Theory group

Massimo Mannarelli
massimo@lngs.infn.it

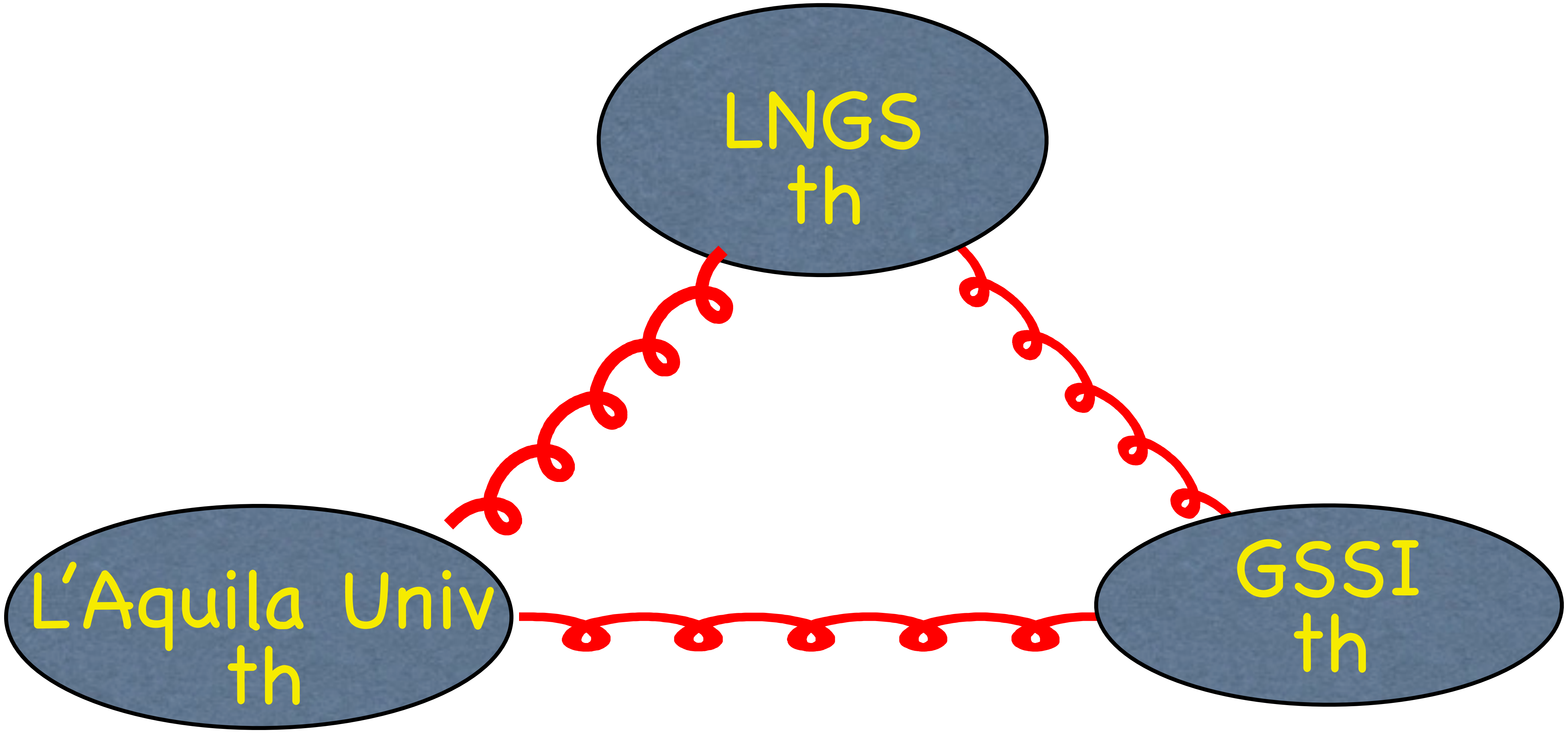
IAPS@Gran Sasso 2016

Outline

- Who we are
- What we do
- One research activity: compact stellar objects
- Conclusions

Who we are

THEORY GROUP



Staff

Vissani, Bhereziani, Villante, Pilo, Mannarelli, Di Carlo, Aloisio, Blasi

Post-docs

Carignano, Evoli, Mammarella, Pagliaroli, Ramazanov, Morlino, Biondi

PhD

Addazi, Giammaria, Recchia, D'Angelo, Ambrogi, Palladino, Celoria

What we do

Lines of research

Collaboration with national and international research groups

Neutrinos: supernova, double beta, sterile, CNO

Particle physics: Lattice QCD, Color superconductors, Superfluids

Compact stars: Neutron stars and strange stars

Astroparticle physics: Cosmic rays

Cosmology/General Relativity: Gravitational waves, Massive gravity, Big Bang Nucleosynthesis

Exotica: Dark matter, Mirror matter

Formal structure

The theory group is organised in "Iniziative Specifiche", virtual experiments having about a 3 years lifetime

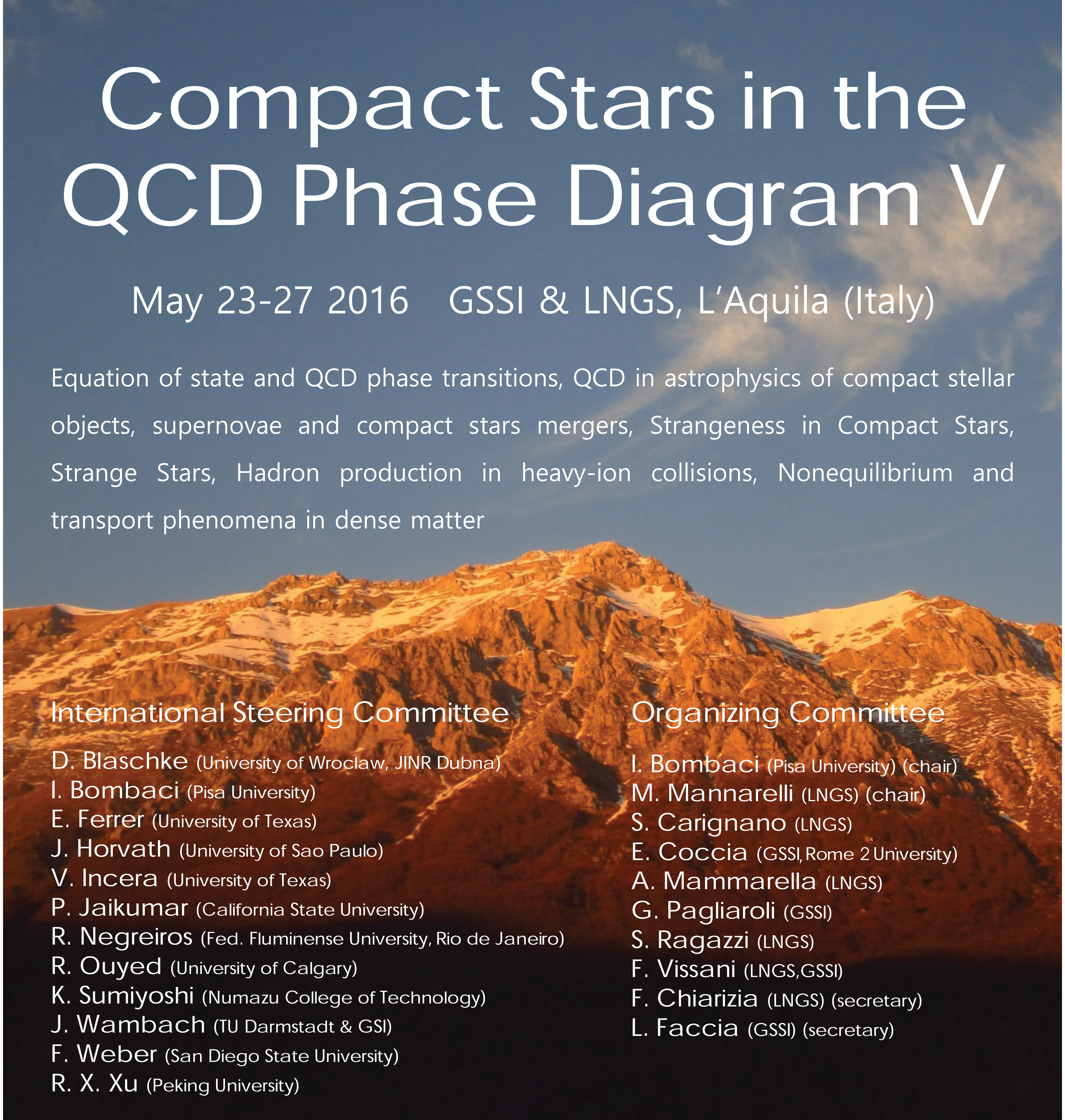
I.S.	Topics	Local coordinator
`Aae`	High energy astrophysics, baryon number violation, neutron oscillations, lepton number violation, axion physics	Zurab Berezhiani
`Indark`	Inflation, dark matter and the large-scale structure of the universe, massive gravity, bigravity	Luigi Pilo
`Npqcd`	Non-Perturbative quantum chromodynamics, lattice simulations	Giuseppe Di Carlo
`Numat`	Nuclear matter and compact stellar objects, color superconductors, meson condensation	Giulia Pagliaroli
`TASP`	Theoretical astroparticle physics, neutrino physics and astronomy, cosmic ray physics	Francesco L.Villante

Activity

Very active group with about **50 publications per year**

The theory group members participate to a large number of international conferences

The research activity is of very high level and on many different fields



Compact Stars in the QCD Phase Diagram V

May 23-27 2016 GSSI & LNGS, L'Aquila (Italy)

Equation of state and QCD phase transitions, QCD in astrophysics of compact stellar objects, supernovae and compact stars mergers, Strangeness in Compact Stars, Strange Stars, Hadron production in heavy-ion collisions, Nonequilibrium and transport phenomena in dense matter

International Steering Committee

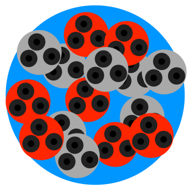
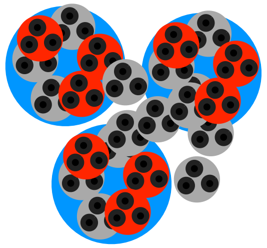
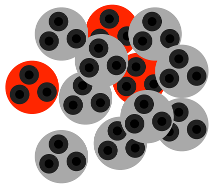
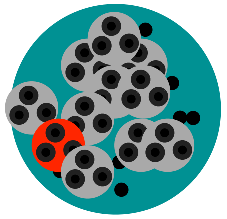
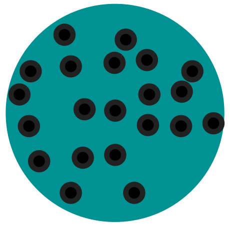
D. Blaschke (University of Wroclaw, JINR Dubna)
I. Bombaci (Pisa University)
E. Ferrer (University of Texas)
J. Horvath (University of Sao Paulo)
V. Incera (University of Texas)
P. Jaikumar (California State University)
R. Negreiros (Fed. Fluminense University, Rio de Janeiro)
R. Ouyed (University of Calgary)
K. Sumiyoshi (Numazu College of Technology)
J. Wambach (TU Darmstadt & GSI)
F. Weber (San Diego State University)
R. X. Xu (Peking University)

