Re-Creating the Big Bang

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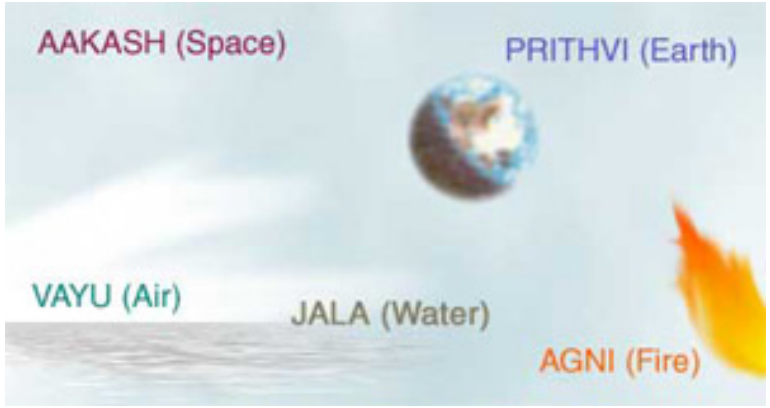
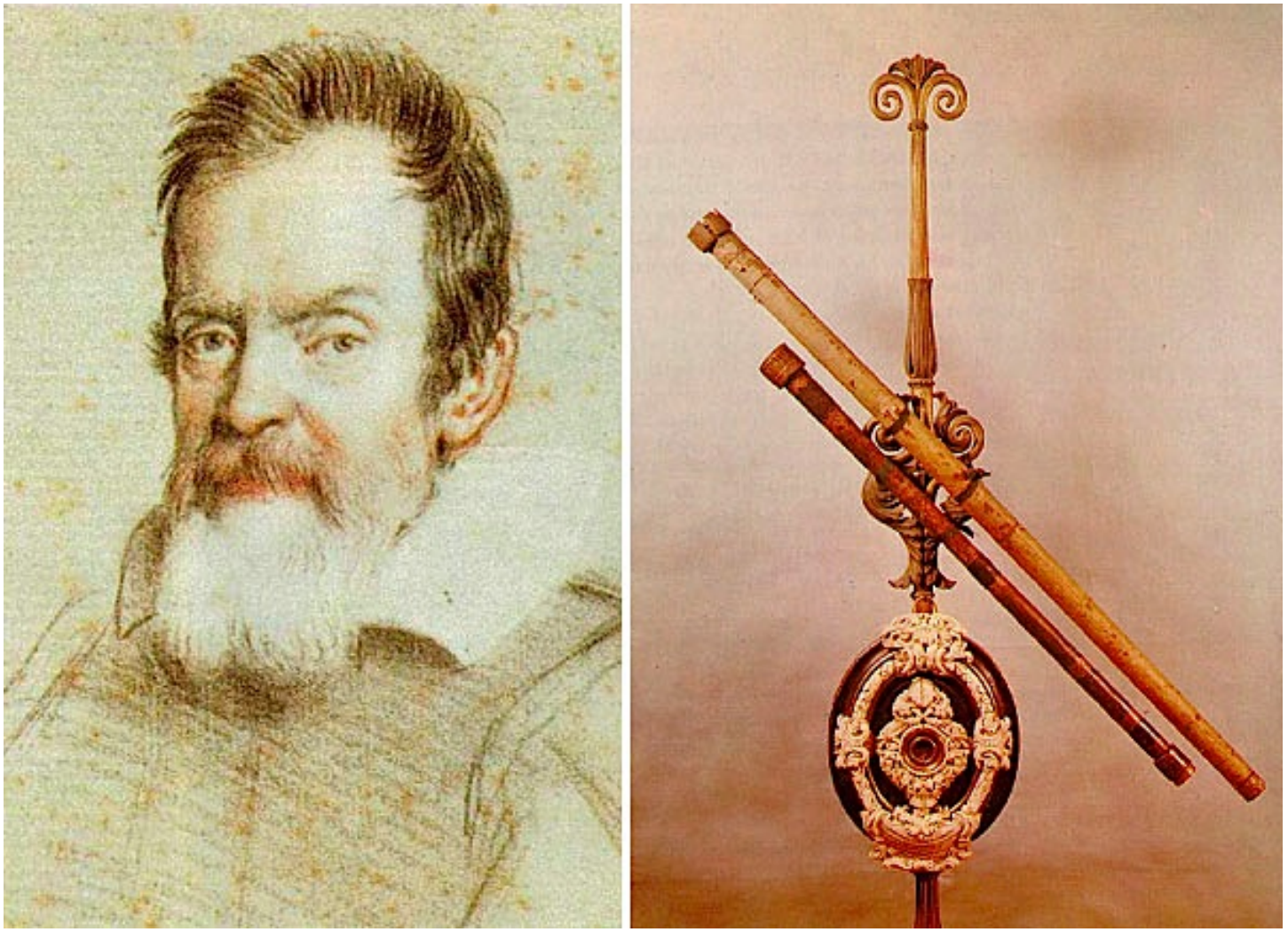
Introduction : What is the Big Bang Theory ?

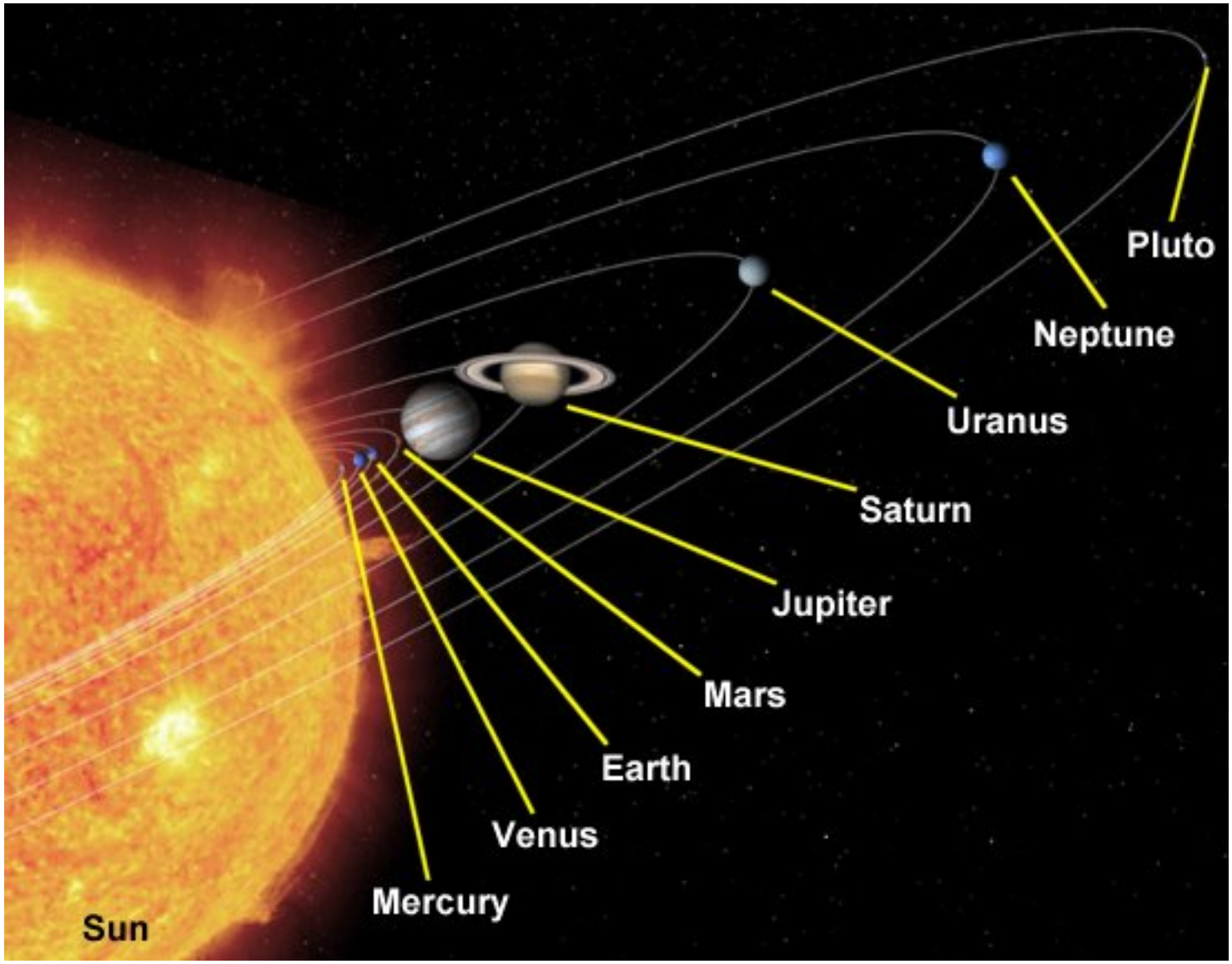


- All civilizations, Babylonian, Greek, and Indian, thought of *classic elements* as the basis of our world. Familiar concept : *Panch mahabhuta*

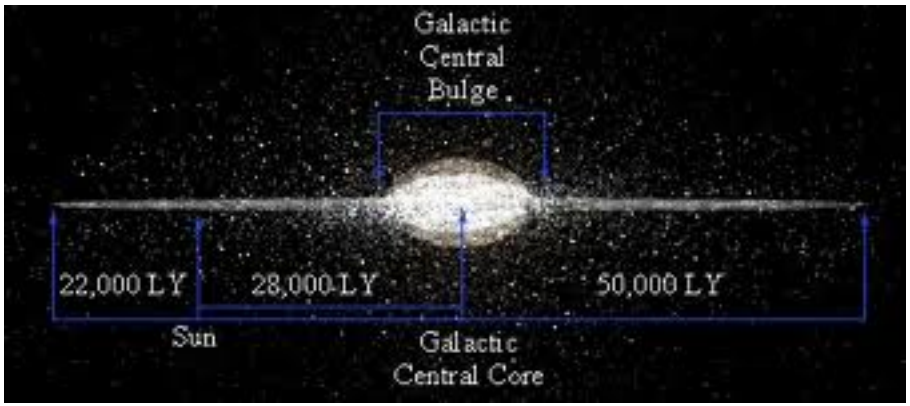
- Atomism — world consists of atoms — was also invented in India (Maharshi Kanada), & Greece (Democritus).

