The phase diagram at finite T and μ_B (and μ_I)

Massimo Mannarelli
INFN-LNGS
massimo@lngs.infn.it

Exploring high-μ_B matter with rare probes
ECT* 11 Oct 2021

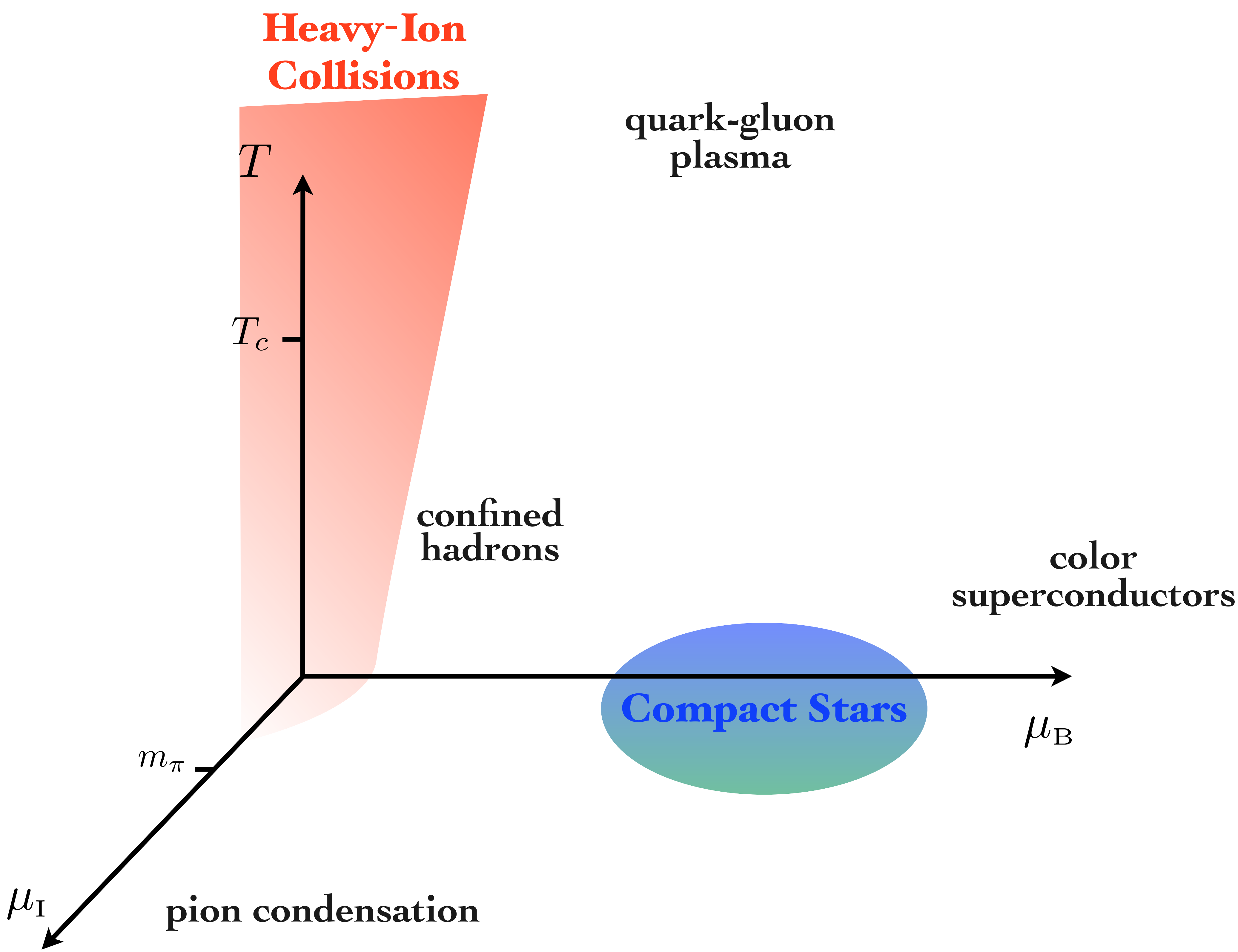
Outline

- **A first approach to the QCD phase diagram**
- **Natural labs**
- **Richness of phases**
- **A second view of the QCD phase diagram**
- **Conclusions**

The phase diagram

What we know… what we would like to know

The QCD phase diagram



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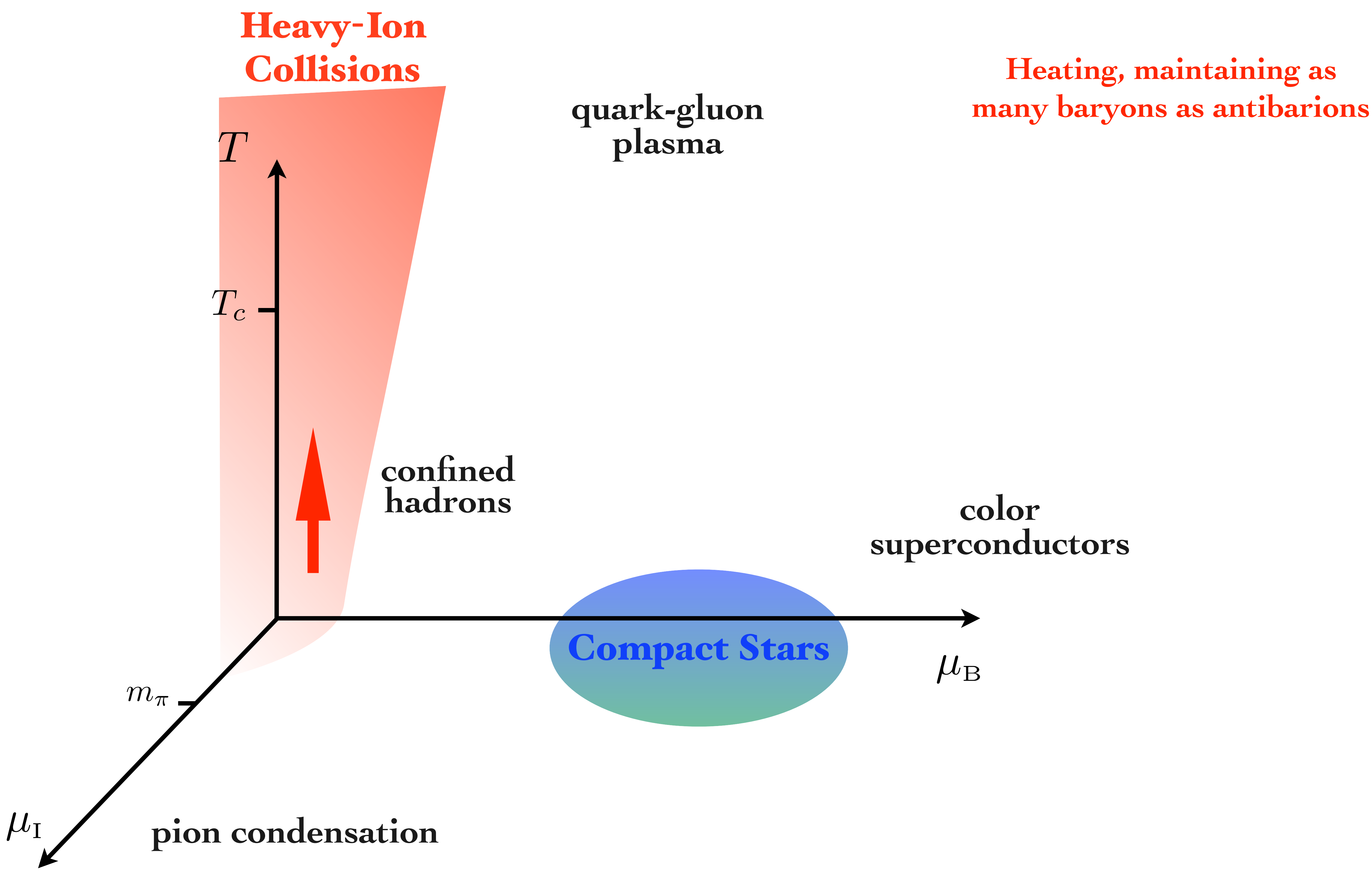

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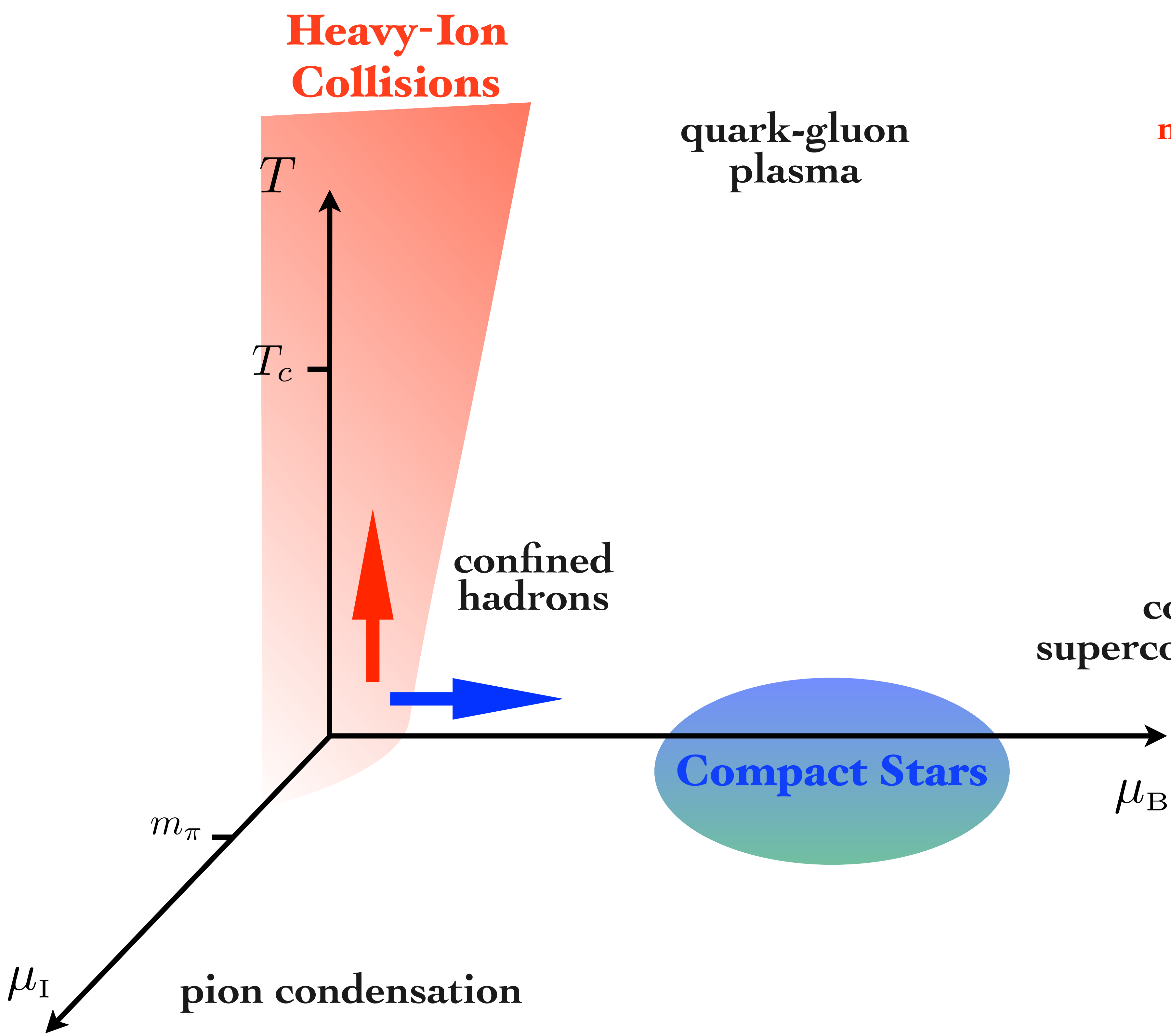

Heating, maintaining as many baryons as antibarions

Compressing, maintaining as many protons as neutrons

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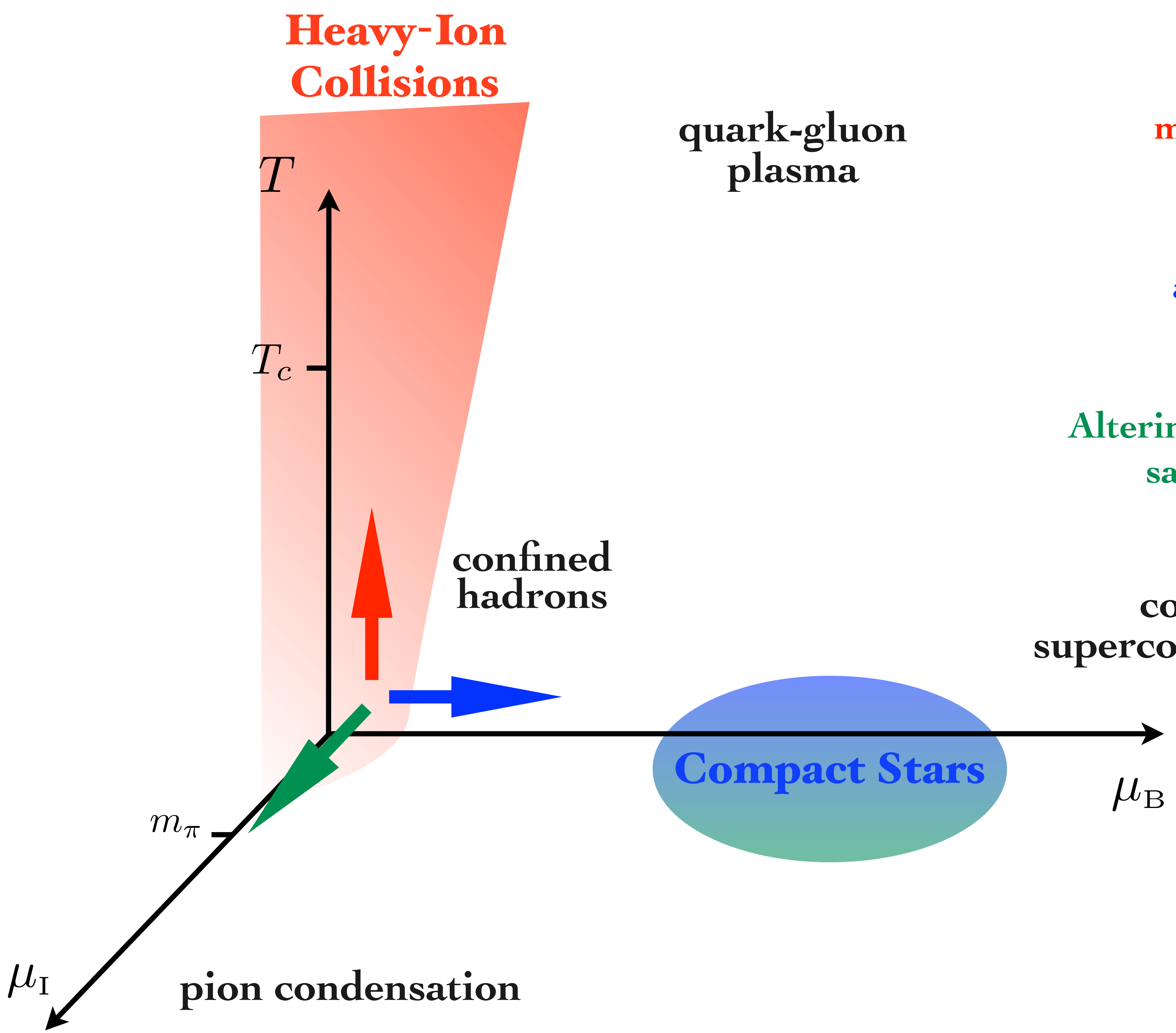

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Compressing, maintaining as many protons as neutrons

Altering, changing chemical composition, say more neutrons than protons

Thermodynamics of hadrons

A thermodynamic description of hadronic matter should include the possible hadrons

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J	Particles (mass in MeV)
0	π^0 (135), $\pi^\pm$ (140), η (547), η' (958), $K^\pm$ (494), $K^0, \bar{K}^0$ (498)
1	$\rho^{\pm,0}$ (771), ω (783), $K^{*\pm}, K^{*0}, \bar{K}^{*0}$ (892), Φ (1020)
$\frac{1}{2}$	p (938), n (939), Λ (1116), $\Sigma^{\pm,0}$ (1193), $\Xi^{0,-}$ (1318)
$\frac{3}{2}$	Δ^{++}, Δ^+, Δ^-, Δ^0 (1232), $\Sigma^{*\pm,0}$ (1385), $\Xi^{*\pm,0}$ (1318), Ω^- (1672)

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Roughly: close to T_c, putting energy into the system increases the number of particles, not the temperature.

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One of the caveats: particles were assumed to be point-like objects.

I.Ya. Pomeranchuk (1951) already noted that a crucial feature of hadrons: their size. A hadron must have its own volume to exist.

Quark liberation

N. Cabibbo and G.Parisi PLB 59, Issue 1, 13 October 1975

"We suggest that the “observed” exponential spectrum is connected to the existence of a different phase of the vacuum in which quarks are not confined."

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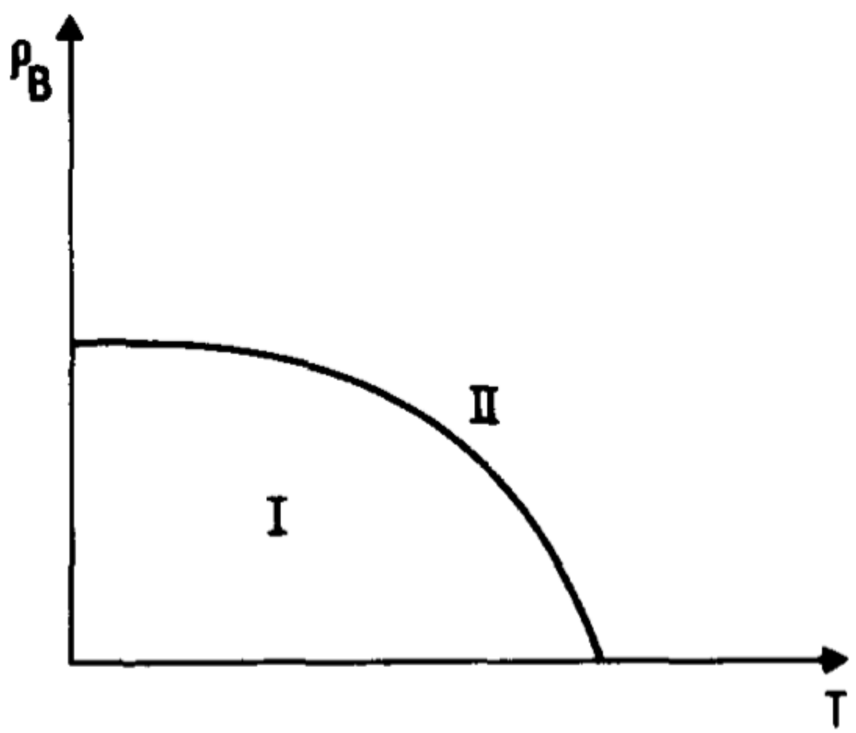

Fig. 1. Schematic phase diagram of hadronic matter. ρ_B is the density of baryonic number. Quarks are confined in phase I and unconfined in phase II.

In the $V \to \infty$ limit the exponential spectrum is typical of second order phase transitions

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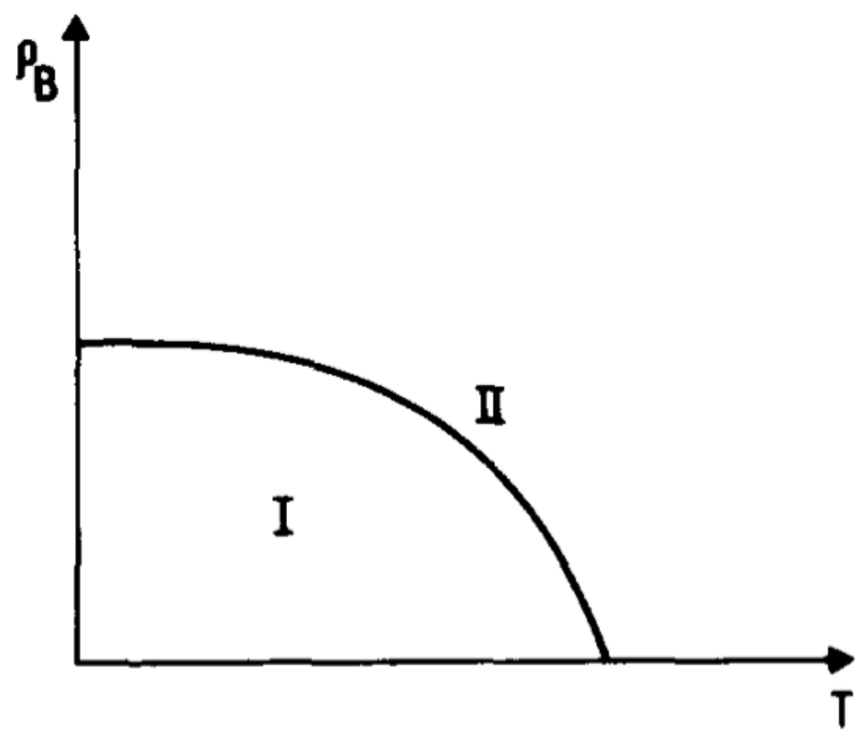

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The behavior of matter close to the phase transition is characterized by a kind of "critical opalescence" of hadrons

Important lesson:

1) **Close to T_c hadronic resonances play a crucial role**

2) **There exists a limiting temperature, T_c, for hadronic matter. If we insist to describe hadronic matter in terms of baryons and mesons at increasing temperature, the description becomes inconsistent.**

3) **The critical temperature is of order m_π**

4) **The pressure of the bootstrap statistical model is in agreement with LQCD calculation below T_c**

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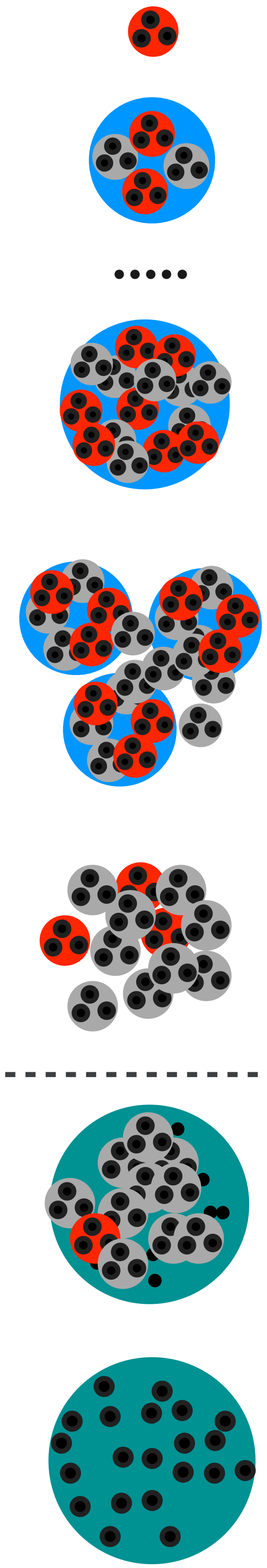
See Redlich and Satz, e-Print: 1501.07523 [hep-ph]
for more on Hagedorn's work.

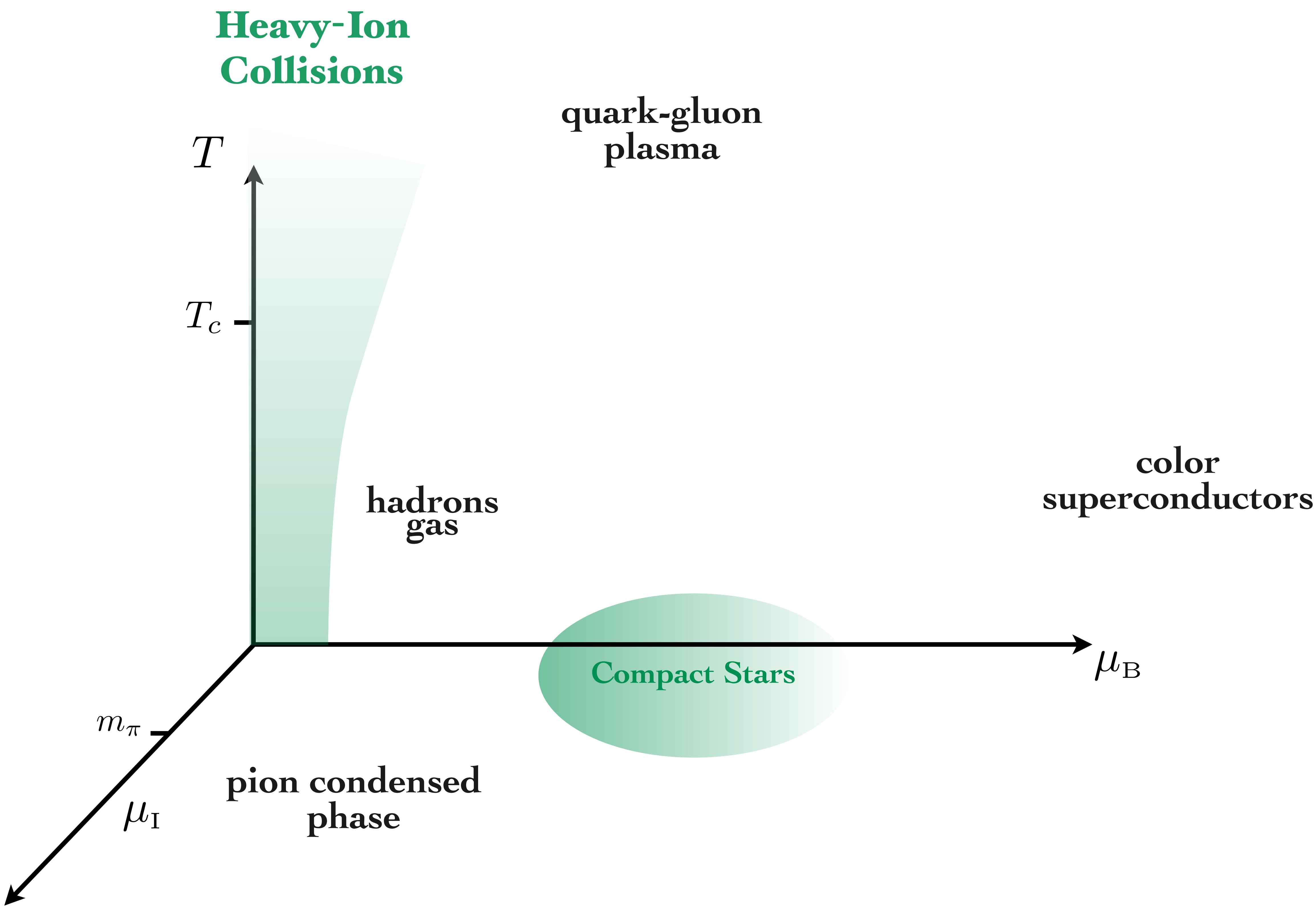
Increasing energy density



	Density	NS part	$\alpha_s \equiv \alpha_s(\mu)$	Degrees of freedom
H				light nuclei
He	10^{-4} g cm^{-3}	atmosphere		
.....				.....
Fe	10 g cm^{-3}	outer crust	confining	heavy nuclei
neutron drip	10^{11} g cm^{-3}	inner crust		
neutron proton soup	10^{14} g cm^{-3}	core		neutrons and protons
quark drip	very large		strong coupling	Cooper pairs of quarks? quarkyonic matter? instantons? glueballs?
quark soup	extreme		weak coupling	quarks and gluons

ρ

Methods



Heavy-Ion Collisions
quark-gluon plasma
T
T_c
hadrons gas
color superconductors
Compact Stars
μ_{B}
m_π
μ_{I}
pion condensed phase

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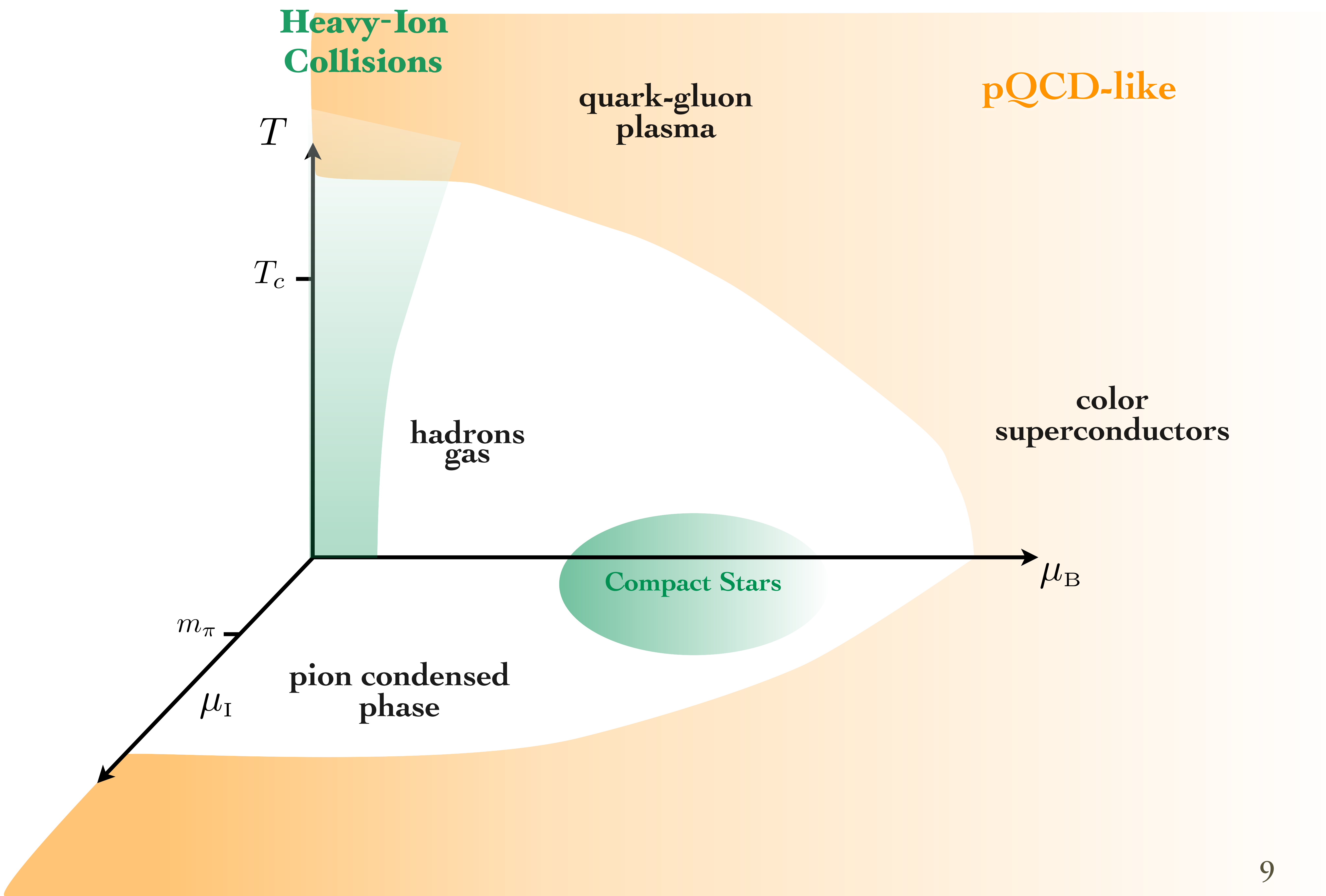

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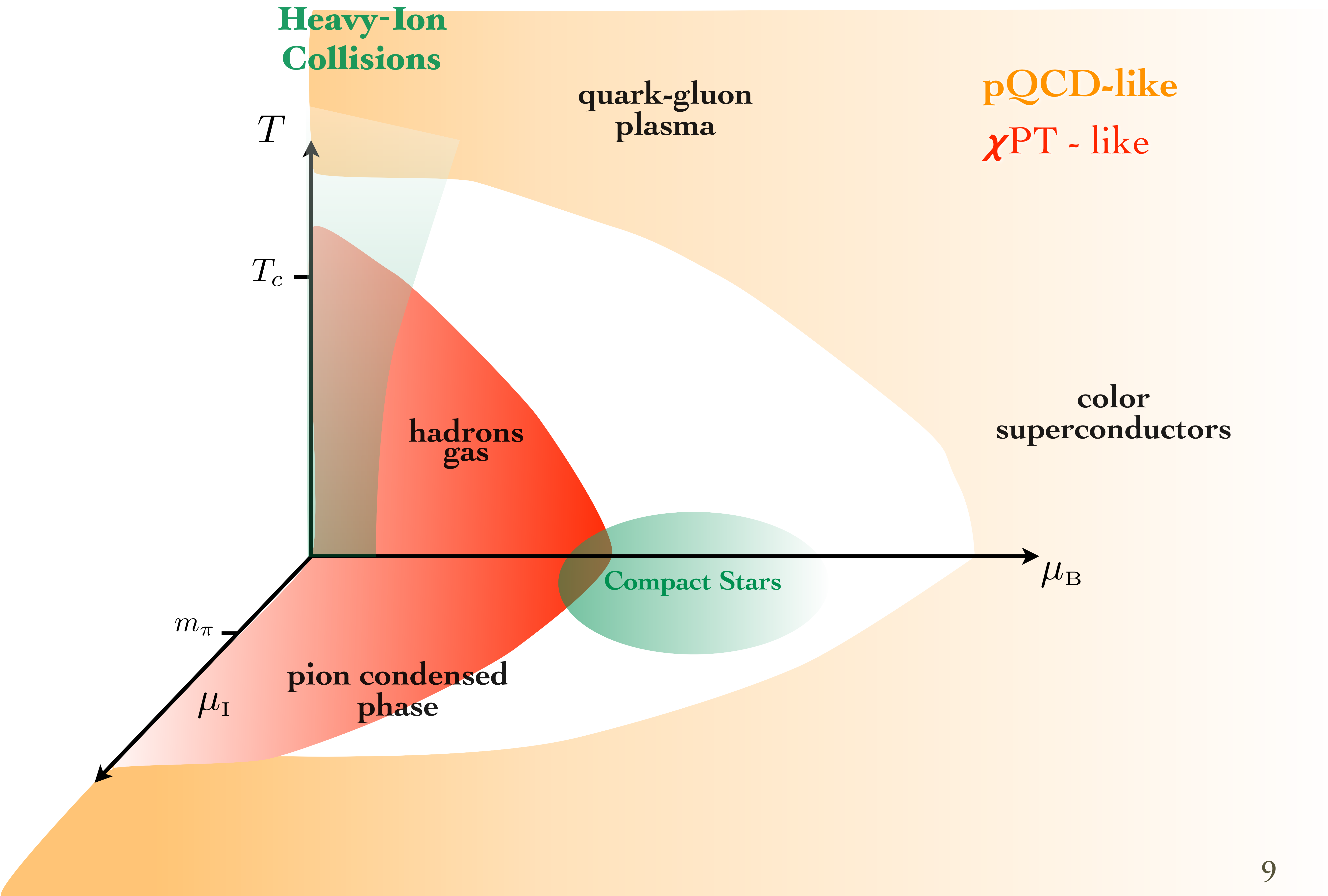
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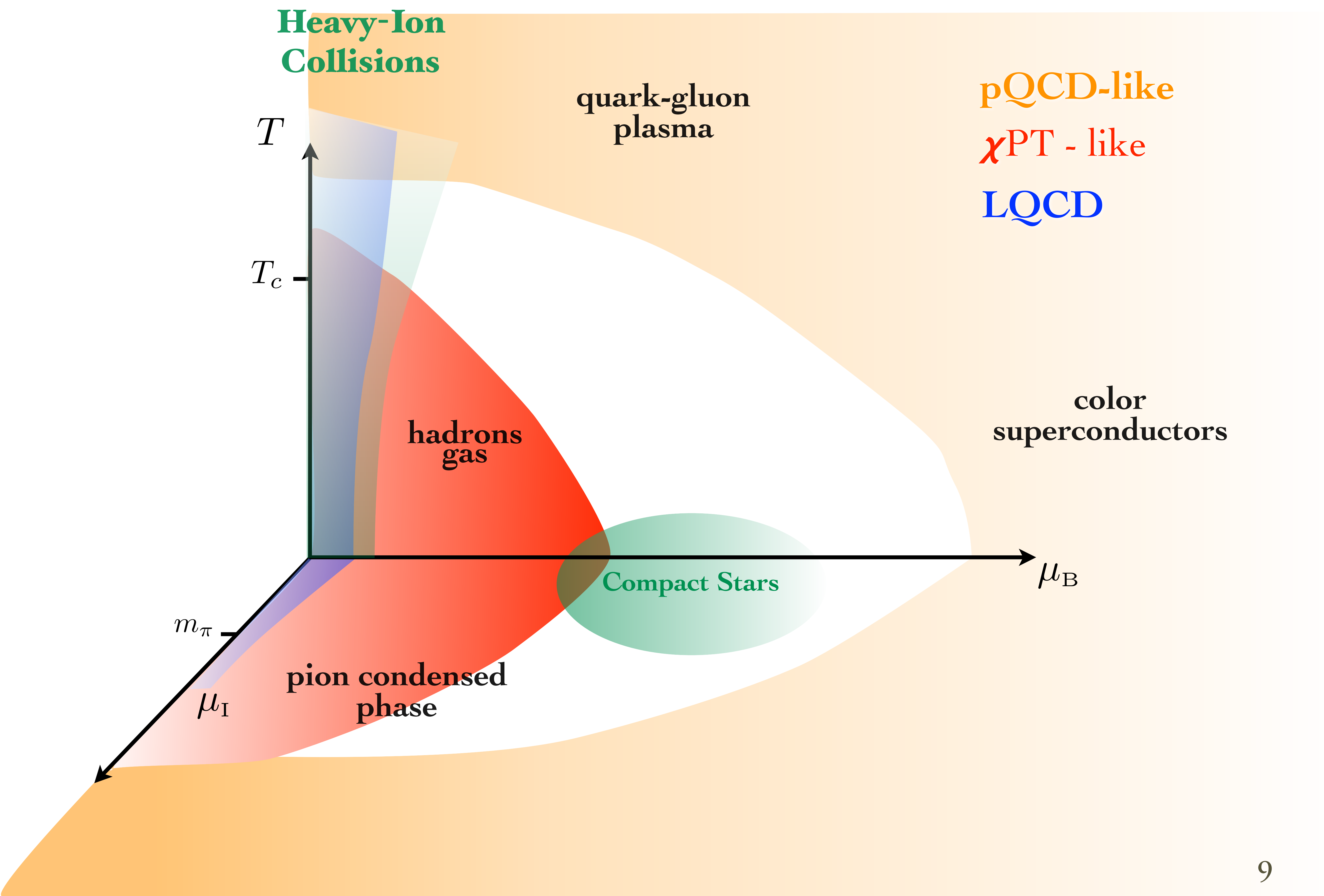
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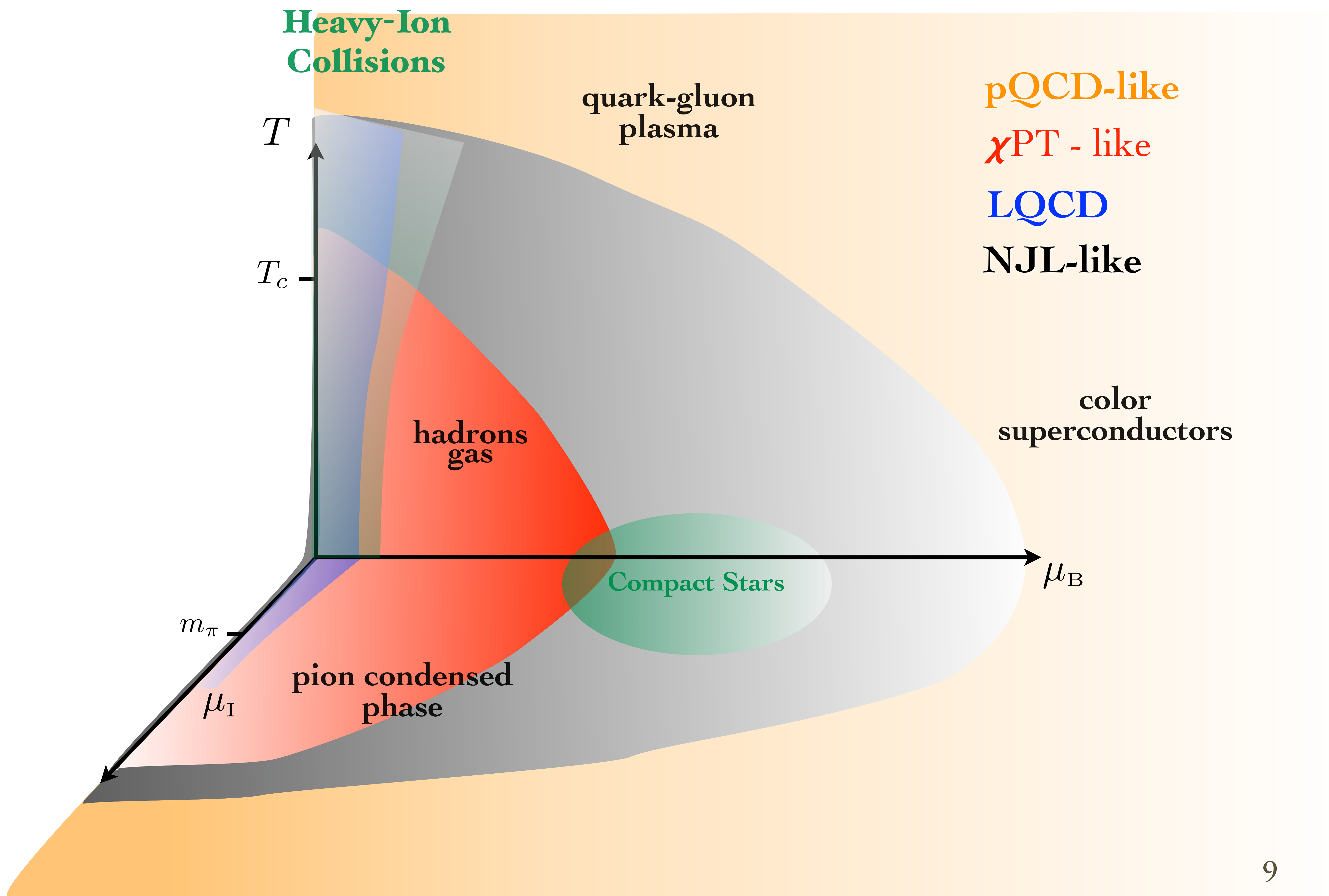
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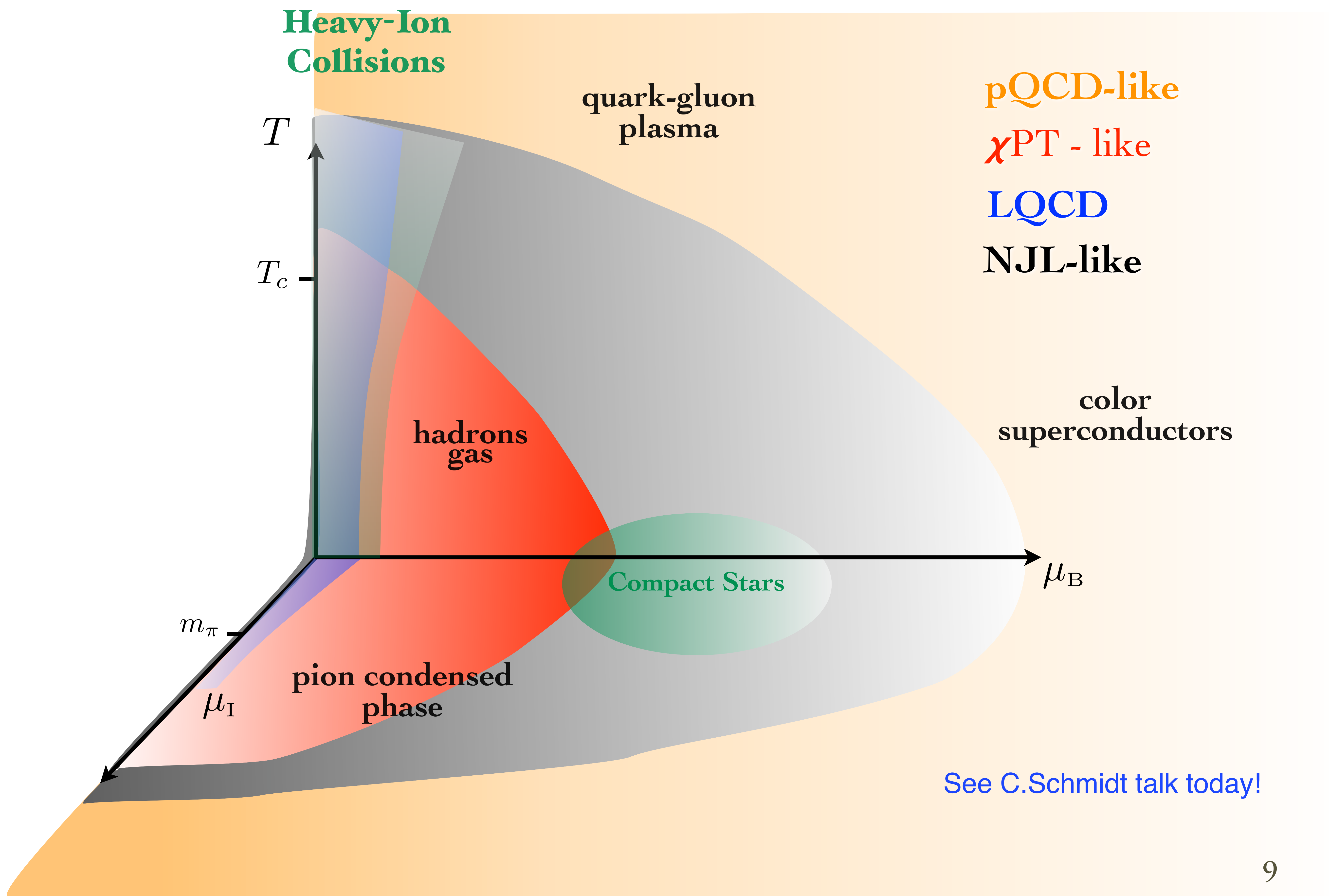
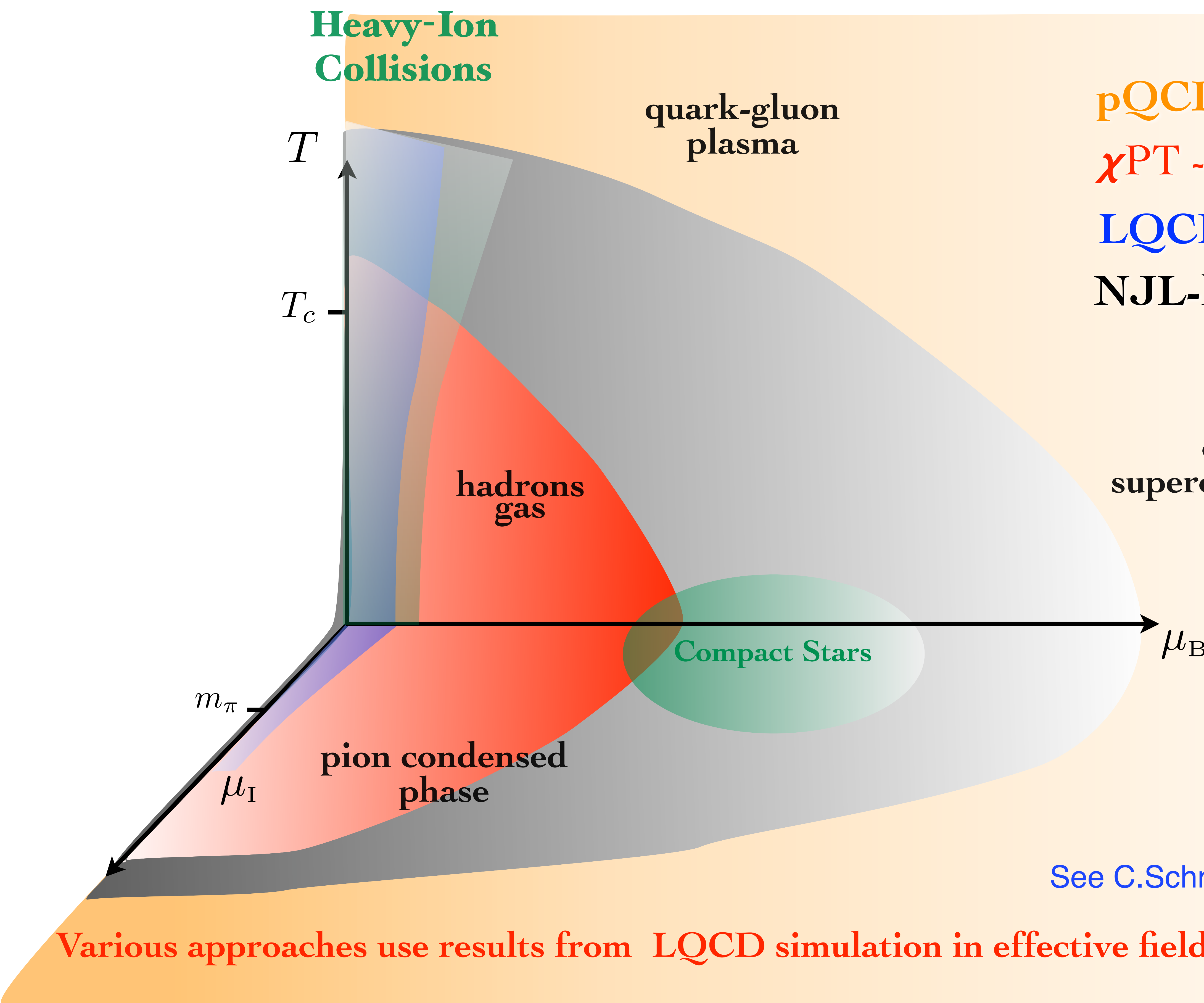


See C.Schmidt talk today!

Methods



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χPT - like

LQCD

NJL-like

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Various approaches use results from LQCD simulation in effective field theories.

Effective field theory: two perspectives

Schematically, two approaches to matter in extreme conditions

1) Understanding the (astro)physical phenomena related to high chemical potential and temperature
2) Understanding QCD in a region in which the correct degrees of freedom ar quarks and gluons

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Schematically, two approaches to matter in extreme conditions

1) Understanding the (astro)physical phenomena related to high chemical potential and temperature
2) Understanding QCD in a region in which the correct degrees of freedom ar quarks and gluons

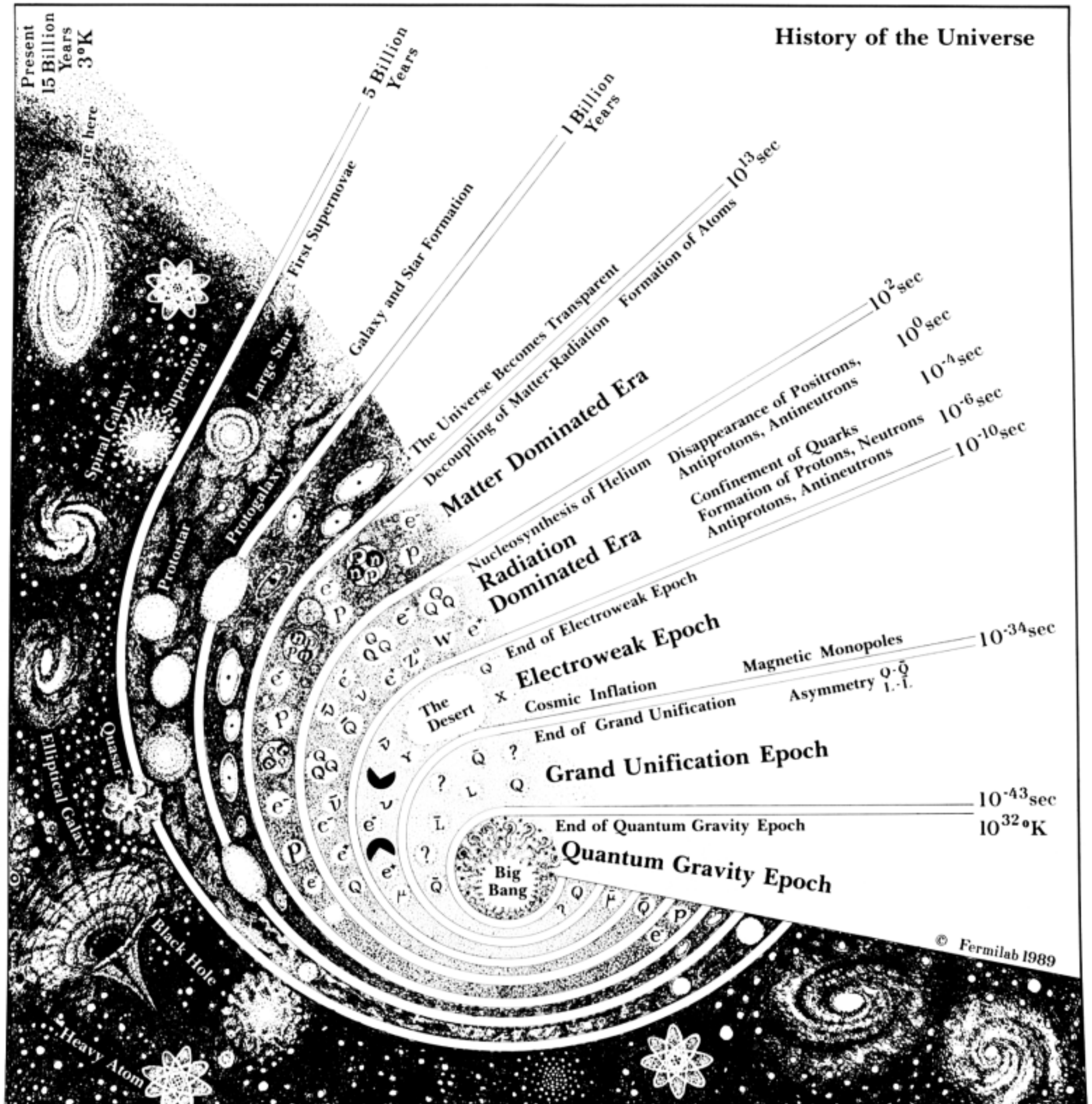
The two perspectives are not mutually exclusive.

However, for those who are interested in (astro)physical phenomena, it is enough to have an effective theory which mimics/reproduces the strong interaction in a sufficiently accurate way.