Organizing Committee

I. Bombaci (Pisa University) (chair)
M. Mannarelli (LNGS) (chair)
S. Carignano (LNGS)
E. Coccia (GSSI, Rome 2 University)
A. Mammarella (LNGS)
G. Pagliaroli (GSSI)
S. Ragazzi (LNGS)
F. Vissani (LNGS,GSSI)
F. Chiarizia (LNGS) (secretary)
L. Faccia (GSSI) (secretary)

Compact stellar objects

Squeezing matter

		Density	$\alpha_s \equiv \alpha_s(\mu)$	Degrees of freedom
	H			
	He	......		light nuclei
......				.....
	Fe	10 g cm^{-3}	confining	heavy nuclei
	neutron drip	10^{11} g cm^{-3}		
	neutron proton soup	10^{14} g cm^{-3}		neutrons and protons
	quark drip	very large	strong coupling	quarks and gluons Cooper pairs of quarks? quarkyonic phase?....
	quark soup	extreme	weak coupling	Cooper pairs of quarks NGBs

ρ

The squeezers: Pulsars

Jocelyn Bell e Antony Hewish in 1967 observed regular radio signal. It seemed a broadcast from a far far away.... television or radio channel.
It was actually a bit boring: it consisted of a radio pulse every 1.33 seconds

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HST + CHANDRA image
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	B0329+54	Crab	B1937+21
Spinning periods	0.7s	33ms	1.5 ms

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Centrifuge
0.04 s

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Centrifuge
0.04 s

It is very COMPACT

It is known to be very MASSIVE

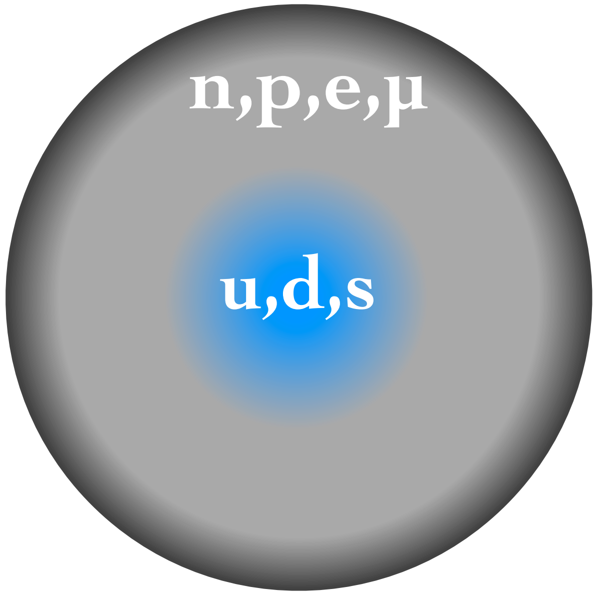
It comes from the Supernova collapse

Classification of CSOs

Stadard Neutron star

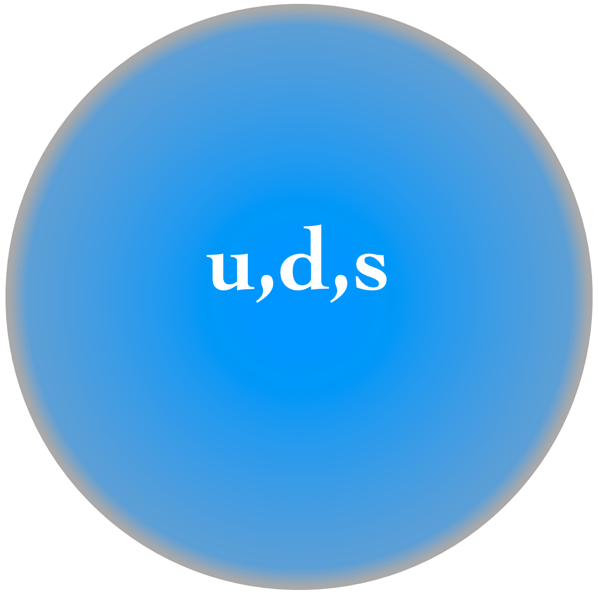
$R \sim 10 \text{ km} \;\; M = 1.4\, M_{\odot}$

Hybrid star



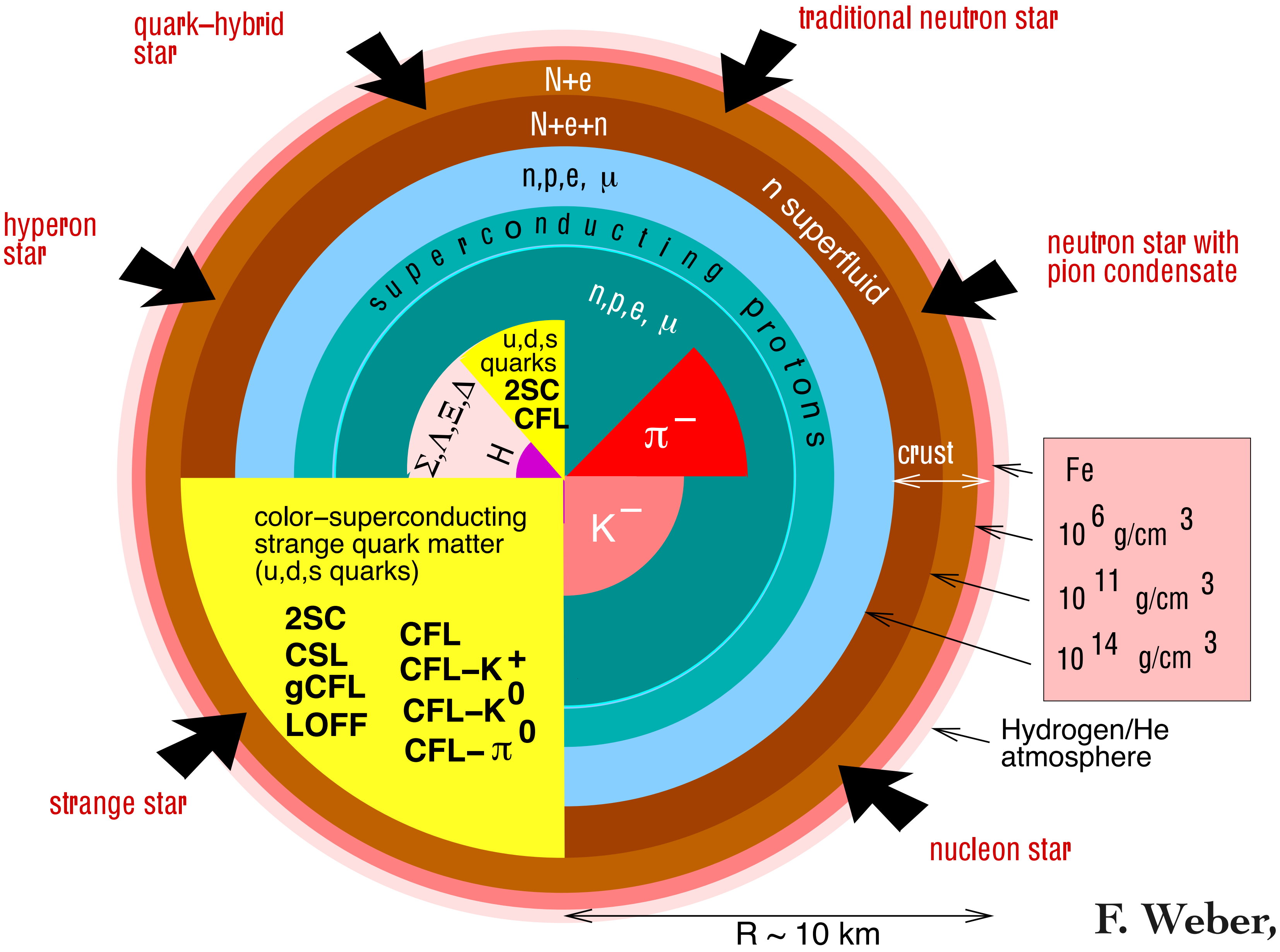
$R \sim 10 \text{ km} \;\; M = 1.4\, M_{\odot}$

