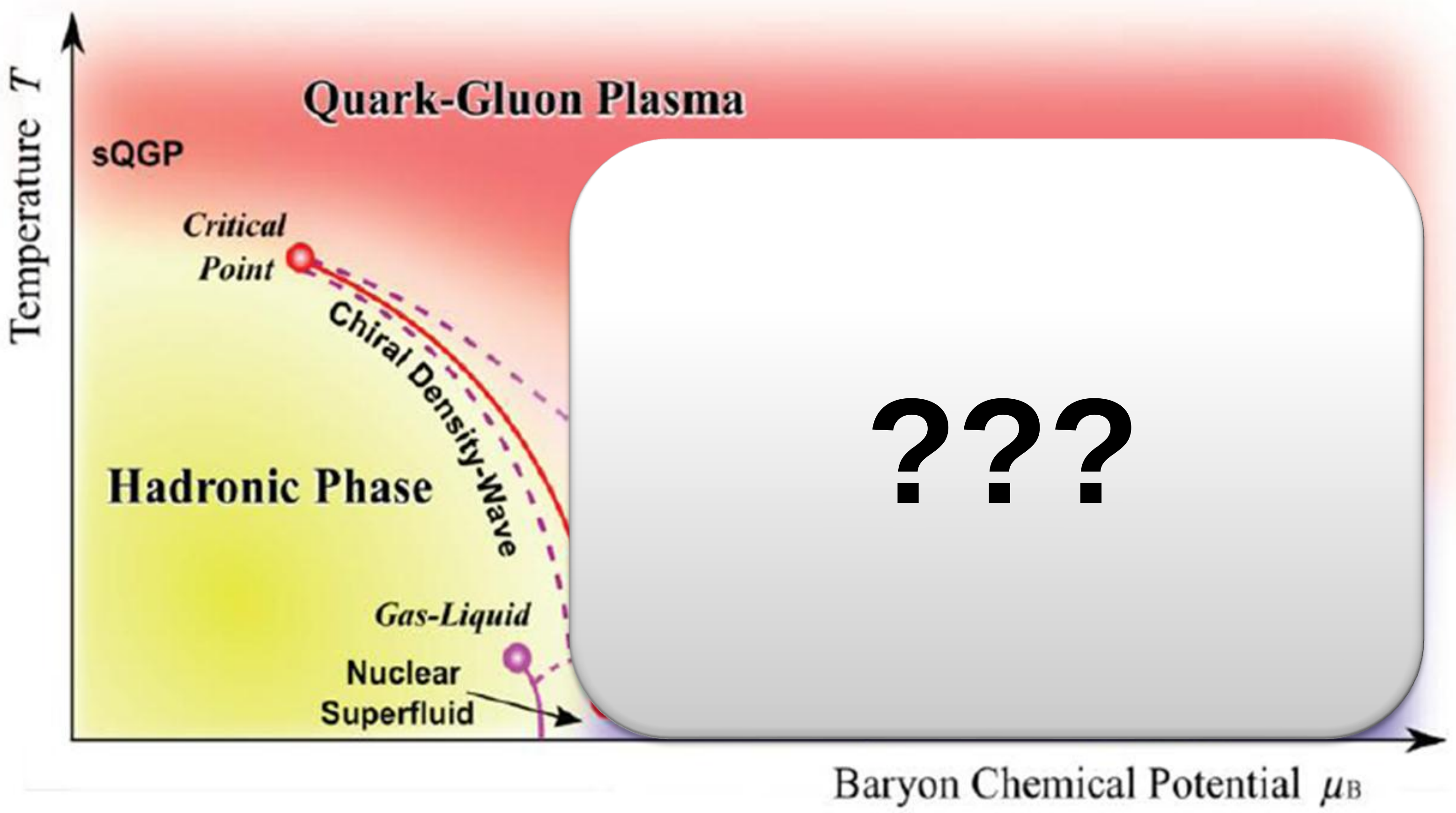
Proton Mass and EoS for Compressed Baryonic Matter

ATHIC 14/11/12

Mannque Rho
(Saclay and Hanyang)

QCD Phase



Temperature T
Quark-Gluon Plasma
sQGP
Critical Point
Chiral Density-Wave
Hadronic Phase
Gas-Liquid
Nuclear Superfluid
???
Baryon Chemical Potential μ_B

Next Era

KoRIA $\rightarrow$ FAIR $\rightarrow$ LIGO

EoS for T~ 60 MeV
& n ~ $4n_0$

Questions

- Now that the higgs-like boson ("H") is discovered, do we understand where the proton mass comes from?

  No

- Is there a connection between "H" and what gives mass to the proton ("h")?

  Yes, with different scales

- How to <u>see</u> "h"?

  Nuclear physics

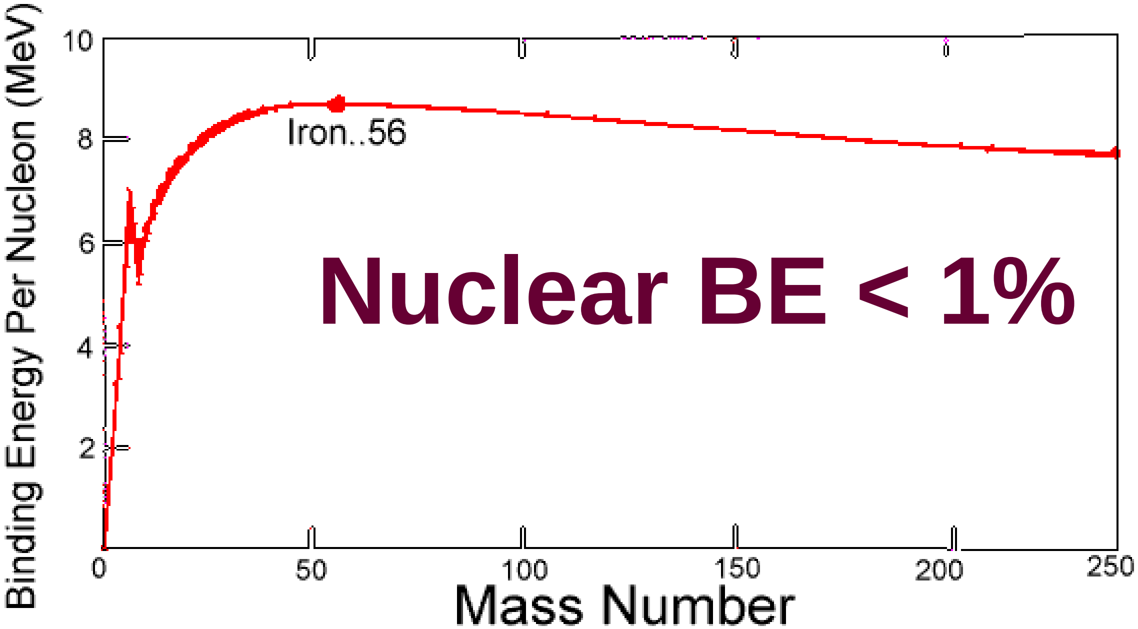
Where does the mass – that *we see* -- come from?

