Mass Generation+Melting with the Strong Force

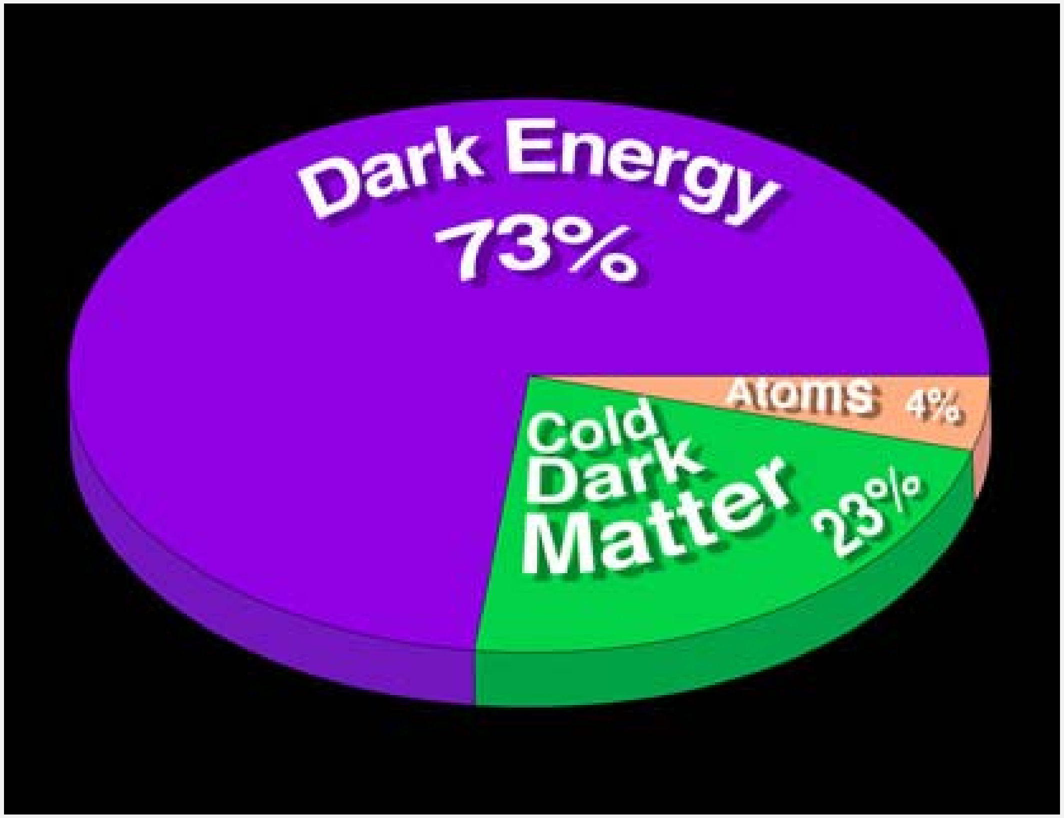
Or: Why the Vacuum is not Empty

Ralf Rapp

Cyclotron Institute +
Dept. of Physics & Astron.
Texas A&M University
College Station, USA

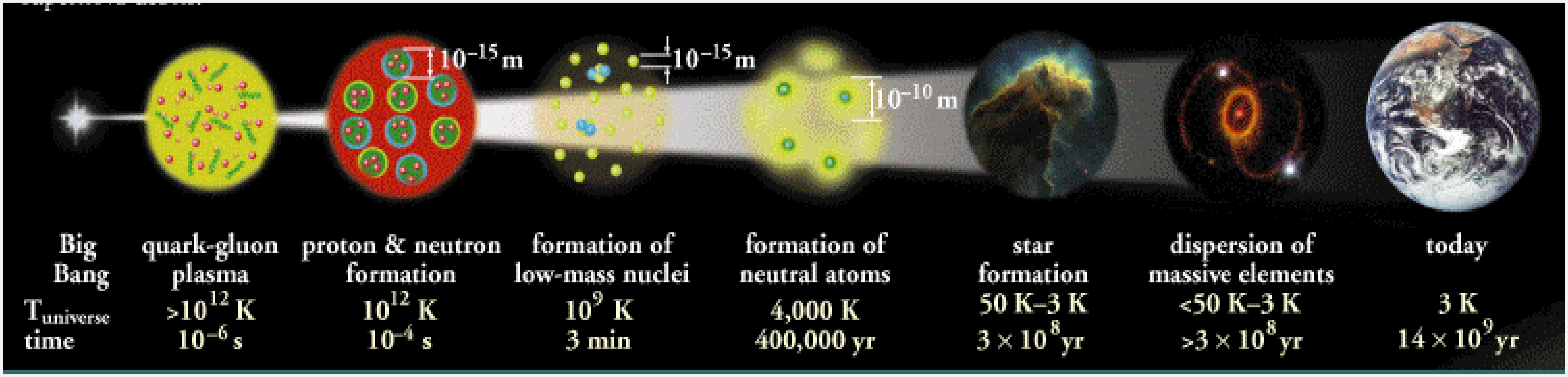
Cyclotron REU Program 2012
Texas A&M University, College Station, 01.08.12

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

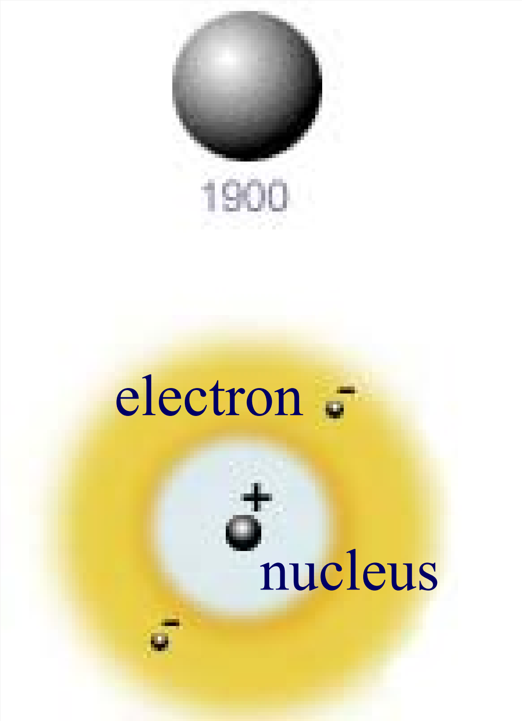
5.) Summary

1.) The Atom and the Micro-Cosmos:

Which Particles are Elementary?

