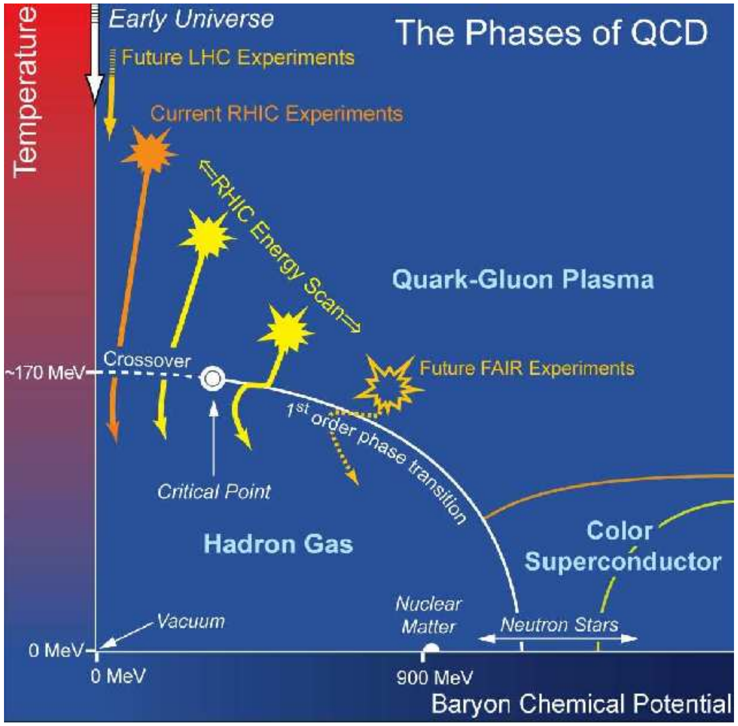
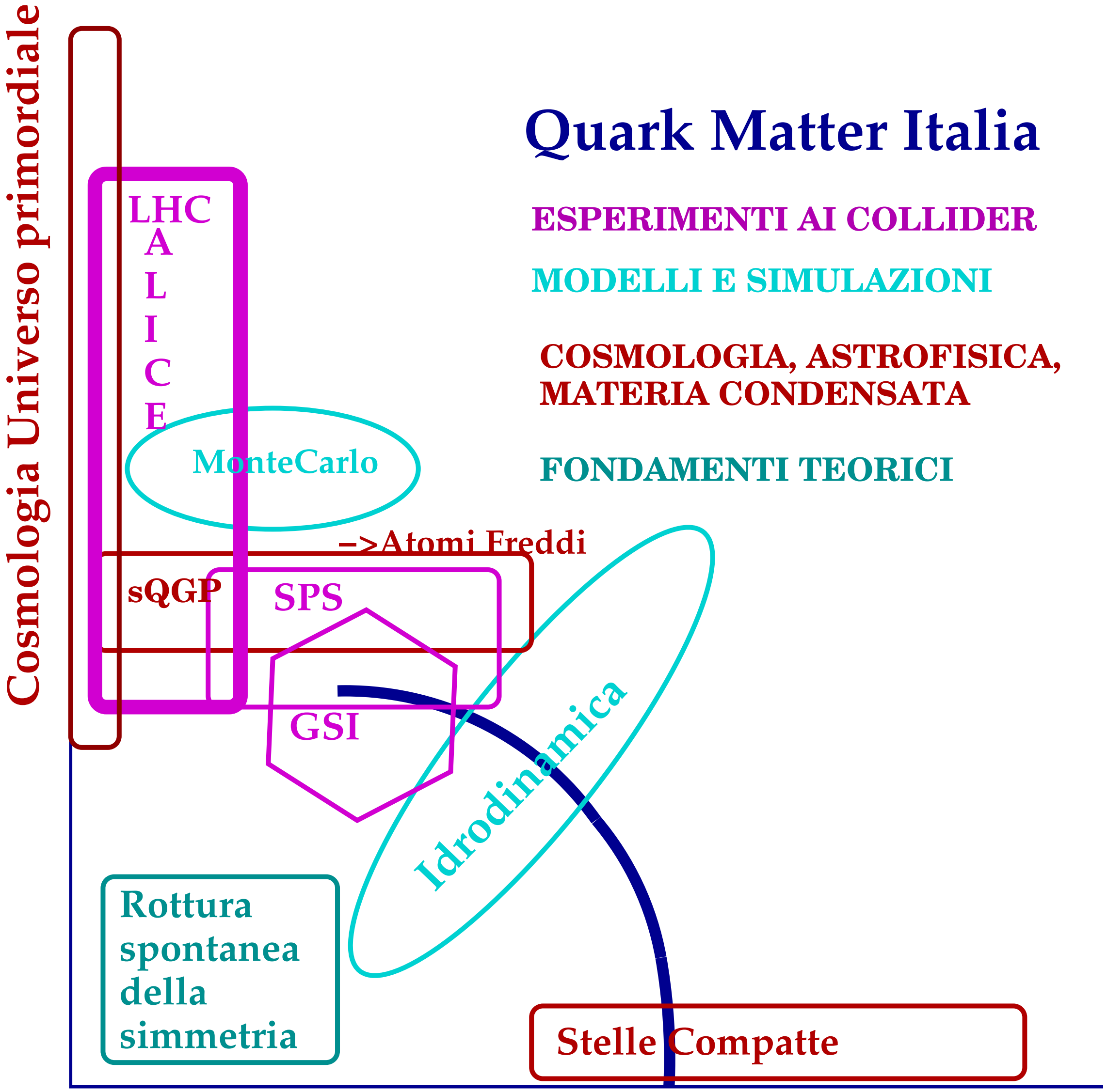
# *BENVENUTI A QUARK MATTER ITALIA!*

