Hidden and Mended Symmetries and Compact Stars

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Nagoya, March 2015

Nature 467, 1081 (2010)

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

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

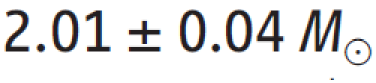
J1614-2230 $1.97 \pm 0.04\ M_{\odot}$

Science 340, 1233232 (2013)

A Massive Pulsar in a Compact Relativistic Binary

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

J0348+0432

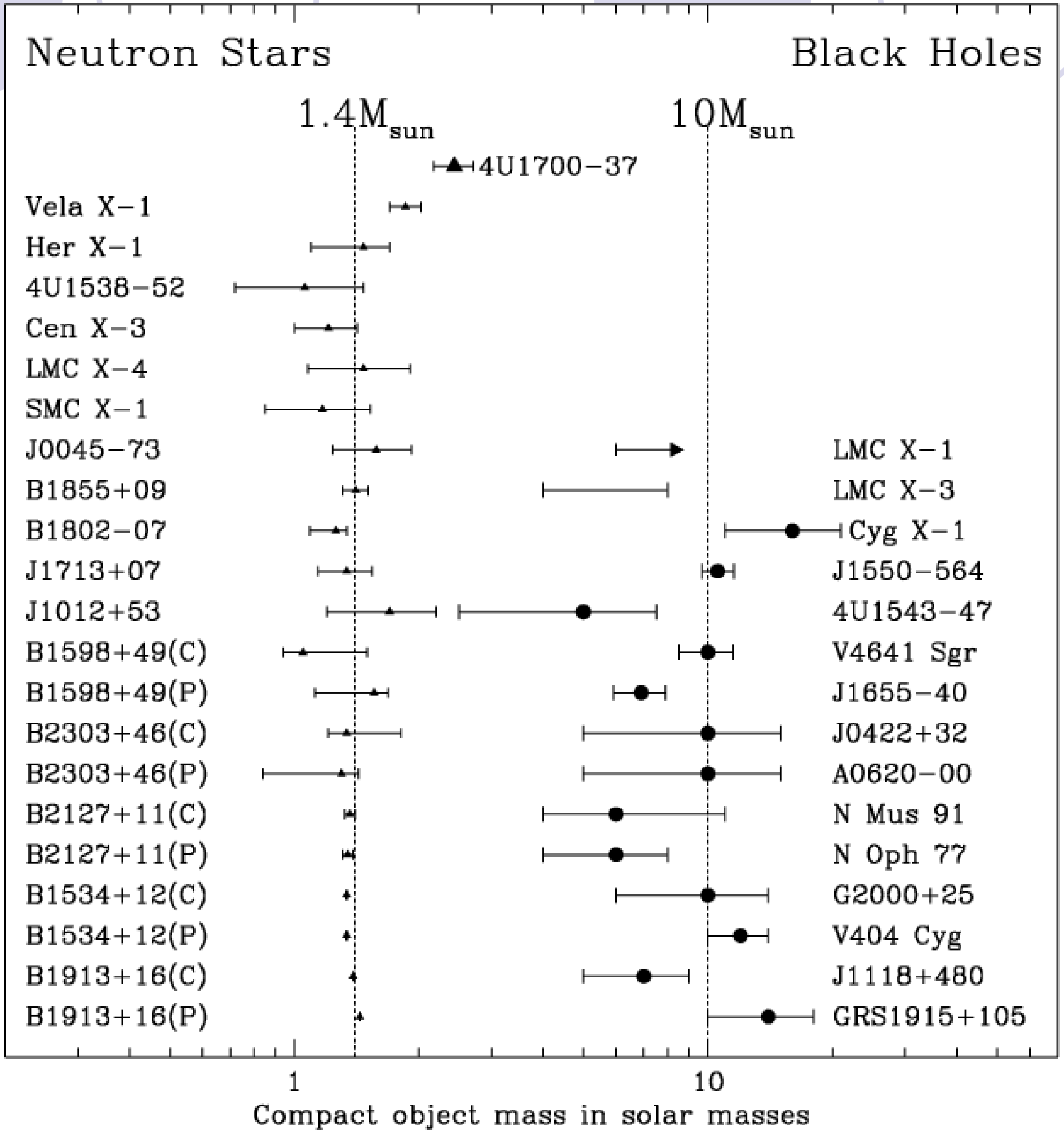


$2.01 \pm 0.04\ M_{\odot}$

Falsify Cherished Ideas

- Kaon condensation at ~ 3 normal nuclear matter density
- Bethe-Brown maximum neutron star mass $M_{max} \approx 1.5\ M_{sun} \rightarrow$ large number of light mass black holes
- "Cosmological natural selection" à la Smolin

Neutron Star Masses ca. 2007



Kaons (K^- s) condense in n-star matter

- Chiral Perturbation Theory (Kaplan & Nelson 1986, Politzer & Wise and others ...) predicts

$$n_c \approx m_K^2 f_K^2 / \Sigma_{KN} \approx (3-4)\; n_0$$

- Condensed kaons soften EoS of n-star matter:
- TOV equation predicts

$$M_{max} \simeq 1.5 M_{\odot}$$

Light mass black holes

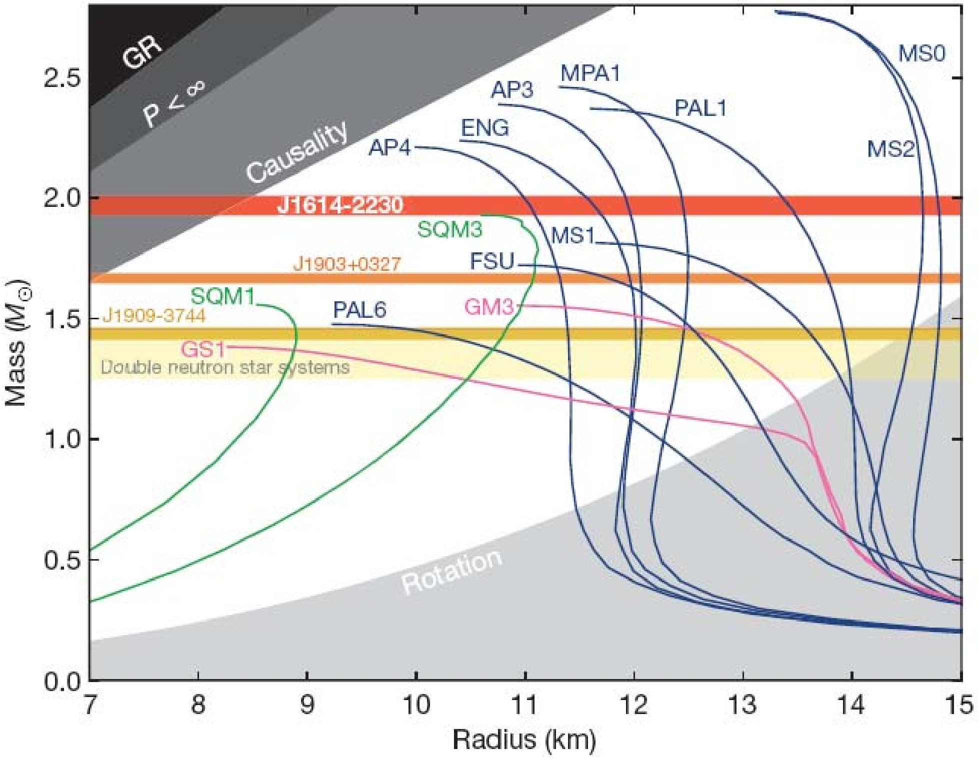
- Increase light-mass BH's (Brown& Bethe 1994) to ~ 10^9 in the galaxy.