Masses of Busan, Molecules, Atoms, Nuclei:

= Sum of masses of constituents

+ ε (binding energy)

Constituents: protons, neutrons (+ electrons)



Nuclear BE < 1%

Mass right around us

•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

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

" *Energy stored in the motion of the (nearly) massless quarks and energy in massless gluons that connect them"*

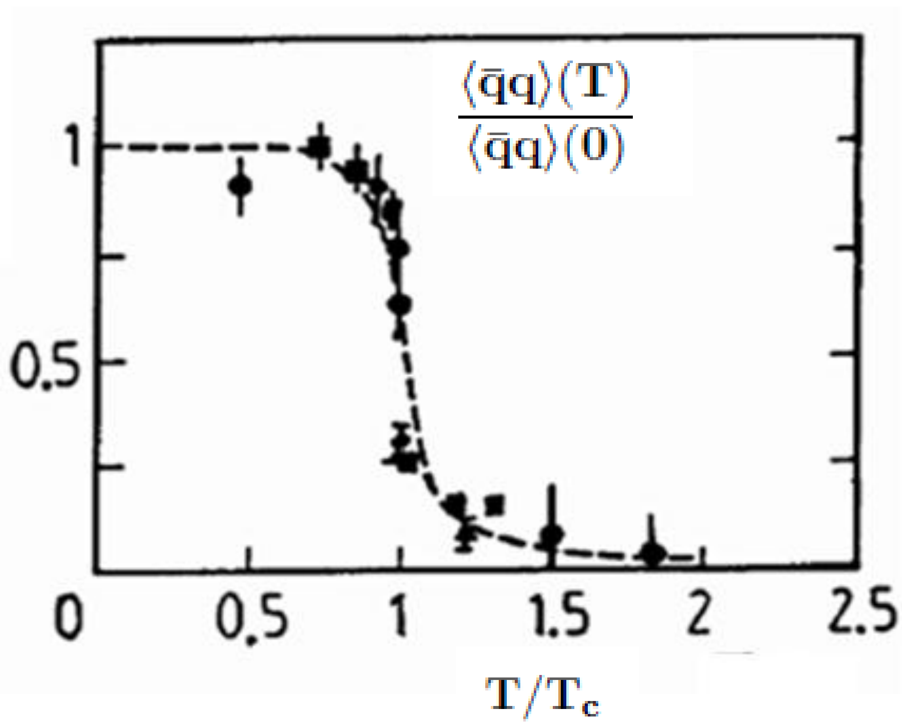
Proton mass ≈ 1 GeV

F. Wilczek: *"Mass without mass"*

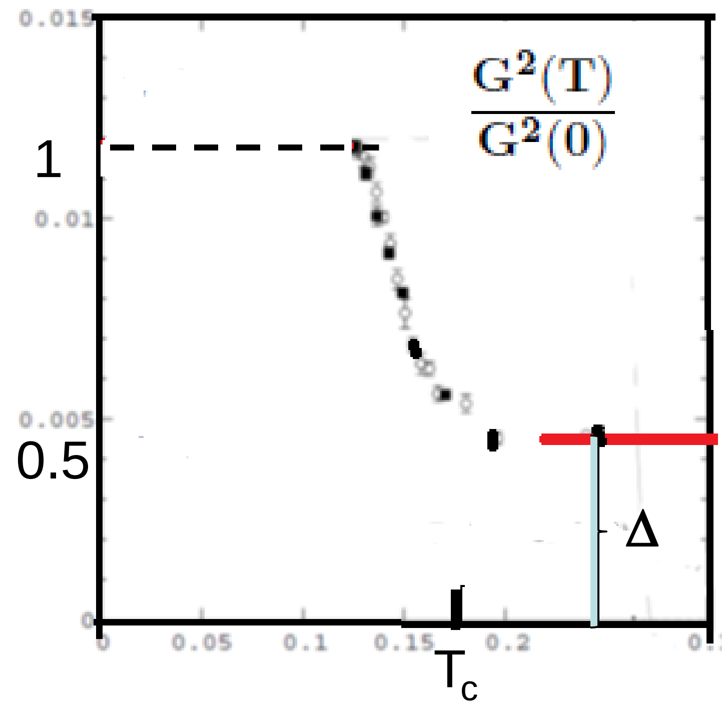
"Shedding" the mass = unbreaking symmetries

Spontaneously Broken Symmetries: Lattice

Chiral Symmetry



Scale Symmetry



Trace anomaly: $$G^2 \equiv \langle\theta^\mu_\mu\rangle = -\frac{\beta(g)}{2g^3}\langle G^a_{\mu\nu}G^{a\mu\nu}\rangle$$

Story of Scalar *named* Dilaton

When chiral symmetry is restored at T_c , scale symmetry Is still broken $\rightarrow$ "explicitly broken" scale symmetry (Δ)

Attribute "spontaneously broken scale symmetry" to

$$\theta_\mu^\mu - \Delta \equiv \Theta_\mu^\mu \sim \chi^4$$

$$\langle \Theta_\mu^\mu \rangle \sim \langle \chi \rangle^4 \rightarrow 0 \ \ \mathrm{as} \ \ \mathrm{T} \rightarrow \mathrm{T_c}$$

At the critical point, both broken chiral symmetry and spontaneously broken scale symmetry are restored

$$\langle \bar{\mathrm{q}}\mathrm{q} \rangle = \langle \chi \rangle = 0$$

"dilaton" = Goldstone boson

NOTE!!

