Why Dense Matter Physics?

Because we simply don't know what's going on out there ...

moreover

It's exciting and challenging!

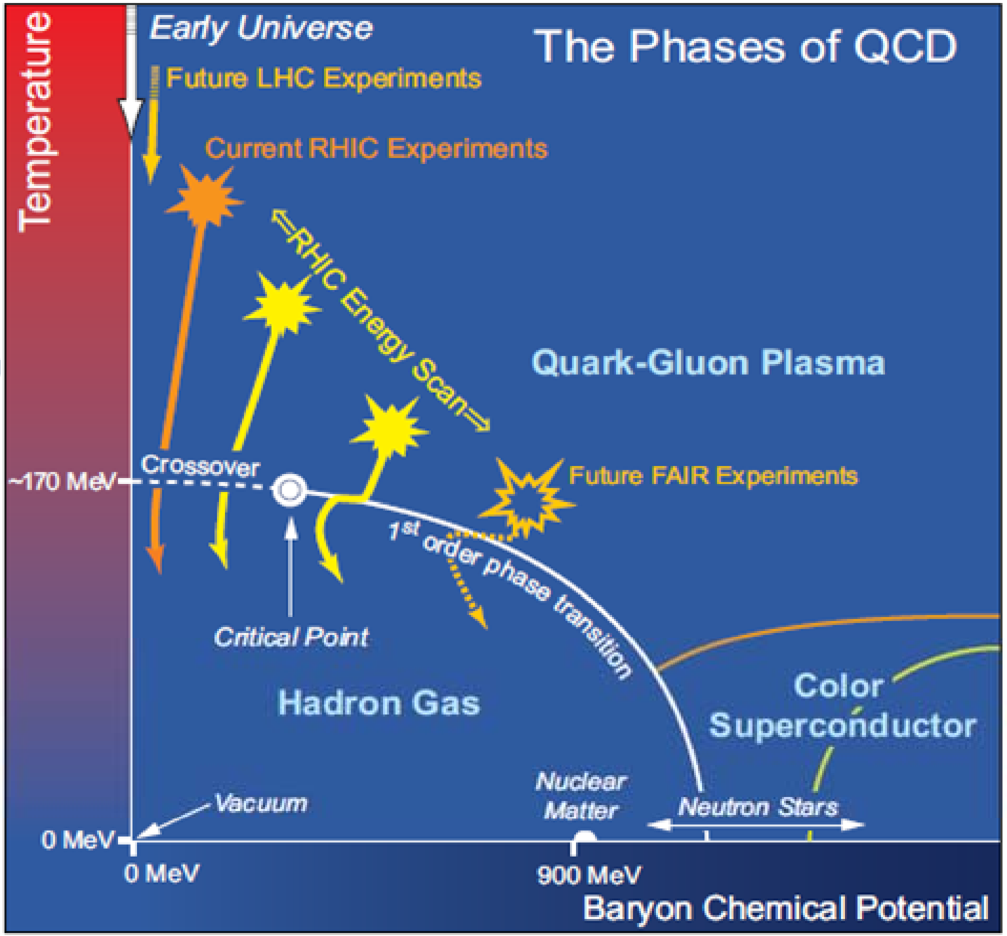
WCU-HIM

Fall 09

Basic Issues

- Phase diagram at low T and high density is more or less unknown. Intellectual challenge. At present, there are no lattice or lab data.
- Physics of dense matter is essential for physics of stable compact stars (e.g., neutron stars), collapse to black holes etc.
- Maximization of black holes in the Universe and its link to cosmology
- ….
- ….
- Conceptual overlap with strongly correlated condensed matter

“Canonical” phase diagram



physics of the early universe

hot: $T \sim 10^{12} K$

experimentally accessible

in Heavy Ion Collisions at

SPS, RHIC, LHC, FAIR

properties of compact stars

dense: $n_B \sim 10 n_{NM}$

DOE NSAC report, 2007

L+J-P=F, 2009 – p.14/24

Don’t believe all!!

The phase diagram at high density is a fantasy!

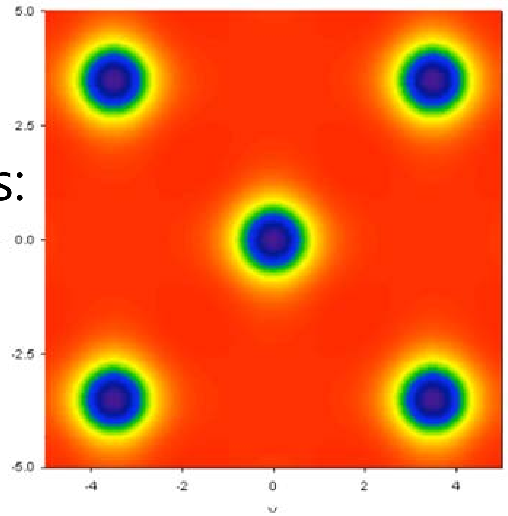
We are totally ignorant beyond nuclear matter density!

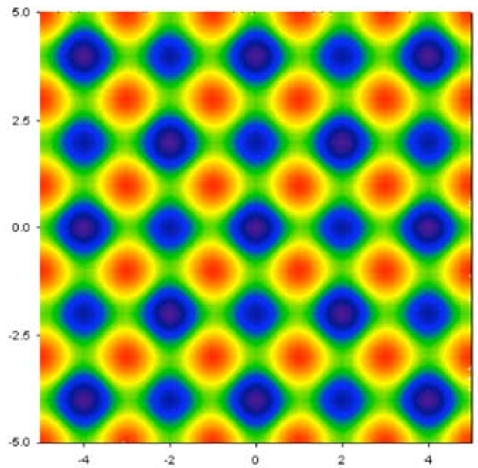
No reliable theoretical tools are forthcoming, need experiments.

What could happen

B.Y. Park et al 1999

Skyrmions: FCC

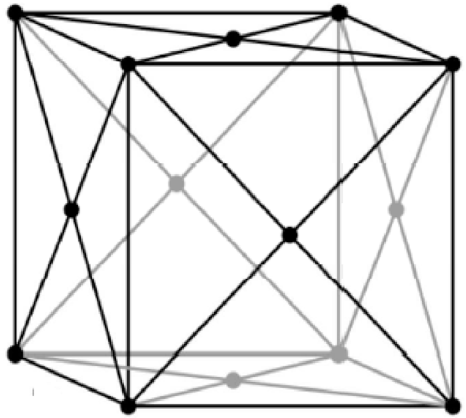


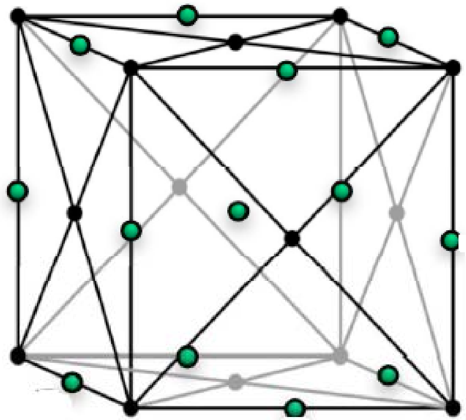


½ skyrmions: CC

Increasing density

Instantons: FCC





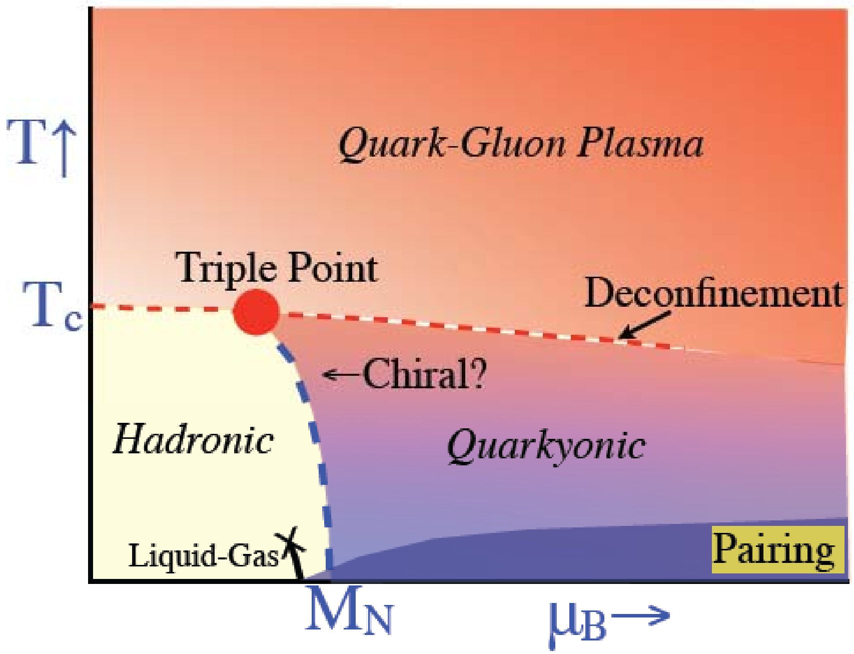
½ instantons (dyons): BCC

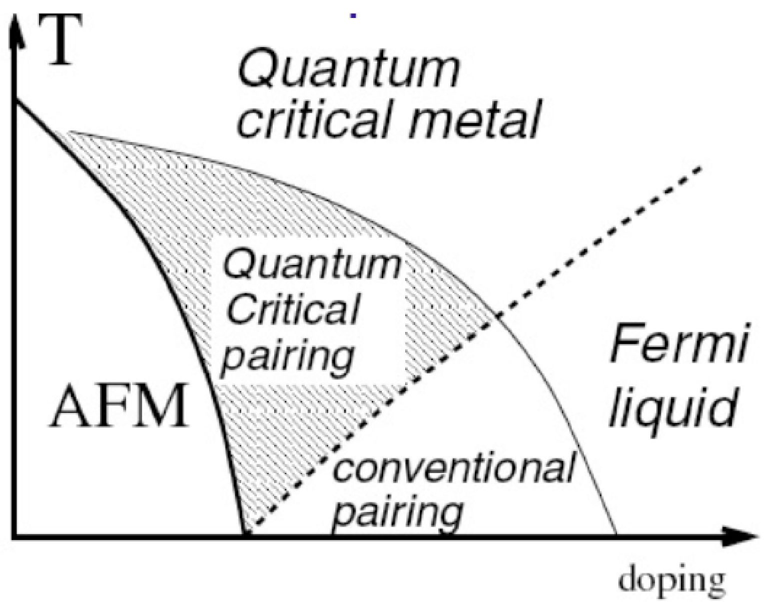
Sin, Zahed, R. 2009

And not least

there are tantalizing analogies to highly correlated condensed matter systems. Are they real?

Hadronic Matter and Condensed Matter





Questions

- **Where does the hadron mass come from?**

- **What do hadrons look like inside nuclei?**

- **Can one “undress” hadrons to the core?**

Hadrons mass

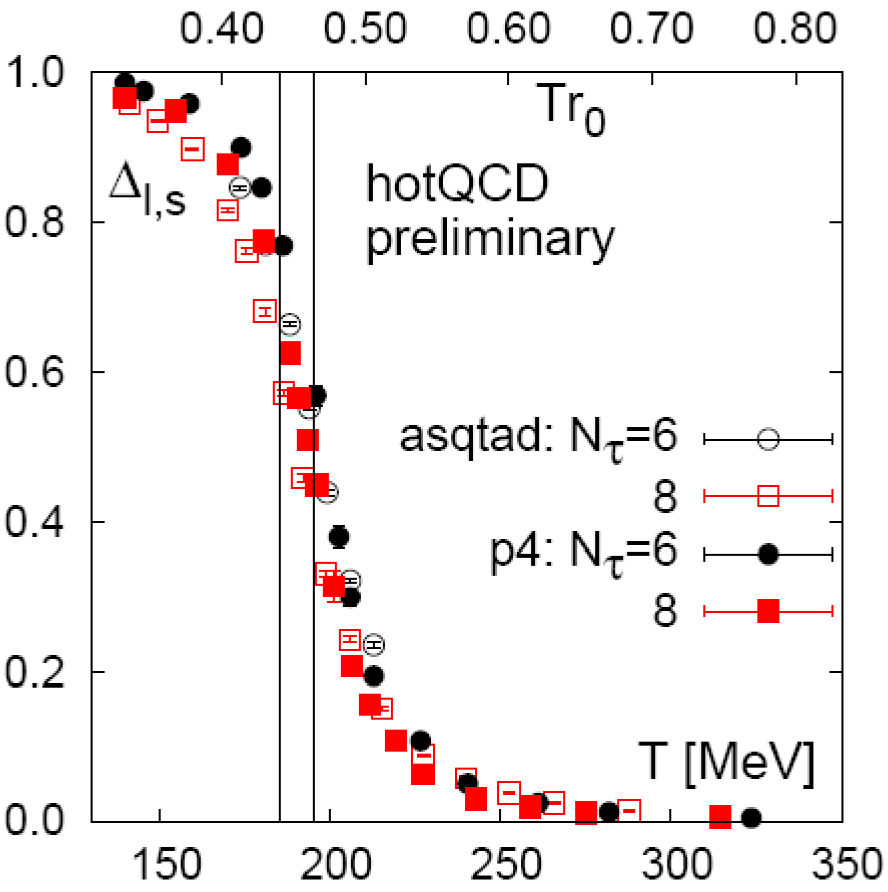
$\Updownarrow$?

Quark condensate

$\Updownarrow$

Chiral symmetry

Quark condensate (in T)



$$D_{\ell,s}(T) = \langle\bar{\psi}\psi\rangle|_\ell - \frac{m_\ell}{m_s}\langle\psi\psi\rangle|_s$$

$$\Delta_{\ell,s}(T) = D_{\ell,s}(T)/D_{\ell,s}(T=0)$$

The condensate "melts" (goes to zero) as temperature goes up, i.e., chiral symmetry gets restored.

