Matter under Extreme Conditions

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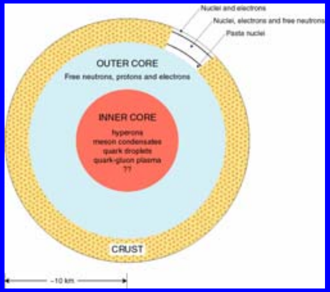
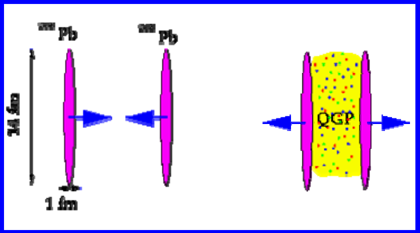
Milestones in study of matter under extreme conditions

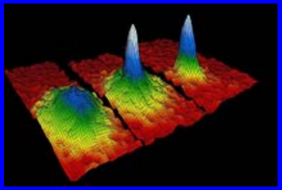
Discovery of pulsars and neutron stars, 1967-68

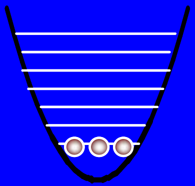


Ultrarelativistic heavy ion collisions, ca. 1985

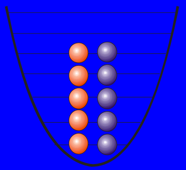


Ultracold atomic Bose-Einstein condensates, 1995

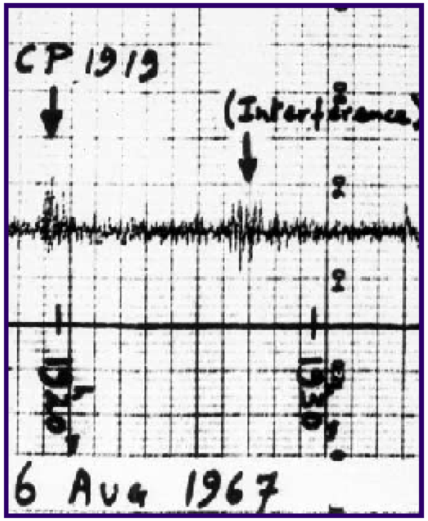




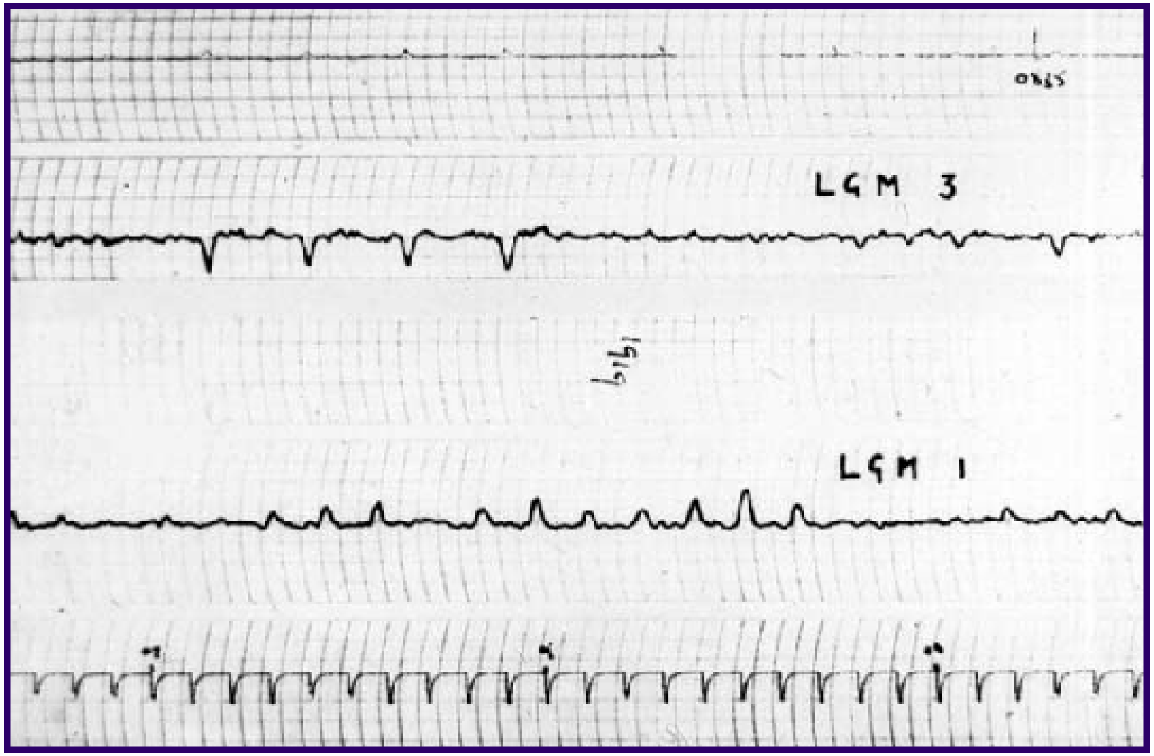
Degenerate (=> superfluid) atomic Fermi gases, 1999-2004



1967 First pulsar detection: PSR1919+21 *Bell & Hewish*



2: The first detection of the first pulsar, occupying about one-quarter inch of chart paper. About five minutes later is a short burst of low level interference. This signal has been high-pass filtered, to remove the telescope's interference pattern. (Mullard Radio Astronomy Observatory.)



3: The bottom trace is of broadcast one-second time pips. The middle trace shows the first recording to reveal the pulsed nature of the pulsar PSR1919. The top trace is of the third pulsar discovered, PSR0834.

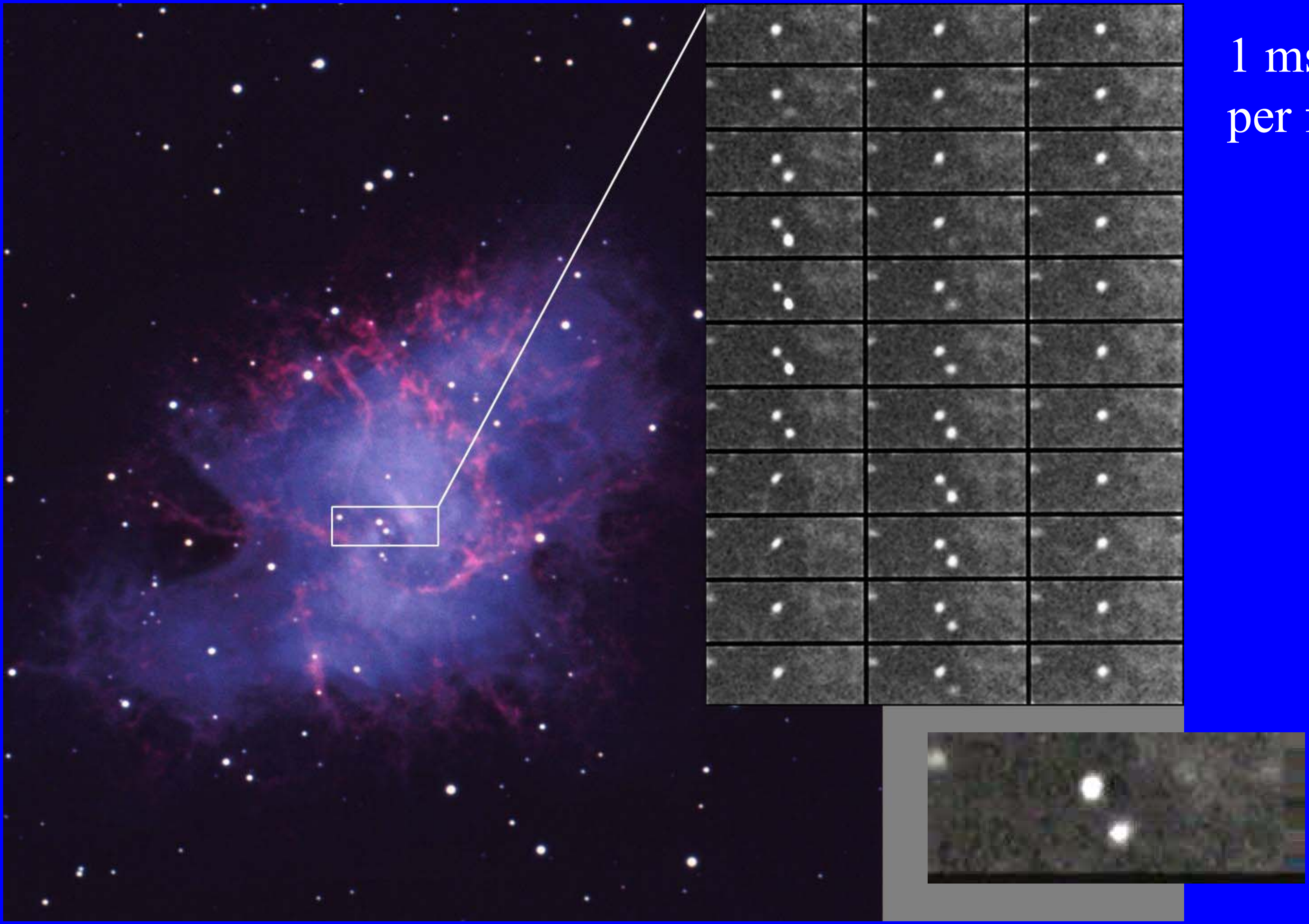
"It was highly unlikely that there would be two lots of little green men on opposite sides of the universe both deciding to signal at the same time to a rather inconspicuous star on a rather curious frequency." Jocelyn Bell

Crab nebula
in optical

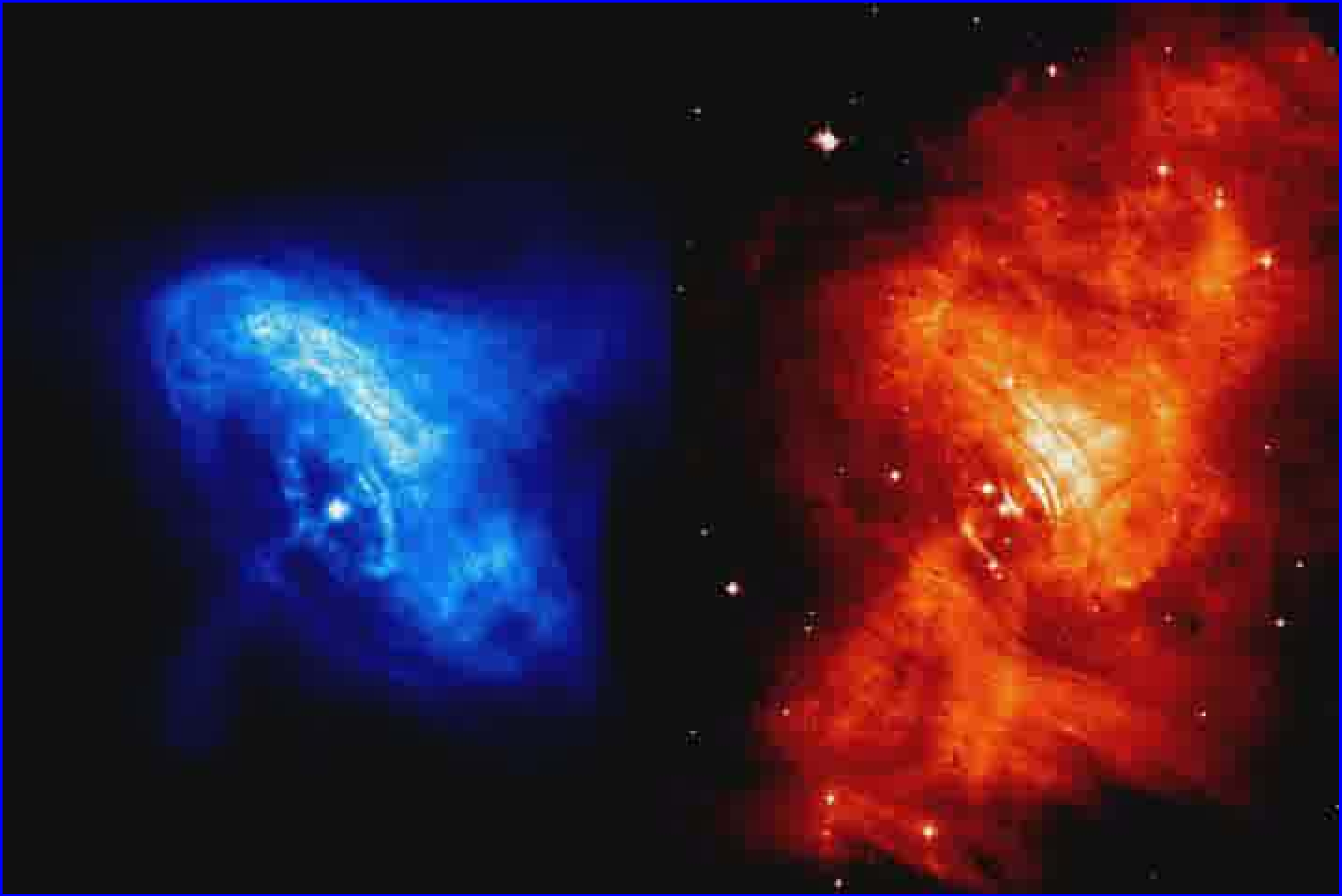
Supernova
July 4, 1054

Observed in
China, Japan,
Korea

Crab Pulsar (period = 1/30 sec)



1 msec
per frame



Crab nebula in x-ray (Chandra) and in optical (Hubble)

Observed neutron stars

> 1400 ns in isolated rotation-powered radio pulsars

$\sim$ 30 millisecond pulsars

> 100 ns in accretion-powered x-ray binaries

$\sim$ 50 x-ray pulsars

intense x-ray bursters (thermonuclear flashes)

Short (10-100 s) gamma-ray bursts (ns-ns, ns-bh mergers)

Soft gamma-ray repeaters -- magnetars ($B \sim 10^{14}$-10^{15}G)

Astrophysical impetus for studying dense matter

Neutron stars

$\rho > \rho_{nm}$, $T < 1\text{-}10$ MeV, $R \sim 10\text{-}12$ km, $M \sim 1.2\text{-}2\, M_\odot$

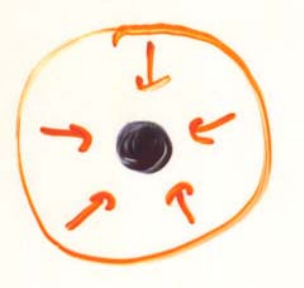
--birth, evolution and cooling (x-ray satellite observations)

--upper mass limits, black hole identification

Supernova and gravitational collapse

-- bounce above ρ_{nm}, energy release

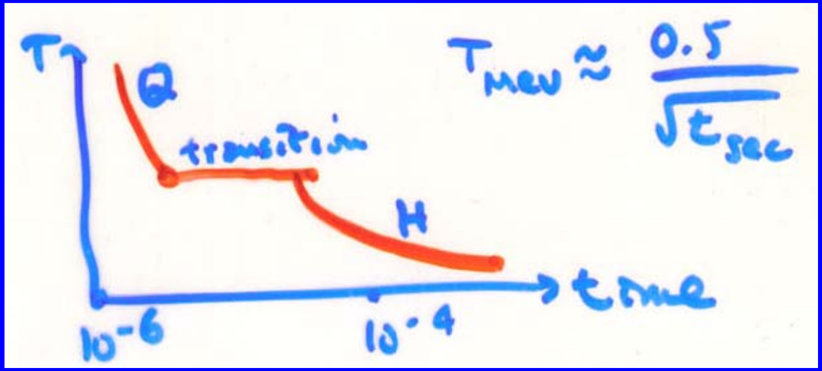
-- hot n-rich nuclei



Cosmology

-- mini- black holes

$M \sim M_{jupiter} \sim 10^{-2} M_\odot$



Cosmic rays

Maximum neutron star mass -- and black holes

Equation of state of matter at high baryon density determines maximum possible neutron star mass, and thus the cut on black holes. Conventional cut on black hole candidates: $M_{max} = 3.2M_\odot$. Improved knowledge of properties of dense matter leads to lower cut:

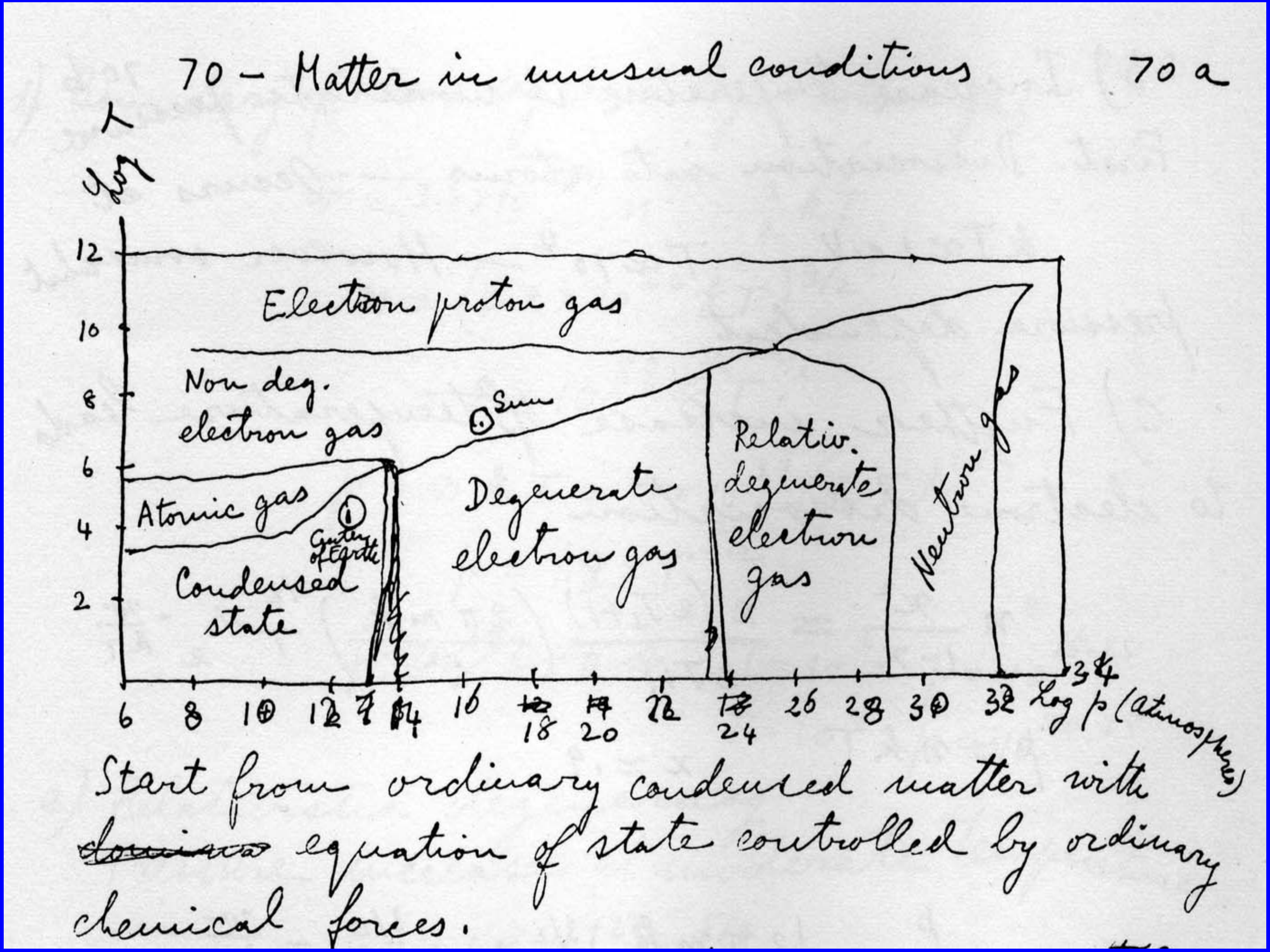
Knowing equation of state to
$\rho = 2\rho_{nm} \Rightarrow M_{ns} < 2.9\ M_\odot$
and to $4\rho_{nm} \Rightarrow M_{ns} < 2.2\text{-}2.3\ M_\odot$.