Who is interested to understand QCD wants an effective theory that in a well defined limit is QCD

Natural labs

High temperature: The Early Universe



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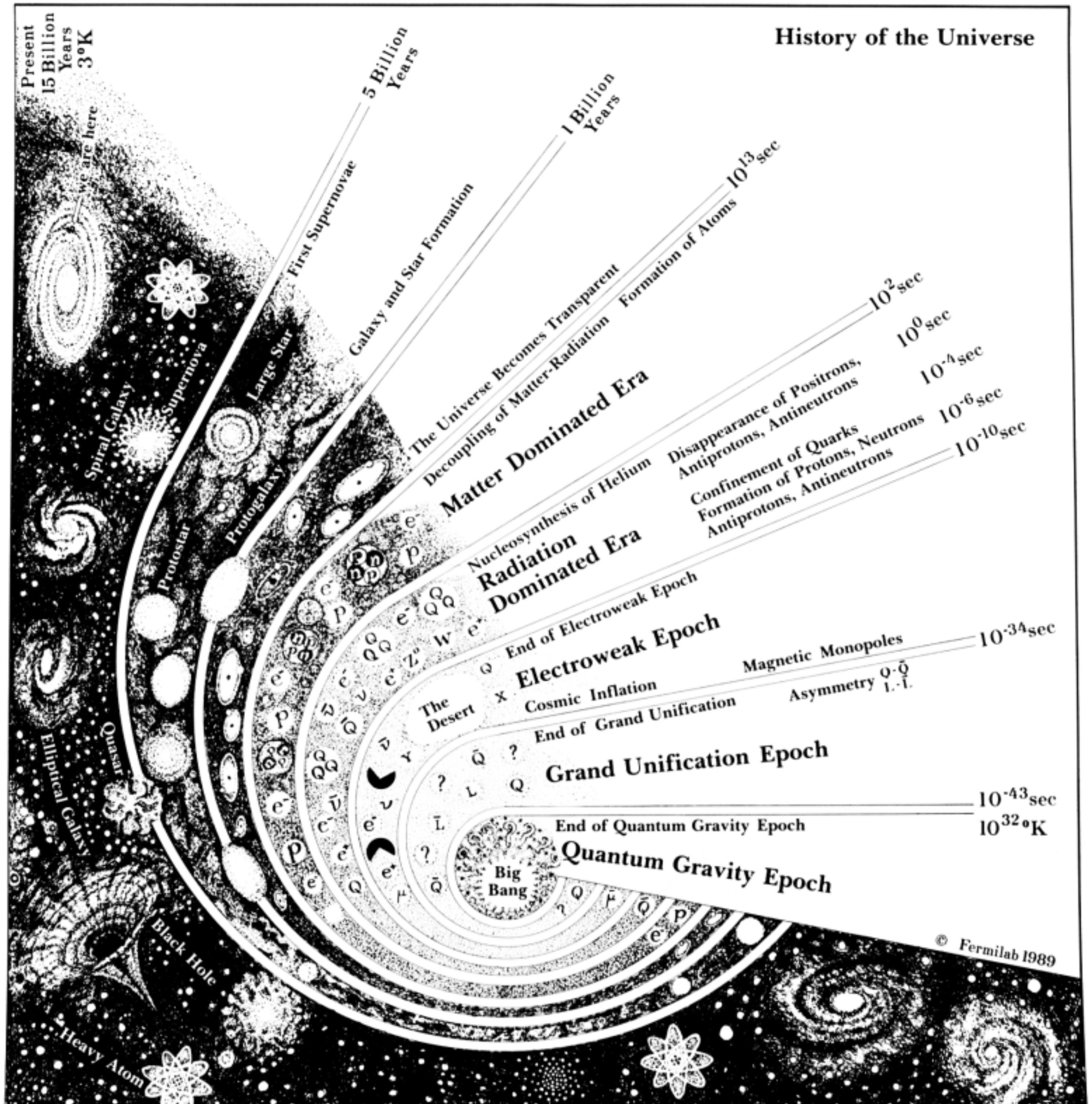

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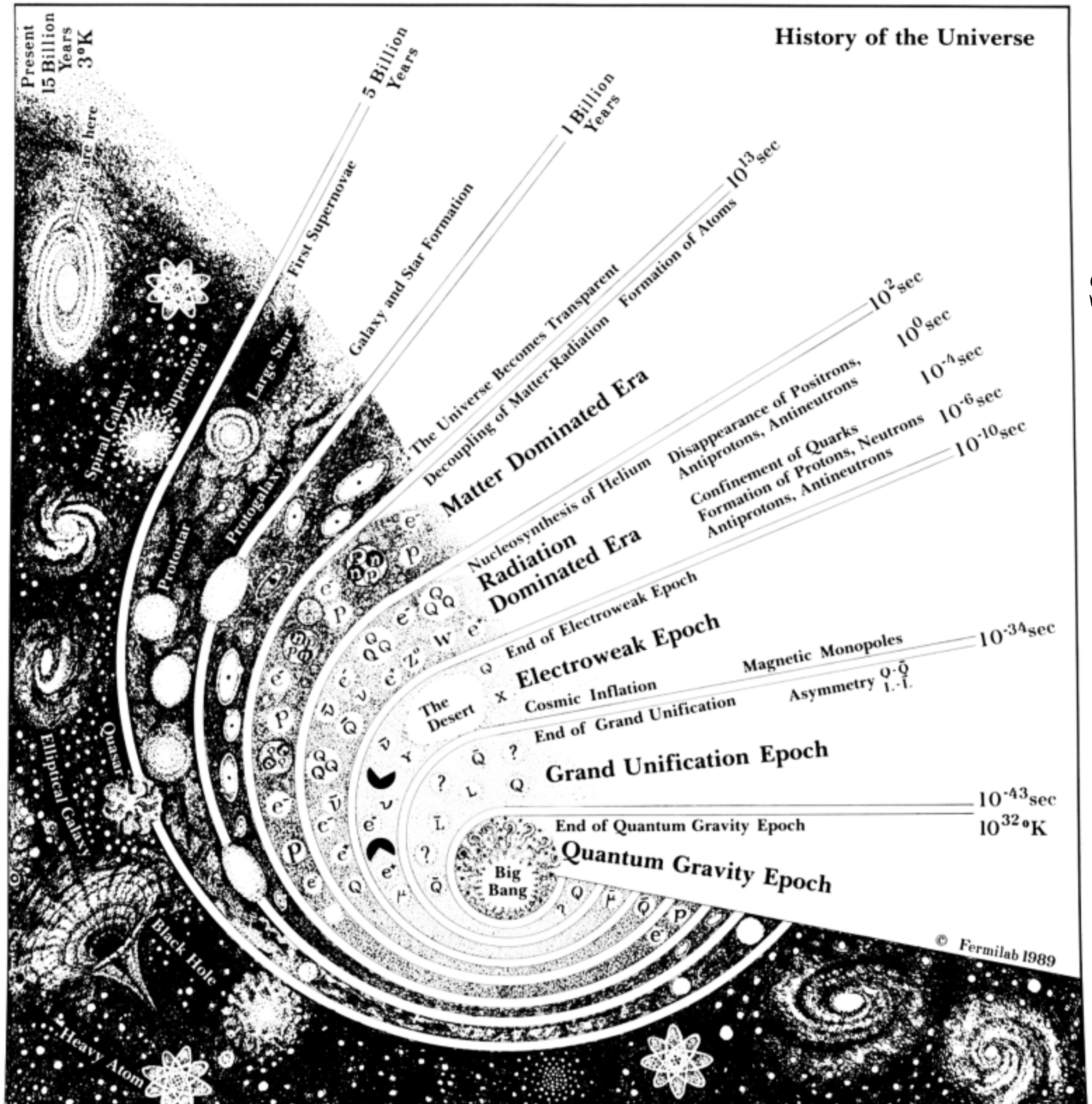

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Scale variation by Friedmann's equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G_N}{3}(\epsilon + 3p)$$

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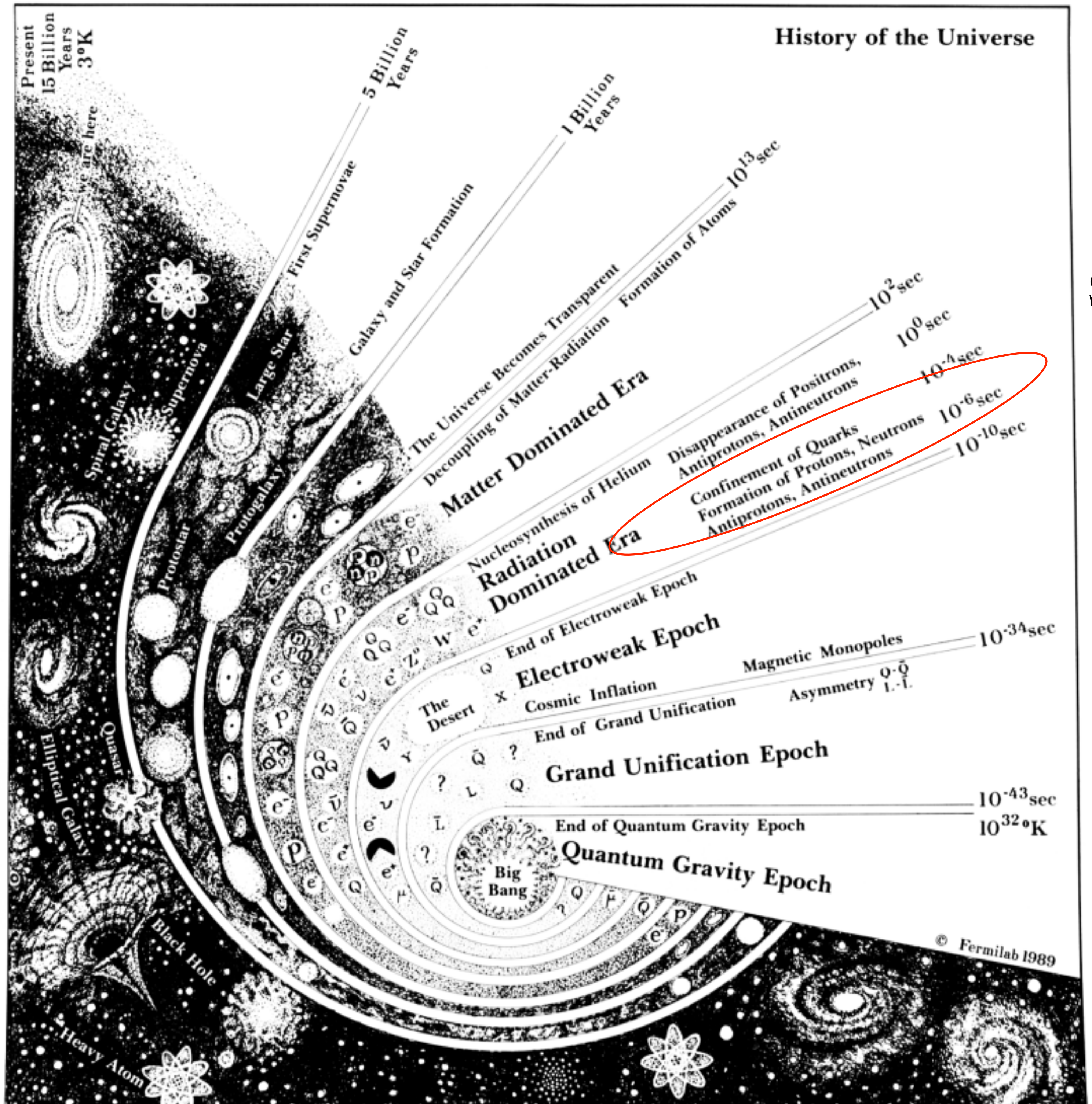

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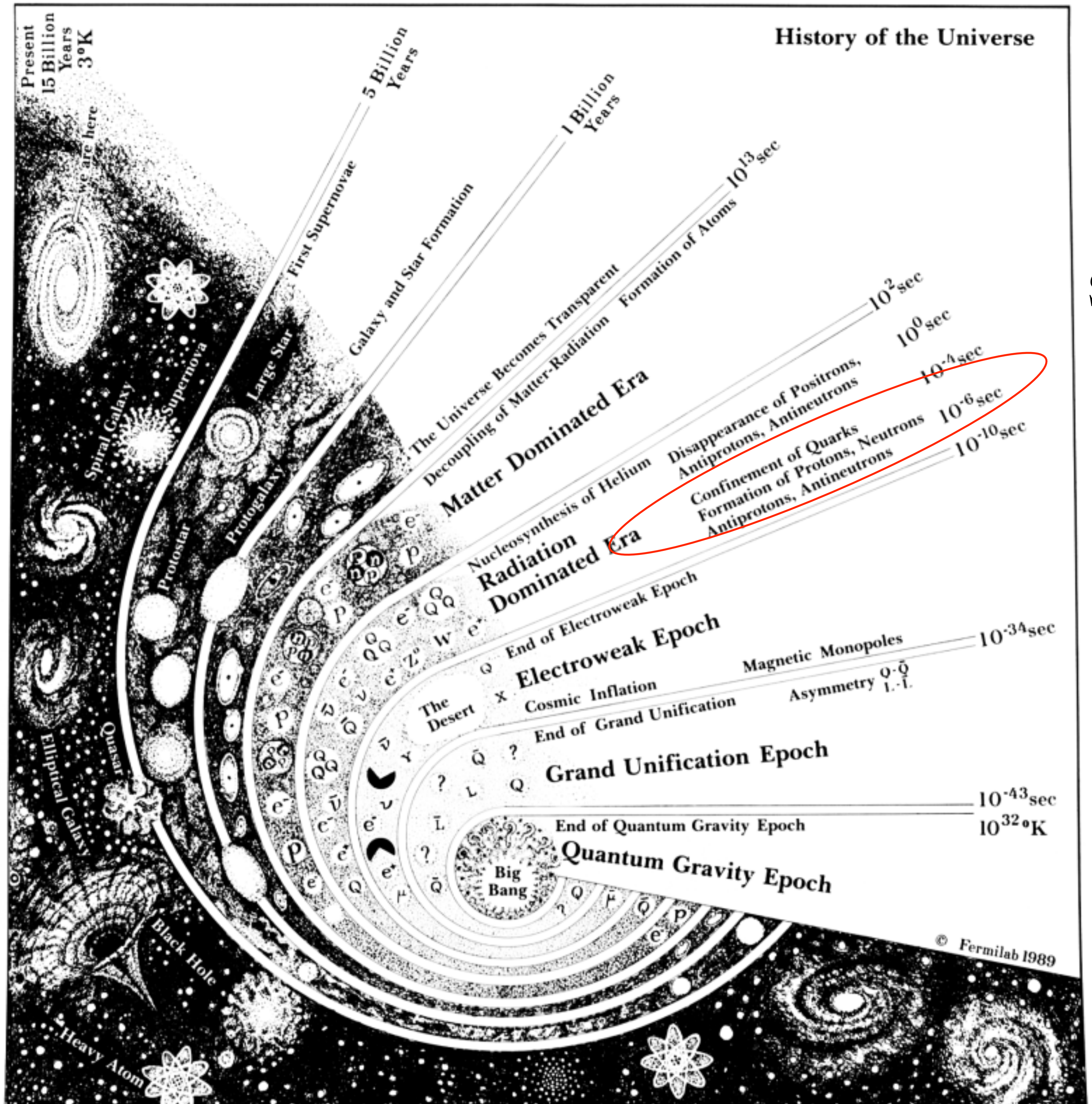

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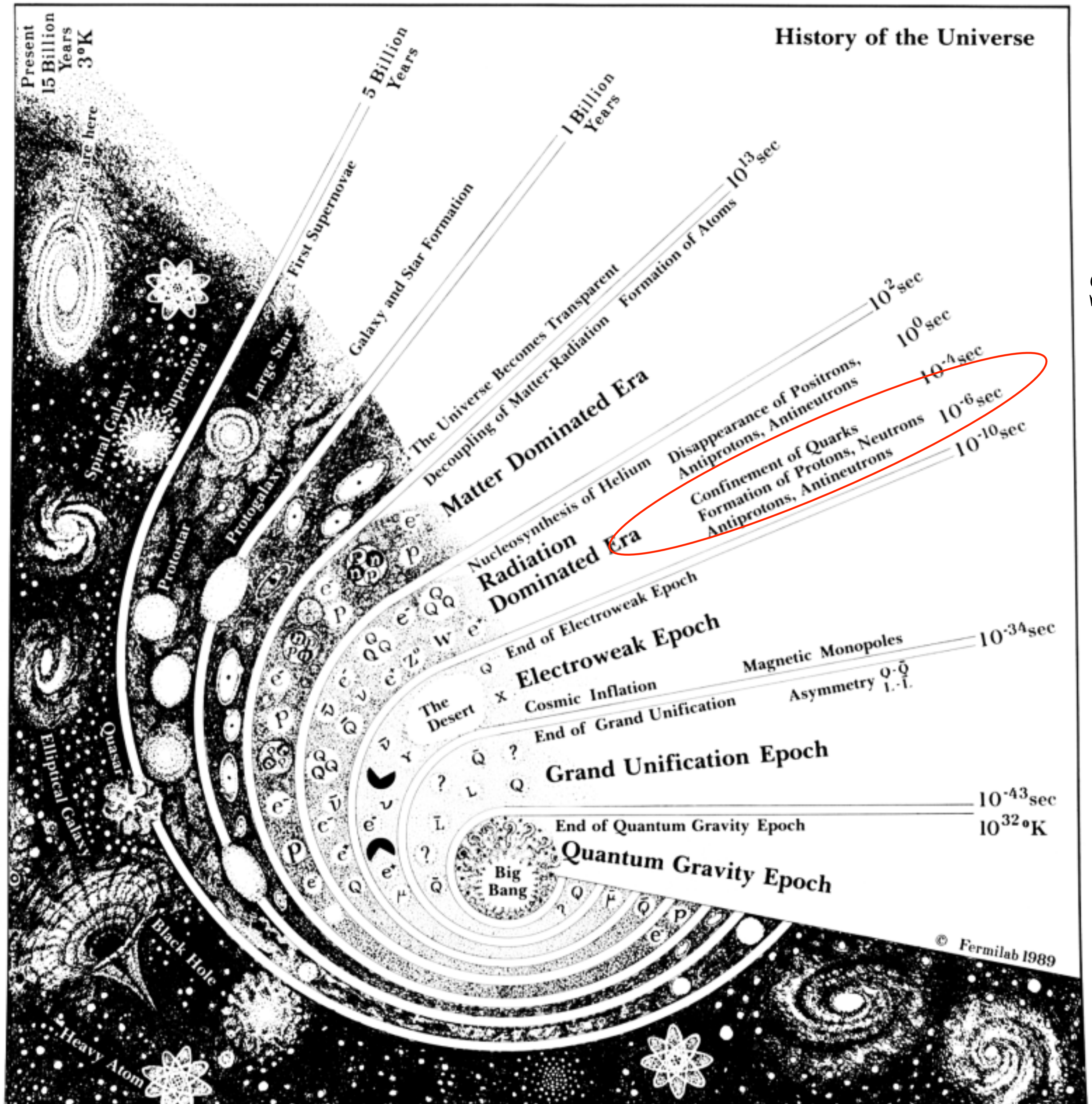

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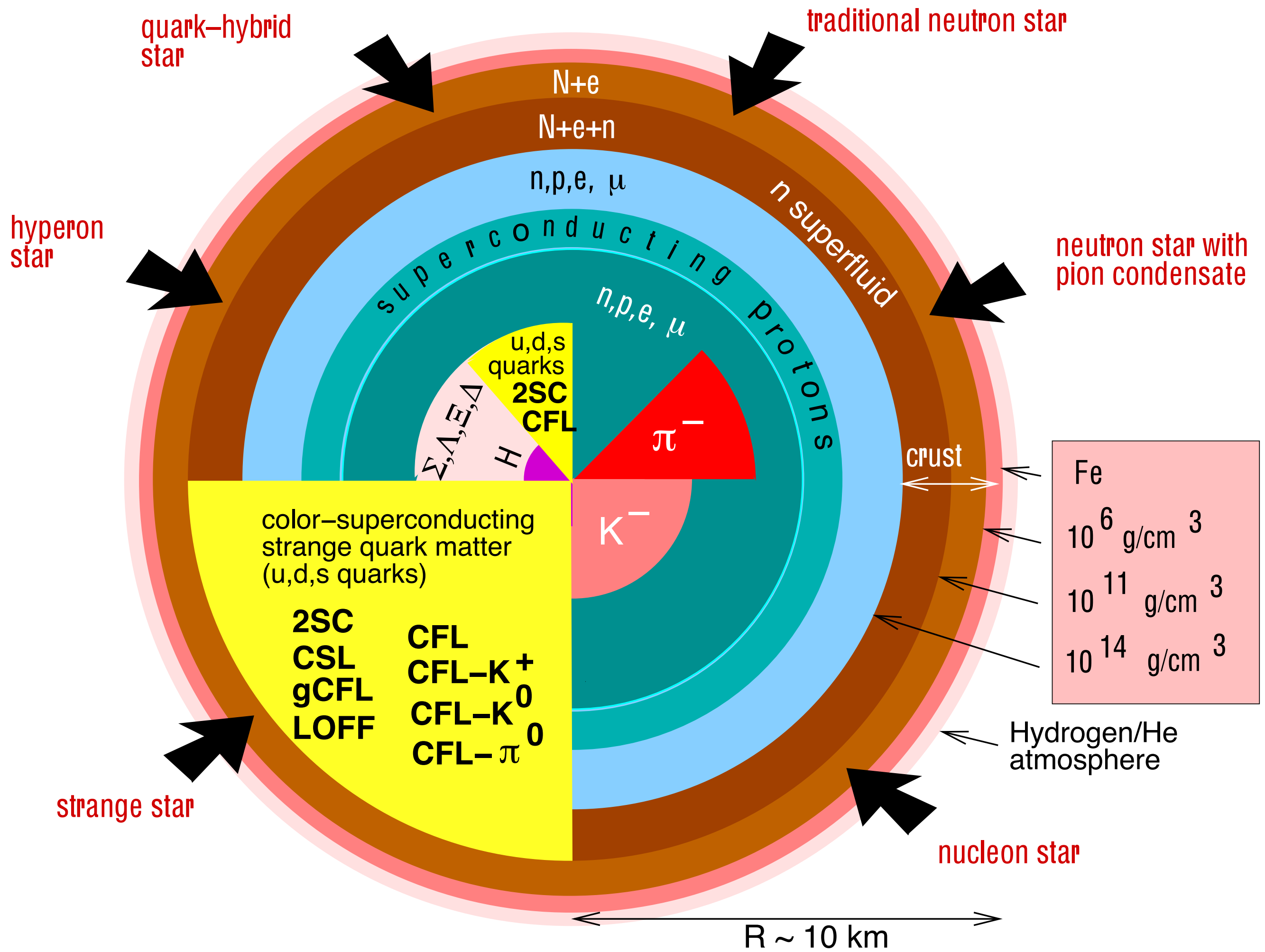
J. Rafelski, Nucl.Phys.B Proc.Suppl. 243-244 (2013)

High baryonic density: Compact stars



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F. Weber, Prog.Part.Nucl.Phys. 54 (2005) 193

Possible deconfined phases of matter

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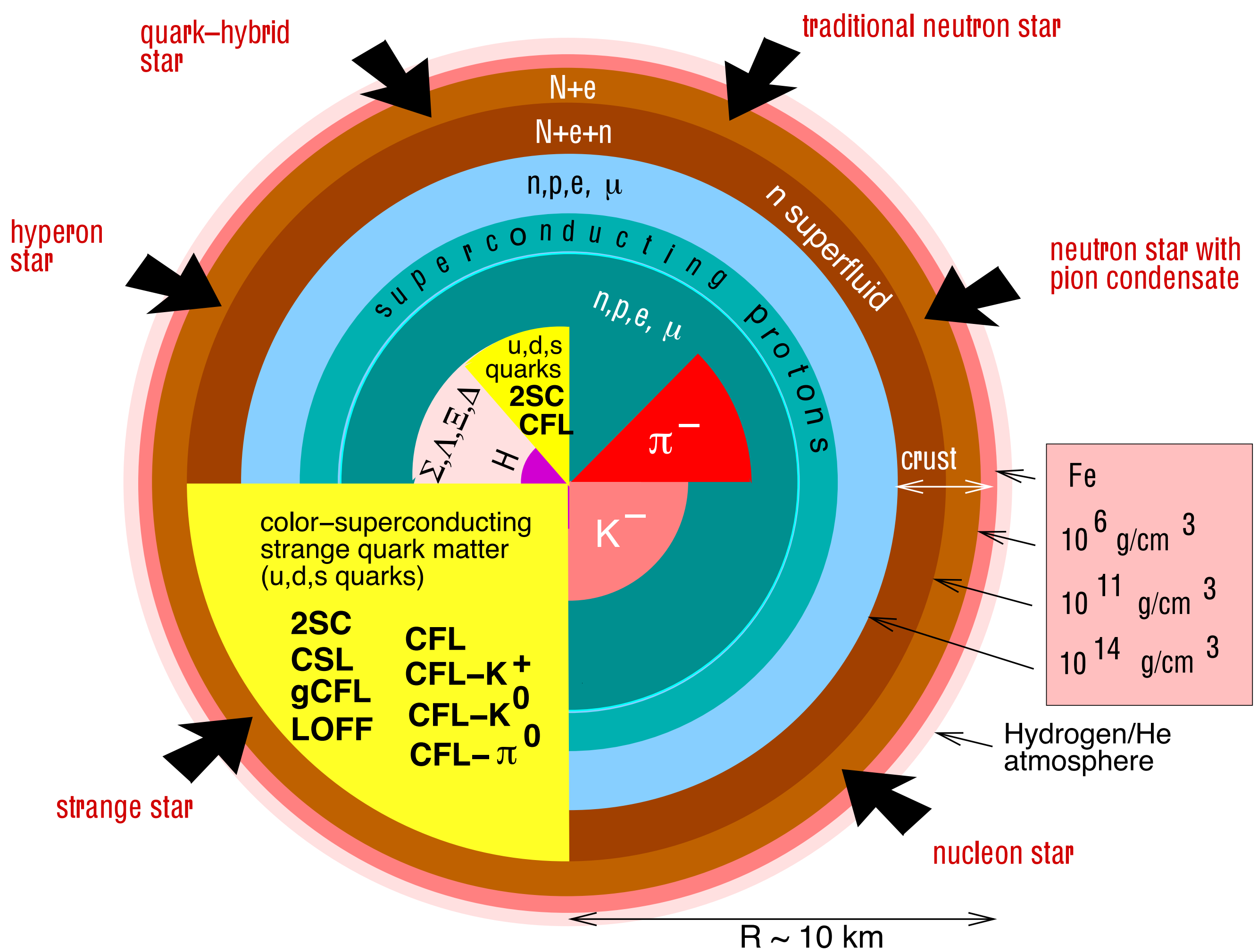

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Experimentally access in labs on Earth? Need to produce neutron rich matter.

Compressing cold matter

Differently from the "lab case", weak equilibrium in Neutron Stars has all the time to work.
Favored isotopes in the NS crust

Neutron rich matter

Isotope	Z/A	$\rho_t(\mathrm{g/cm^3})$	μ_e (MeV)
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Neutron rich matter

many electrons

neutron drip

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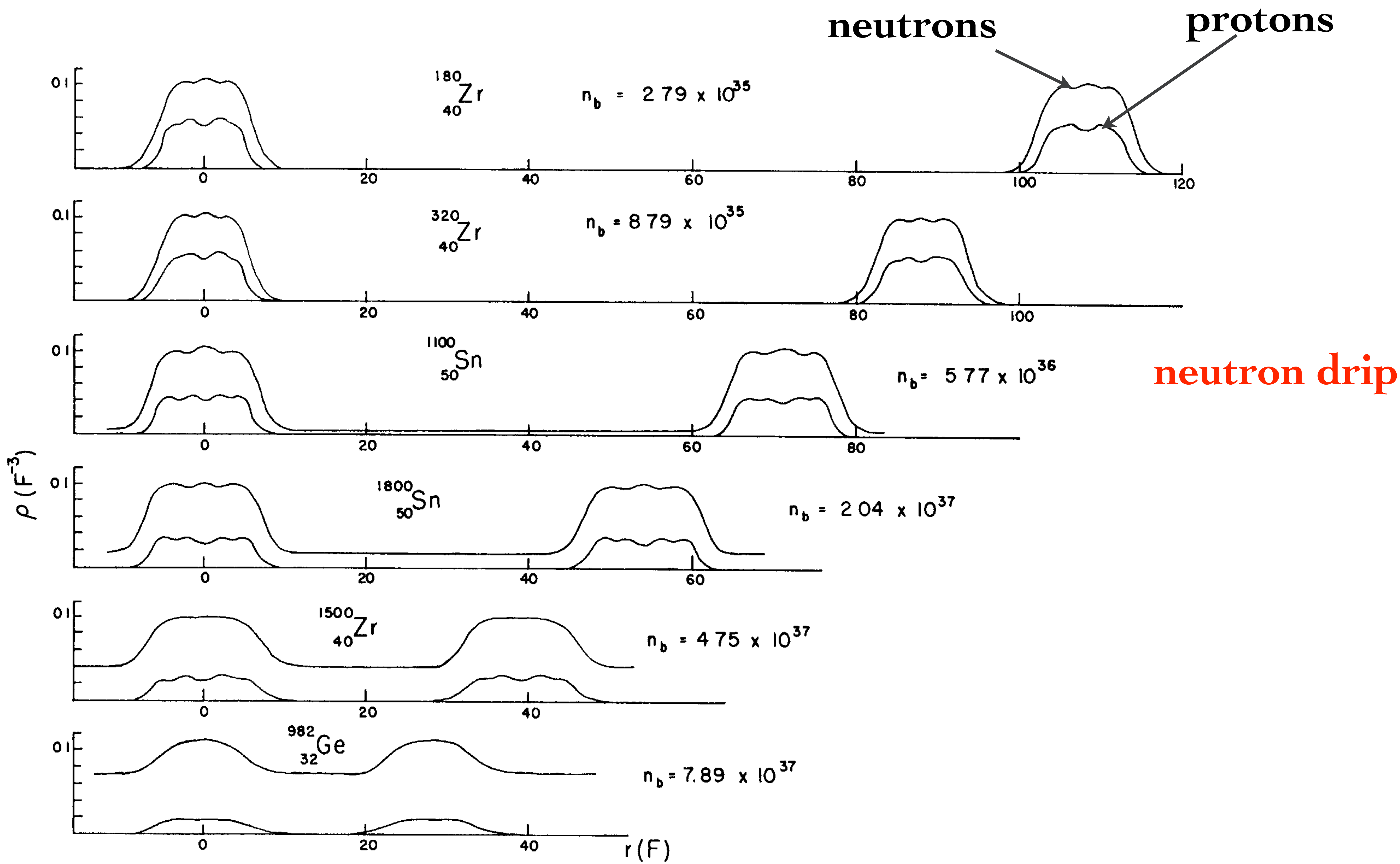
Inner crust $10^{11}\ \mathrm{g\ cm^{-3}} < \rho < 10^{14}\ \mathrm{g\ cm^{-3}}$



Proton and neutron density profiles along the lines joining two nuclei

J. W. Negele and D. Vautherin, Nucl. Phys. A207, 298 (1973).

Quantum chromoynamics

UV freedom, IR confinement

$$\mathcal{L}_{\rm QCD} = \bar\psi(i\gamma^\mu D_\mu + \mu\gamma_0 - M)\psi - \frac{1}{4}F_a^{\mu\nu}F^a_{\mu\nu}$$

quark fields: $\psi_{\alpha,i}$

$\alpha,\beta = 1,2,3$ **color indices**

$i,j = 1,\ldots,6$ **flavor indices**

gluon gauge fields: $\mathbf{A}^a$

$a = 1,\ldots,8$ **adjoint color index**

QCD non-Abelian gauge theory, non-perturbative at energy scales below $\Lambda_{\rm QCD} \sim 200$ MeV

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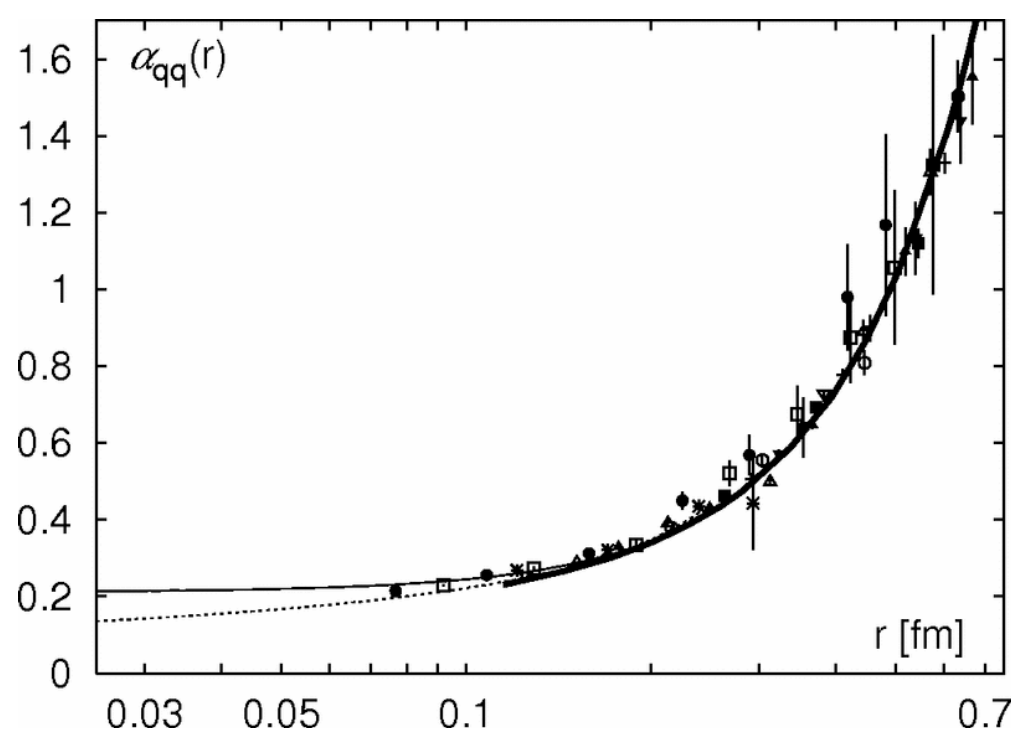
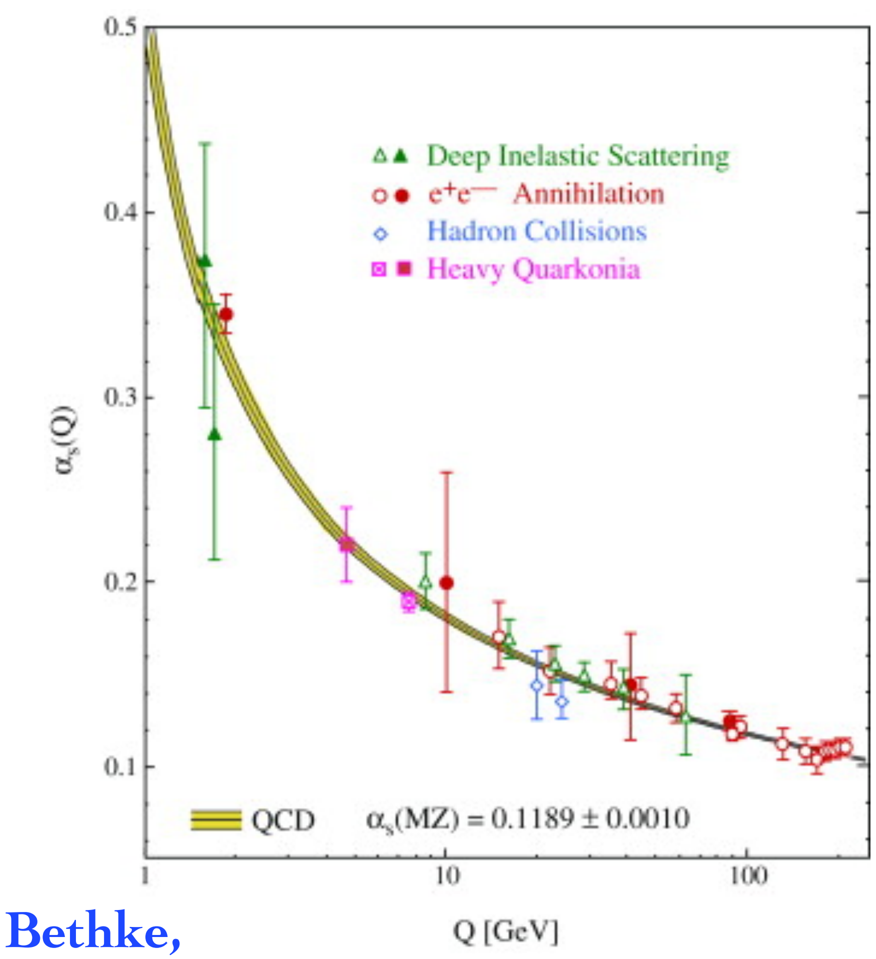


Kaczmarek and Zantow
Physical Review D 71(11):114510



S. Bethke,
Prog.Part.Nucl.Phys. 58 (2007) 351-386

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gluon gauge fields: $\mathbf{A}^a$

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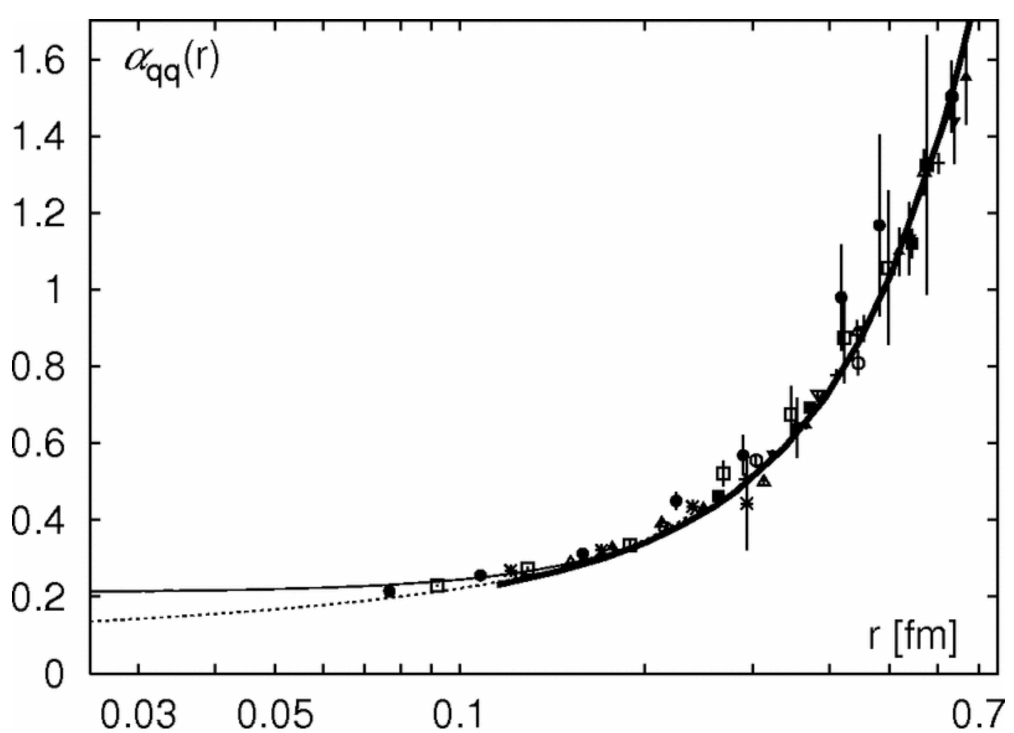
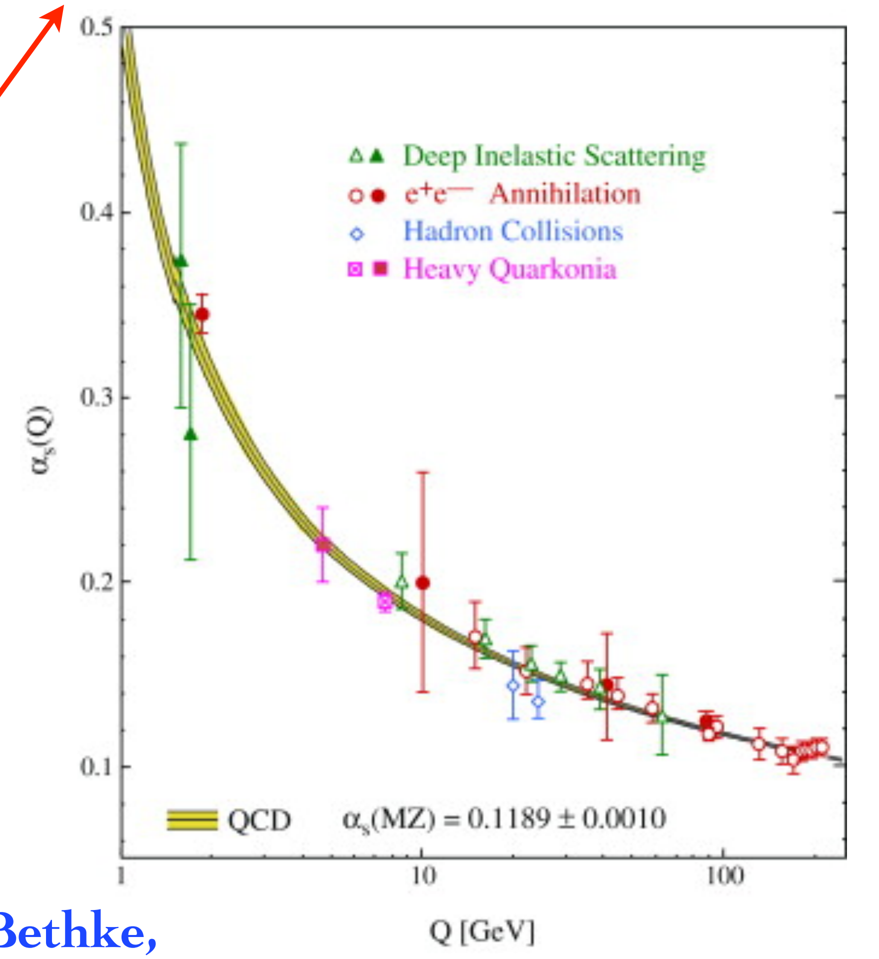
QCD non-Abelian gauge theory, non-perturbative at energy scales below $\Lambda_{\text{QCD}} \sim 200$ MeV



confinement



Kaczmarek and Zantow
Physical Review D 71(11):114510

S. Bethke,
Prog.Part.Nucl.Phys. 58 (2007) 351-386

UV freedom, IR confinement

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}(i\gamma^\mu D_\mu + \mu\gamma_0 - M)\psi - \frac{1}{4}F_a^{\mu\nu}F_{\mu\nu}^a$$

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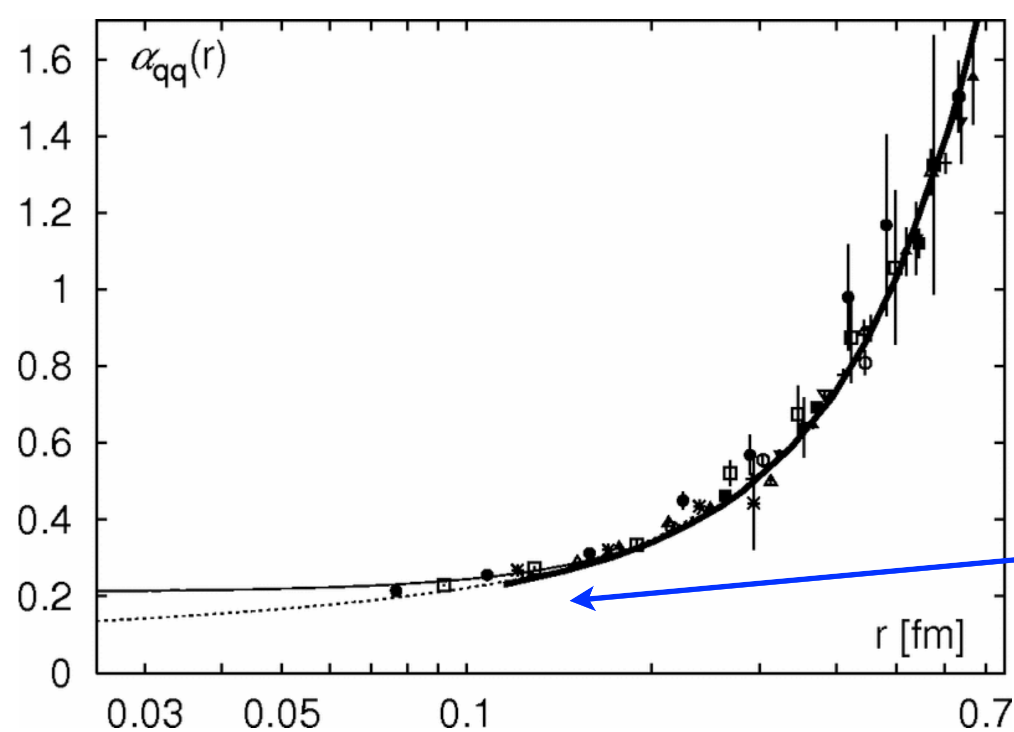

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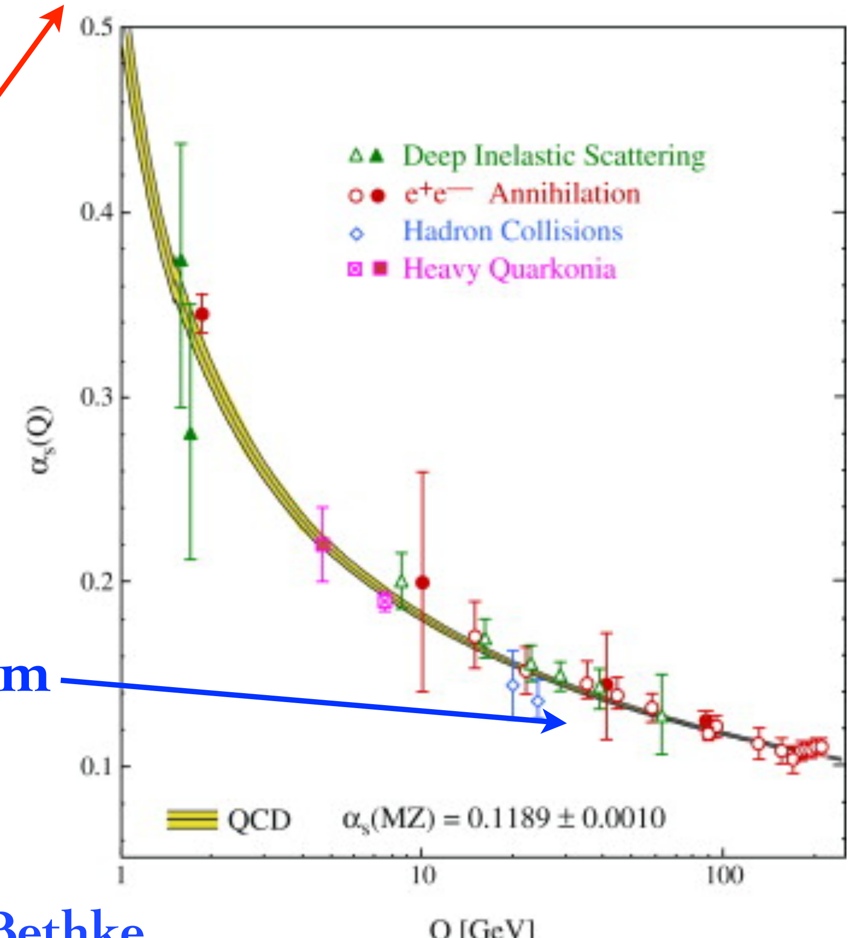
asymptotic freedom



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Symmetries

$m = 0$

Three flavor massless quark matter

gauge group **global chiral symmetry** **global baryonic number**

$$SU(3)_{\rm c} \times \underbrace{SU(3)_{\rm L} \times SU(3)_{\rm R}}_{\supset\, [U(1)_{\rm e.m.}]} \times U(1)_{\rm B}$$

$m \to \infty$

Quenched QCD (pure Yang-Mills)

Polyakov loop

$$L = \mathcal{P} \exp \left[i \int_0^\beta dx_4 A_4 \right]$$

remarkably $e^{-\beta F_q} = \langle L \rangle$

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Deconfinement and chiral symmetry breaking

m: mass of quark fields

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Center symmetry: $Z(N_c)$, broken at T_D (first order phase transition)

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QCD T_D and T_χ are pseudo-critical temperatures

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To keep in mind

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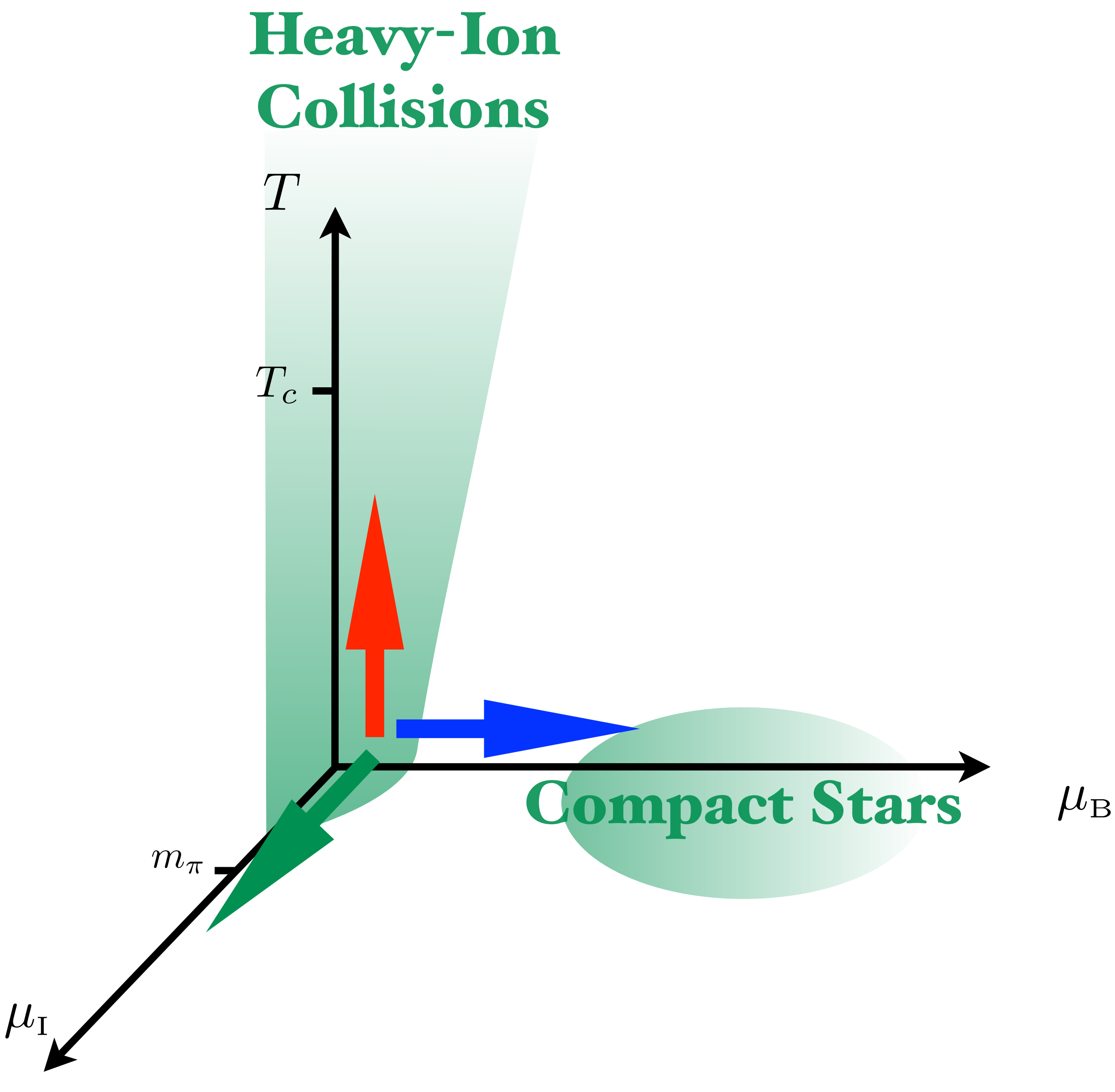
3) Apart from these theory group arguments, it is important to have a phenomenological description of confinement (and chiral symmetry breaking) as associated to a change of degrees of freedom.

Heating, compressing or altering?