Un incontro per discutere le tematiche della conferenza *Quark Matter*
e le interazioni con ricerche affini.




From NSAC Long Range Plan

# Quark Matter Italia



# SIMMETRIE
# DIAGRAMMA DI FASE
# PUNTO CRITICO

## I Fenomeni:

- Confinamento–Deconfinamento

- Rottura spontanea della simmetria Motivazione per il Premio Nobel 2008: *For the discovery of the mechanism of spontaneous broken symmetry in sub-atomic physics*

## Chiral symmetry breaking

Quark interactions with instantons
- change chirality ($\mathcal{P}$ and $\mathcal{T}$ odd),
- lead to quark condensate

$$\langle \bar{q}q \rangle = -(230\ \mathrm{MeV})^3,\ \langle g^2 G^2 \rangle = (850\ \mathrm{MeV})^4$$

$$\varepsilon_0 \approx 500\ \mathrm{MeV/fm}^3$$

Quark propagating in the background of the quark condensate obtains dynamical “constituent quark” mass

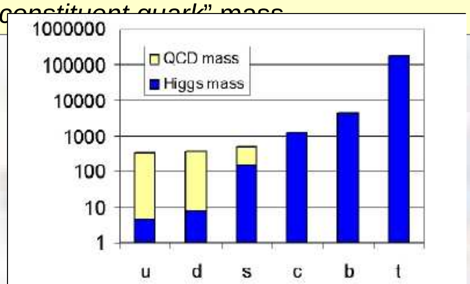
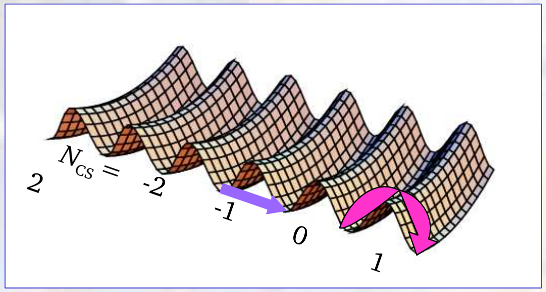



FIG. 1: Masses of the six quark flavors. The masses generated by electroweak symmetry breaking (current quark masses) are shown in dark blue; the additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses) are shown in light yellow. Note the logarithmic mass scale. Berndt Müller