What does this do hadrons??

DeTar 2008

Hadron mass

Trace anomaly of QCD

$$\theta^{\nu}_{\nu}\Big|_{QCD} = \frac{\beta(g)}{2g} G^{a}_{\mu\nu} G^{a\mu\nu} + (1+\gamma) m_q \bar{q} q$$

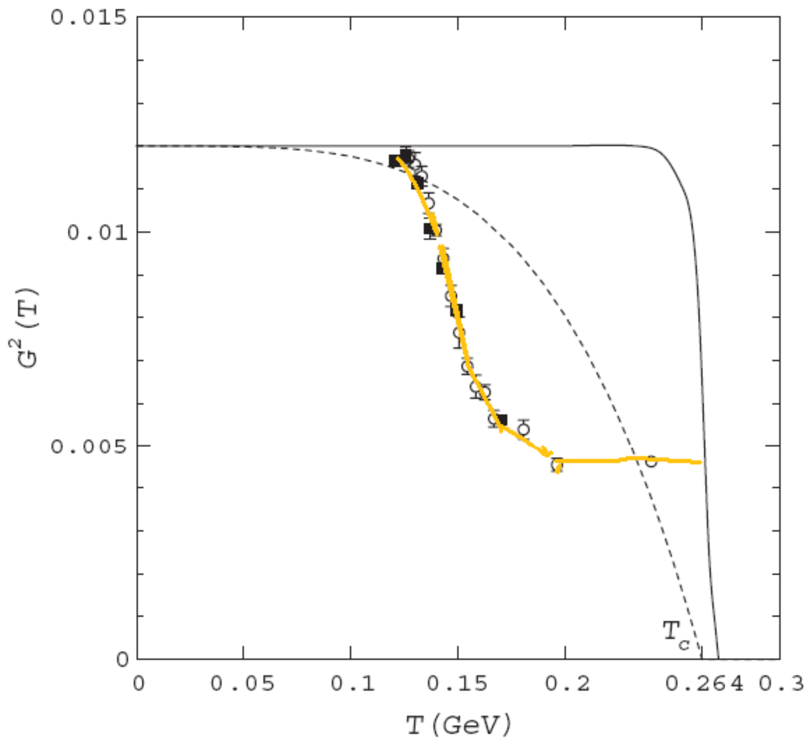
Ignore for $m_q \rightarrow 0$

Mass of hadron "h"

$$M_h \sim (1/4)(\langle h|\theta_{\mu}{}^{\mu}|h\rangle - \langle 0|\theta_{\mu}{}^{\mu}|0\rangle)$$

So the scaling of "h" mass is related to the scaling of the gluon condensate in the presence of quarks

Lattice with dynamical quarks



D.E. Miller 2006

Two-dilaton picture

H.K. Lee and MR 2009

"soft" "hard"

$$\langle G^2 \rangle = \langle G_s^2 \rangle + \langle G_h^2 \rangle$$
$$\sim \langle \chi_s^4 \rangle + \langle \chi_h^4 \rangle \quad \text{"dilaton"}$$

At chiral restoration $\langle \chi_s \rangle \to 0$
But $\langle \chi_h \rangle \neq 0$, as QCD coupling "*g*" remains non-zero

Note

At chiral restoration, $\langle \bar{\psi}\psi \rangle \to 0$
so the dilaton condensate *and* chiral condensate are related.

Mass scaling

In two-dilaton picture

"Brown-Rho scaling": Hadron masses scale with $<\chi_s>$ or equivalently with $\langle\bar{\psi}\psi\rangle$, so the scaling signals chiral symmetry/"soft" scale symmetry restoration.

Widely misquoted and
Misunderstood relation !!!

How to "see" the scaling?

This is a very subtle issue!!

Present Status: Temperature

(Define  $\equiv$ strictly personal **"% trustfulness"**)

Theory:

- There are no lattice data or other model-independent predictions for light-quark hadrons (i.e., N, N*, ρ, ω, ...)
- Hidden local symmetry theory with the assumption that *quasiparticle description makes sense*:

Predicts $m_V(T)/\ m_V(0) \approx \langle\bar{\psi}\psi\rangle(T)\ /\ \langle\bar{\psi}\psi\rangle(0)$

~70% very near T_c

Caveat: hadrons are not *quasiparticles* at high T (and n)?

Experiments: Dilepton "fiasco"

- CERES etc.: No conclusion
- NA60: Experiment: > 90%(?)

  Conclusion "BR scaling is ruled out": ~ 0%

Dileptons are "blind" to BR scaling both in T (and density)

Brown, Holt, Harada, Rho and Sasaki 2009

~ 50%

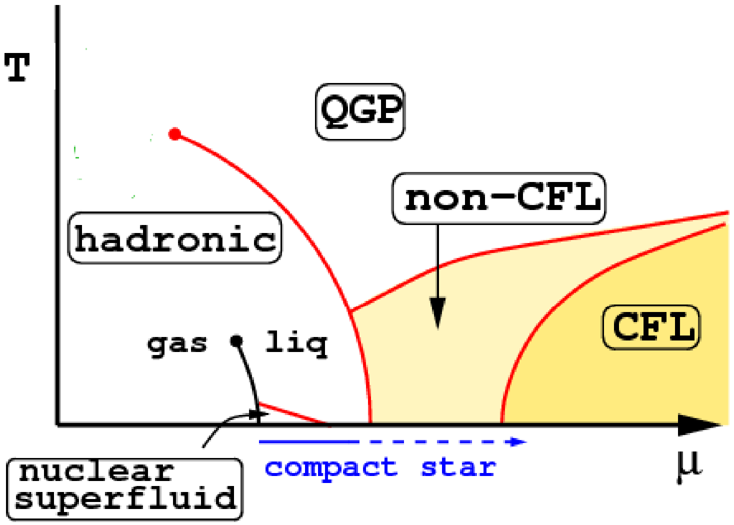
What's seen? Just on-shell vector mesons in nuclei !

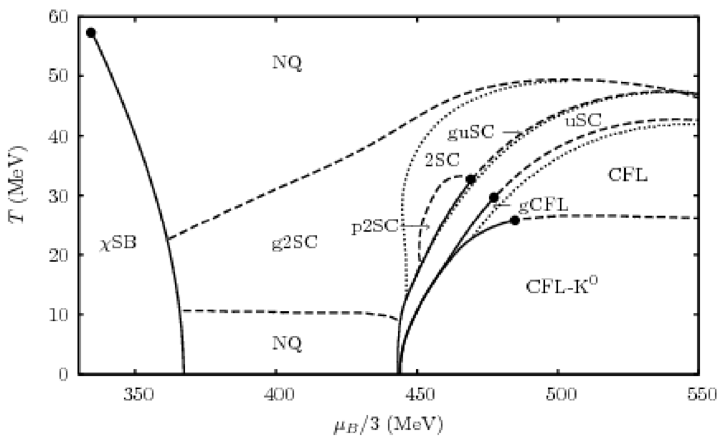
Dense Matter

It's dreadful!

Theorists have been busy with models
with limited reliability and no experiments.

 ~ 0%





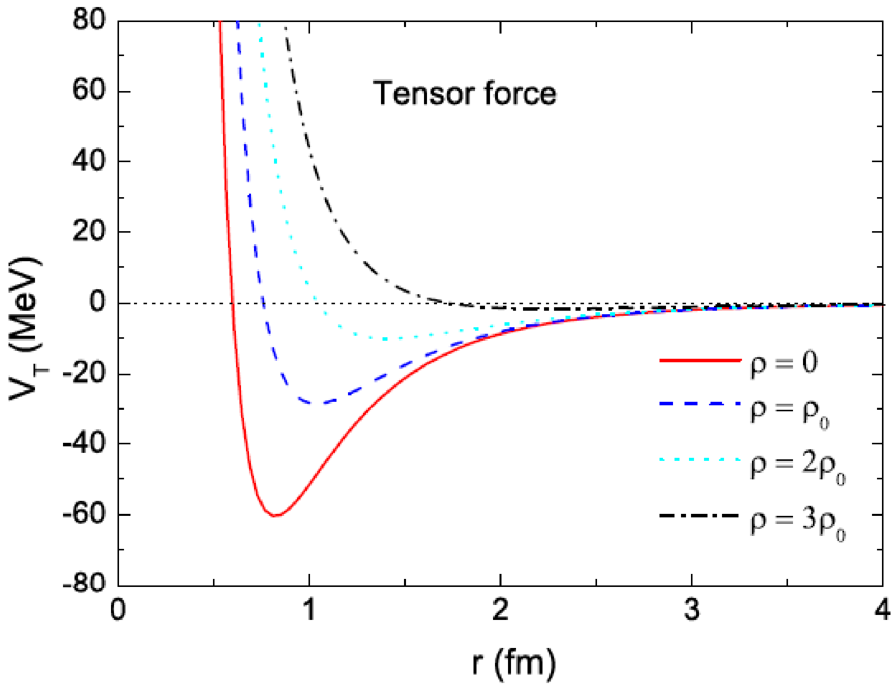
Things we are sure of

BR scaling reduces tensor forces

G.E. Brown & MR 1990

$$V_\rho^T(r) = \frac{f_{N\rho}^2}{4\pi} m_\rho \tau_1 \tau_2 \left(-S_{12} \left[\frac{1}{(m_\rho r)^3} + \frac{1}{(m_\rho r)^2} + \frac{1}{3 m_\rho r} \right] e^{-m_\rho r} \right),$$

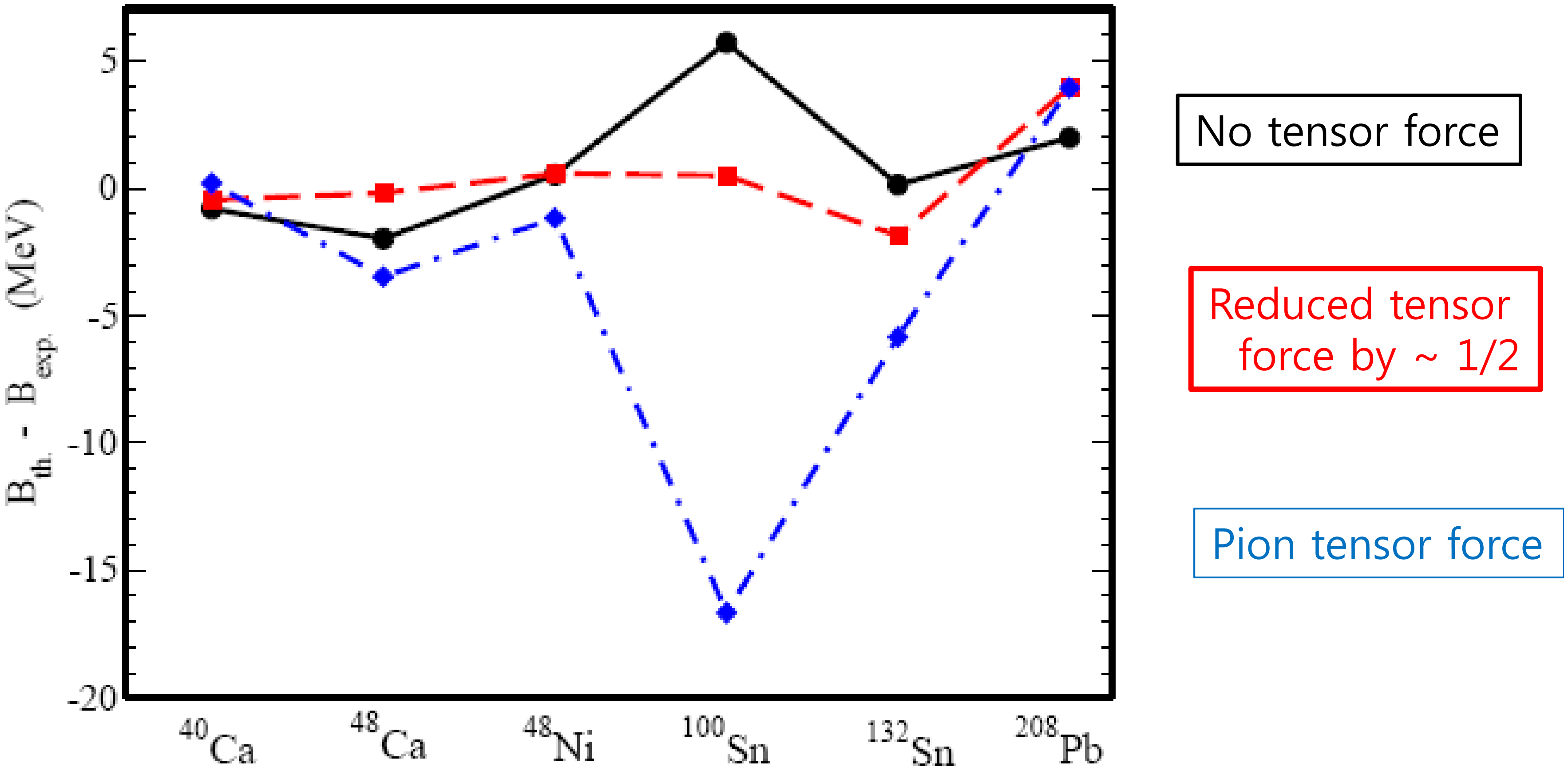
$$V_\pi^T(r) = \frac{f_{N\pi}^2}{4\pi} m_\pi \tau_1 \tau_2 \left(S_{12} \left[\frac{1}{(m_\pi r)^3} + \frac{1}{(m_\pi r)^2} + \frac{1}{3 m_\pi r} \right] e^{-m_\pi r} \right).$$



