Proton Mass Mystery And Neutron Stars

Now that the Higgs boson is discovered, does one know where the proton mass comes from ?

Problem for “RAON” anticipated in 2000 at KIAS

Mannque Rho

CEA Saclay

Collaboration

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The Question

- The proton mass is measured accurately

$$m_P = 938.27200 \pm 0.00004 \ MeV \approx 1 \ GeV$$

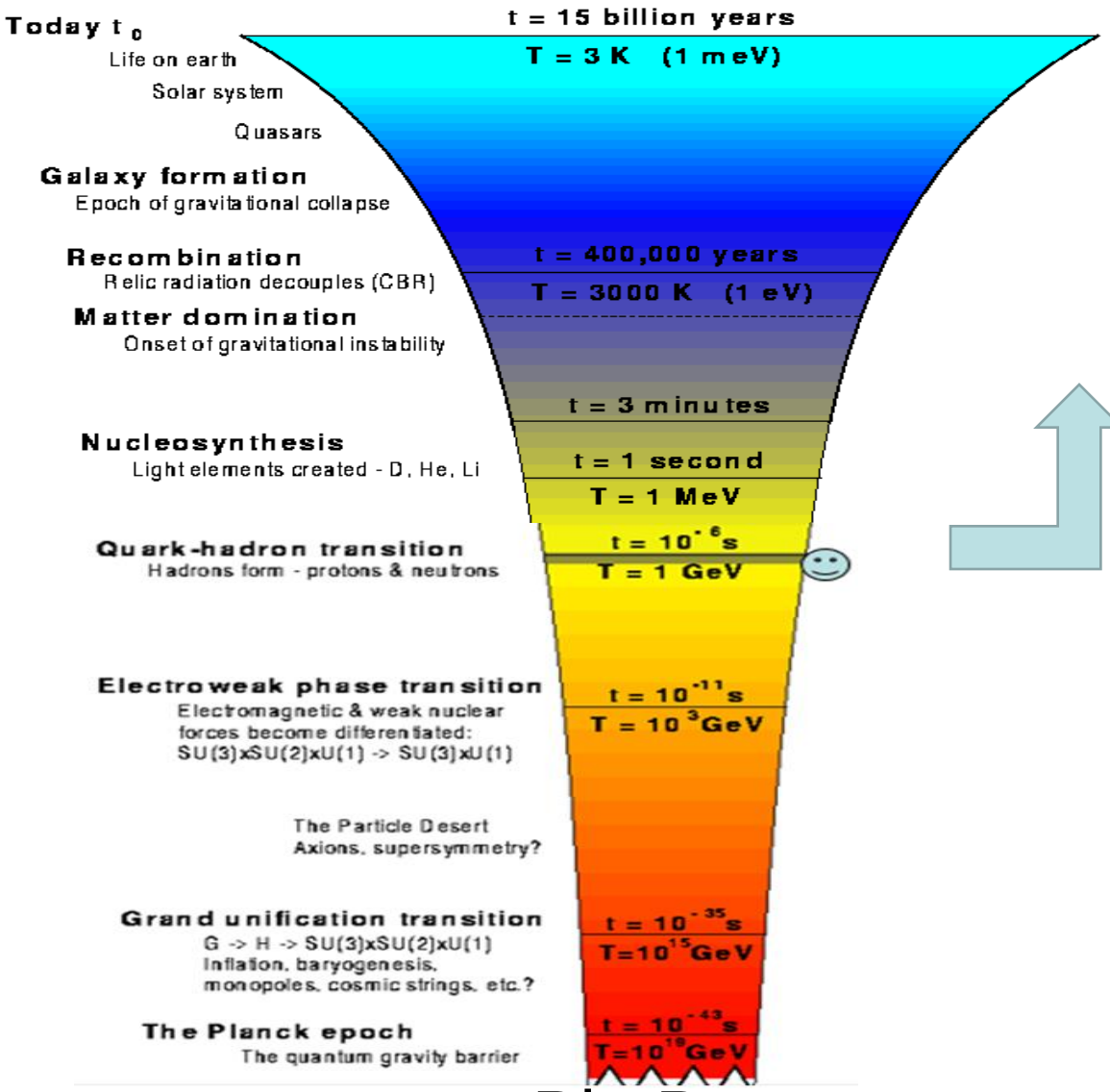
- The bulk (more than 90%) of the matter around us is made of

protons and neutrons

- But where does the proton mass come from??? Is THE BIG QUESTION

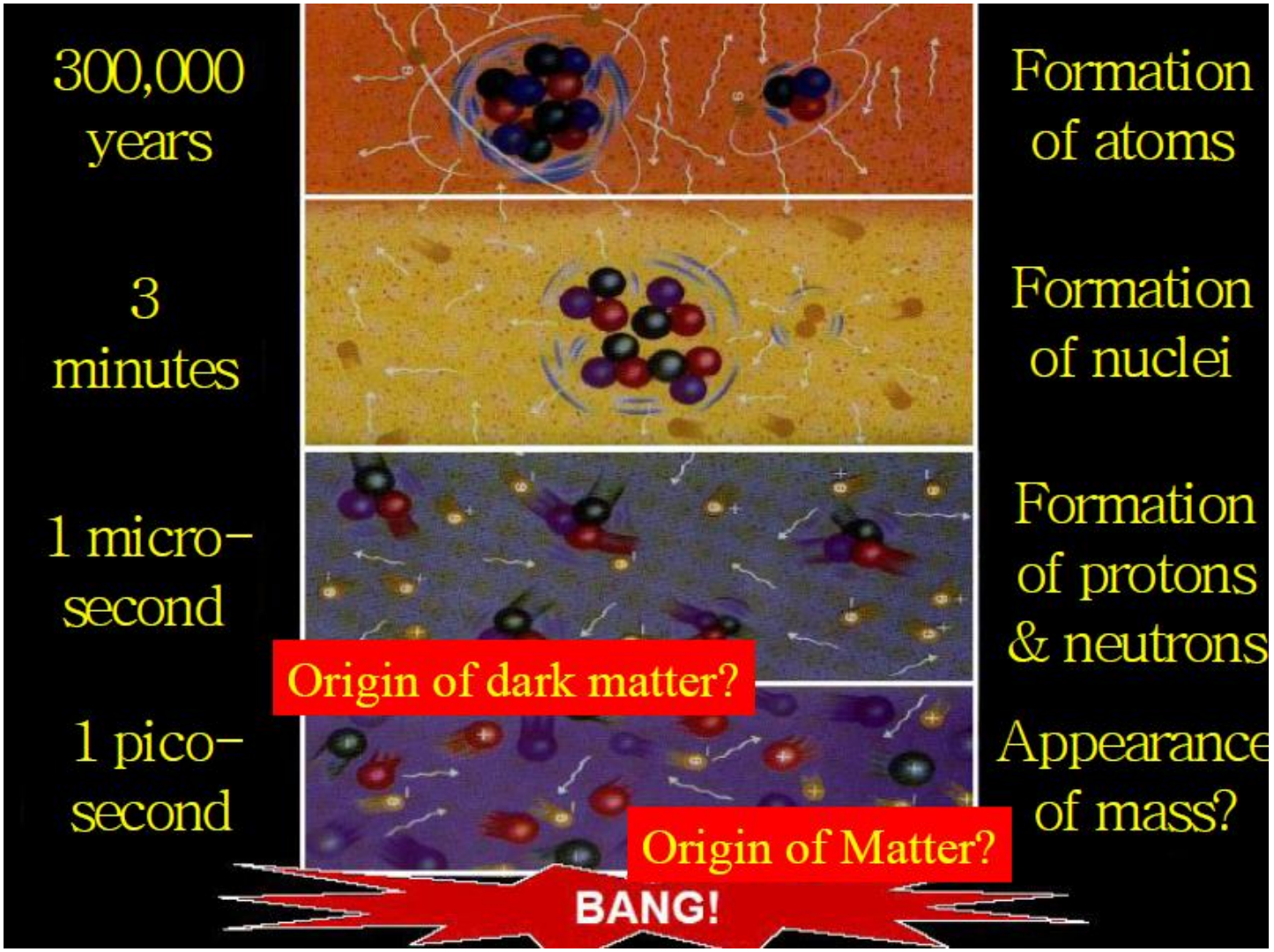
This MYSTERY is intimately
Connected with
the ***Early Universe***
And
Super Dense Matter
as in compact stars

Origin of Matter



"Visible" Matter

Big Bang



Proton mass Appears here

Superdense matter is fascinating ….

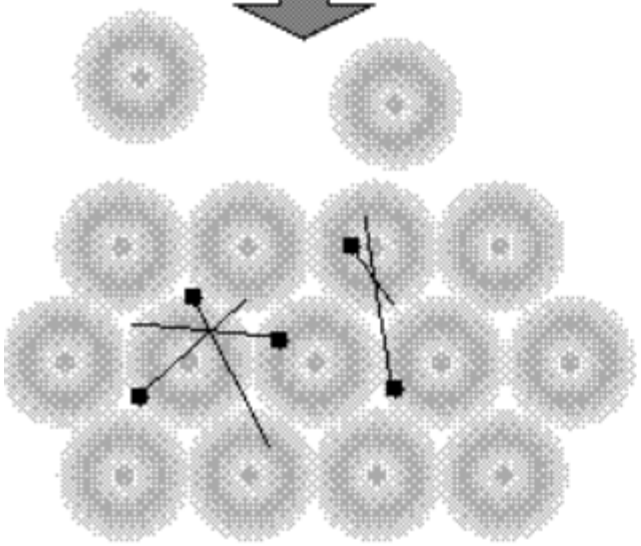
Squash Manhattan to a teaspoonful

Or compress Boing 747 into a small grain of sand!!!

