From Quarks to Nuclei to Compact Stars and Back

Formulating nuclear physics from first principles

Mannque Rho, Saclay

Chiral Nuclear Dynamics II

From Quarks to Nuclei to Compact Stars

Mannque Rho

World Scientific

Weinberg ‘folk theorem’

(‘F-theorem’)

“What is quantum field theory, and what did we think it is?” hep-th/9702027.

“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.

‘F-theorem’ continued

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. ... “

“F-proof”: It’s hard to see how it can go wrong

‘F-Corollary’

“Effective field theory was first used in this way to calculate processes involving soft π mesons, that is, π mesons with energy less than about $2\pi F_\pi \sim 1200$ MeV. The use of effective quantum field theories has been extended more recently to nuclear physics where although nucleons are not soft they never get far from their mass shell, and for that reason can be also treated by similar methods as the soft pions.

‘F-Corollary’ continued

Nuclear physicists have adopted this point of view, and I gather that they are happy about using this new language because it allows one to show in a fairly convincing way that what they've been doing all along is the correct first step in a consistent approximation scheme.”

Outline

- 1970's – 1980's: Cheshire cat, confinement - deconfinement, MIT bag ↔ Stony Brook "little bag" ↔ skyrmions
- 1990's: Weinberg "F-theorem": quarks to hadrons to nuclei to dense/hot matter to neutron stars and black holes
- 2000's: Holographic duality, back to Cheshire cat.

Objective of Fundamental Principles in Nuclear Physics

- Recover and sharpen the standard nuclear physics approach, put it in the framework of the Standard Model.
- Make precise predictions that play a key ingredient in other areas of science, e.g., solar evolution and neutrino mass.
- Quest for new states of matter created under extreme conditions

QCD is the First Principle

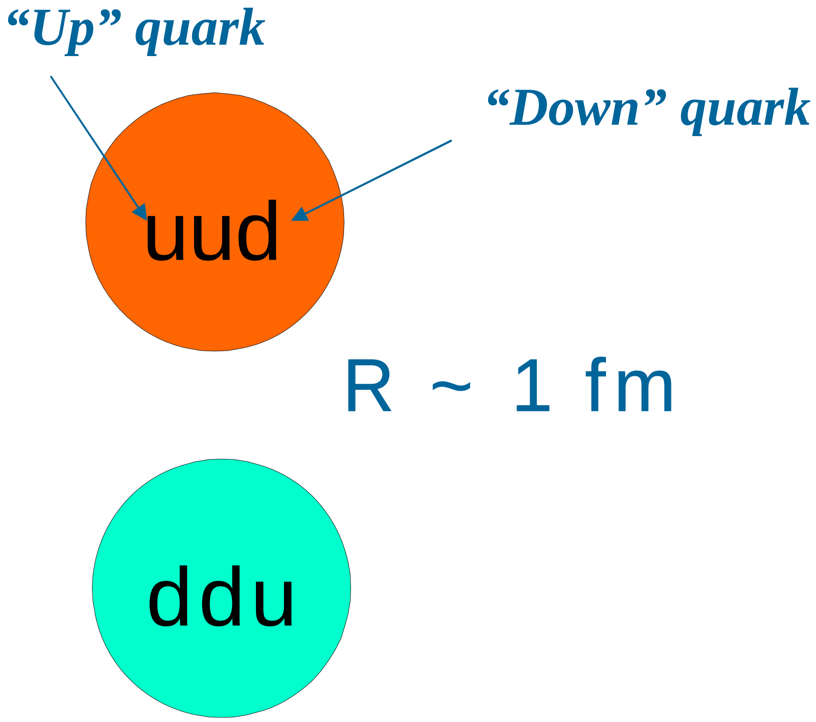
$$\mathcal{L}_{QCD} = \overline{\psi}(i\gamma_\mu D^\mu - M)\psi - \frac{1}{2} Tr G_{\mu\nu} G^{\mu\nu}$$

QCD Nucleon

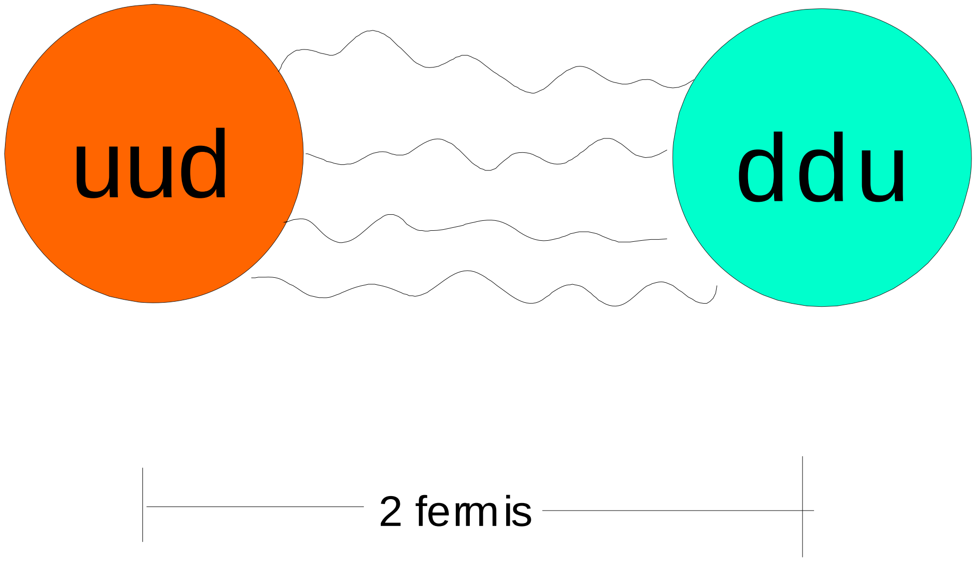
MIT Bag (1970's)