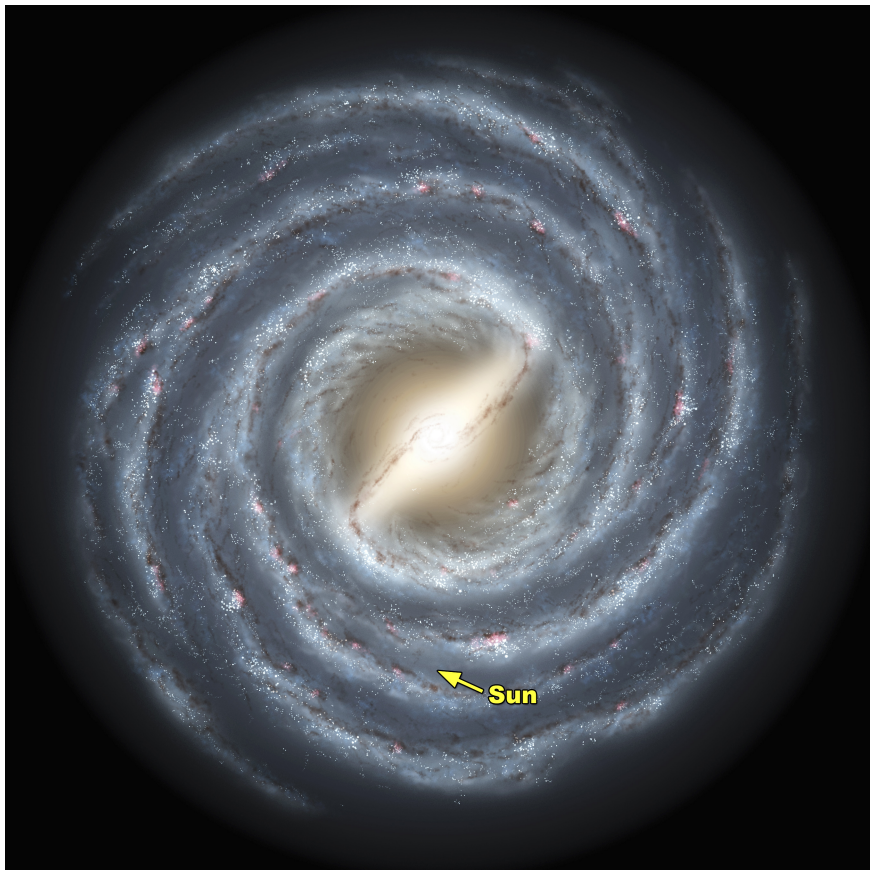


Galileo Galilei — The Father of Modern Science & his telescope.

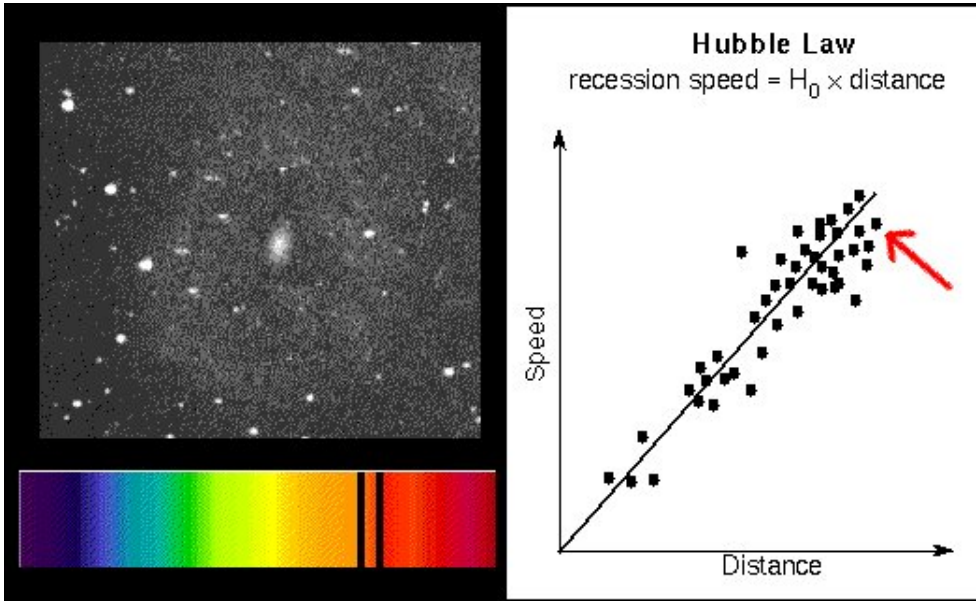


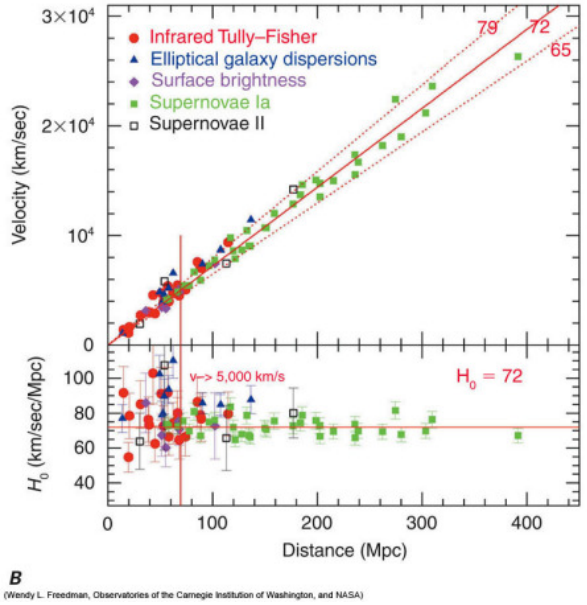
Sizes shown to scale but *not* distances.





Our Sun in Our Milky Way Galaxy (1 light year $= 9.46 \times 10^{12}$ kilometers)


Hubble Law
recession speed = $H_0 \times$ distance
Speed
Distance


Infrared Tully–Fisher
Elliptical galaxy dispersions
Surface brightness
Supernovae Ia
Supernovae II
79
72
65
Velocity (km/sec)
H_0 (km/sec/Mpc)
v–> 5,000 km/s
H_0 = 72
Distance (Mpc)
B
(Wendy L. Freedman, Observatories of the Carnegie Institution of Washington, and NASA)

- Hubble's Expansion Law. $\Longrightarrow$
  Past : Universe was Denser, although
  Now : It is Rarer.

