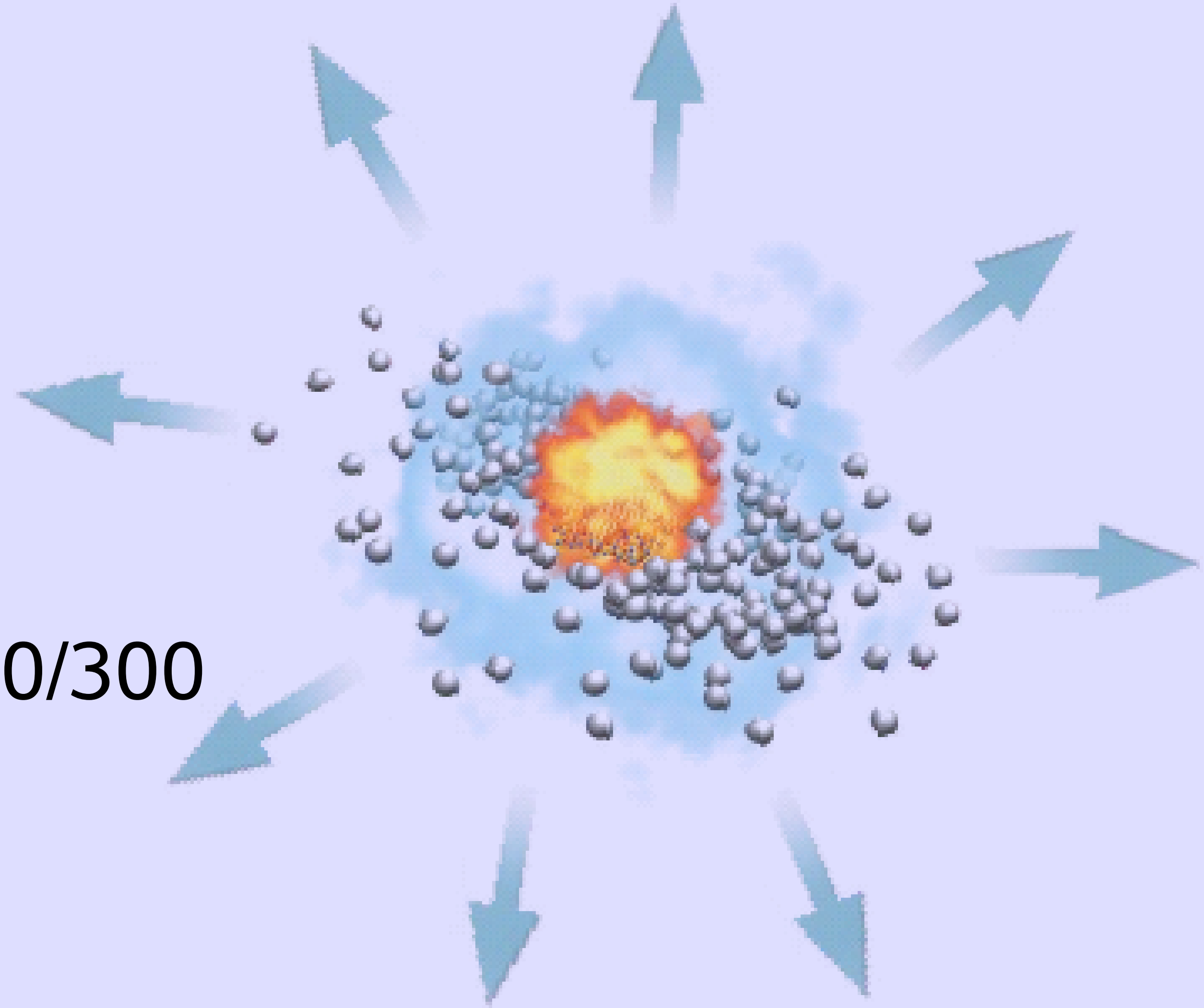
Dense Baryonic Matter (DBM)

- Introduction
- GSI: SIS-18
  - Experiments
  - Results
- GSI Future: SIS-100/300
  - CBM
- Outlook



Introduction

How dense are Baryons?

nucleon mass, ...

$$m_N \approx 939\, MeV/c^2 = 1.67 \cdot 10^{-24}\, g$$

... volume, ...