## Strong CP problem




$$|\theta\rangle = \sum_n e^{in\theta} |n\rangle$$

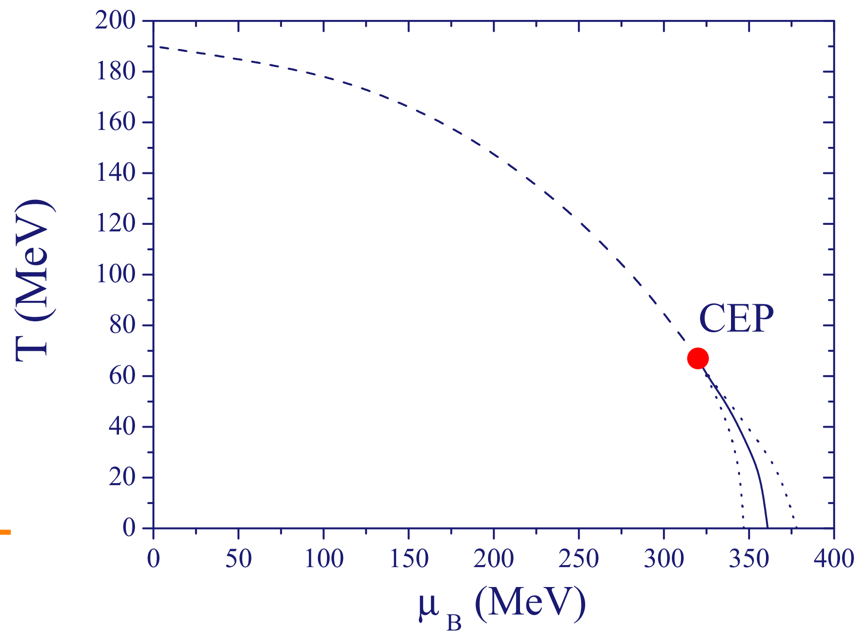
If $\theta \neq 0$ QCD vacuum breaks $\mathcal{CP}$.
Experiment (neutron EDM): $\theta < 10^{-10}$
→ strong $\mathcal{CP}$ problem

In HIC there can be created metastable $\mathcal{P}$-odd domains leading to observable effects


T.D. Lee, PRD 8 1226 (1973)
Morley, Schmidt, Z.Phys. C26, 627 (1985)
Kharzeev, Pisarski, Tytgat, PRL81:512(1998)
Kharzeev, Pisarski, PRD61:111901(2000)
Voloshin, PRC62:044901(2000)
Kharzeev, Krasnitz, Venugopalan, PLB545:298(2002)
Finch, Chikanian, Longacre, Sandweiss, Thomas, PRC65 (2002)

Phase diagram of the SU(3) NJL model

$$\mathcal{L} = \bar{q}\,(i\partial\cdot\gamma - \hat{m})\,q + \frac{g_S}{2}\sum_{a=0}^{8}\Big[(\bar{q}\lambda^a q)^2 + (\bar{q}(i\gamma_5)\lambda^a q)^2\Big] + g_D\Big[\det\big[\bar{q}(1+\gamma_5)q\big] + \det\big[\bar{q}(1-\gamma_5)q\big]\Big]\,.$$




