The Origin of the Visible Mass in the Universe

Or: Why the Vacuum is not Empty

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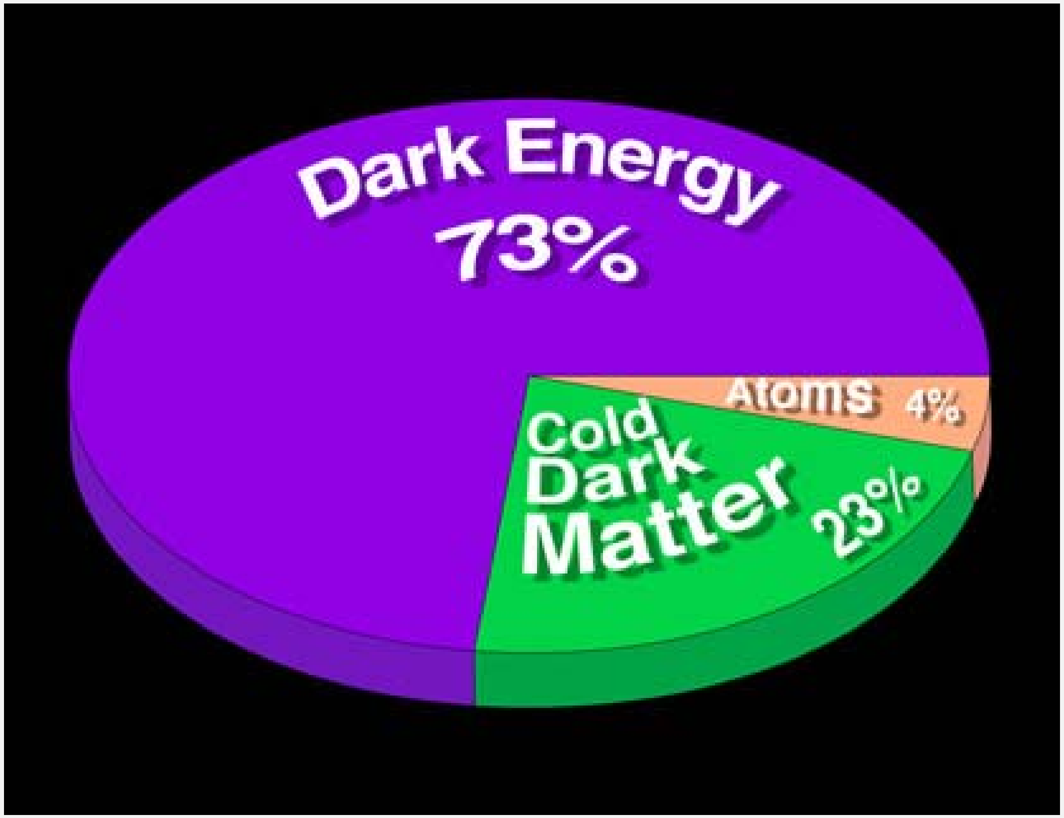
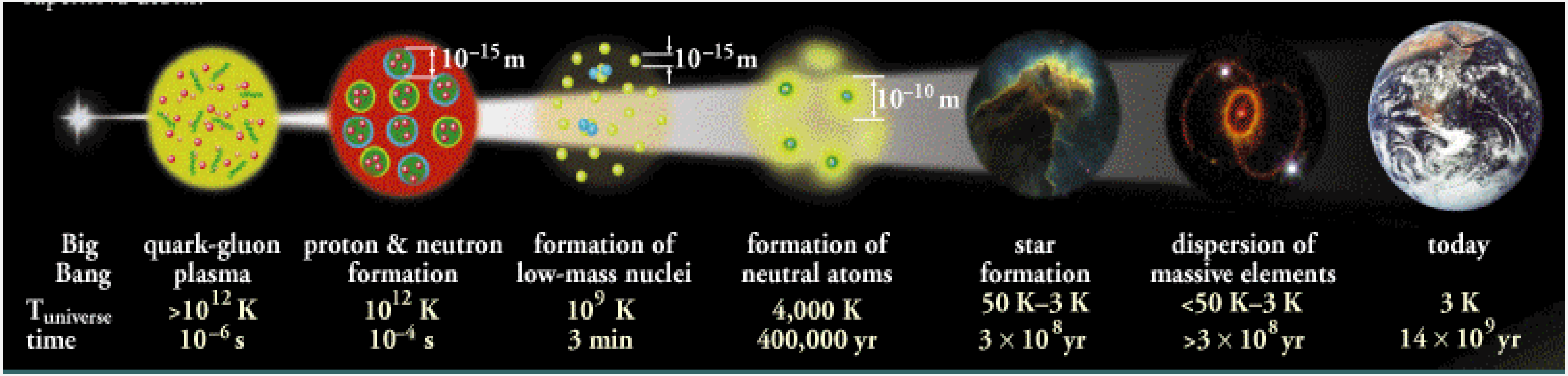
The Cosmic Pie of Matter and Energy



- Expanding Universe
  ↔ Dark Energy
  not at all understood!
- Star / Galaxy Motion
  ↔ Dark Matter
  New Particles?
- Mass of Visible Matter
  ↔ Weight / Inertia
  A Dense Vacuum?

Nuclear Physics and the Universe



- **Quark-Gluon Plasma: T>200MeV (<0.000001 sec.)**
- **Phase transition to Hadronic Matter (Mass Generation, Quark Confinement), T≈170MeV (0.00001 sec.)**
- **Low-mass nuclei: H (p), d (pn), ^{3}He, ^{4}He, ^{7}Li (3 min.)**
- **Heavy elements in star collapses: supernovae (still today)**
- **Exotic forms of (quark) matter in neutron stars (still today)**

Outline

1.) The Atom and the Micro-Cosmos

- Which Particles are Elementary?
- What is the World Made of?

2.) Elementary Particles and Their Interactions

- ”Matter Particles” vs. “Force Carriers”
- Fermions vs. Bosons

3.) The Strong Interactions: Quarks and Gluons

- The World of Hadrons
- 2 Puzzles: Quark Confinement and Quark Masses
- The Non-Emptiness of the Vacuum

4.) Heavy-Ion Collisions and Quark-Gluon Plasma

- ”Evaporating” the Vacuum
- Dissolving Mass into Energy

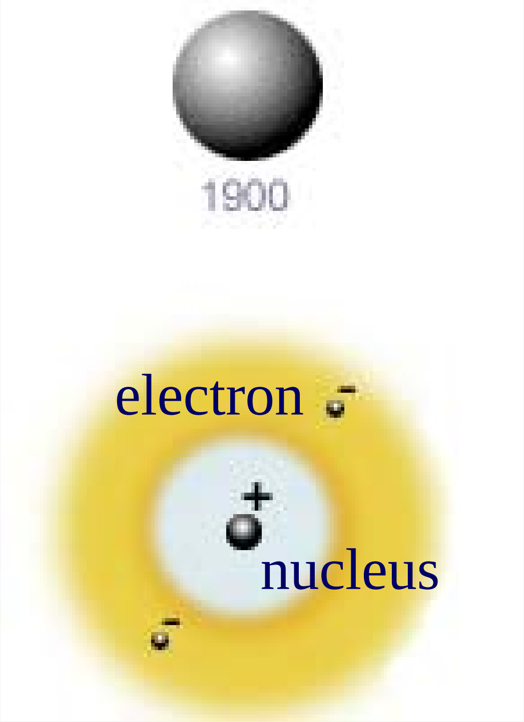
5.) Summary

1.) The Atom and the Micro-Cosmos:

Which Particles are Elementary?