At n ~ $3n_0$, attraction disappears

Tensor forces and nuclear BE

Lalazissis et al arXiV:0909.2364

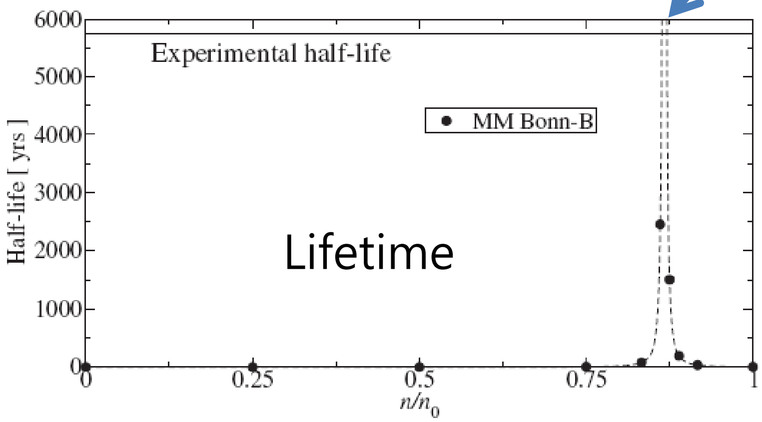


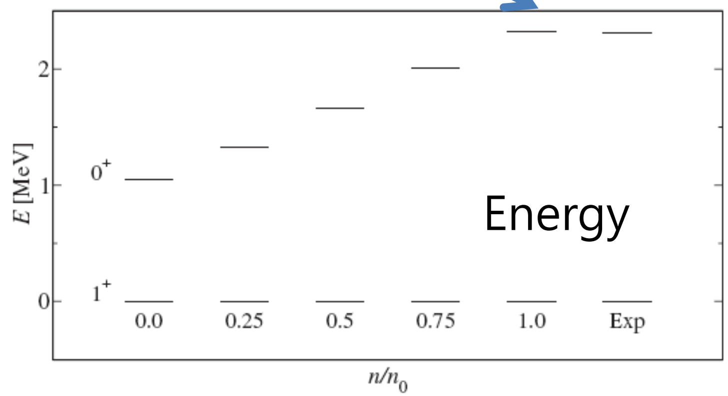
^{14}C dating & BR scaling

Holt et al 2008

- Carbon 14 has a long life-time $\tau = 5730$ yrs ~ $1/|M_{GT}|^2$
- M_{GT} is controlled by the tensor forces given by the π and ρ exchanges
- In medium the properties of the mesons are affected by density, e.g., by BR scaling; increased ρ tensor suppresses the GT matrix element.

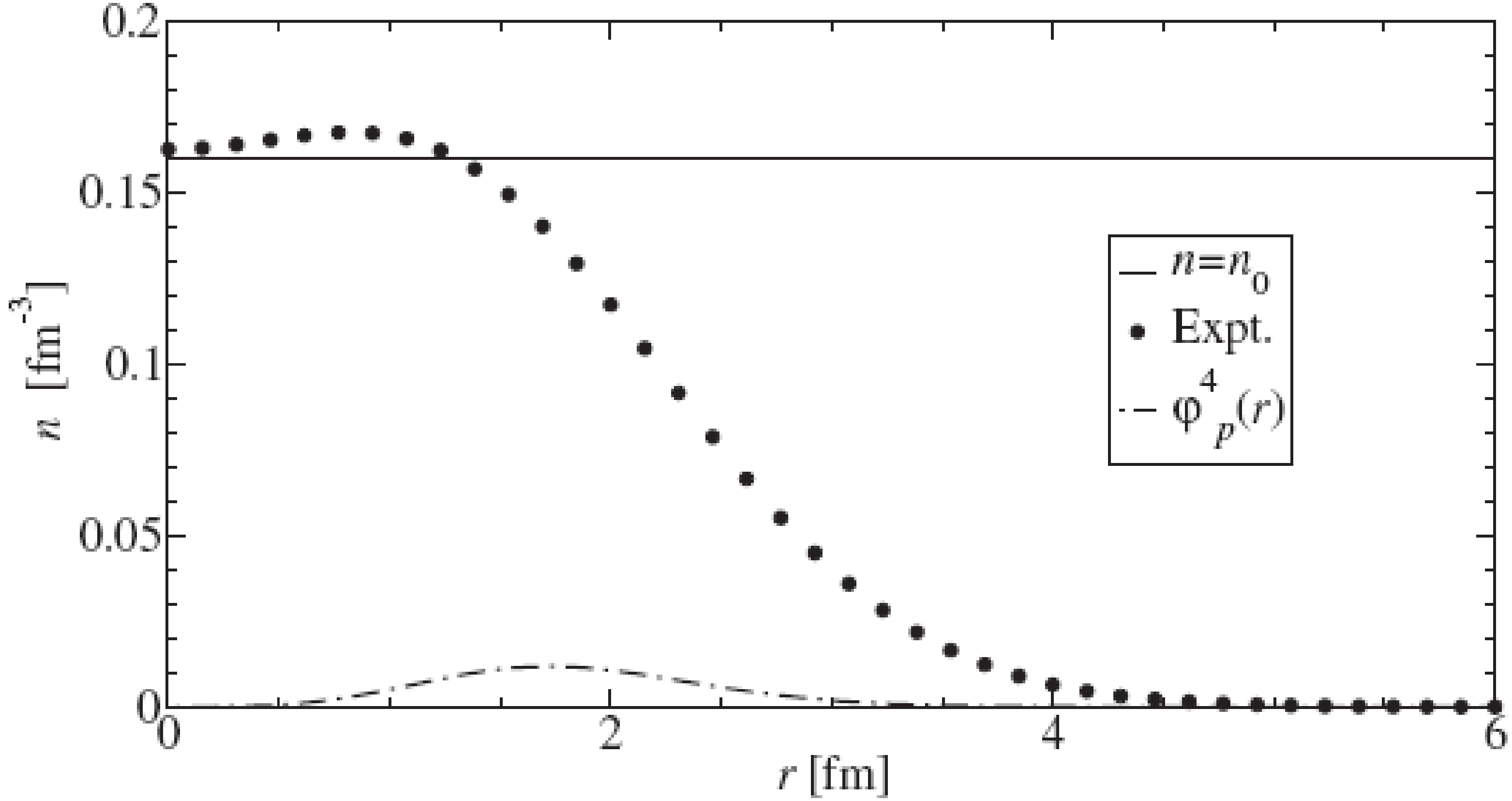
With $\Phi(n_0) \equiv m_\rho(n_0)/m_\rho(0) \approx 0.85$





Probing nuclear matter in ^{14}C

Holt et al 2008

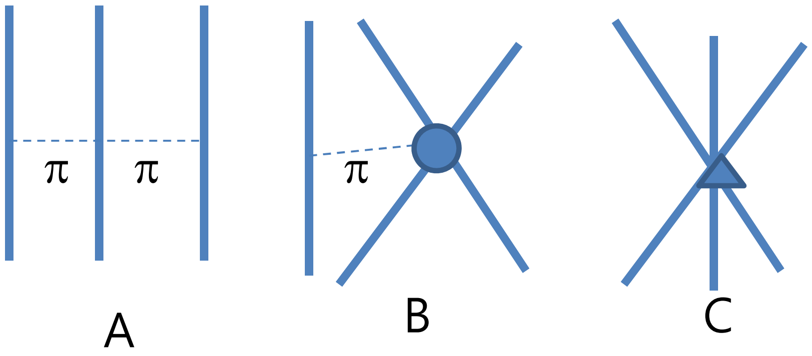


Wave function

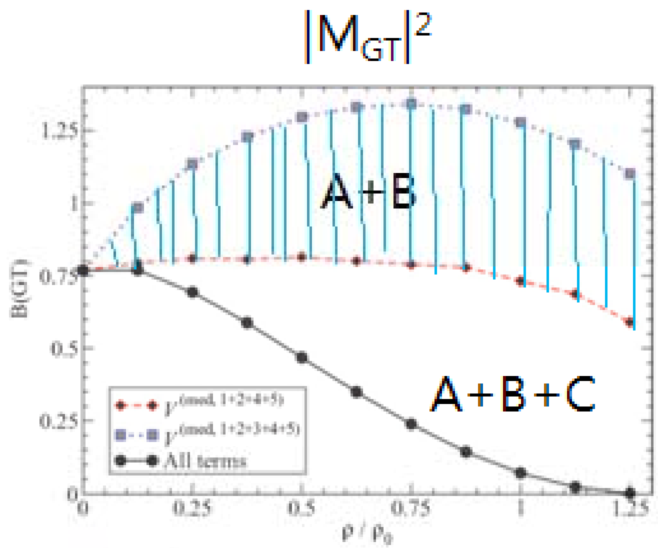
Carbon 14 with 3-body (or many-body) forces

Holt, Kaiser, Weise 2009

- No BR scaling but add many-body



Ignore 4-body



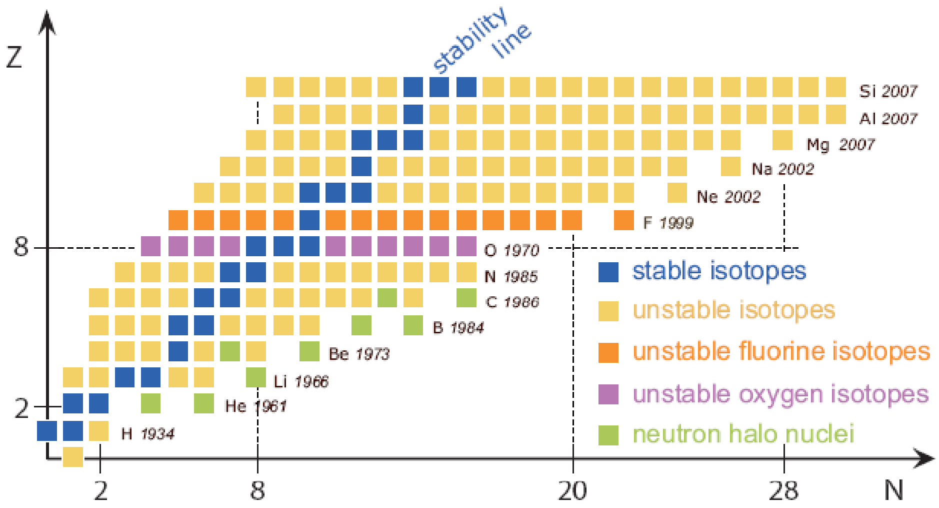
BR scaling ↔ Many-body forces

Chiral Symmetry !!

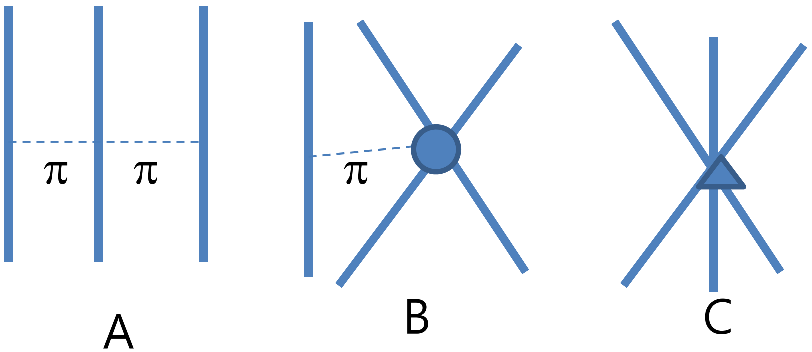
Oxygen drip line

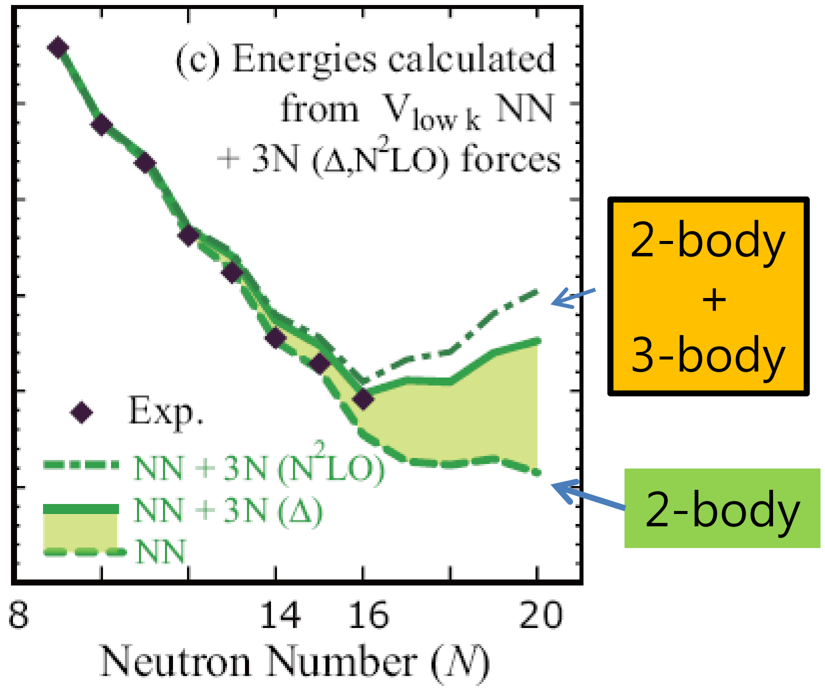
Oxygen neutron drip line is ALSO explained by the same 3-body (n-body) forces