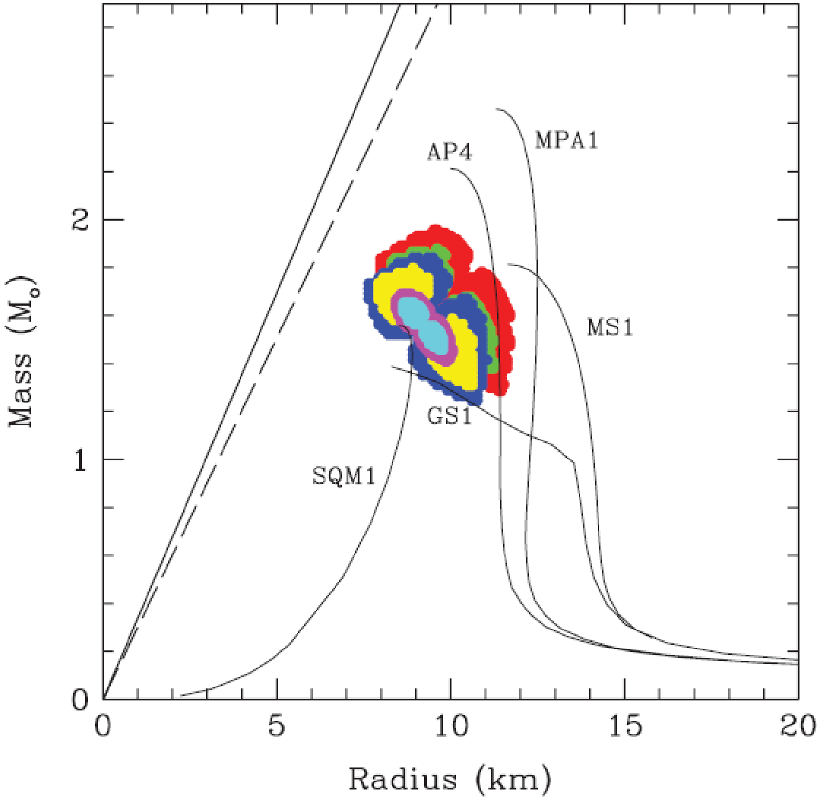
Cosmological natural selection

(Smolin 2004)

“Bouncing black hole singularity leading to new region of space-time behind the horizon of every black hole”, thus maximizes BH and the complexity of the multiverse?

Initial impact





Demorest et al, Nature 467, 1081 (2010)

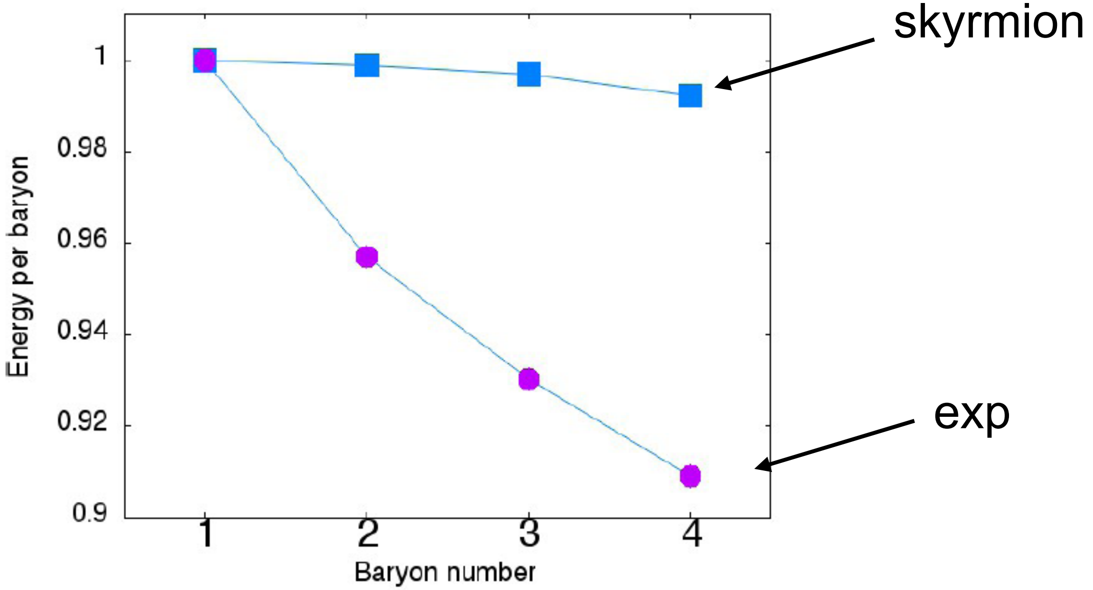
“All equations of state with kaon condensation, hyperons …
other than strongly interacting strange quark matter
are *ruled out by this star*” !!

Revamp (?) old cherished notions in nuclear dynamics

- Infinite tower of vector mesons as hidden gauge fields: Dimensional deconstruction, holographic baryons …
- Scalar meson as a pseudo-Nambu-Goldstone: IR fixed point ("Crewther-Tunstall dilaton") ???
- Mended symmetries …π, σ, ρ, a_1

Binding energy puzzle

Large N_c QCD $\rightarrow E_B/A \sim N_c \Lambda_{QCD}$ *violently* at odds with Nature



Tower of vector mesons

$$\mathcal{S} = \frac{N_c \lambda}{54\pi^3} \int \sqrt{-g}\, \frac{1}{8} \mathrm{Tr}\left(\mathcal{F}_{\Gamma\Delta} \mathcal{F}^{\Gamma\Delta}\right)\, d^4x\, dz + \frac{N_c}{24\pi^2} \int \omega_5(\mathcal{A})\, d^4x\, dz$$

$$\Gamma, \Delta, \ldots = 0, 1, 2, 3, z, \quad I, J, \ldots = 1, 2, 3, z, \quad i, j, \ldots = 1, 2, 3.$$

Large N_c & large λ EFT for QCD

- ❖ Top-down: Sakai-Sugimoto hQCD
- ❖ Bottom-up: Son-Stephanov “moose”

Consider SS’ hQCD: *U(2)*

To O($N_c\lambda$), the metric is flat and the CS does not contribute, hence no ω mesons enter

→ 5D SU(2) YM theory in flat space.

→ Baryons as instantons

Sutcliffe's observation

P. Sutcliffe 2011

$$E_{\mathrm{YM}} = -\frac{1}{8}\int \mathrm{Tr}(F_{IJ}F_{IJ})\, d^3x\, dz$$

$$E_{\mathrm{YM}} \geq 2\pi^2\,|N|, \quad N = -\frac{1}{16\pi^2}\int \mathrm{Tr}(F_{IJ}\,{}^\star F_{IJ})\, d^3x\, dz,$$