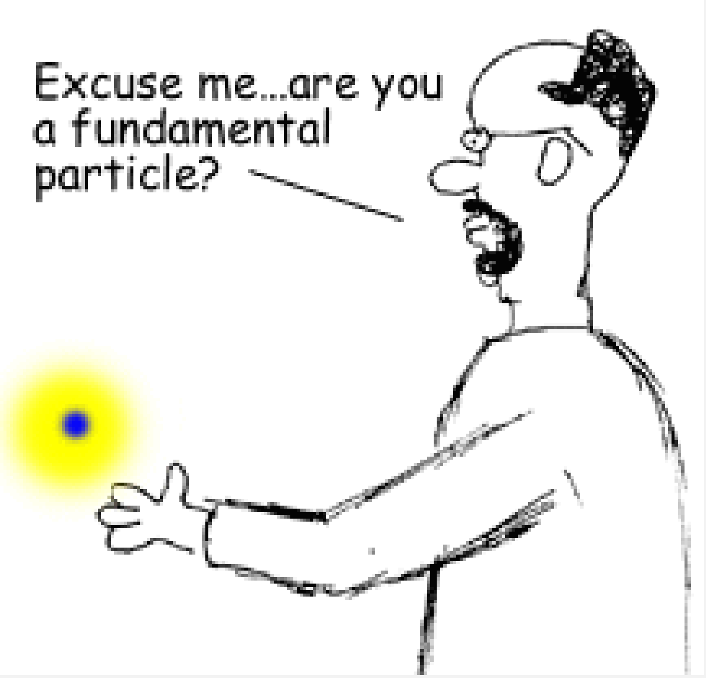
- Scientists (Philosophers) have always been wondering:
  What happens if one keeps dividing matter?
- Notion of the "**atom**" (**ατομοσ** = greek for "indivisible")

But:



Rutherford (1911):

- most of the atom is "empty space"
- mass is concentrated in the atomic **nucleus**

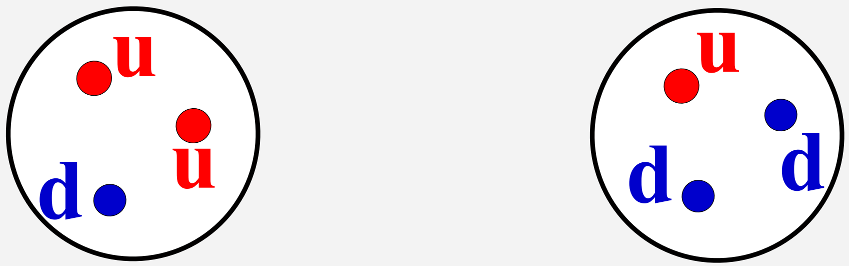


⇒ **subatomic particles**

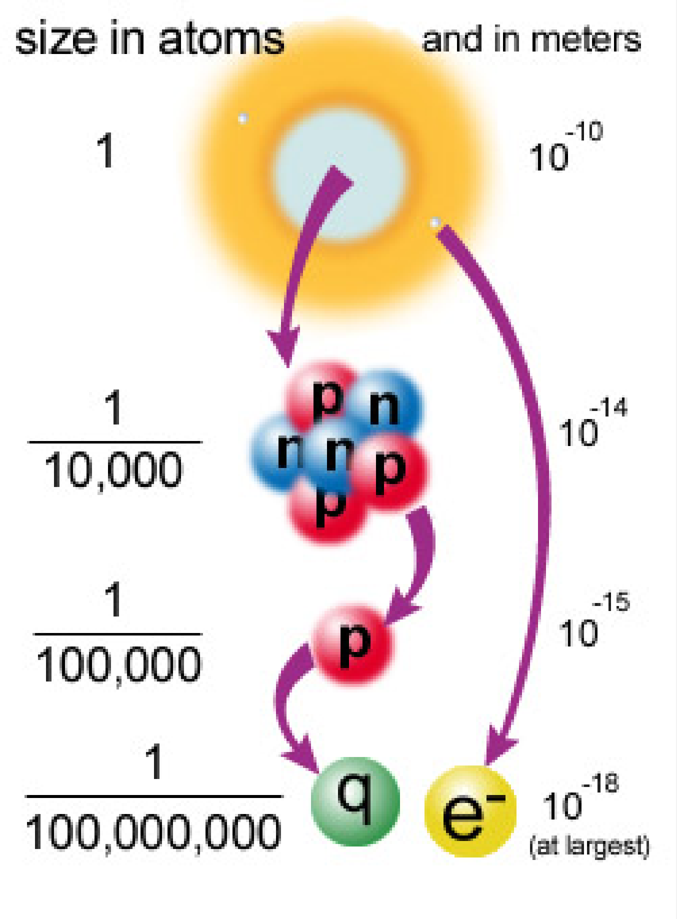
1.2 The Atom and the Micro-Cosmos:

What is the World Made of?

- electrons are elementary (as far as we know), atomic **nucleus** is **NOT**
- nuclei are composed of **nucleons** = protons and neutrons
- each nucleon is made of **3 quarks**:



proton^{+} = (uud) **neutron^{0} = (udd)**



up-quark: charge $+2/3$, mass m_u=3MeV/c^2

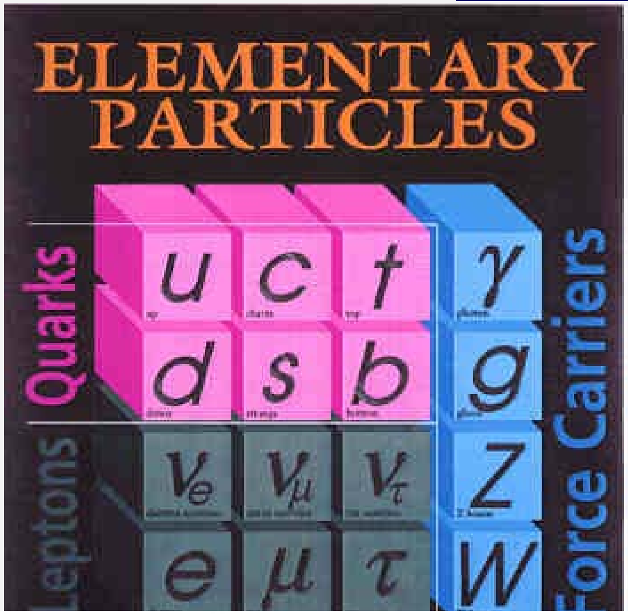
down-quark: $-1/3$, m_d=6MeV/c^2

electron : **-1** , m_e=0.5MeV/c^2

But: nucleon mass $m_p = m_n$=940MeV/c^2

2.) Elementary Particles and Interactions

What holds Matter together?