Strange star



$R \sim 0 - 10 \text{ km} \;\; M < 2.5\, M_{\odot}$

Compact stellar objects

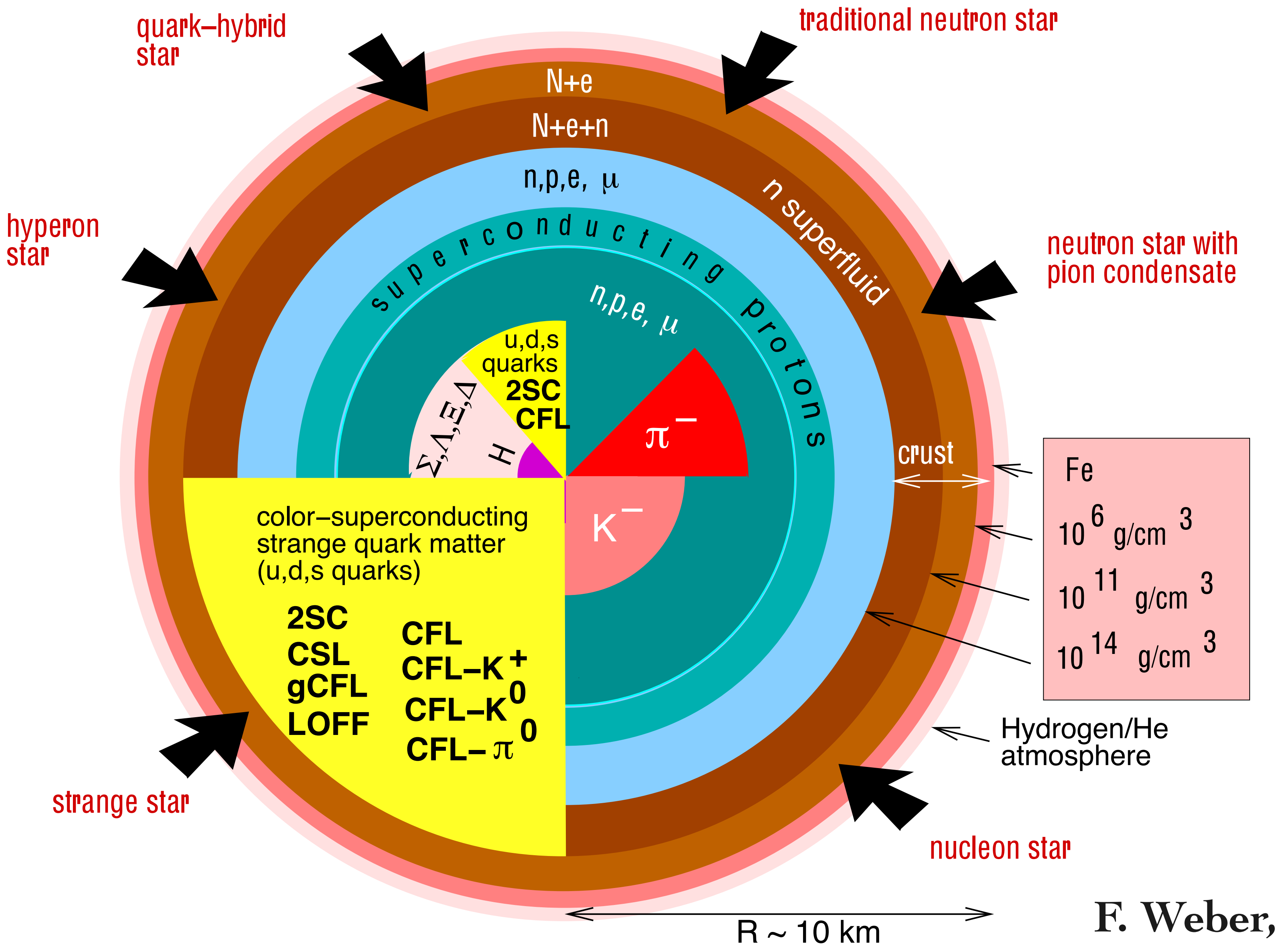


F. Weber, Prog.Part.Nucl.Phys. 54 (2005) 193

Surface temperature in sufficiently old compact stars $< 10^6 \mathrm{K}$

Mass $1.2 M_\odot < M < 2 M_\odot$

Compact stellar objects



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“Probes”
cooling
glitches
instabilities
mass-radius
magnetic field
GW
……

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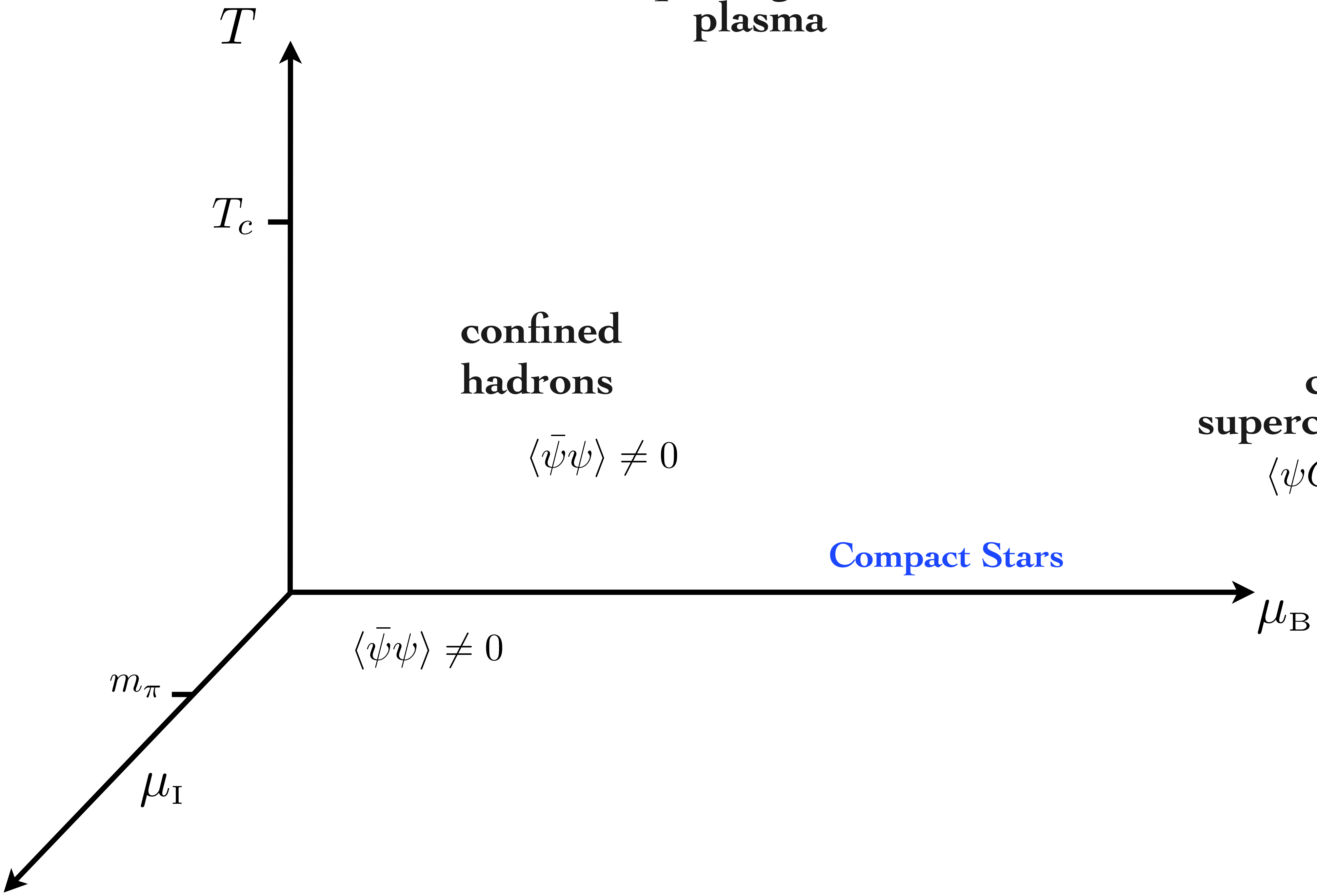
Quark matter phase diagram



quark-gluon
plasma

confined
hadrons

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

color
superconductors

$\langle\psi C\gamma_5\psi\rangle$

CFL

Compact Stars

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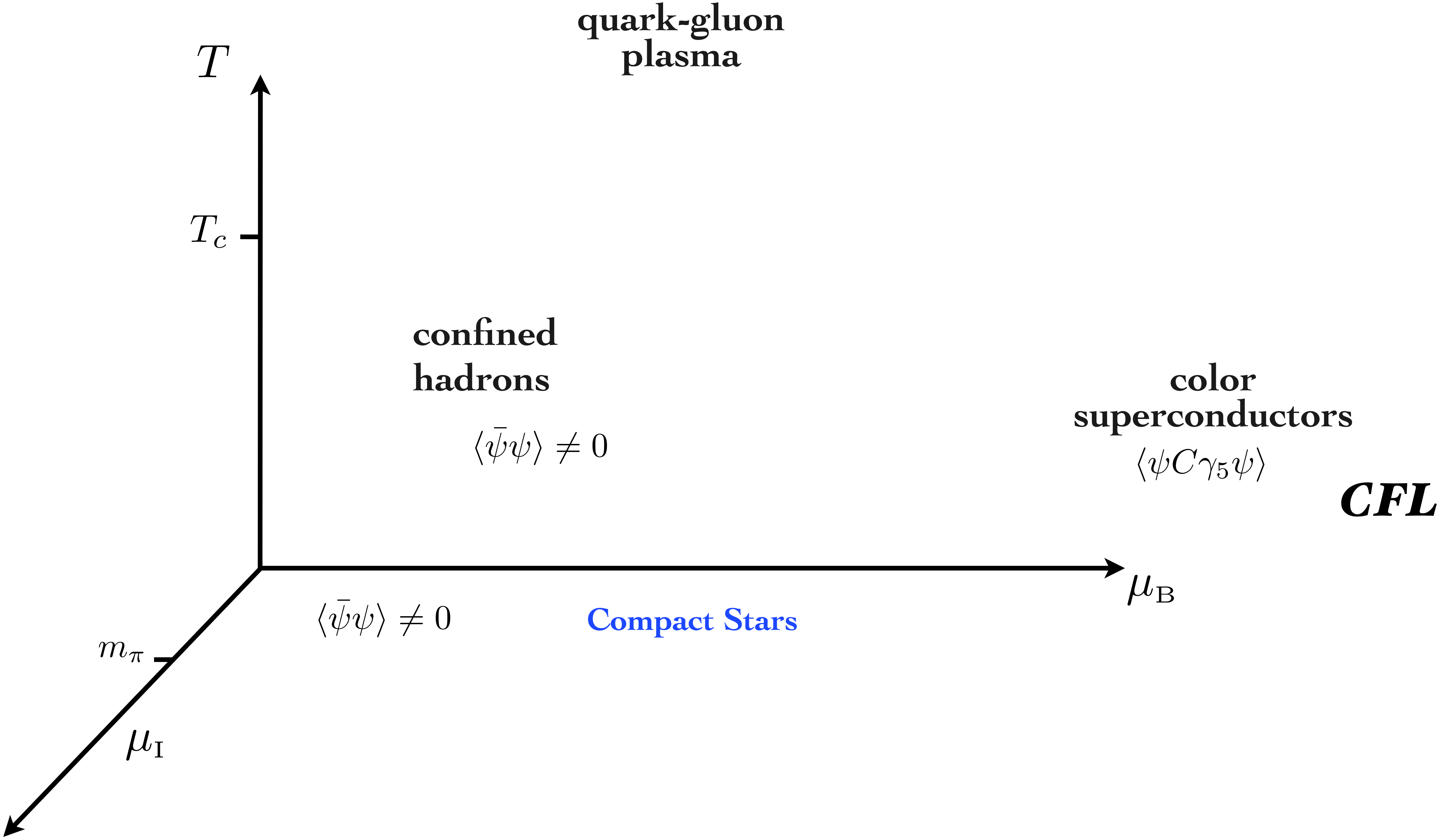
Quark matter phase diagram



