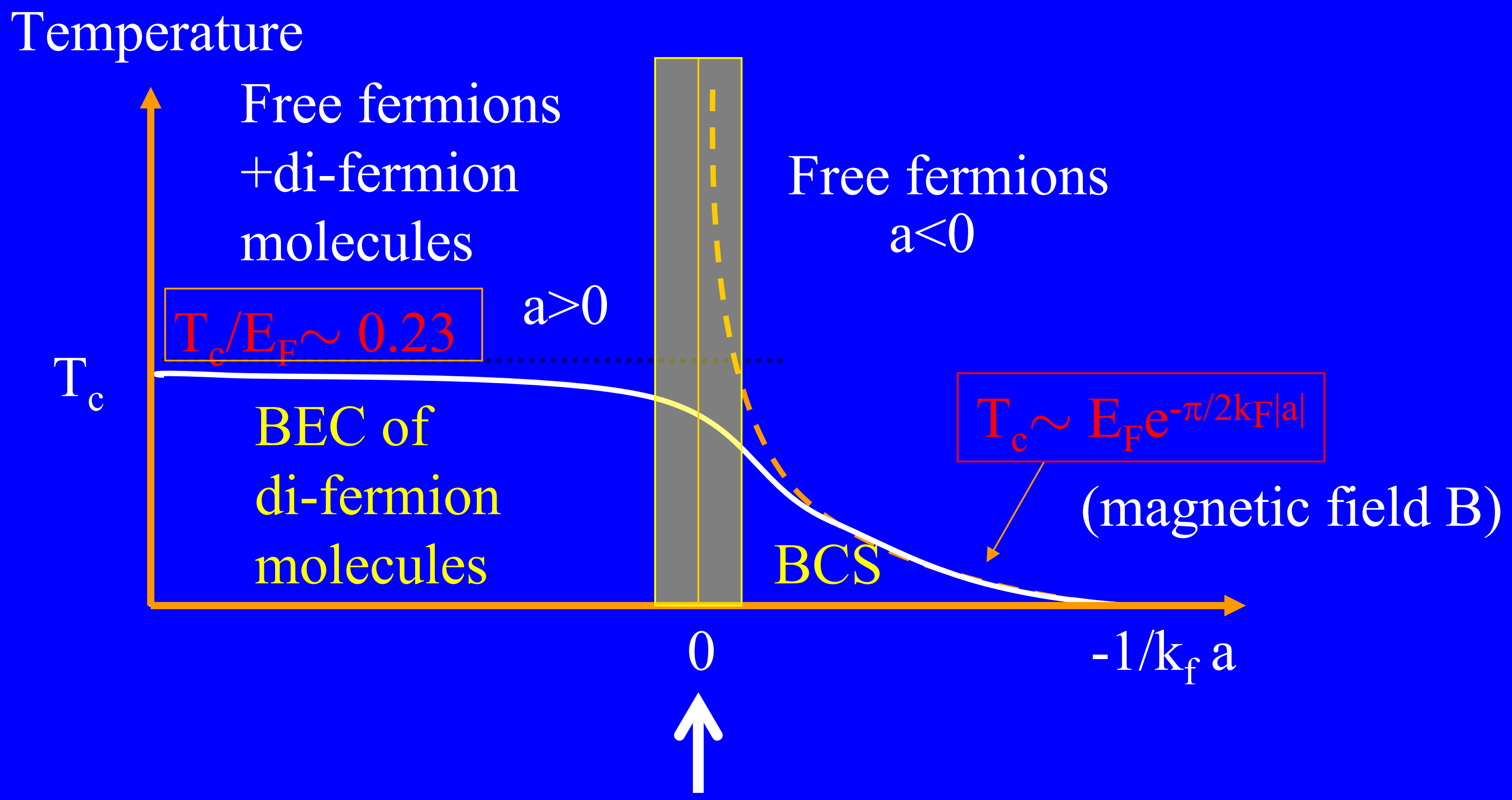
Continuously transform from molecules to Cooper pairs:

D.M. Eagles (1969)
A.J. Leggett, J. Phys. (Paris) C7, 19 (1980)
P. Nozières and S. Schmitt-Rink, J. Low Temp Phys. 59, 195 (1985)



^{6}Li

Phase diagram of cold fermions vs. interaction strength



Temperature

Free fermions
+di-fermion
molecules

a>0

Free fermions
a<0

$T_c/E_F \sim 0.23$

T_c

$T_c \sim E_F e^{-\pi/2k_F|a|}$

(magnetic field B)