$$V_N \approx \frac{4}{3}\pi\, 1\, fm^3 = 4.2 \cdot 10^{-39}\, cm^3$$

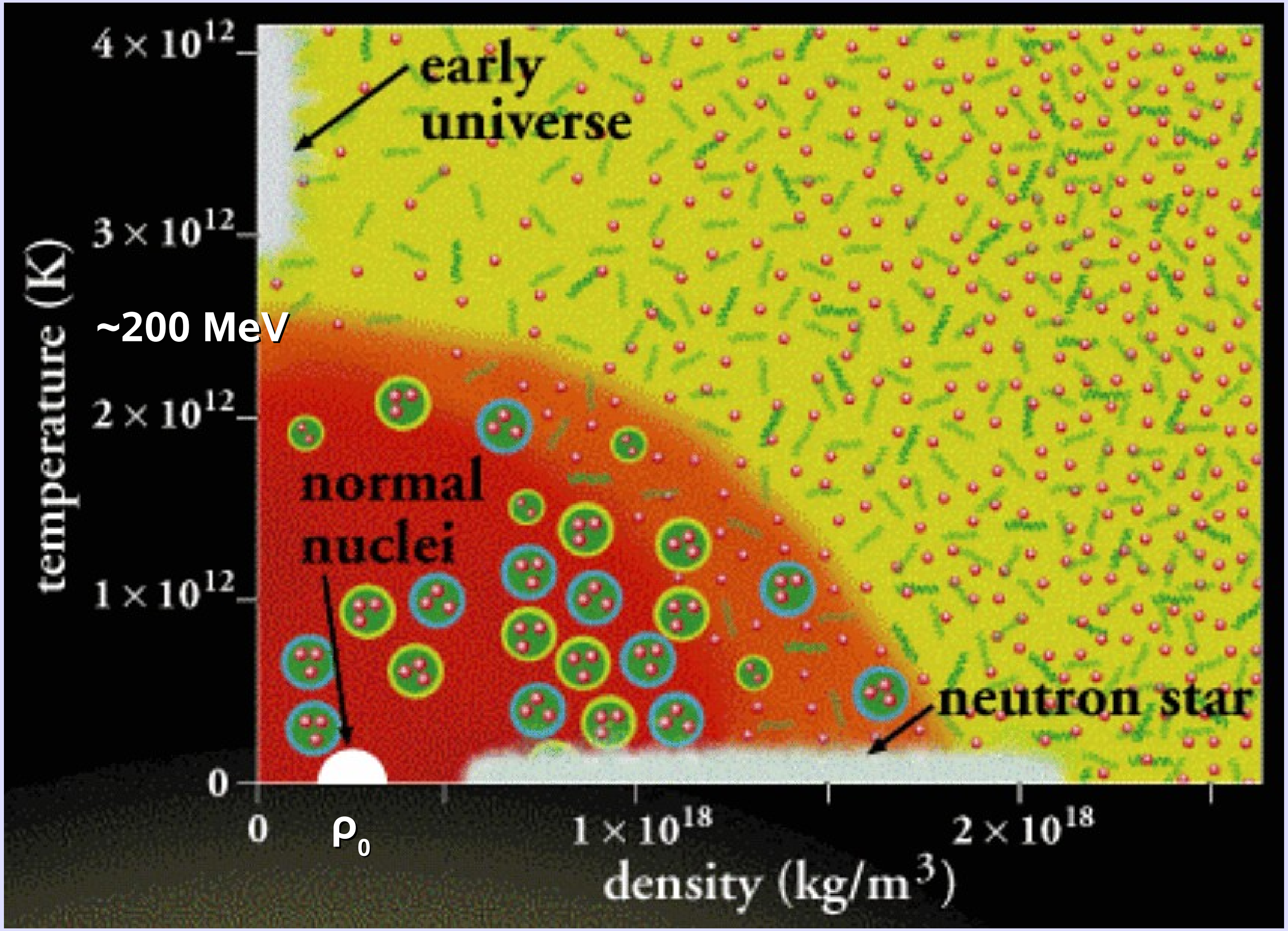
... and density

$$\rho_N = \frac{m_N}{V_N} \approx 4 \cdot 10^{14}\, g/cm^3$$

Baryons are pretty dense already !!!

Phase Diagram of Nuclear Matter

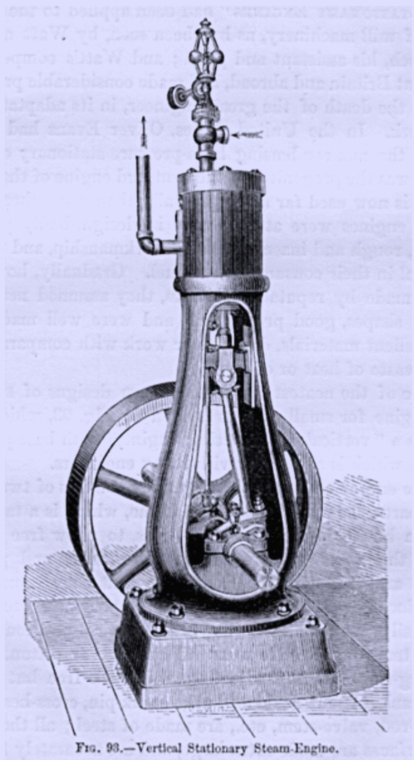
- normal nucl. matter: liquid (droplet model)
- hadron gas (final state of heavy-ion coll.)
- quark-gluon plasma (?)
- possible solid phase inside neutron stars

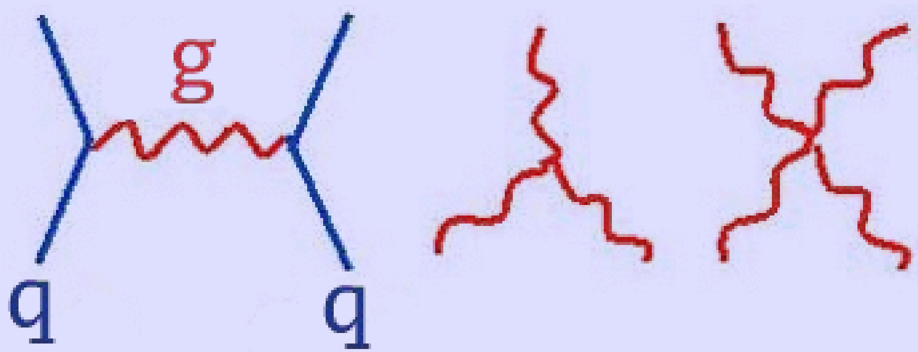


(ABC's of Nuclear Science, LBL)

Our Playground

- playing with nuclear matter requires
  - thermodynamics
  - quantum chromodynamics
- things we can study:
  - neutron stars
  - heavy-ion collisions
- other tools:
  - satellites, telescopes
  - accelerators, detectors





