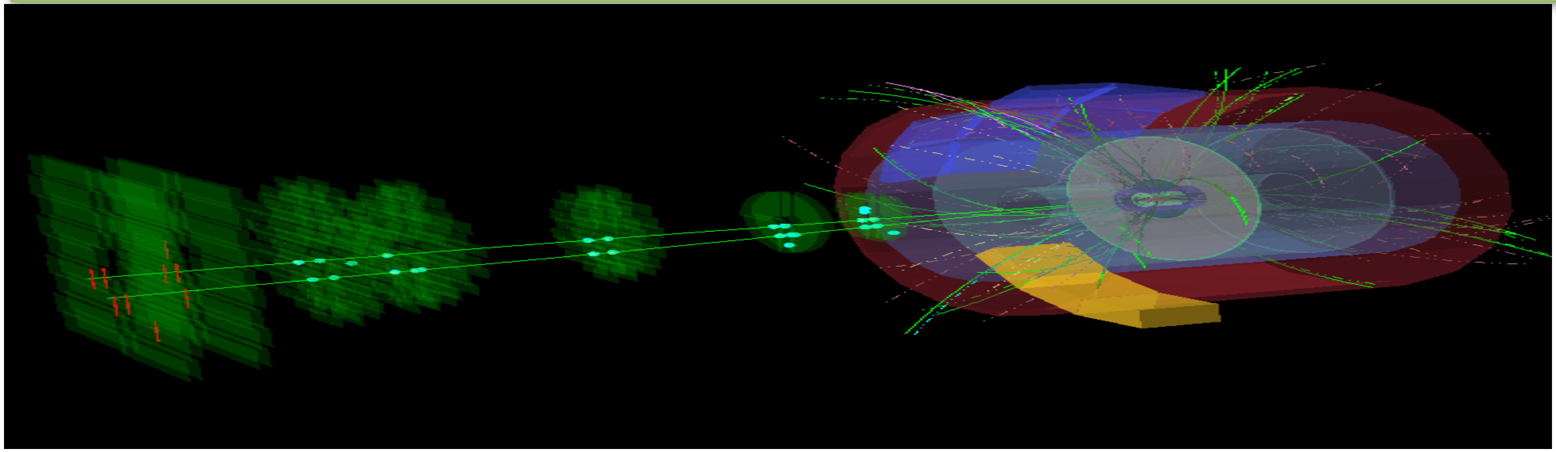
Introduction to Heavy-Ion Physics



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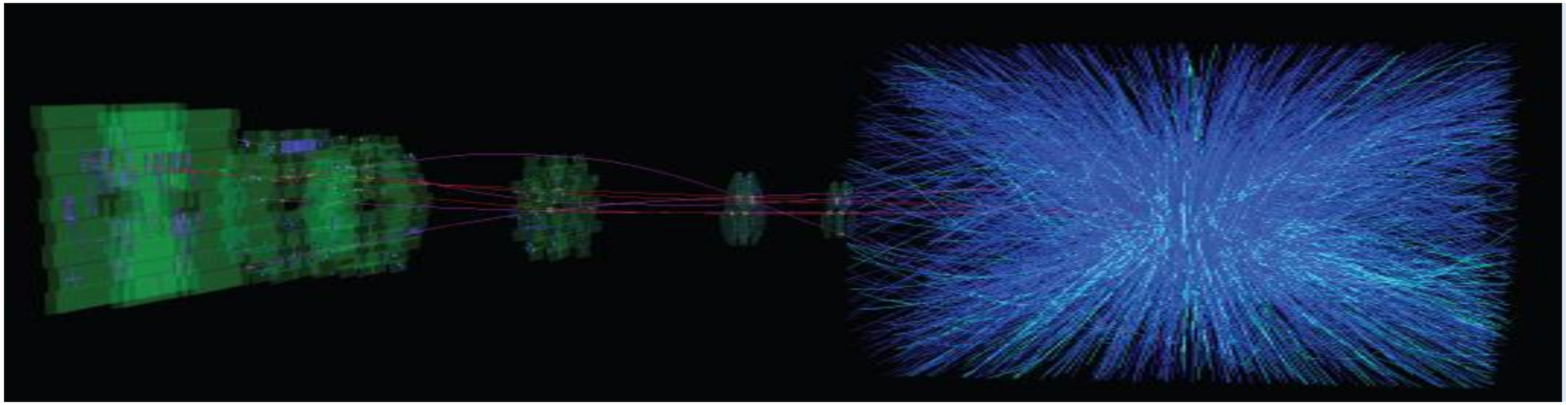
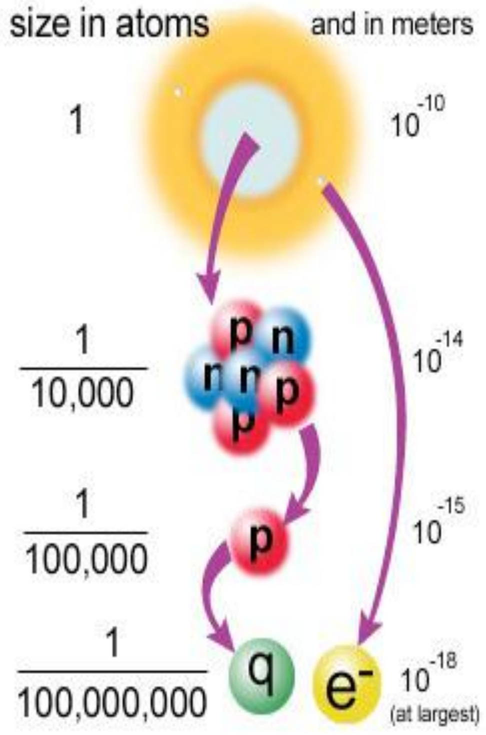


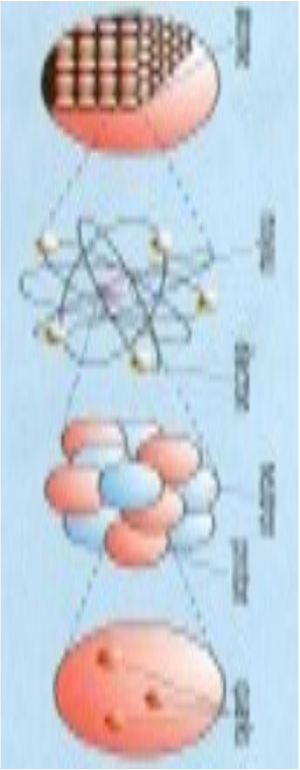
Outline

- Part I:
    - Two sides of the strong force
    - QGP and phases of matter
- Part II:
    - Where and how to look for it
- Outlook

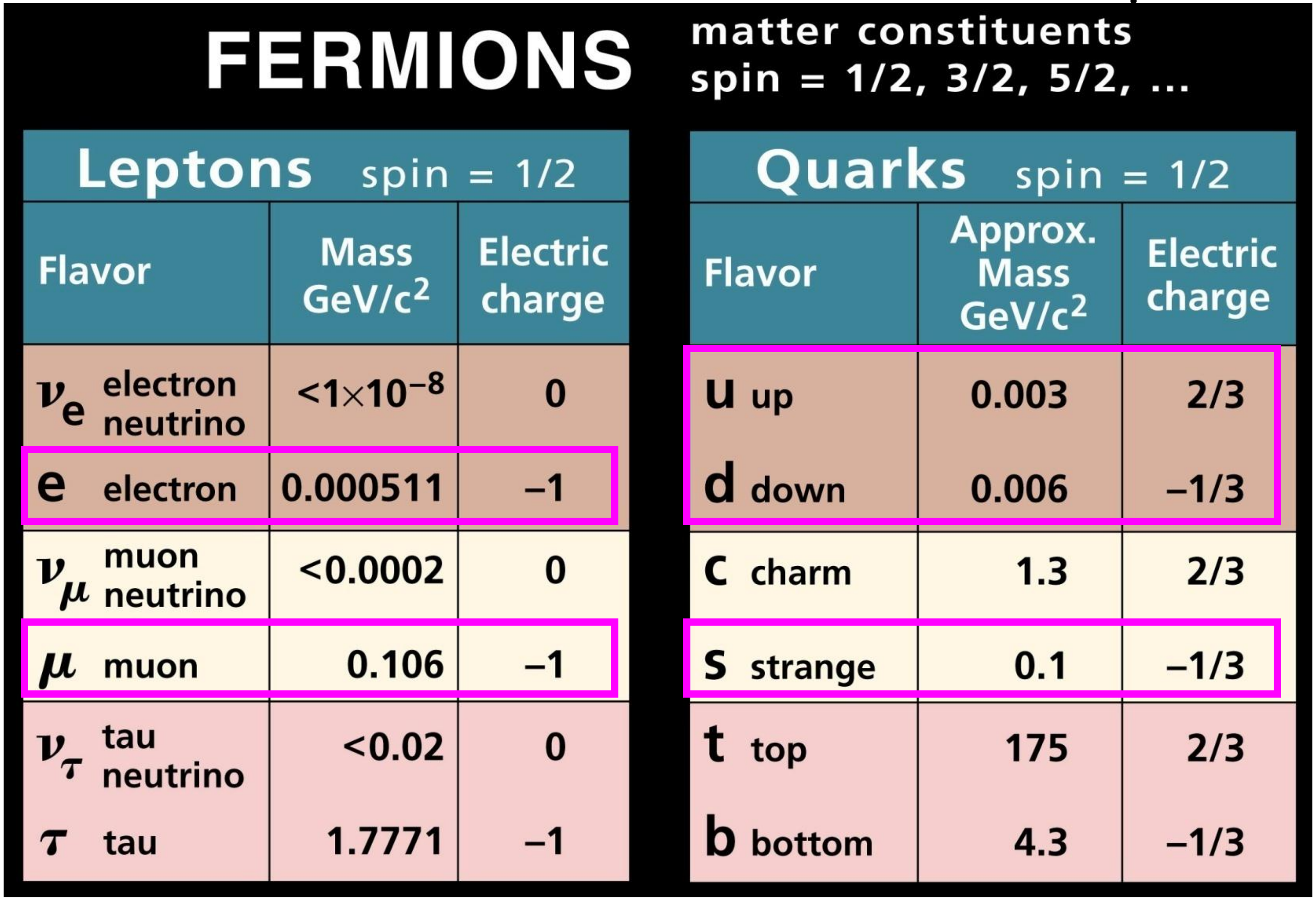
Building blocks of matter

- Matter is made of molecules
- Molecules are built out of atoms
- Atoms are made of nuclei and electrons
- Nuclei are assemblies of protons and neutrons
- Protons and neutrons are quarks bound together...





Fundamental Particles: Quarks & Leptons



FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

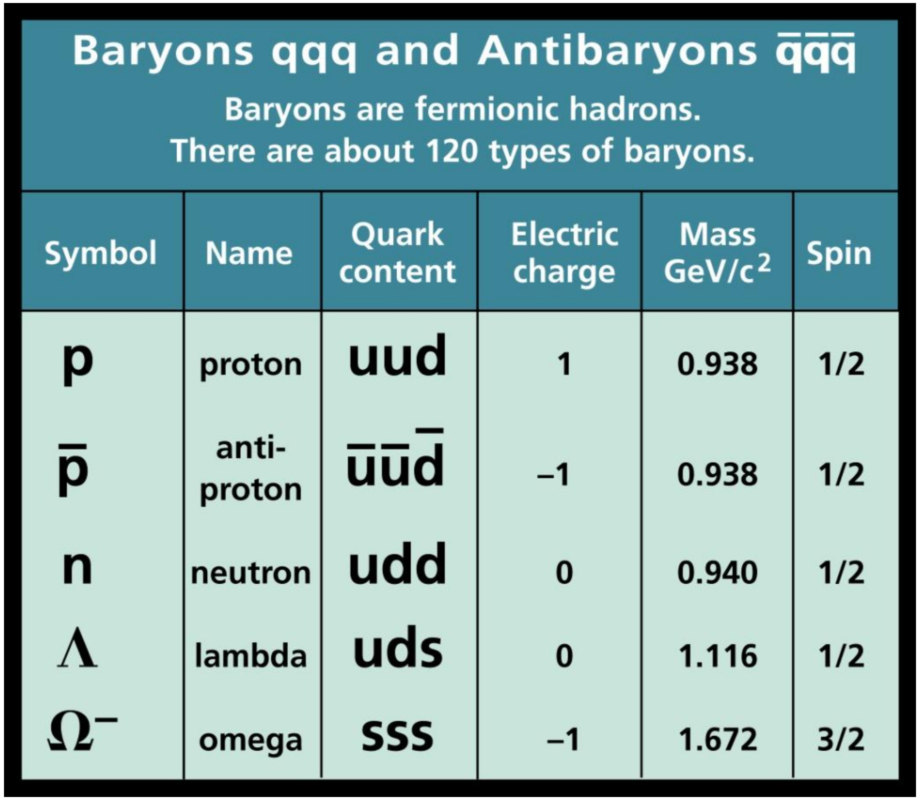
Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

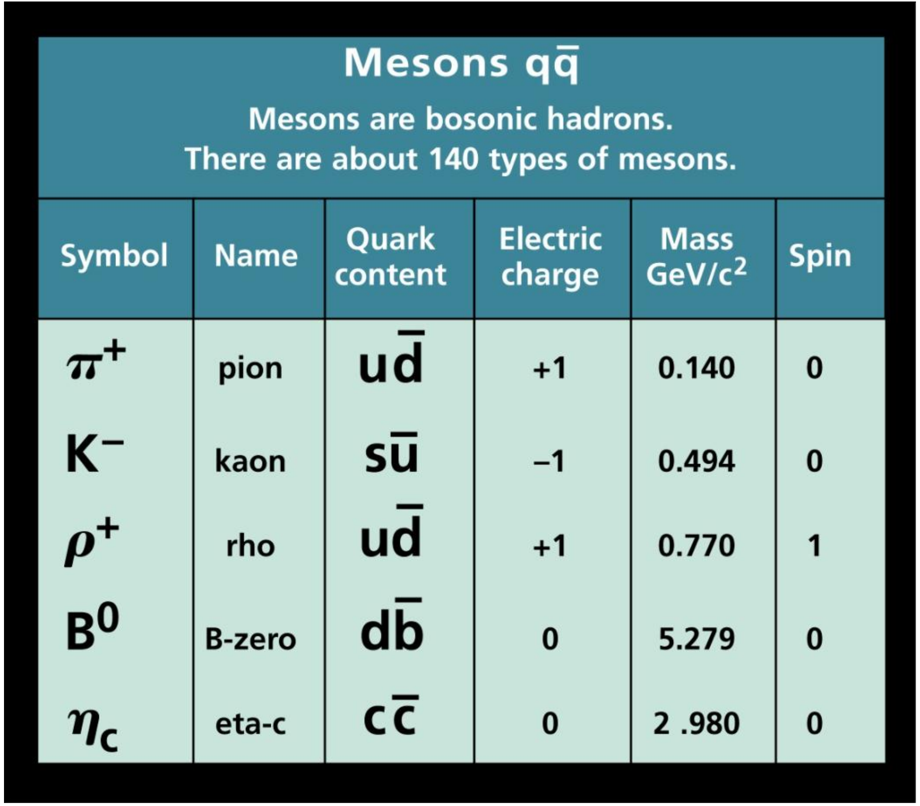
Not-so-fundamental: Mesons & Baryons



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2



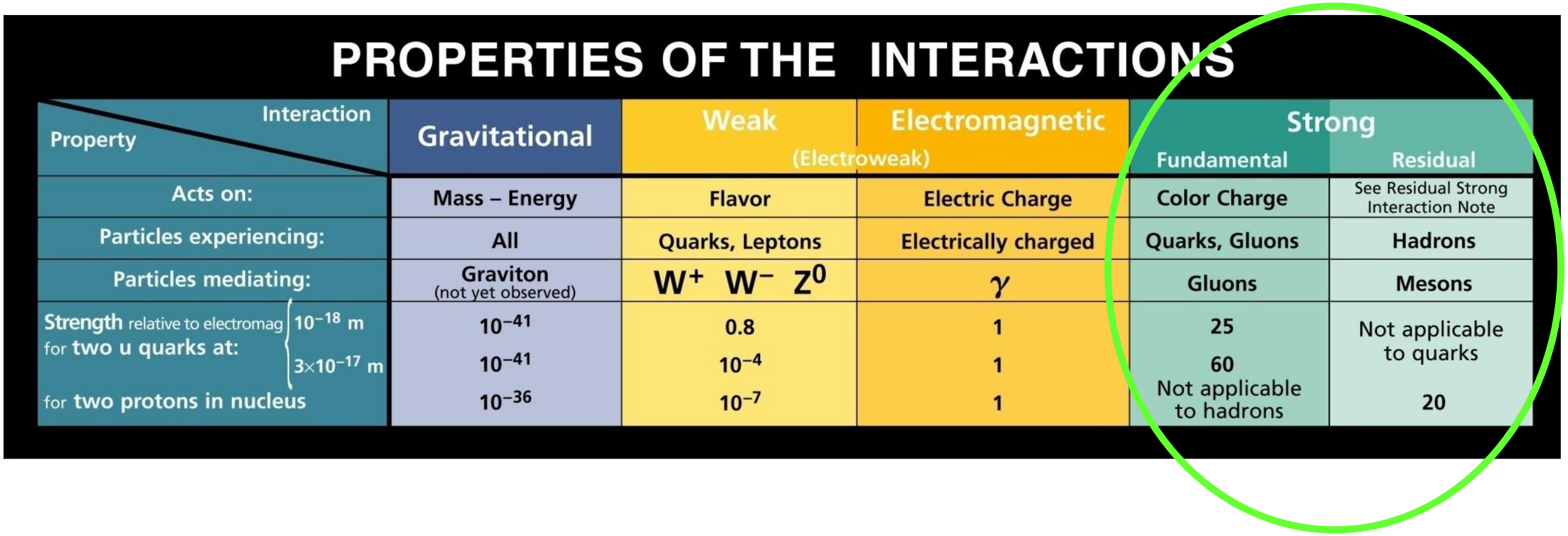
Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

But what determines the structure of hadrons??

Quantum Chromodynamics

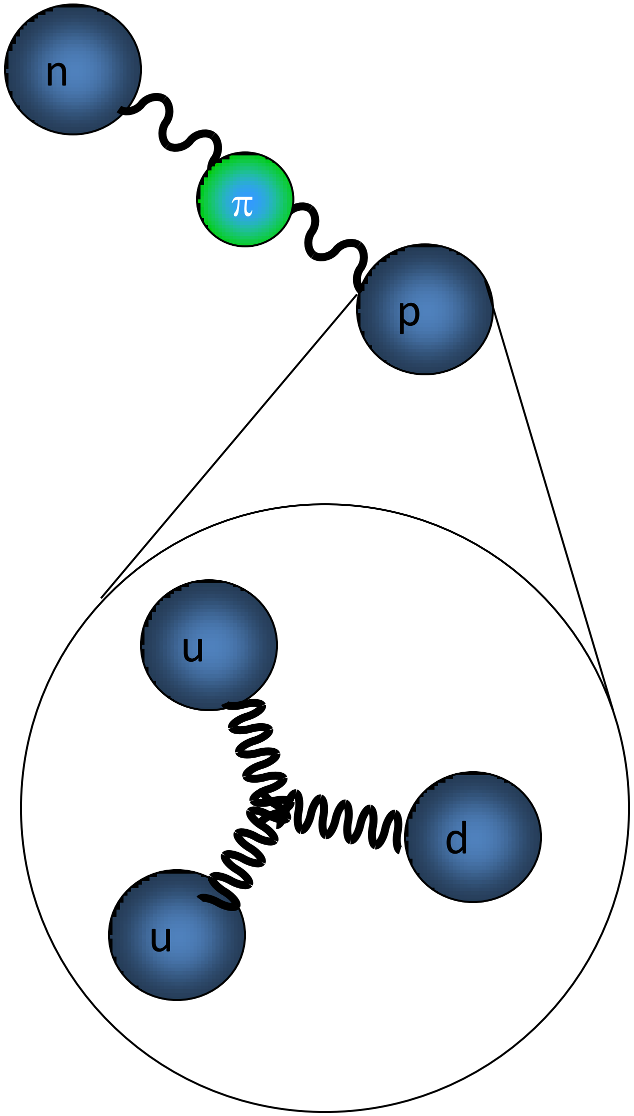


PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Fundamental?   Residual?

