Phases of Quantum Chromodynamics at Extremes

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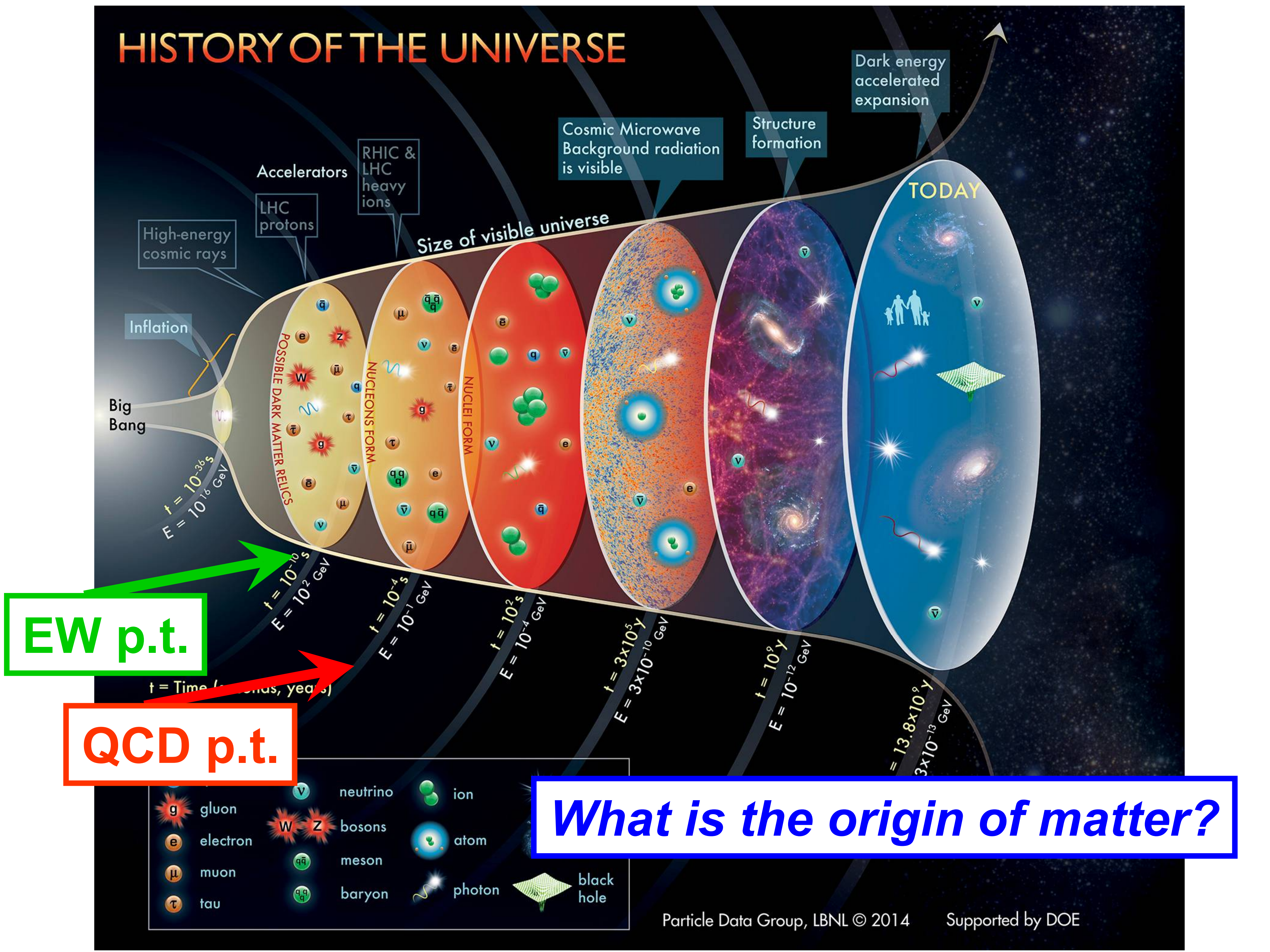
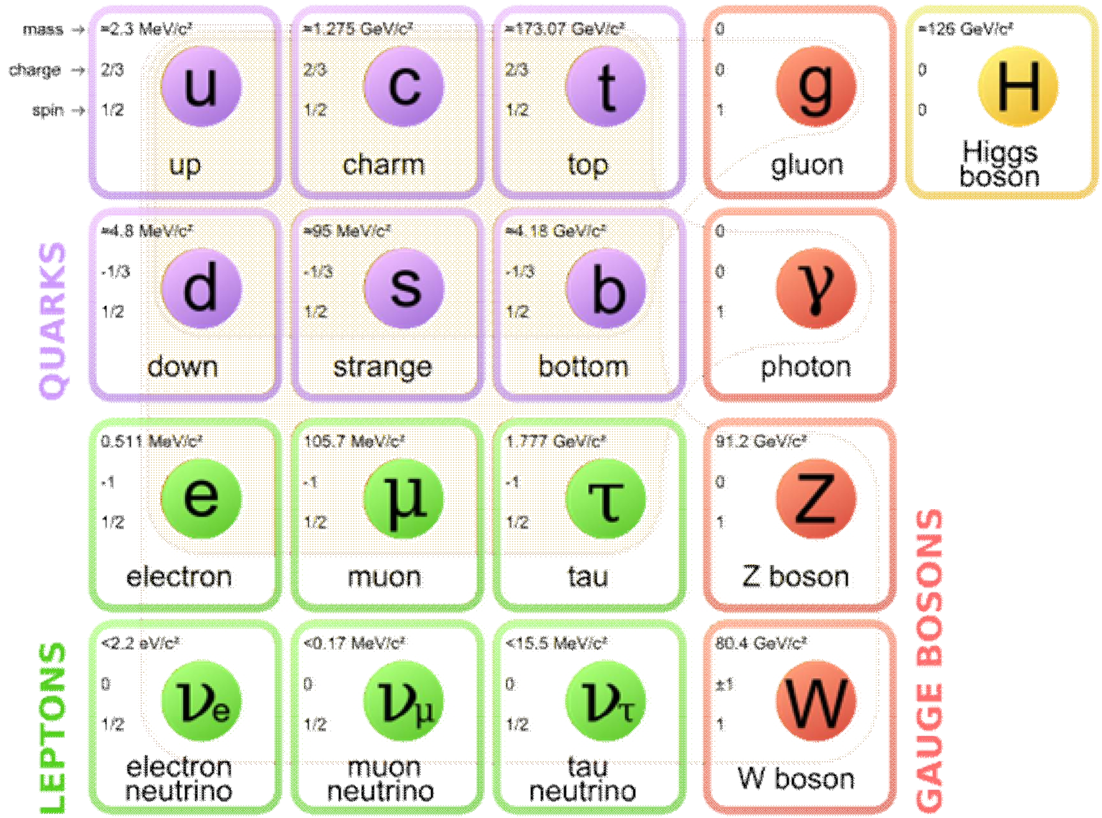


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Size of visible universe
TODAY
Big Bang
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
E = 10^-1 GeV
t = 10^2 s
E = 10^-4 GeV
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
3x10^-13 GeV
EW p.t.
QCD p.t.
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
black hole
What is the origin of matter?
Particle Data Group, LBNL © 2014
Supported by DOE

EM, Weak & Strong: Standard Model

- What is an elementary particle?
  - Minimal composition of ordinary matter
  - No substructure, or substructure unknown



Gauge principle

- Known elementary particles – 37

  18 quarks/6 leptons/12 gauge bosons/1 Higgs
- What is the guiding principle?