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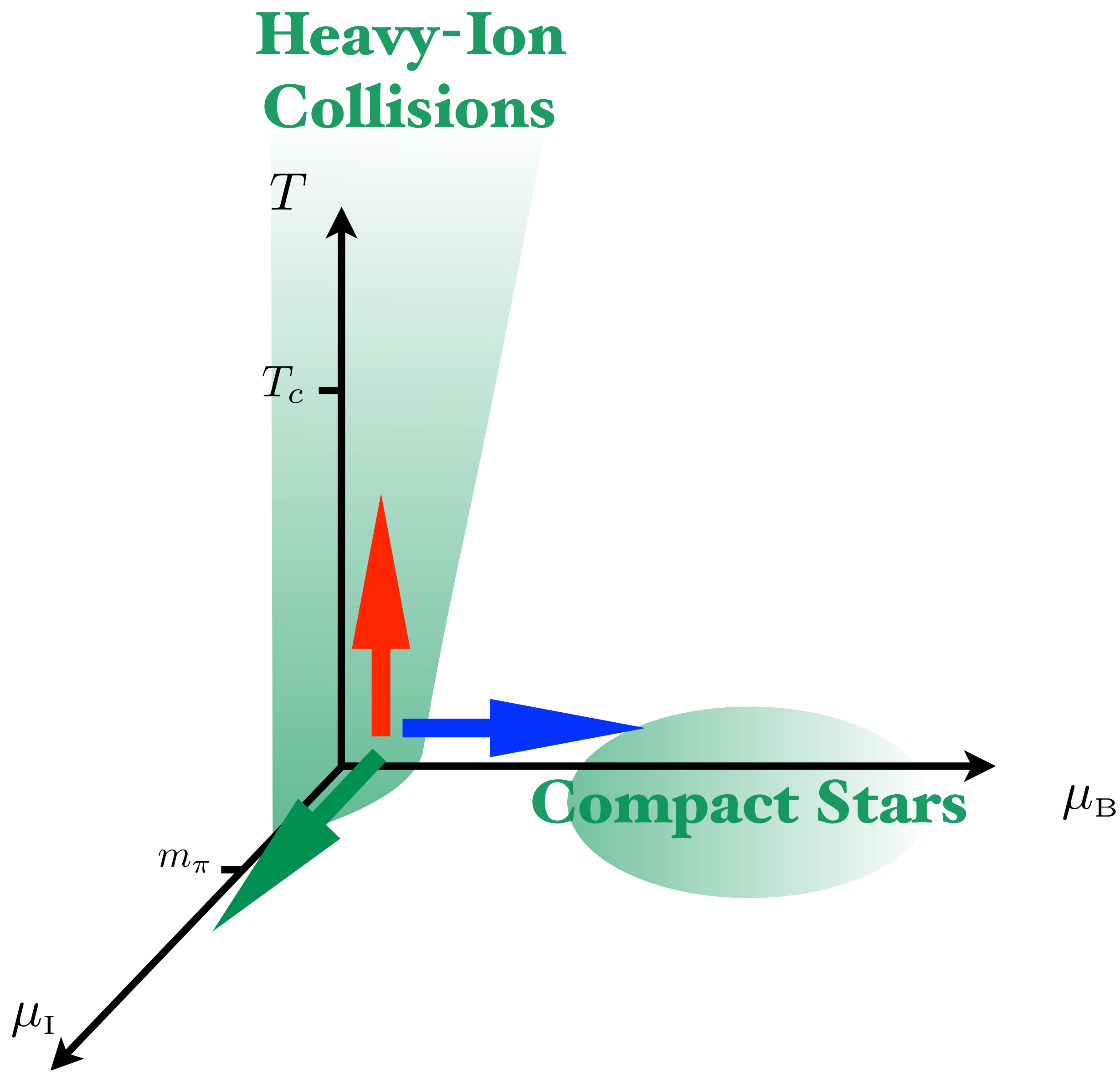

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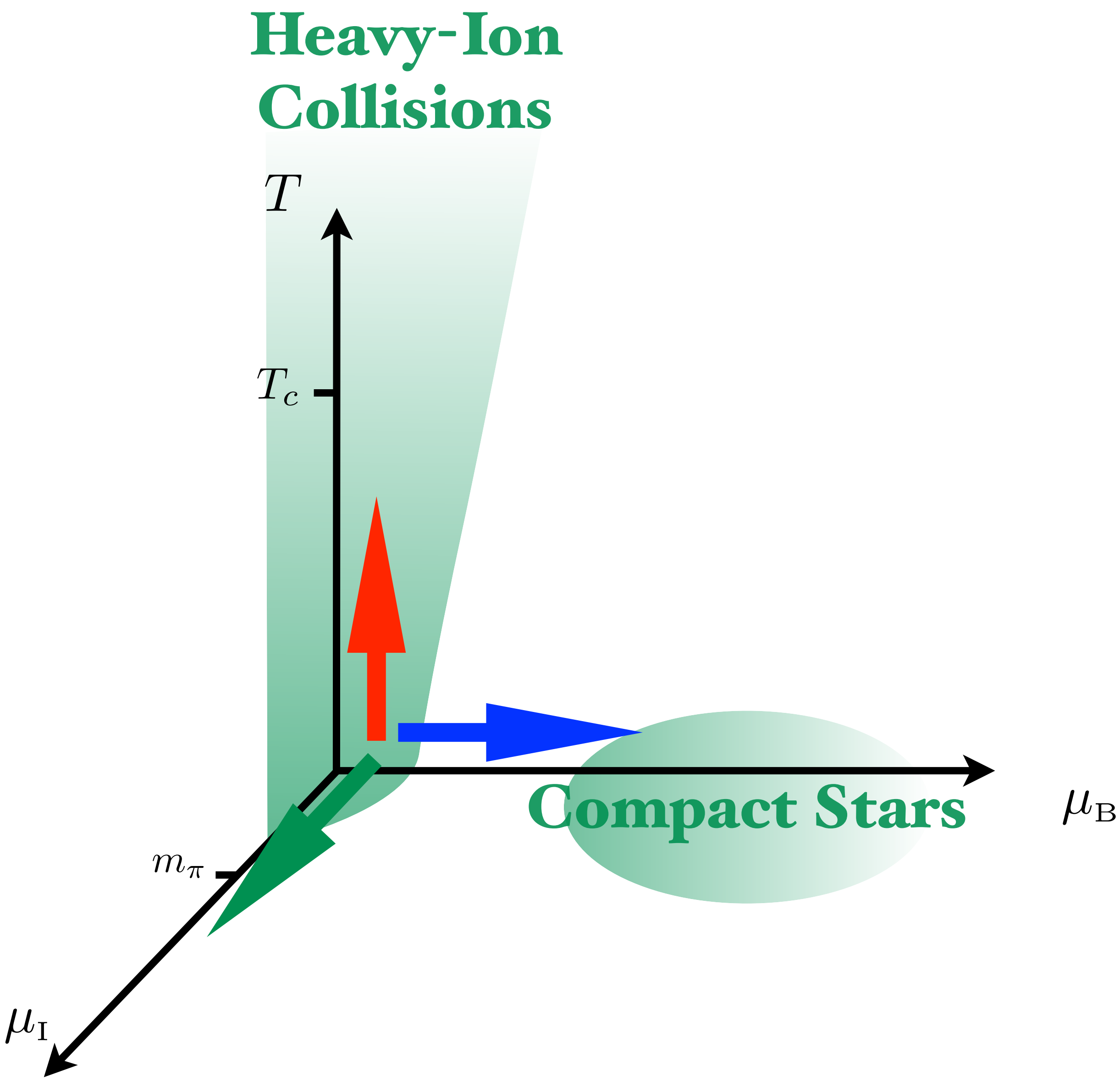

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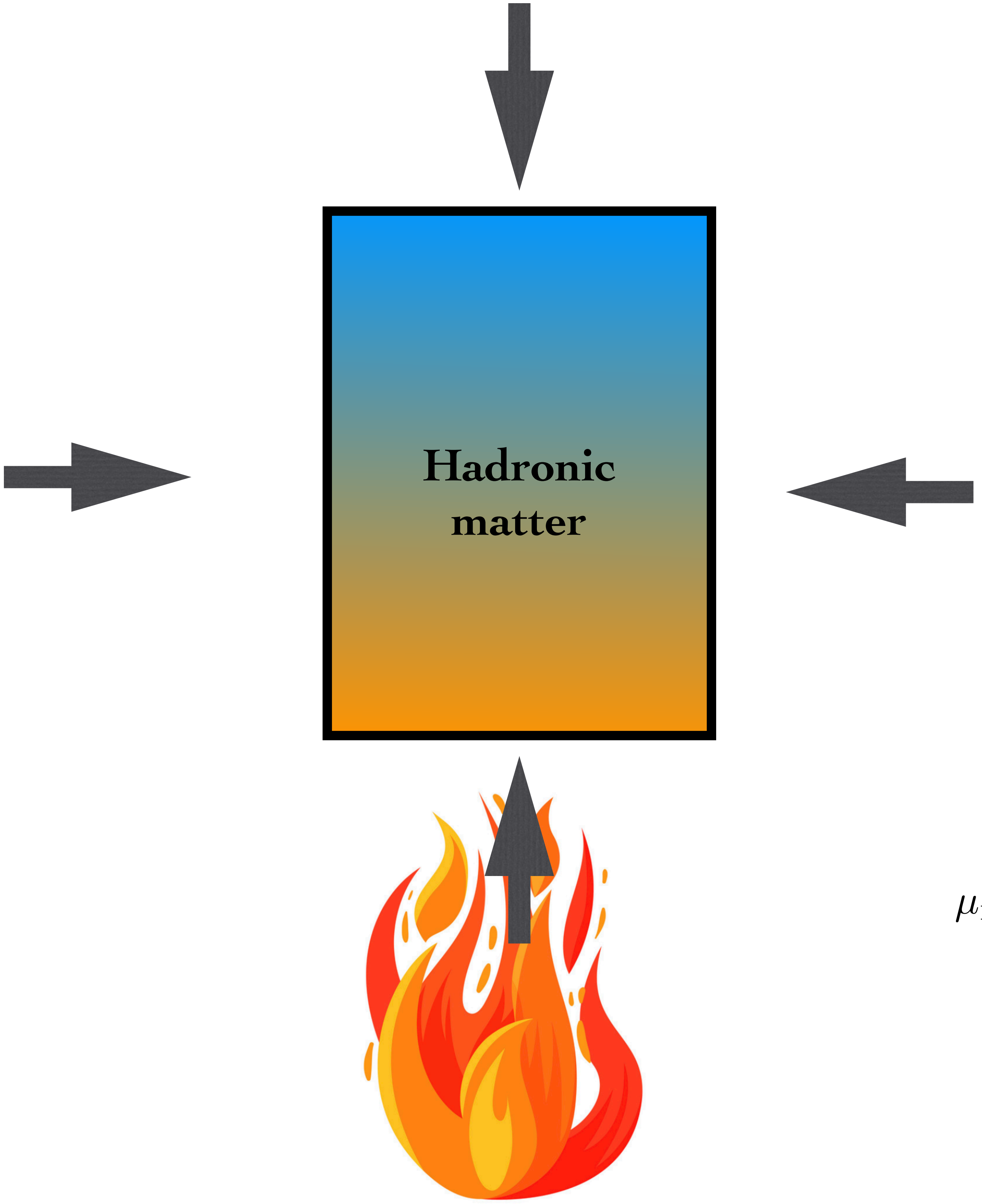

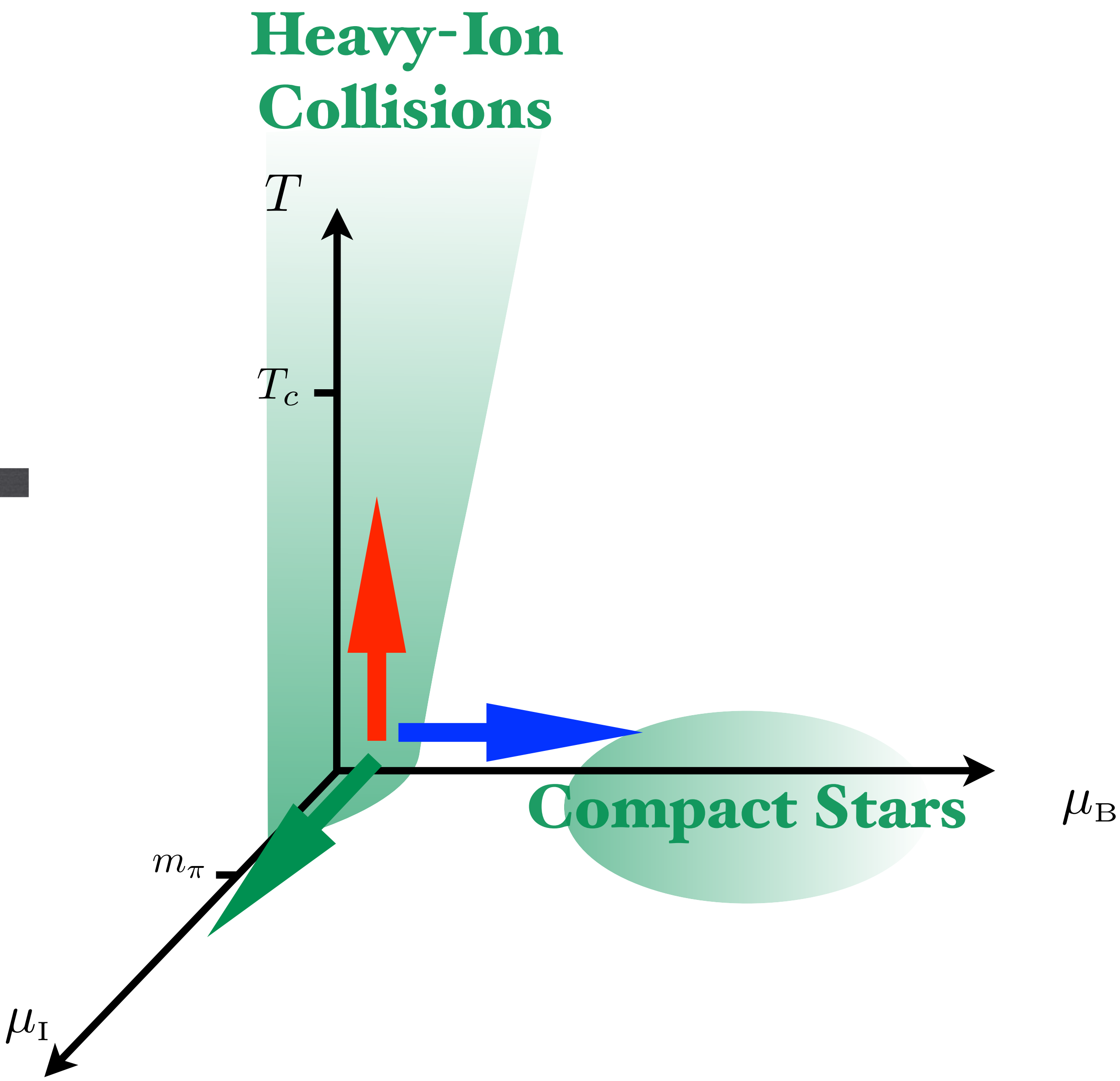

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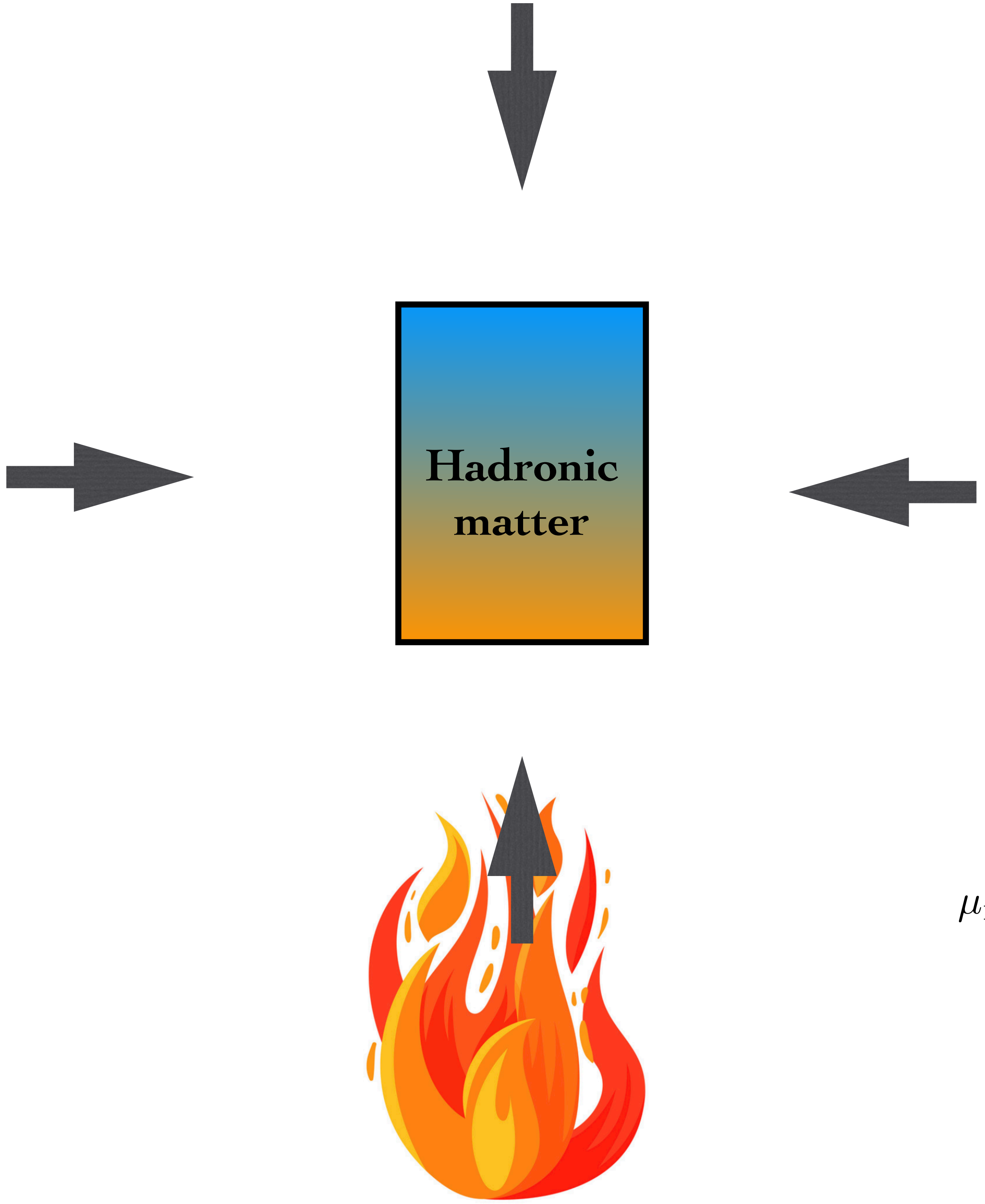

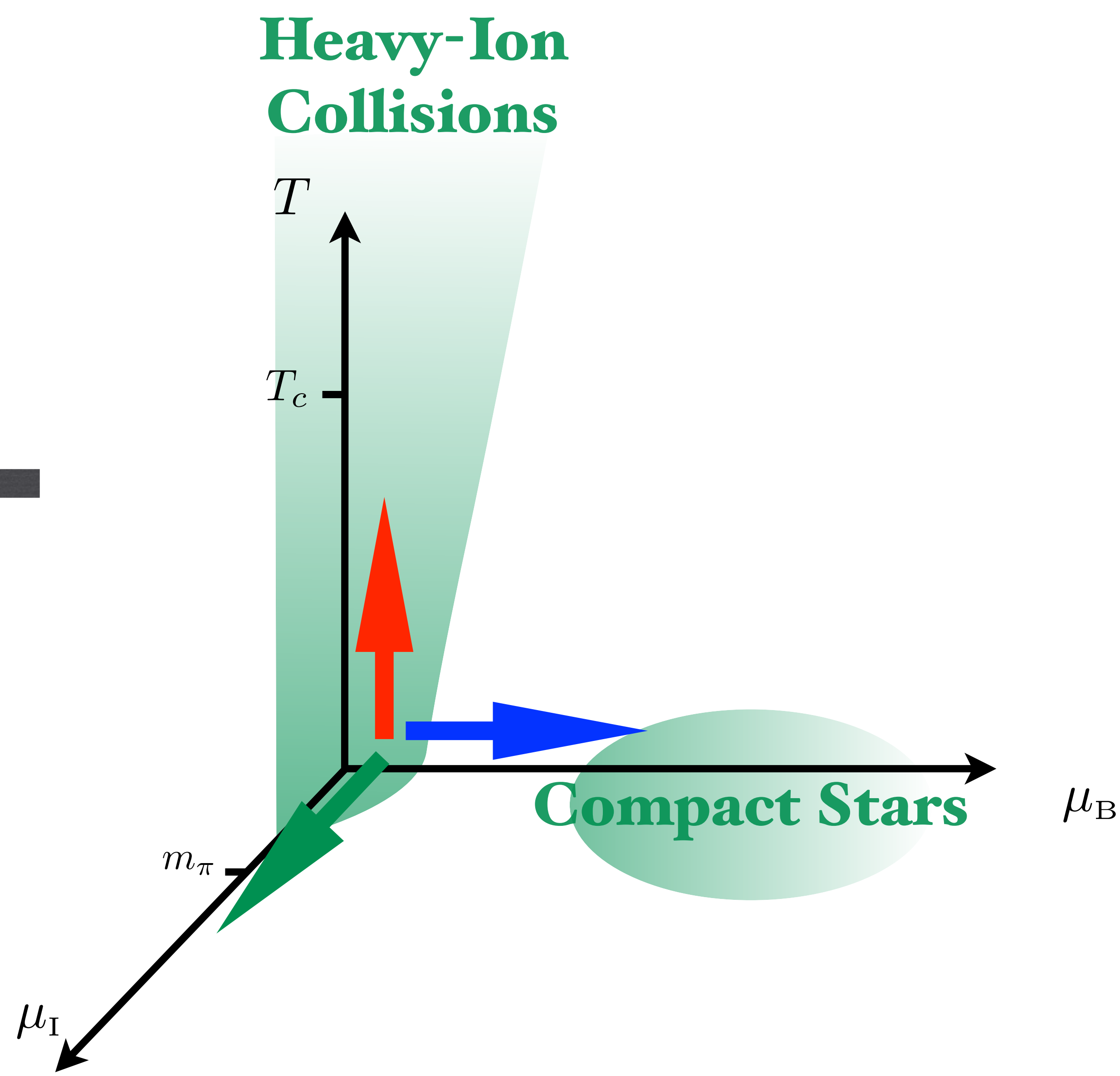

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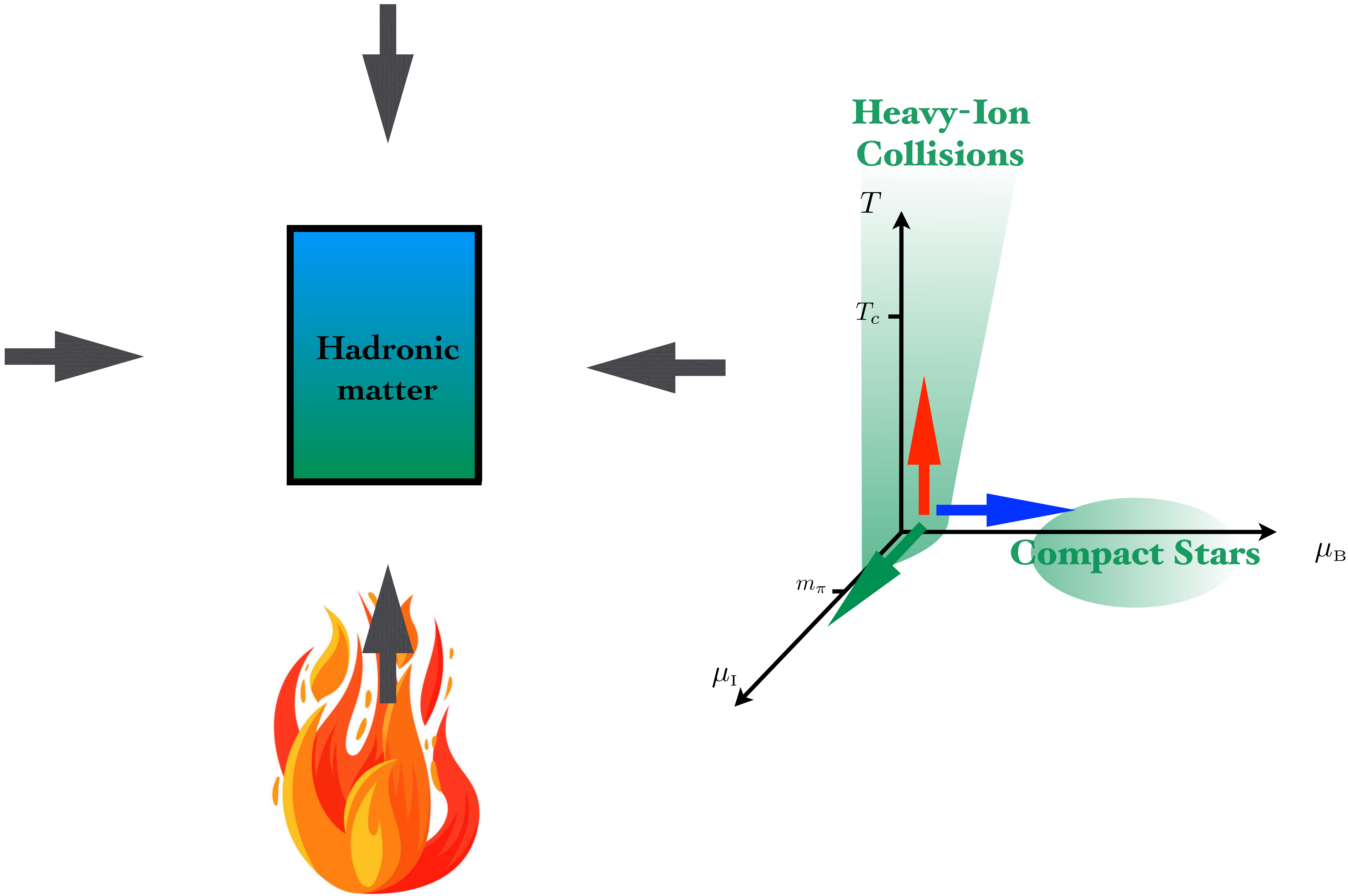


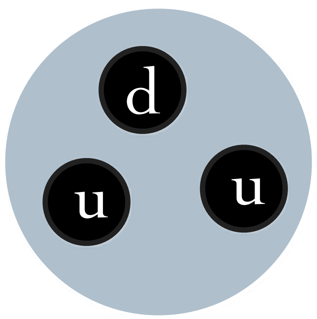
Hadronic phase

Hadronic phase

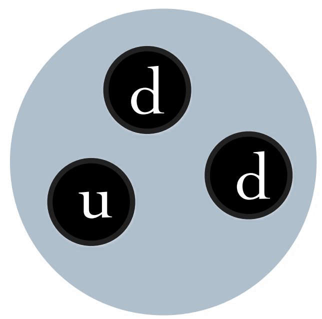
CONFINED HADRONS

BARYONS

proton



neutron



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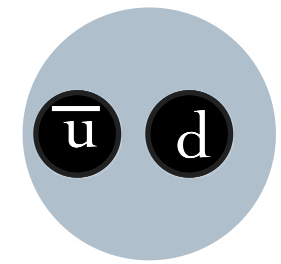
$$r_n \sim 1\mathrm{fm} = 10^{-15}\mathrm{m}$$

MESONS

pions



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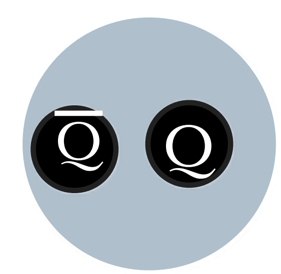
C. Patrignani et al. (PDG)

Heavy mesons



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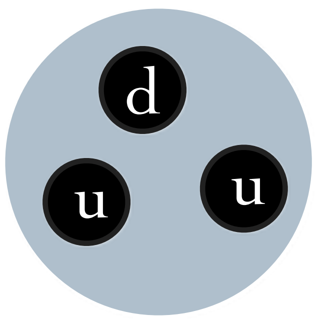

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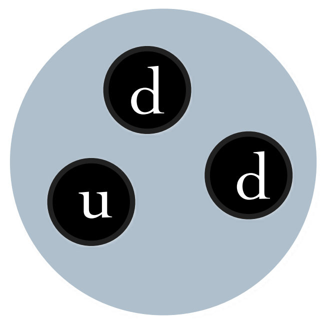

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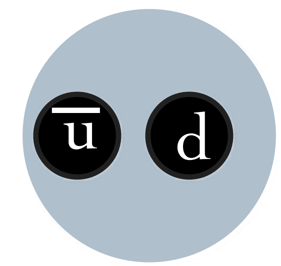

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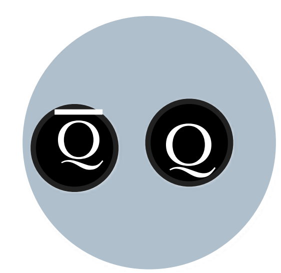

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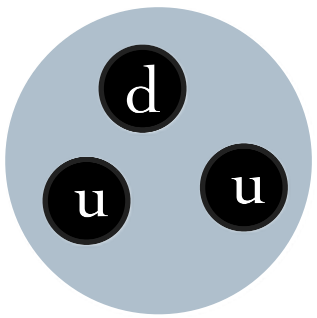

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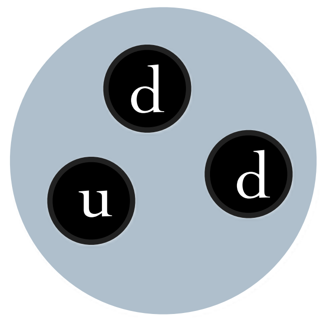

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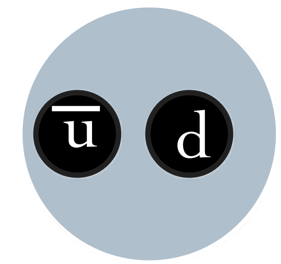

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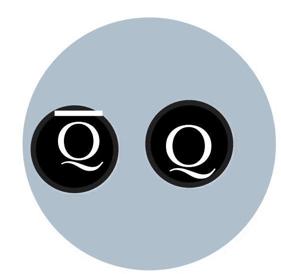

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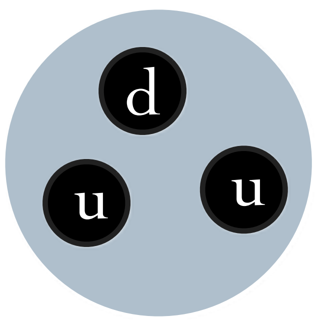

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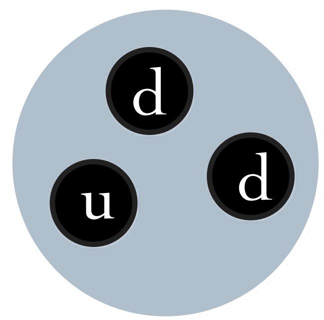

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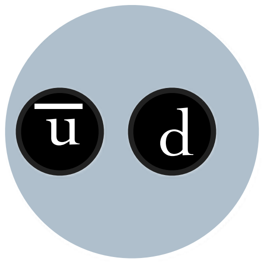

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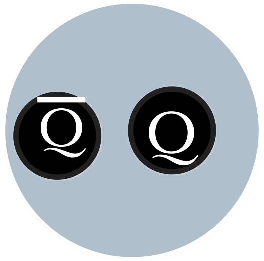

Nonrelativistic object

The double role of mesons

Pions can be associated with the spontaneous chiral symmetry breaking

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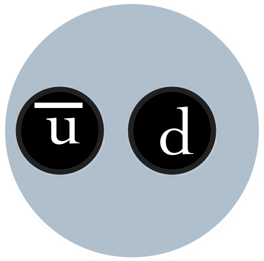

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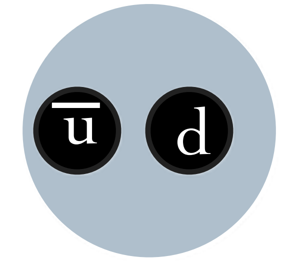

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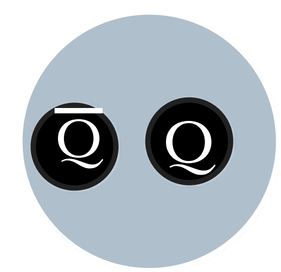
Heavy mesons can be thought as bound states of heavy quarks:
The mass of a heavy meson is smaller than the mass of its constituents.

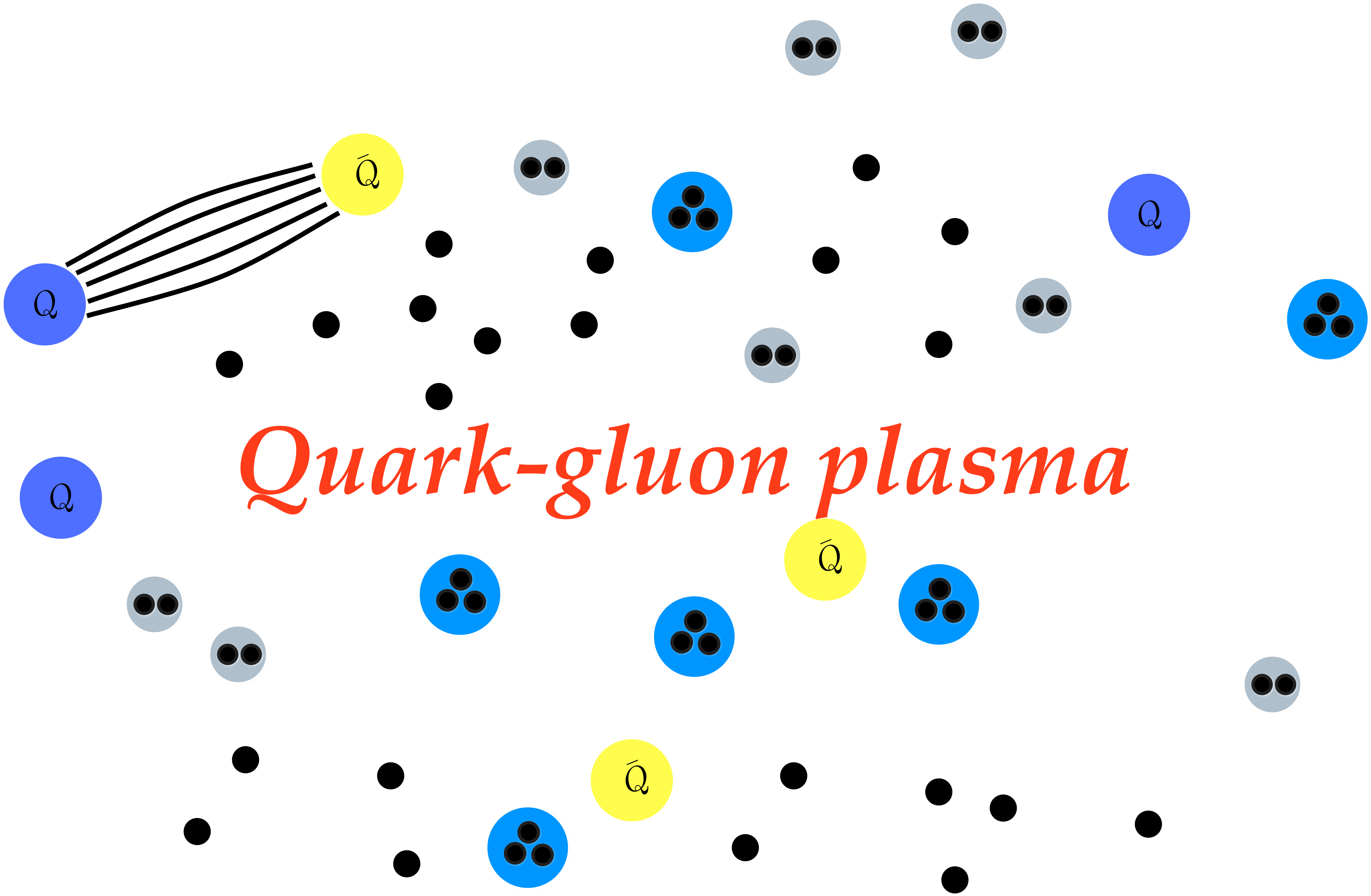
Good for probing confinement

Heavy mesons



Nonrelativistic models

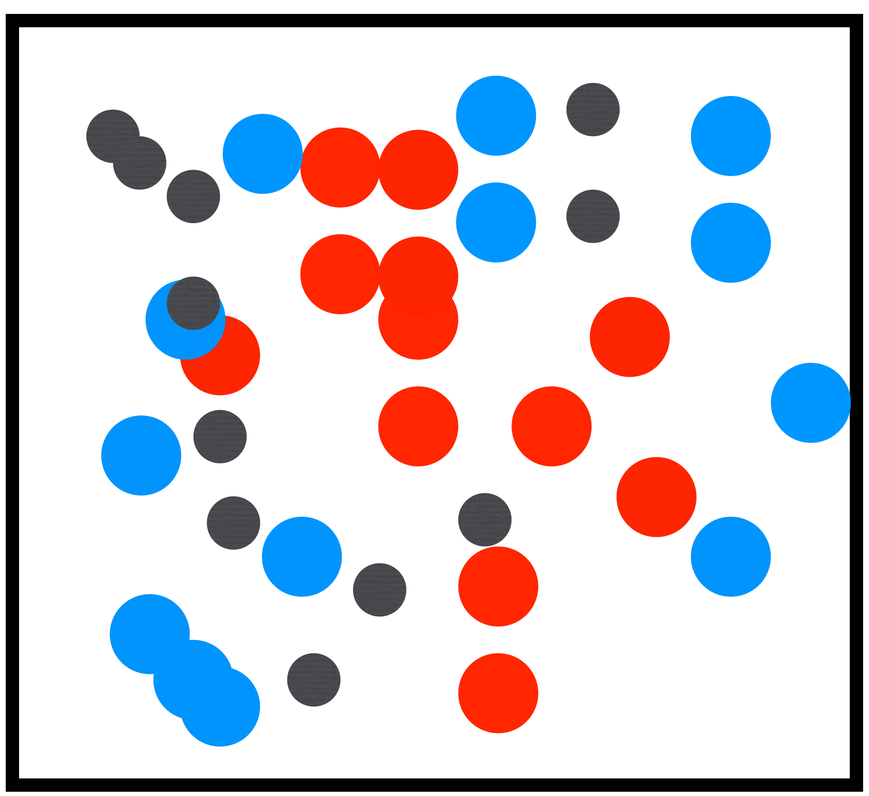
Quark-gluon plasma



Deconfinement by increasing temperature

Mesons Baryons Anti Baryons

Increasing T
Fixed low μ_B



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At a critical temperature there is saturation:
the nucleons lose their identity and start to overlap.
Quarks and gluons are liberated

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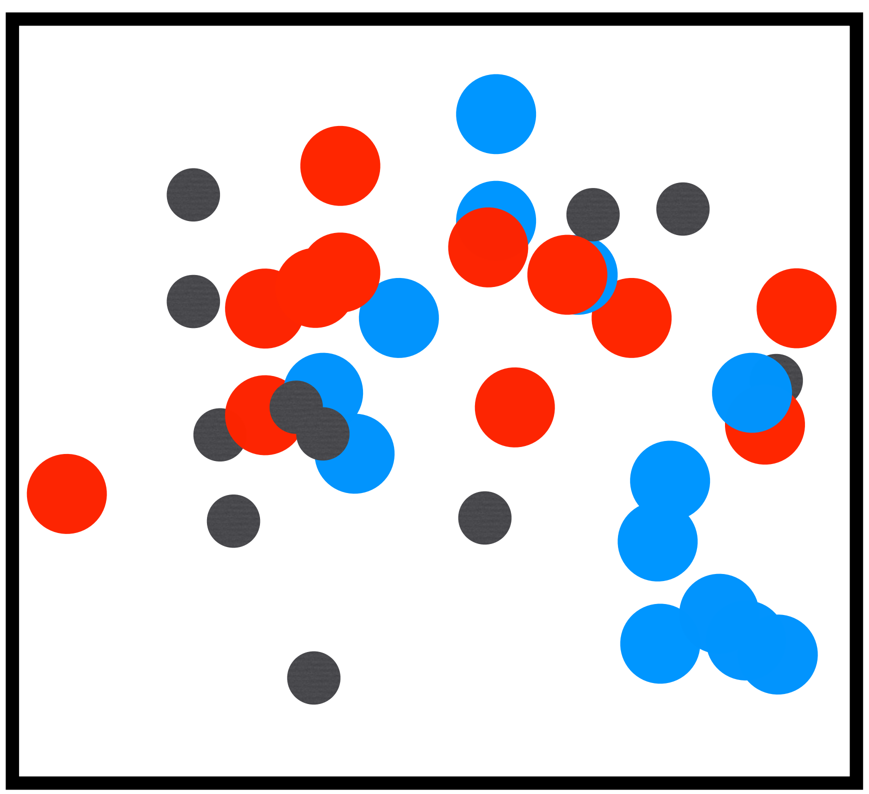

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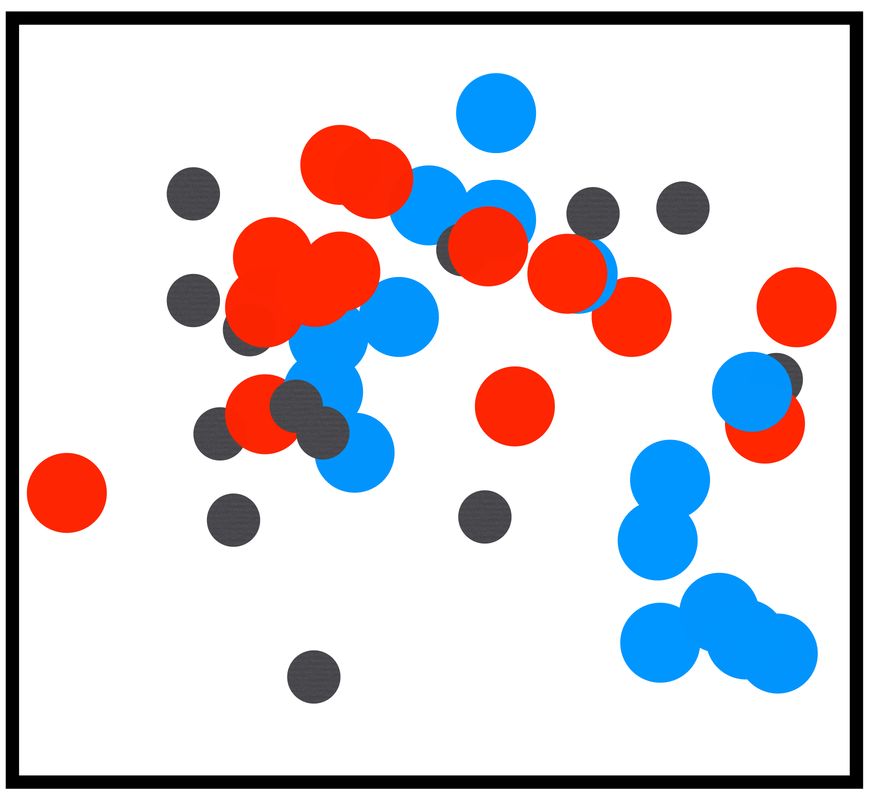

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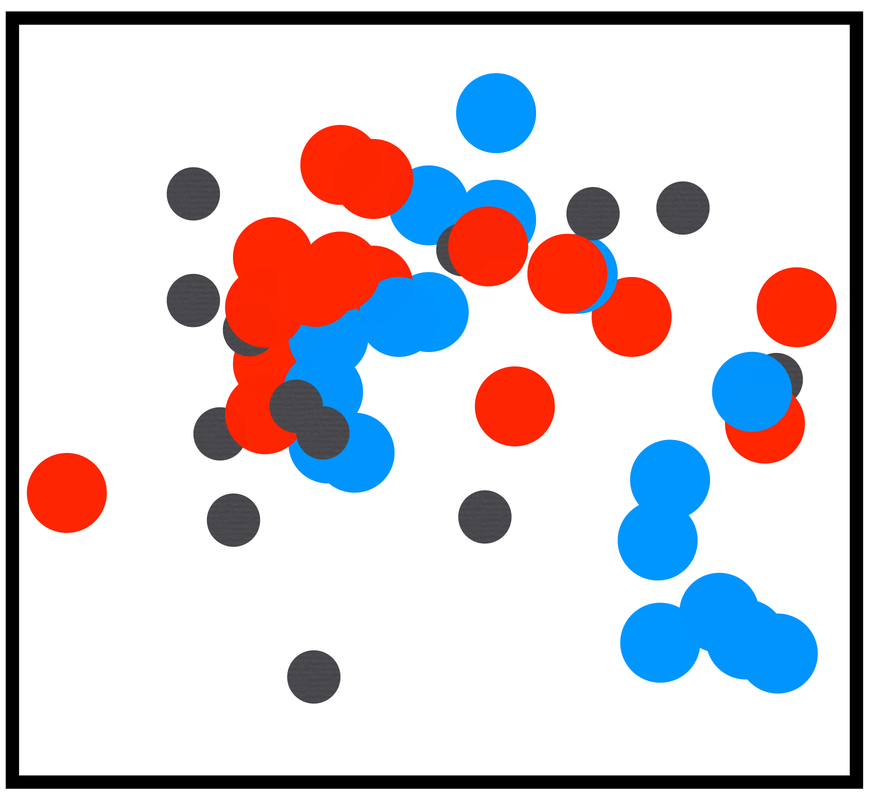

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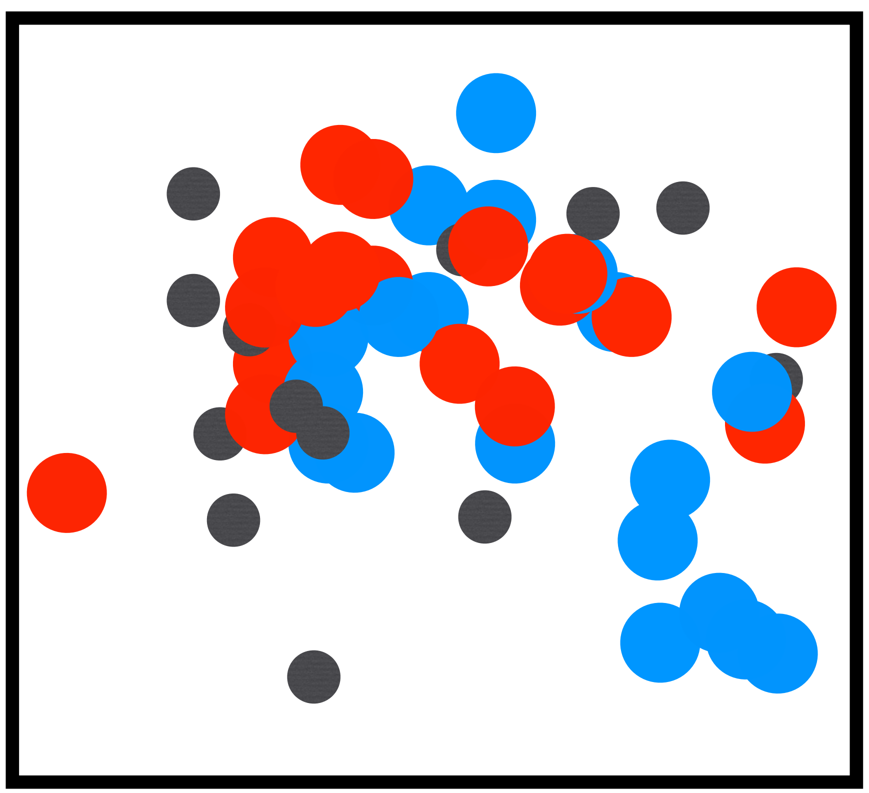

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Deconfinement by increasing temperature

Mesons Baryons Anti Baryons

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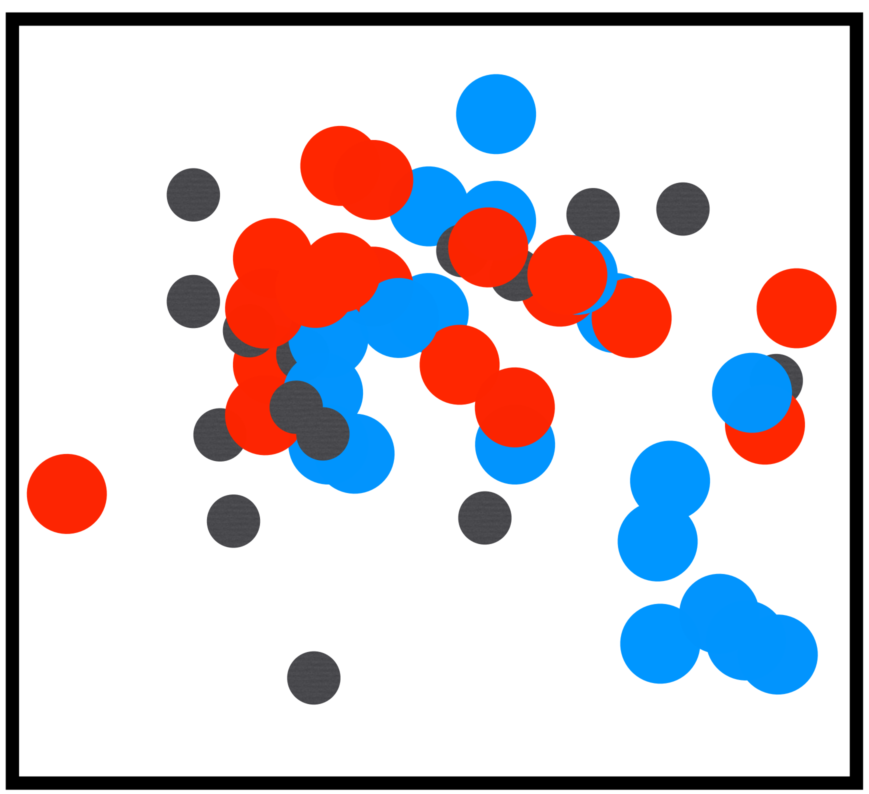
Fixed low μ_B



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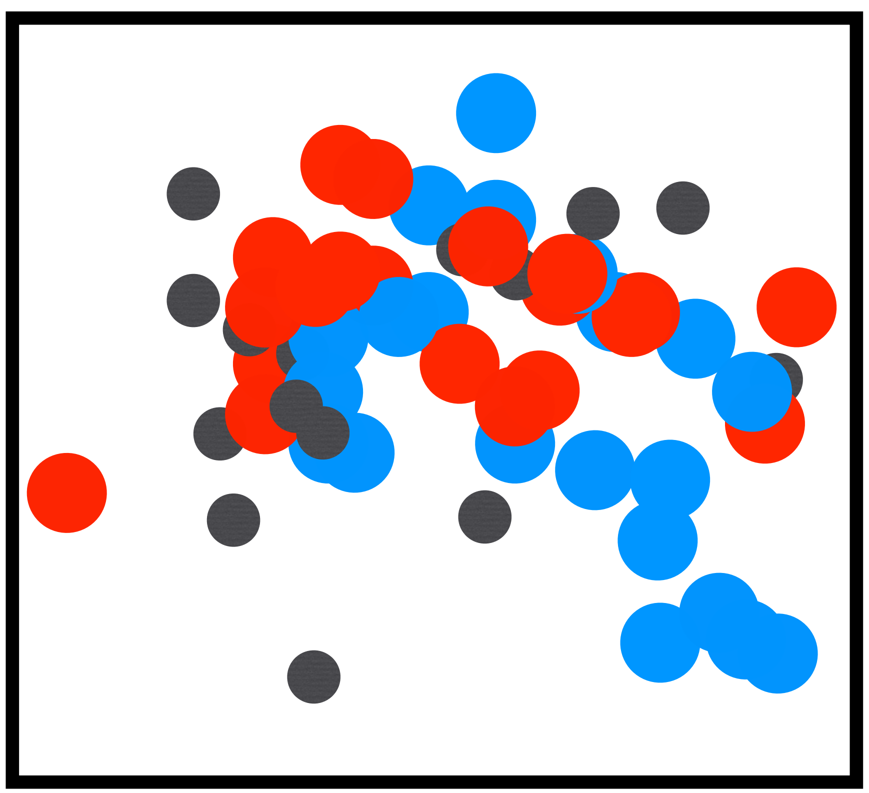

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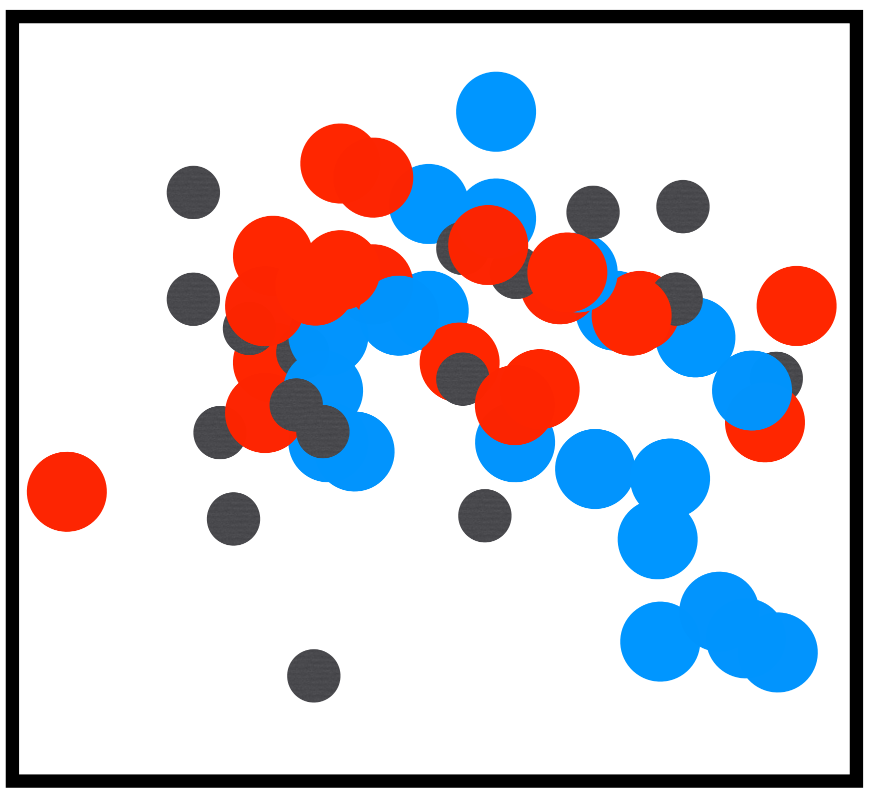

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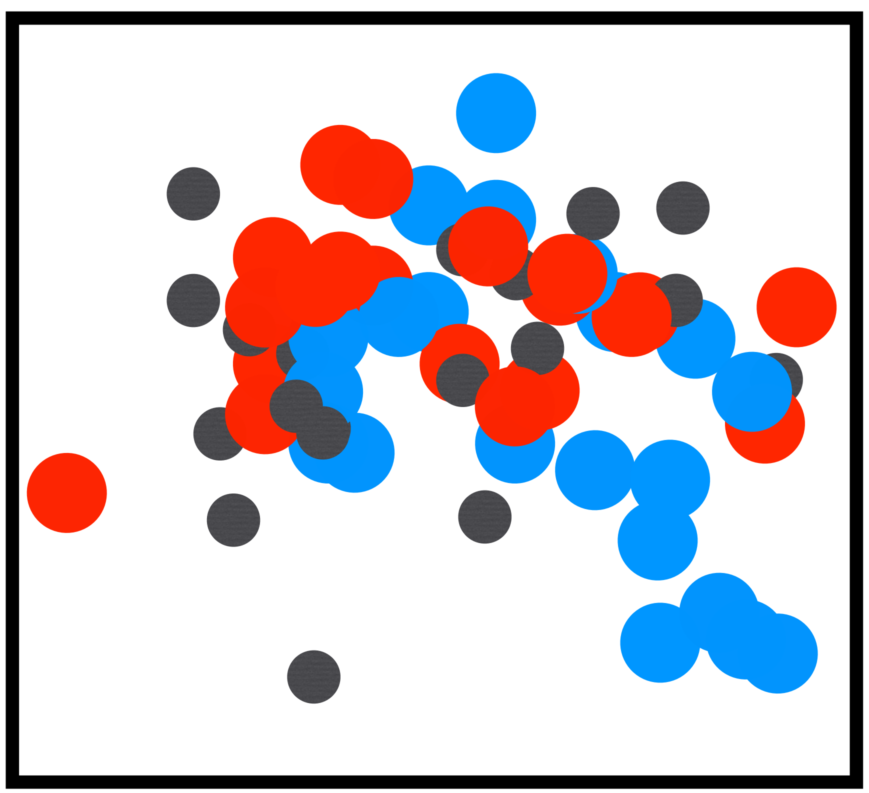

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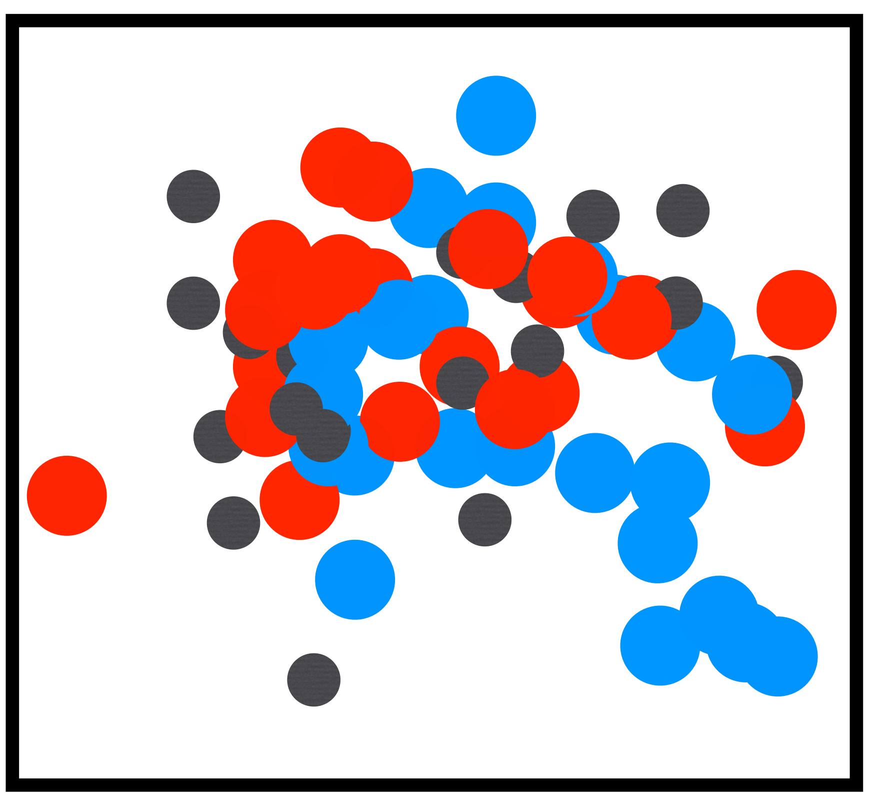

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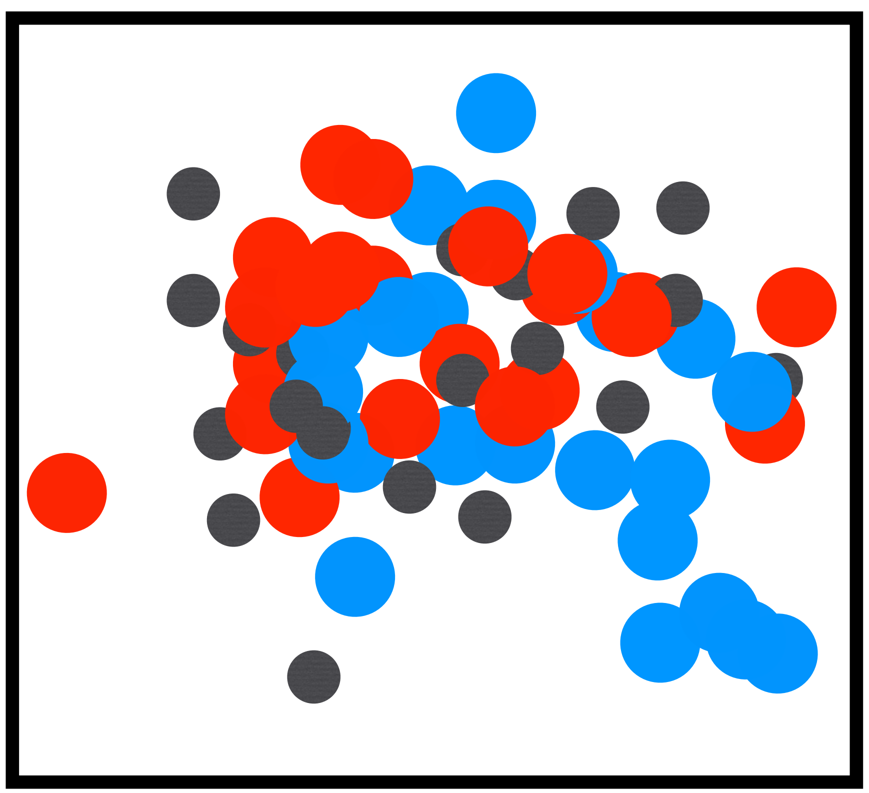