Proton

Neutron



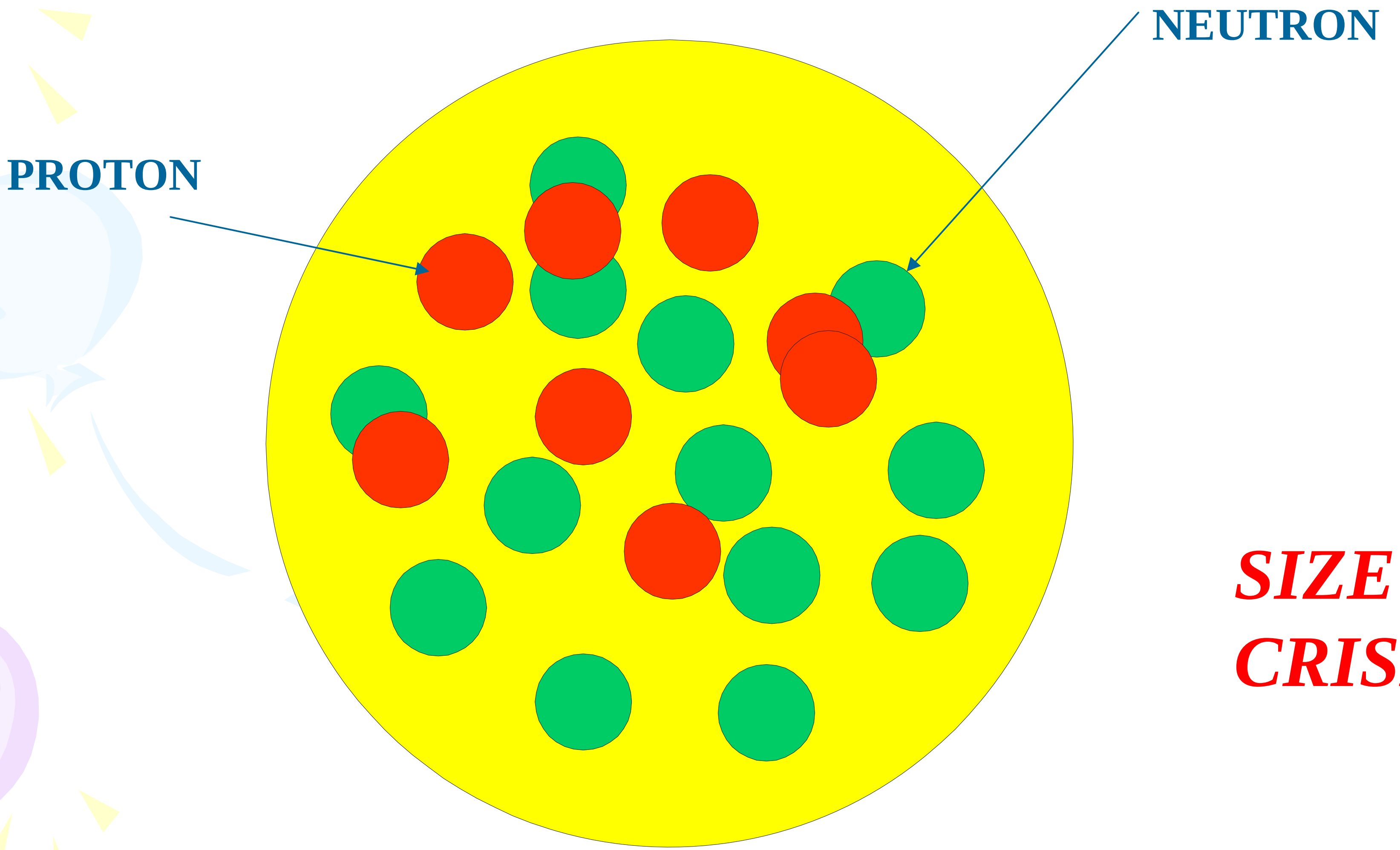
DEUTERON



Do the bags of R ~ 1 fm overlap?

Heavy Nucleus

Grapefruits in the salad bowl !!!???

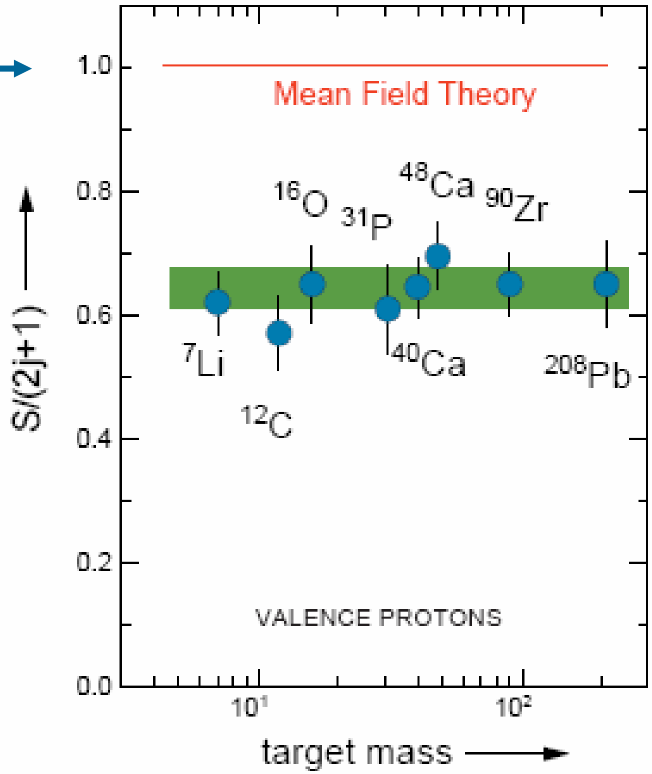


SIZE CRISIS?

Size Problem

- MIT bags ⇨ pea soup in ^{208}Pb ?

But shell model →



Spectroscopic Factor ~ single particleness

Something amiss

A Way out

Cheshire cat

⇕

"Origin" of the proton mass

Cheshire Cat

Alice in the wonderland

↔

↔

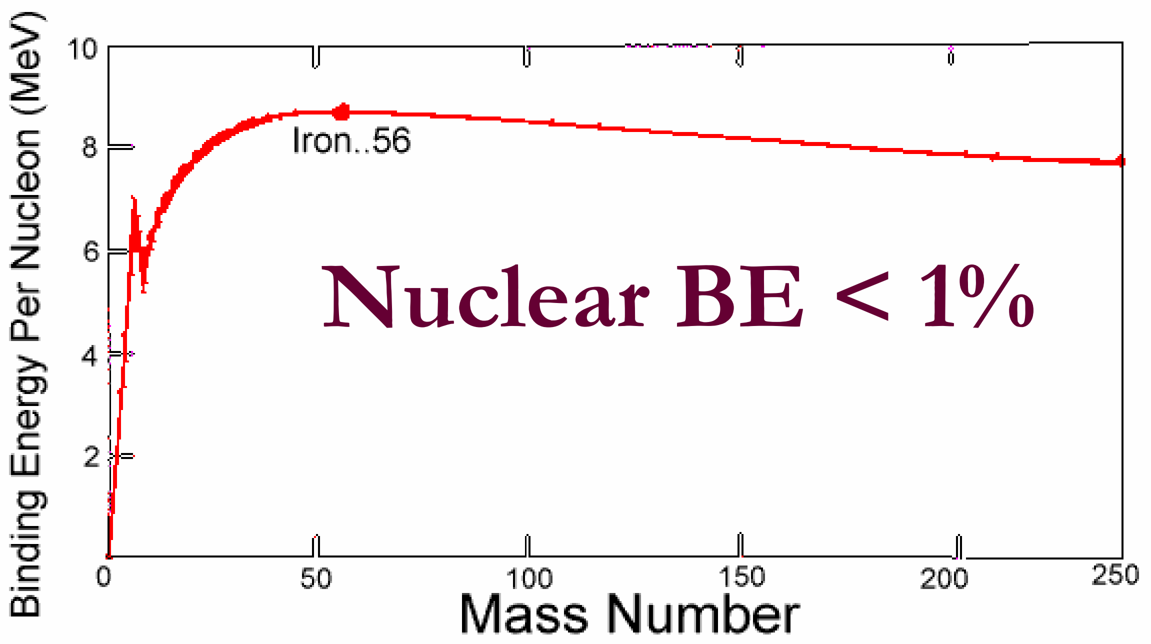
Where does the mass come from?

For Molecules, Atoms, Nuclei

Constituents: protons, neutrons, electrons

Masses =sum of masses of constituents

+ tiny binding energy



A 'Mass' Problem

- Proton/Neutron Mass=938/940 MeV

Constituents: Quarks and gluons

- Proton= uud ; Neutron= udd

Sum of "current-quark" masses ≈ 10 MeV

Where do ~ 99% of the mass come from?

QCD Answer

- QCD on lattice explains the proton mass within ~ 10% .

F. Wilczek *“ Energy stored in the motion of the (nearly) massless quarks and energy in massless gluons that connect them”*

⇨ Proton mass ≈ 1 GeV

“Mass without mass”

- Technically, “chiral symmetry spontaneously broken (χSB)”

à la Nambu/Goldstone

Order Parameter

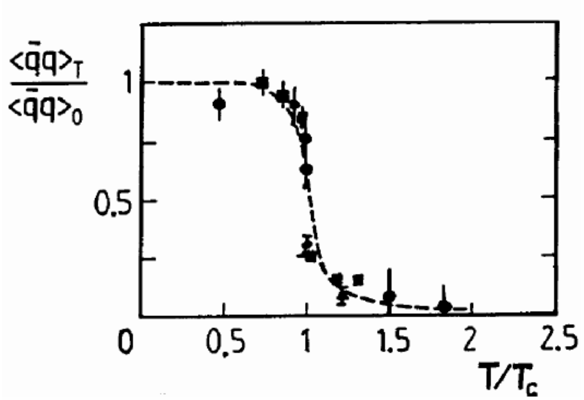
Quark condensate: $<\bar{q}q>$

$\neq 0$ χS broken

$= 0$ χS restored

- $<\bar{q}q> \approx -(0.23 \pm 0.03\ \text{GeV})^3 \rightarrow$ Proton mass $\approx$ 1 GeV
- Mass disappears when $<\bar{q}q> \rightarrow 0$?