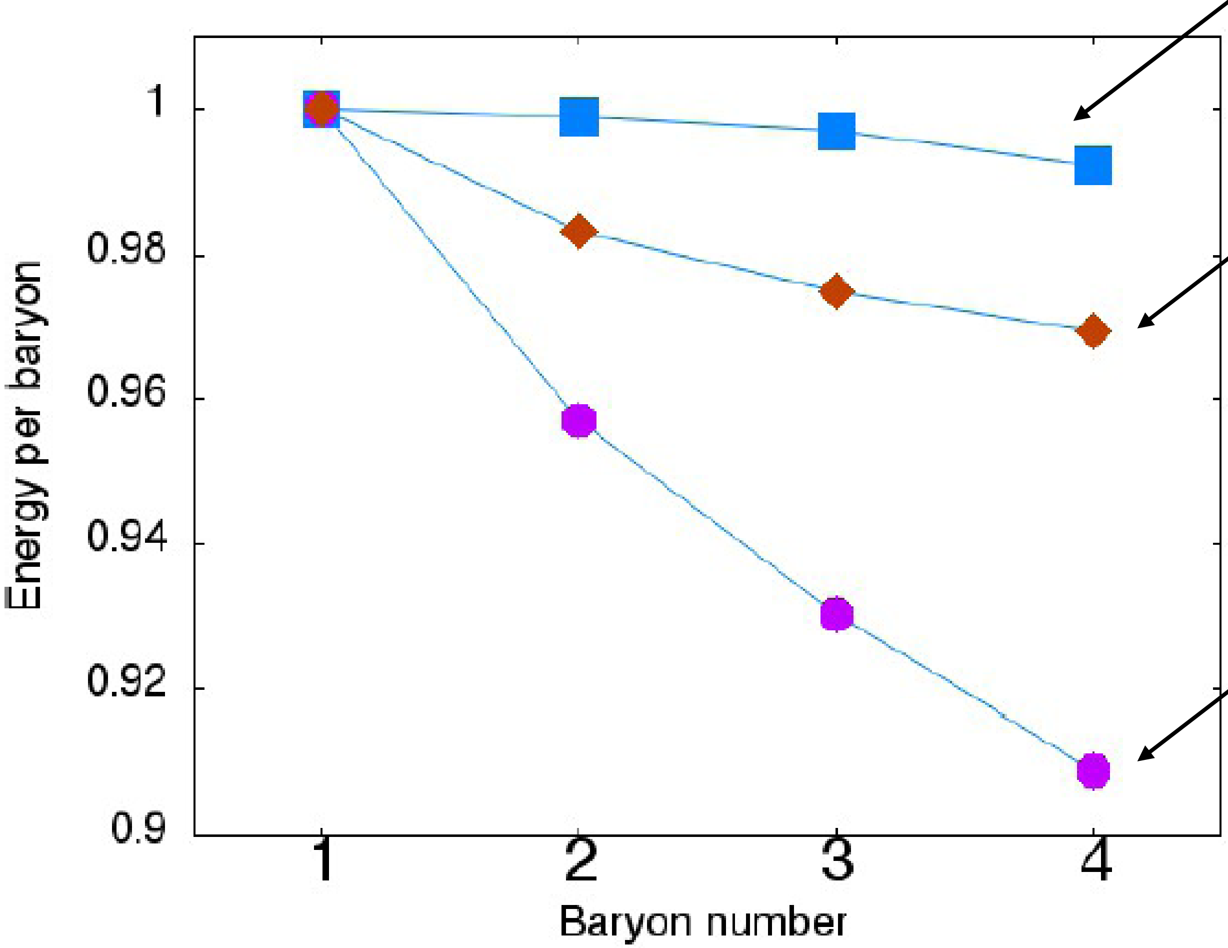
Self dual solution → BPS soliton

Dimensional deconstruction by Klein-Kaluza
→ ∞ tower of ρ's and a_1's and π ↔ HLS

$$\boldsymbol{U(x) = e^{i\pi(x)/f_\pi} = \mathcal{P}\int_{-\infty}^{\infty} A_z(x,\xi)d\xi}$$

→ Skyrmion in an infinite tower of iso-vector vectors

Packing with vectors



exp

π, ρ, $\mathbf{a_1}$

π

Baryonic matter is a BPS matter?

How far can one go if one starts with a BPS matter?

$$E = \int d^3x[\kappa \mathcal{B}_0^2 + V(U)]$$

$$\mathcal{B}^\mu = \frac{1}{24\pi^2}\epsilon^{\mu\nu\rho\sigma}\mathrm{Tr}L_\nu L_\rho L_\sigma, \ L_\mu = U^\dagger \partial_\mu U$$

Adam, Wereszczynski et al. 2013

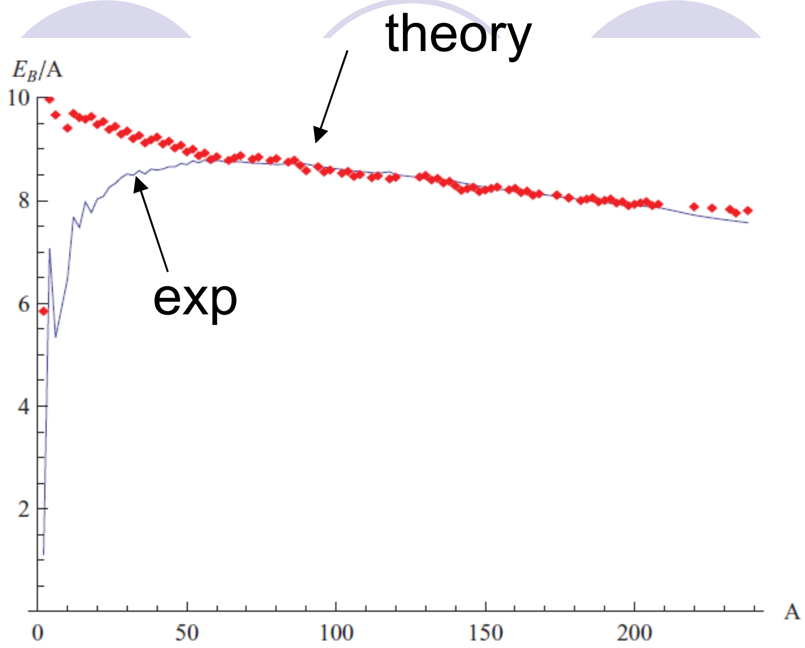
BPS matter

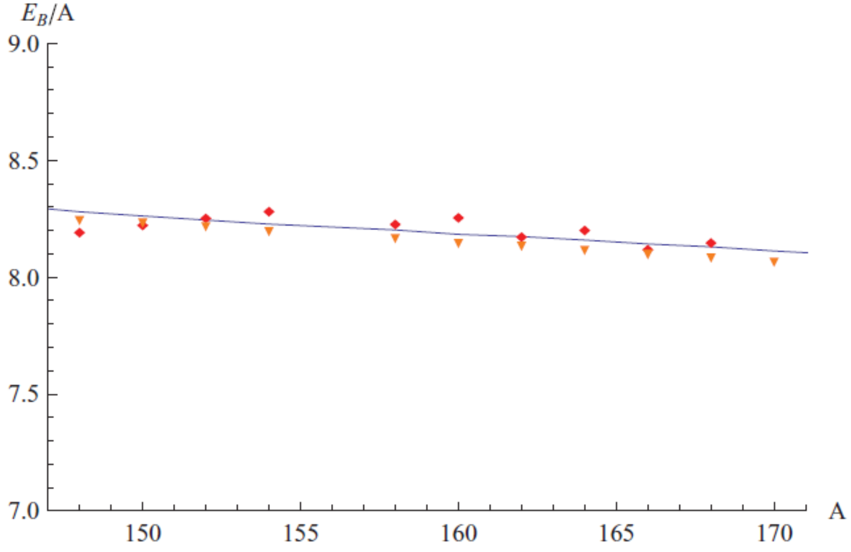
Corrections: Coulomb, isospin breaking ..

Parameters: 3

Predicts: Incompressible Fermi liquid, reproduces Bethe-Weiz\”acker formula

But this cannot be the true story!!





Both ω and σ ≡ *f_0(500)* must figure

$$\mathcal{S} = \frac{N_c \lambda}{54\pi^3} \int \sqrt{-g}\, \frac{1}{8} \mathrm{Tr}\left(\mathcal{F}_{\Gamma\Delta}\mathcal{F}^{\Gamma\Delta}\right) d^4x\, dz + \frac{N_c}{24\pi^2} \int \omega_5(\mathcal{A})\, d^4x\, dz$$

$$E = aN_c\lambda\,(1 + O(1/\lambda) + \ldots)$$

- At O(1) in (…), BPS matter that “seems” to work
- At O(1/λ), both ω ∊ U(1) and space-warping enter and bring havoc!

Relativistic mean field theory (à la Walecka)

≈ Landau Fermi liquid theory

- Vector (ω) mean field → ~ 1/3 GeV repulsion per nucleon
- “Scalar” (?) mean field → ~ 1/3 GeV attraction per nucleon
- Near cancellation giving ~ 16 MeV binding energy

QCD sum rule supports this feature

How Walecka model works

- The small BE of nuclear matter is given by

$$V_\omega = \frac{g_\omega^2}{m_\omega^2}\langle\omega_0\rangle \approx 275\mathrm{MeV}, \quad V_s = -\frac{g_s^2}{m_s^2}\langle s\rangle \approx -350\mathrm{MeV}$$

$$-BE \approx\sim +60\mathrm{MeV} + V_\omega + V_s \Longrightarrow \text{- 16 MeV}$$

This is supported by the QCD sum rules. But with $m_s \approx 600$ MeV.

