Pseudoconformal Structure of Dense Nuclear Matter

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A Possible New Phase of Thermal QCD

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(Dated: Jun 17, 2019)

Using lattice simulations, we show that there is a phase of thermal QCD, where the spectral density $\rho(\lambda)$ of Dirac operator changes as $1/\lambda$ for infrared eigenvalues $\lambda < T$. This behavior persists over the entire low energy band we can resolve accurately, over three orders of magnitude on our largest volumes. We propose that in this "IR phase", the well-known non-interacting scale invariance at very short distances (UV, $\lambda \to \infty$, asymptotic freedom), coexists with very different interacting type of scale invariance at long distances (IR, $\lambda < T$). Such dynamics may be responsible for the unusual fluidity properties of the medium observed at RHIC and LHC. We point out its connection to the physics of Banks-Zaks fixed point, leading to the possibility of massless glueballs in the fluid. Our results lead to the classification of thermal QCD phases in terms of IR scale invariance. The ensuing picture naturally subsumes the standard chiral crossover feature at "T_c" $\approx$ 155 MeV. Its crucial new aspect is the existence of temperature $T_{\rm IR}$ (200 MeV $< T_{\rm IR} <$ 250 MeV) marking the onset of IR phase and possibly a true phase transition.

Challenges in Nuclear Physics

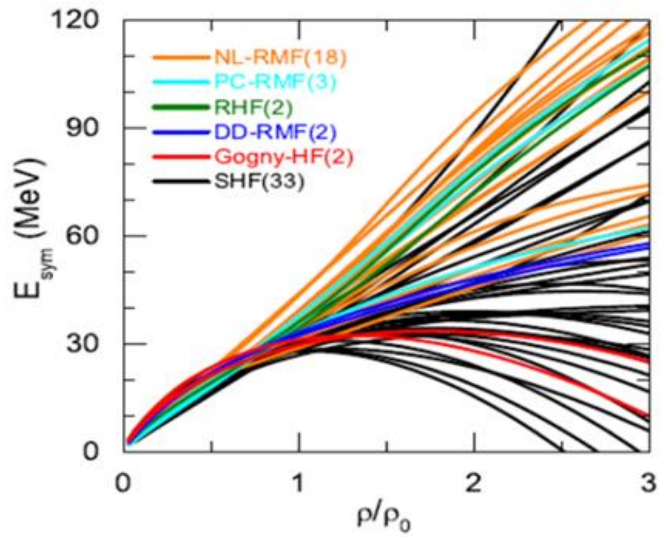
- EoS of nuclear matter:
  At high density $\sim 2.0\ n_0$, mess.

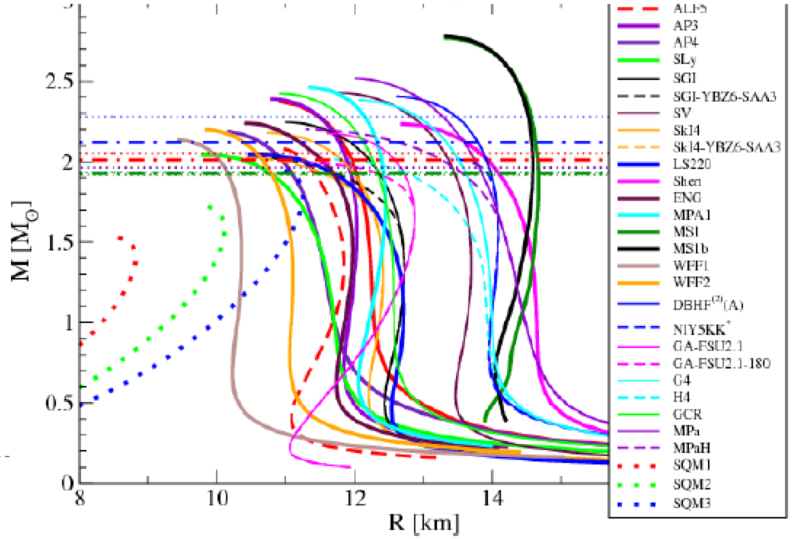
  - What is the matter made of?
  - How to simulate the nuclear force?

- Cannot be accessed by lattice simulation (sign prob.)

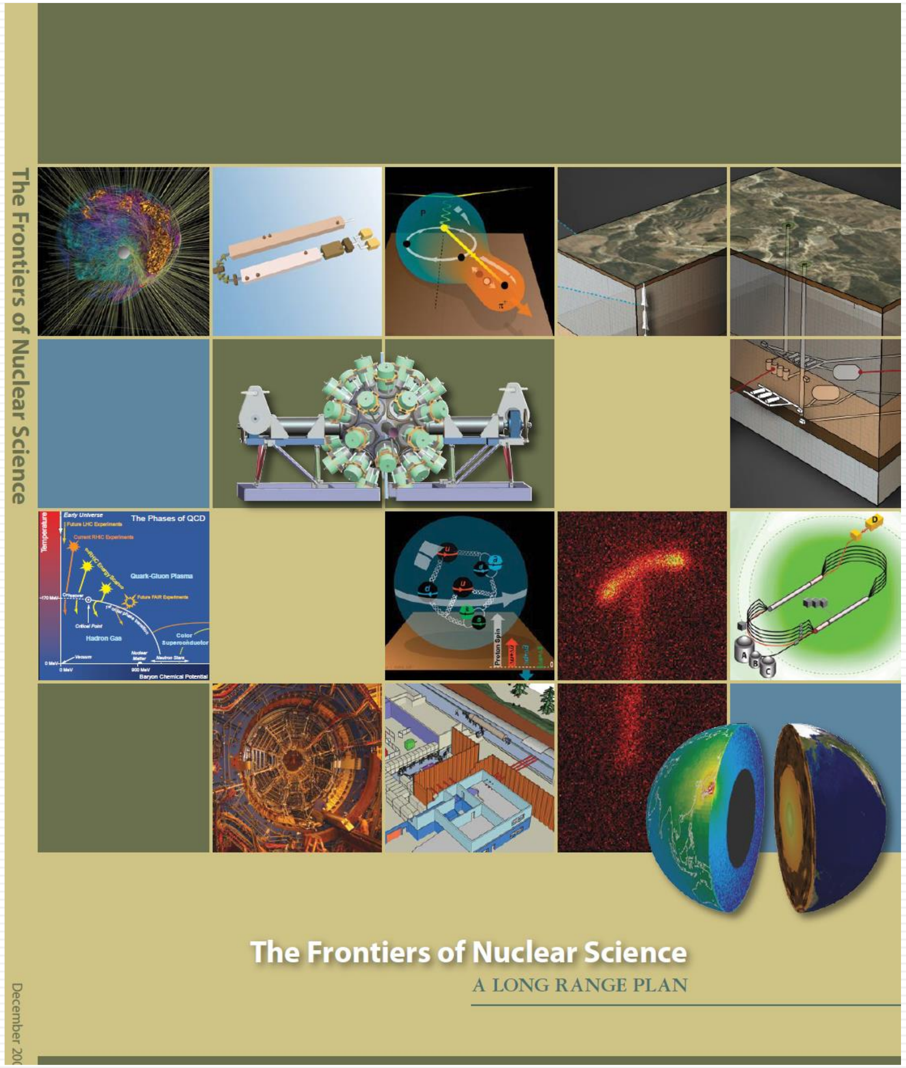
  Cannot be distinguished from QCD.