- It is not $\langle \bar{q}q \rangle$ but $<\chi>$ that enters in BR scaling !!!

- Dilepton measurements?

Beautiful experiments

- Did they probe $<\chi>$ or $\langle \bar{q}q \rangle$?

Neither

Dilatons at TeV and GeV Scales

Electroweak

- $\Lambda_{ew} \sim 4\pi f_h \sim 3$TeV
- Higgs-like technidilaton χ_h
- Large anomalous dimension
- $m_h = 125$ GeV $<< \Lambda_{ew}$
- EW (techni) skyrmion at mass ~ ♠ TeV
- Dark matter candidate

QCD

- $\Lambda_{chiral} \sim 4\pi f_\pi \sim 1$ GeV
- σ-like dilaton χ
- strong 2-quark, 4-quark and gluonium mixing
- $m_\sigma \approx 0.6$ GeV $< \Lambda_{chiral}$
- Baryonic skyrmion at mass ~ ♥ GeV
- Physics of compact stars

The Proton Mass

$$m_N = m_{spontan}(\langle\chi\rangle) + m_{explicit}(\Delta)$$

$$\downarrow \qquad\qquad\qquad \downarrow$$

$$0 \qquad \langle\bar{q}q\rangle \rightarrow 0 \qquad m_0$$

- ❖ m_0 is chirally invariant
- ❖ If m_0 is large, parity-doubling in baryons
- ❖ If too small, nuclear physics goes haywire

❖ Where does m_0 come from and how large is nuclear physics problem.

Calculating the proton mass

- Start low energy with chiral symmetry: π
- Gauge equivalence $\rightarrow$ HLS: π, ρ, ω ...
  Large $N_c \rightarrow \Lambda_{\text{chiral}} \sim 4\pi f_\pi \sim 1$ GeV
- Trace anomaly $\rightarrow$ dilaton χ

$$\mathcal{L}^{EFT}(\pi, \rho, \omega, \chi)$$

Only unknown: dilaton mass

Baryons appear as skyrmions
so the proton is a skyrmion

Same story with techni-skyrmion
at ~ 10 TeV

Ellis and Karliner 2012

How Does Dilaton Affect Proton?

- Heavy dilaton with mass >> $\Lambda \approx 4\pi f_\pi$
  $\rightarrow m_N \approx 1500$ MeV

- Light dilaton with mass < Λ
  $\rightarrow m_N \approx 900$ MeV

So proton prefers low-mass dilaton

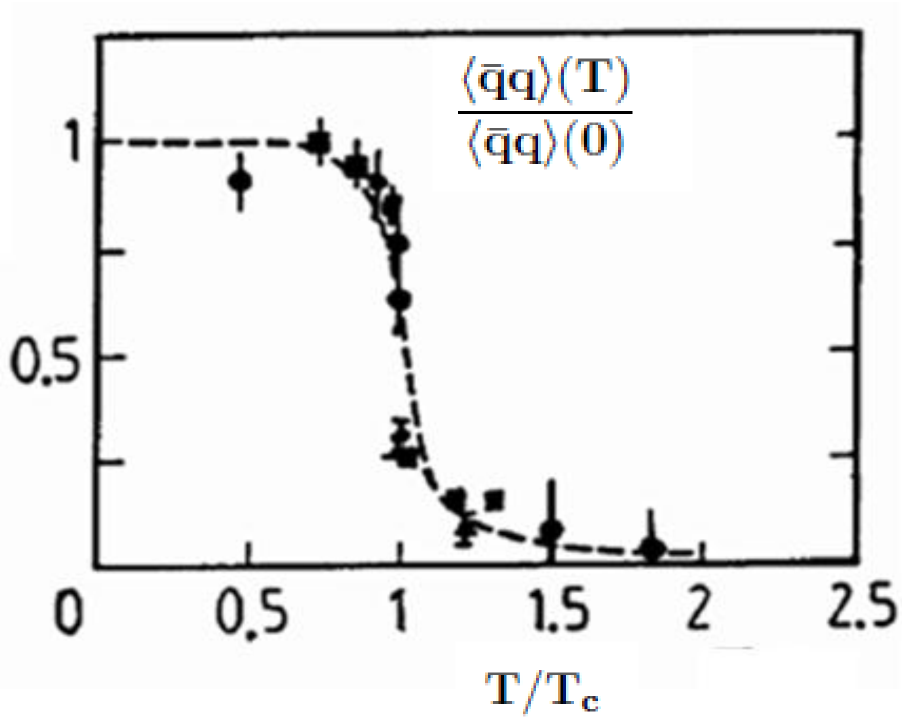
Dense Matter

Same reasoning in density as in temperature.
Has been shown in terms of the bag constant treated à la RMF theory