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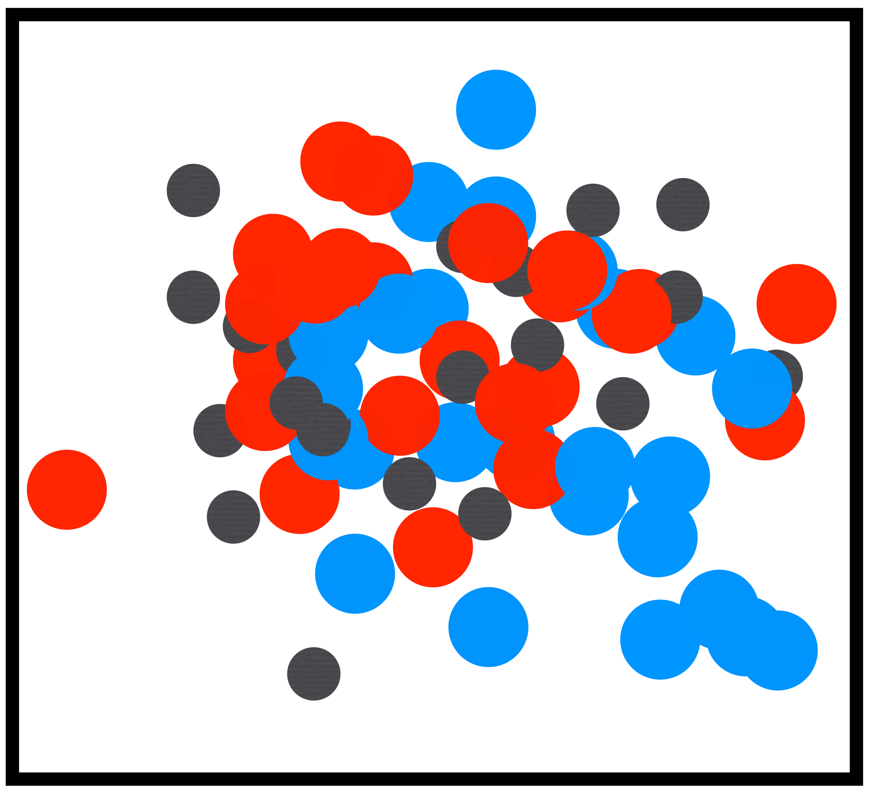

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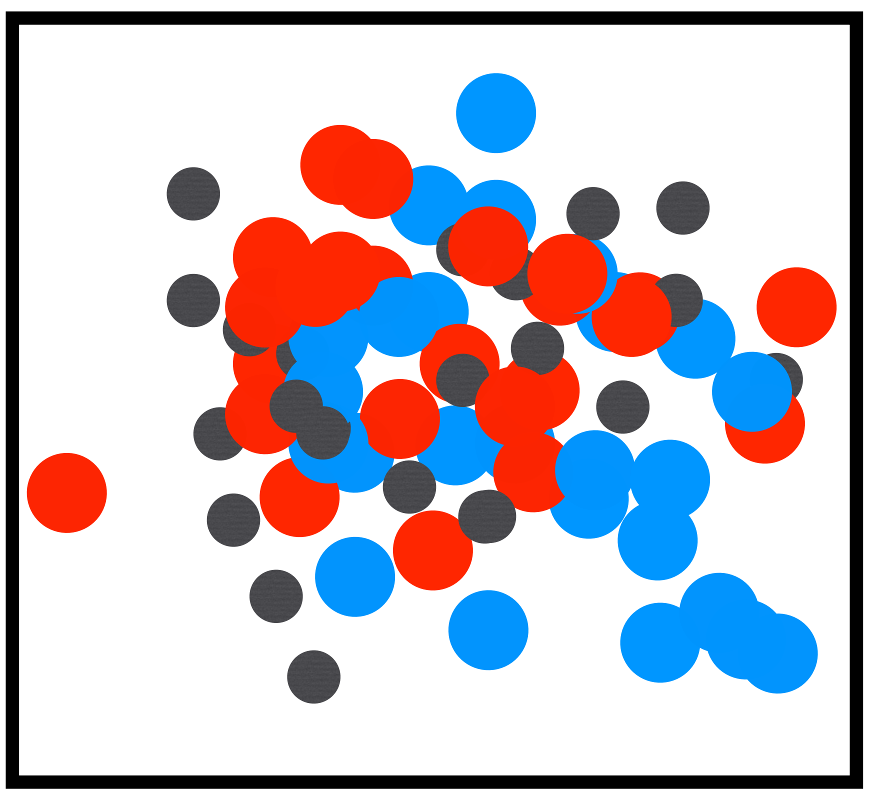

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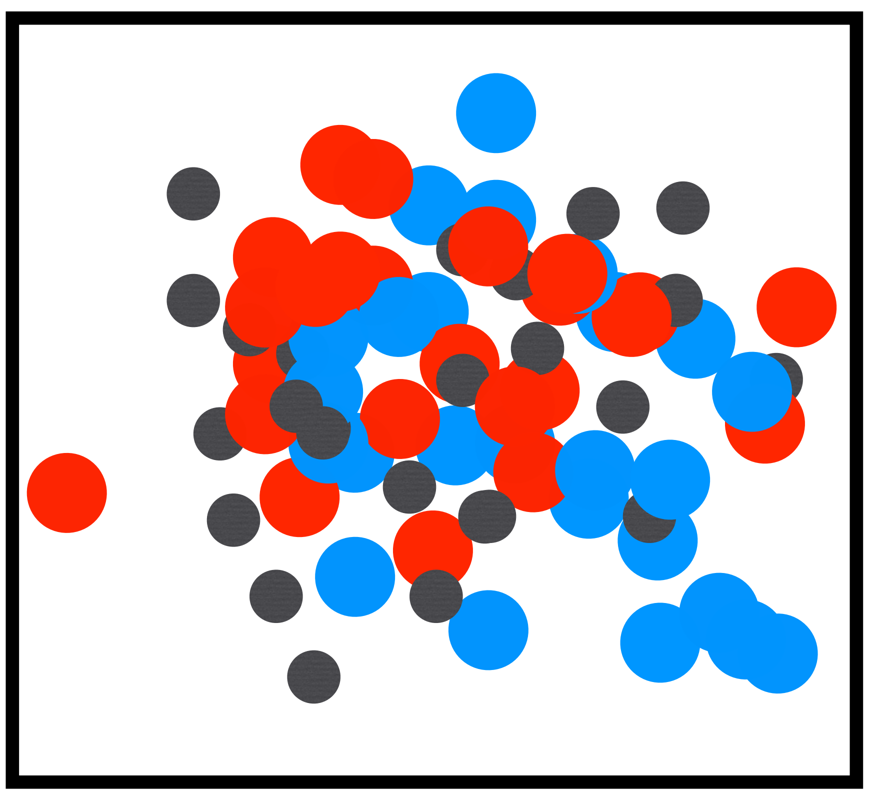

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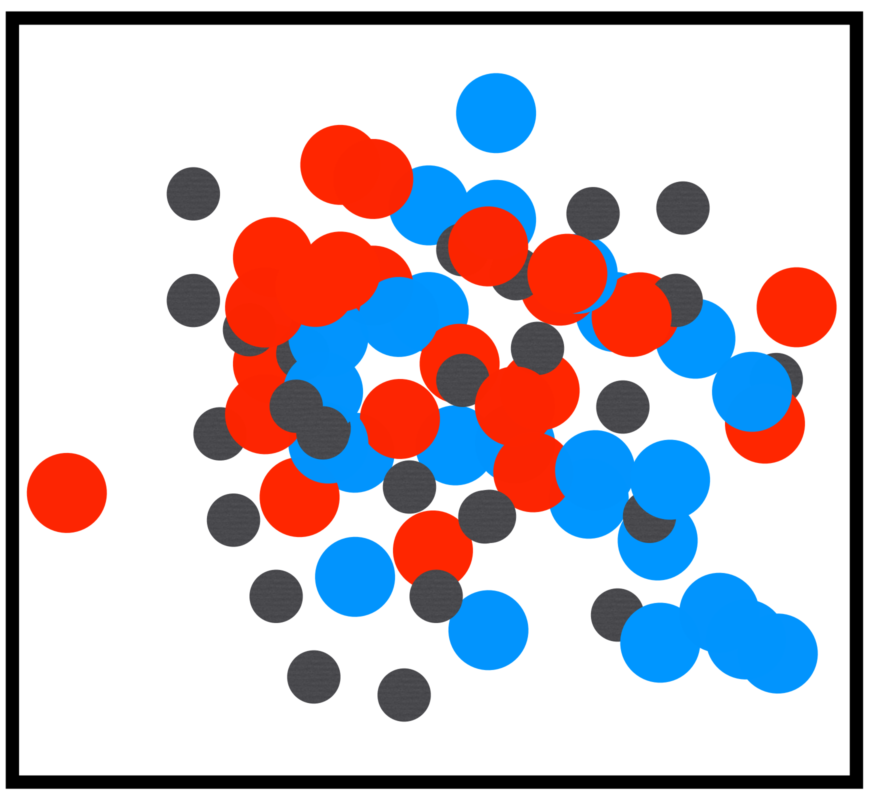

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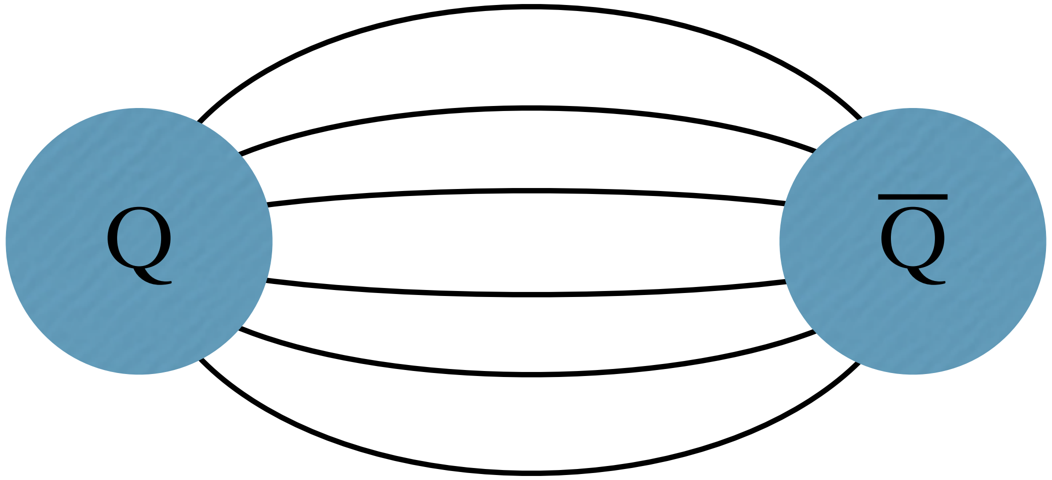
Heavy quarkonia as probes



VACUUM
Anti-screening

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2) **It is a bound state**
3) **Strong decay is OZI suppressed**
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$$V(r) \sim \sigma r - \frac{\alpha}{r}$$

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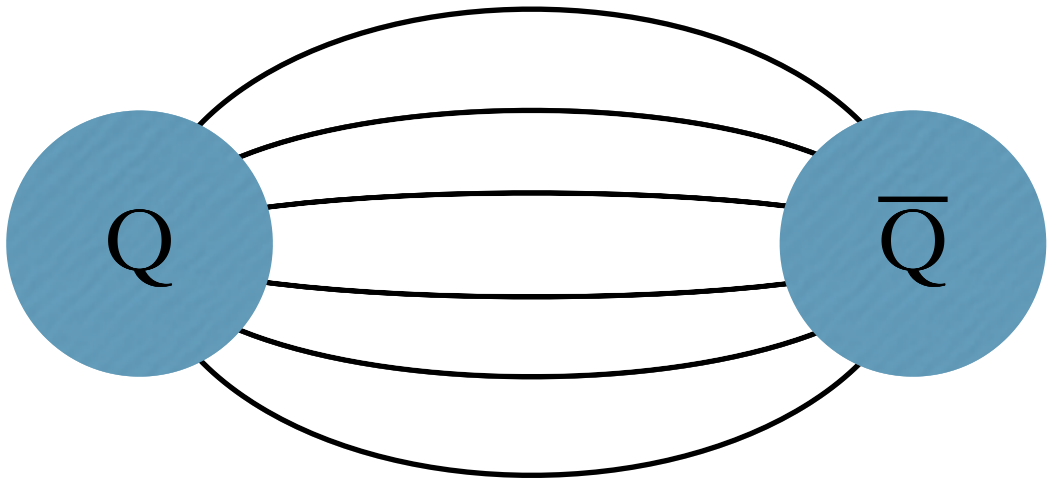

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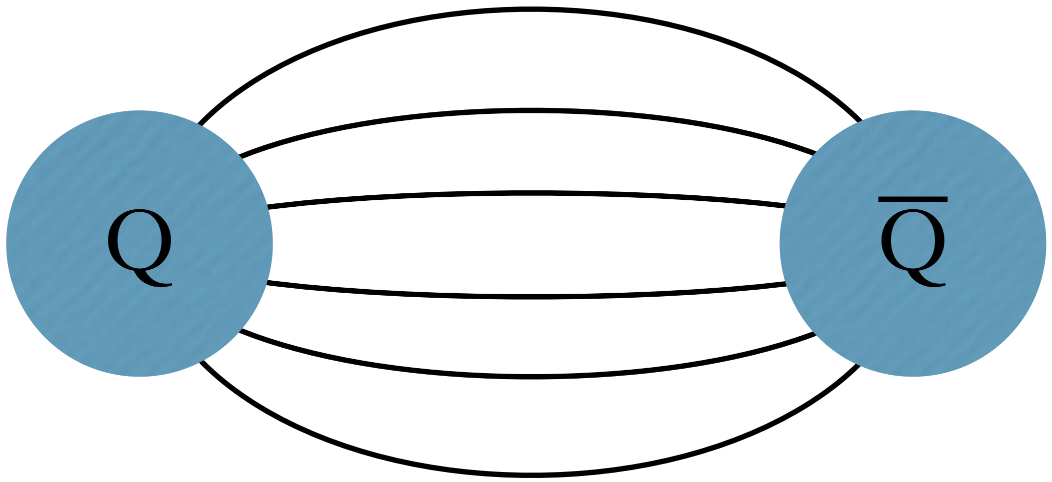

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Debye screening

Landau damping

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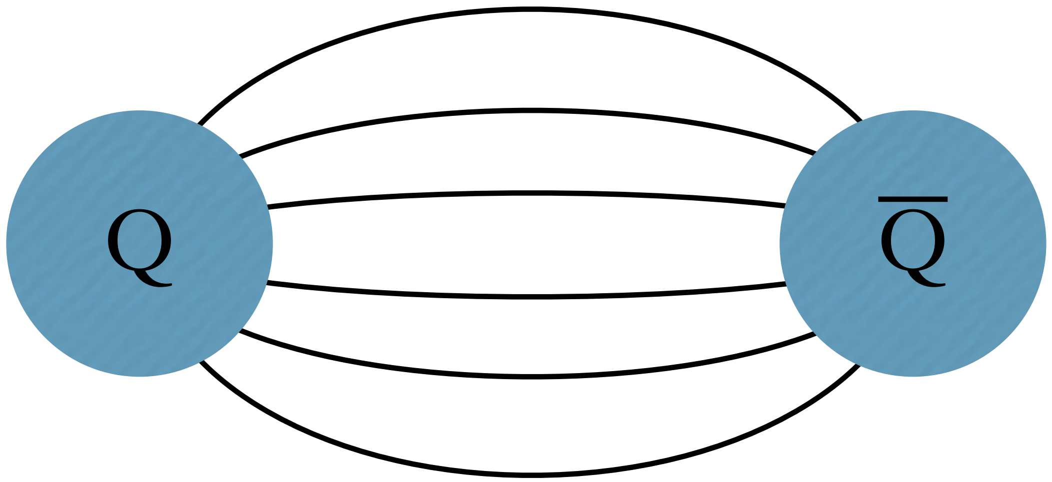

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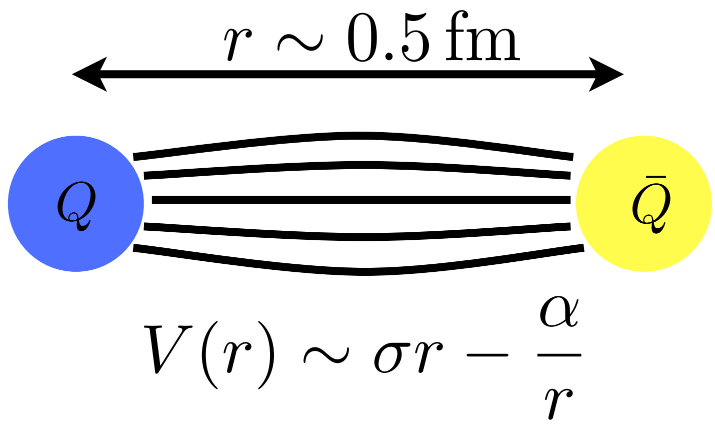
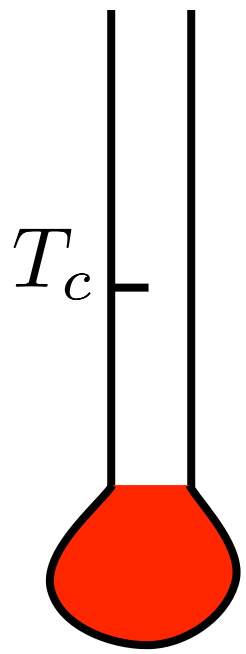
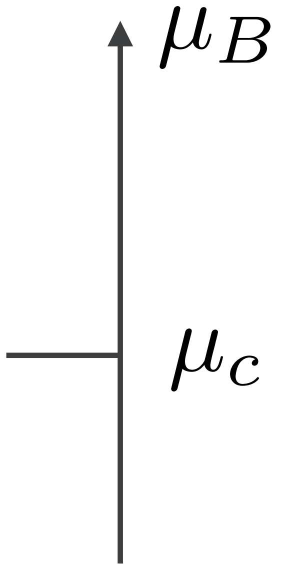
Debye screening — **Landau damping**

See Tuesday talks for dicepton signals!

Debye Screening







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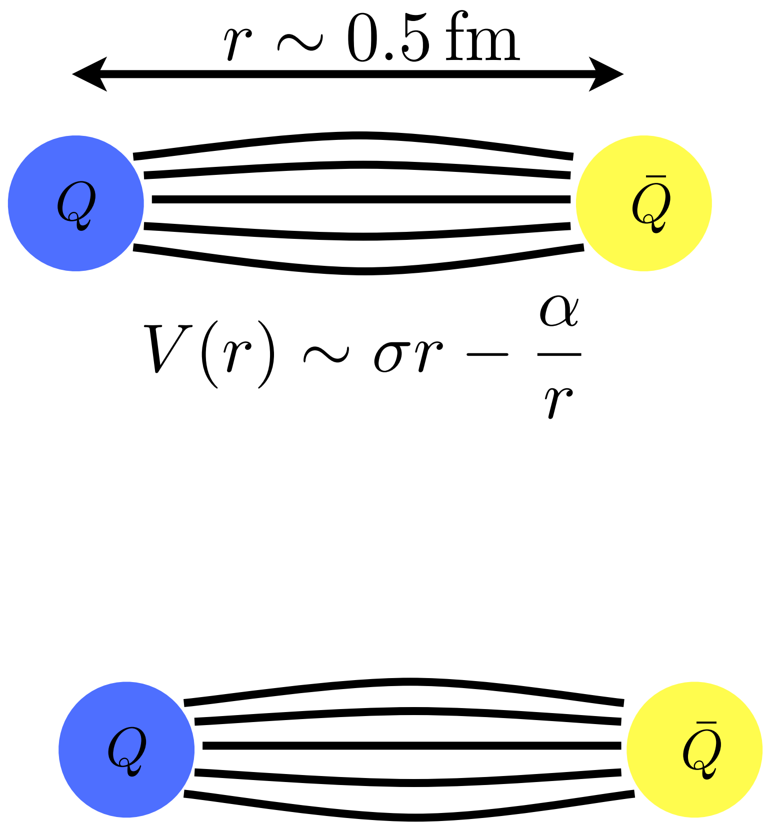

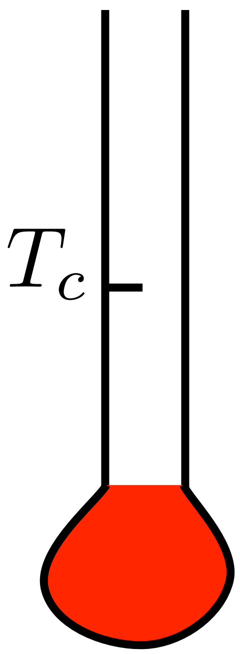

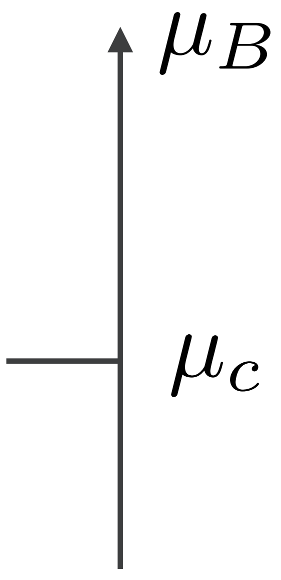

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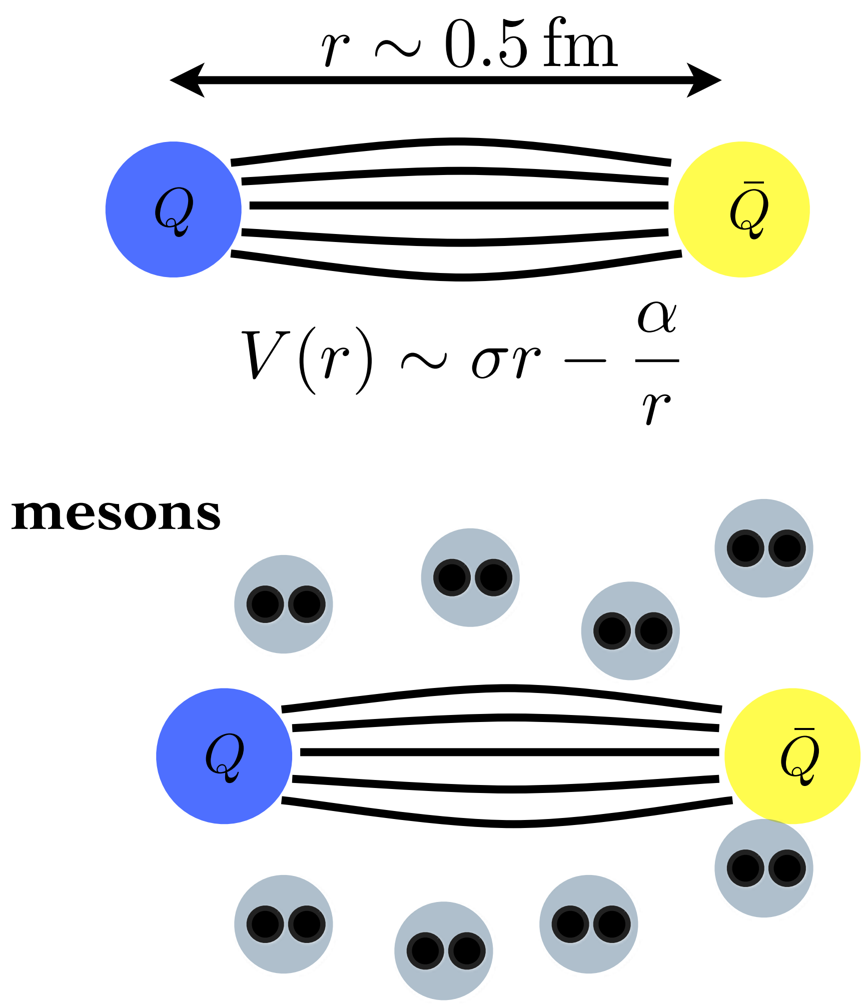

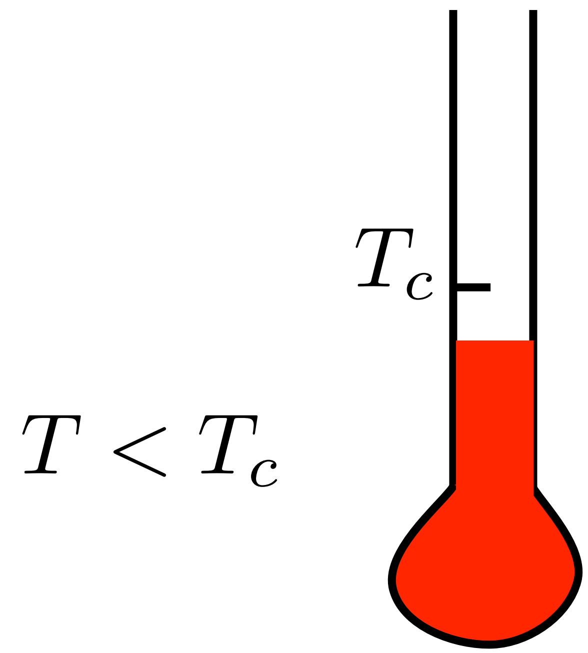

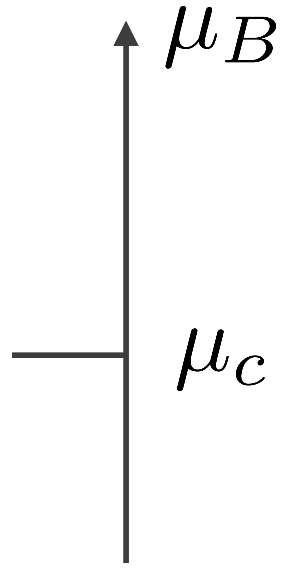

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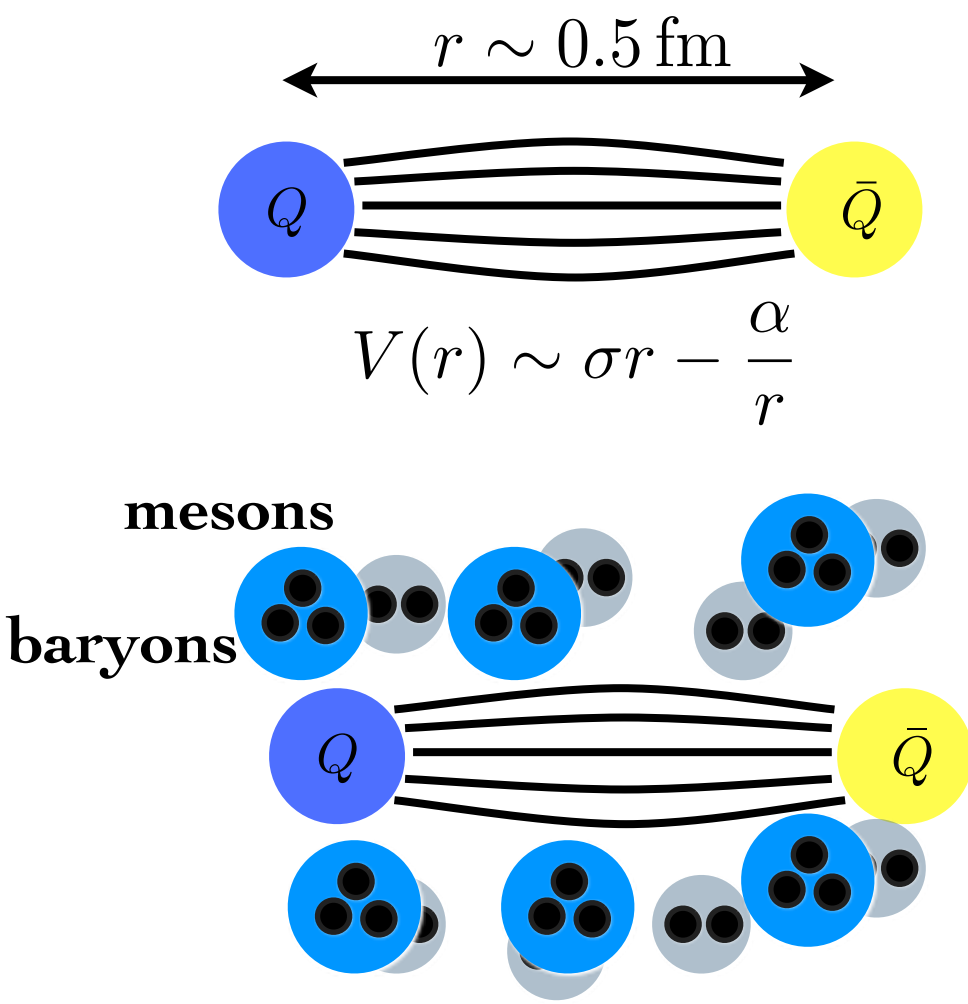

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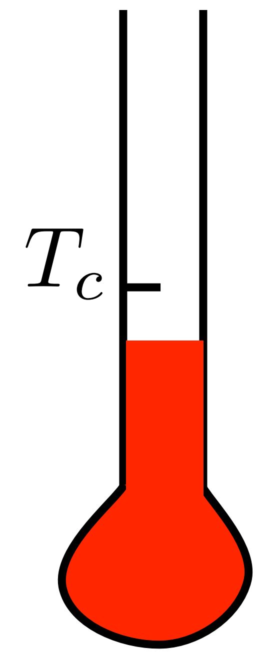

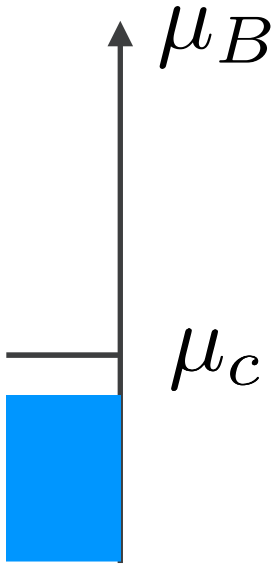

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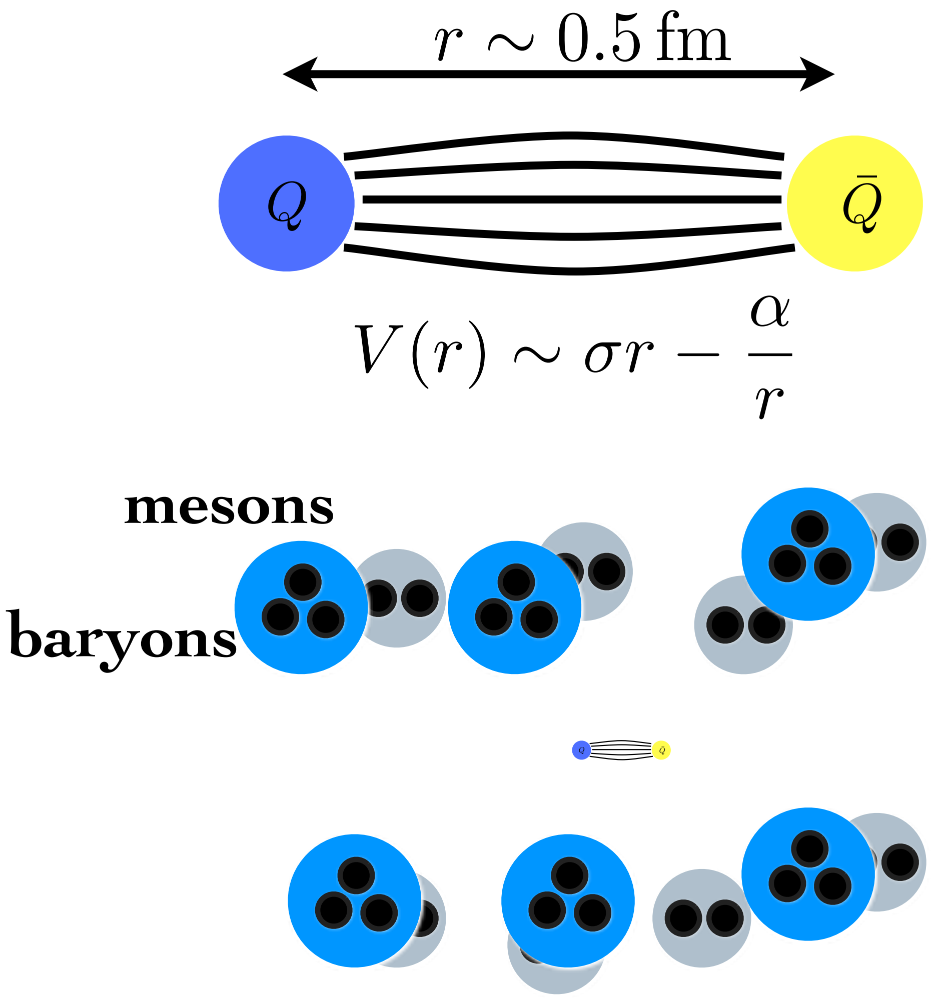

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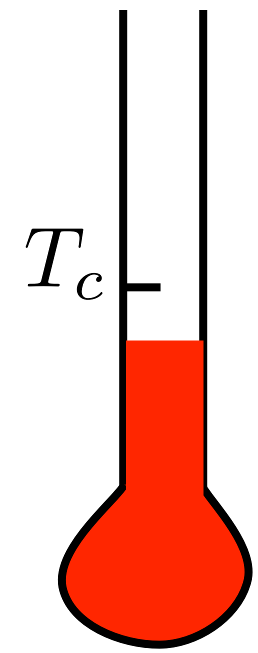

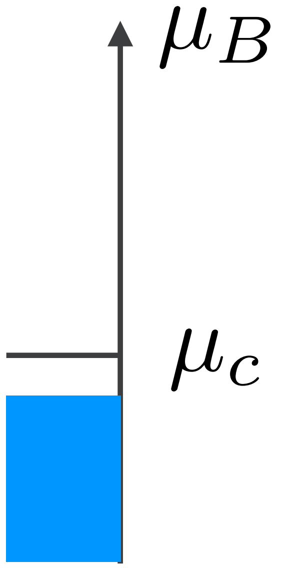

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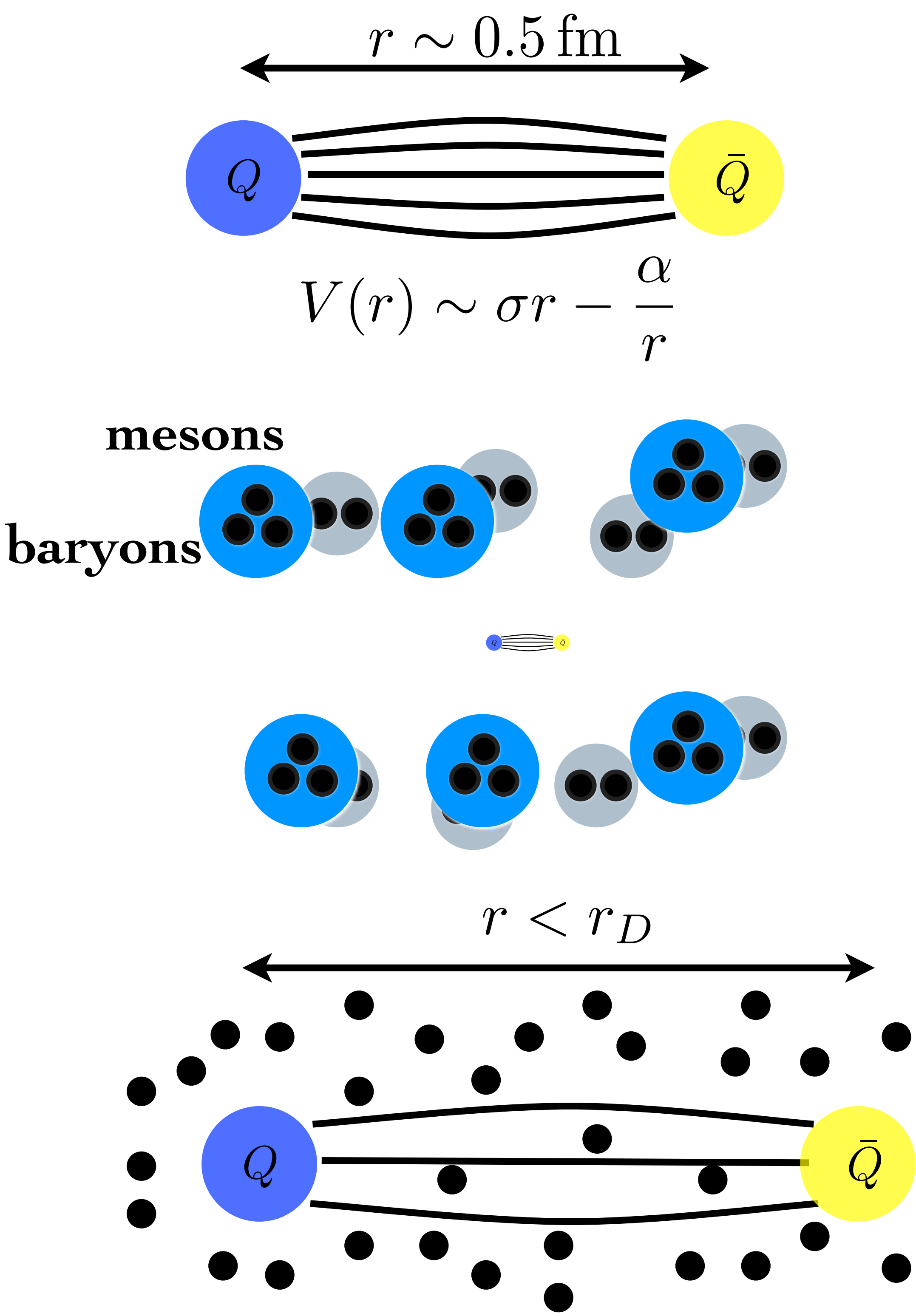

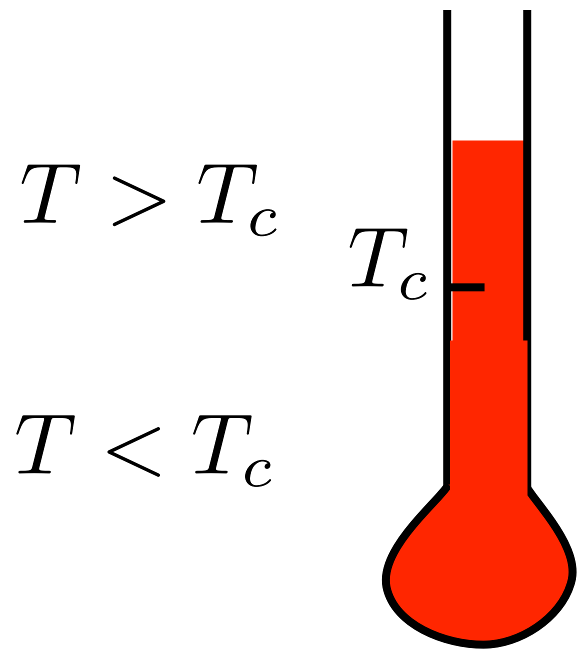

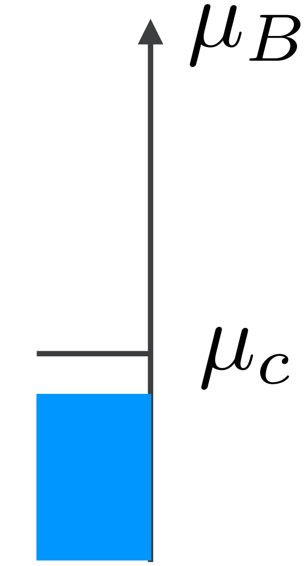

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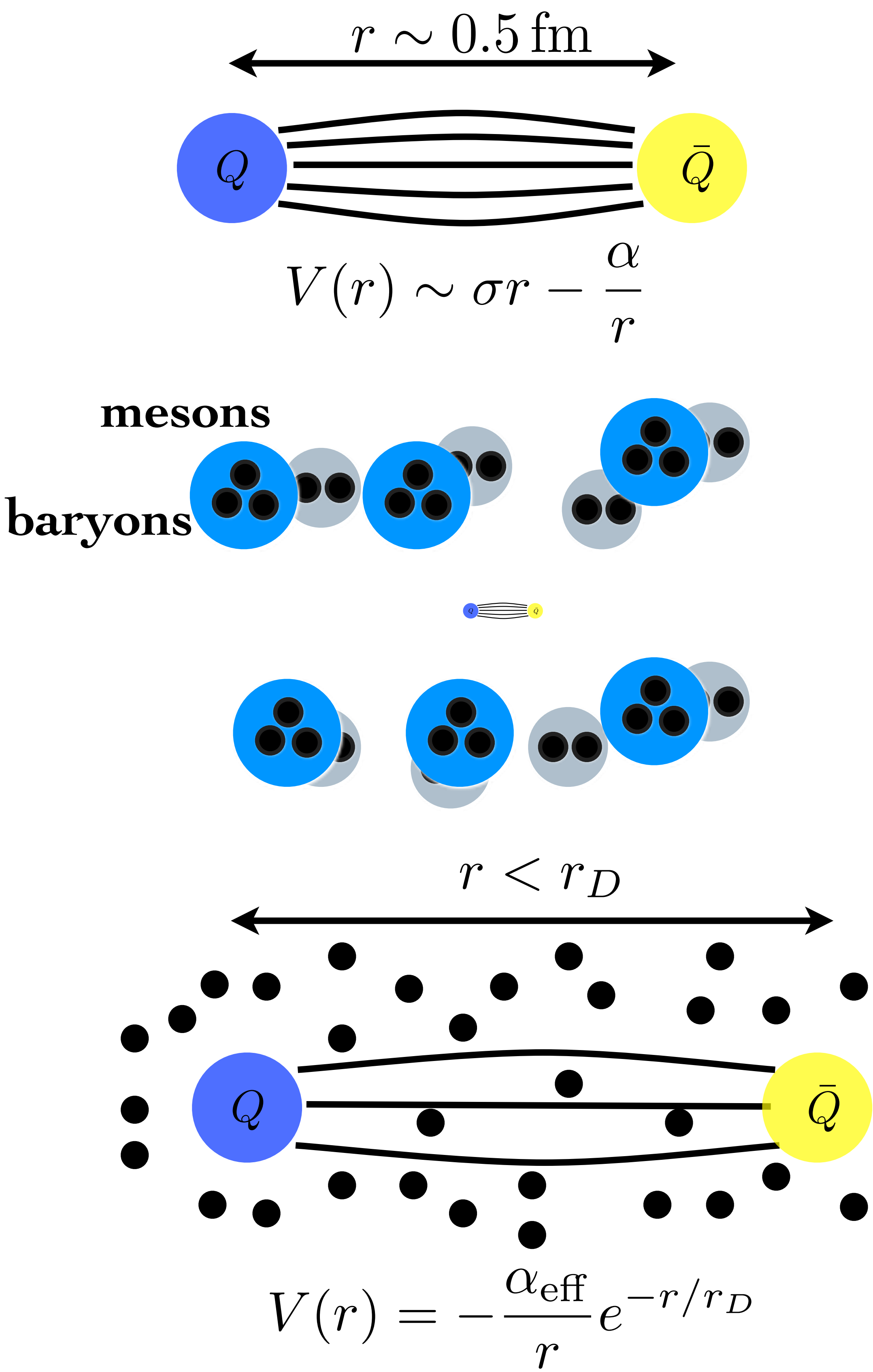

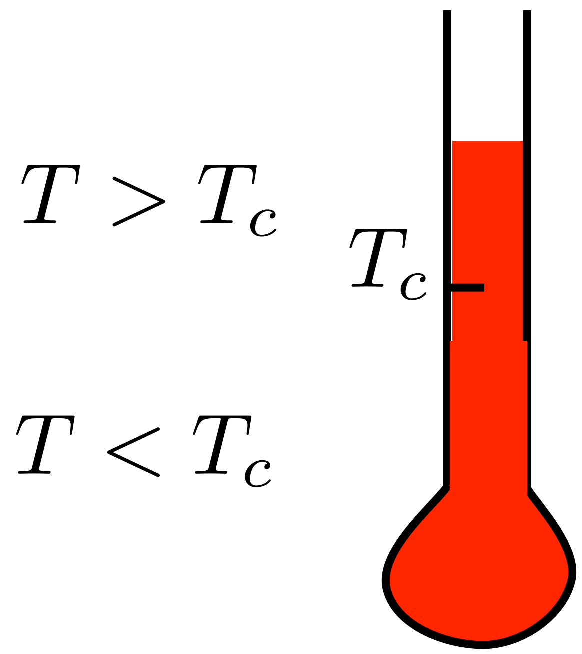

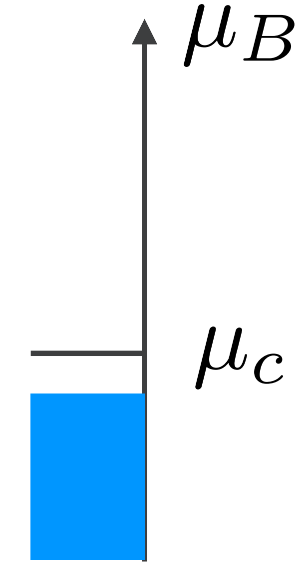

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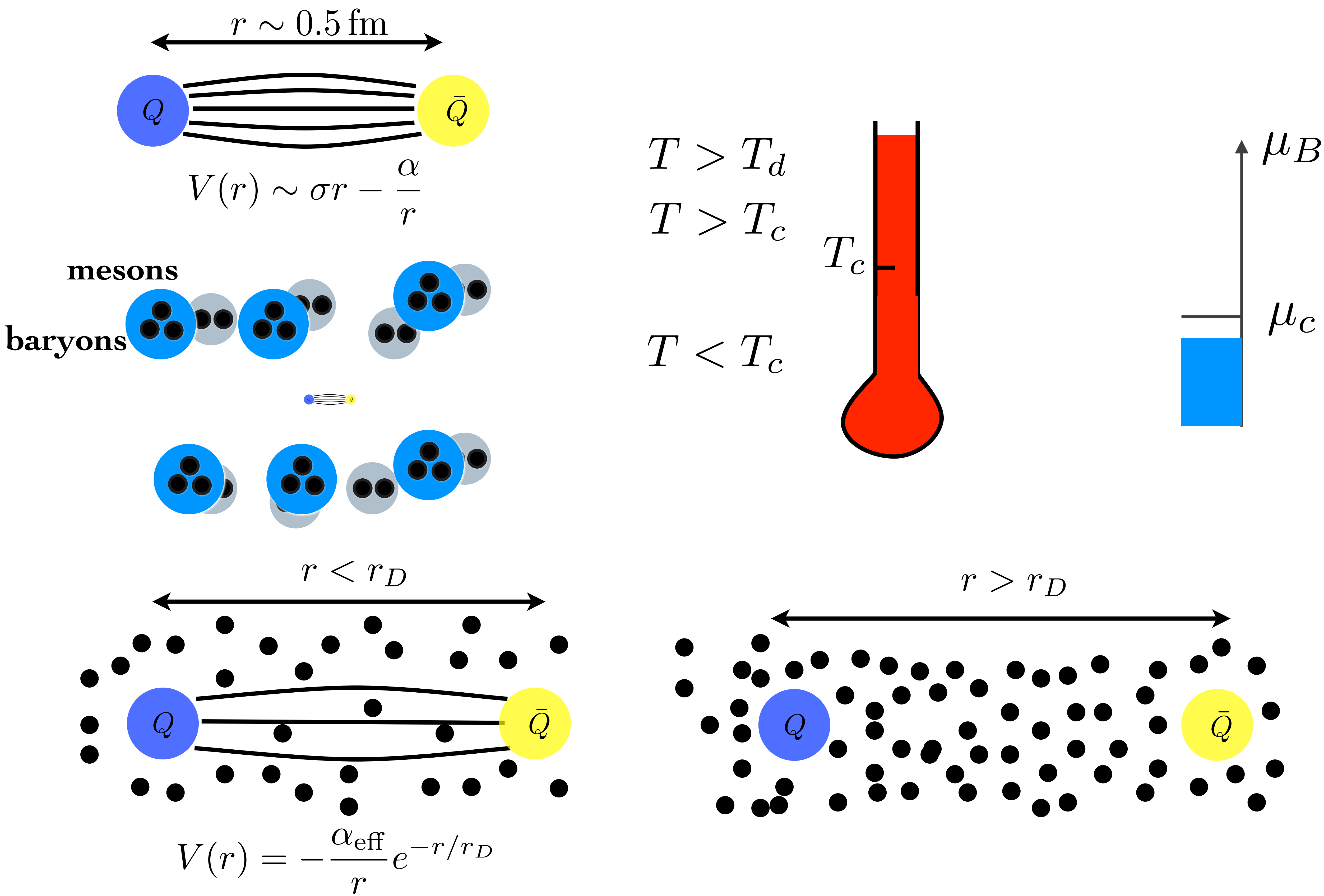

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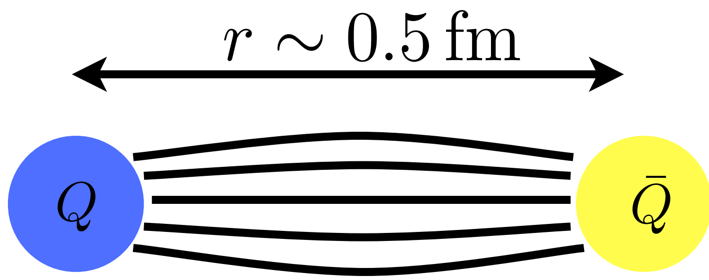

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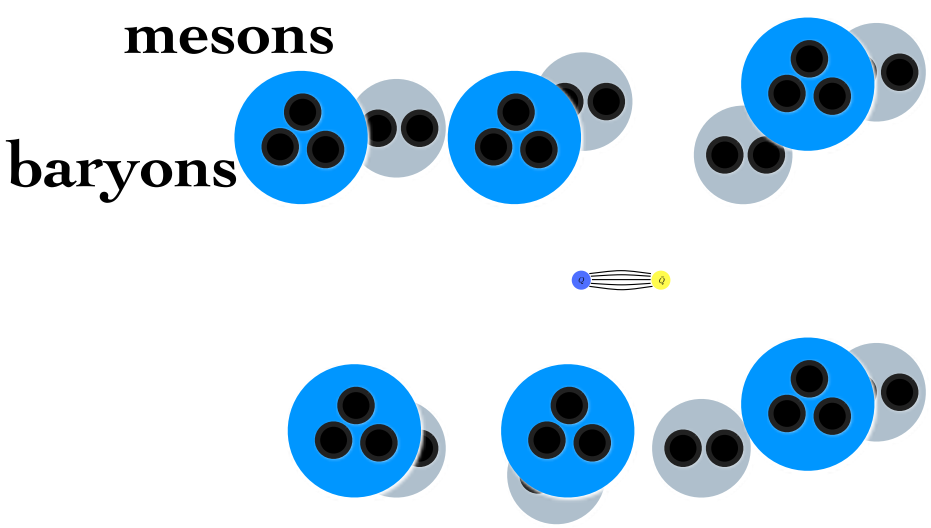

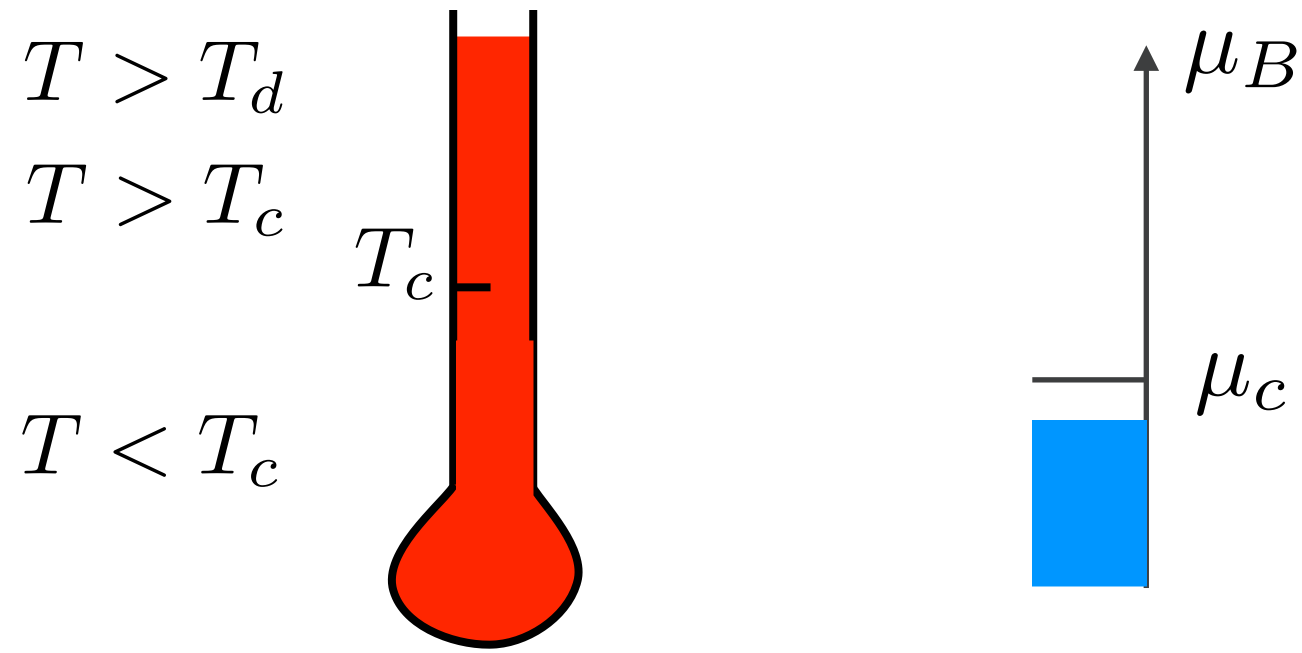

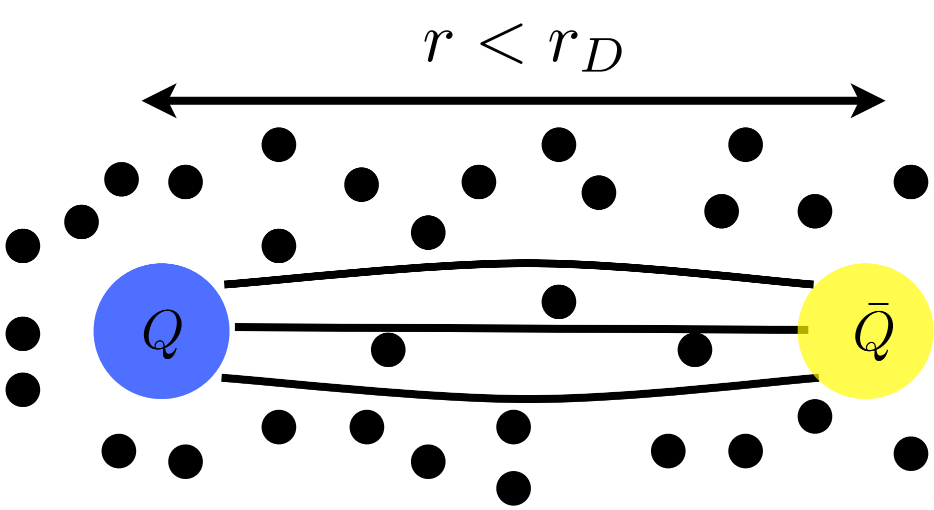

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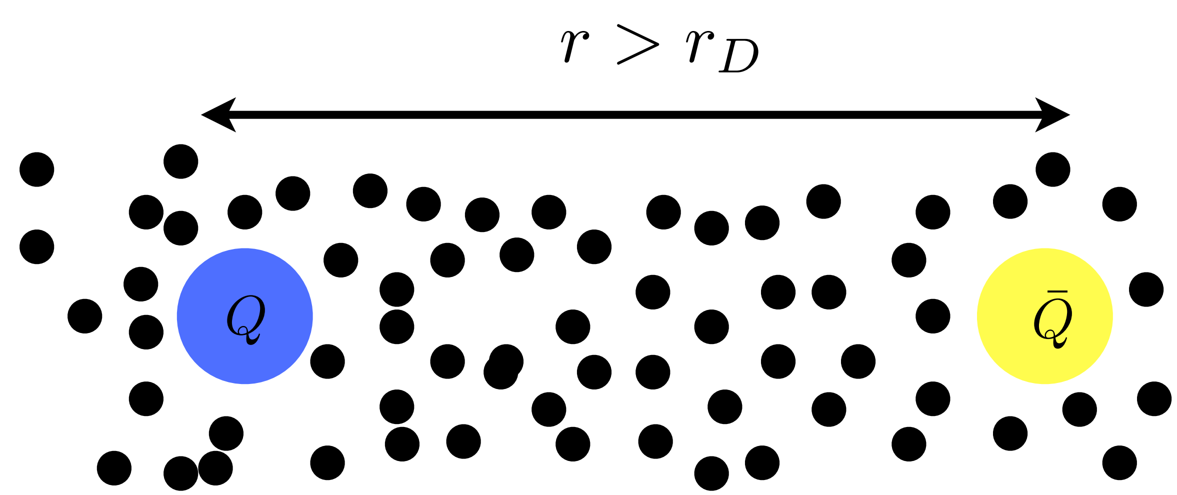

The plasma screens chromo-electric fields: thermal unbinding Matsui and Satz, (1986).