Otsuka, Suzuki, Holt, Schwenk, Akaishi 2009

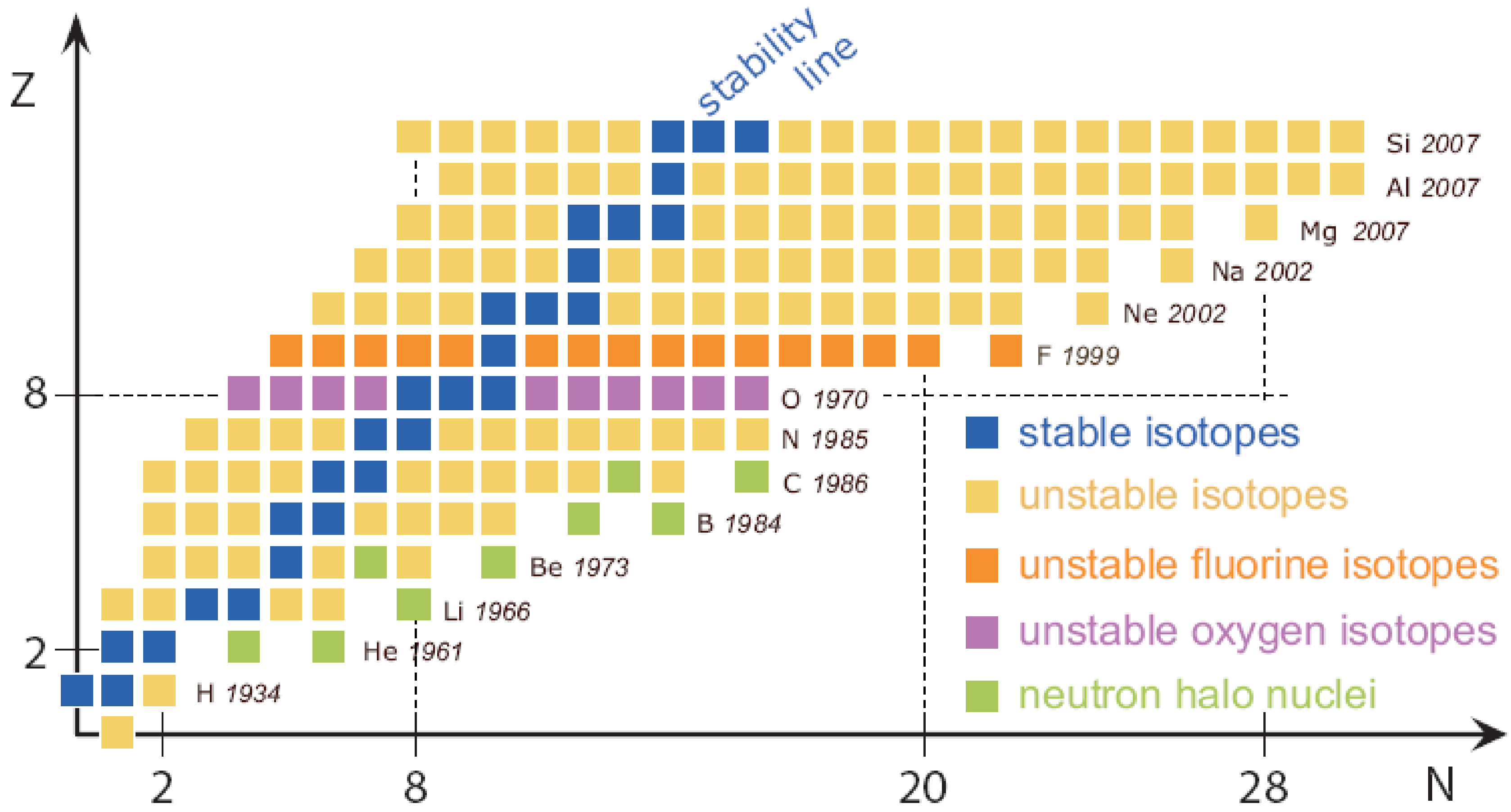


KoRIA?



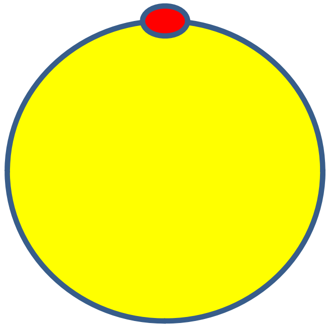


Nuclear isotopes



Also quasiparticles in heavy nuclei

Probe the proton on top of Fermi sea



$\mathbf{J} = g_\ell (\mathbf{k}/m_N) \qquad |\mathbf{k}| = k_F$

g_ℓ =orbital gyromagnetic ratio

$\equiv 1 + \delta g_\ell$

$\delta g_\ell^{exp} = 0.23 \pm 0.03$ from Pb208

Landau-Migdal Fermi liquid theory

$\delta g_\ell^{th} = (4/9)(1/\Phi - 1 + \text{pion term})$

≈ 0.22 with $\Phi(n_0) \approx 0.8$

B. Friman & MR 96

"Backflow" in many-body

Bottom line
(to theorists)

Walecka mean field theory is just Landau-Migdal
Fermi liquid theory, first shown by T. Matsui in 1981.

BR conjecture

Hidden local symmetry theory in the presence of baryons
(as skyrmions) in the mean field (which gives BR scaling)
is Kohn-Sham density functional theory which at nuclear
saturation point is at the Landau Fermi liquid fixed point.

Needs to be proven rigorously

How It Works

Illustration with a recent analysis:
Lalazissis et al, arXiV:0909.1432

9 parameters, 5 from Particle Data Table, 4 fit globally

$$
\begin{aligned}
\mathcal{L} \;=\; & \bar{\psi}\left(\gamma(i\partial - g_\omega\omega - g_\rho\vec{\rho}\vec{\tau} - eA) - m - g_\sigma\sigma\right)\psi \\
& + \frac{1}{2}(\partial\sigma)^2 - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega^2 \\
& - \frac{1}{4}\vec{R}_{\mu\nu}\vec{R}^{\mu\nu} + \frac{1}{2}m_\rho^2\vec{\rho}^{\,2} - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{3}g_2\sigma^3 + \frac{1}{4}g_3\sigma^4
\end{aligned}
$$

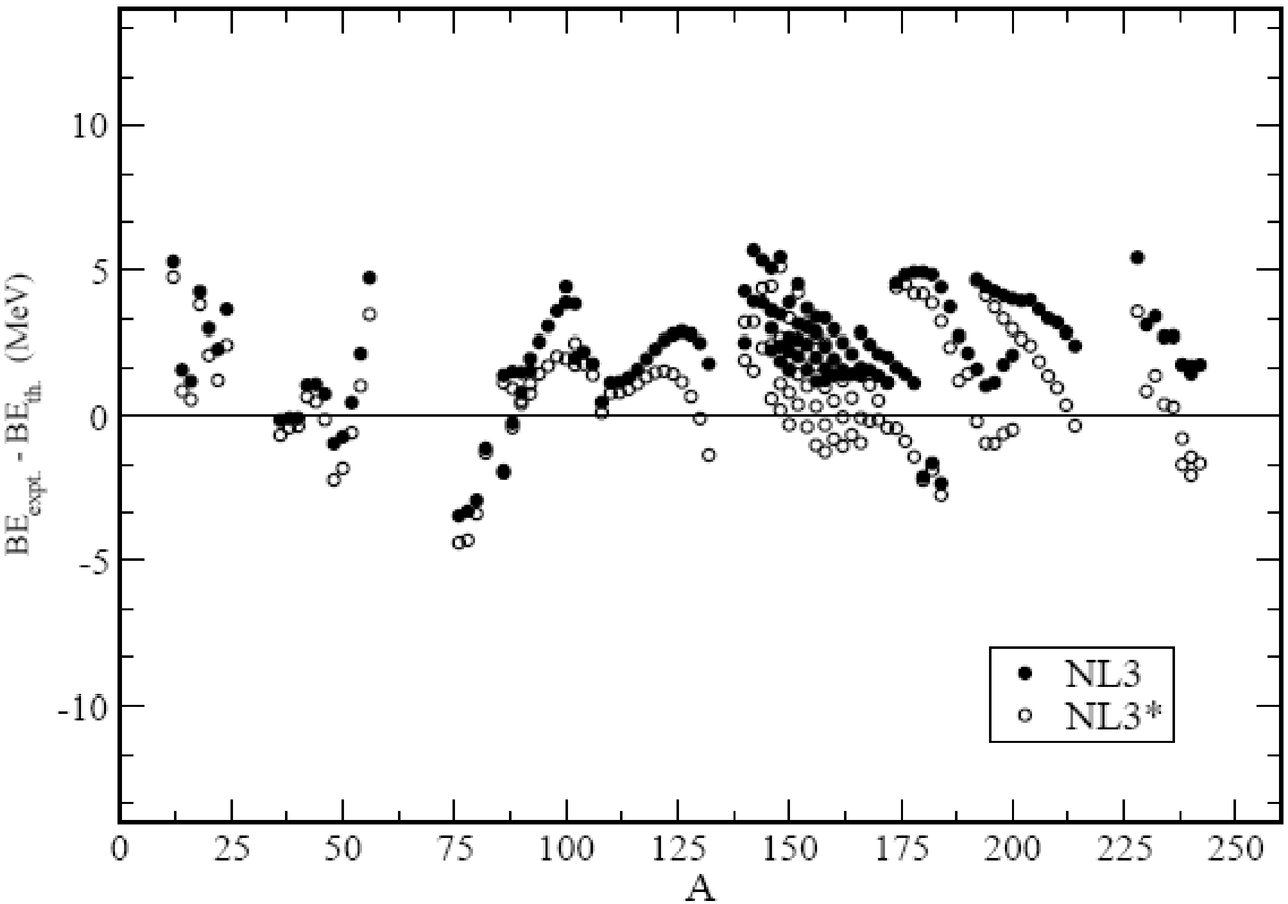
Nuclear matter properties		
ρ_0	$= 0.150$	(0.148) fm^{-3}
$(E/A)_\infty$	$= 16.31$	(16.30) MeV
K	$= 258.28$	(271.76) MeV
J	$= 38.6$	(37.4) MeV
m^*/m	$= 0.594$	(0.60)

Binding Energies

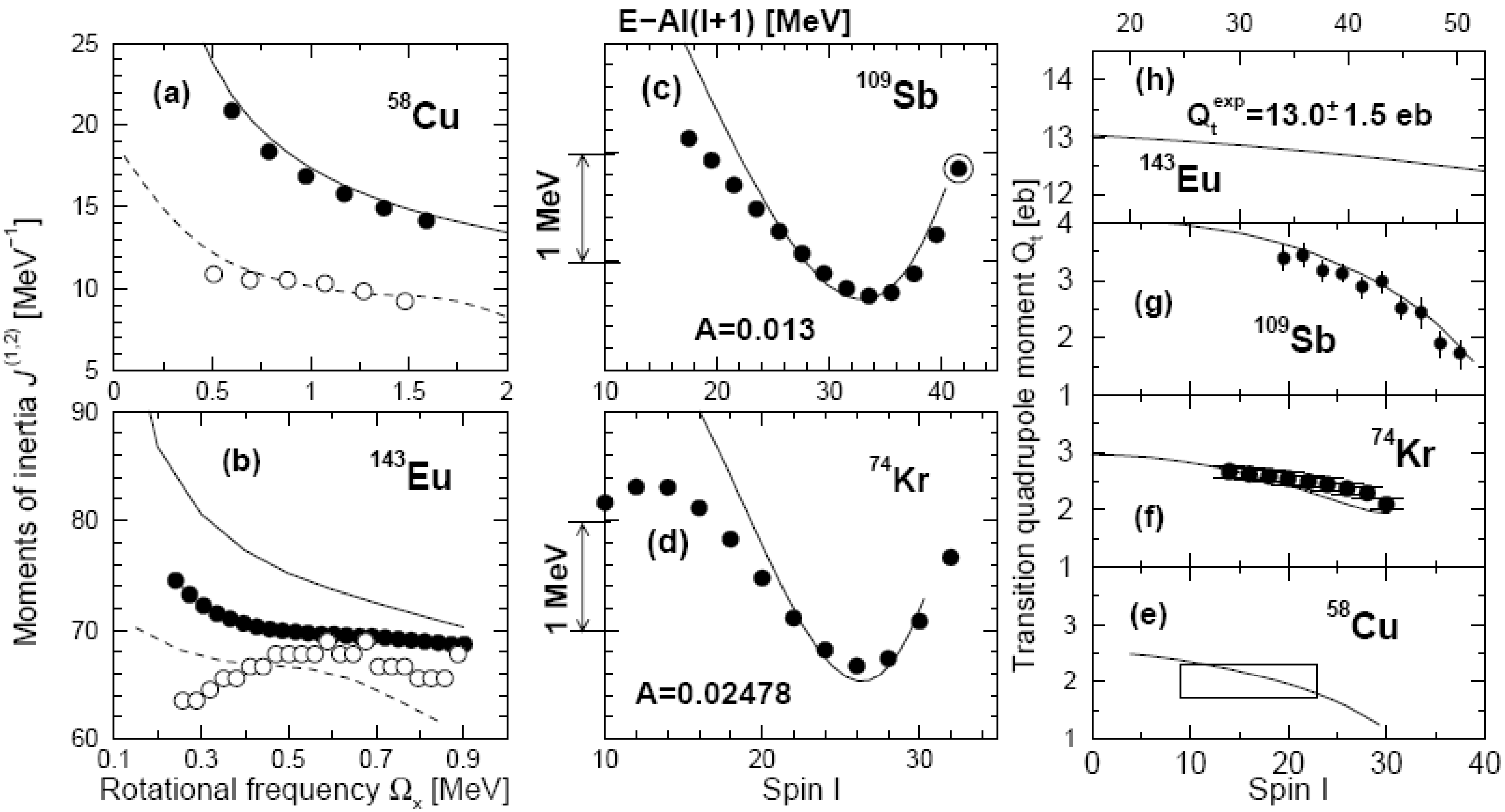
	B.E.(MeV)	r_c (fm)	r_n-r_p(fm)
^{16}O	-128.112(-127.619)	2.735(2.730)	-0.15
^{40}Ca	-341.578(-342.052)	3.470(3.485)	-0.14
^{48}Ca	-413.615(-415.990)	3.470(3.484)	0.14
^{72}Ni	-612.168(-613.152)	3.892	0.26
^{90}Zr	-782.368(-783.891)	4.263(4.272)	0.04 (0.07)
^{116}Sn	-986.512(-988.680)	4.604(4.626)	0.10 (0.12)
^{124}Sn	-1048.324(-1049.962)	4.655(4.674)	0.22 (0.19)
^{132}Sn	-1101.550(-1102.850)	4.636	0.29
^{204}Pb	-1608.100(-1607.505)	5.432(5.486)	0.19
^{208}Pb	-1638.230(-1636.430)	5.508(5.505)	0.23 (0.20)
^{214}Pb	-1660.119(-1663.290)	5.566(5.562)	0.26
^{210}Po	-1649.024(-1645.210)	5.544	0.20

