Interações Fortes em Condições Extremas

(second lecture)

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Second Lecture

- ★ First question you should ask: WHY??
  - Motivation and some disturbing facts
- ✳ Collective effects x "fundamental" physics
- ★ Second question you should ask: WHERE??
  - Accelerator experiments, astro, early universe
- ✳ My focus: the EoS
- ★ Third question you should ask: HOW??
  - Theory, models, etc

First question you should ask: WHY??

Confinement: one of the 6 unsolved Millennium Problems...



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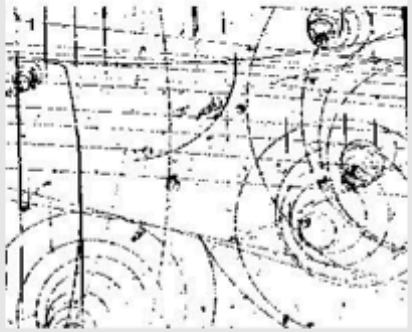
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Yang-Mills and Mass Gap

The laws of quantum physics stand to the world of elementary particles in the way that Newton's laws of classical mechanics stand to the macroscopic world. Almost half a century ago, Yang and Mills introduced a remarkable new framework to describe elementary particles using structures that also occur in geometry. Quantum Yang-Mills theory is now the foundation of most of elementary particle theory, and its predictions have been tested at many experimental laboratories, but its mathematical foundation is still unclear. The successful use of Yang-Mills theory to describe the strong interactions of elementary particles depends on a subtle quantum mechanical property called the "mass gap:" the quantum particles have positive masses, even though the classical waves travel at the speed of light. This property has been discovered by physicists from experiment and confirmed by computer simulations, but it still has not been understood from a theoretical point of view. Progress in establishing the existence of the Yang-Mills theory and a mass gap and will require the introduction of fundamental new ideas both in physics and in mathematics.

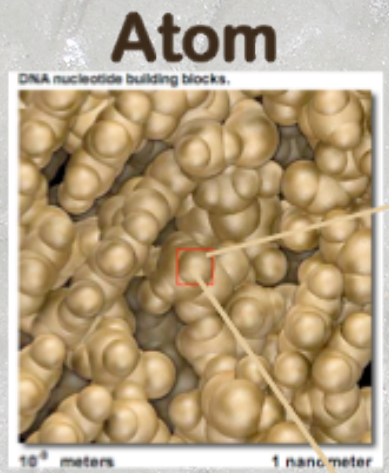
- The Millennium Problems
- Official Problem Description — Arthur Jaffe and Edward Witten
- Report on the Status of the Yang-Mill Millenium Prize Problem by Michael Douglas (April 2004).
- Lecture by Lorenzo Sadun at University of Texas (video)

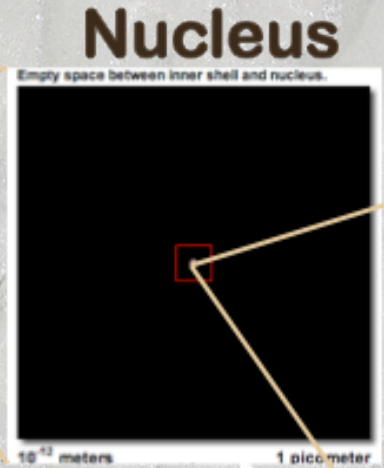


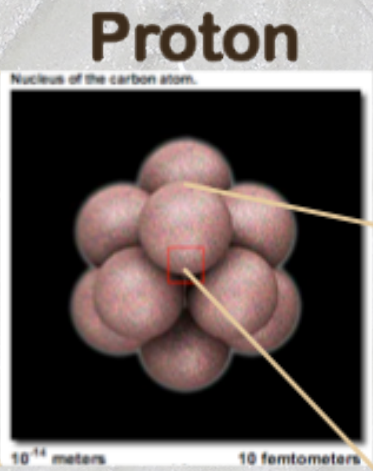
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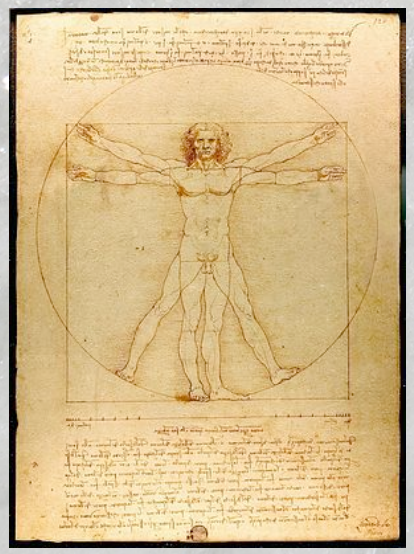
Not only a cute (and very tough!) math problem...

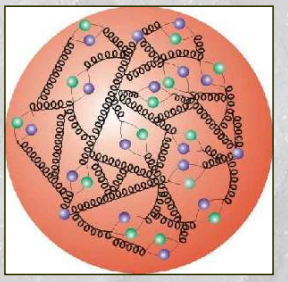






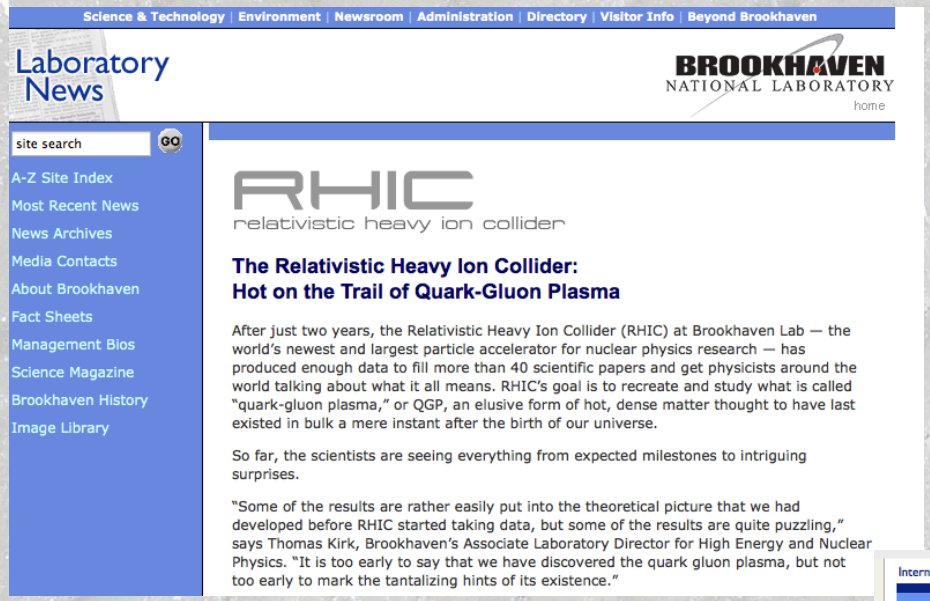






(Univ. Oxford)

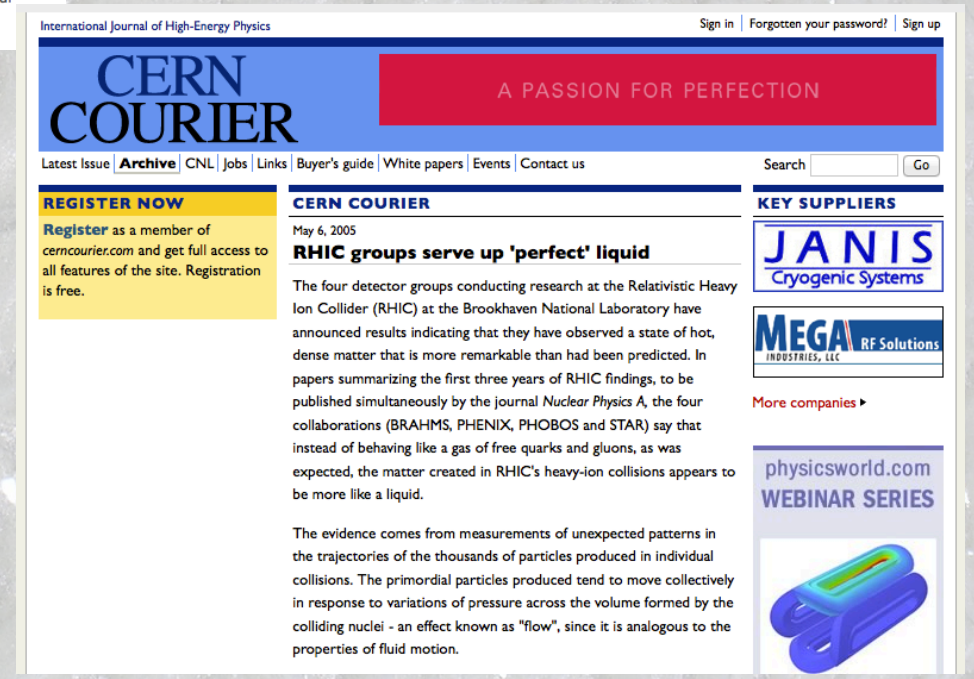
Real origin of mass...
Sorry, Higgs!