⇨ *many new small mass black hole candidates*

Mass function: $f_{opt} = (M_x^3 \sin i)/(M_x + M_{optical})^2 < M_x$
in low mass x-ray binaries

ex. Nova muscae, $f_{opt} = 3.1 \pm 0.4$
GRO J1655-40, $f_{opt} = 3.16 \pm 0.15$

E. Fermi: *Notes on Thermodynamics and Statistics* (1953)



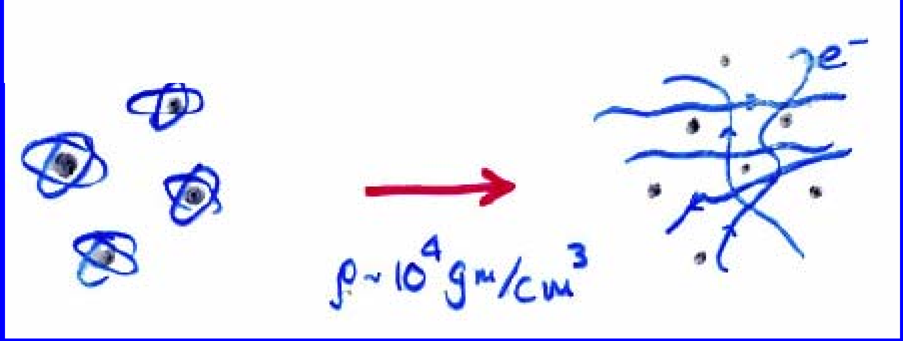
70 — Matter in unusual conditions

70 a

Start from ordinary condensed matter with ~~dominan~~ equation of state controlled by ordinary chemical forces.

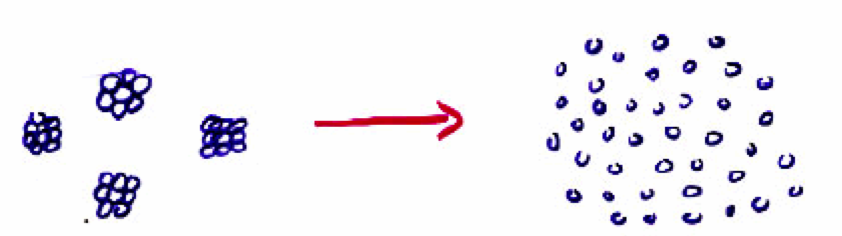
Compress matter to form new states

Atoms



Plasma

Nuclei

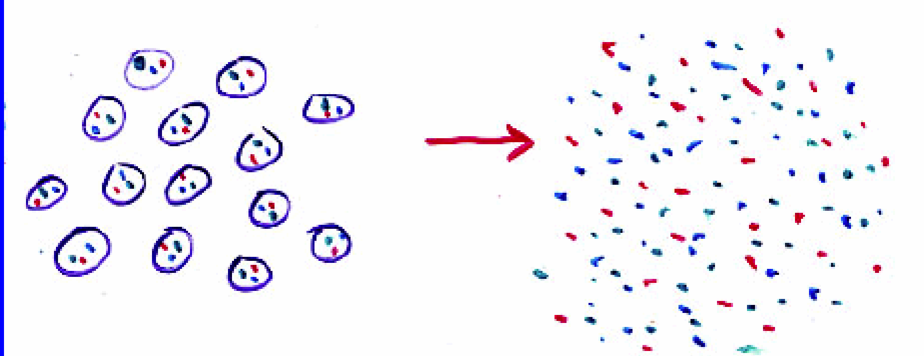


Nuclear matter

$\rho \sim 2.5 \times 10^{14}$ gm/cm^3 = ρ_{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.

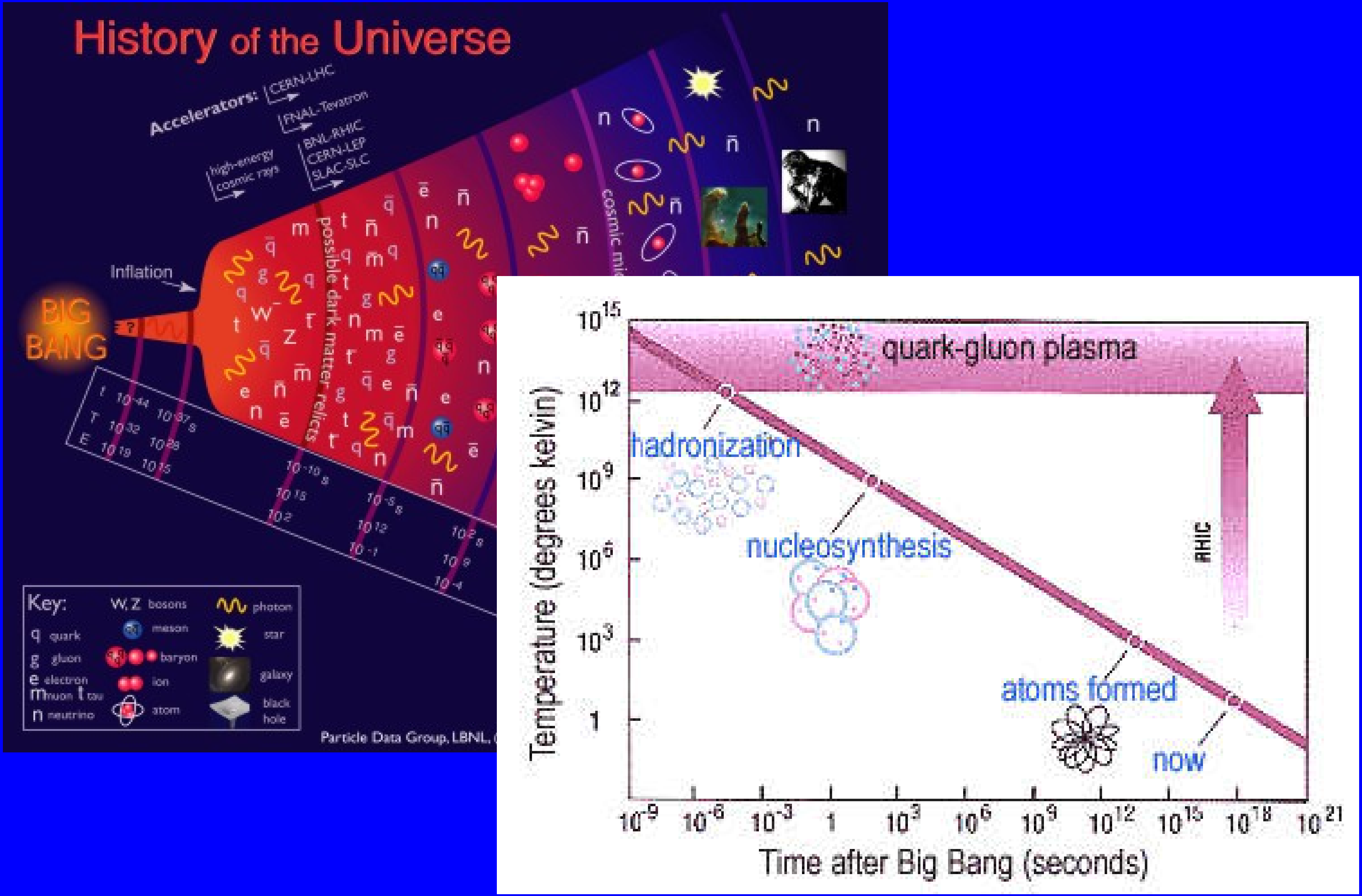
Flavor	Charge/|e|	Mass(MeV)
u	2/3	5 *(2.1-3.5)*
d	-1/3	10 *(2.1-3.5)*
s	-1/3	150 *(54-92)*
c	2/3	1300
b	-1/3	4200
t	2/3	175000

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 $t < 1\mu$ sec ($T > 100$ MeV).

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

Evolution of early universe



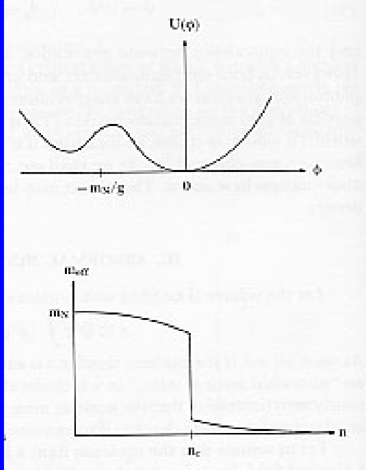
What are the properties of matter under extreme conditions? High temperature, high densities!

Early hadronic pictures:

Lee-Wick abnormal matter

Hagedorn hadronic resonance gas

Walecka mean field model

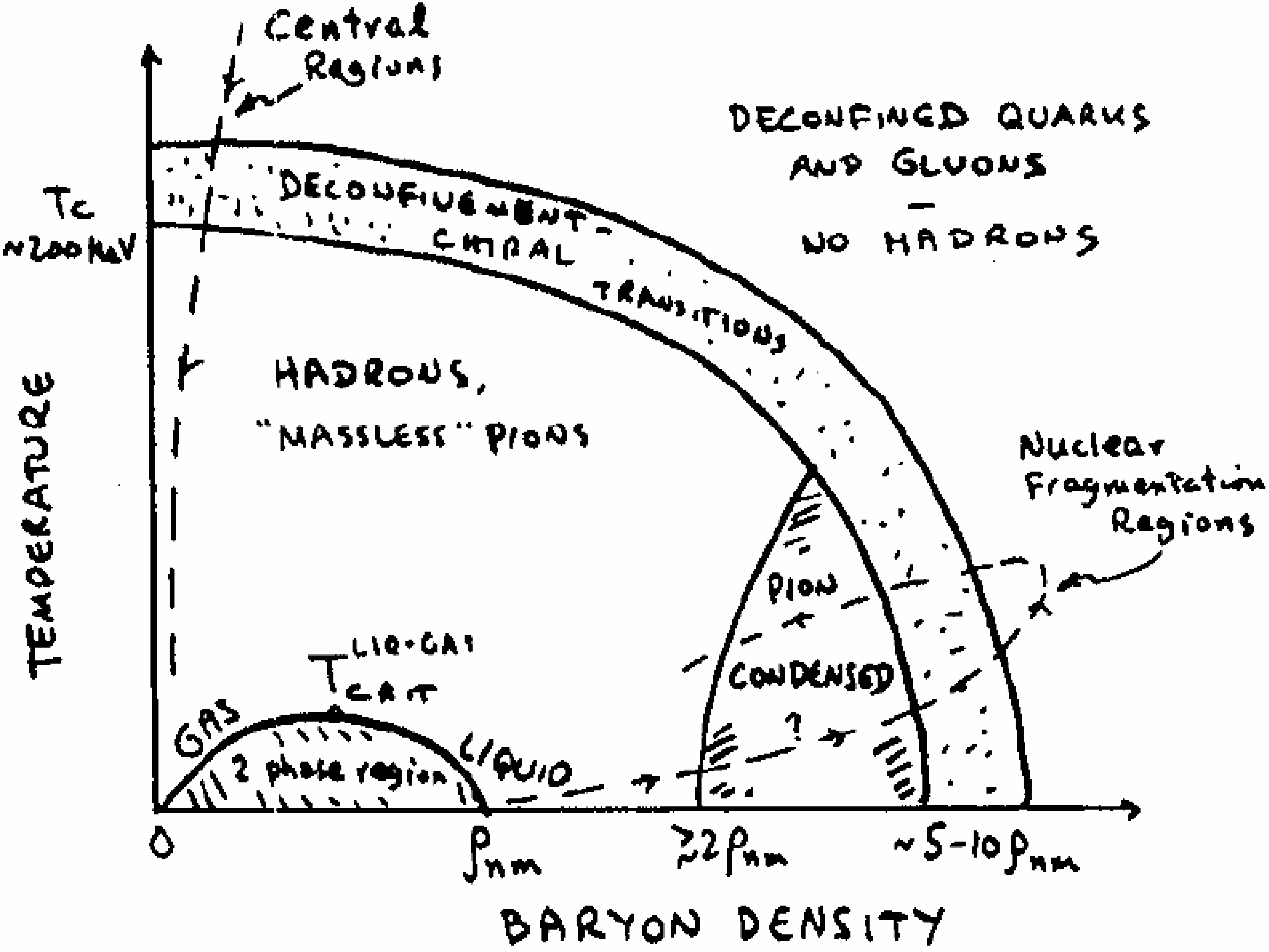


Quark matter ("quark soup") as ultimate state (1970-75):

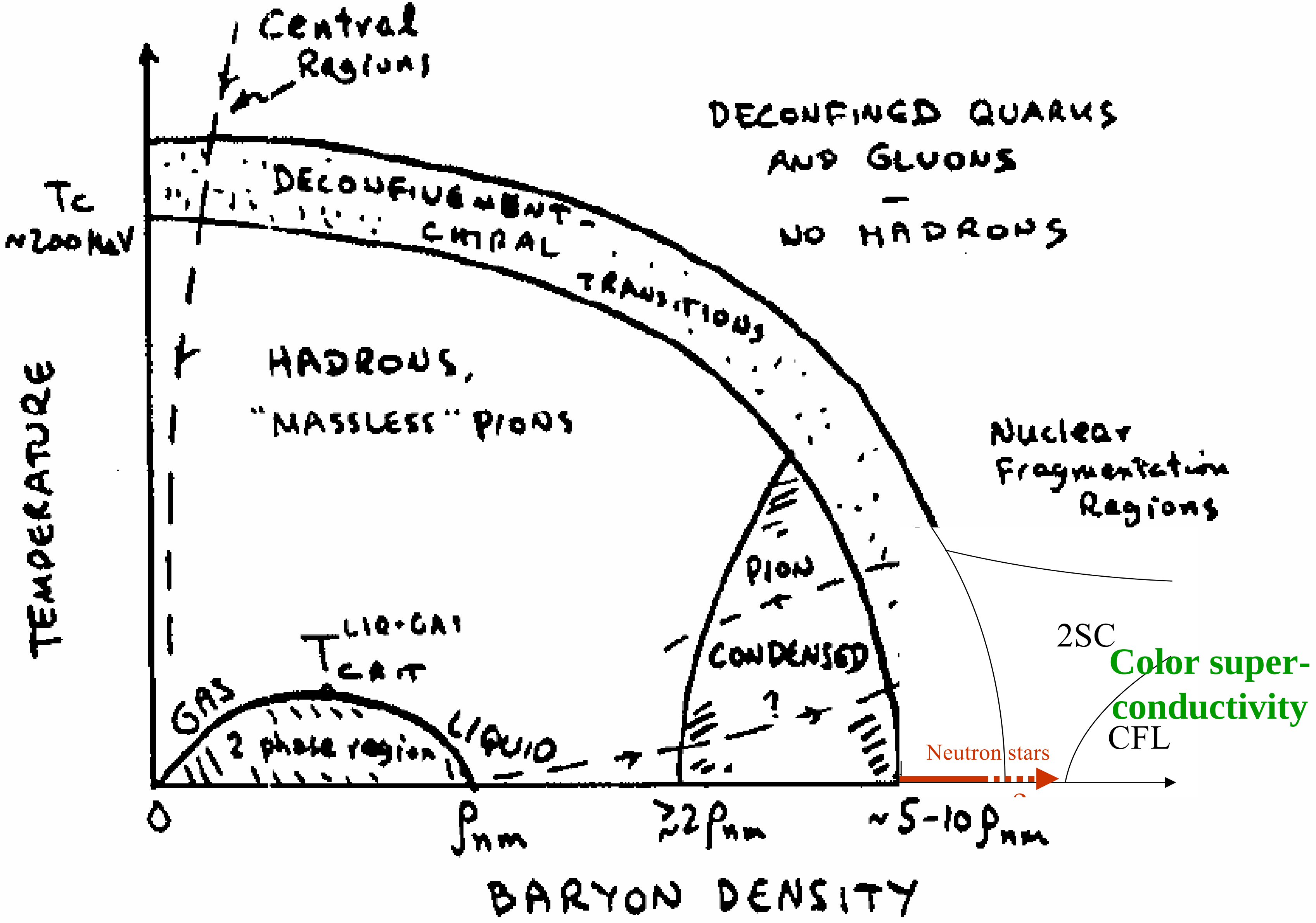
Asymptotic freedom of QCD ⇔ at ultrahigh densities or temperatures "quarks interact weakly."

Quark matter in neutron stars: "Can a neutron star be a giant MIT bag?"