Theory (Experiment)

Absolute deviations of BE from experiments



Rotational states

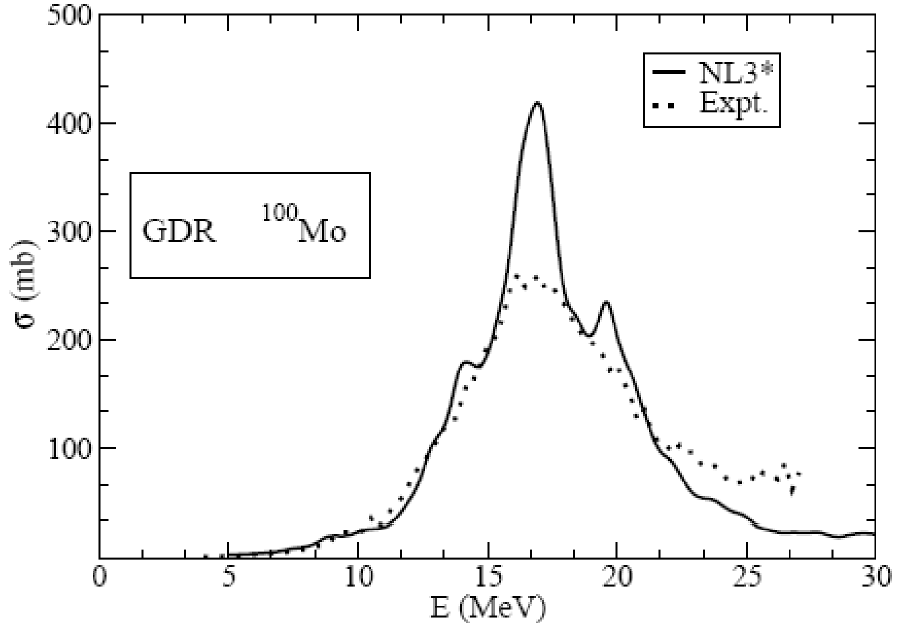


Giant resonances

GMR=giant monopole
GDR=giant dipole

^{208}Pb

	Exp.	NL3	NL3*
GMR	14.1 ± 0.3	14.04	13.90
GDR	13.3 ± 0.1	12.95	12.95



Up to nuclear matter density

We are certain we know

Carbon-14 dating, neutron drip lines, Landau quasiparticle picture etc etc all indicate:

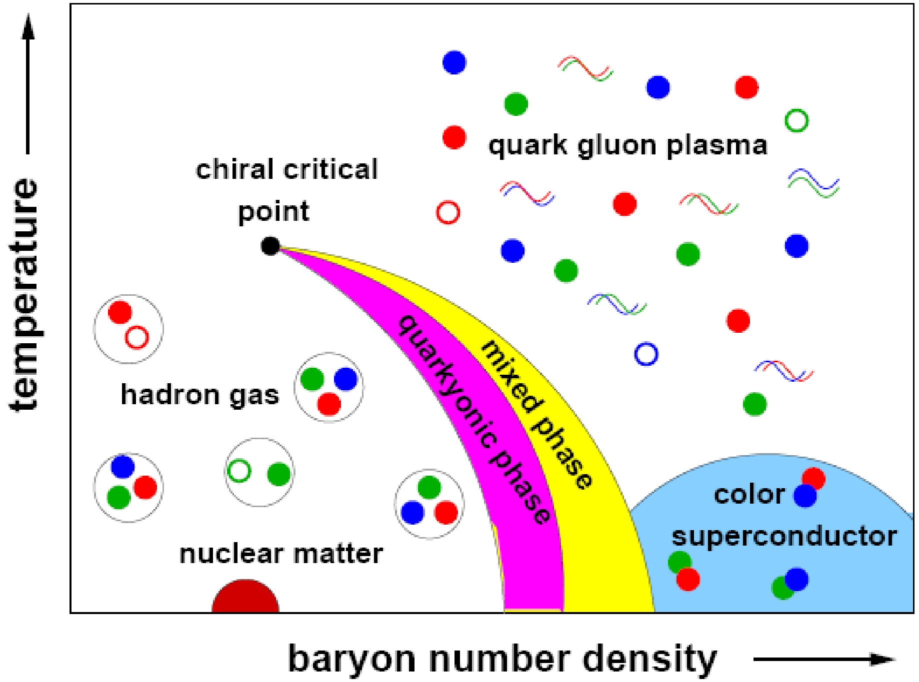
BR scaling ↔ Many-body forces
↔ Many-body interactions

All subsumed in chiral symmetry up to ~ n_0 !!

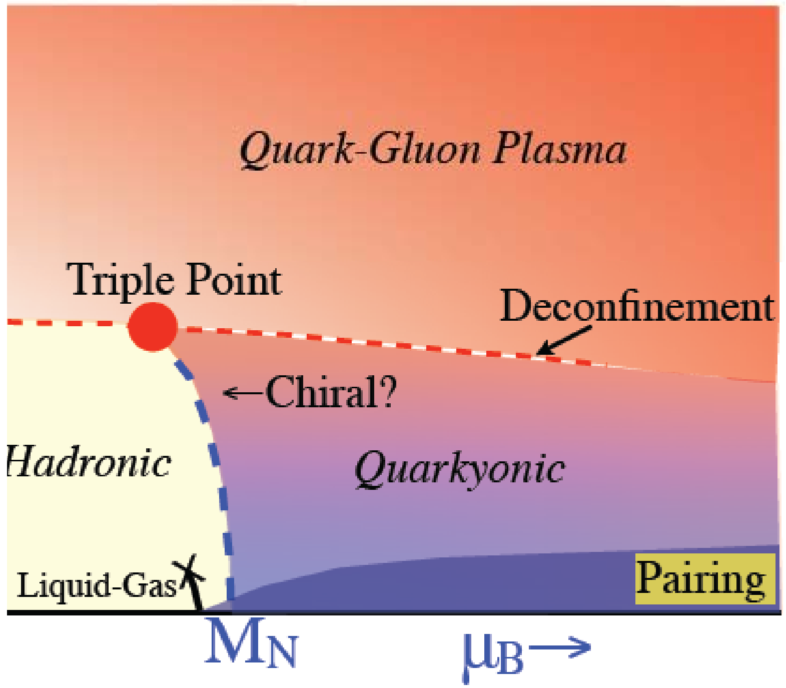
So how does one isolate smoking-gun signal(s) for chiral restoration????

Beyond n_0 it's a wilderness!!

Guessing game



Karsch



McLerran

Both could be totally wrong!!

Glaringly missing in most of the popular phase diagrams in the market is (to me) the most plausible scenario (BLR), that is,

Brown-Lee-Rho

Kaon condensation
in compact stars

"If Nature chooses this scenario, it will render *moot all other scenarios."*

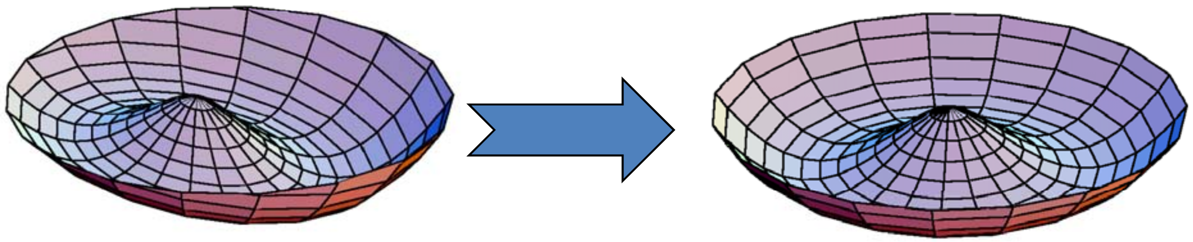
G.E. Brown

Open problem: Falsify it!

Strange Goings-On

m_π ~ 0, m_K ~ 1/2 GeV

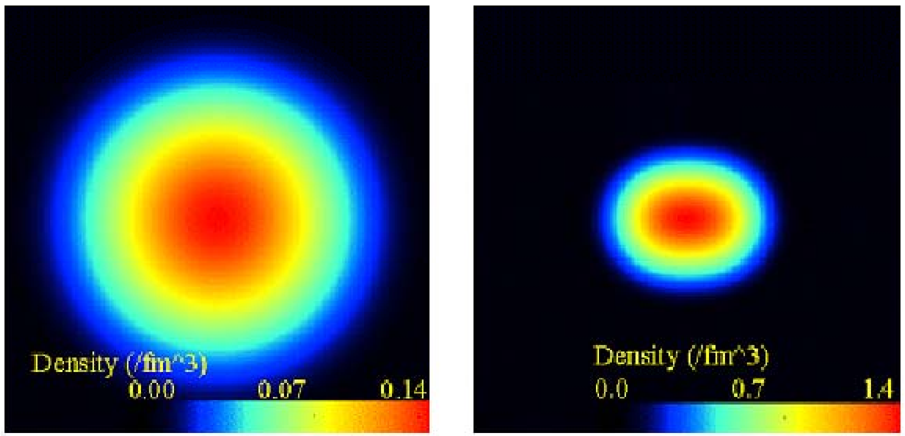
Dropping mass "restores" *SU(3) symmetry* and produces attraction



Attractive potential $\mathbf{P_K}$

$m_K^* = m_K + \mathbf{P_K}\,(n)$

$\mathbf{P_K}\,(n=n_0) \approx -\,200$ MeV



(a) ^{3}He

(b) ^{3}HeK$^-$

T. Yamazaki & coll.

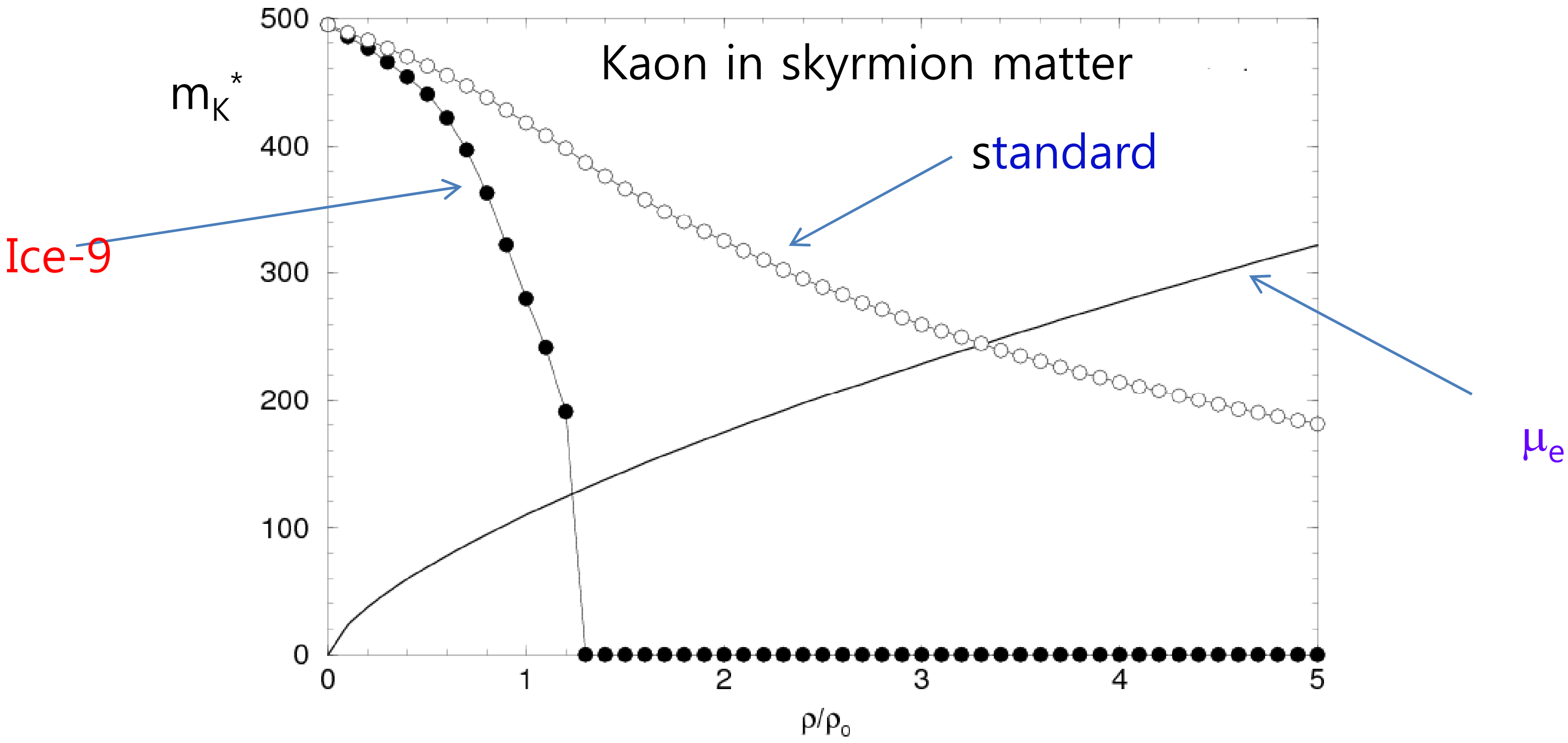
n ~ n_0

n ~ 9n

Not yet confirmed

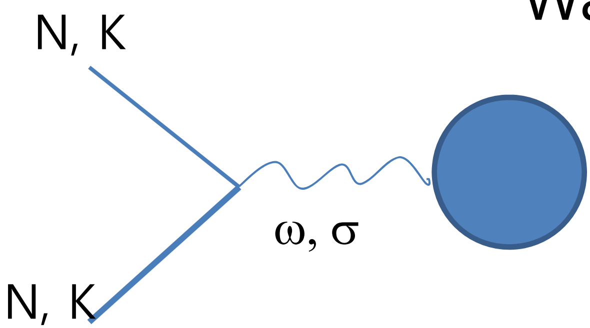
Ice-9 Phenomenon

Kurt Vonnegut's "Cat's Cradle"



m_K^* *drops* in nuclear matter

Walecka model



Background n

N = (qqq)
K = (s anti-q)