# Il punto critico da NJL

Costa, Ruivo, de Sousa 2008

# QCD Models : Critical Point

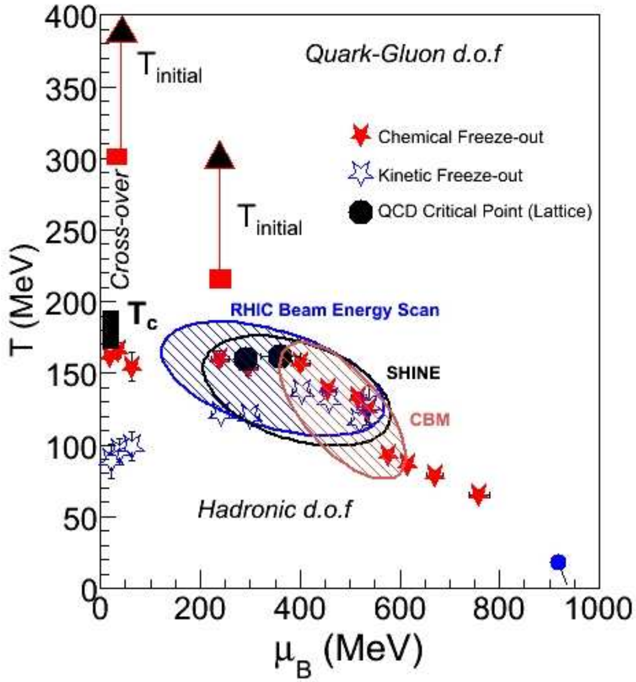
Compilation by Mikhail Stephanov

| Model/Approach | $(T_E, \mu_E)$MeV | Work |
|---|---|---|
| Nambu-Jona Lasinio (NJL) Model | (40,1050),(55,1440)<br>(46,996),<br>(101, 633) | Asakawa, Yazaki 1989<br>Scavenius et al 2001<br>Berges, Rajagopal 1998 |
| Linear $\sigma$-model | (93,645) | Scavenius et al 2001 |
| Ladder QCD (Cornwall, Jackiw, Tomboulis - CJT effective potential) | (95, 837) | Hatta, Ikeda 2002 |
| Random Matrix Model | (120,700) | Halasz, et al (1998) |
| Statistical bootstrap principle | (171,385) | Antoniou, Kapoyannis 2002 |

QM09 : C. Sasaki

Need first principle calculations - Lattice

# Current Status




Lattice and other QCD based models :

$\mu_B$ = 0 - Cross-over

$T_C$ ~ 170-195 MeV

$\mu_B$ > 160 MeV - QCD critical point

Experiments :

See distinct signatures that relevant d.o.f are quark and gluons

[$T_{initial}$(direct photons) > $T_C$(Lattice)]

No signatures of QCD critical point established, possible hints at SPS.

New distinct signatures proposed by Lattice and QCD based model calculations.

Future program :

Exploring the QCD phase diagram needs to be vigorously pursued to know properties of basic constituents of matter under extreme conditions.

# Phase Diagram

**chemical freeze-out systematics (statistical model fits of hadron yields) versus phase transitions from LQCD**

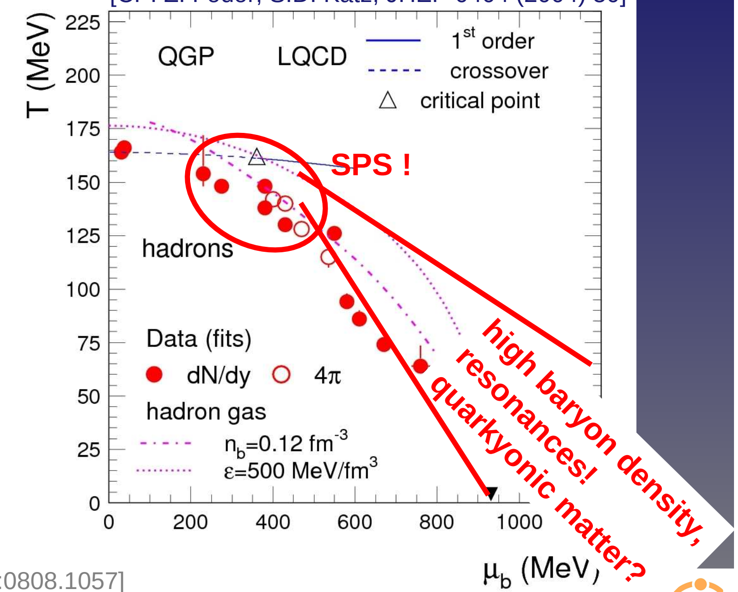
- RHIC – crossover at low $\mu_B$
- SPS – finite $\mu_B$: 1st order phase transition, CP?

Onset of deconfinement at ~ 30*A* GeV?!

CP?

Medium properties?