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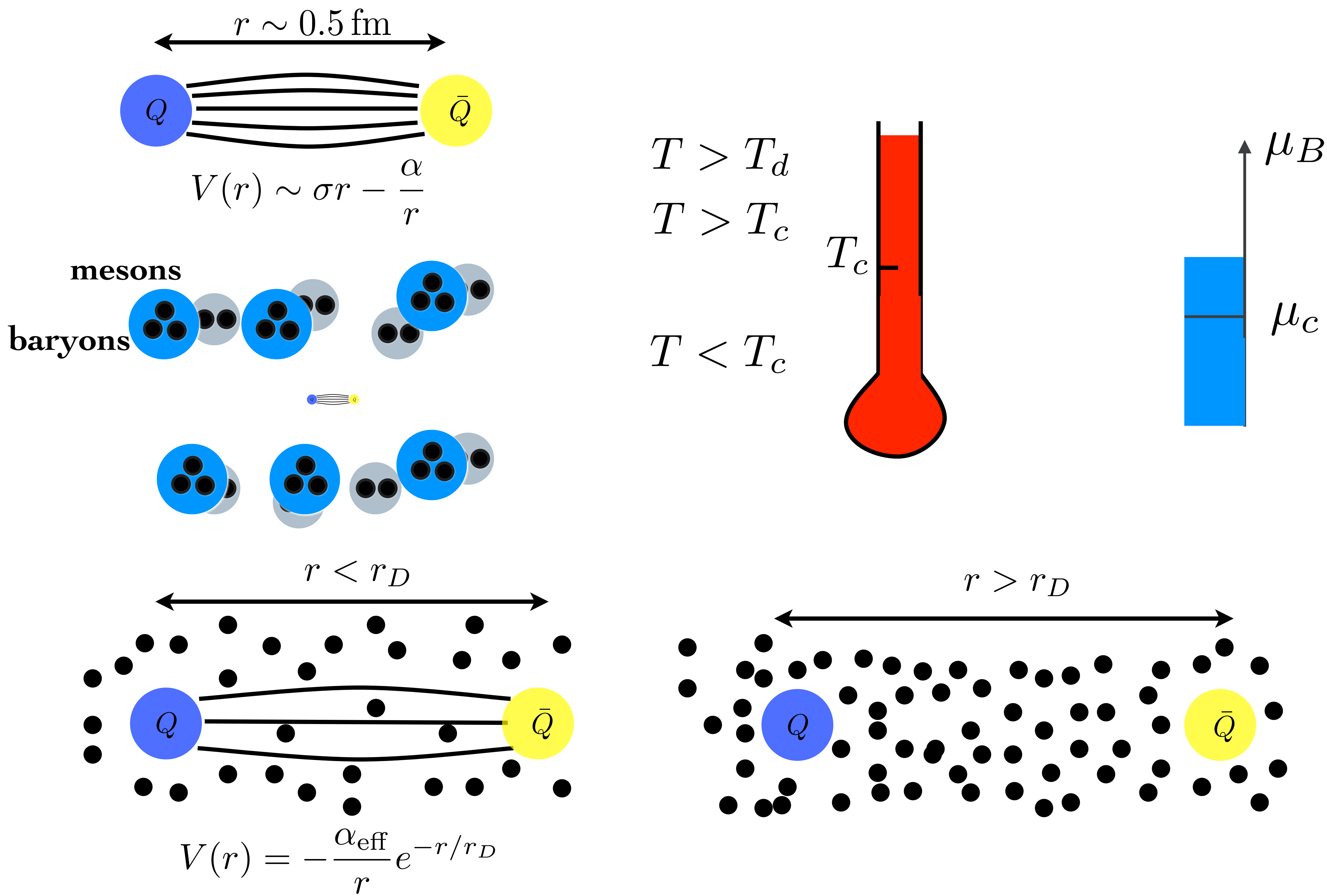

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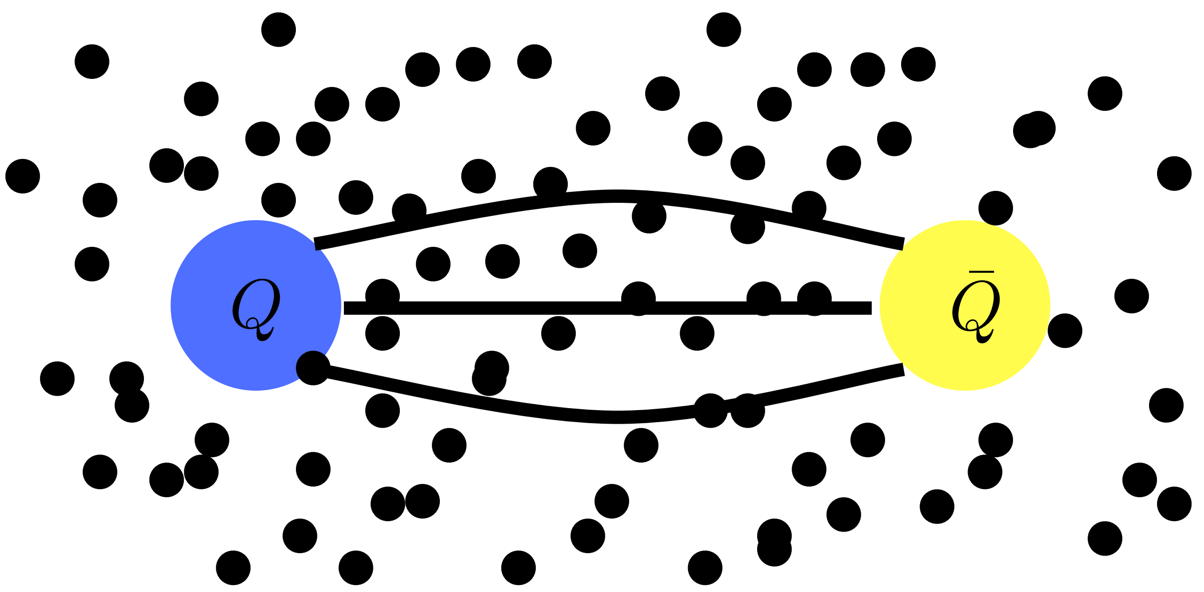
Expect similar effect by μ_B: Kakade and Patra, (2015), Carignano and Soto, (2020).

Landau damping

In a thermal medium, no strictly stationary bound state exists.
Interactions with the particles of the medium imply a finite lifetime for all states.



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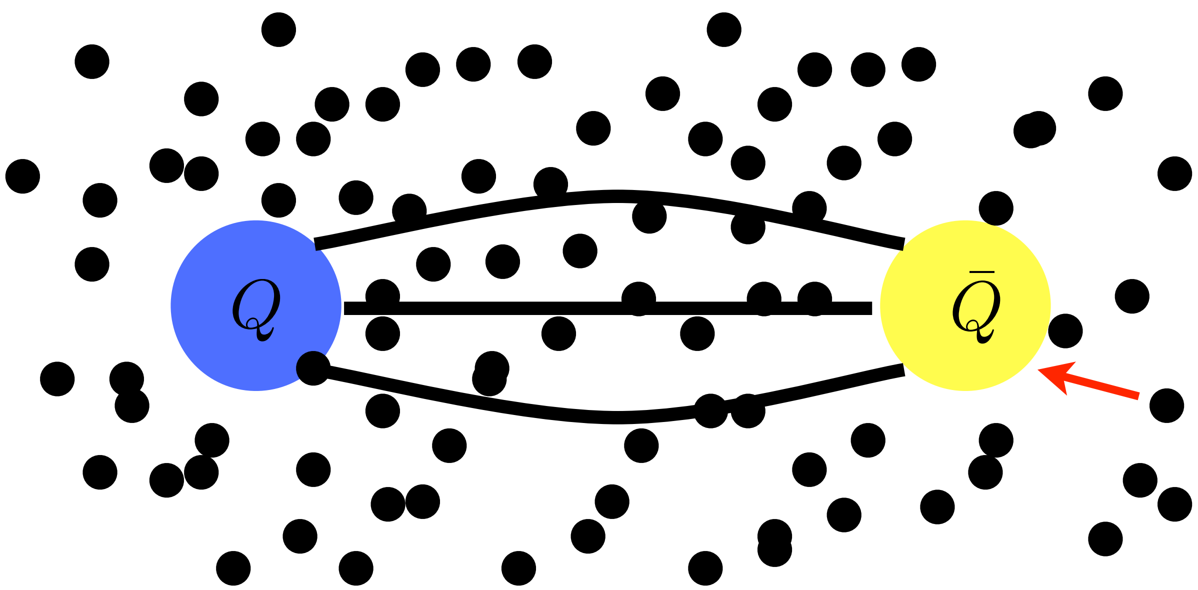

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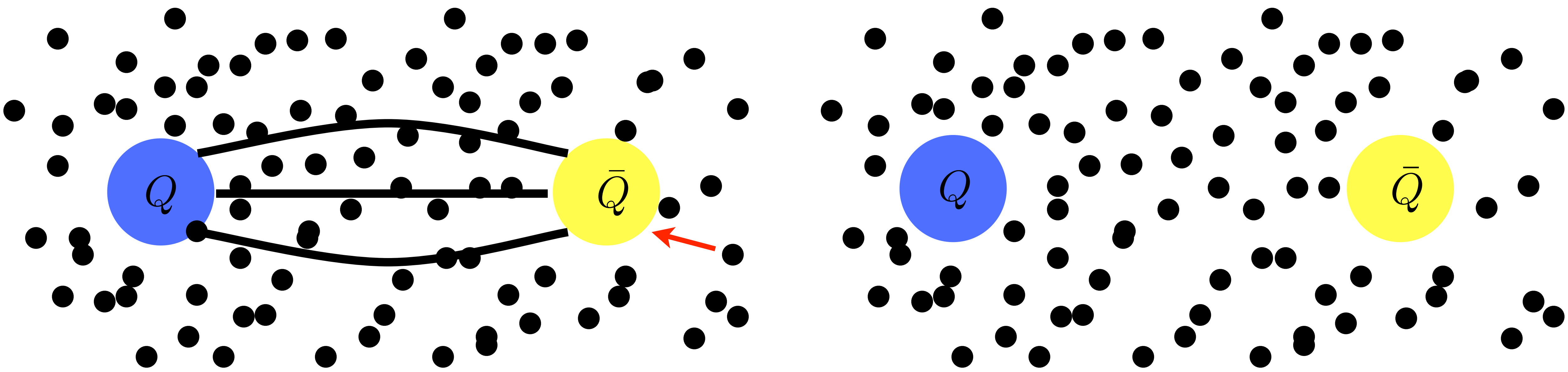

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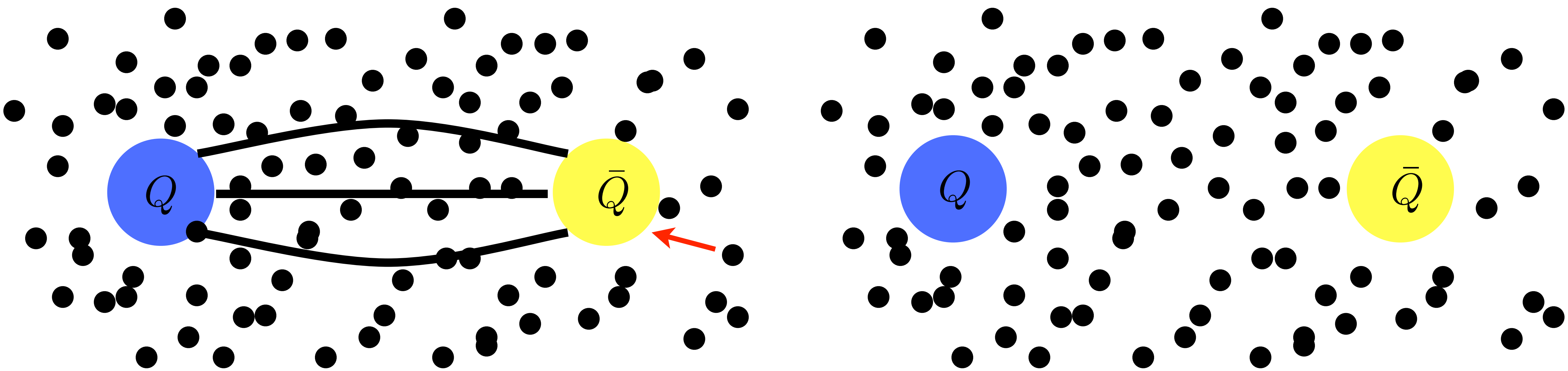

Broadening of the energy levels $\leftrightarrow$ imaginary part of the energy eigenvalues.
In a Schroedinger equation this corresponds to an imaginary part of the potential.

M. Laine et al. JHEP 0703, 054 (2007)

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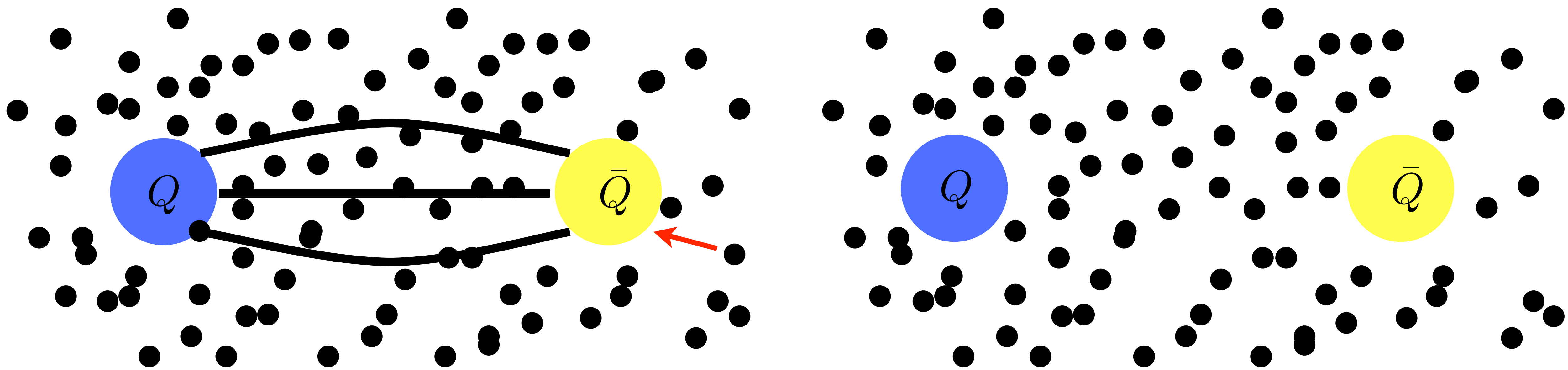

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See thursday talks on quarkonium!

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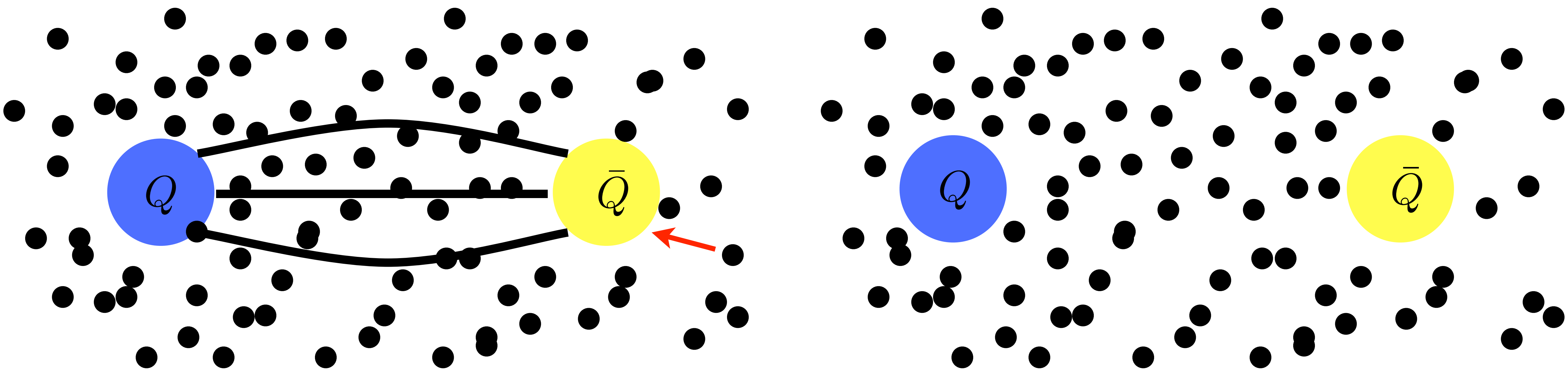

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"Brownian motion" of Heavy Quarks (HQs) in the QGP
While propagating in the QGP heavy quarks interact with in-medium quarks and gluons

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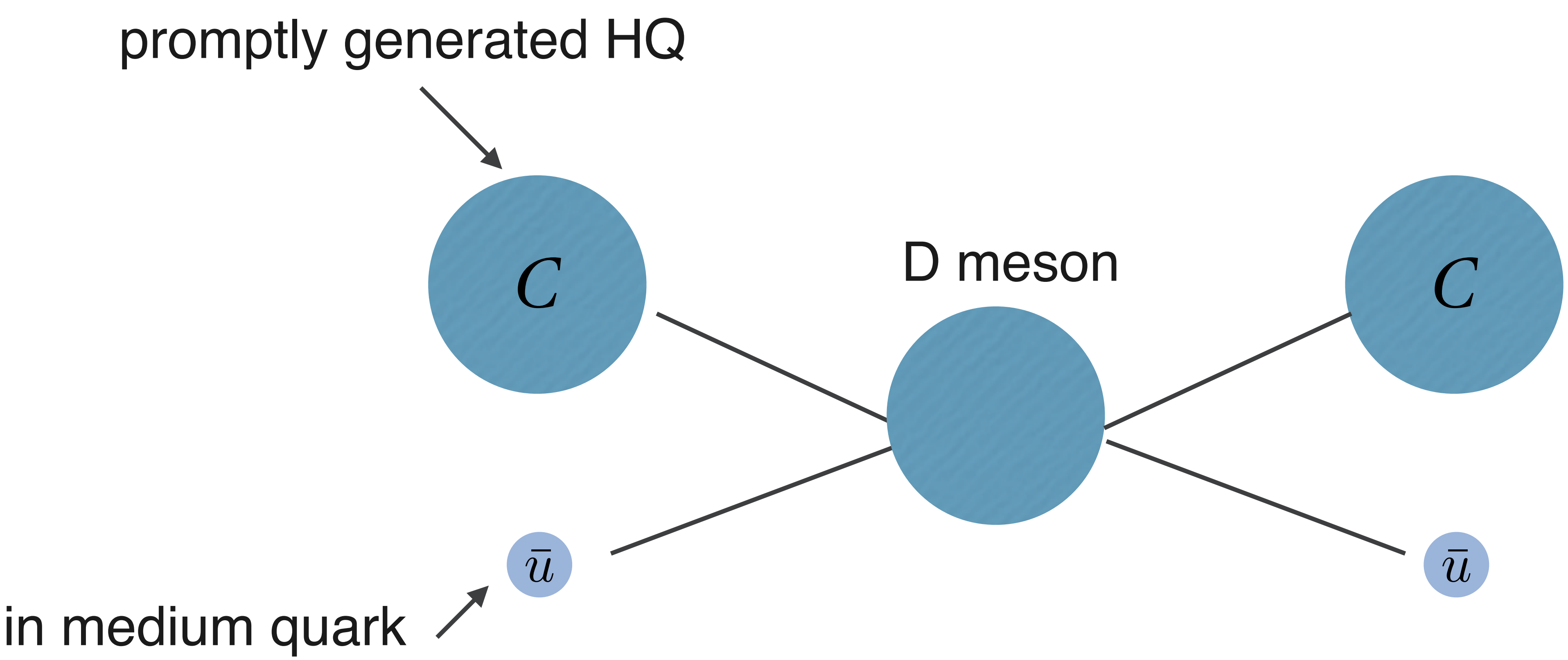
(resonant) scattering of heavy quarks with a light quark



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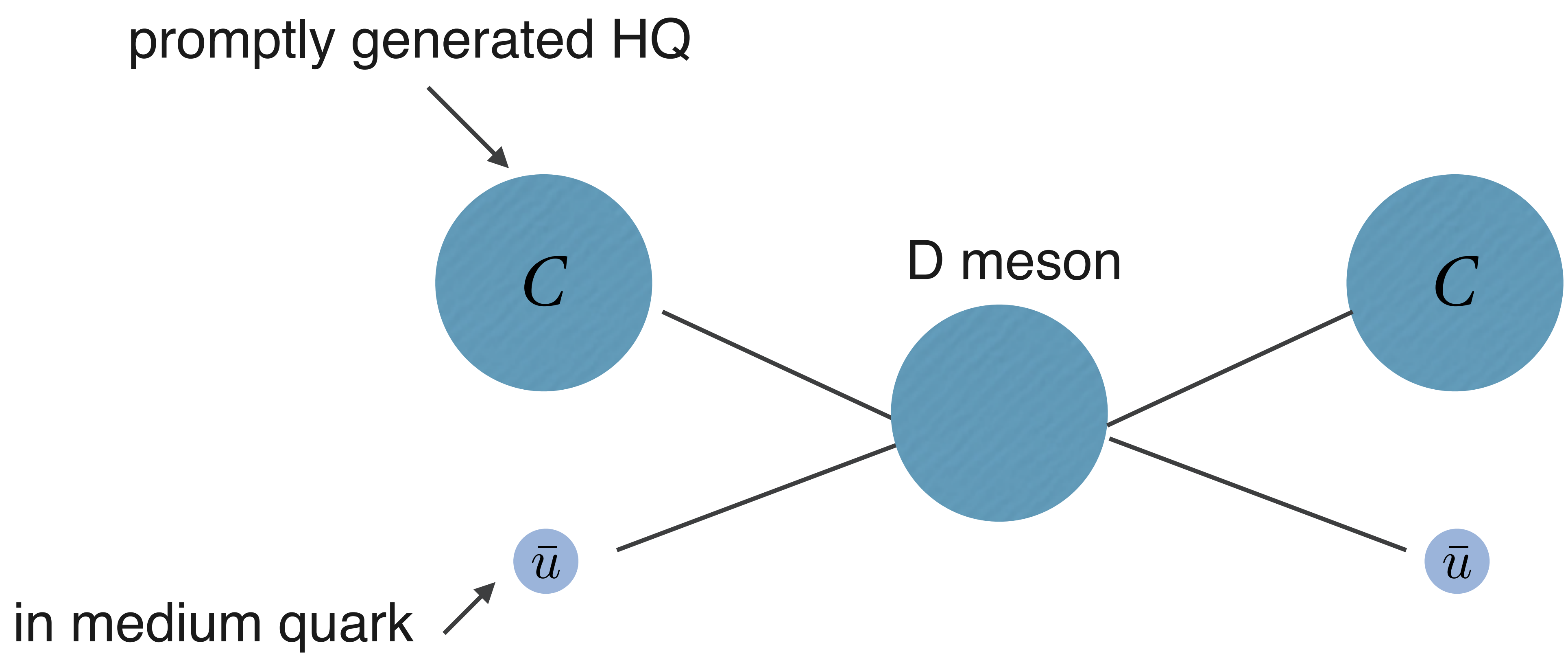

Replacing the light quark with a heavy quark, one has quarkonia generation Thews et al. (2001)

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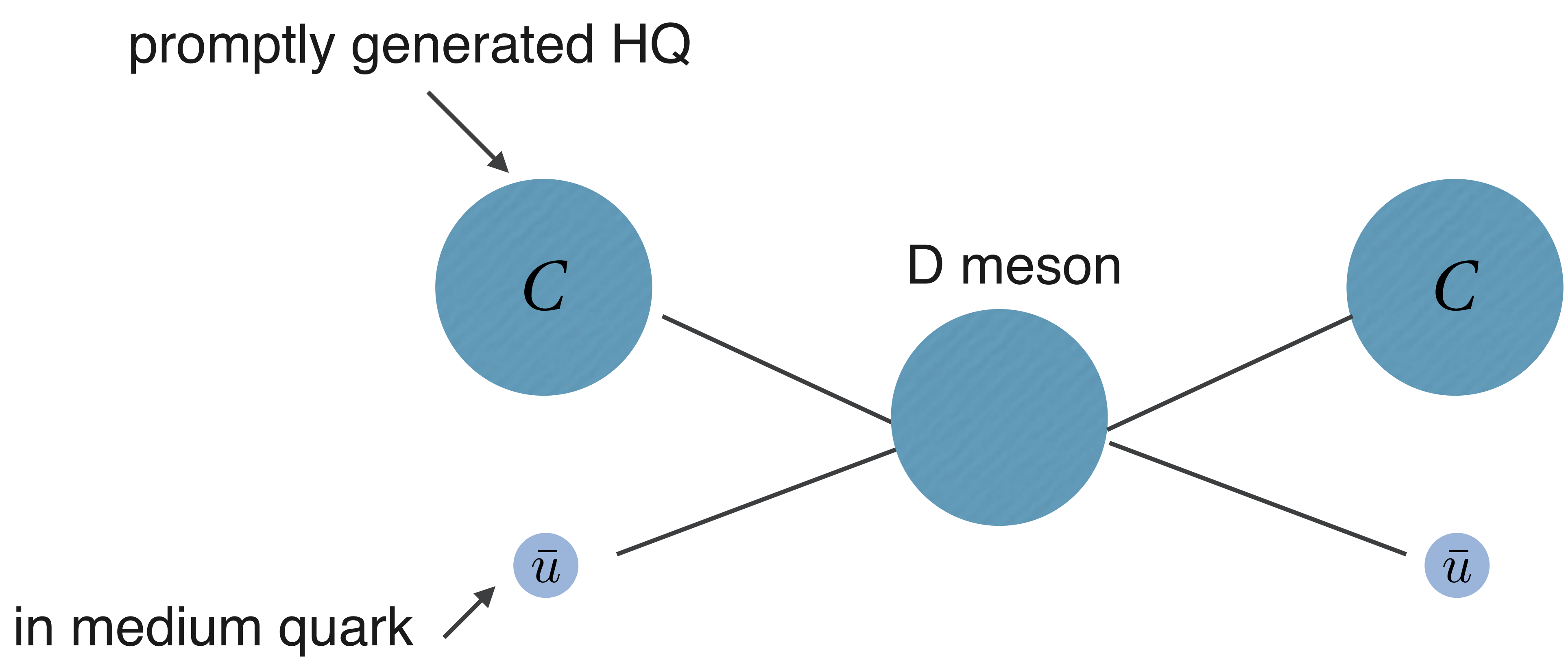

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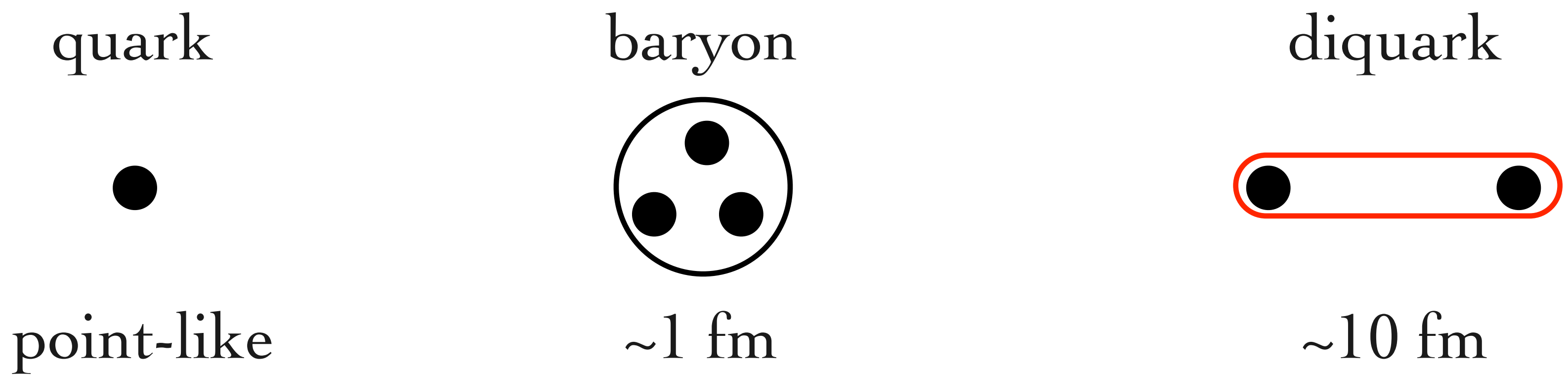
See Tuesday and Wednesday talks!

Color superconductor

Deconfinement by baryonic density increase



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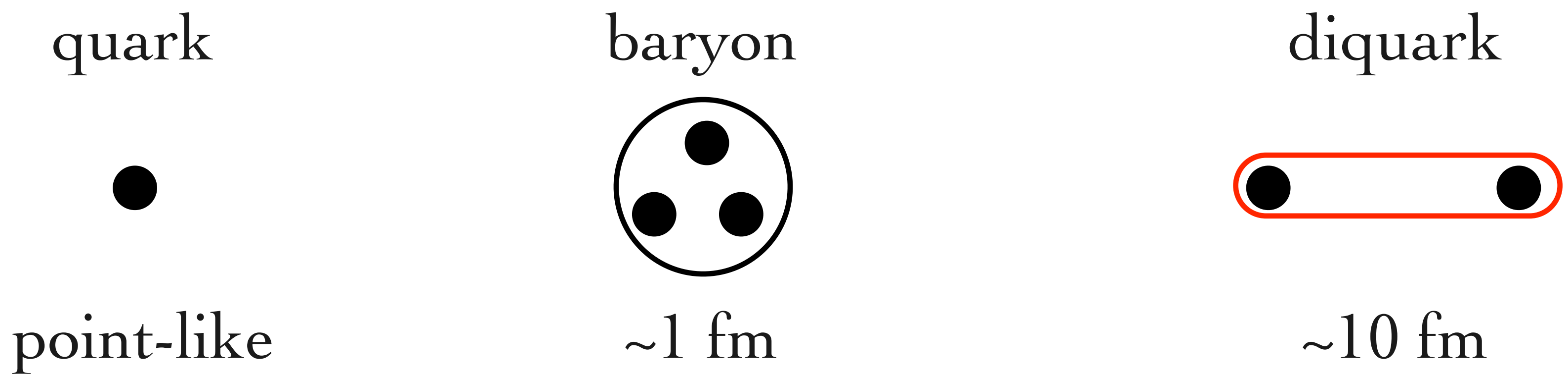
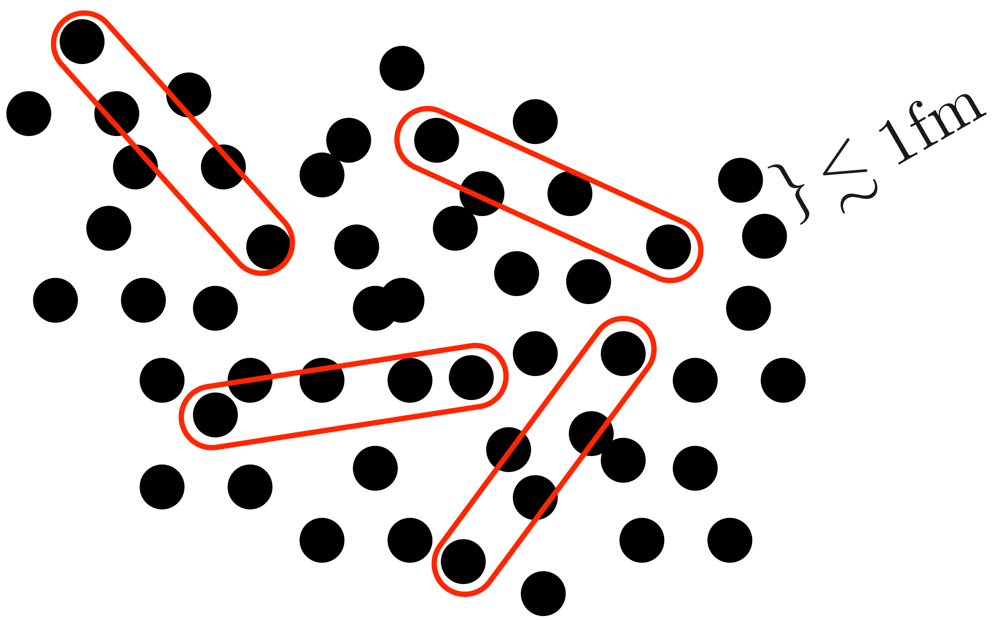


Very high density (Compact Star inner core)



Liquid of quarks with correlated diquarks

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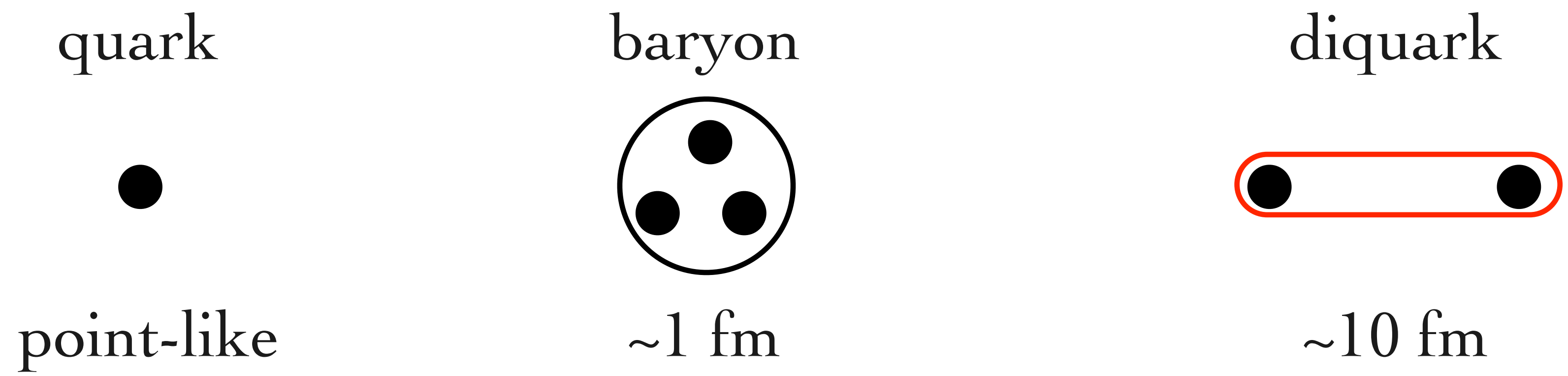
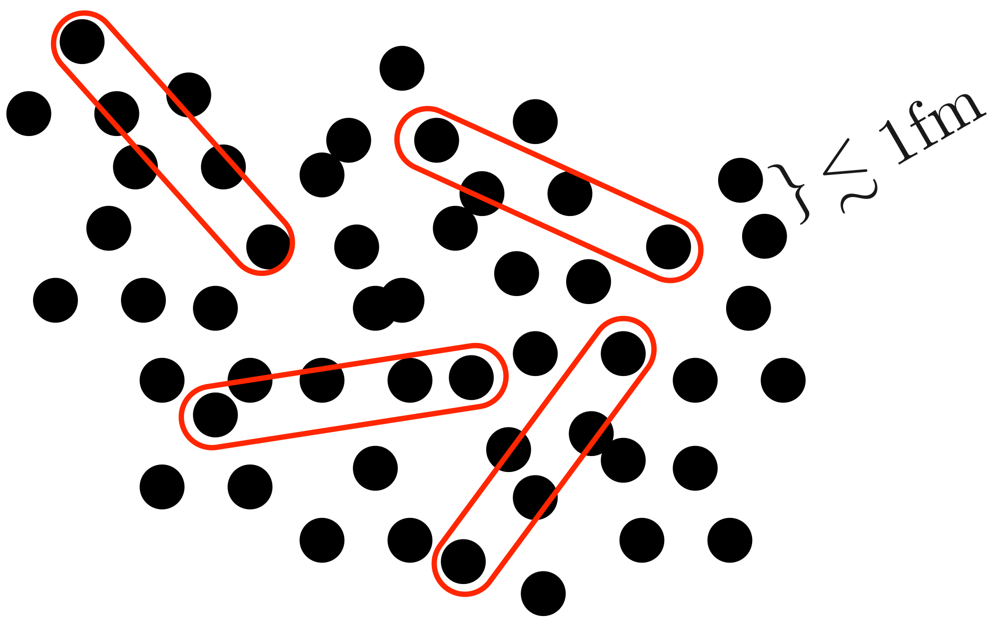


Very high density (Compact Star inner core)

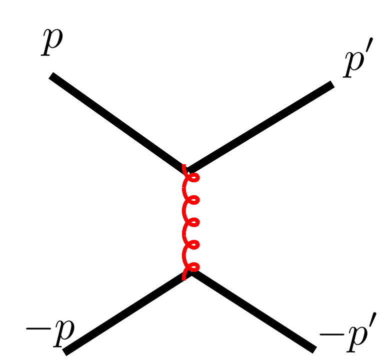


Liquid of quarks with correlated diquarks

Attractive interaction (perturbative)

$$3 \times 3 = \bar{3}_A + 6_S$$

attractive channel



$p, p' \simeq p_{\mathrm{F}}$

The interaction model

We have to use a model for QCD at densities reachable in compact stars.

One possibility is a NJL-like model with the same global symmetries of QCD

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One possibility is a NJL-like model with the same global symmetries of QCD

Free Lagrangian

$$\mathcal{L}_0 = \bar{\psi}(i\gamma^\mu\partial_\mu - M + \mu\gamma_0)\psi$$

+

Contact interaction

$$\mathcal{L}_{\rm int} = -g\,\bar{\psi}\gamma_\mu\lambda^A\psi\bar{\psi}\gamma^\mu\lambda^A\psi$$

coupling constant

spin, color, flavor structure

$$M = \mathrm{diag}(m, m, m_S)_{ij}$$

$$\mu \equiv \mu_{ij,\alpha\beta}$$

Diquark Condensate

Quark fields $\psi_{\alpha i}$

$\alpha, \beta = 1, 2, 3$ **color indices**

$i, j = 1, 2, 3$ **flavor indices**

Mixture of **9 different fermions**. Six of them are relativistic, three are non relativistic

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Mixture of **9 different fermions**. Six of them are relativistic, three are non relativistic

General color superconducting condensate

color structure

$$\langle \psi_{\alpha i} C \gamma_5 \psi_{\beta j} \rangle \propto \sum_{I=1}^{3} \Delta_{\mathrm{I}} \varepsilon^{\alpha \beta I} \epsilon_{ijI}$$

flavor structure

gap parameters

It has a color charge **It has a flavor charge** **It has a baryonic charge**

The corresponding symmetries are broken, locked or mixed

Color Flavor Locked phase

Condensate

$$\langle \psi_{\alpha i} C \gamma_5 \psi_{\beta j} \rangle \sim \Delta_{\mathrm{CFL}}\, \epsilon_{I\alpha\beta}\epsilon_{Iij}$$

Pairing of quarks of all flavors and colors

Alford, Rajagopal, Wilczek Nucl.Phys. B537 (1999) 443

Symmetry breaking

$$SU(3)_c \times \underbrace{SU(3)_L \times SU(3)_R}_{\supset U(1)_{\mathrm{Q}}} \times U(1)_B \to \underbrace{SU(3)_{c+L+R}}_{\supset U(1)_{\tilde{\mathrm{Q}}}} \times Z_2$$

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- Breaking of $\mathrm{SU(3)_c}$: 8 gauge bosons become massive. It is like having 8 (interacting) photons with a Meissner mass.
- χSB: 8 (pseudo) Nambu-Goldstone bosons (NGBs) **as in the hadronic phase!**
- $\mathrm{U(1)_B}$ breaking: 1 NGB. This is a genuine superfluid mode.

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The system is at the same time a (color) superconductor and a (baryonic) superfluid

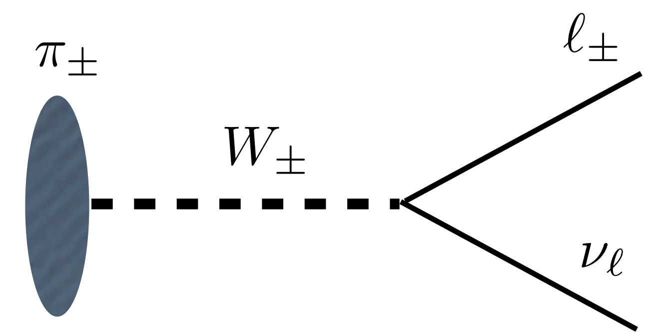
Meson condensation

Pion condensation

Stabilization

The pion decay can be Pauli blocked
for a large lepton chemical potential

pion decay in vacuum



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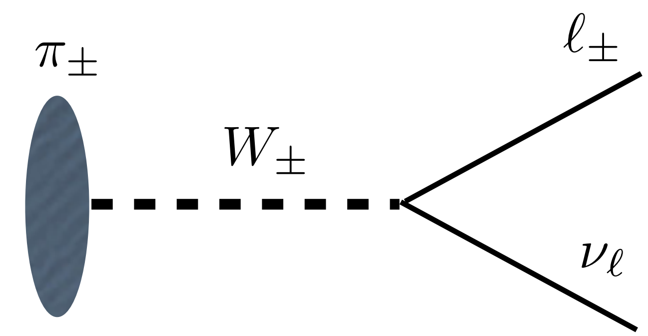

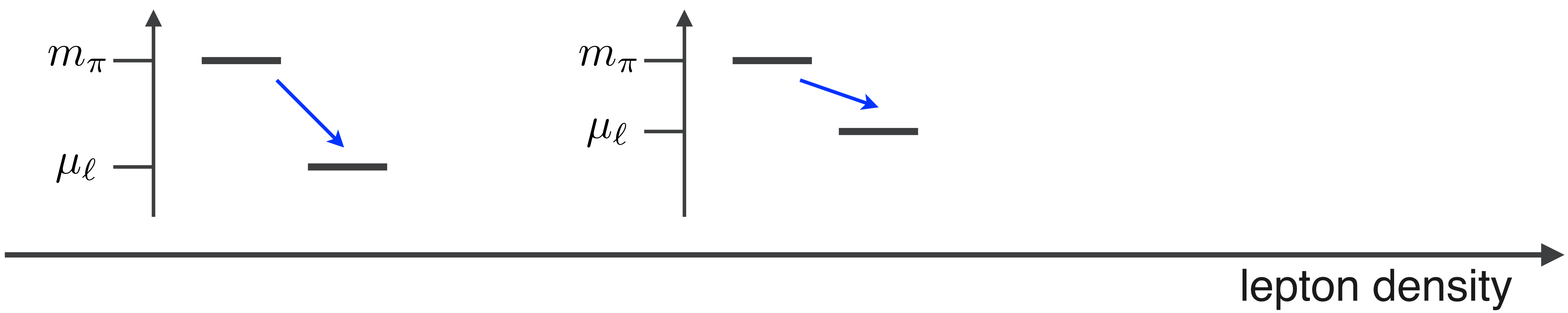

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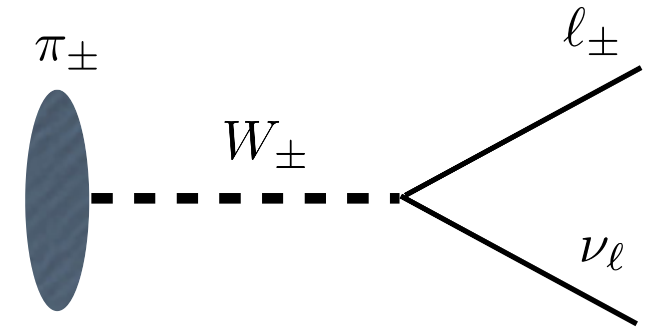

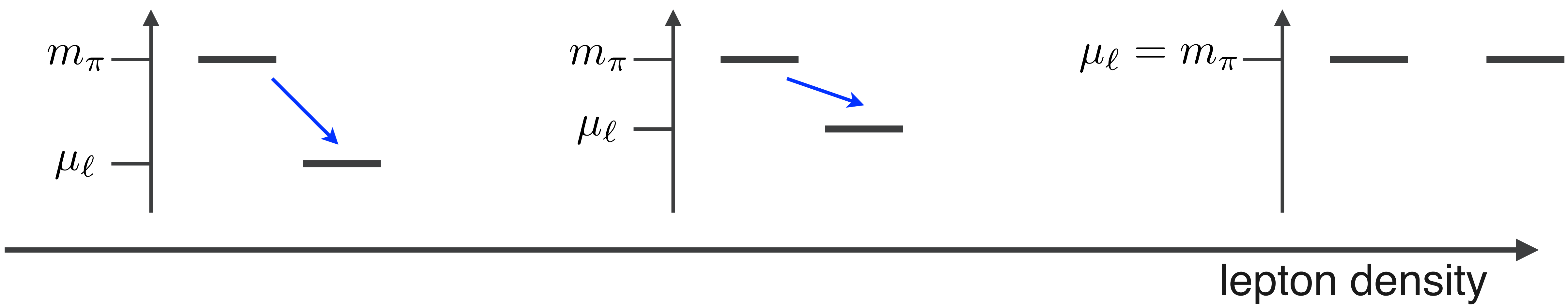

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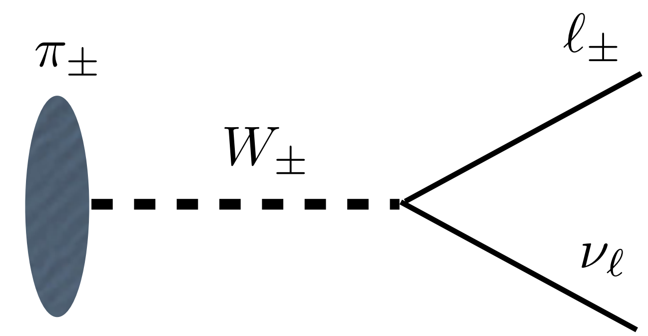
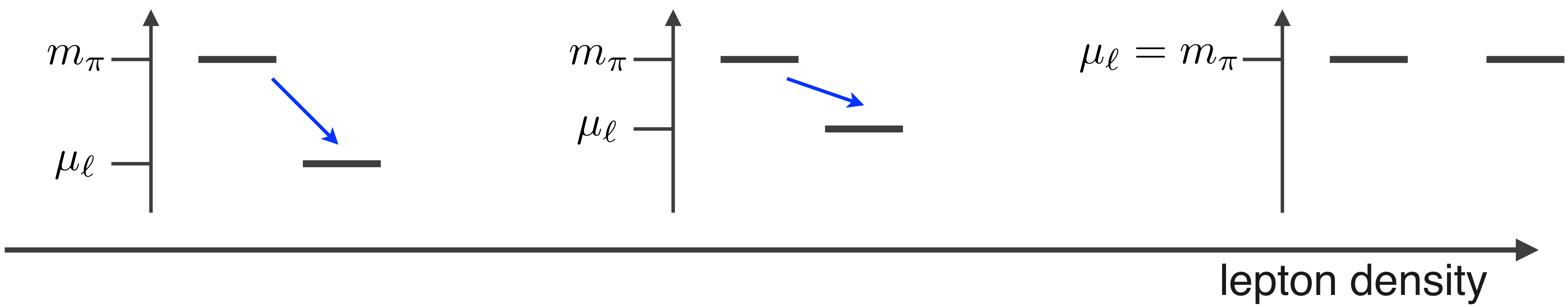




Energy spectrum splitting
Stark-like effect

$$E_{\pi^0} = \sqrt{m_\pi^2 + p^2}$$

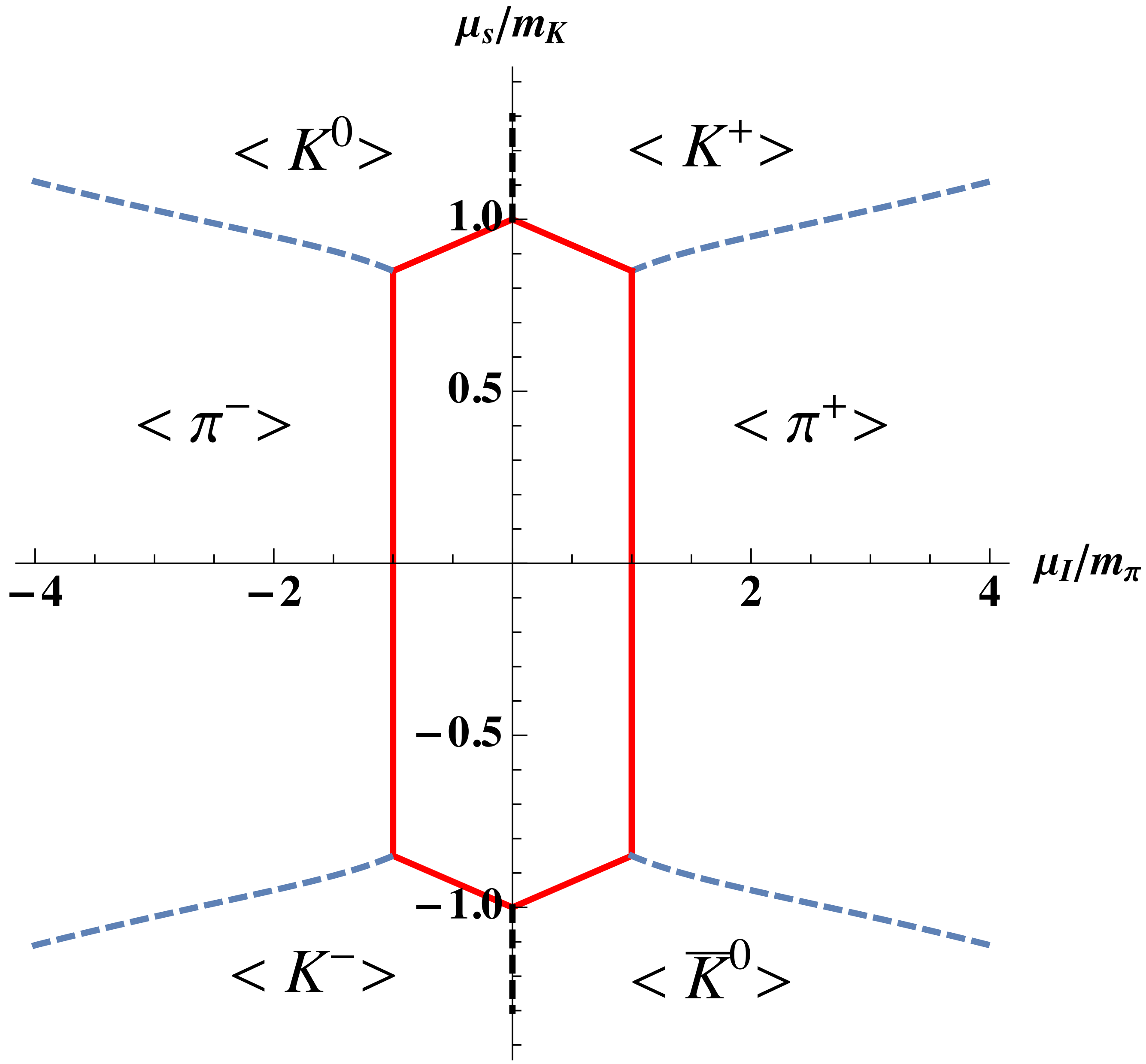
$$E_{\pi^-} = +\mu_I + \sqrt{m_\pi^2 + p^2}$$

$$E_{\pi^+} = -\mu_I + \sqrt{m_\pi^2 + p^2}$$

$$\boxed{m_{\pi^+}^{\text{eff}} = m_\pi - \mu_I} \longrightarrow$$

At $\mu_I = m_\pi$ a massless mode appears:
pion condensation $\langle \bar{\psi} \sigma_2 \gamma_5 \psi \rangle$

Phases of meson condensates



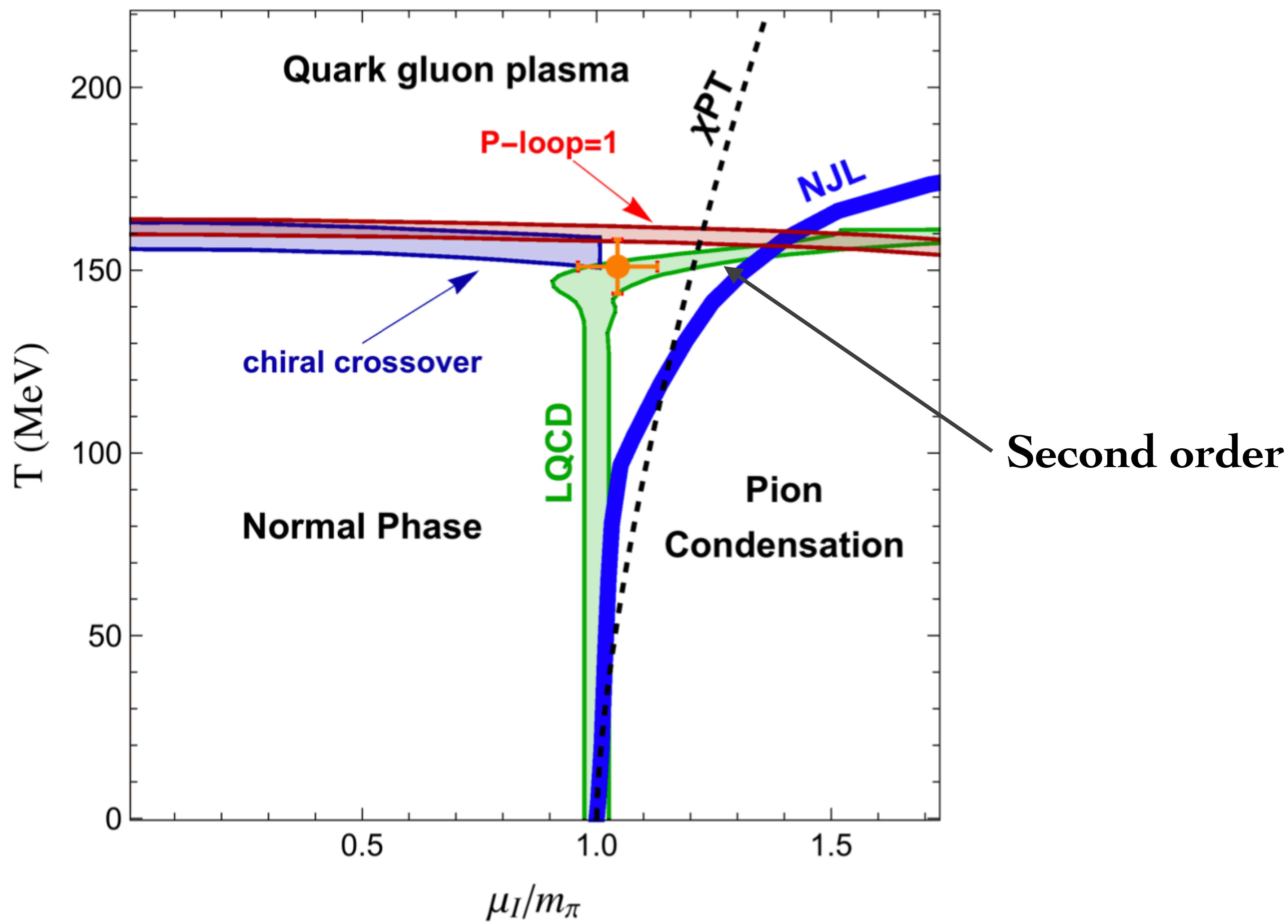
Dashed: first order
Solid: second order

Kogut and Toublan PhysRevD.64.034007

MM, Particles 2, no.3, 411-443 (2019)

At asymptotic μ_I and/or μ_S matter should be deconfined in a rather unusual way

T-μ_I phase diagram



Combination of LQCD by Brandt et al, PRD 97, 054514 (2018) with effective field methods.