Densest “visible” object in the Universe

Mass < 1.4 solar masses

GRAVITY



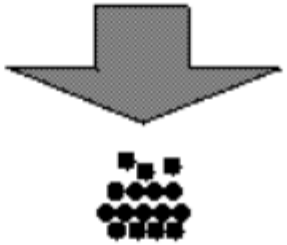
White Dwarf

Electrons run out of room to move around. Electrons prevent further collapse. Protons & neutrons still free to move around.

Stronger gravity => more compact.

Mass > 1.4 solar masses
but mass < 3 solar masses

GRAVITY

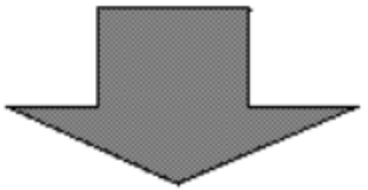


Neutron Star

Electrons + protons combine to form neutrons. Neutrons run out of room to move around. Neutrons prevent further collapse. Much smaller!

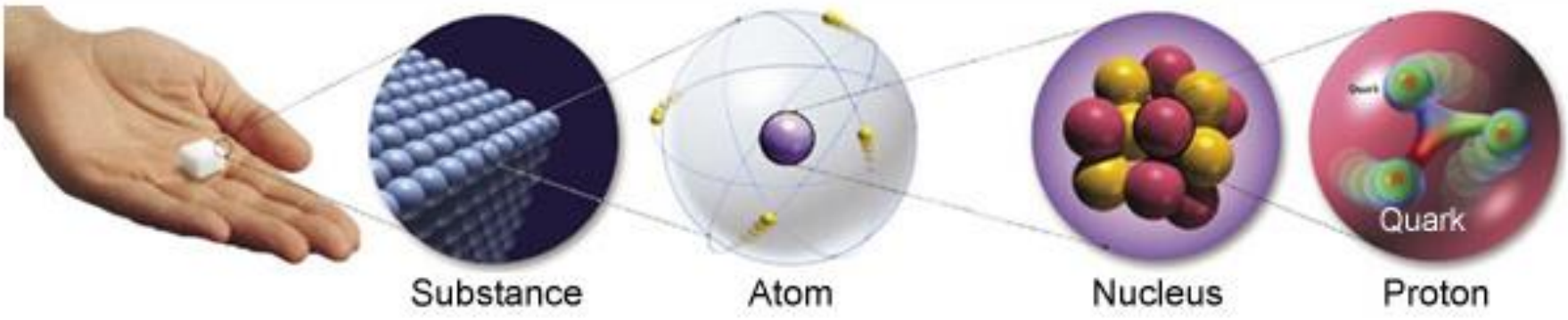
Mass > 3 solar masses

GRAVITY



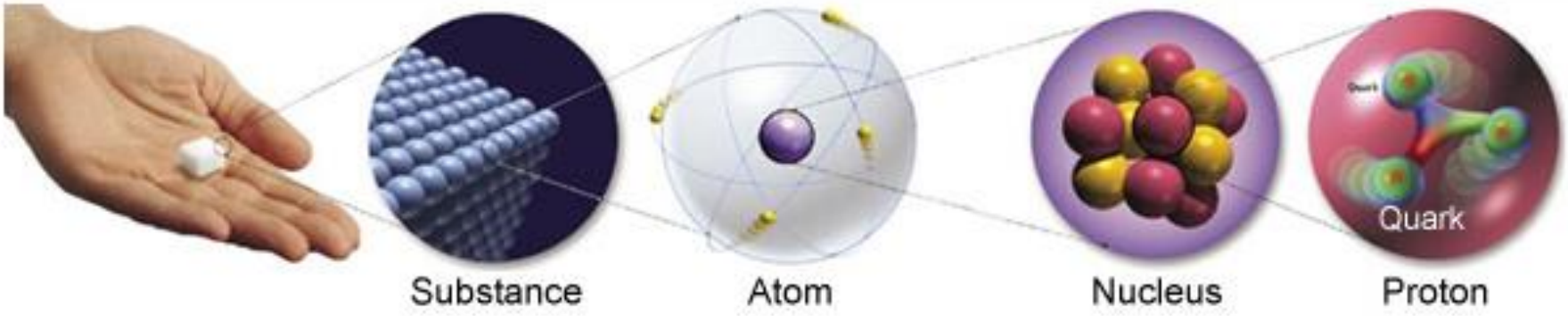
Black Hole

Gravity wins! Nothing prevents collapse.



Chemistry ← molecular ←atomic
←nuclear physics ← proton/neutron ← ??? ← quarks

Stuff around us



- Proton mass: m_P = 938.272046 ± 0.000021 MeV
- Lead 208 nucleus "^{208}Pb": 0.9926 x 208m_P

More than 99% of the mass of the lead nucleus (^{208}Pb) with 208 nucleons (82 P, 126 N) comes from the simple sum of the nucleon (proton) mass.

$$\therefore \; Mass\ of\ stuff\ around\ us$$
$$= (0.99..) \times number\ of\ nucleons \times proton\ mass$$

WikipediA

"For the proton, of mass m_p= 938 MeV, the bound quarks only contribute about 10 MeV to its mass; the bulk of it arises out of ***QCD chiral symmetry breaking***."

"Yoichiro Nambu was awarded the 2008 Nobel prize in physics for his understanding of this phenomenon."

"Nambu mechanism:"

"If chiral symmetry is made `unbroken'
the proton mass must then disappear"

Nambu-Jona-Lasinio (1961)

... Our model Hamiltonian, though very simple, has been found to produce results which strongly simulate the general characteristics of real nucleons and mesons. It is quite appealing that both the ***nucleon mass*** and the pseudo-scalar ***`pion'*** are of the same dynamical origin, and the reason behind this can be easily understood in terms of (1) classical concepts such as attraction or repulsion between particles, and (2) the γ_5 symmetry.

Quark Masses

Light Quarks: q= u, d, s $\quad m \equiv m_u \approx m_d \approx m_s \approx 0$

"Chiral symmetry"

Relevant to "stuff" around us

"QCDLite"

Heavy Quarks: Q= c, b, t $\quad M \equiv m_c \approx m_b \approx m_t \approx \infty$

"Heavy-quark symmetry"

Irrlevant to "stuff" around us

Puzzling

"We find that ~ 90% of the proton (and neutron) mass, and therefore ~ 90% of ordinary matter, emerges from an idealized theory – QCDLite -- whose ingredients are entirely massless."

F, Wilczek 2012

A deep philosophical, not just physics, problem of "Mass without Mass" and "Something for Nothing"

$$m_P = \sum \text{"??"}$$

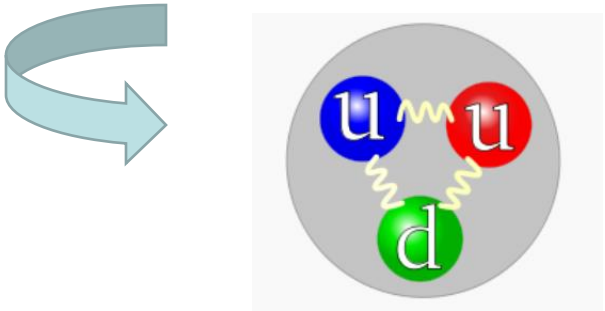
What is “??” ?

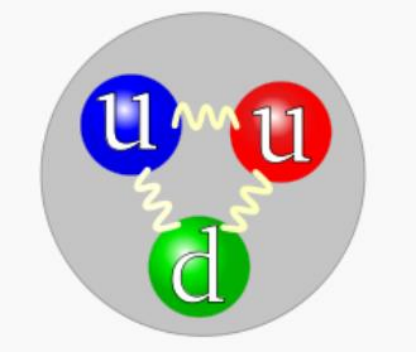
“?? Stuff”

- Colored quarks: q, q, q; q=(u,d,s, ….)
- Massless gluons

QCD says

Proton is made up of 3 (nearly) massless quarks (2u+1d) & massless gluons





$m_u \approx 2.5$ MeV, $m_d \approx 5.7$ MeV
from Higgs mechanism

Englert & Higgs 2013

Naïvely

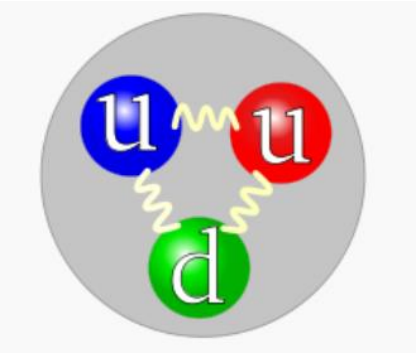
$M_{proton} = 2m_u + m_d + \text{“}\clubsuit\text{”}$

$= 10.7\ MeV + \text{“}\clubsuit\text{”}$

cf. *Nature ~ 1000 MeV*

Sum of constituent (quark) masses does not work!

99% of the proton mass is *missing!*



An interpretation of what QCD says

Up and down quarks are spin ½ fermions with tiny mass which can be ignored, so they satisfy massless Dirac equation interacting with exchange of massless gluons ("colored photons")

Confinement

Quarks are *NOT seen* at all, so must be "confined."