Lattice QCD



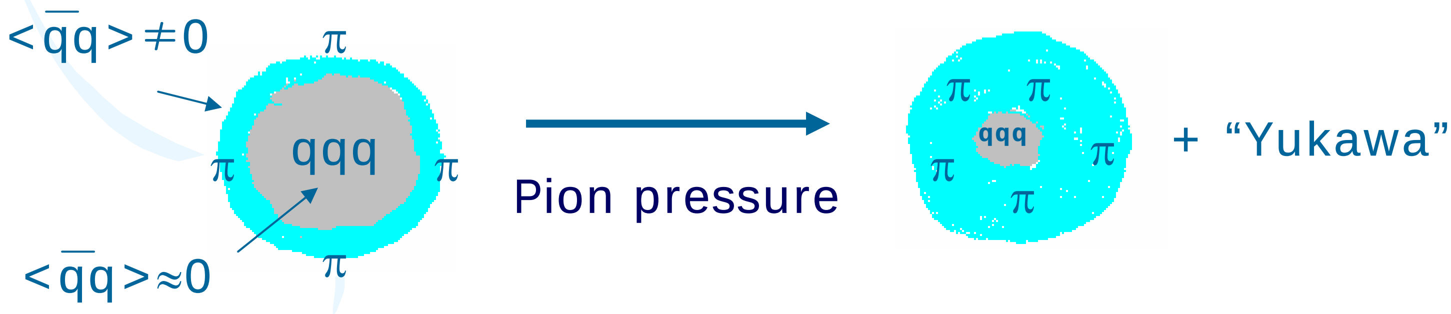
Stony Brook "Little Bag"

G.E. Brown and MR 1979

Shrink the bag to ~ 1/3 fm from ~ 1 fm

- How?

χSB → pions as (pseudo)Goldstone bosons



- This reasoning was *not* quite correct!

Enter Cheshire Cat in *Infinite Hotel*

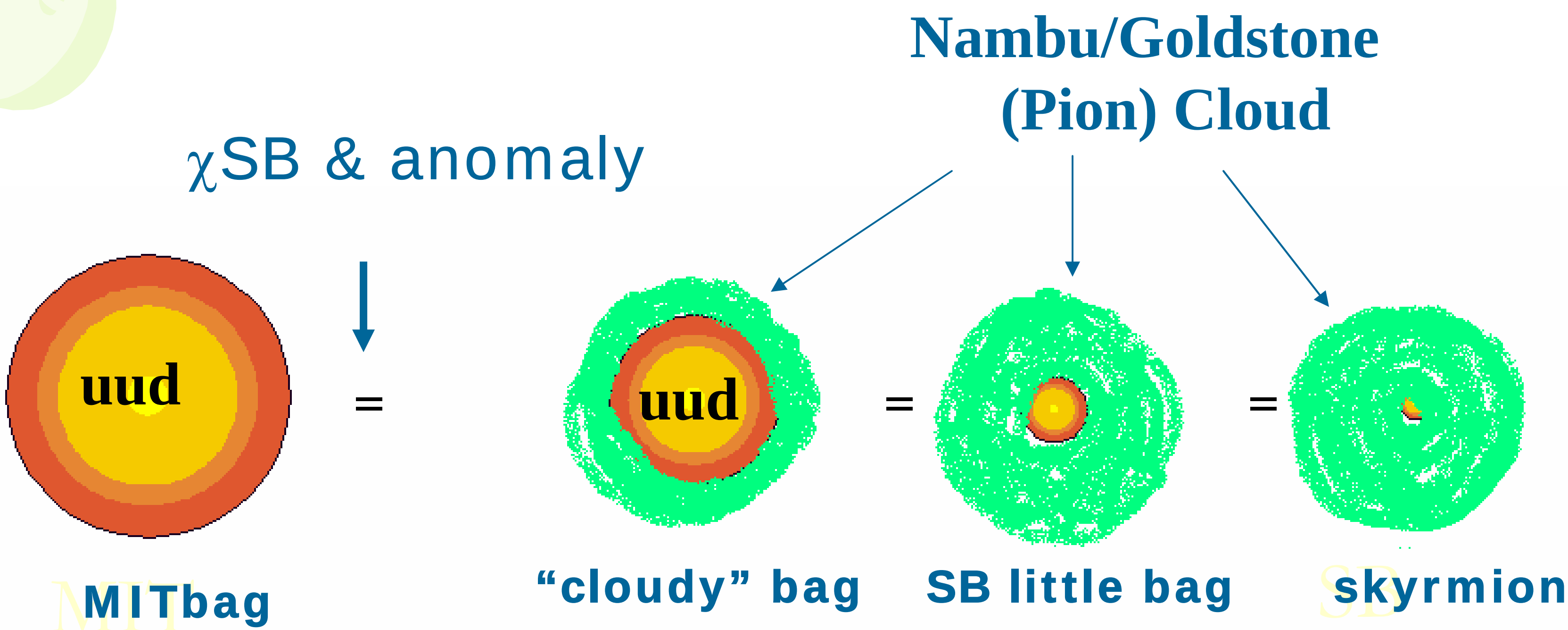
Nadkarni, Nielsen and Zahed 1985

- Bag radius (confinement radius) is a *gauge* ("redundant") degree of freedom

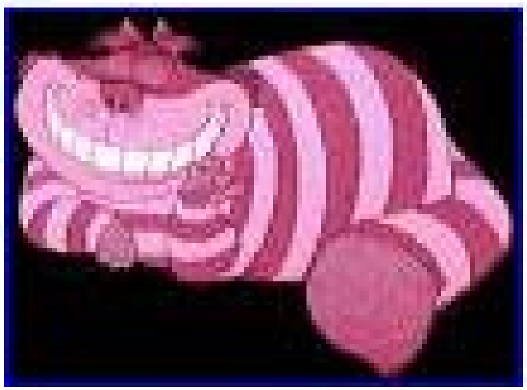
$\therefore$ Low-energy physics should not depend upon the bag or confinement size