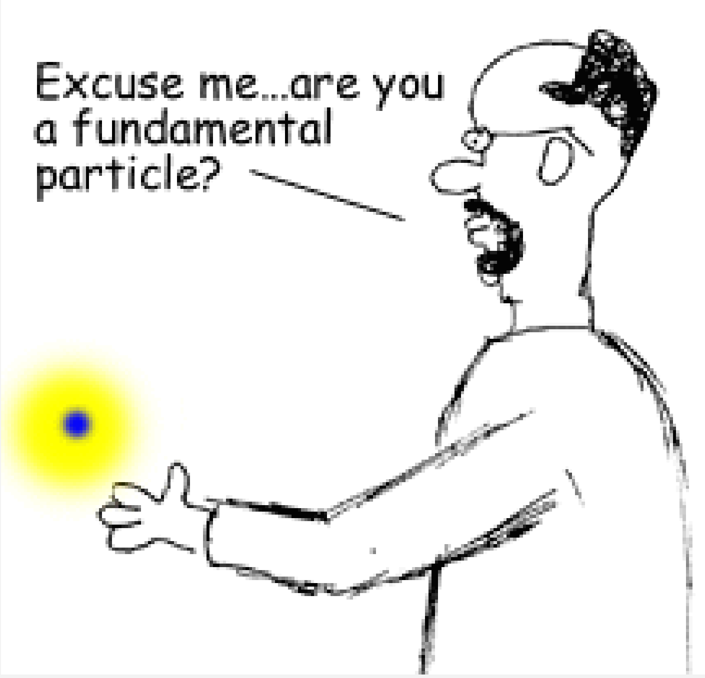
- What happens if one keeps dividing matter?
- Notion of the "**atom**" (ατομοσ = greek for "indivisible")

But:



Rutherford (1911):

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

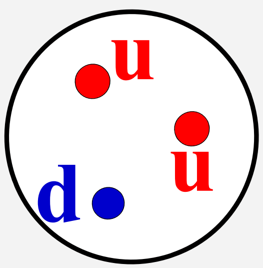


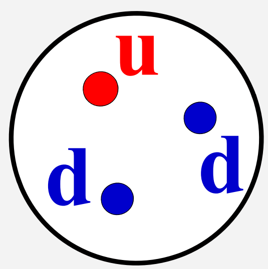
⇒ **subatomic particles**

1.2 The Atom and the Micro-Cosmos:

What is the World Made of?

- electrons elementary, atomic **nucleus** is **NOT**
- nuclei composed of **nucleons** = **p**, **n**
- each nucleon is made of **3 quarks**:



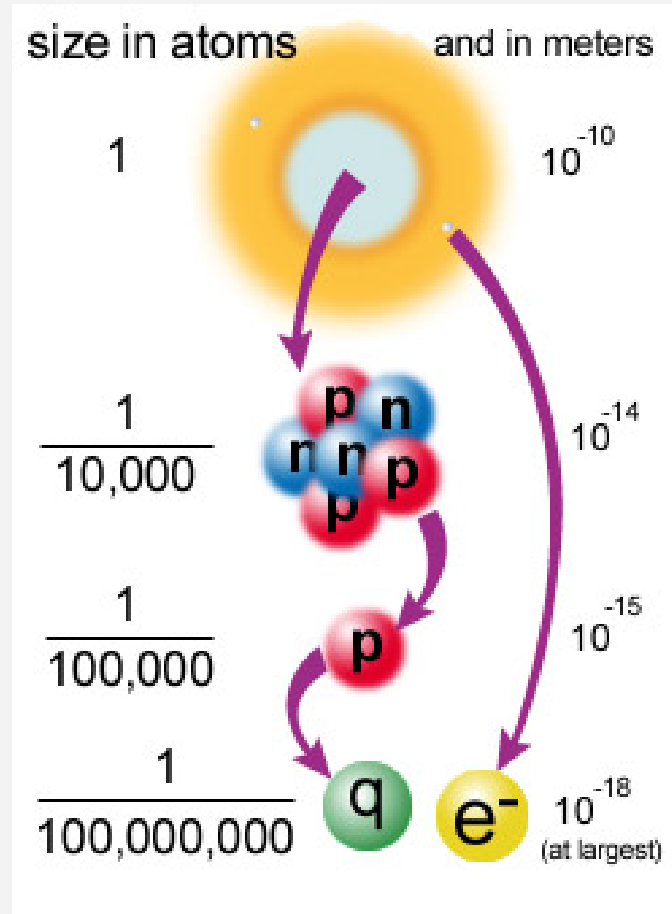


proton^{+} = (**uud**)　　**neutron^{0}** = (**udd**)

up-quark: charge **+⅔** , mass **m_u ~3 MeV/c^2**

down-quark: **-⅓** , **m_d ~6 MeV/c^2**

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

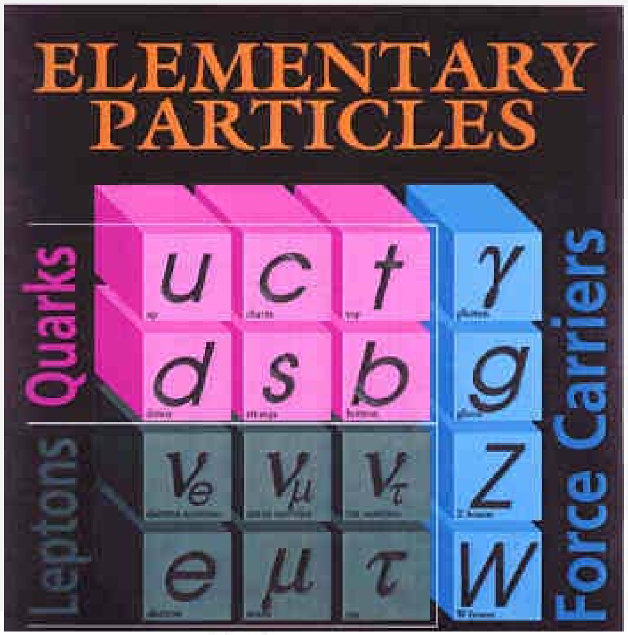


But: nucleon mass

m_p=m_n=940 MeV/c^2

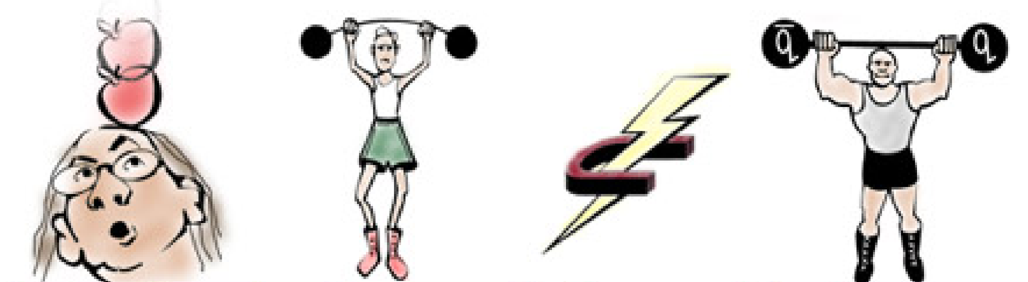
2.) Elementary Particles and Interactions

What holds Matter together?