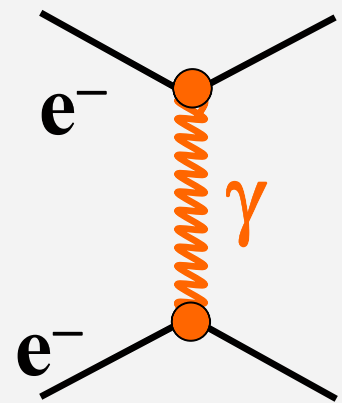


- in addition to stable matter (**u , d , e$^-$, ν_e**)
  2 more "generations" of elementary particles
  (**quarks** + **leptons**):
  charm + **strange** quark, **muon + neutrino**
  top + **bottom** quark, **tau + neutrino**

Force Carriers and Strength

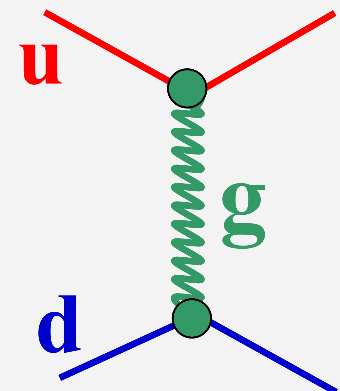
	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W$^+$ W$^-$ Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W$^+$ W$^-$	Quarks and Gluons

elec-mg.



α_{em}=0.01

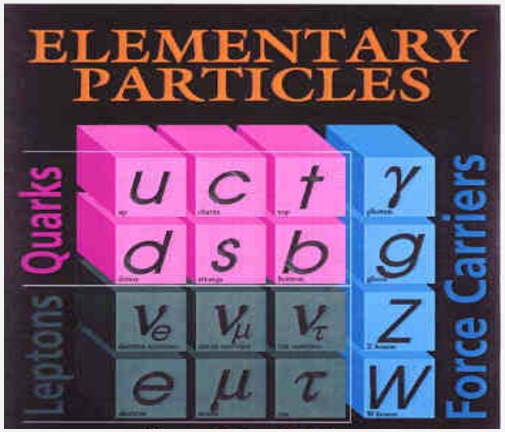
strong



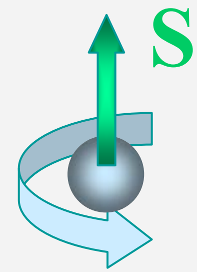
α_S=1

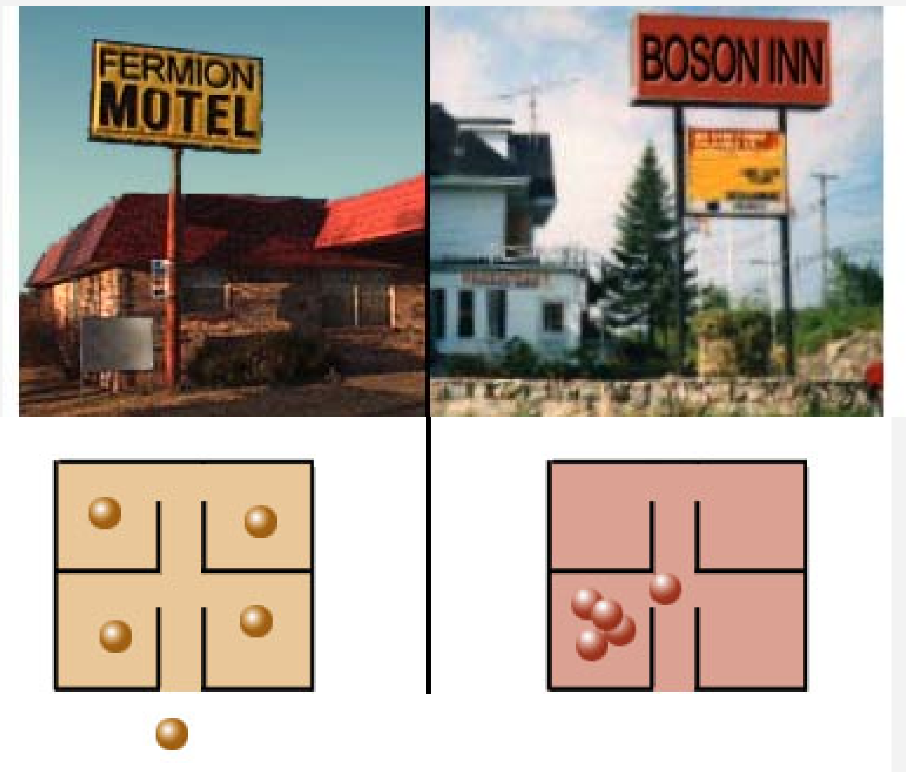
2.2 Elementary Particles and Interactions

The Nature of Matter vs. Force Particles



- Elementary **Matter** Particles (quarks+leptons): spin **S=½** **"Fermions"** (half-integer **S**)
- Elementary **Force** Particles (**g**, **γ**, **W±**, **Z**): spin **S=1** **"Bosons"** (integer **S=0,1,2,…**)

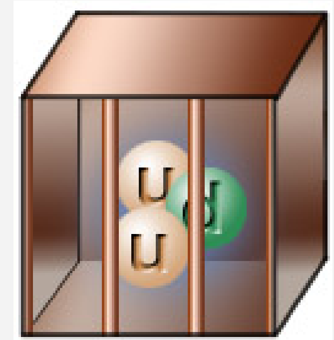




- **Fermion Motel:** only one identical fermion per room! (**Pauli Exclusion Principle**) ⇒ electronic shell structure of atoms
- **Boson Inn:** identical bosons per room preferred! (**Bose-Einstein Condensation**)

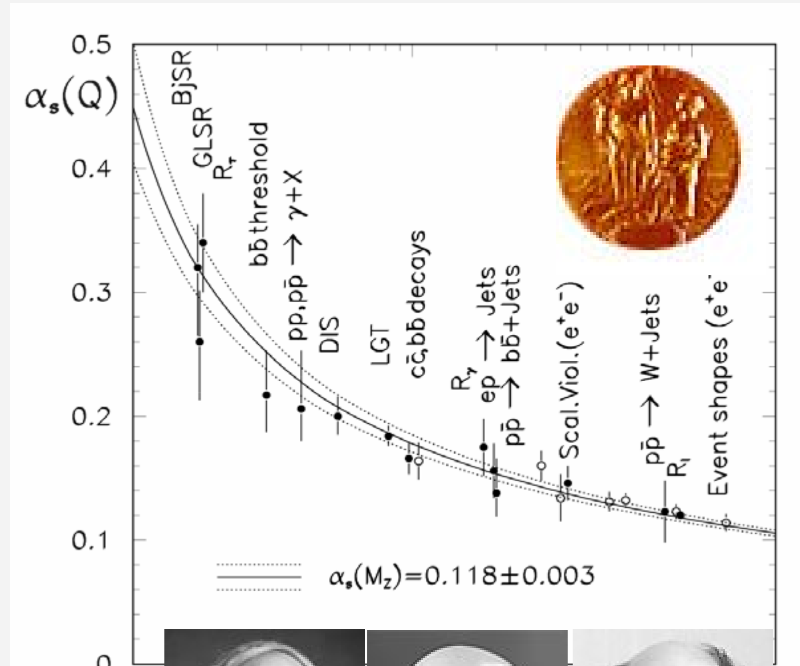
3.) The Strong Force: Quarks + Gluons

The Confinement of Quarks



- In Nature, quarks have never been observed in isolation: "**Confinement**"
- Quarks "glued" together by gluons ("rubber" band)
  → the interaction strength (charge) increases with distance!!