T

quark-gluon plasma

T_c

confined hadrons

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CFL

μ_{B}

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

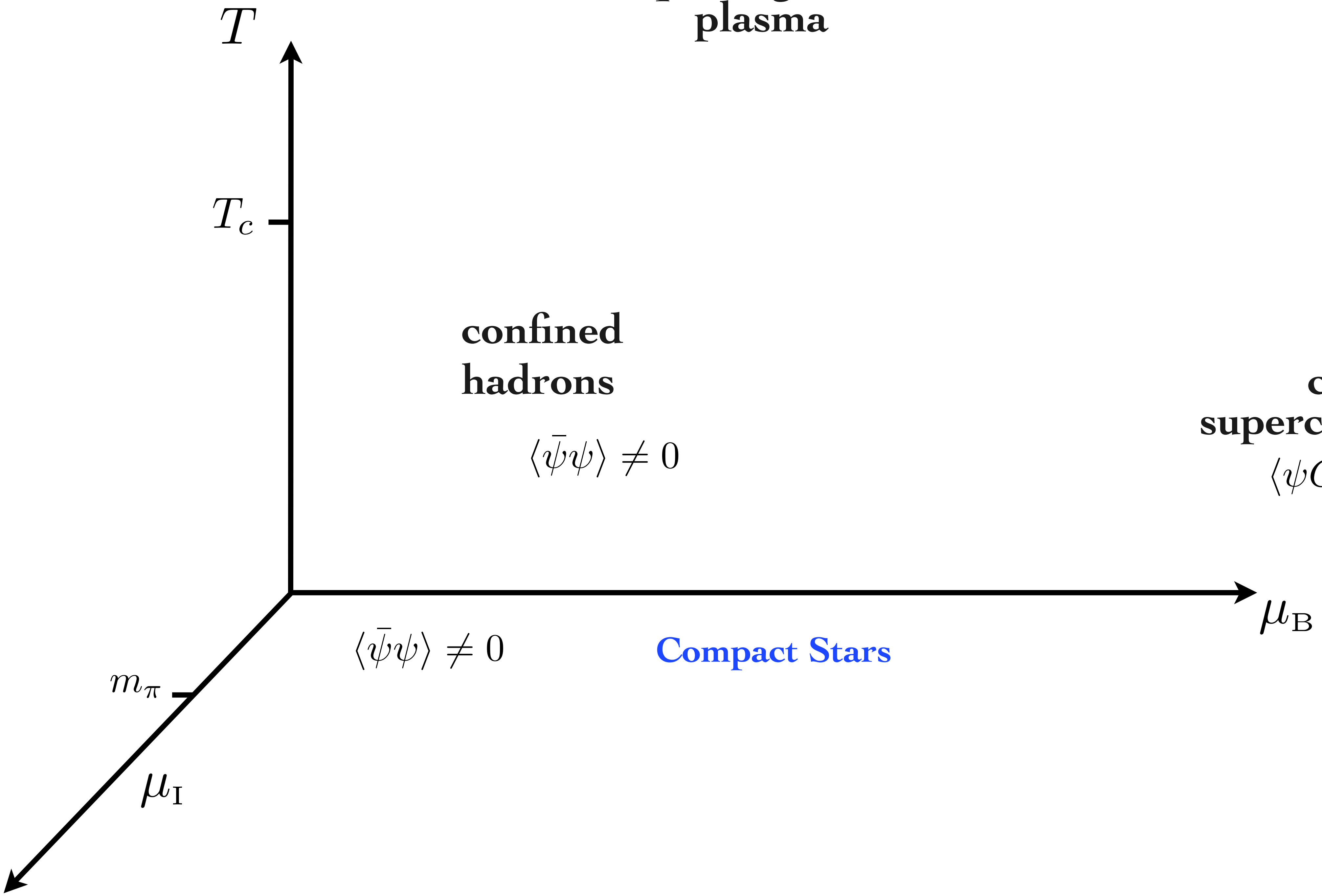
Compact Stars

m_π

μ_{I}

Quark matter phase diagram

SOME METHODS



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Compact Stars

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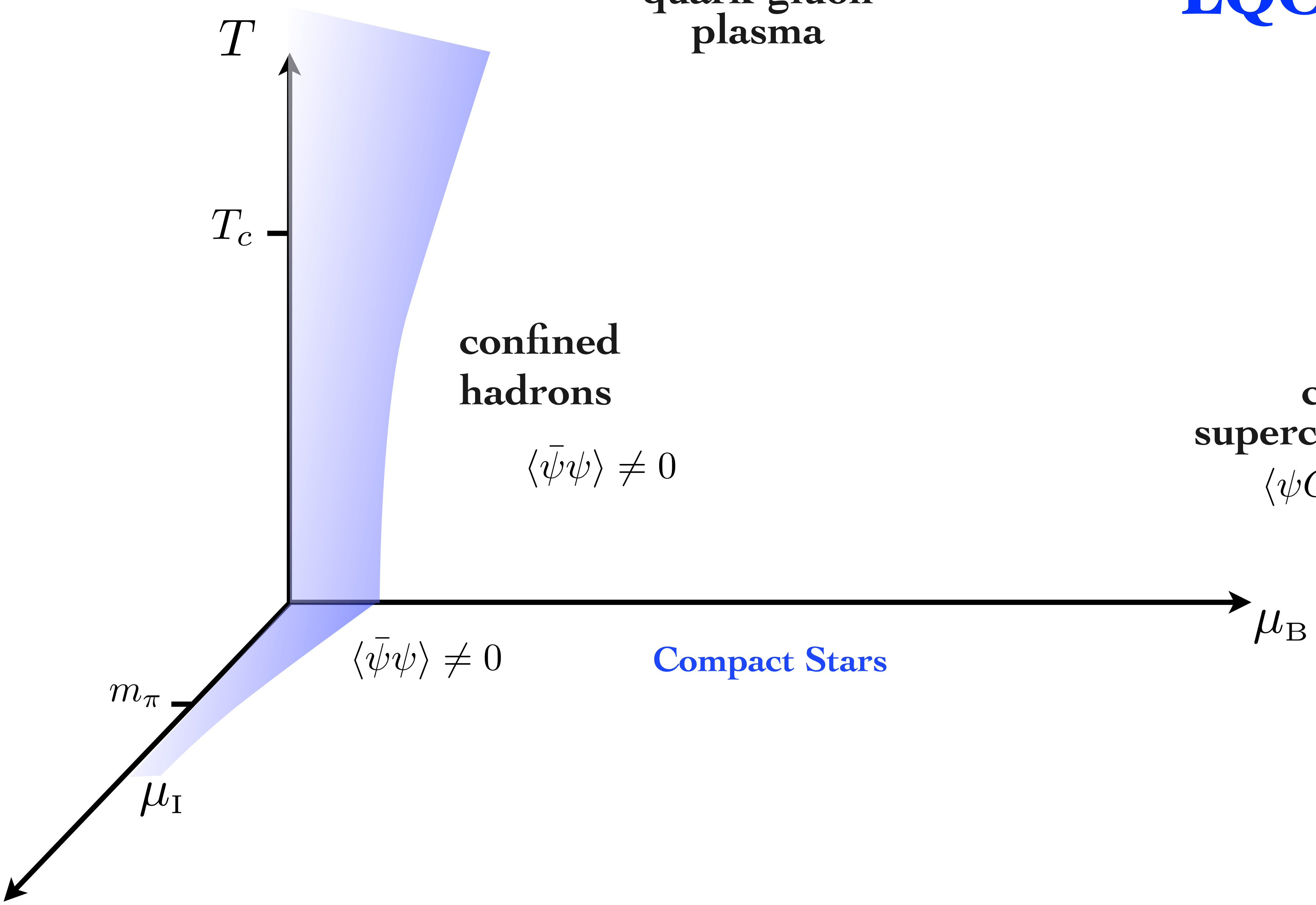
SOME METHODS

LQCD



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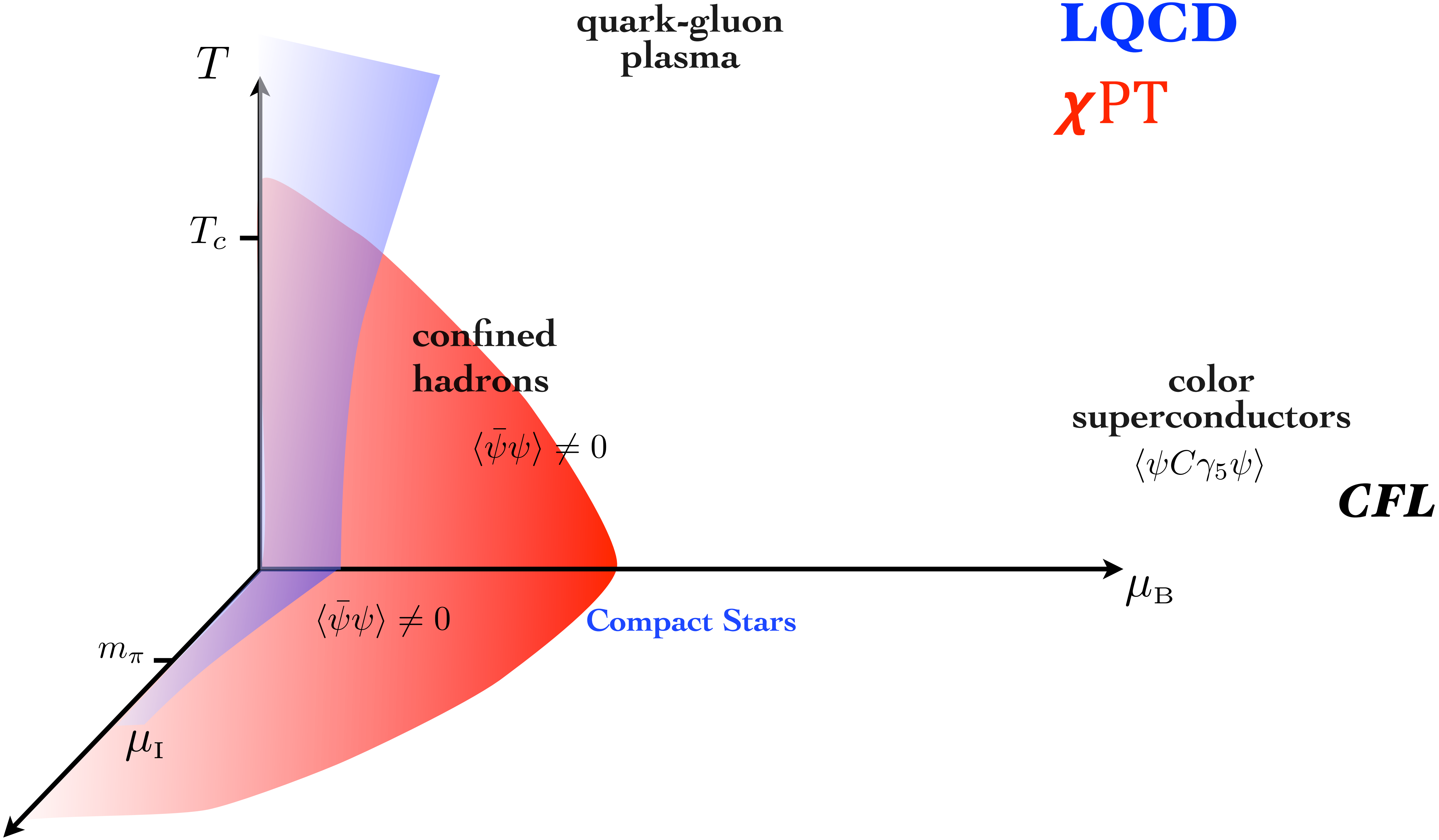
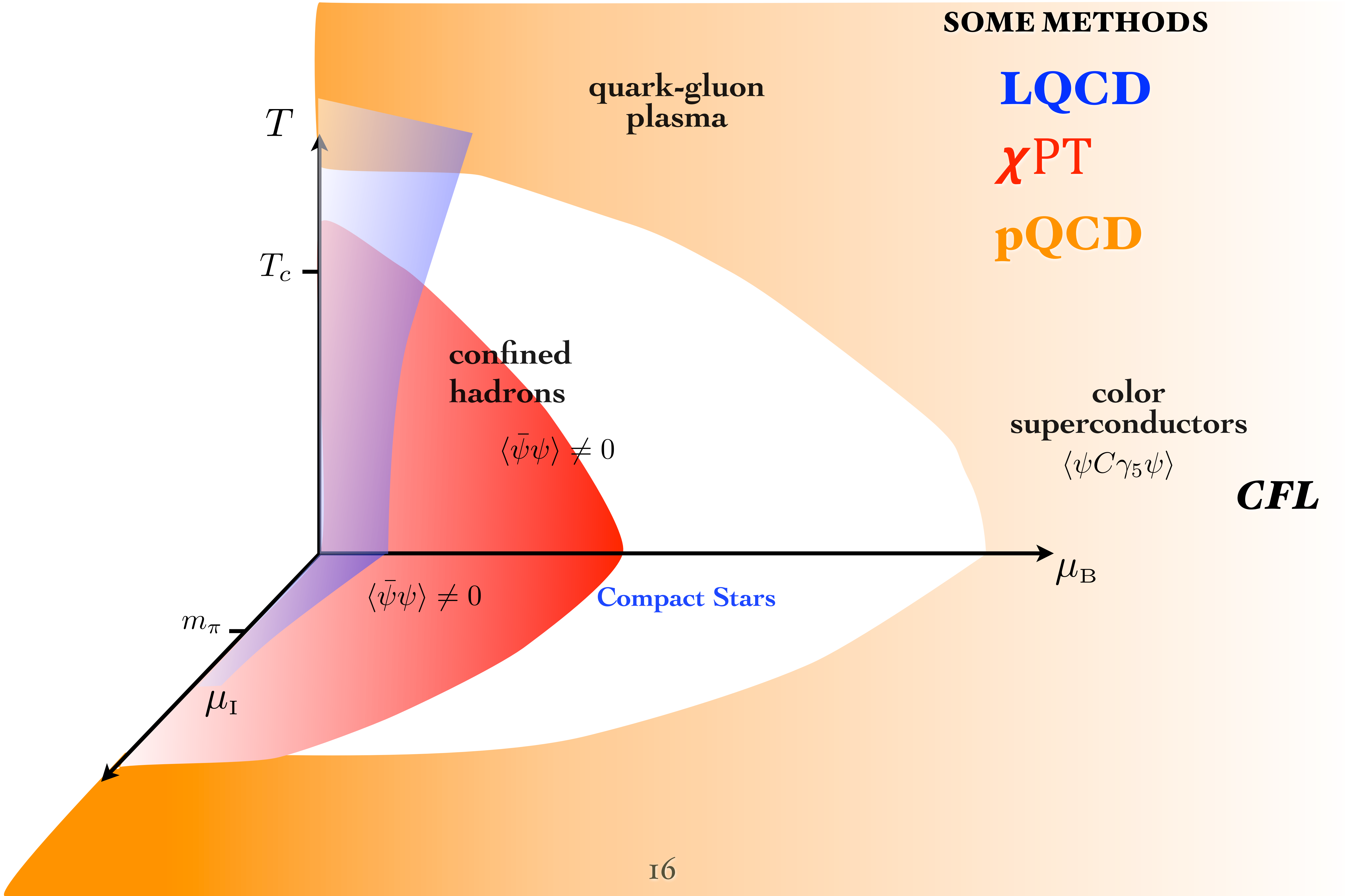
SOME METHODS