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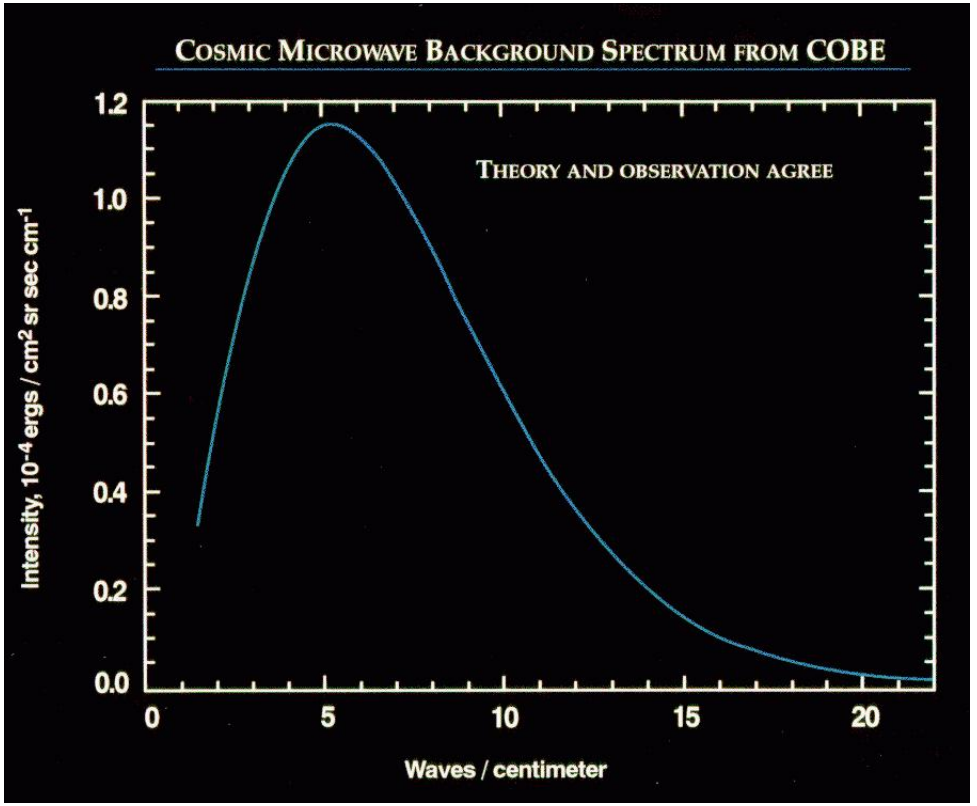
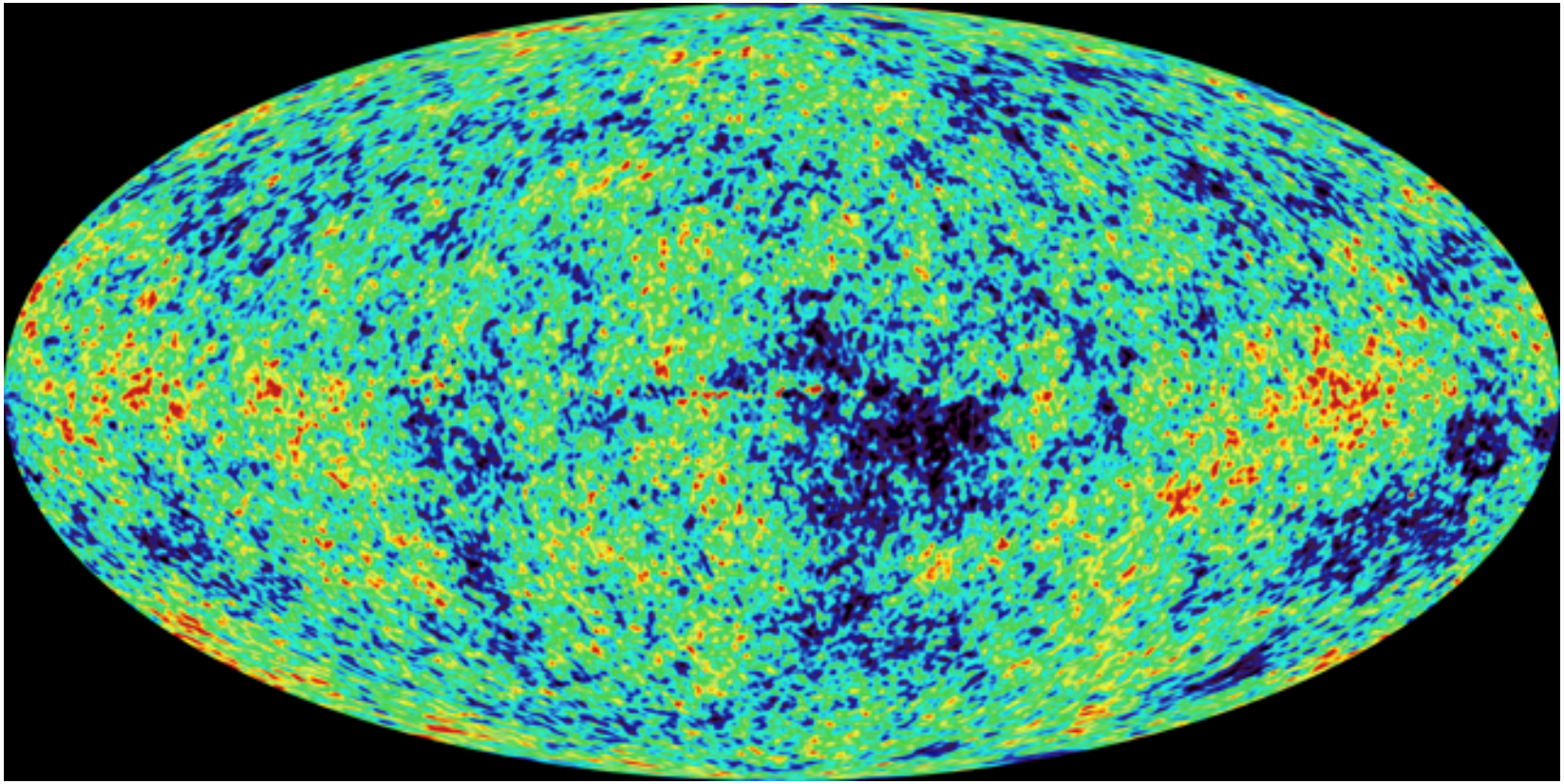
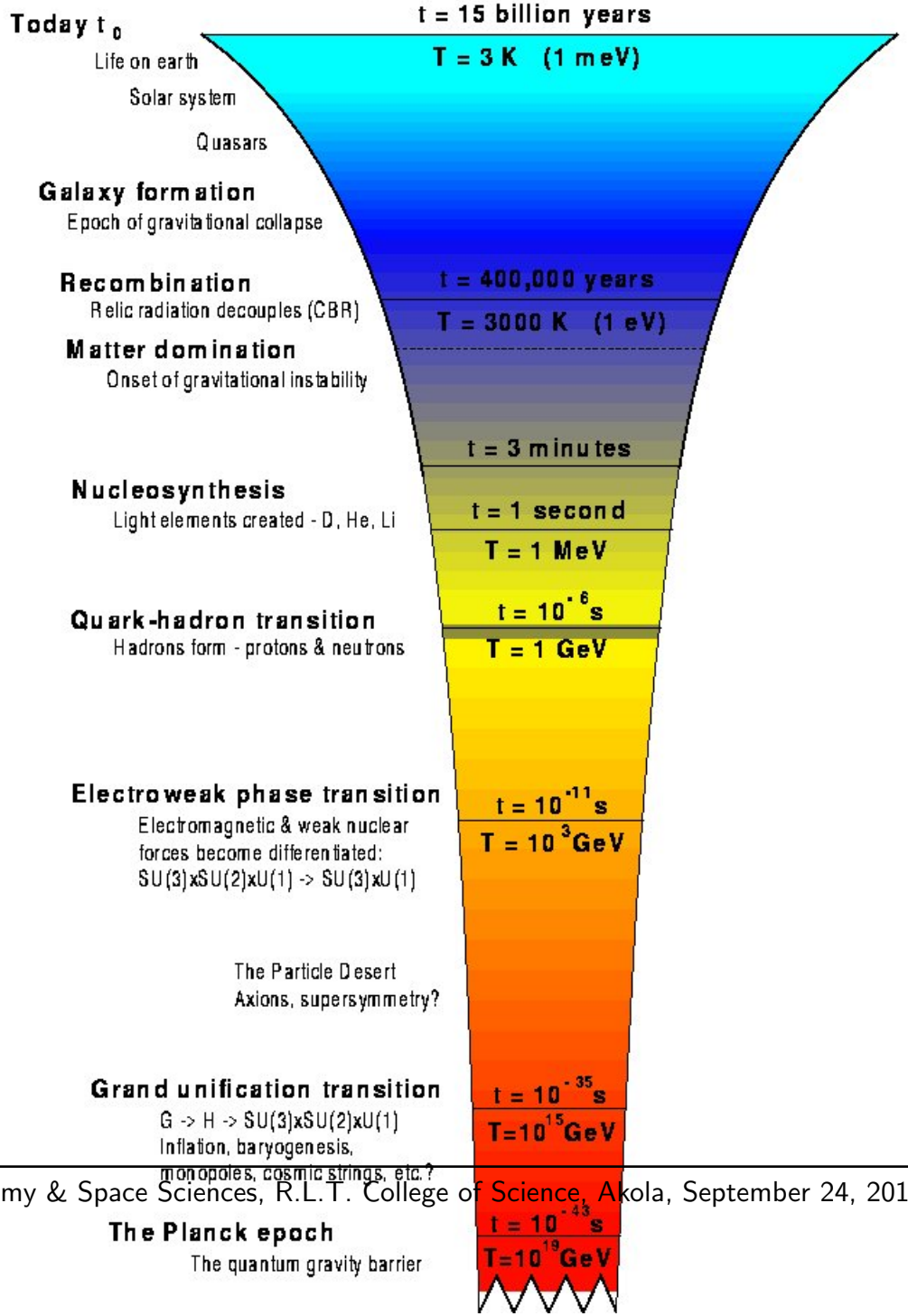
- Cosmic Microwave Background Radiation (CMBR) — Strongest Evidence. (1978 & 2006 Nobel Prizes)
  - Most perfect black body radiation spectrum.
  - $T \sim 3000^\circ$ K, red-shifted due to expansion $T \sim 2.726^\circ$ K.



Earliest WMAP-snap of Universe: Our Universe at the age of 380,000 years.



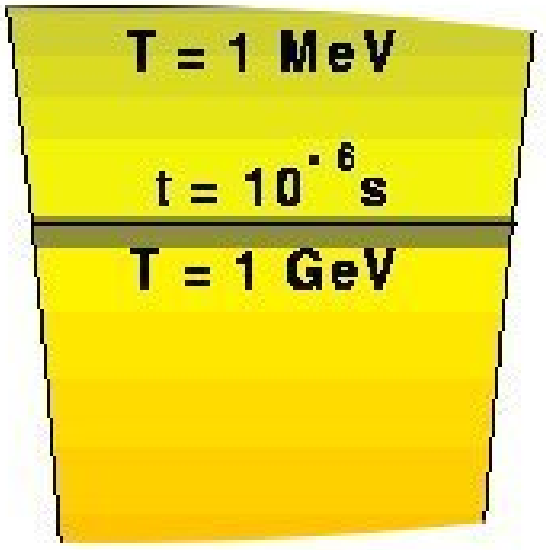
Why Re-Create the Early Universe ?


Today t_0
t = 15 billion years
T = 3 K (1 meV)
Life on earth
Solar system
Quasars
Galaxy formation
Epoch of gravitational collapse
Recombination
Relic radiation decouples (CBR)
t = 400,000 years
T = 3000 K (1 eV)
Matter domination
Onset of gravitational instability
t = 3 minutes
Nucleosynthesis
Light elements created - D, He, Li
t = 1 second
T = 1 MeV
Quark-hadron transition
Hadrons form - protons & neutrons
$t = 10^{-6}$ s
T = 1 GeV
Electroweak phase transition
Electromagnetic & weak nuclear forces become differentiated:
SU(3)xSU(2)xU(1) -> SU(3)xU(1)
$t = 10^{-11}$ s
$T = 10^{3}$ GeV
The Particle Desert
Axions, supersymmetry?
Grand unification transition
G -> H -> SU(3)xSU(2)xU(1)
Inflation, baryogenesis,
monopoles, cosmic strings, etc.?
$t = 10^{-35}$ s
$T=10^{15}$ GeV
The Planck epoch
The quantum gravity barrier
$t = 10^{-43}$ s
$T=10^{19}$ GeV

Why Re-Create the Early Universe ?

Quark-hadron transition

Hadrons form - protons & neutrons



♡ To Establish the Physics at the earliest epoch so far, at a few microseconds.

♠ To extend the validity of Big Bang Theory to such epochs, OR expose its limitation.

Strong Interactions

- Known Interactions and Particles a century ago: Electromagnetism, Gravity and Electrons, Atoms.