  New D.O.F enters? Quark-gluon enters? ……





Challenges in Nuclear Physics



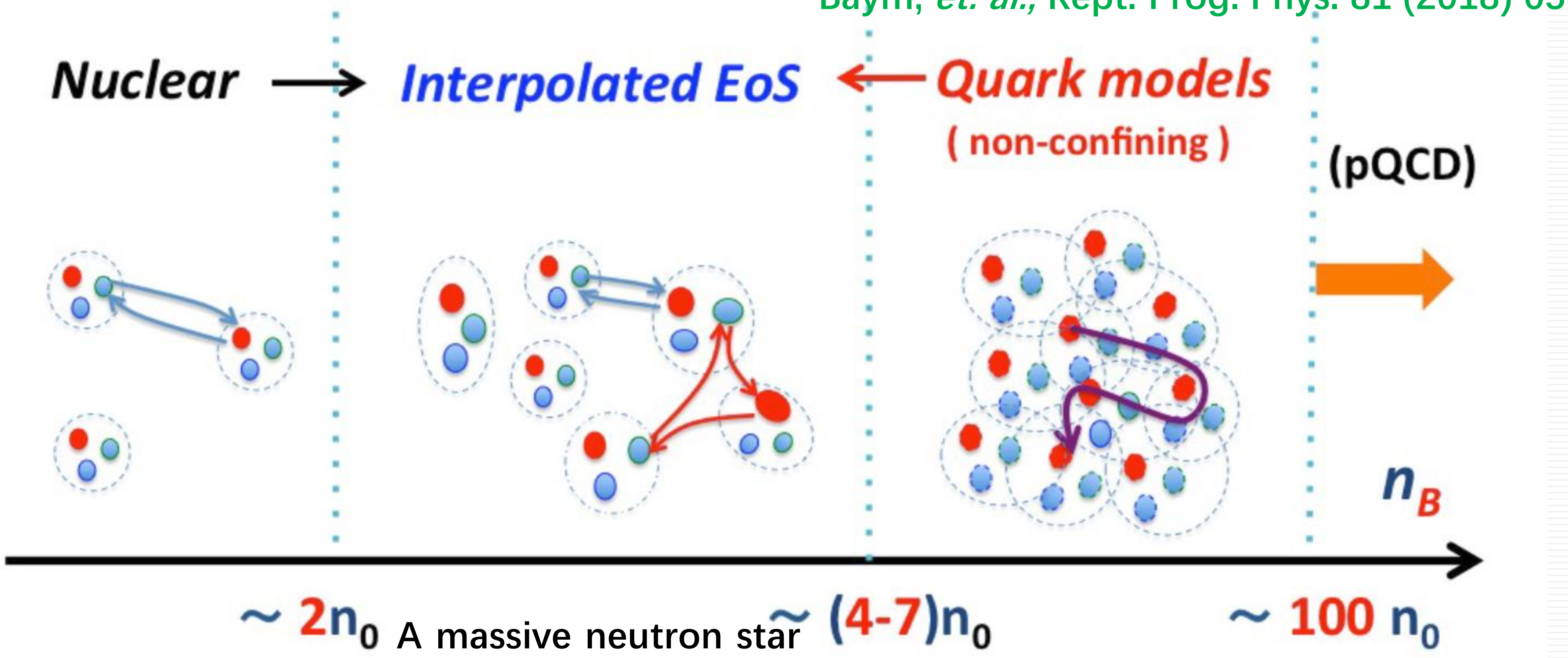
Nuclei and Nuclear Astrophysics

- **What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes?**
- **What is the origin of simple patterns in complex nuclei?**
- **What is the nature of neutron stars and dense nuclear matter?**
- **What is the origin of the elements in the cosmos?**
- **What are the nuclear reactions that drive stars and stellar explosions?**

dominated by quantum phenomena. One of the most important scientific challenges for the next decade is a quantitative exploration of this new state of matter.

Crossover from Hadrons to Quarks

Baym, *et. al.,* Rept. Prog. Phys. 81 (2018) 056902.



A massive neutron star of mass $M \sim 2.3\ M_{solar}$ with central density $n_c \sim (5\text{-}7)n_0$ contains quarks in some form.

Promising?

- Tidal deformability:

$$\Lambda < 800 \quad \rightarrow \quad \Lambda = 300^{+420}_{-230}$$

$$\rightarrow \quad \Lambda = 190^{+390}_{-120}$$

$$of\ R = 11.9^{+1.4}_{-1.4}\ km$$

C. Y. Tsang, *et al.*, 1807.06571

- Massive neutron stars:

$(1.97 \pm 0.04)M_{\odot}$ *Nature, 467(2010),1081.*

$(2.01 \pm 0.04)M_{\odot}$ *Science, 340(2013), 448.*

$(2.17^{+0.11}_{-0.10})M_{\odot}$ *arXiv: 1904.06759.*

- Shapes of GWs (future).

- Constraint the EoS of dense nuclear matter ?
- Structure of massive neutron star?

Issues on Sound velocity in nuclear matter

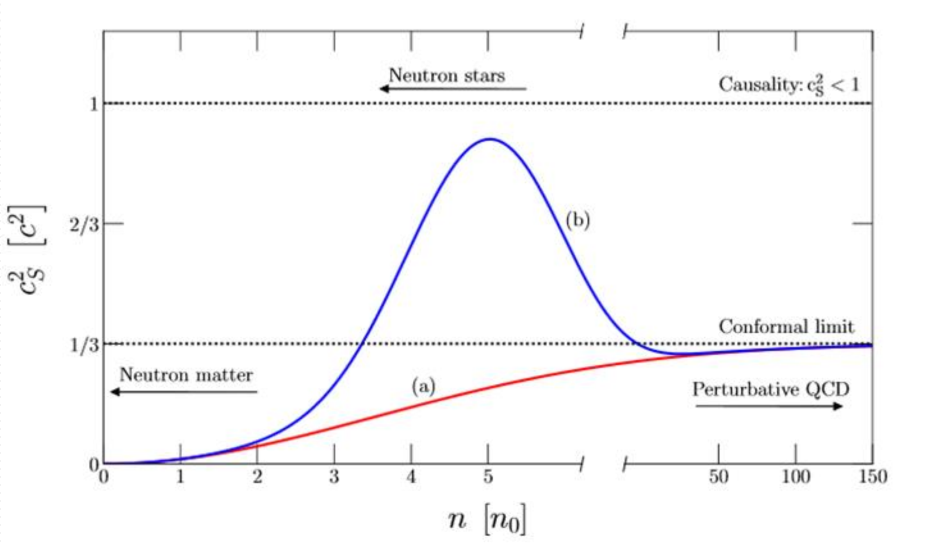
- Naive causality: $v_s \leq 1$; However, if the nuclear matter is made of ultrarelativistic massless particles, $\boldsymbol{v_s \leq 1/\sqrt{3}}$ (the upper bound from conformal symmetry). Whether or not such an upper bound can be saturated in dense nuclear matter should be settled by observation.

- Combine with the EoS of hadronic matter that describes correctly the nuclear matter properties around n_0, the existence of neutron stars with mass $\approx$ $\boldsymbol{2.0\, M_{solar}}$ ***is not consistent with bound*** $\boldsymbol{v_s \leq 1/\sqrt{3}}$.

  PRL114, 031103 (2015); APJ860, 149 (2018); PRC95, 045801 (2017); MNRAS478, 1377 (2018).

Issues on Sound velocity in nuclear matter

"Standard Scenario"



We found that the conformal limit of $c_S^2 \leqslant 1/3$ is in tension with current nuclear physics constraints and observations of two-solar-mass NSs, in accordance with the findings of Bedaque & Steiner (2015). If the conformal limit was found to hold at all densities, this would imply that nuclear physics models break down below $2n_0$.

S. Reddy et al, 2018

We are disagreeing!

Pseudoconformal model for dense matter

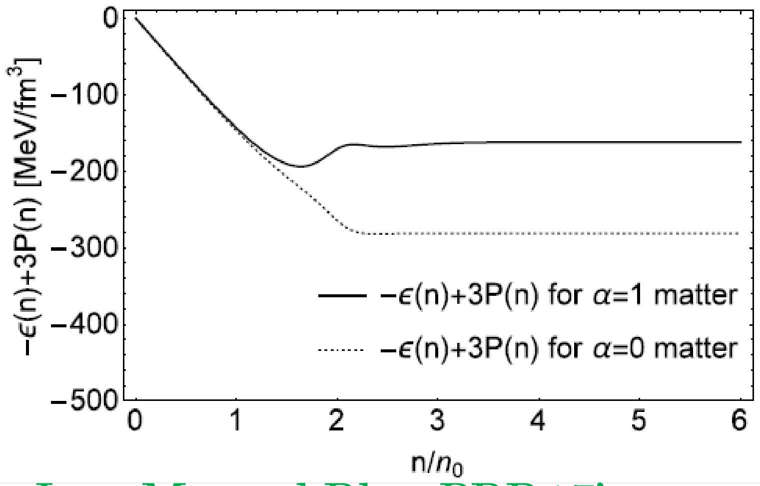
$$\langle\theta^{\mu}_{\mu}\rangle = \langle\theta^{00}\rangle - \sum_i \langle\theta^{ii}\rangle = \epsilon - 3P \quad = 4V(\langle\chi\rangle) - \langle\chi\rangle \left.\frac{\partial V(\chi)}{\partial\chi}\right|_{\chi=\langle\chi\rangle}$$