PHASE DIAGRAM OF NUCLEAR MATTER



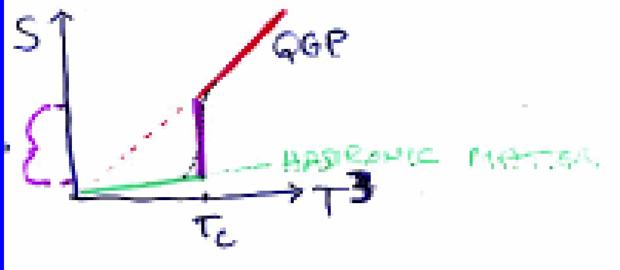
PHASE DIAGRAM OF NUCLEAR MATTER



Quark-gluon plasma state

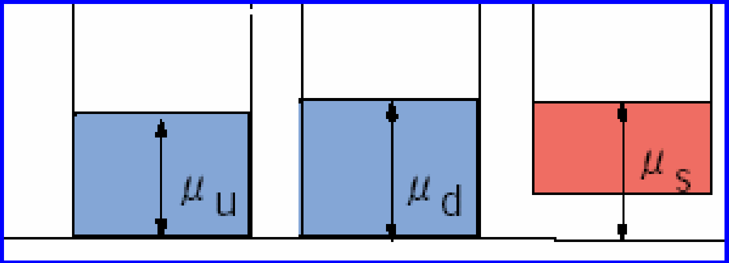
Degrees of freedom are deconfined quarks and gluons

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?)



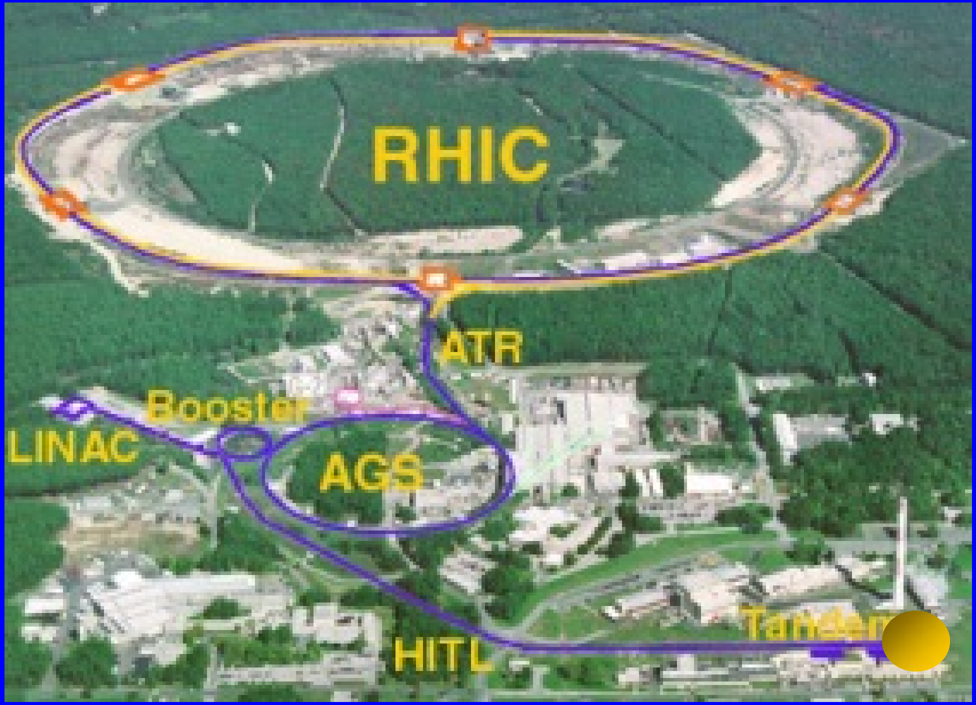
核子重如牛
對撞生新態

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

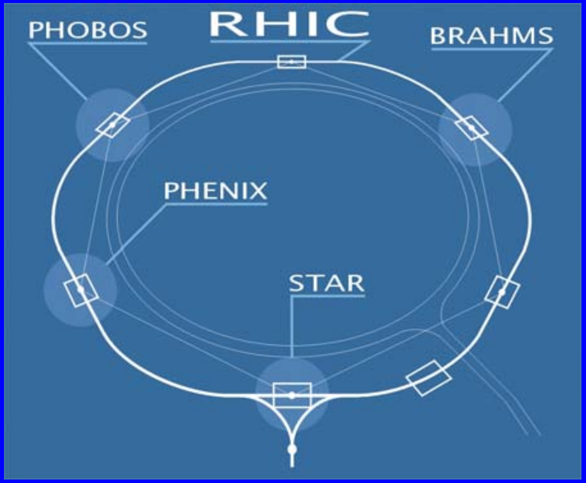
T.D. Lee

Creating high energy density matter in the lab

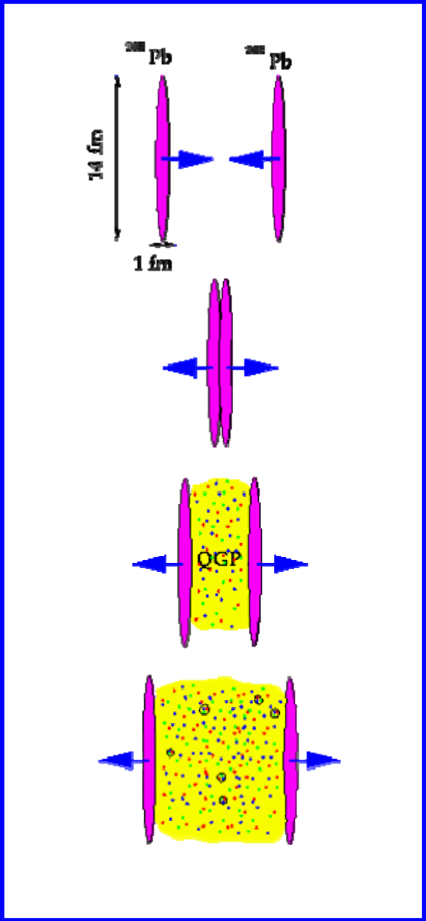
Relativistic Heavy Ion Collider (Brookhaven) since 2000. Colliding beams 100 GeV/A
Large Hadron Collider (CERN) in 2008-9. 2700 GeV/A
FAIR (GSI) ca. 2015 to 45 GeV/A



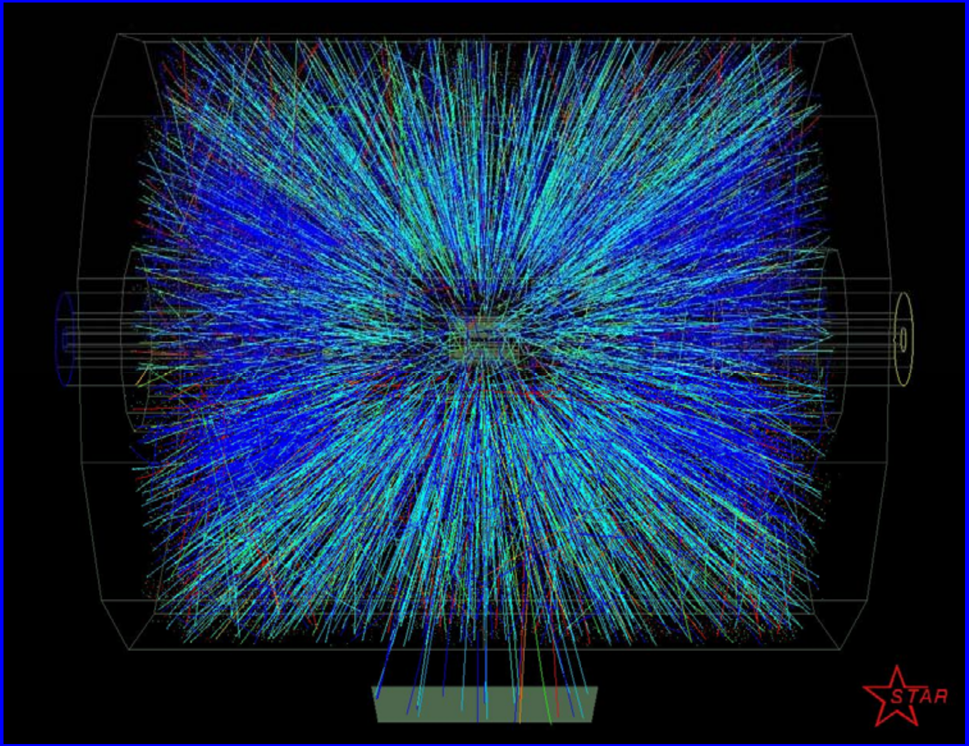
T. Hirano



$$Au(197 \times 100GeV)+Au(197 \times 100GeV)$$



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



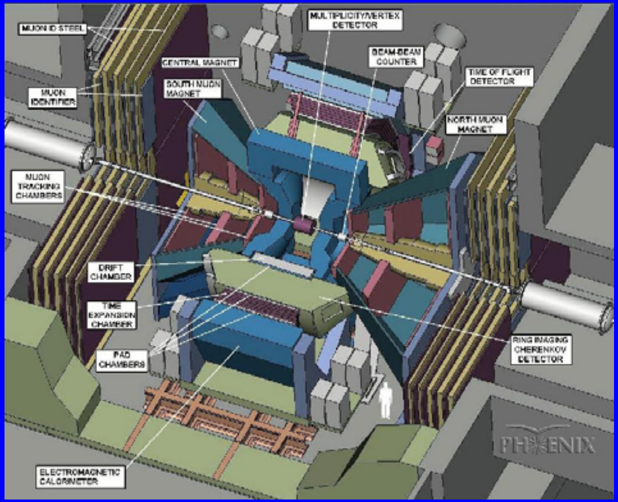
What collisions actually look like in the lab. STAR detector

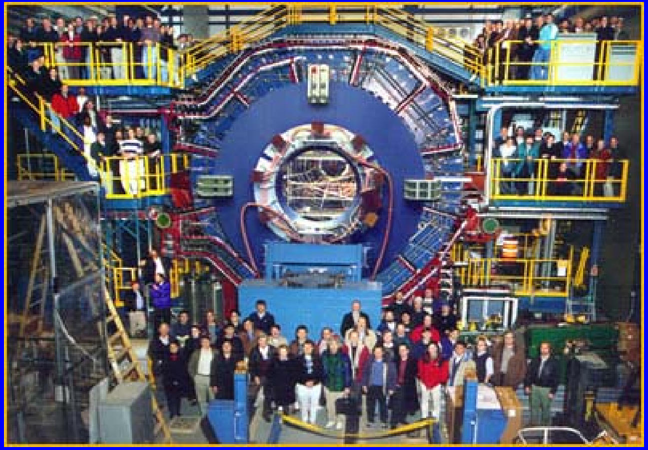
Two major detectors at RHIC

- PHENIX
- STAR

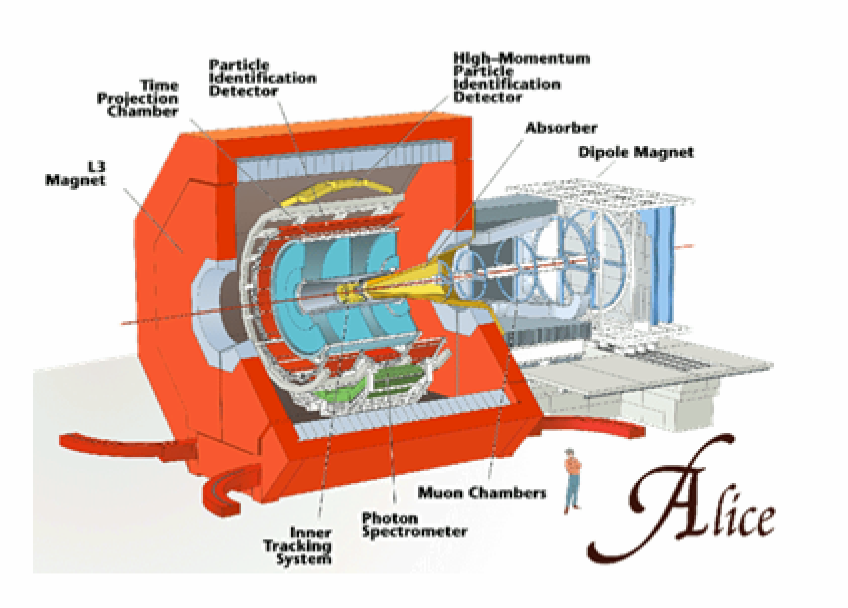
Two smaller detectors

- 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 × 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

Ultracold trapped atomic clouds

Deconfined quark-gluon plasmas

made in ultrarelativistic heavy ion collisions

T ~ 10^2 MeV ~ 10^{12} K (temperature of early universe at ~1μ sec)

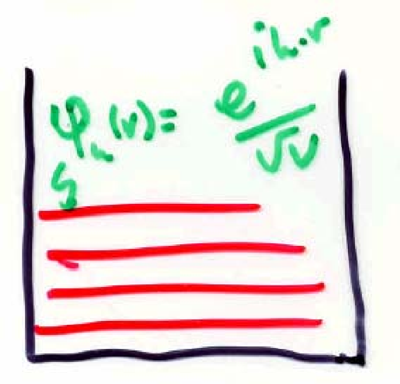
Trapped cold atomic systems:

Bose-condensed and BCS fermion superfluid states

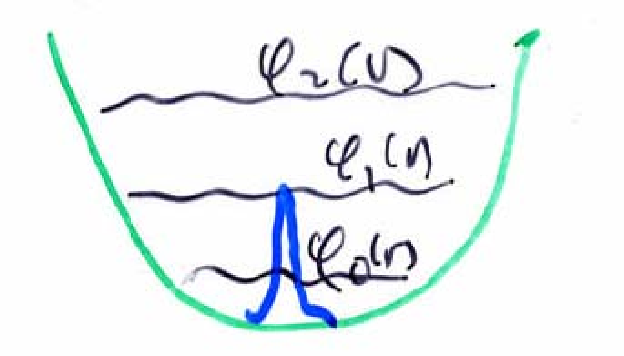
T ~ nanokelvin (traps are the coldest places in the universe!)

Although these systems are separated by ~21 decades in characteristic energy scales, they have intriguing and unexpected overlaps.

Cold atoms: trapped bosons and fermions



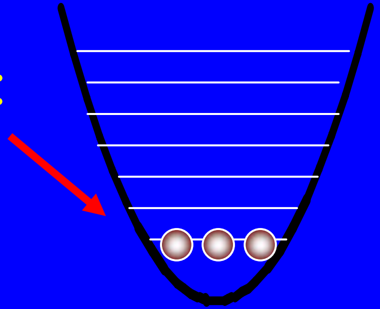
Box

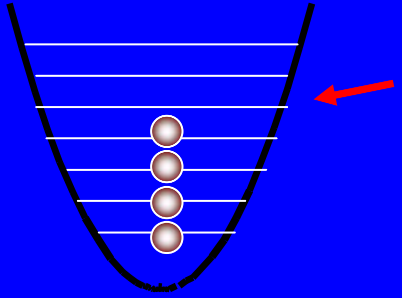


Potential well (trap)

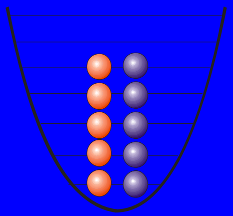
Statistics:

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





Degenerate Fermi gas



=> BCS pairing

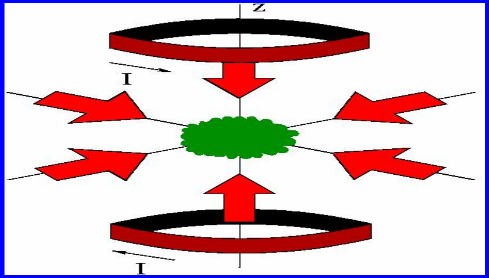
Trapped atomic experiments in a nutshell

Warm atomic vapor

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

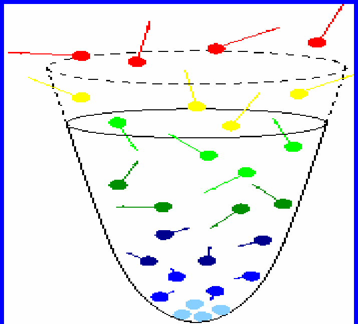
3 -

Magneto-optical trap



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

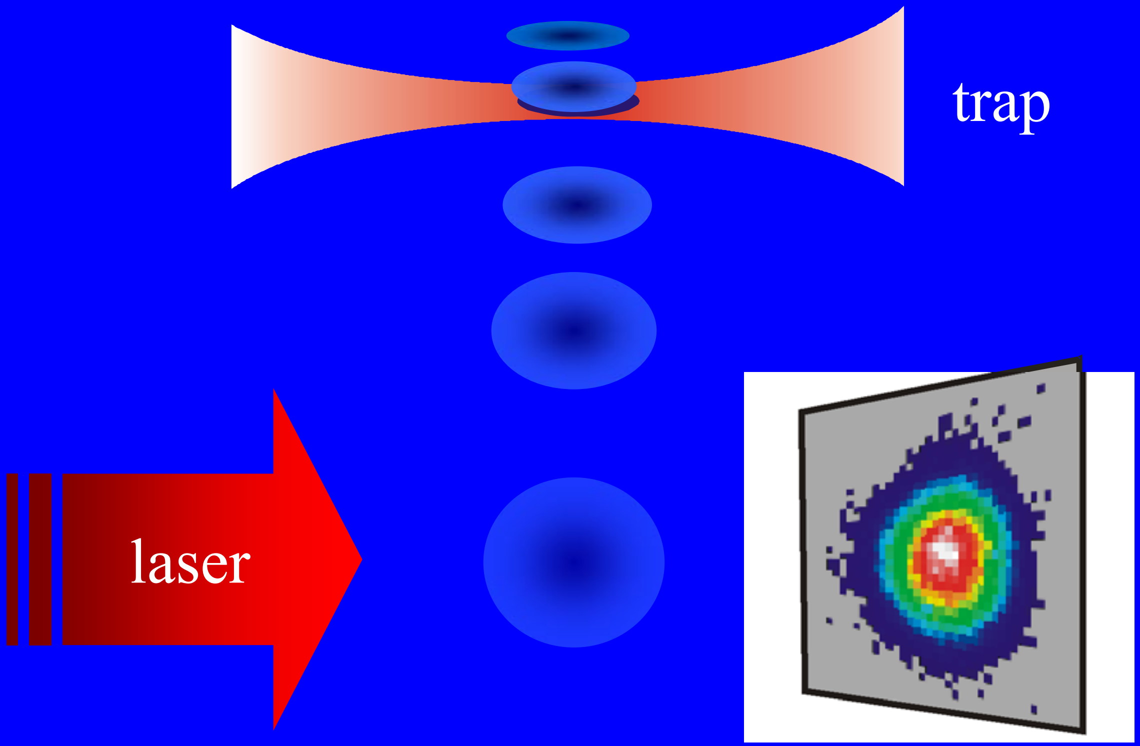
Evaporatively cool in magnetic (or optical) trap



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 :