The Strong Force (I)



Nuclei are held together by exchanging mesons (but deuterons are easy to break apart)

Nucleons are held together by exchanging gluons

Both are two manifestations of the “strong” force, but nucleons and quarks are very different…

The Strong Force (II)

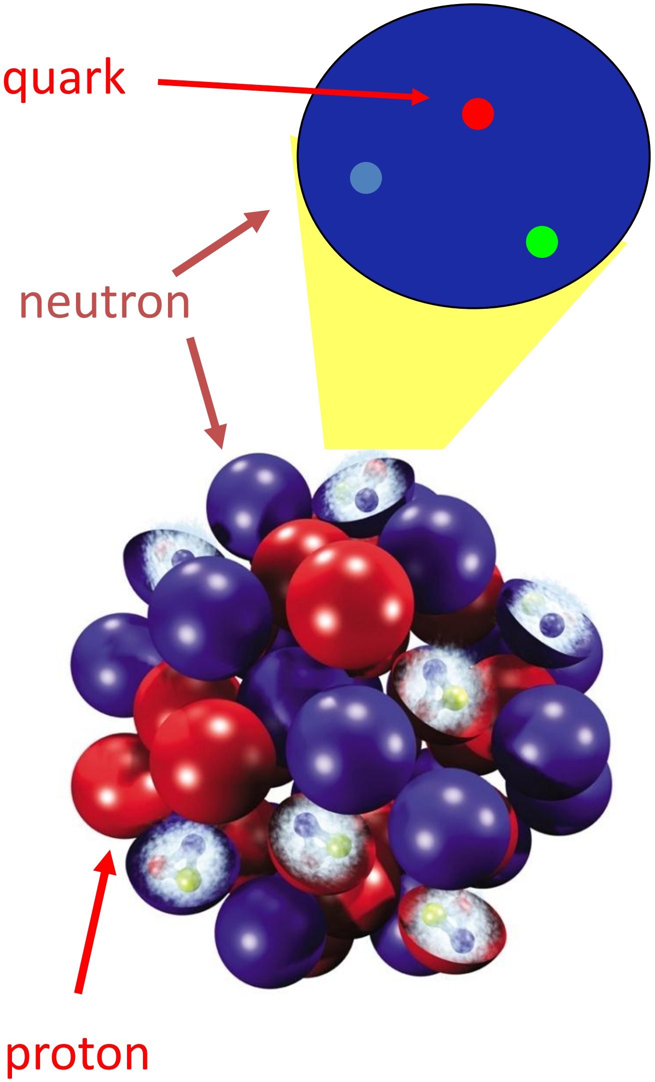
The nuclei are composed of:

- protons (positive electric charge)
- neutrons (no electric charge)

They do not blow up thanks to the
"strong nuclear force"

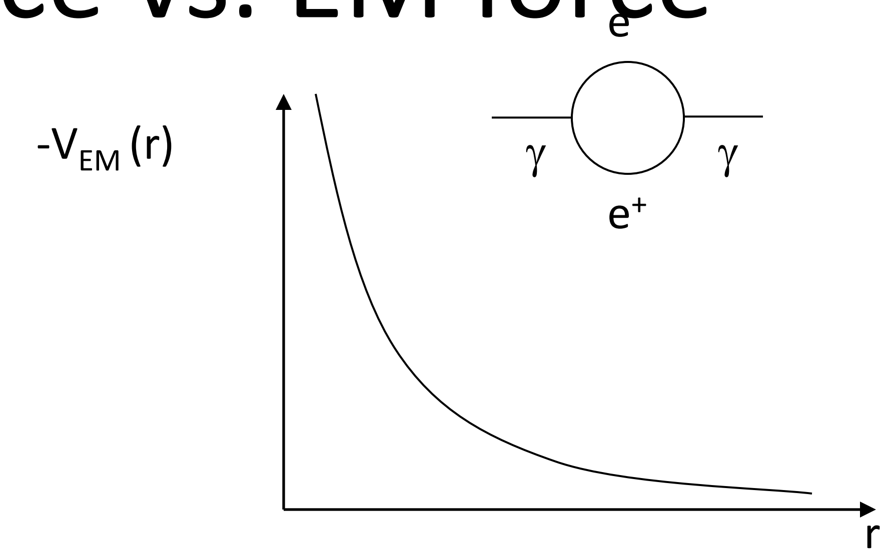
- overcomes electrical repulsion
- determines nuclear reactions

- results from the more fundamental colour force (QCD)
  → acts on the colour charge of **quarks** (and gluons!)
  → it is the least well understood force in Nature

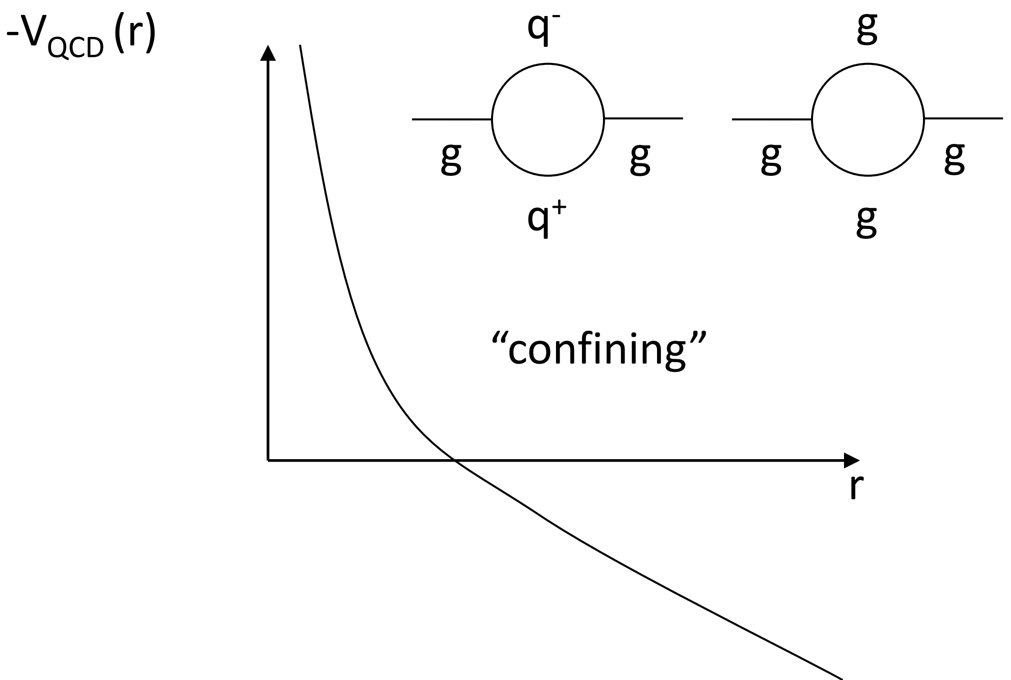


Strong Force vs. EM force

EM force only couples to charged electrons: electron-positron pairs screen force around bare charge:
$V \sim -1/r^2$

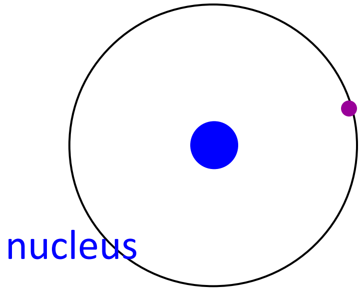


Colour force couples to charged quarks *and* gluons: leads to "anti-screening" of bare color: Force → constant, even at r→infinity!
$V \sim -1/r^2 + Cr$



Analogies and differences

to study the structure of an atom…

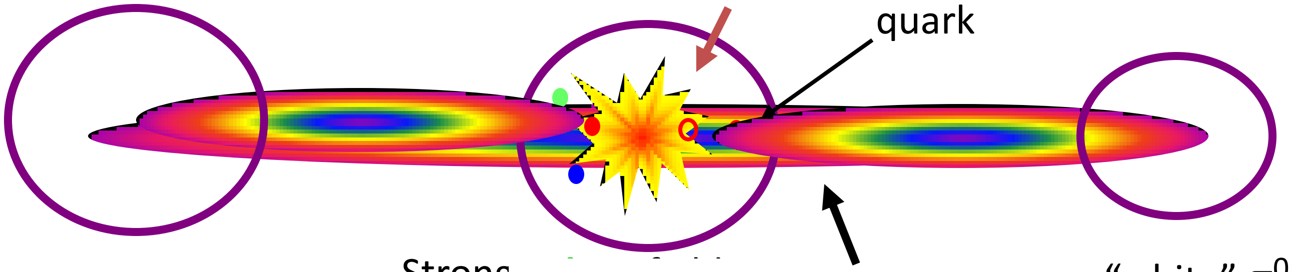

electron

nucleus

neutral atom

…we can split it into its constituents

Confinement: fundamental & crucial (but *not* well understood!) feature of strong force


quark-antiquark pair
created from vacuum

quark

“white” proton
(confined quarks)

Strong

Energ

$E = mc^2$

“white” proton

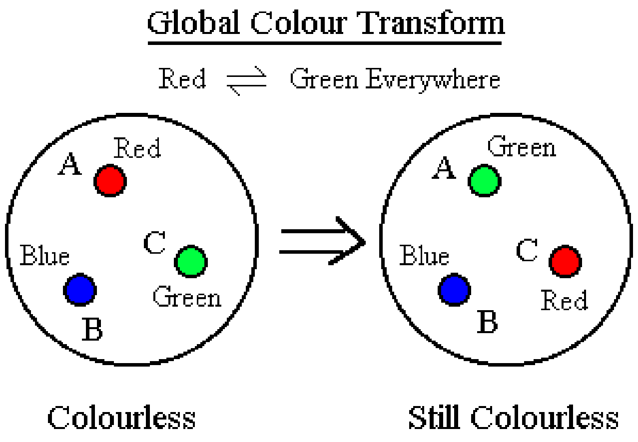
aration!

“white” π^0
(confined quarks)

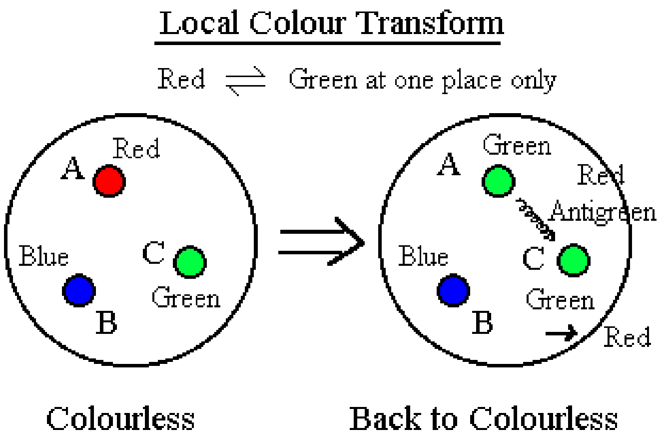
Slides courtesy: Carlos Lourenço, CERN PH-EP

Nature doesn’t like bare colour

The stable universe is symmetric under global colour transformations – gauge symmetry!



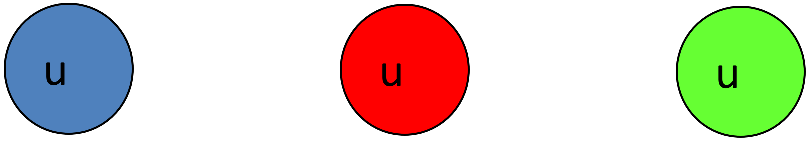
Local colour transformations are allowed only if we can exchange color to neutralize them – color dynamics!



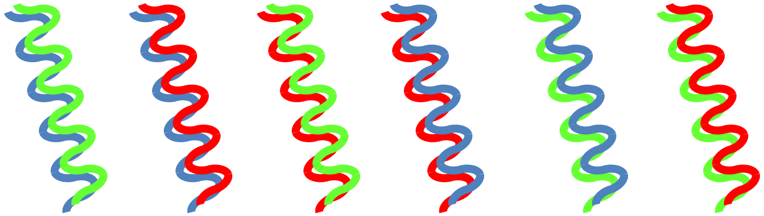
What’s so special about q & g?

Quarks and gluons are both “coloured” objects!
Colour is “simply” a “charge” (but more complicated)

Quarks carry a
single colour

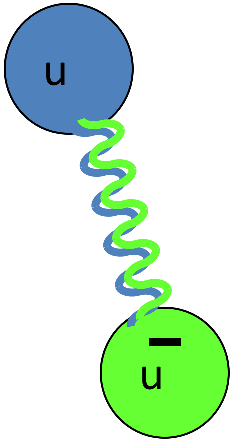


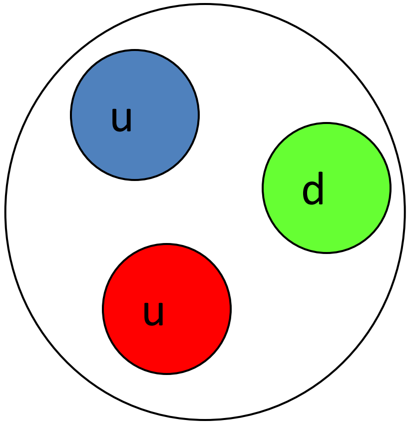
Gluons carry
color & anti-colour



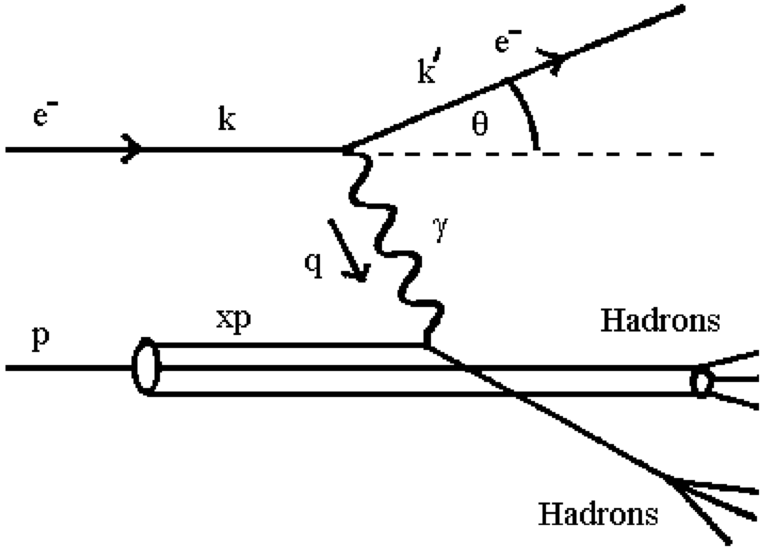
…

Mesons & Baryons
are “colourless” objects
(RBG or R+(anti-R), etc.)





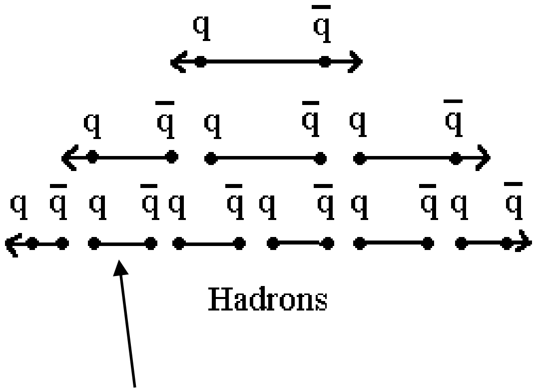
We can’t pull protons apart!



Here is a “deep inelastic”
scattering experiment:
Strike one quark with
a virtual photon
(need high energies to get
small wavelengths!)

Pulling proton apart only leads to more hadrons!
(Energetically favorable to do so)

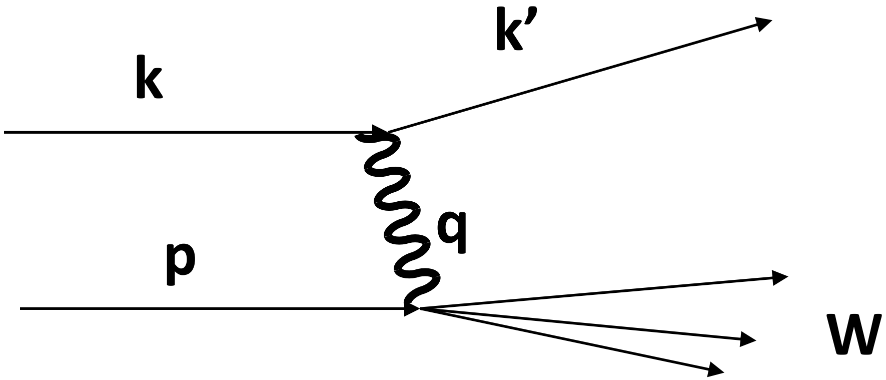
We call this “string breaking”
(Lund model of “hadronization”)



Quark-antiquark pairs
“popped” out of the vacuum

Detour into Deep Inelastic Scattering (DIS)

- Need two variables: angle and E’



$$p^{\nu} = \left(m, \vec{0}\right) ,$$

$$k^{\mu} = \left(E, \vec{k}\right) = \left(E, 0, 0, k\right) ,$$

$$k'^{\mu} = \left(E', \vec{k}'\right) = \left(E', k' \sin\theta, 0, k' \sin\theta\right)$$

$$\nu = \frac{p \cdot q}{m} = \left(E - E'\right)$$

Energy lost by electron

$$x = \frac{-q^2}{2m\nu} \equiv \frac{Q^2}{2m\nu} = \frac{Q^2}{2m\left(E - E'\right)}$$

$$y = \frac{q \cdot p}{k \cdot p} = 1 - \frac{E'}{E}$$

$$W^2 = M^2 + 2M\nu - Q^2$$

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2 \cos^2(\theta/2)}{4E^2 \sin^4(\theta/2)} \left[W_2\left(\nu, Q^2\right) + 2W_1\left(\nu, Q^2\right) \tan^2(\theta/2)\right]$$

Bjorken Scaling

- In 1968, Bjorken postulated that

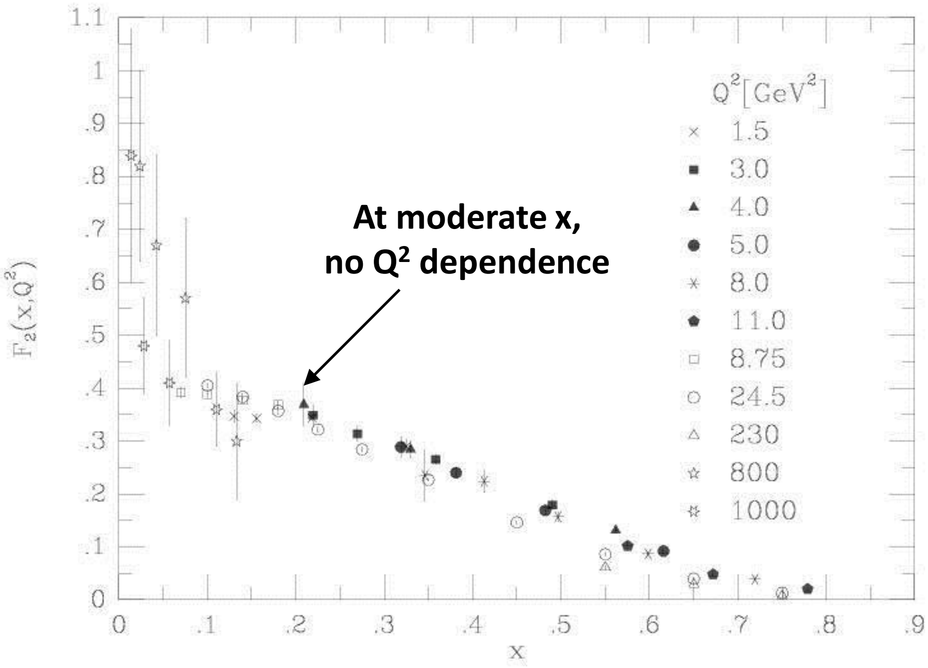
$$W_2 = \frac{1}{\nu}F(\omega) \qquad \omega = \frac{2M\nu}{q^2}$$

- Thus, there is no characteristic momentum scale

→ no characteristic size

→ constituents are point-like

Observation of Scaling!