Deconfinement: matter put under extreme conditions…

… can behave in unexpected ways.

In spite of the fantastic success of the Standard Model, we don't understand a few essential mechanisms…



Another why? (this one is, of course, enough!)

The behavior of QCD at high temperature is of obvious interest. It provides the answer to a childlike question:
What happens if you keep making things hotter and hotter?

The behavior of QCD at large net baryon density (and low temperature) is also of obvious interest. It answers yet another childlike question: What will happen when you keep squeezing things harder and harder?

(Frank Wilczek, Phys. Today, August 2000)

The Nobel Prize in Physics 2004:
"for the discovery of asymptotic freedom in the theory of the strong interaction"

Physicist's question:

What is the inner structure of matter and the nature of strong interactions under extreme conditions of temperature and density?

- **Experiments:** "squeeze", "heat", "break"
- **Theory:** in-medium quantum field theory, i.e.
  - finite-temperature QCD
  - finite-density QCD
  - effective models

➢ Some disturbing "facts" about confinement:

- Confinement seems to be a property of hadrons.
- Confinement seems to be present in QCD.
- Lattice: evidence of confinement in pure gauge and QCD.
- There seems to be a confinement scale (masses, f_π, Λ_{QCD}).

➢ Some annoying problems:

- Theory is nonperturbative at relevant scales.
- Lattice is great but not perfect, and not Nature.
- "seems" is pretty annoying in all the "facts" above...

➢ We don't know that much, so we need a lot of input...

To make progress in understanding (or at least in collecting facts), we need it all:

- Experiments and observations
- Lattice
- Theory
- Effective models

And also combinations whenever possible. Because...

- Experiments are really expensive, hard and "dirty".

- Lattice has still several limitations (not only hardware...).

- Theory (QCD) can be (barely) solved in very specific situations (usually away from the interesting region).

- Effective models capture just part of the game.



In terms of thermodynamics, or many-body or statistical mechanics, the basic ideas are:

✧ Perturbing the (confined) vacuum to study confinement by

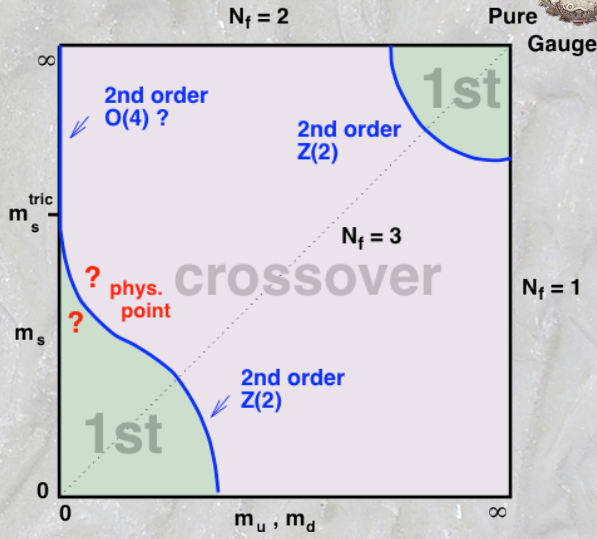
- heating (temperature)
- squeezing or unbalancing species (chemical potentials: baryon number, isospin, strangeness, ...)
- using classical external fields (magnetic, ...)

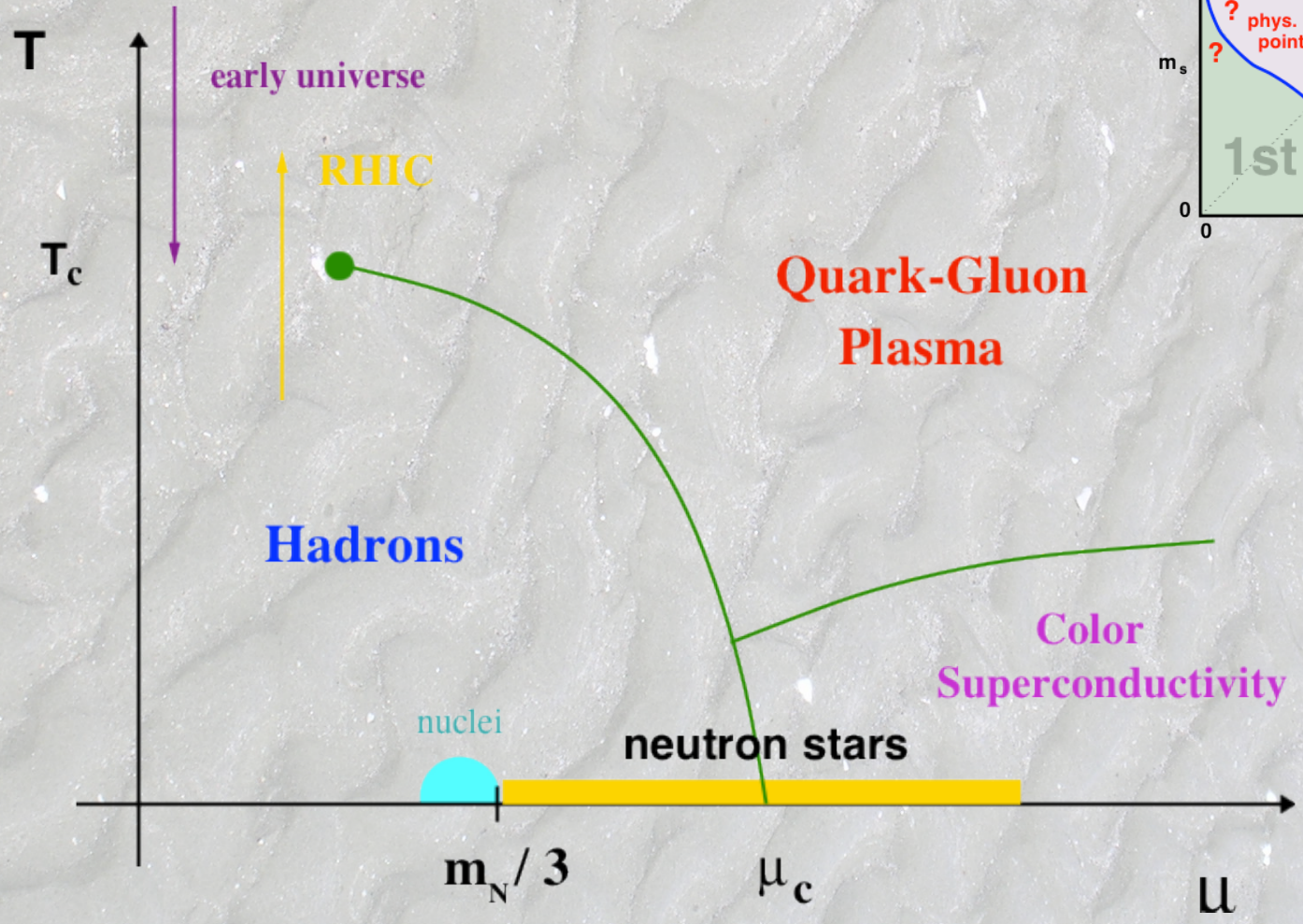
and taking the system away from confinement and back.

✧ Relating (or not) confinement to other key properties of strong interactions and QCD (chiral symmetry, etc).