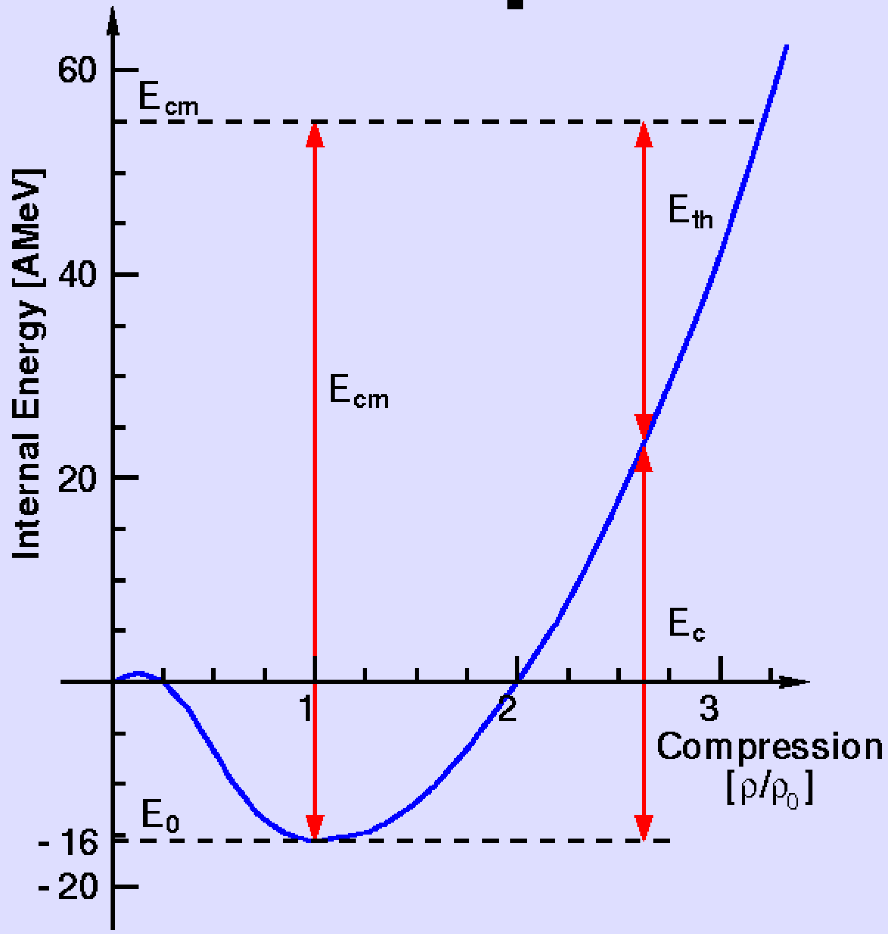
The Equation of State (EOS) (I)

- a thermodynamical system in equilibrium can be described by an EOS using certain state variables:

$$p = k_B \cdot \frac{N T}{V}, \qquad p = p(V, N, T)$$

- in thermodynamical equilibrium:
  - entropy S is maximal
  - state variables are constant
- apply this concept to nuclear matter

The Equation of State (EOS) (II)



saturation density of nuclear matter
ρ_0 = 0.17 fm^{-3} = 0.16 GeV/fm^3

- example: internal energy

$$E(\rho,T)=E_{th}(\rho,T)+E_c(\rho,T=0)+E_0$$

- (in)compressibility

$$K_\infty=9\rho_0^2\left[\frac{d^2E_c}{d\rho^2}\right]_{\rho=\rho_0}$$

  - soft EOS: K ≈ 200 MeV
  - stiff EOS: K ≈ 400 MeV

→ determines neutron star mass limit

A QCD Problem: Quark Masses

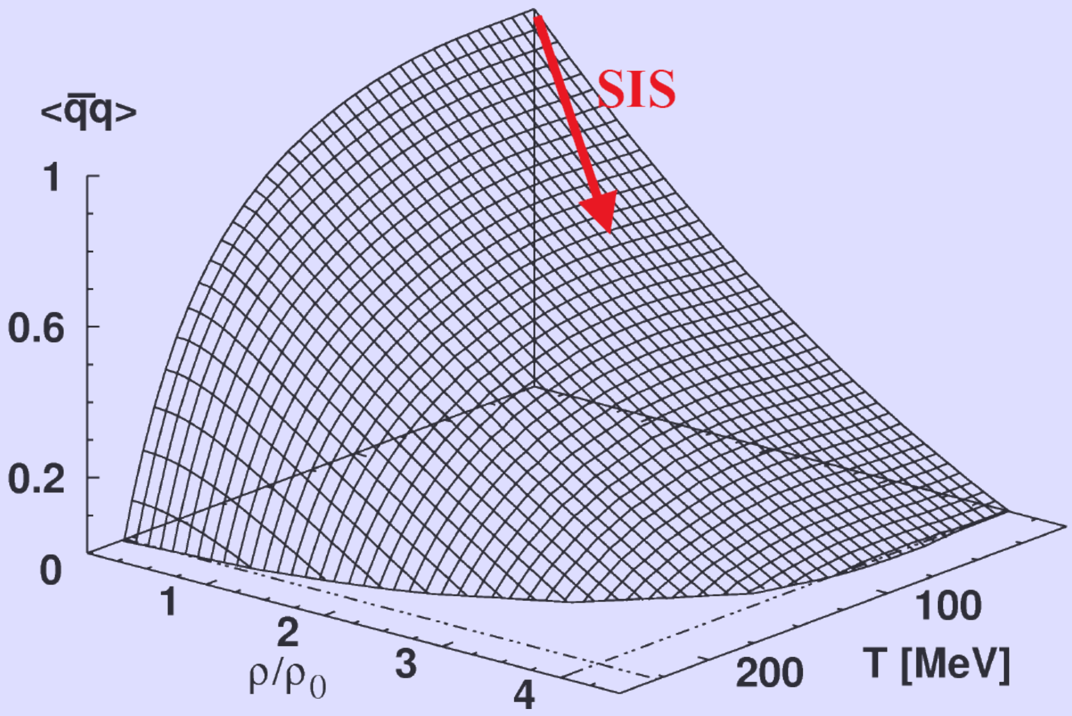
$$L_{QCD} = \bar{q}\left(i\,\partial_{\mu} - g\,A_{\mu}^{a}\frac{\lambda^{a}}{2}\right)q - \bar{q}\,m_{q}\,q - \frac{1}{4}F_{\mu\nu}^{a}F^{\mu\nu\ a}$$