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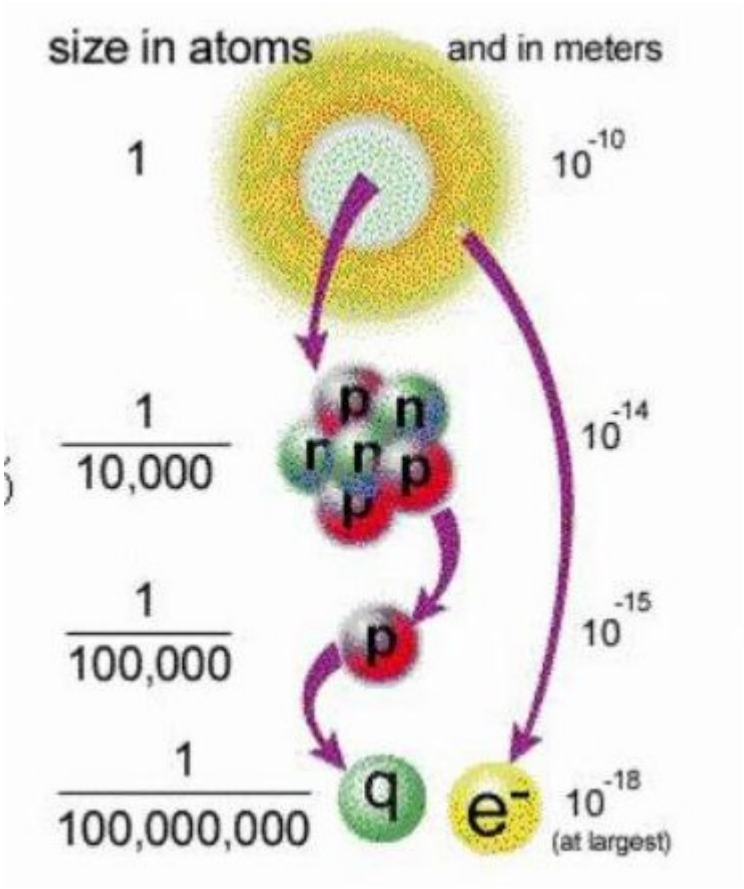
- Quarks and Leptons – Basic building blocks : Proton (uud), Neutron (udd), Pion $(u\bar{d})$....

- A Variety of Vector Bosons : Carriers of forces.



	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

Strengths in a ratio $10^{-39} : 10^{-5} : 10^{-2} : 1$

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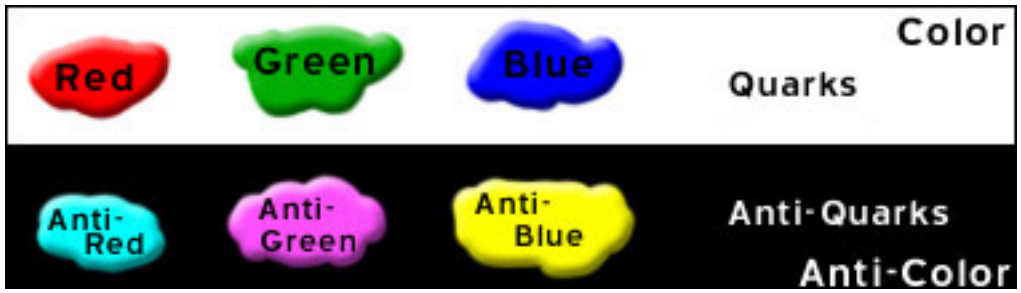

(Anti-)Quarks come in three (anti-)colours, making gluons also coloured.

Visible Mass of the Universe

- Most visible mass of our Universe is in protons & neutrons, i.e., up & $down$ quarks.

- Moreover, Proton or Neutron mass $\simeq 100 \times (2\ up + 1\ down)$ masses: Very unusual since proton mass mostly arises from interactions.

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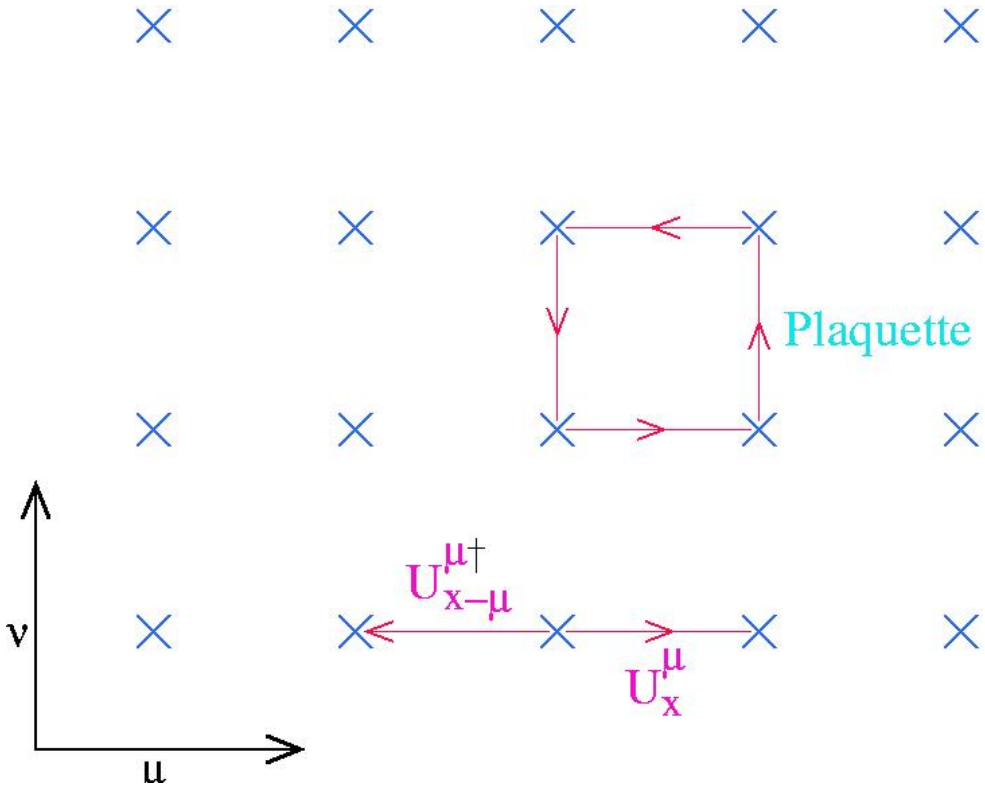
- Theory of quark-gluon interactions — Quantum Chromo Dynamics (QCD) — has to explain this factor : QCD on Space-Time Lattice does it !

- The same lattice QCD **predicts** a transition to a new state of matter – Quark Gluon Plasma – as well as its properties. This QGP filled our universe 10-20 μs after the big bang.

Basic Lattice QCD

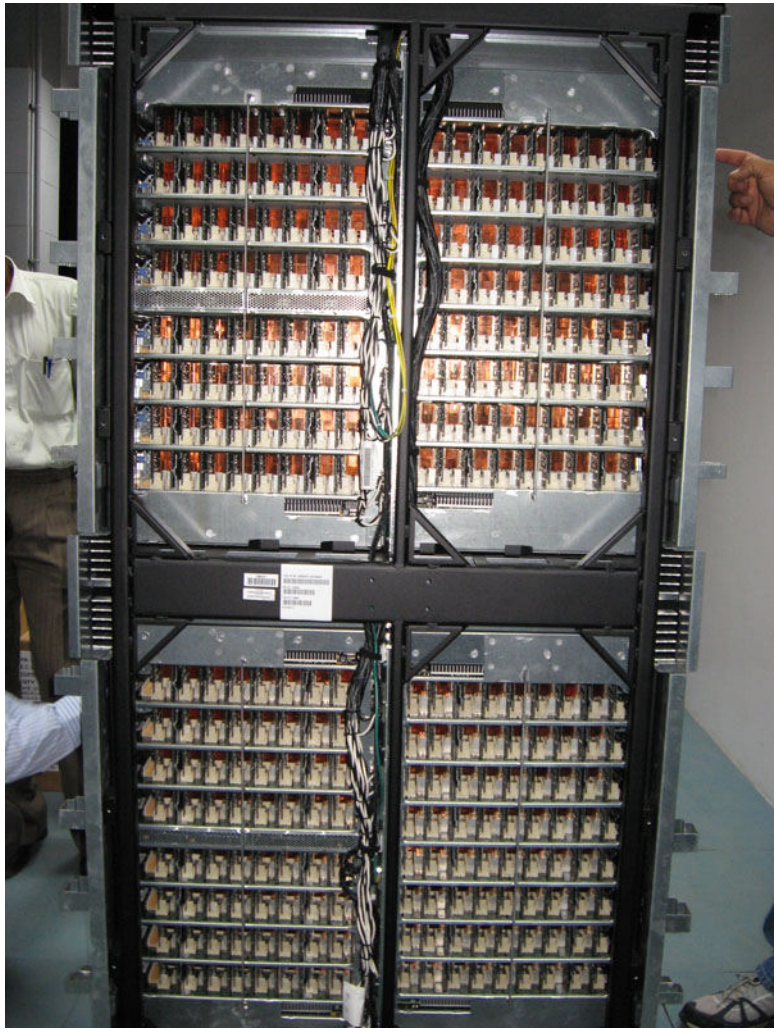
- Discrete space-time : Lattice spacing a UV Cut-off.
- Quark fields $\psi(x)$, $\bar{\psi}(x)$ on lattice sites.
- Gluon Fields on links : $U_\mu(x)$
- Gauge invariance : Actions from Closed Wilson loops, e.g., plaquette.
- Fermion Actions : Staggered, Wilson, Overlap..