Story of Cheshire Cat

Alice in the wonderland

Lewis Carol

↔

↔

Quantum Cheshire Cat:
Even Weirder Than Schrodinger's

How QCD gives mass is

A story of chiral symmetry breaking by "jail"
Or how the quarks escape from the "jail"

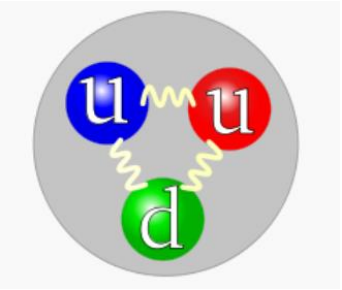
Massless quarks obey Dirac equation

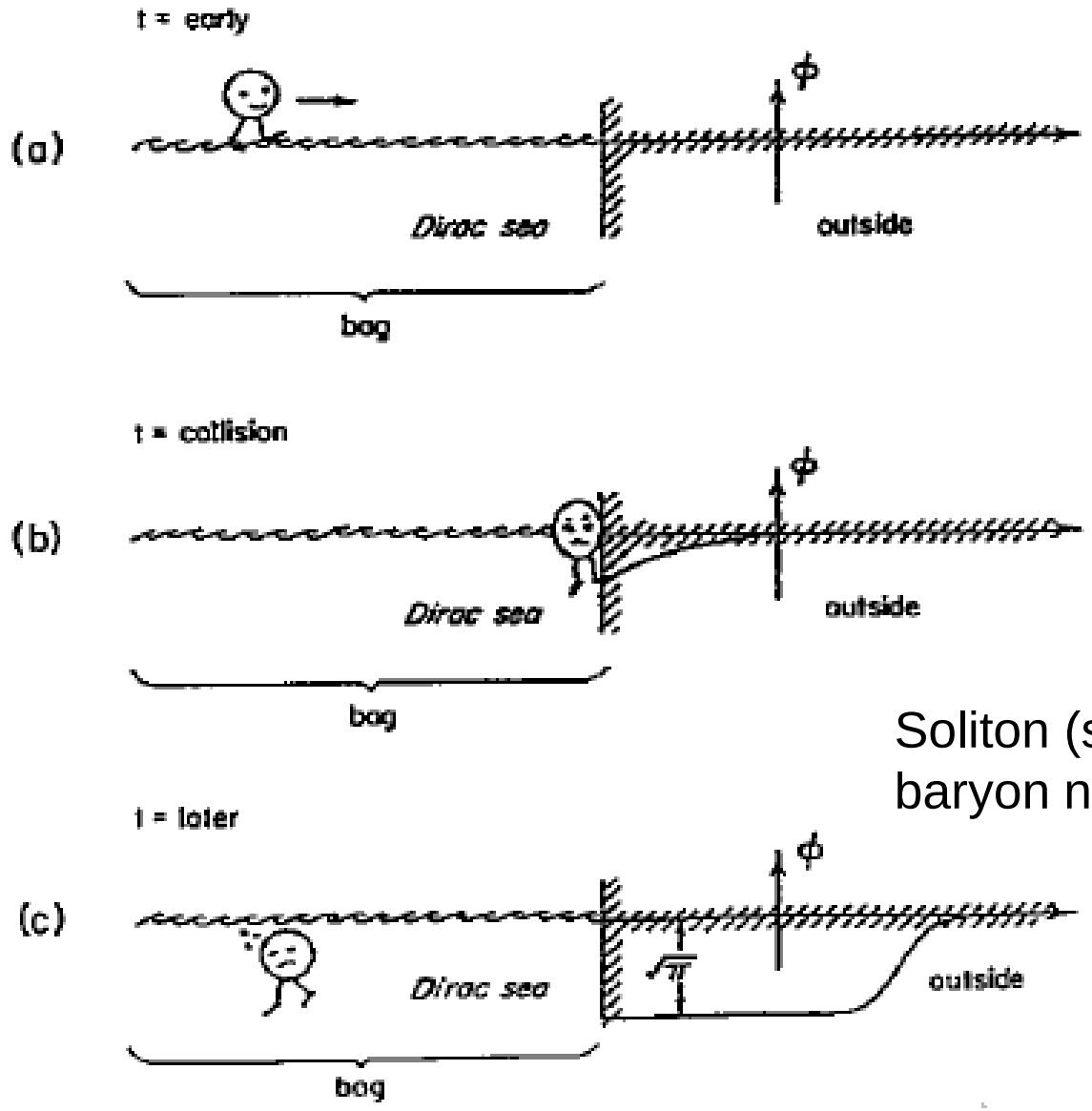
Think in terms of one dimension

- L(eft-going) quark must *always* go left
- R(ight-going) quark must *always* go right

Unless the "vacuum" blocks the path
and breaks chiral symmetry

Courtesy
H.B. Nielsen





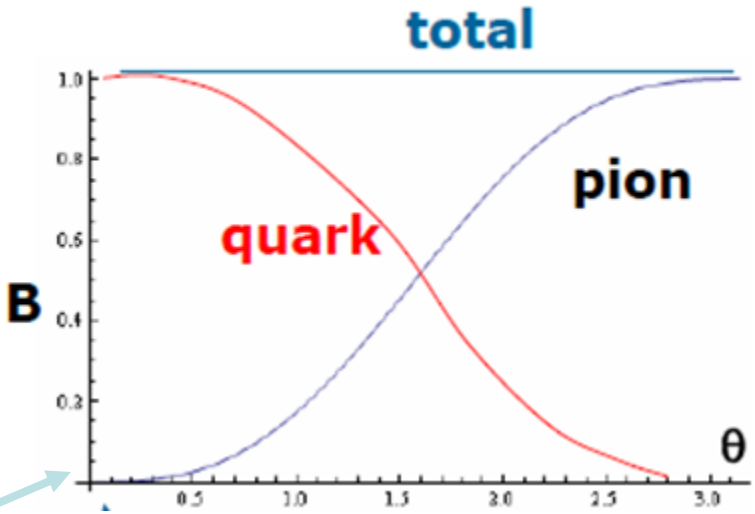
Soliton (skyrmion) carries baryon number

In 4D

Baryon charge:

GEB, Goldhaber, R 1983
Goldstone, Jaffe 1983

$$B = B_{out} + B_{in} = 1$$



$$L_{QCD} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu}$$

$$L_{EFT} = \frac{f_\pi^2}{4}\mathrm{Tr}(\partial_\mu U \partial^\mu U^+) + \bullet\bullet\bullet$$

Color anomaly

Nielsen, Wirzba, Zahed, R. 1991

- Classically color is “confined” inside the bag

$$\hat{n} \cdot \boldsymbol{E}^a = 0, \ \hat{n} \times \boldsymbol{B}^a = 0.$$

- But η’ coupled to quarks at the surface induces quantum anomaly and deposits color charge at the surface.
- Color charge leaks out into the meson sector and violate *color gauge invariance, so must* be stopped by the gauge-noninvariant surface classical counter term

$$S_{CT} = -\frac{g_c^2 N_F}{8\pi^2} \int_{\partial V} d\beta A_0^a \hat{\boldsymbol{n}} \cdot \boldsymbol{B}^a \eta' / f_0.$$

$\rightarrow$ Restore gauge invariance at the quantum level.

(*cf*. Green-Schwarz : First string revolution)

→ Cheshire Cat Action

$$S = S_V + S_{\overline{V}} + S_{\partial V}\,,$$

$$S_V = \int_V d^4x \left(\bar{\psi} i \not{D} \psi - \frac{1}{2g_c^2} \mathrm{tr}\, G_{\mu\nu} G^{\mu\nu} \right)$$

$$S_{\overline{V}} = \frac{f^2}{4} \int_{\overline{V}} d^4x \left(\mathrm{Tr}\, \partial_\mu U^\dagger \partial^\mu U + \frac{1}{4N_f} m_{\eta'}^2 (\mathrm{Tr ln} U - \mathrm{Tr ln} U^\dagger)^2 + \ldots \right)$$

$$S_{\partial V} = \frac{1}{2} \int_{\partial V} d\Sigma^\mu \left\{ (n_\mu \bar{\psi} U^{\gamma_5} \psi) + i \frac{g_c^2}{16\pi^2} K_{5\mu} (\mathrm{Tr}\, \mathrm{ln} U^\dagger - \mathrm{Tr}\, \mathrm{ln} U) + \ldots \right\}$$

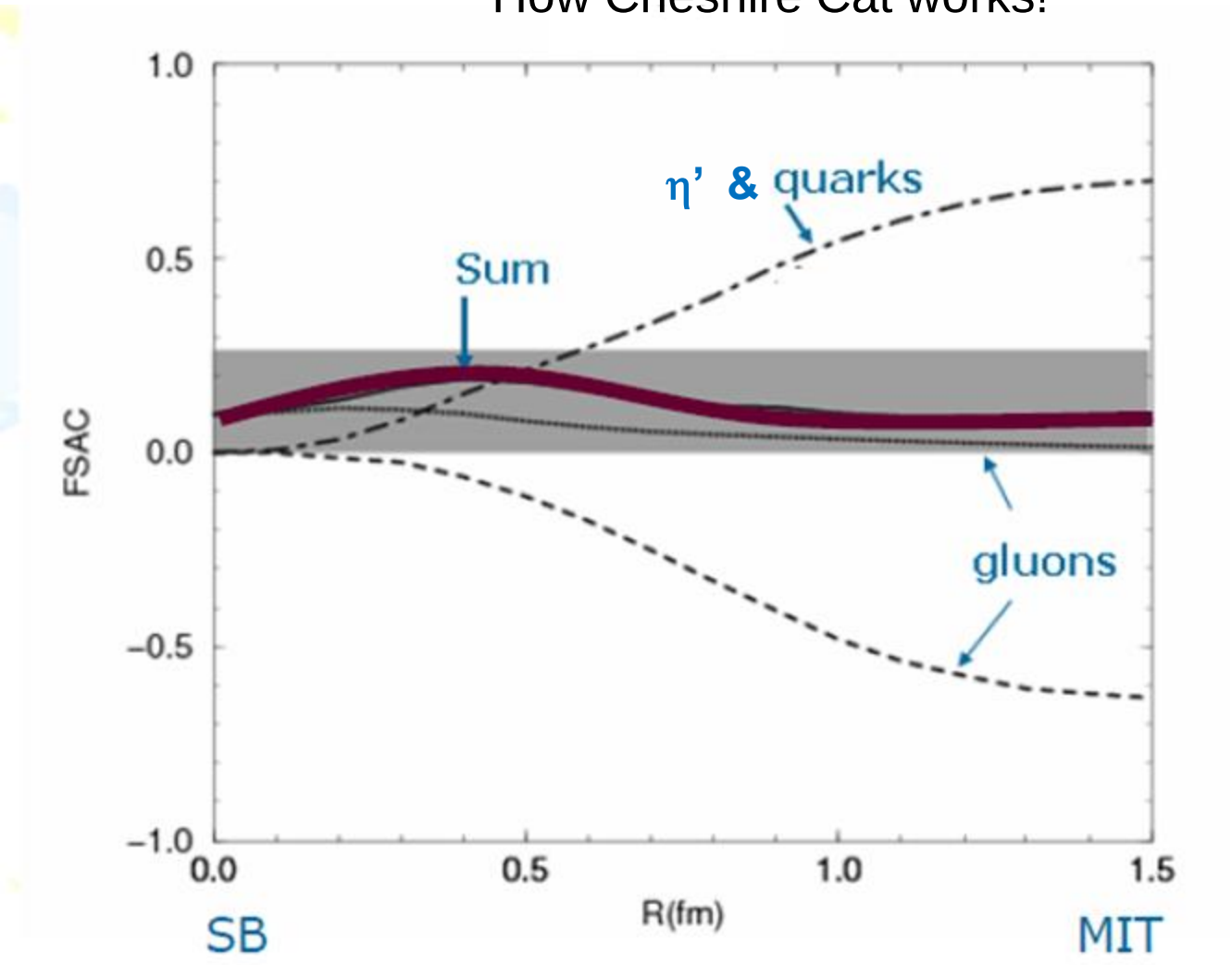
Color anomaly cancelled by the surface term