- QCD features:
  - asymptotic freedom (well tested at high ***q***, pQCD)
  - color confinement
- not so well tested: low ***q***, non-perturbative regime

→ quark mass discrepancy:
  - constituent masses: ~300 MeV/c² (*u*,*d*), ~500 MeV/c² (*s*)
  - current (bare) masses: ~2-5 MeVc² (*u*,*d*), ~150 MeV/c² (*s*)
- non-zero m_q break chiral symmetry explicitly

The Quark Condensate

- strong condensation of $\bar{q}q$ pairs in the vacuum breaks chir. symm. spontaneously
- effective QCD theories predict decrease of **<$\bar{q}q$>** with increasing ***T*** and ***ρ***
- GOR rel. predict change of particle properties:



W. Weise, Prog. Theor. Phys. Suppl. 149 (2003) 1

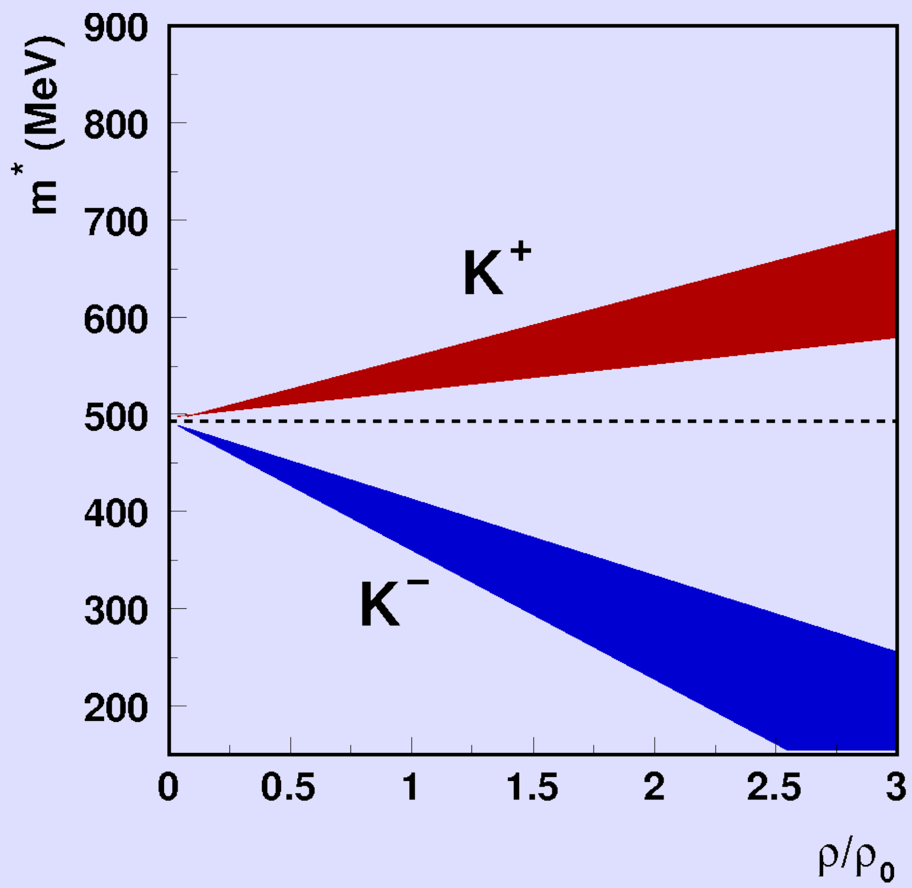
$$m_\pi^2 f_\pi^2 = -\frac{1}{2}(m_u + m_d)\langle \bar{u}u + \bar{d}d \rangle + O(m_u^2)$$

$$m_K^2 f_K^2 = -\frac{1}{2}(m_q + m_s)\langle \bar{q}q + \bar{s}s \rangle + O(m_s^2)$$