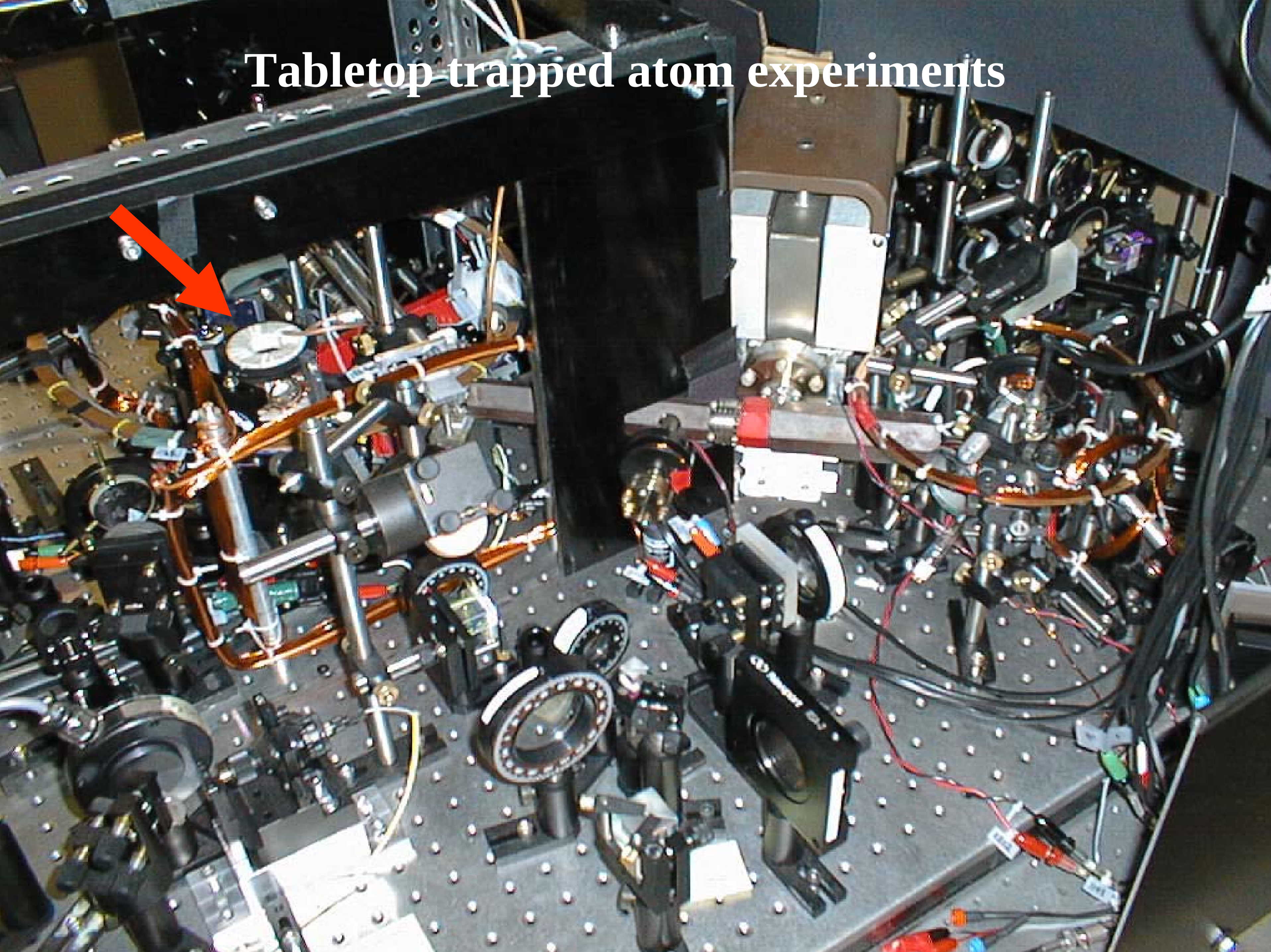
To probe system, release from trap, let expand and then image with laser:



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-	1.3×10^{9}y
^{41}K	3/2+				
^{85}Rb	5/2-		^{86}Rb	2-	18.6d
^{87}Rb	3/2-	4.75×10^{10}y			
^{131}Cs	5/2+	9.7d	^{132}Cs	2+	6.5d
^{133}Cs	7/2+				
^{135}Cs	7/2+	2.3×10^{6}y	^{134}Cs	4+	2.06y
^{209}Fr	9/2-	50.0s	^{208}Fr	7+	59.1s

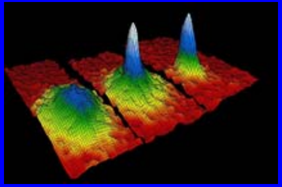
Tabletop trapped atom experiments



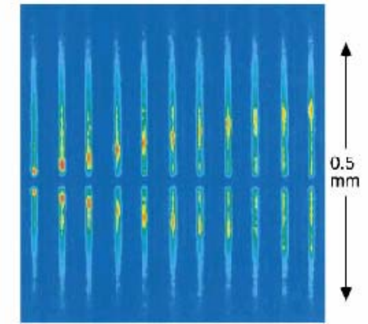
Early days of ultracold trapped atomic gases

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

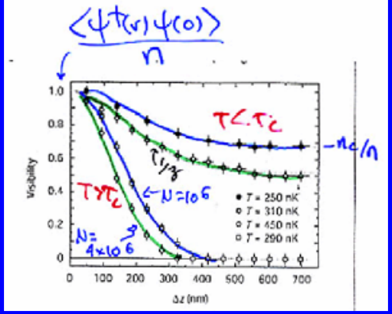
*Structure of condensate.



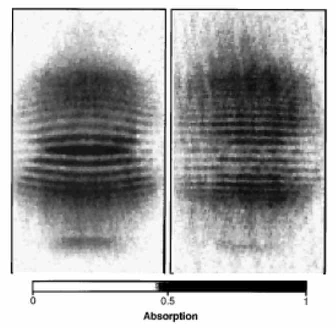
*Elementary modes: breathing, quadrupole, short wave sound, …



*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.

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

Newer 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

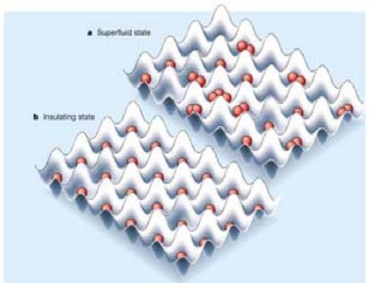
a = s-wave scattering length

Realize through atomic Feshbach resonances

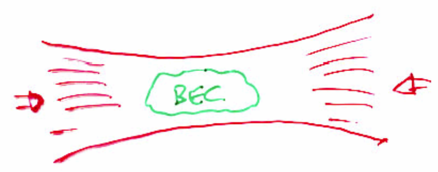
Newer directions in ultracold atomic systems, II

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

Common problems of cold atom and high energy nuclear physics:

Small clouds with many degrees of freedom ~ 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

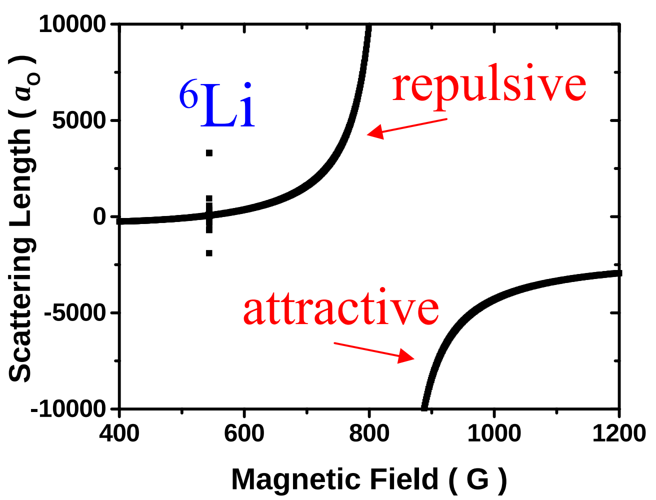
In cold atoms, effective atom-atom interaction is short range and s-wave:

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

a = s-wave atom-atom scattering length.

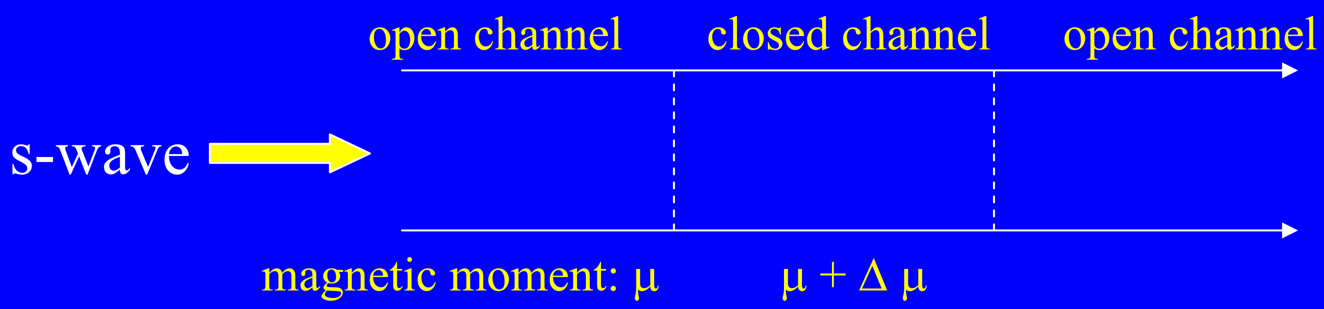
Cross section: $\sigma=8\pi a^2$

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



open channel closed channel open channel

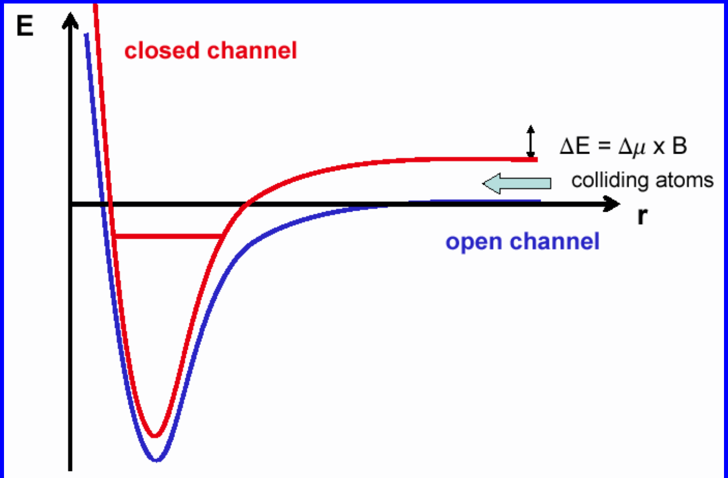
s-wave

magnetic moment: μ $\quad \mu + \Delta\,\mu$

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

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

Low energy scattering dominated by bound state closest to threshold

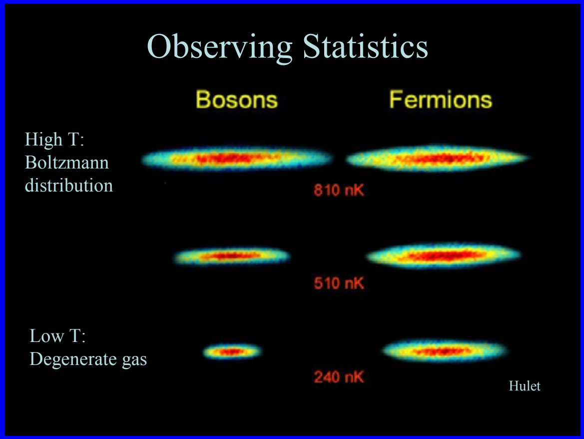


Adjusting magnetic field, B, causes level crossing and resonance, seen as divergence of s-wave scattering length, a:

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

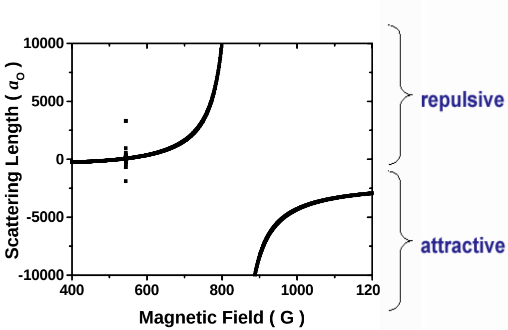
Degenerate ultracold atomic Fermi gases

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," force range << interparticle spacing << scattering length, only relevant length scale is the interparticle spacing.

At temperatures ~ 0.2 of the degeneracy temperature (T_f), create BCS paired superfluids

Both systems scale-free in strongly coupled regime

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

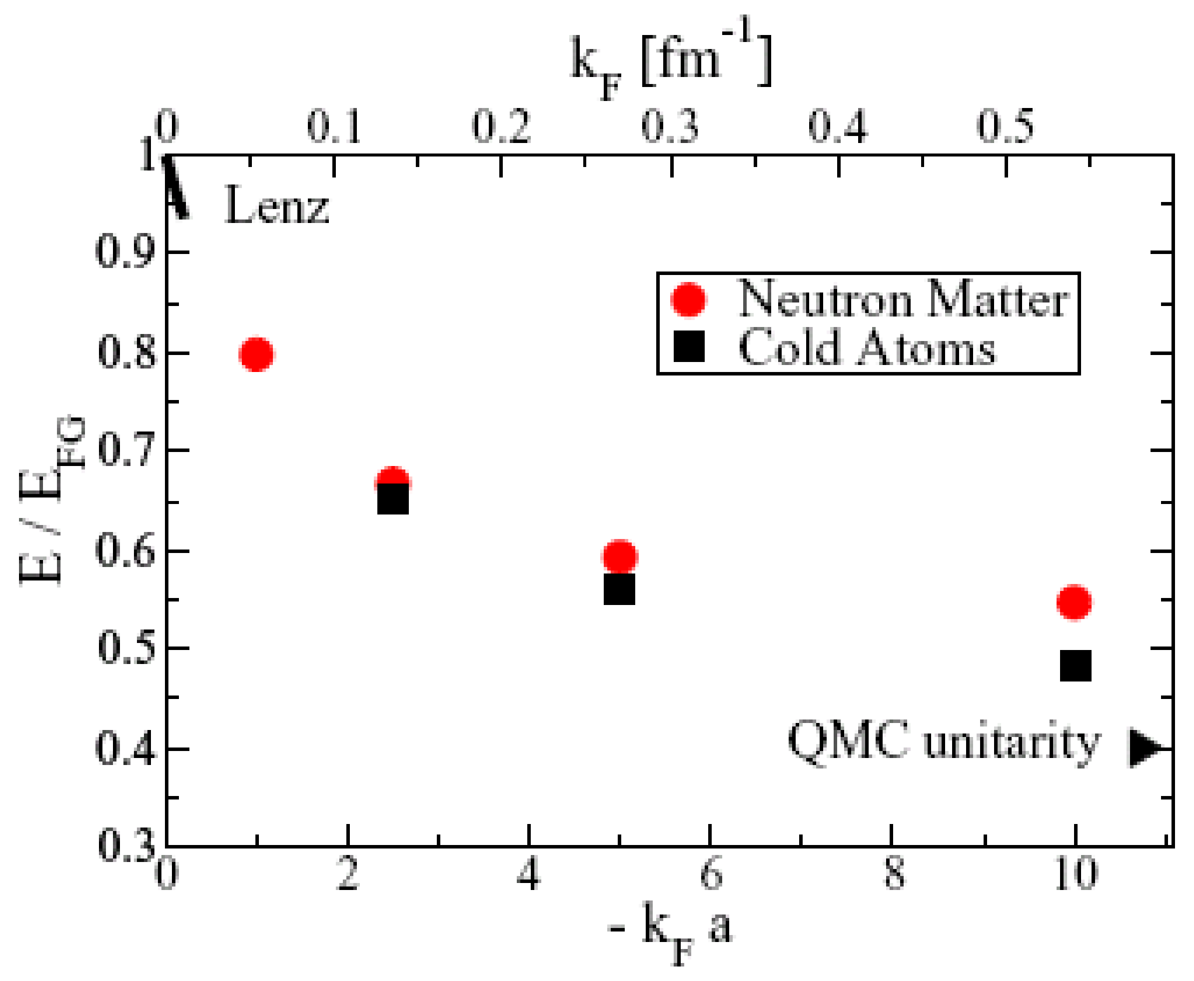
In cold atoms near resonance only length-scale is density.
No microscopic parameters enter equation of state:

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

β is a universal parameter. No systematic expansion

Theory: $\beta = -0.60\ (0.2)$ *Green’s Function Monte Carlo, Gezerlis & Carlson (2008)*
Experiment: -0.54(5) *Rice*

Remarkably similar behavior of ultracold fermionic atoms and low density neutron matter (a_{nn}= -18.5 fm)