BEC of
di-fermion
molecules

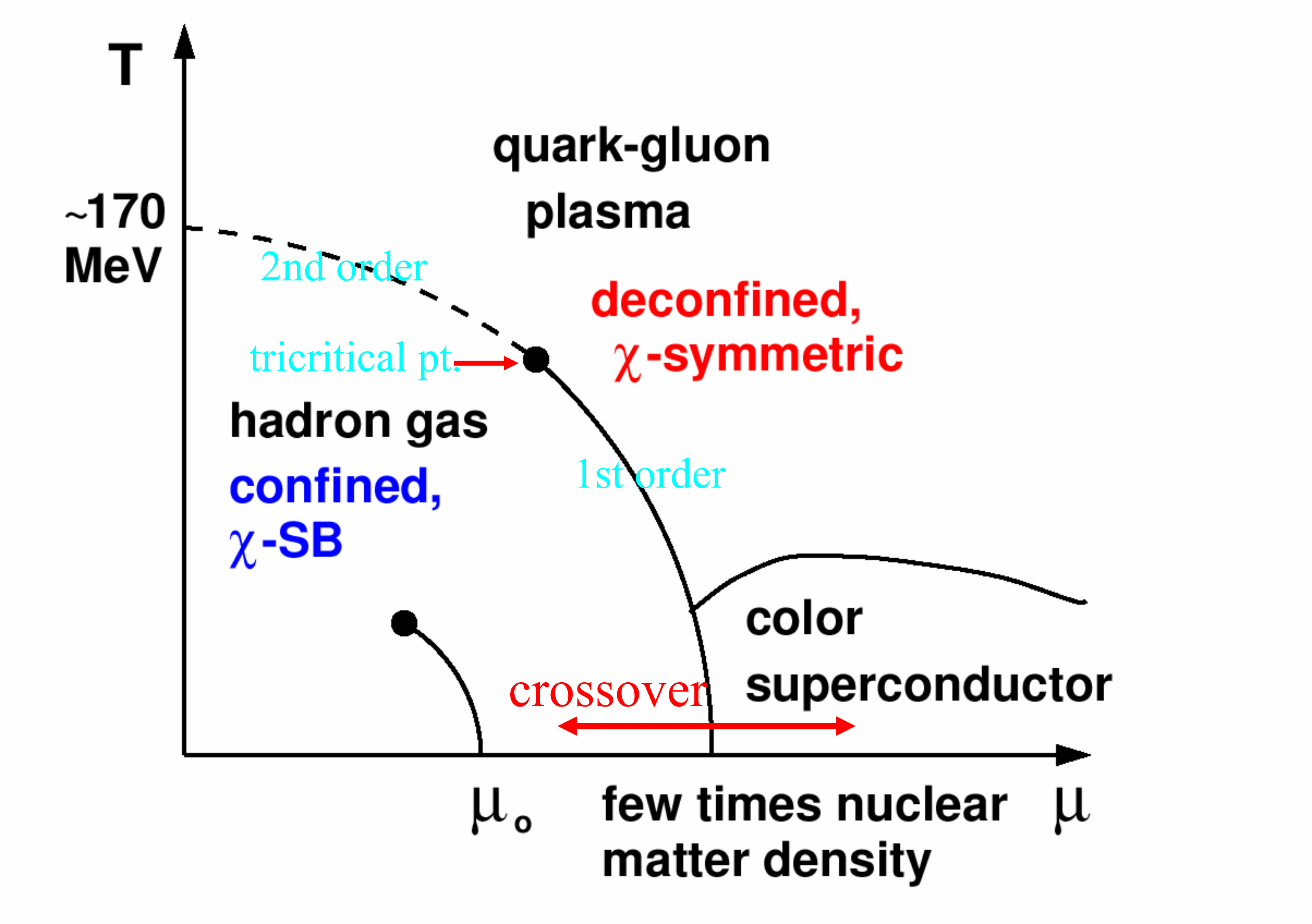
BCS

0

$-1/k_f\, a$

Unitary regime -- crossover
No phase transition through crossover

Phase diagram of quark gluon plasma

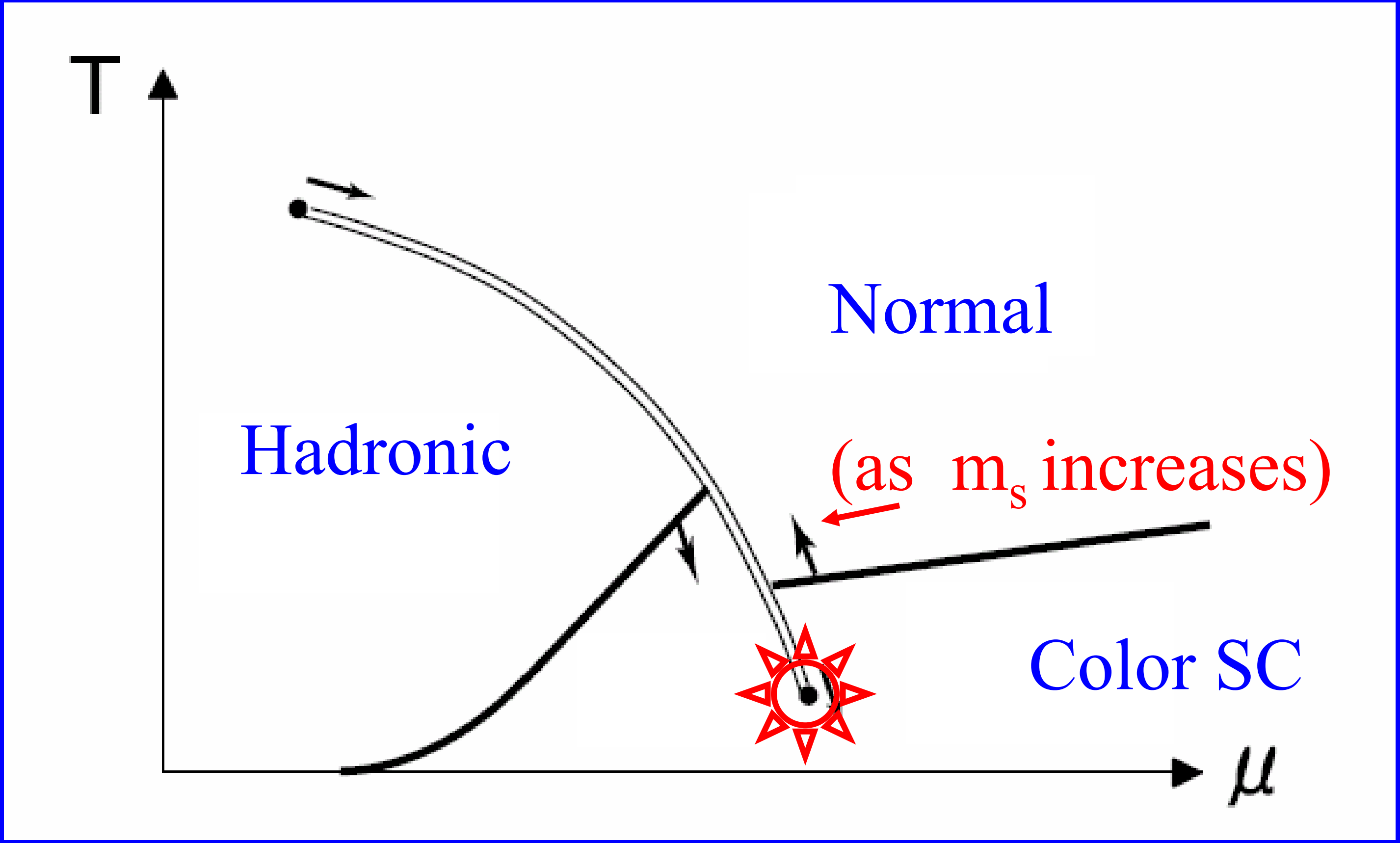


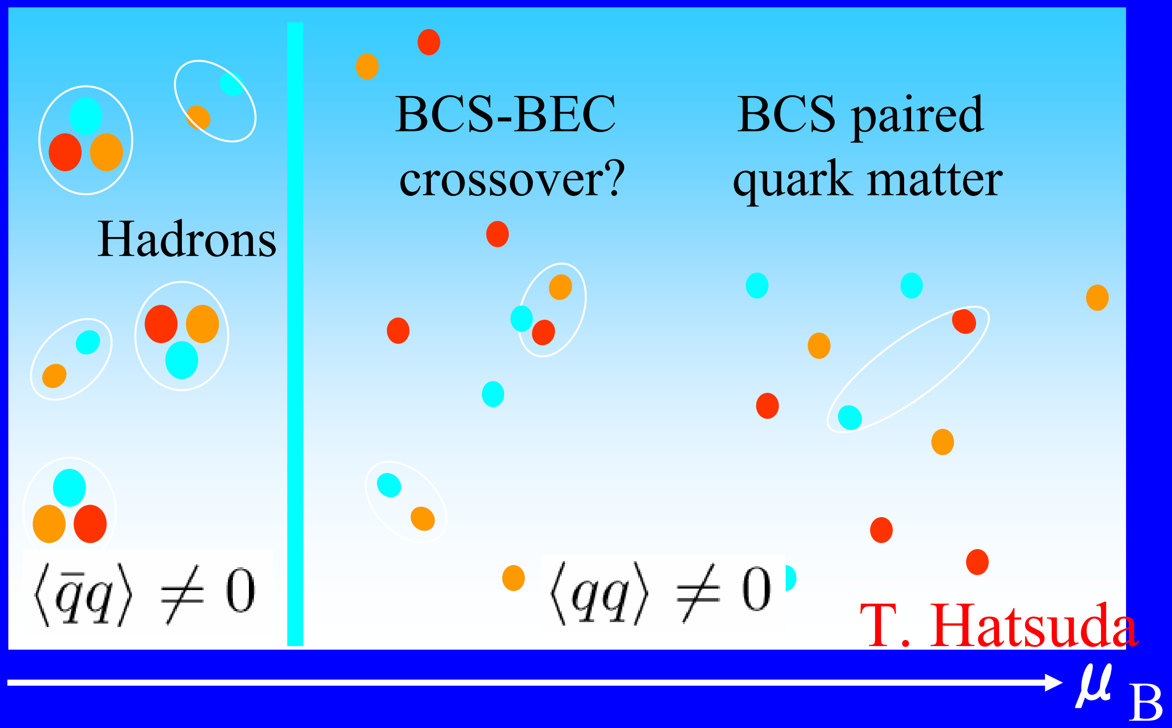
Karsch & Laermann, hep-lat/0305025

New critical point in phase diagram:

induced by chiral condensate – diquark pairing coupling via axial anomaly

Hatsuda, Tachibana, Yamamoto & GB, PRL 97, 122001 (2006)





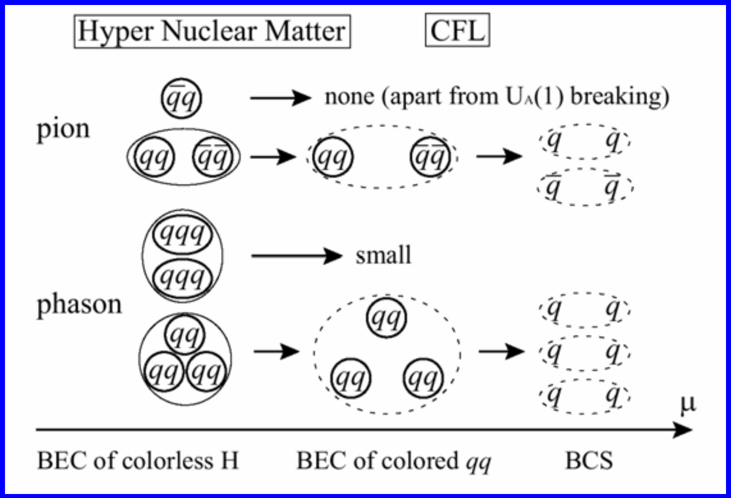
T. Hatsuda

Abuki, Itakura & Hatsuda, PRD65, 2002

In SU(2)$_C$:

hadrons <=> 2 fermion molecules,

paired deconfined phase <=> BCS paired fermions

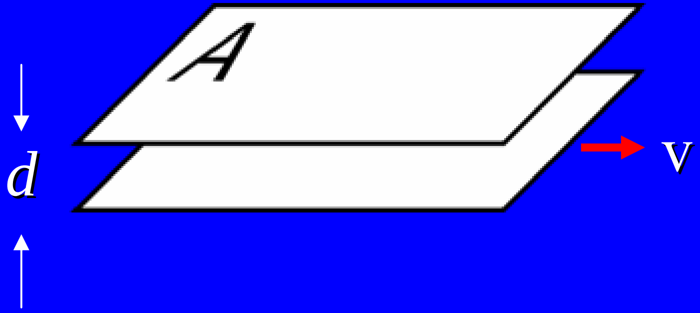


Possible structure of crossover

Fukushima, hep-ph/0403091

Viscosity in elliptic flow in heavy ion collisions and in Fermi gases near unitarity

Strong coupling leads to low first viscosity η,
seen in expansion in both systems



Shear viscosity η:

$F = \eta A v / d$

Stress tensor

$$T^{ij}_{diss} = \eta\left(\frac{\partial v_i}{\partial x^j} + \frac{\partial v_j}{\partial x^i} - \frac{2}{3}\delta_{ij}\nabla\cdot v\right) + \zeta\delta_{ij}\nabla\cdot v$$

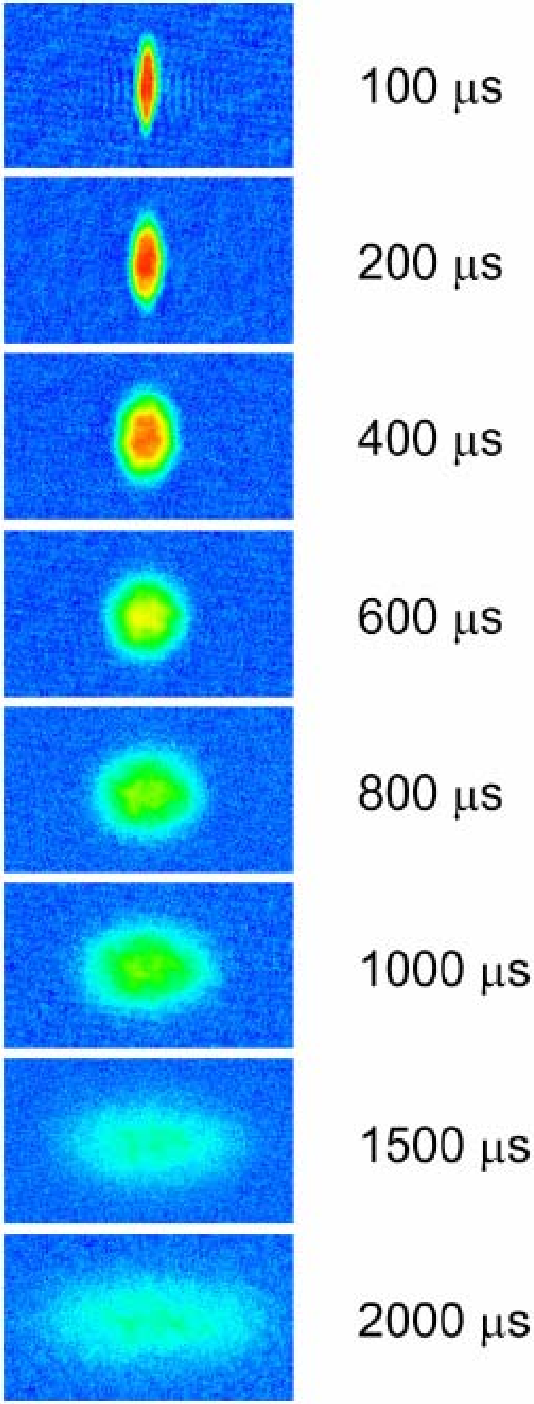
First viscosity

$$\eta \sim \rho\bar{v}^2\tau \sim \frac{1}{|M|^2}$$

τ = scattering time

Strong interactions => small η

Strongly coupled ^{6}Li expansion

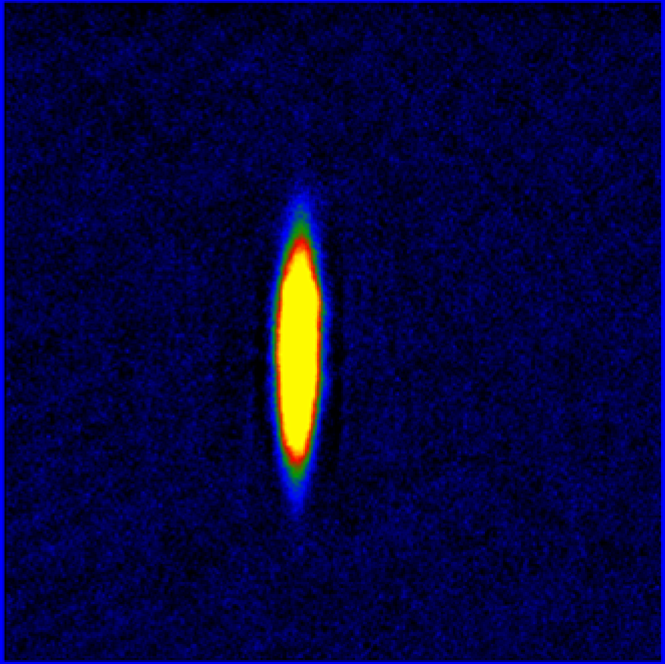


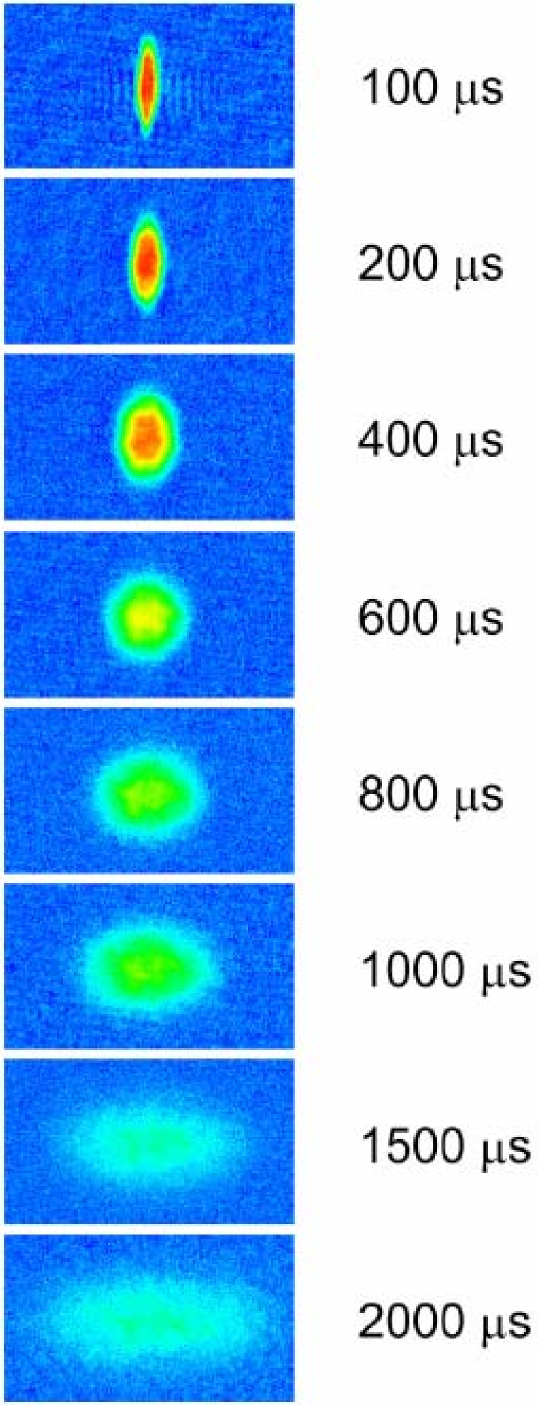
Free Expansion:

K. M. O’Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, and J. E. Thomas, Science Dec 13 2002: 2179

Turn off trap: cloud expands

Compare with expansion of weakly coupled system →





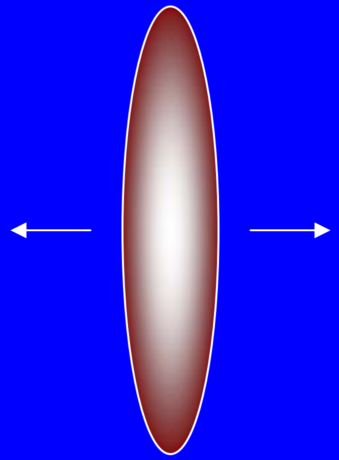
Strongly coupled ^{6}Li expansion

Free Expansion:

K. M. O'Hara, S. L. Hemmer, M. E. Gehm, S. R. Granade, and J. E. Thomas, Science Dec 13 2002: 2179

Turn off trap: cloud expands

Pressure gradient largest in narrow direction



Expands asymmetrically

Similar to elliptic flow in heavy ion collisions

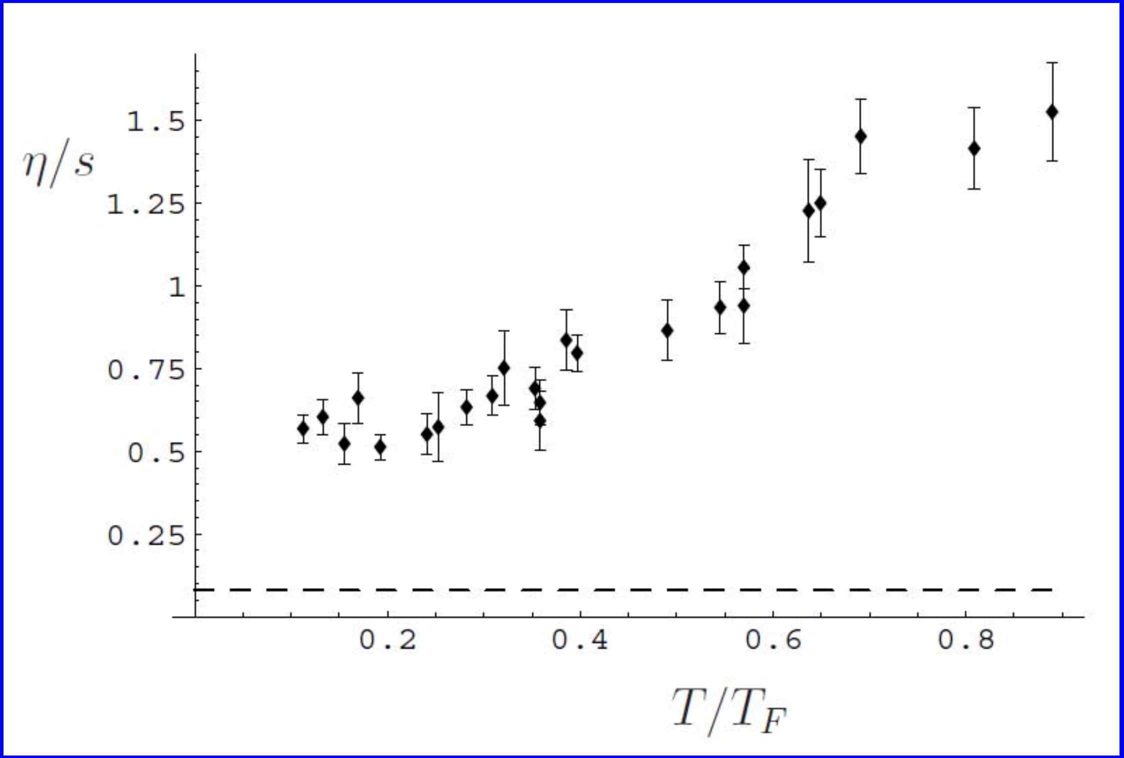
Find equation of state by fitting expansion with ideal (zero viscosity) hydrodynamics

Viscosity extracted from radial breathing mode

Expt: J. Kinast, A. Turlapov, J.E. Thomas, PRL 94, 170404 (2005)

Theory: T. Schaefer, cond-mat/0701251.

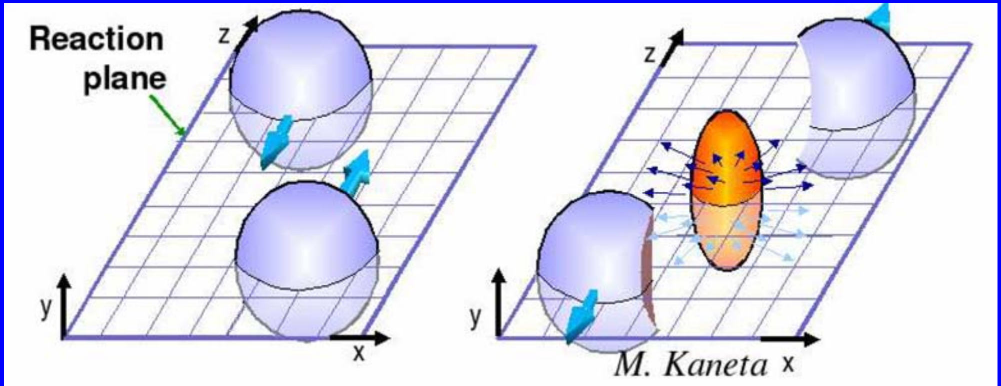
Ratio of shear viscosity to entropy density ($\hbar$=1)

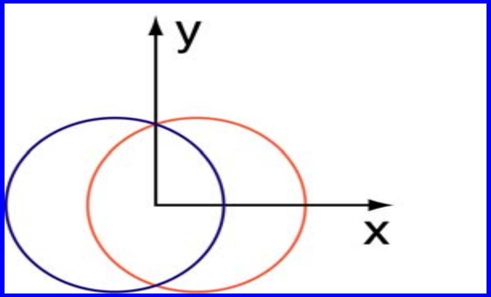


Temperature/ Fermi temperature

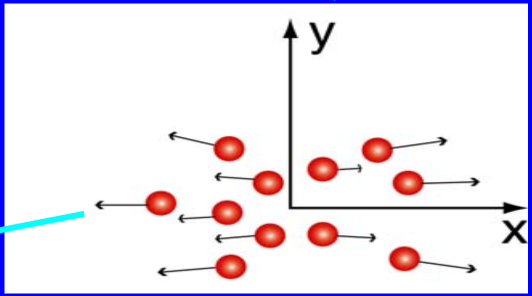
Collectivity: Elliptic flow in non-central collisions:

anisotropic in ϕ (= azimuthal angle in x,z plane)