  → Symmetry dictates interactions uniquely!
- Gauge structure of SM

  → SU(2) x U(1) x SU(3)/U(1)em x SU(3)

  Weak & EM   Strong

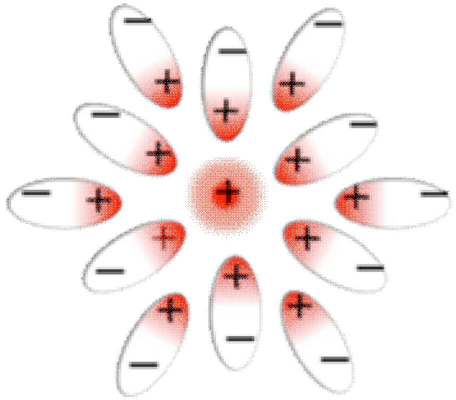
What is QCD?

Quantum Chromodynamics (QCD): strong force

→SU(3) gauge theory: rot. inv. in color space

- Quarks and gluons carry color charges.
- Gluon self-interactions
- Anti-screening of color charges

  cf. QED: electric charges screened



increasing resolution → smaller color charges

higher energy → weaker QCD interaction

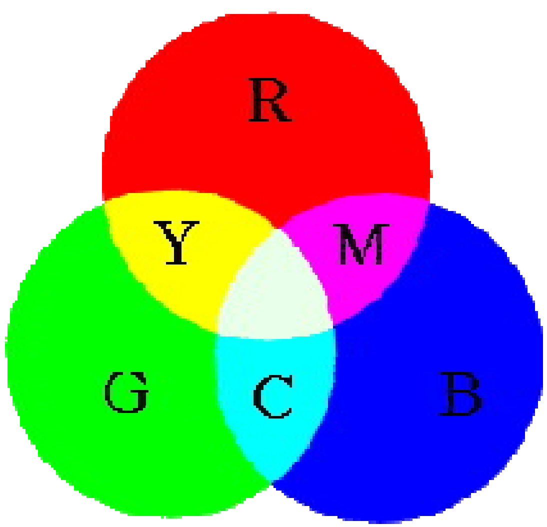
Asymptotic freedom

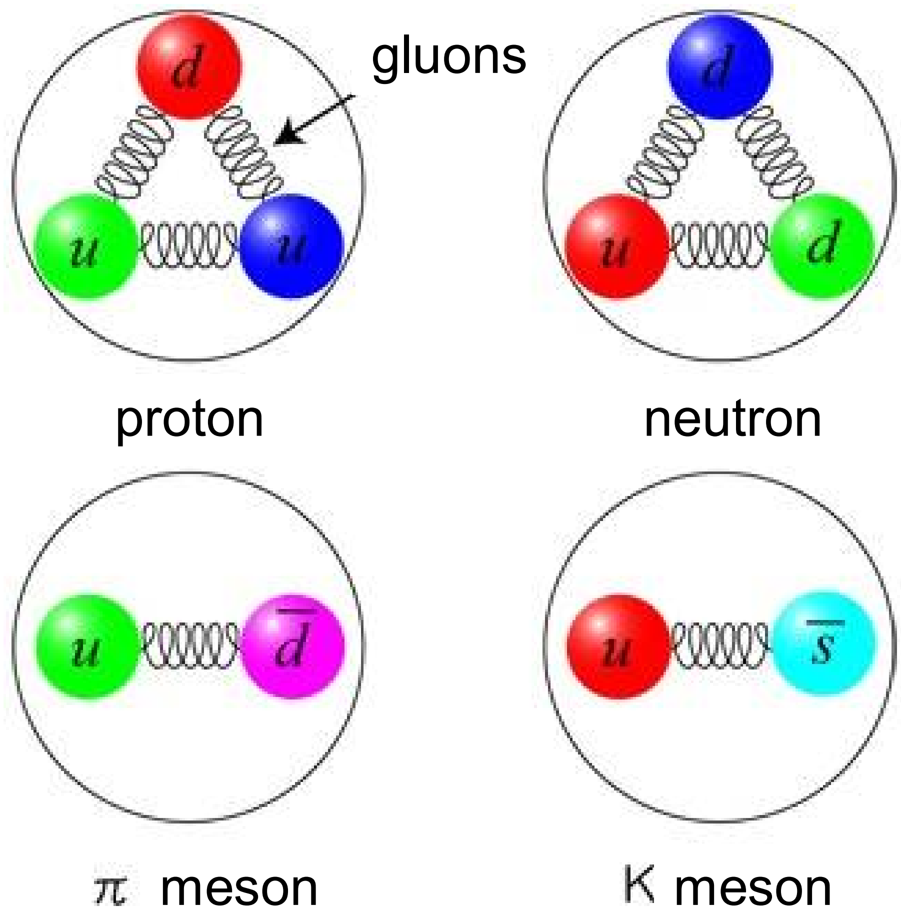
Isolated single quark?

Quarks are confined! → composite states

Hadrons: white/singlet under SU(3) rot.

- Baryons (3 quarks)
- Mesons (2 quarks)
- Exotic hadrons



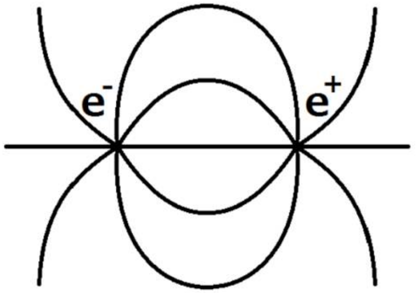


Quark confinement

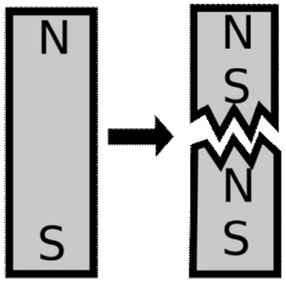
Phenomenology well described by

Coulomb (1/r) + linear (r) potential.

- separate 2 quarks → color flux tubes

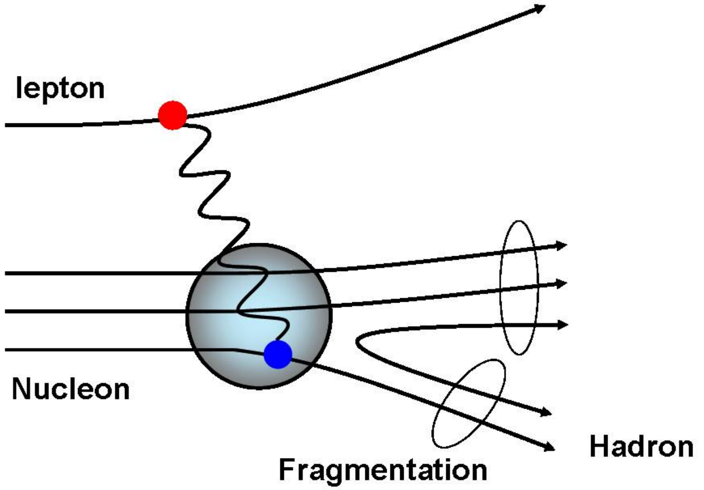


- separate them further → exceed threshold energy of $q\overline{q}$ pair creation → tubes broken and a meson created.
- cf. a bar magnet



How to "see" quarks?