At moderate x, no Q^2 dependence

Feynman's Parton Model

- Feynman postulated that protons were made of pointlike constituents "partons"
- They share momentum of proton

$$f(x)dx$$

Probability of parton having between *x* and *x+dx* of proton's momentum

- Natural interpretation in terms of quarks

$$\int dx\ x\left[u(x)+\bar{u}(x)+d(x)+\bar{d}(x)+\cdots\right]=1$$

$$\int dx\ \left[d(x)-\bar{d}(x)\right]=1 \qquad \int dx\ \left[u(x)-\bar{u}(x)\right]=2 \qquad \int dx\ \left[s(x)-\bar{s}(x)\right]=0$$

"Sum Rules"

Explanation of Scaling

- Feynman’s picture makes sense in the “infinite-momentum” frame
- If partons are massless, real particles:

$$p'^2 = (p+q)^2 = (xP+q)^2 = 0$$

$$(xP+q)^2 = -Q^2 + 2M\nu x = 0$$

Feynman $$x = \frac{Q^2}{2M\nu} = \frac{1}{\omega}$$ **Bjorken**

Modern DIS language

$$F_1 = MW_1 \quad F_2 = \nu W_2 \quad \frac{d^2\sigma}{dq^2 dx} = \frac{4\pi\alpha^2}{q^4}\left[(1-y)\frac{F_2(x,q^2)}{x} + y^2\frac{2xF_1(x,q^2)}{x}\right]$$

$$2xF_1 = F_2$$

Callan-Gross Relation
(spin ½ partons!)

$$\boxed{\frac{d^2\sigma}{dQ^2 dx} \approx \frac{4\pi\alpha^2}{Q^4}\left[\frac{F_2(x,Q^2)}{x}\right]}$$

F_2 contains E-M structure of proton!

For moderate x, no Q^2 dependence $F_2(x,Q^2) \rightarrow F_2(x)$

Structure Functions & PDFs

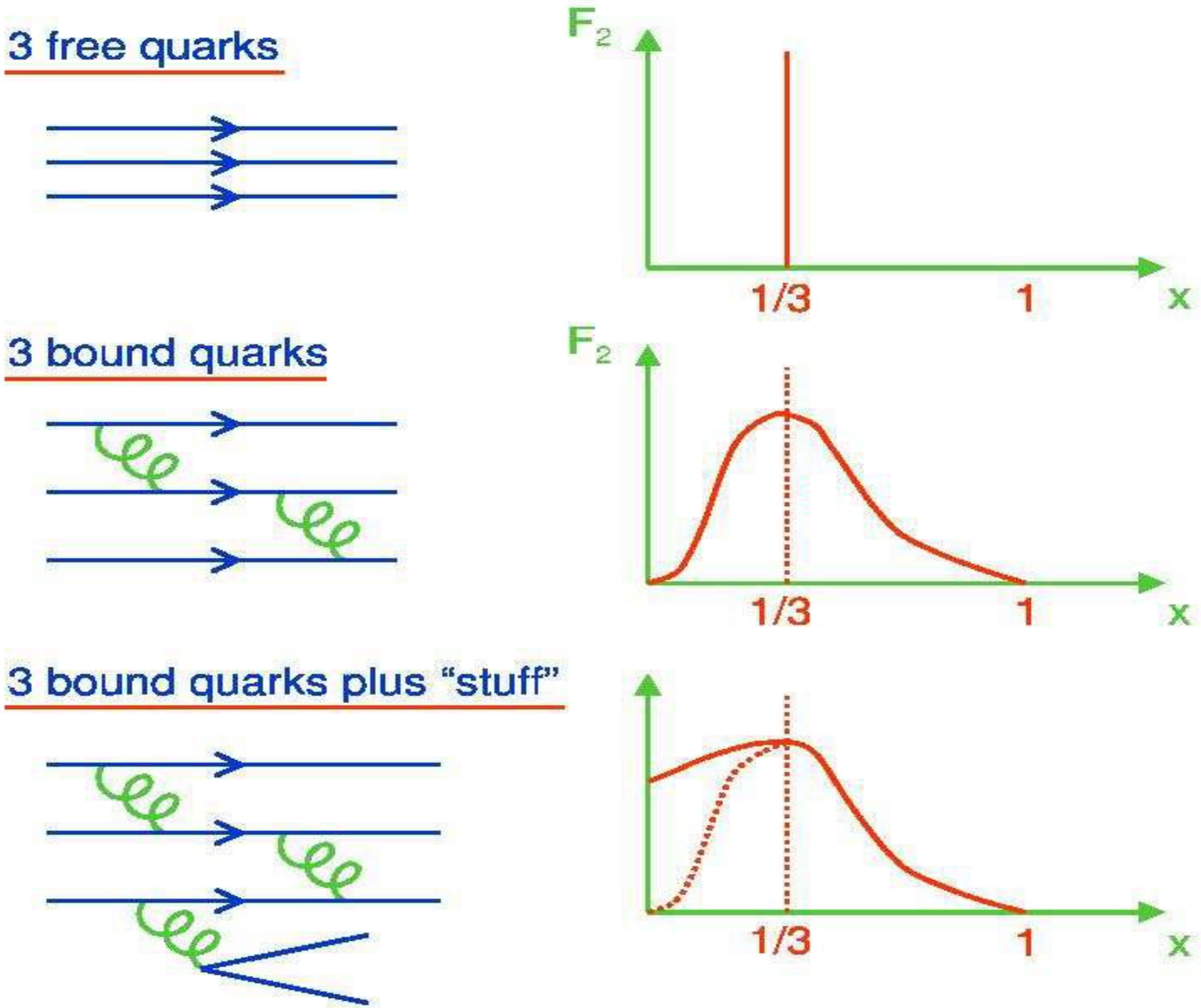
- We measure structure functions
  - F_2 from DIS of electrons on protons
  - F_3 from DIS of neutrinos
- We infer “Parton Distribution Functions”

$$F_2 = \sum_i x q_i^2 \left[f_i(x) + \bar{f}_i(x) \right]$$

$$F_3 = \sum_i q_i^2 \left[f_i(x) - \bar{f}_i(x) \right]$$

- Crucial feature: PDFs are universal!
  - Can measure ep and predict νp

What is $F_2\,(x)$?


3 free quarks
F2
1/3
1
x
3 bound quarks
F2
1/3
1
x
3 bound quarks plus "stuff"
1/3
1
x

Are quarks the whole story?

- Proton is described as a “bag” containing free charged quarks
- But let’s put some pieces together:

$$\int xu(x)dx = 2\int xd(x)dx \qquad F_2(x) = x\left[\frac{4}{9}u(x) + \frac{1}{9}d(x)\right]$$

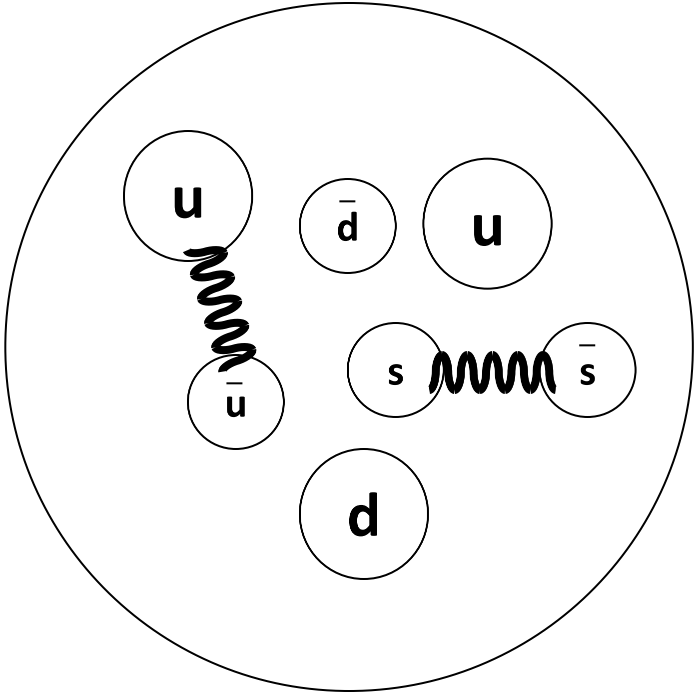
$$\int F_2(x)dx = \int xd(x)dx \approx 1/6$$

$$\int xd(x)dx + \int xu(x)dx \approx 1/2$$

Quarks carry only half the proton momentum!

Adding QCD

- We have been talking about “valence” quarks
- Quarks are not completely free in the nucleon
  - Bound by gluons – we should see them
  - There are also “sea” quarks – quantum fluctuations



QCD leads to “Evolution”

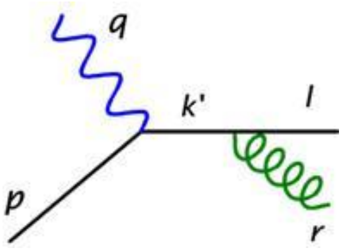
- As you hit the proton harder, you resolve shorter lived fluctuations – gluons & sea
- The quarks you see can come from several sources

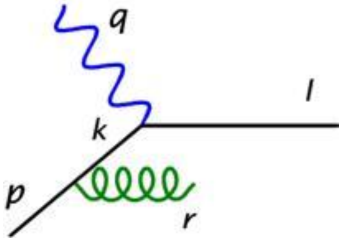
“Dokshitzer-Gribov-Lipatov-Altarelli-Parisi” (DGLAP)

$$\frac{dq(x,Q^2)}{d\ln Q^2} = \alpha_s\left(Q^2\right)\int_{y=x}^{y=1}\left\{q(y,Q^2)P_{qq}\left(\frac{x}{y}\right)+G(y,Q^2)P_{qg}\left(\frac{x}{y}\right)\right\}$$

Quark radiates gluon, and so loses energy

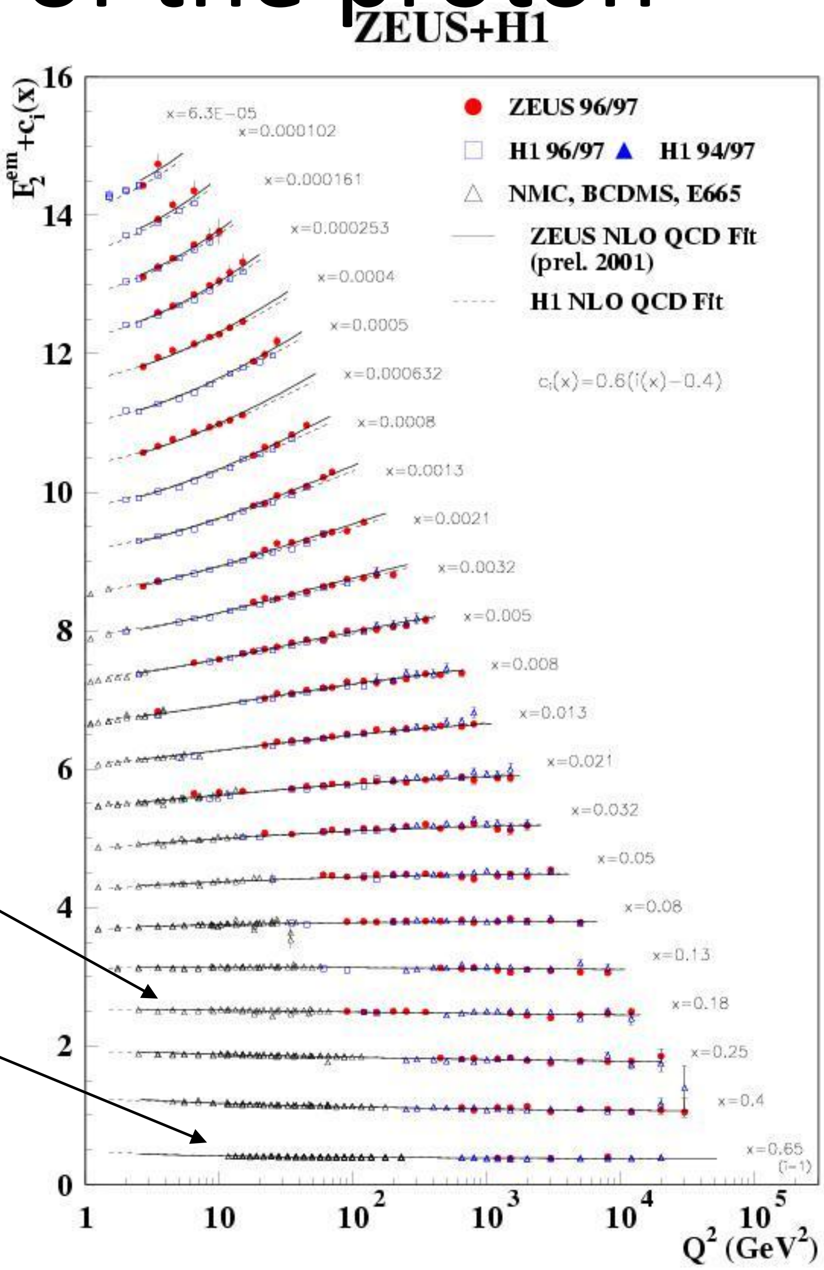
Gluon splits to q-anti-q, each one with a fraction of gluon x

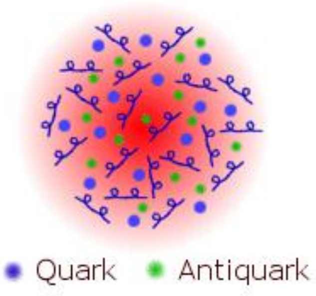




QCD Structure of the proton

- Higher energies let us push down to lower x
- HERA data
  - 30 GeV electron/positron
  - 900 GeV proton
- All features expected from QCD are seen
  - Scaling at x~.2
  - Violations of scaling



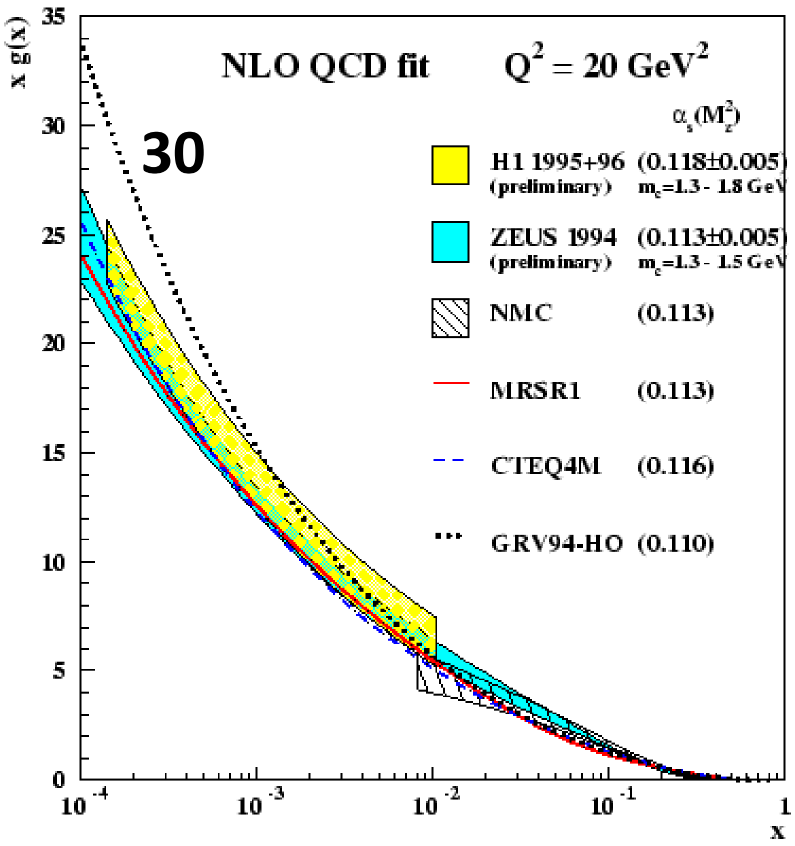


Proton has a Gluon PDF as well!