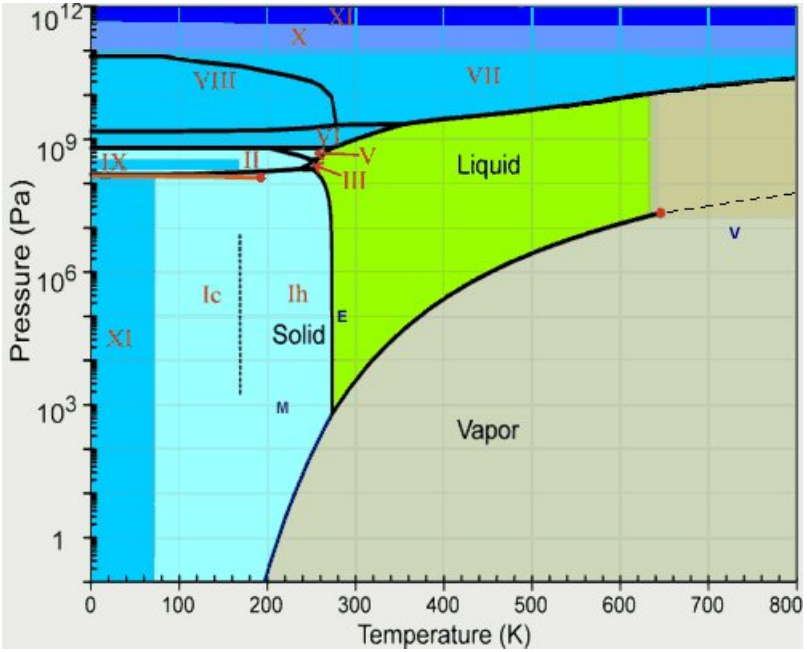
Our Workhorse

CRAY X1 of I L G T I , T I F R, Mumbai

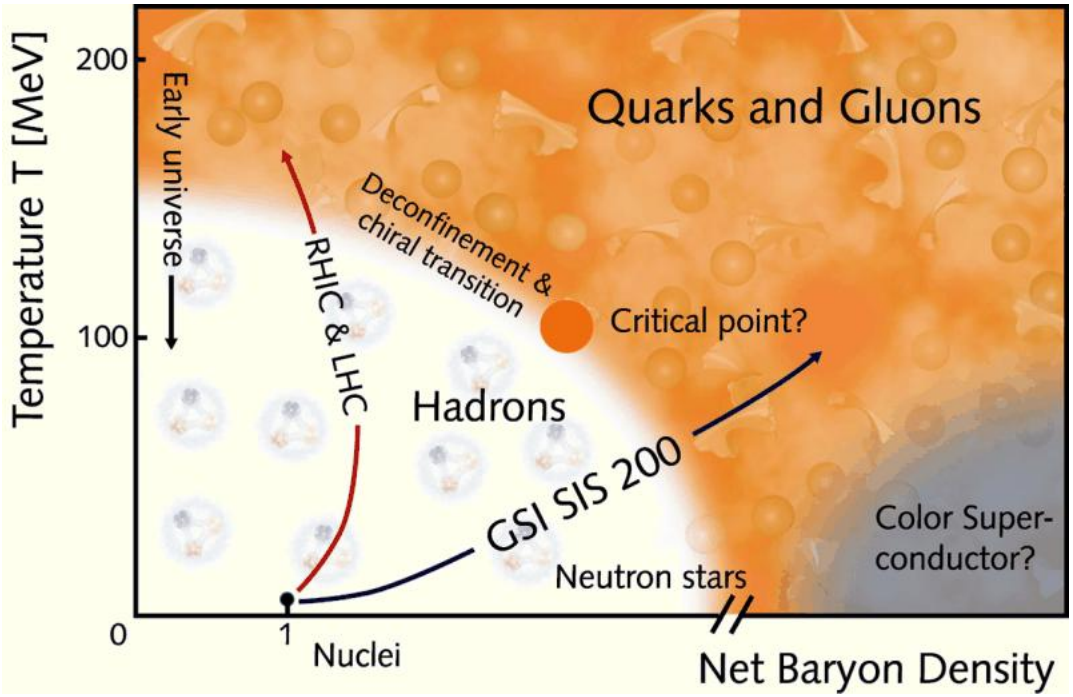
Our New Workhorse: IBM Blue Gene/P



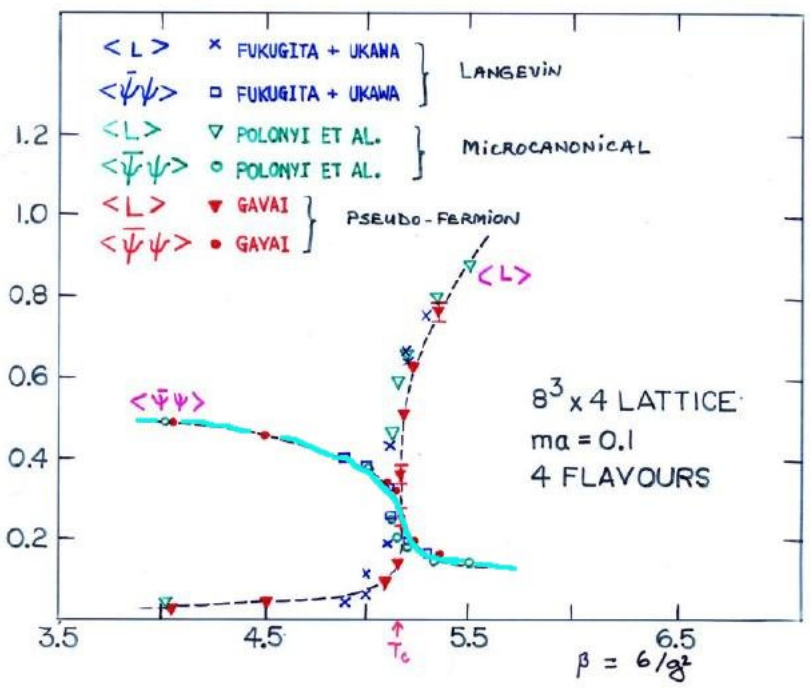
Phase Diagrams of Matter

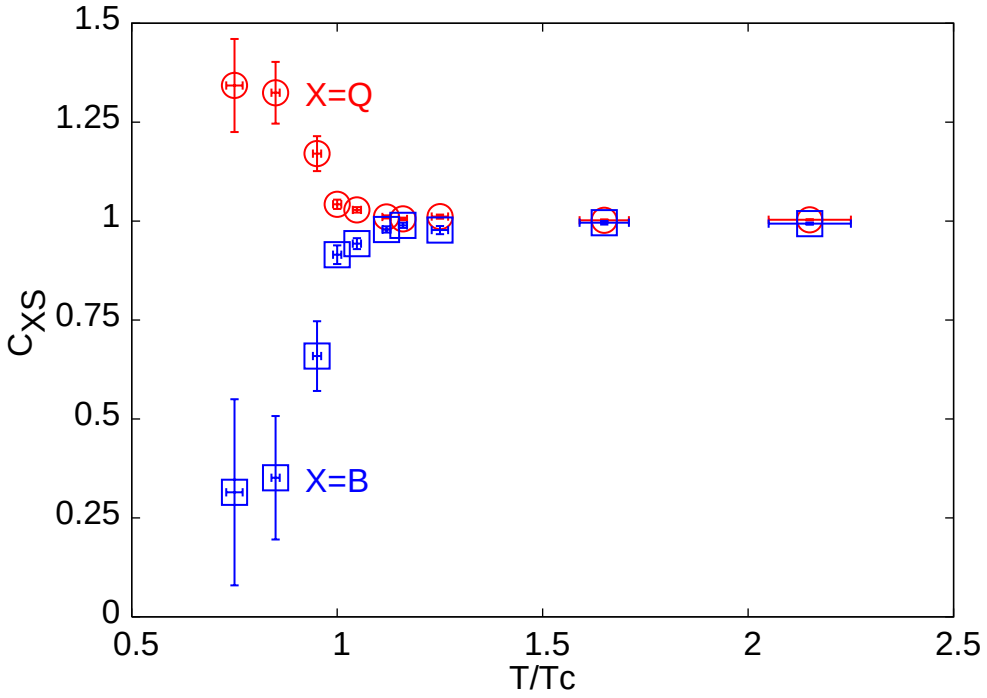


Phase Diagram of Water.



Phase Diagram of Nuclear Matter.

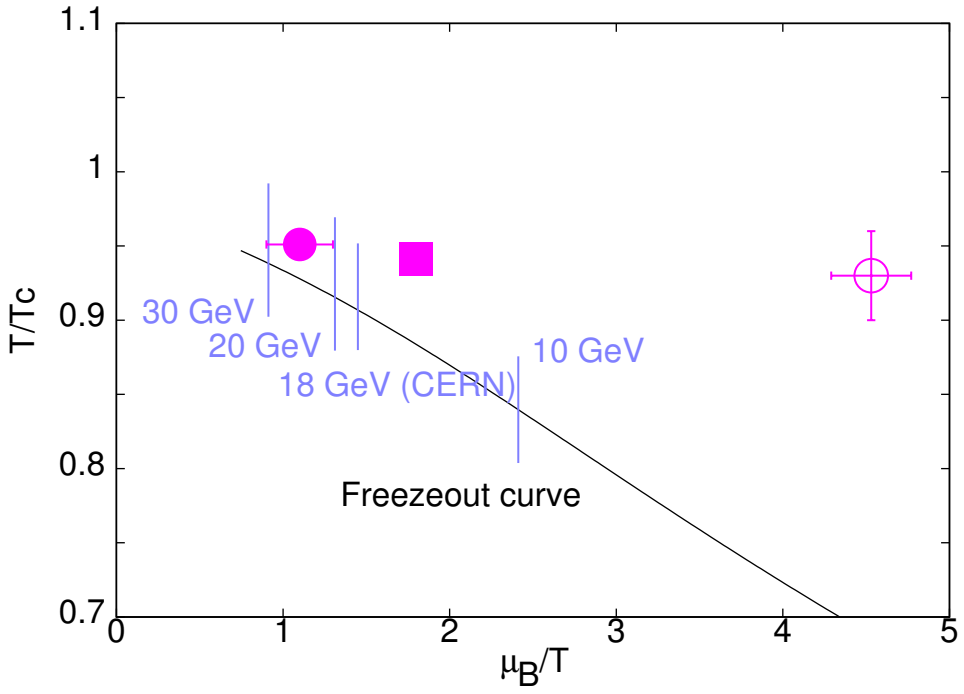




Gavai and Gupta, Phys. Rev. D73, 2006.

- The Transition Temperature $T_c \sim 175$ MeV (about 2 Trillion °K).
- Interaction induced mass "melts" at T_c : Chiral Symmetry Restored !
- Quarks behave as if "free" for $T \geq T_c$: Relevant for Heavy Ion Physics.