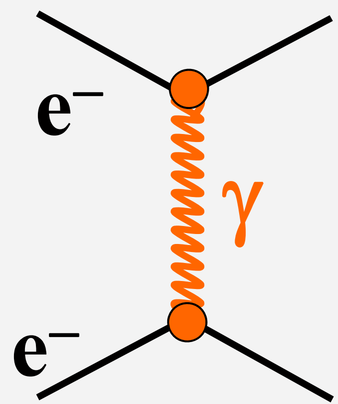
- in addition to stable matter (**u , d , e⁻ , ν_e**)
  2 more "generations" of elementary particles
  (**quarks** + **leptons**):
  charm + **strange** quark, **muon** + **μ-neutrino**
  top + **bottom** quark, **tau** + **τ-neutrino**

Force Carriers and Strength



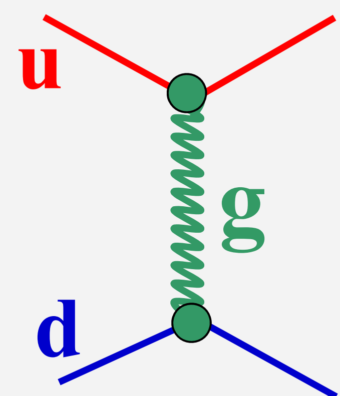
	Gravity	Weak (Electroweak)	Electromagnetic	Strong
Carried By	Graviton (not yet observed)	W^+ W^- Z^0	Photon	Gluon
Acts on	All	Quarks and Leptons	Quarks and Charged Leptons and W^+ W^-	Quarks and Gluons

elec-mg.



$\alpha_{em} \approx 0.01$

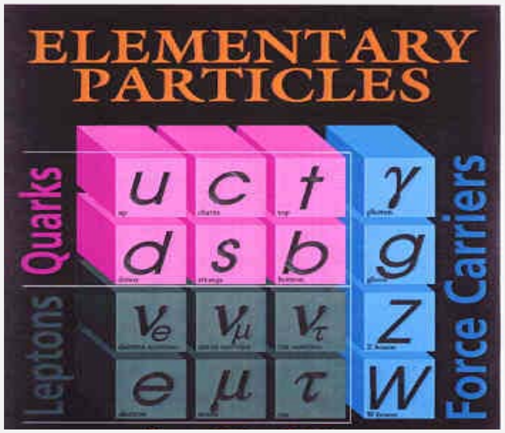
strong



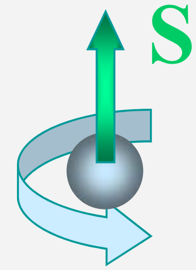
$\alpha_S \approx 1$

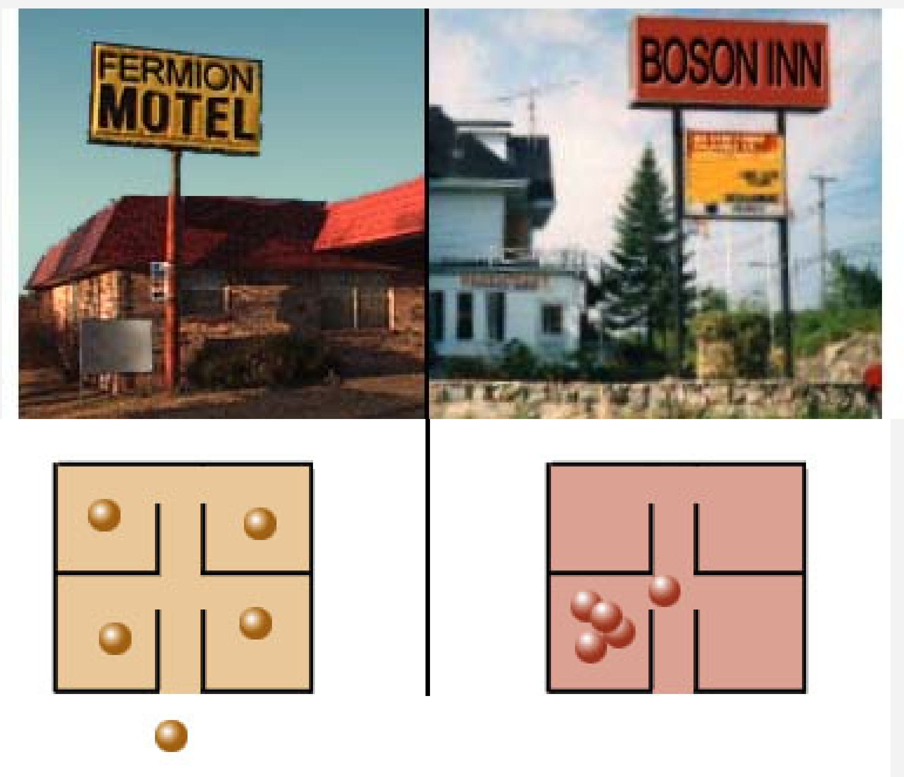
2.2 Elementary Particles and Interactions

The Nature of Matter vs. Force Particles



- **Matter** Particles (quarks+leptons):
  spin **S=½** "**Fermions**" (half-integer **S**)
- **Force** Particles (**g**, γ, **W**$^{\pm}$, **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**)

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 Interaction: Quarks and Gluons

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

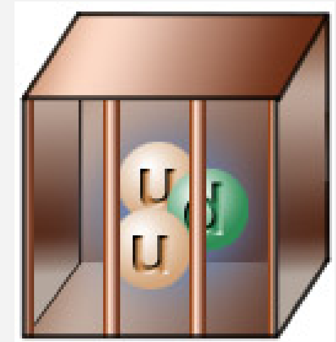
4.) Heavy-Ion Collisions and Quark-Gluon Plasma