LQCD

χPT



Quark matter phase diagram



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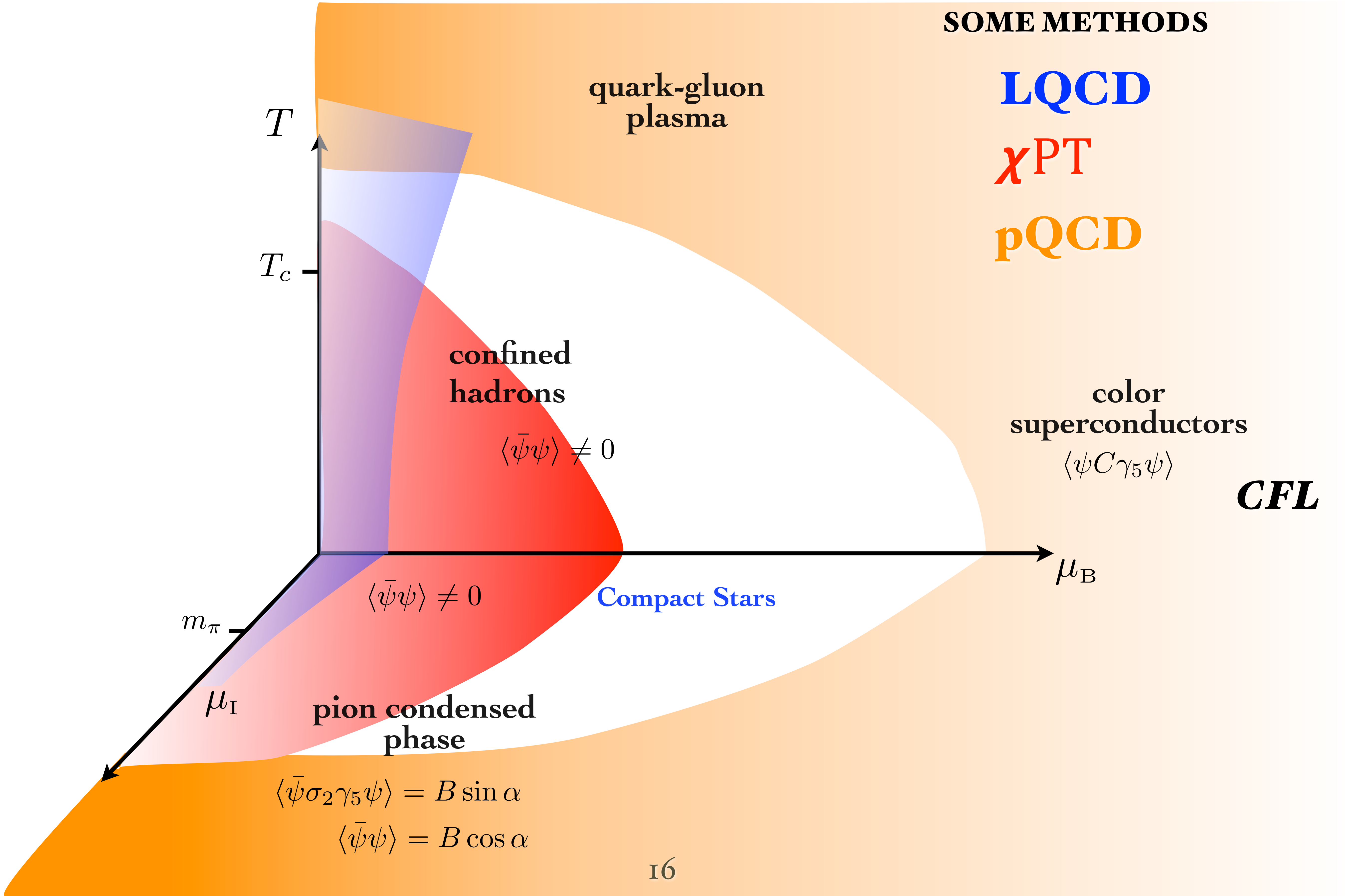

SOME METHODS

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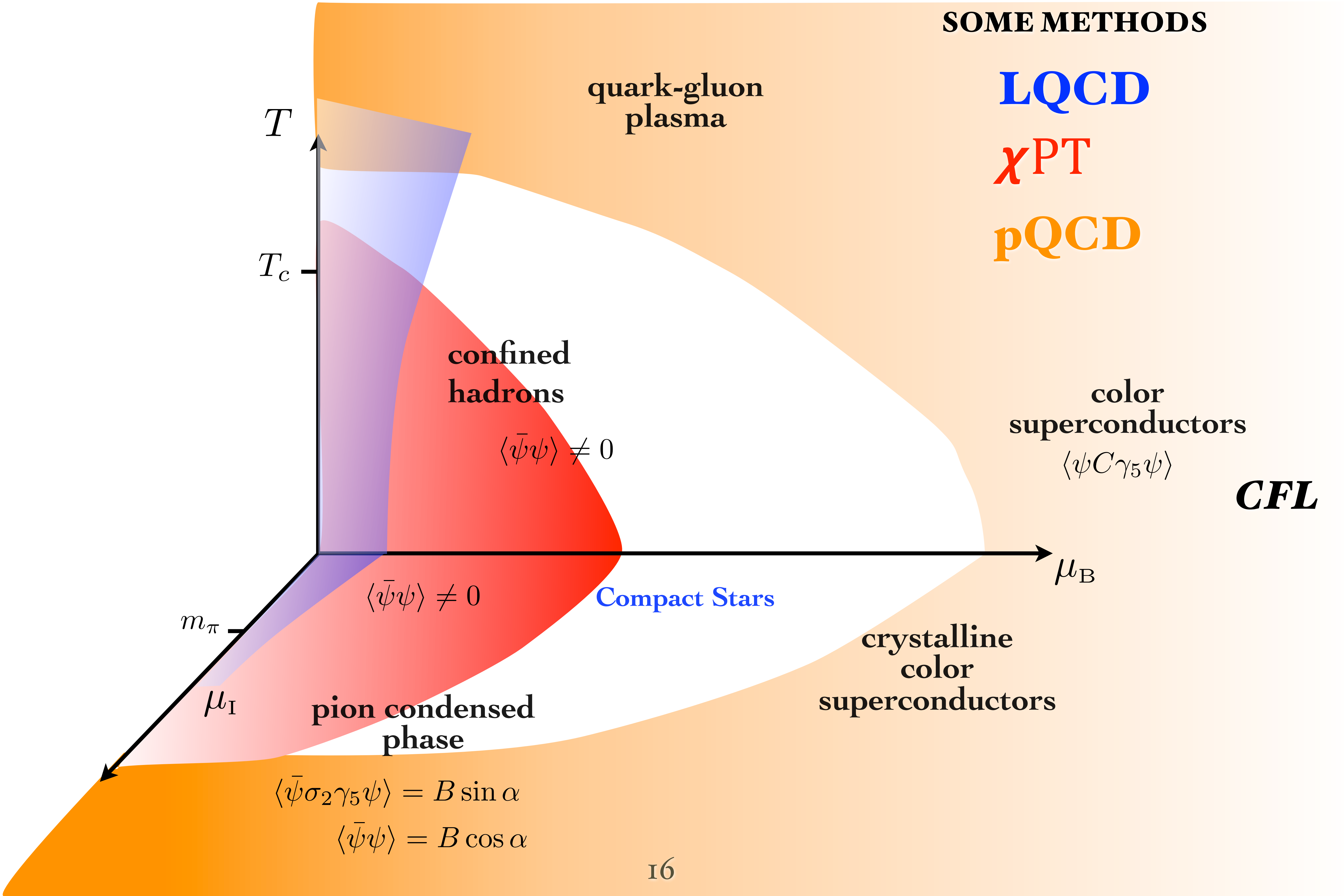