- Critical Point in Nuclear Matter phase diagram located (R. V. Gavai & S. Gupta, PRD 2005 i& PRD 2008)



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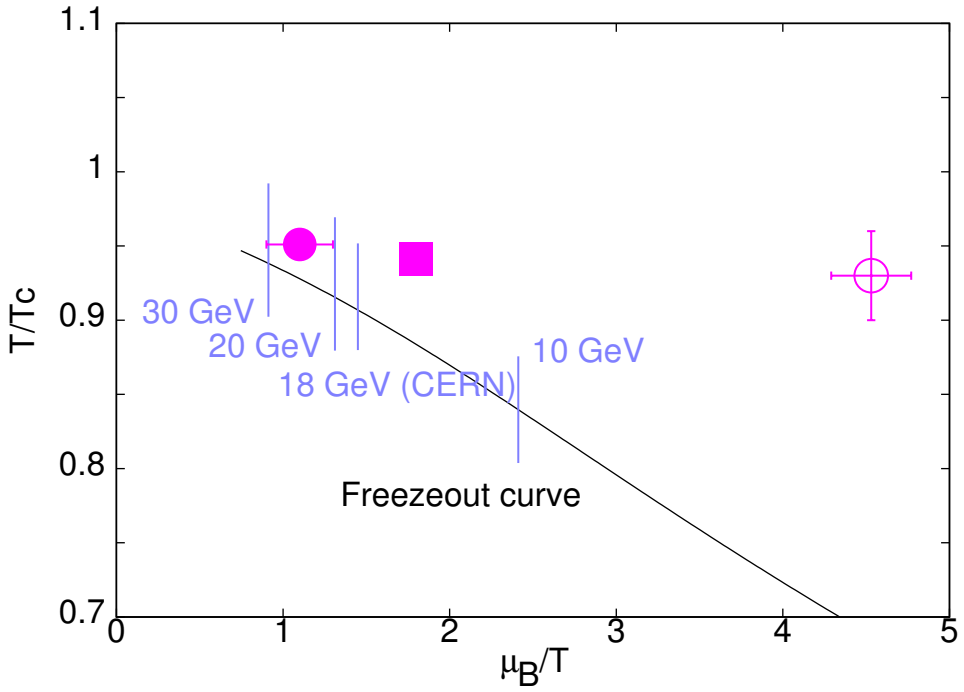

- Experimental search to test our prediction going on at RHIC, New York, USA and will be continued at FAIR, Darmstadt, Germany.

How to do it ?

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- QGP in Early Universe — About $10 - 20\mu$s after the Big Bang and in possibly Cores of Dense Neutron Stars.

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- Necessary Conditions for QGP production :
  - High Energy Density, $\approx$ 1-3 GeV/fm^3 $\sim 1.8 - 5.4 \times 10^{15}$ gm/cc^3.
  - Large System Size, $L \gg \Lambda_{QCD}^{-1} \sim 1$ fm $= 10^{-15}$ meter.
  - Many particles

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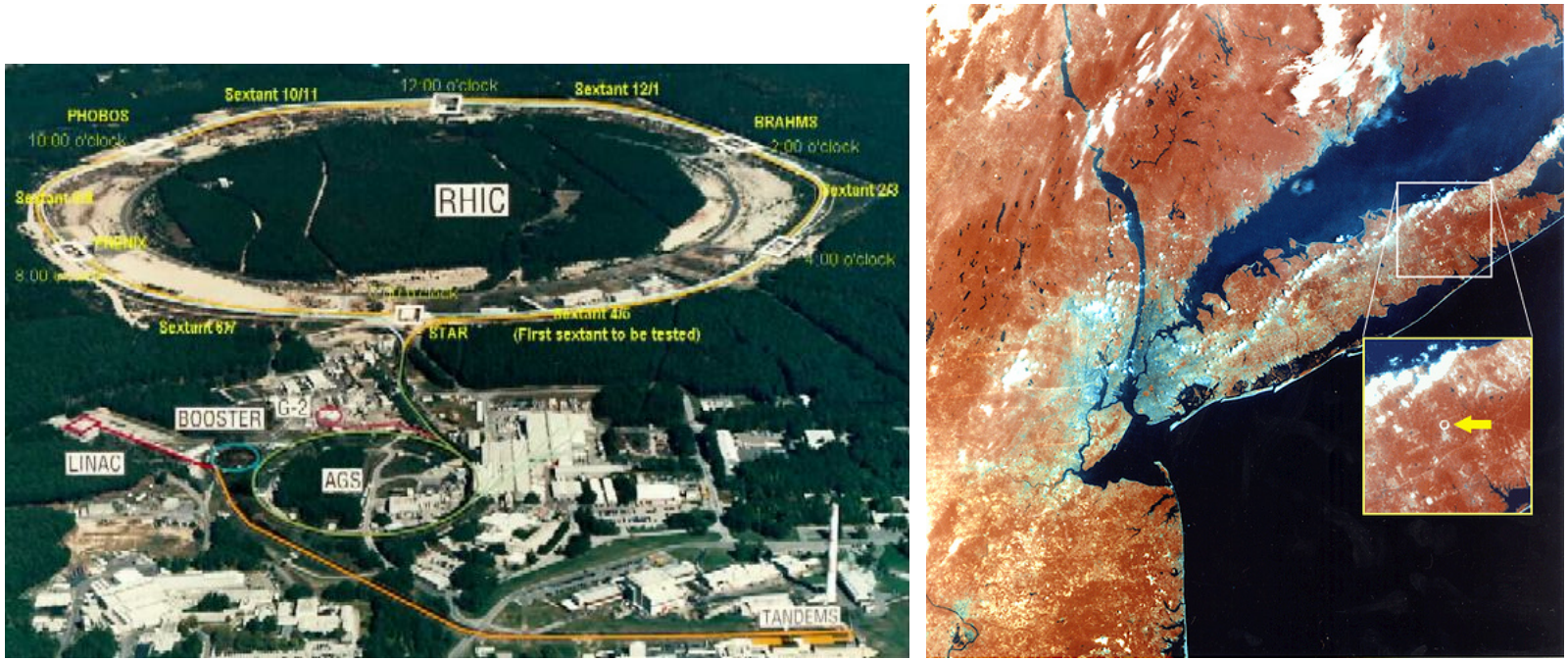
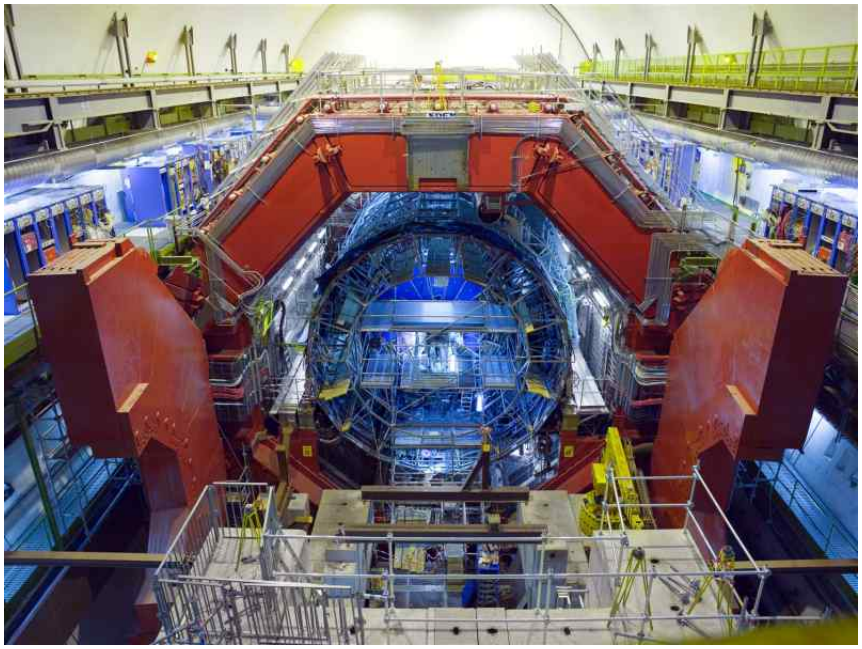
  - Many particles
- Quark-Gluon Plasma can be, and may **indeed** have been, produced in Heavy Ion Collisions in CERN, Geneva and BNL, New York.



RHIC complex at Brookhaven National Laboratory, New York:
Aerial view (left) and Space Shuttle view (right).

The ring of the Large Hsdron Collider (LHC) at CERN, Geneva in Switzerland (left) and a view of the ALICE detector (right).

$\Longrightarrow$ Heavy Ion Collisions at 99.5-99.995 % Velocity of Light.

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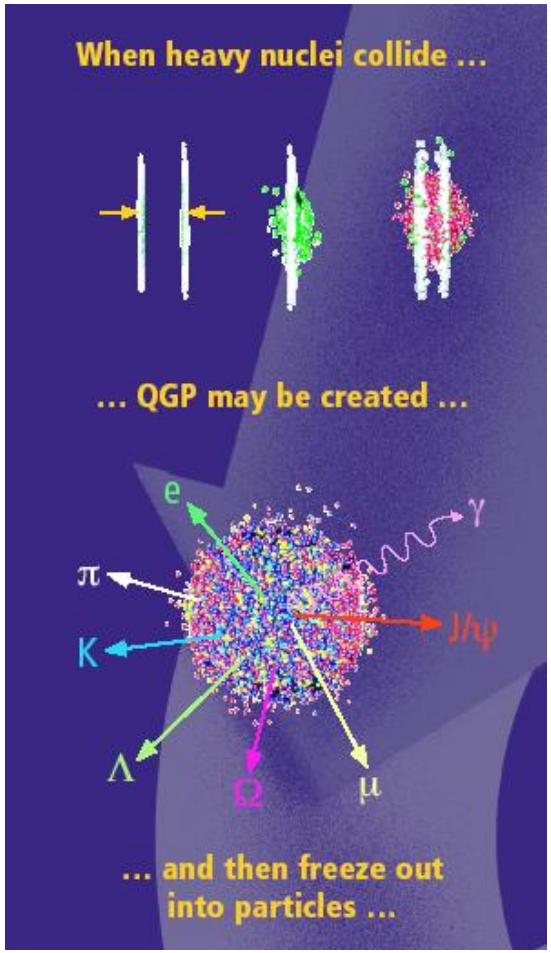