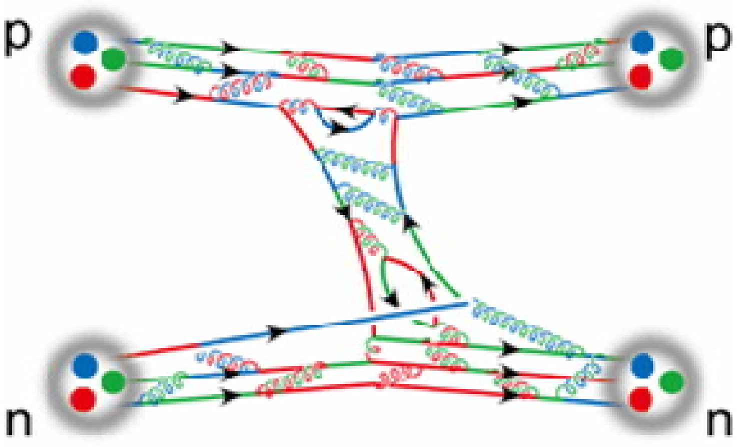
- High-energy particle collisions



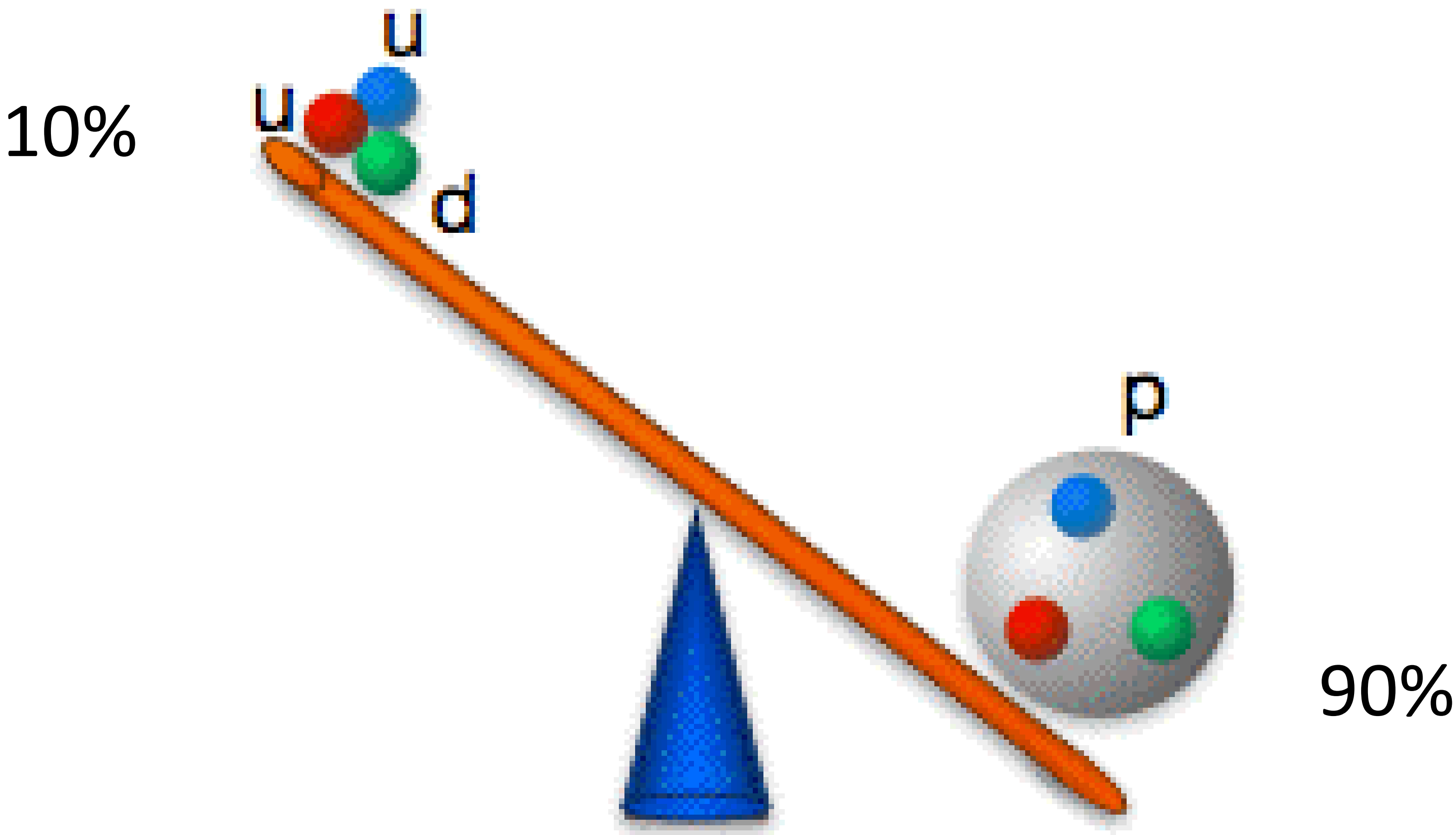
Internal structure of a proton: a jet of hadrons

- Microscopic picture of nuclear forces

Quark-gluon reactions, nonlinear quantum effects

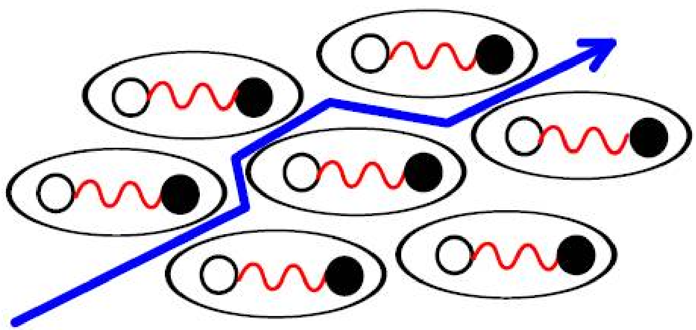


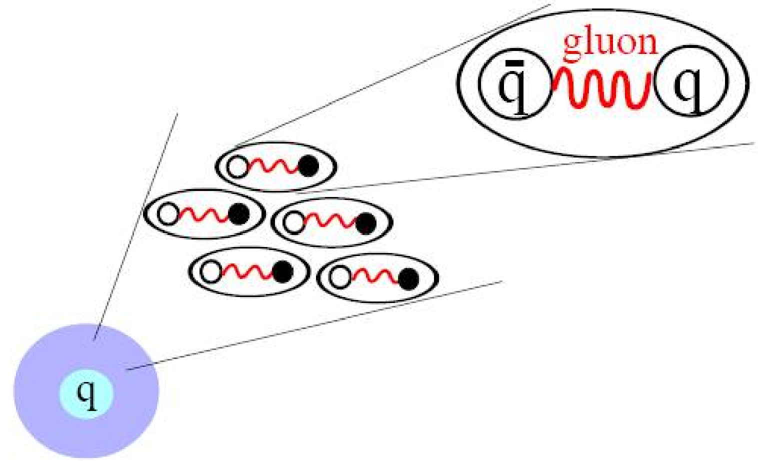
The proton mass



The ground state is not empty!