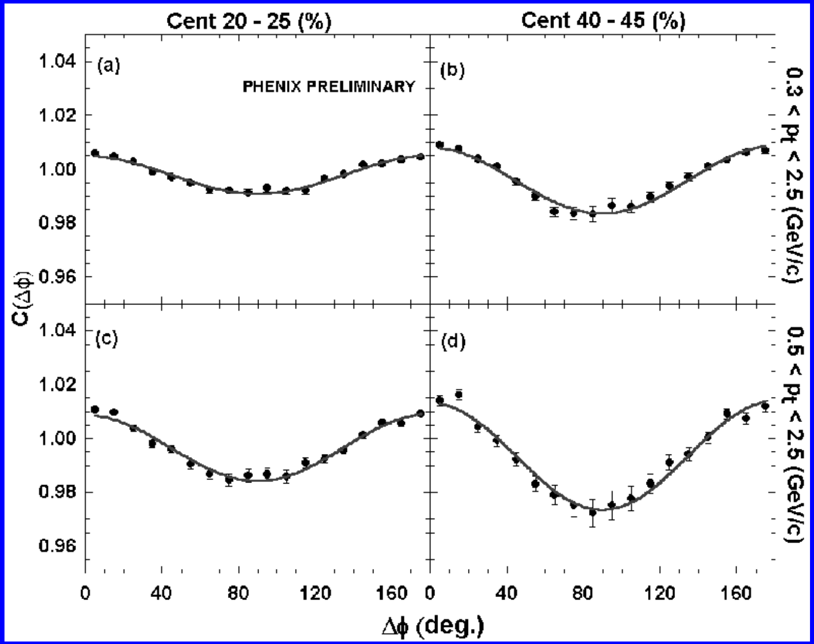




Almond shape overlap region in coordinate space



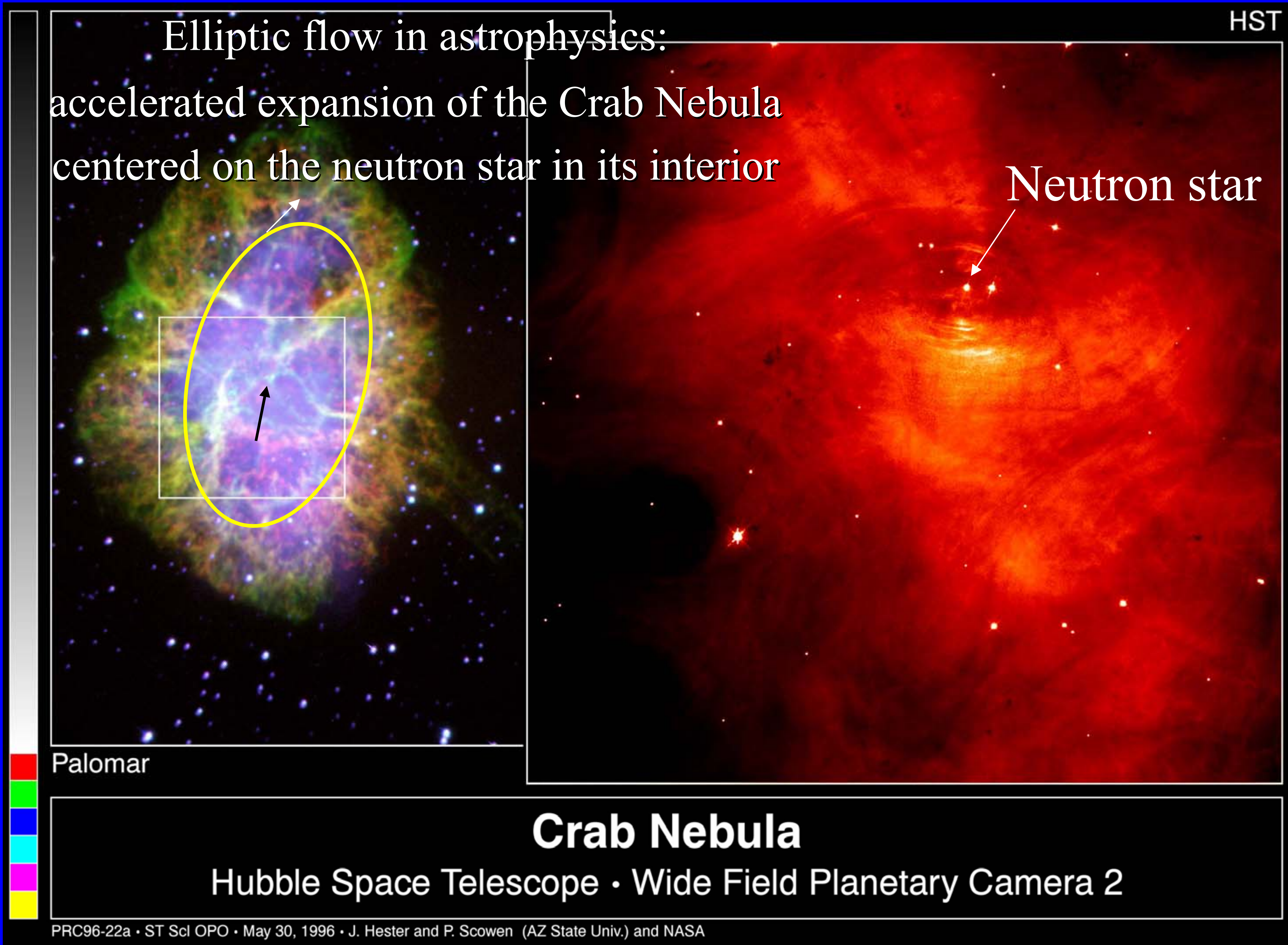
momentum space



$$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \dots$$

where $p_\perp$ = momentum in x,y plane

Elliptic flow in astrophysics: accelerated expansion of the Crab Nebula centered on the neutron star in its interior



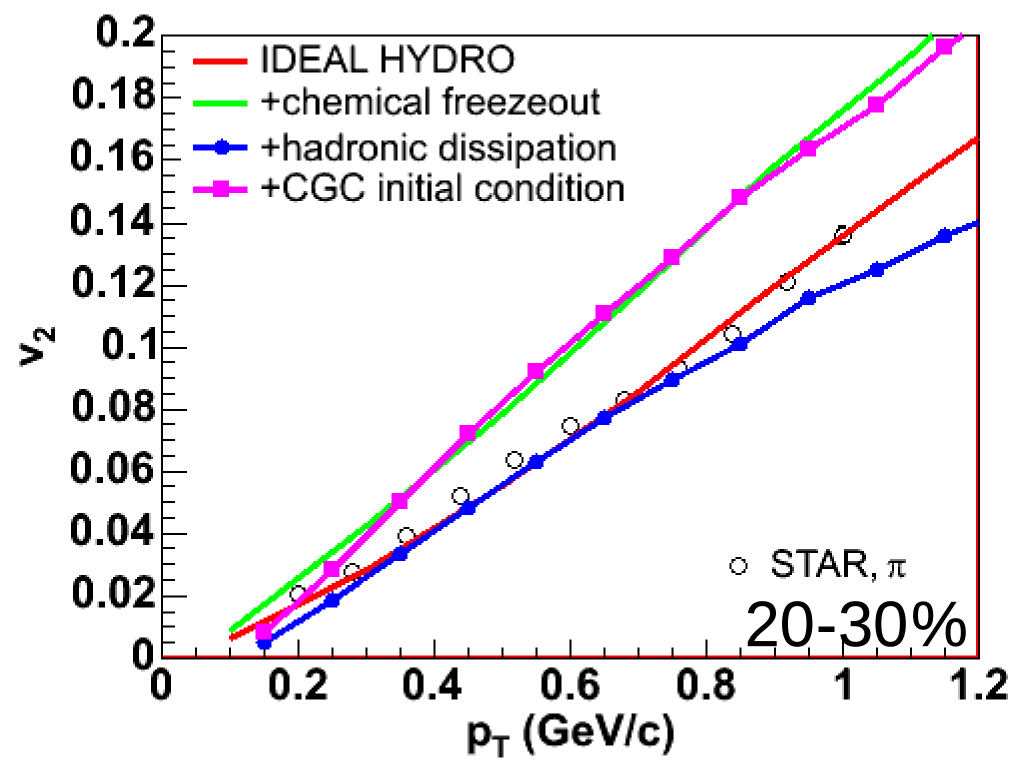
Crab Nebula

Hubble Space Telescope • Wide Field Planetary Camera 2

PRC96-22a • ST ScI OPO • May 30, 1996 • J. Hester and P. Scowen (AZ State Univ.) and NASA

Hydrodynamic predictions of $v_2(p_T)$

Elliptic flow => almost vanishing viscosity in quark-gluon plasma



From T. Hirano

Conjectured lower bound on ratio of first viscosity to entropy density, s:

$$\boxed{\eta > \hbar\, s/4\pi}$$

Kovtun, Son, & Starinets,
PRL 94, 111601 (2005)

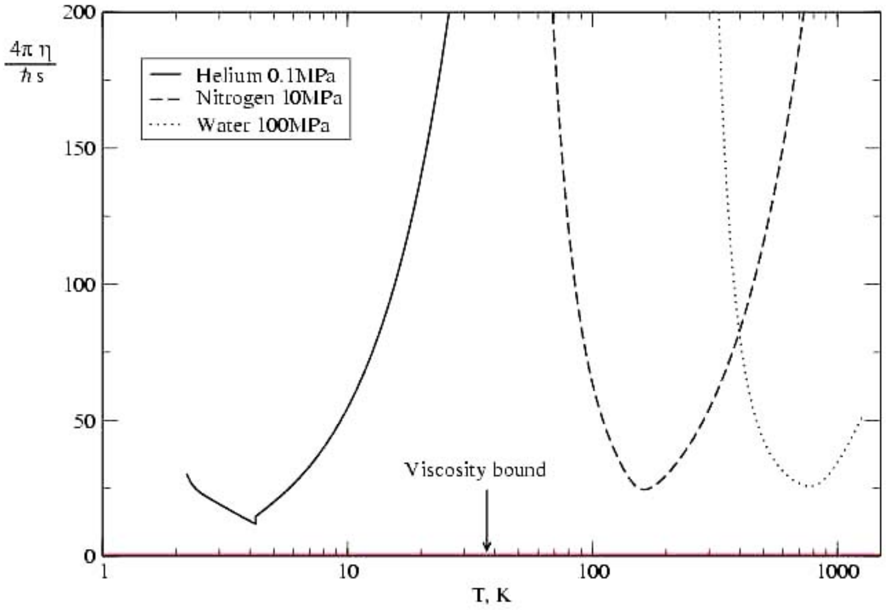


Figure 1: The viscosity-entropy ratio for some common substances.

(Exact result in $\mathcal{N}$=4 supersymmetric Yang-Mills theory in large N_c)

$$\boxed{\eta \sim n_t\, m\, v^2 \tau = n\, p\, \lambda, \quad s \sim n_t}$$

n_t = no. of degrees of freedom producing viscosity
$p = mv$ = mean particle momentum > $\hbar$ / (interparticle spacing)
λ = mean free path

Bound ⇔ $\boxed{\text{mean free path > interparticle spacing}}$

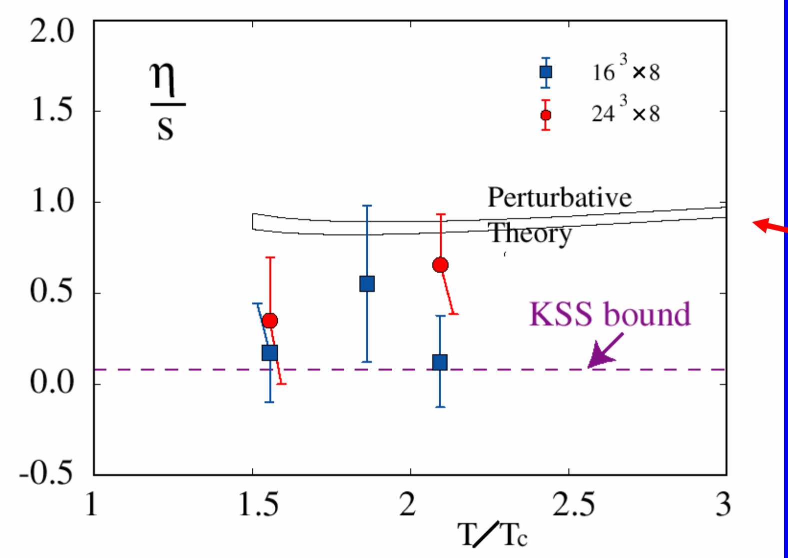
Strongly coupled systems approach viscosity lower bound

Cold fermions in normal state at unitarity:

$$\eta \sim n\hbar\, T/T_f, \quad s \sim n\, T/T_f \Rightarrow \boxed{\eta/s \sim \hbar}$$

G. Bruun and H. Smith, cond-mat/06012460

Lattice calculations of first viscosity in qcd:



Nakamura & Sakai, hep-lat/0510039

Perturbative qcd limit:

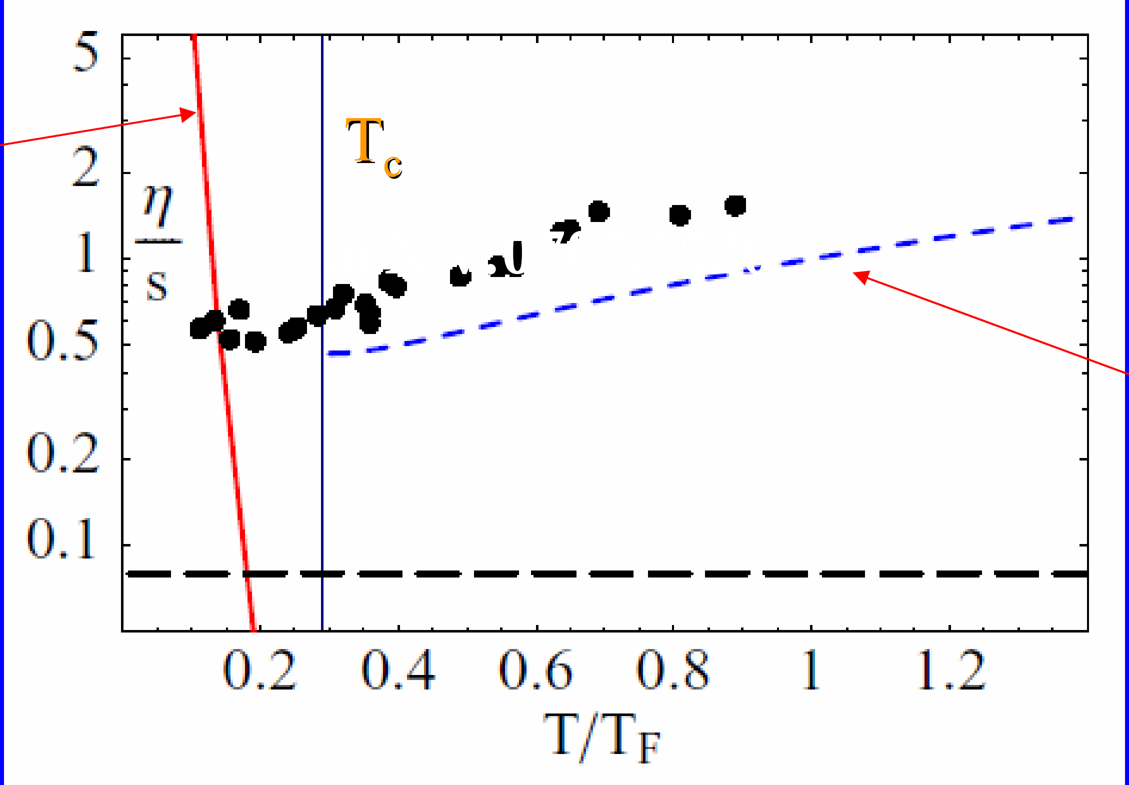
$$\eta \sim T^3/(\alpha_s^2 \ln \alpha_s)$$

$$\eta/S \sim 1/\alpha_s^2 \ln \alpha_s$$

GB, Monien, Pethick & Ravenhall, PRL 64(1990)