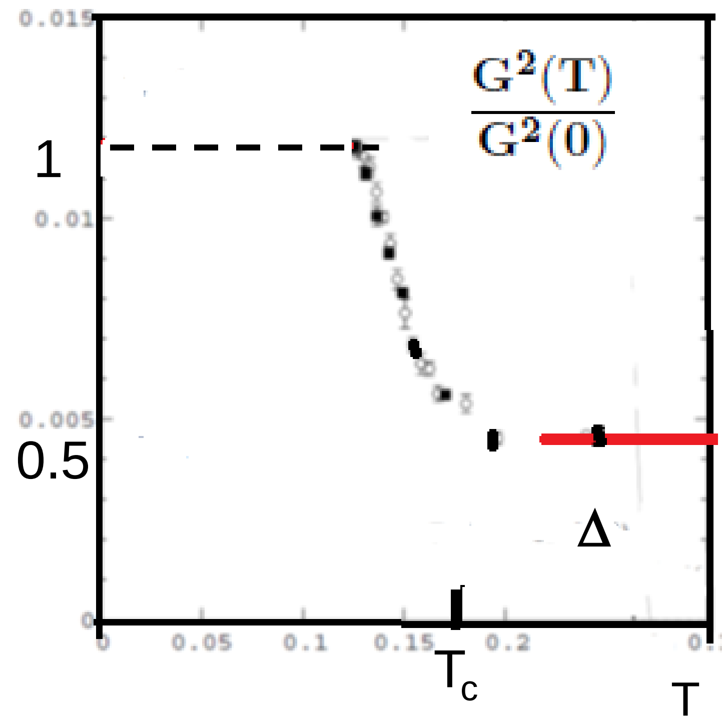
When chiral symmetry is restored, SBSS is restored, but there is explicit symmetry breaking (i.e., non-zero bag constant).

Spontaneously Broken Symmetries: Lattice

Chiral Symmetry



Scale Symmetry



In-Medium

The dilaton as Walecka σ meson binds nucleons against strong short-distance repulsion at normal density.

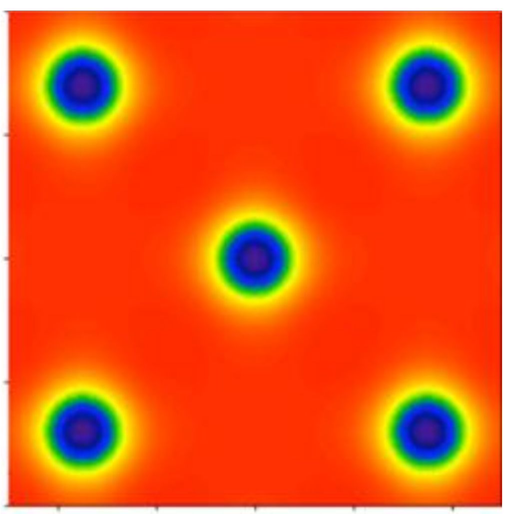
The mechanism that brings the scalar mass from the chiral scale down to ~ 600 MeV must play a crucial role as density increases in nuclear and neutron-star matter.

Put skyrmions on crystal
and squeeze $\rightarrow$ dense matter

Skyrmions on crystal

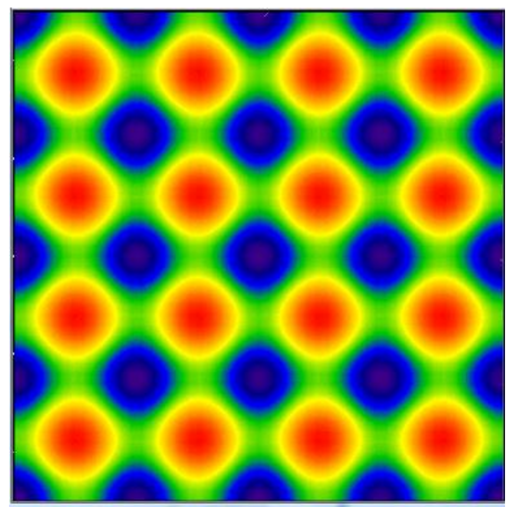
- Simulate dense matter by putting skyrmions in FCC crystals and squeeze them: ½-skyrmions in CC appear at $n_{1/2} \approx (1.5\text{-}2.0)\, n_0$

$$\mathbf{U} = \mathbf{e}^{\mathbf{2i}\pi/\mathbf{f}_\pi}$$



skyrmions

$$\mathbf{U} = \xi_{\mathbf{L}} \xi_{\mathbf{R}}^\dagger, \quad \xi_{\mathbf{L},\mathbf{R}}$$