- R can be shrunk to zero $\rightarrow$ skyrmion

Quarks/gluons ⟺ **"Smile of the Cheshire Cat"**



Equivalent description of the proton

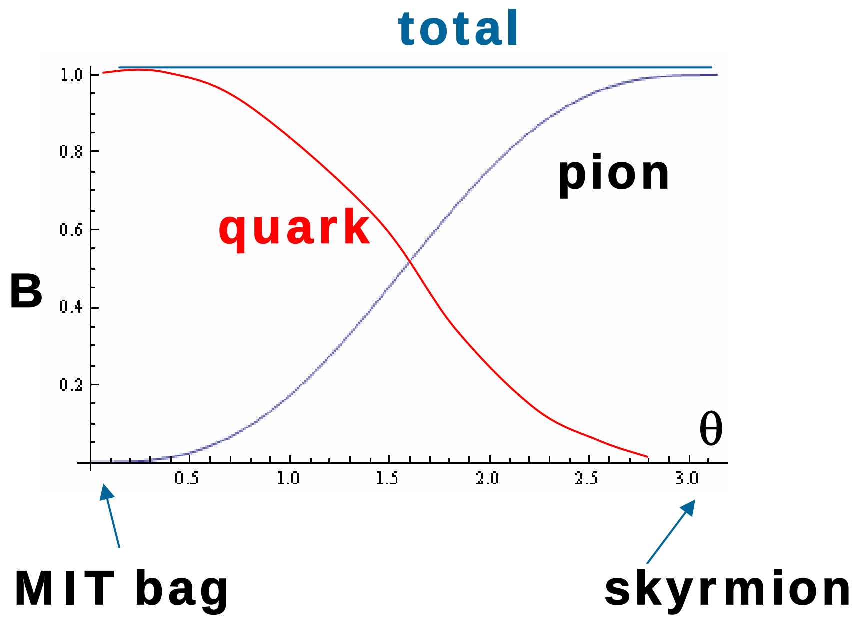


MIT

Stony Brook

Baryon Number

❖ Topological invariant



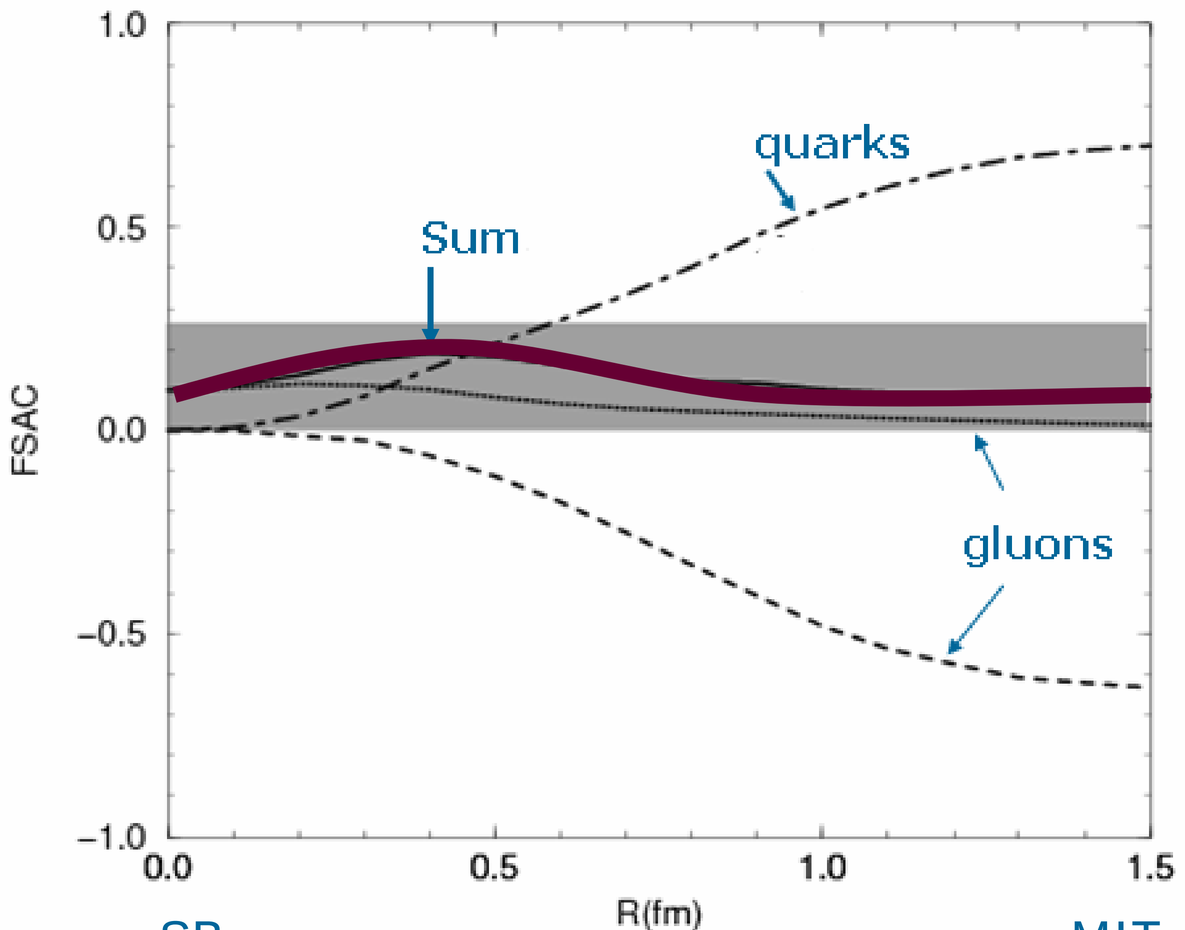
$$L_{QCD} = \bar{\psi}(i\gamma_\mu D^\mu - m)\psi - \frac{1}{2}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu}$$

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

$$U = \exp(i\tau \bullet \pi / f_\pi)$$

g_A^0 ~ "Proton spin"

Non-topological ~ dynamical

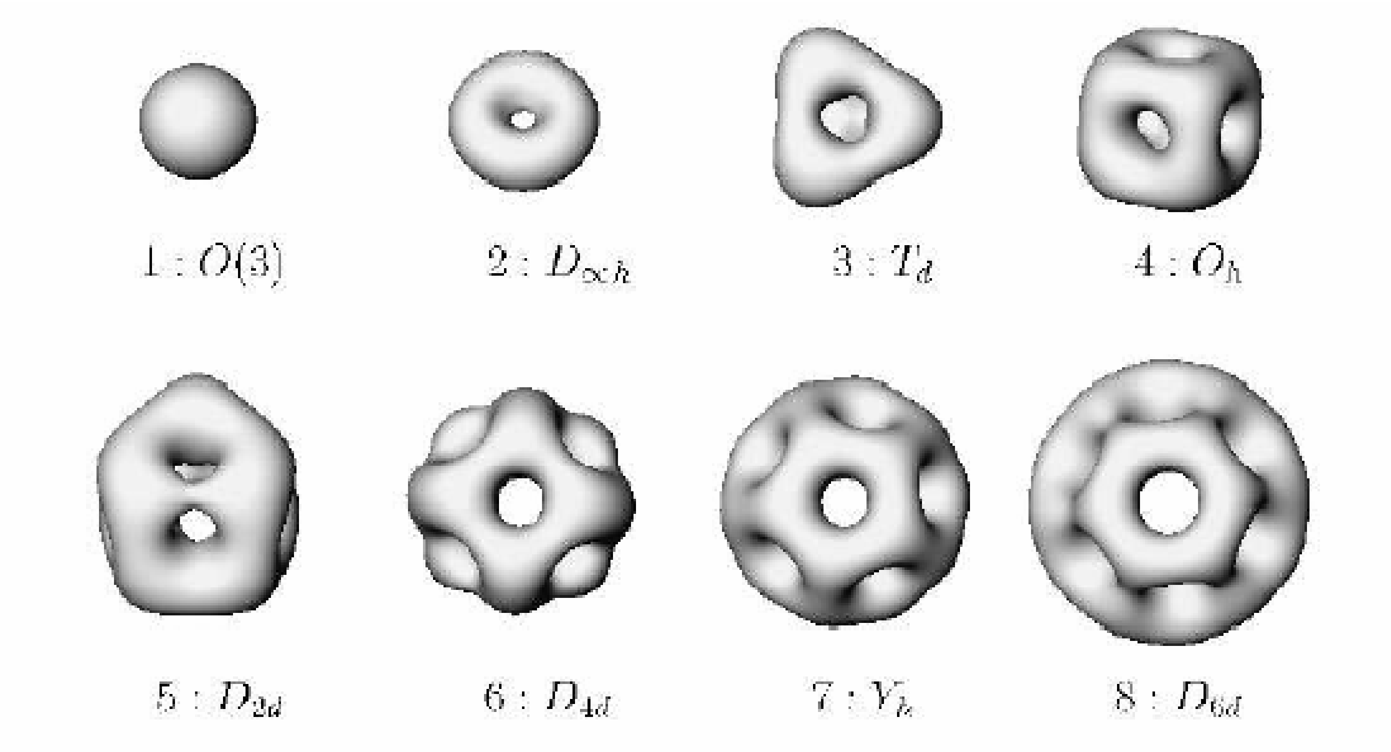


SB

MIT

Nuclei as skyrmions

Manton, Sutcliffe et al 2008



Classical, need to be quantized (in progess)

‘F-theorem’ applied to nuclei

Relevant degrees of freedom: Low-mass hadrons

π (140), ρ (770), ω (780), ..., N (940)

- For $E \ll m_\pi (140) \ll m_N (940)$

$\mathcal{L}_N = N^\dagger (i\partial_t + \nabla^2/2M) N + c(N^\dagger N)^2 + \ldots$ *“Pionless Lagrangian”*

Local field

galilean invariance etc.

- For $E \sim m_\pi \ll m_N$

$\mathcal{L} = \mathcal{L}_N + \mathcal{L}_\pi + \mathcal{L}_{\pi N}$

$\mathcal{L}_\pi = (f_\pi^2/4)\, \mathrm{Tr}(\partial_\mu U \partial^\mu U^\dagger) + \ldots$ $\quad U = \exp(2i\pi/f_\pi)$

Chiral invariance, Lorentz invariance ..

Strategy Chiral Lagrangian

- Pions play a crucial role à la Weinberg
- Applicable for E < $m_\rho = 770$ *MeV*
- Match to highly sophisticated ‘standard nuclear physics approach’ refined since decades:

Weinberg F-corollary “ ... *it allows one to show in a fairly convincing way that what they've been doing all along is the correct first step in a consistent approximation scheme*”

1990 – 2000 : QCD to EFT of nuclei

How does it fare with Nature?