M.M. Particles 2 (2019) no.3, 411-443

The phase diagram

Identify the hadronic phases by quark condensates

In each phase different quark condensates are realized

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$$\langle \bar{\psi}\psi \rangle$$

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no condensate

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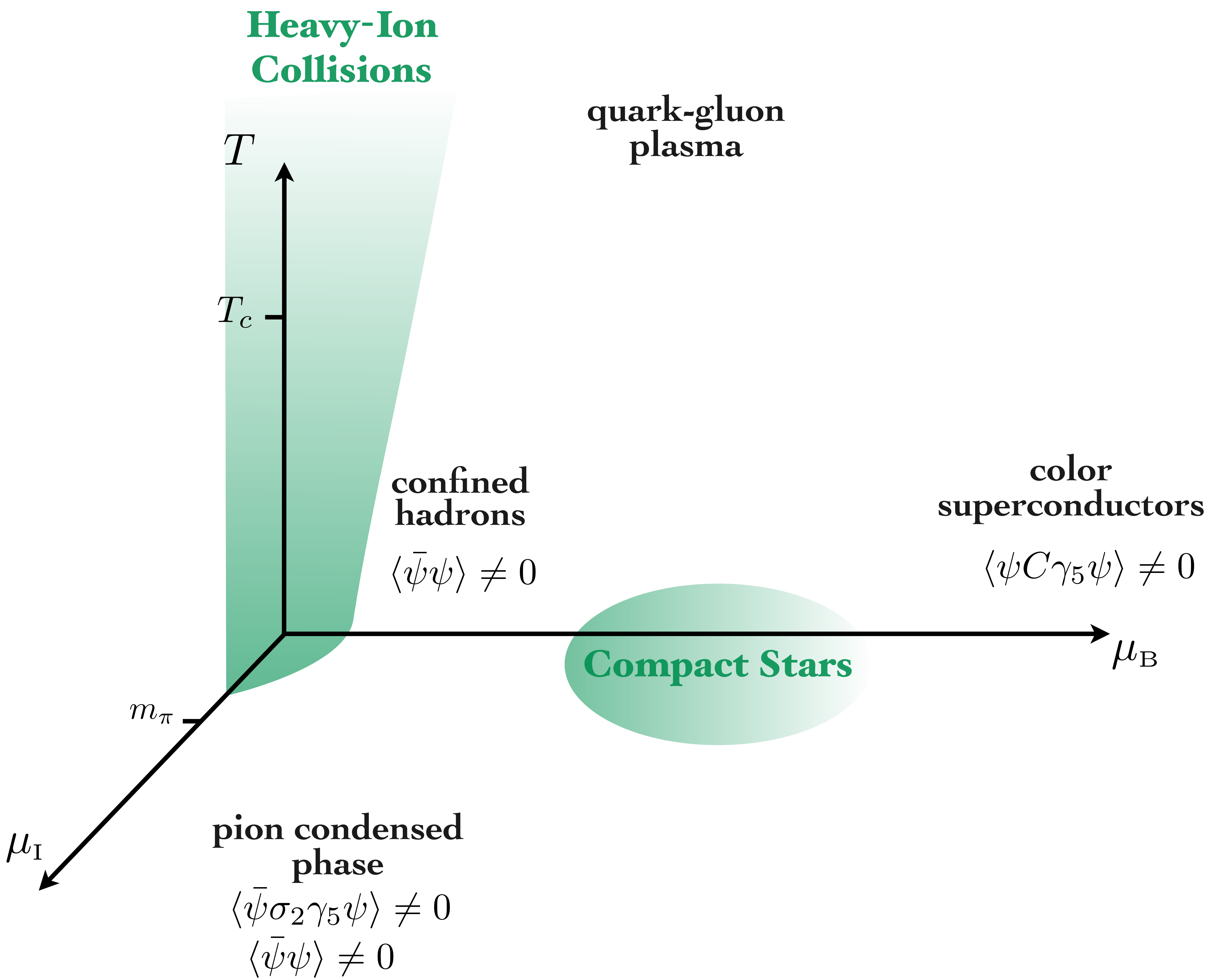
Quark-gluon plasma
no condensate

Each quark condensate **breaks** or **locks** the symmetries of QCD in a different way

The QCD phase diagram



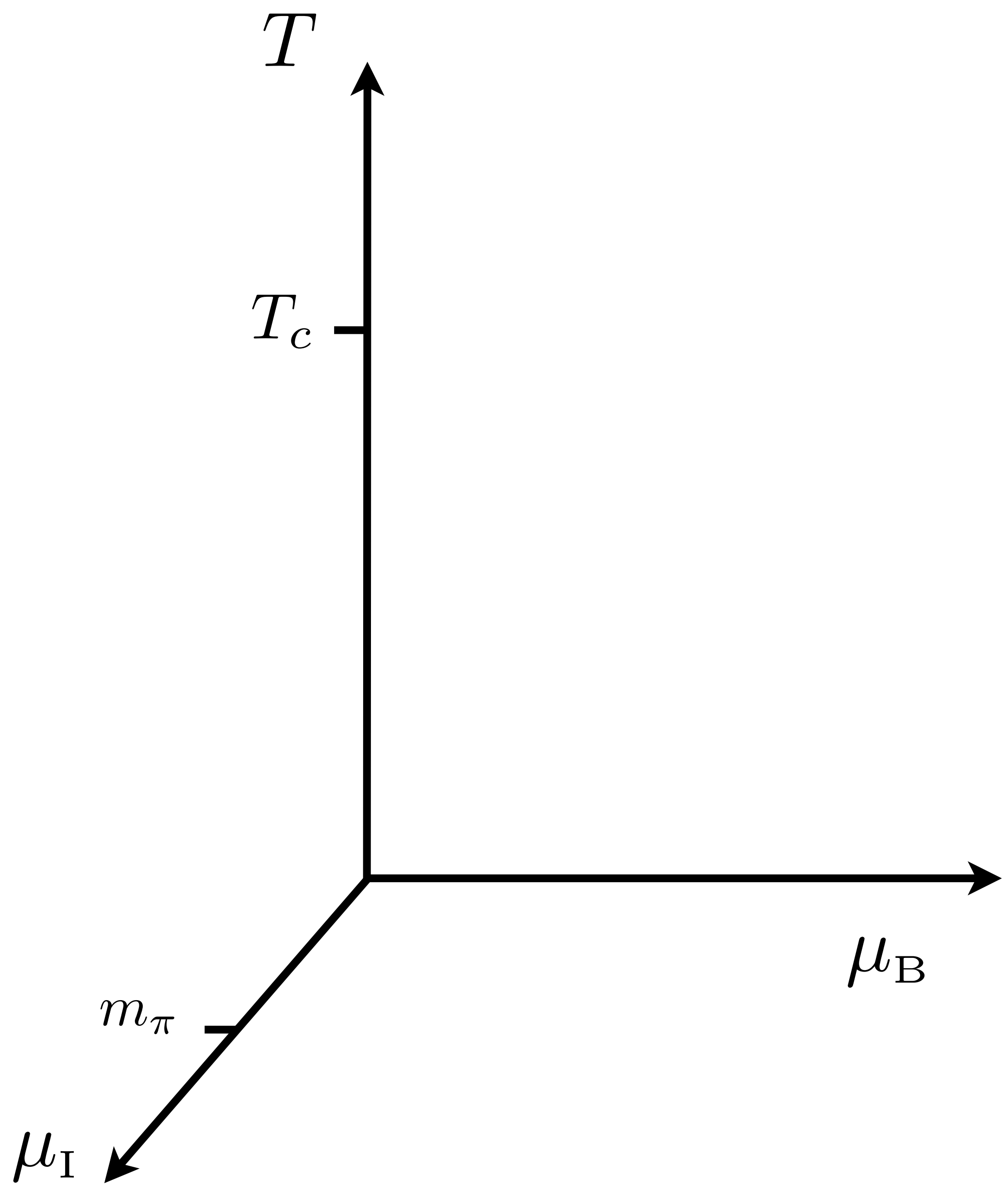
A symmetry breaking path (two flavor quark matter)

$\mu_I = m_{u,d} = 0$

$\psi_L \to U_L \psi_L$

$\psi_R \to U_R \psi_R$

$$\underbrace{SU(2)_L \times SU(2)_R \times U(1)_B}_{\supset [U(1)_{\text{e.m.}}]}$$



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reduce T below T_c

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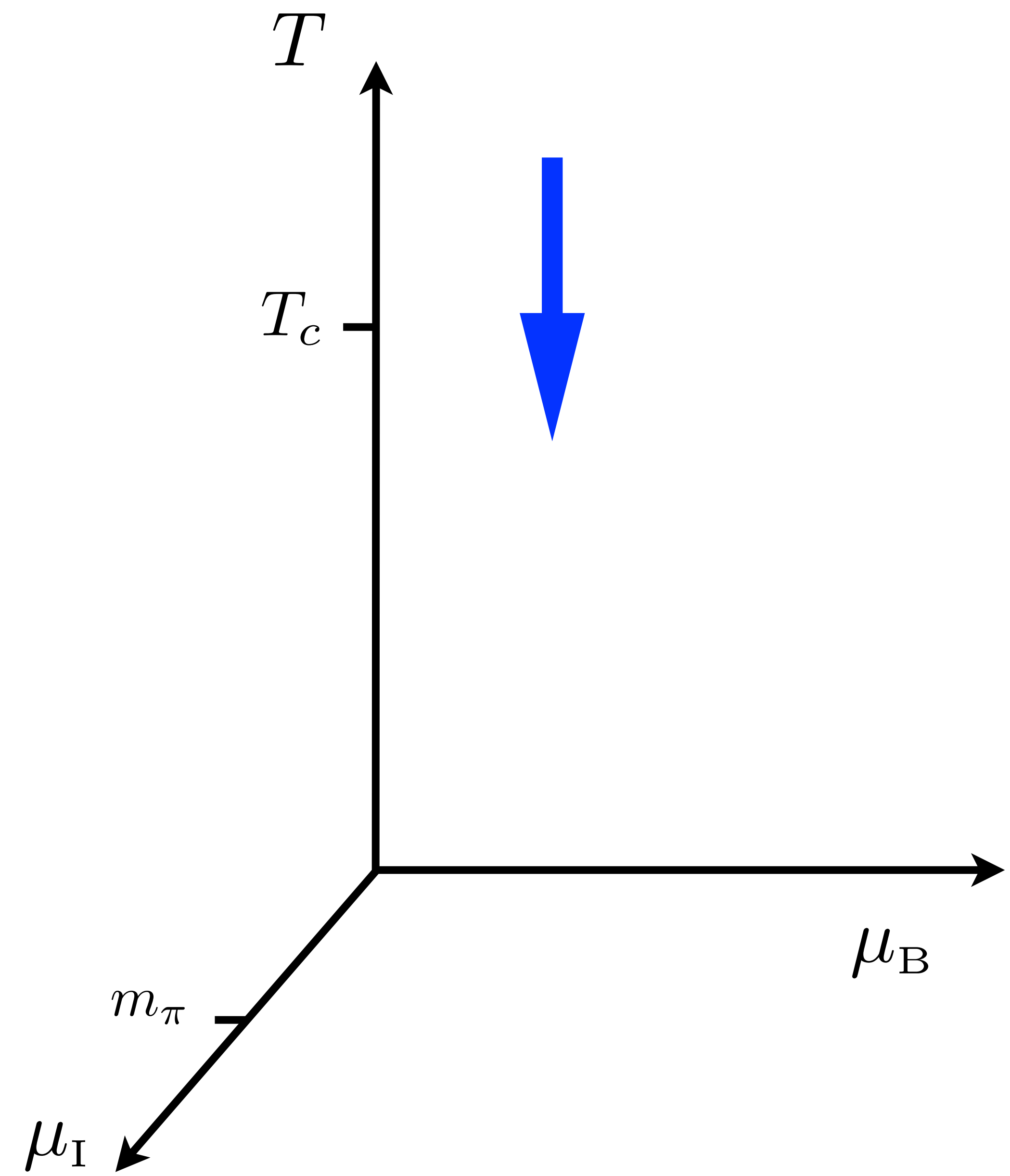

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Spontaneous chiral symmetry breaking $\langle \bar{\psi}\psi \rangle \neq 0$

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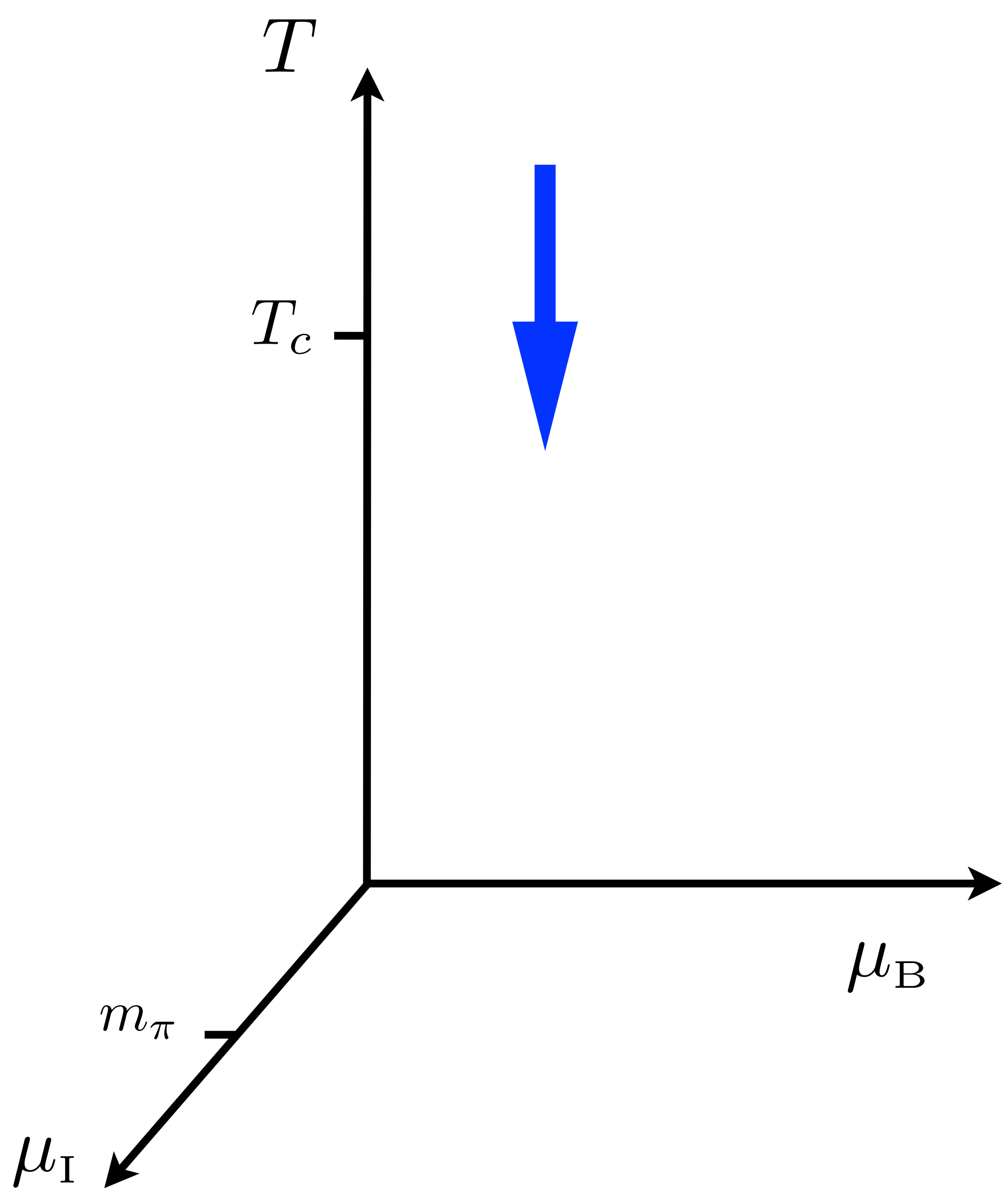
invariant under $U_L = U_R = e^{i\boldsymbol{\sigma}\cdot\boldsymbol{\theta}}$

Pions are the (pseudo) NGBs



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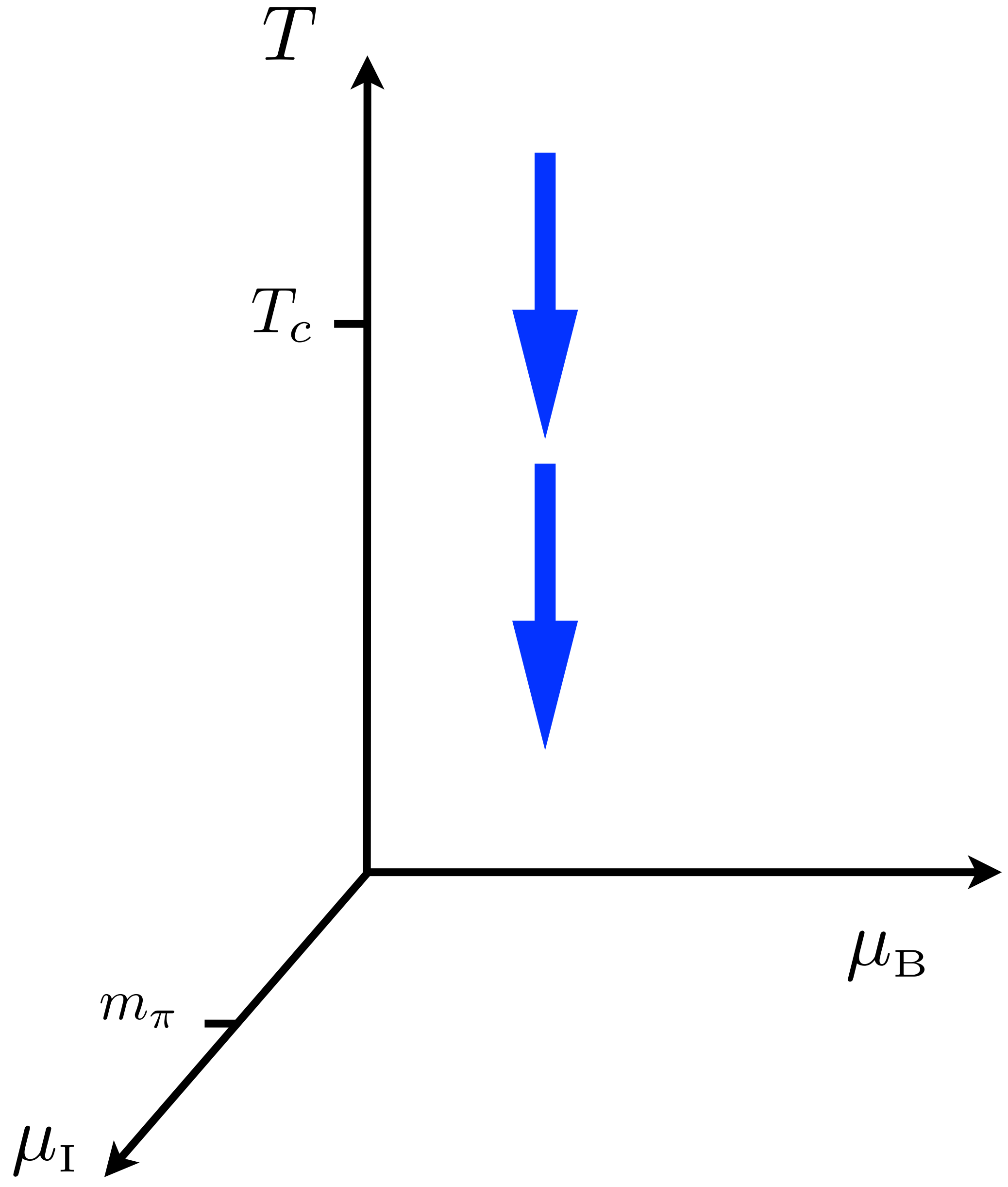

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Increase μ_I

Explicit symmetry breaking

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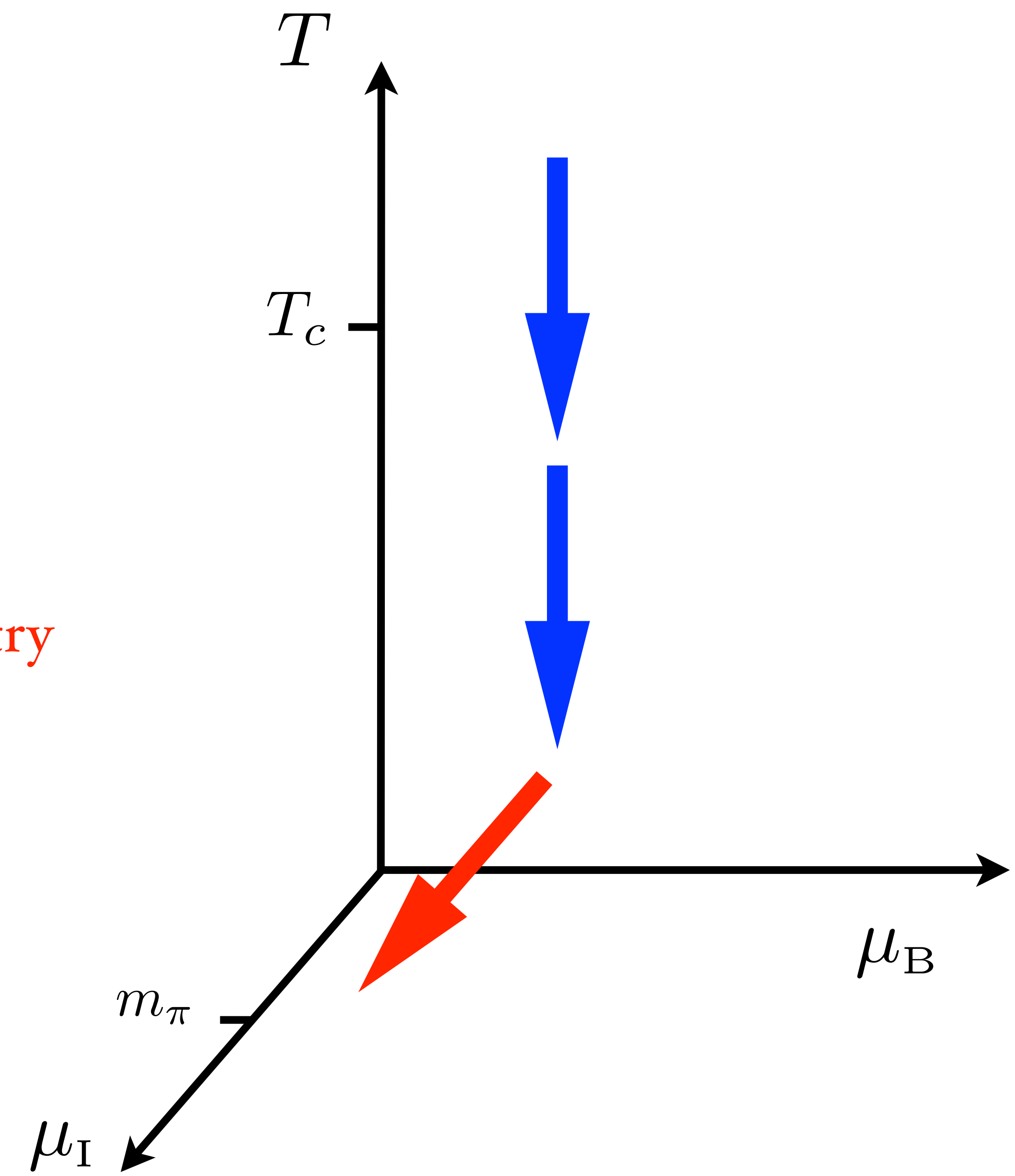

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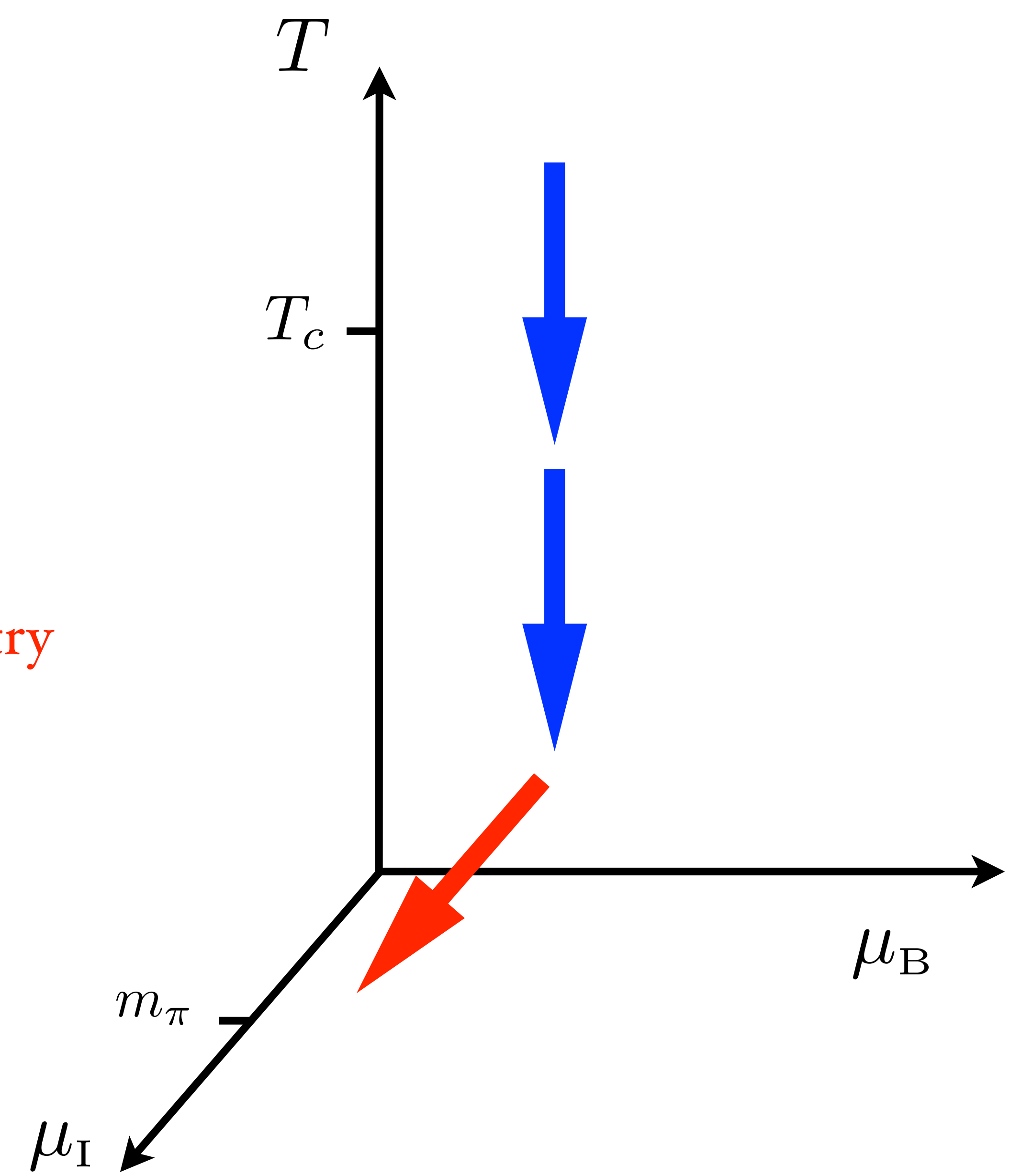

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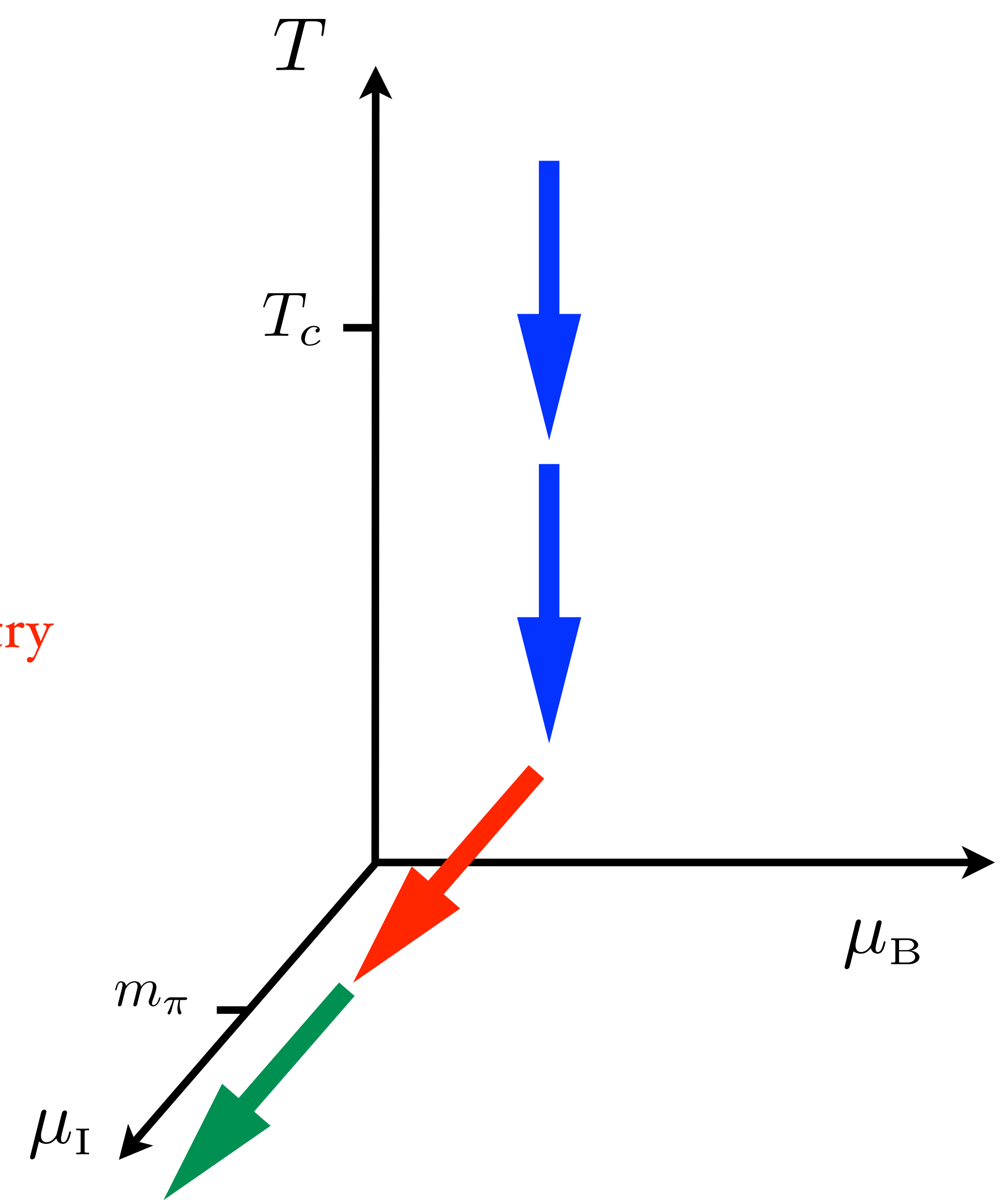
$$\underbrace{U(1)_{\mathrm{B}}}_{\not\supset [U(1)_{e.m.}]}$$



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Spontaneous symmetry breaking (meson condensation)

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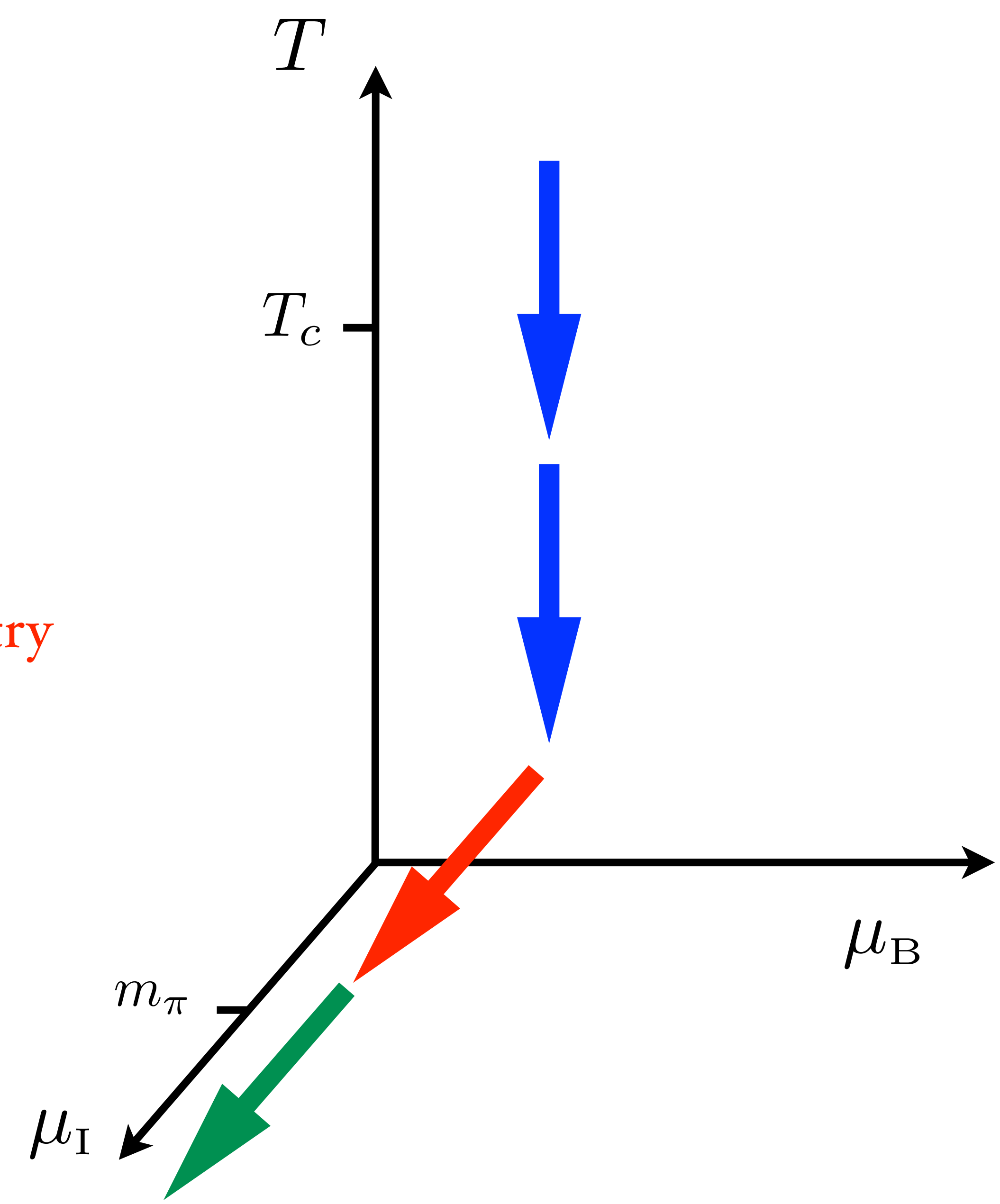
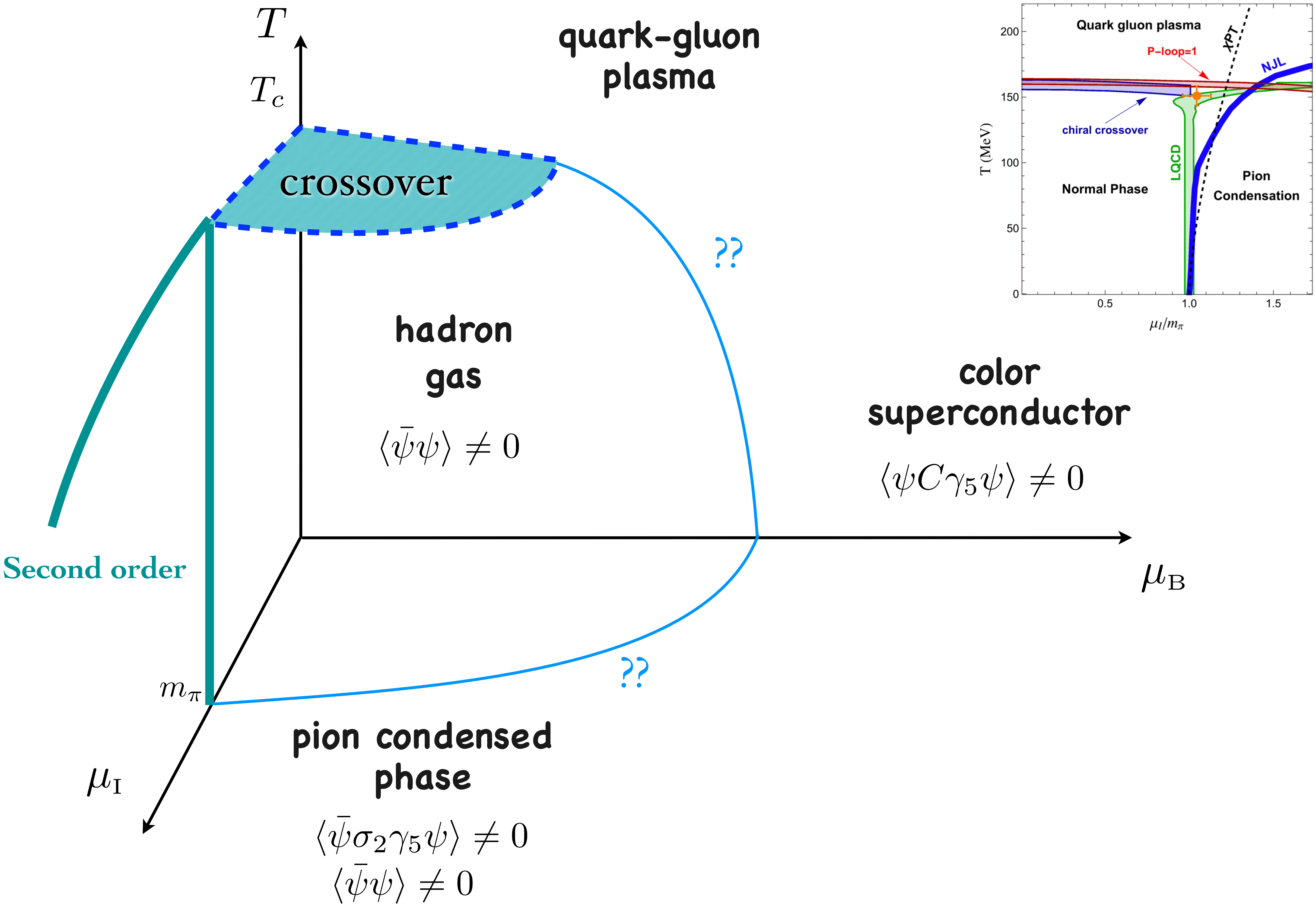
$\langle\bar{\psi}\sigma_2\gamma_5\psi\rangle \neq 0$

$$\underbrace{U(1)_{\mathrm{B}}}_{\not\supset [U(1)_{e.m.}]}$$

One NGB



Revisiting the QCD phase diagram



M.M. Particles 2 (2019) no.3, 411-443

Conclusions

- **Chiral symmetry and quark confinement pertain to two different limits of QCD**

- **They should be approximately realized in real QCD**

- **Any physically sound tool to explore QCD should be used, even going to unphysical parameter space**

- **There is a richness of phases due to a rich particle spectrum**

Thanks for your attention!

Back up

Effective field theories

Effective field theories

If we do not use QCD we want theories that preserve (part of) its symmetries
and that are capable of describing the symmetry breaking patterns

Lattice QCD	Effective field theories
Discretization on a lattice. Does not work at large baryonic densities	Describe global symmetries of QCD Lack the gauge field dynamics

Qualitative picture

Any effective theory can be characterized by

1) separation scale
2) particle content
3) matching condition
4) method of regularization/cancelation of divergencies

QCD is a renormalizable theory: any divergency can be removed.

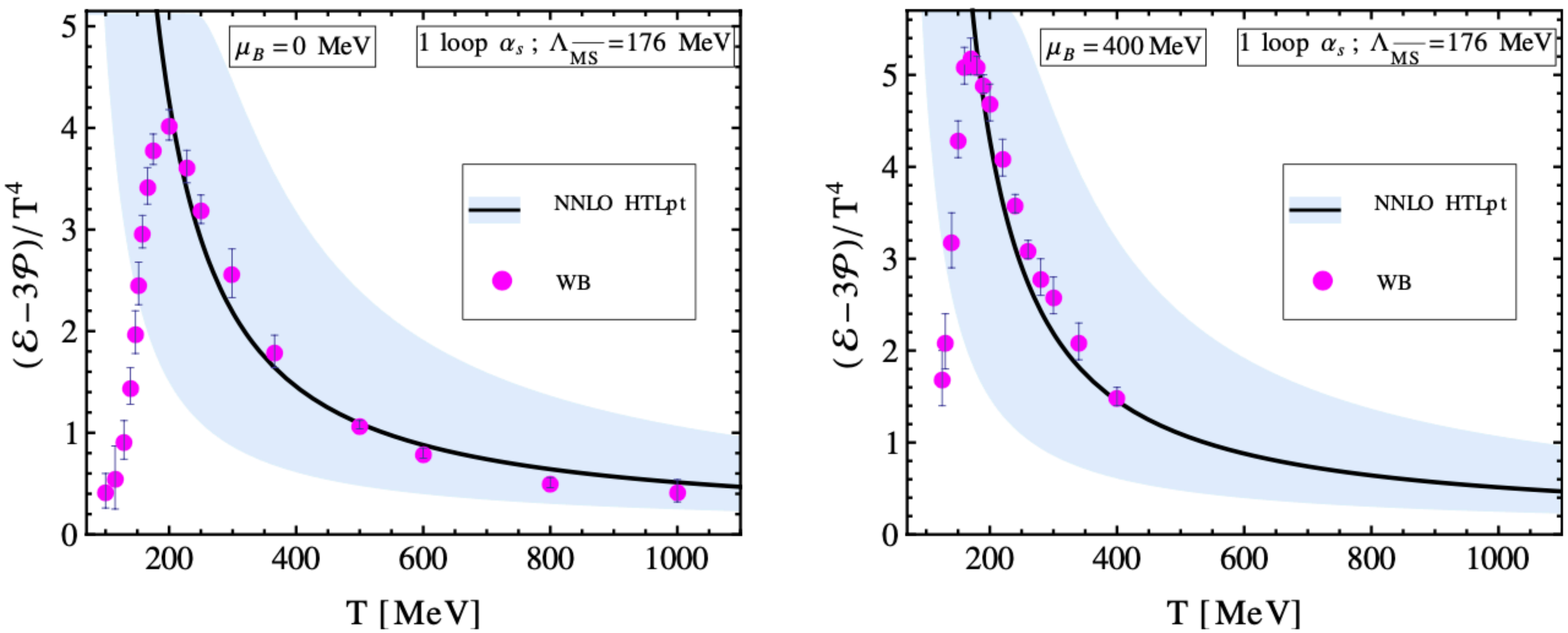
This results in a theory which has been very successfully compared to experiments. No UV scale has appeared so far. In other words, if QCD is the low energy EFT of a more fundamental one, we still have not found the breaking scale.

When dealing with EFT of QCD, we always have to keep in mind that there exists a breaking scale. The scale is associated to a change of degrees of freedom or to an internal inconsistency of the EFT.
Example: chiral perturbation theory is a low-energy theory with breaking scale $\Lambda_\chi \sim 1\,\mathrm{GeV}$

Beyond this point one has to consider the mesonic resonances, baryons and then quarks and gluons. Which means changing the degrees of freedom, of interaction etc. This is not impossible, it is only extremely hard and does not seem to be simpler than solving QCD itself.

Hard thermal loop (HTL)

Resummed perturbation theory



Pion condensation

More on the method

- **The $\mathcal{O}(p^2)$ Lorentz invariant chiral Lagrangian density for pions**

$$\mathcal{L} = \frac{F_0^2}{4}\mathrm{Tr}(D_\nu \Sigma D^\nu \Sigma^\dagger) + \frac{F_0^2 m_\pi^2}{2}\mathrm{Tr}(\Sigma)$$

- $\mathrm{SU}(2)$ **variational vev**

$$\bar{\Sigma} = e^{i\boldsymbol{\alpha}\cdot\boldsymbol{\sigma}} = \cos\alpha + i\boldsymbol{n}\cdot\boldsymbol{\sigma}\sin\alpha$$

Pion condensation

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encode medium effects

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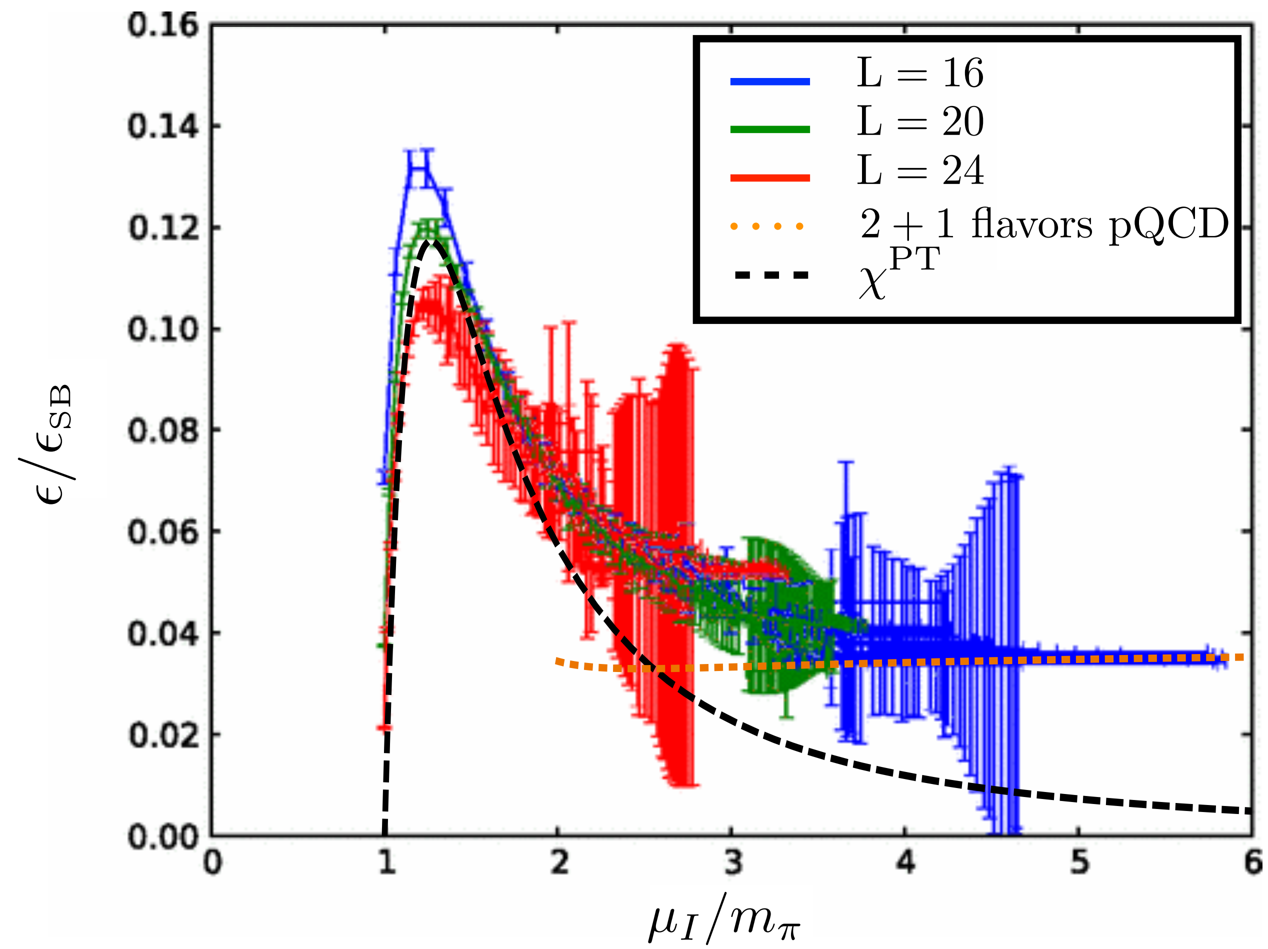
$$\epsilon_{SB} = \frac{N_c N_f}{4\pi^2}\mu_I^4$$

factor $\sim \frac{1}{16}$ missing



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variational parameters

Lattice QCD simulations

W. Detmold, K. Orginos, and Z. Shi, Phys. Rev. D86, 054507 (2012)

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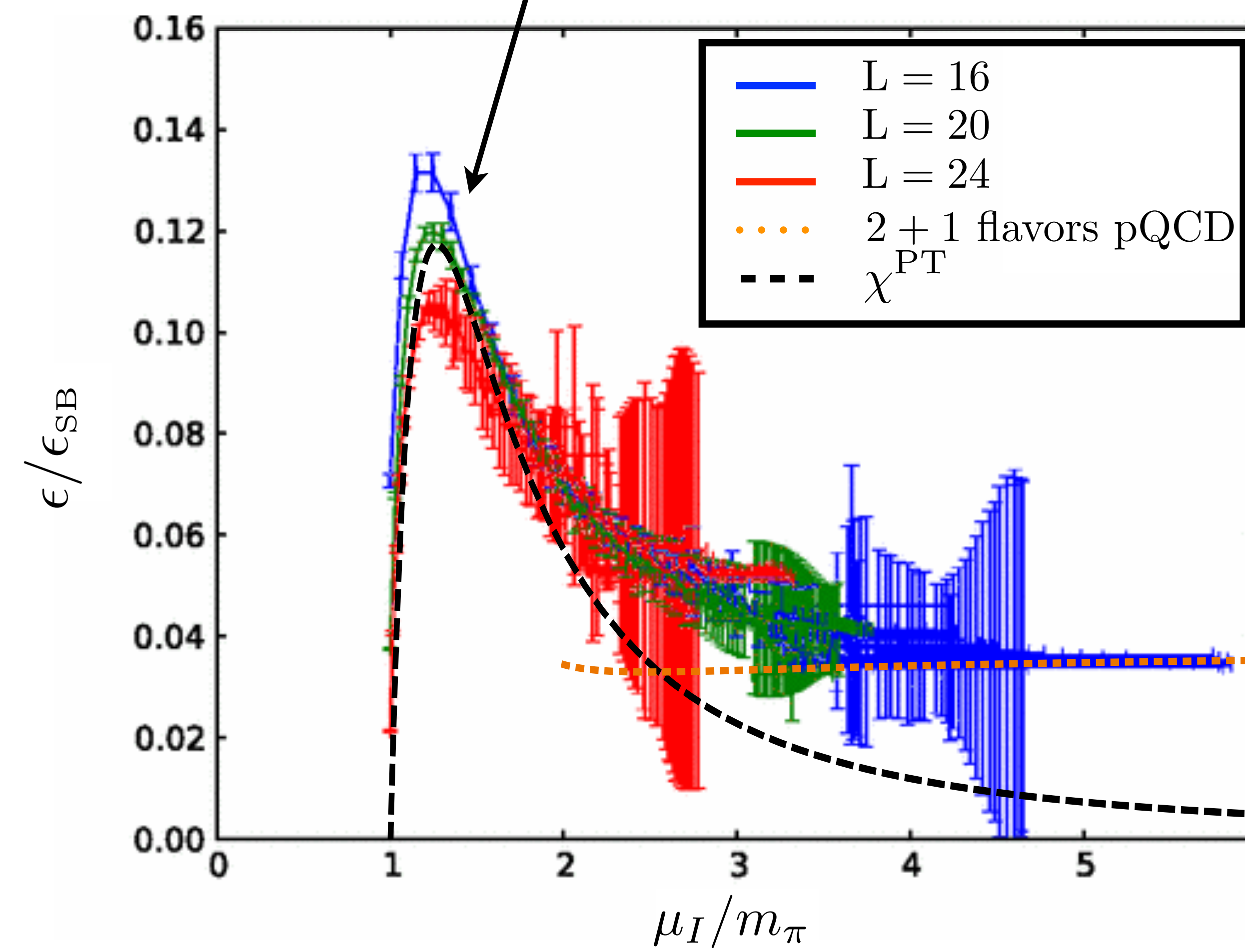

Pion condensation

More on the method

- The $\mathcal{O}(p^2)$ Lorentz invariant chiral Lagrangian density for pions

encode medium effects

$$\mathcal{L} = \frac{F_0^2}{4}\mathrm{Tr}(D_\nu \Sigma D^\nu \Sigma^\dagger) + \frac{F_0^2 m_\pi^2}{2}\mathrm{Tr}(\Sigma)$$