M. Gell-Mann, R. J. Oakes and B. Renner, Phys. Rev. 175 (1968) 2195

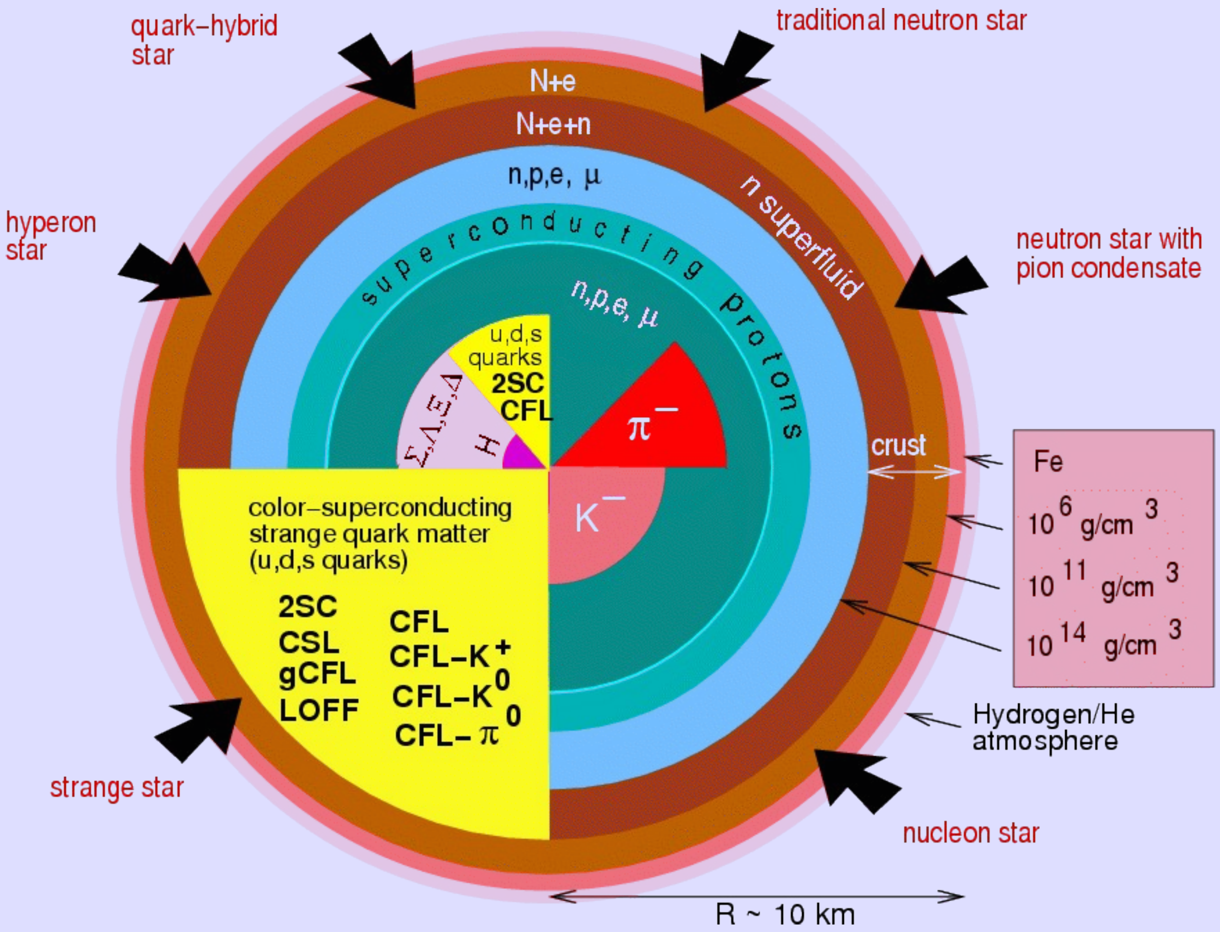
Consequence: In-Medium Effects

- chir. symm. can be restored in hot & *dense* nuclear matter
- observables: produced particles
  - masses, widths (ρ,ω,...)
  - yields, spectra (K^+,K^-...)
- different situations:
  - ρ,ω : short lifetime (~ 10^{-23} s)
  - K,Λ : long lifetime (10^{-8} – 10^{-10} s)



Where to look for DBM now?