- ”Evaporating” the Vacuum
- Dissolving Mass into Energy

5.) Summary

3.) The Strong Force: Quarks + Gluons

The Confinement of Quarks



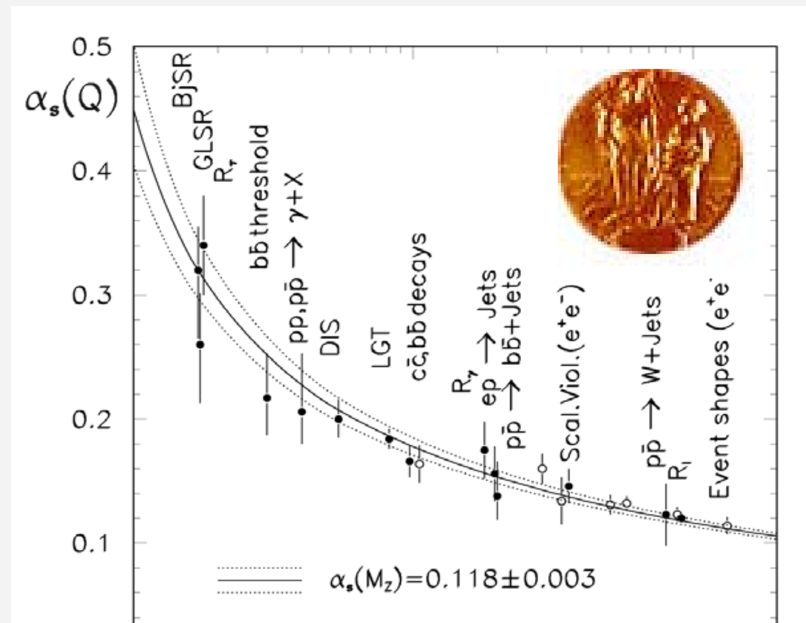
- In Nature, quarks never observed in isolation:

  "**Confinement**"

- Quarks "glued" together by gluons ("rubber" band)

  → the interaction strength increases with distance!!

$\mathbf{F_s(r) = \mathit{const}}$



- 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

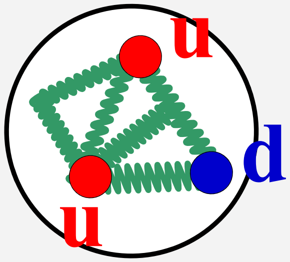
  [Gross, Politzer and Wilczek]

3.2 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**: $\mathbf{p}=(\mathbf{uud})$, $\Lambda=(\mathbf{uds})$, …

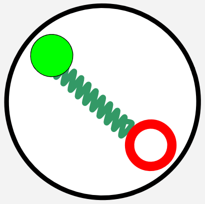
    S=3/2: $\Delta^{++}=(\mathbf{uuu})$, $\Omega^{-}=(\mathbf{sss})$, …



  - mesons: quark-antiquark composites (bosons!)

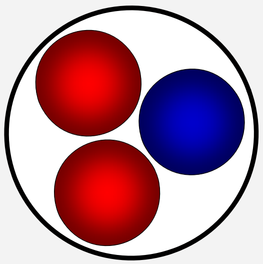
    e.g.: **S=0**: $\pi^{+}=(\mathbf{u\bar{d}})$, $\pi^{0}=(\mathbf{u\bar{u},d\bar{d}})$, $\mathbf{K}^{-}=(\mathbf{s\bar{u}})$, …

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



Puzzle: Why are hadrons so much heavier than quarks?

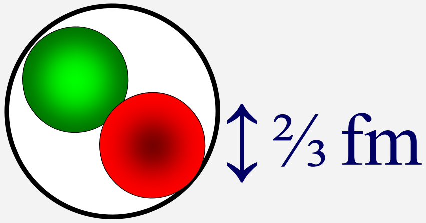
(proton-mass = **940 MeV/c²** >> $\mathbf{3m_q}$ **= 15 MeV/c²**)



Preliminary answer:

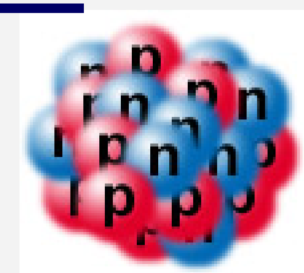
hadronic building blocks are "**constituent quarks**"

= extended objects with mass $\mathbf{M_q \sim 350\ MeV/c^2}$



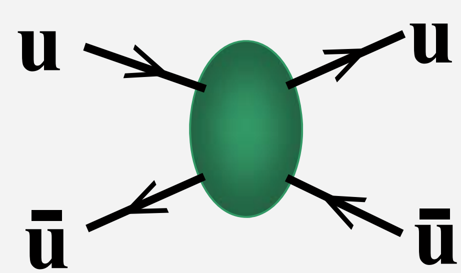
3.3 Strong Force: Mass Generation

- 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!!)

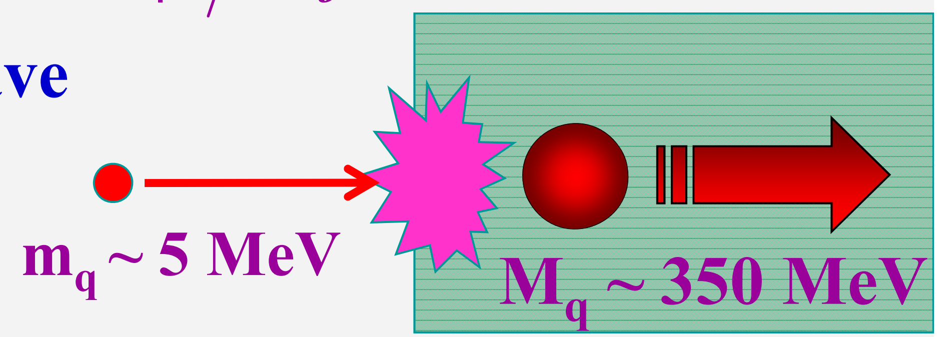


^{208}Pb=624 quarks

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??

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 Interaction: 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

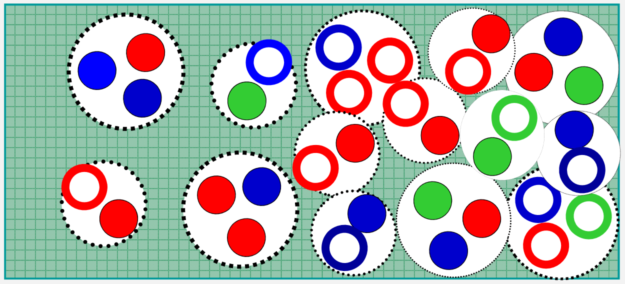
- ”Evaporating” the Vacuum
- Dissolving Mass into Energy

5.) Summary

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

Strongly Interacting Matter: From Nuclei to QGP

Heat and evaporate the Vacuum!