Shear viscosity of Fermi gas at unitarity

G. Rupak & T. Schaefer, arXiv:0707.1520

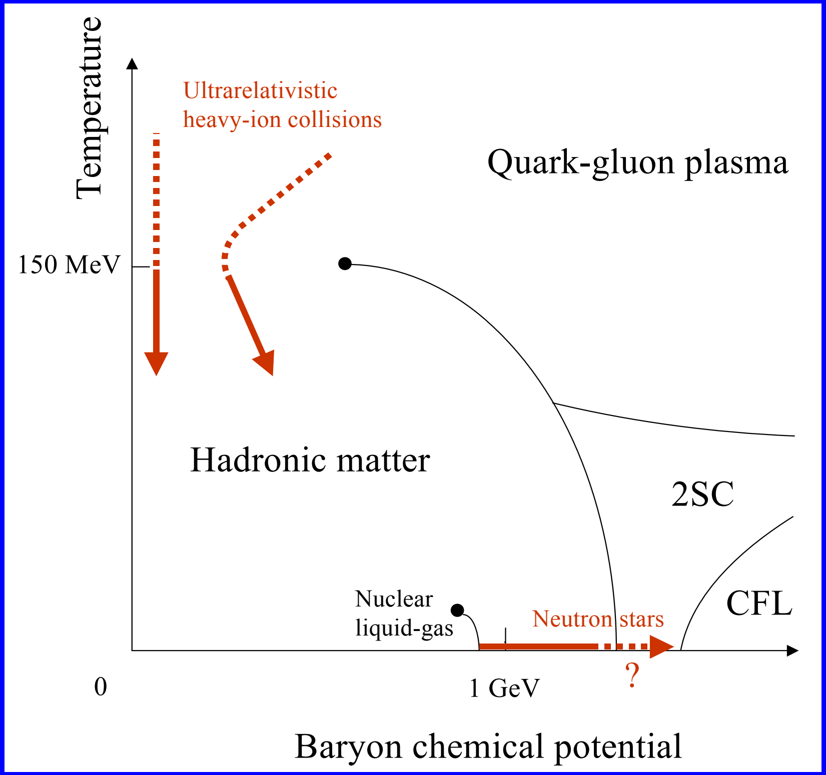


G. M. Bruun & H. Smith, PRA 75, 043612 (2007).

Shear viscosity/ entropy density ratio vs. T/T_F

Color pairing in quark matter

Review: Rajagopal & Wilczek, hep-ph/0011333

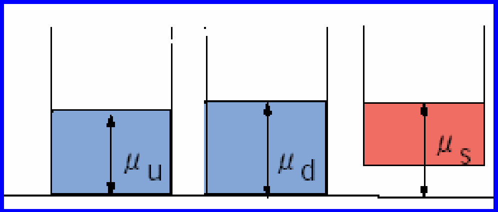


Superfluidity

condensate of paired quarks => superfluid baryon density (n_s)

Color Meissner effects

transverse color fields screened on spatial scale ~ London penetration depth ~ $(\mu/g^2 n_s)^{1/2}$



Two interesting phases:

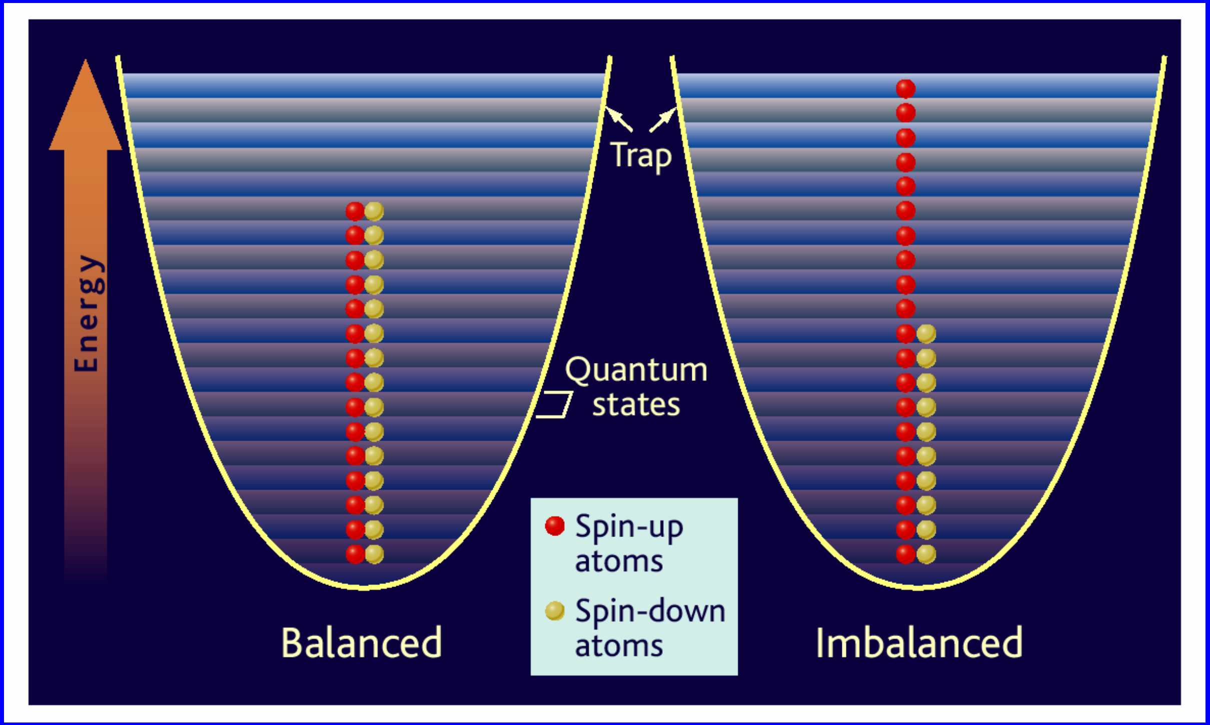
2SC (u,d)

$\langle u_R d_B \rangle$

Color-flavor locked (CFL) ($m_u = m_d = m_s$)

$\langle u d \rangle = \langle d s \rangle = \langle s u \rangle$

Superfluidity and pairing for unbalanced systems

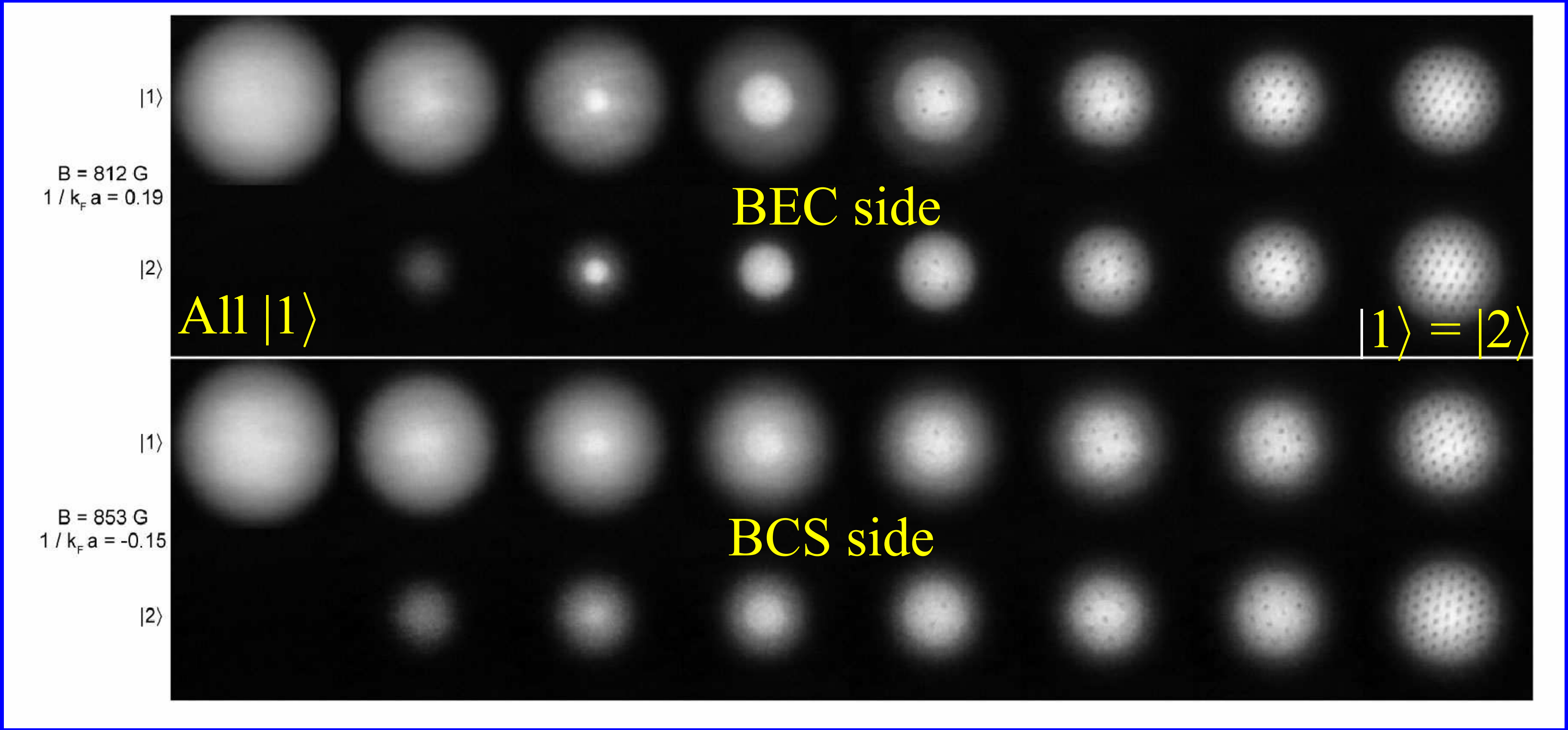


Trapped atoms: change relative populations of two states by hand

QGP: balance of strange (s) quarks to light (u,d) depends on

ratio of strange quark mass m_s to chemical potential μ (>0)

Vortices as marker of superfluidity (MIT)