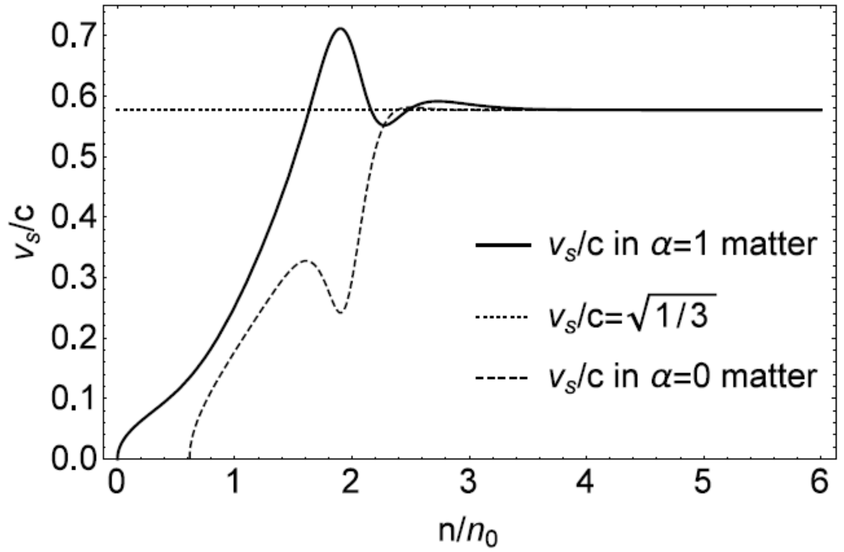
TEMT is given solely by dilaton condensate

In medium: $\left(\theta^{\mu}_{\mu} \propto \langle\chi\rangle^4 \propto m_N^{*4} \propto f_\pi^{*4}\right)$

The relation between TEMT and sound velocity

$$\frac{\partial}{\partial n}\langle\theta^{\mu}_{\mu}\rangle = \frac{\partial\epsilon(n)}{\partial n}(1 - 3v_s^2) = 0 \qquad v_s^2/c^2 = \frac{\partial P(n)}{\partial n} \Big/ \frac{\partial\epsilon(n)}{\partial n}$$



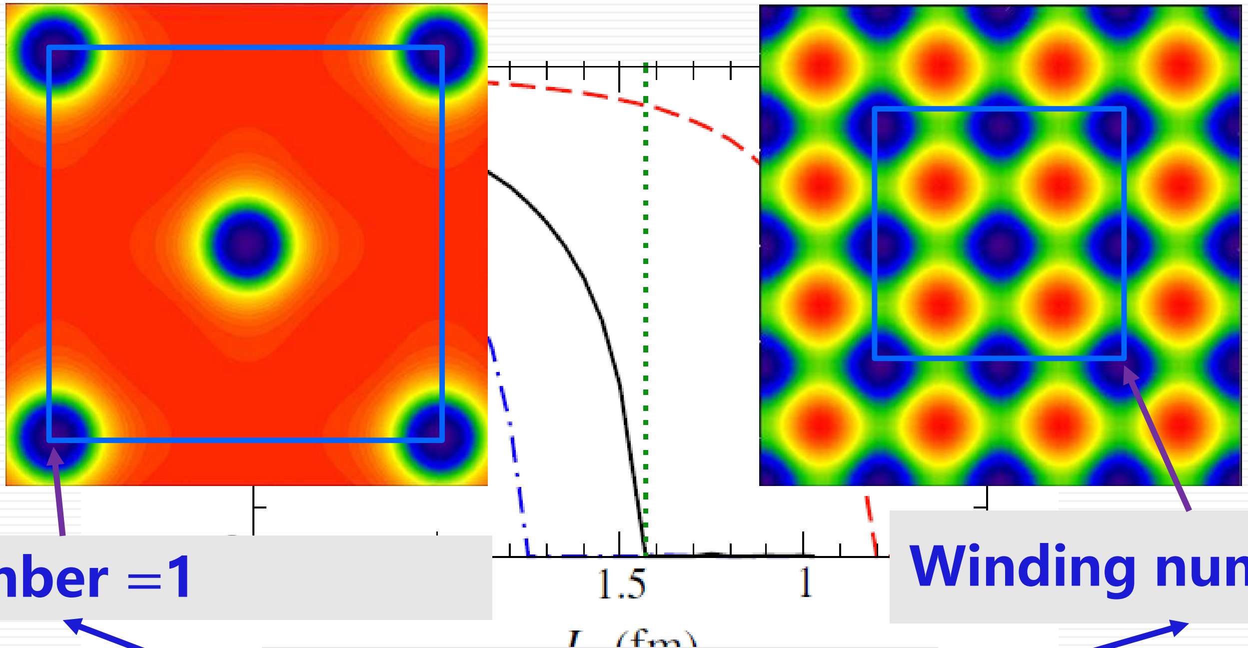


Paeng, Kuo, Lee, Ma and Rho, PRD17'.

What is the solid foundation of the PCM ?

- Topology Change
- Emergent symmetry
  - Hidden local flavor symmetry
  - Hidden scale symmetry

Topology change



Winding number $=1$

Winding number $= \frac{1}{2}$

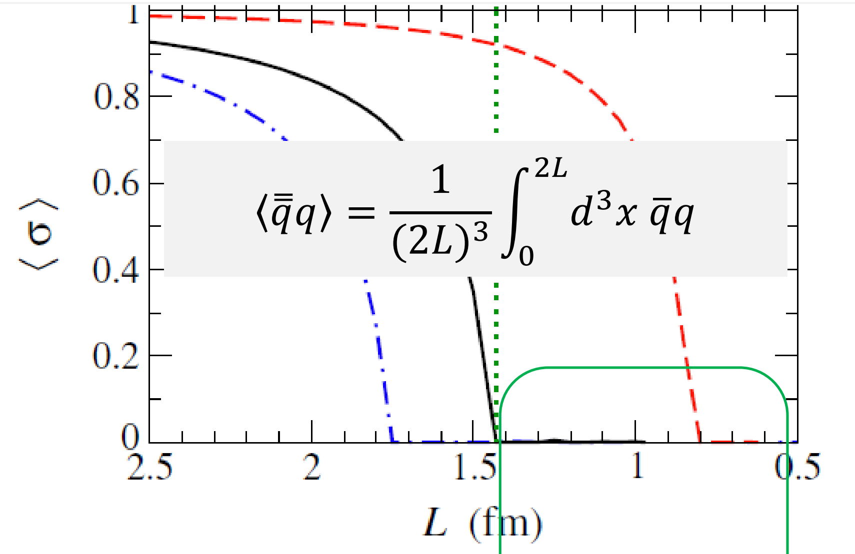
Topology transition

- An intrinsic mathematic properties of QCD at low energy.
- Model and crystal independent.

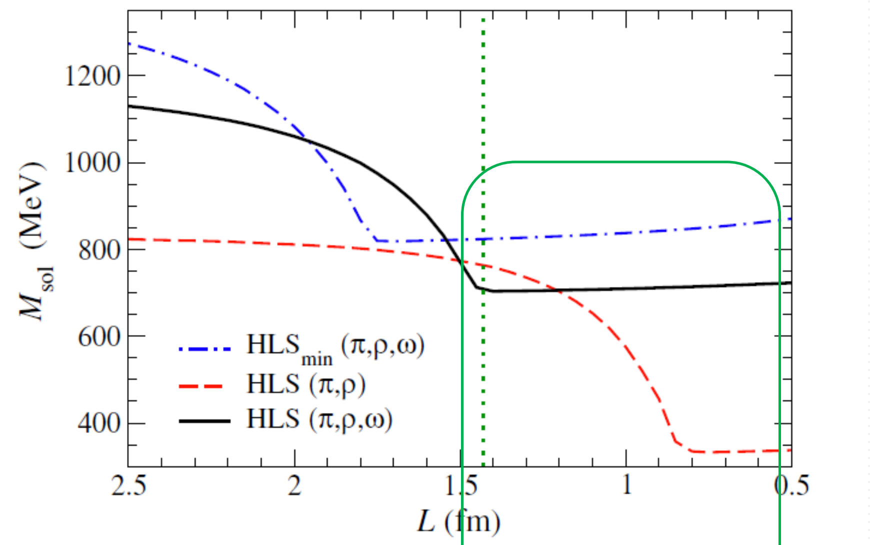
YM and M. Rho, Sci. China Phys.Mech.Astron. 17'.