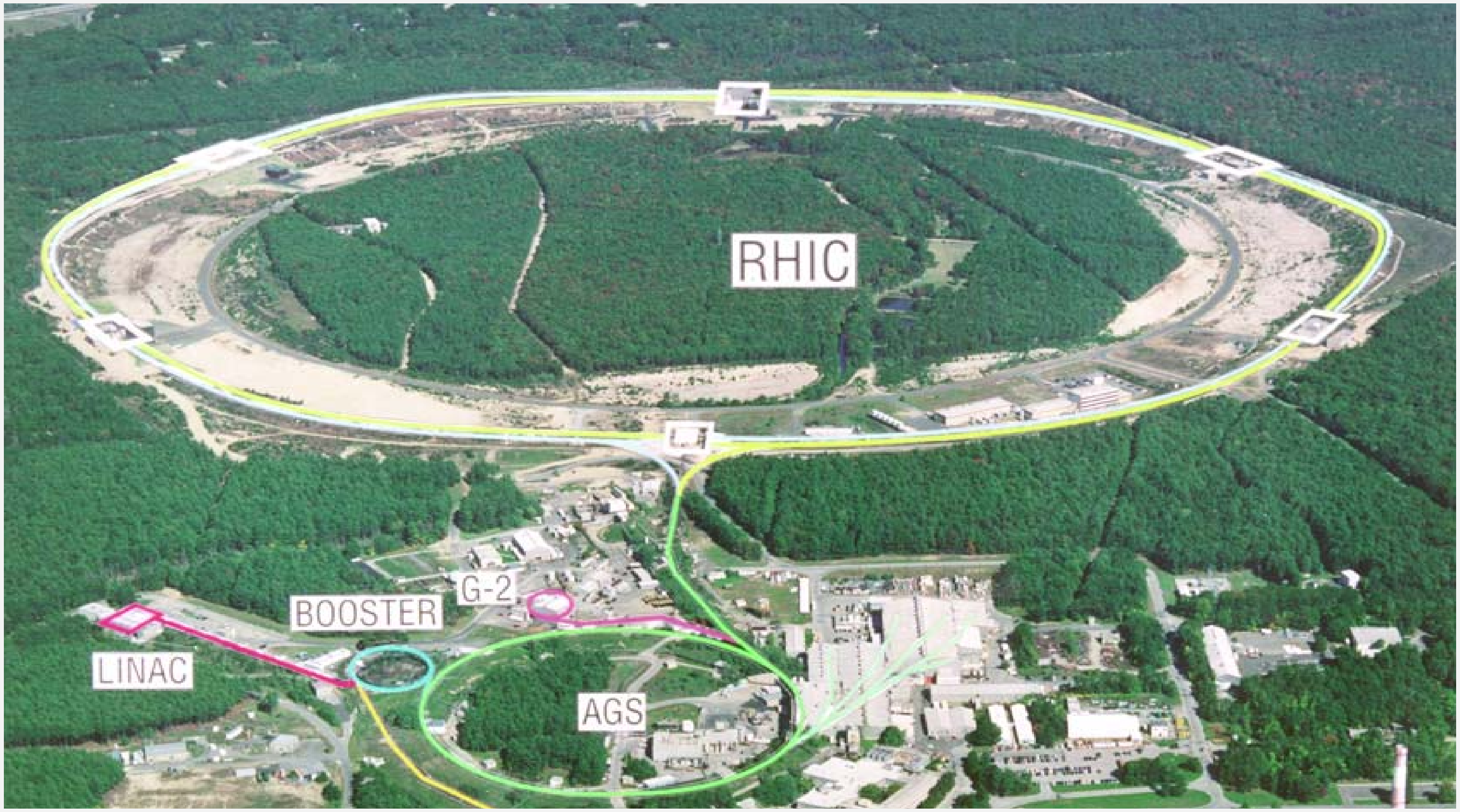


Nuclear Matter dissolves into **Quark-Gluon Plasma (QGP):**

- hadrons overlap, quarks liberated $\Rightarrow$ **Deconfinement!**
- $\langle \bar{q}q \rangle$ condensate "evaporates", $M_q \rightarrow m_q$ $\Rightarrow$ **Mass dissolves!**
- required temperature **~200 MeV ≈ $4 \cdot 10^{12}$ °F**
- **100,000** times hotter than inside the sun!
- Early Universe ~**0.00001 sec** after Big Bang!!

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

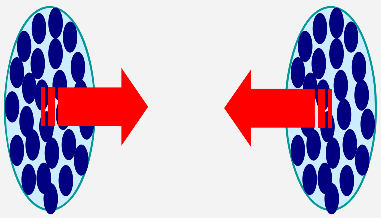
Answer: The Relativistic Heavy-Ion Collider!



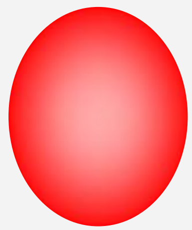
Accelerate Gold-Nuclei to **100 GeV/nucleon** and collide them!

(even more powerful accelerator (**LHC**) is running at the European Center for Nuclear Research (**CERN**) in Geneva)

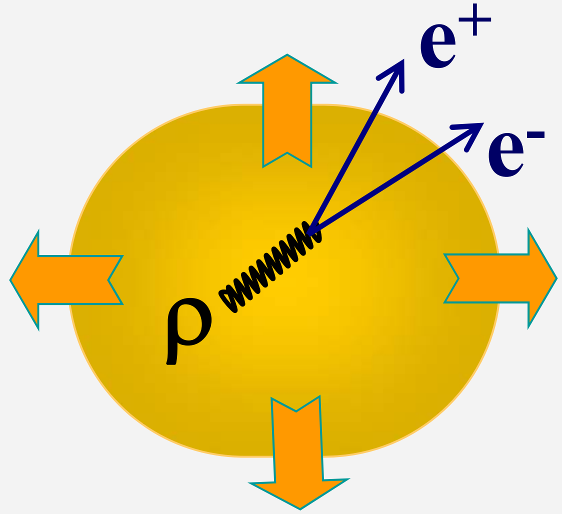
4.2 Recreating the “Little Bang” in the Laboratory