In the “chiral-bag gauge,” physics should not depend on the bag radius R

FSAC (flavor singlet axial charge: g_A^0)

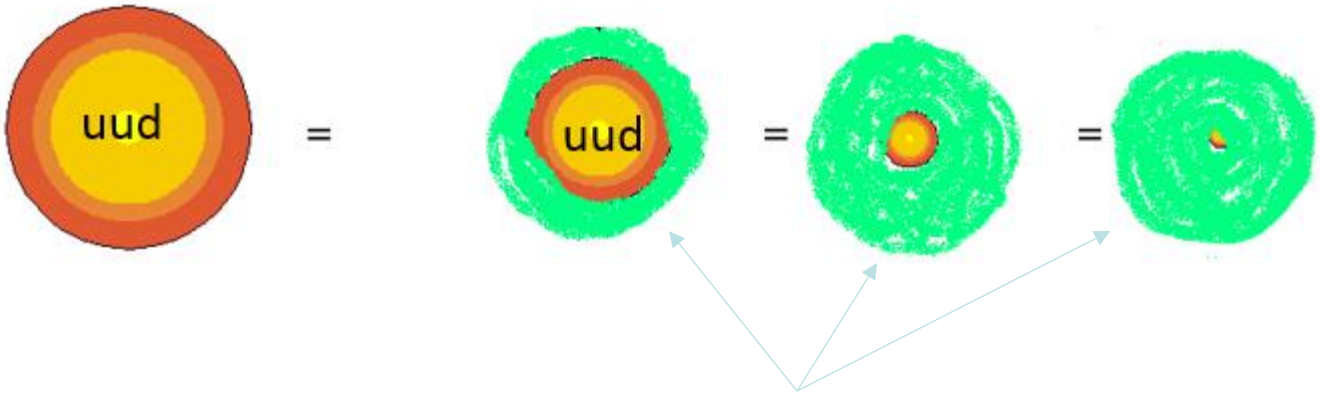
Hee-Jung Lee, Byung-Yoon Park, Min, Vento, R. 1999

How Cheshire Cat works!

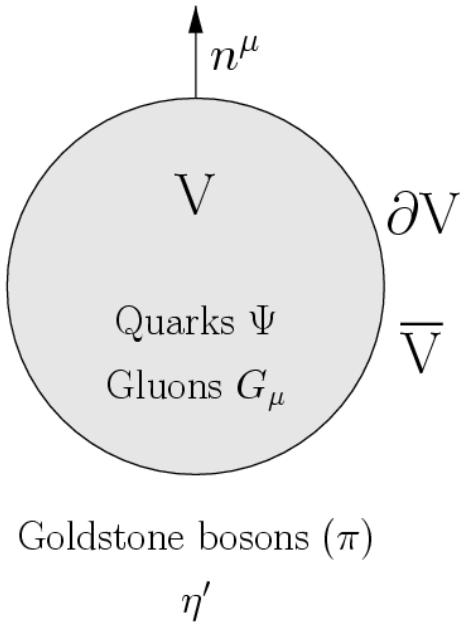


FSAC has nothing to do with the proton spin!!!

Cheshire Cat Phenomenon (CCP)

proton 

Pion cloud



- Baryon charge ***anomaly,*** leaked charge carried by skyrmion.
- Color charge ***anomaly*** (quantum), leaking stopped by surface (classical) counter term.
- Wess-Zumino terms match inside and outside.

$\therefore$ Bag radius is a *"gauge artifact"*.

"Cheshire Cat" is a Gauge Theory"

"Bag" is a *gauge artifact*, hence physics should not depend on it.

A proof in (1+1)D Damgaard, Nielsen and Sollacher 1994

Gauge condition: $\Phi[\theta, \chi, \bar{\chi}] = 0$

$$\delta(\Phi[\theta, \bar{\chi}, \chi]) = \int [db] e^{i \int d^2x \, b \, \Phi}$$

$$= \int [db] e^{i \int d^2x \; \mathcal{L}_{g.f.}}$$ Faddeev-Popop

$$\delta_\alpha \mathcal{L}_{g.f.} = -\frac{1}{\pi}\{(1-\Delta)+\Delta\}\alpha$$

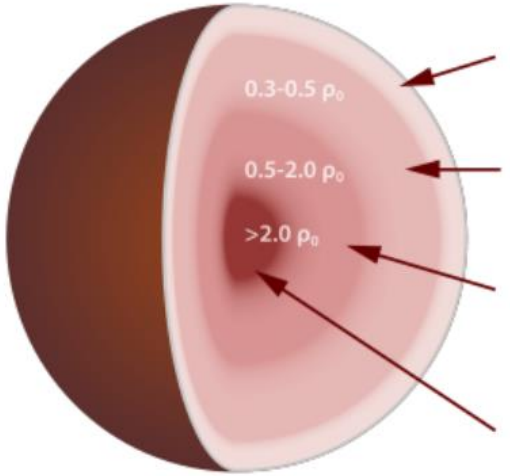
"Chiral bag gauge" $\Delta(x) = \Theta(x-z)$ $z = \hat{r}R$

How to “unbreak” chiral symmetry

Tweak $\Sigma \neq 0 \rightarrow \Sigma = 0$ by compressing matter to ~ 10 times nuclear matter density

- In laboratory (strong interactions)
- In space (gravity)

Neutron stars can decipher the mystery



outer crust 0.3-0.5 km
ions, electrons

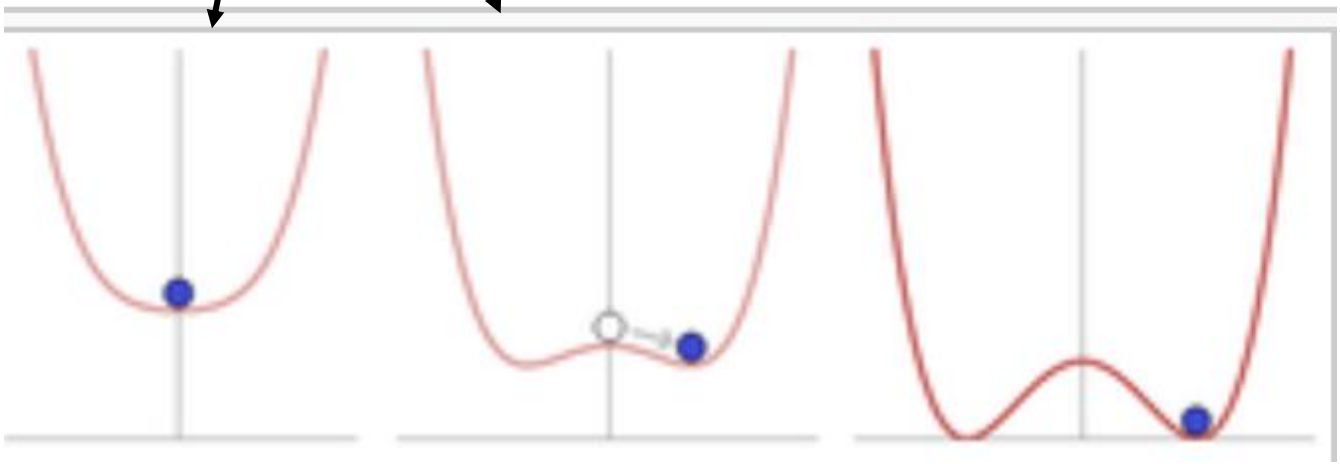
inner crust 1-2 km
electrons, neutrons, nuclei

outer core ~ 9 km
neutron-proton Fermi liquid
few % electron Fermi gas

inner core 0-3 km
quark gluon plasma?

Gravity At Work

Potential V



Condensate Σ	**= 0**	**≠ 0**	**≠ 0**
Density	**> 4 ρ_0**	**≈ ρ_0**	**< ρ_0**

Density increase

Dense Matter Meets Gravity

- Dense matter: solve QCD $\rightarrow$ EoS (Unknown)
  (Pressure vs. energy density)
- Gravity: Einstein Equation (Known)

TOV (Tolman-Oppenheimer-Volkov) Equation

$\Rightarrow$ Stable compact stars (+ Black Holes)

Mass (M) vs. Radius (R) etc. ….