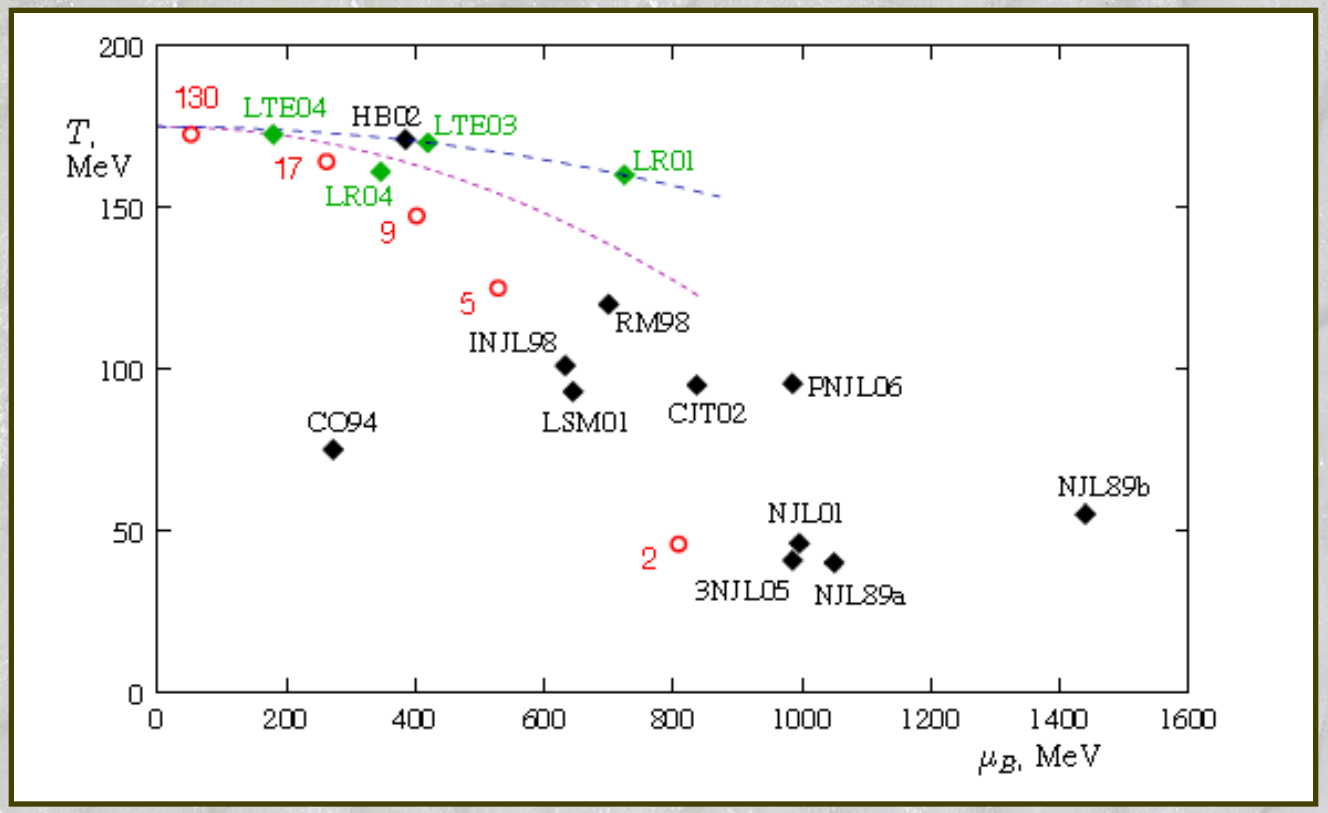
✧ Trying to draw all possible phase diagrams of QCD and "cousin theories" to learn basic facts.

Example – cartoon of a phase diagram:





Example of "we don't know that much": position of the critical endpoint of QCD:



[Stephanov (2006)]

- Model predictions, lattice, freeze-out points in HIC

Second question you should ask: WHERE??

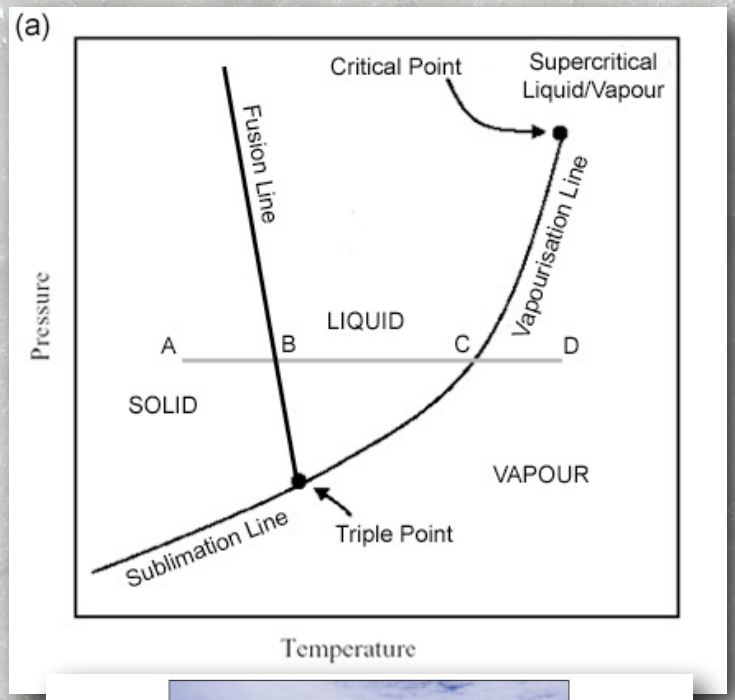
But before that, let's discuss an important point...

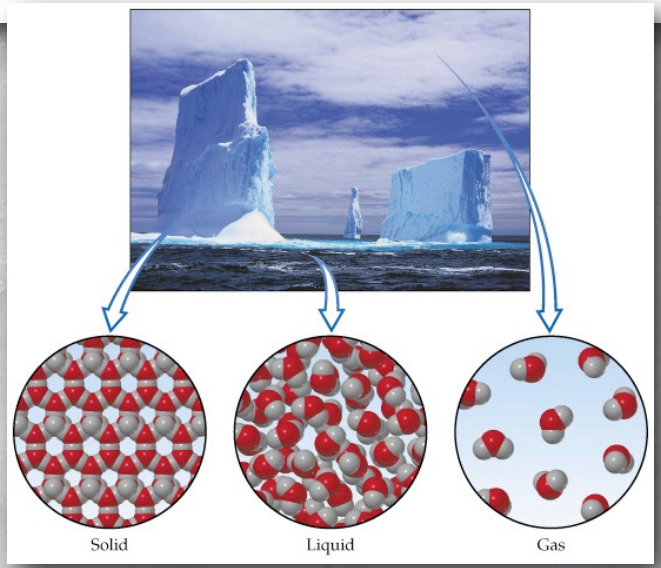
Collective effects x microscopic ("fundamental") physics

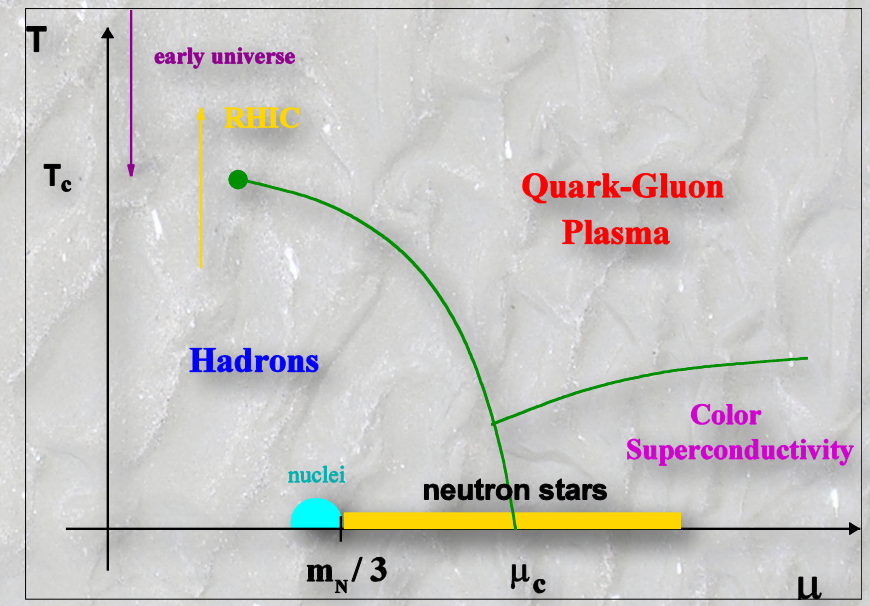


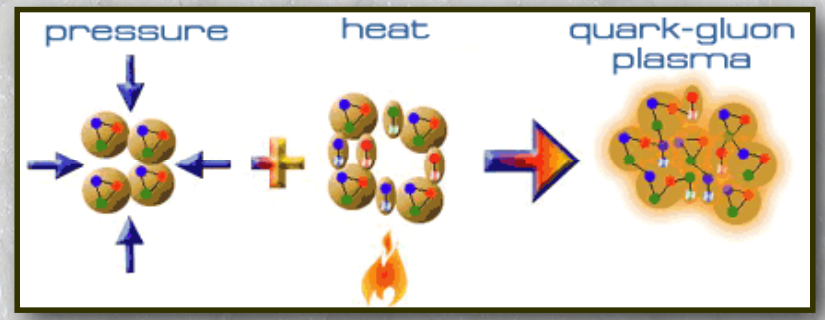


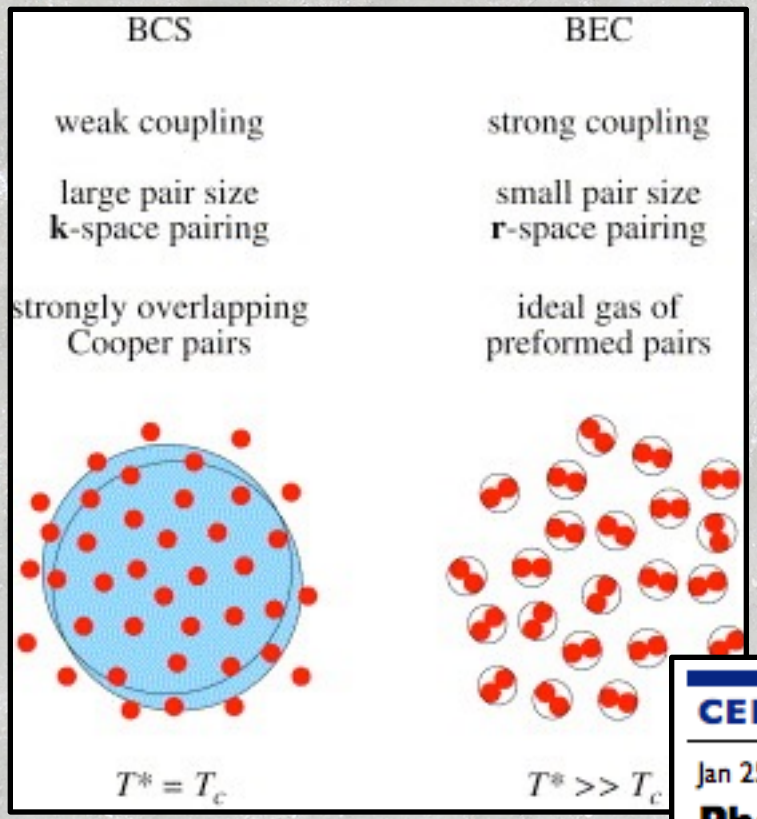
Collective effects x microscopic ("fundamental") physics