[A. Andronic priv. com., analysis in Phys. Lett. B 673 (2009) 142]
[CP: Z. Fodor, S.D. Katz, JHEP 0404 (2004) 50]



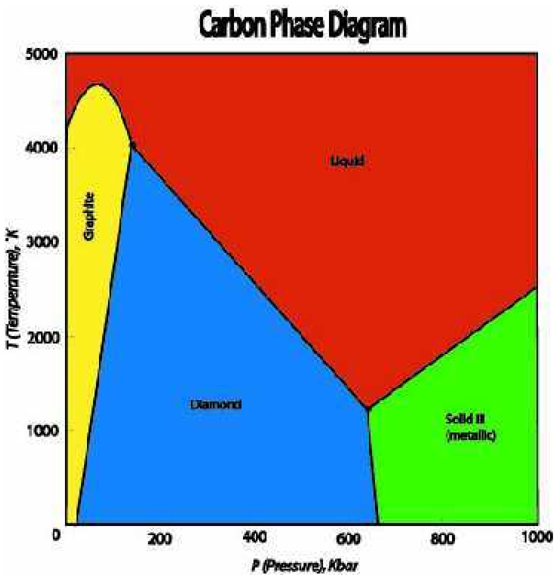

[quarkyonic matter: L. McLerran arXiv:0808.1057]

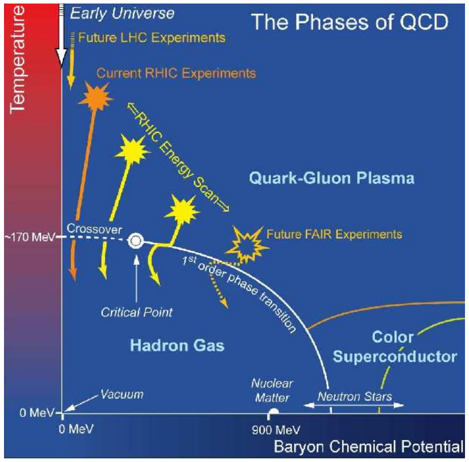
# *QCD e MATERIA CONDENSATA: MATERIA FREDDA e SQGP*

# TITOLO DELLA NOBEL LECTURE 2008

*Spontaneous Symmetry Breaking in Particle Physics : a case of cross fertilization*