How does the BPS encapsulate this huge cancellation?

What is this “scalar”?

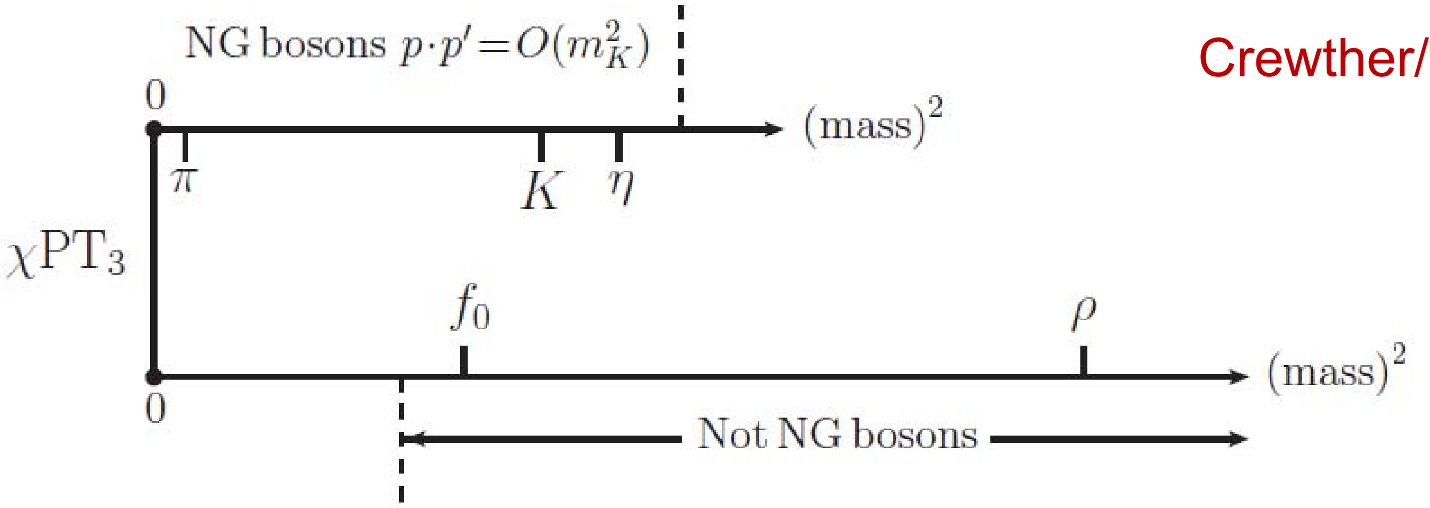
It is NOT the σ in the linear sigma model.
If it were, nuclear matter will collapse.

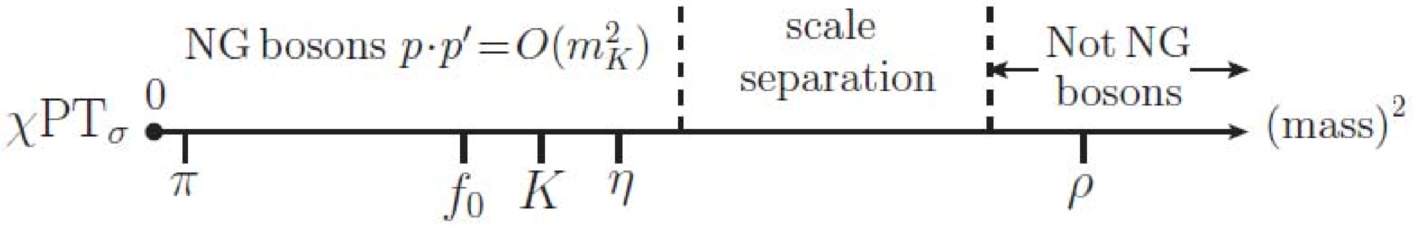
It must be a chiral singlet. But cannot be gluonium which lies too high.

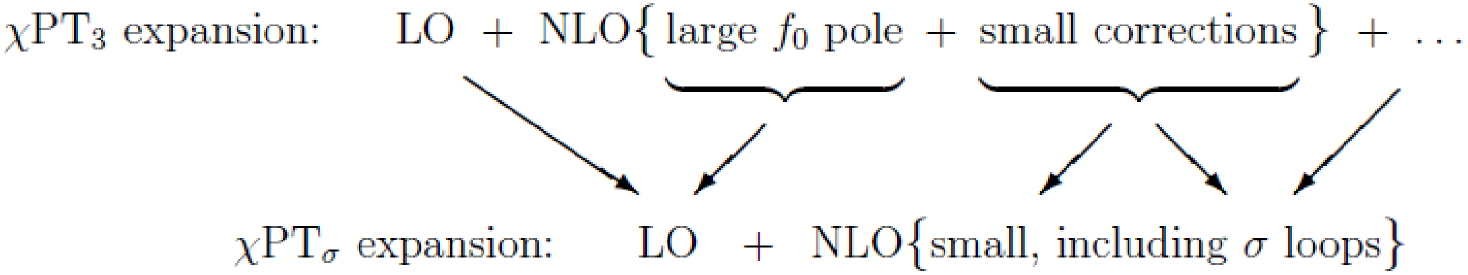
It is not in Sakai-Sugimoto holographic QCD model. Can concoct one but much too heavy, so too short-ranged to counter the ω repulsion.

Possible candidate: Dilaton …joining pions …
Pseudo-Nambu-Goldstone bosons

Crewther/Tunstall







$$\chi\text{PT}_3 \text{ expansion:} \quad \text{LO} + \text{NLO}\{\underbrace{\text{large } f_0 \text{ pole}} + \underbrace{\text{small corrections}}\} + \ldots$$

$$\chi\text{PT}_\sigma \text{ expansion:} \quad \text{LO} + \text{NLO}\{\text{small, including } \sigma \text{ loops}\}$$

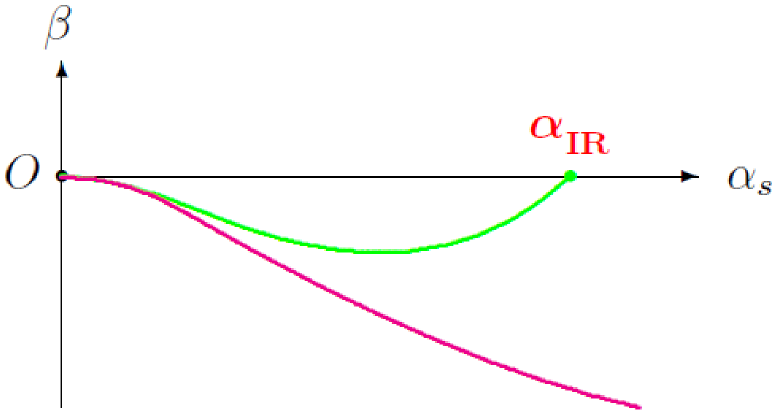
In particle physics, it explains, among others, *ΔI* = ½ rule ….