Half-skyrmions

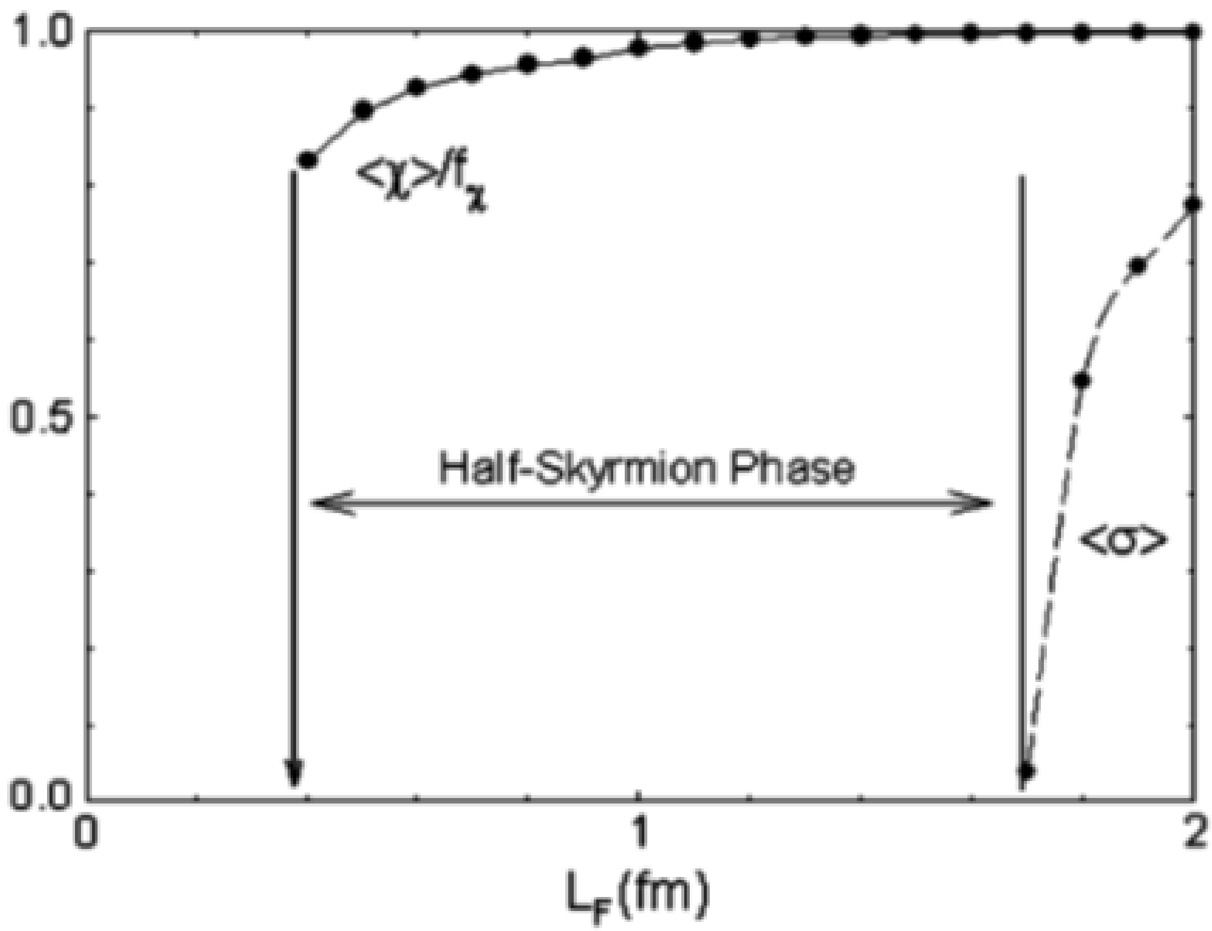
Half-Skyrmion Phase

- $\langle \bar{q}q \rangle \rightarrow 0$ *on the average* but $<\chi> \neq 0$
- And π is present, i.e., $f_\pi \neq 0$
- And baryons (bound ½-skyrmions) are present

Inhomogeneous
Quarkyonic?

Half-skyrmion phase

"Topological phase transition"



$$\sigma \sim \bar{q}q$$

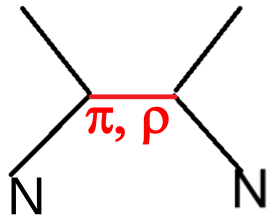
Topology change

G.E. Brown & MR, 2008

Parameters of the effective Lagrangian change at the point of topology change

$\rightarrow$ Drastic effect on tensor force

Tensor forces



$$V_M^T(r)/(C_M)^2 = S_M \tau_1 \cdot \tau_2 S_{12} (R_M^*)^2 m_M^\star Y(x_M^*)$$

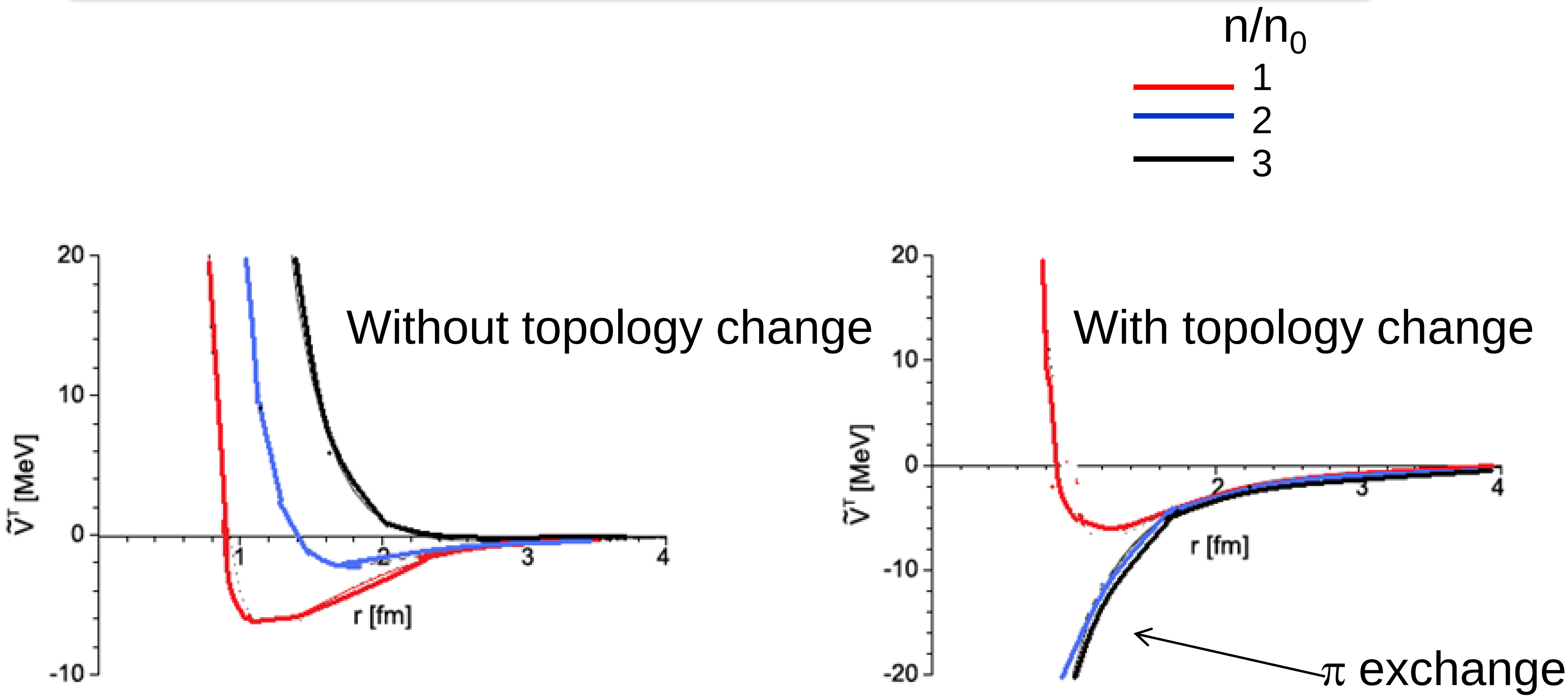
with

$$Y(x_M^*) = \left[\frac{1}{(x_M^*)^3} + \frac{1}{(x_M^*)^2} + \frac{1}{3x_M^*}\right] e^{-x_M^*}$$