- Strong int. → quark-antiquark pair formed



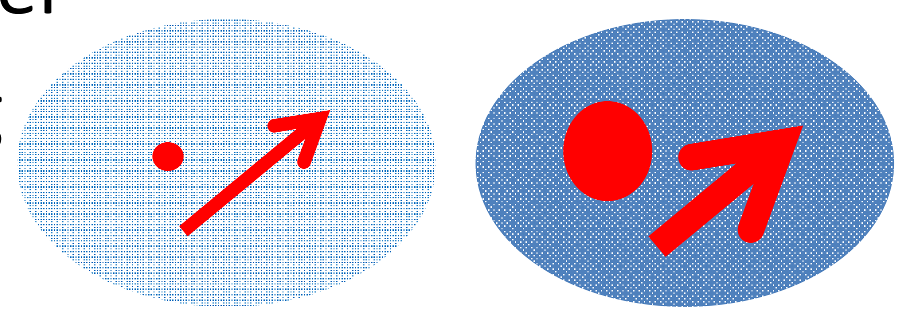


- “bare” quark → “dressed” (massive) quark
- VEV $\bar{q}q$: order parameter

→ Spontaneous breaking

of chiral symmetry

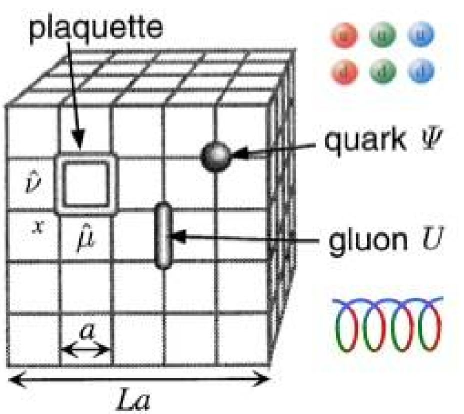
LL + RR + LR + RL

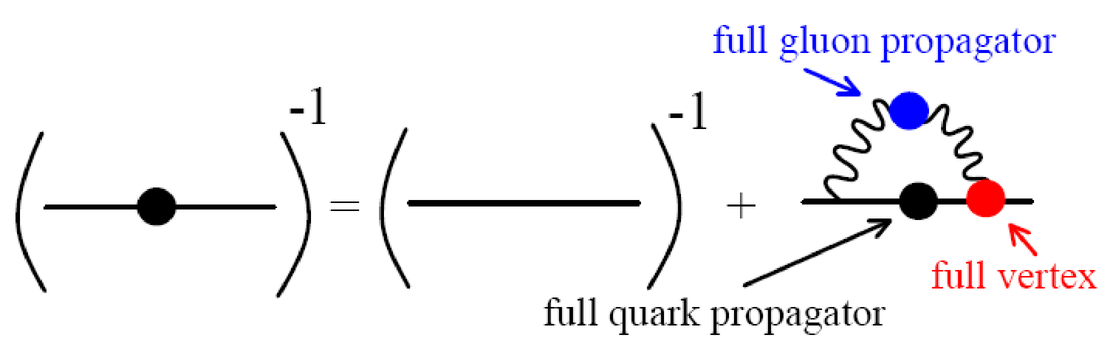


QCD in low energy

Asymptotic freedom → pQCD not valid!

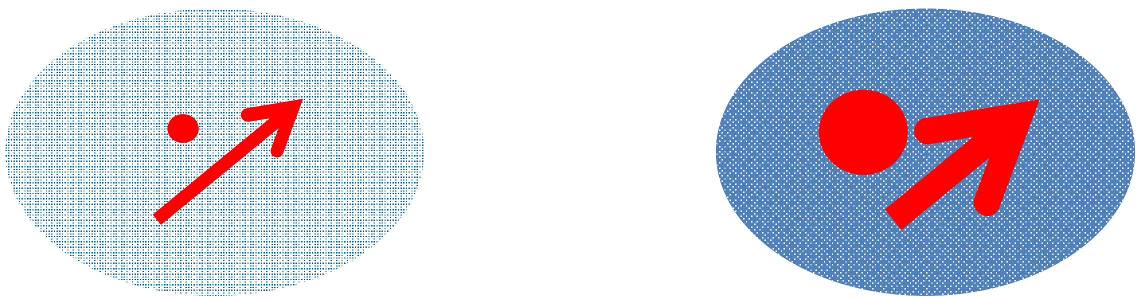
- Lattice gauge theory: MC simulations on a discretized space – first principles calc.
- Integral equations: e.g. Schwinger-Dyson eq.
- Effective theory: relevant d.o.f. & symmetries





$t \approx 10^{-10}$ sec

today

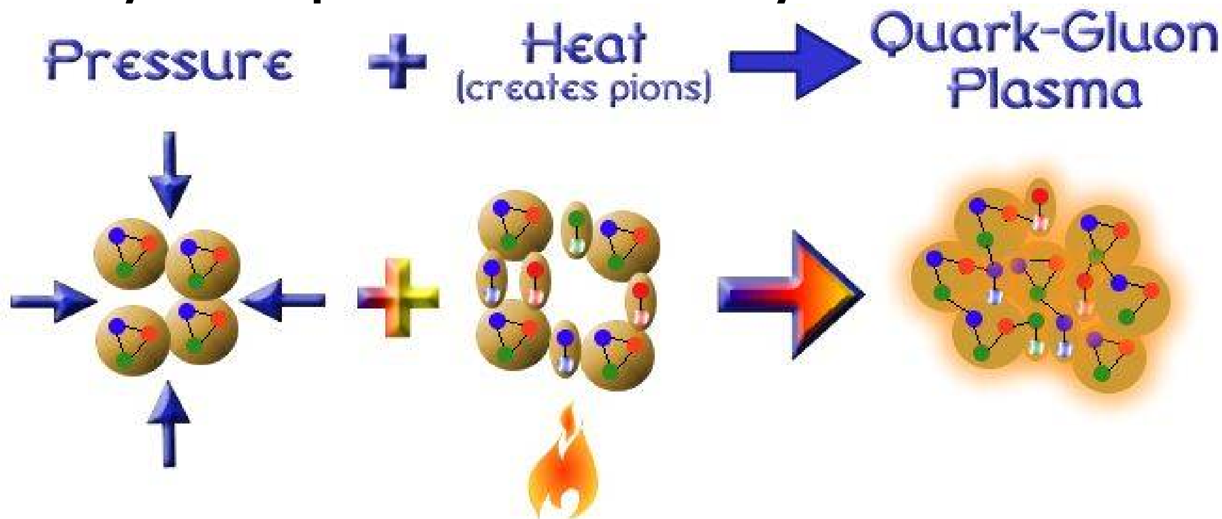


HOW TO PROBE THE QCD PHASE TRANSITION?

QCD at high temp./density

- Early Universe: $T \approx 2\times10^{12}\,K$

  cf. the core of the Sun: $T \approx 10^{7}\,K$
- Neutron stars: $\rho \approx (5-10)\rho_0$
- Let’s heat/compress ordinary matter!