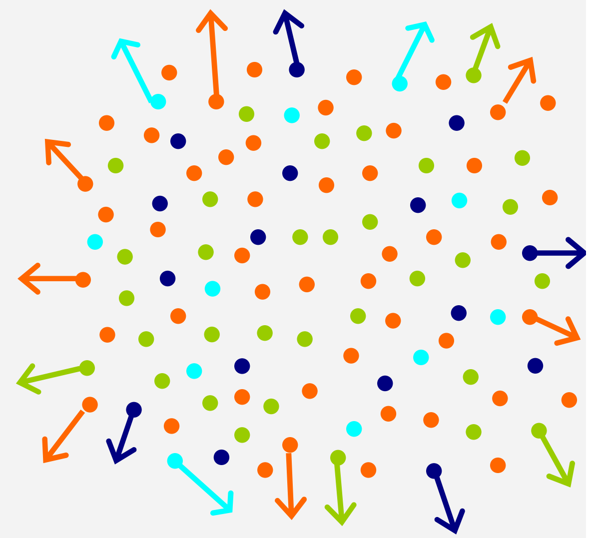


Au + Au



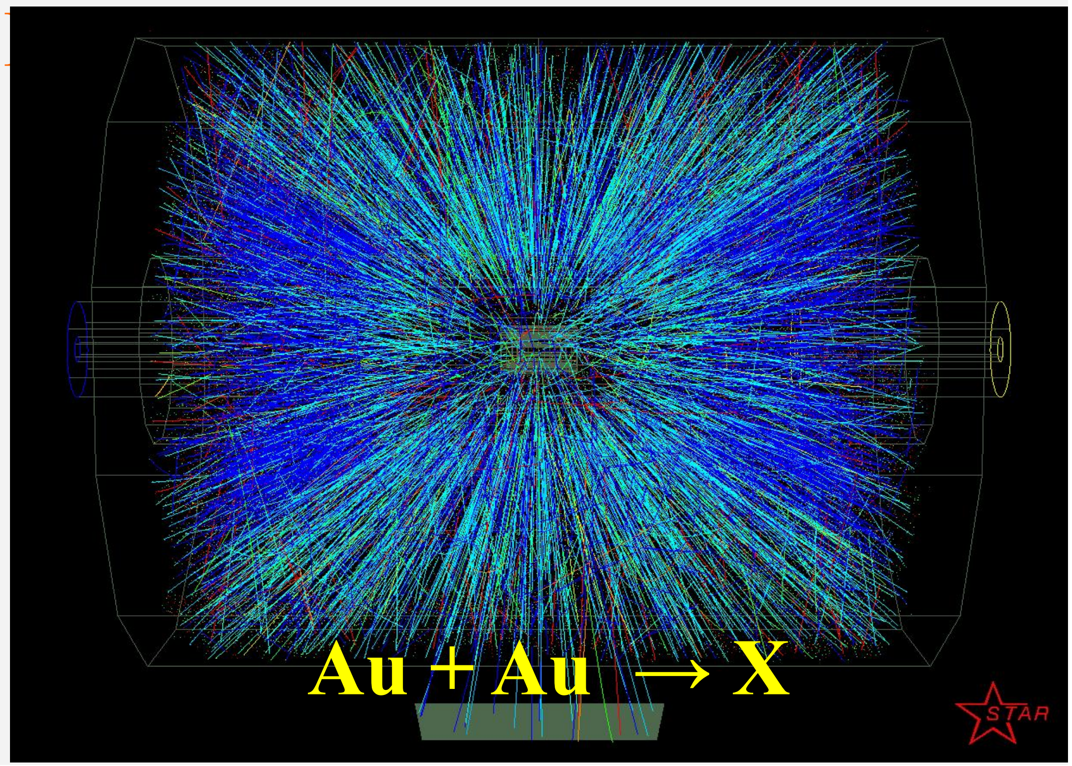
QGP ?!
($\tau \approx 2\cdot10^{-23}$s)





How to look for particles inside the matter?

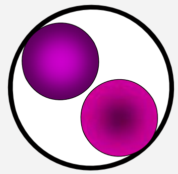
Watch out for electron-positron decays of the ρ(770)-meson!



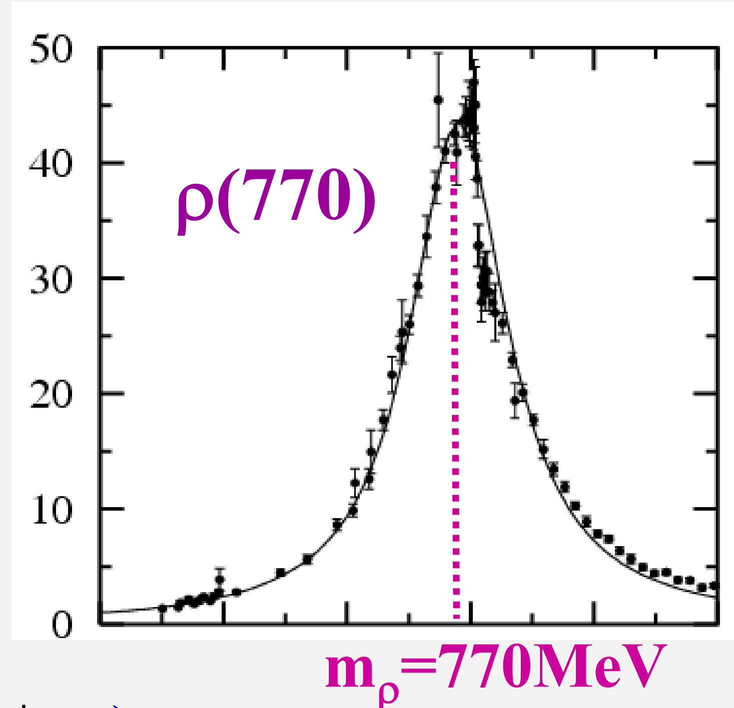
4.3 The ρ-Meson in Vacuum and its Decays

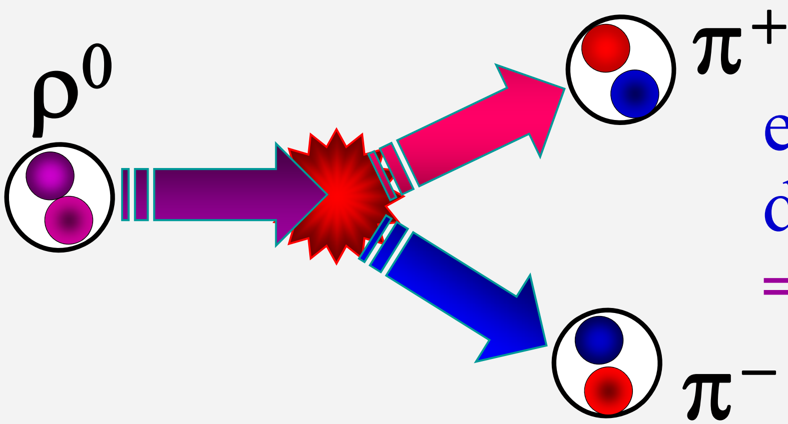
In Vacuum:

- mass of the ρ^0-meson (= $\mathbf{u\bar{u},d\bar{d}}$) is well measured, $\mathbf{m_\rho}$**=770MeV** ≈ 2 "constituent quarks":



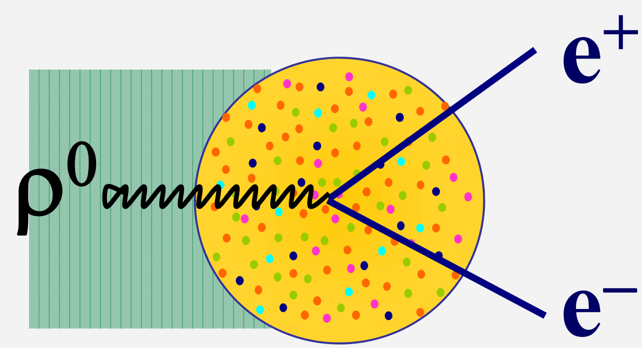
- ρ-meson unstable, lifetime ~ **$4\cdot10^{-24}$sec**





energy of decay products ($\pi^+\pi^-$) = mass of the parent particle (ρ^0)!