Topology change: Parity doublet structure

Y. L. Ma, et al, Phys. Rev. D88 (2013), 014016; Phys. Rev. D90 (2014) no.3, 034015.



$$\langle\bar{q}q\rangle = \frac{1}{(2L)^3}\int_0^{2L} d^3x\,\bar{q}q$$



High density region(small L): **Quark condensate vanishes** **However** **Nucleon mass is non-zero**

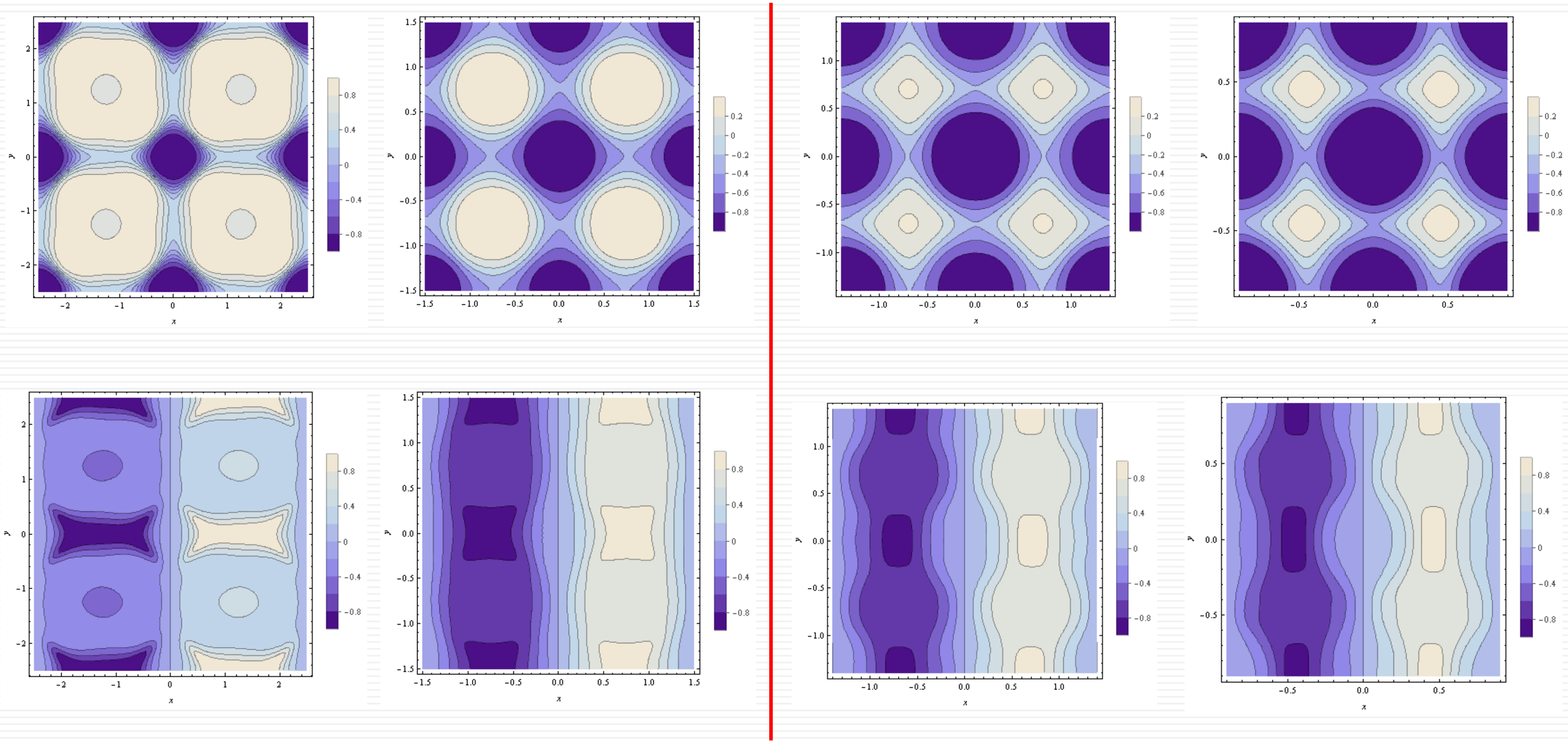
- **Nucleon mass is not solely from chiral symmetry breaking, it include a chiral invariant part. parity doubling structure.**

Agree with Y. Motohiro, *et al*, Phys.Rev. C92 (2015) no.2, 025201

Inhomogeneous quark condensates

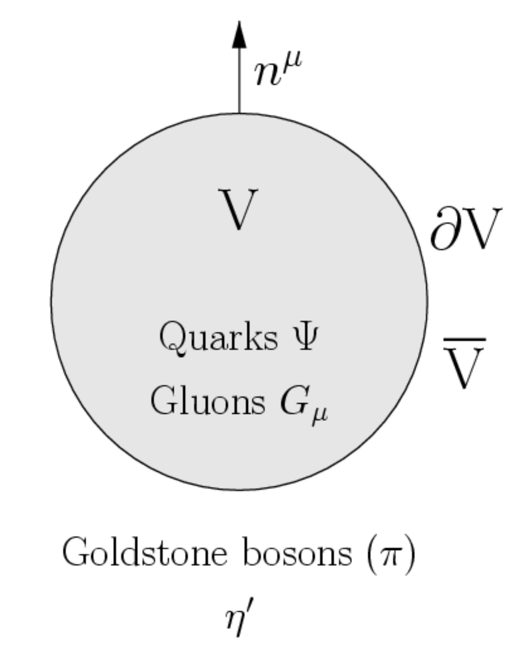
M. Rho, H. K. Lee, YM and M. Harada, PRD(2015).

1. Local chiral symmetry breaking (dense effect):



Topology change: Chashire Cat principle

The Cheshire Cat



“How hadrons transform to quarks”

Baryon charge:

$$B_{out} = \frac{1}{\pi}[\theta(R) - \frac{1}{2}\sin 2\theta(R)]$$

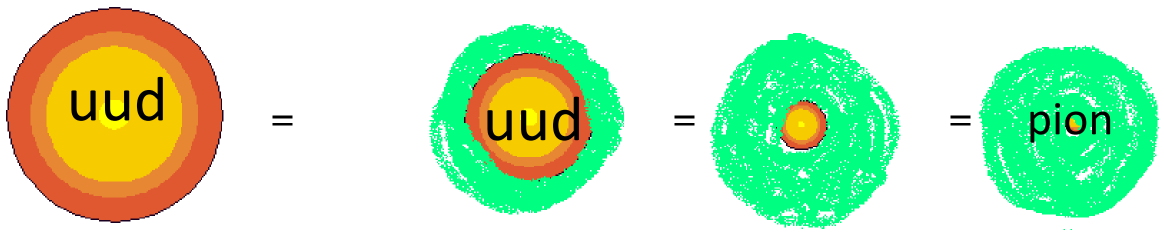
$$B_{in} = 1 - \frac{1}{\pi}[\theta(R) - \frac{1}{2}\sin 2\theta(R)]$$

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

Brown, Goldhaber, Rho 1983
Goldstone, Jaffe 1983

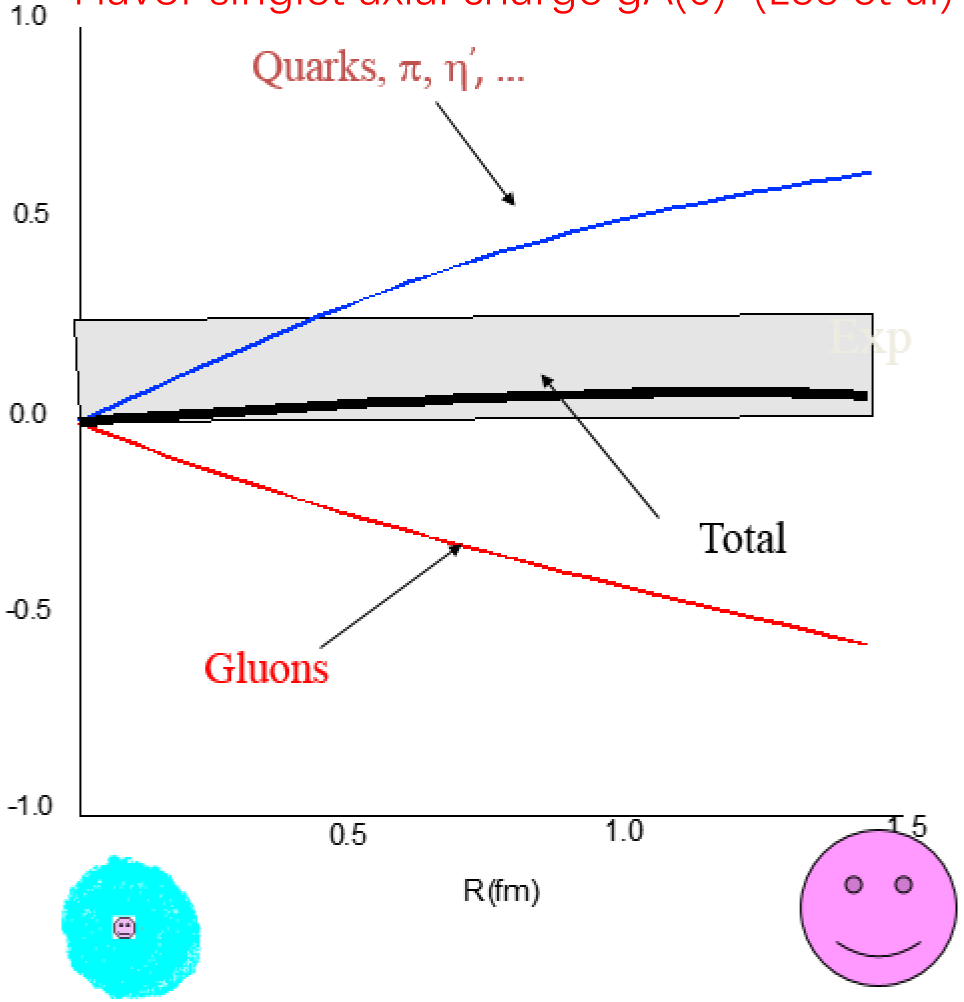
Topology change: Chashire Cat principle

Proton



Equivalent description of the proton

Flavor singlet axial charge gA(0) (Lee et al)



Hidden flavor local symmetry

Redundancy in the decomposition

$$U(x) = \xi_L \; h(x)\, h(x)^\dagger \; \xi_R{}^\dagger$$

$$h(x) \in SU(2)_{L+R} \times U(1)_{L+R}$$

ρ meson

ω meson

The idea -- that is totally different from what one could call "standard" in nuclear community - is that rho (and w, in a different way) is "hidden gauge field" (HLS in the literature).