$F_s(r) = const$



- theoretically not yet understood
  (recall electric force: $F_e(r) = \alpha_{em}/r^2$)

- "**asymptotic freedom**" at small distances explained → Nobel Prize in Physics 2004

  [Gross, Politzer and Wilczek]

0.

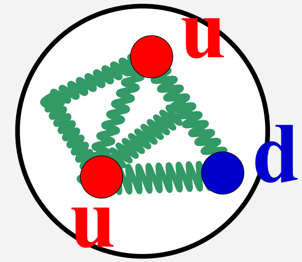
n]

3.2 The Strong Force: The World of Hadrons

- Quarks only appear as composites = hadrons
- two types of hadrons:
  - baryons: bound states of 3 quarks (fermions!)

    e.g.: **S=1/2**: **p**=(**uud**), Λ=(**uds**), …

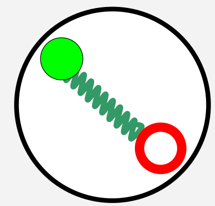
    S=3/2: Δ^{++}=(**uuu**) , Ω^{-}=(**sss**), …



  - mesons: quark-antiquark composites (bosons!)

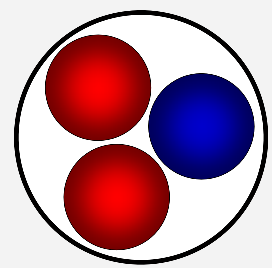
    e.g.: **S=0**: π^{+} =($u\bar{d}$), π^{0}=($u\bar{u}$,$d\bar{d}$), **K**$^{-}$=($s\bar{u}$), …

    S=1: ρ^{+} =($u\bar{d}$), ρ^{0} =($u\bar{u}$,$d\bar{d}$), ρ^{-} =($u\bar{d}$), , …



Puzzle: Why are hadrons so much heavier than quarks?

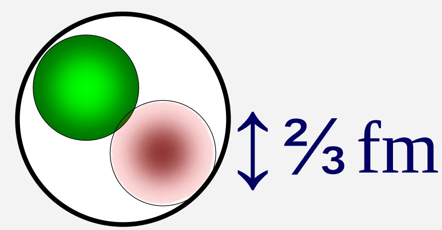
(proton-mass = **940MeV/c²** >> **3m$_q$ = 15MeV/c²**)



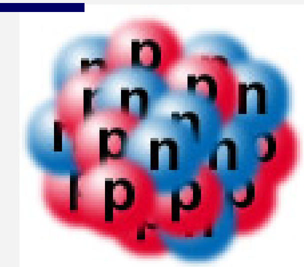
Preliminary answer:

hadronic building blocks are "**constituent quarks**"

= extended objects with mass **M$_q$~350MeV/c²**



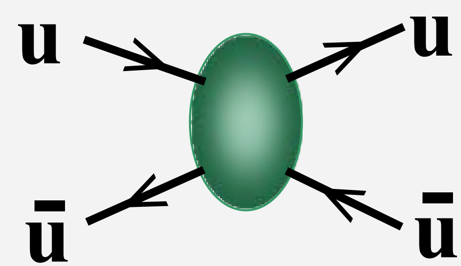
3.3 Strong Force: Mass Generation



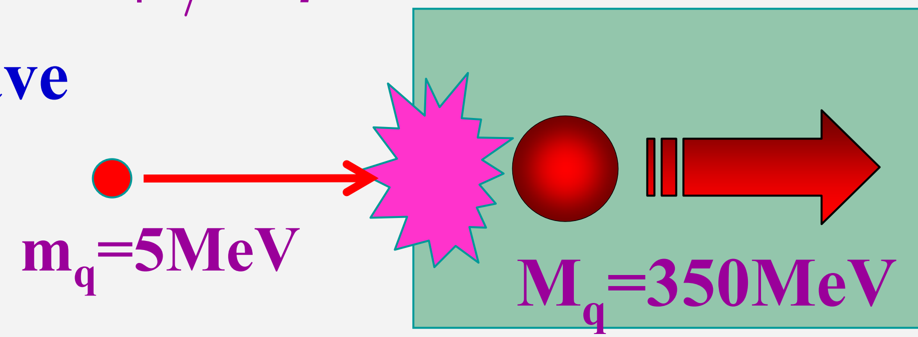
- The **real question**: how to quarks become so massive?
  (note: this is asking for **>98%** of the **mass of all visible matter** – a very fundamental question!!)

^{208}**Pb=624 quarks**

Our current best (most likely) answer:



- **strong quark-antiquark** attraction **(many gluons)**
- **Bose-condensation** of **($q\bar{q}$)** pairs
- dense **"liquid"** fills the **vacuum**! $\langle 0|\bar{d}d+\bar{u}u|0\rangle \approx 5\, fm^{-3}$
- **quarks moving through the liquid have large mass** (~⅓ of the proton mass) !!

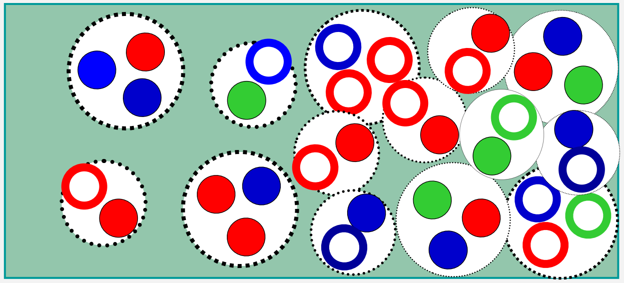


⇒ our mass is due to a (very) dense vacuum!!
Can we test this? E.g. evaporate the vacuum??

4.) Heavy-Ion Collisions and Quark-Gluon Plasma

Strongly Interacting Matter: From Nuclei to QGP

Heat and evaporate the Vacuum!