- In nuclear matter, $V_N\ (n_0) \approx -\ S_N\ (n) \approx 300$ MeV
  so $P_N\ (n_0) = V_N\ (n_0)\ +\ S_N\ (n) \approx 0$

- In kaonic matter, $V_K\ (n_0) \approx S_K\ (n) \approx -100$ MeV
  so $P_K\ (n_0) = V_K\ (n_0)\ +\ S_K\ (n) \approx -200$ MeV

~ Agrees with Yamazaki

$\mu_e \nearrow$ in neutron-star matter

As density n increases, more electrons populate the stars, so μ_e tends to go up. How this happens depends sensitively on all aspects of *nuclear interactions*, among which the symmetry energy E_S -- which reflects deviation from charge symmetry -- plays an important role.

$$E_S = E(0) + c\,(1-2x)^2 + \ldots$$

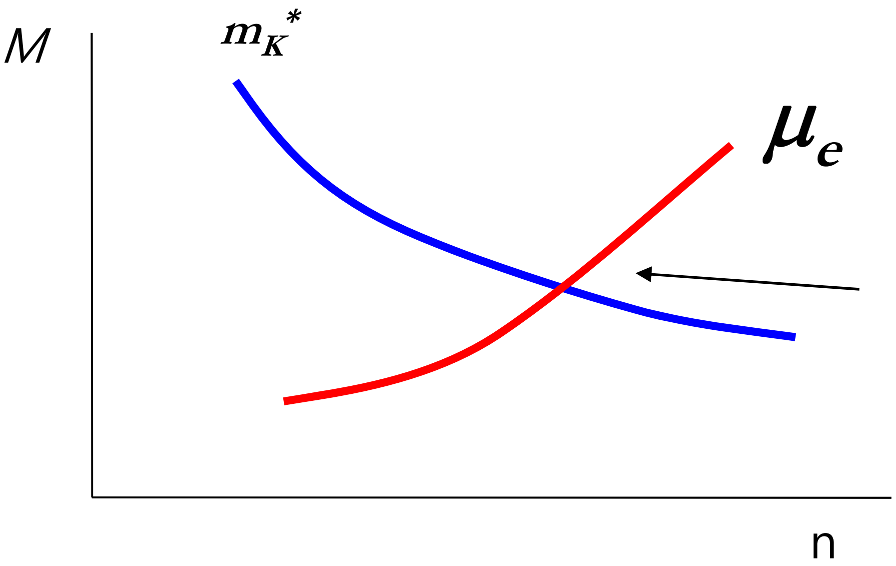
$x = N/(P+N)$

Note: The same *symmetry energy E_S* figures in the neutron drip line.

But unknown beyond n_0 !!

Kaons condense in compact stars

Chang-Hwan Lee's thesis

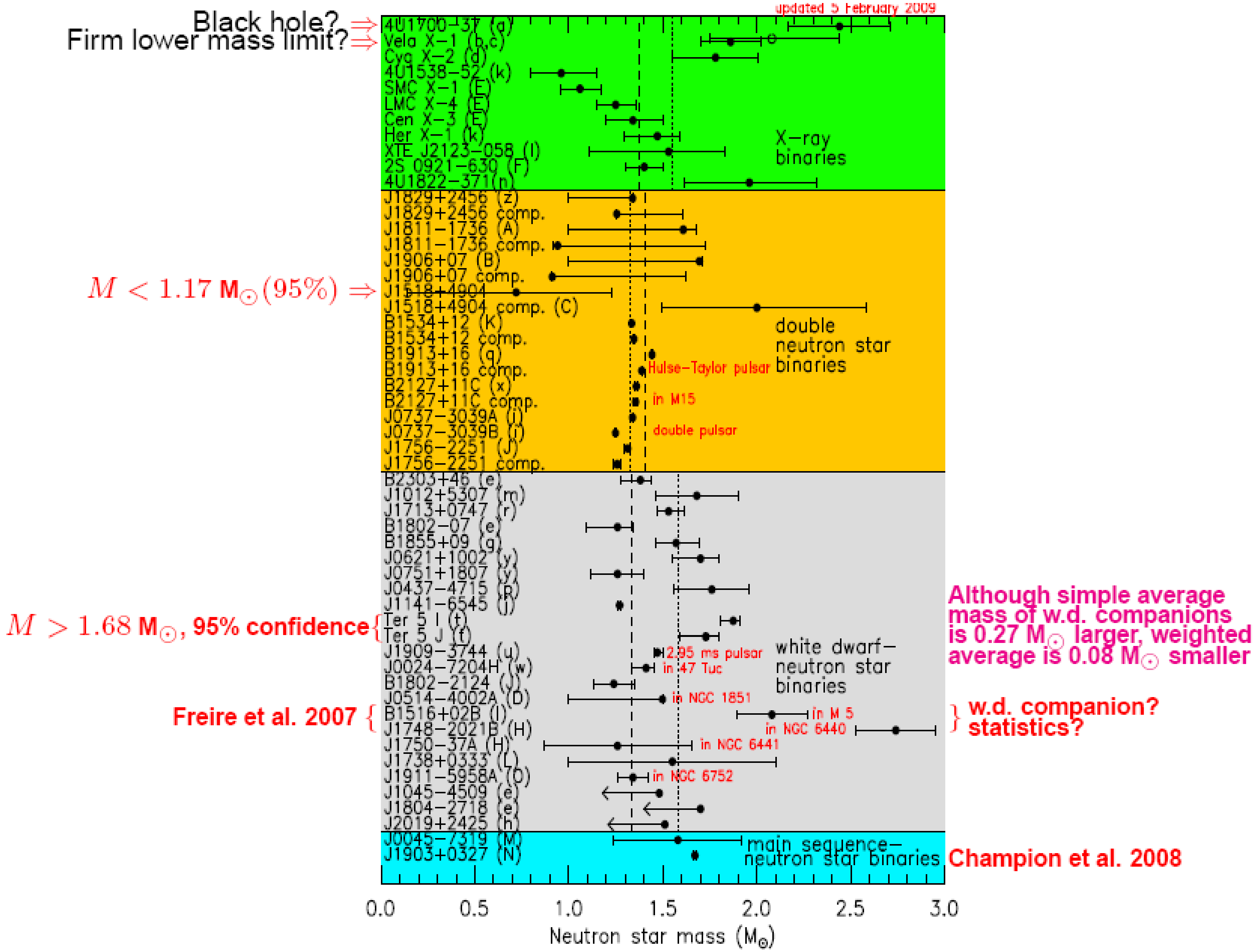


$$e^- \rightarrow K^- + \nu$$

$$n_c^K \approx 3n_0 < n_{<\bar{q}q>\rightarrow 0}$$

Kaons bose-condense, softening the EOS and can trigger star collapse. This can happen before any other phase transitions, e.g., color SC, can take place

February 3, 2009



Observations

- Well-measured neutron stars (binary pulsars) have masses $M \approx 1.4 - 1.5\ M_\odot$
- Hulse-Taylor pulsar has the mass $M=1.4408 \pm 0.0003\ M_\odot$ which sets a lower bound for black-hole formation.
- Black holes formed at a (much) lower mass would be inconsistent with carbon abundances in the Universe.

Black holes must, if any, be formed at $M \geq 1.45\ M_\odot$?

Kaon Condensation, Black Holes, and Cosmological Natural Selection

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It is argued that a well-measured double neutron-star binary in which the two neutron stars are more than 4% different from each other in mass or a massive neutron star with mass $M \gtrsim 2M_\odot$ would put in serious doubt or simply falsify the following chain of predictions: (1) a nearly vanishing vector meson mass at chiral restoration, (2) kaon condensation at a density $n \sim 3n_0$, (3) the Brown-Bethe maximum neutron-star mass $M_{max} \approx 1.5M_\odot$, and (4) Smolin's "cosmological natural selection" hypothesis.

DOI: 10.1103/PhysRevLett.101.091101 PACS numbers: 97.60.Jd, 97.60.Lf, 98.80.Bp, 98.80.Qc

Maximizing Number of BHs

Bethe-Brown conjecture:
With kaon condensation at $\sim 3n_0$, the minimum (maximum) mass of a black hole (neutron star) is

$$M_{min}^{BH} \sim 1.5 M_{\odot} \equiv M_{BB} .$$

- The minimum mass of BH cannot be lower than the Hulse-Taylor mass $M_{HT} = 1.4408 \pm 0.0003\ M_{\odot}$ since the latter is "seen."
- Furthermore it cannot be lower because of the carbon abundances required. So $M_{min}^{BH} > M_{HT}$
- With BR scaling, 3-body forces are damped at $n > \sim n_0$, so ineffective in preventing kaon condensation. This implies that M_{min}^{BH} cannot be much greater than M_{BB}

Kaons in dense matter

"BH maximiztion hypothesis"

The Cosmos: Black Holes

- Maximization of black holes≈ maximization of the entropy.

$$S_H = \frac{k_B}{4} \frac{\text{surface area of horizon}}{(\text{Planck length})^2} = 1.05 \times 10^{77} k_B \left(\frac{M}{M_\odot}\right)^2.$$

A star of solar mass has ~ 10^{57} nucleons with entropy ~ 1 per nucleon.

So when Fe goes into black holes, the entropy is increased by a factor of 10^{20} per particle.

Fundamental law of nature is that a system moves toward equilibrium so as to maximize the entropy. Thus the maximization of the number of black holes.

The Cosmos: Multiverse

Lee Smolin, *The Life of the Cosmos*

The Problem of ~ 10^{100} Universes

- "Cosmological natural selection (CNS)"

  "A bouncing black hole singularity leads to a new expanding region of space time, i.e., a universe, behind the horizon of every black hole."

  Maximization of black holes ⇔ *CNS.*

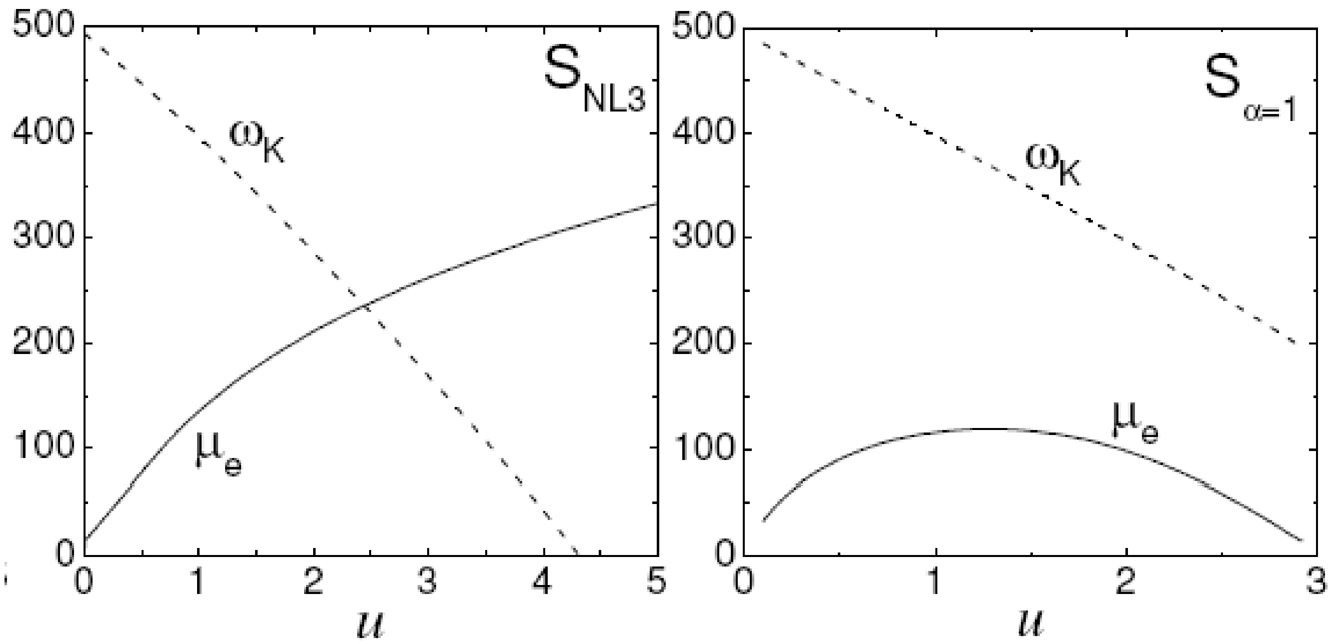
  This scenario offers an alternative to the anthropic principle with eternal inflation – that the universe is eternally inflating, endlessly spawning "pocket universes" (a la string theory).