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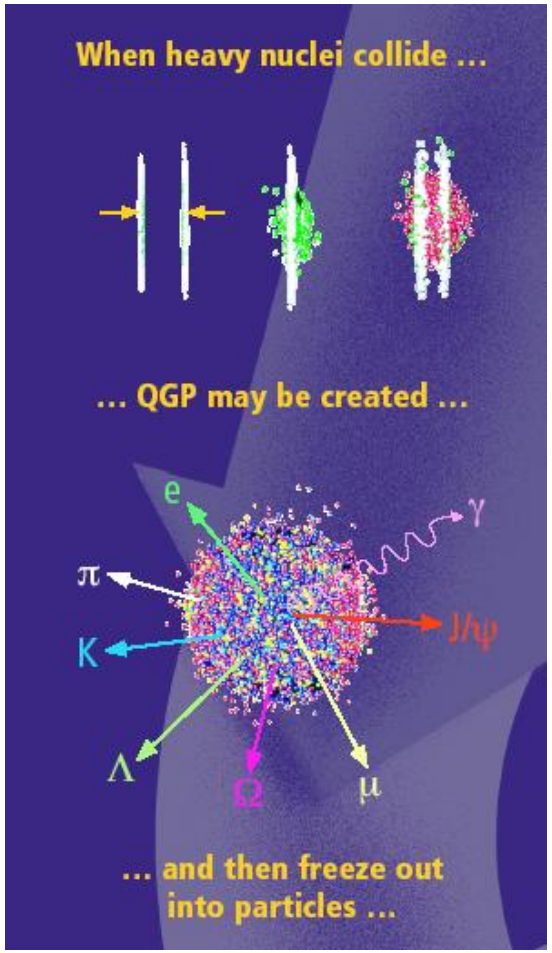
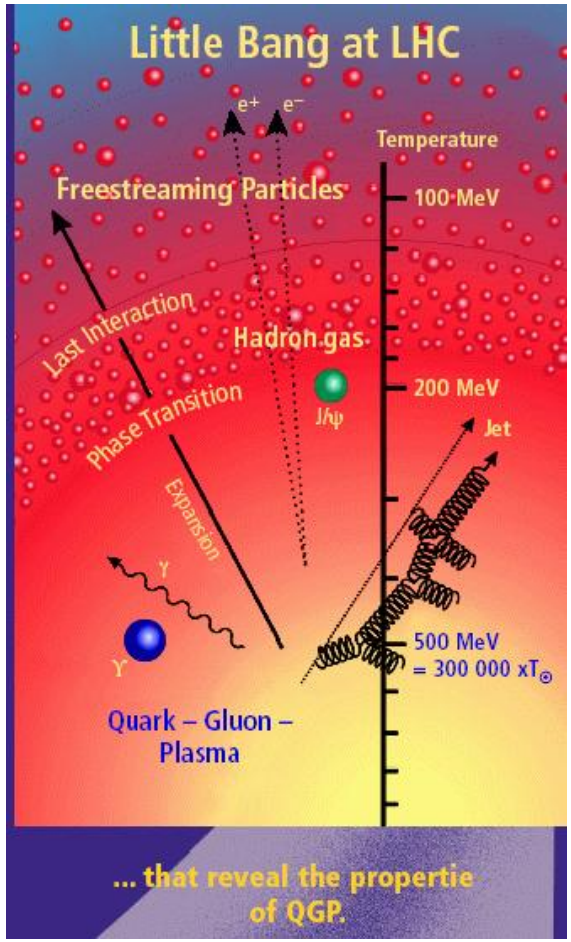
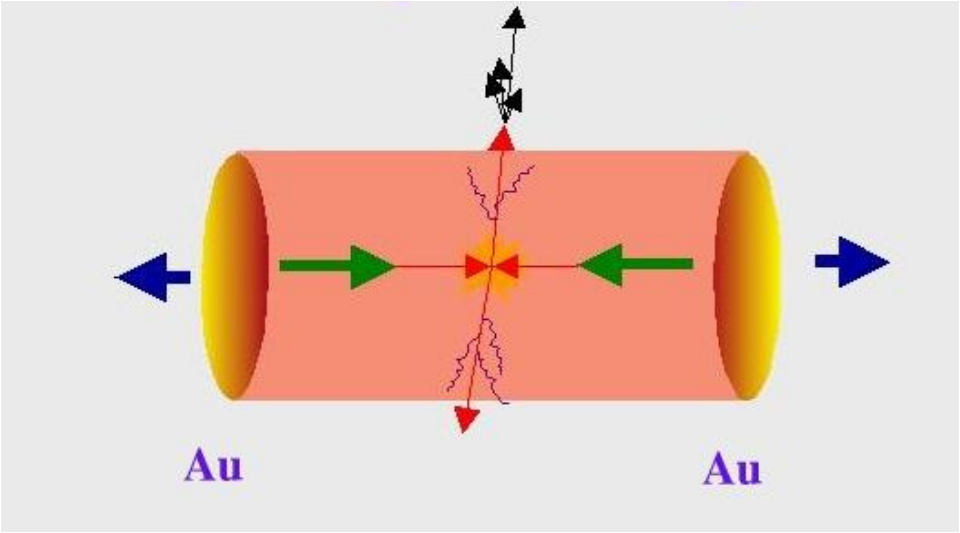




Fireball of QGP condenses into hadrons in $\approx 10^{-23}$ seconds.

How to look for QGP

- Jet Quenching :



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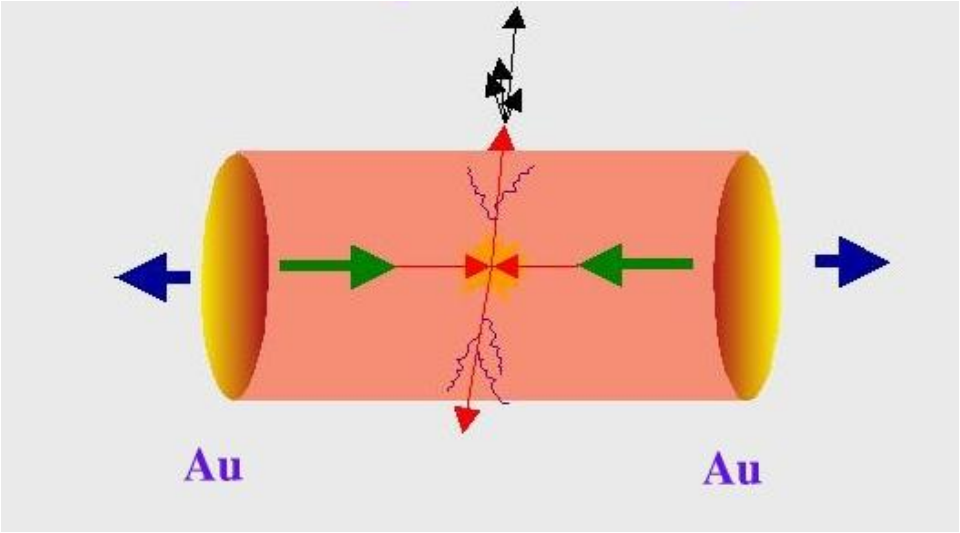

- Jet Quenching :
  - Rare, Highly Energetic Scattering produce jets of particles : $g + g \rightarrow g + g$.
  - Quark-Gluon Plasma, any medium in general, interacts with a jet, causing it to lose energy – Jet Quenching.

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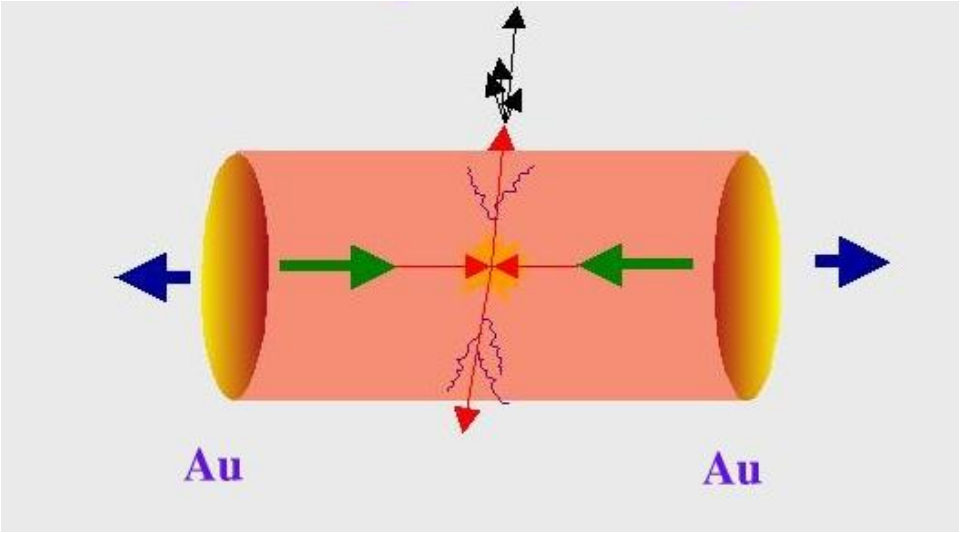

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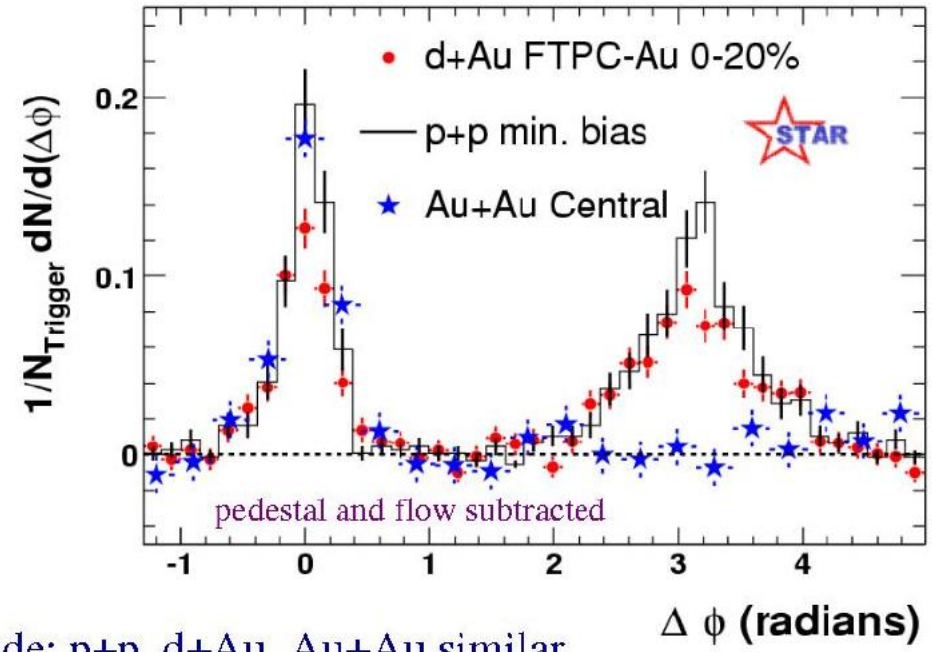
  - On-Off test possible – Compare Collisions of Heavy-Heavy nuclei with Light-Heavy or Light-Light.