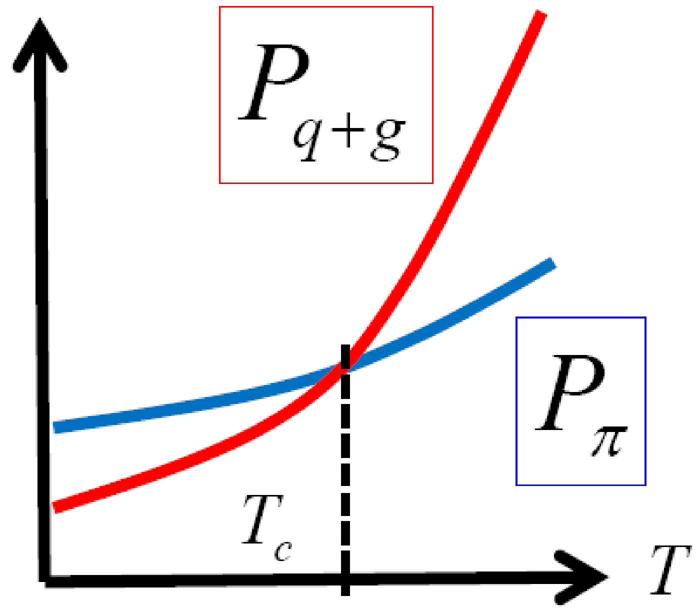


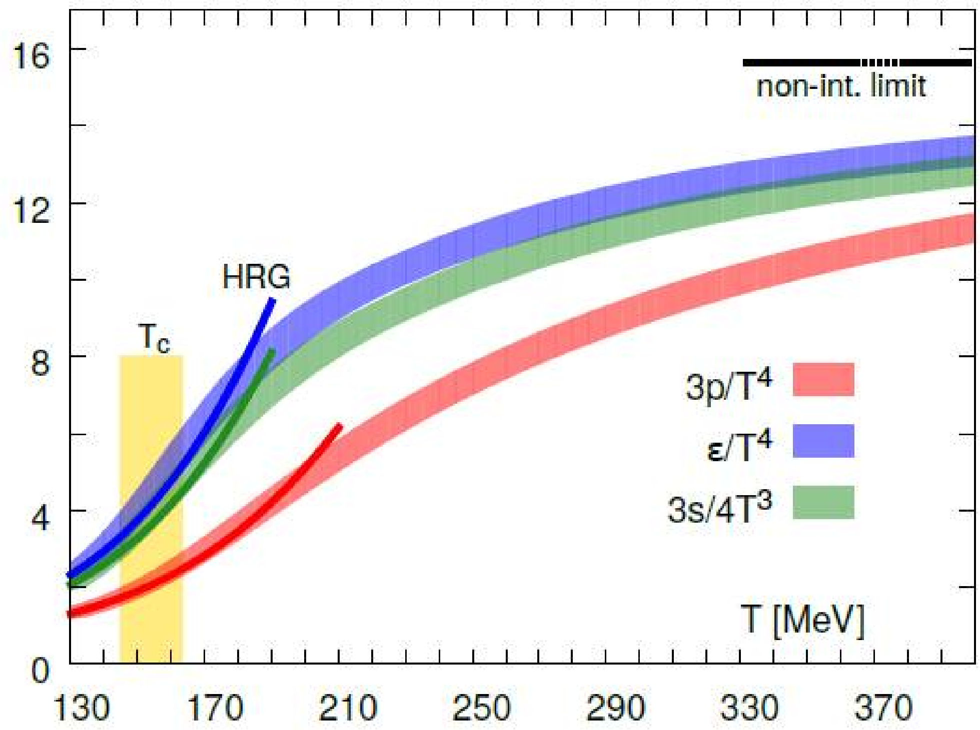
  - via QGP formation, “dressed” → “undressed” quark
  - Main goal in heavy-ion collision experiments

Quark-Hadron phase transition

- Illustration in a simple model
  - Liberation of d.o.f. $d_\pi = 3 \rightarrow d_q + d_g = 40$
- EoS from Lattice QCD: a crossover

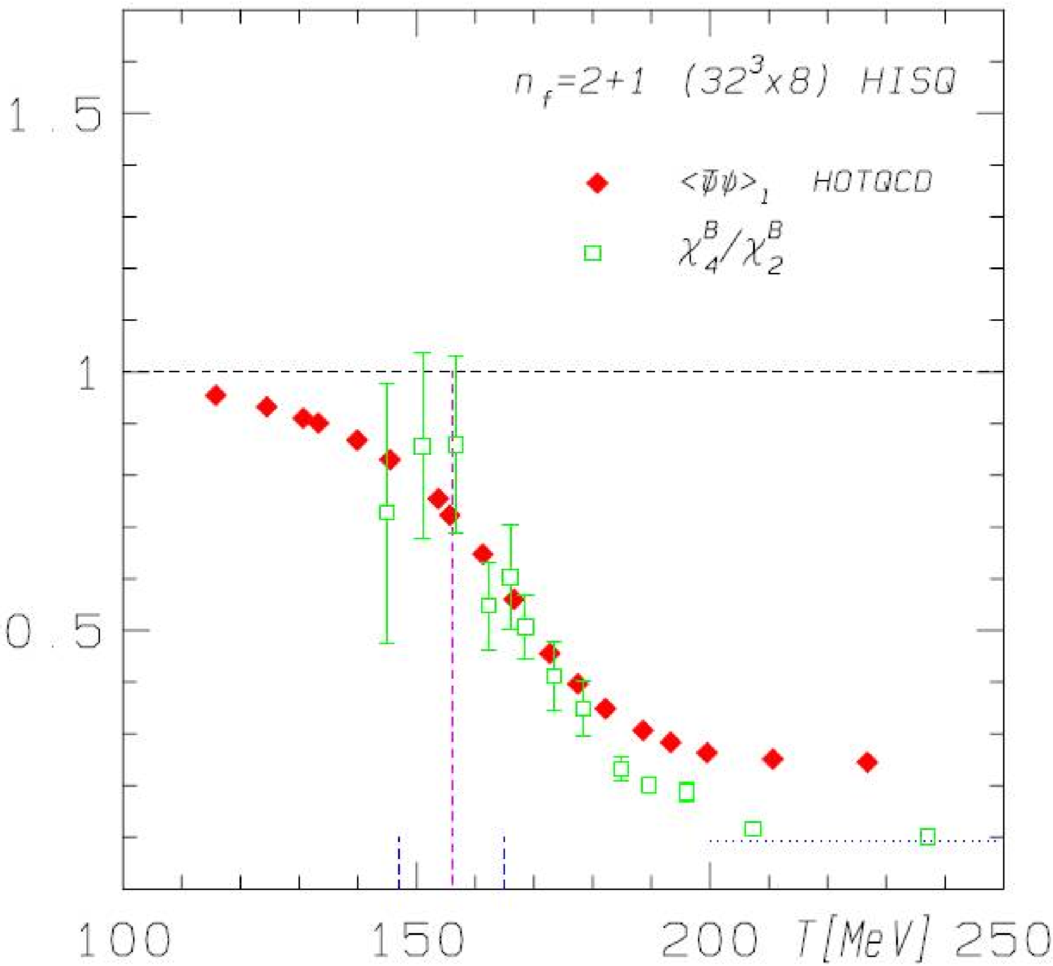
$$\chi_{\bar{q}q} = \partial^2 P / \partial m_q{}^2 \approx V^0 \qquad (V^1 : 1st, V^{2/3} : 2nd)$$





Hot QCD at $\mu \approx 0$

- ❑ Restoration of chiral sym. at Tc=154 MeV
- ❑ Deconfinement
- ✓ Conserved charges
- ✓ Comprehensive comparison to Hadronic scenario
- ❑ Tdec ≈ Tc



Chiral-confinement interplay in cold dense QCD

How to model dense QCD?