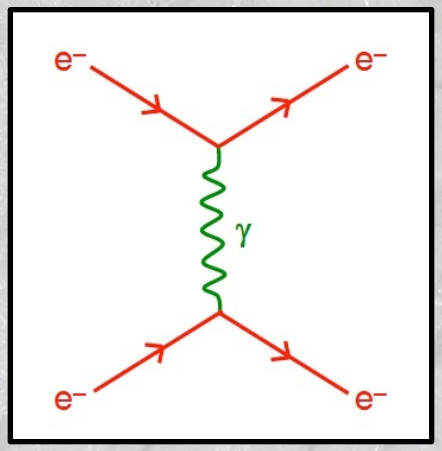


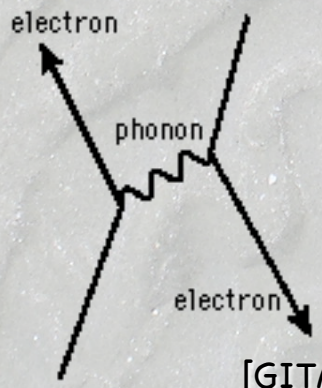






[Chen et al (2005)]



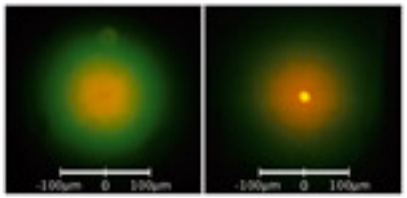


[GITAM]

CERN COURIER

Jan 25, 2011

Photons form a Bose-Einstein condensation



Bose-Einstein condensation

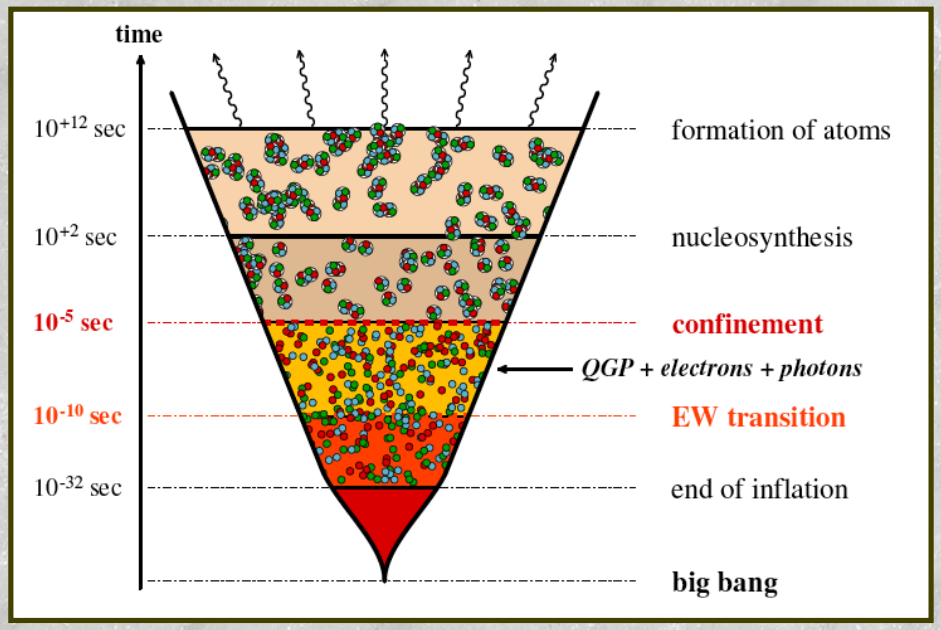
At first glance, the idea of a Bose-Einstein condensate of photons seems ridiculous: photons have zero chemical potential, which is to say that their numbers are not conserved as temperature varies. Indeed, there is no Bose-Einstein condensation of photons in blackbody radiation. Remarkably, Martin Weitz of the University of Bonn in Germany and colleagues have found a way round this.

Now, ok, back to the...

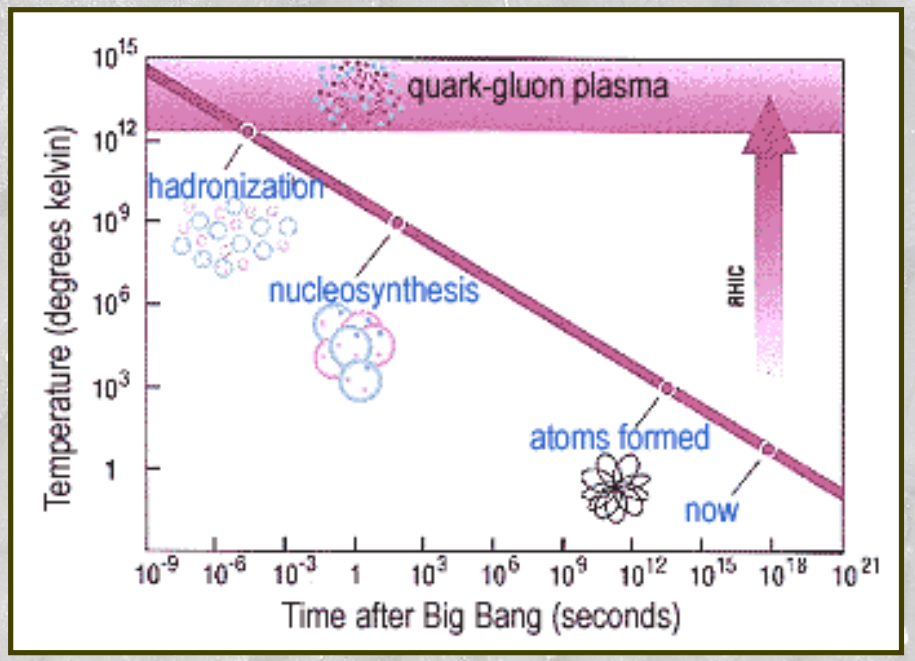
Second question you should ask:
WHERE??

Experiments and observations

First time: the early universe



(RHIC)



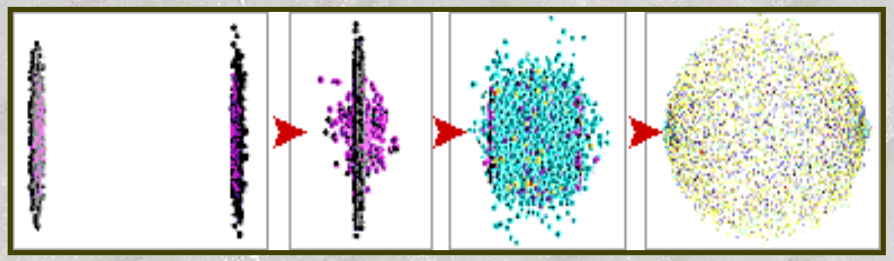
(RHIC)

Temperature-driven transitions (very low μ)