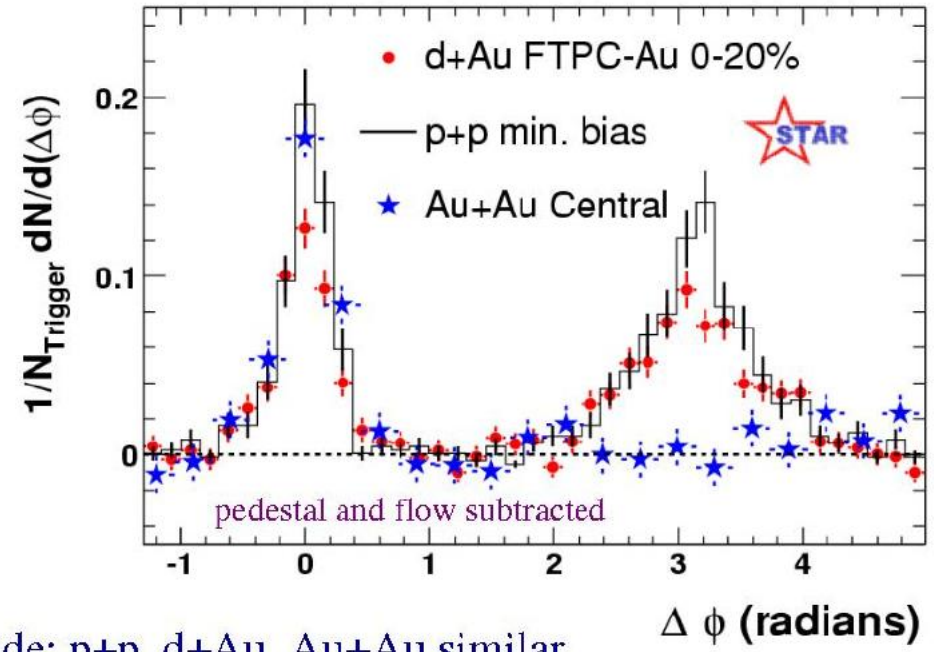
Azimuthal distributions



Near- side: p+p, d+Au, Au+Au similar

Back- to- back: Au+Au strongly suppressed relative to p+p and d+Au

Azimuthal distributions



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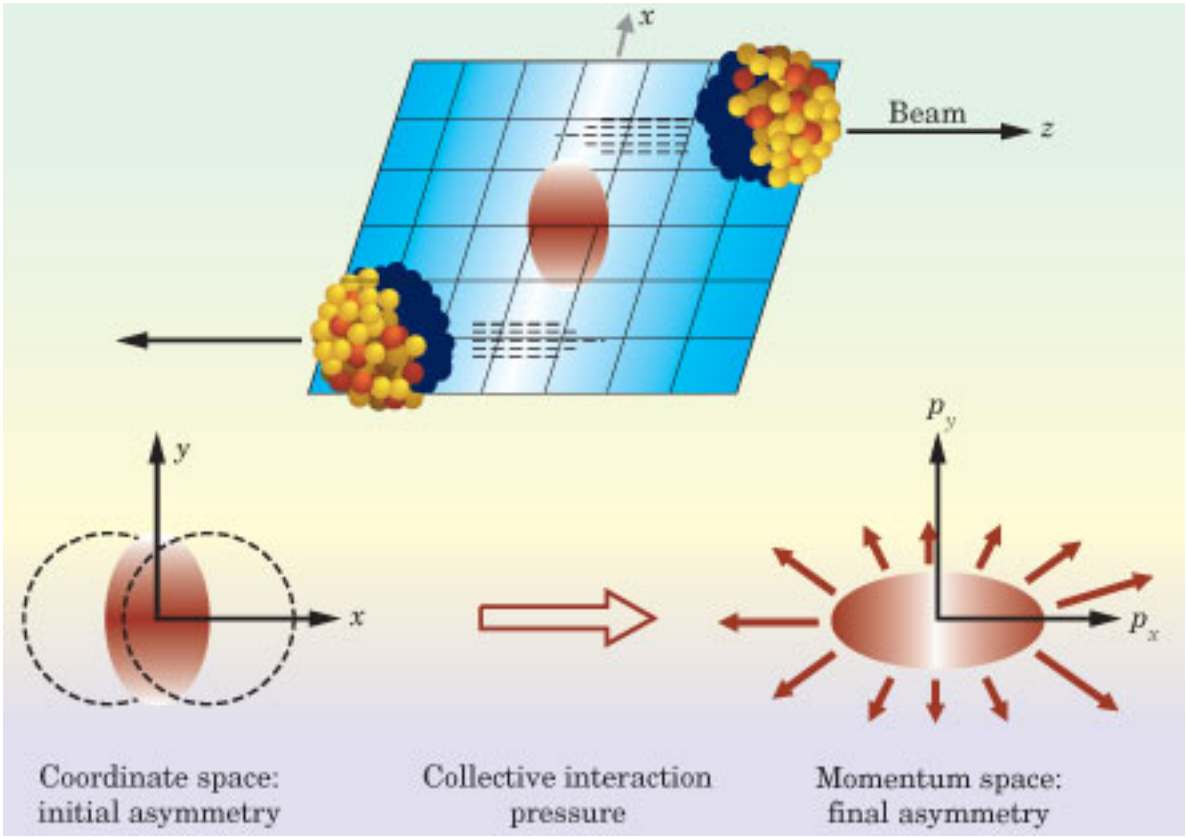
- Debye Screening of Quarks $\Longrightarrow$ No binding to Hadrons — Anomalous J/ψ Suppression

Elliptic Flow

♡ For asymmetric collisions of two nuclei, with their centres not aligned :



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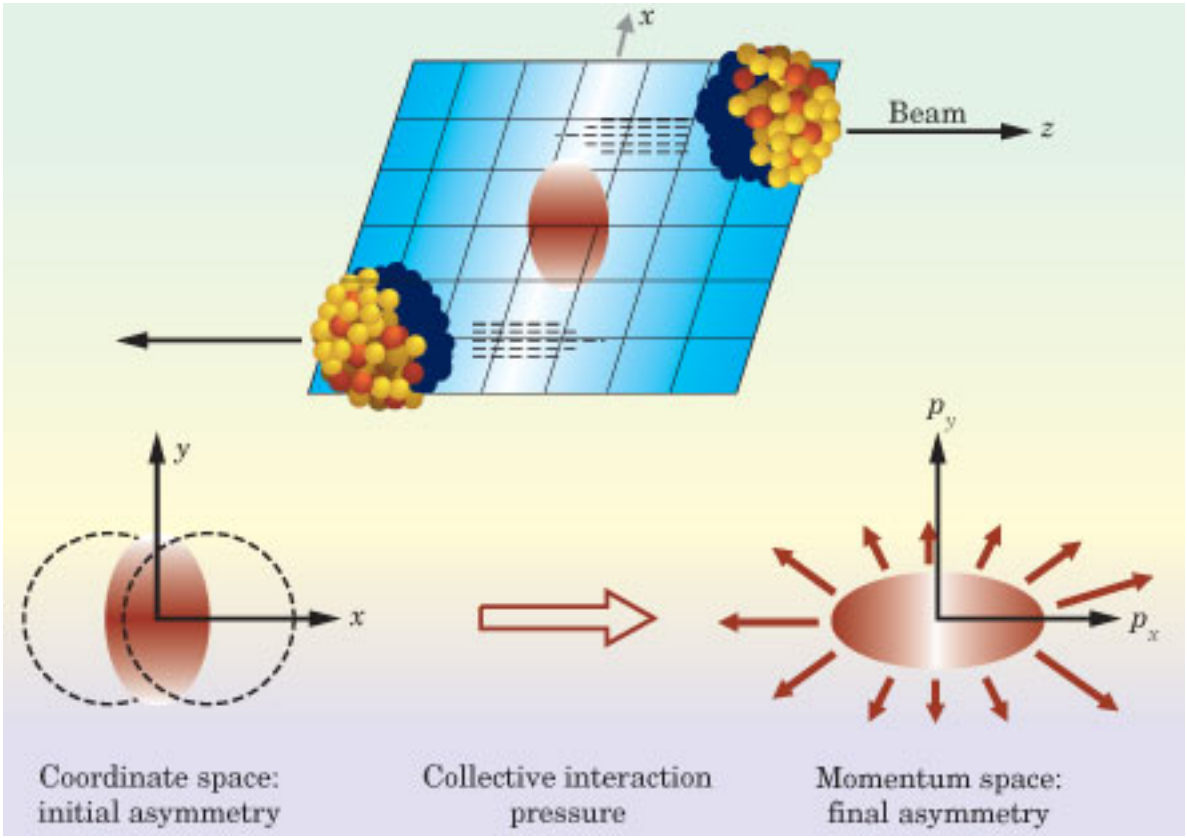

♢ Anisotropic Flow & QGP as Perfect Liquid

Summary

- The new Quark-Gluon Plasma phase filled our Universe at about 10-20 μs.
- Theory **predicts** such new states of strongly interacting matter and is able to shed light on the properties of the Quark-Gluon plasma phase.
- Our results on Critical Point have spurred its experimental search. We find that correlations of quantum numbers suggest QGP to have quark-like excitations.

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- Theory **predicts** such new states of strongly interacting matter and is able to shed light on the properties of the Quark-Gluon plasma phase.
- Our results on Critical Point have spurred its experimental search. We find that correlations of quantum numbers suggest QGP to have quark-like excitations.
- Heavy Ion Collisions in CERN Geneva, and BNL, New York, have seen tell-tale signs of QGP : Jet Quenching, flow of a 'fluid'...
- Many surprises and more excitement, including Critical Point search, likely at the LHC, RHIC & FAIR.