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variational parameters

Lattice QCD simulations

W. Detmold, K. Orginos, and Z. Shi, Phys. Rev. D86, 054507 (2012)

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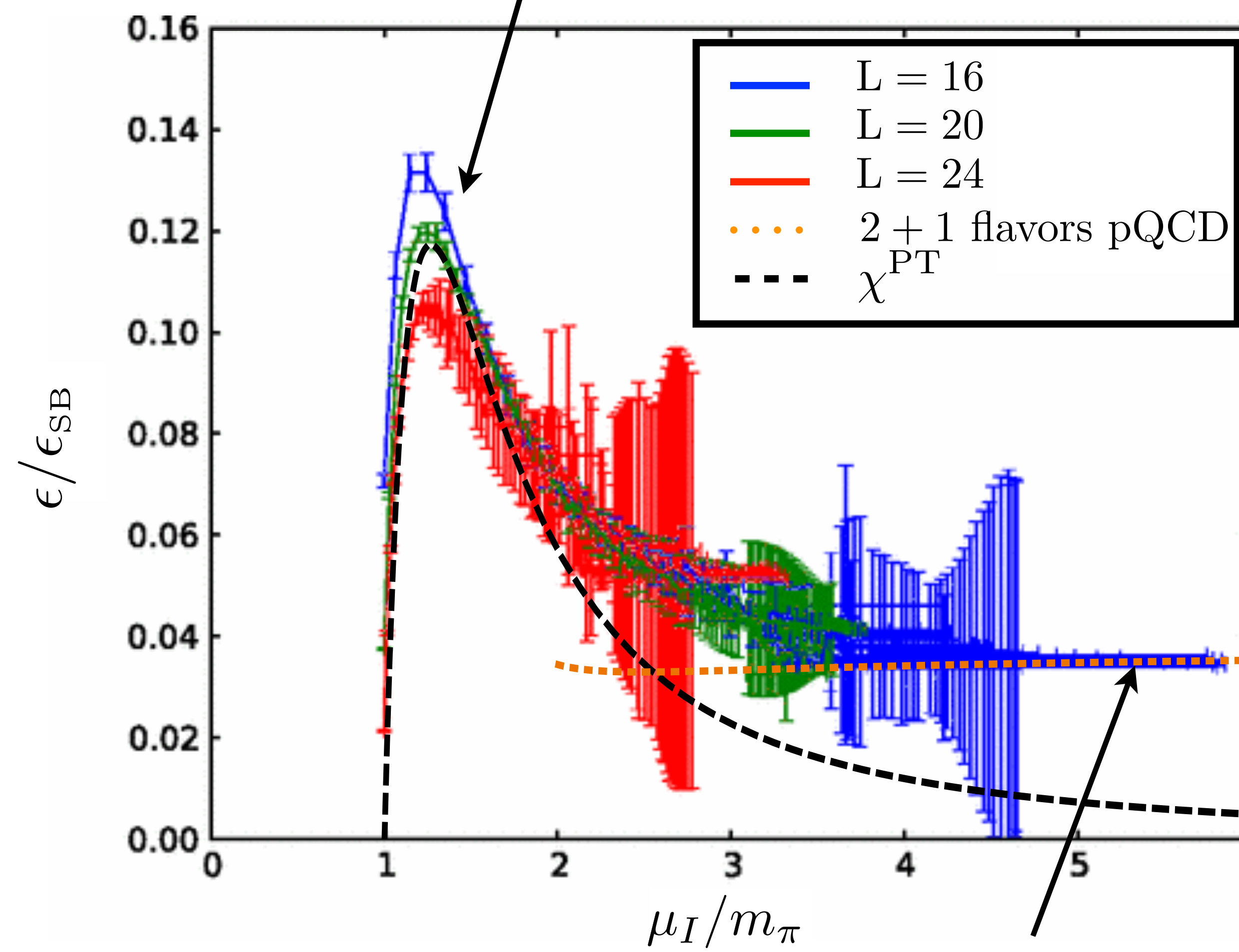

pQCD

T. Graf, et al. Phys. Rev. D 93, 085030 (2016)

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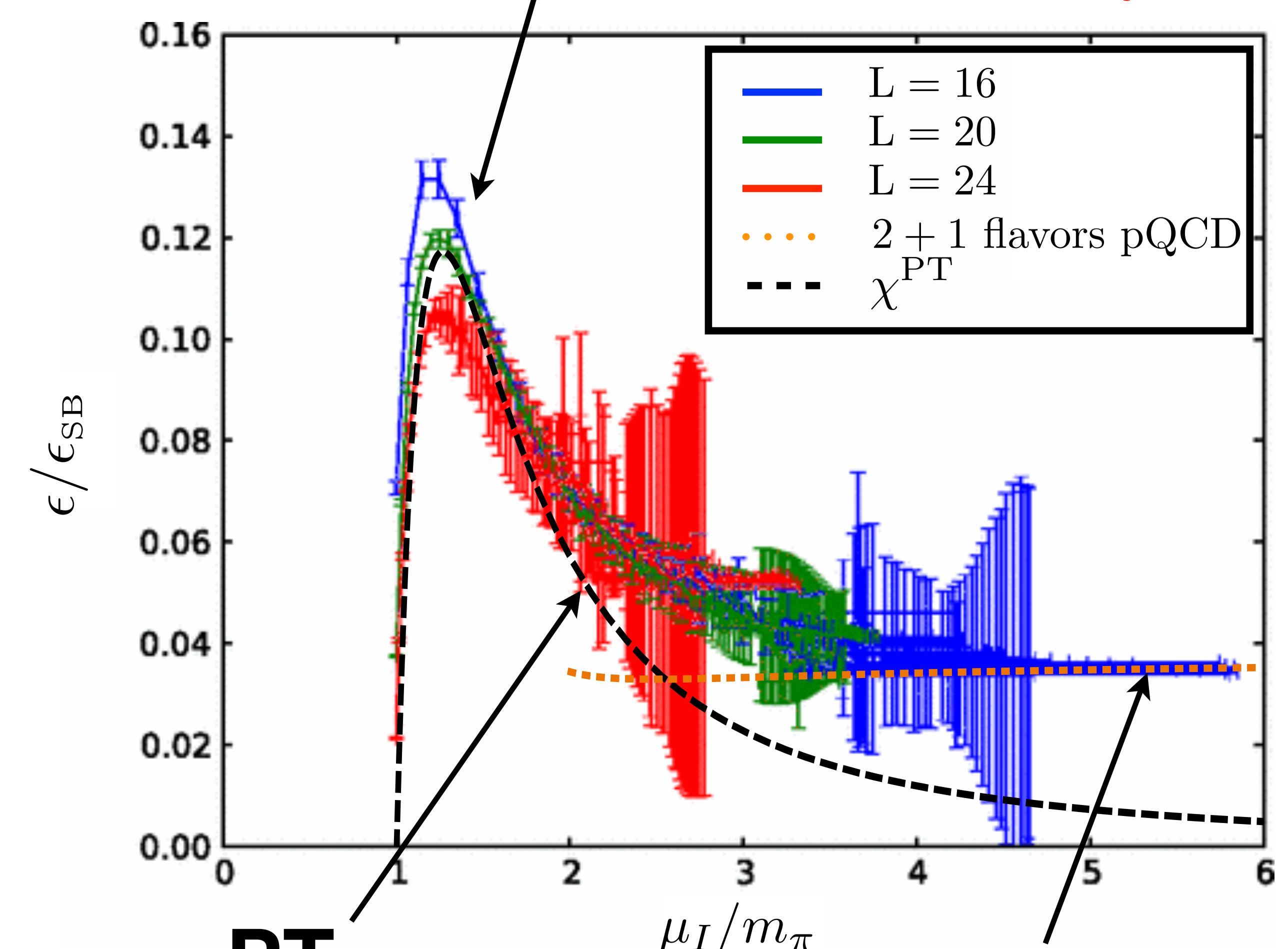

χPT

pQCD

S. Carignano, A. Mammarella, MM Phys.Rev. D93 (2016) no.5, 051503

T. Graf, et al. Phys. Rev. D 93, 085030 (2016)

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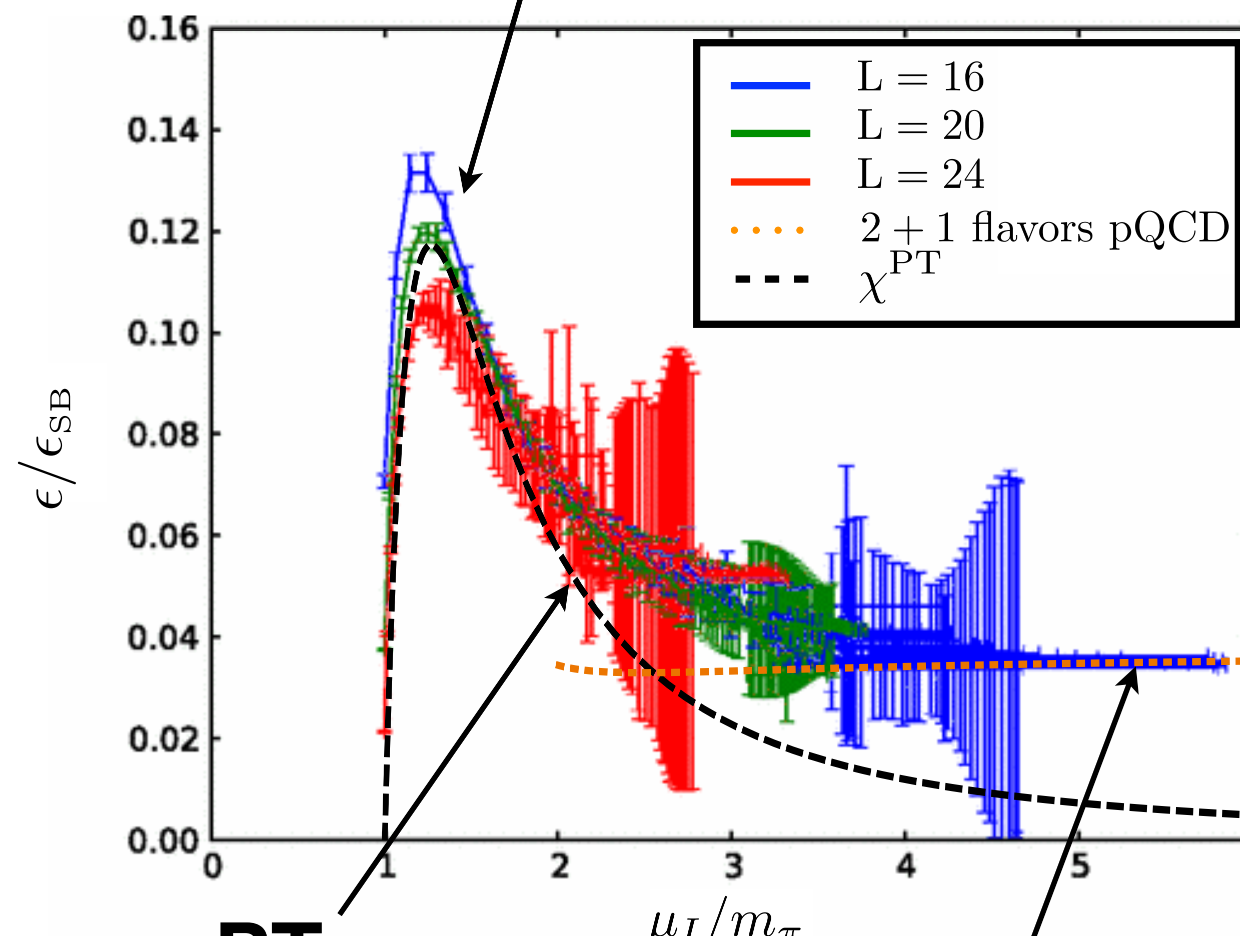

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pQCD

T. Graf, et al. Phys. Rev. D 93, 085030 (2016)

Our method gives an ANALYTIC expression for the peak

$$\mu_{I,\mathrm{LQCD}}^{\mathrm{peak}} = \{1.20, 1.25, 1.275\} m_\pi \qquad \mu_{I,\chi\mathrm{PT}}^{\mathrm{peak}} = (\sqrt{13}-2)^{1/2} m_\pi \simeq 1.276\, m_\pi$$

Variational approach

$$\bar{\Sigma} = \mathbf{1}_2 \cos\alpha \pm i\mathbf{n}\cdot\sigma \sin\alpha$$

Static Lagrangian

$$\mathcal{L}_0(\alpha, \mu_I, n_3) = F_0^2 m_\pi^2 \cos\alpha + \frac{F_0^2}{2}\mu_I^2 \sin^2\alpha(1 - n_3^2)$$

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Maximising the Lagrangian

for $\mu_I < m_\pi$	$\cos\alpha = 1$	$\mathcal{L}_0$ independent of $\boldsymbol{n}$
for $\mu_I > m_\pi$	$\cos\alpha_\pi = m_\pi^2/\mu_I^2$	$n_3 = 0$ residual $O(2)$ symmetry

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The vacuum has been tilt in some direction in isospin space

We now look for solutions in which the rotation is local

More about the leading order Lagrangian

The $\mathcal{O}(p^2)$Lorentz invariant Lagrangian density for pions

$$\boxed{\mathcal{L} = \frac{F_0^2}{4}\mathrm{Tr}(D_\nu \Sigma D^\nu \Sigma^\dagger) + \frac{F_0^2 m_\pi^2}{2}\mathrm{Tr}(\Sigma)}$$

Trick for introducing the isospin. We define the covariant derivative

$$D_\mu \Sigma = \partial_\mu \Sigma - \frac{i}{2}[v_\mu, \Sigma]$$

Gasser and Leutwyler, Annals Phys. 158, 142 (1984)

Formally preserving the Lorentz invariance

Then we take $$v^\mu = \mu_I \, \sigma_3 \, \delta^{\mu 0}$$

BEC of pions!

Rotated condensates

$$\langle \bar{u}u \rangle = \langle \bar{d}d \rangle \propto \cos\alpha$$
$$\langle \bar{d}\gamma_5 u + \mathrm{h.c.} \rangle \propto \sin\alpha$$

Control parameter $\gamma = \frac{\mu_I}{m_\pi}$

Pressure

$$P = \frac{f_\pi^2 m_\pi^2}{2}\gamma^2 \left(1 - \frac{1}{\gamma^2}\right)^2$$

Ground state occupation number

$$n_I = f_\pi^2 m_\pi \gamma \left(1 - \frac{1}{\gamma^4}\right)$$

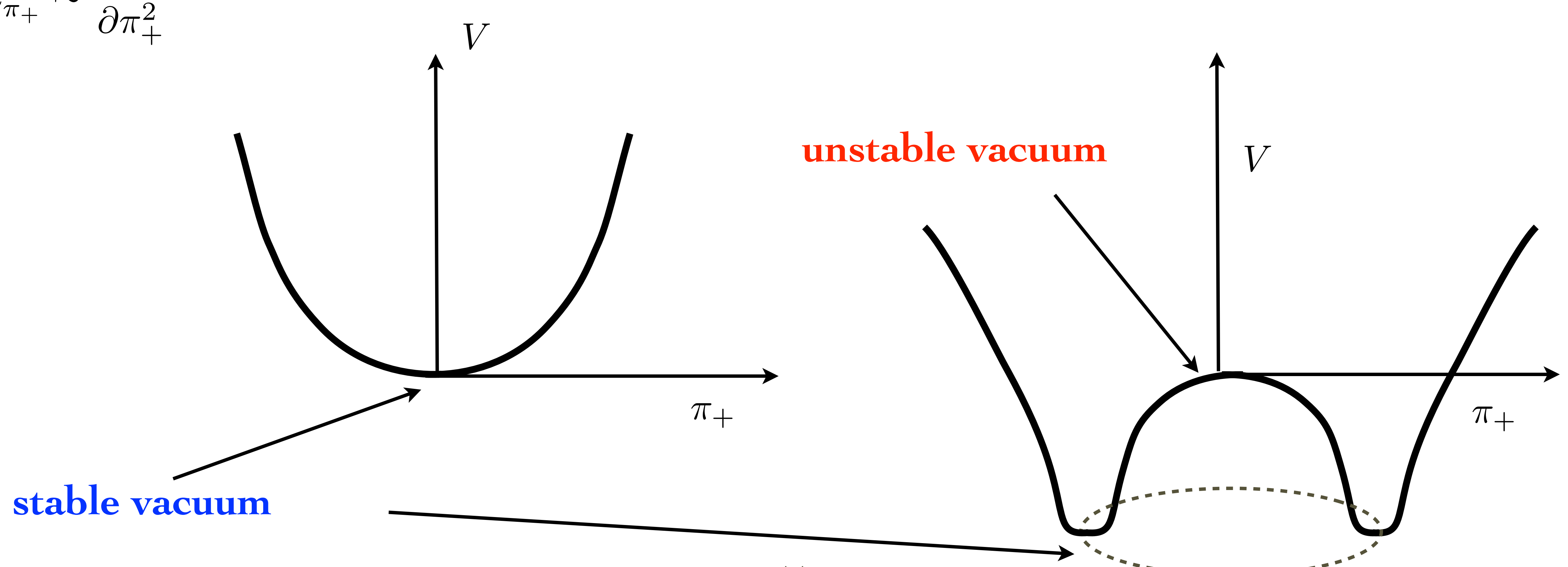
Pion fluctuations

Mass splitting
proportional to the isospin charge

$$m_{\pi^0} = m_\pi$$
$$m_{\pi^-} = m_\pi + \mu_I$$
$$m_{\pi^+} = m_\pi - \mu_I$$

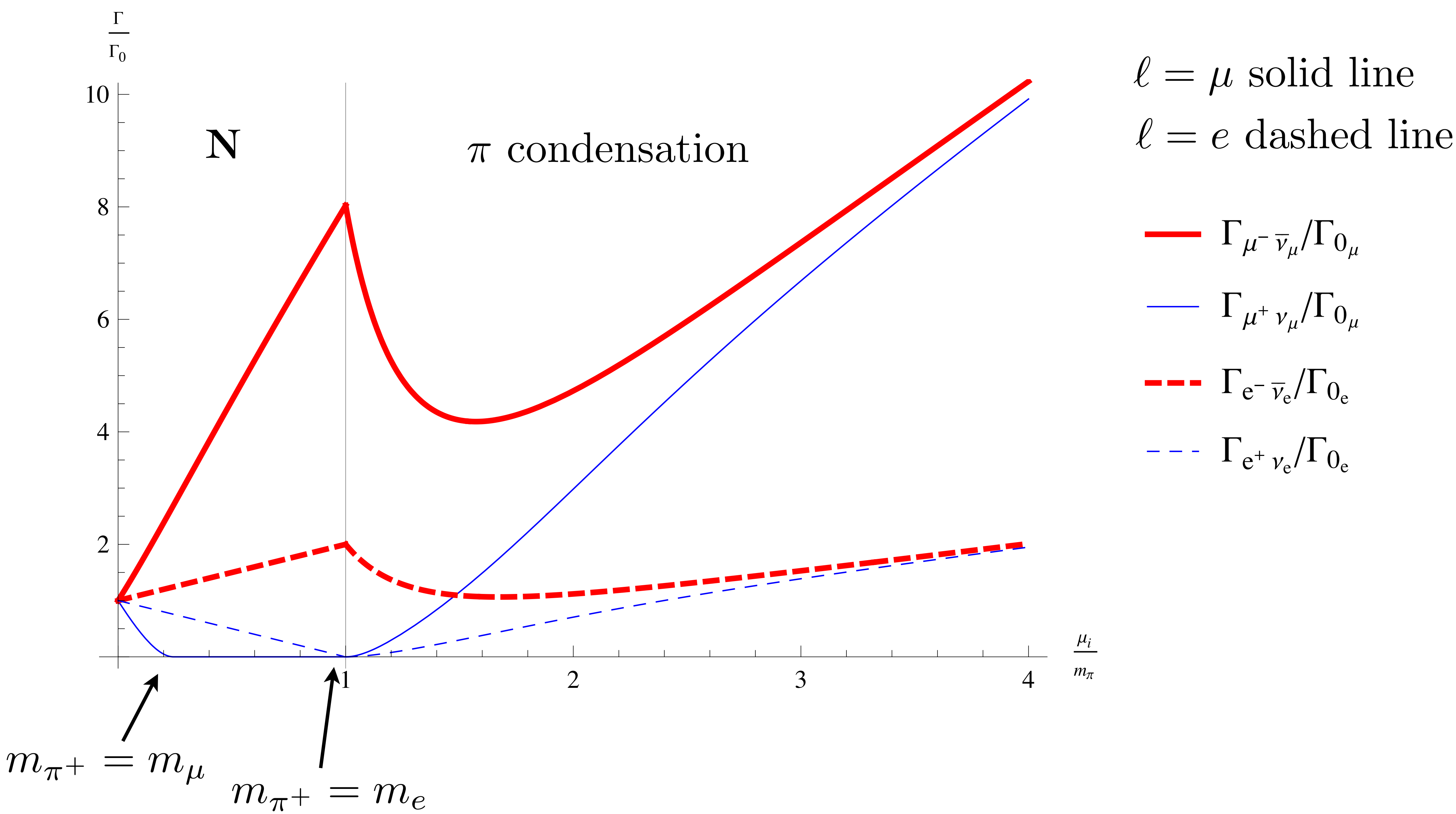
The meson mass vanishes at the phase transition

$$m^2_{\pi_+} \sim \frac{\partial^2 V}{\partial \pi_+^2}$$



Leptonic decays

Processes $\tilde{\pi}_- \to \ell^{\pm}\nu_\ell$**and** $\tilde{\pi}_+ \to \ell^{\pm}\nu_\ell$

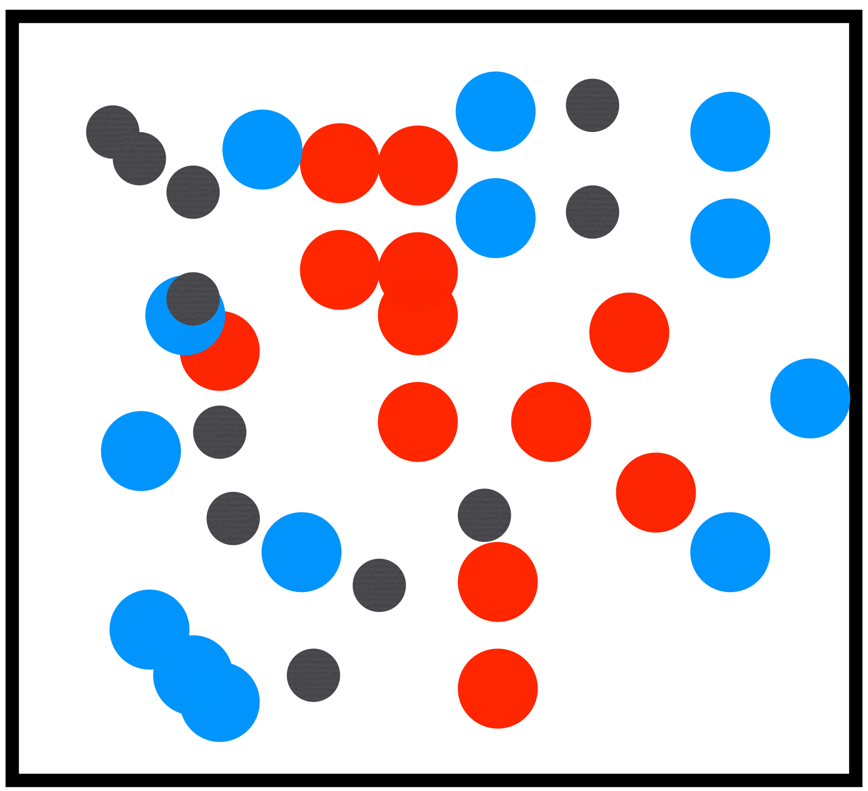


A. Mammarella and M.M. Phys.Rev. D92 (2015) 8, 085025

Deconfinement by increasing temperature

Pions ● Baryons ● Anti Baryons ●

Increasing T
Fixed low μ_B



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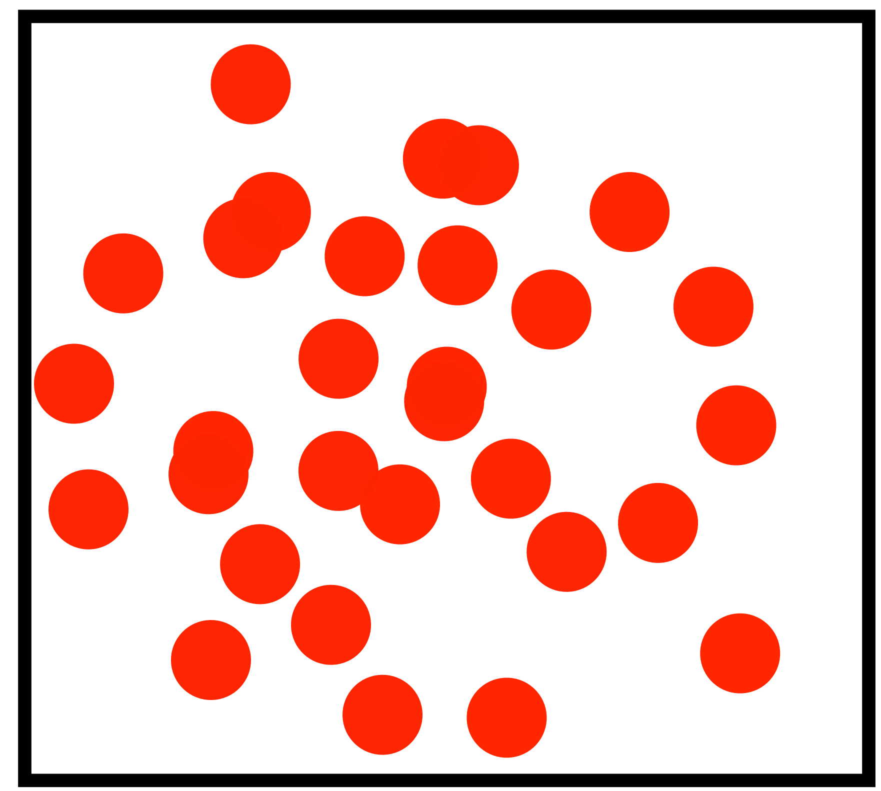

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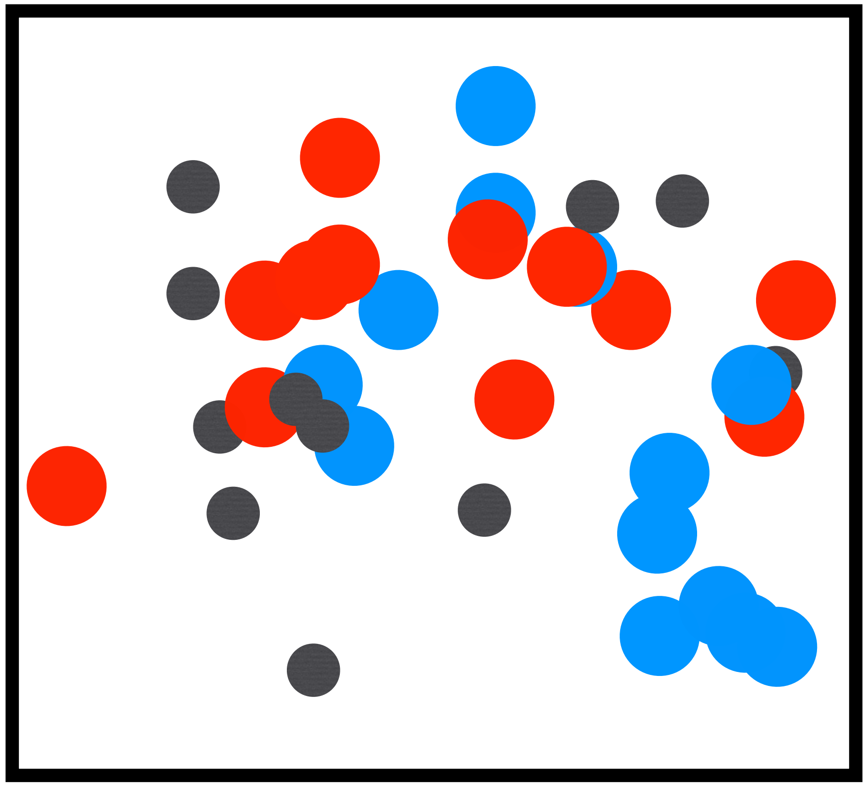

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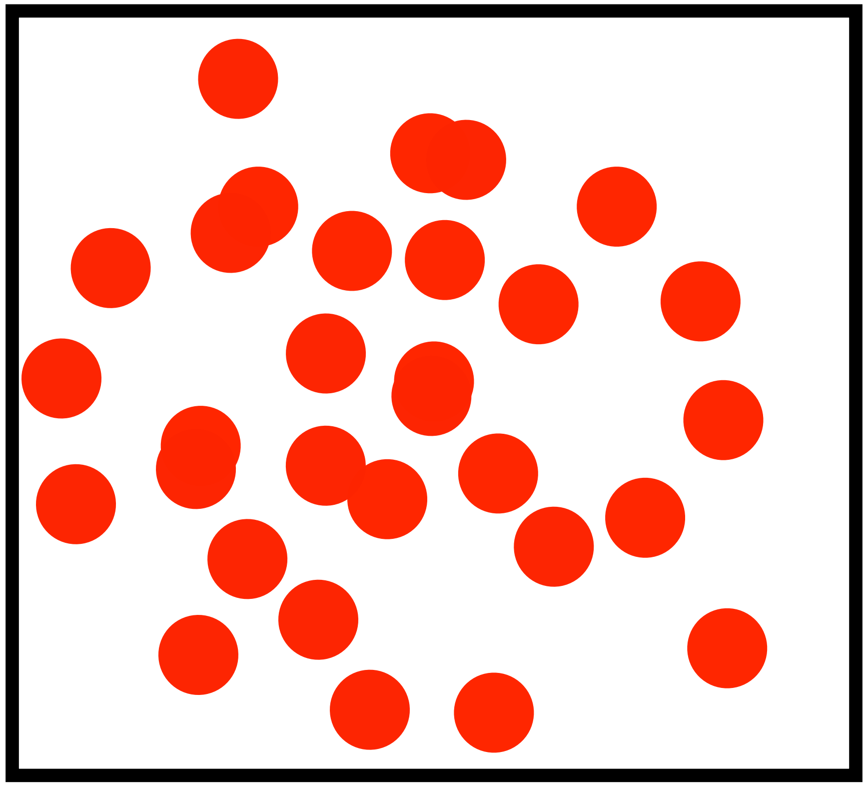

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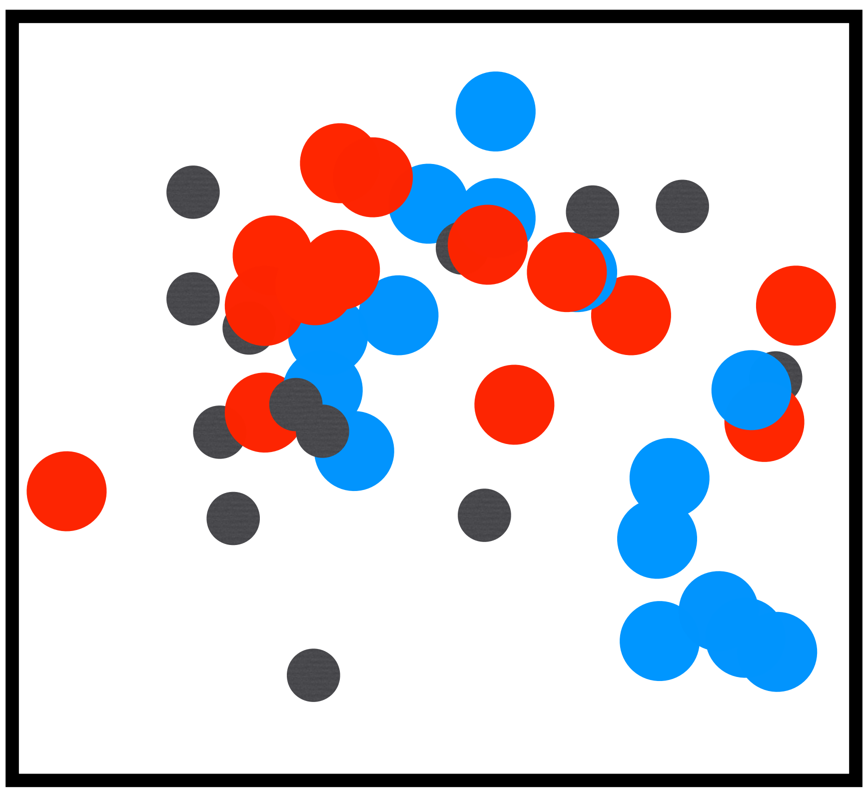

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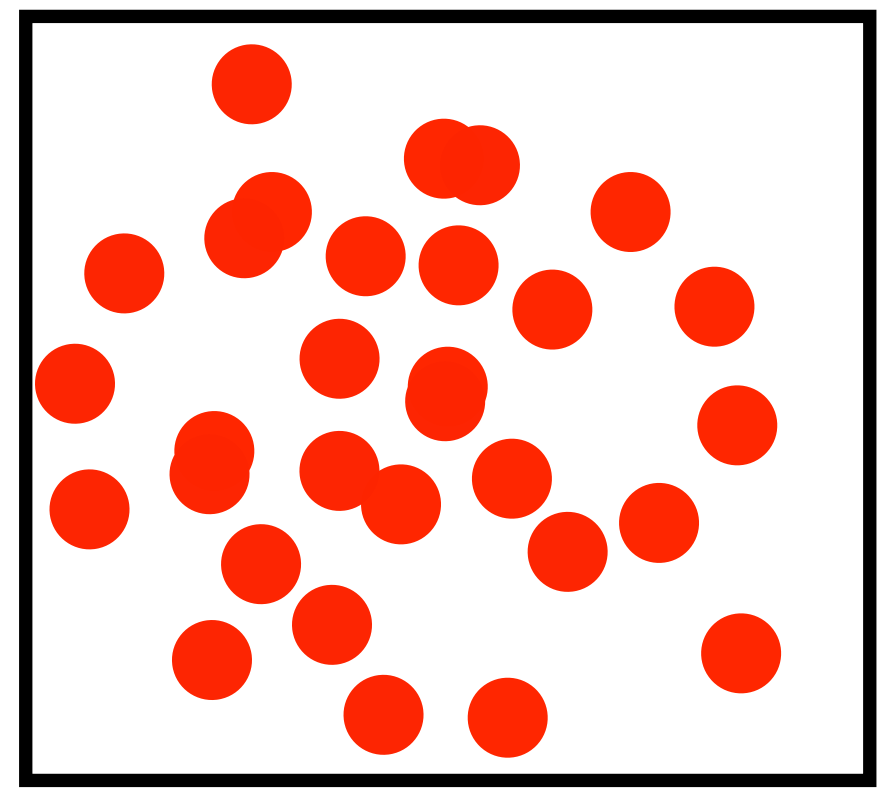

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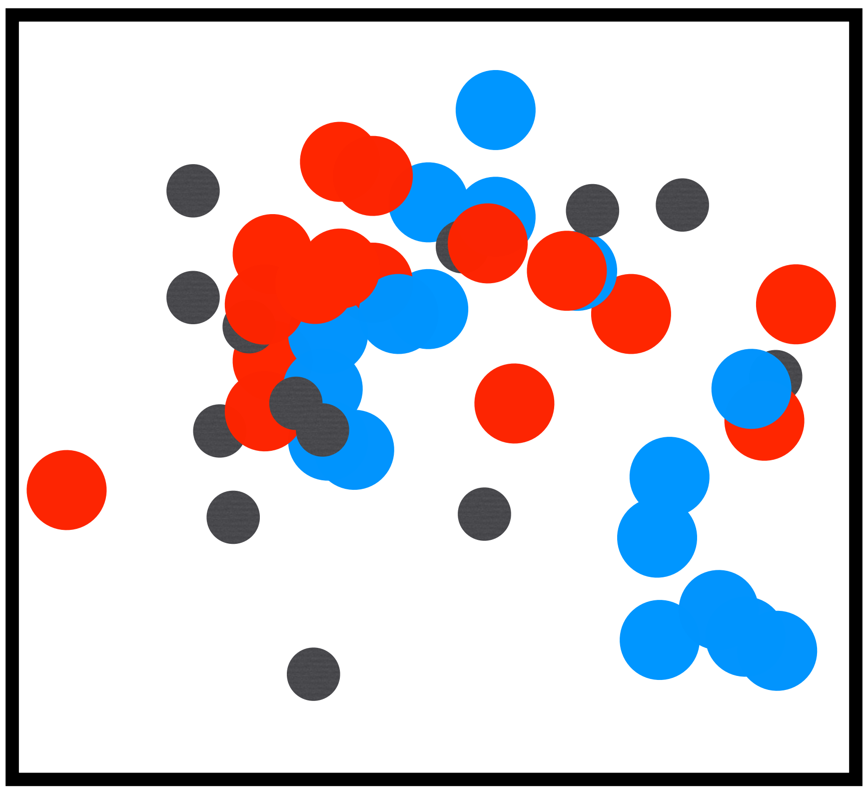

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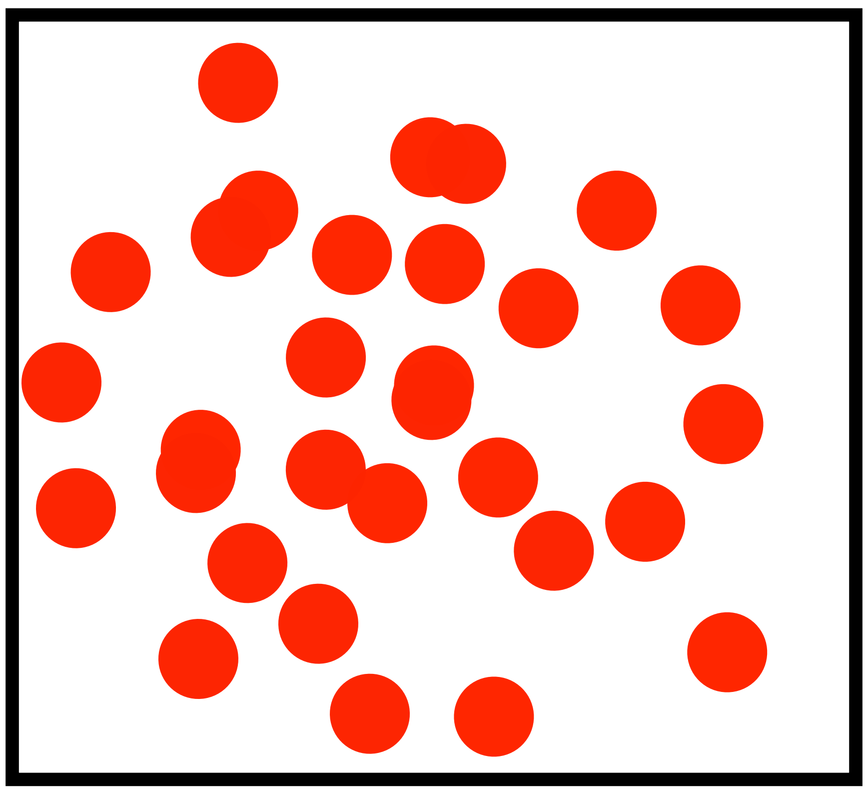

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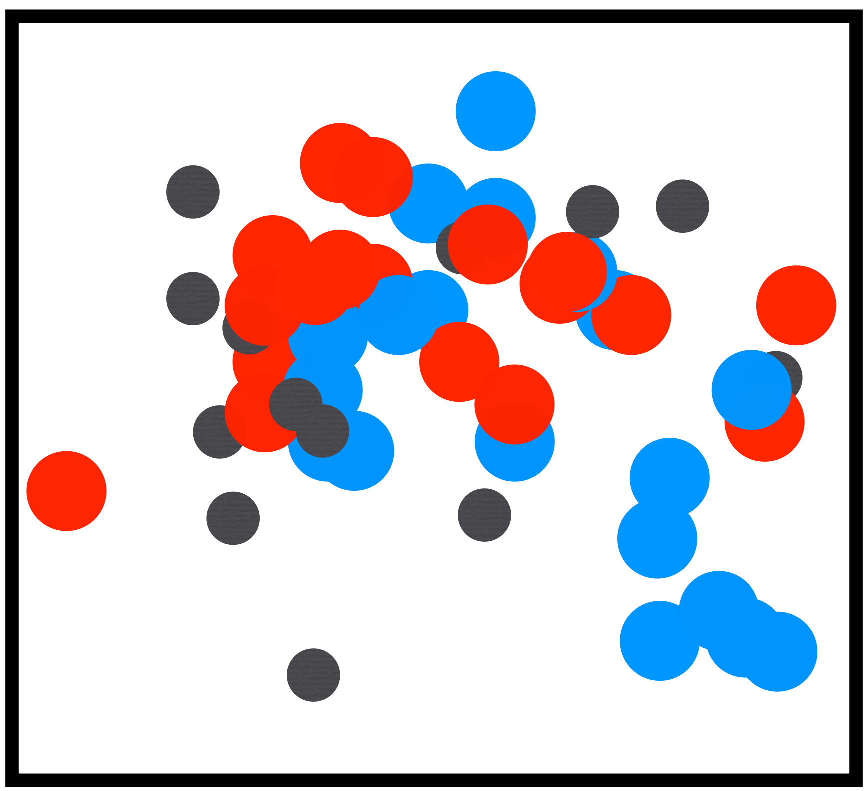

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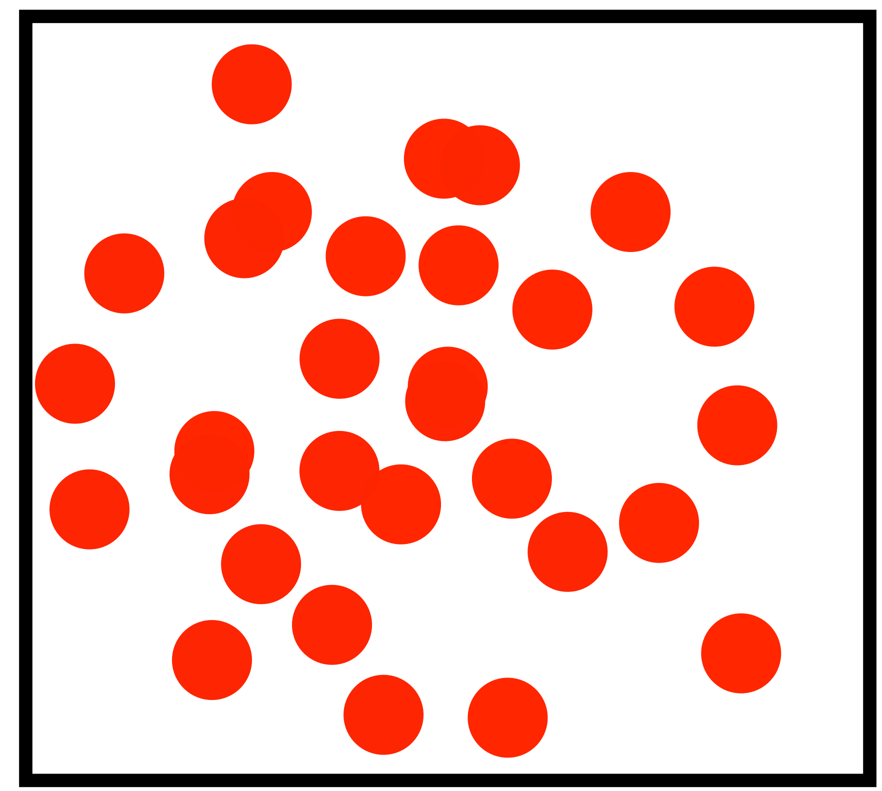

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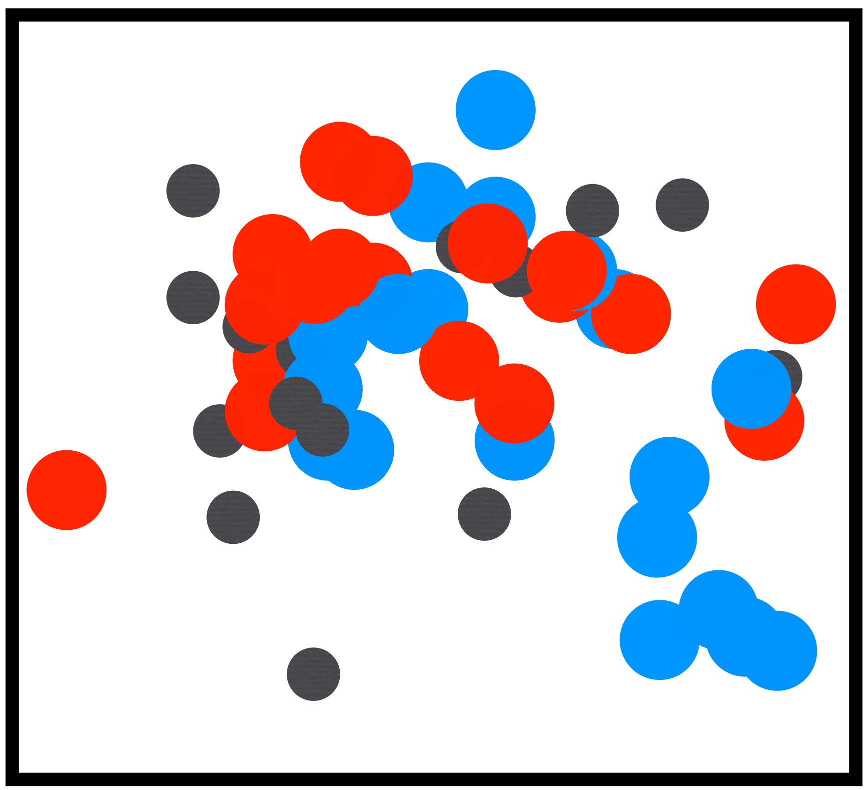

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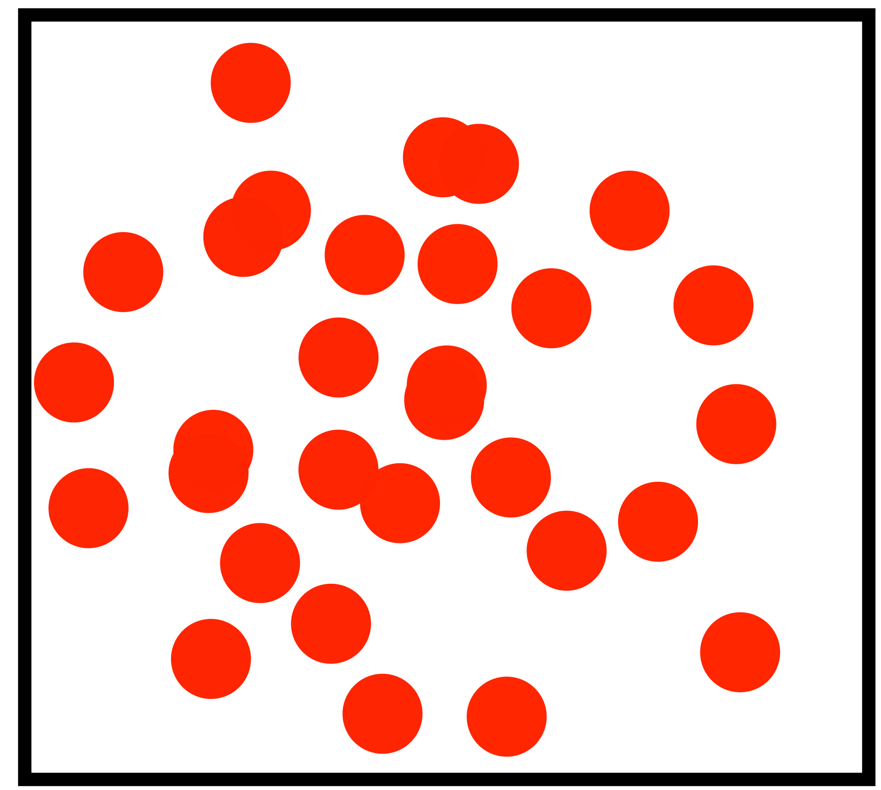

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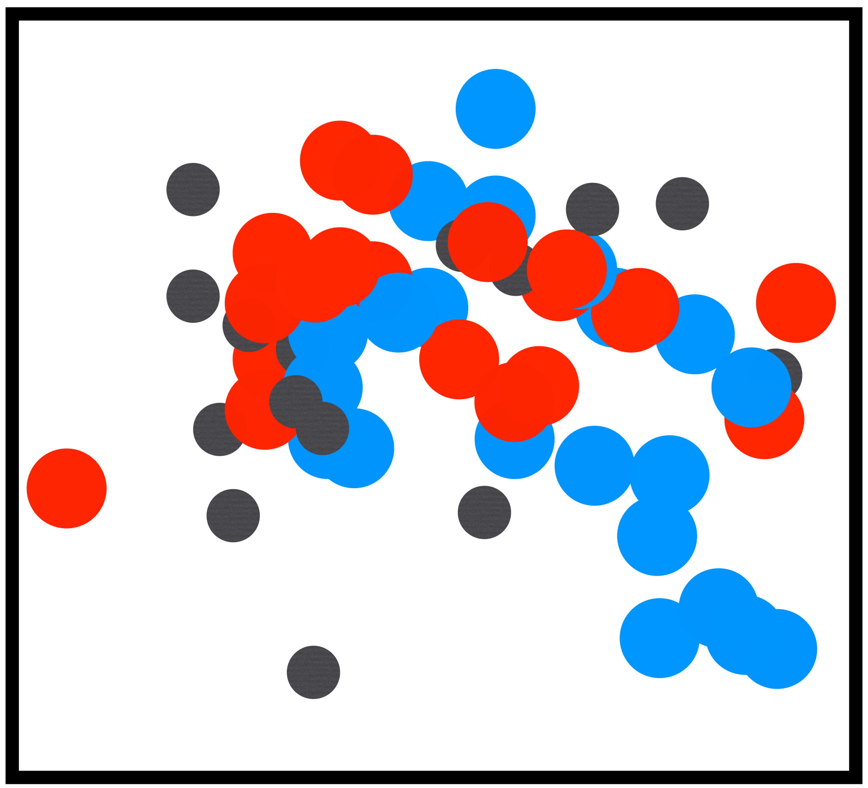

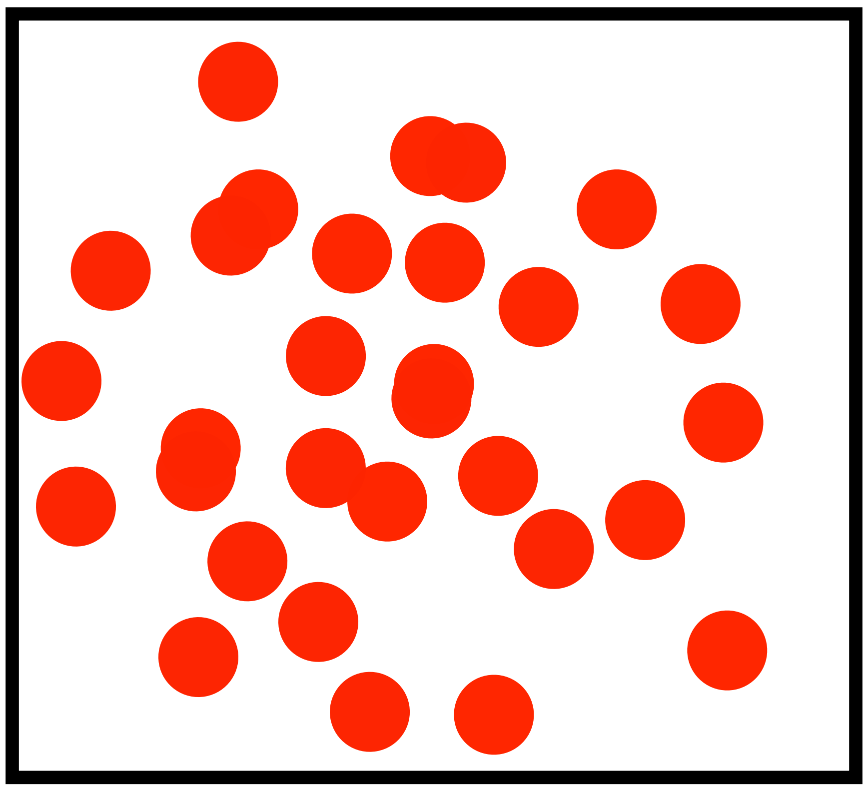

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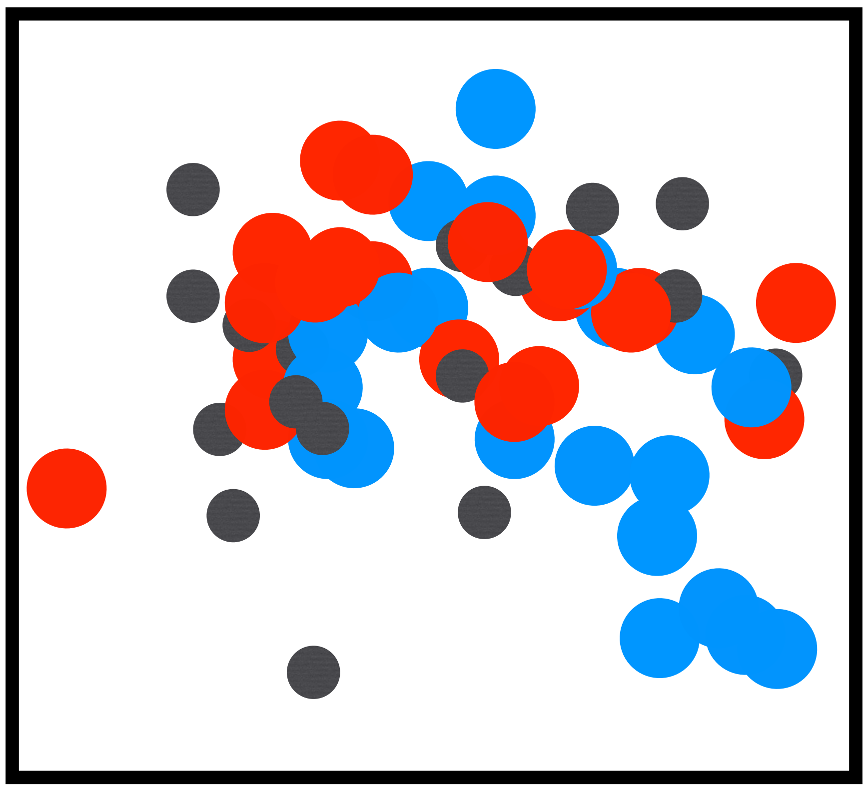

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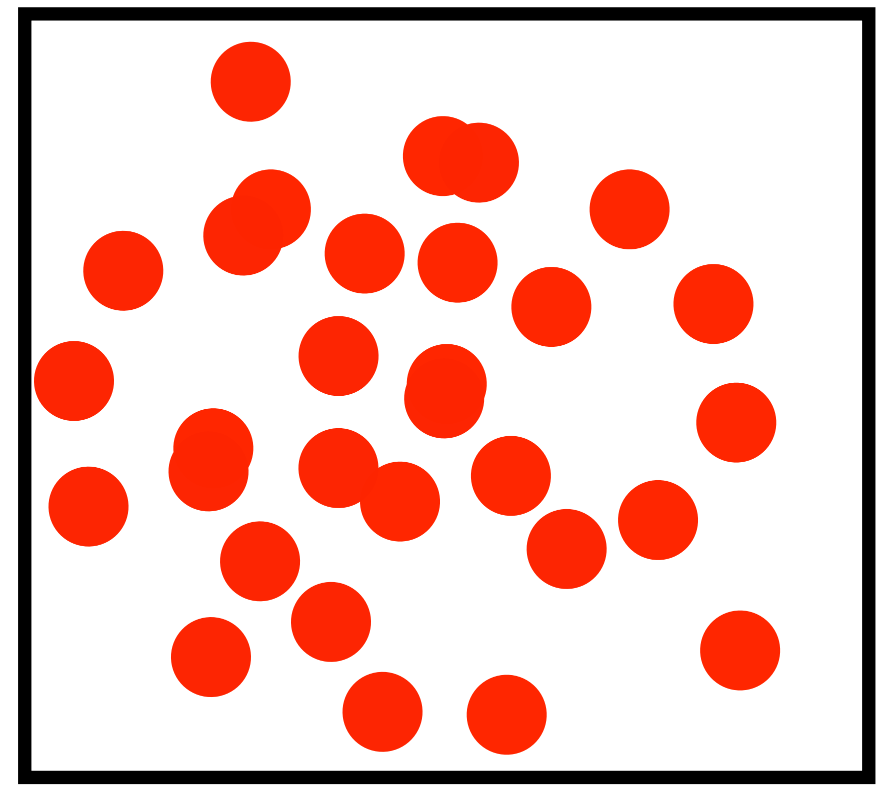

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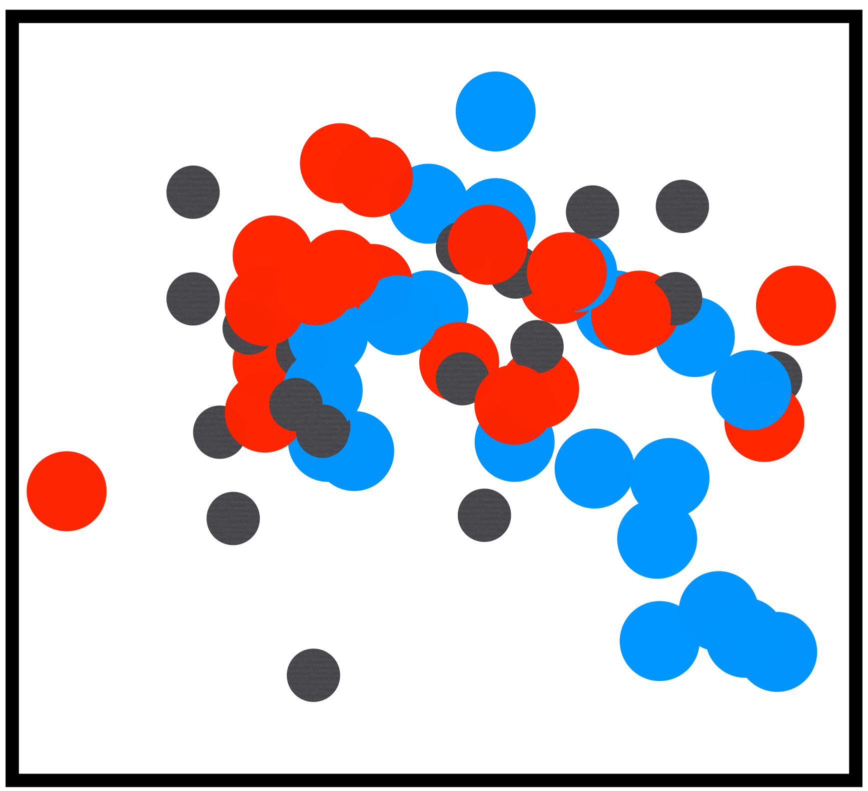