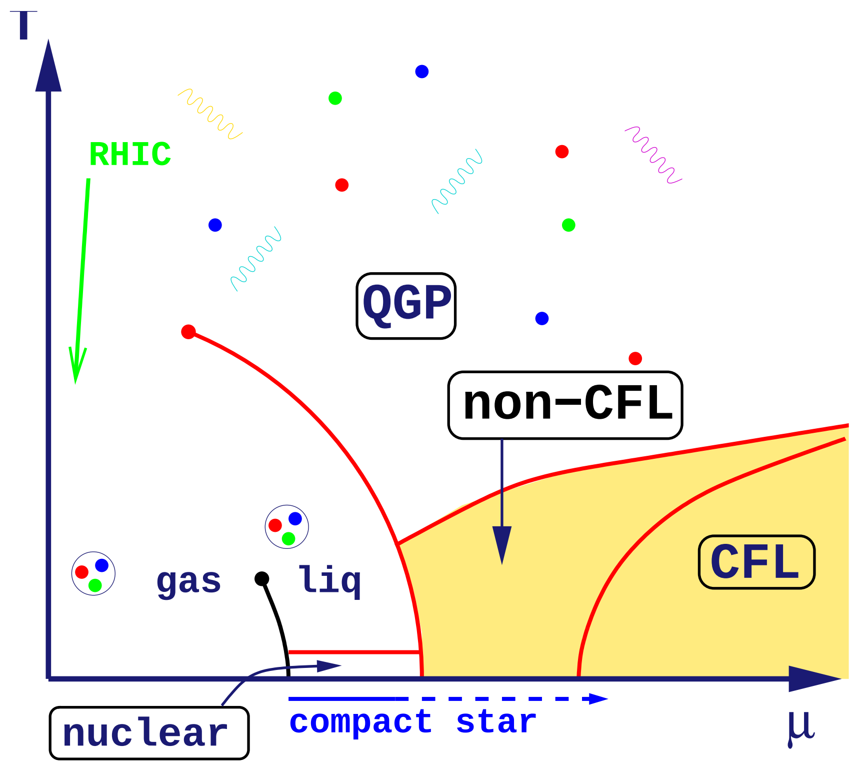
# CARBON VS QCD PHASE DIAGRAM



# THE CONDENSED MATTER PHASE OF QCD

Alford Rajagopal Wilczek; Shuryak Schaefer Velokvsky



# QGP E MATERIA CONDENSATA : LA NUOVA SFIDA

## $\eta/s$ e' 'piccolo' a RHIC

$$\eta = \epsilon\tau_{\rm mft}$$

$\epsilon$ : Densita' di energia

$\tau_{\rm mft}$ : Cammino libero medio

'Grande' $\eta/s$ = Grande Cammino Libero Medio = Teoria Quasi Libera

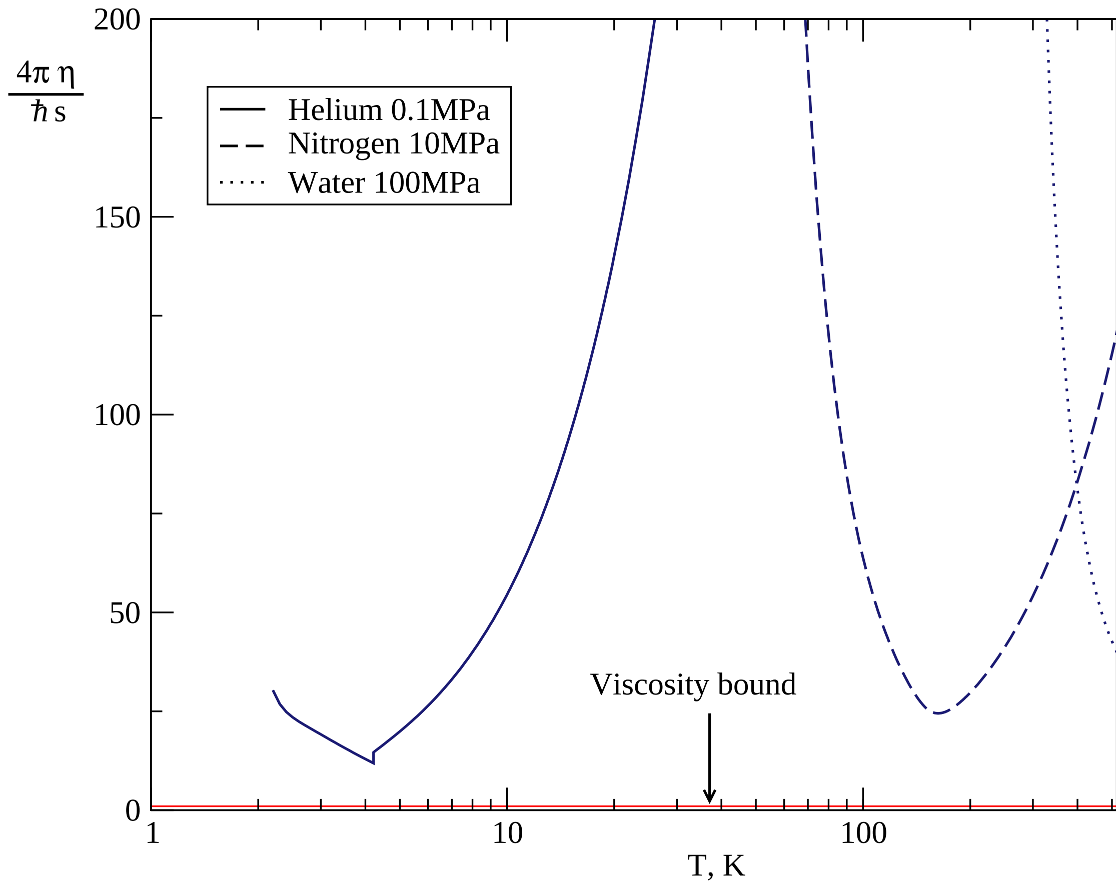
'Piccolo' $\eta/s$ = Plasma fortemente interagente