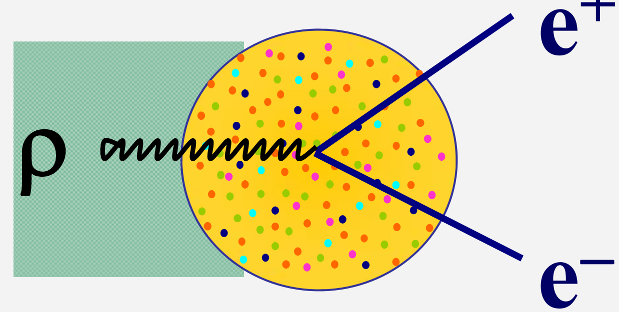
But what happens to the ρ-meson mass in a hot medium (QGP) ??



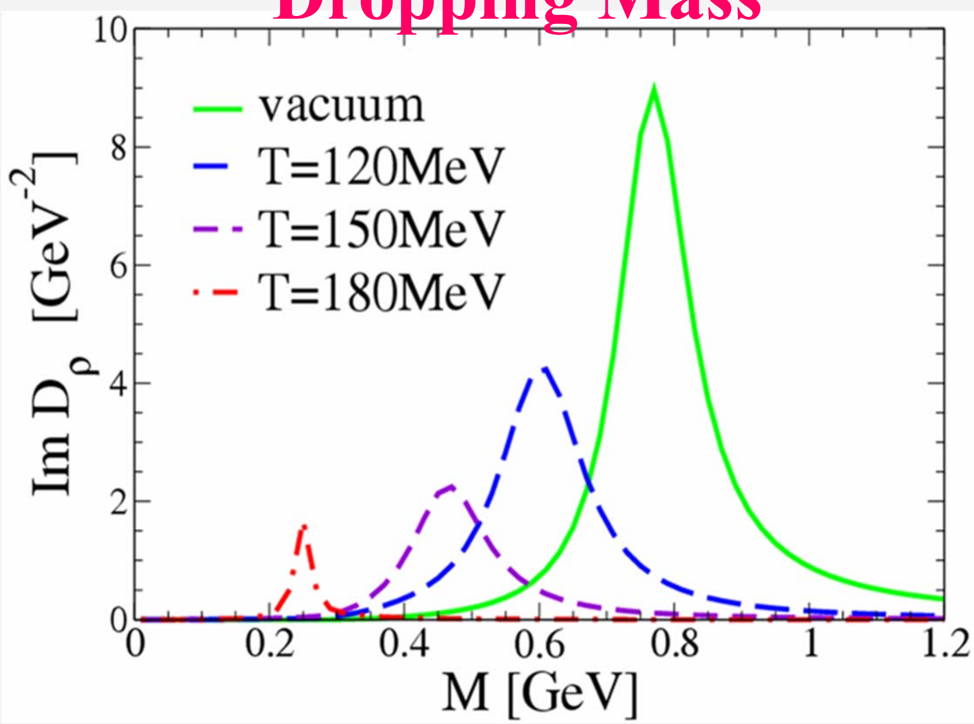
4.4 The ρ-Meson in a Hot Medium

Different theoretical predictions:

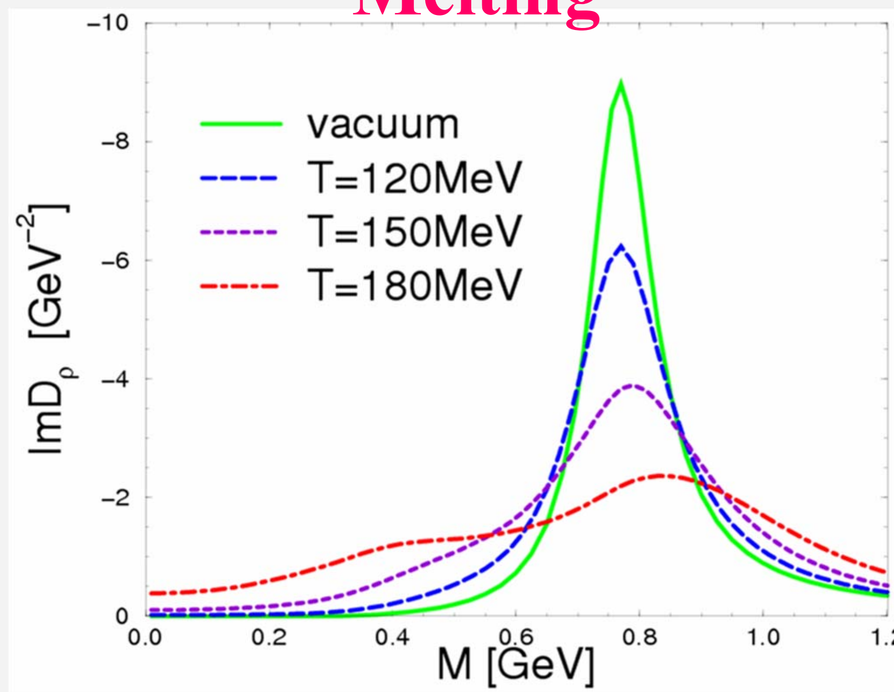
- m_ρ "drops" to zero (quarks lose their mass)
- interactions of the ρ within the hot+dense gas: ρ-meson "melts" (broad mass distribution)



"Dropping Mass"



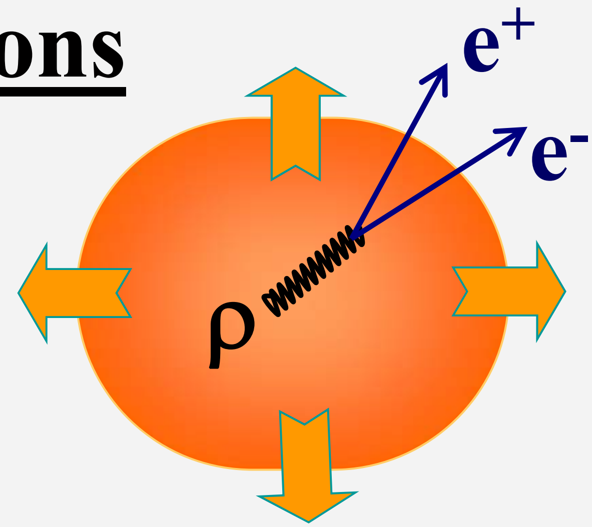
"Melting"