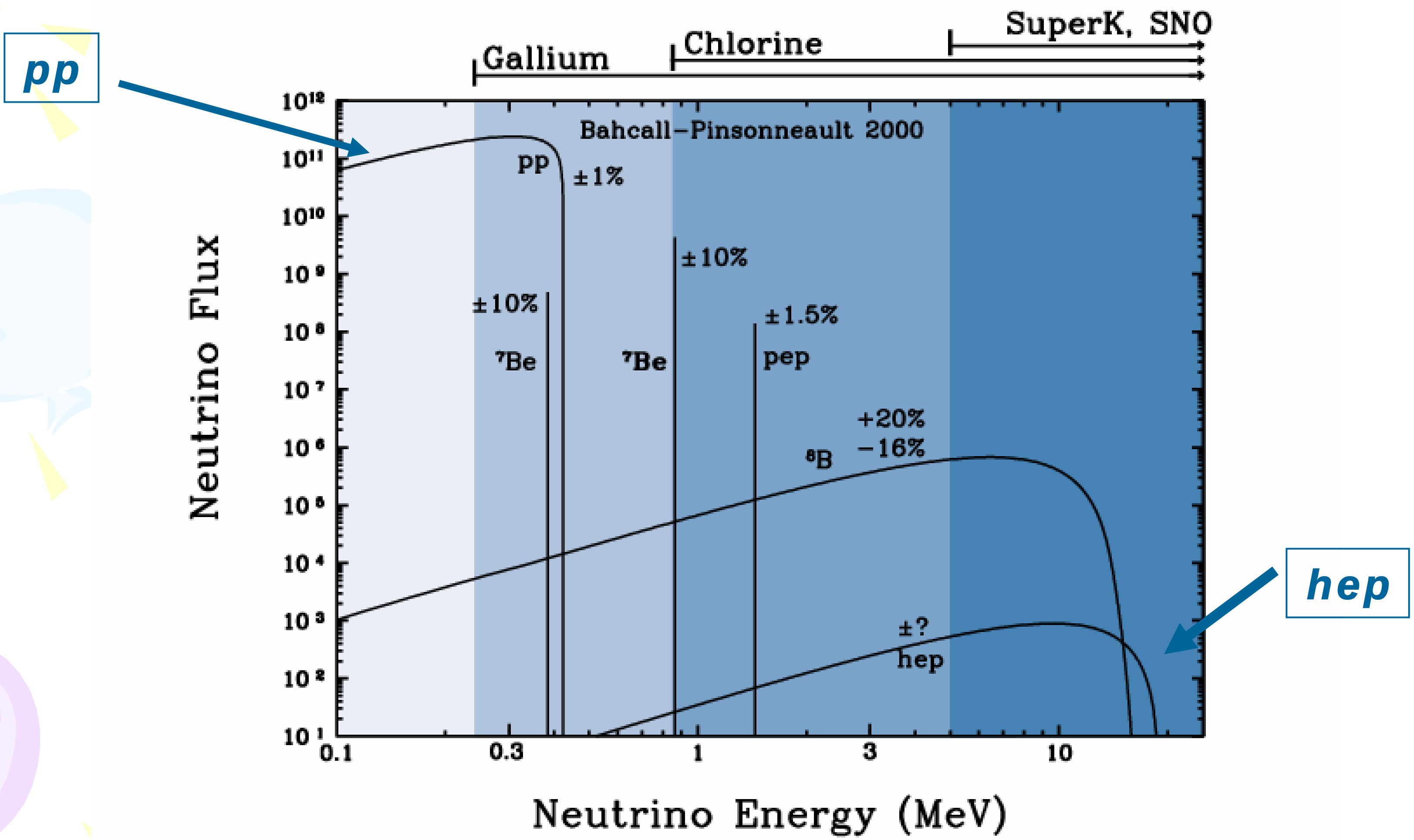
- *Parameter free calculations*
  accurate to better than 97%

  - Thermal $n+p \rightarrow d+\gamma$:
    $\sigma^{th} = 334 \pm 2$ mb (exp: 334.2 ± 0.5 mb)
  - $\mu^- + {}^3He \rightarrow \nu_\mu + {}^3H$
    $\Gamma^{th} = 1499 \pm 16$ Hz (exp: 1496 ± 4 Hz)
  - $\mu^{th}({}^3H) = 3.035 \pm 0.013$ (exp: $2.979 \pm$.....)

    $\mu^{th}({}^3He) = -2.198 \pm 0.013$ (exp: $-2.128 \pm$.....)

- *Predictions: solar neutrinos*

Solar Neutrino Spectrum



Tortuous History of *hep* Theory

1950-2001

S-factor in 10^{-20} MeV-b unit

'52 (Salpeter)	630	Single particle model
'67 (Werntz)	3.7	Symmetry group consideration
'73 (Werntz)	8.1	Better wave functions (P-wave)
'83 (Tegner)	4~25	D-state & MEC
'89 (Wolfs)	15.3±4.7	Analogy to ^{3}He+n
'91 (Wervelman)	57	^{3}He+n with shell-model
'91 (Carlson et al.)	1.3	VMC with Av14
'92 (Schiavilla et al.)	1.4-3.1	VMC with Av28 (N+Δ)
'01 (Marcucci et al.)	9.64	CHH with Av18 (N+Δ) + *p*-wave

Serious wave "function overlap" problem

Bahcall's challenge to nuclear physics

J. Bahcall, hep-ex/0002018

"The most important unsolved problem in theoretical nuclear physics related to solar neutrinos is the range of values allowed by fundamental physics for the *hep* production cross section"

Predictions

T.S. Park et al, 2001

Solar neutrino processes

- $p + p \rightarrow d + e^{+} + \nu_e$

$S_{pp} = 3.94 x (1 \pm 0.0025)$ x 10^{-25} MeV-b

- $p + {}^{3}He \rightarrow {}^{4}He + e^{+} + \nu_e$

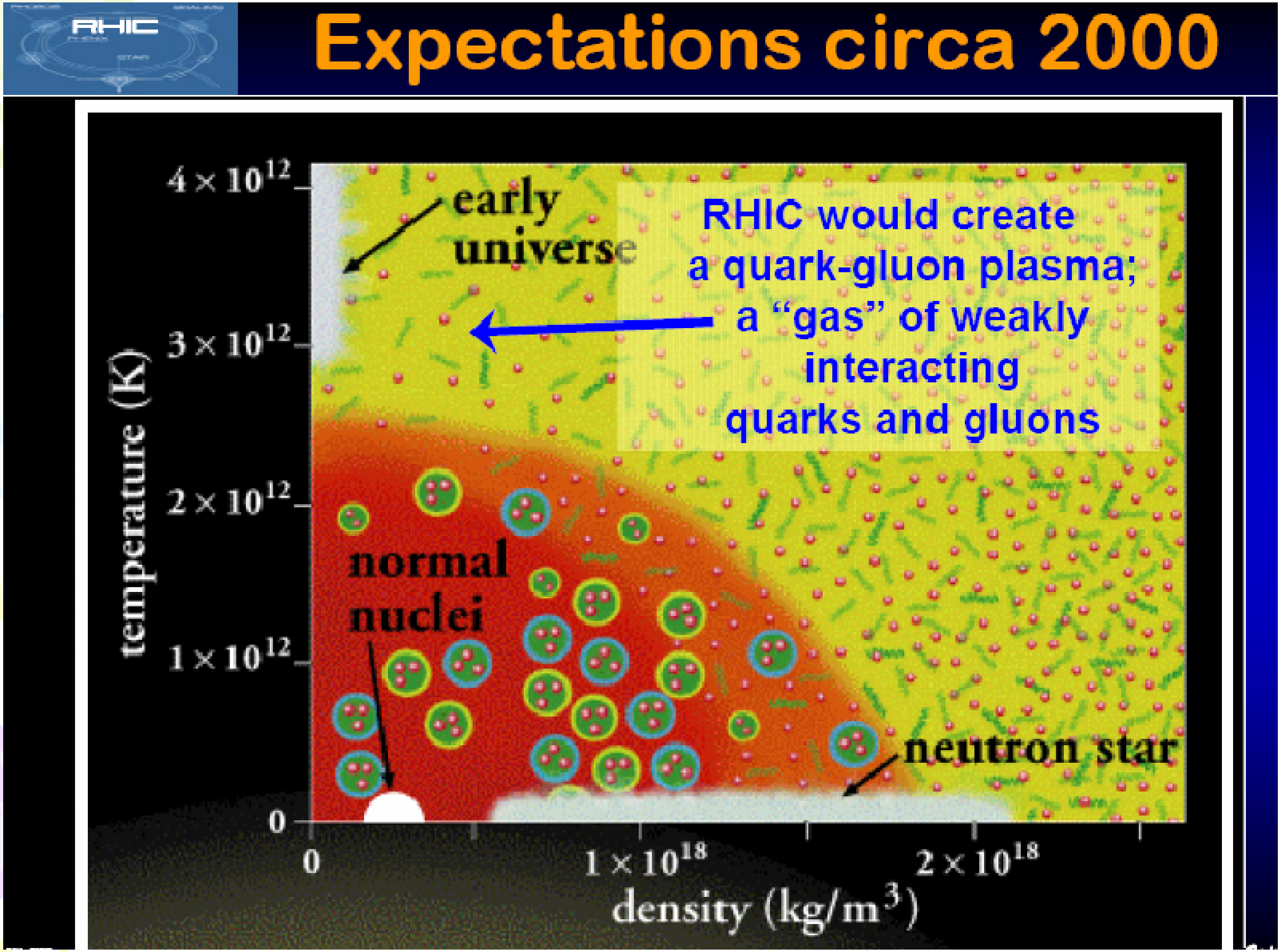
$S_{hep} = (8.6 \pm 1.3)$ x 10^{-20} keV-b

Awaits experiment!