- From global fits, one can extract even the gluon structure of the proton as a function of x and Q^2
- If gluons were not self-coupling, one might expect $g(x) \sim 1/x$
- Instead, $g(x)$ rises rapidly at low x

$$g(x) \sim \frac{1}{x^{1+\lambda}}$$

- This is EXTREMELY important for RHIC + LHC physics

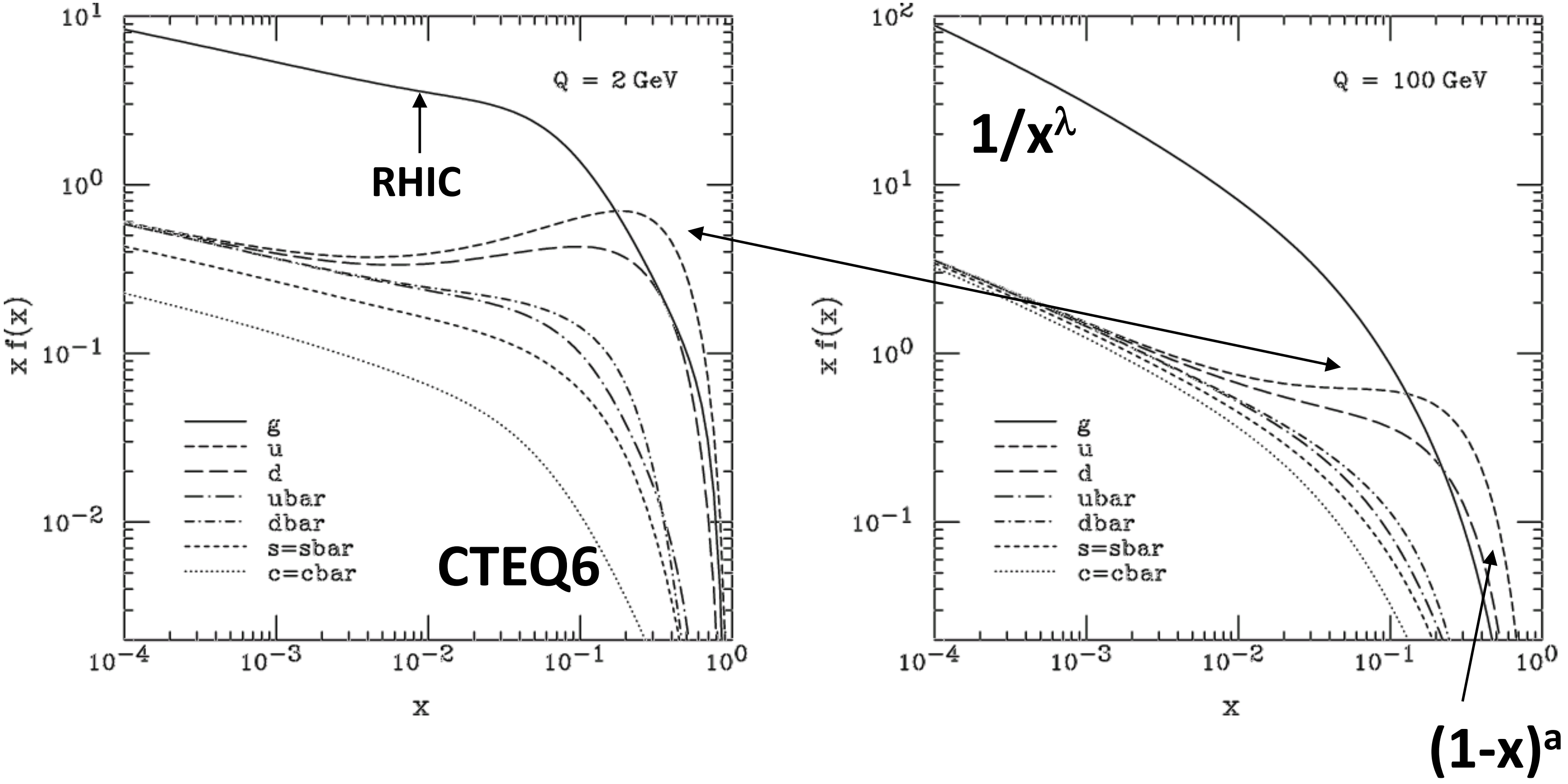


Putting it all together

- DIS data sets exist at many different systems & energies
- Theorists can do calculations and make global fits to the data to extract PDFs

- CTEQ
- MRST
- GRV

Theoretical Collaborations



RHIC

CTEQ6

$1/x^\lambda$

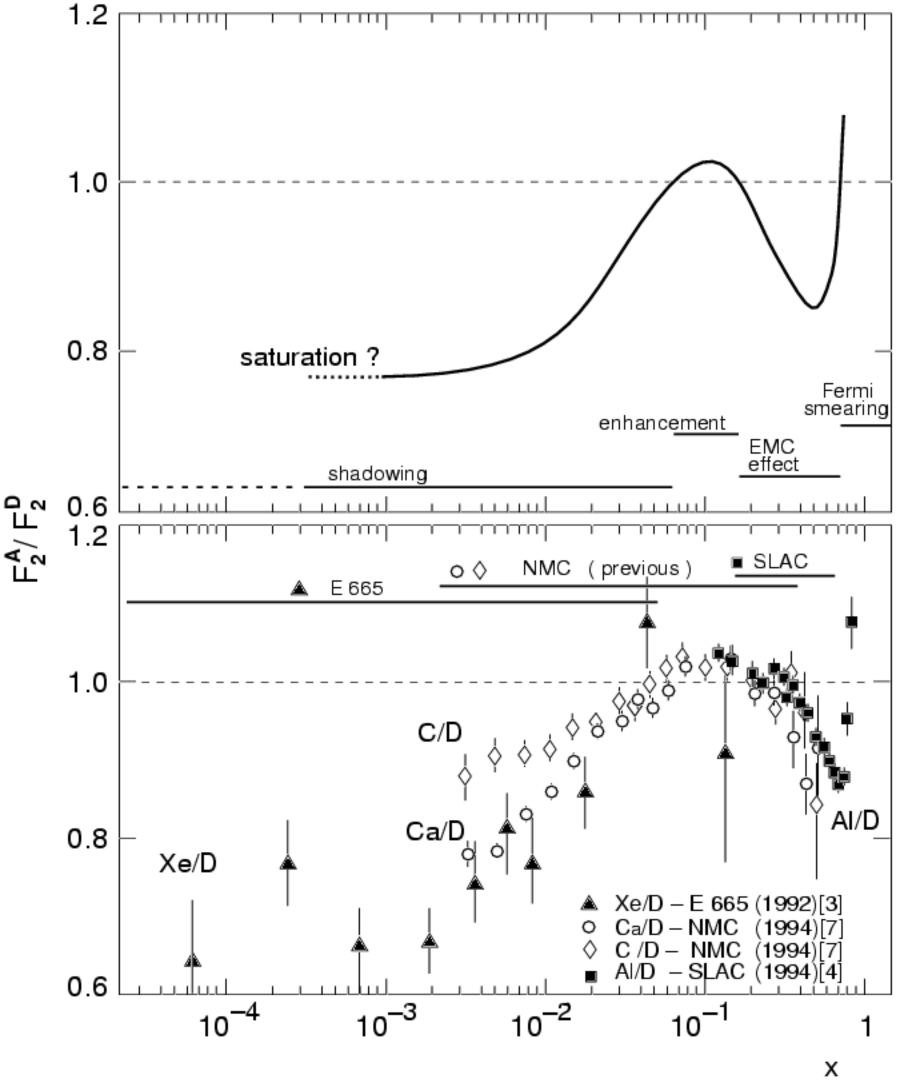
$(1\text{-}x)^a$

Is a nucleon always a nucleon?

- We know that nucleons are bound in nuclei
  - Is their structure modified?
- Studied by ratios, divided by number of nucleons

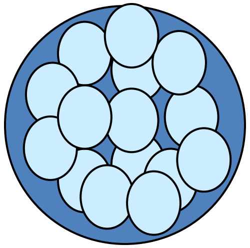
$$\frac{F_2^A}{F_2^N} = \frac{\sigma_A}{A\sigma_N}\left(x, Q^2\right)$$

- Different regions of x revealed different effects
  - “EMC effect”
  - “Shadowing”
  - “Saturation”

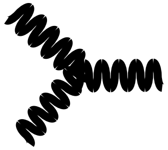


Parton Saturation

- Gluon distribution rises rapidly at low-x
- Gluons of x~1/(2mR) overlap in transverse plane with size 1/Q

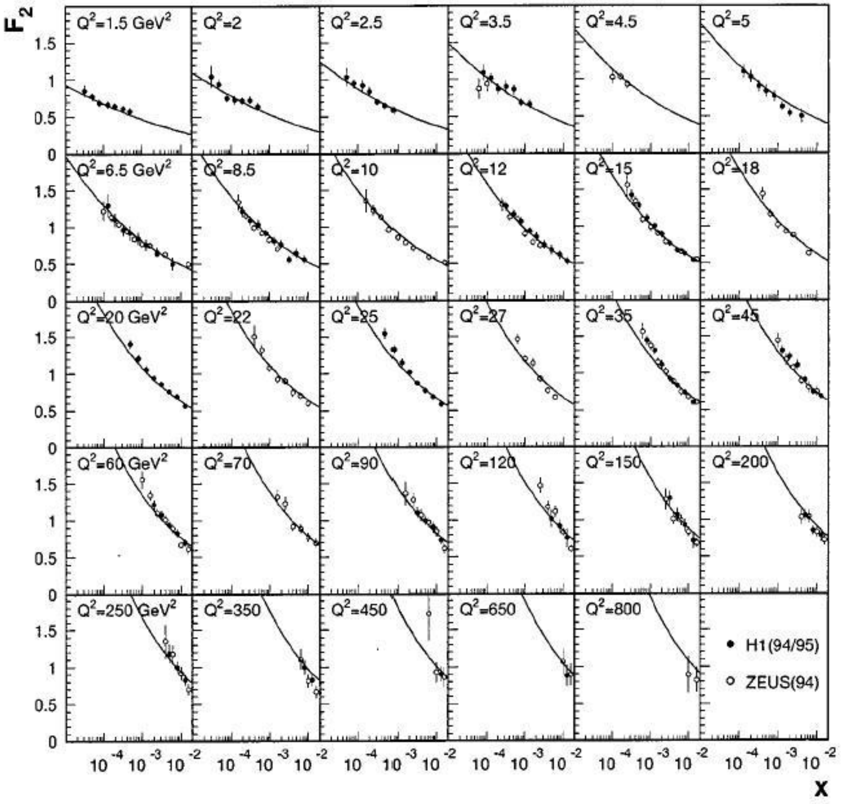


- Below "saturation" scale Q_s^2 gluon recombination occurs



- Saturation scale measures density of partons in the transverse plane
  - Increases with A and/or √s

Saturation describes HERA data!

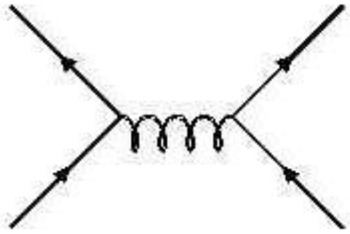


$$Q_s^2 = \alpha_s\left(Q_s^2\right) xG_A\left(x, Q_s^2\right) A^{1/3}$$

Scale depends on **thickness**

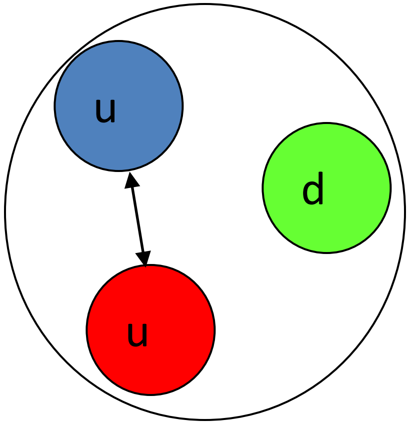
Two regimes of QCD

"Perturbative QCD" (pQCD)
means that rigourous calculations
can be done with Feynman integrals.
Well defined for quarks and gluons
(generically callled "partons")



$Q^2 > 1$ GeV

However, the particles we observe
in nature are in the regime of
"Non-perturbative QCD" (npQCD):
baryons & mesons ("hadrons")



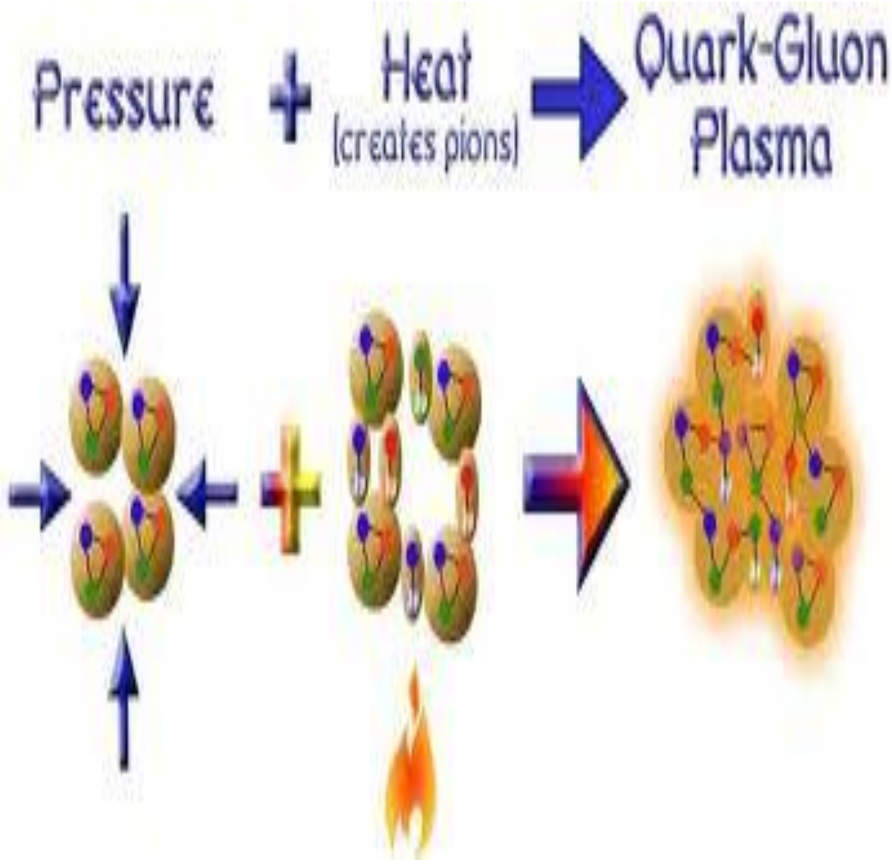
$Q^2 << 1$ GeV

At large distances (r~1fm) one can
no longer write down Feynman diagrams
and compute QM amplitudes etc.
→ No-one "understands" hadronization!

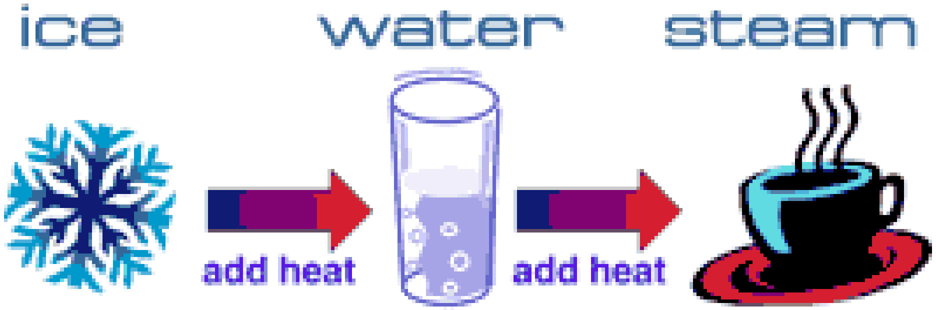
What have we learned?

- QCD is a rich theory
- Interactions qualitatively depend on the scale
  - Long wavelength – hadrons, npQCD
  - Short wavelength – partons, pQCD
- Colour force is confining – no free partons
  - Pulling out a parton causes it to hadronize
  - Not understood theoretically, just modelled
- How else can we try and understand QCD?
  - How do we understand other forces in nature?