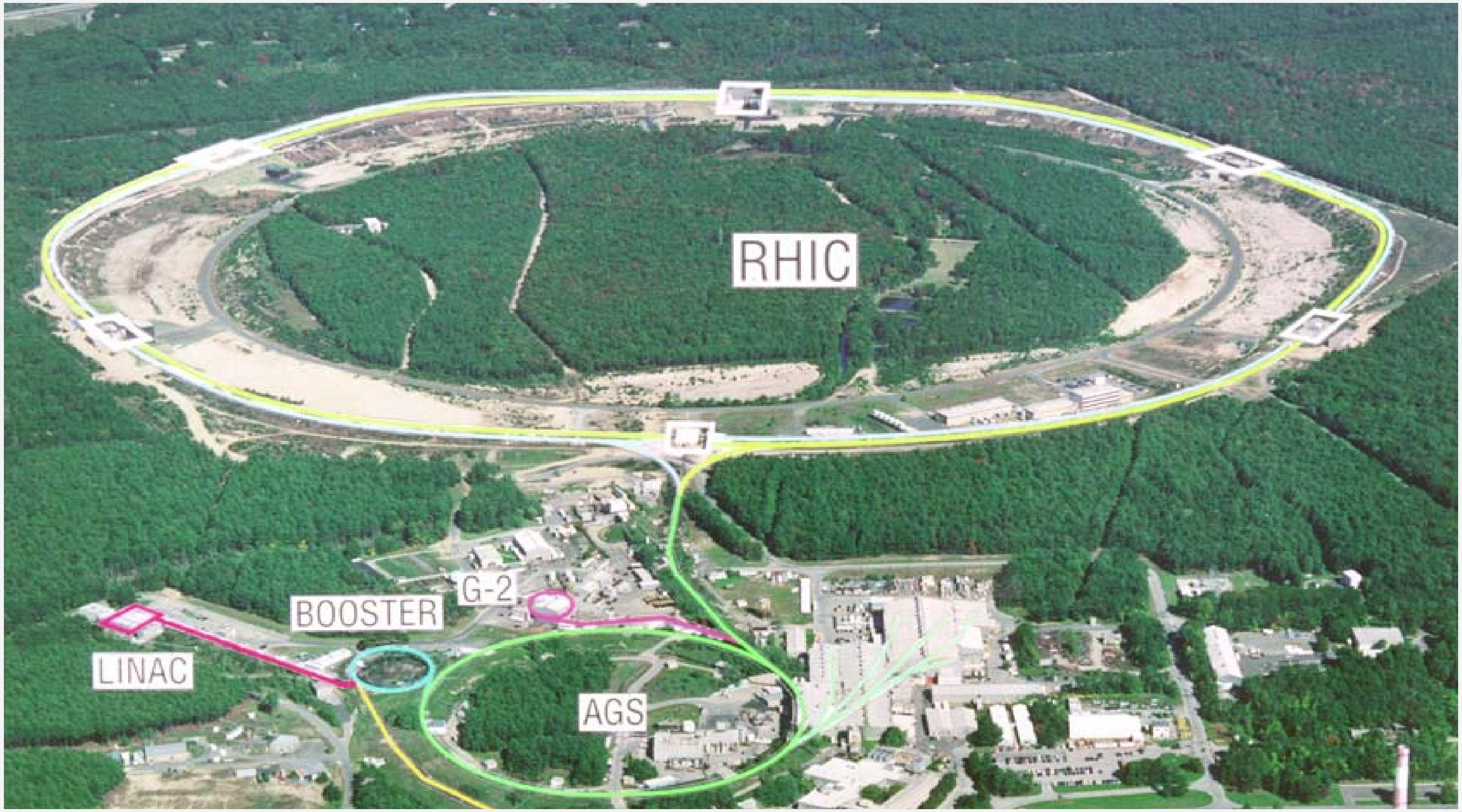


Nuclear Matter dissolves into the **Quark-Gluon Plasma (QGP):**

- hadrons overlap, quarks are liberated ⇒ **Deconfinement!!**
- $\langle\bar{q}q\rangle$ condensate "evaporates", $M_q \rightarrow m_q$ ⇒ **Mass dissolves!!**
- required temperature is **~200MeV ≈ $4 \cdot 10^{12}$ °F**
- **100,000** times hotter than inside the sun!!
- early universe ~**0.000001 sec** after the Big Bang!!

How do we pump this enormous amount of energy into the vacuum??

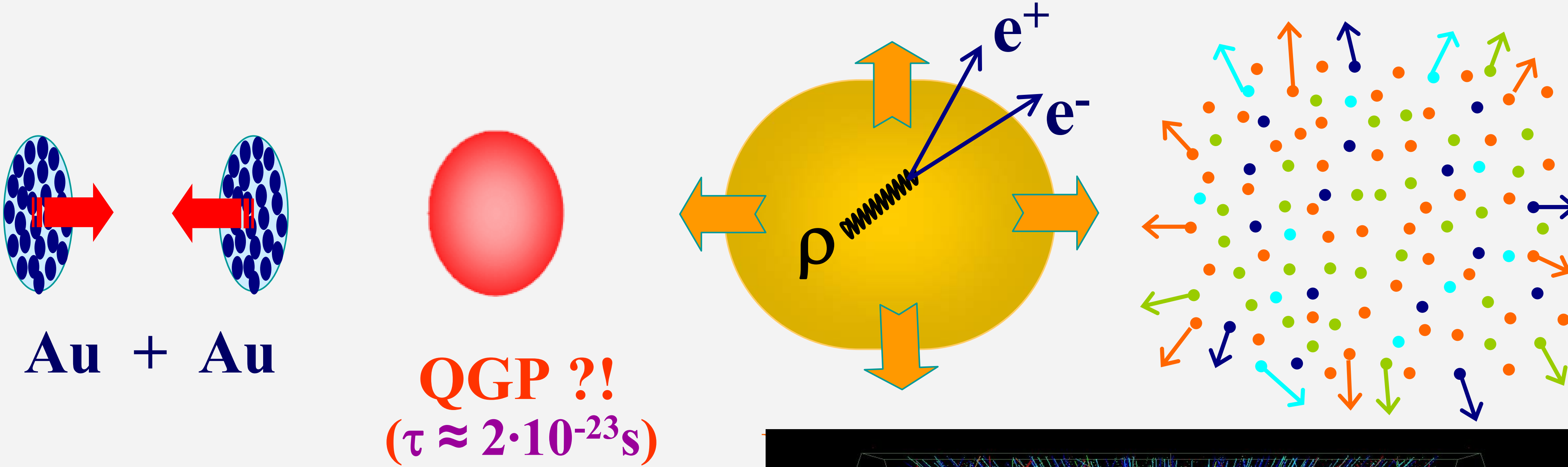
Answer: The Relativistic Heavy-Ion Collider!!