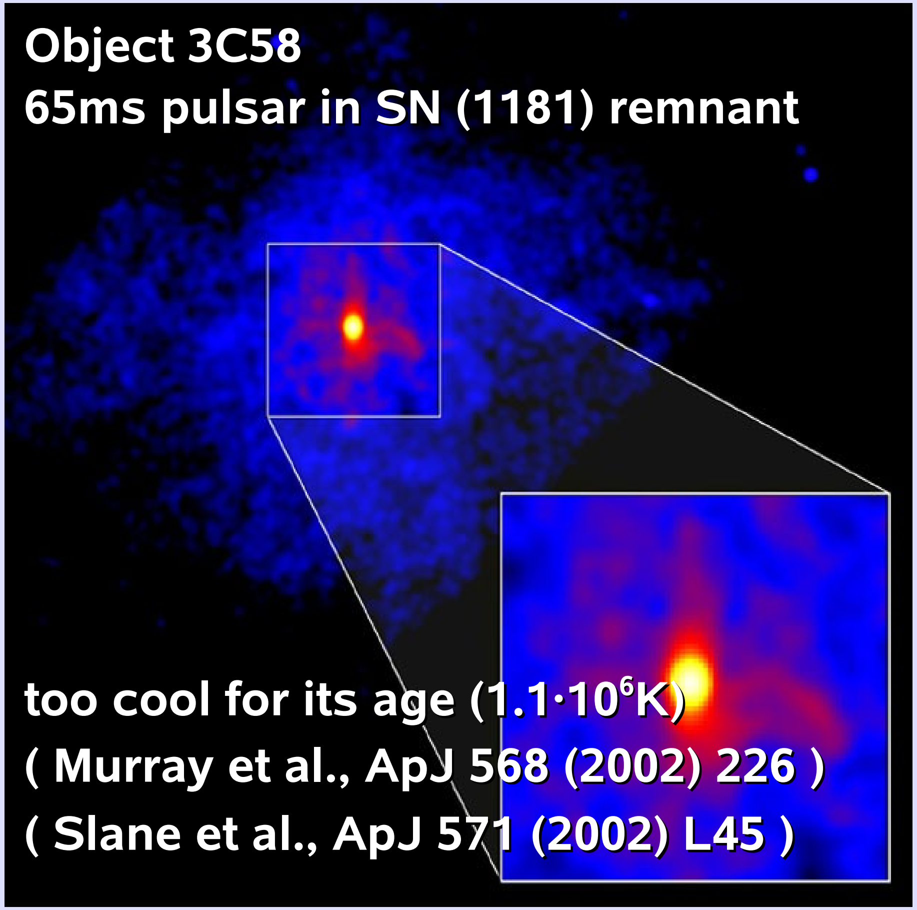
DBM in Space: Neutron Stars

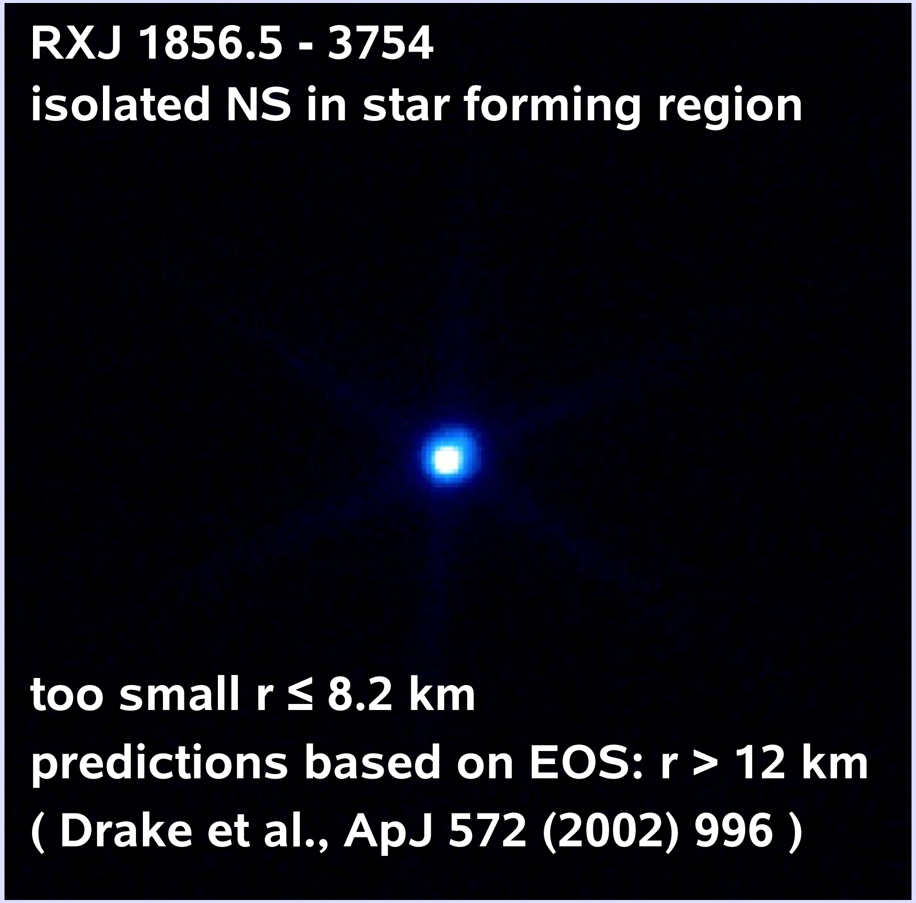


F. Weber, Prog.Part.Nucl.Phys. 54 (2005) 193

- produced in supernova explosions
- compact: $m \approx 1\text{-}2\ M_{sun}$, $r > 12$ km
- high rotation velocities (ms pulsars)
- high densities ($\rho \leq 10\rho_0$)
- upper mass limit depends on EOS of nuclear matter
- multiple scenarios for internal structure

Two interesting Candidates

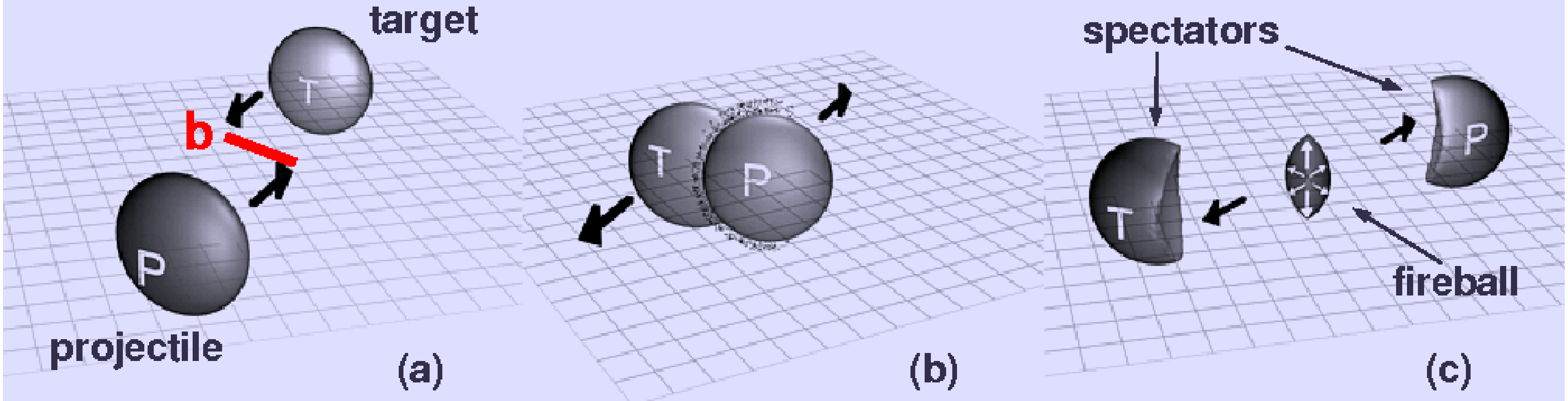




Cooling Mechanism? **Quark Star?**

(observed with Chandra and the Hubble Space Telescope)