- ❑ Lattice simulations invalid → model analyses
- ❑ Good model must possess
  - Correct properties of nuclear ground state
    - ✓ Saturation density, binding energy, compressibility
    - ✓ Rather big chiral-inv. mass m0 ≈500-800 MeV favored
      [Zschiesche et al. (07), Gallas et al. (11)]
  - Correct degrees of freedom
    - ✓ Nucleons at low density/quarks at high density

→ How to realize the 2^{nd} property?

[Benic et al. 2015]

Quark-nucleon hybrid model

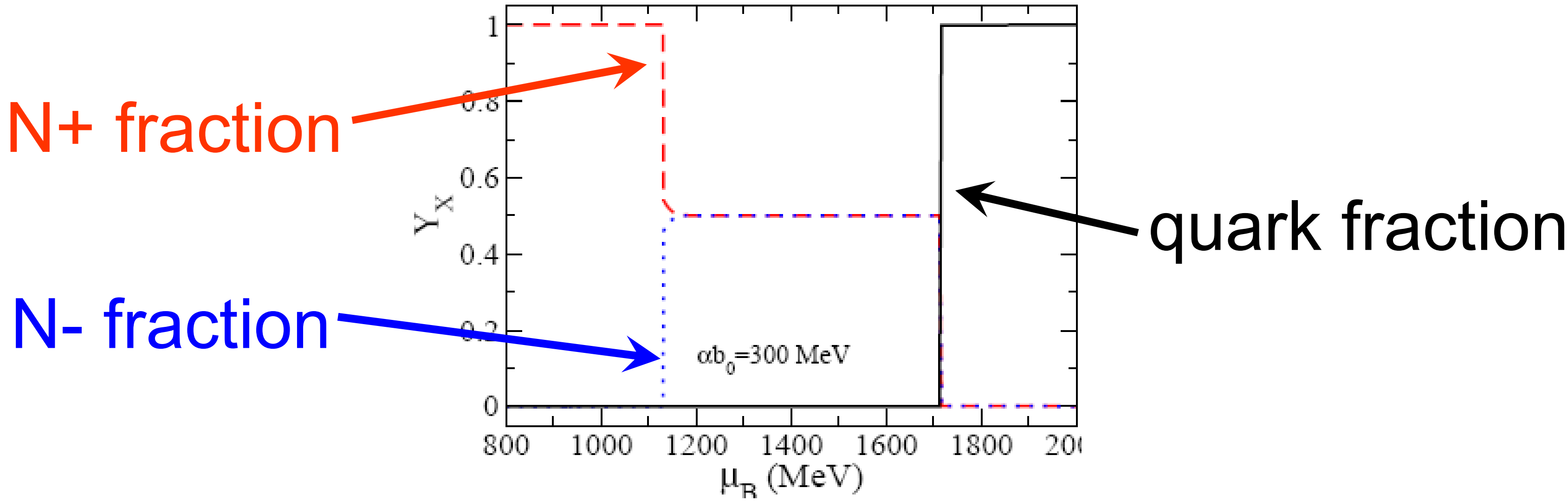
- How to suppress quarks at low density?
  - IR/UV cutoff “b” in Fermi dist. functions
  - from const. “b” to a VEV of a scalar field b
- Chiral & deconf. p.t. in a single framework

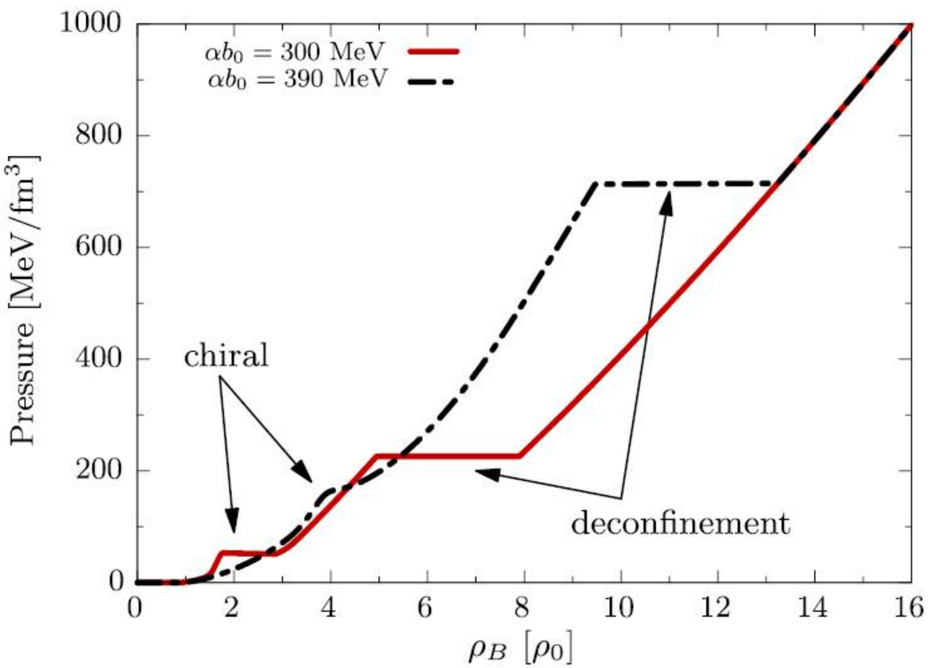
$$\int_0^{\langle b \rangle} dp\, f_N(p;T,\mu) \rightarrow \int_0^{0} dp\, f_N(p;T,\mu) = 0$$

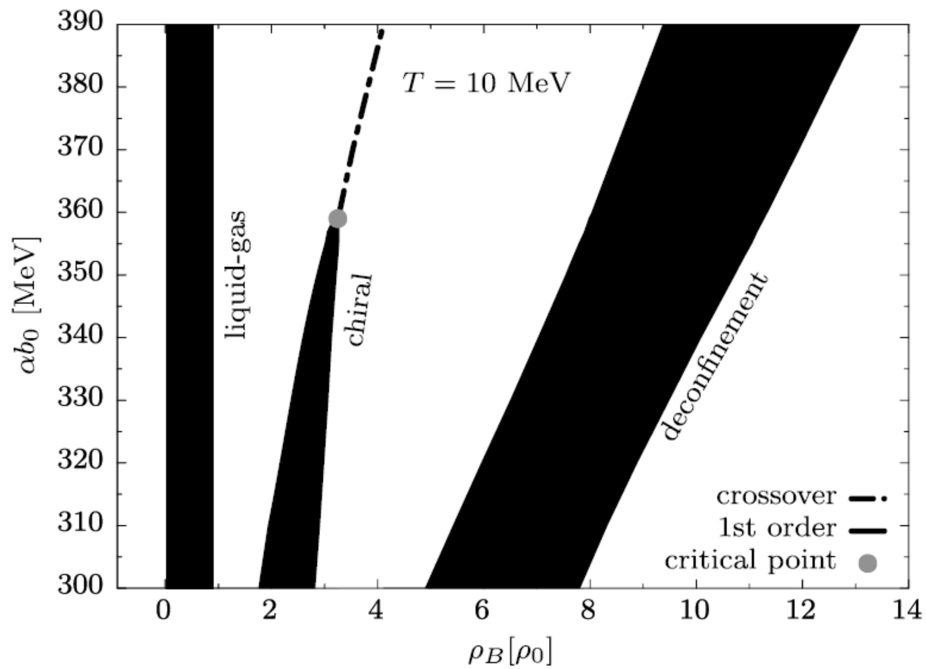
$$\int_{\langle b \rangle}^{\infty} dp\, f_Q(p;T,\mu) \rightarrow \int_0^{\infty} dp\, f_Q(p;T,\mu)$$