Bando, *et al* 89; Harada & Yamawaki, 03

$$\hat{\alpha}_{\parallel\mu} = \frac{1}{2i}(D_\mu \xi_R \cdot \xi_R^\dagger + D_\mu \xi_L \cdot \xi_L^\dagger$$

$$\hat{\alpha}_{\perp\mu} = \frac{1}{2i}(D_\mu \xi_R \cdot \xi_R^\dagger - D_\mu \xi_L \cdot \xi_L^\dagger$$

$$V_\mu(x) = \frac{g_\rho}{2}\rho_\mu^a \tau^a + \frac{g_\omega}{2}\omega_\mu I_{2\times 2},$$

$$\mathcal{L}_M = f_\pi^2 \mathrm{tr}\left[\hat{\alpha}_{\perp\mu}\hat{\alpha}_\perp^\mu\right] + a_\rho f_\pi^2 \mathrm{tr}\left[\hat{\alpha}_{\parallel\mu}\hat{\alpha}_\parallel^\mu\right] + (a_\omega - a_\rho) f_\pi^2 \mathrm{tr}\left[\hat{\alpha}_{\parallel\mu}\right] \mathrm{tr}\left[\hat{\alpha}_\parallel^\mu\right] - \frac{1}{2}\mathrm{tr}\left[\rho_{\mu\nu}\rho^{\mu\nu}\right] - \frac{1}{2}\mathrm{tr}\left[\omega_{\mu\nu}\omega^{\mu\nu}\right].$$

Hidden flavor local symmetry

Suzuki Theorem：

PHYSICAL REVIEW D **96,** 065010 (2017)

Inevitable emergence of composite gauge bosons

Mahiko Suzuki

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(Received 18 July 2017; published 15 September 2017)

A simple theorem is proved: When a gauge-invariant local field theory is written in terms of matter fields alone, a composite gauge boson or bosons must be formed dynamically. The theorem results from the fact that the Noether current vanishes in such theories. The proof is carried out by use of the charge-field algebra

This theorem holds for rho if there is a sense of massless rho at some parameter space. The HLS with the redundancy elevated to gauge theory, treated à la Wilsonian RG, has (Harada & Yamawaki,01') a fixed point at $g_\rho = 0$. The KSRF relation $m_\rho^2 \propto f_\pi^2 g_\rho^2$ holds to all loop orders, hence at the fixed point, called vector manifestation (VM) fixed point, there "emerges" a gauge field.

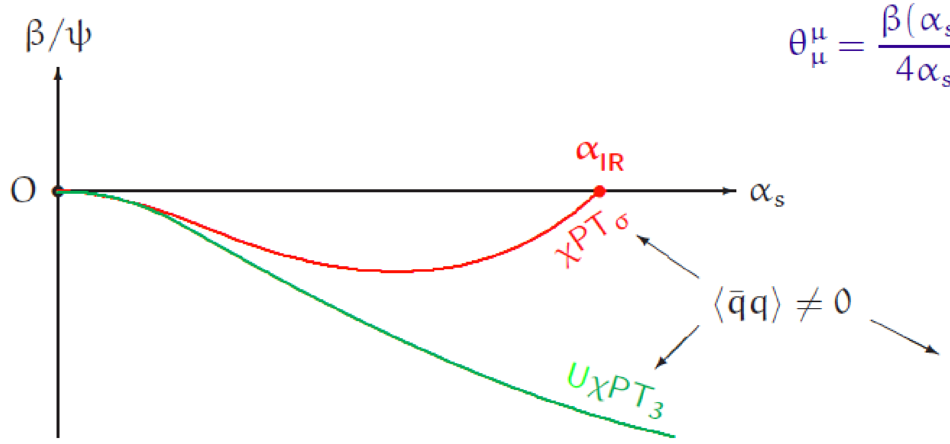
Our premise: that there is a VM fixed point at high density at which $m_r \to 0$. Where this point is located is not known precisely but for compact-star physics, it lies at $n > \sim 20\, n_0$.

Hidden scale symmetry

$f_0(500)$ is a pNGB arising from (noted $m_{f_0} \cong m_K$). The SB of SS associated + an explicit breaking of SI.

Assumption: There is an Nonperturbative IR fixed point in the running QCD coupling constant α_s.

EB of SI: Departure of α_s from IRFP + current quark mass.



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

IR fixed point: $\beta(\alpha_{IR}) = 0$

$\chi PT_\sigma \Rightarrow$ expand in θ^μ_μ

$\alpha_s \lesssim \alpha_{IR}$, $m_{u,d,s} \sim 0$

about scale-*dependent* $|vac\rangle$

$\Rightarrow$ NG bosons π, K, η, σ.

Crewther and Tunstall , PR**D91**, 034016

- Trace anomaly in QCD

$$\partial_\mu D^\mu = \frac{\beta(\alpha_s)}{4\alpha_s} Tr\,(G_{\mu\nu} G^{\mu\nu})$$

A possible way to introduce a scalar meson.

PHYSICAL REVIEW D VOLUME 21, NUMBER 12 15 JUNE 1980

Effective Lagrangian with two color-singlet gluon fields

Joseph Schechter
Physics Department, Syracuse University, Syracuse, New York 13210
(Received 10 December 1979)

An effective Lagrangian with scalar and pseudoscalar "matter" fields as well as scalar and pseudoscalar (gauge-invariant) color-singlet gluon fields is constructed. It is a representation of quantum chromodynamics in that it has the same symmetry structure as that theory. The present model is a generalization of a one-(pseudoscalar) gluon-field effective Lagrangian which compactly summarizes the results of the $1/N_c$ approximation, gives a simple picture for the "U(1) problem," and essentially reduces to a type of generalized σ model. The new feature here is that, in addition to the chiral-anomaly equation, the trace-anomaly equation is automatically fulfilled. This gives a framework for discussion of the properties of a 0^+ color-singlet gluon field. The model may be formulated either so that this field is eliminated by a constraint

Hidden scale symmetry

A Possible New Phase of Thermal QCD

Andrei Alexandru[1] and Ivan Horváth[2]

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Using lattice simulations, we show that there is a phase of thermal QCD, where the spectral density $\rho(\lambda)$ of Dirac operator changes as $1/\lambda$ for infrared eigenvalues $\lambda < T$. This behavior persists over the entire low energy band we can resolve accurately, over three orders of magnitude on our largest volumes. We propose that in this "IR phase", the well-known non-interacting scale invariance at very short distances (UV, $\lambda \to \infty$, asymptotic freedom), coexists with very different interacting type of scale invariance at long distances (IR, $\lambda < T$). Such dynamics may be responsible for the unusual fluidity properties of the medium observed at RHIC and LHC. We point out its connection to the physics of Banks-Zaks fixed point, leading to the possibility of massless glueballs in the fluid. Our results lead to the classification of thermal QCD phases in terms of IR scale invariance. The ensuing picture naturally subsumes the standard chiral crossover feature at "T_c" ≈ 155 MeV. Its crucial new aspect is the existence of temperature $T_{\rm IR}$ (200 MeV $< T_{\rm IR} <$ 250 MeV) marking the onset of IR phase and possibly a true phase transition.

我们提出，在这一“红外相”，在短距处众所周知的无相互作用的的标度不变性与长距处完全不同种类的标度不变性共存。 …… 得到流体中存在无质量胶球的可能性。我们的结果可以推出在热QCD相中划分出红外标度不变的部分。

致密区域存在类似的情况?