DBM on Earth: Heavy-Ion Collisions

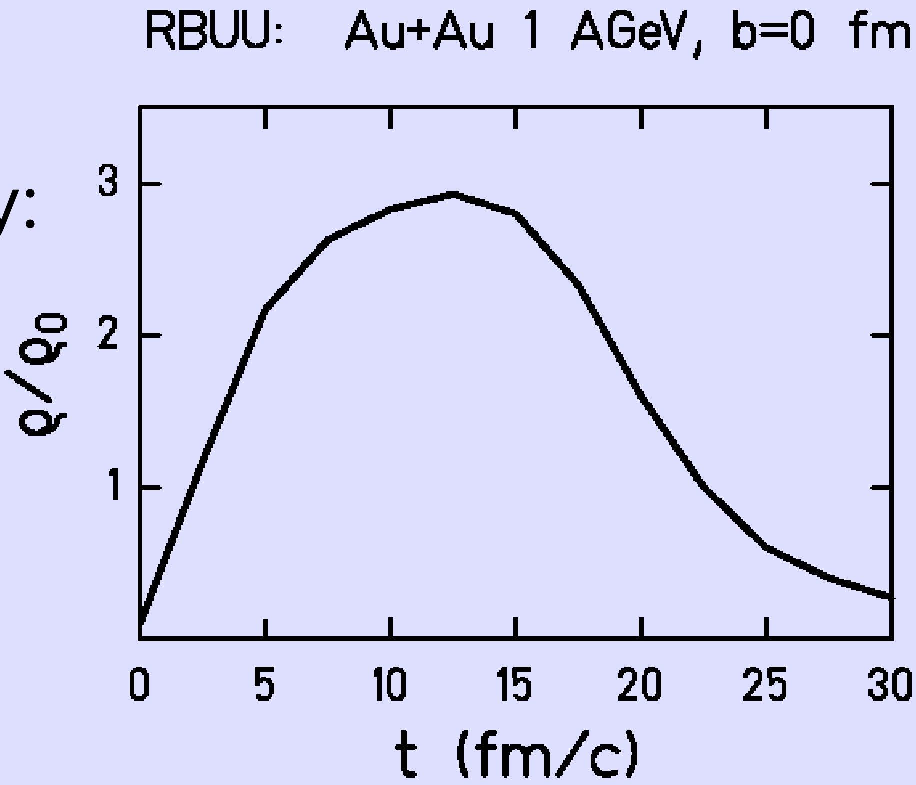


- impact param. ***b***: - defines collision centrality
  - ~ measured charged particle multiplicity
- central collisions: highest densities, many collisions
  - particle production
- peripheral collisions: pressure gradients, shadowing
  - particle emission patterns (flow)

Heavy-Ion Collisions (II)

- Facilities: **SIS**, AGS, SPS, RHIC, LHC
  E ~ 100 AMeV – 2.7 ATeV

- situation at 2 AGeV beam energy:
  - velocity: $\beta \approx 0.9$
  - time scale:
    $$t \approx 5 - 10\ fm/c \approx 2 \cdot 10^{-23}\ s$$
  - density: $\rho \approx 2 - 3 \cdot \rho_0$



X.S. Fang et al., NPA 575 (1994) 766

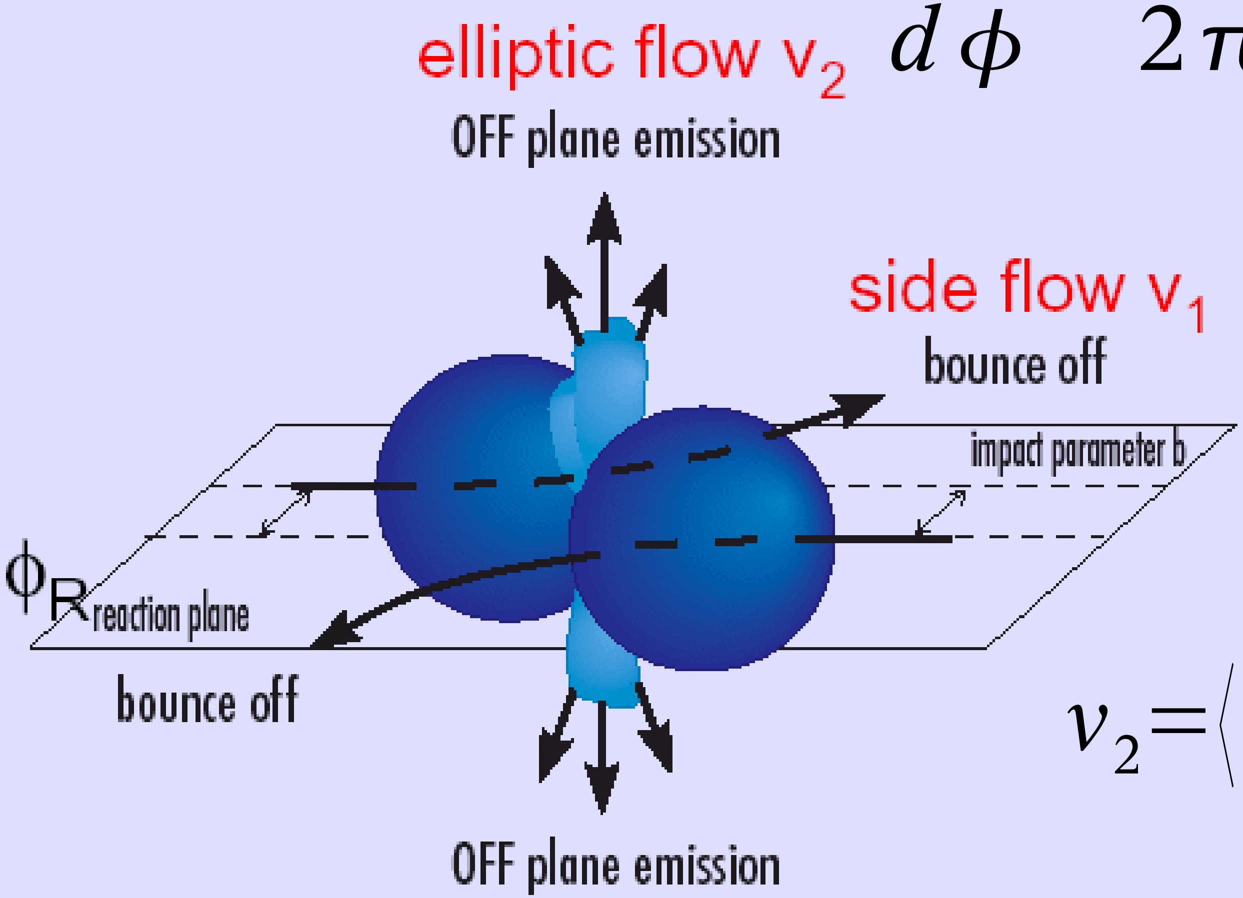
Observables in Nucl. Coll.