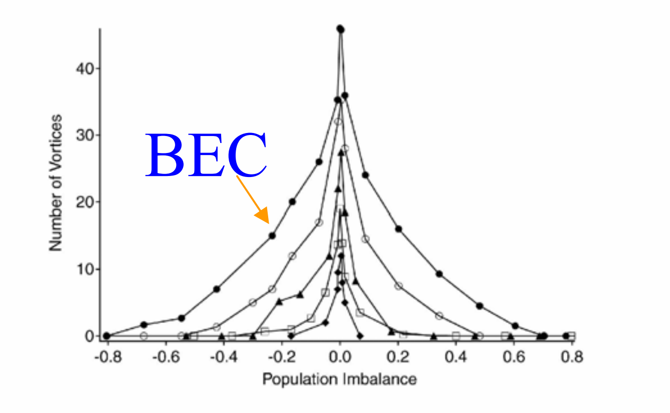


BEC side

All $|1\rangle$

$|1\rangle = |2\rangle$

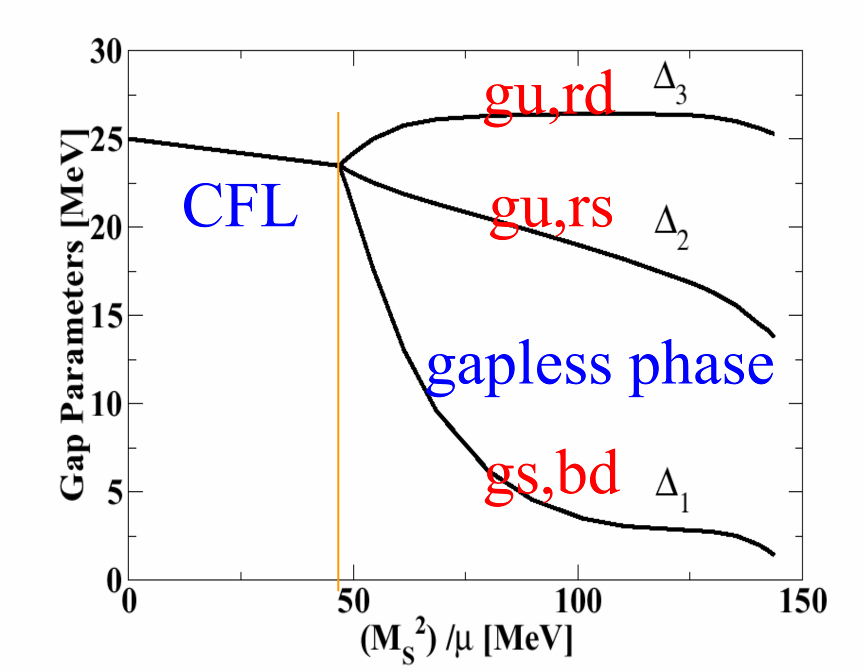
BCS side



BEC

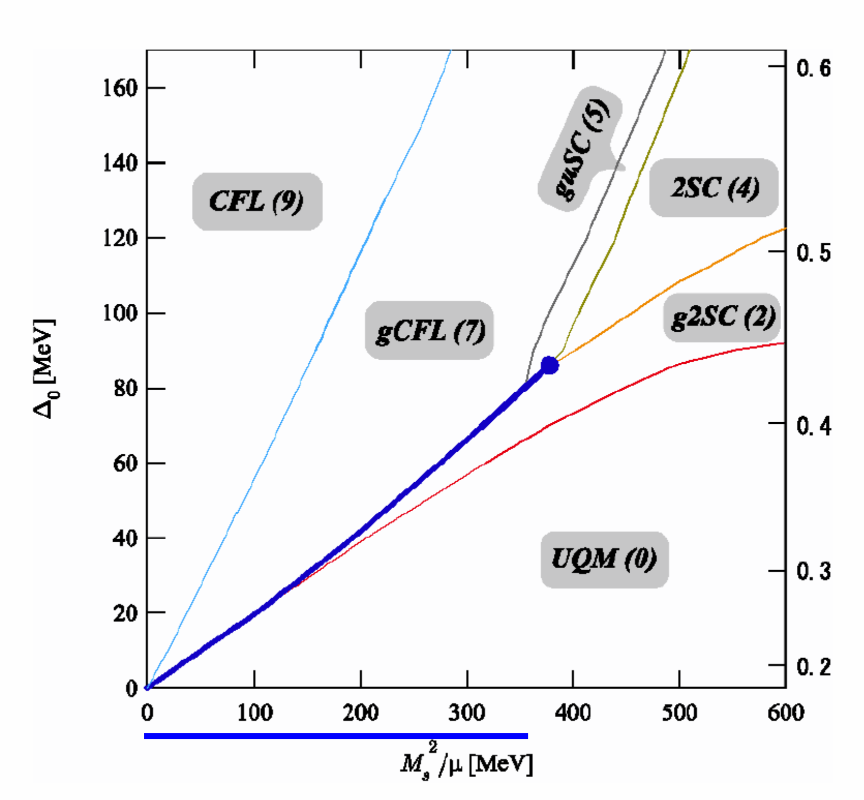
No. of vortices vs. population imbalance

Color superconductor with $m_{strange} \neq m_{light}$



Decreasing pairing of strange quarks with increasing m_s

Alford, Kovaris & Rajagopal, hep-ph/0311286



Phase diagram in Δ_{CFL}, m_s^2 plane

Abuki, Kitazawa, & Kunihiro, PLB 615, 102 (2005)

In gapless phase for unbalanced color superconductors, Meissner screening length can be imaginary (superfluid mass density < 0)

M. Huang; M. Alford; and collaborators

Proposed resolutions

*Phase separation.
(Cf. neutron-rich nuclei with a neutron skin.)

*FFLO state with crystalline ordering.

*Gluon condensate

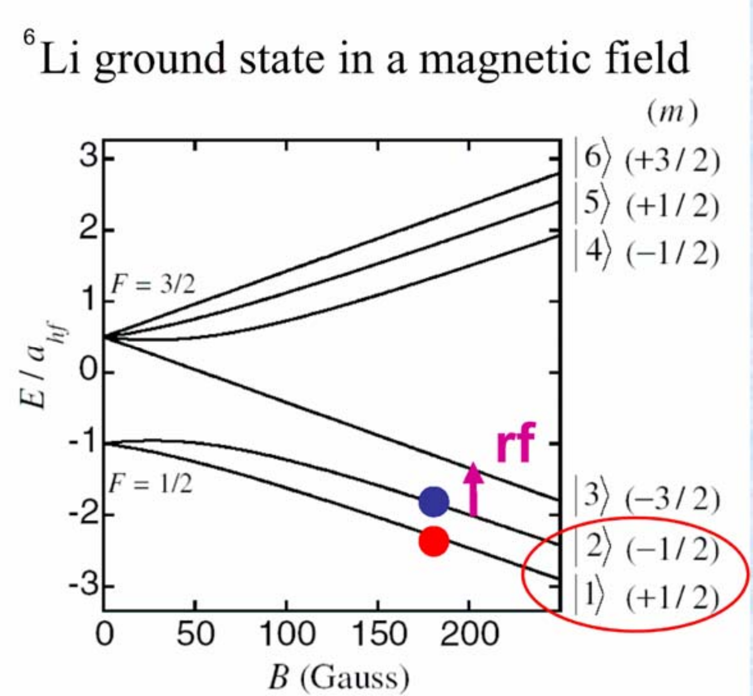
*Current carrying states with non-zero spatially dependent order parameter, $\sim e^{i\, k \cdot r}$ (*T. Schäfer, nucl-th/0602067)*

…

Experiments on ^{6}Li with imbalanced populations of two hyperfine states, $|1\rangle$ and $|2\rangle$

MIT: Zwierlein et al., Science 311, 492 (2006); Nature 442, 54 (2006).

Rice: Partridge et al., Science 311, 503 (2006) cond-mat/0605581

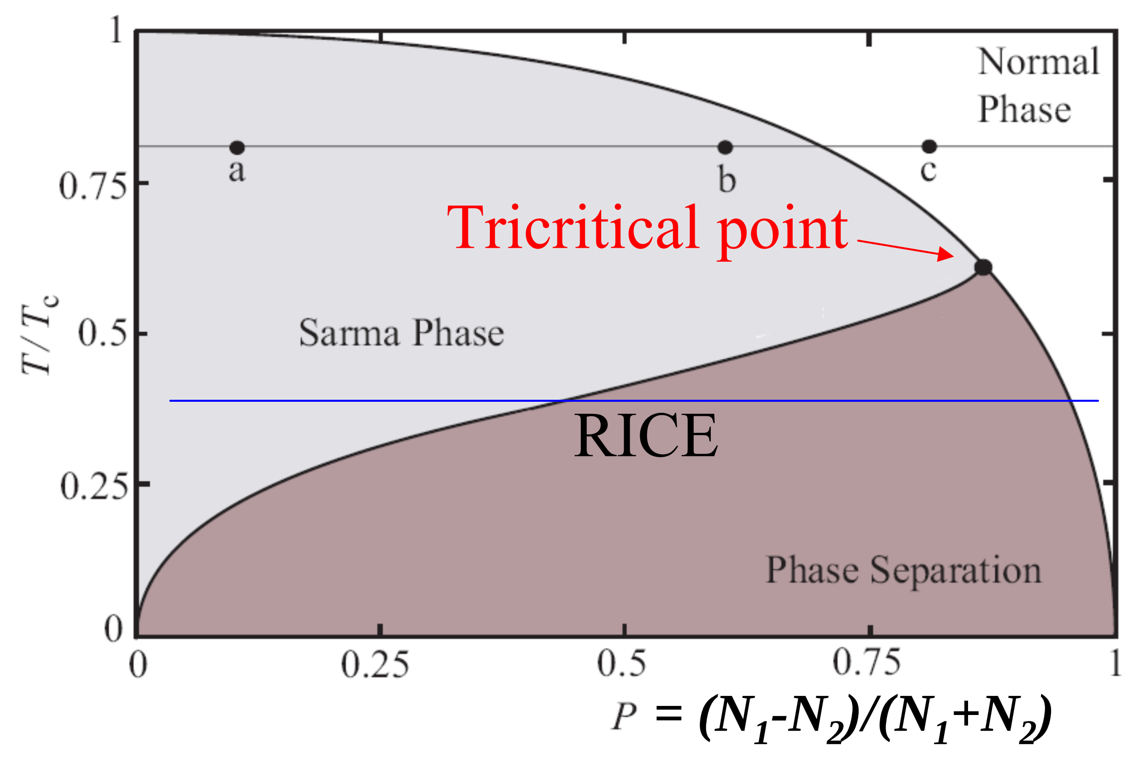


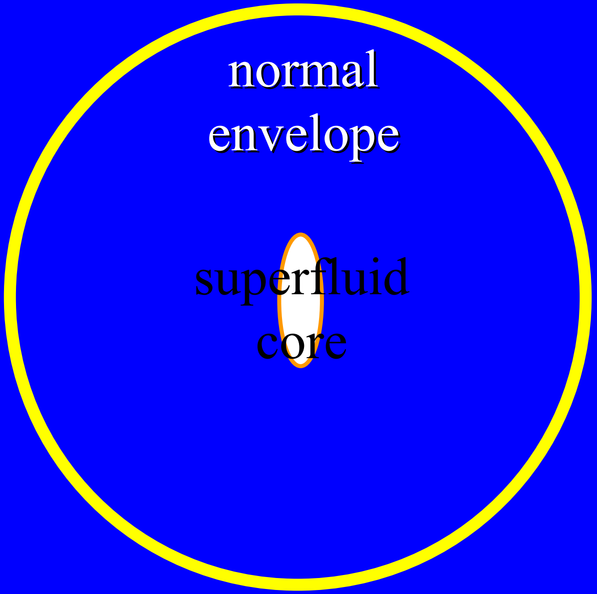
Fill trap with n_1 $|1\rangle$ atoms, and n_2 $|2\rangle$ atoms, with $n_1 > n_2$.

Study spatial distribution, and existence of superfluidity for varying n_1:n_2.