A. Gezerlis and J. Carlson, Phys. Rev. C 77, 032801(R) (2008)

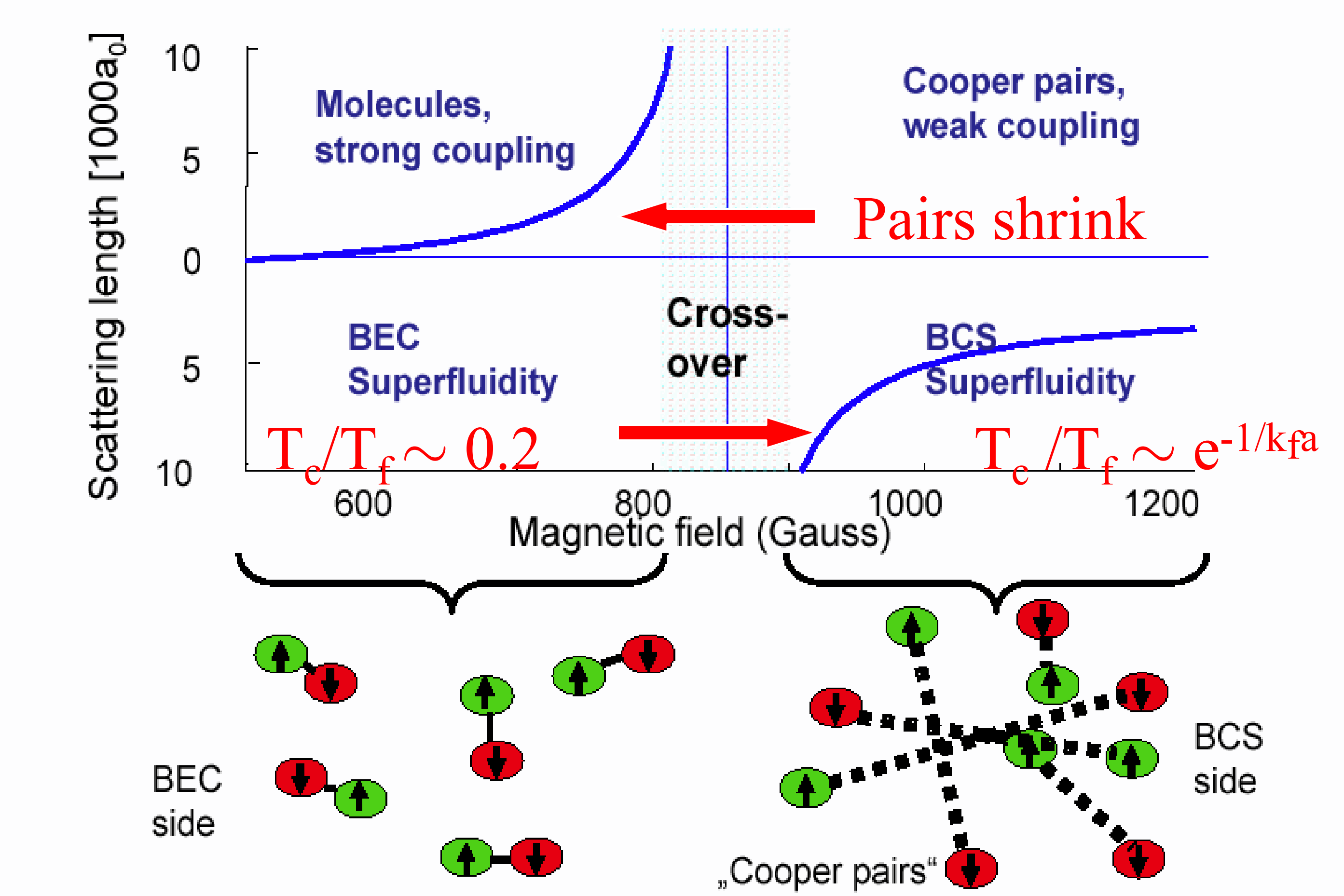
BEC-BCS crossover in Fermi systems

Continuously transform from molecules to Cooper pairs:

D.M. Eagles (1969)

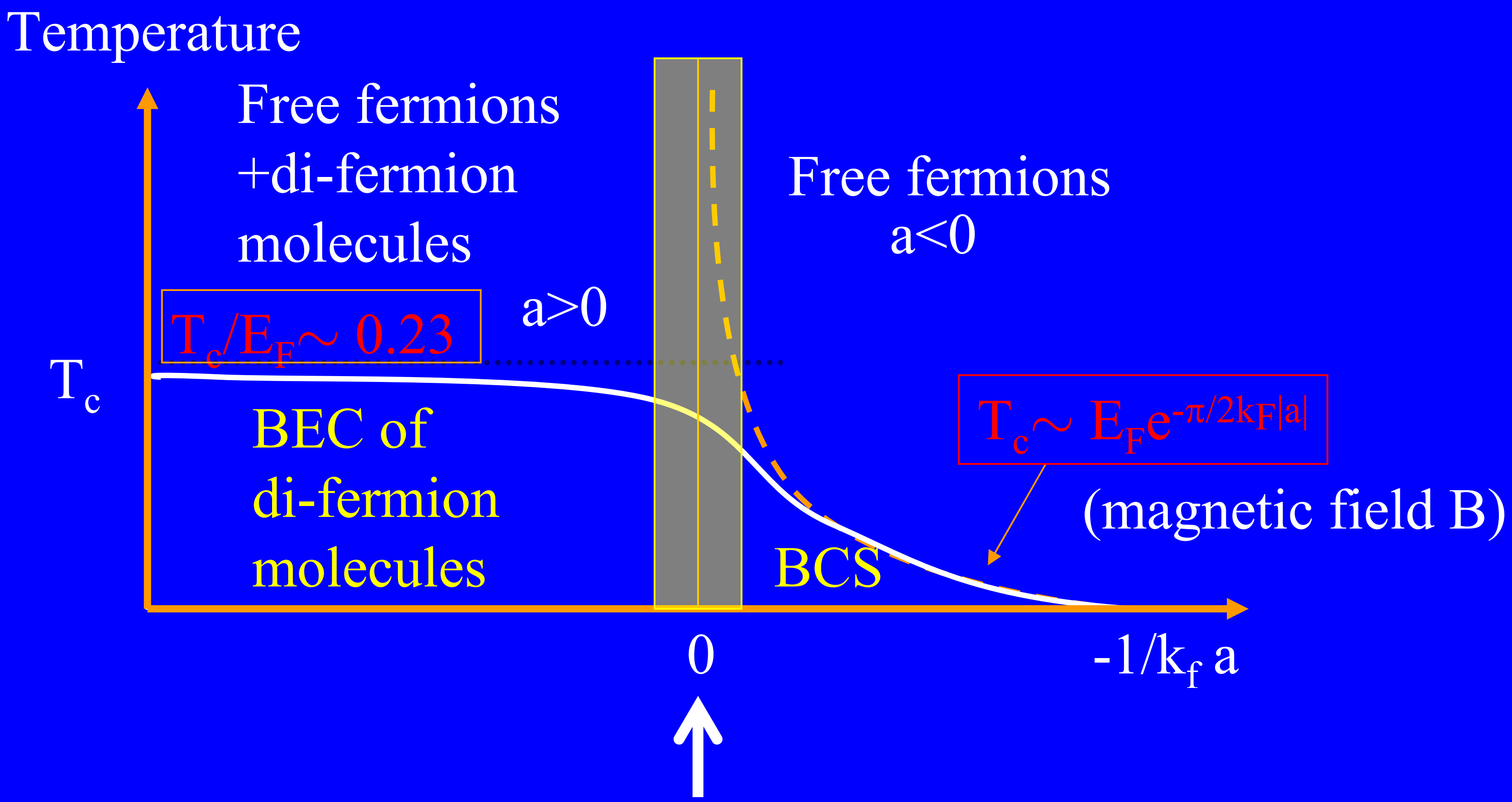
A.J. Leggett, J. Phys. (Paris) C7, 19 (1980)

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

$T_c/E_F \sim 0.23$

a>0

T_c

BEC of
di-fermion
molecules

Free fermions
a<0

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

(magnetic field B)

BCS

0

$-1/k_f\,a$

Unitary regime -- crossover

No phase transition through crossover

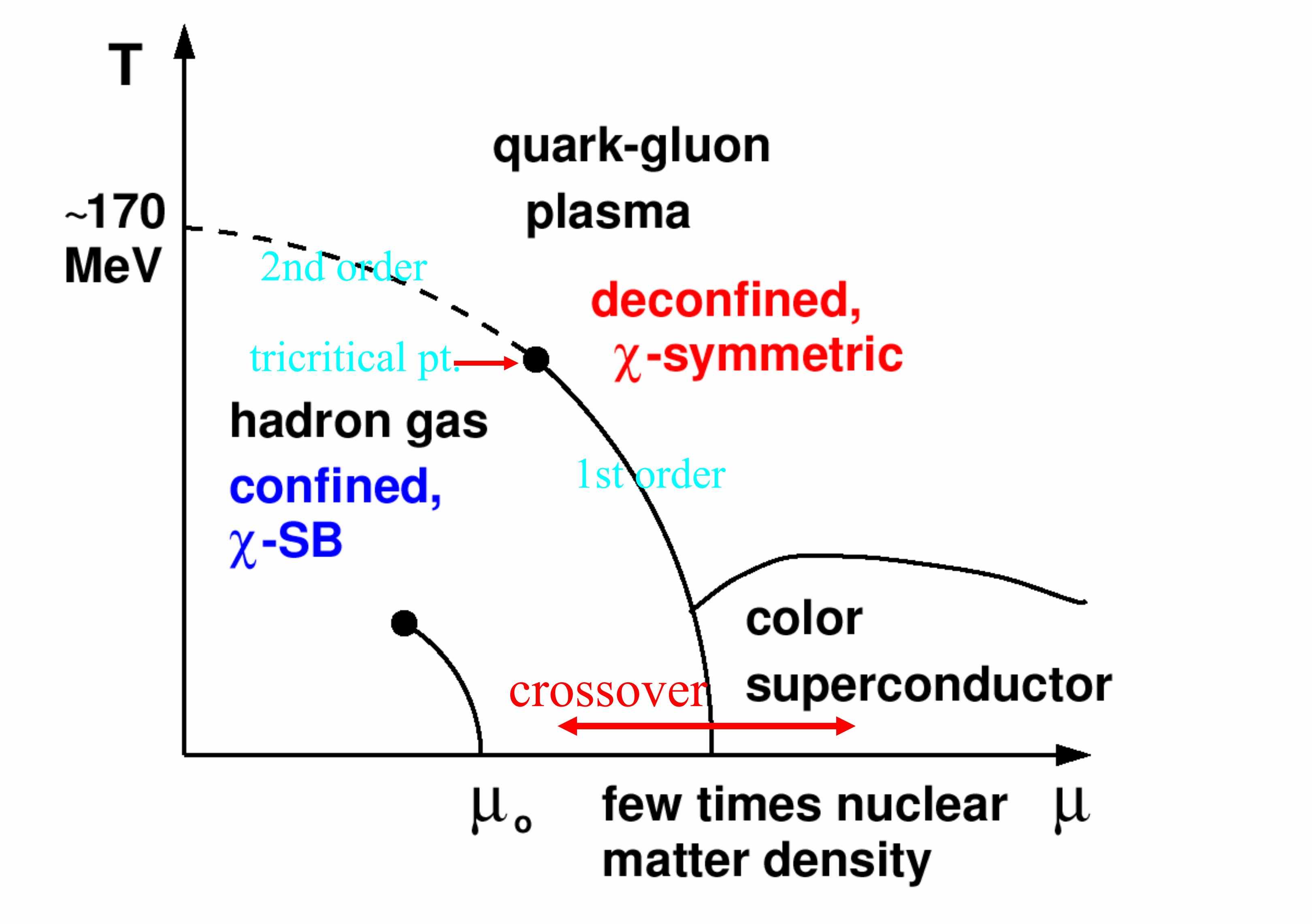
Striking relation of Bose-Einstein condensation and BCS pairing

The two phenomena developed along quite different paths

"Our pairs are not localized ..., and our transition is not analogous to a Bose-Einstein condensation."
BCS paper Oct. 1957

"We believe that there is no relation between actual superconductors and the superconducting properties of a perfect Bose-Einstein gas. The key point in our theory is that the virtual pairs all have the same net momentum. The reason is not Bose-Einstein statistics, but comes from the exclusion principle... ." *Bardeen to Dyson, 23 July 1957*

Phase diagram of quark gluon plasma

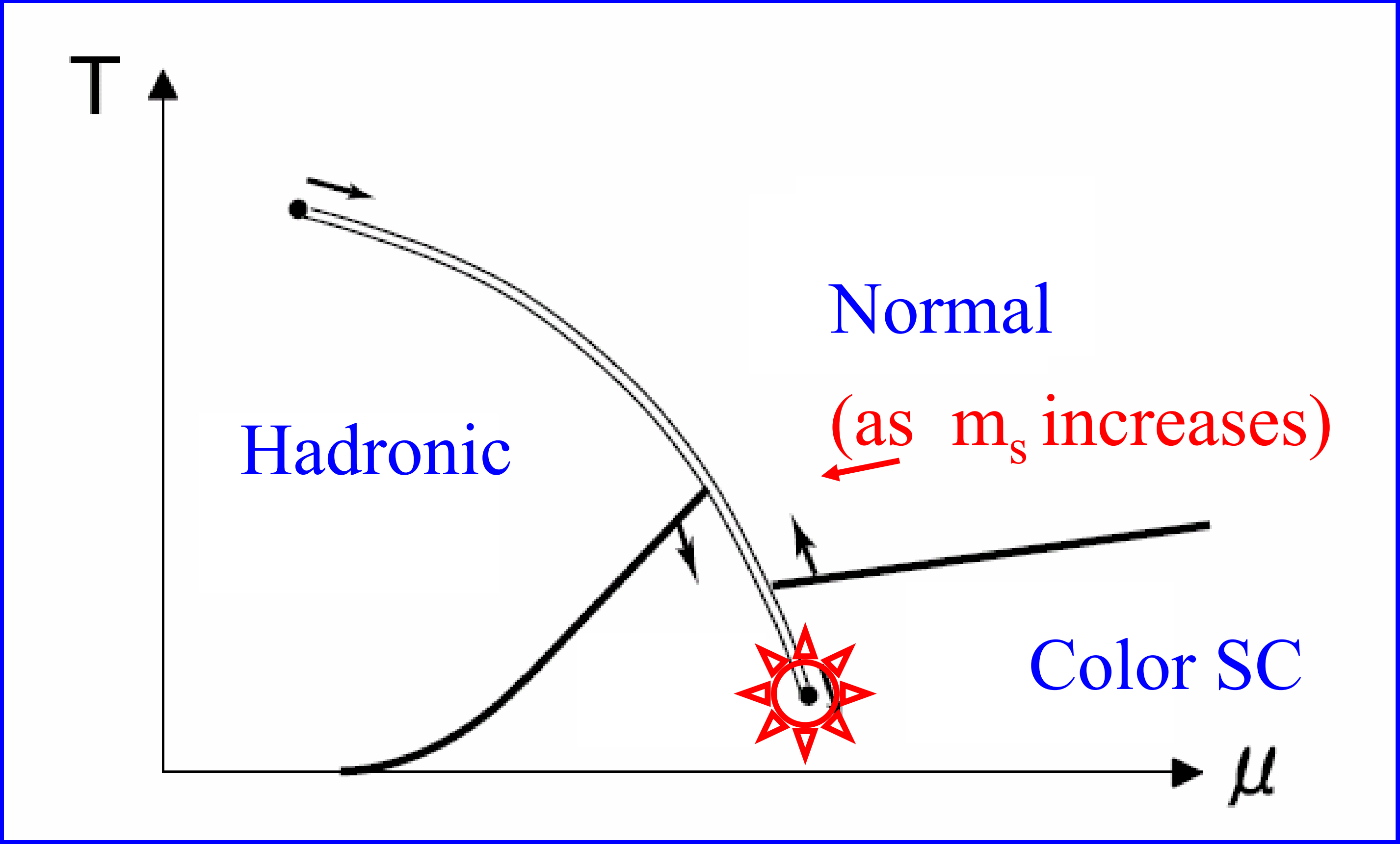


Karsch & Laermann, hep-lat/0305025

New critical point in phase diagram:

induced by chiral condensate – diquark pairing coupling via axial anomaly

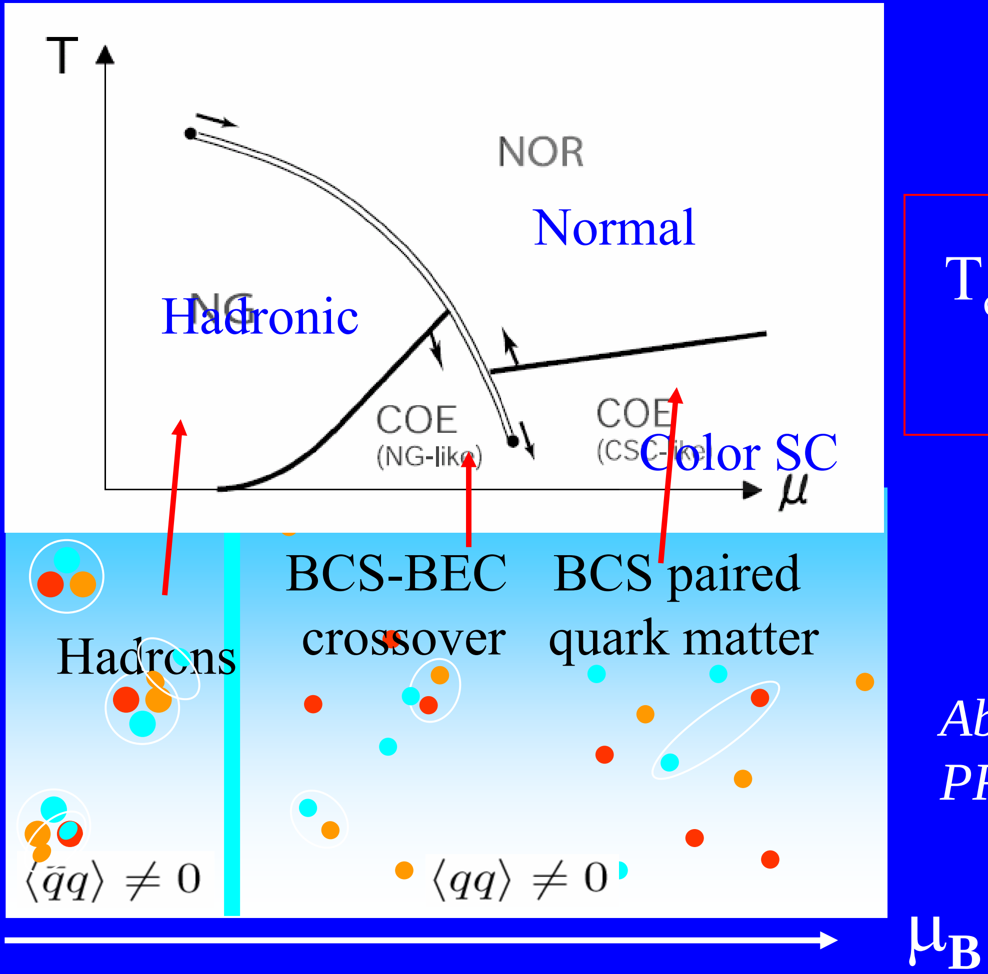
Hatsuda, Tachibana, Yamamoto & GB, PRL 97, 122001 (2006); PRD 76, 074001 (2007)

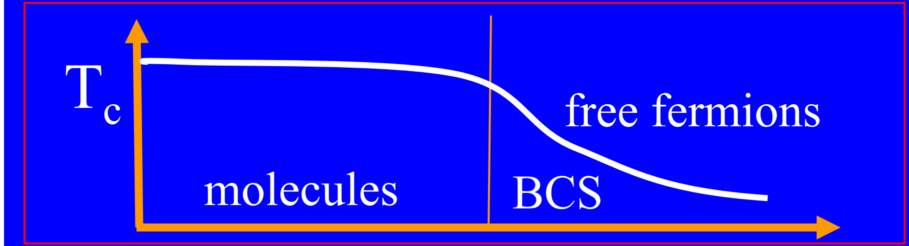


Deconfinement transition vs. BEC-BCS crossover

In SU(2)$_C$: Hadrons <=> 2 fermion molecules.
Paired deconfined phase <=> BCS paired fermions

In SU(3)$_C$





Abuki, Itakura & Hatsuda, PRD65, 2002

Limitations of equation of state based on nucleon-nucleon interactions

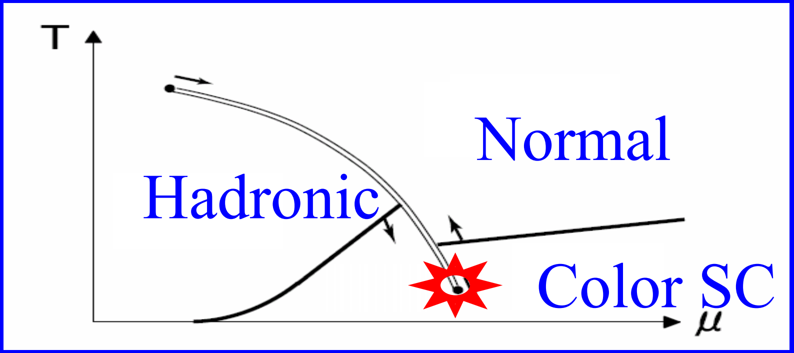
Accurate for neutron star matter in neighborhood of n_{nm}.