- What do we have to look at in order to learn about DBM?
  - the sky...
  - as many particles as possible in a heavy-ion collision

- particle observables
  - phase-space distributions
  - production cross sections, total yields
  - particle emission (flow) patterns
  - particle correlations
- event characterization
  - centrality
  - reaction plane (flow)

Flow in Nuclear Collisions

$$\frac{dN}{d\phi} = \frac{1}{2\pi}\left(1 + \sum_{n=1}^{\infty} 2 v_n \cos(n\phi)\right)$$

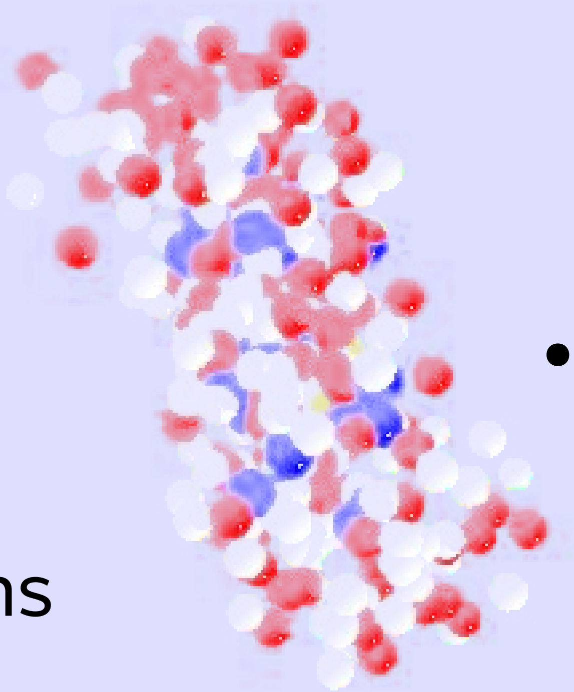


$$v_1 = \langle \cos(\phi_{em}) \rangle = \left\langle \frac{p_x}{p_t} \right\rangle$$

$$v_2 = \langle \cos(2\phi_{em}) \rangle = \left\langle \frac{p_x^2 - p_y^2}{p_t^2} \right\rangle$$

What do Models tell us ?

- experimental observations alone mostly do not tell the full story
- interpretation requires detailed comparison to model calculations



- there exist different classes of models
  - transport models
  - thermal models
  - hydrodynamical models
- each model type treats different aspects of a heavy-ion collision
  - time evolution
  - particle spectra, yields
  - equilibration

Transport Models

- study the dynamical evolution in a HIC
- describe collision in fully microscopic way
- input:
  - transport equation (e.g. BUU)
  - potential(s)
  - cross sections
- variety of models available (...QMD)

$$\frac{\partial f}{\partial t} + \vec{v} \cdot \vec{\nabla}_r f - \vec{\nabla}_r U \cdot \vec{\nabla}_p f = -\frac{1}{(2\pi)^6} \int d^3p_2 d^3p_{2'} d\Omega \frac{d\sigma}{d\Omega} v_{12}$$
$$\times \{[f f_2(1-f_{1'})(1-f_{2'}) - f_{1'} f_{2'}(1-f)(1-f_2)]$$
$$\times (2\pi)^3 \delta^3(\vec{p} + \vec{p}_2 - \vec{p}_{1'} - \vec{p}_{2'})\}$$

$$f = f(\vec{r}, \vec{p}, t)$$

(single particle phase-space density)

$$U(\rho) = A \cdot \left(\frac{\rho}{\rho_0}\right) + B \cdot \left(\frac{\rho}{\rho_0}\right)^\sigma$$

$\sigma > 1$
A < 0 (attractive part)
B > 0 (repulsive part)

Thermal Models

$$n_i = \frac{N_i}{V} = \frac{g_i}{2\pi^2}\int_0^\infty \left[\exp\left(\frac{E_i(p)-\mu_i}{T}\right)+\varepsilon\right]^{-1} p^2 dp$$

ε = +1 (Fermions)
ε = -1 (Bosons)

$$\mu_i = \mu_B B_i - \mu_S S_i - \mu_{I_3} I_{3i}$$

Baryon number $V\sum_i n_i B_i = Z + N$

Strangeness $V\sum_i n_i S_i = 0$

Isospin $V\sum_i n_i I_{3i} = \frac{Z-N}{2}$

- assume thermal and chemical equilibrium
- only two parameters needed: ***T*** and ***μ***
- chemical potential composed of several quantum numbers
- fix quantum numbers with conservation laws
- use canonical description at SIS

Phase Diagram: What do we know ?

- transport models: time evolution (ρ(t))
- thermal models: chemical freeze-out
- Lattice QCD: existence of a critical point (?)
- RHIC: new state is quite opaque and not dilute