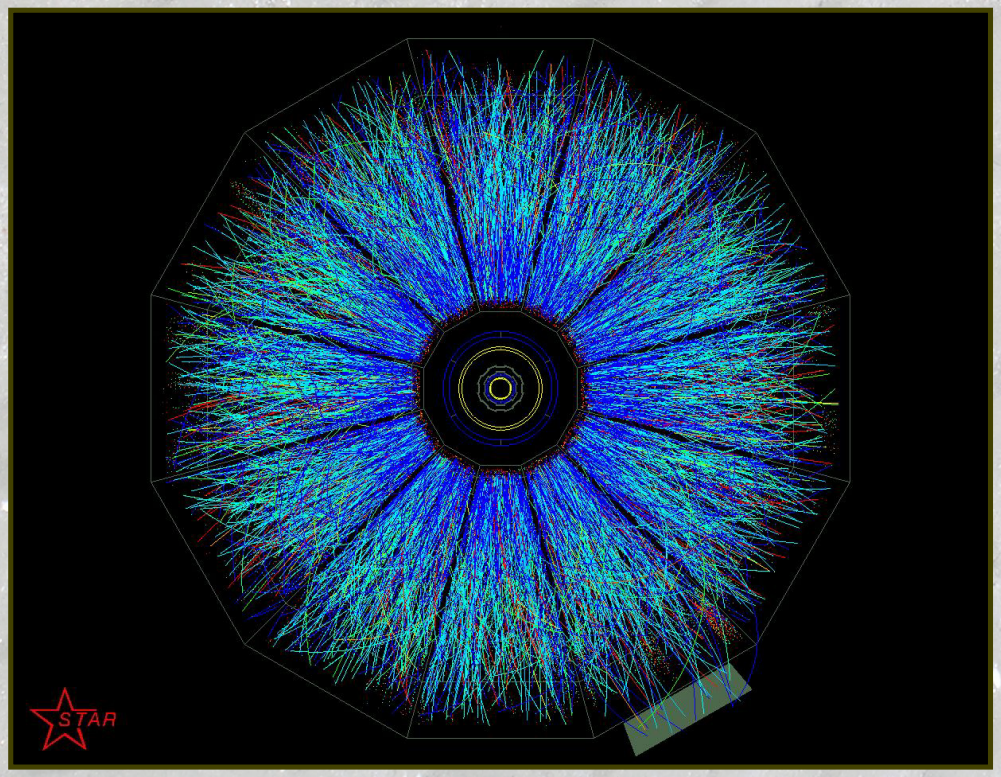
Observables: relics from that time?

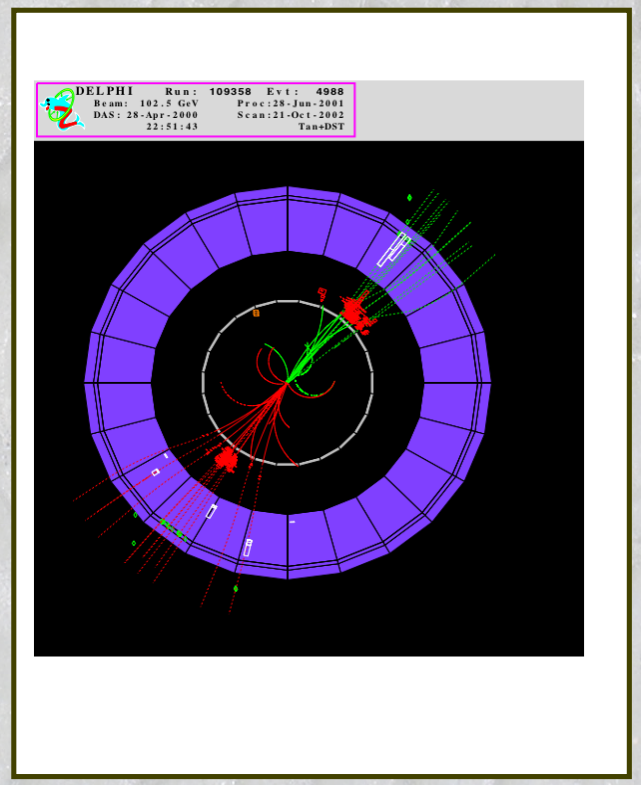
In the lab – heavy ion collisions ("Little Bang")





LEP: $e^+ + e^- \rightarrow q\,\bar{q}$ (≈200 GeV)





Big Bang vs. Little Bang

Using a simple approximation for the EoS, $3p \approx \epsilon \approx \frac{\pi^2}{30} N(T) T^4$ we can estimate the typical sizes:

Early universe (Big Bang):

The radius of the universe, as given by the particle horizon in a Robertson-Walker spacetime, where the scale factor grows as $a(t) \sim t^n$, is given by ($n=1/2$, $N \sim 50$ for QCD)

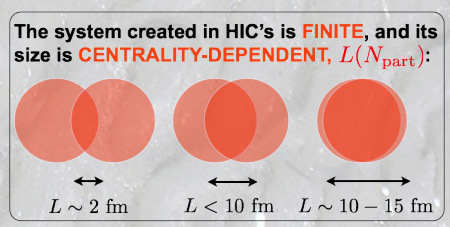
$$L_{univ}(T) \approx \frac{1}{4\pi} \left(\frac{1}{1-n} \right) \left(\frac{45}{\pi N(T)} \right)^{1/2} \frac{M_{Pl}}{T^2} = \frac{1.45 \times 10^{18}}{(T/\text{GeV})^2 \sqrt{N}} \text{ fm}$$

The system is essentially in the thermodynamic limit!

Heavy ion collisions (Little Bang):

$$L_{QGP} \leq 10 - 15 \text{ fm}$$

The system can be very small!



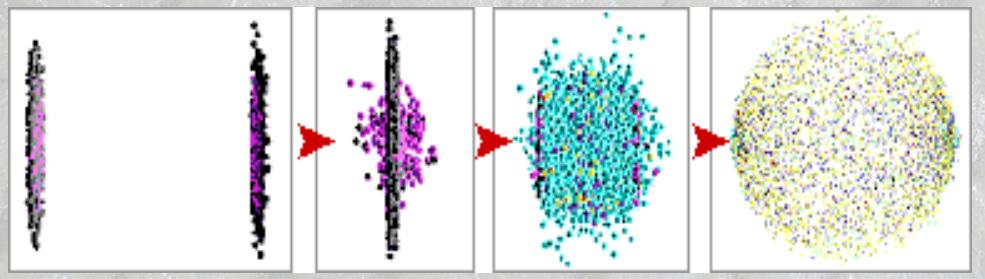
Huge differences in (time and length scales) between Big and Little Bangs...

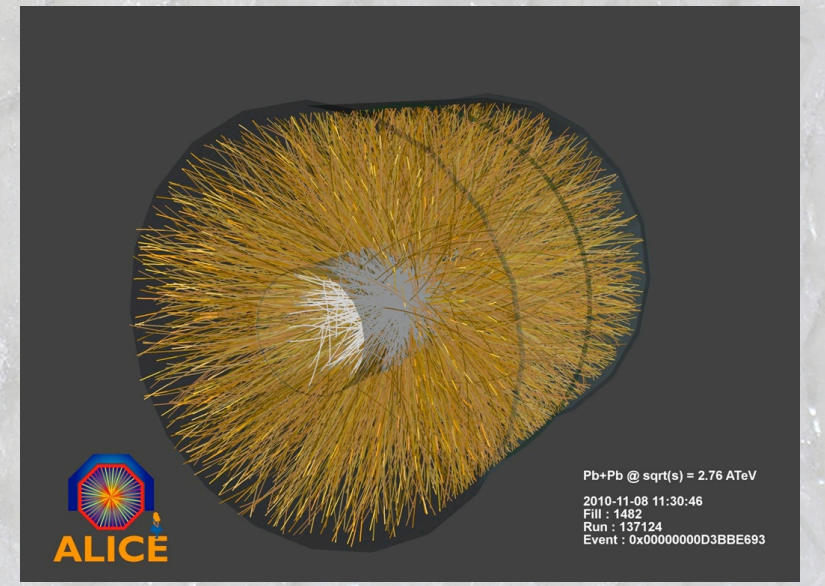
Some scales:

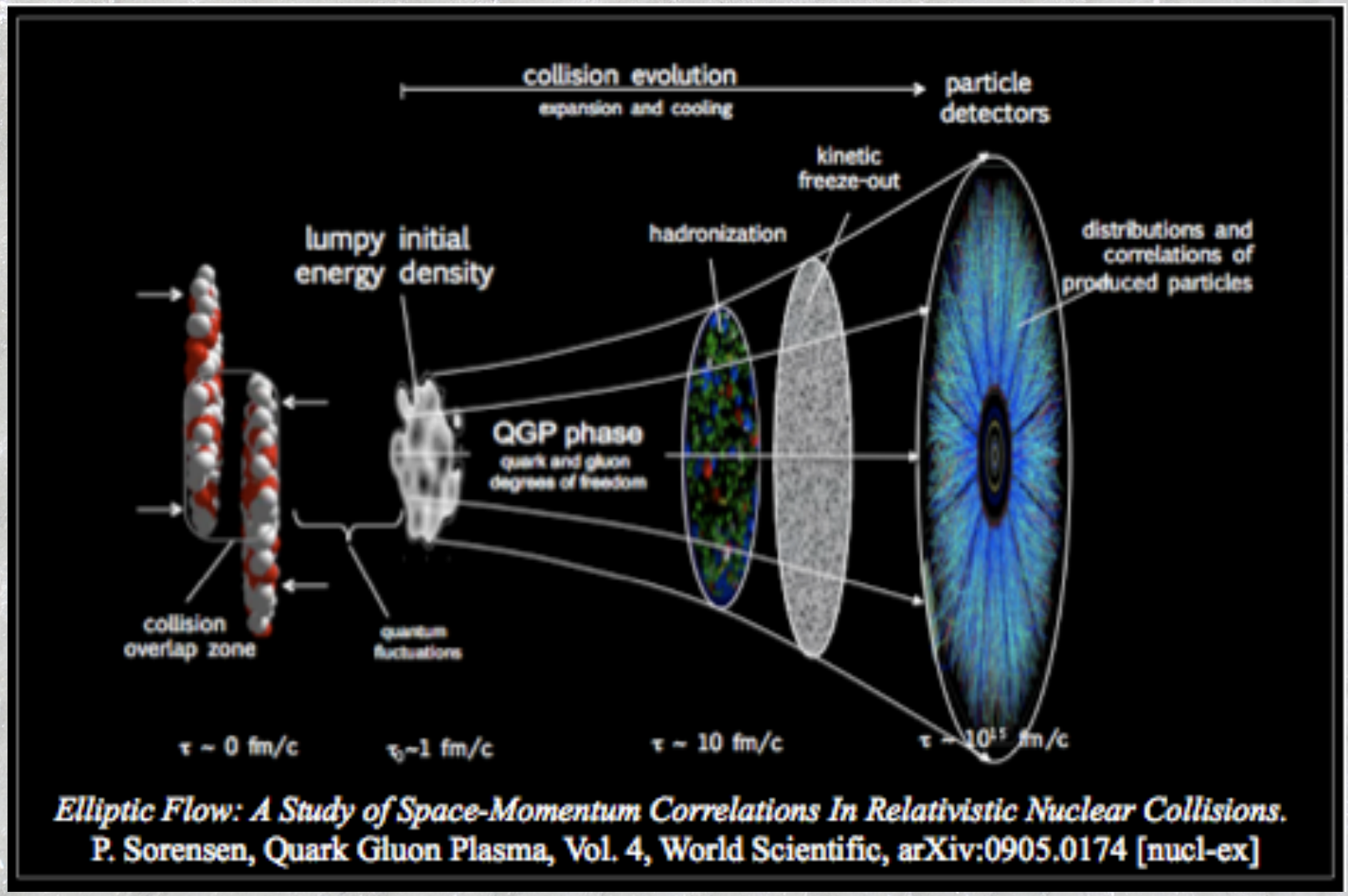
- Electroweak transition ~ 100 GeV -> way too high...

- Chiral & deconfinement transitions ~ 150 MeV

QCD phase transitions in the lab!
(very low μ, temperature-driven)



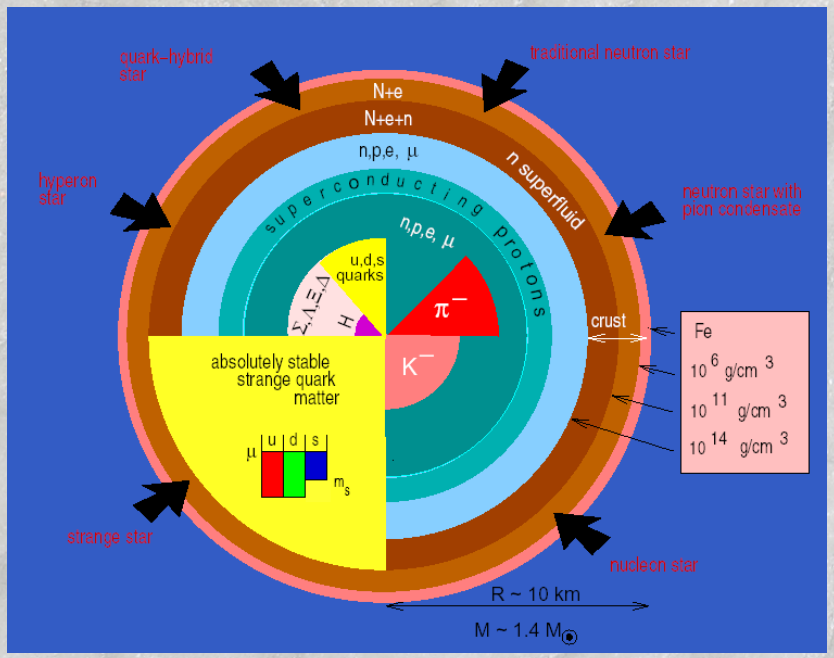



collision evolution
expansion and cooling
particle detectors
kinetic freeze-out
lumpy initial energy density
hadronization
distributions and correlations of produced particles
QGP phase
quark and gluon degrees of freedom
collision overlap zone
quantum fluctuations
τ ~ 0 fm/c
τ0~1 fm/c
τ ~ 10 fm/c
τ ~ 10^13 fm/c
Elliptic Flow: A Study of Space-Momentum Correlations In Relativistic Nuclear Collisions.
P. Sorensen, Quark Gluon Plasma, Vol. 4, World Scientific, arXiv:0905.0174 [nucl-ex]

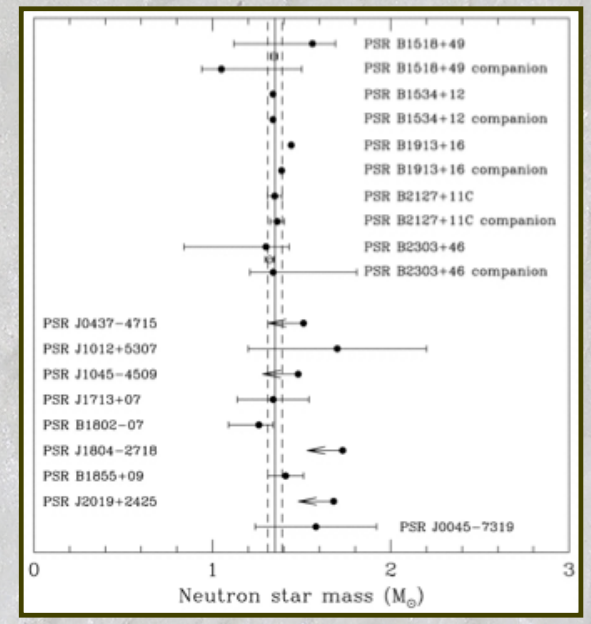
Compact stars (structure, supernovae, etc)

- New phases, condensates, color superconductivity, etc in the core.

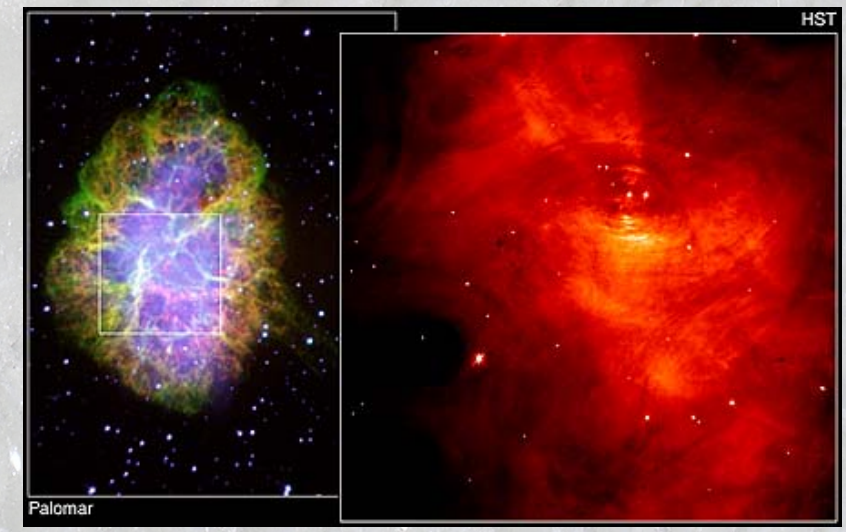
- Deconfinement and χ symmetry might affect explosion mechanism via EoS.



(F. Weber, 2000)



(Thorsett & Chakrabarty, 1999)



(NASA)

Some extreme numbers:

RHIC:

$v_{beam} \approx 0.99995\ c$

$T_c \approx 200\ MeV \approx 2 \times 10^{12}\ K$

⟹ QFT at "high" temperature

Compact stars:

$n_0 = 3 \times 10^{14}\ g/cm^3 = 0.16\ fm^{-3}$

$n_{core} \approx (4 - 15)\ n_0$ $\quad [\langle n_{Earth} \rangle \approx 5.5\ g/cm^3]$

$M \approx 1 - 2$ solar masses $\quad [M_S \approx 2 \times 10^{33}\ g]$

$R \approx 6 - 16\ Km$ $\quad [R_S \approx 7 \times 10^5\ km]$

⟹ QFT at "high" density + General Relativity

Third question you should ask:
HOW??
(theory, models, etc)

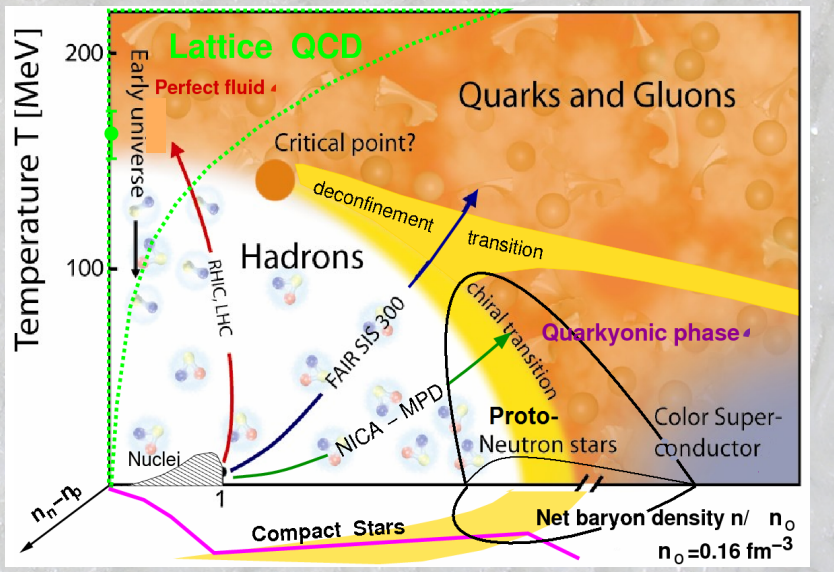
But before that, let me state my focus here, and why so...