Beyond few n_{nm} :
cannot describe forces in terms of static few-body potentials.
Characteristic range of nuclear forces $\sim 1/2m_\pi$ =>
importance of 3 and higher body forces $\sim n/(2m_\pi)^3 \sim 0.4n/\{\mathrm{fm}\}^{-3}$.
For $n >> n_{nm}$, no well defined expansion.

Further hadronic degrees of freedom enter

Cannot describe high density matter in terms of well-defined "asymptotic" laboratory particles.

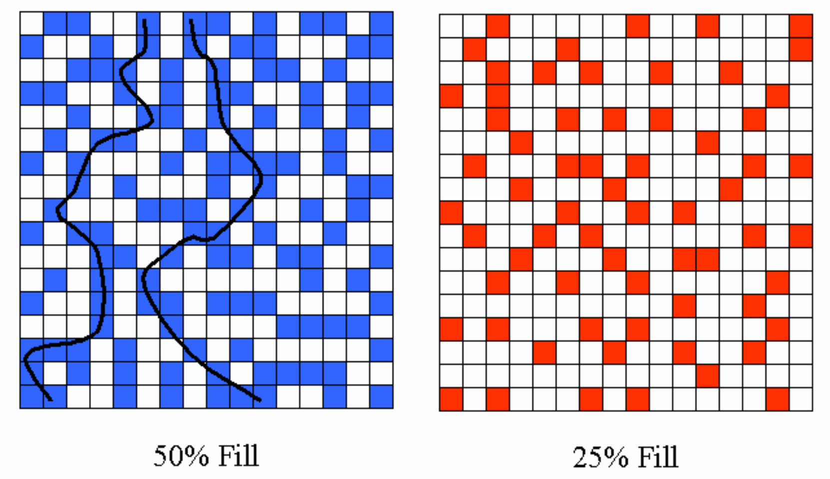
More realistically, expect gradual onset of quark degrees of freedom in dense matter



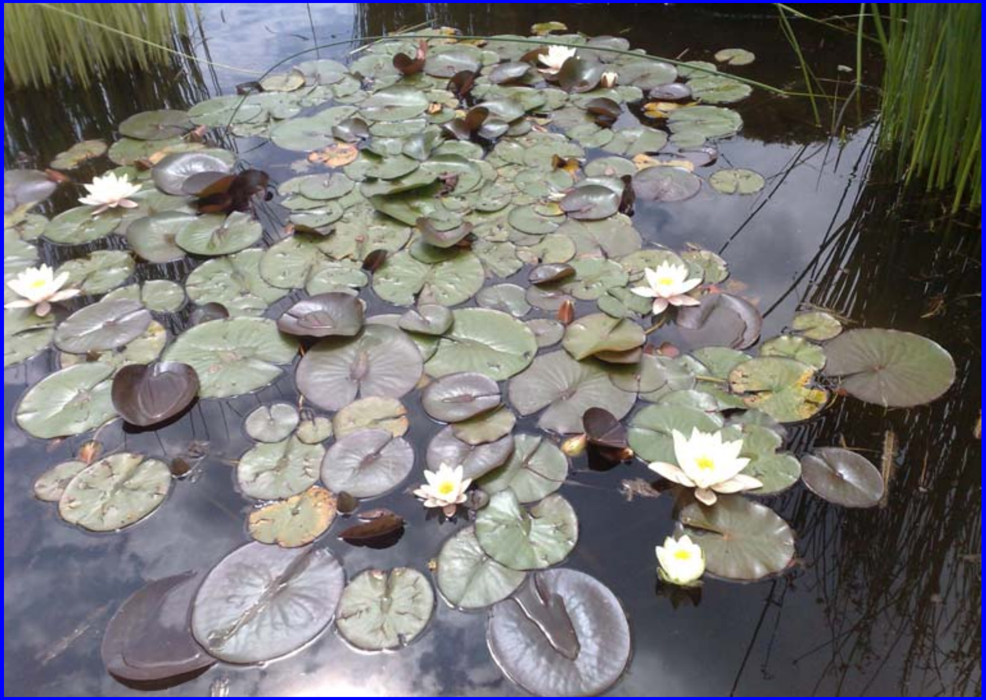
New critical point suggests transition to quark matter is a crossover at low T

Consistent with percolation picture, that as nucleons begin to overlap, quarks percolate [*GB, Physica (1979)*] :

$$n_{perc} \sim 0.34\ (3/4\pi\ r_n^3)\ \ \mathrm{fm}^{-3}$$

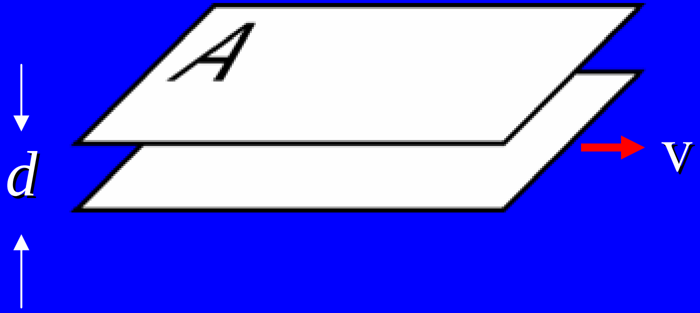


Quarks can still be bound even if deconfined.



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 = η 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

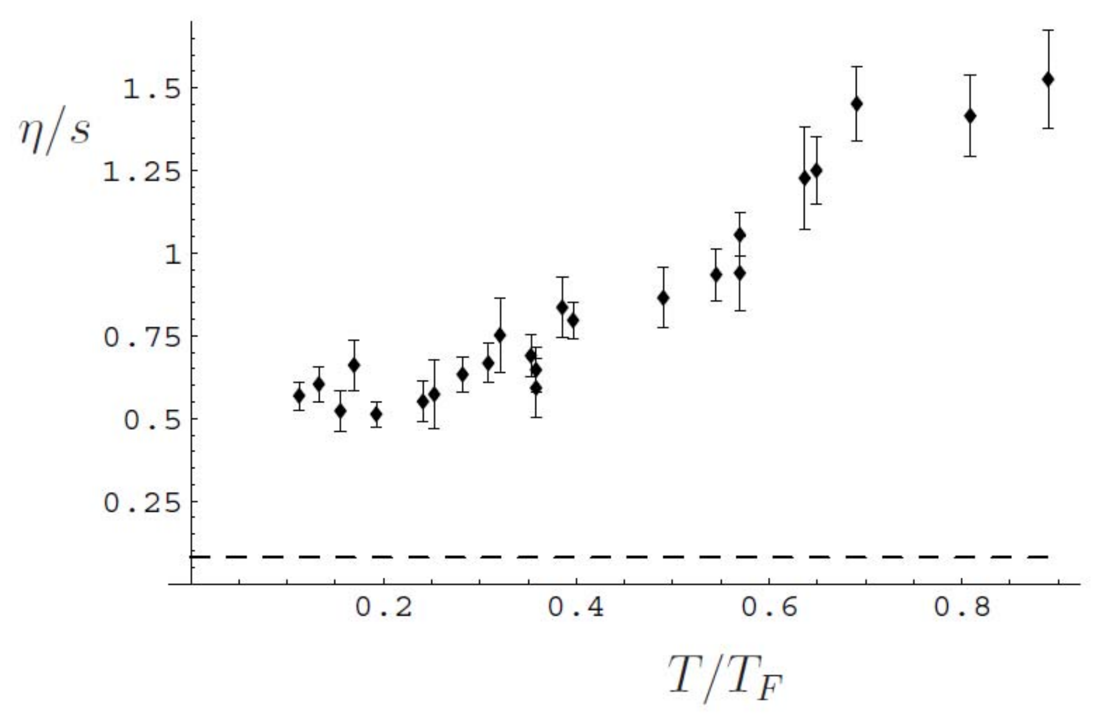
Strong interactions => small η

Viscosity extracted from radial breathing mode

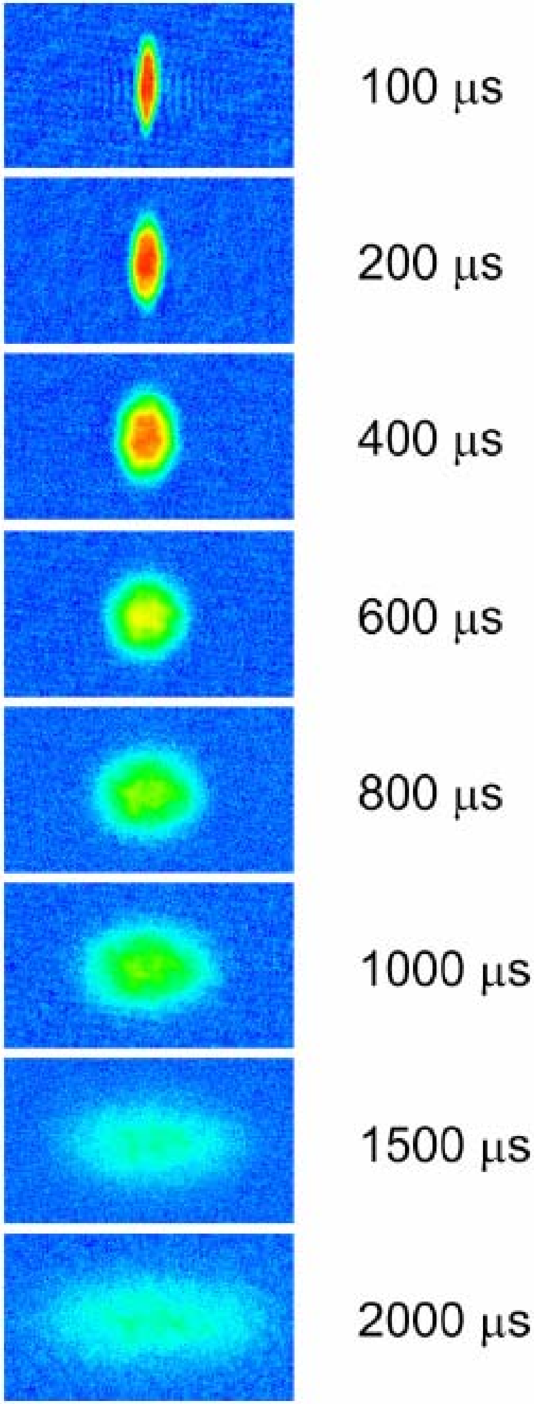
Expt: J. Kinast, A. Turlapov, J.E. Thomas, PRL 94, 170404 (2005)

Theory: T. Schaefer, Phys. Rev. A 76, 063618 (2007)

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



Temperature/ Fermi temperature



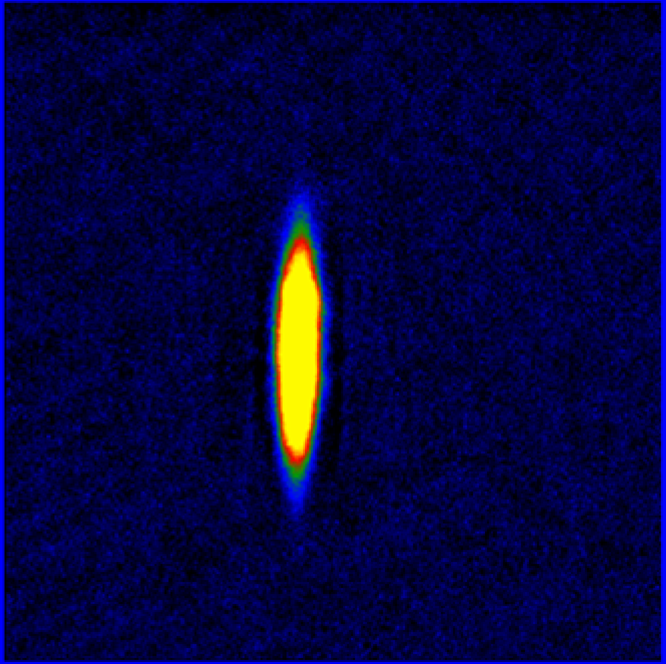
Strongly coupled ^{6}Li expansion

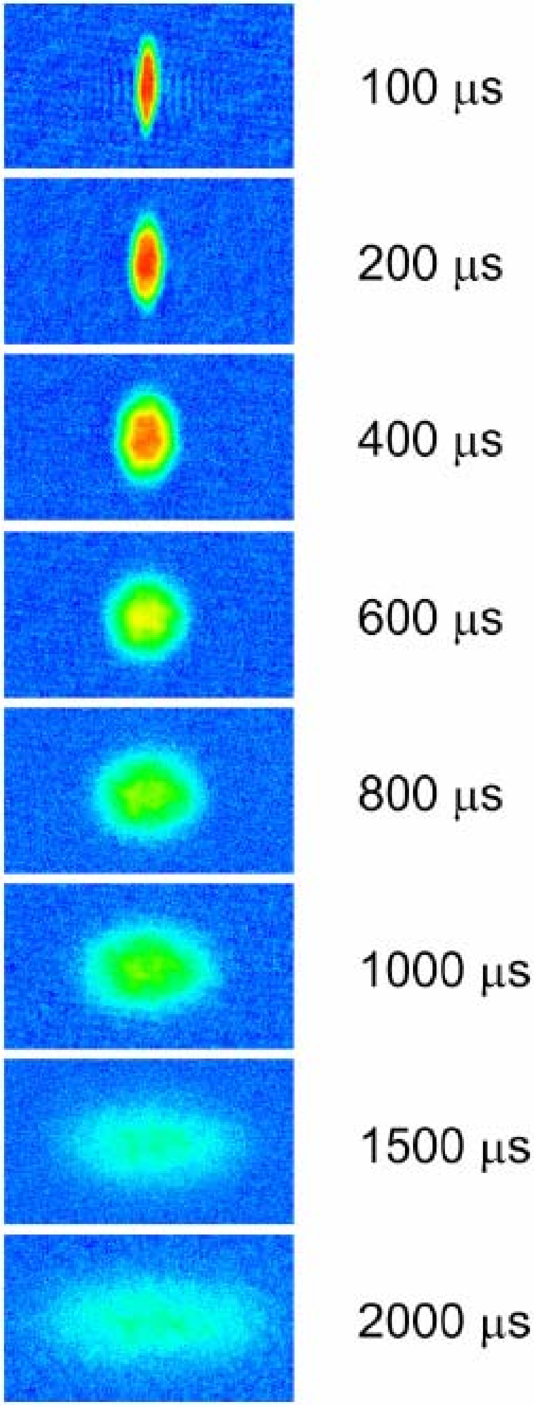
Free Expansion:

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 →





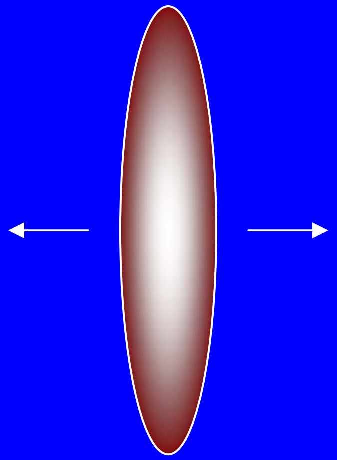
Strongly coupled ^{6}Li expansion

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



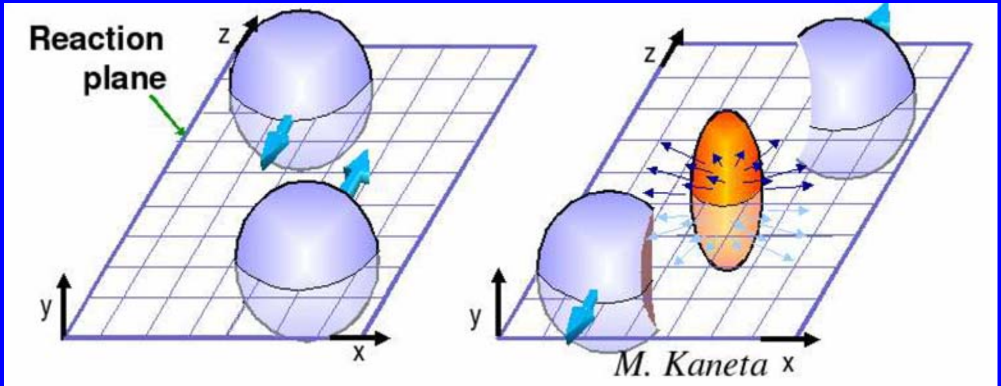
Expands asymmetrically

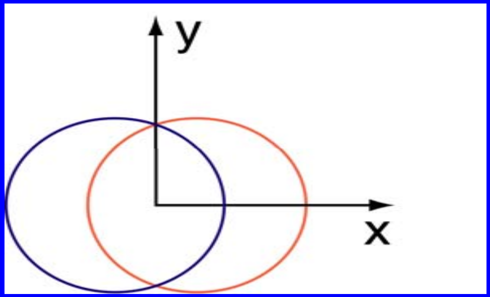
Similar to elliptic flow in heavy ion collisions

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

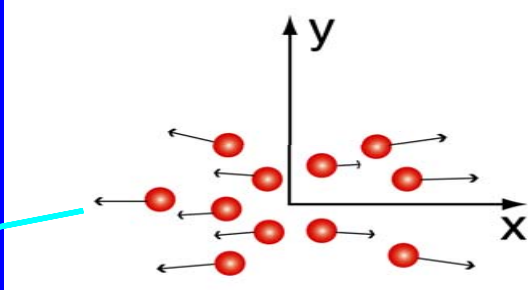
Collectivity: Elliptic flow in non-central collisions:

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

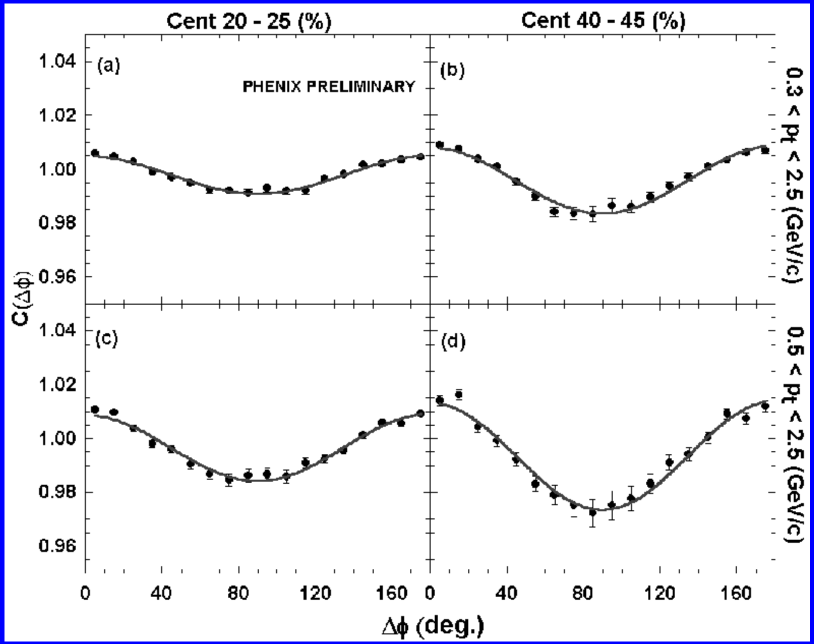




Almond shape overlap region in coordinate space



momentum space

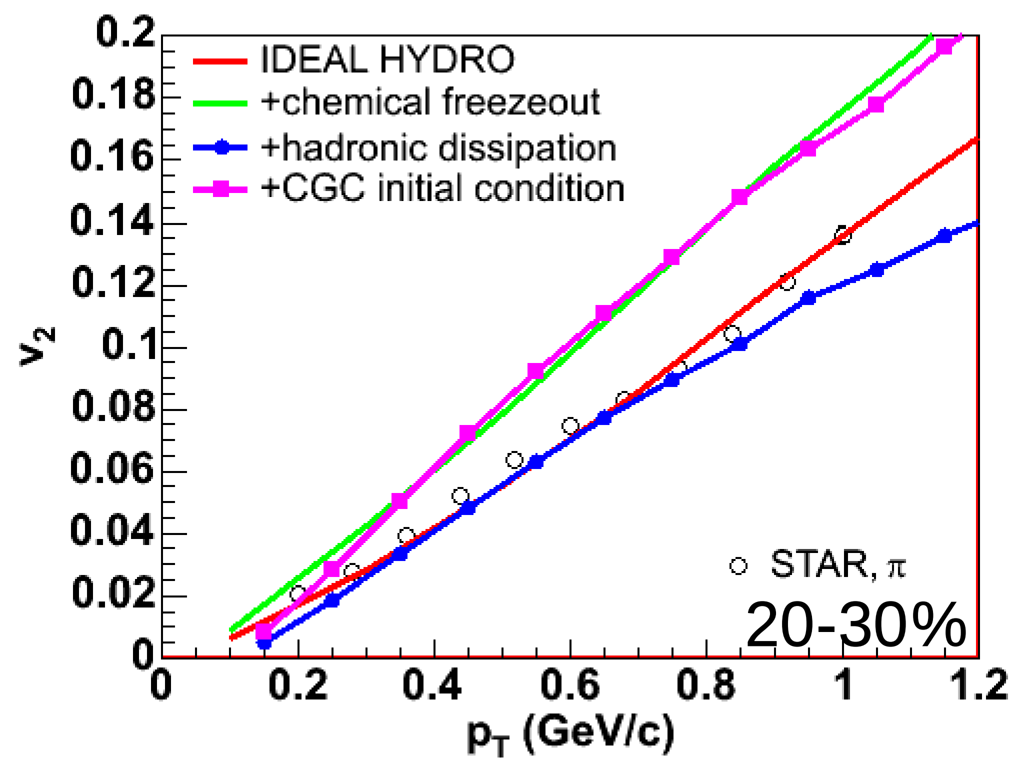


$$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$$

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

Hydrodynamic predictions of $v_2(p_T)$

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



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)

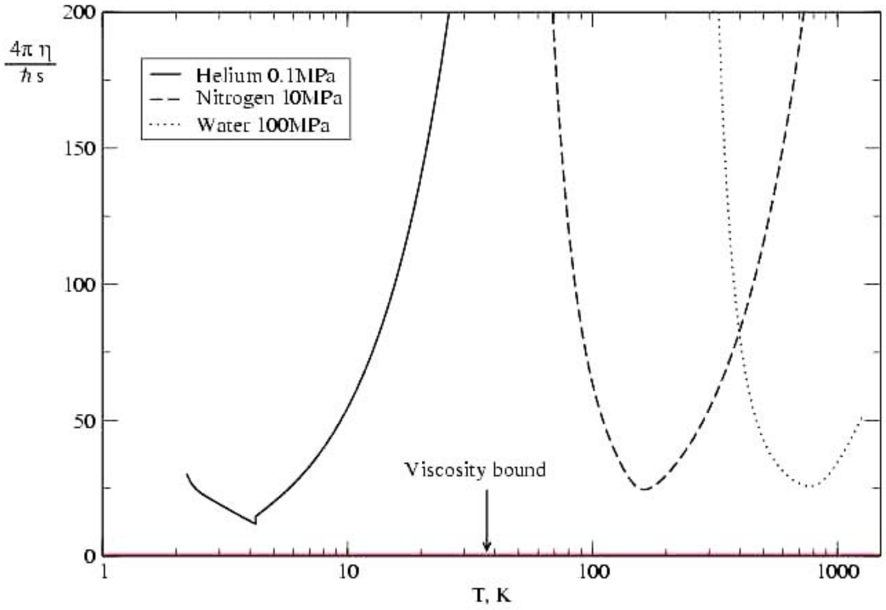


Figure 1: The viscosity-entropy ratio for some common substances.

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

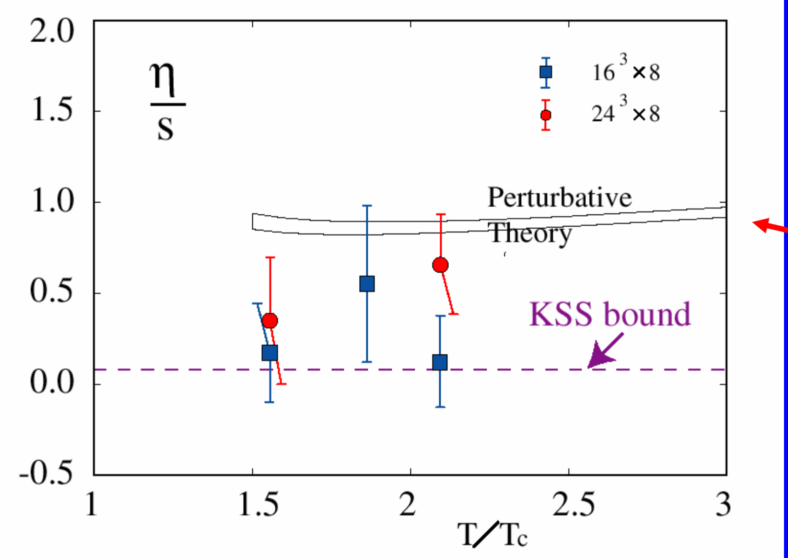
Strongly coupled systems approach viscosity lower bound

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, Phys. Rev. A 75, 043612 (2007)

Lattice calculations of first viscosity in qcd:



Nakamura & Sakai, hep-lat/0510039

Perturbative qcd limit:

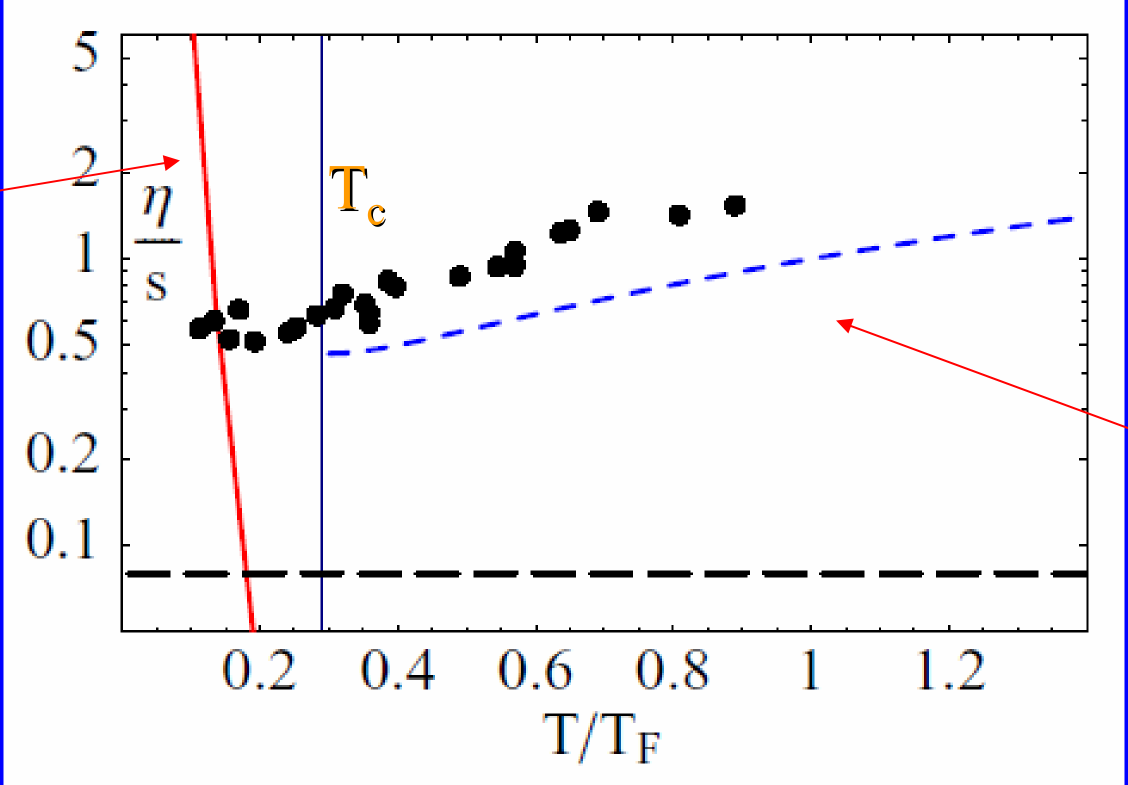
$\eta \sim T^3/(\alpha_s^2 \ln \alpha_s)$

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

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

Shear viscosity of Fermi gas at unitarity

G. Rupak & T. Schaefer, PRA 76, 053607 (2007)

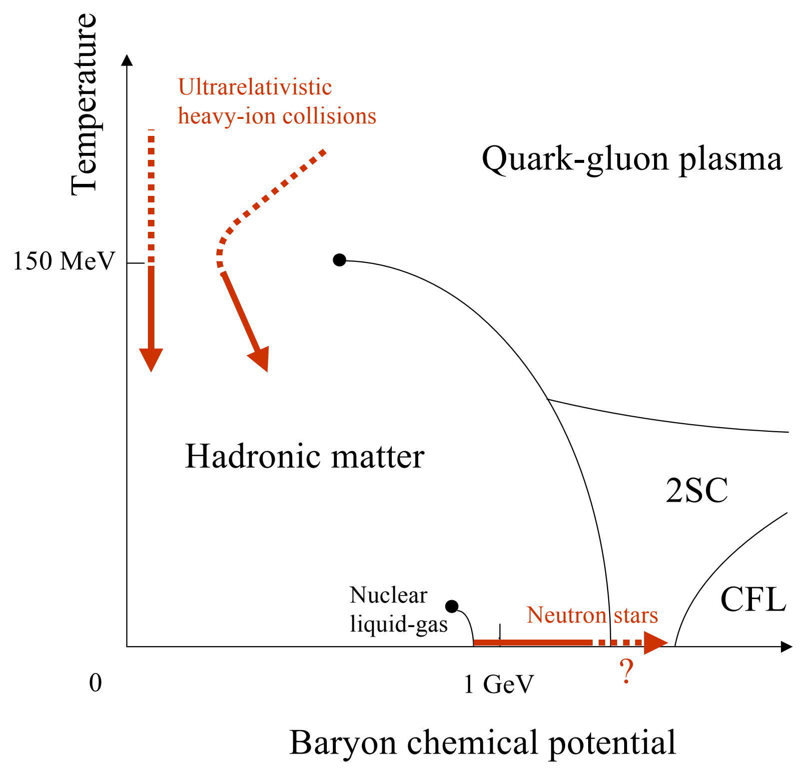


G. M. Bruun & H. Smith, PRA 75, 043612 (2007)

Shear viscosity/ entropy density ratio vs. T/T_F

Color pairing in quark matter

Review: Alford, Rajagopal, Schaefer, & Schmitt, RMP (in press); arXiv:0709.4635

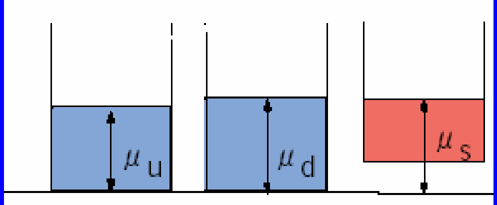


Superfluidity

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

Color Meissner effects

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



Two interesting phases:

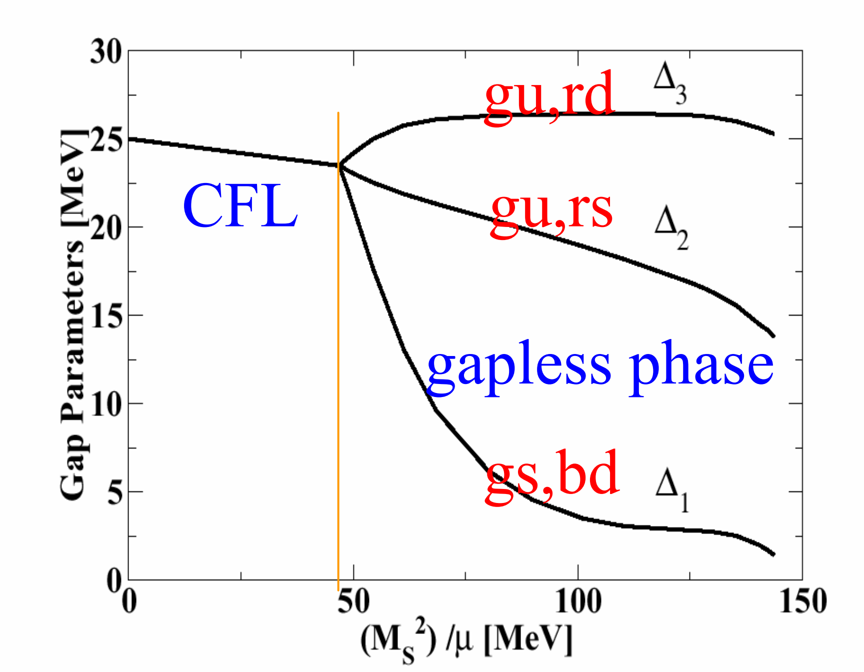
2SC (u,d)

$\langle u_R d_B \rangle$

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

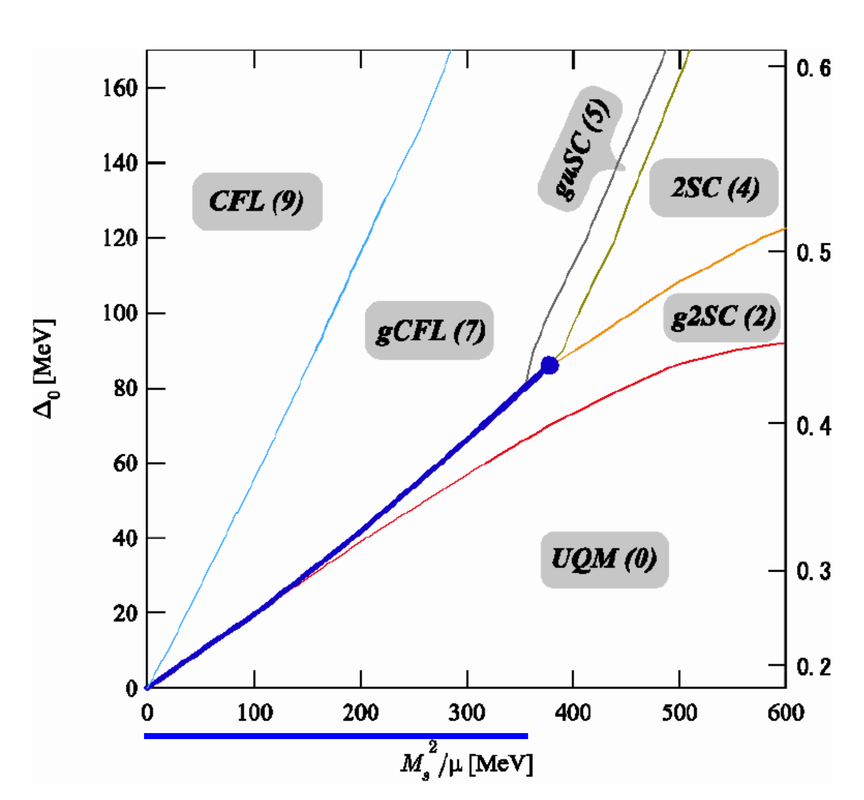
$\langle u d \rangle = \langle d s \rangle = \langle s u \rangle$