$\sigma = f_0(500)$ as a dilaton

Crewther-Tunstall (CT) Model

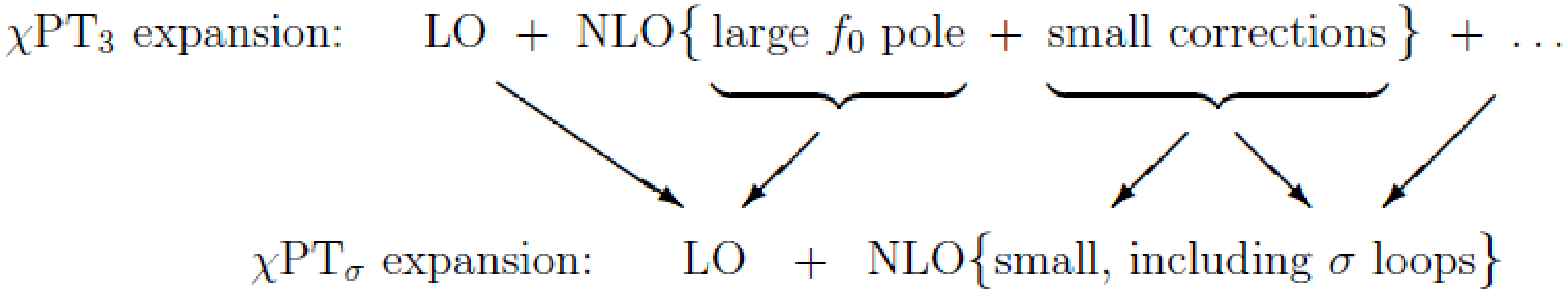
R.J. Crewther and L.C. Tunstall, arXiv: 1312.3319

Nuclear physics around the IR fixed point
At IR fixed point, there is massless dilaton σ. Dilaton mass is $\propto (\alpha_{IR} - \alpha_s)$, explicit breaking, and $\propto m_q$, *current quark mass*.
The two effects are connected to each other.



They say “Not in QCD”
No-go theorem?

Assumption: f_0 *(500) is a pseudo-NG of* SBSS



$$\chi\mathrm{PT}_3\ \text{expansion:}\qquad \mathrm{LO} + \mathrm{NLO}\Big\{\underbrace{\text{large } f_0 \text{ pole}} + \underbrace{\text{small corrections}}\Big\} + \ \dots$$

$$\chi\mathrm{PT}_\sigma\ \text{expansion:}\qquad \mathrm{LO} + \mathrm{NLO}\{\text{small, including } \sigma \text{ loops}\}$$

$\rightarrow \chi\mathrm{PT}_\sigma$

Even if not in matter-free space, could make sense in medium
Perhaps an emergent symmetry due to strong correlation?

Trace anomaly

$$\theta^{\mu}_{\mu} = \frac{\beta(\alpha_s)}{4\alpha_s} G^2 + (1+\gamma_m)\sum m_q \bar{q} q$$

EFT

$$\xrightarrow{???} c\beta'\chi^{4+\beta'} - (1+\gamma_m)\mathrm{Tr}(MU^{\dagger} + h.c.)\chi^{(3-\gamma_m)}$$

What it does in nuclear physics …

- Define decay constant f_σ and "conformal compensator" χ

$$\chi = f_\sigma e^{\frac{\sigma}{f_\sigma}}$$

- Implement χ^n *in* HLS Lagrangian à la spurion and put scale symmetry breaking potential V(χ) (e.g. of CT). Call it χHLS Lagrangian. Breakings of chiral symmetry and scale symmetry get locked to each other.

$$f_\sigma \approx f_\pi$$

- Do RMF with this χHLS Lagrangian à la Walecka.

- In baryonic matter, all hadron masses slide in medium with $f_\sigma(n) = \langle\chi\rangle(n) \equiv f_\sigma^*$.

Nuclear medium up to *n* near n_0

- For others than pseudo-Goldstones

$$\boxed{m_M^*/m_M \approx m_B^*/m_B \approx f_\sigma^*/f_\sigma \approx f_\pi^*/f_\pi}$$

Exp

Works OK up to n_0 and slightly above ..

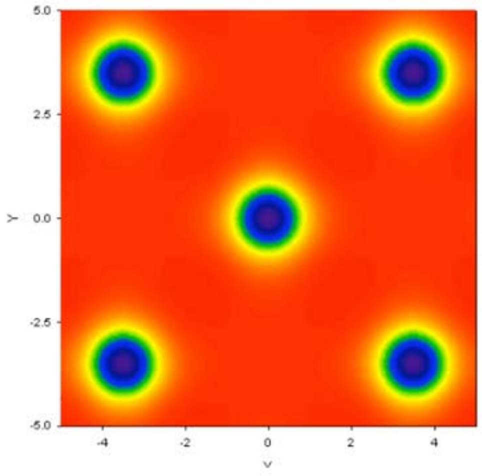
- What happens at higher densities is
  a BIG challenge to nuclear theorists…

Intervene in dense baryonic matter

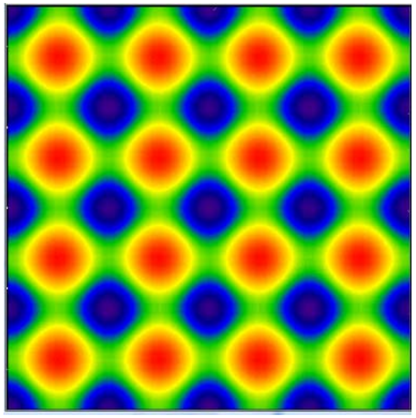
- Topological effects
- Hidden gauge fields
- Mended symmetries

Topological effect

- At high density, baryonic matter crystalizes.
- In large N_c QCD, it is a skyrmion crystal
- At density $n_{1/2} \sim (2\text{-}3)n_0$, baryon number 1 skyrmions franctionize into half-skyrmions (similarly in condensed matter)