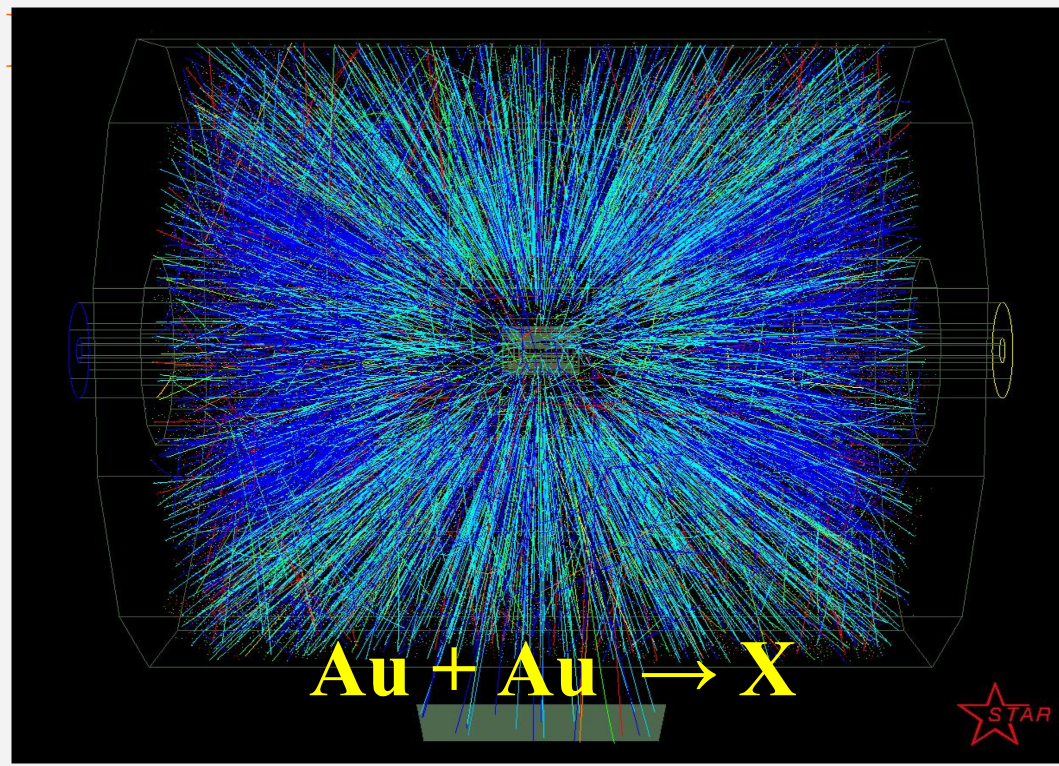


Accelerate Gold-Nuclei to 200GeV/nucleon and collide them!

(even more powerful accelerator (LHC) to start soon at the European Center for Nuclear Research (CERN) in Geneva)

4.2 Recreating the “Little Bang” in the Laboratory





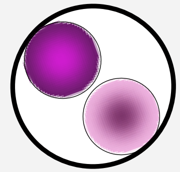
How to look for particles inside the matter?

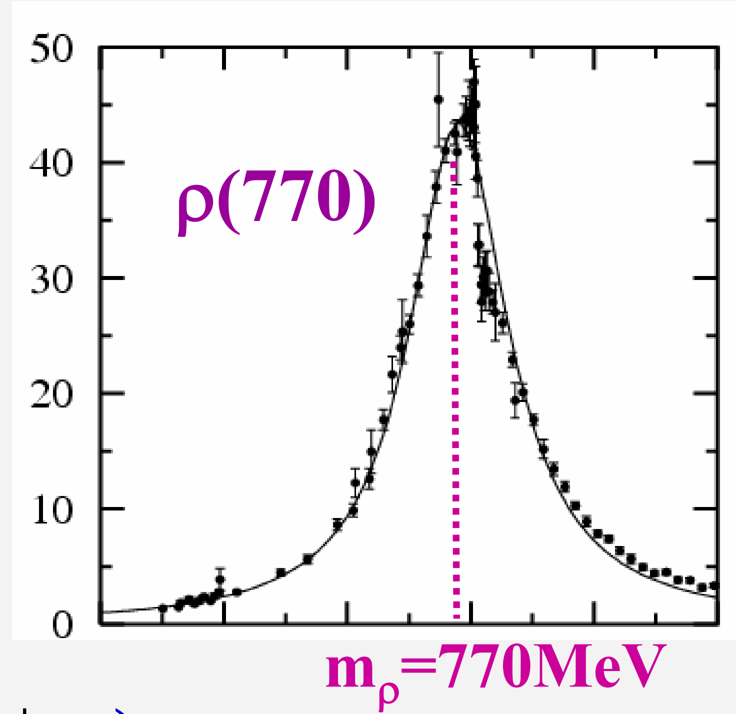
Watch out for electron-positron decays of the ρ(770)-meson!

4.3 The ρ-Meson in Vacuum and its Decays

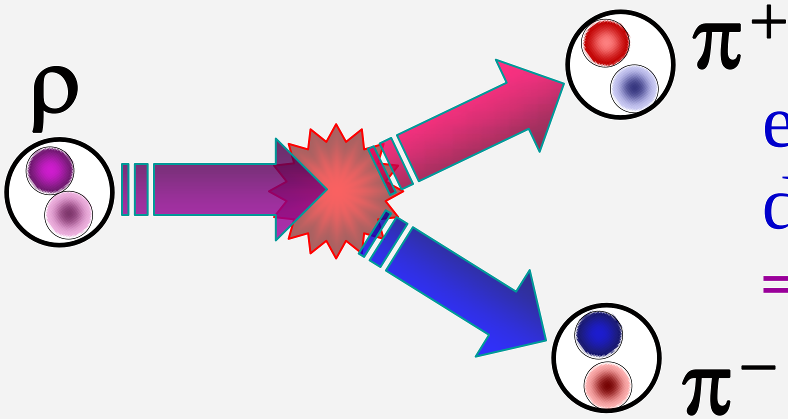
In Vacuum:

- mass of the ρ-meson (= **u$\bar{u}$,d$\bar{d}$**) is well measured, **m_ρ=770MeV** ≈ 2 "constituent quarks":



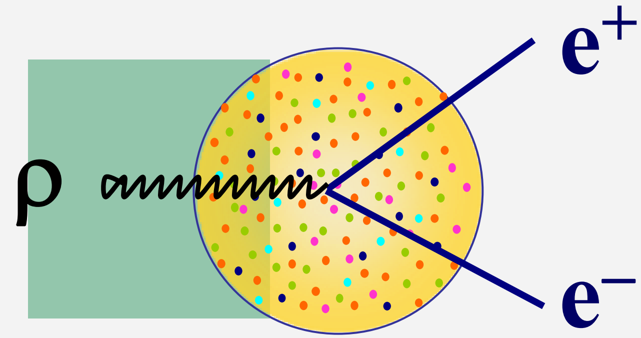


- ρ-meson unstable, lifetime ~ **$4\cdot10^{-24}$sec**



energy of
decay products ($\pi^+\pi^-$)
= mass of the parent particle (ρ)!