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



Decreasing pairing of strange quarks with increasing m_s

Alford, Kovaris & Rajagopal, Phys.Rev.Lett. 92 (2004) 222001



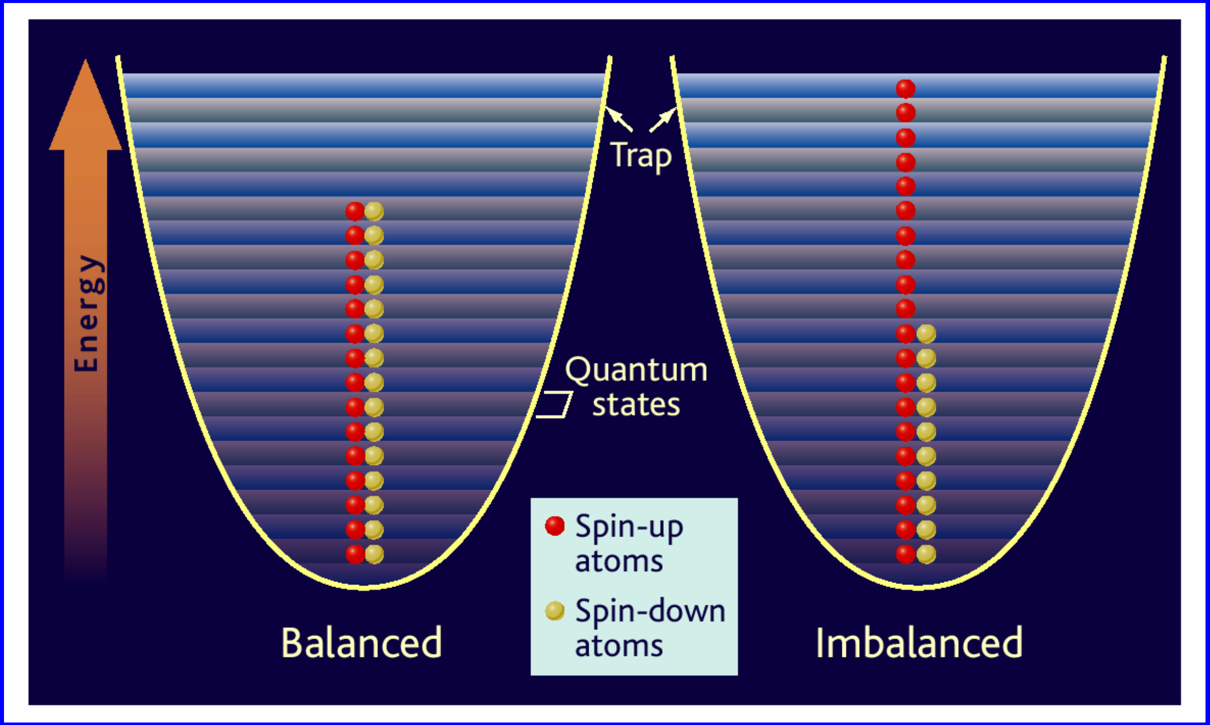
Phase diagram in Δ_{CFL}, m_s^2 plane

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

Superfluidity and pairing for unbalanced systems



Trapped atoms: change relative populations of two states by hand

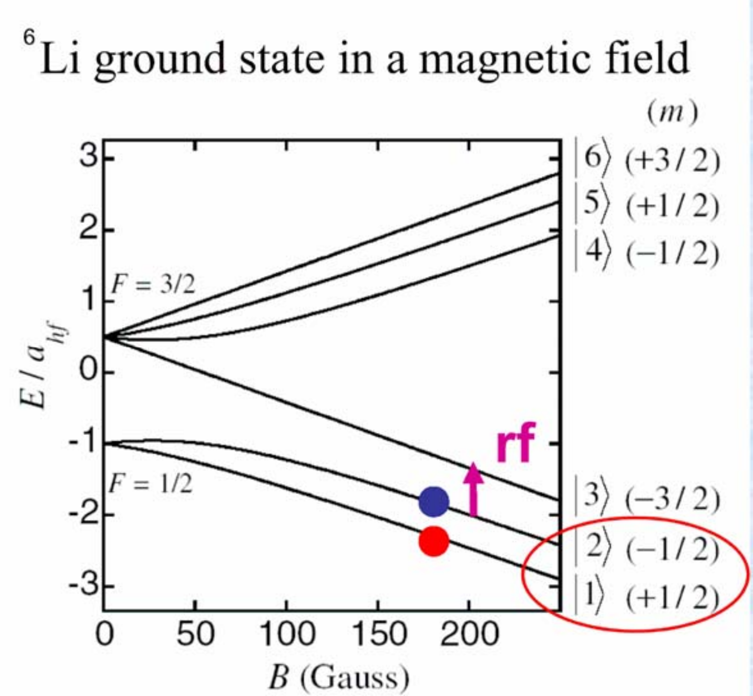
QGP: balance of strange (s) quarks to light (u,d) depends on

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

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); Shin, Schnuck, Schirotzek, & Ketterle, arxiv/0709.3027

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

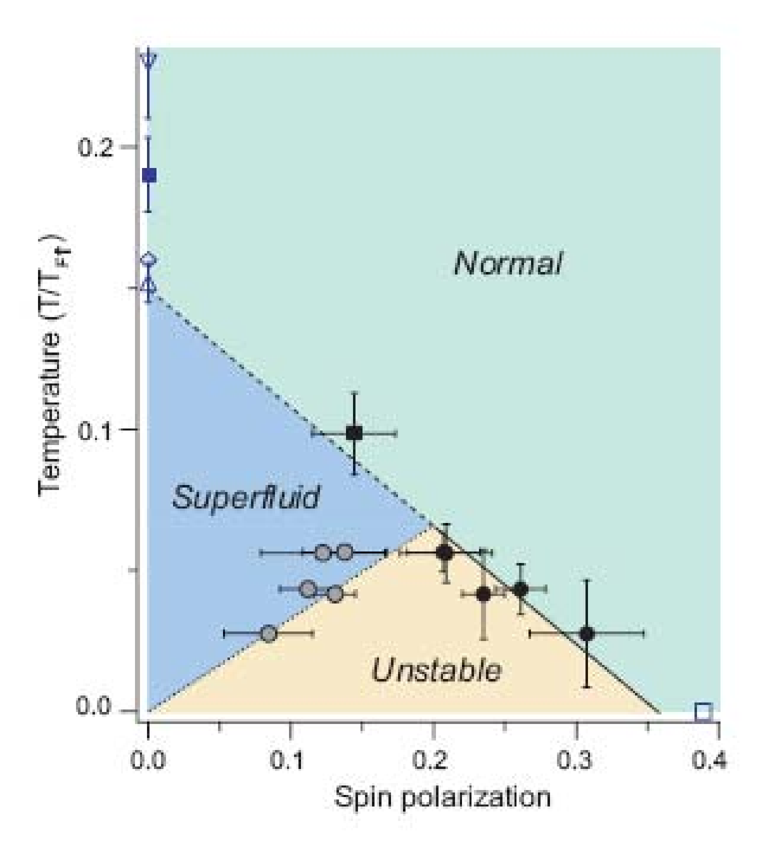


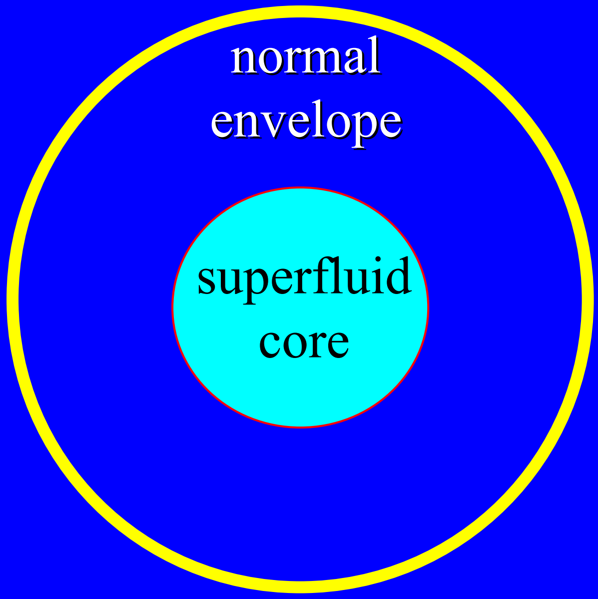
Fill trap with n_1 $|1\rangle$ atoms, and n_2 $|2\rangle$ atoms, with $n_1 > n_2$.

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

Phase diagram of trapped imbalanced Fermi gases

Shin, Schnuck, Schirotzek, & Ketterle, arxiv/0709.3027



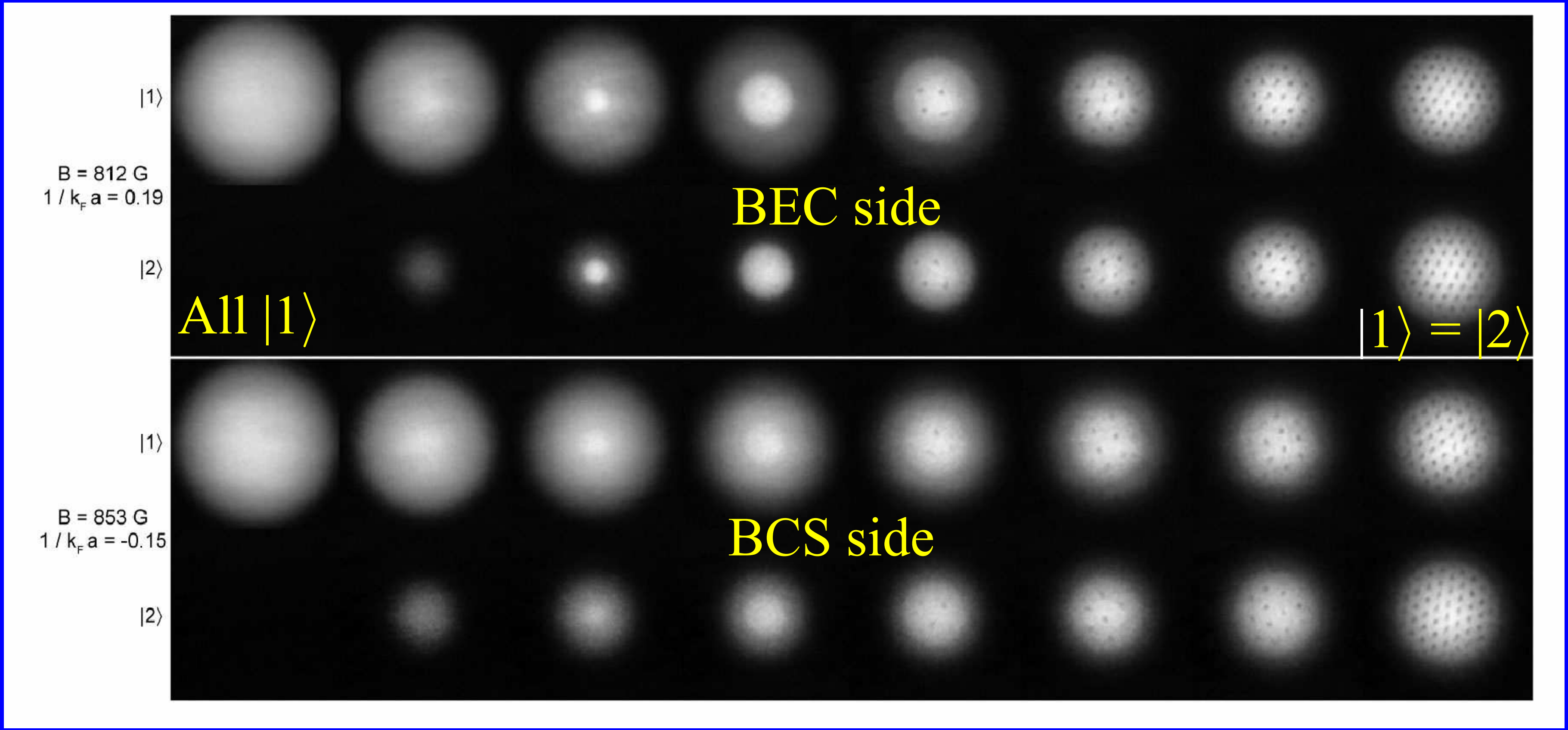


normal envelope

superfluid core

Trap geometry

Vortices as marker of superfluidity (MIT)

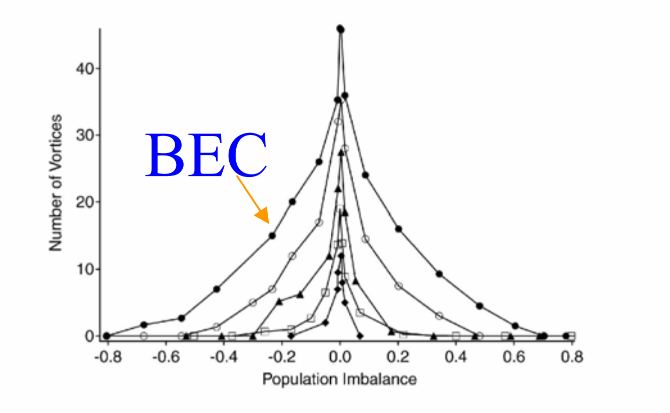


BEC side

All $|1\rangle$

$|1\rangle = |2\rangle$

BCS side



BEC

No. of vortices vs. population imbalance

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

Electrons in a metal

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

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

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

Dusty interstellar plasmas

Laser-induced plasmas (NIF, GSI)

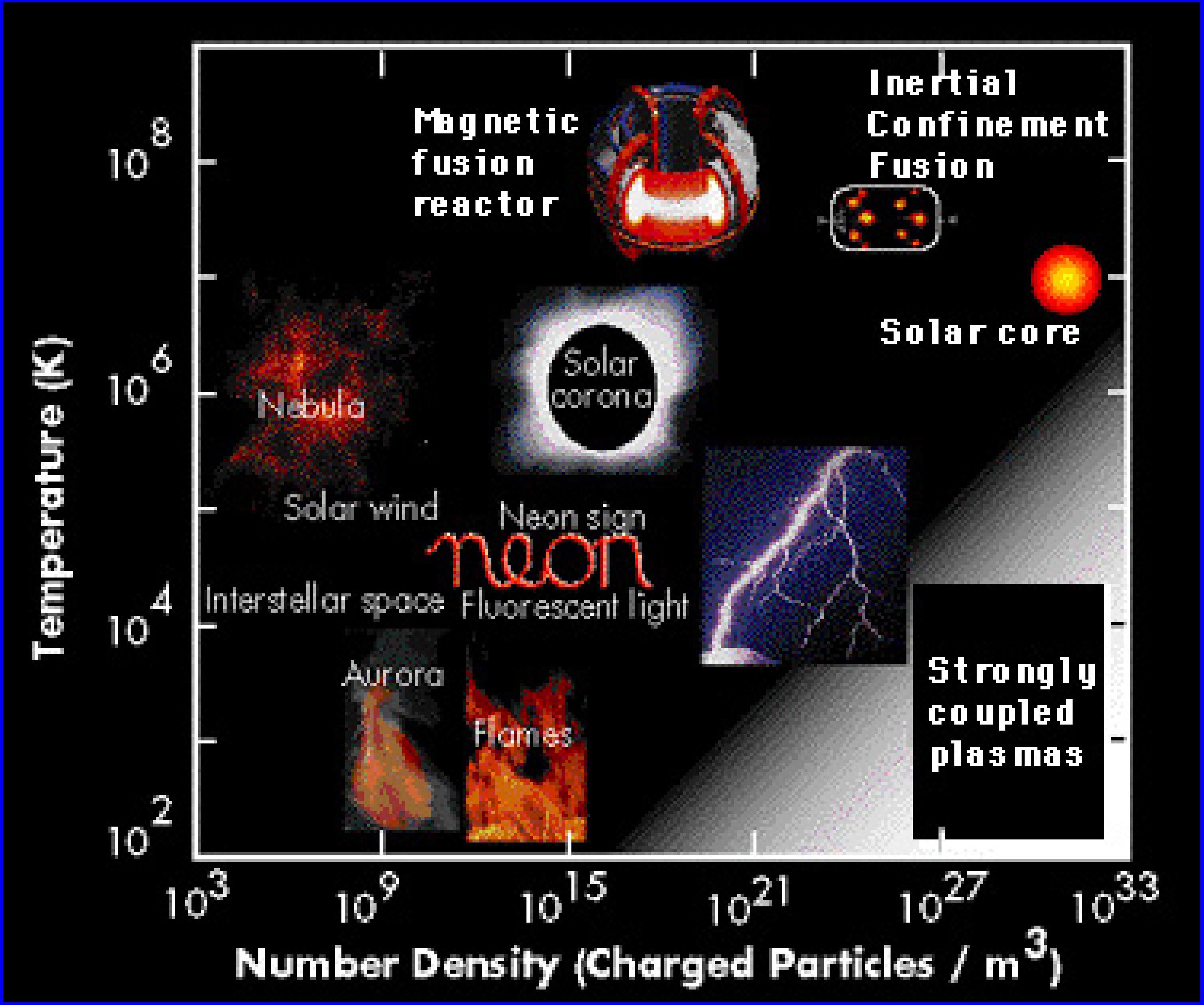
Quark-gluon plasmas

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

Ultracold trapped atomic plasmas

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

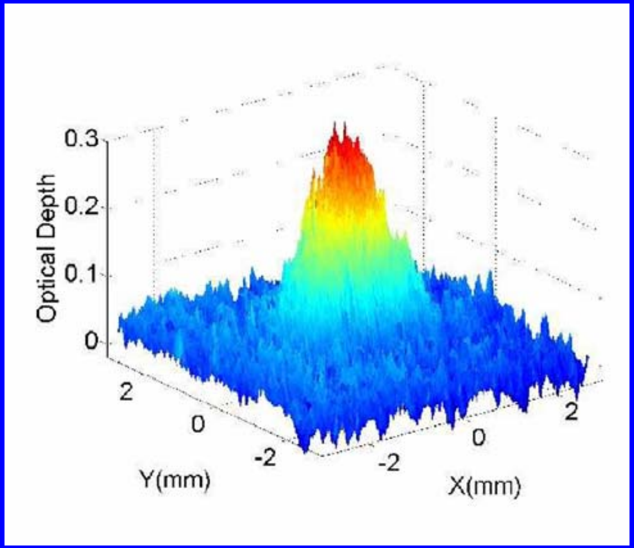
Non-degenerate plasma, $E_{\text{ke}} \sim T \Rightarrow \Gamma = E_{\text{int}}/E_{\text{ke}} \sim e^2/r_0 T$


Magnetic fusion reactor
Inertial Confinement Fusion
Solar core
Nebula
Solar corona
Solar wind
Neon sign
neon
Interstellar space
Fluorescent light
Aurora
Flames
Strongly coupled plasmas
Temperature (K)
10^8
10^6
10^4
10^2
10^3
10^9
10^{15}
10^{21}
10^{27}
10^{33}
Number Density (Charged Particles / m^3)

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, $T_{ion} = 10\mu K - 4mK$, $n = 2\times 10^9/cm^3$, $N \sim 2\times 10^5$
Expand plasma to measure



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

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

-...

THE END