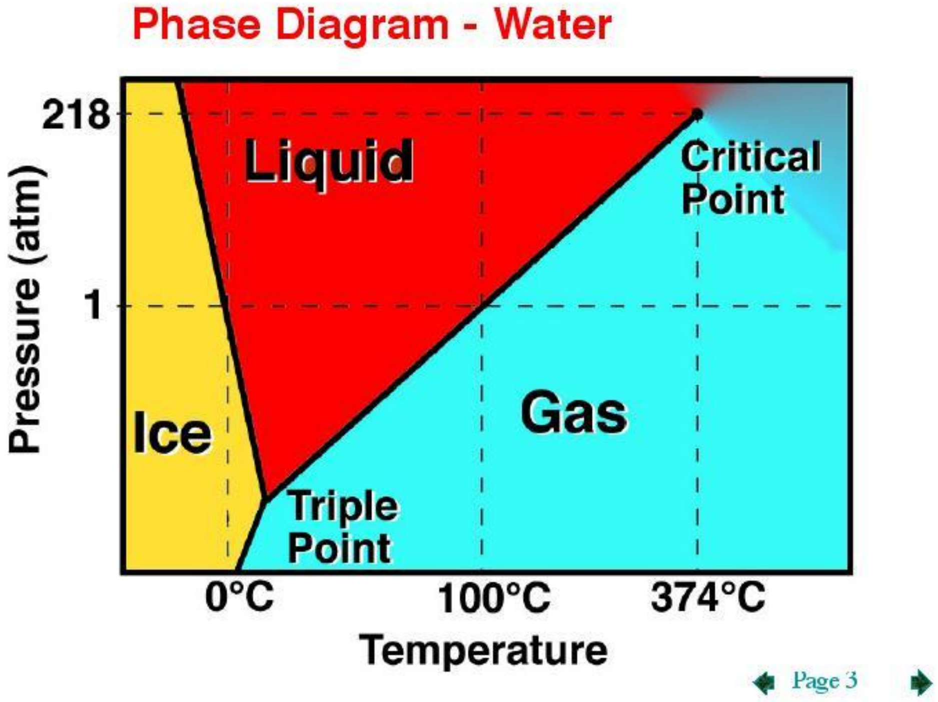
Enter the QGP

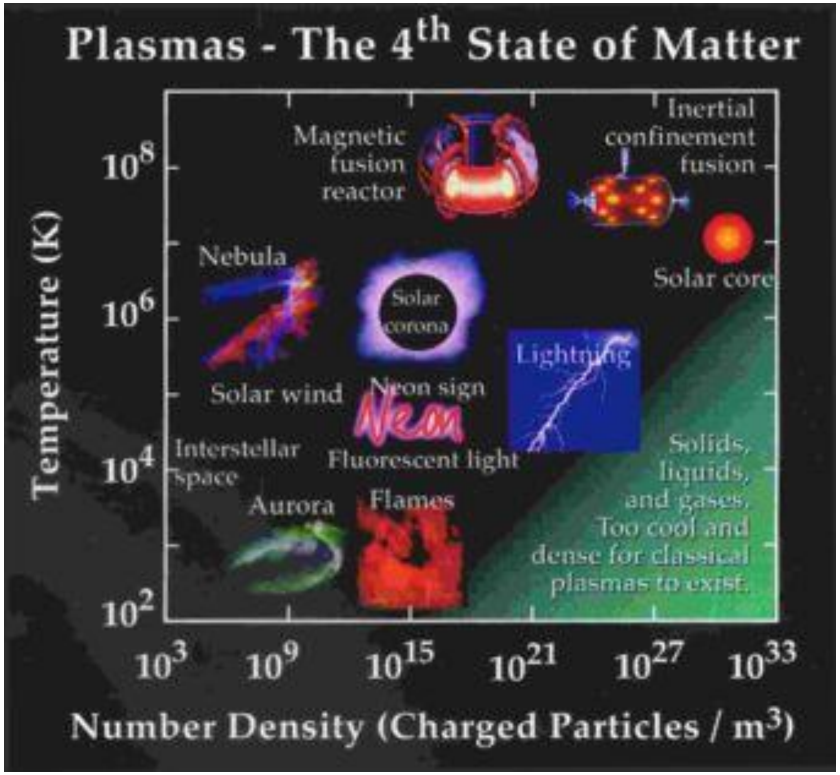


Back to Basics: Phases of Normal Matter



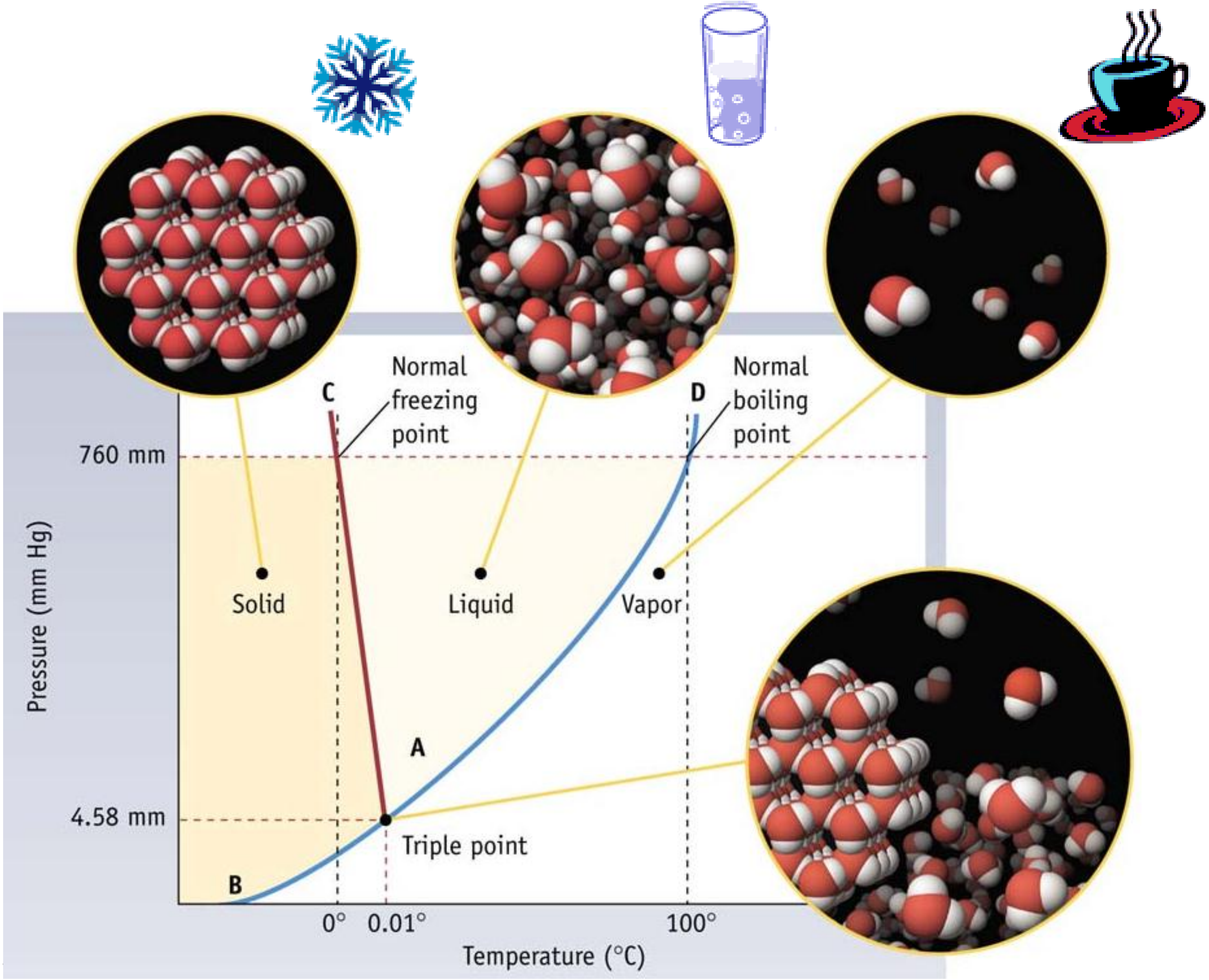
solid liquid gas





Electromagnetic interactions determine phase structure of normal matter

The phase diagram of water



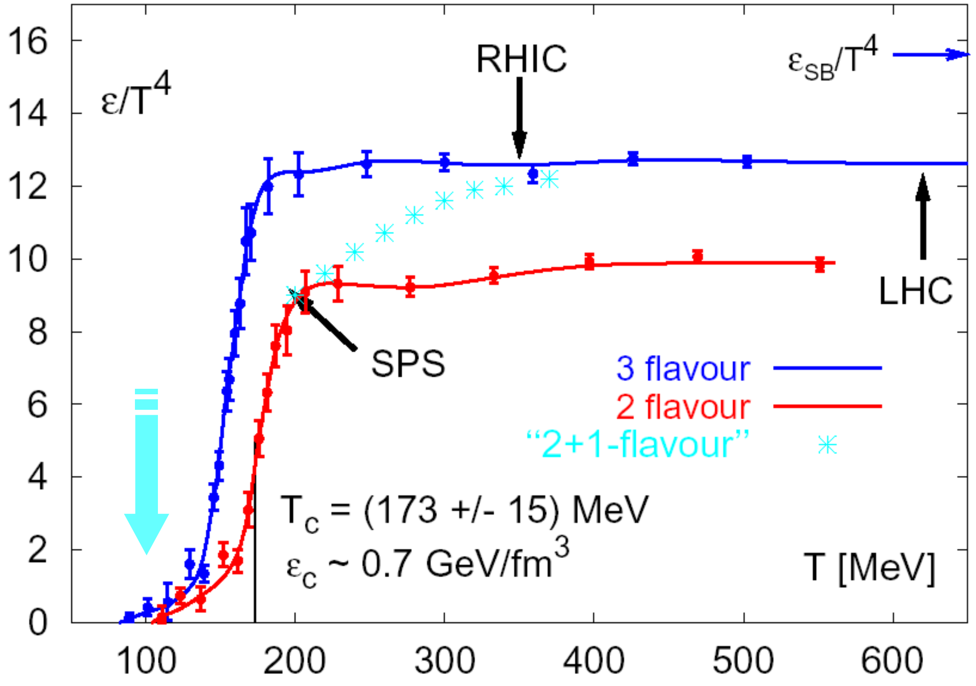
Creating a state of deconfined quarks and gluons

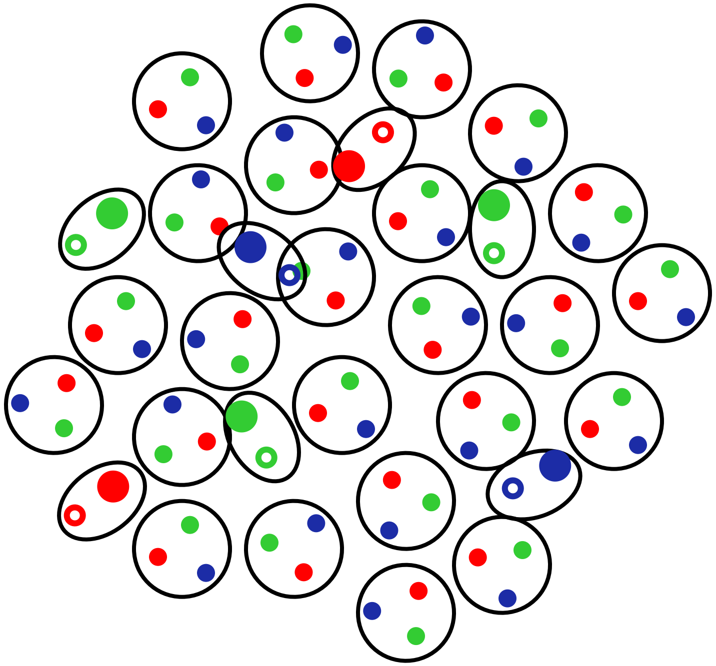
To understand the strong force and the phenomenon of confinement:
we must create and study a system of deconfined quarks (and gluons)

- by heating
- by compression

→ *deconfined colour matter !*

Lattice QCD calculations



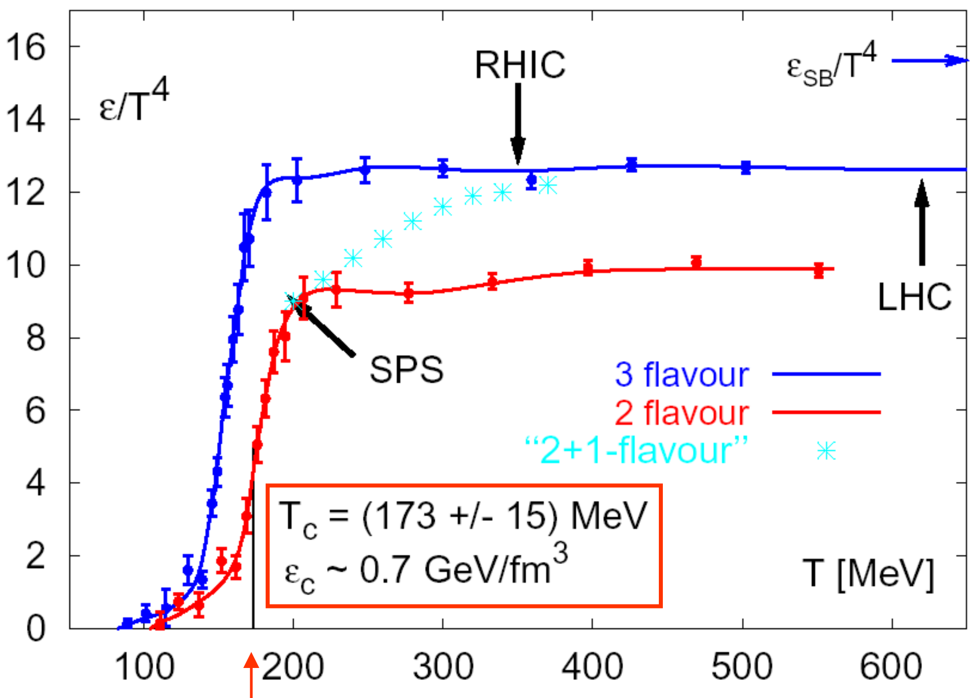


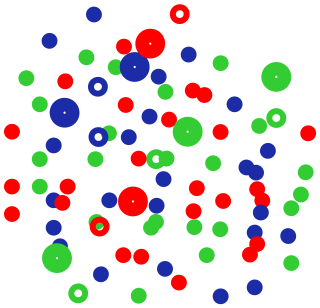
Quark Gluon Plasma
deconfined !

Slide courtesy: Carlos Lourenço, CERN

Expectations from Lattice QCD calculations

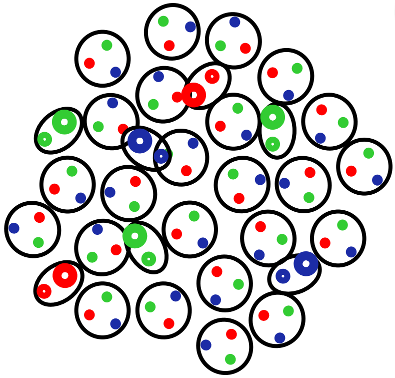
ε/T^4 ~ number of degrees of freedom





deconfined
QCD matter:
many d.o.f.

hadronic
matter:
few d.o.f.

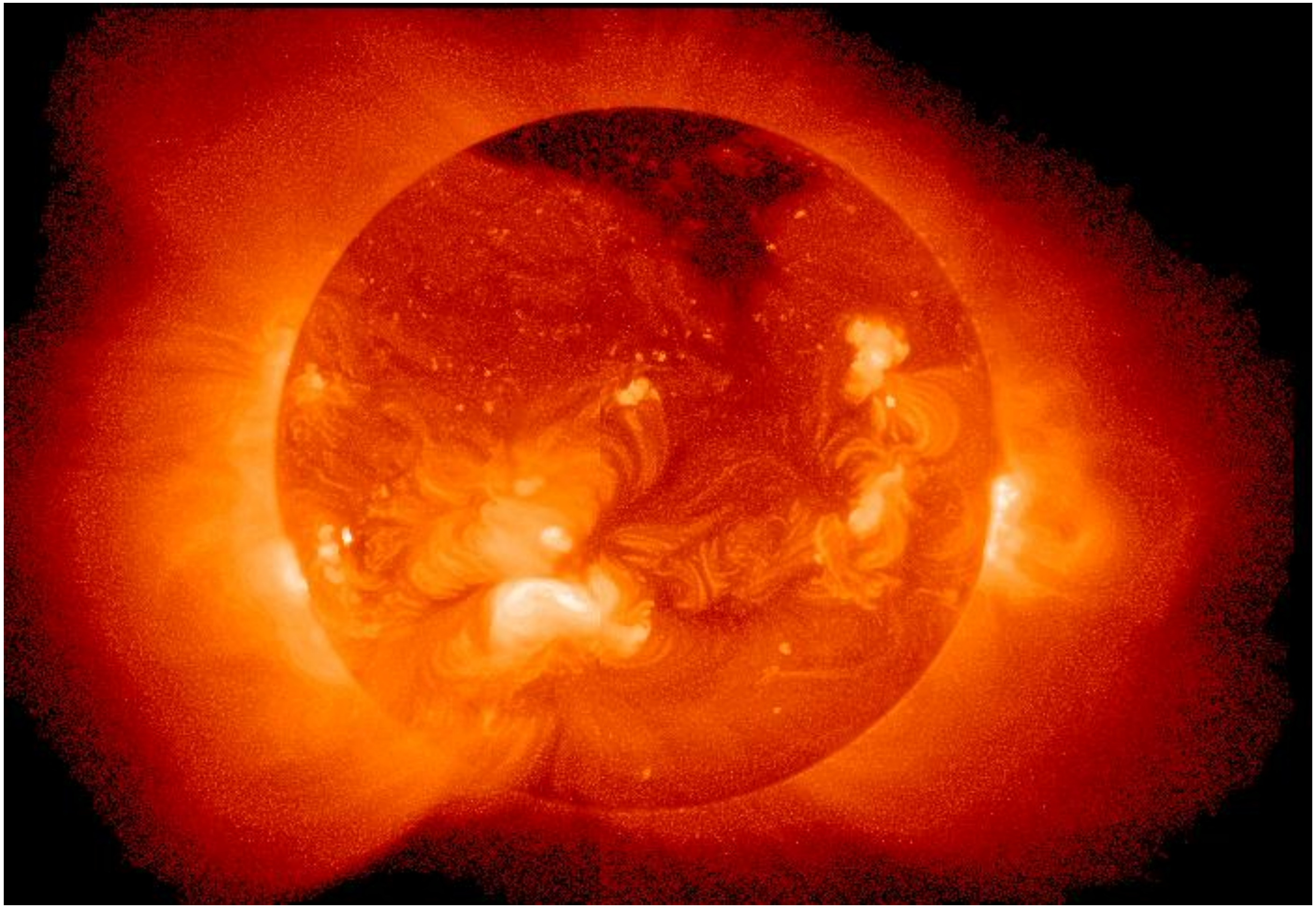


QCD lattice calculations indicate that, above a critical temperature, T_c, or energy density, ε_c, strongly interacting matter undergoes a phase transition to a new state where the quarks and gluons are no longer confined in hadrons

How hot is a medium of T ~ 173 MeV?

Slidescourtesy: Carlos Lourenço, CERN PH-EP

Temperature at the center of the Sun ~ 15 000 000 K

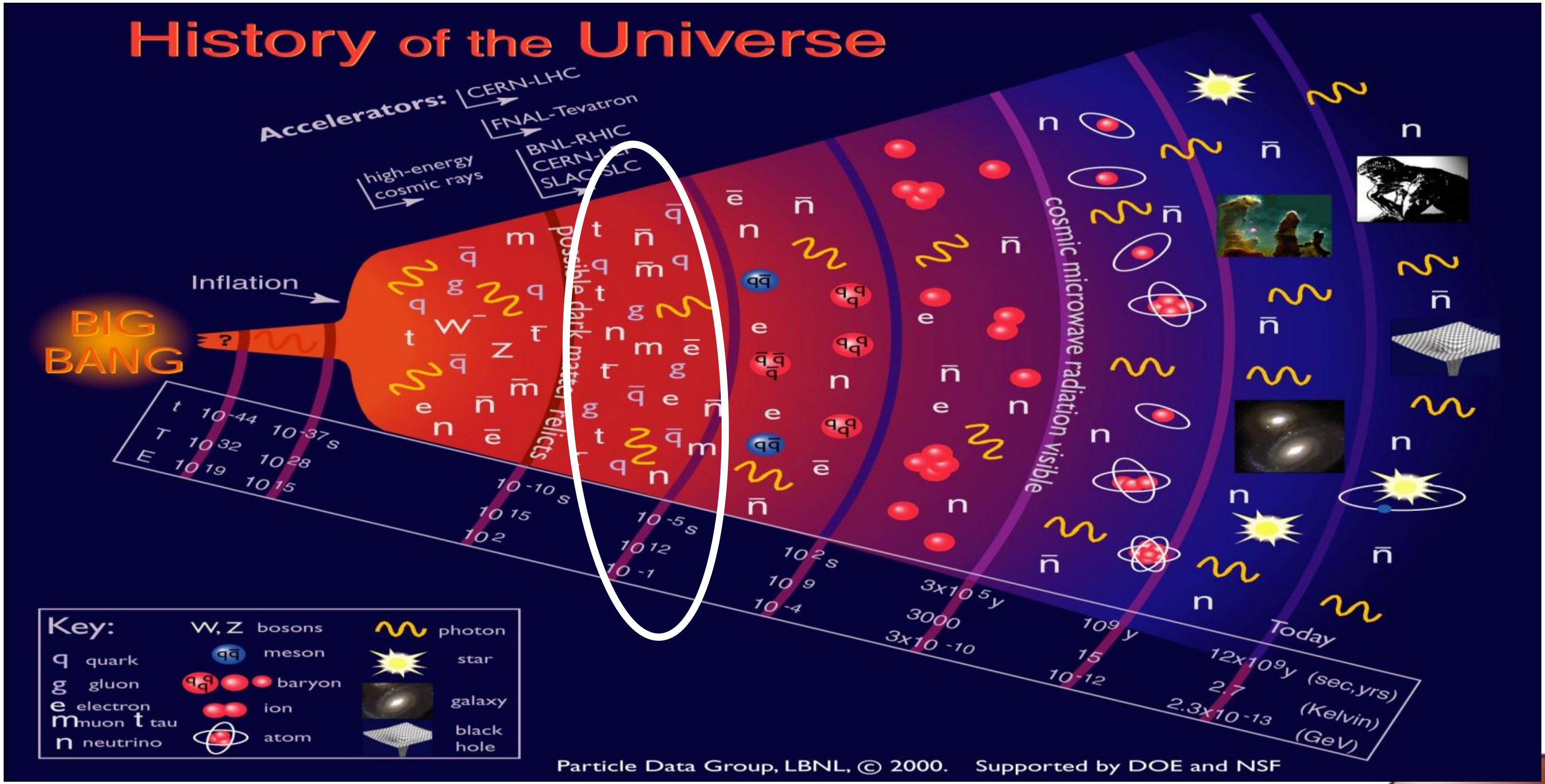


Temperature of the matter created in heavy ion collisions

$T_c \approx$ 173 MeV ~ 2 000 000 000 000 K ... it's pretty hot!