where $M = \pi, \rho$, $S_{\rho(\pi)} = +1(-1)$, $x_M^* = m_M^* r$ and $R_M^* = f_{MN}^* / f_{MN}$. The crucial (very well-known) feature to note is that the two forces come with an opposite sign.

Tensor forces play a crucial role in shell evolution

Changes to Tensor Forces



(a) (b)

Scenarios

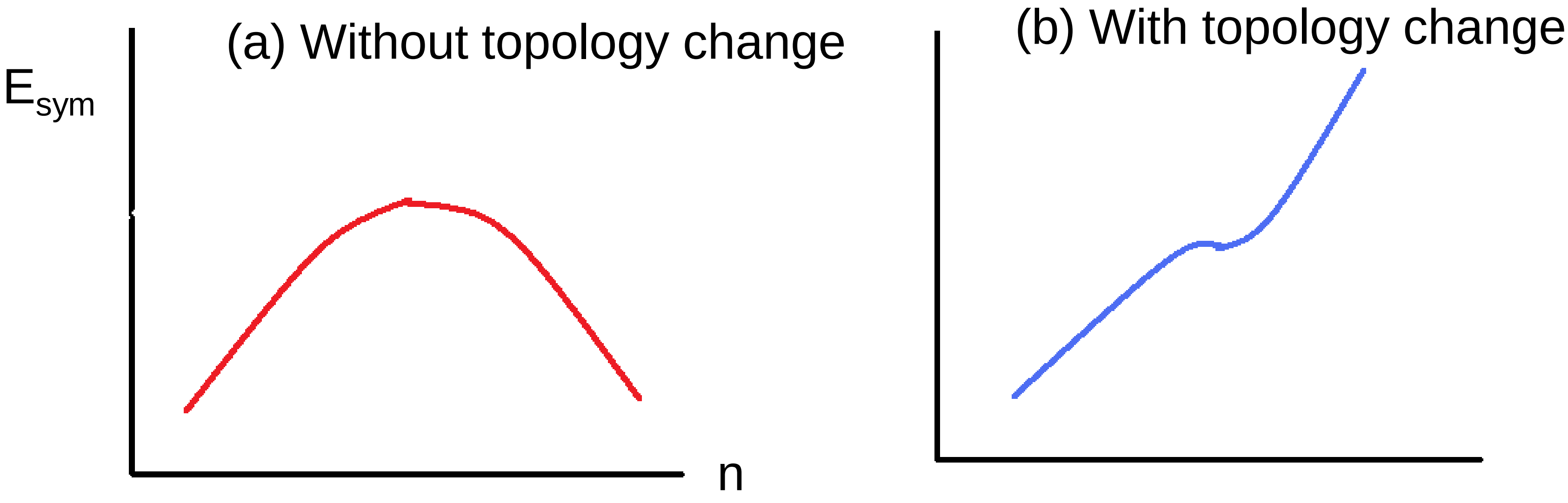
In

Nuclear structure ⇨ KoRIA physics

Effect on Symmetry Energy

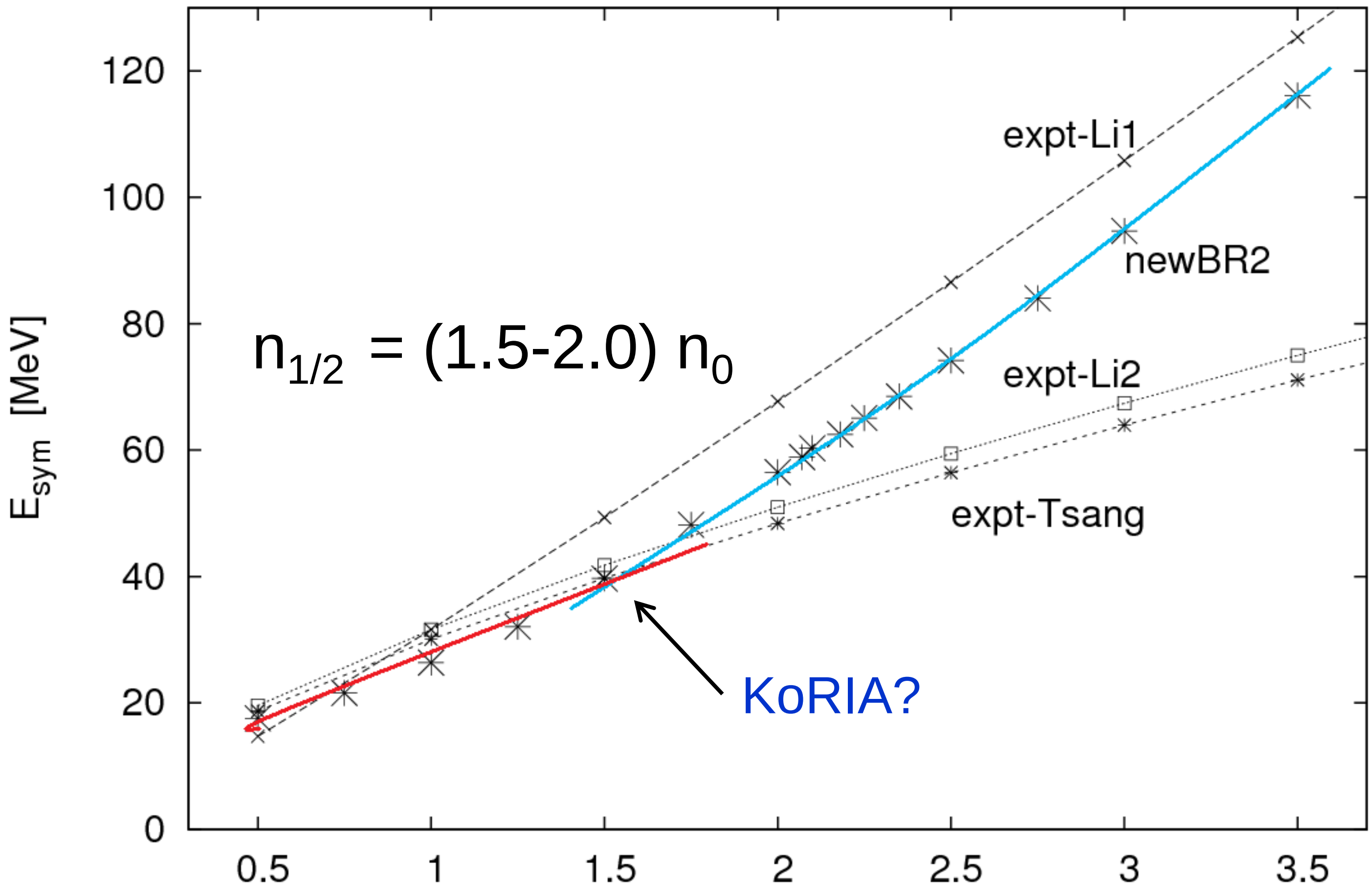
"Symmetry energy is dominated by the tensor forces":