Nature 467, 1081 (2010)

A two-solar-mass neutron star measured using Shapiro delay

J1614-2230 $1.97 \pm 0.04\ M_\odot$

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]

Science 340, 1233232 (2013)

A Massive Pulsar in a Compact Relativistic Binary

J0348+0432 $2.01 \pm 0.04\ M_\odot$

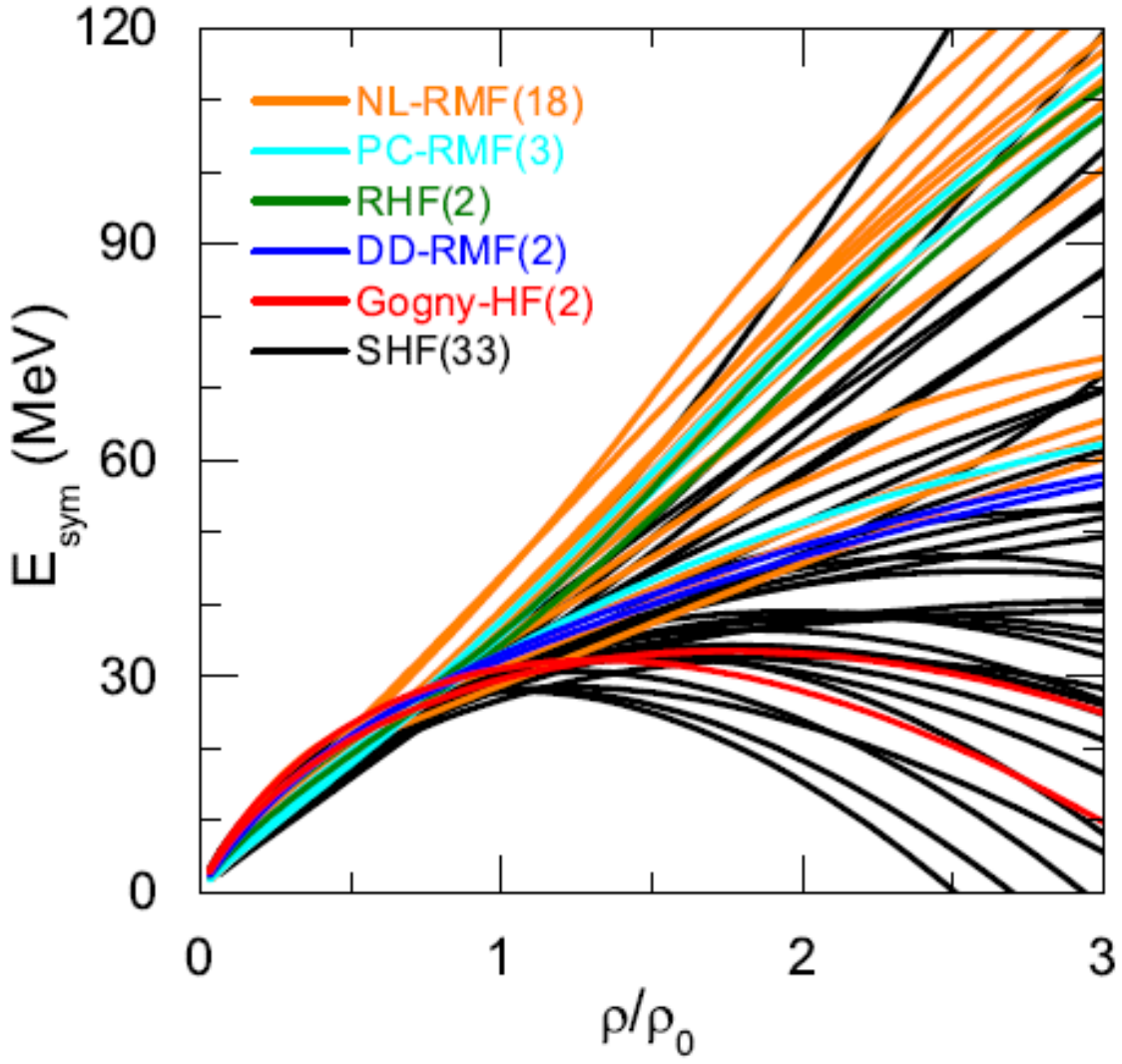
John Antoniadis,* Paulo C. C. Freire, Norbert Wex, Thomas M. Tauris, Ryan S. Lynch, Marten H. van Kerkwijk, Michael Kramer, Cees Bassa, Vik S. Dhillon, Thomas Driebe, Jason W. T. Hessels, Victoria M. Kaspi, Vladislav I. Kondratiev, Norbert Langer, Thomas R. Marsh, Maura A. McLaughlin, Timothy T. Pennucci, Scott M. Ransom, Ingrid H. Stairs, Joeri van Leeuwen, Joris P. W. Verbiest, David G. Whelan

Challenge: Dense Matter

"Mass gap" in QCD remains unsolved, so the EoS is not (mathematically) known.
This is the famous "Clay Millenium Math Problem"

We don't understand!!

L.-W. Chen 1506.09057



Two Laws of Physicists

Tsung-Dao Lee

- First law:

  Without experimentalists, theorists tend to drift.

- Second law:

  Without theorists, experimentalists tend to falter.

For mathematicians

One-million $ Clay Millenium problem

Let mathematicians solve
"Clay Millenium Math Problem"

Physicists resort to T.D. Lee's law:

Guess EoS from Nature (experiments)

$\rightarrow$ Effective field theory (EFT)

What makes physicists different from mathematicians!

Weinberg Folk Theorem

"What is quantum field theory, and what did we think it is?" 1997

"When you use quantum field theory to study low-energy phenomena, then according to the folk theorem you're not really making any assumption that could be wrong, unless of course Lorentz invariance or quantum mechanics or cluster decomposition is wrong, provided you don't say specifically what the Lagrangian is. As long as you let it be the most general possible Lagrangian consistent with the symmetries of the theory, you're simply writing down the most general theory you could possibly write down."

Folk Proof: "It's hard to see how it can go wrong…"

From Topology: Skyrmions

Atiyah and Manton arXiv: 1609.02816

We propose a new geometrical model of matter, in which neutral atoms are modelled by compact, complex algebraic surfaces. Proton and neutron numbers are determined by a surface's Chern numbers. Equivalently, they are determined by combinations of the Hodge numbers, or the Betti numbers. Geometrical constraints on algebraic surfaces allow just a finite range of neutron numbers for a given proton number. This range encompasses the known isotopes.

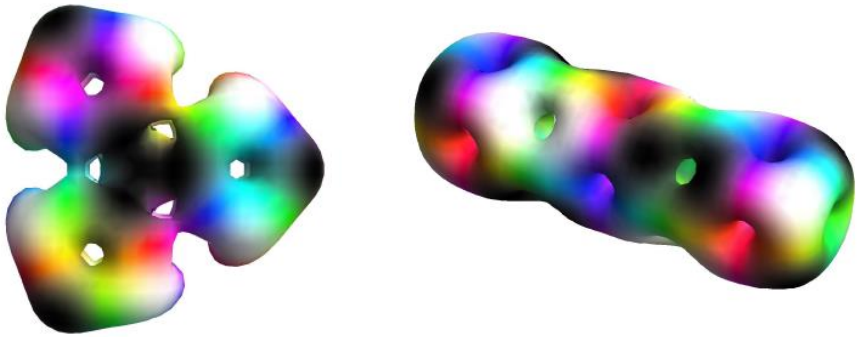
In the limit $N_c \to \infty$ in QCD, baryons as skyrmions: Hoyle states in C-12

Lau & Manton 2014

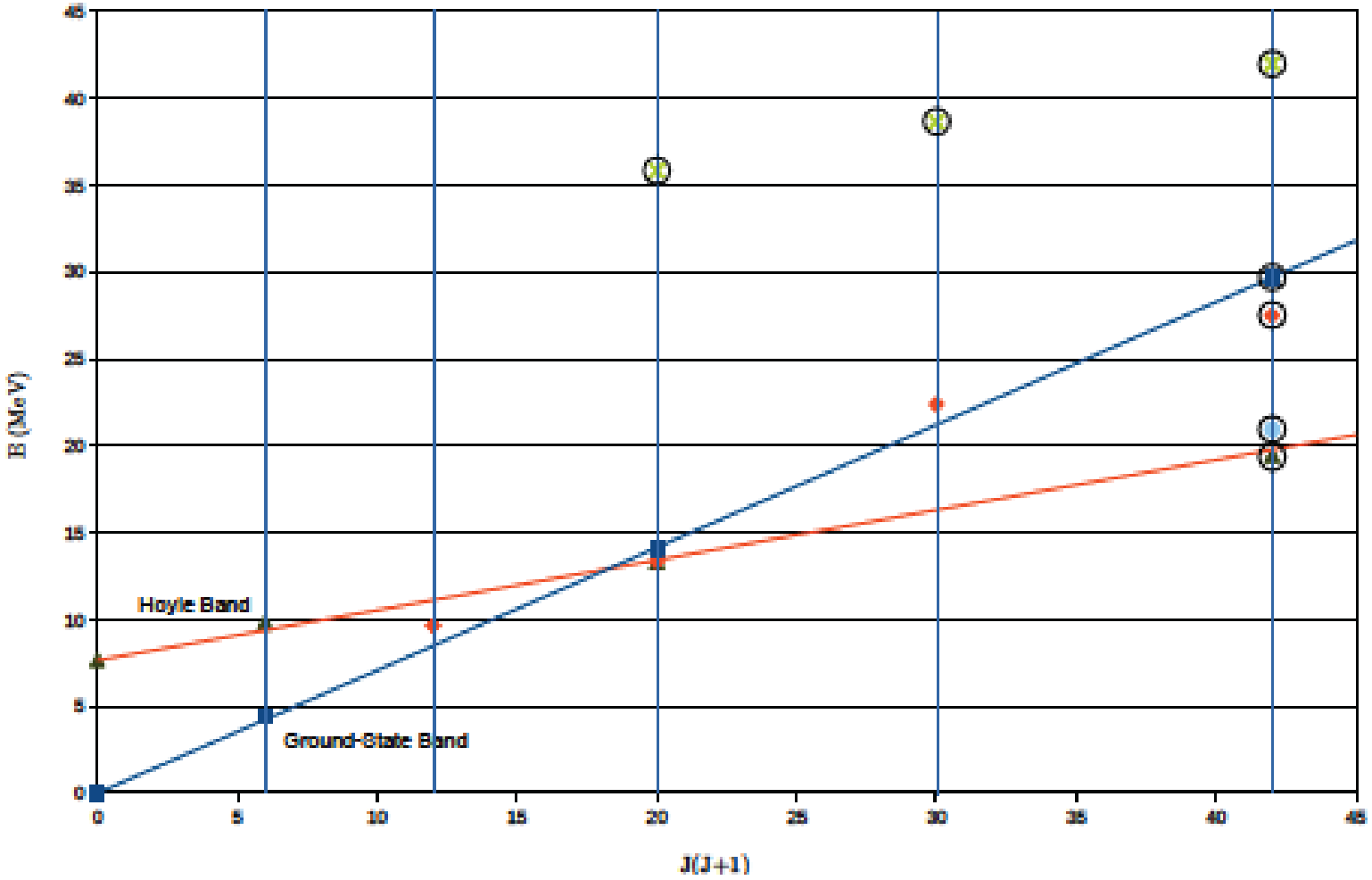
$$L = \int \left\{ -\frac{1}{2} \mathrm{Tr}\,(R_\mu R^\mu) + \frac{1}{16} \mathrm{Tr}\,([R_\mu, R_\nu][R^\mu, R^\nu]) + m^2 \,\mathrm{Tr}\,(U - 1_2) \right\} d^3x$$