Matter under extreme conditions

Quest for new states of matter – New physics

‘Phase diagram’



What happens as $\langle \bar{q}q \rangle \to 0$?

One possibility is that other light degrees of freedom than the pions start figuring

Hidden/emergent gauge symmetries

- At very low energies, only pions figure

$\mathcal{L} = (f_\pi^2/4)\mathrm{Tr}[\partial^\mu U \, \partial_\mu U^\dagger] + \ldots$ "Current algebra"

$U = \exp(2i\pi/f_\pi) \in SU(N)_L x SU(N)_R / SU(N)_{V=L+R}$

Nucleons emerge as skyrmions

- As energy increases, exploit "gauge symmetry"

Vector mesons ρ, ρ', ..., ω, ω', ... figure with dropping masses à la Brown-Rho

Nucleons emerge as instantons or skyrions

Gauge symmetry is a redundancy

Famous case: ***charge-spin separation*** of electron

e(x)≡ electron, f(x)≡ "new electron," b(x)≡ "boson"

$$e(x) = b(x)\, f^{+}(x)$$

- Invariance: $b(x) \to e^{ih(x)} b(x),\ \ f(x) \to e^{ih(x)} f(x)$
- Endow with a gauge field: $a_\mu \to a_\mu + \partial_\mu h(x)$

"emergent" gauge filed

What we are concerned with

- Emerging ρ (770) (and ω)

$$U(x) = e^{2i\pi(x)/f_\pi} = \xi_L^+ \xi_R, \ \xi_{L/R} = e^{i\sigma(x)/f_\sigma} e^{\mp i\pi(x)/f_\pi}$$

- Invariance under $\xi_{L/R} \to h(x)\xi_{L/R} \quad h(x) \in SU(N)_{L+R}$
- "Emergent" SU(N) gauge fields $\rho_\mu \to h(x)(\rho_\mu + i\partial_\mu)h^+(x)$

Excitation energy → m_ρ ~ 800 MeV

Bando et al 1986
Harada & Yamawaki 2003

Emerging "infinite tower" of vectors

ρ, ρ', ..., ω, ω', ..., a_1 ...

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

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

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

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

- This form descends ALSO from string theory!
- Harada-Yamawaki theory is a truncated HLS theory at the lowest vector mesons ρ, ω.

Matching HLS to QCD

Masayasu Harada &
Koichi Yamawaki
Phys. Rep. 381 (2003) 1-233

QCD (quarks, gluons)

(T,n) $\Lambda \approx 1\,GeV$ "matching scale"

EFT (pions, vector mesons …)

Wilsonian renormalization group flow

$T \rightarrow T_c$

$n \rightarrow n_c$

"Vector manifestation (VM)" fixed point

Vector Manifestation

In the chiral limit

$$As\ (T,n) \to (\mathrm{T_c}, n_c)$$

$$m_\rho \sim g \sim m_{\text{const quark}} \propto \langle \bar{q}q \rangle \to 0$$

$$f_\pi = g = m_\rho = m_\pi = 0$$

"VM fixed point"

$$a = 1$$

→ All light-quark hadrons lose mass at the VM point

"VM (or BR) scaling"

VM scaling in nuclei?

Dropping mass tagged to $\langle \bar{q}q \rangle$
Precursor in nuclear structure

- ❖ Warburton ratio
- ❖ carbon-14 dating
- ❖ others

Warburton Ratio ε_{MEC}

E. Warburton 91

Warburton defined/measured in nuclei

$$\varepsilon_{MEC} \equiv \langle f \,|\, A_0 \,|\, i \rangle_{\exp} \,/\, \langle f \,|\, A_0 \,|\, i \rangle_{impulse\ approx}$$

for the weak axial-charge transition

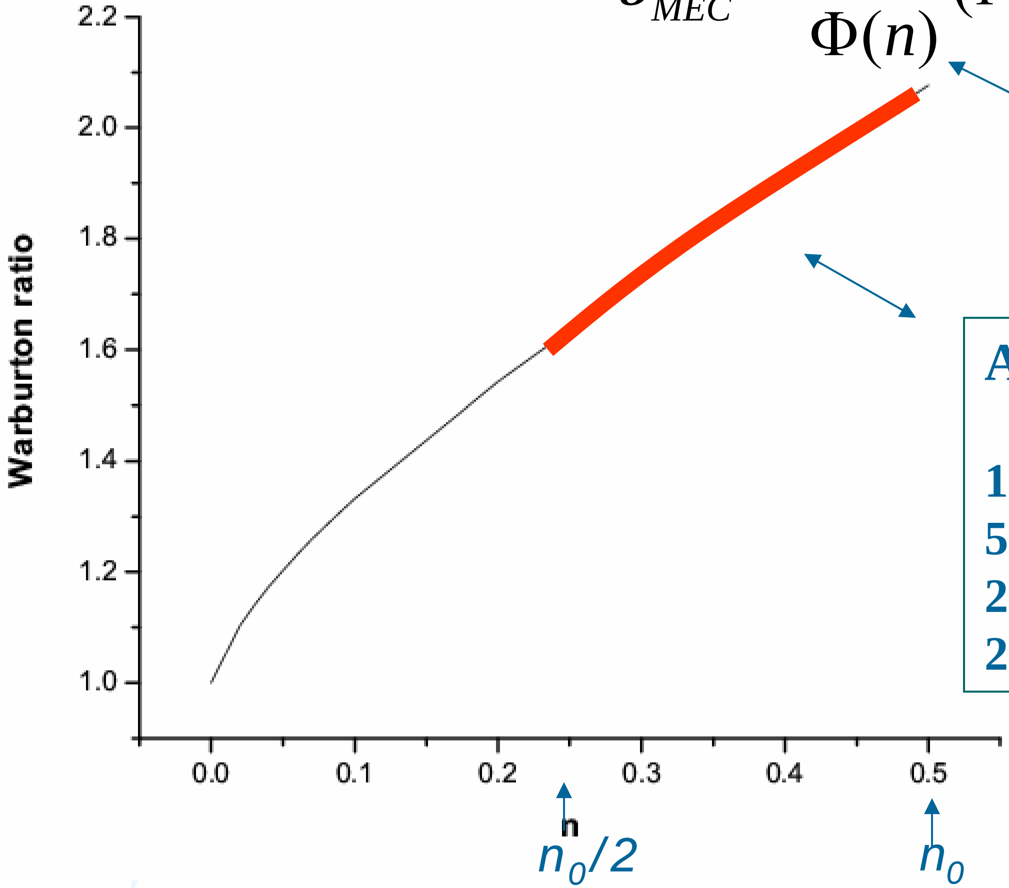
$$A(J^{+/-}) \rightarrow A(J^{-/+})\, e\, \nu \quad \Delta T = 1$$