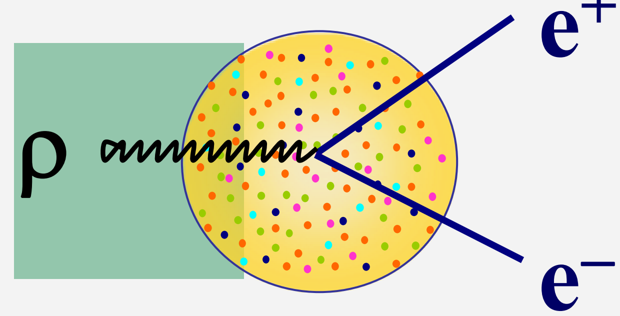
But what happens to the ρ-meson mass in a hot medium (QGP) ??



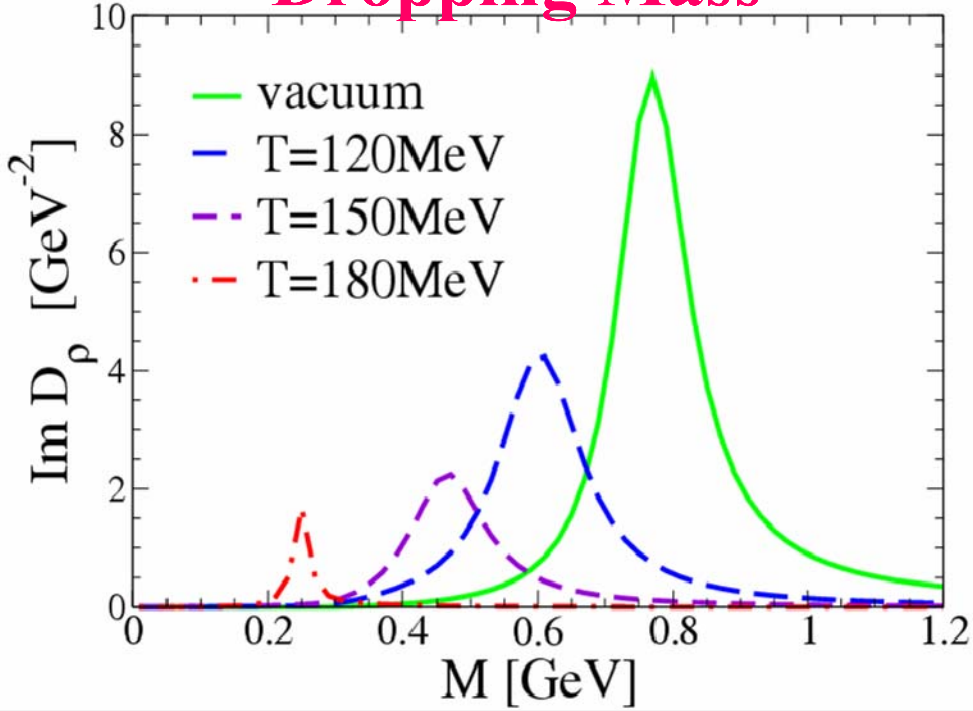
4.4 The ρ-Meson in the Hot Medium

Different theoretical predictions:

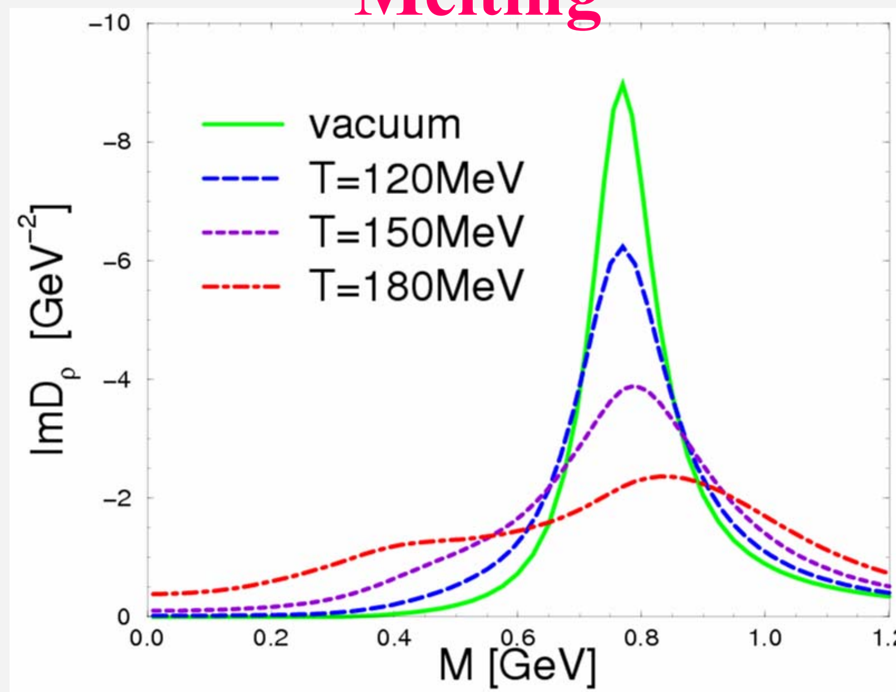
- **m_ρ** "drops" to zero (quarks lose their mass)
- interactions of the ρ within the hot+dense gas: ρ-meson "melts" (broad mass distribution)



"Dropping Mass"

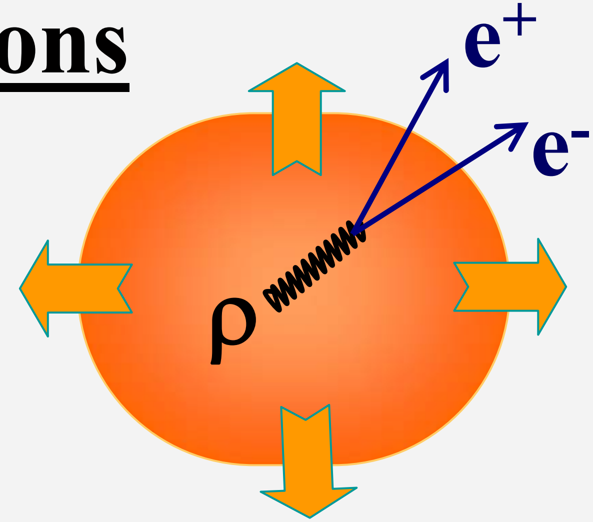


"Melting"