Highly Controversial!!

Beware: A torpedo?

This Bethe-Brown-Lee-Rho-Smolin (BBLRS) scenario will be falsified by the symmetry energy suggested by FOPI π^-/π^+ ratio

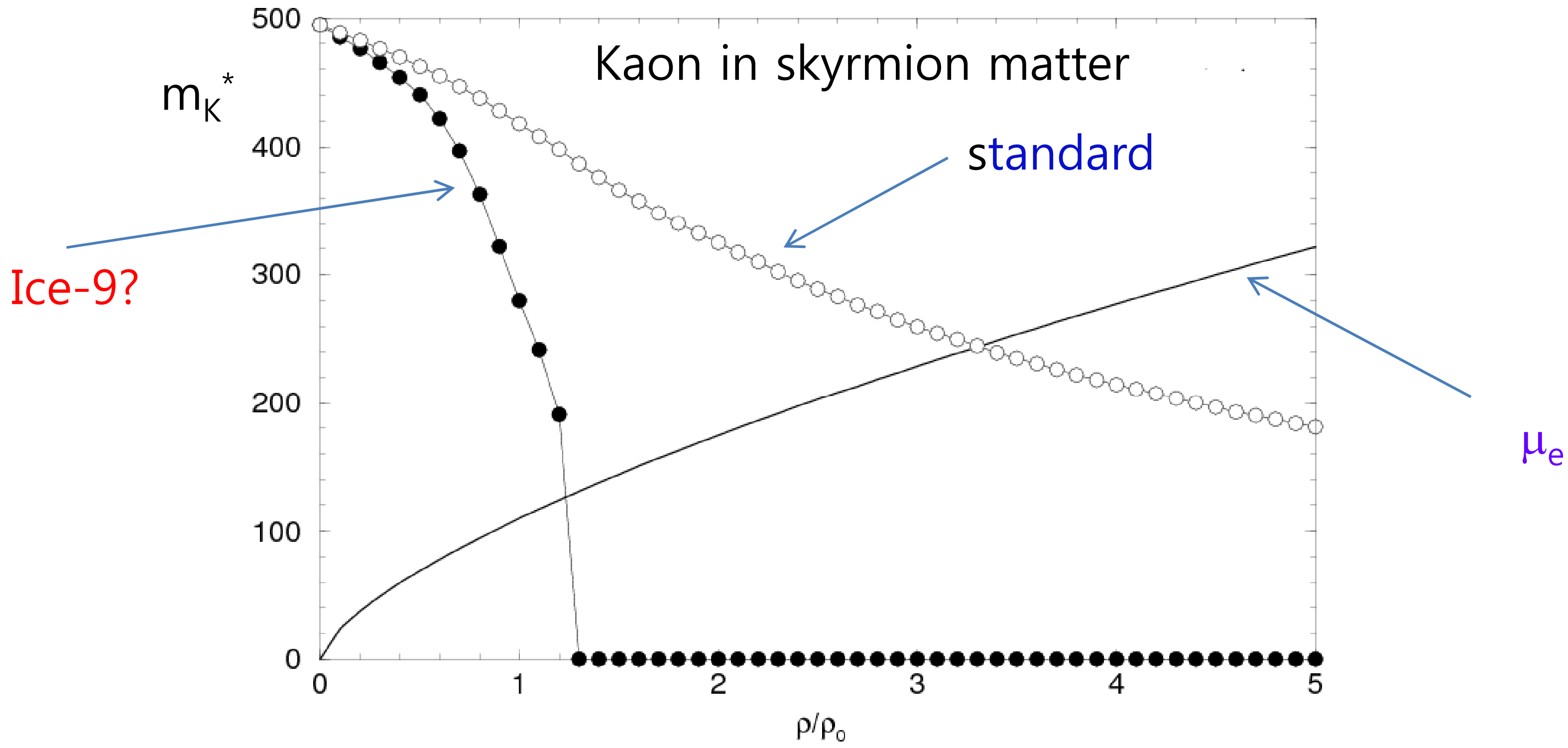
BBLR | Bao-An Li π^-/π^+ ratio



H.K. Lee
& K. Kim 09

"Ice-9" Phenomenon

Kurt Vonnegut's "Cat's Craddle"



B.Y. Park, J.-I. Kim, MR 2009

Variation Scenario is also interesting

Assume no kaons condense at densities $n > \sim(2\text{-}3)n_0$. Other things can happen before quarks appear

Quarkyonic matter

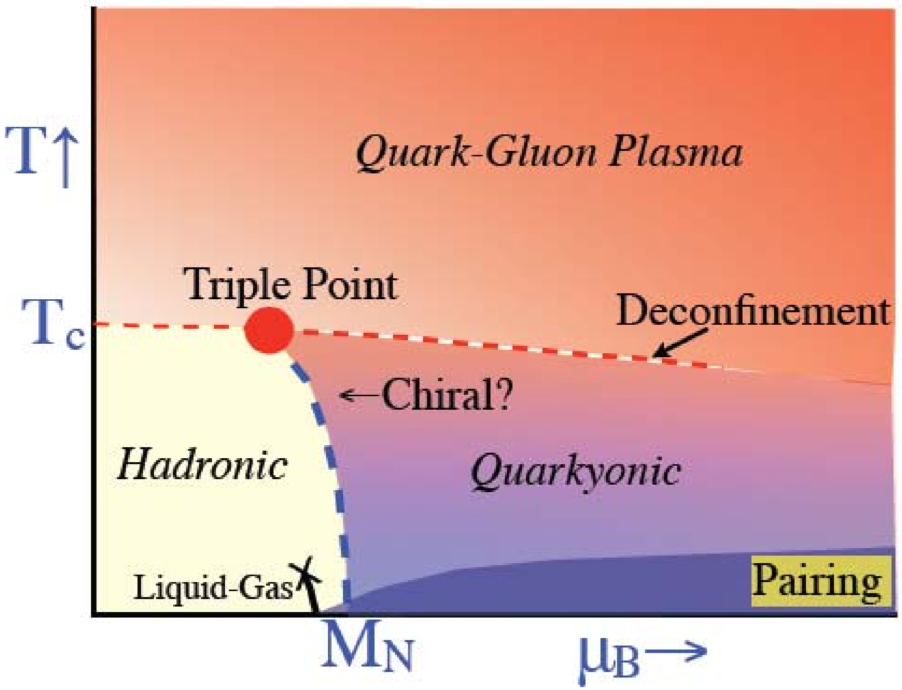
Half-skyrmion (pseudogap) matter**

?

Deconfined quantum critical phase

** Alias "dyonic salt"

Quarkyonic matter



In large N_c where QCD can be handled, there is a baryonic phase with confinement but with (possibly) chiral symmetry restored.

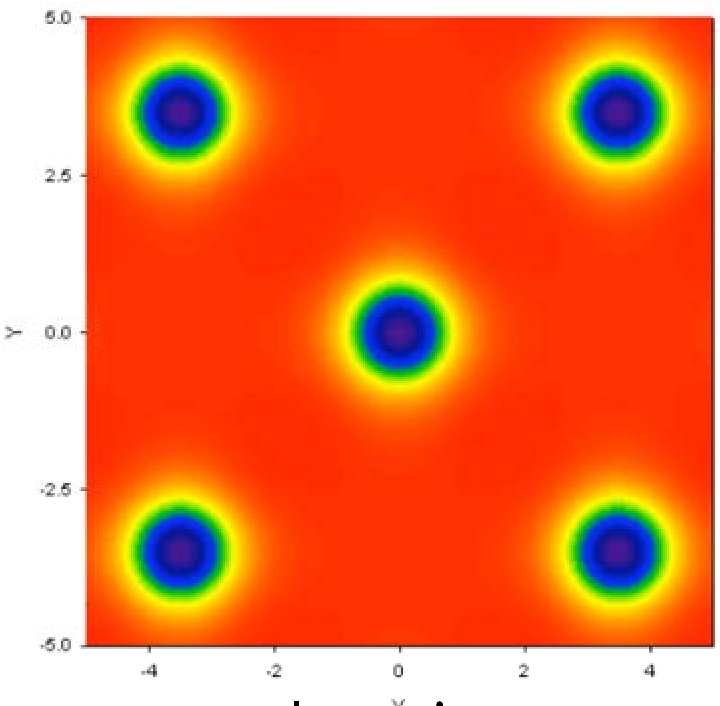
McLerran & Pisarksi 08

What is this phase and what does it do to kaon condensation – if any – and to neutron stars?