$$R_\mu = (\partial_\mu U) U^\dagger, \quad \textbf{\textit{Only pions}}$$

Treat to $O(1/N_c)$ à la rotational quantization and generate rotational states. Two symmetries D_{3h} and D_{4h} for C-12



Only one parameter: *m* (pion mass)


B (MeV)
J(J+1)
Hoyle Band
Ground-State Band
0
5
10
15
20
25
30
35
40
45

Hidden *Local* (Gauge) Symmetry

$$\mathbf{U} = \mathbf{e}^{\mathbf{2i\pi/f_\pi}} = \xi_L \xi_R^\dagger, \quad \xi_{L,R} \in SU(2)_{L,R}$$

$$\xi_{L,R} \to \xi_{L,R} h^\dagger(x) \quad h(x) \in SU(2)_{L+R}$$

Elevate to gauge symmetry → "hidden" local symmetry
→ Vector meson (ρ, ω, a_1) scale

Bando, Kugo, Yamawaki 1988
H. Georgi 1989
Harada, Yamawaki 2003

$$\mathcal{L}_{hls} = \frac{f_\pi^2}{2}\left\{\mathrm{Tr}(D_\mu \xi_L)^2 + \mathrm{Tr}(D_\mu \xi_R)^2\right\} + \kappa \mathrm{Tr}(D_\mu U)^2$$

Spontaneous SB

Infinite tower by “moose” construction à la Georgi

$\rho, \rho', \ldots, \omega, \omega', \ldots, a_1 \ldots$

$$U(x) = e^{2i\pi/f_\pi} = \Sigma_0 \Sigma_1 \Sigma_2 \bullet\bullet\bullet \Sigma_\infty$$

- 5-Dimensionally deconstructed QCD (Son & Stephanov 04)

$$S = \int d^4x dz \frac{-1}{2g(z)^2} \sqrt{g} Tr(F_{AB} F^{AB}) + \bullet\bullet\bullet$$

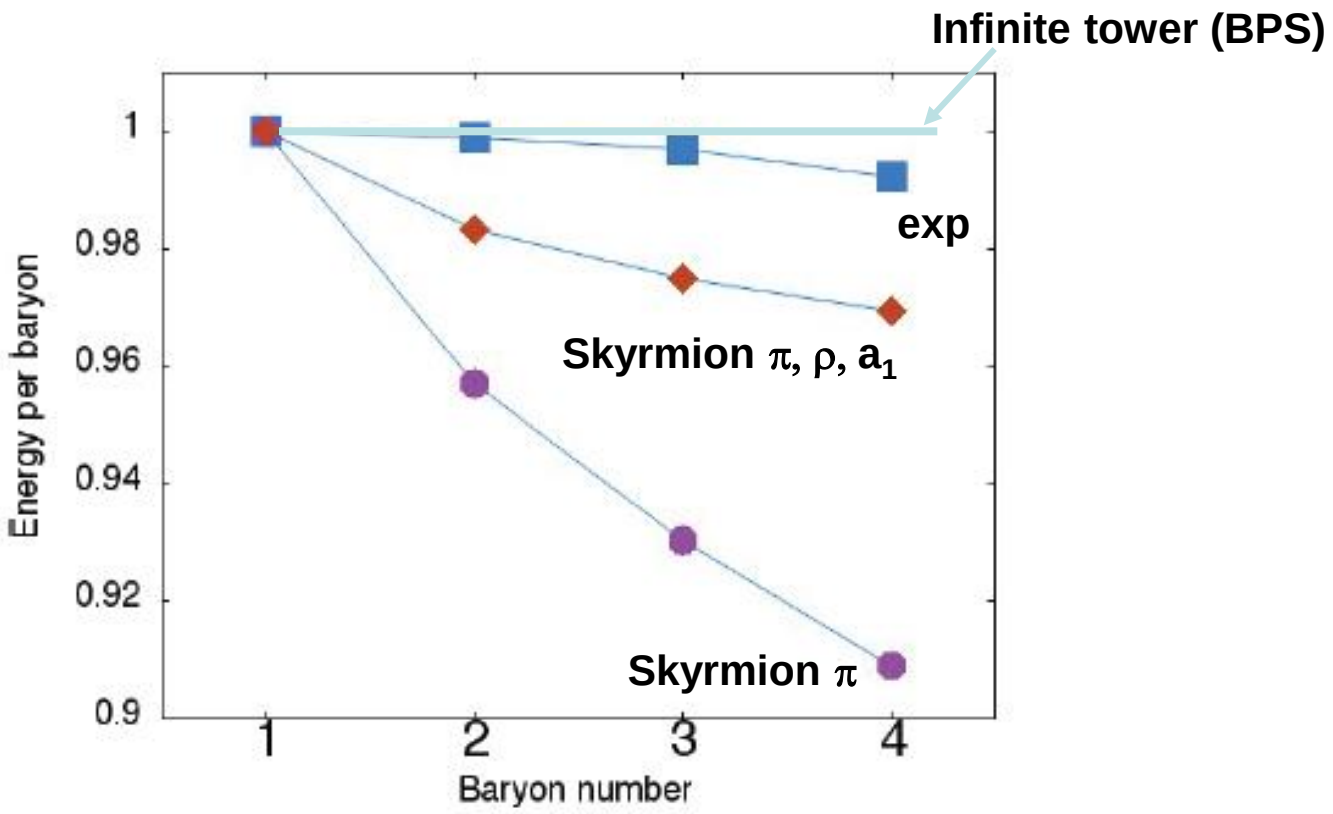
$$A, B = 0, 1, 2, 3, z$$

Descends from string theory to holographic QCD !

Sakai & Sugimoto 2005

Working of vector mesons

Sutcliffe 2011



Infinite Tower of Vector Mesons
$\rightarrow$ BPS Nuclei

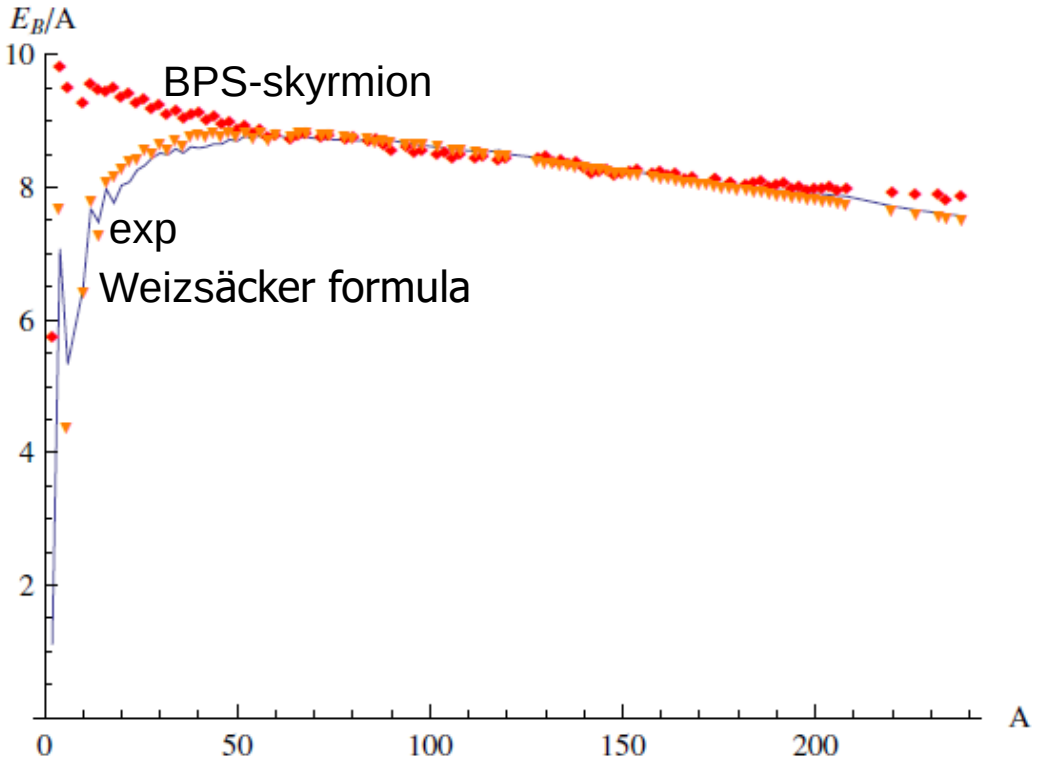
"BPS" nuclei are gotten when the space is flat
& N_c & λ ('t Hooft constant)$\rightarrow\infty$!!