SOME METHODS

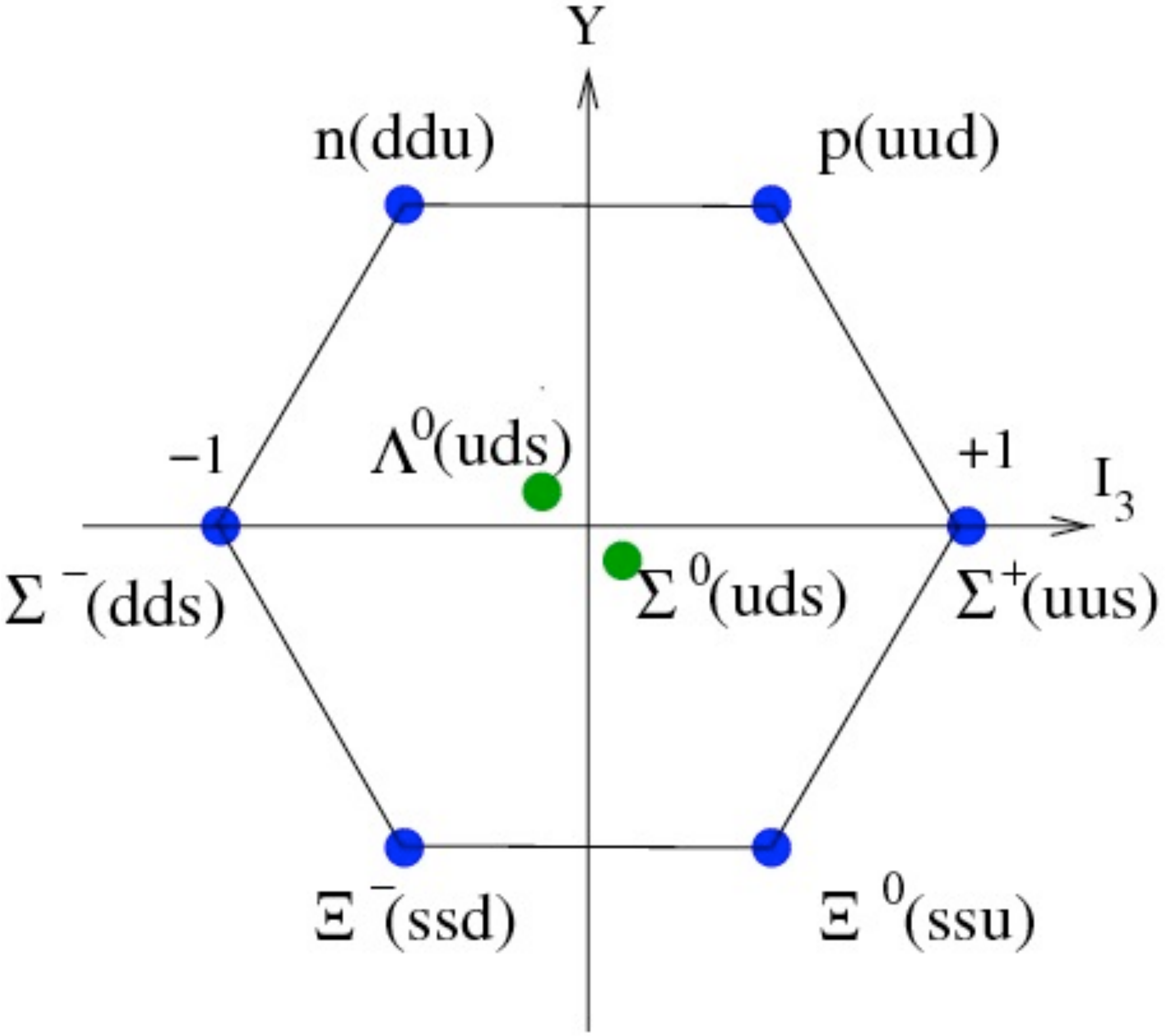
LQCD

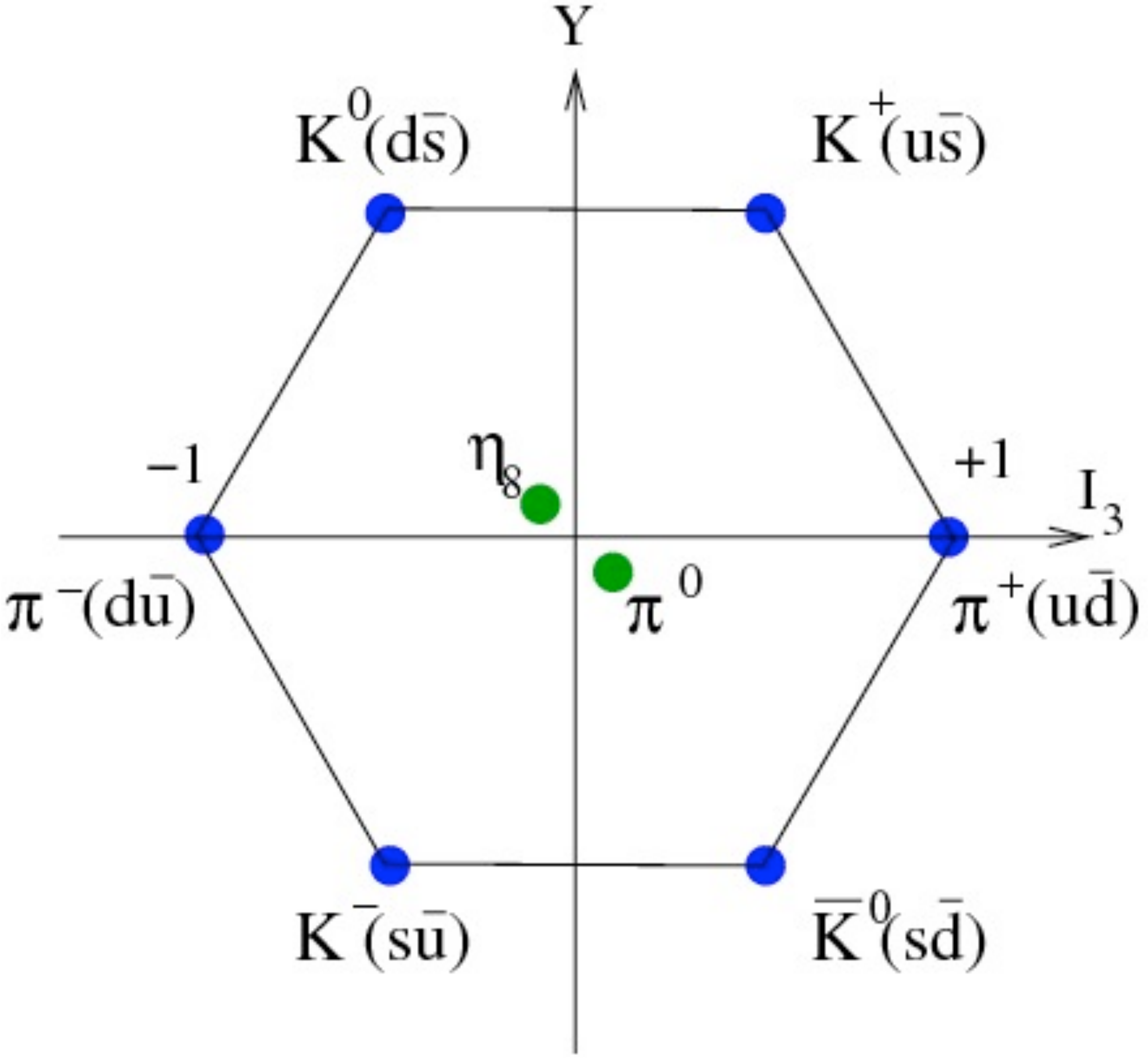
χPT

pQCD

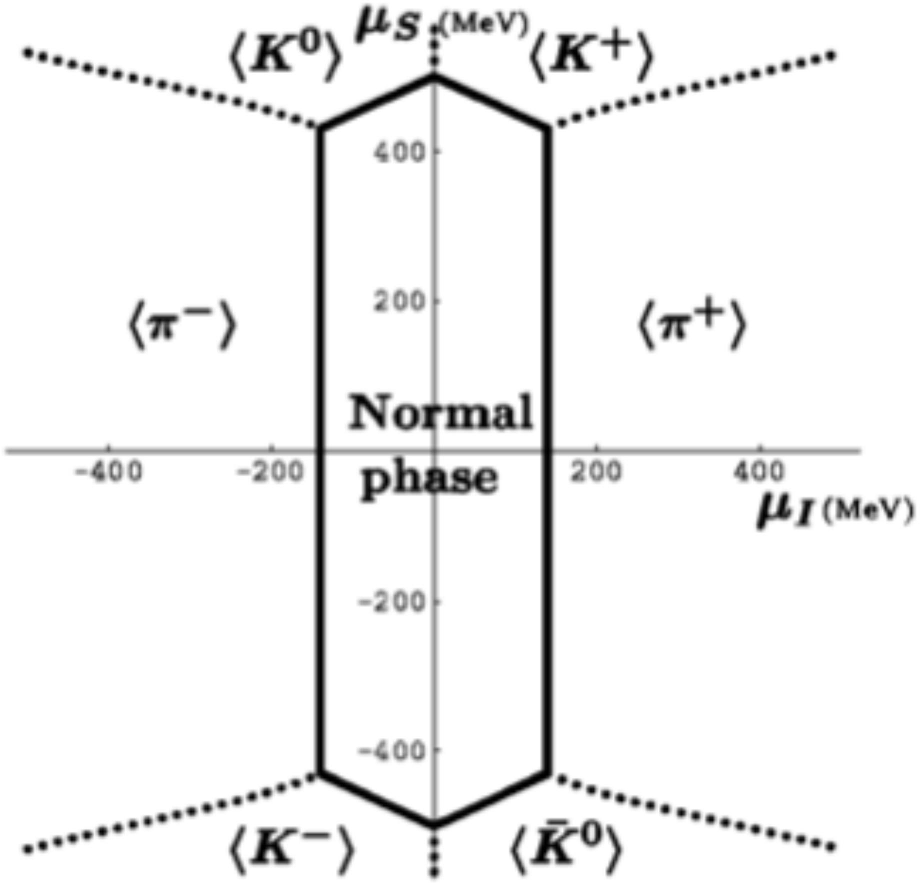
Isospin quantum number

The strong interaction does not distinguish between the proton and the neutron. This lead Schroedinger in 1932 to assume that there is an internal degree of freedom: the isospin