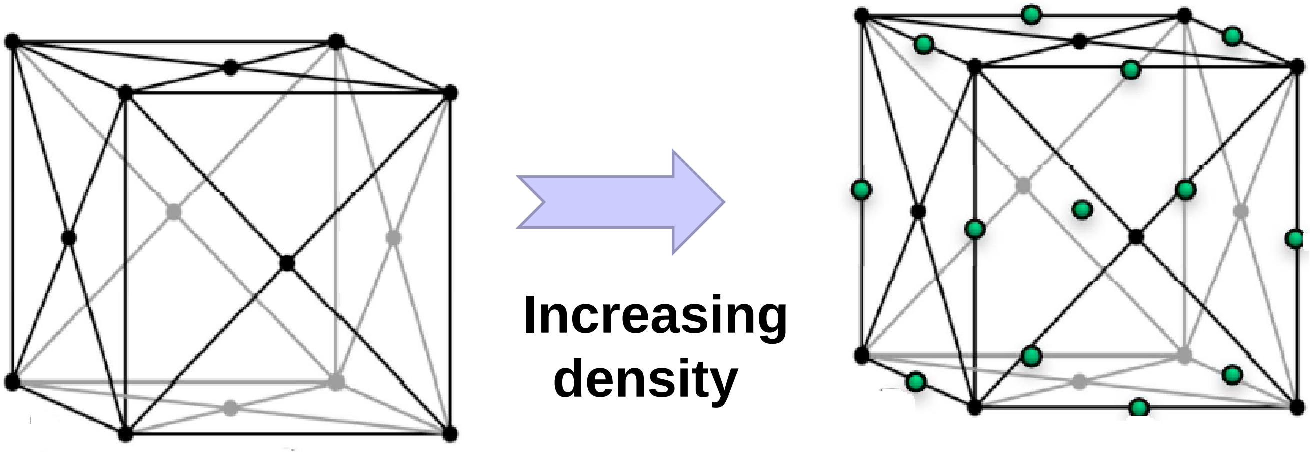
skyrmions



half-skyrmions

Or with ∞ tower of vector mesons (hQCD): *"dyonic salt"*

Sin, Zahed, R. 2010; Bolognesi, Sutcliffe 2013



Increasing density

Instantons: FCC

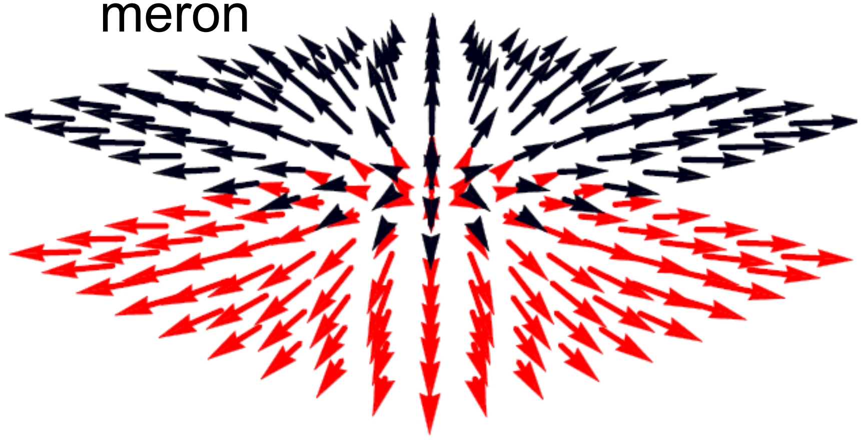
½ instantons (dyons): BCC

In condensed matter

Fascinating things happen in strongly correlated systems

Example: ½-skyrmions in chiral superconductivity

S. Chakravarty, C.S. Hsu 2013



meron

anti-meron

½-skrmions condense

→ superconductivity

Heavy fermion: URu_2Si_2

(Polar Kerr effect)

What hidden gauge symmetry suggests

Bando, Kugo, Yamawaki …1985
Harada & Yamawaki 2001, 2003

Assume $\langle \bar{q}q \rangle \to 0$ in the chiral limit at a density n_c , then HLS predicts that as density (n) approaches n_c

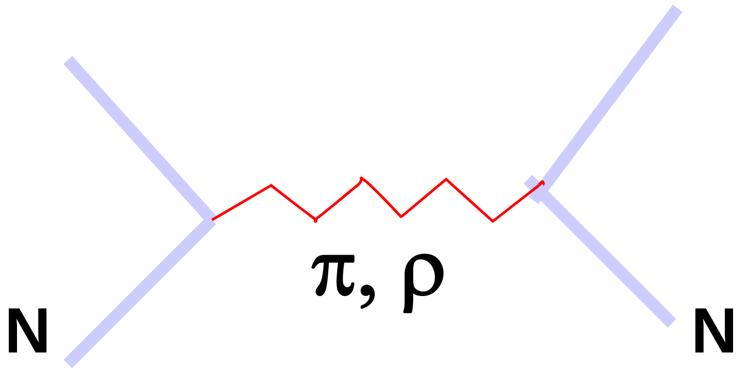
$$\frac{m_\rho(n)}{m_\rho(0)} \to \frac{g(n)}{g(0)} \to \frac{\langle \bar{q}q \rangle (n)}{\langle \bar{q}q \rangle (0)} \to 0$$

❖ Therefore approaching n_c → $m_\rho \approx m_{a_1} \approx m_\pi$
❖ Dilaton limit fixed point → $m_\sigma \approx m_\pi$

"Mended symmetries" put together π, σ, ρ, a_1

→ *Drastic consequence* on nuclear tensor forces and *Drastic simplification* of high density physics!!

Tensor forces are dominated by π & ρ



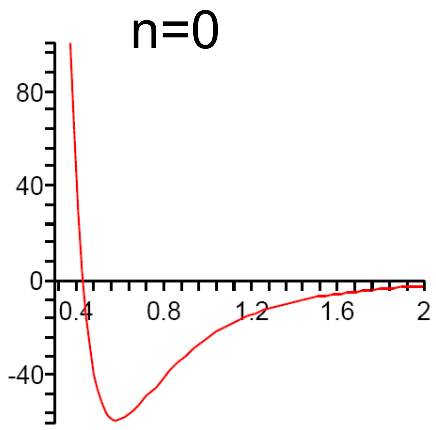
$$V_M^T(r) \quad = S_M \frac{f_{NM}^2}{4\pi} m_M \tau_1 \cdot \tau_2 S_{12}$$
$$\left(\left[\frac{1}{(m_M r)^3} + \frac{1}{(m_M r)^2} + \frac{1}{3 m_M r} \right] e^{-m_M r} \right)$$

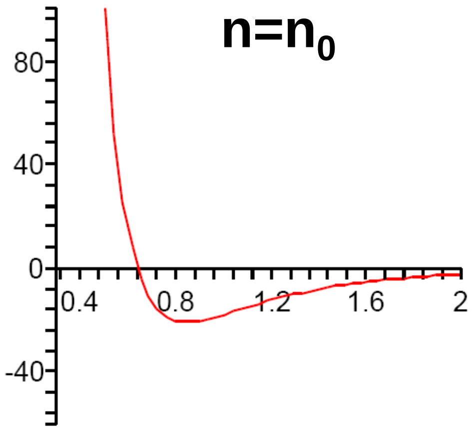
$$M = \pi, \rho, \; S_{\rho(\pi)} = +1(-1)$$

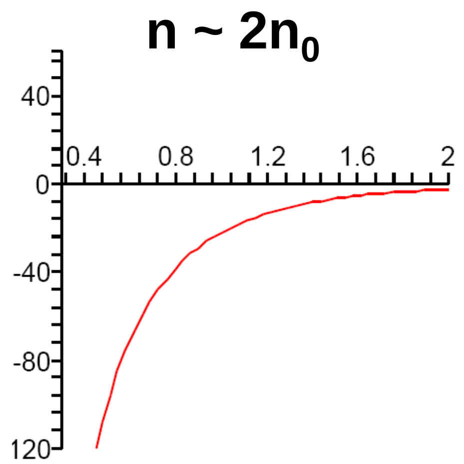
$$V_M^T(r) = S_M \frac{f_{NM}^2}{4\pi} m_M \tau_1 \cdot \tau_2 S_{12} \left(\left[\frac{1}{(m_M r)^3} + \frac{1}{(m_M r)^2} + \frac{1}{3 m_M r} \right] e^{-m_M r} \right)$$

$$M = \pi, \rho, \; S_{\rho(\pi)} = +1(-1)$$

Topology effect and *g*→ 0 effect suppress ρ tensor


n=0


n=n$_0$


n ~ 2n$_0$

Skyrmion
structure

skyrmion phase

½-skyrmion phase

Impact on Equation of State

For matter with excess of neutrons (i.e., neutron star) the “symmetry energy” E_{sym} plays a dominant role

$$E(n,\delta) = E(n,0) + E_{sym}\delta^2 + \mathcal{O}(\delta^4)$$

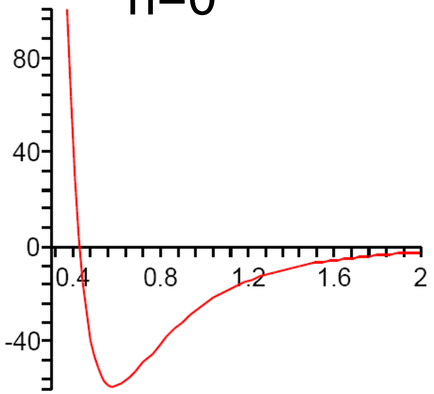
$$\delta = (n_p - n_n)/(n_n + n_p)$$

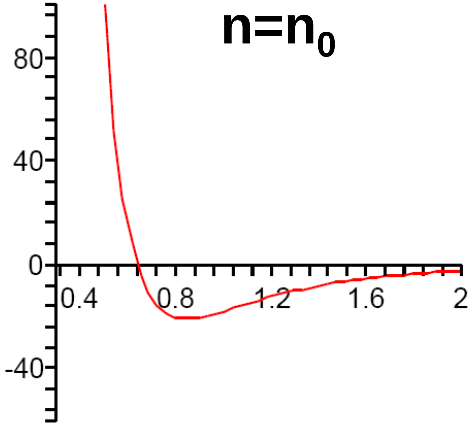
The tensor forces dominate the symmetry energy