Phase diagram of trapped imbalanced Fermi gases

K. B. Gubbels, M. W. J. Romans, and H. T. C. Stoof, cond-mat/0606330



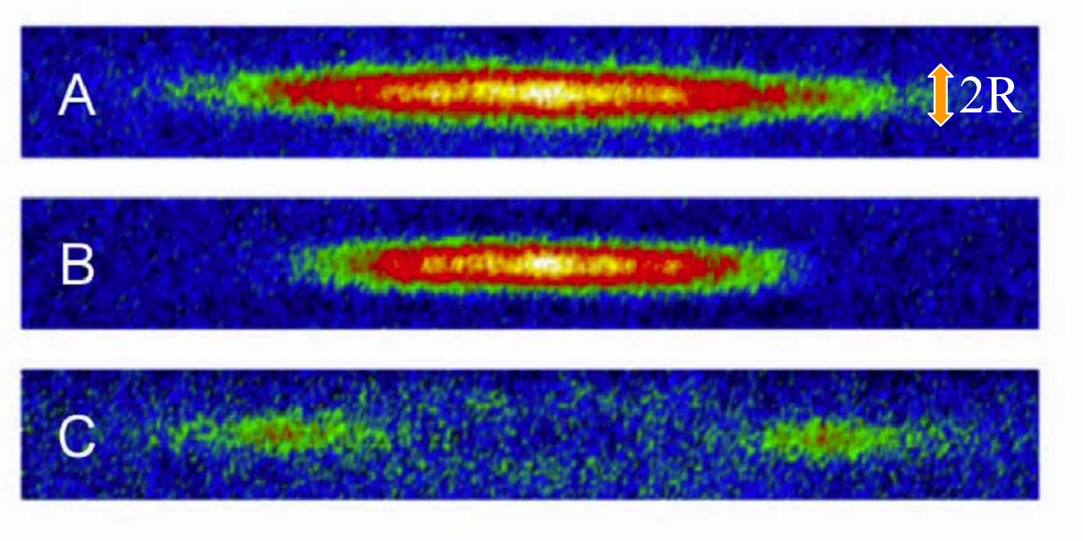


Trap geometry

Sarma: second order transition to normal phase with increasing radius with gapless superfluid near boundary

Phase separation: first order transition

Spatial separation of condensate and unpaired atoms



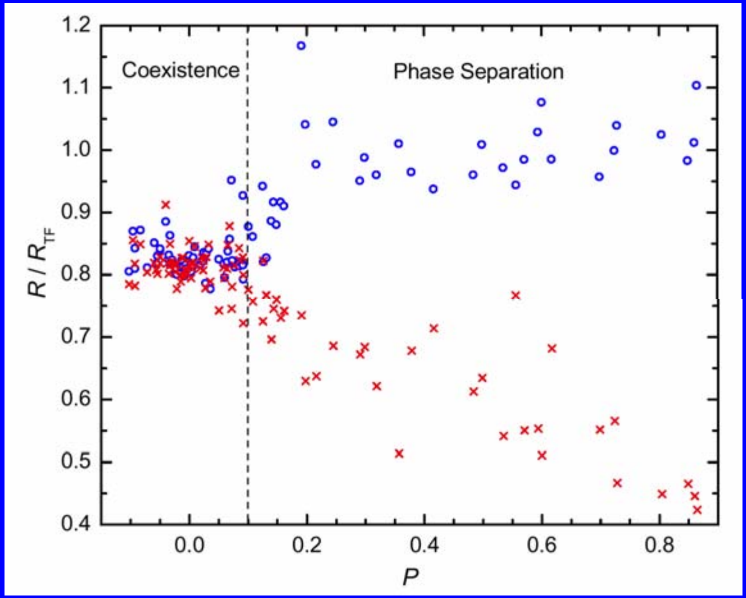
majority state

minority state

unpaired atoms

Rice

At unitary, B=830G



Axial radius of cloud vs. polarization

Phase separation:

BEC side: repulsion between atoms and molecules.

BCS side: quasiparticle energy gap expels unpaired atoms from condensate.

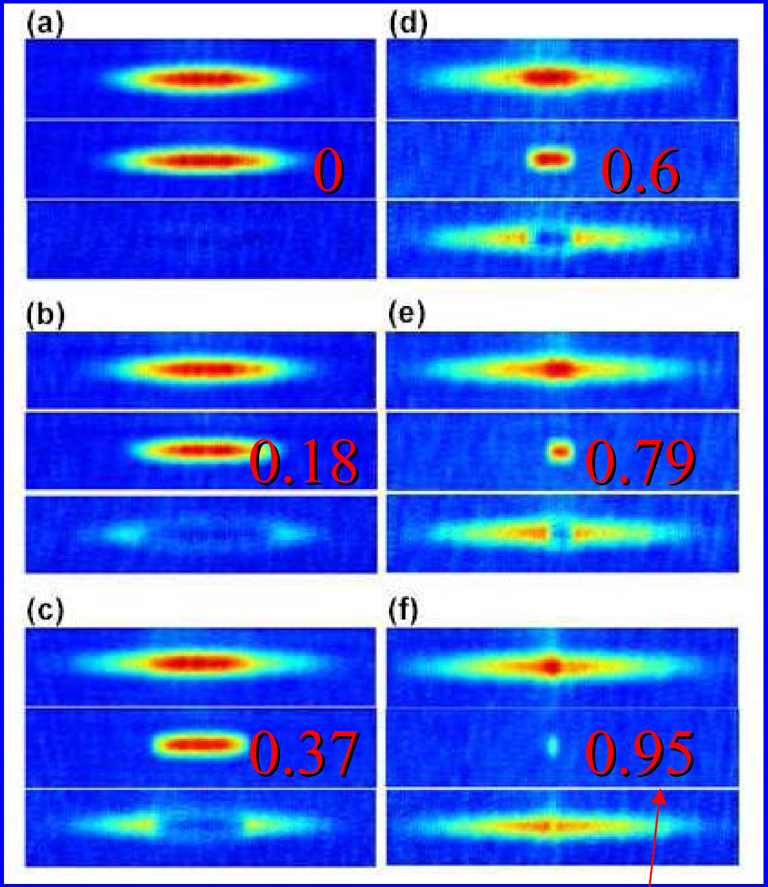
Spatial separation vs. polarization

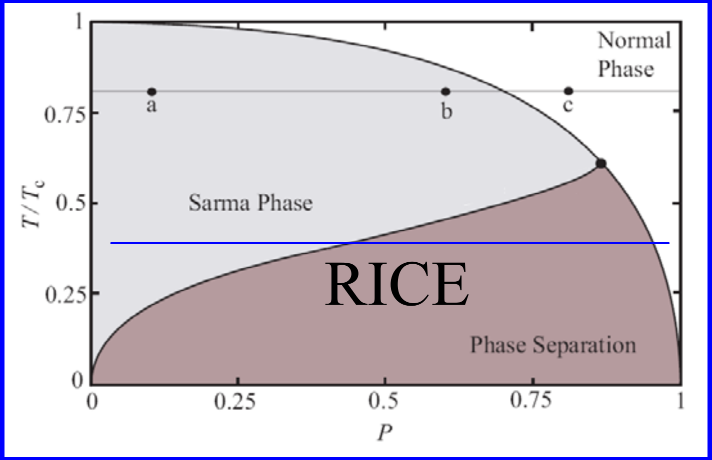
Partridge, Li, Liao, Hulet, Haque & Stoof, cond/mat 0608455