手征-标度有效理论。

bsHLS effective field theory

$$\mathcal{L} = \mathcal{L}^{M}_{\chi PT_\sigma}(\pi,\chi,V_\mu) + \mathcal{L}^{B}_{\chi PT_\sigma}(\psi,\pi,\chi,V_\mu) - V(\chi)$$

$$\mathcal{L}^{M}_{\chi PT_\sigma}(\pi,\chi,V_\mu) = f_\pi^2\left(\frac{\chi}{f_\sigma}\right)^2 \mathrm{Tr}[\hat{a}_{\perp\mu}\hat{a}_{\perp}^{\mu}] + a f_\pi^2 \left(\frac{\chi}{f_\sigma}\right)^2 \mathrm{Tr}[\hat{a}_{\parallel\mu}\hat{a}_{\parallel}^{\mu}] + \frac{1}{2g^2}\mathrm{Tr}[V_{\mu\nu}V^{\mu\nu}] + \frac{1}{2}\partial_\mu\chi\partial^\mu\chi$$

$$\mathcal{L}^{B}_{\chi PT_\sigma}(\psi,\pi,\chi,V_\mu) = \mathrm{Tr}(\bar{B}i\gamma_\mu D^\mu B) - \frac{\chi}{f_\sigma}\mathrm{Tr}(\bar{B}B) + \cdots$$

$$V(\chi) \approx \frac{m_\sigma^2 f_\sigma^2}{4}\left(\frac{\chi}{f_\sigma}\right)^4\left[\ln\left(\frac{\chi}{f_\sigma}\right) - \frac{1}{4}\right].$$

$$m_N \propto \langle\chi\rangle \sim \mathrm{constant}$$

Li, Ma and Rho, PRD95,114011 (2017);
YM & M. Rho, PRD18

Implement topology transition to EoS

Hadron properties have different scales in $n < n_{1/2}$ and $n > n_{1/2}$

Different scaling behavior: Φ_I and Φ_{II}

Imbed the quanlitative conclusion to bsHLS

IDD

Beyond mean field

Calculate $V_{low\ k}$

$\mathrm{DD}_{\mathrm{induced}}$

EoS for nuclear matter with IDD

Φ_I: Predictions agree with the nuclear matter at low density.

Φ_{II}: Density independent.

Parameter free EoS for DM: $E/A = -m_N + X^\alpha x^{1/3} + Y^\alpha x^{-1},\ n \gtrsim n_{1/2}.$

Pseudo-conformal model

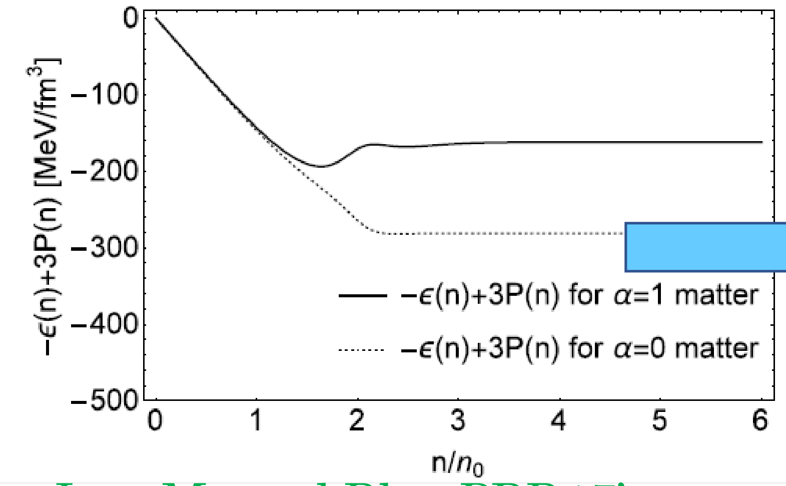
$$\langle\theta^{\mu}_{\mu}\rangle = \langle\theta^{00}\rangle - \sum_i \langle\theta^{ii}\rangle = \epsilon - 3P \quad = 4V(\langle\chi\rangle) - \langle\chi\rangle \frac{\partial V(\chi)}{\partial\chi}\Big|_{\chi=\langle\chi\rangle} .$$

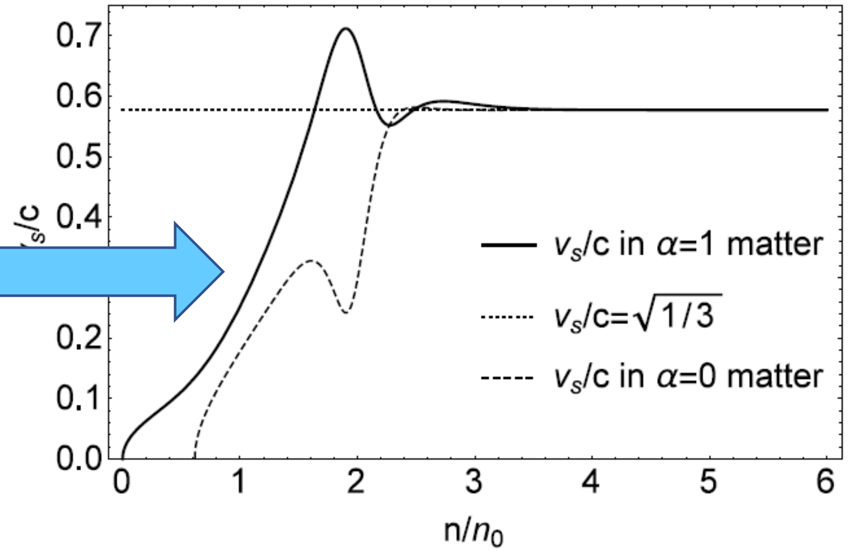
TEMT is given solely by dilaton condensate

In medium: $(\theta^{\mu}_{\mu} \propto \langle\chi\rangle^4 \propto m_N^{*4} \propto f_\pi^{*4})$

The relation between TEMT and sound velocity

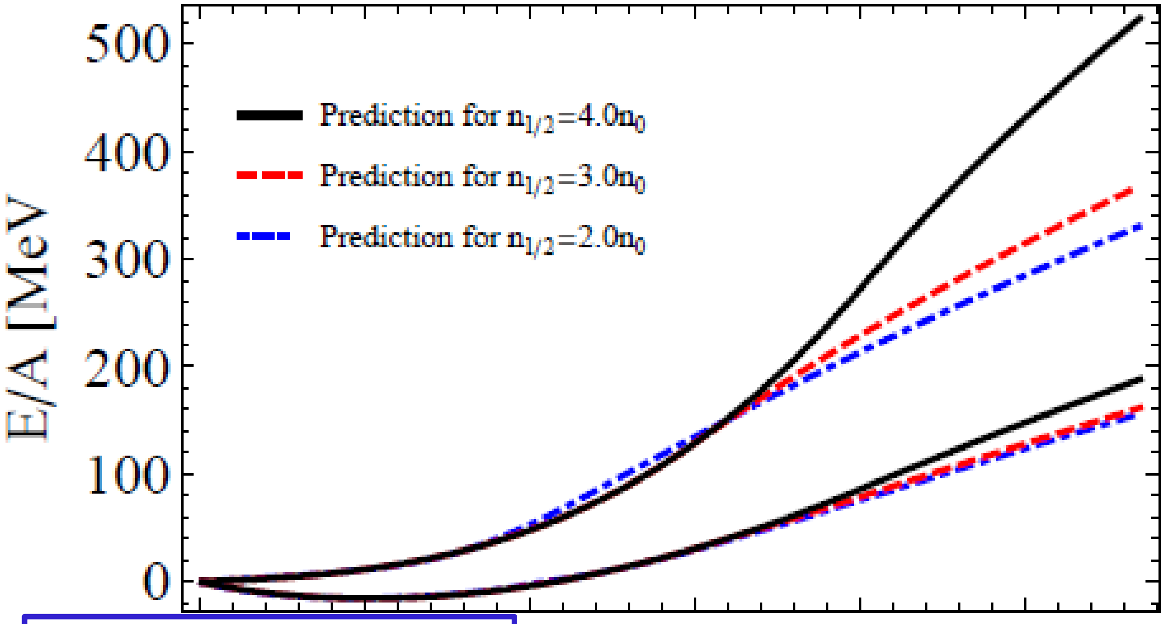
$$\frac{\partial}{\partial n}\langle\theta^{\mu}_{\mu}\rangle = \frac{\partial\epsilon(n)}{\partial n}(1 - 3v_s^2) = 0 \qquad v_s^2/c^2 = \frac{\partial P(n)}{\partial n} \Big/ \frac{\partial\epsilon(n)}{\partial n}$$





Paeng, Kuo, Lee, Ma and Rho, PRD17'.