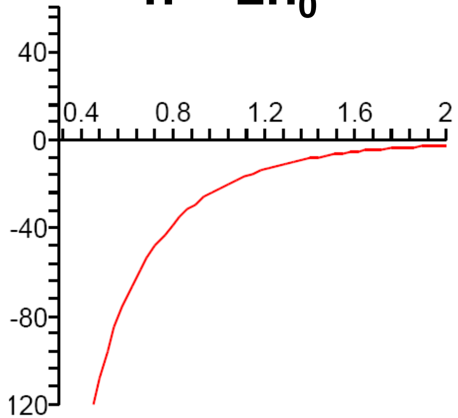
$$E_{sym} \approx C\langle (V_{tensor})^2 \rangle / \Delta E$$

$$\Delta E \approx 200\ MeV$$

Topology effect and $g \rightarrow 0$ effect suppress ρ tensor
HLS in action


n=0


$n=n_0$


$n \sim 2n_0$

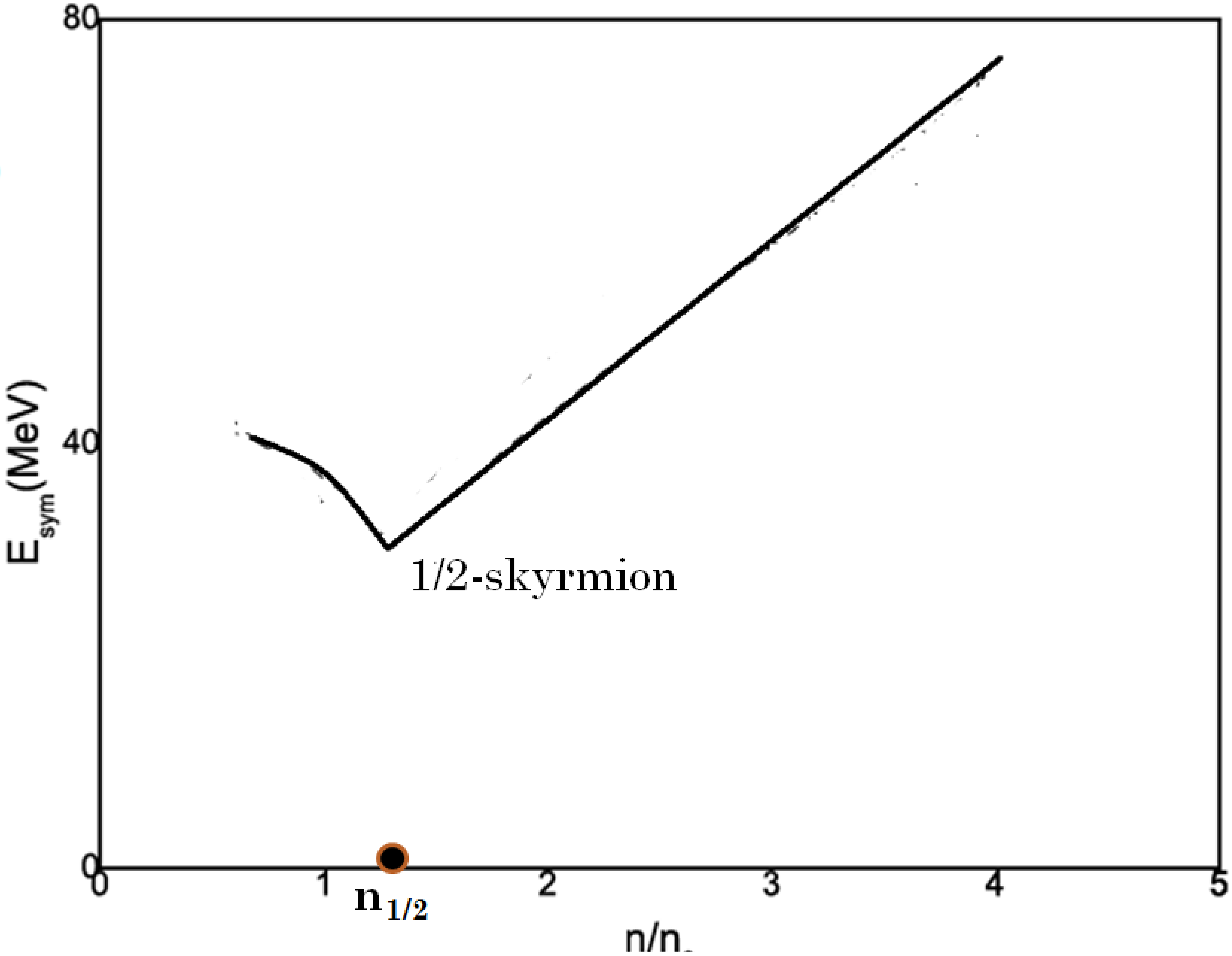
“Cuspy” symmetry energy

Nuclear symmetry energy

$$E(n,\delta) = E(n,0) + E_{sym}\delta^2 + \mathcal{O}(\delta^4)$$

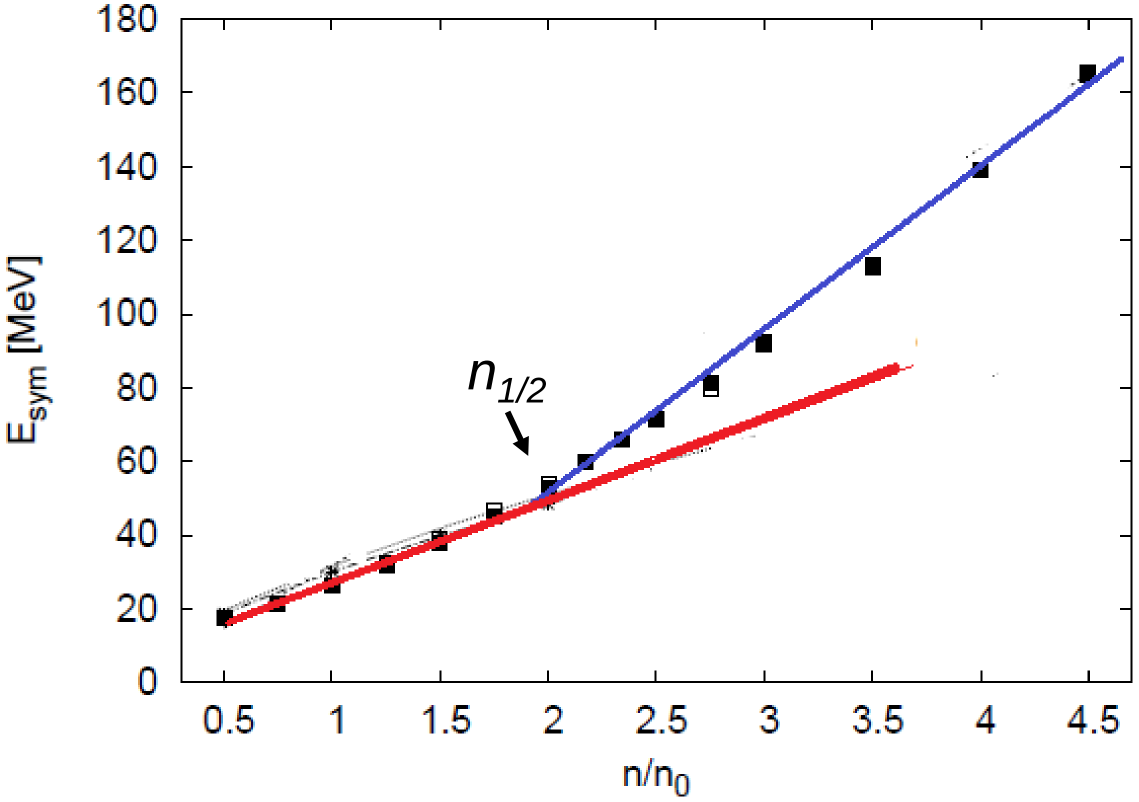
$$\delta = (n_p - n_n)/(n_n + n_p)$$

$$\boldsymbol{E_{sym} \propto |V_T|^2/(200\ \mathrm{MeV})}$$



Confront “Nature”