$$E_{sym} \propto \frac{|V_T|^2}{\overline{E}}$$ Schematically predicts



Symmetry Energy E_{sym}

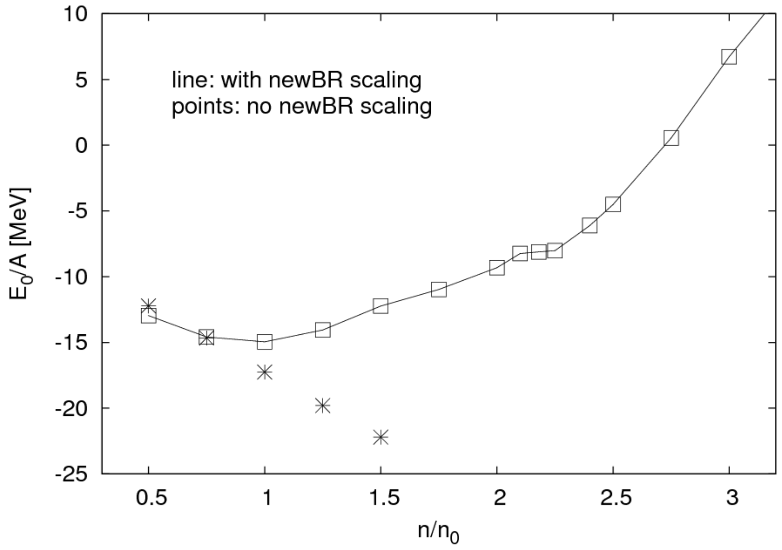
Dong, Kuo, Lee, Rho



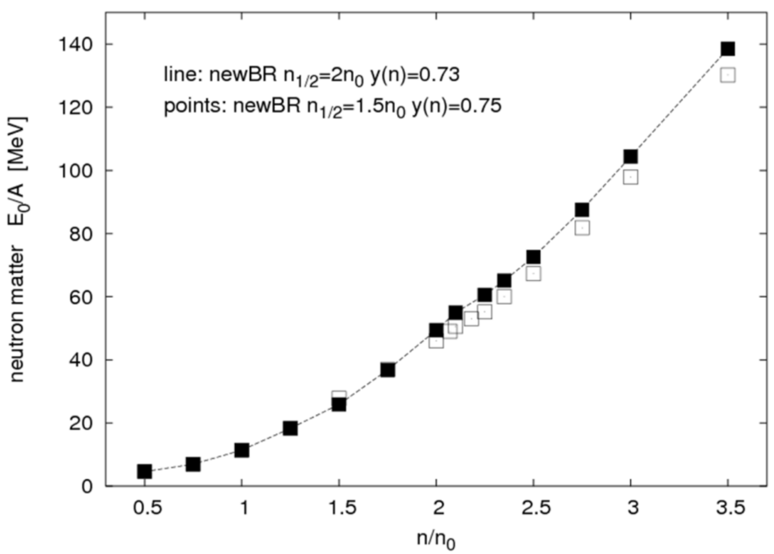
Gives missing explanation for transition from “soft” to “hard” EoS!