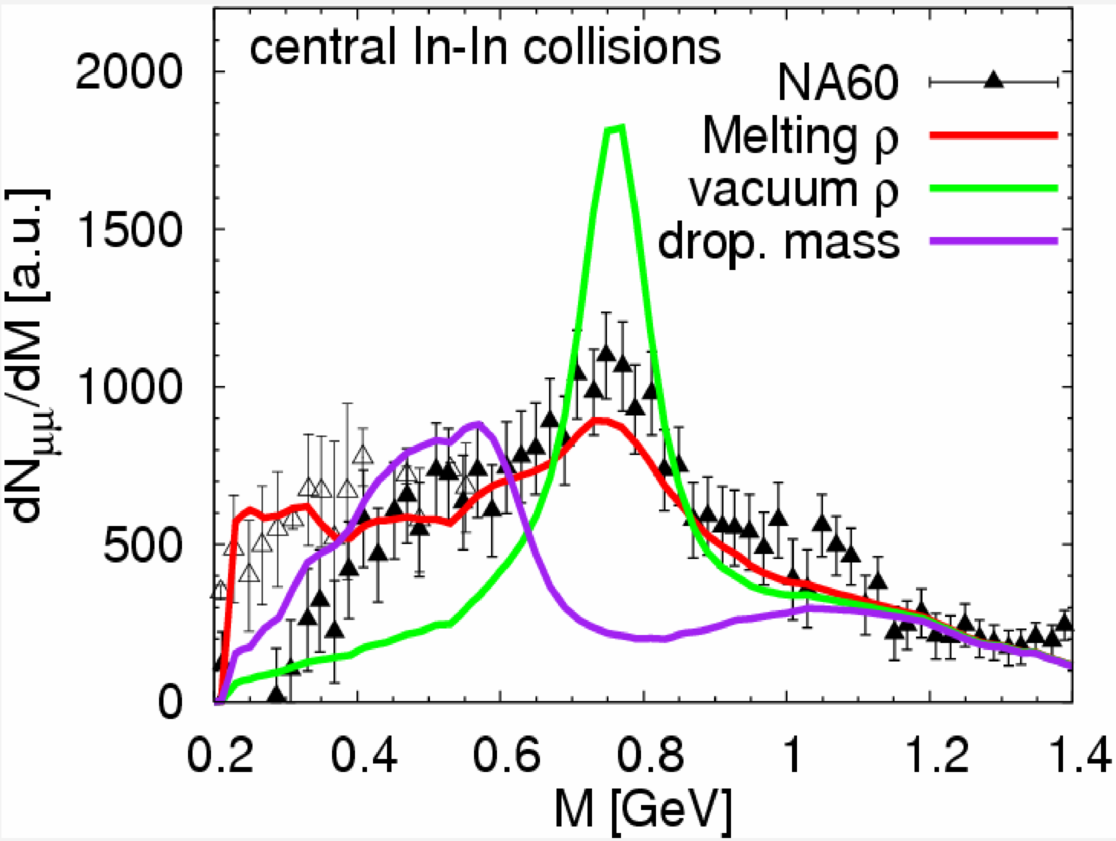
Which scenario is correct? Experiments have to tell us …

4.5 e^+e^- Spectra in Nuclear Collisions



- account for $\rho \to e^+e^-$ decays over the entire "fireball" expansion history

New $\mu^+\mu^-$ Data [NA60 Experiment, CERN]



- **experimental data favor the "Melting" scenario**
- **advanced theoretical investigations required to arrive at definite conclusions (ongoing at Texas A&M)**

We are getting closer to the origin of (visible) mass in the universe!

5.) Summary

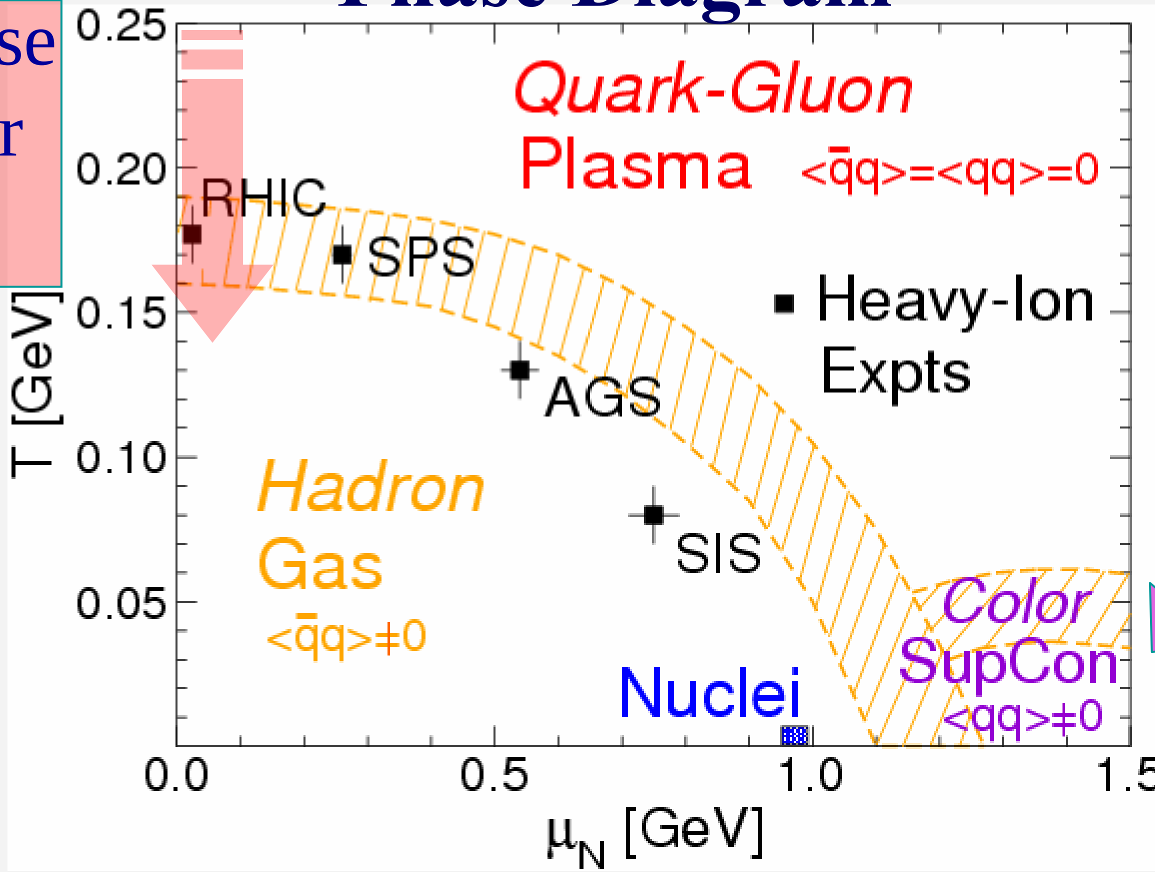
- Atom → Nucleus → Nucleons → Quarks (elementary!)
- Quarks are confined to Hadrons (baryons and mesons)
  - not yet understood!!
- Quarks acquire a large mass within hadrons:
  ↔ the vacuum is a "dense liquid" of ($\bar{q}q$) condensate!!
  ⇒ more than 98% of the visible mass in the universe!!
- Collisions of Heavy Nuclei at High Energies:
  → Heat the vacuum and recreate the early universe:
  - deconfine quarks and gluons
  - evaporate vacuum condensates and dissolve mass into energy!
  - ρ-meson decays to dileptons to investigate the origin of mass

very exciting research ahead …

2.1 Hot+Dense QCD Matter in Nature

Phase Diagram

Early Universe
(few μs after
Big Bang)



Compact
Stellar Objects
(Neutron Stars)

In the laboratory: high-energy collisions of heavy nuclei!

Objective: to create matter at temperatures $T > T_c \approx 170 MeV$

and energy densities $\varepsilon > \varepsilon_c \approx 1 GeV fm^{-3}$