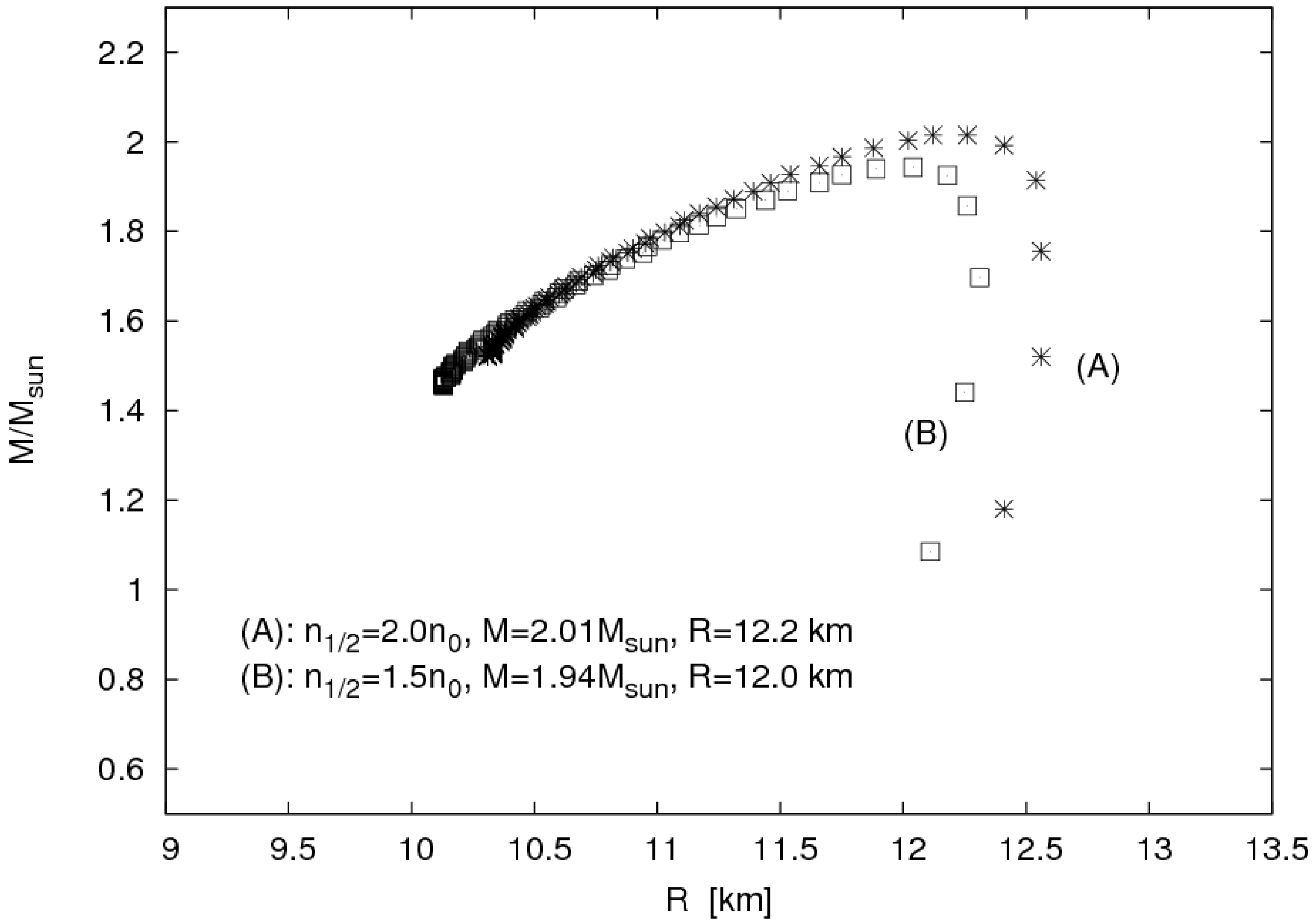
Dong, Kuo et al 2013



Checked by experiment up to ~ $2n_0$

Compact Star $M_\odot^{max}$ vs. R

Dong, Kuo, Lee, Rho 2012



Shapiro measure

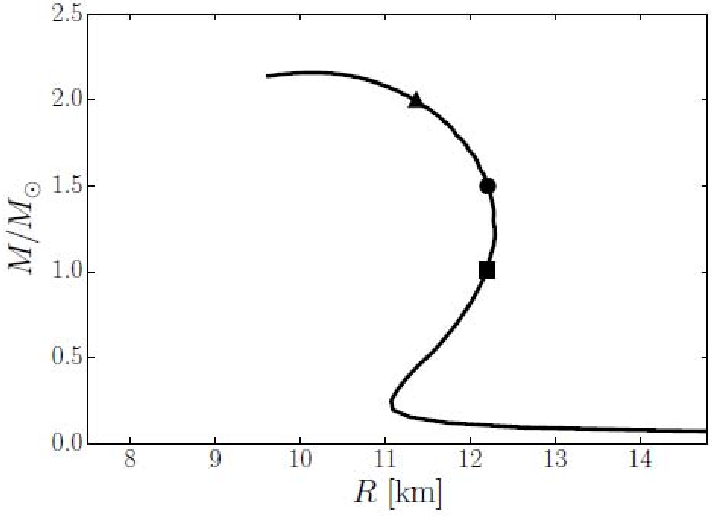
$M = 1.97 \pm 0.04\ M_\odot$

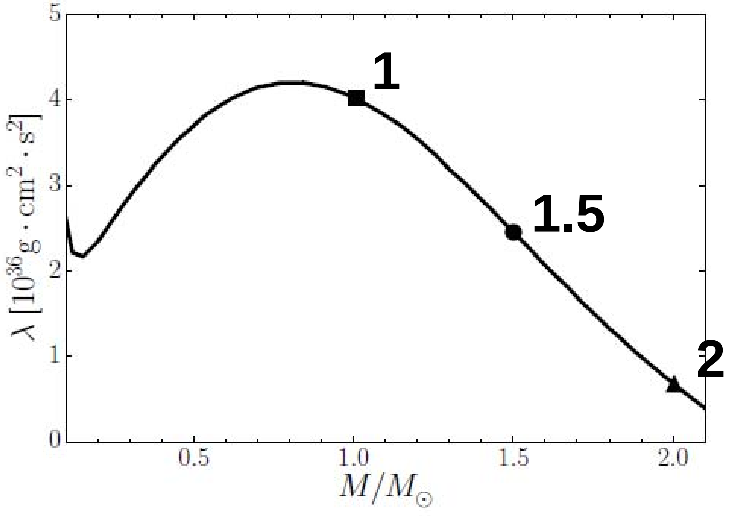
R = 11-15 km

Gravity wave: aLIGO & aVIRGO

Tidal deformability parameter λ

Gravitational waves from coalescing binary neutron stars carry signal for tidal distortion of stars, sensitive to EoS. Claim is that can be accurately measured!





Nature simplifies at high density

- Near nuclear matter density and slightly above, the strong scalar (σ) attraction and the strong vector (ω) repulsion “kill” each other leaving a small binding

  ⇔ Landau Fermi liquid structure
- Forms a near BPS matter at increasing density
- Fluctuation on top of the matter in neutron-rich matter is dominated by the pionic tensor force, with the opposing ρ tensor strongly suppressed

  Pions take over at high density

  → π condensed crystal matter

Summary

Physics in dense matter indicates

- Interplay of infinite tower of hidden local symmetries.
- Light scalar, possibly dilaton, must be there, perhaps in an “emergent” scale symmetry.
- Concept of “mended symmetries” in action.
- At high density, role of topology, giving rise to weakly interacting quasiparticles with NG scalars; physics could become simpler at high density!!
- Compact stars provide probe for the densest matter “visible” in the Universe via GW.