EoS

Dong, Kuo et al 2012



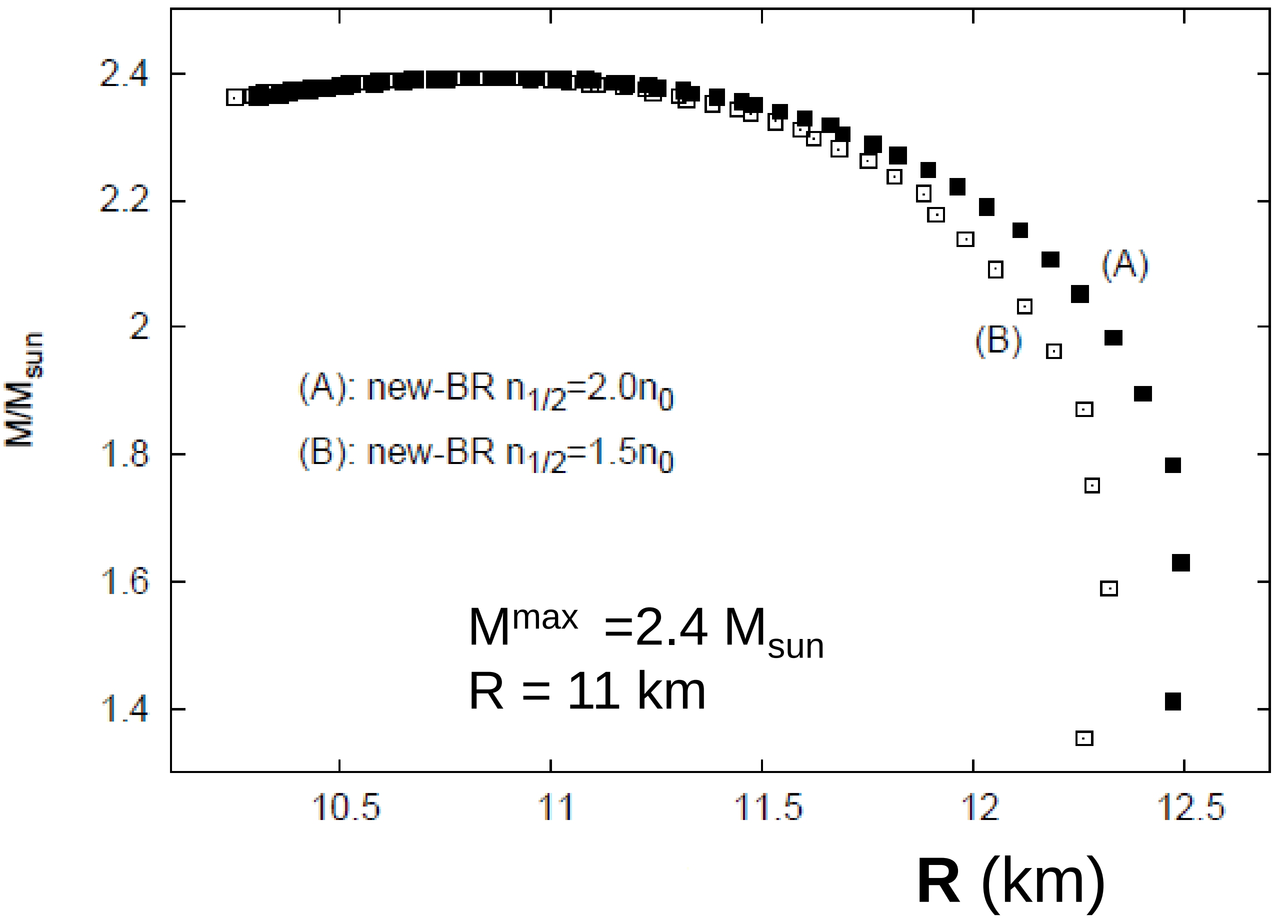
Symmetric matter



Neutron matter

Compact Star M^{max} vs. R

Dong, Kuo, Lee, Rho 2012

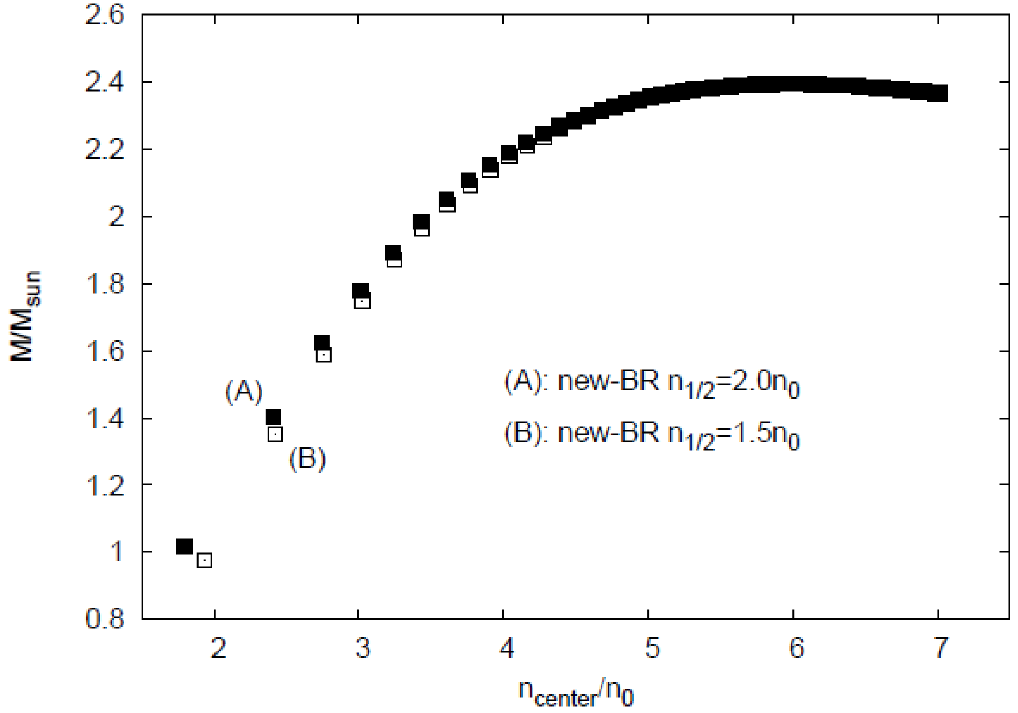


Shapiro delay

$M = 1.97 \pm 0.04\ M_{\odot}$

R = 11-15 km

Maximum density in 2.4 M_{solar}



~ 5.5 $n_0 \rightarrow$ arena of FAIR and LIGO

Summary

- ❖ Dense baryonic matter (at KoRIA, FAIR…) will unbreak ``*bit by bit*” chiral/scale symmetry

- ❖ Will probe origin of the proton mass tied to the trace anomaly and the dilaton (resembling technidilaton for higgs-like boson)

- ❖ Mass and radius of compact stars will uncover the mystery of proton mass.

- ❖ *Gravity wave (LIGO) will measure EoS at T~ 60 MeV and n ~ 4 n_0. Will communicate with FAIR!!*