Motivation

In the early stages of the Universe; Quarks and gluons were reaming freely

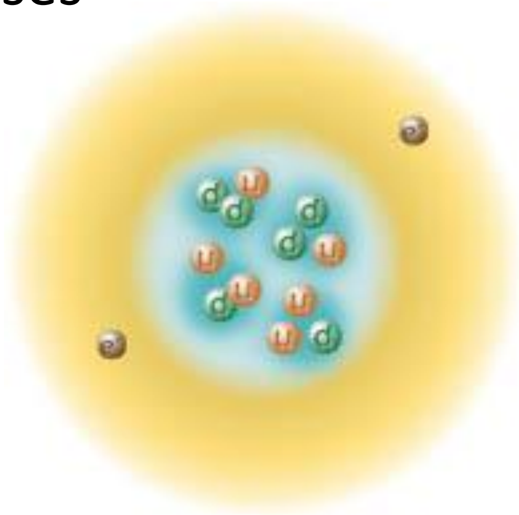


Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

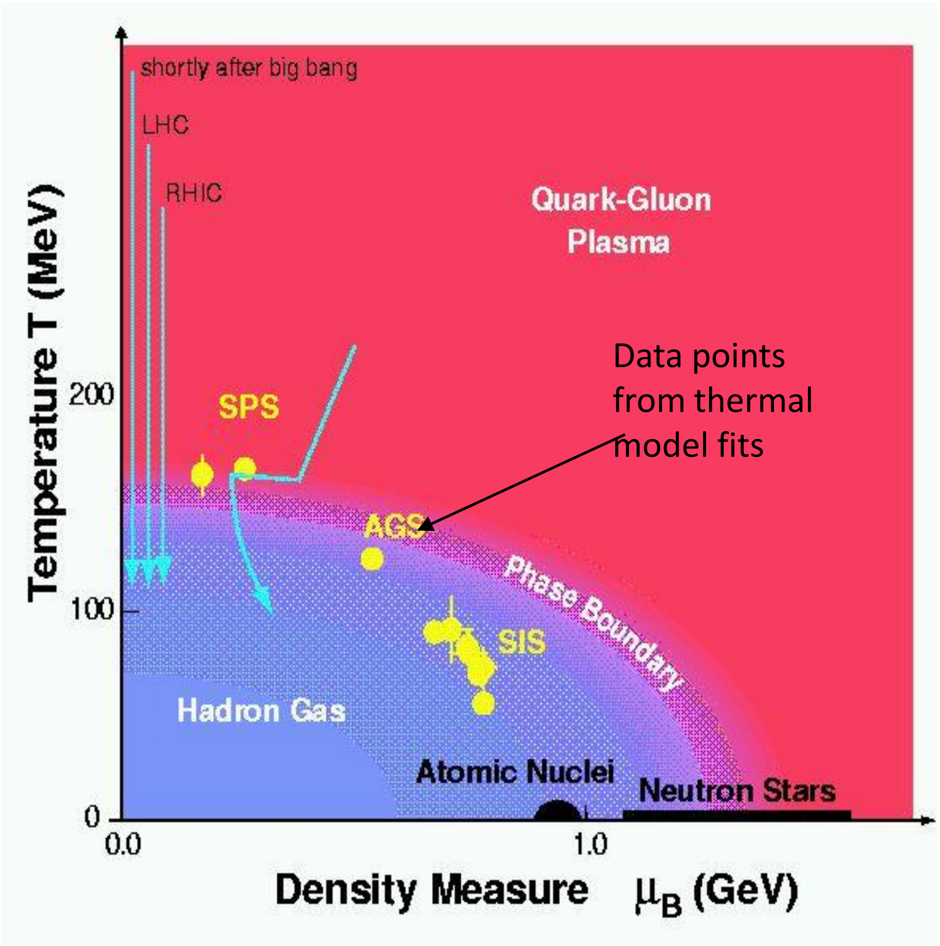
As the universe cooled down, they got confined and have remained imprisoned ever since...

Phases of QCD Matter

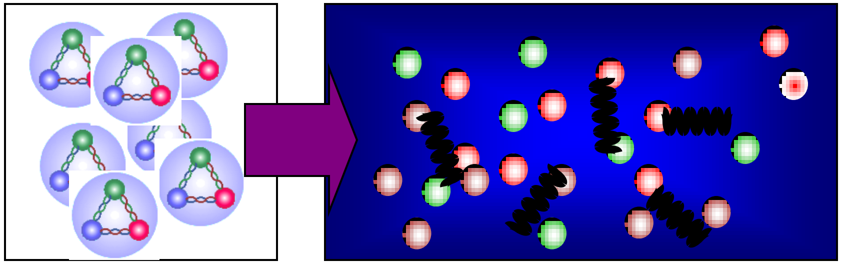
- We have strong interaction analogues of the familiar phases



- Nuclei behave like a liquid
  - Nucleons are like molecules
- **Quark Gluon Plasma**
  - “Ionize” nucleons with heat
  - “Compress” them with density
- New state of matter!

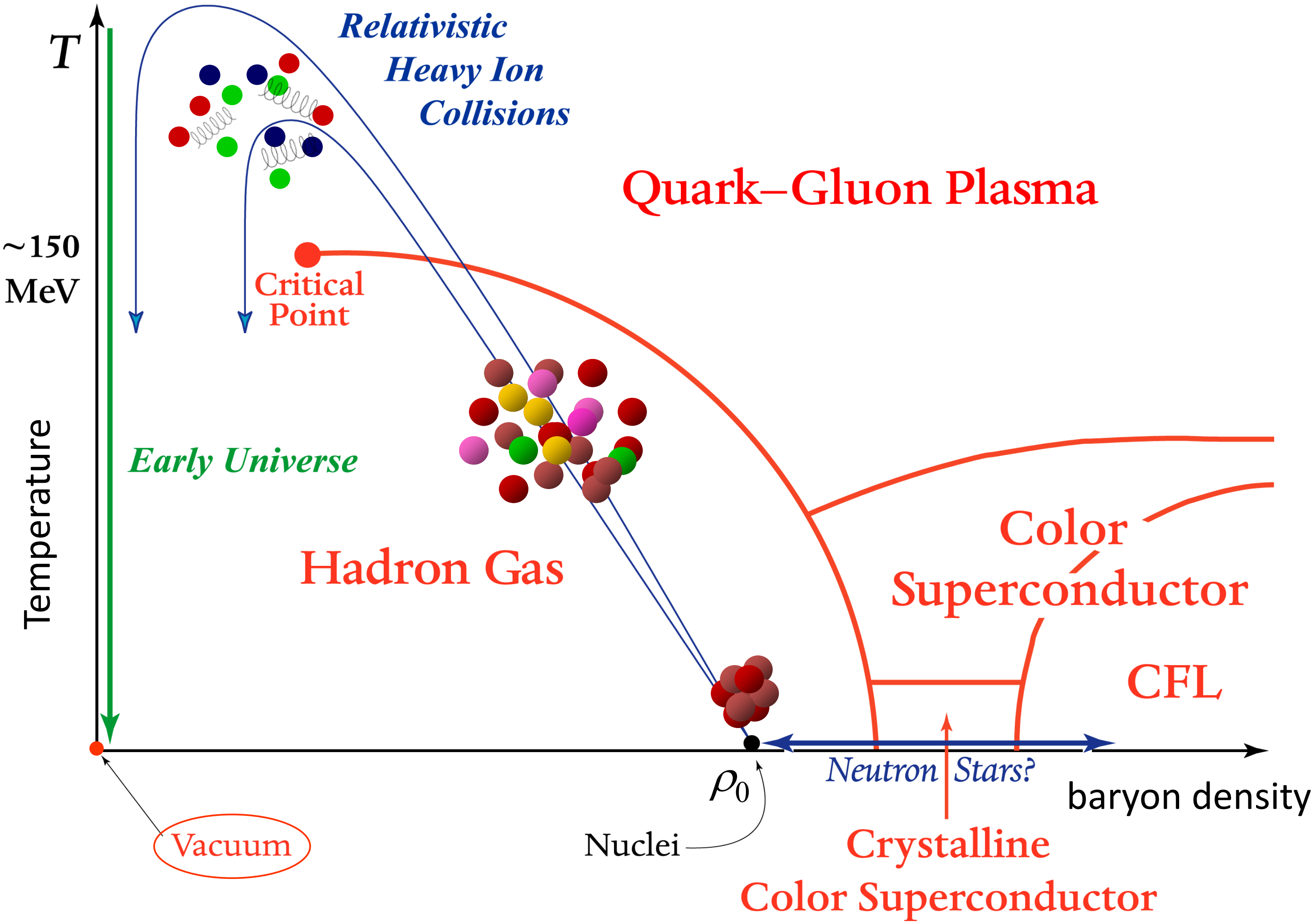


Data points from thermal model fits



The true phase diagram of QCD (?)

The true phase diagram ~~may actually be~~ is substantially more complex,



Exploring the Phases of Nuclear Matter

Can we explore the phase diagram of nuclear matter ?

- We think so !
  - by colliding nuclei in the lab
  - by varying the nuclei size (A) and colliding energy ($\sqrt{s}$)
  - by studying spectra and correlations of the produced particles

- Requirements
  - system must be at equilibrium (for a very short time)

    ⇒ system must be dense and large

Can we find and explore the Quark Gluon Plasma ?

- We hope so !
  - by colliding large nuclei at very high energies

- How high ?
  - QCD calculations on the lattice predict:
    - Critical temperature: $T_c \approx 173$ MeV
    - Critical energy density: $6 \times$ normal nuclear matter

11 Science Questions for the New Century

1. What Is Dark Matter?
2. What Is the Nature of Dark Energy?
3. How Did the Universe Begin?
4. Did Einstein Have the Last Word on Gravity?
5. What Are the Masses of the Neutrinos,
   and How Have They Shaped the Evolution of the Universe?
6. How Do Cosmic Accelerators Work and What Are They Accelerating?
7. Are Protons Unstable?
8. What Are the New States of Matter at Exceedingly High Density and Temperature?
9. Are There Additional Space-Time Dimensions?
10. How Were the Elements from Iron to Uranium Made?
11. Is a New Theory of Matter and Light Needed at the Highest Energies?