*A viscosity bound conjecture.*—**Kovtun Son Starinets**

*We speculate that the ratio $\eta/s$ has a lower bound*

$$\frac{\eta}{s} > \frac{\hbar}{4\pi k_B}$$

*for all relativistic quantum field theories at finite temperature and zero chemical potential. The inequality is saturated by theories with gravity duals.*



200
150
100
50
0
$\frac{4\pi\,\eta}{\hbar\,s}$
Helium 0.1MPa
Nitrogen 10MPa
Water 100MPa
Viscosity bound
1
10
100
T, K

# Is an Ultra-Cold Strongly Interacting Fermi Gas a Perfect Fluid?

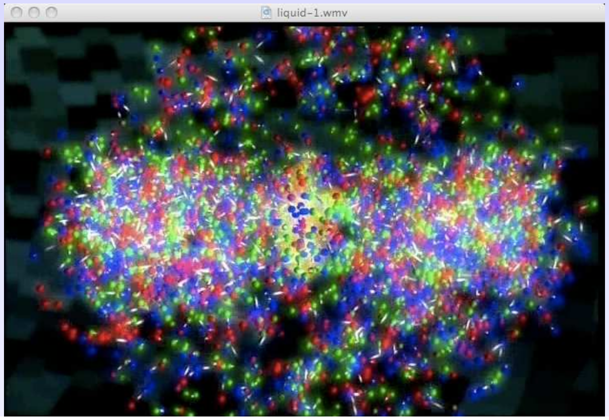
Duke Physics
Atom Cooling and Trapping

**John E. Thomas**

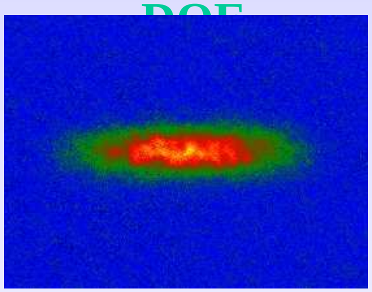
<u>Support:</u>

**ARO**
**NSF**
**DOE**

"JETLAB" Group




**Quark-gluon plasma $T = 10^{12}$ K**
**Computer simulation of RHIC collision**



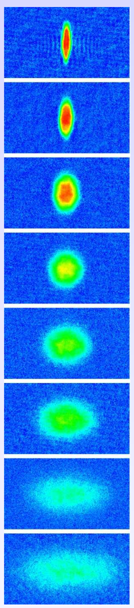
**Ultracold atomic Fermi gas**

**$T = 10^{-7}$ K**

# Strongly Interacting Systems in Nature

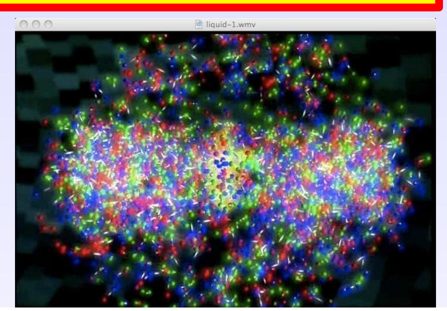
Duke Physics
Atom Cooling and Trapping

- Ultracold Atomic $^6$Li Gas
- Quark-Gluon Plasma
- High $T_c$ Superconductors
- Neutron Matter
- Black Holes in String Theory



**Strongly Interacting $^6$Li gas**
**$T = 10^{-7}$ K**

Duke, Science (2002)