Half-skyrmions and pseudogap

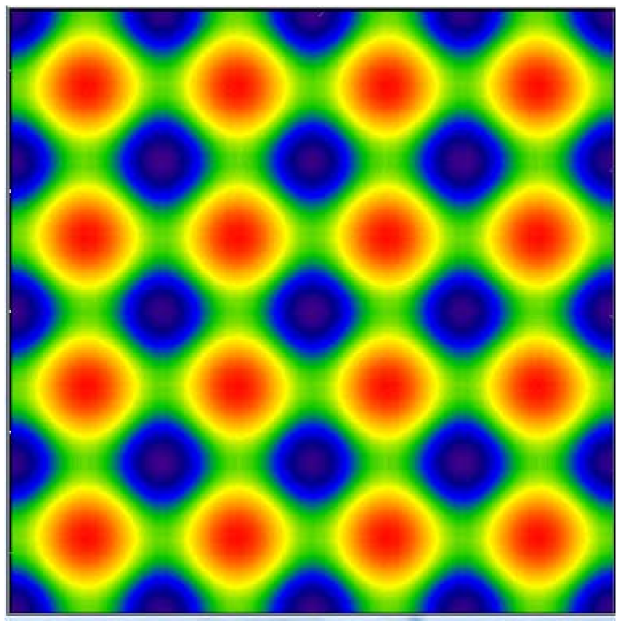
B.-Y. Park et al since 1999

Simulate dense matter by putting skyrmions
in FCC crystals and squeeze them



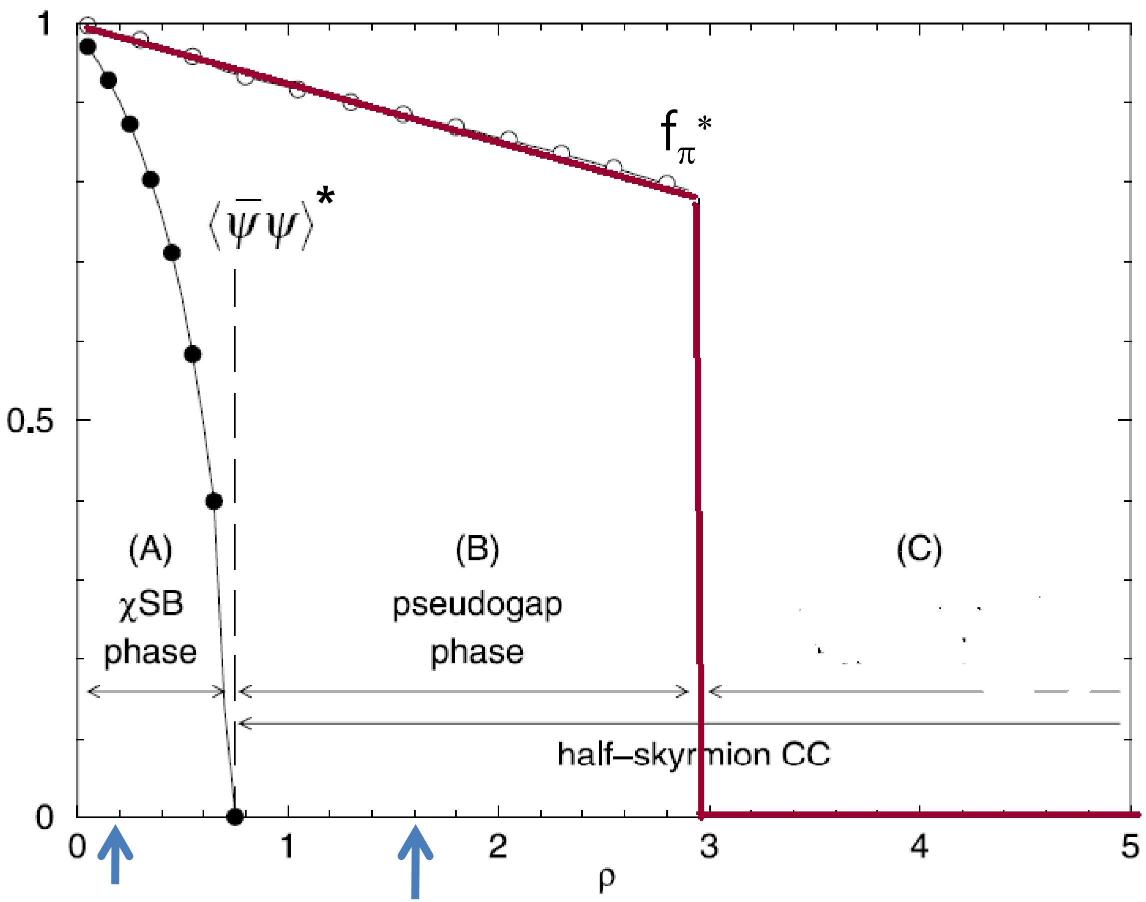
skyrmions

Increasing
density



½ skyrmions

Skyrmion phase diagram



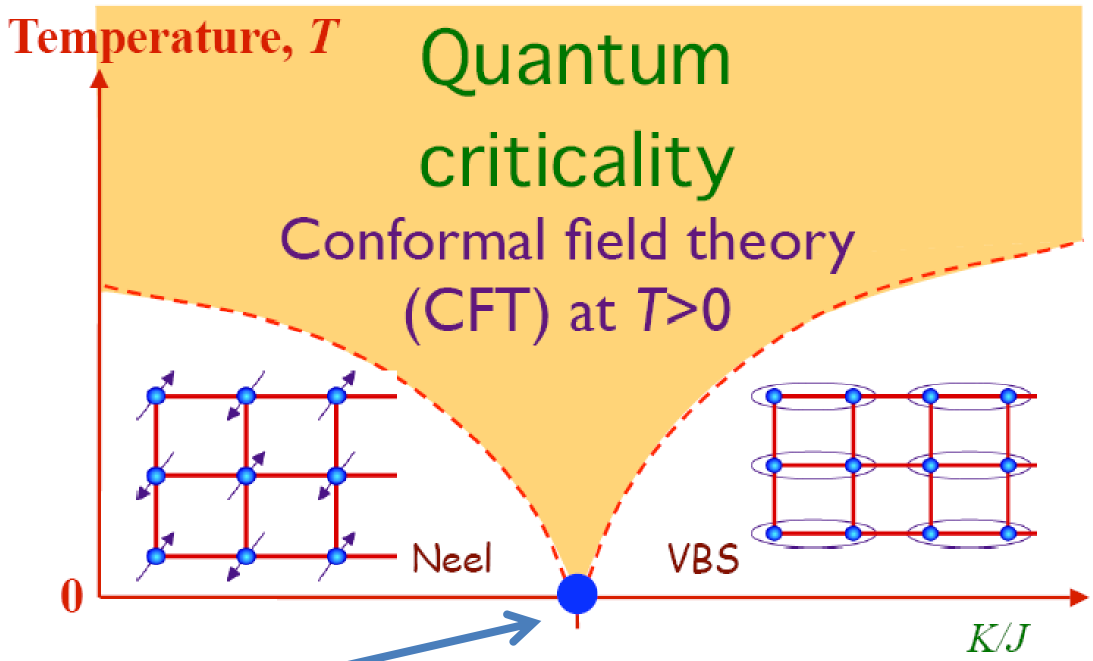
skyrmions

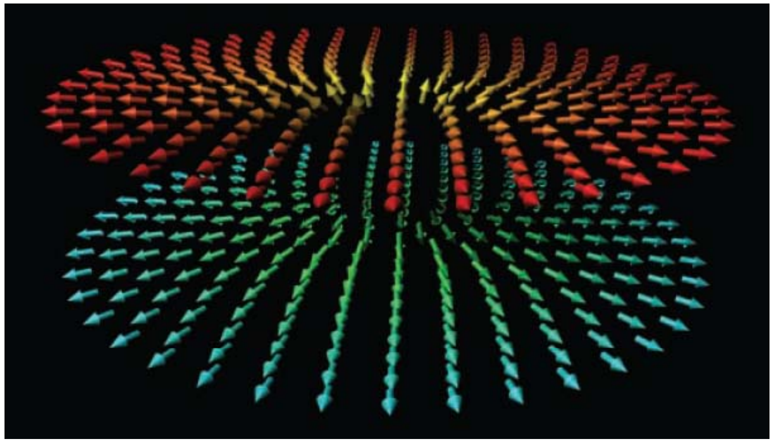
½ skyrmions ~ "quarkyonic"

Intriguing analogy to condensed matter systems

Neel-VBS transition

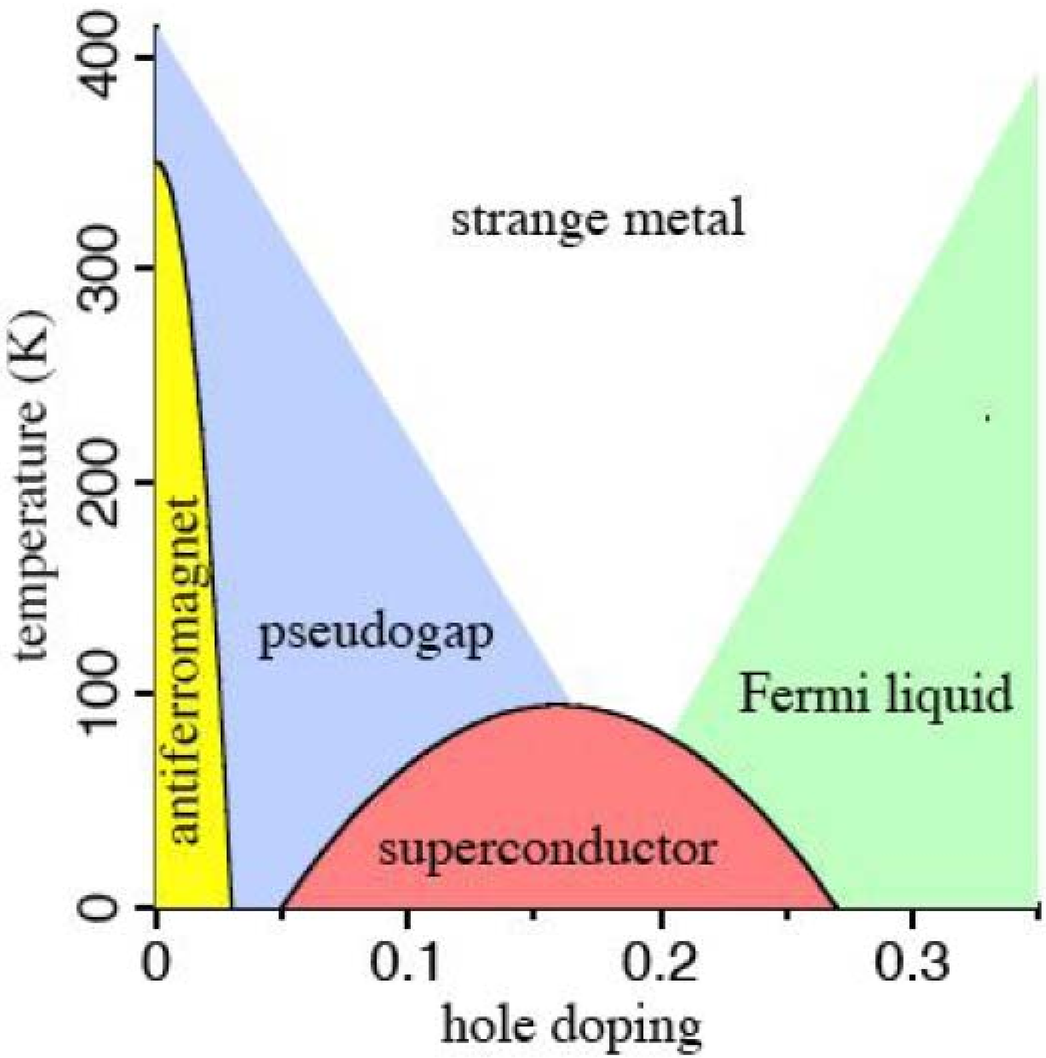
Senthil et al 08

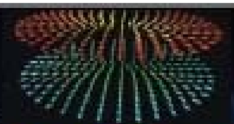




½ skyrmions
or merons

Phase diagram of cuprate High - T_c superconductors





THE MULTIFACETED SKYRMION

This is a sequel to the World Scientific volume edited by Gerald E Brown in 1994 entitled "Selected Papers, with Commentary, of Tony Hilton Royle Skyrme". There has been a series of impressive developments in the application of the skyrmion structure to wide-ranging physical phenomena. The first volume was mainly focused on the rediscovery of the skyrmion in 1983 in the context of Quantum Chromodynamics (QCD) and on its striking role in nuclear physics. Since 1994, skyrmions have been found to play an even greater role not only in various aspects of particle physics and astrophysics but also most remarkably in condensed matter physics. It is also proving to be fruitful in dense hadronic matter relevant to compact stars, a system difficult to access by other approaches. The recent discovery of holographic baryons in gravity/gauge duality which correspond to skyrmions in the infinite tower of vector mesons provides a valuable confrontation of string theory with nature, particularly in the regime of strong coupling that QCD proper has difficulty in accessing. This volume consists of contributions from the active researchers who have made important progress in these three areas of theoretical physics — condensed matter physics, nuclear and particle physics, and string theory.

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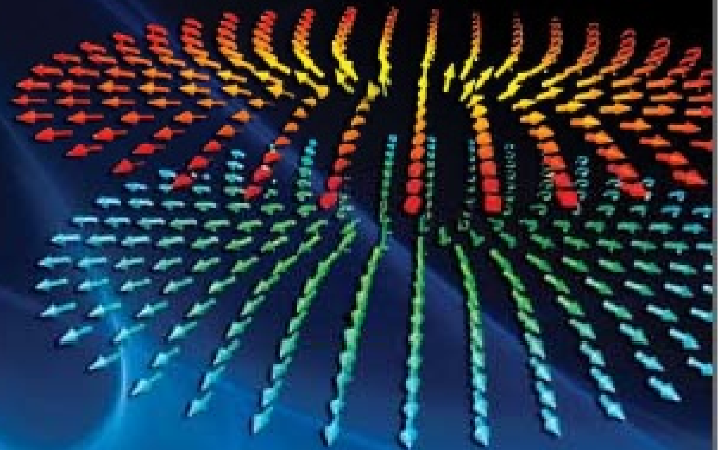
THE MULTIFACETED SKYRMION

Brown
Rho

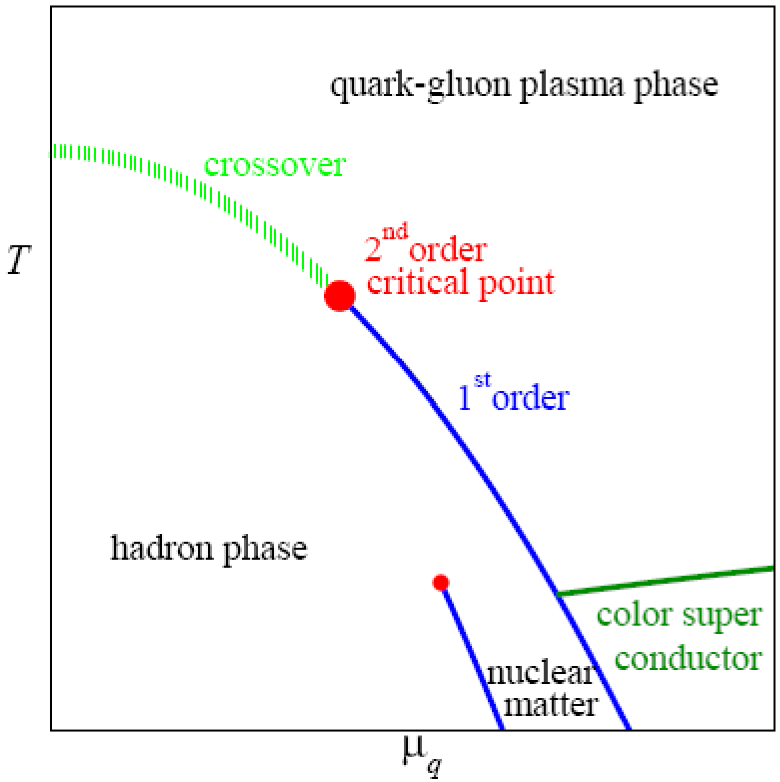
THE MULTIFACETED SKYRMION



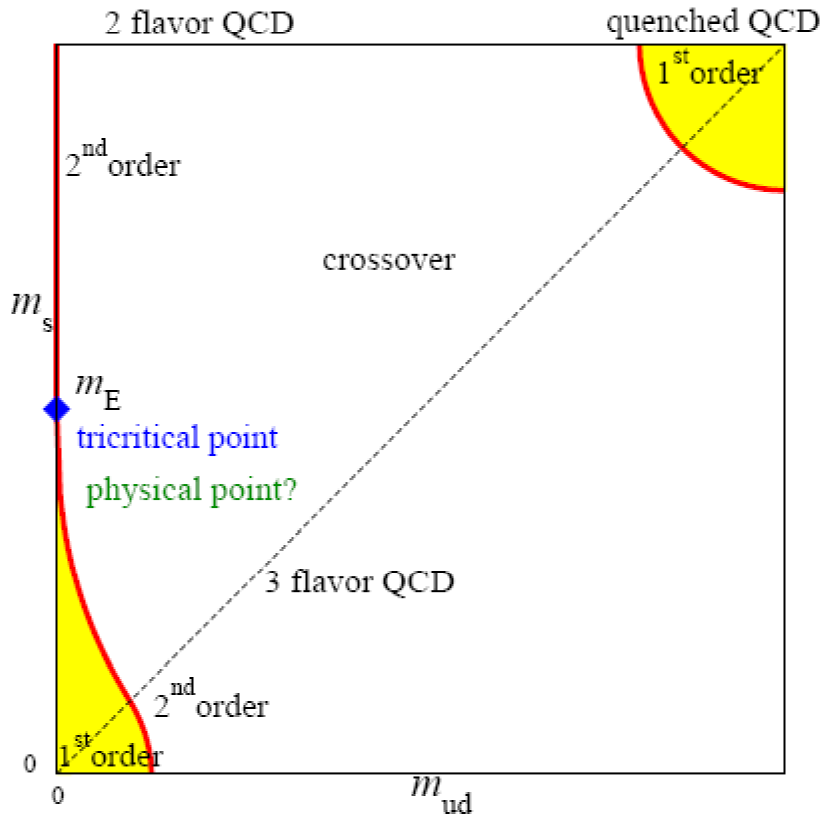
Gerald E Brown
Mannque Rho
editors

World Scientific

End



quark-gluon plasma phase
crossover
2nd order
critical point
1st order
hadron phase
color super
conductor
nuclear
matter
T
μq



2 flavor QCD
quenched QCD
1st order
2nd order
crossover
ms
mE
tricritical point
physical point?
3 flavor QCD
2nd order
1st order
0
0
mud