Focus: the equation of state (EoS)

Why? Because, besides carrying all the thermodynamic equilibrium info we may want, it is also the basic crucial ingredient for dynamics, structure, etc.

1. Phase diagram structure (every detail):

pressure(T,μ,B,etc)



2. Structure of compact stars:

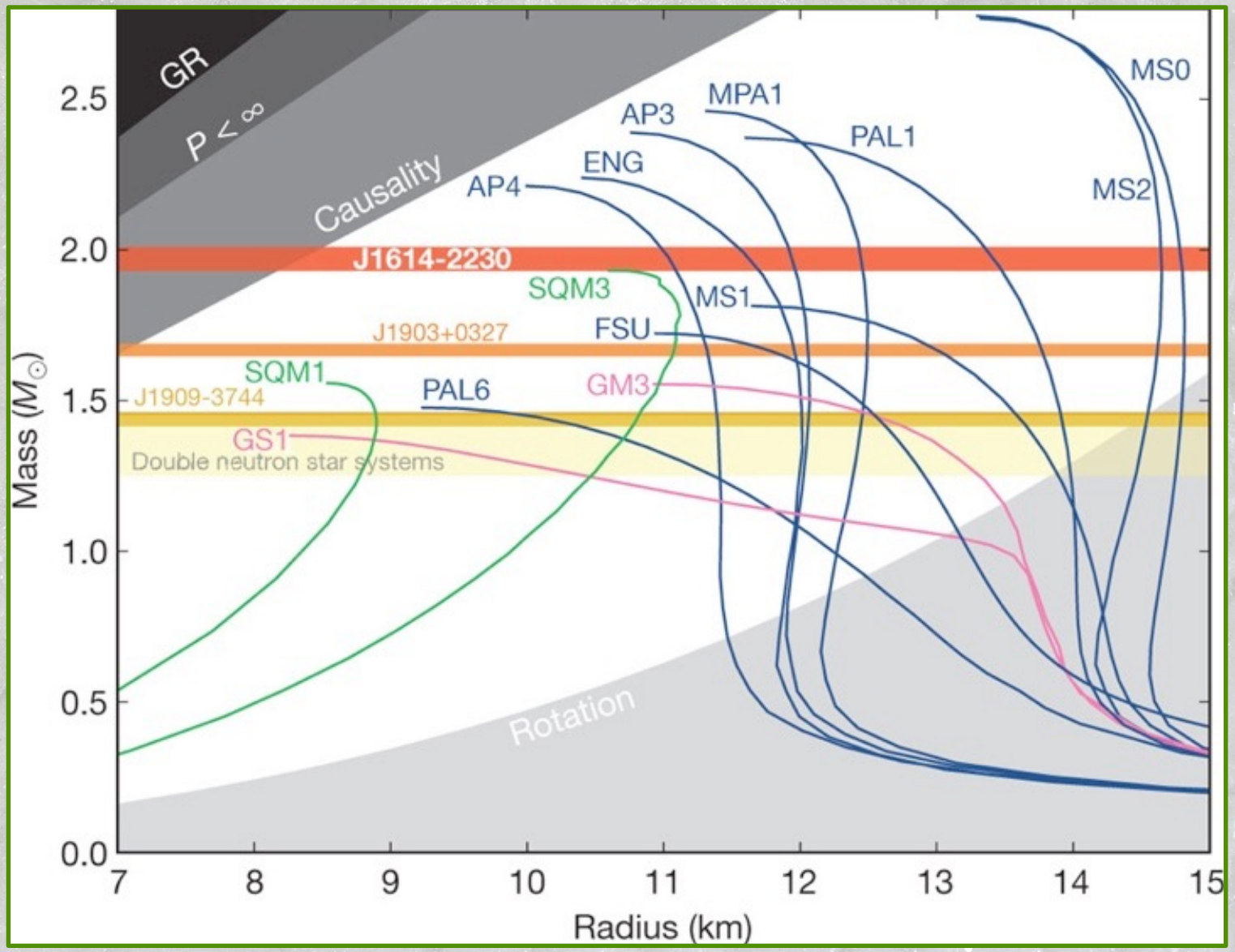
Tolman-Oppenheimer-Volkov equations:

- Einstein's GR field equations
- Spherical symmetry
- Hydrostatic equilibrium

$$\frac{dp}{dr} = -\frac{G\mathcal{M}(r)\epsilon(r)}{r^2\left[1-\frac{2G\mathcal{M}(r)}{r}\right]}\left[1+\frac{p(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 p(r)}{\mathcal{M}(r)}\right]$$

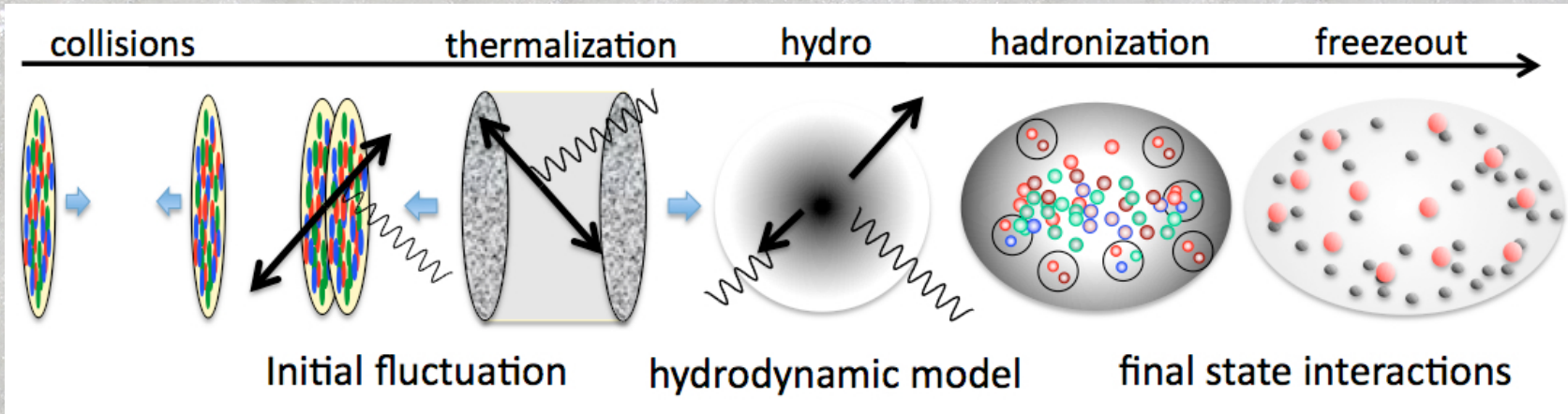
$$\frac{d\mathcal{M}}{dr} = 4\pi r^2 \epsilon(r) \;\; ; \;\; \mathcal{M}(R) = M$$

- Given the EoS p = p(e), one can integrate the TOV equations from the origin until the pressure vanishes p(R) = 0
- Different EoS's define different types of stars: white dwarfs, neutron stars, quark stars, strange stars, ...