Found large enhancement in heavy nuclei

$$\varepsilon_{MEC} = 1.9 \leftrightarrow 2.1$$

Prediction

$$\varepsilon^{th}_{MEC} = \frac{1}{\Phi(n)}(1+\kappa_{pion}(n))$$



BR scaling

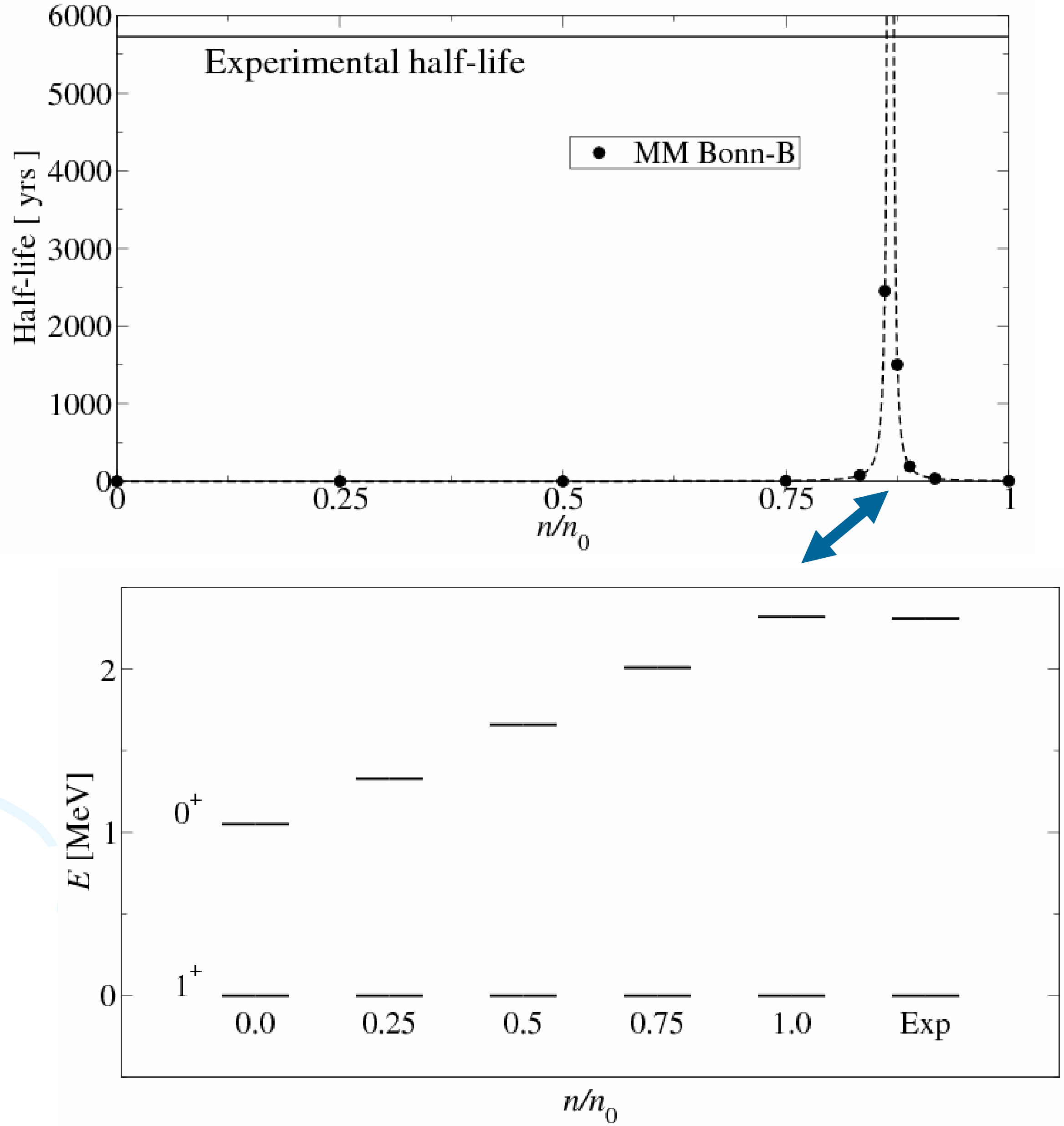
In units of m_π^3

A	Exp
12	1.64±0.05
50	1.60±0.05
205	1.95±0.05
208	2.01±0.10

Carbon-14 dating

Tensor force fine-tuned by BR scaling!

Holt et al 2008



Hadronic matter at high temperature and/or density

Large efforts in heavy-ion collisions at CERN and RHIC

But no smoking gun signal yet

Relegate to the future

High Density Regime

Compact stars
and
Black Holes

Questions:

- What happens as density increases to that of compact stars?
- Does hadronic physics matter for the collapse of stars?
- Are the plethora of high density matter observable?

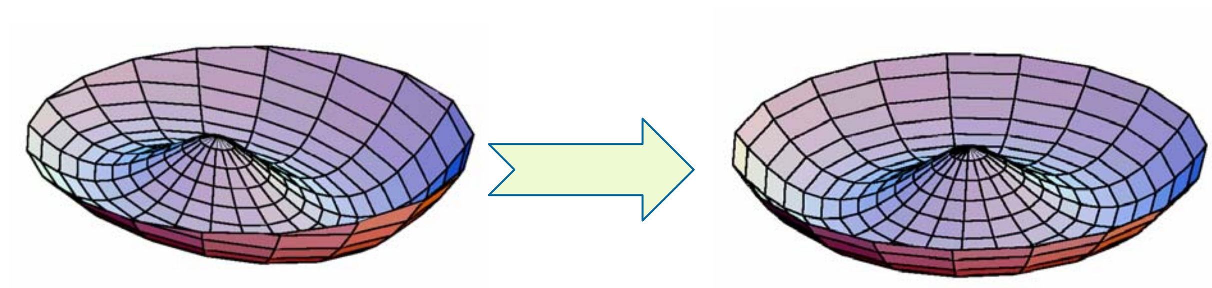
Assertion:

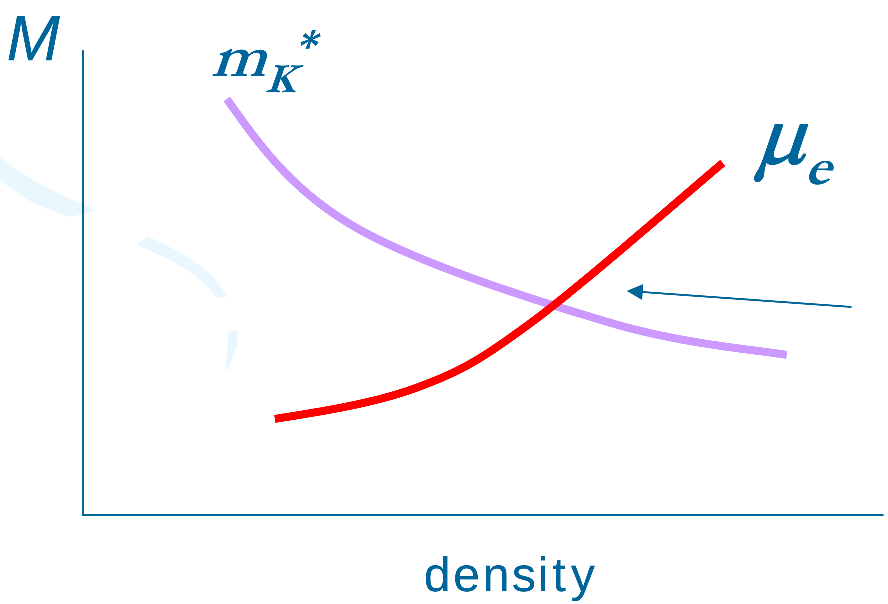
- The first – and possibly last (?) – phase change is that kaons condense at relatively low density

Kaons condense in compact stars

$m_\pi \sim 0, \; m_K \sim 1/2$ GeV

Dropping mass "restores" *SU(3)* symmetry





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

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

Kaons condense

Consequences

A scenario proposed

PRL **101**, 091101 (2008) PHYSICAL REVIEW LETTERS week ending 29 AUGUST 2008

Kaon Condensation, Black Holes, and Cosmological Natural Selection

G. E. Brown,[1] Chang-Hwan Lee,[2] and Mannque Rho[3]

[1]*Department of Physics and Astronomy, SUNY, Stony Btook, New York 11794, USA*
[2]*Department of Physics, Pusan National University, Busan 609-735, Korea*
[3]*Institut de Physique Théorique, CEA Saclay, 91191 Gif-sur-Yvette Cédex, France*

(Received 29 February 2008; published 28 August 2008)

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 $M \lesssim 2M_{\odot}$ 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

i. A lot of light-mass black holes in the Universe
ii. "BH-Nothingness" after kaon condensation

Bethe-Brown Mass

"Stars more massive than $M_{max}^{BB} \approx 1.6\ M_{\odot}$
collapse into black holes"

Why? Because such massive stars have condensed kaons which soften the EOS and trigger instability.