It seems that the study of Quark Matter... matters

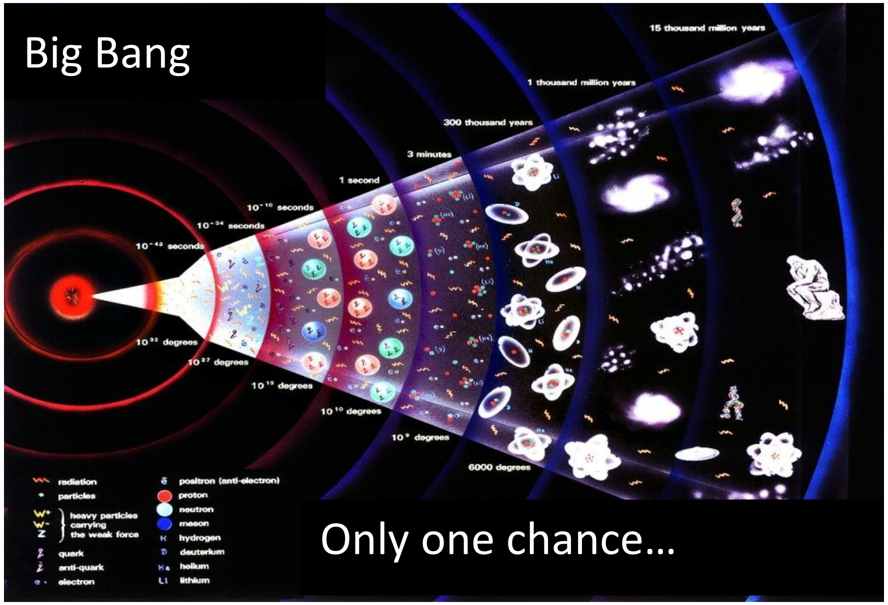
SCIENTIFIC AMERICAN

MAY 2006
WWW.SCIAM.COM

Quark Soup

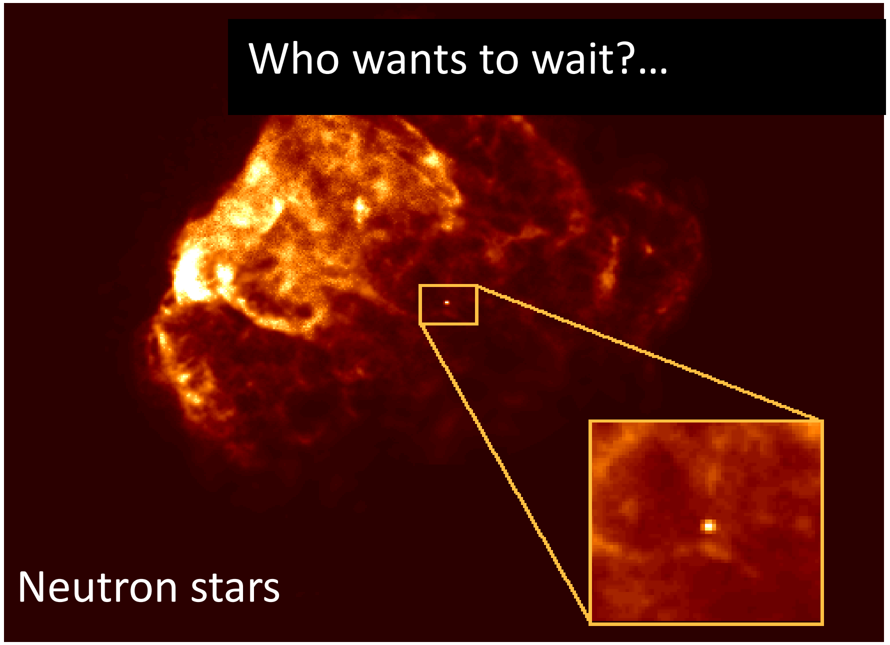
PHYSICISTS RE-CREATE THE LIQUID STUFF OF **THE EARLIEST UNIVERSE**

Where to study QCD matter


Big Bang

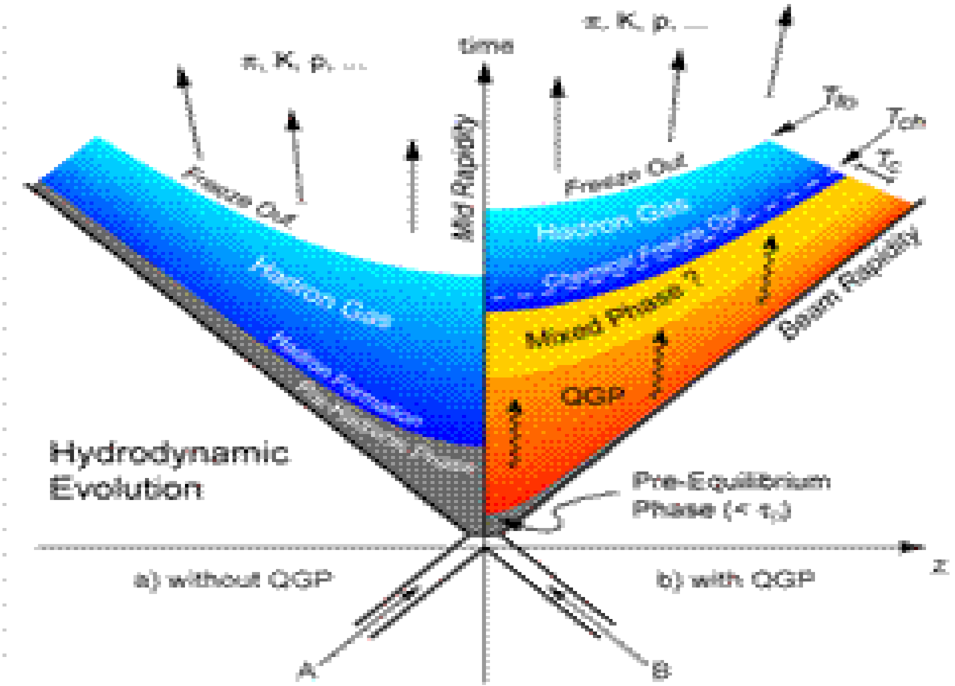
Only one chance…


Lattice QCD


Who wants to wait?…

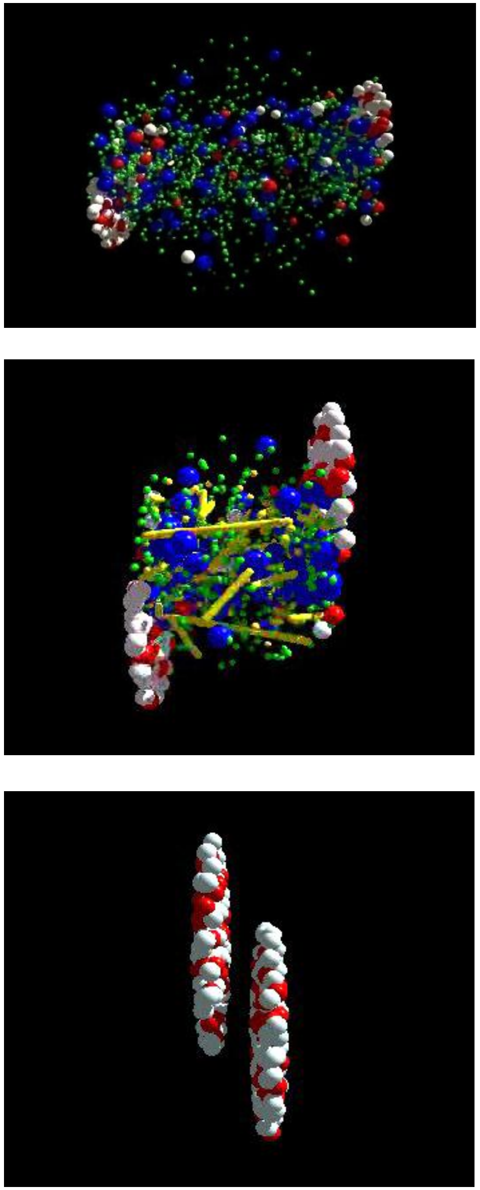
Neutron stars

The time evolution of the matter produced in HI collisions



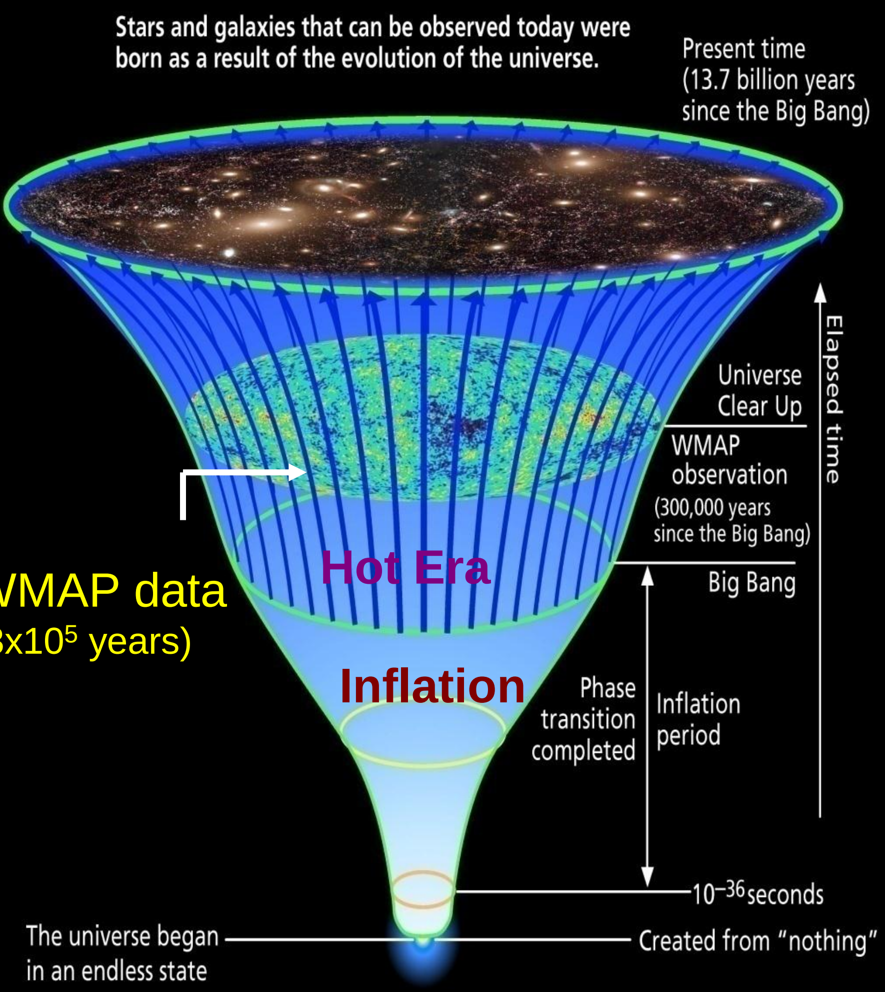
soft physics regime

hard (high-p_T) probes



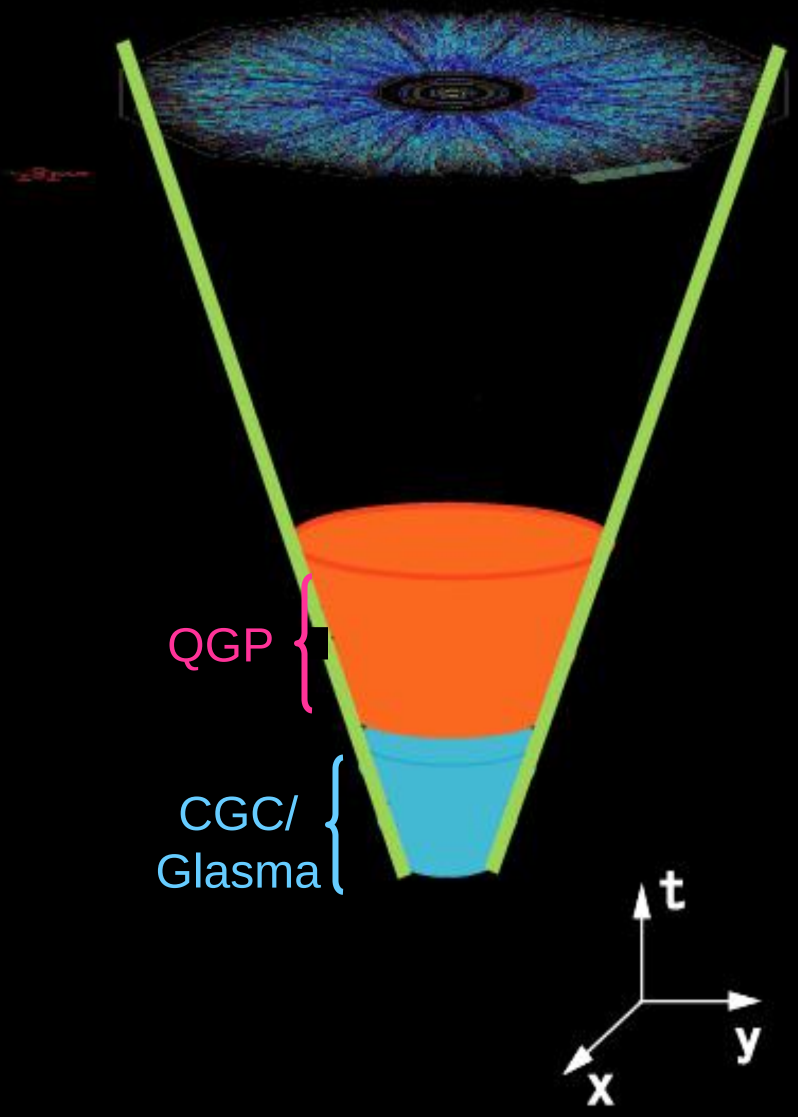
- Chemical freeze-out (at $T_{ch} \leq T_{fo}$):
  end of inelastic scatterings; no new particles (except from decays)
- Kinetic freeze-out (at $T_{fo} \leq T_{ch}$):
  end of elastic scatterings; kinematical distributions stop changing

Big Bang



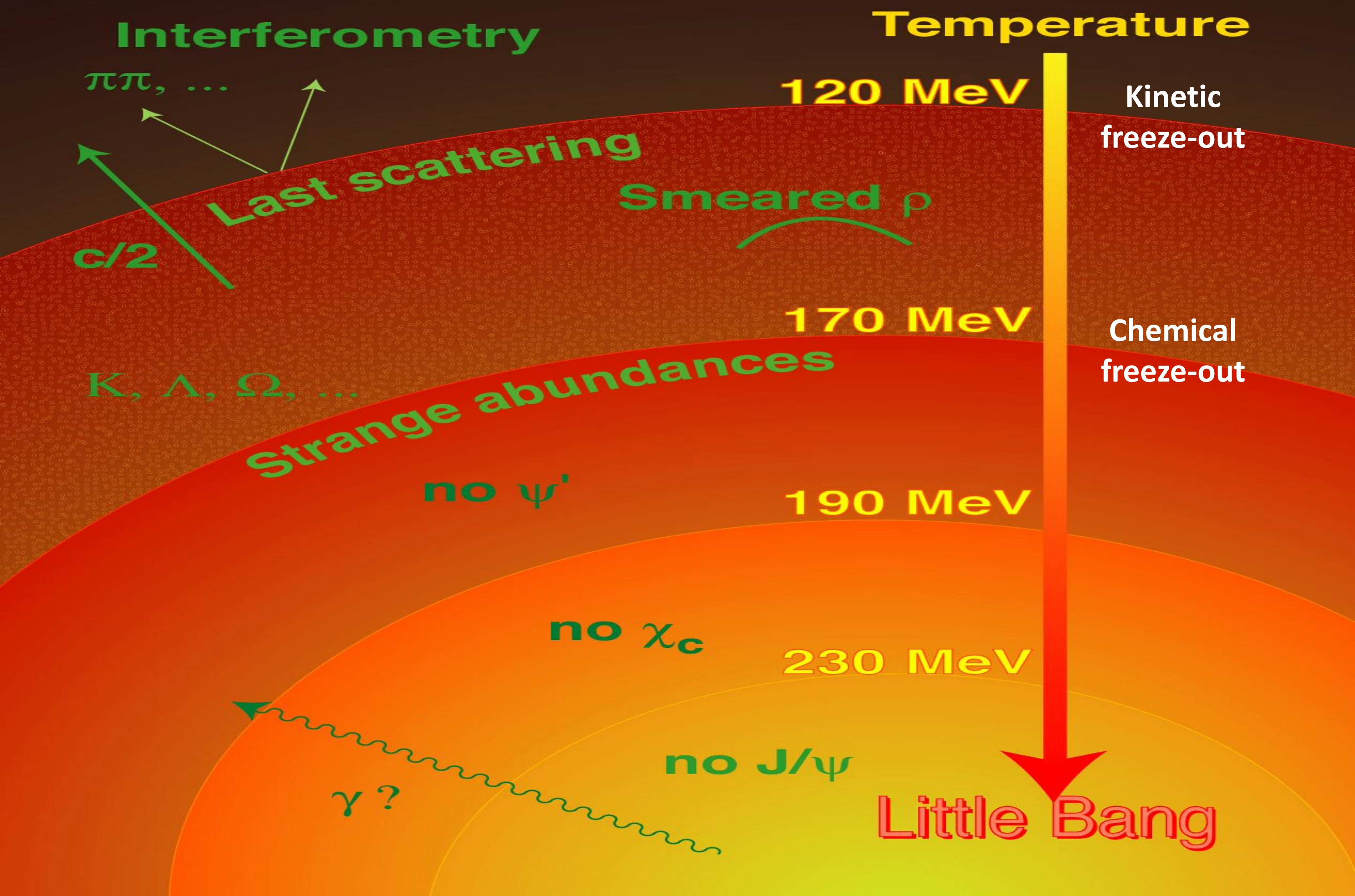
WMAP data
(3x10^5 years)

Little Bang



Plot by T. Hatsuda

Towards A New State of Matter



Interferometry

$\pi\pi$, ...

Last scattering

c/2

Smeared ρ

K, Λ, Ω, ...

Strange abundances

no ψ'

no χ_c

γ ?

no J/ψ

Temperature

120 MeV

Kinetic freeze-out

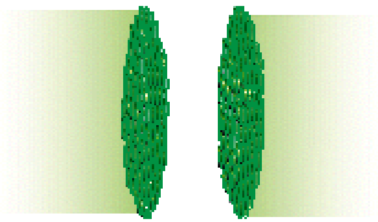
170 MeV

Chemical freeze-out

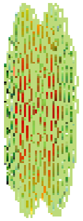
190 MeV

230 MeV

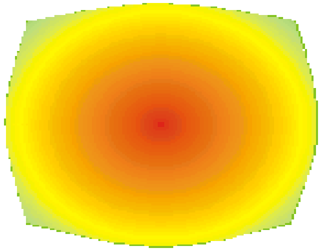
Little Bang



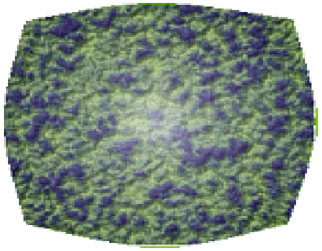
CGC



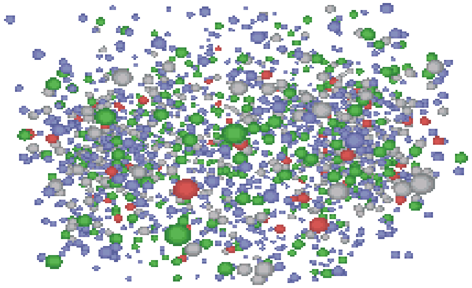
Initial Singularity



Glasma



sQGP



Hadron Gas

Gribov, Levin and Ryskin 1984

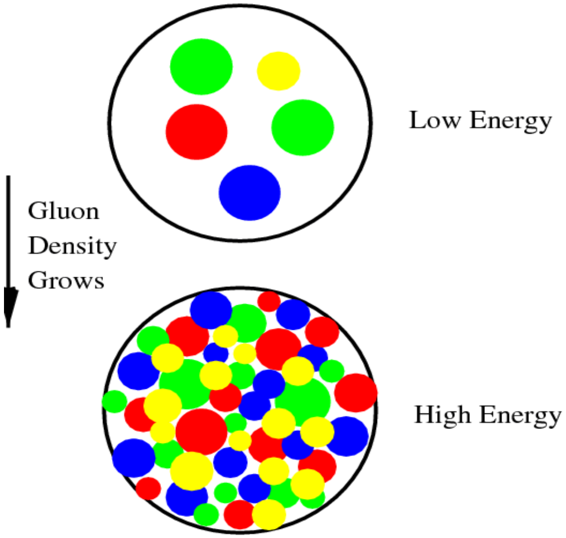
Mueller 1994

McLerran and Venugopalan 1994

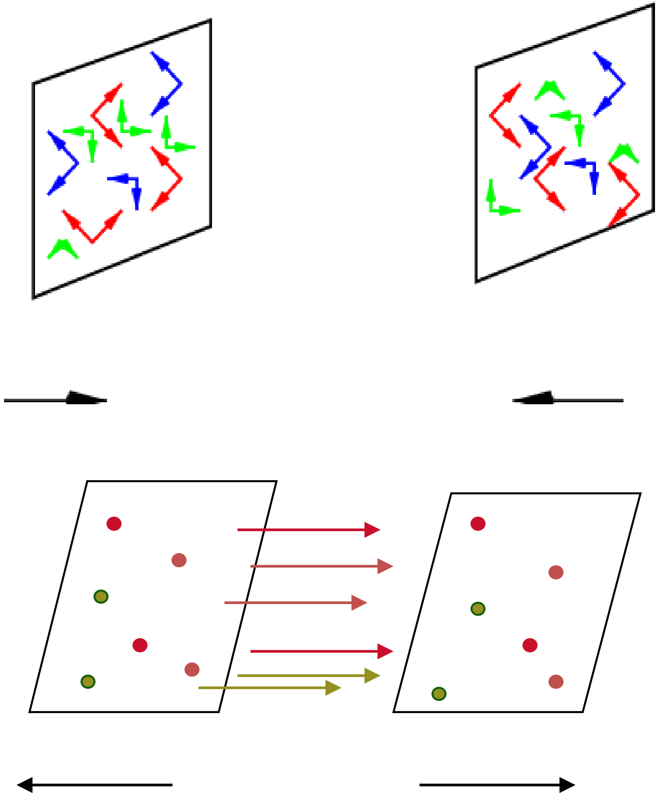
Iancu

Kovchegov

New York-Tel Aviv-Paris-Helsinki-Frankfurt



High Energy Density Gluonic Matter



Thermalization?

Two labs to recreate the Big-Bang

- **AGS** : 1986 - 2000
- Si and Au beams ; up to 14.6 A GeV
- only hadronic variables

- **RHIC** : 2000 - ?
- Au beams ; up to sqrt(s) = 200 GeV
- 4 experiments

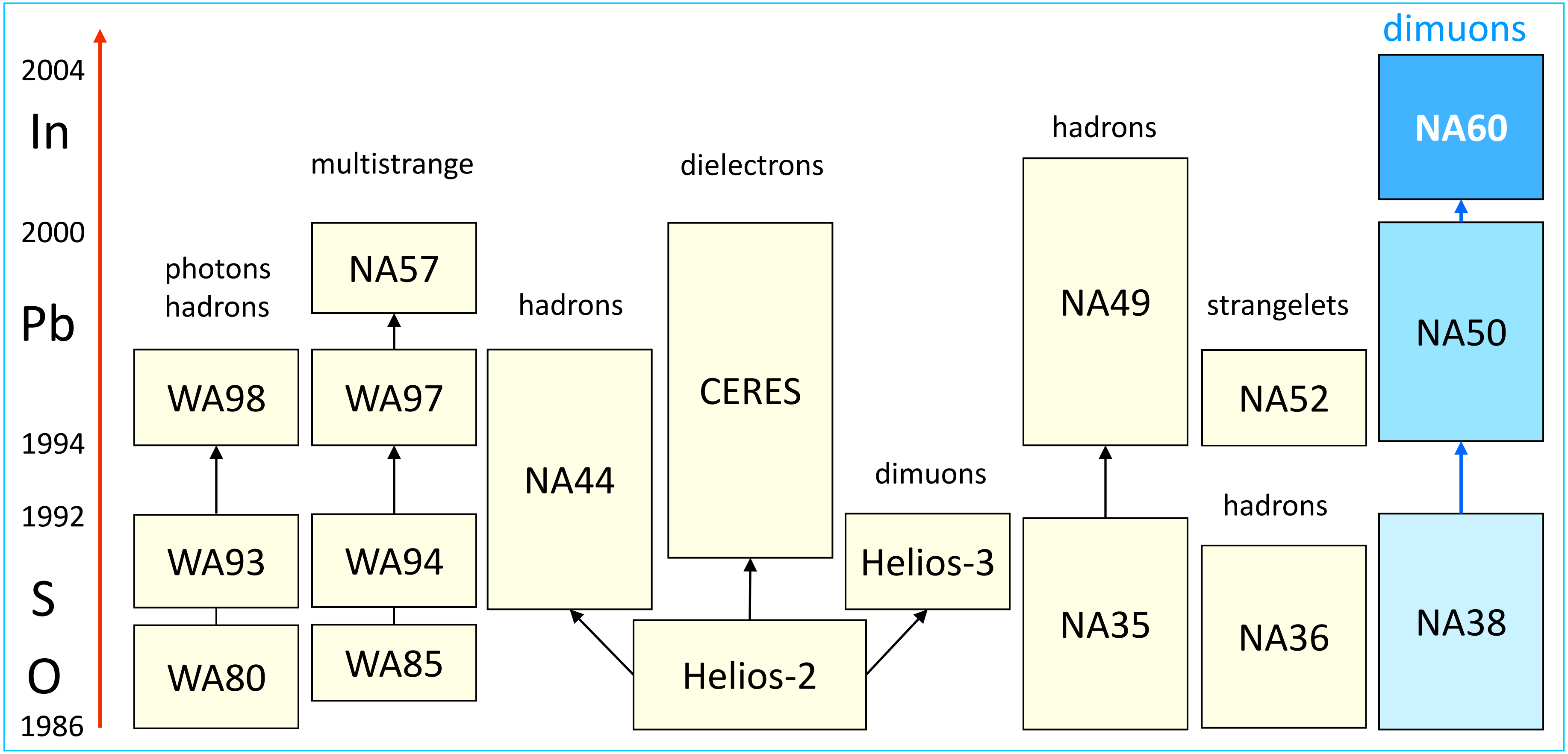
- **SPS** : 1986 - 2003
- O, S and Pb beams ; up to 200 A GeV
- hadrons, photons and dileptons

- **LHC** : 2008 - ?
- Pb beams ; up to √s = 5.5 TeV
- ALICE, CMS and ATLAS

The CERN SPS heavy ion physics program

Since 1986, many SPS experiments studied high-energy nuclear collisions to probe high density QCD matter

- 1986 : Oxygen at 60 and 200 GeV/nucleon
- 1987 – 1992 : Sulphur at 200 GeV/nucleon
- 1994 – 2002 : Lead from 20 to 158 GeV/nucleon
- 2003 : Indium at 158 GeV/nucleon
- and p-A collisions: reference baseline



Some QGP Diagnostics

	Why	What
Global Observables	Is initial state dense enough?	• Particle Multiplicities • Energy Density
Collective Behaviour	Is QGP a thermalized state?	• Hadron Yields • Elliptic Flow
Hard Probes	Formed early, probe medium	• Energy loss of jets • Charm production

Heavy-Ion Colliders

Facility	Location	System	Energy (CMS)
AGS	BNL, New York	Au+Au	2.6-4.3 GeV
SPS	CERN, Geneva	Pb+Pb	8.6-17.2 GeV
RHIC	**BNL, New York**	**Au+Au**	**200 GeV**
LHC	CERN, Geneva	Pb+Pb	5.5 TeV

3 orders of magnitude! (by 2009)

However, RHIC data only makes sense in context:

Facility	Location	System	Energy (CMS)
ISR	CERN	p+p	24-63 GeV
SPS	CERN	p+A	20 GeV
Tevatron	FNAL	p+A	13-38 GeV
LEP/LEP2	CERN	e+ + e-	91-210 GeV
UA1/UA5	CERN	pbar+p	200-900 GeV
Tevatron	FNAL	pbar+p	630-1800 GeV

We want to understand strong interactions in all forms

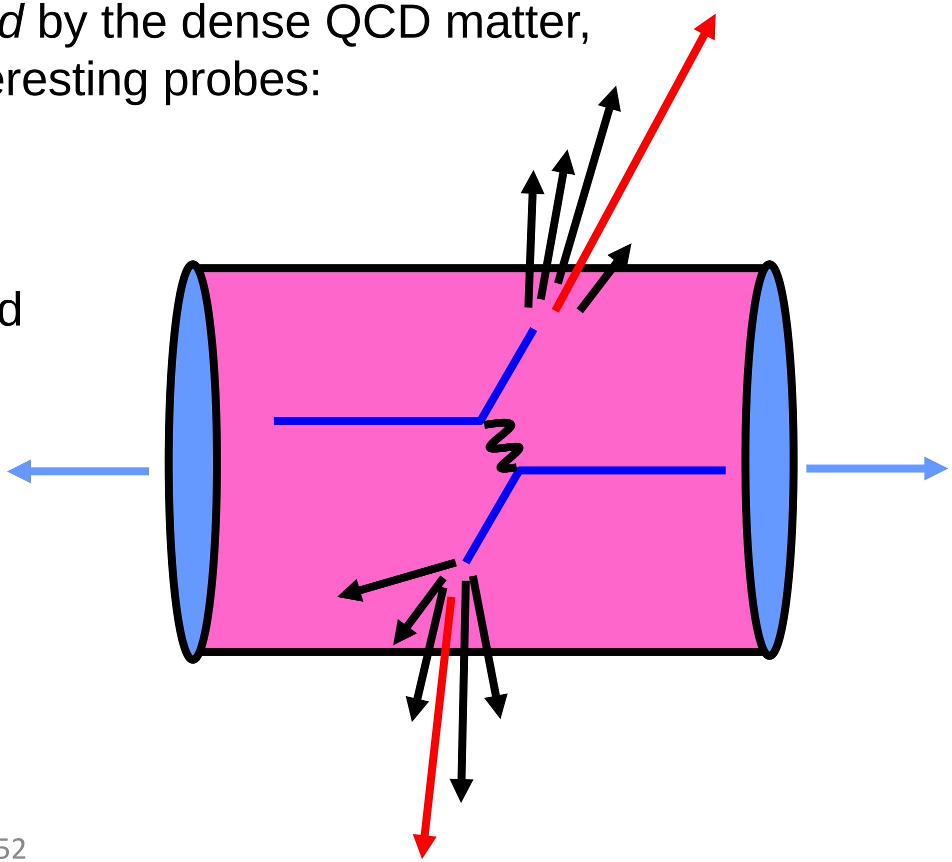
Challenge: creating and calibrating the probes

The “probes” must be *produced* together with the system they probe!