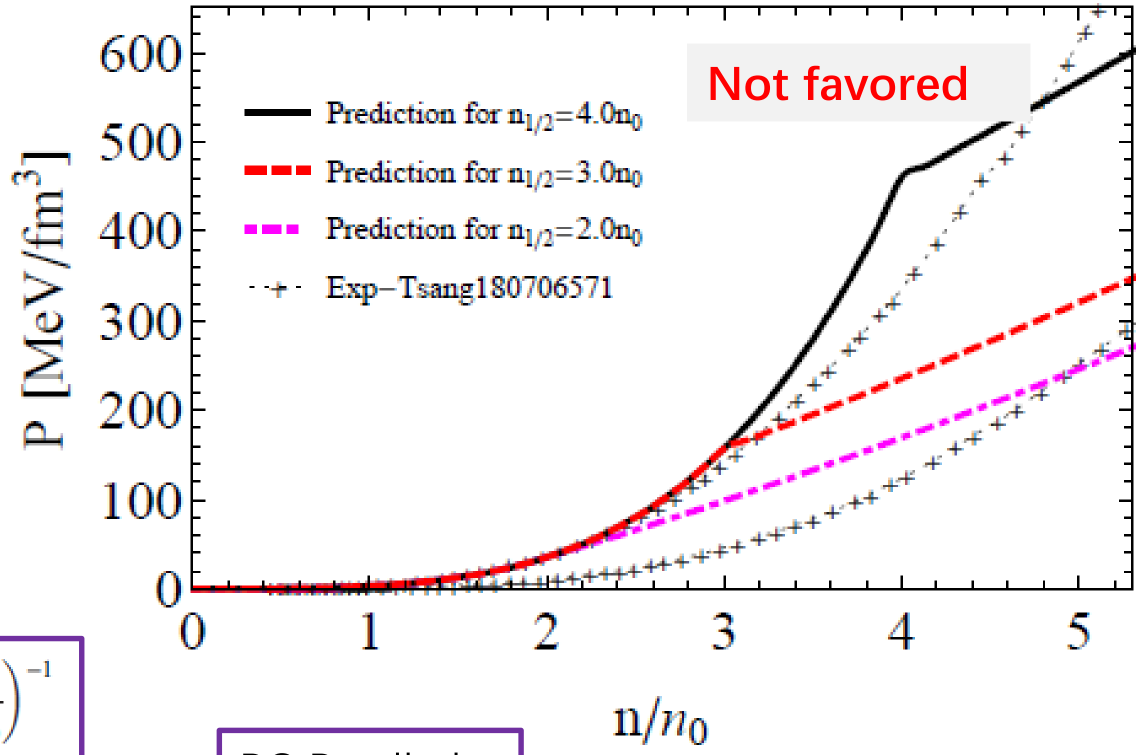
Emergent scale symmetry in medium



$$E_0/A = A_I\left(\frac{n}{n_0}\right) + B_I\left(\frac{n}{n_0}\right)^{D_I}.$$

Fitted function

$$E_0/A = -m_N + B\left(\frac{n}{n_0}\right)^{1/3} + D\left(\frac{n}{n_0}\right)^{-1}$$



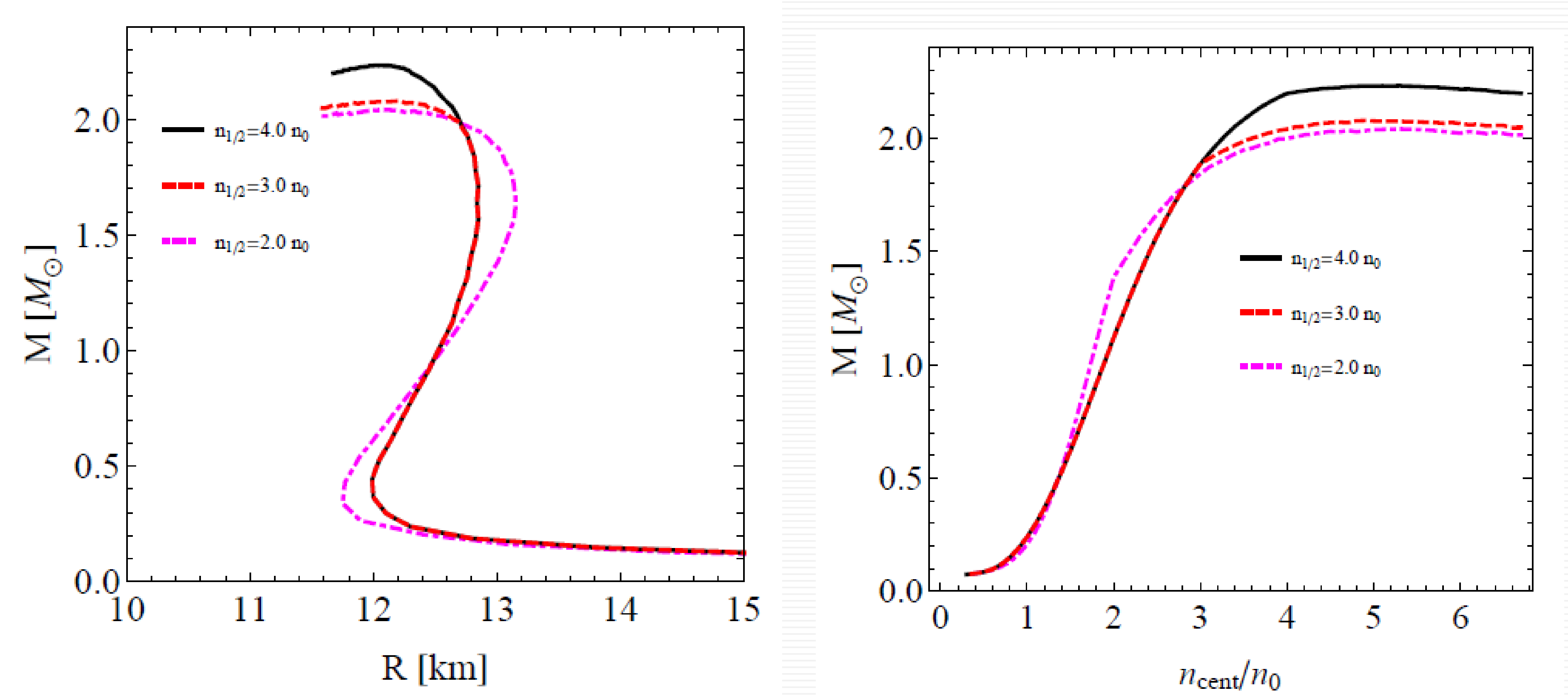
Not favored

PC Prediction

The value of $n_{1/2}$, to be constraint by observation.

Paeng, Kuo, Lee, Ma and Rho, PRD17'; Ma and Rho 18'.