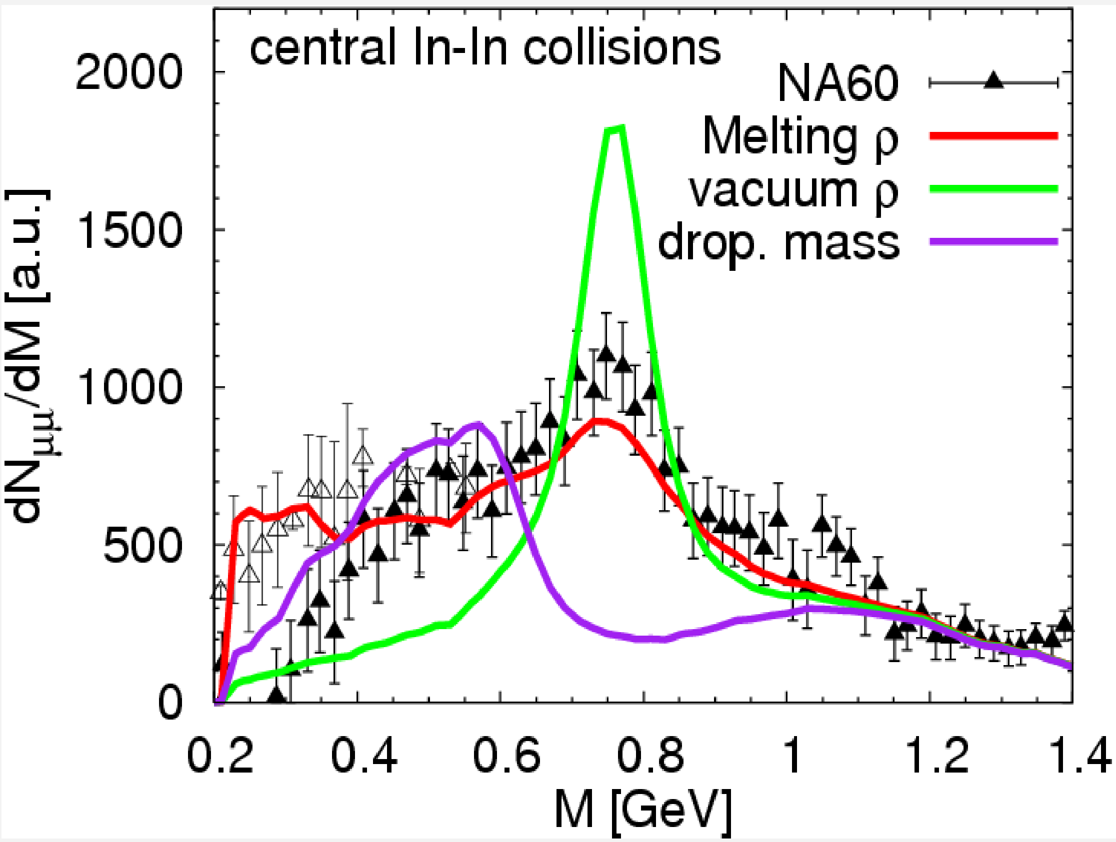
Which scenario is correct? Experiments have to tell us …

4.5 e^+e^- Spectra in Nuclear Collisions

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



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



- **experimental data favor the "melting" scenario**
- **advanced theoretical investigations required for definite conclusions … (ongoing at Texas A&M)**

We are getting close to the secret of (visible) mass in the Universe…

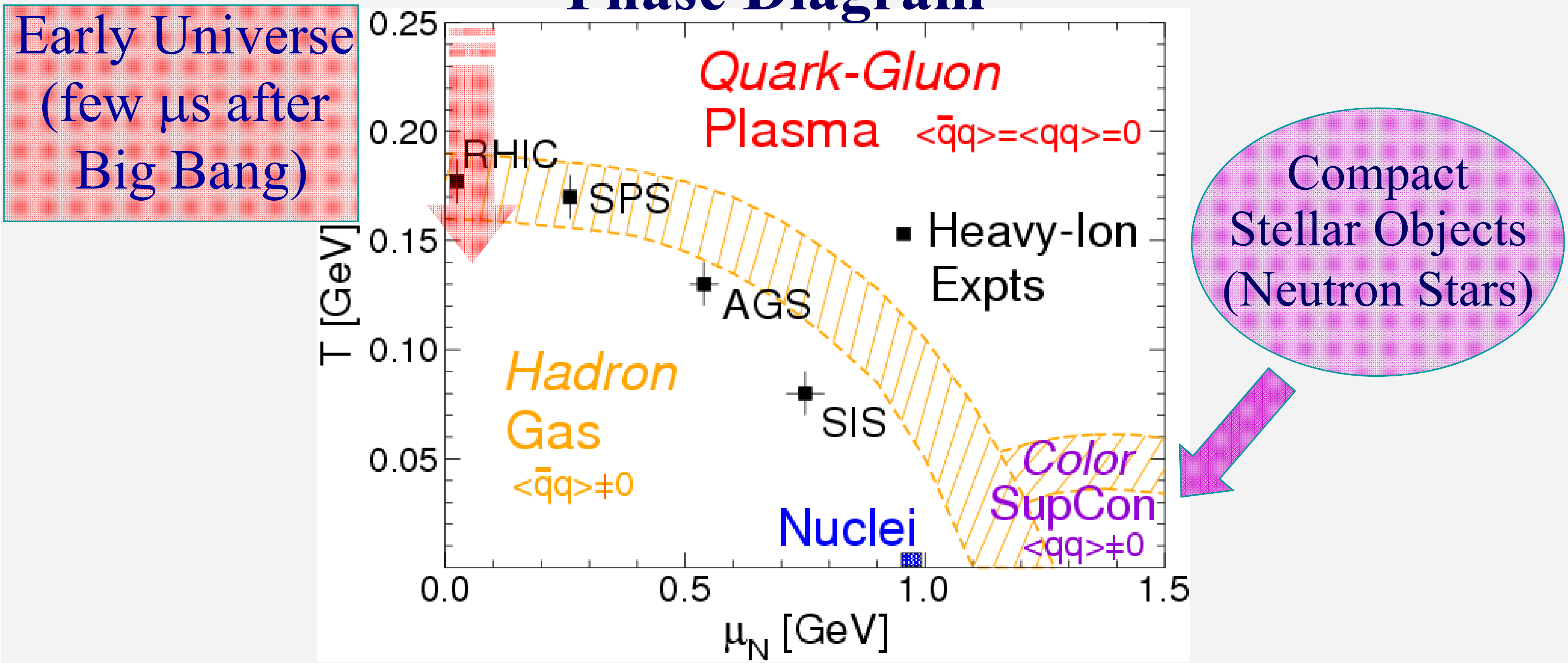
5.) Summary

- 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 $\langle\bar{q}q\rangle$ 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 condensate 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



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

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

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