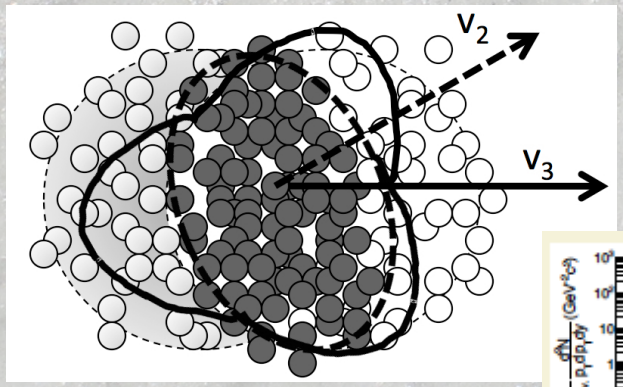


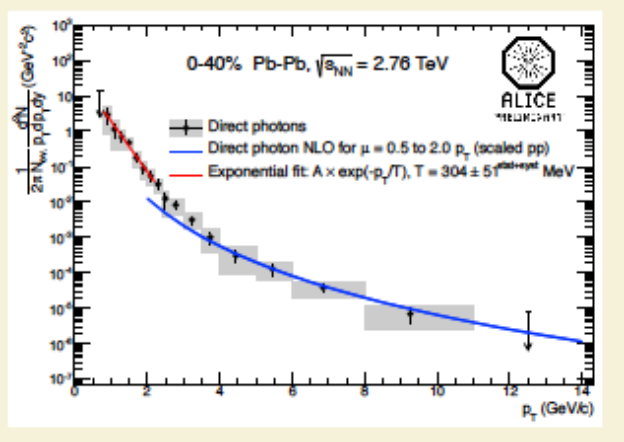
[Demorest et al (2010)]

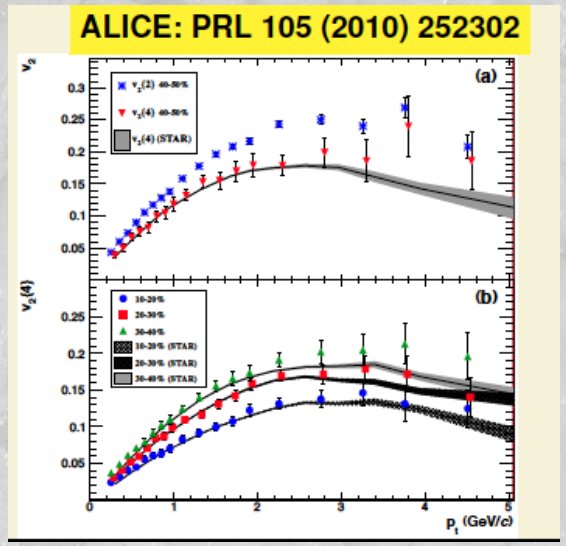
3. Hydro in heavy ion collisions:



[Nonaka et al (2012)]







Ideal hydrodynamics

- The fundamental equation of hydrodynamics is simply the conservation of energy-momentum,

$$\partial_\mu T^{\mu\nu} = 0$$

and of the baryon number,

$$\partial_\mu (n_{_B} v^\mu) = 0$$

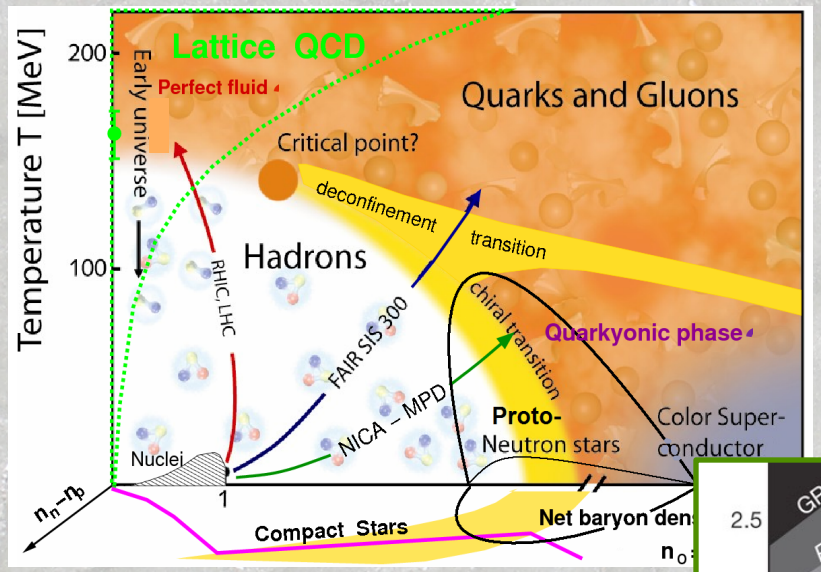
- The unknown functions are :
  - $p(t, \vec{x}), \epsilon(t, \vec{x}), n_{_B}(t, \vec{x})$
  - $v^\mu(t, \vec{x})$ (3 unknowns only, since $v_\mu v^\mu = 1$)

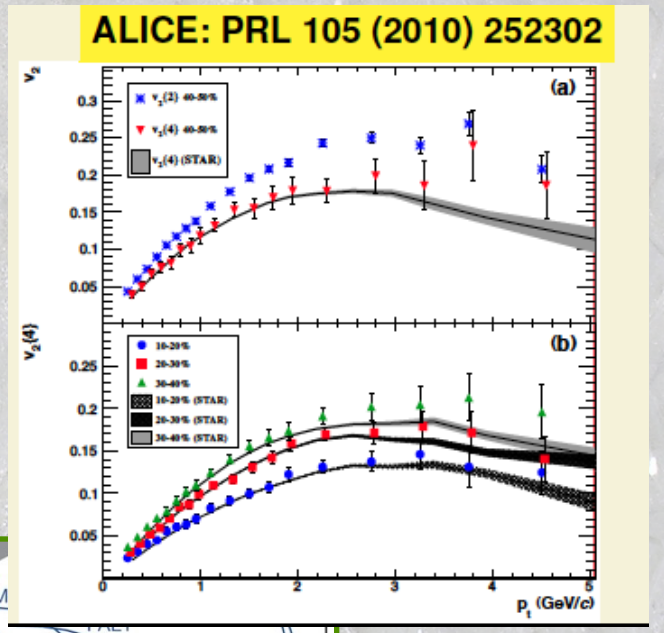
- $\partial_\mu T^{\mu\nu} = 0$ and $\partial_\mu (n_{_B} v^\mu) = 0$ give only 5 equations

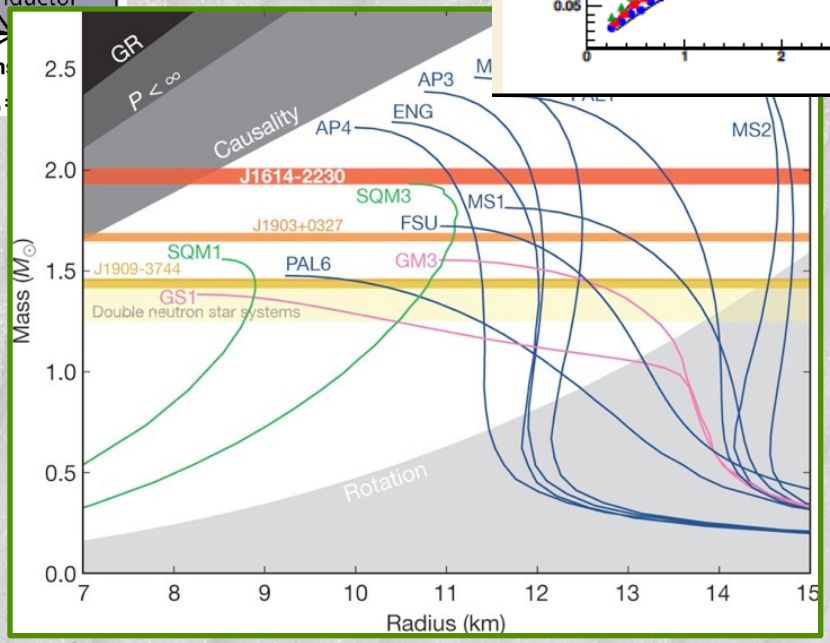
- An additional constraint comes from the equation of state of the matter under consideration, as a relation between the local pressure p and energy density ϵ

[Gelis (2012)]

So, it is clear that we REALLY need the EoS:







Now, ok, back to the...

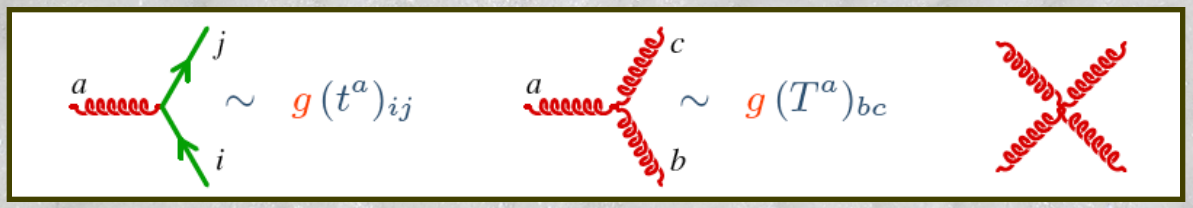
Third question you should ask:
HOW??
(theory, models, etc)

Theory (QCD)

The theory is, in principle, given:

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \sum_f \overline{\psi}_f (i\gamma^\mu \partial_\mu - m_f - ig\gamma^\mu A^a_\mu \tau^a)\psi_f$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f^{abc} A^b_\mu A^c_\nu$$



Then: compute the thermodynamic potential, blah blah...

Well, it's not so simple...



So, we need to talk about QCD...

Next lecture!

Third Lecture

- ★ Introduction and motivation
- ★ Evidence for quarks, gluons & color
- ★ The QCD Lagrangian
- ★ Asymptotic freedom & the vacuum of QCD
- ★ Effective field theory basic recipe
- ★ Summary