BPS skyrmions

Adam, Naya, Sanchez-Guillen & Wereszynski 2013

BPS skyrmion matter is relativistic non-barotroipic perfect fluid.

With 3 parameters and a small correction from Coulomb and isospin breaking.



And compact stars?

Hidden *Scale* Symmetry: Story of "σ"≈f_0 *(500)*

"Scale invariance is `hidden' in linear sigma model or NJL model"

K. Yamawaki, arXiv:1605.01951

Gell-Mann-Levy linear σ model

$$\mathcal{L}_{L\sigma} = \frac{1}{2}\left[(\partial_\mu \hat{\sigma})^2 + (\partial_\mu \hat{\pi}_a)^2\right] - \frac{\hat{\mu}^2}{2}(\hat{\sigma}^2 + \hat{\pi}_a^2) - \frac{\lambda}{4}(\hat{\sigma}^2 + \hat{\pi}_a^2)^2$$

Redefine fields

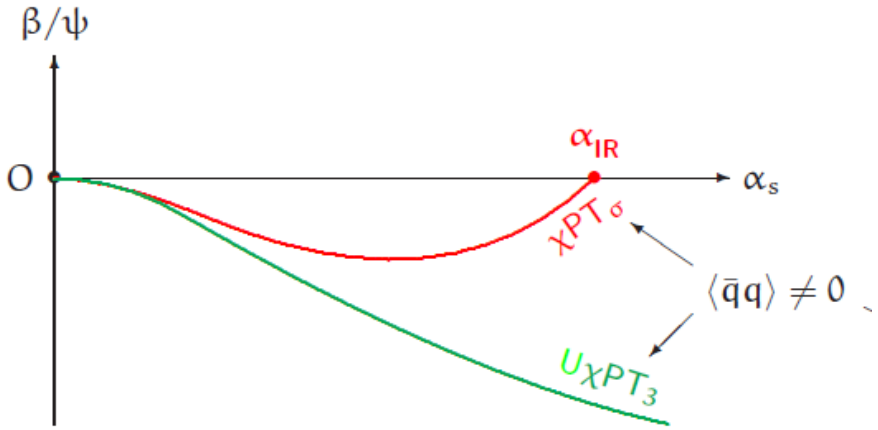
$$\mathcal{L}_{L\sigma} = \frac{1}{2}(\partial_\mu \sigma)^2 + \frac{1}{4}\sigma^2 \cdot \mathrm{tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) - \frac{\lambda}{4}\left(\sigma^2 - f^2\right)^2$$

(a)Strong coupling → nonlinear sigma model, no scalar, ChPT etc.
(b) Weak coupling → scale invariance with dilaton χ, absent in medium-free QCD due to trace anomaly

Density probes from (a) to (b)
Scale symmetry may emerge in medium.

Daring Idea: IR fixed point (β=0)

IR fixed point with $f_\phi = f_\pi$ in QCD for $N_F = 3 \rightarrow \phi = f_0(500)$
with $\langle \chi \rangle = \langle \bar{q}q \rangle \neq 0$ Crewther and Tunstall 2015



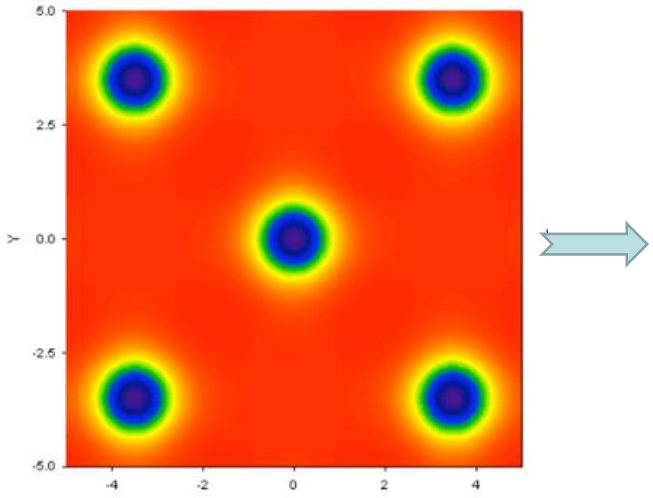
$$\theta^\mu_\mu = \frac{\beta(\alpha_s)}{4\alpha_s} G^2 + (1+\gamma_m) \sum_{q=u,d,s} m_q \bar{q} q$$

$\Rightarrow$ NG bosons π, K, η, σ.

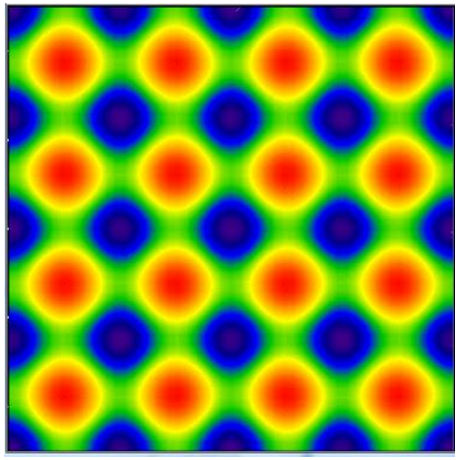
Topology Change

At $n=n_{1/2}$ skyrmions fractionize to half-skyrmions
This is a ***robust*** prediction

Goldhaber/Manton, Gudnason/Nitta



skyrmions



Half-skyrmions

Scenario for $n > n_{1/2}$

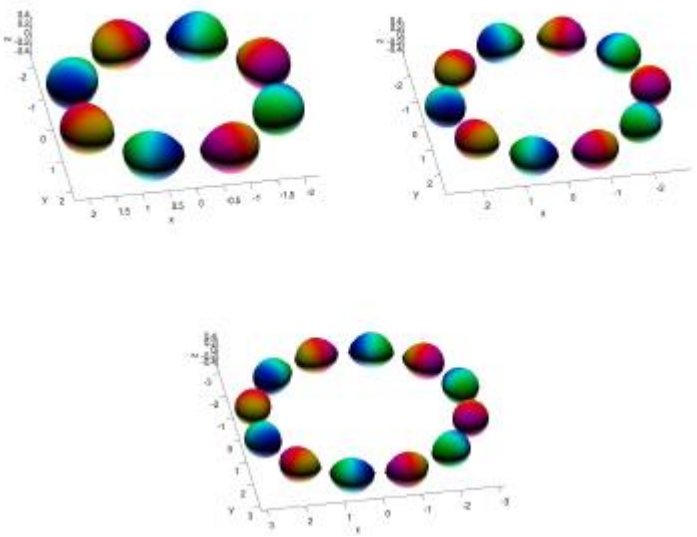
Gudnason and Nitta, PRD 91 (2015)

Break chiral symmetry explicitly

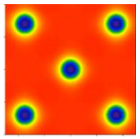
$$SU(2)_L \times SU(2)_R \to SU(2)_{L+R} \to O(2)$$

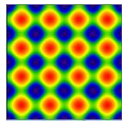
$$V(U) = m^2 n_4^2, \quad U \equiv \mathbf{n} \cdot \mathbf{t}$$

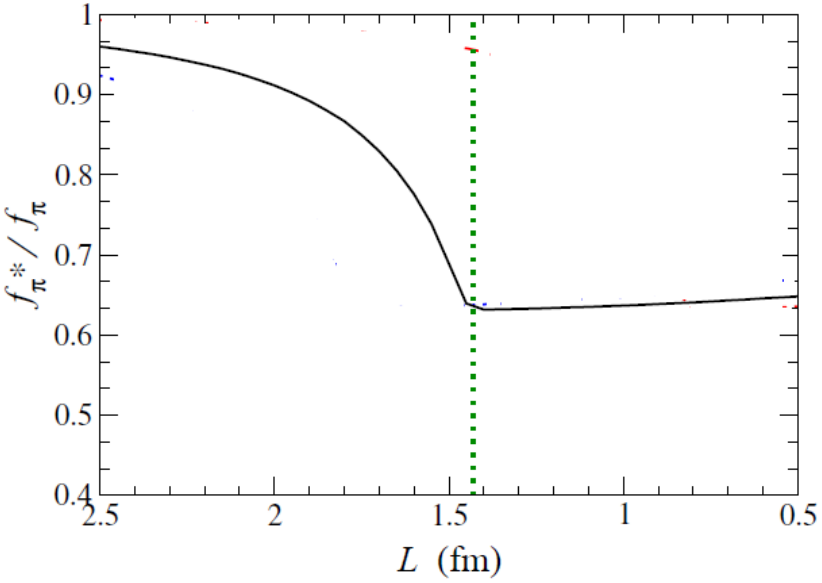
Half-skyrmion molecules A=4,5,6

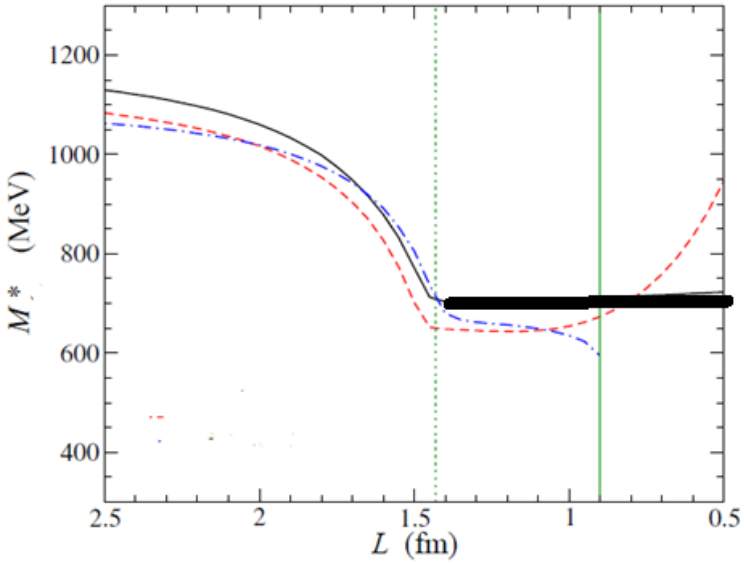


Topology ***change:*** Skyrmions → ½ -skyrmions in dense matter









$m_N \rightarrow$ ~ 800 MeV

as $\Sigma \rightarrow 0$.