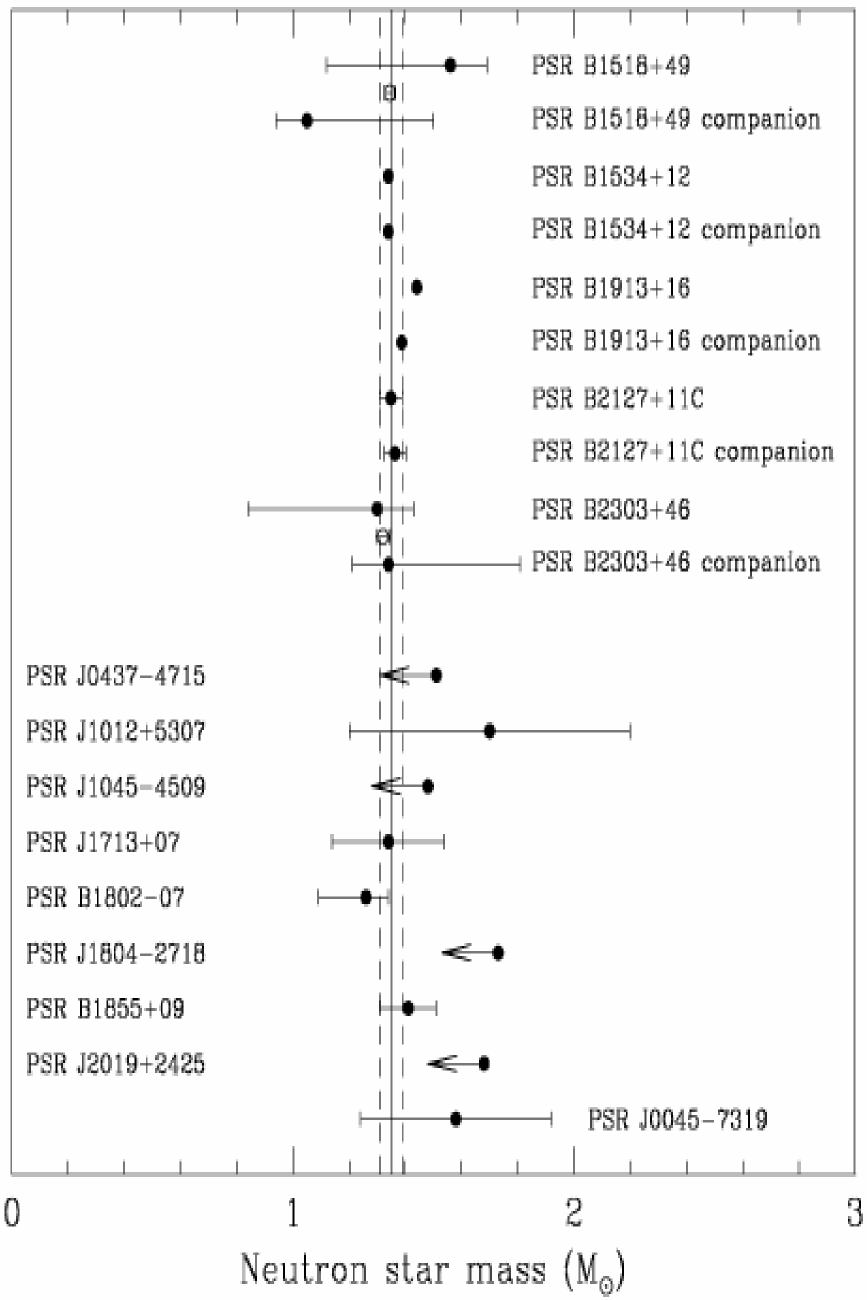
"No proof. It's a conjecture to be checked by nature ."

What to do?

a) "Find a compact star with mass $M > M_{max}^{BB}$ "
b) "Find binary pulsars with mass difference > 4%"

If found, the following will be invalidated

a) Maximization of black holes in the Universe
b) Mechanism for "Cosmological Natural Selection"
c) Kaon condensation, VM, "hadronic freedom"



X-ray Binaries			
4U1700−37	$2.44^{+0.27}_{-0.27}$	Vela X-1	$1.86^{+0.16}_{-0.16}$
Cyg X-1	$1.78^{+0.23}_{-0.23}$	4U1538−52	$0.96^{+0.19}_{-0.16}$
SMC X-1	$1.17^{+0.16}_{-0.16}$, 1.05 ± 0.09	XTE J2123−058	$1.53^{+0.30}_{-0.42}$
LMC X-4	$1.47^{+0.22}_{-0.19}$, 1.31 ± 0.14	Her X-1	$1.47^{+0.12}_{-0.18}$
Cen X-3	$1.09^{+0.30}_{-0.26}$, 1.24 ± 0.24	2A 1822−371	> 0.73
Neutron Star - Neutron Star Binaries			
1518+49	$1.56^{+0.13}_{-0.44}$	1518+49 companion	$1.05^{+0.45}_{-0.11}$
1534+12	$1.3332^{+0.0010}_{-0.0010}$	1534+12 companion	$1.3452^{+0.0010}_{-0.0010}$
1913+16	$1.4408^{+0.0003}_{-0.0003}$	1913+16 companion	$1.3873^{+0.0003}_{-0.0003}$
2127+11C	$1.349^{+0.040}_{-0.040}$	2127+11C companion	$1.363^{+0.040}_{-0.040}$
J0737−3039A	$1.337^{+0.005}_{-0.005}$	J0737−3039B	$1.250^{+0.005}_{-0.005}$
J1756−2251	$1.40^{+0.02}_{-0.03}$	J1756−2251 companion	$1.18^{+0.03}_{-0.02}$
Neutron Star - White Dwarf Binaries			
B2303+46	$1.38^{+0.06}_{-0.10}$	J1012+5307	$1.68^{+0.22}_{-0.22}$
J1713+0747	$1.54^{+0.007}_{-0.008}$	B1802−07	$1.26^{+0.08}_{-0.17}$
B1855+09	$1.57^{+0.12}_{-0.11}$	J0621+1002	$1.70^{+0.32}_{-0.29}$
J0751+1807	$2.20^{+0.20}_{-0.20}$	J0437−4715	$1.58^{+0.18}_{-0.18}$
J1141−6545	$1.30^{+0.02}_{-0.02}$	J1045−4509	< 1.48
J1804−2718	< 1.70	J2019+2425	< 1.51
Neutron Star - Main Sequence Binaries			
J0045−7319	$1.58^{+0.34}_{-0.34}$		

J0751+1807

Nice et al 2005

Observation in neutron star–white dwarf binary of $2.2 \pm 0.2\ m_\odot$ led to *pitched activities*

- ❖ strong repulsive N-nucleon forces (with $N \geq 3$)
- ❖ crystalline color-superconducting stars
- ❖ etc etc producing ~ one paper a week

This would unambiguously “kill” the BB conjecture

But (!) new analysis in 2007 corrects the 2005 value to 1.26+0.14/-0.12!!

BB still OK!

Summary

- We went to skyrmions from quarks
- We went to nuclei via skyrmions via F-theorem
- We went to compact stars via nuclear matter via hidden local symmetry
- Enter string theory:

Sakai and Sugimoto showed (2005) that hadrons at low energy $E < M_{KK}$ could be described by the 5D action ***top-down*** from AdS/CFT:

$$S = -\int d^4x dz \frac{1}{4e^2(z)} Tr[F_{AB}F^{AB}] + \bullet\bullet\bullet + S_{CS}$$

Arises also ***bottom-up*** from current algebra by "deconstruction"

Back to Cheshire Cat

Kim & Zahed 2008

Nucleon is an instanton in 5D≈ a skyrmion in 4D
In the infinite tower of vector mesons

Hong, Yee, Yi, R 2007; Hashimoto, Sakai, Sugimoto 2008

First confirmation of Sakurai's 1960's idea of VD

EM form factors

$$F_\pi(Q^2) = \sum_{n=0}^{\infty} \frac{g_{\rho_n} g_{\rho_n \pi\pi}}{Q^2 + m_{\rho_n}} \approx \frac{1}{1 + Q^2/m_V^2}$$ "Monopole"

$$F_N(Q^2) = \sum_{n=0}^{\infty} \frac{g_{\rho_n} g_{\rho_n NN}}{Q^2 + m_{\rho_n}} \approx \left(\frac{1}{1 + Q^2/m_D^2}\right)^2$$ "Dipole"

Numerically

$$\left.\begin{aligned} m_V &\approx m_\rho = 0.77\ \mathrm{GeV} \\ m_D &\approx 0.78\ \mathrm{GeV} \end{aligned}\right\}$$ Close to nature!!

Implications on
Heavy ions
Compact stars ?

Future

Thanks for the attention!