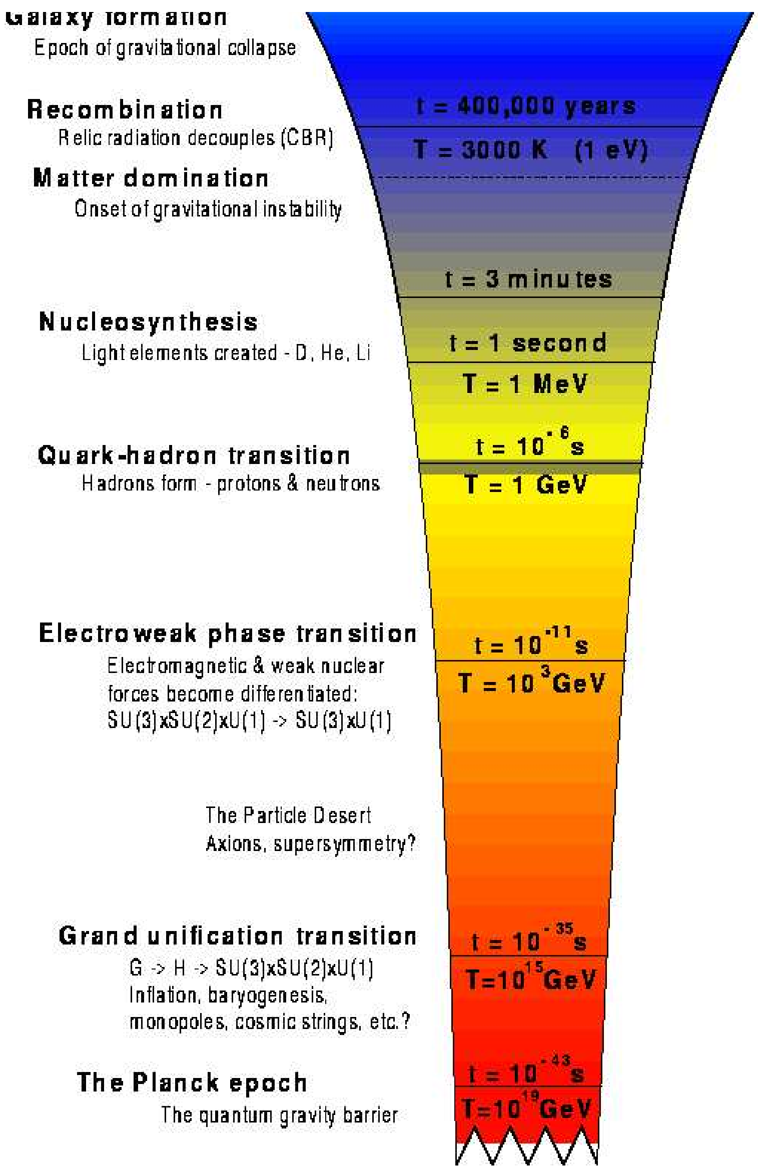
**Quark-gluon plasma $T = 10^{12}$ K**

**Similar "Elliptic" Flow**

# *LE ALTISSIME TEMPERATURE*

# THE HISTORY OF THE UNIVERSE

From Cambridge Cosmology Group




← Standard Cosmology

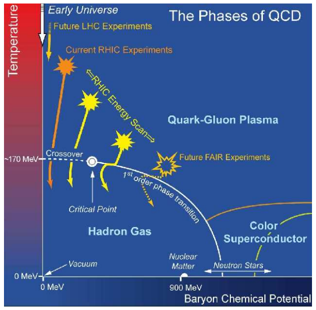
← Particle Cosmology

1. GeV $\simeq 10^{13}$ K

← Quantum Cosmology

# $T \simeq 100$ MeV : Una frontiera

QCD : $T_c \simeq 200$ MeV
Carbonium $T_c \simeq 4000$ K $\simeq 0.3$ eV




**The two phase diagrams on the same scale!**

From **Kerson Huang** and **Steven Weinberg**
Phys. Rev. Lett. **25** (1970)
"*There are now plausible theoretical models for the thermal history of the Universe back to the time of helium synthesis, when the temperature was 0.1 to 1 MeV. Our present [1970] theoretical apparatus is really* **inadequate** *to deal with much earlier time, say when $T \simeq 100 MeV$.*"

# Lo strumento: QCD, la Teoria di campo delle interazioni forti

$$\mathcal{L} = \mathcal{L}_{YM} + \bar{\psi}(i\gamma_\mu D_\mu + m + \mu\gamma_0)\psi$$

Come calcolare?? $\longrightarrow$ **Lattice!**

Cosa misurare?? $\longrightarrow$


Tocca a te ALICE!