Where the mass comes from???

Skyrmion is a "***magnetic monopole***"
in "hidden $U(1)_\zeta$ symmetry"

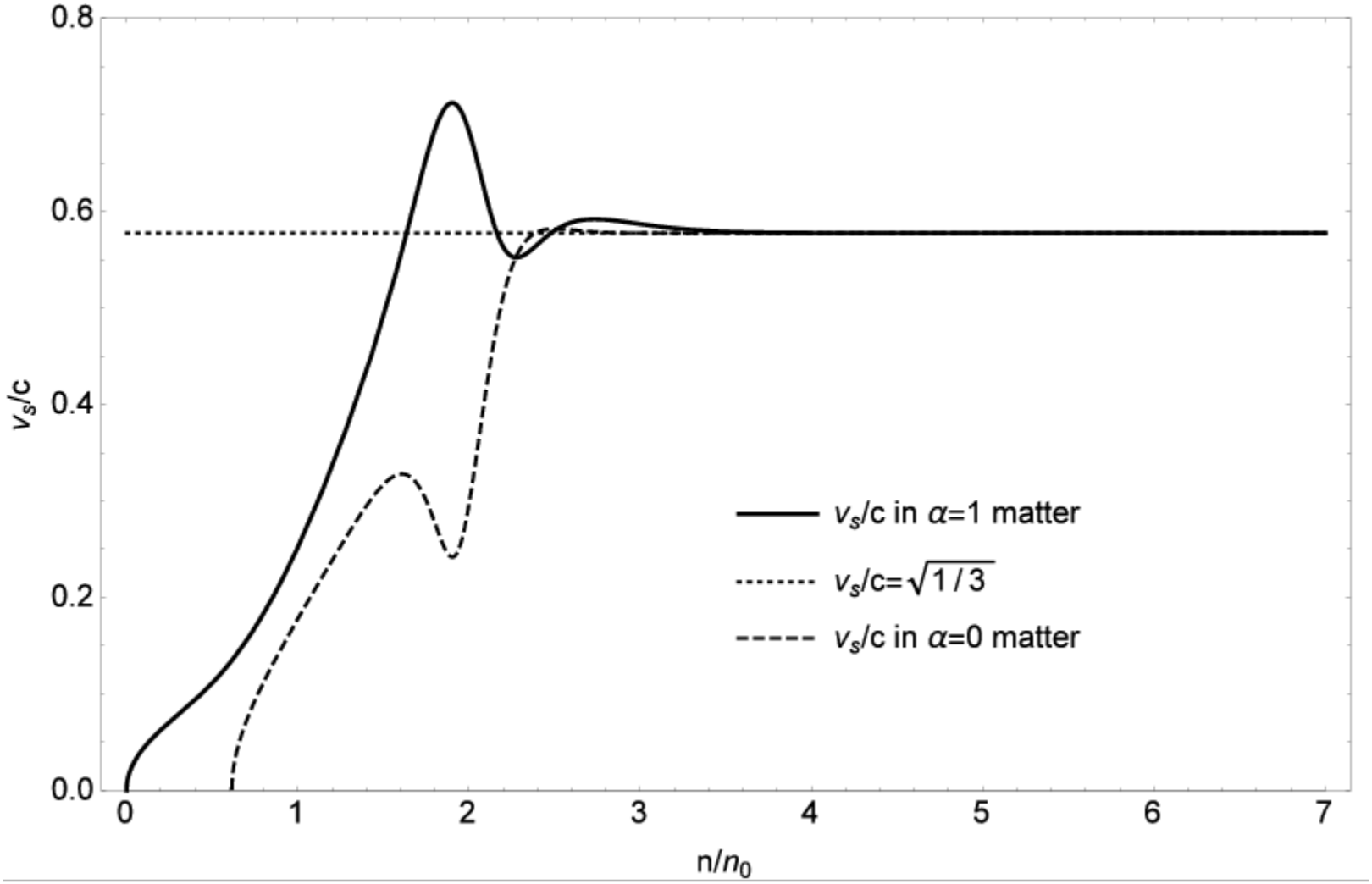
For $n < 2n_0$. skyrmion matter =*Fermi liquid pierced with "monopole"* flux and for $n > 2n_0$, half-skyrmion matter =*Fermi liquid pierced with "meron" or "dyon"* flux.

$(v_s/c)^2 \to 1/3$ and $\theta_\mu{}^\mu = \partial_\mu D^\mu = 0$ with $f_\phi = f_\pi \neq 0$.

Emergent symmetry!

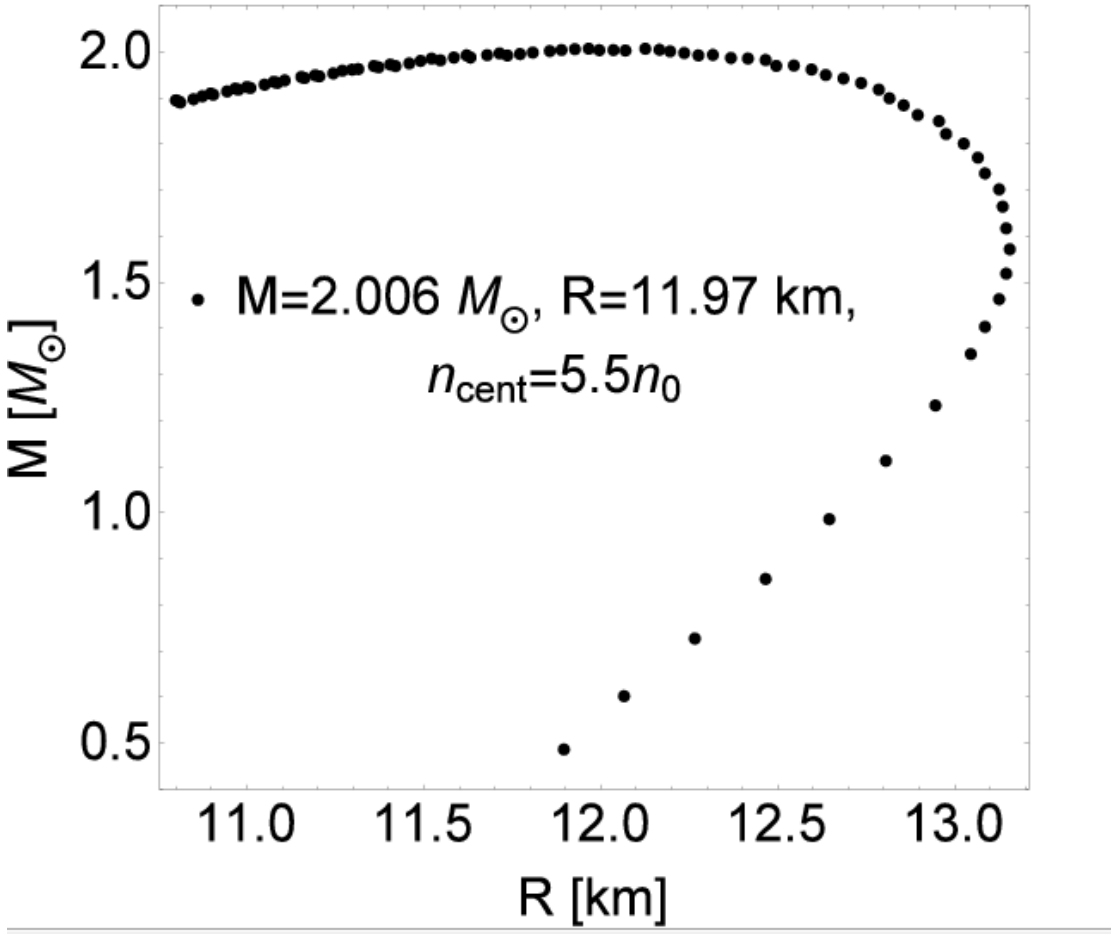
Precursor to ***conformal invariance***!(?)

Won-Gi Paeng



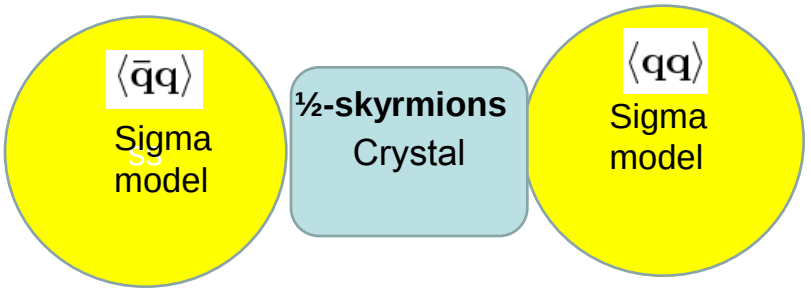
TOV

Won-Gi Paeng



Conclusion: Cheshire Cat at work
Deconfined quantum critical?

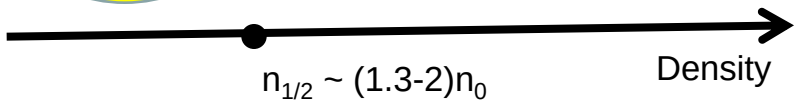
(A)



Hong, Zahed, R. (1999)

"superqualiton"

duality



(B) Baryons→ Quarkyonic→ CFL

Fukushima, Kojo 2016