Isospin asymmetric matter



solid line: second order

dotted line: first order

Kogut and Toublan PhysRevD.64.034007

In the condensed phases, a superfluid of charged bosons: a superconductor!

$$M_D^2 = M_M^2 = F_0^2 e^2 (\sin\alpha)^2$$

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

Mixing and mass splitting

In the condensed phases mesons mix and have nontrivial mass splitting

$$\begin{pmatrix} \tilde{\pi}_+ \\ \tilde{\pi}_- \end{pmatrix} = \begin{pmatrix} U_{11} & U_{12} \\ U_{21} & U_{22} \end{pmatrix} \begin{pmatrix} \pi_+ \\ \pi_- \end{pmatrix}$$

mass eigenstates ↑

charge eigenstates ↑

$$U_{ij} \equiv U_{ij}(m_\pi, \mu_I, {\color{red}E})$$

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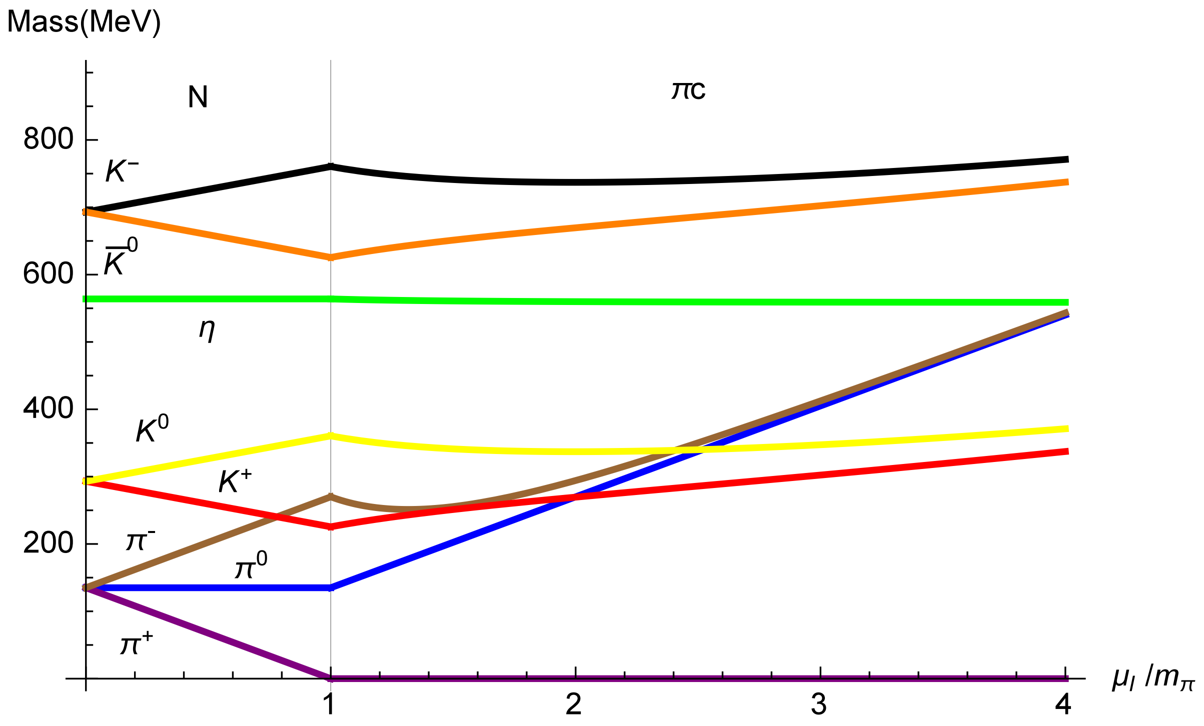

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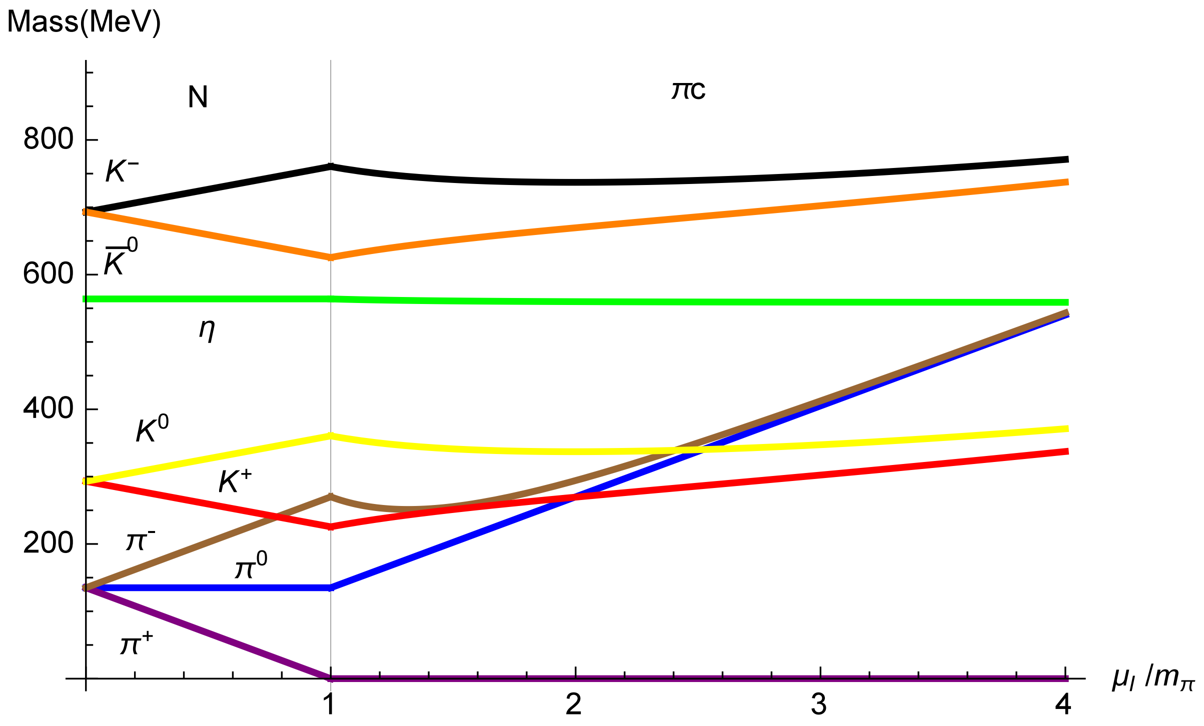
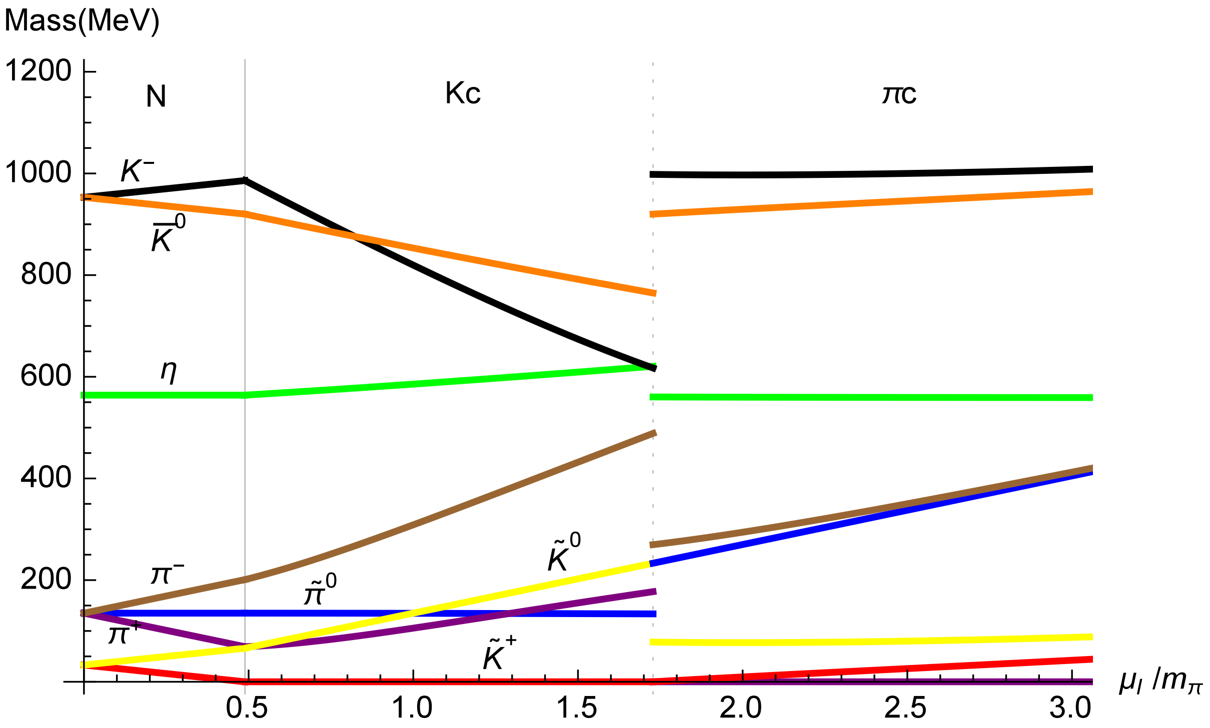
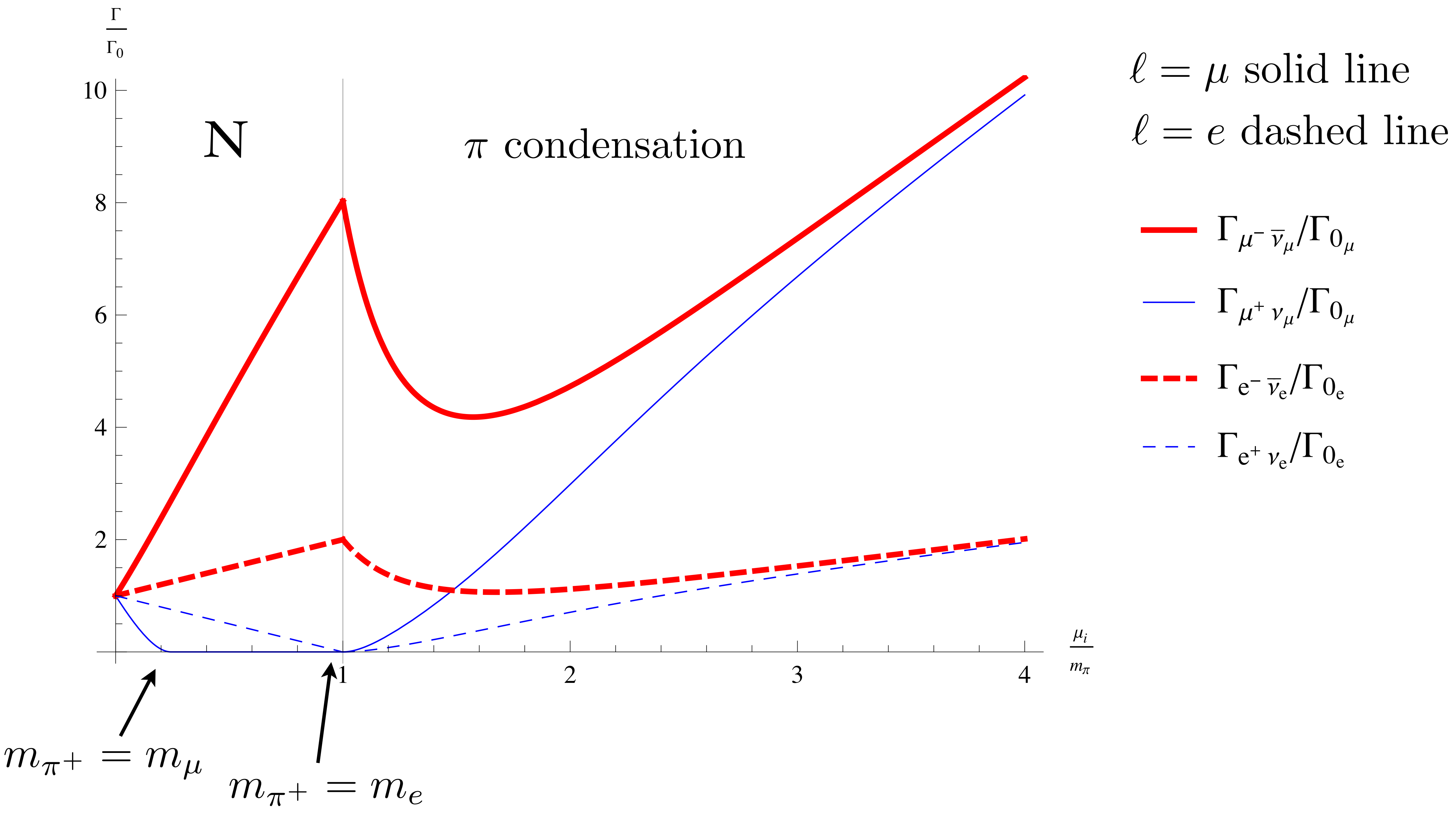