[Marczenko, CS, 2017]

Onset of different fermions





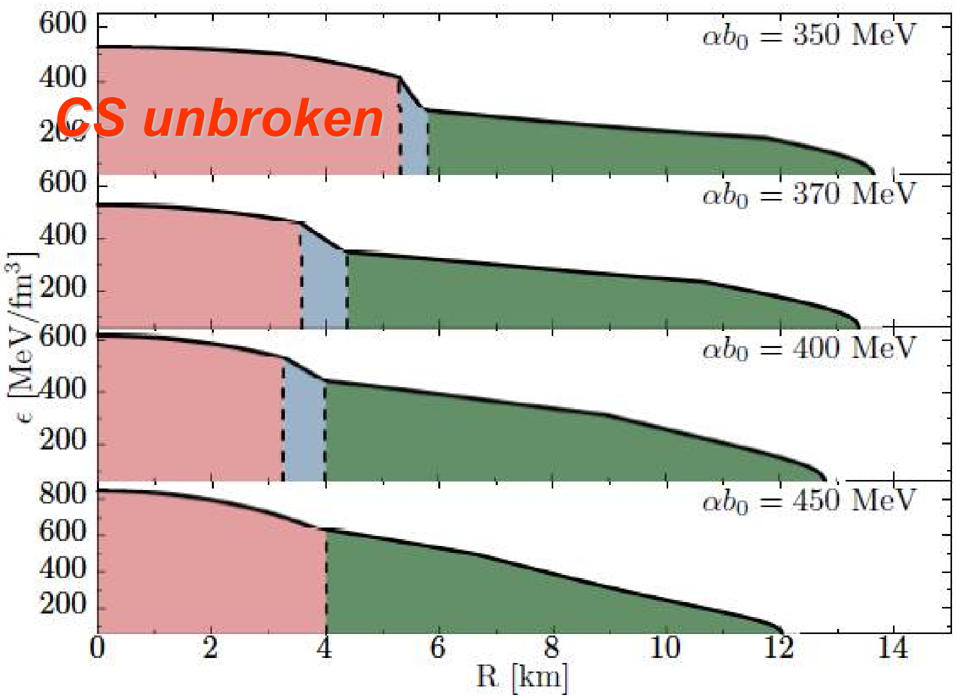


[Marczenko, Blaschke, Redlich, CS, 2018]

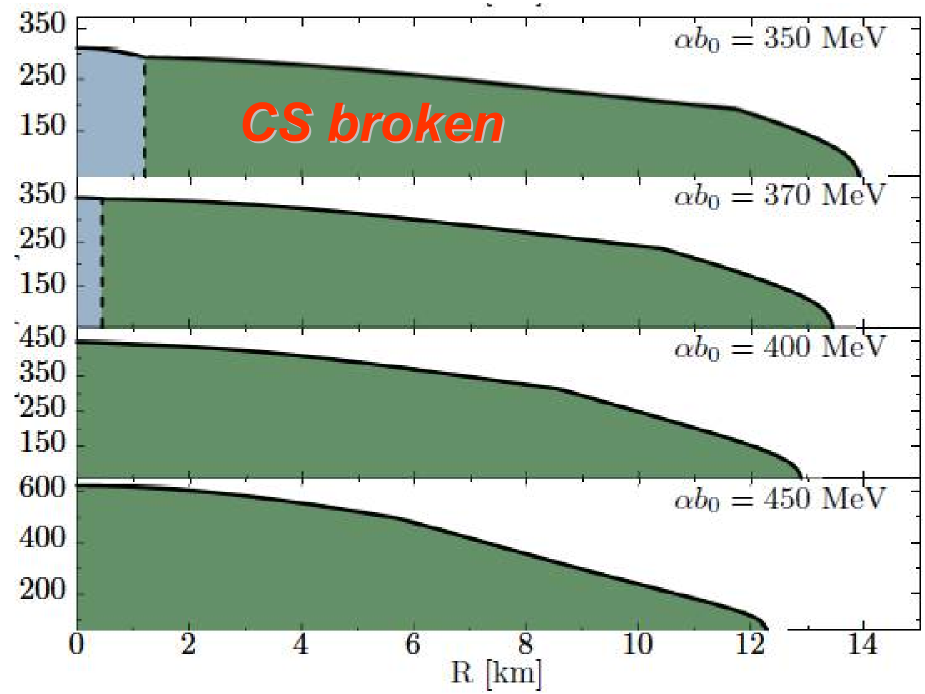
Neutron stars

- β -equilibrium and charge neutrality
- Constraints on the mass and compactness of a star → hadronic scenario w/o deconf.quarks