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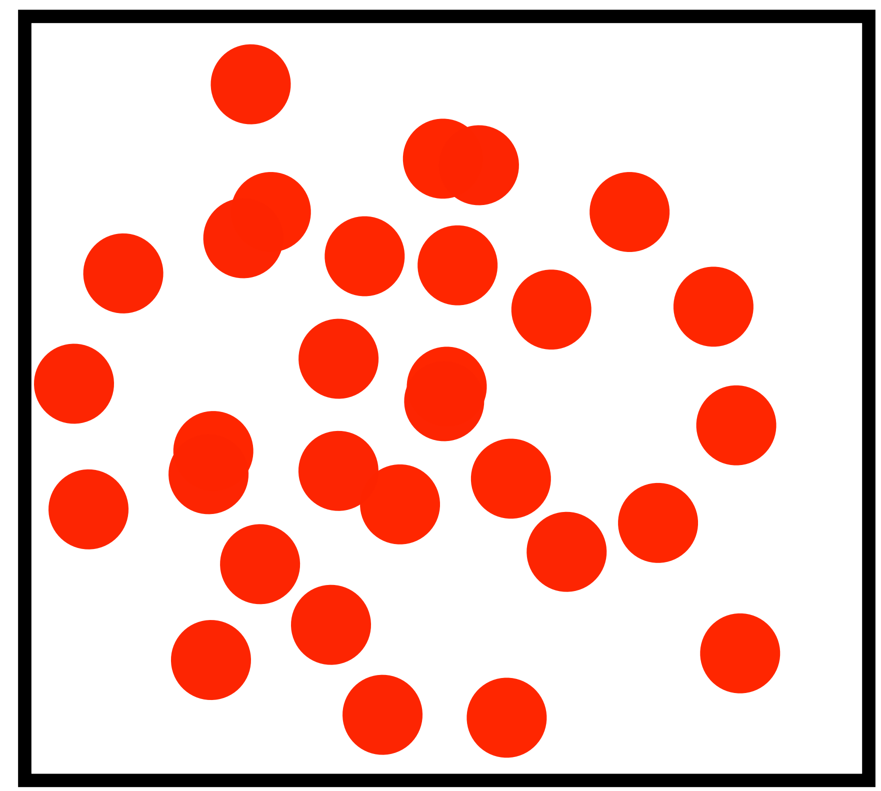

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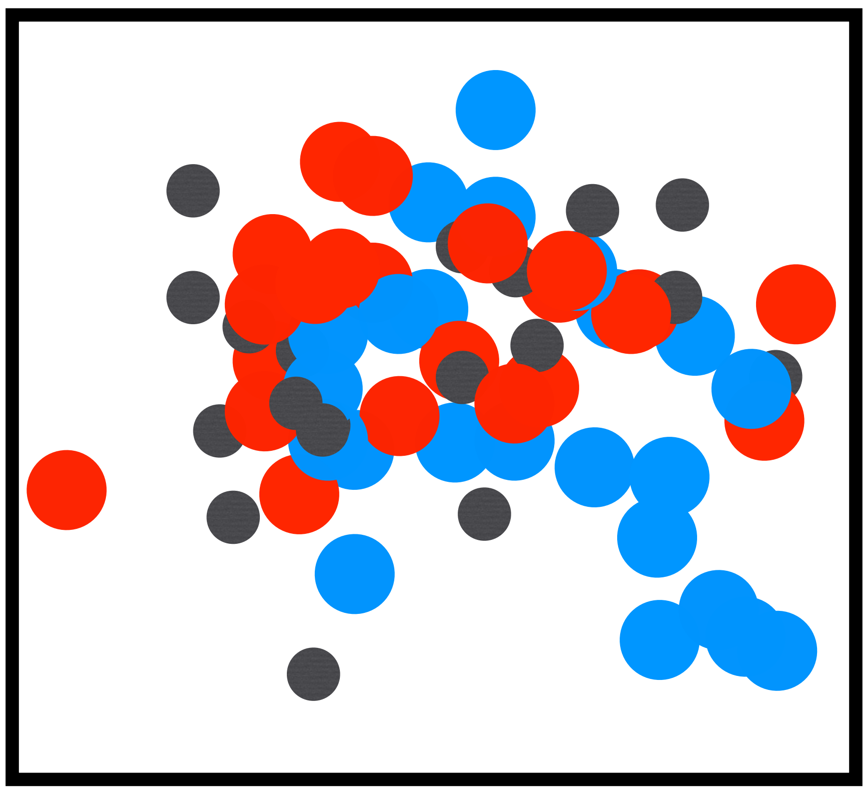

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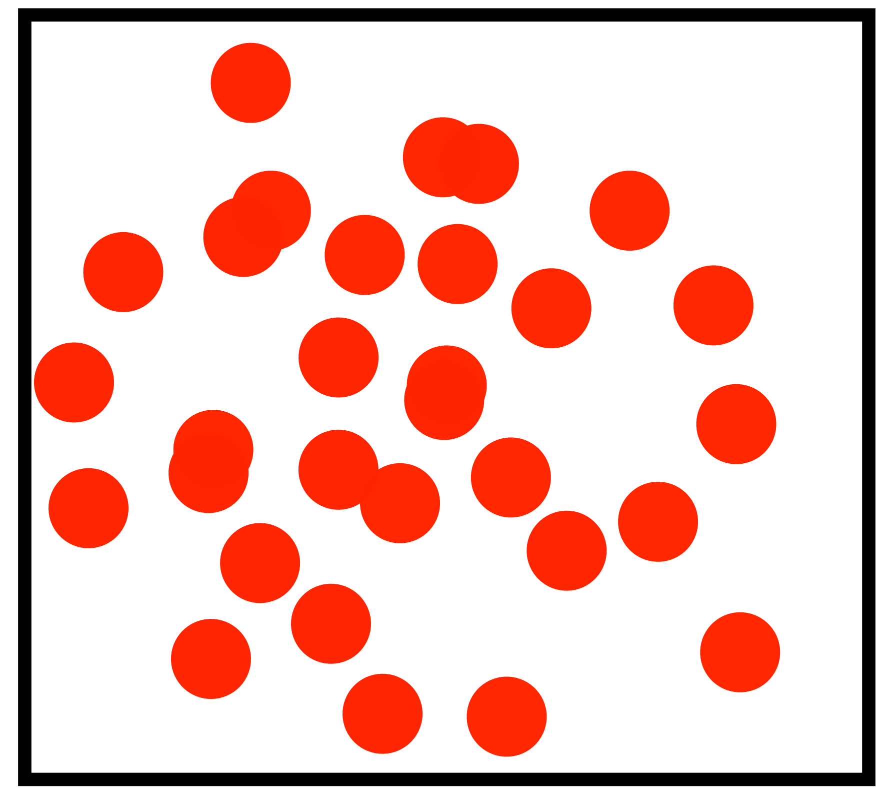

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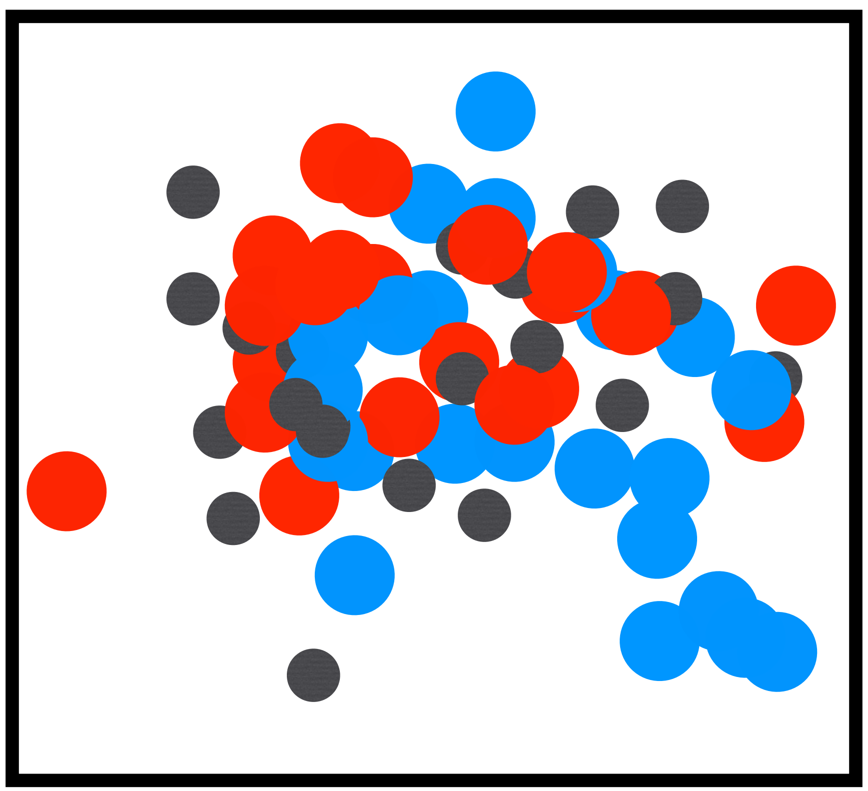

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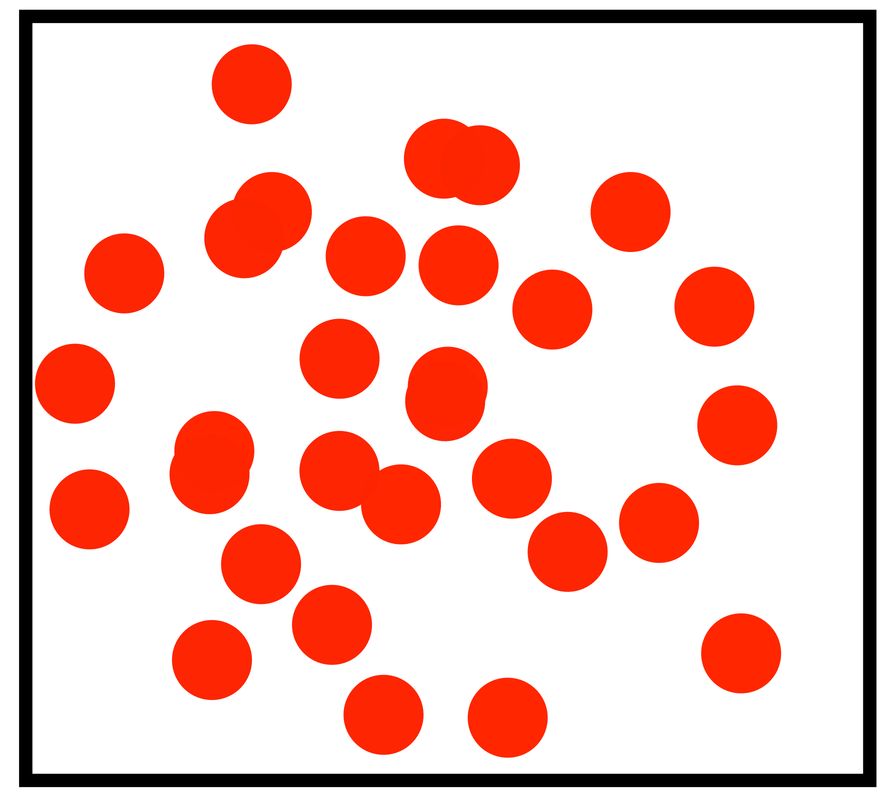

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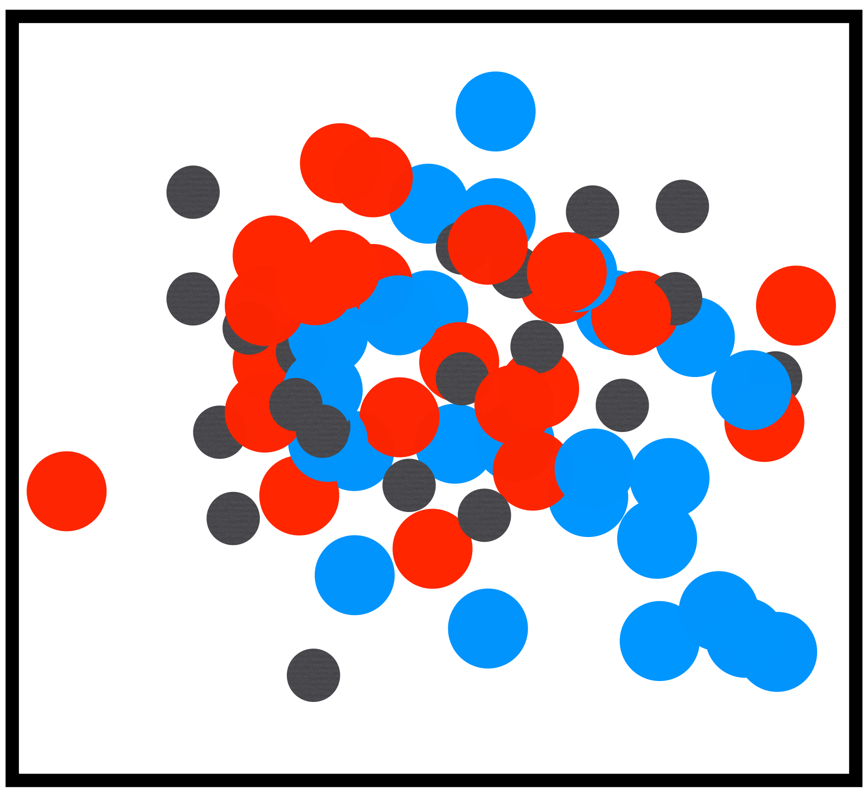

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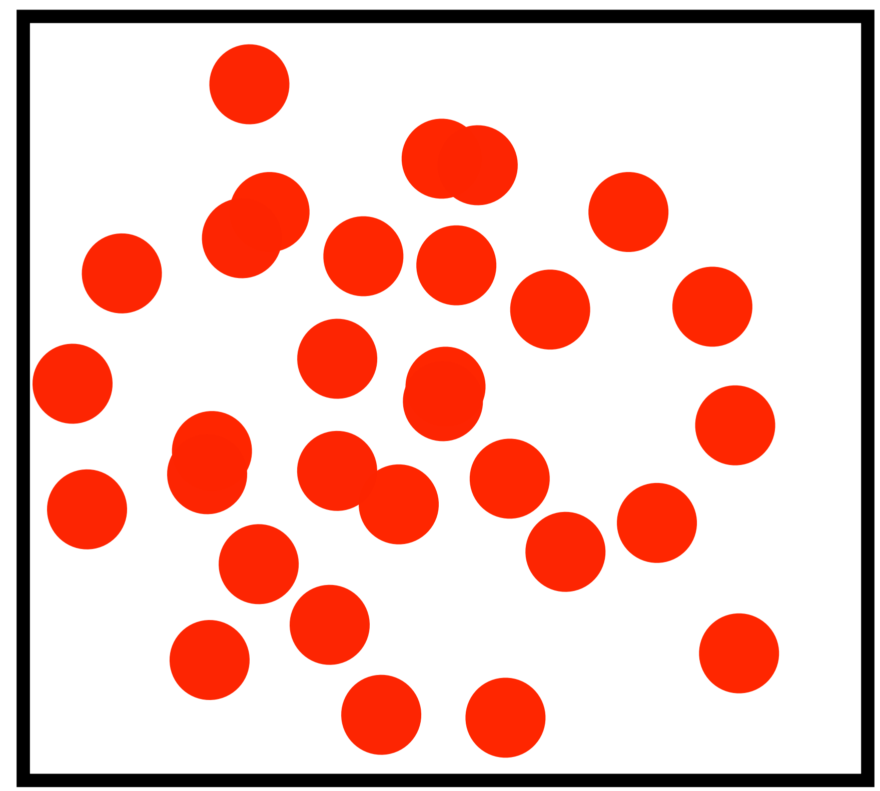

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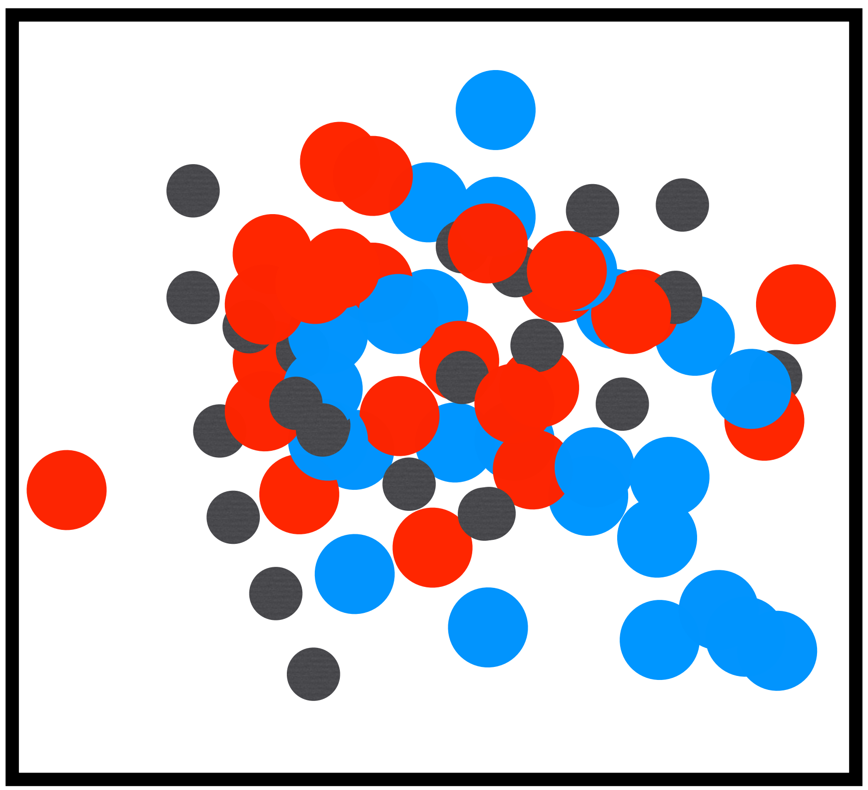

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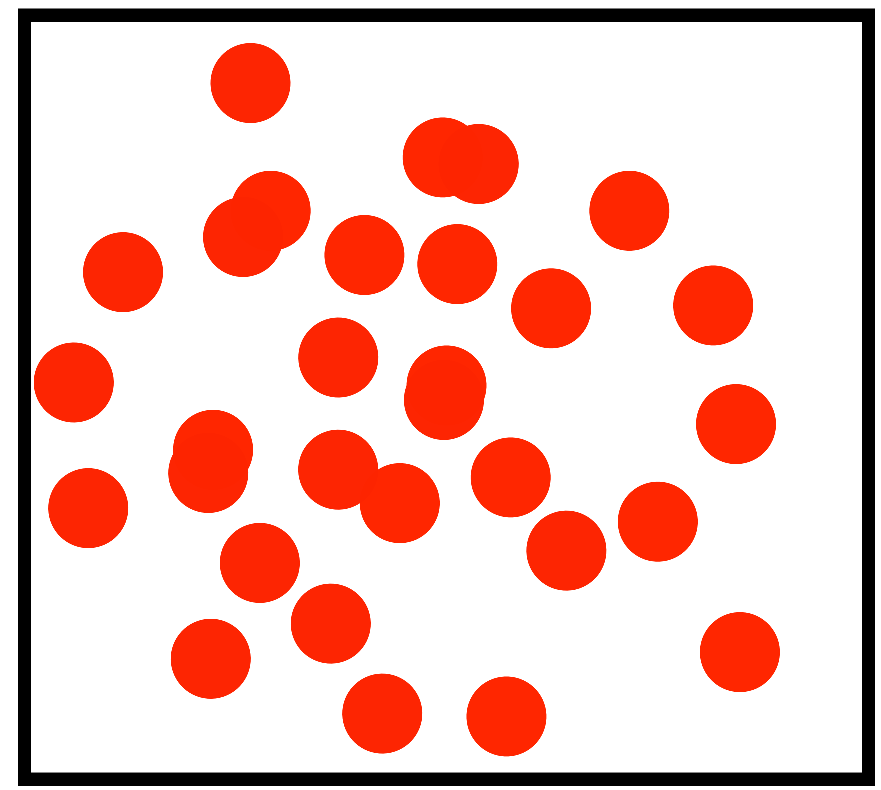

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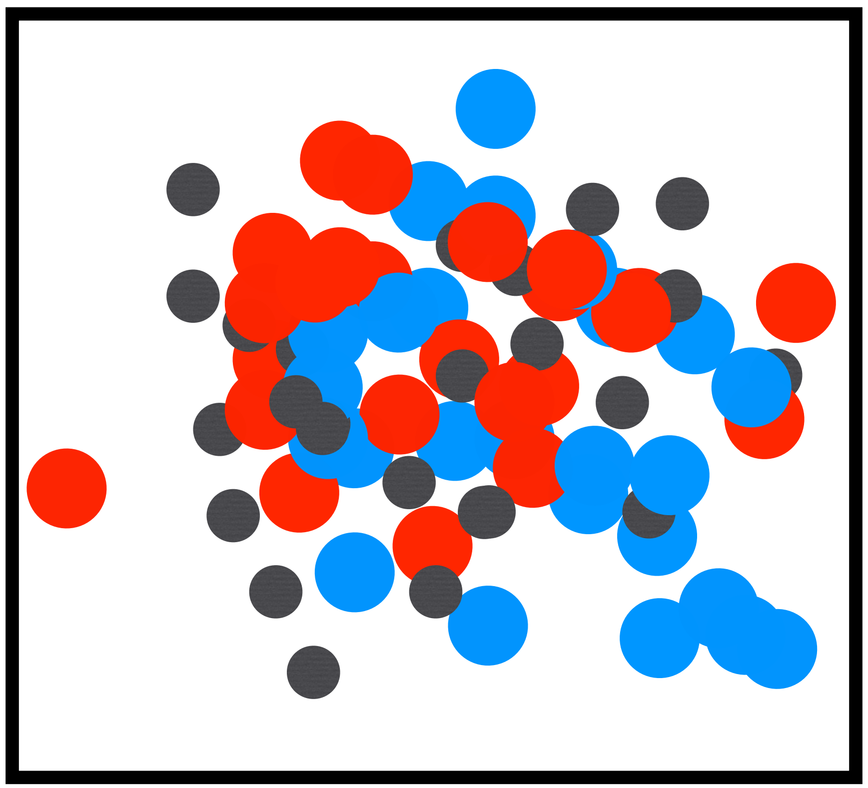

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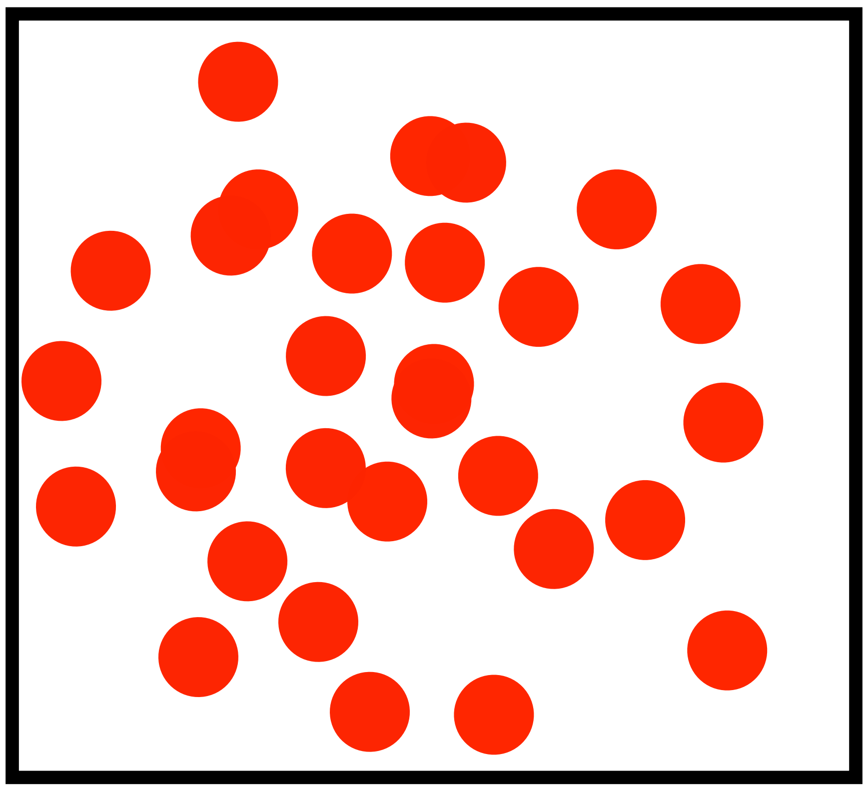

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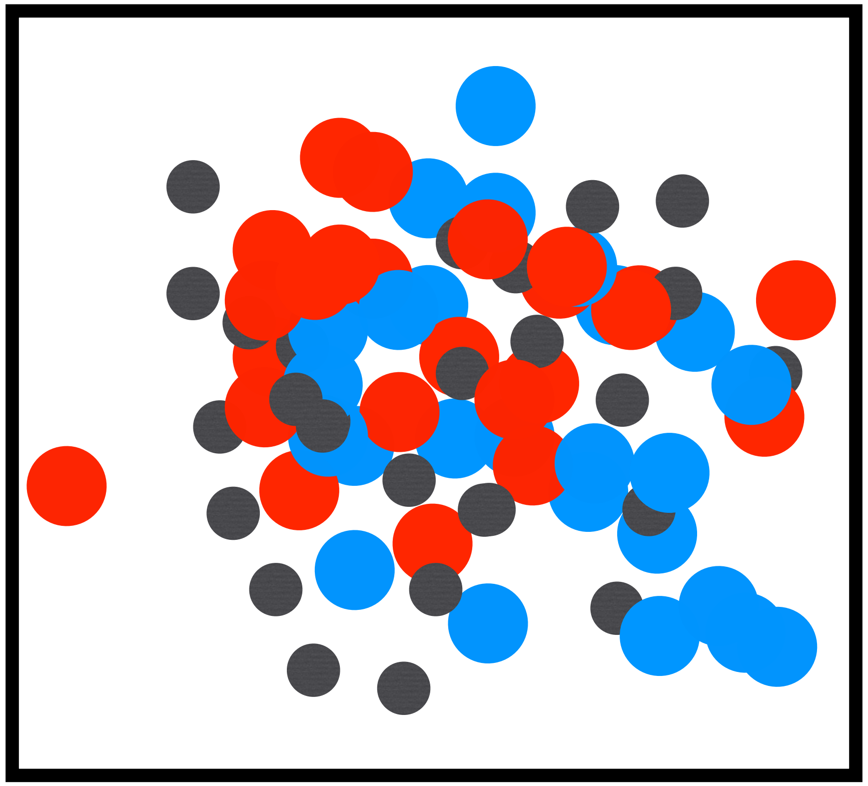

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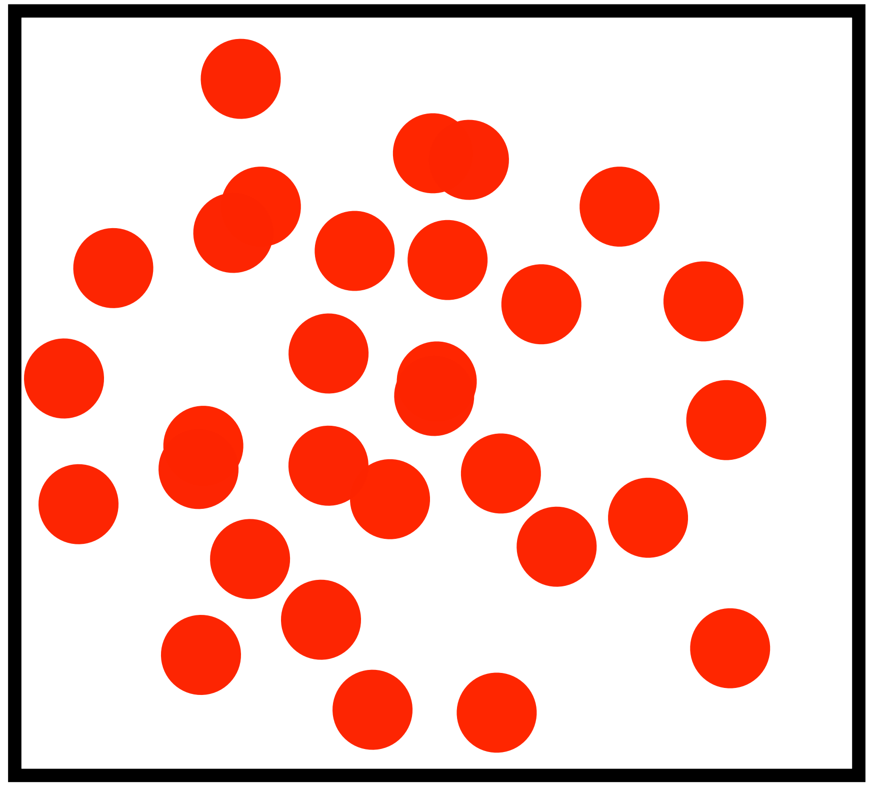

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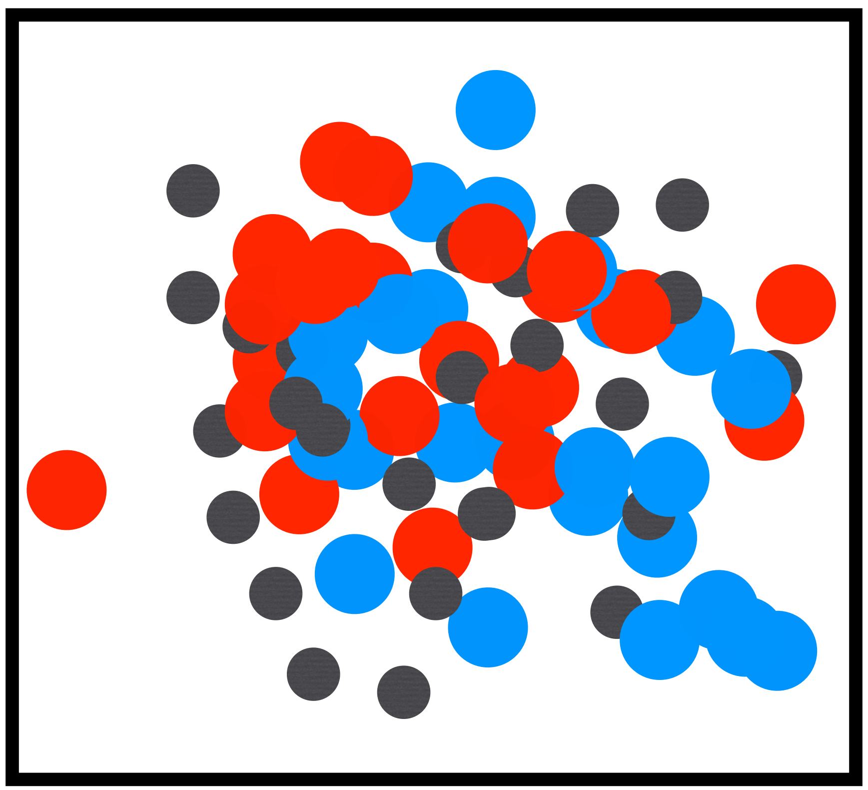

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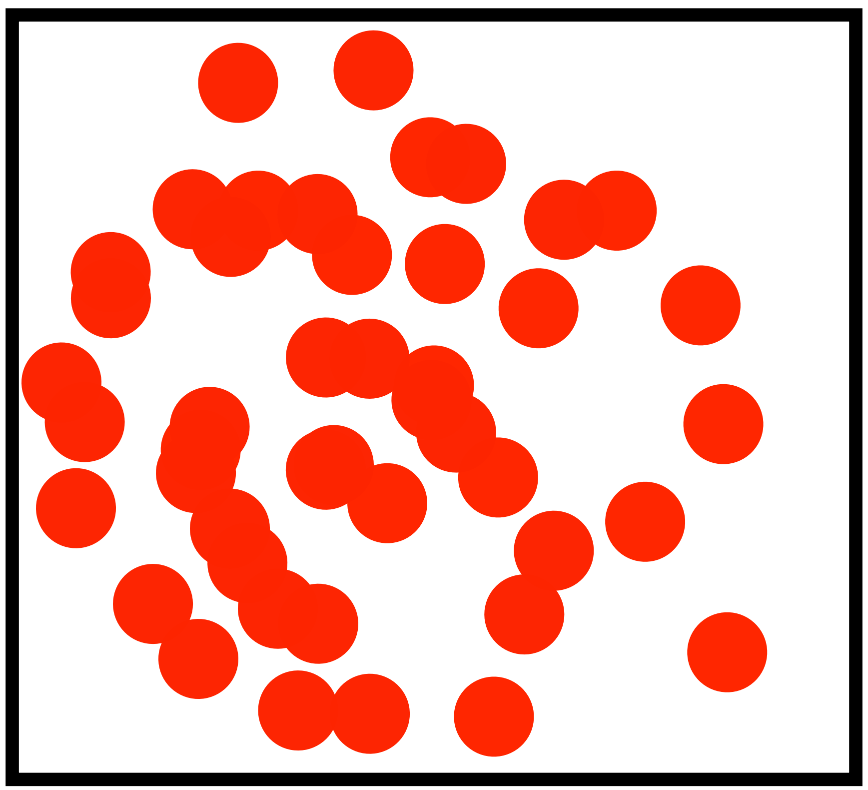

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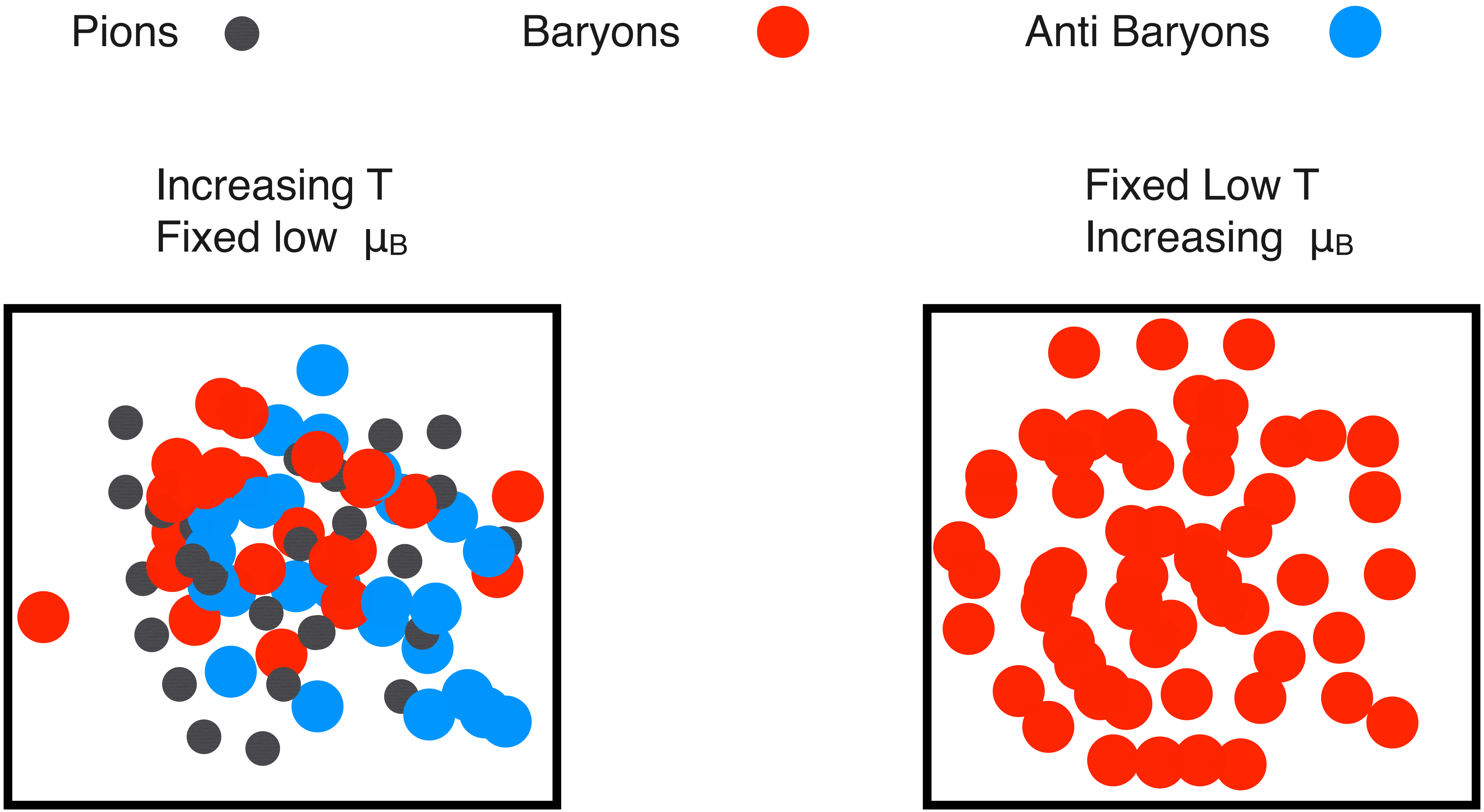

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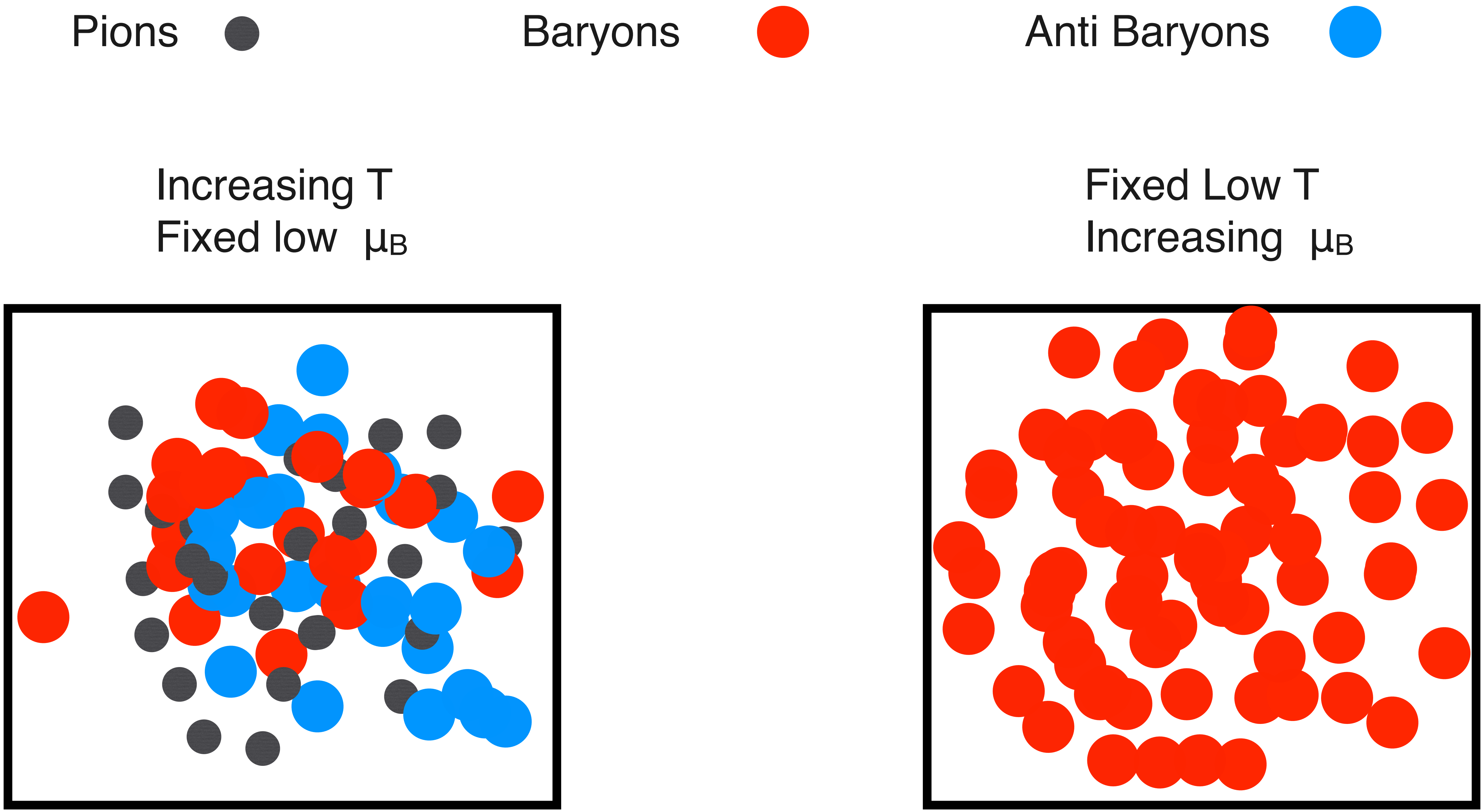

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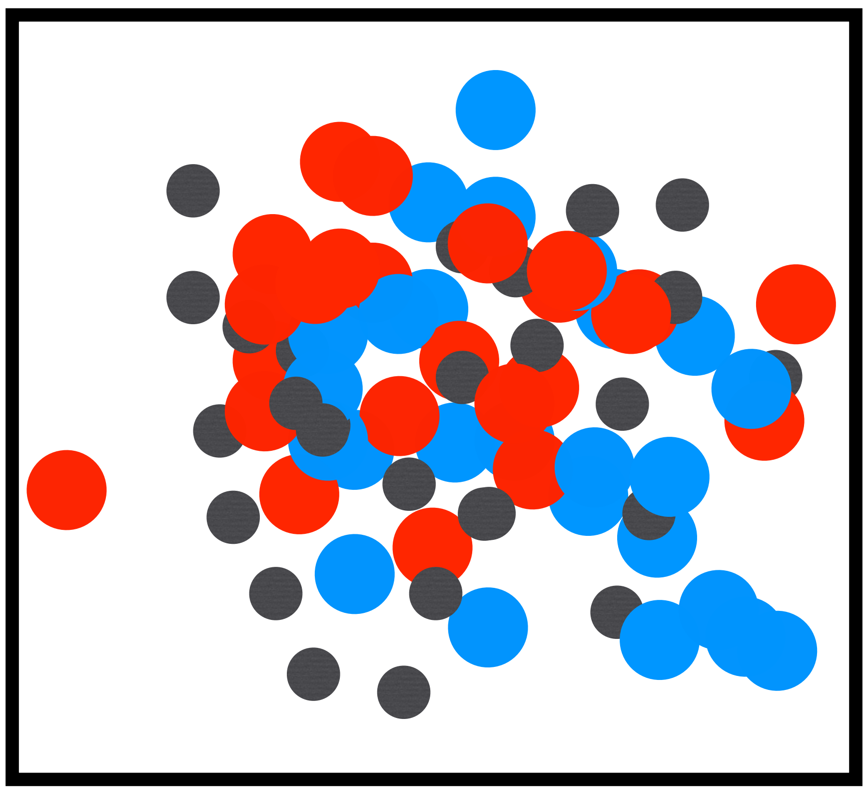

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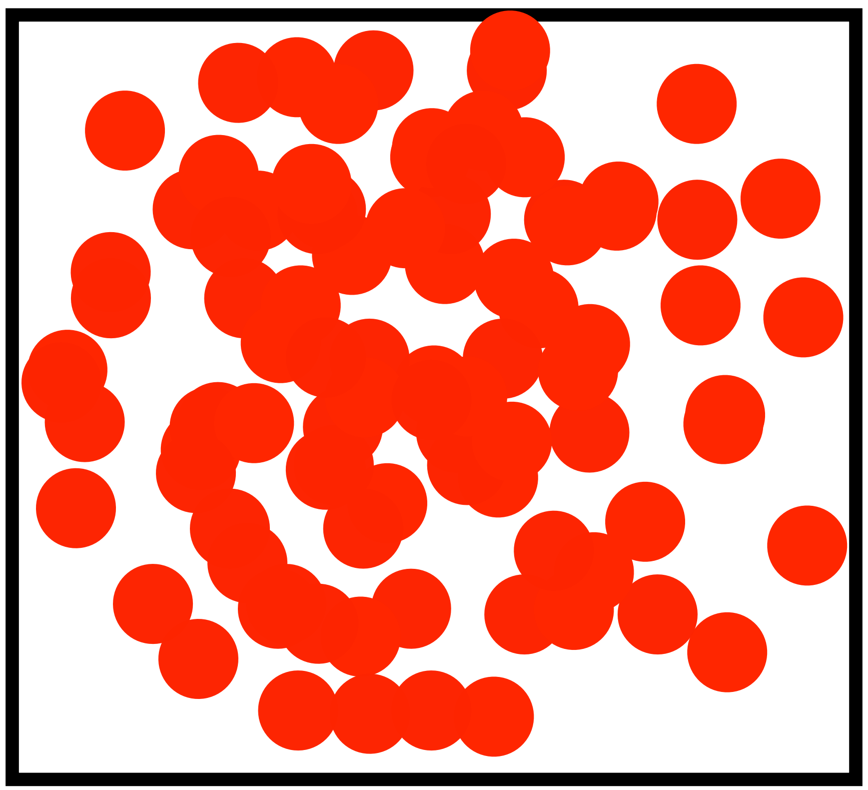
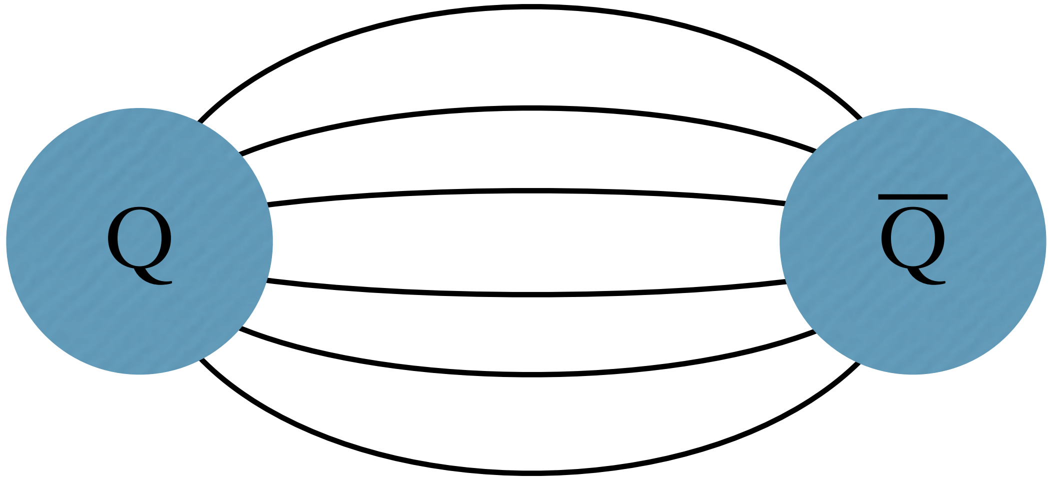


Color screening



VACUUM
Anti-screening

M. Laine et al. JHEP 0703, 054 (2007)

See Thursday talks

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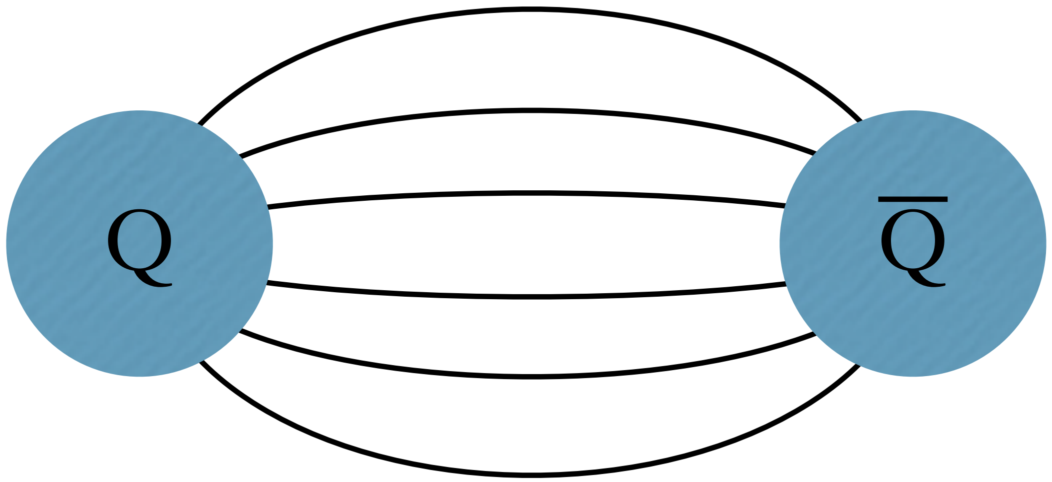

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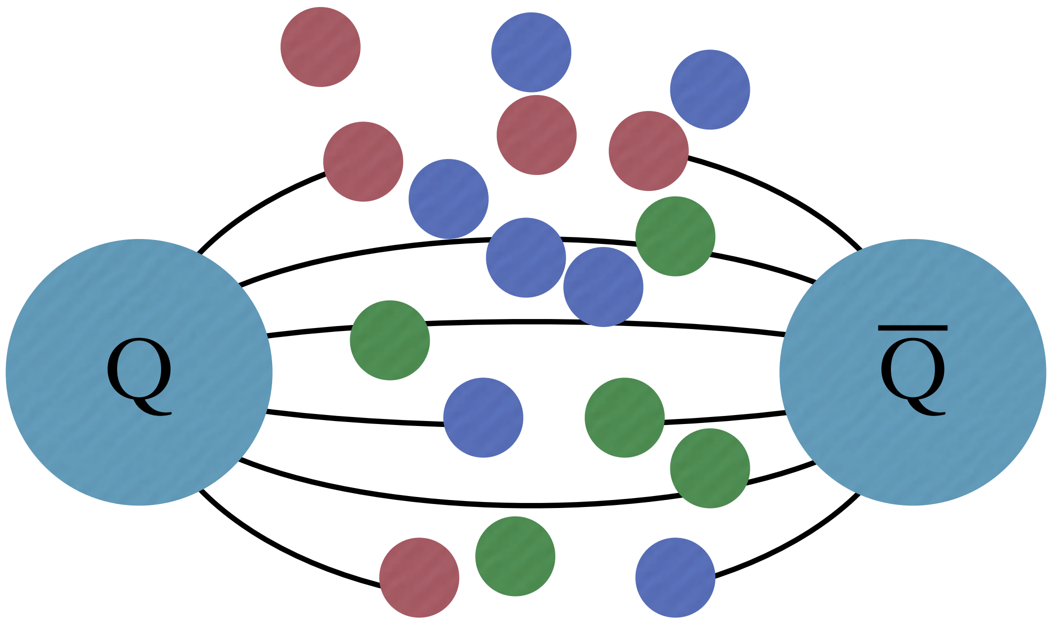

QGP
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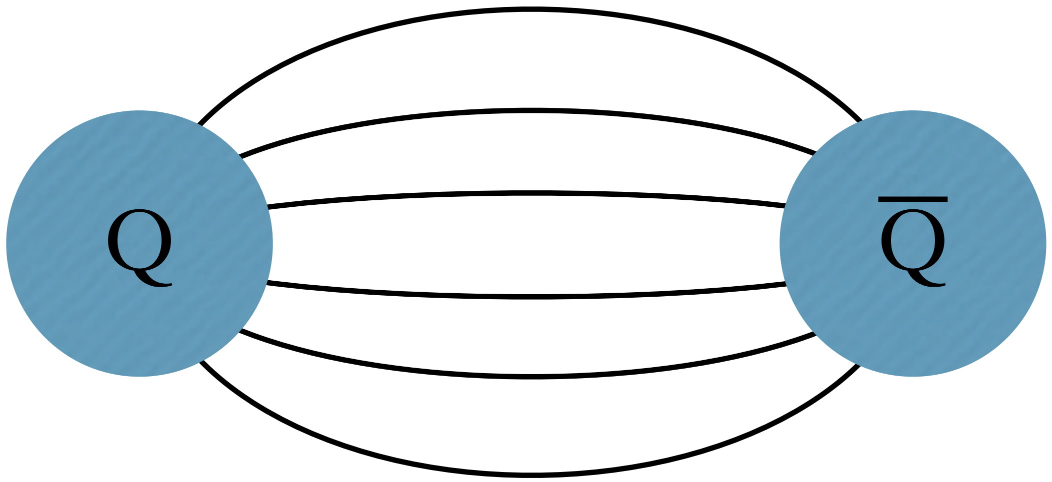

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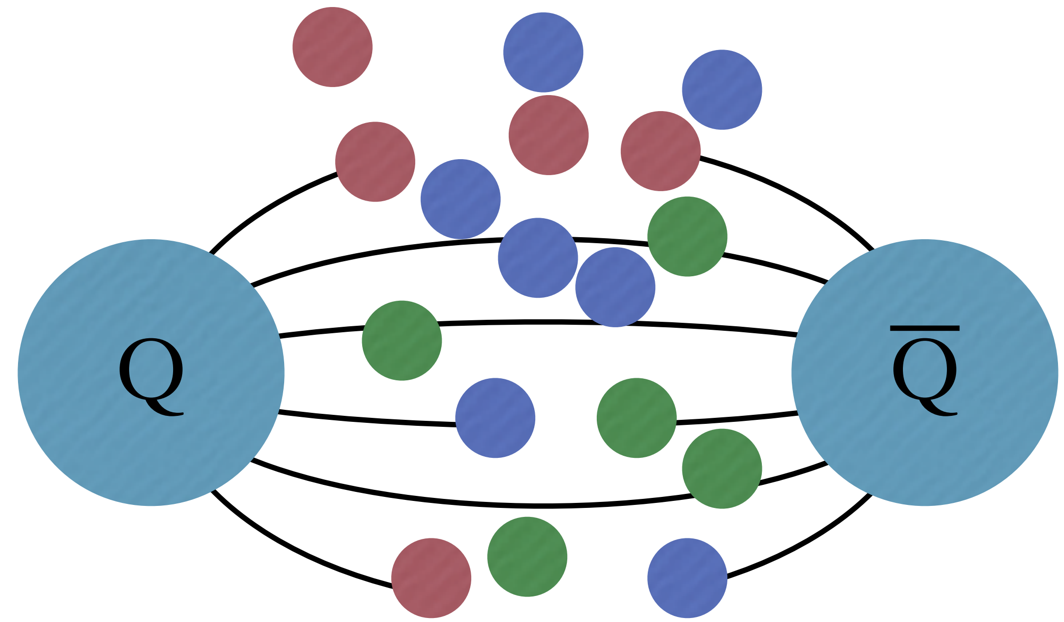

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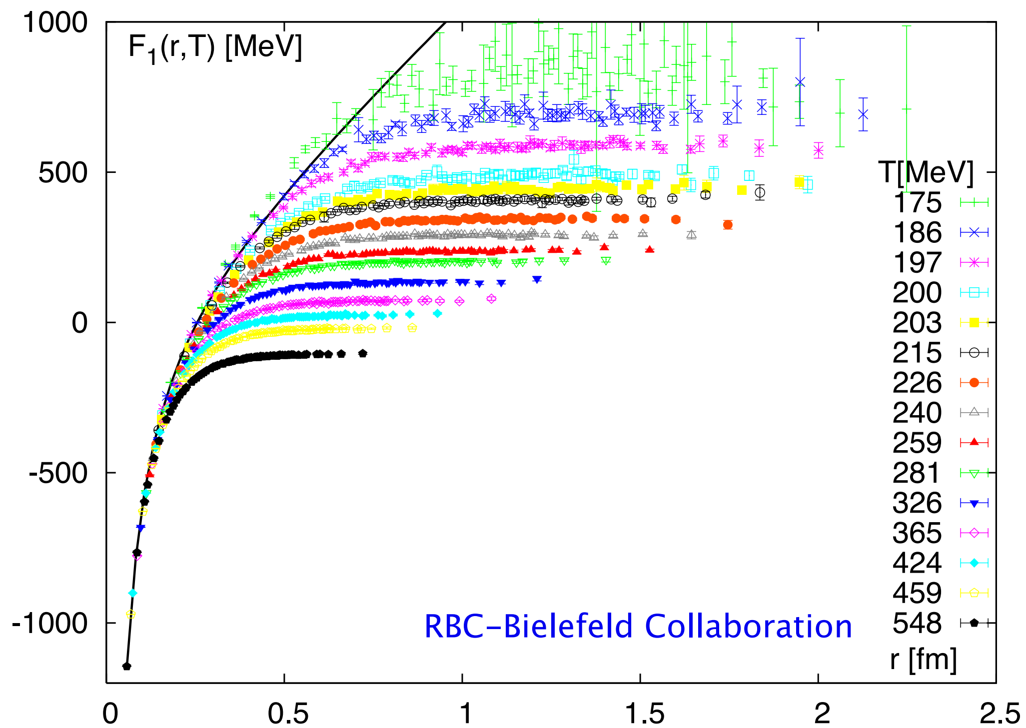

Pioneering work by Matsui and Satz
Charmonia melting by Debye Screening
Phys.Lett. B178 (1986) 416-422

One can use quarkonia melting as a "thermometer" of the QGP temperature

Landau damping is a competitive phenomenon
M. Laine et al. JHEP 0703, 054 (2007)

See Thursday talks