They must be created very early in the collision evolution, so that they are there before the matter to be probed (the QGP) is formed:
hard probes (jets, quarkonia, ...)

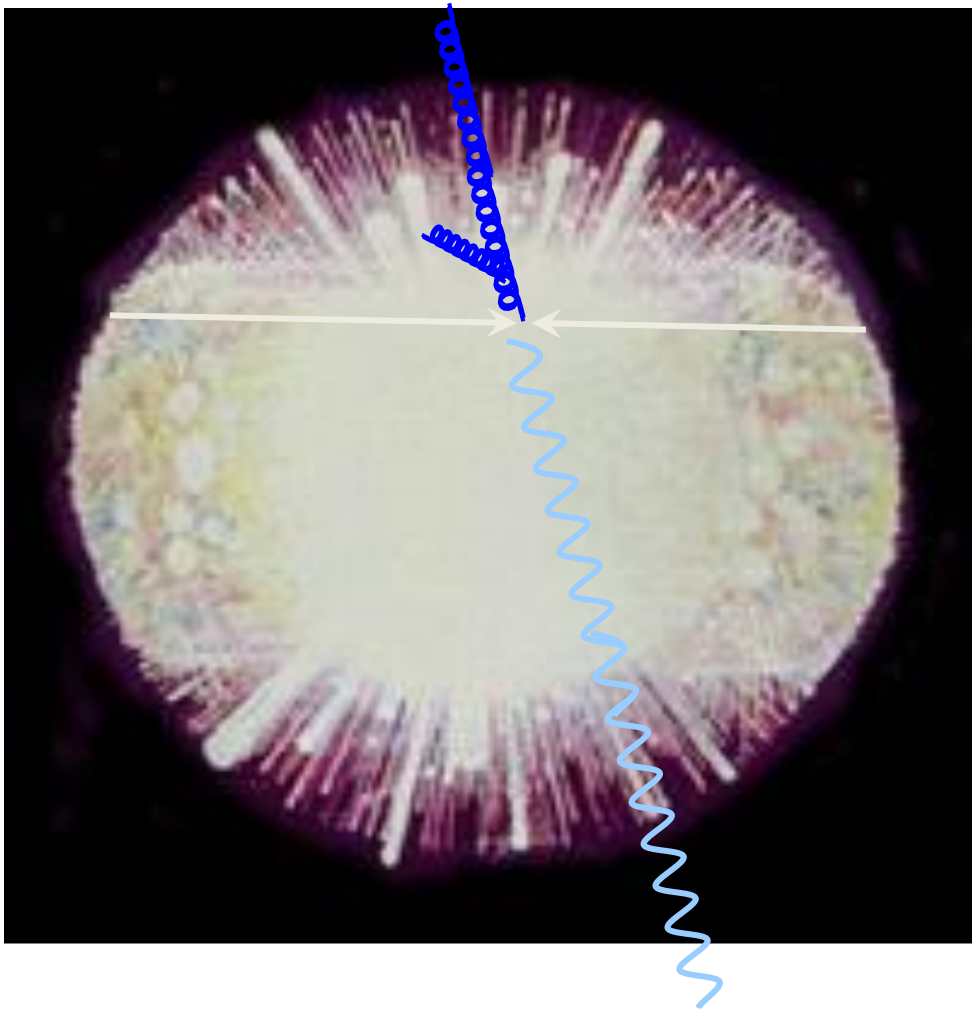
We must have “trivial” probes, *not affected* by the dense QCD matter, to serve as baseline reference for the interesting probes:
photons, Drell-Yan dimuons

We must have “trivial” collision systems, to understand how the probes are affected in the *absence* of “new physics”:
pp, p-nucleus, d-Au, light ions



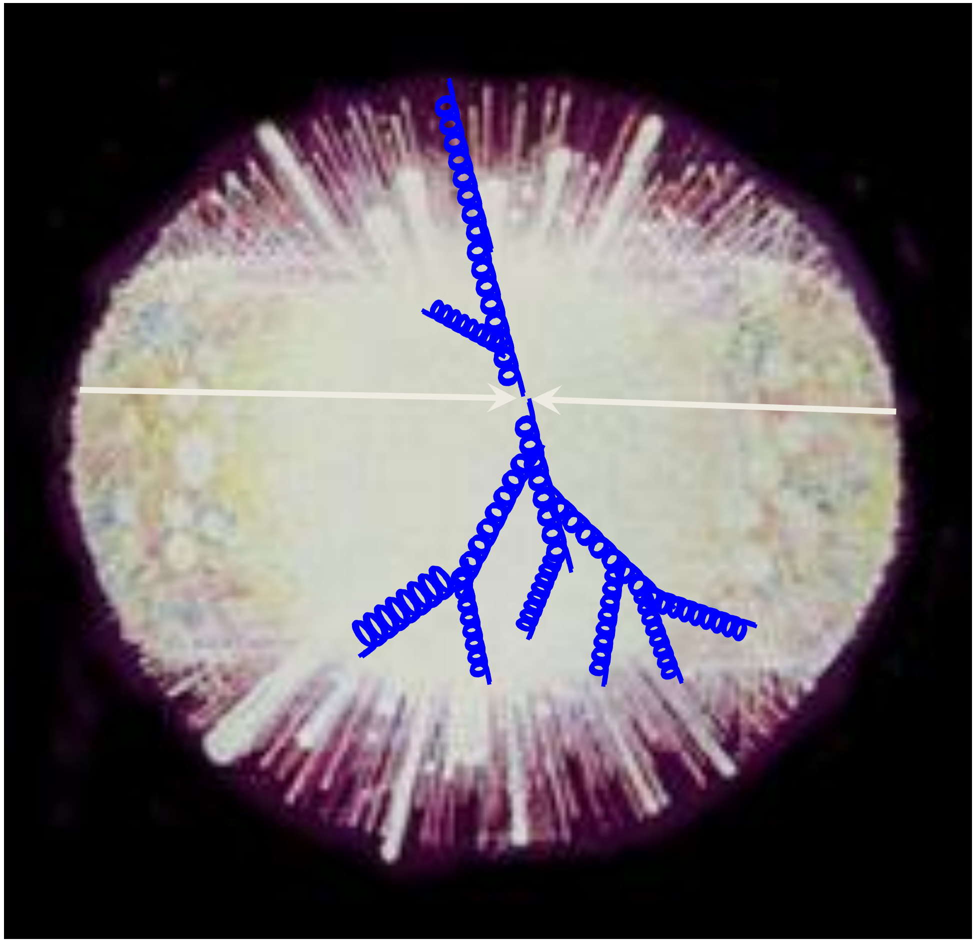
The photons shine through the dense QCD matter

High energy photons created in the collision are expected to traverse the hot and dense QCD plasma without stopping

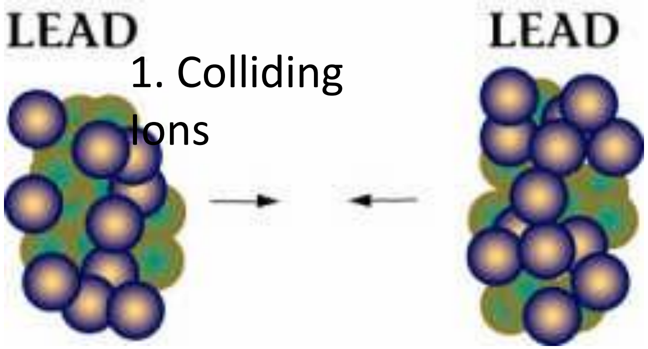


The quarks and gluons get stuck

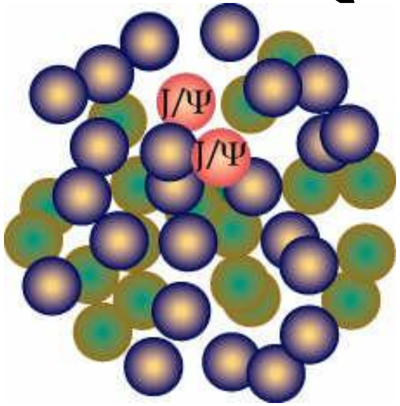
High energy quarks and gluons created in the collision are expected to be absorbed while trying to escape through the deconfined QCD matter



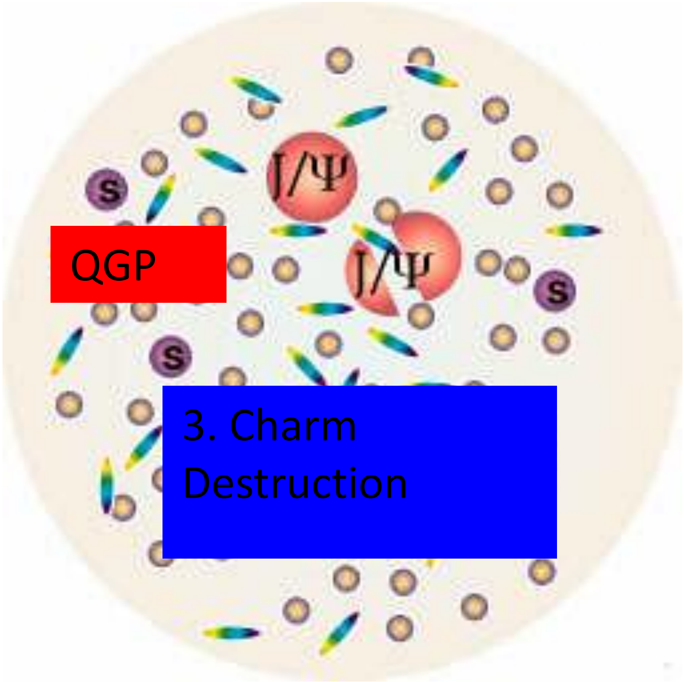
J/Ψ Suppression in a QGP



1. Colliding Ions

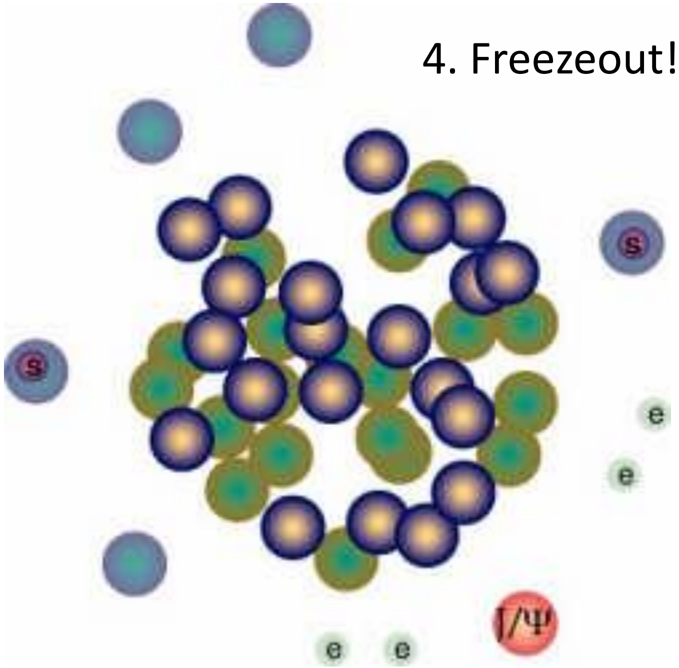


2. Charm Production



QGP

3. Charm Destruction



4. Freezeout!

Quarkonia, heavy ions and the QGP?

History:

- J/ψ suppression as a QGP signature (1986, Matsui and Satz- Phys. Lett. B178 (4): 416)

- NA38, NA50, NA60 @ SPS
- PHENIX, STAR @ RHIC

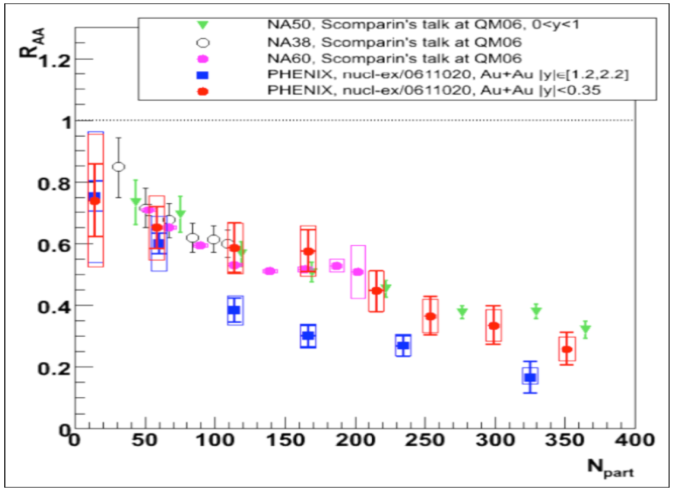
Left open questions:

- similar suppression @ RHIC & SPS
- larger suppression at larger rapidity
- cold nuclear matter effect - still weakly constrained
- statistical hadronization, recombination?

⇒that could be answered by the LHC

enhanced J/ψ production yields @ LHC (Thews et al. Phy. Rev. C 63(5):054905 (2001))?

machine	SPS	RHIC
$\sqrt{s_N}$ (GeV)	17	200



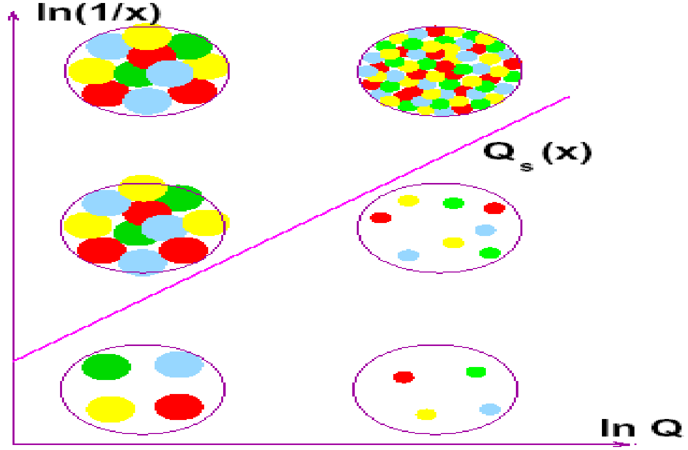
Goals of the Field

Matter under extreme Temperature & density

- QGP:
  - Does QCD become simpler at high T, high density?
  - What is the phase diagram of QCD?
  - Do the lattice predictions agree with nature?
- Strongly-interacting systems
  - Can we understand the evolution of a system of two colliding nuclei?
  - Can we understand the early phase of a system by observing the late phase?

When does saturation set in?

- **The Colour Glass Condensate (CGC)**
  - Colour –because partons (gluons in particular) are coloured.
  - Glass –disordered system; gluon distributions frozen on timescale of collision.
  - Condensate –high phase-space occupancies



The kinematical range accessible

Small x

higher initial parton density

qualitatively different matter produced at LHC mid-rapidity?

tests of saturation phenomena?

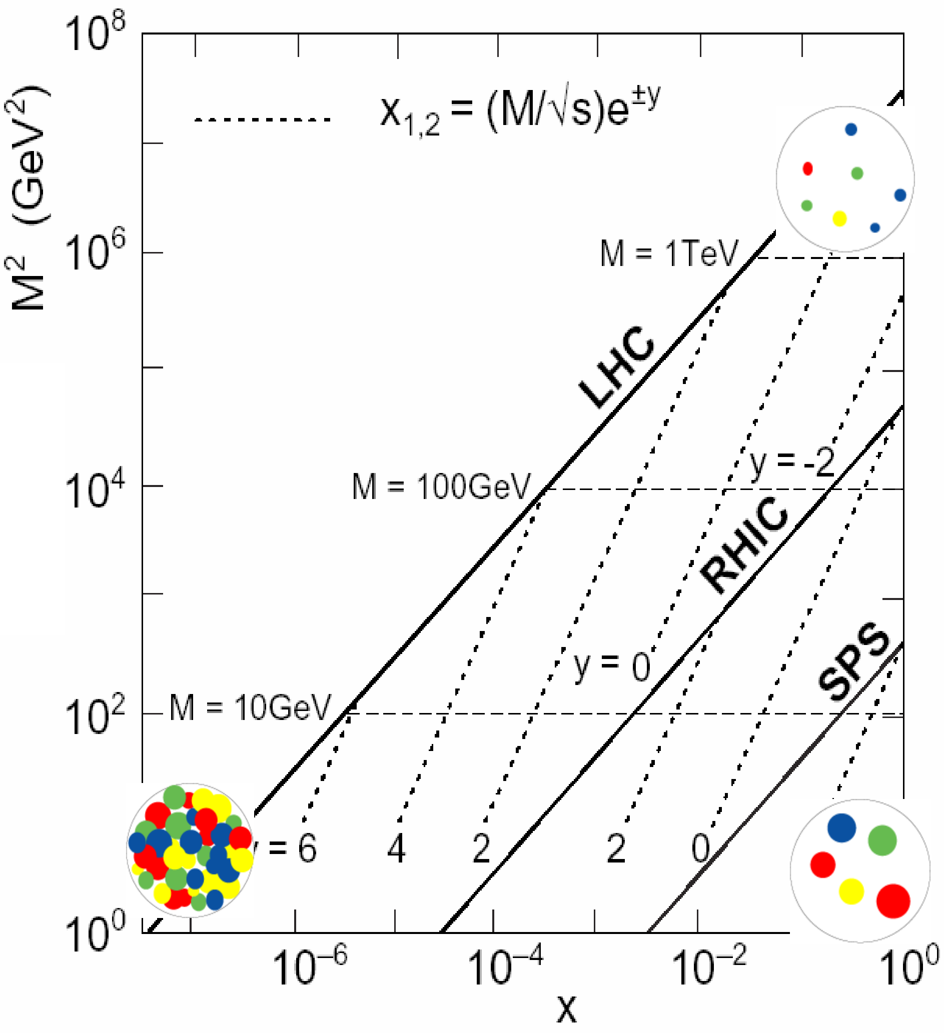
- bulk observables
- pt-spectra in scaling regime
- rapidity vs. $\sqrt{s_{NN}}$ dependence
- …

Large Q^2

abundant yield of hard probes

precise tests of properties of produced matter

- color field strength
- collective flow
- viscosity
- …



Intermission

End of Part I