A. Mammarella and M.M. Phys.Rev. D92 (2015) 8, 085025

Leptonic decays

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



$\ell = \mu$ solid line

$\ell = e$ dashed line

$m_{\pi^+} = m_\mu$

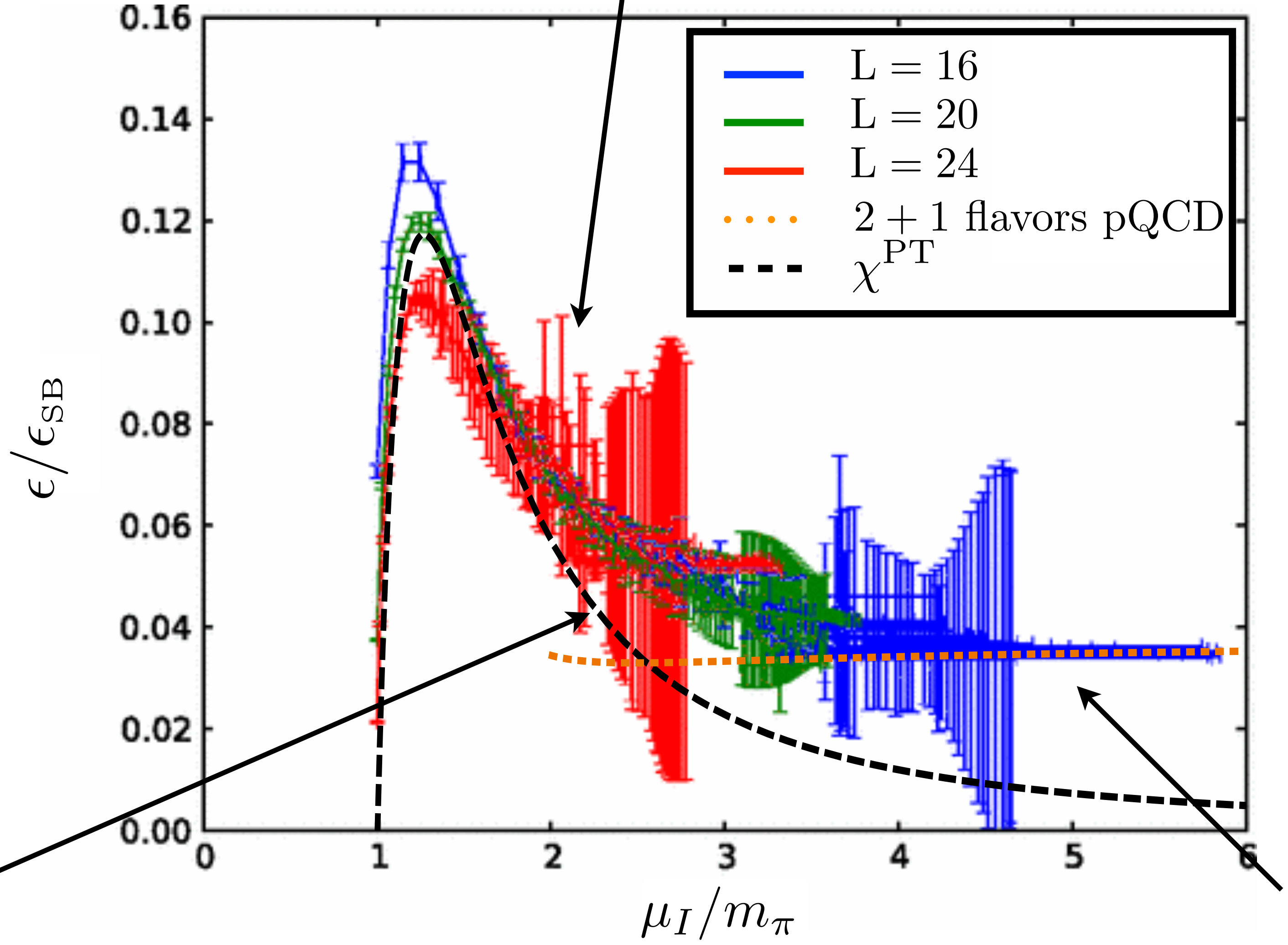
$m_{\pi^+} = m_e$

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

Comparison with different methods

Microcanonical lattice QCD simulations

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



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

***χ*PT**

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

pQCD

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

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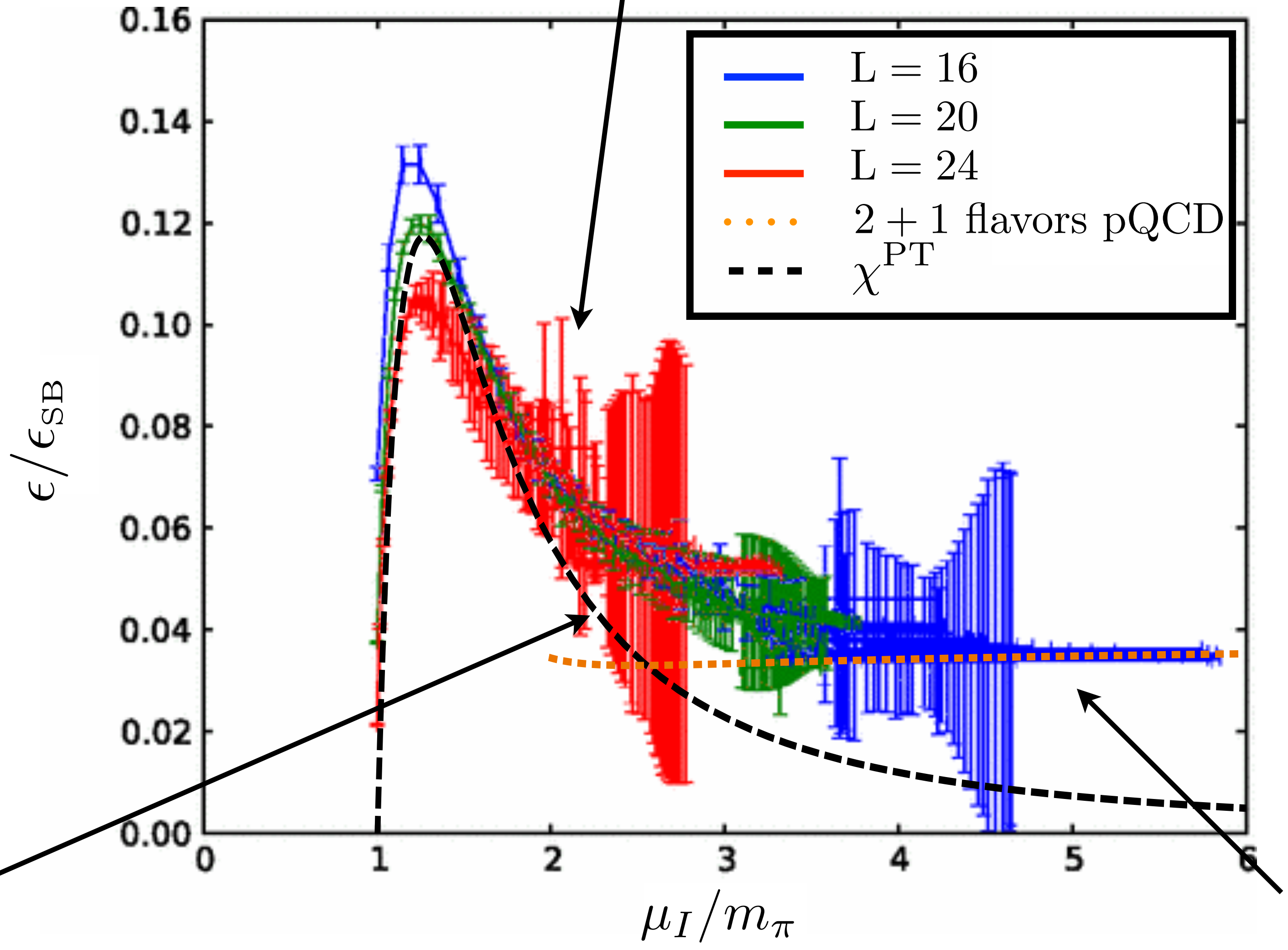

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S. Carignano, A. Mammarella and M.M. Phys.Rev. D93 (2016) no.5, 051503

pQCD

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

Leading order ***χ***PT correctly reproduces the peak structure

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

Conclusions

- The theory group consists of three entities: LNGS, GSSI and L'Aquila Univ.

- We work on many different topics and many open problems in physics

- One of the hot topics is the study of matter in extremes of density