N_1

N_2

N_1-N_2



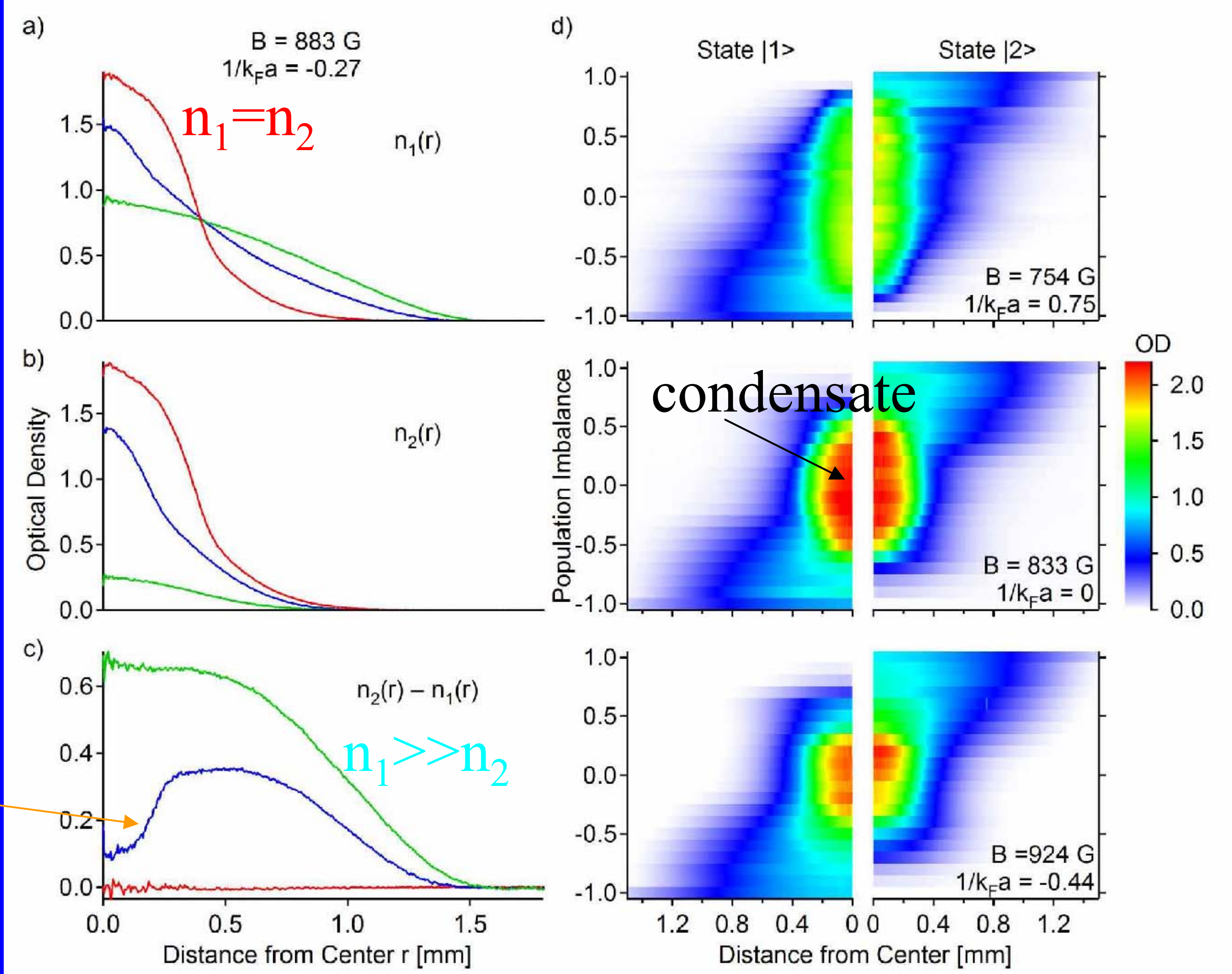


$$P = (N_1-N_2)/(N_1+N_2)$$

Spatial distribution in trap

2.3×10^7

^{6}Li atoms



$n_1=n_2$

condensate

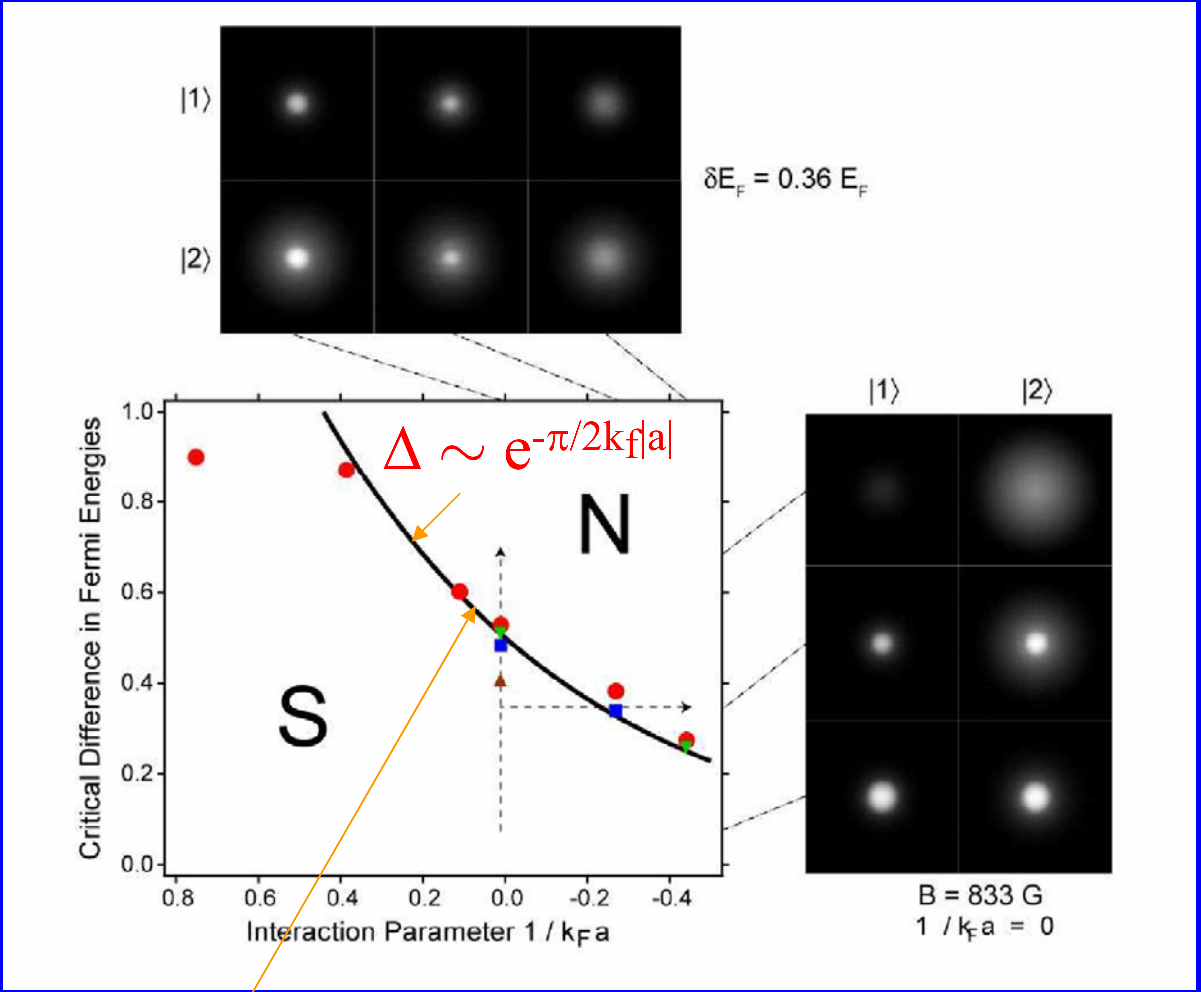
$n_1>>n_2$

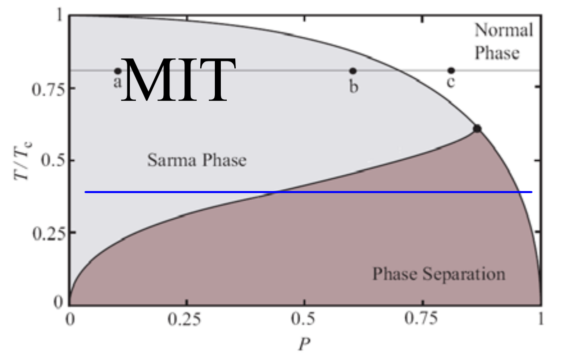
phase separation

MIT

No evidence of spatial modulation expected in FFLO state

Critical imbalance vs. coupling strength





New quantum phase transition: limit of superfluidity, at $\delta\mu \simeq \Delta$

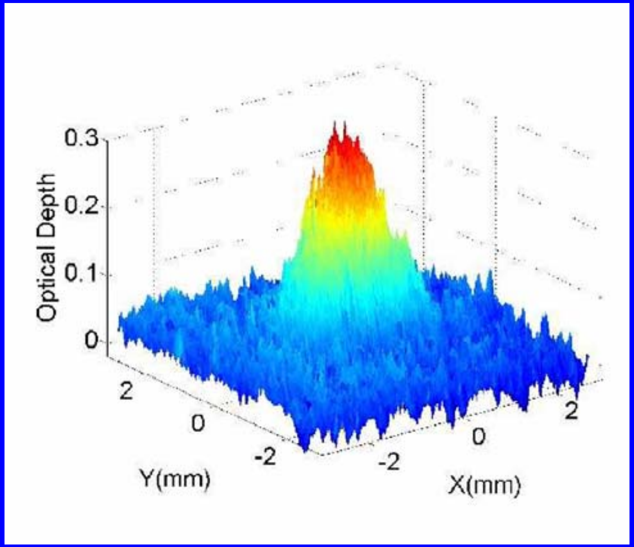
At unitarity $P_c = (N_1 - N_2)/(N_1 + N_2) = 70(5)\%$

(Zwielein et al, cond-mat/0605258)

Ultracold neutral atomic plasmas

Killian, Kulin, Bergeson, Orozco, Orzel, & Rolston, PRL 83, 4776 (1999),
Kulin, Killian, Bergeson, & Rolston, PRL85, 318 (2000),
Killian, Chen, Gupta, Laha, Martinez, Mickelson, Nagel, Saenz, & Simien,
Proc. 12th Int. Cong. on Plasma Phys., 2004, physics/0410019,
Roberts, Fertig, Lim, & Rolston, physics/0402041.

Produce by photoionizing trapped cold atomic gas., e.g., Xe, Sr.
In Xe, reach
$T_e = 0.1 - 10^3$ K, $T_{ion} = 10\mu$K - 4mK, $n = 2\times 10^9/\text{cm}^3$, $N \sim 2\times 10^5$
Expand plasma to measure



Optical depth of an Sr plasma
$N = 7\times10^7$, $n\sim 2\times 10^{10}/\text{cm}^{-3}$

Strongly coupled plasmas: $\Gamma = E_{\mathrm{interaction}} / E_{\mathrm{kinetic}} >> 1$

Electrons in a metal

$E_{\mathrm{int}} \sim e^2/r_0$ $\quad$ r_0 = interparticle spacing $\sim \hbar / k_f$

$E_{\mathrm{ke}} \sim k_f^2/m \Rightarrow \Gamma \sim e^2/\hbar v_f = \alpha_{\mathrm{eff}}$

$v_f \sim 10^{-2}\text{-}10^{-3}c \Rightarrow \alpha_{\mathrm{eff}} \sim 1\text{-}5$

Dusty interstellar plasmas

Laser-induced plasmas (NIF, GSI)

Quark-gluon plasmas

$E_{\mathrm{int}} \sim g^2/r_0,\ r_0 \sim 1/T,\ E_{\mathrm{ke}} \sim T \Rightarrow \Gamma \sim g^2 \gg 1$

Ultracold trapped atomic plasmas

$\Gamma \sim n_9^{1/3}/T_K$ $\quad$ [where $n_9 = n/10^9\ /\mathrm{cm}^3$ and $T_K = (T/\ 1\mathrm{K})$]

Non-degenerate plasma, $E_{\mathrm{ke}} \sim T \Rightarrow \Gamma = E_{\mathrm{int}}/E_{\mathrm{ke}} \sim e^2/r_0T$

Ultracold plasmas analog systems for gaining understanding of plasma properties relevant to heavy-ion collisions:

-kinetic energy distributions of electrons and ions

-modes of plasmas: plasma oscillations

-screening in plasmas

-nature of expansion – flow, hydrodynamical (?)

-thermalization times

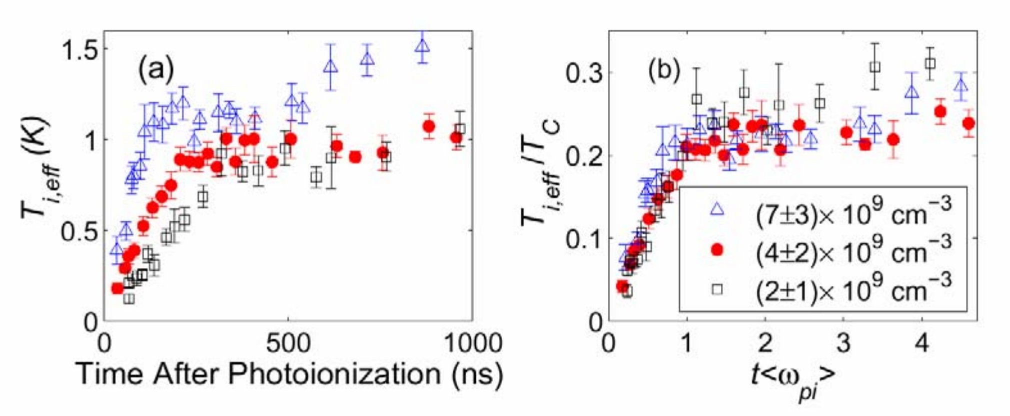
-correlations

-interaction with fast particles

-viscosity

-…

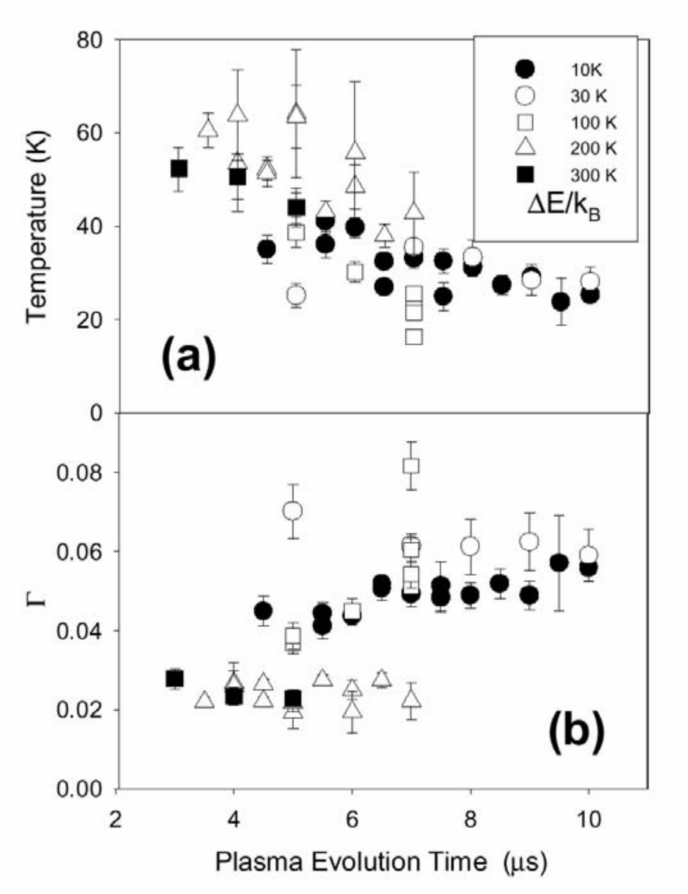
Evolution of plasma temperatures



Ion temperature vs. time

T. C. Killian et al., physics/0410019

Thermal equilibration on times $\ll 1/\omega_{\text{plasma}}$ At short times, release of correlation energy heats the ions.



Electron temp. vs. time (Xe)

J.L. Roberts et al., physics/0402041