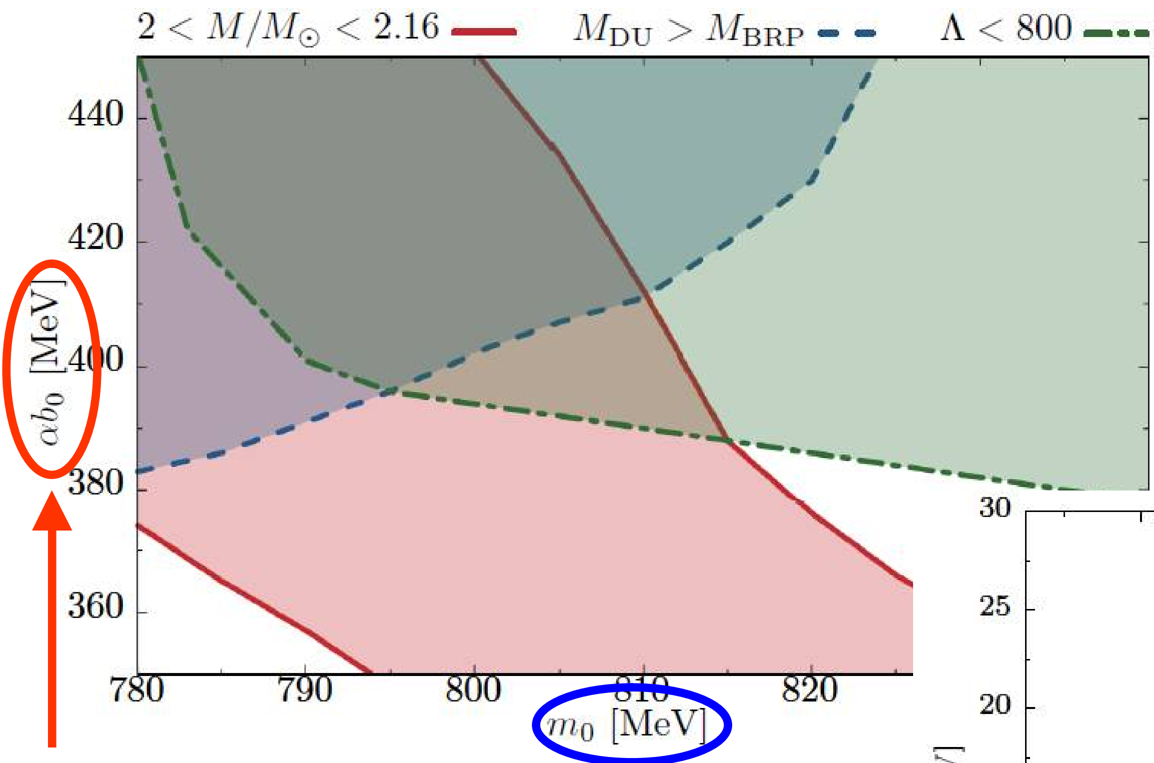
2.05*SM NS



1.97*SM NS



Toward QCD phase diagram

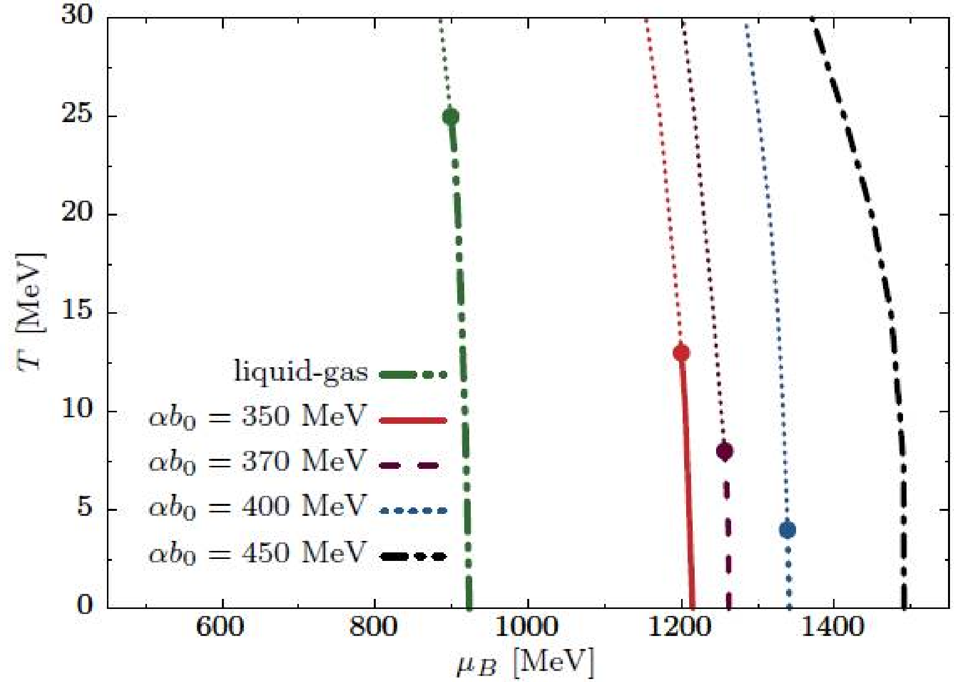


IR cutoff

Chiral-inv. mass

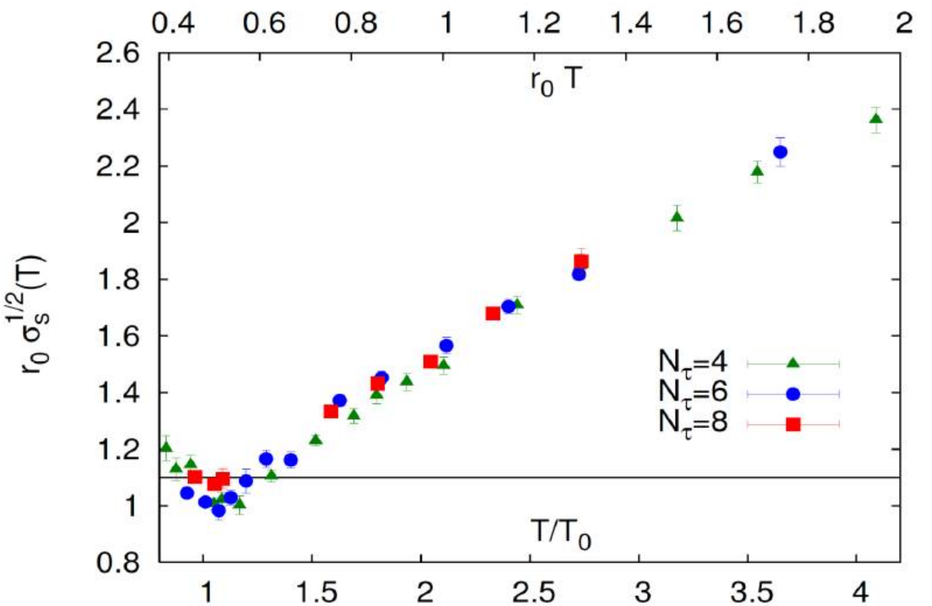
✓Mass
✓Cooling
✓Tidal deformability
in the binary merger

CP disfavored?

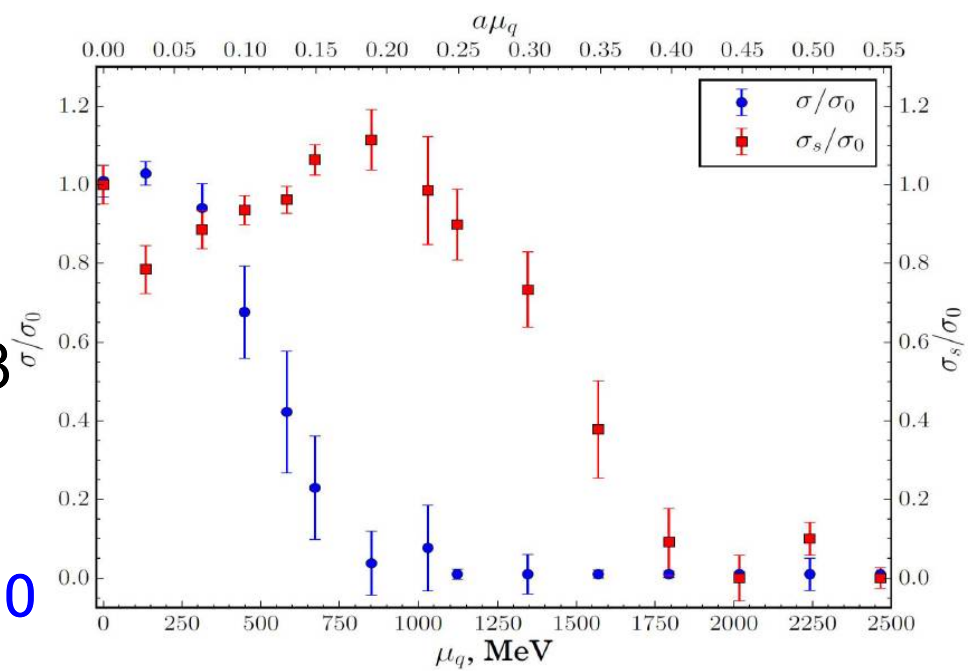


Fate of confinement: hot vs. dense

❑Non-pert. color-mag. sector → perturbative!



← SU(3)c, T >0, μ = 0;
Cheng et al., PRD 2008
[mpi = 220 MeV].



→ SU(2)c, T = 0, μ > 0;
Bornyakov et al., JHEP 2018
[mpi = 740 MeV].

✓m0(μ =0) vs. m0($\mu \neq$0)

✓Color-mag.monopoles at $\mu \neq 0$

Summary

Phase diagram: all science fiction?

- ❑What we know is very limited:
  - ✓Crossover at $\mu \approx 0$, Tc ≈ 154 MeV, remnant of O(4)
  - ✓Nuclear liquid-gas phase transition, CP
- ❑Interplay between CSB and confinement
- ❑Modifications of hadrons: mass & width
- ❑Toward more realistic description of QCD