Massive star properties

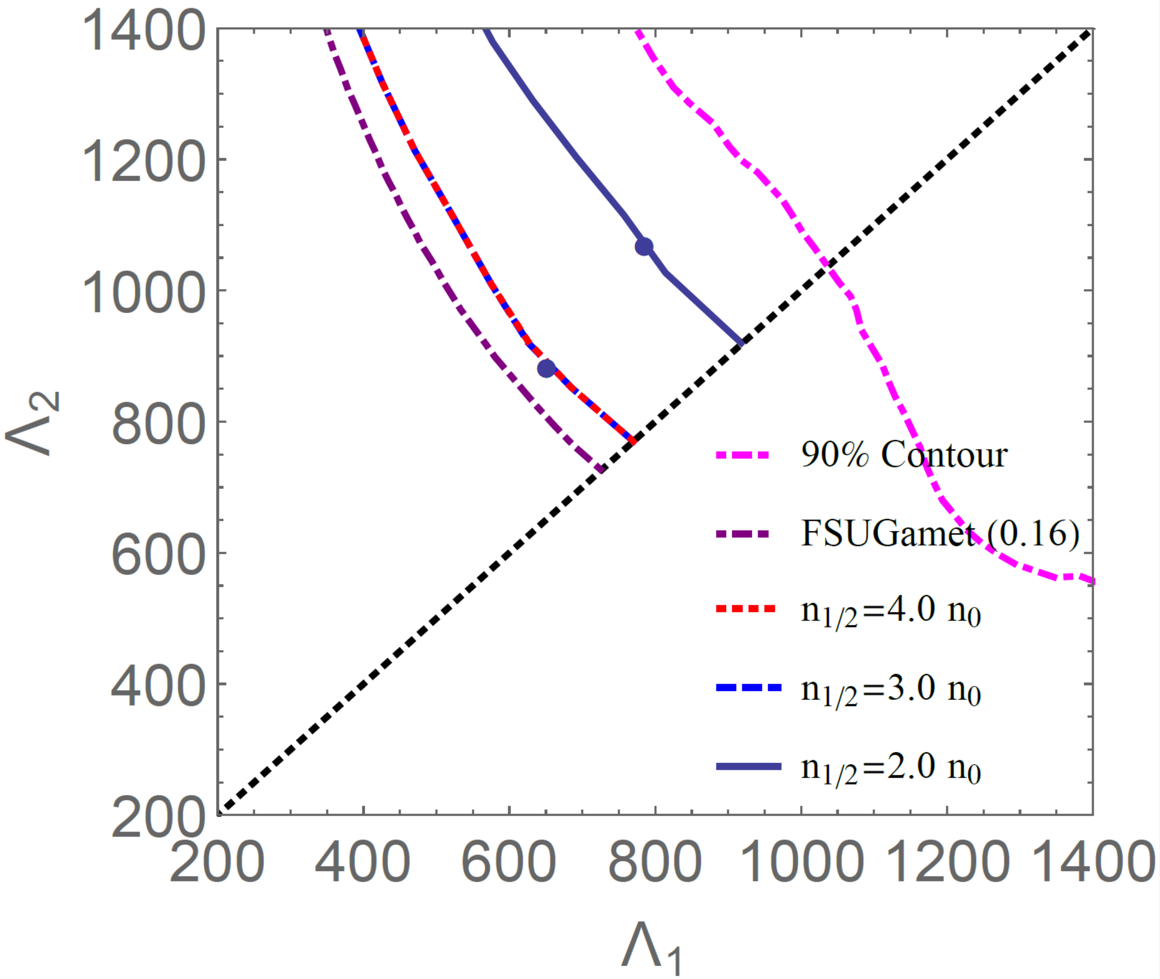


Accommodate massive star $\geq 2.0\ M_{solar}$

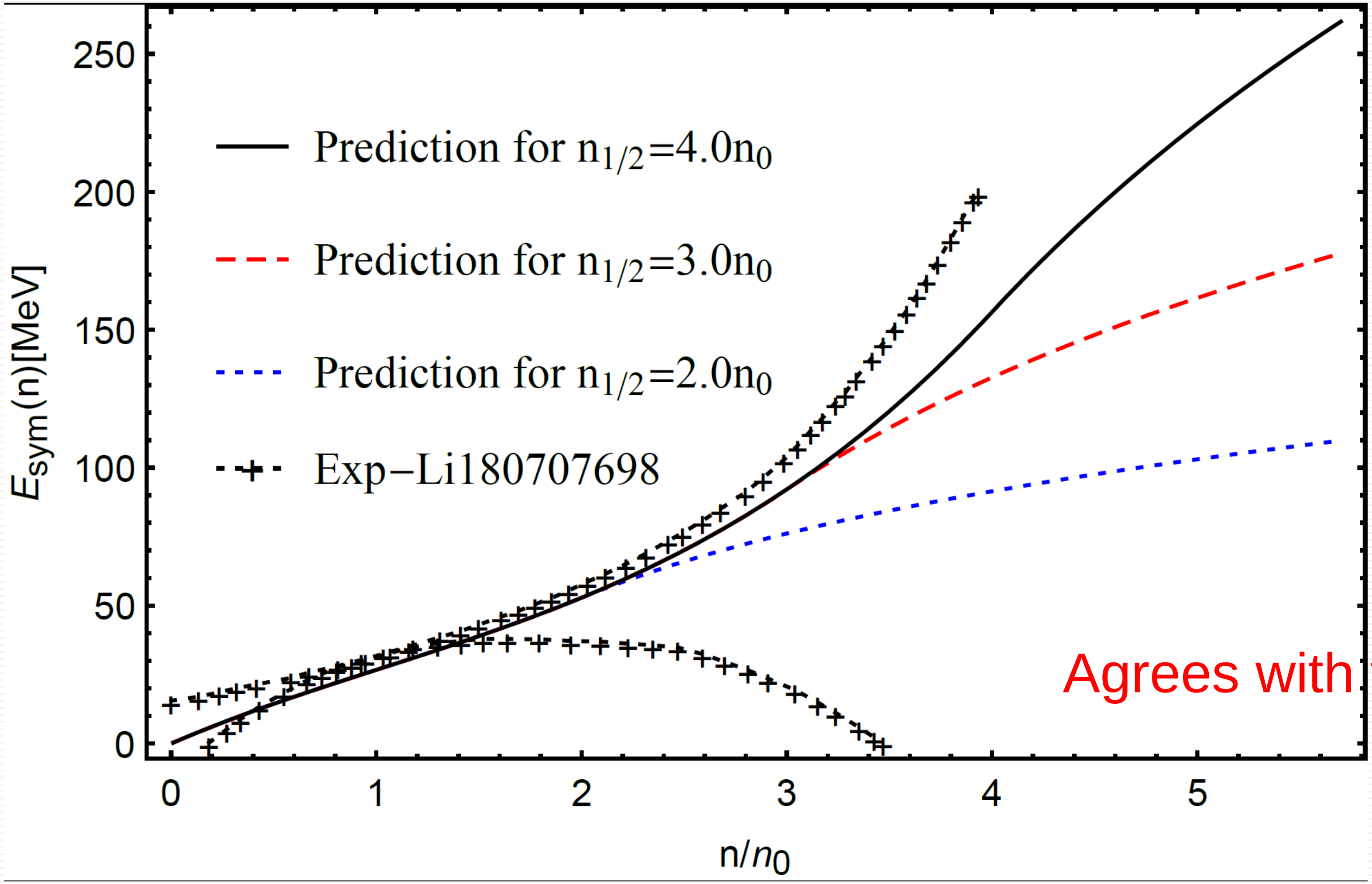
Ma and Rho, 18'; Ma, Lee, Paeng and Rho, 18'; Paeng, Kuo, Lee, YM and Rho PRD17'

Tidal deformability

$$\mathcal{M} = \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} = 1.188\, M_\odot.$$

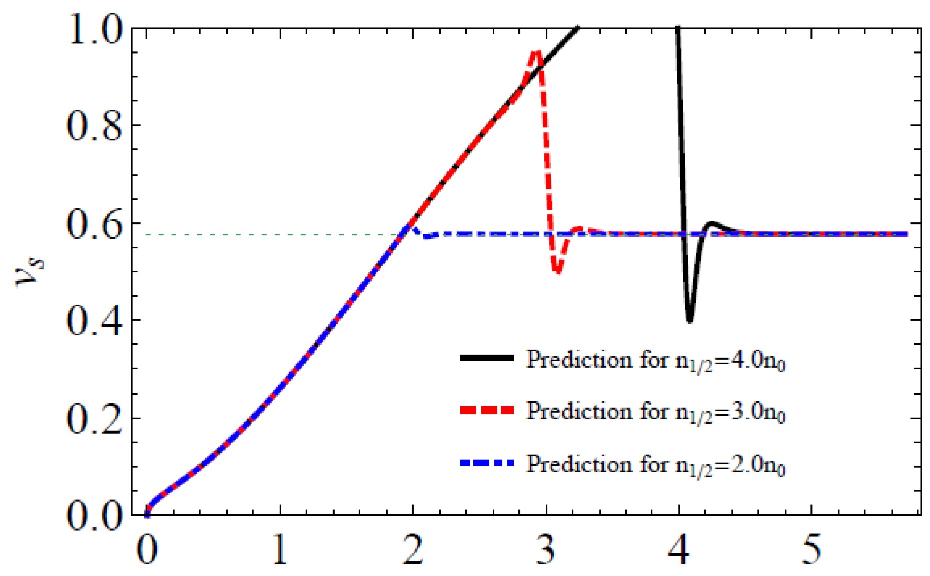


Symmetry energy



Agrees with the constraint !

Sound velocity



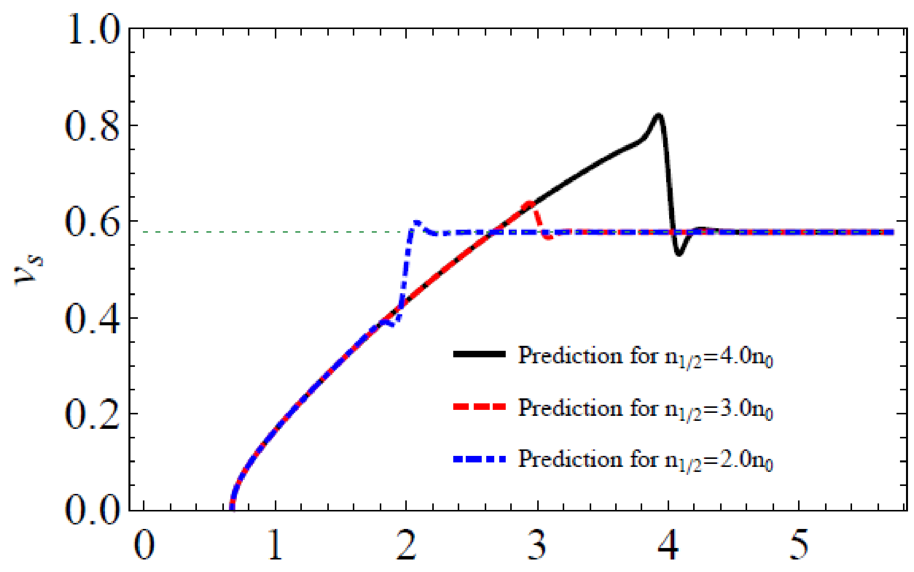


TABLE I. Properties of compact stars with different masses and $n_{1/2}/n_0$.

$M/M_\odot$	n_{cent}/n_0			$\Lambda/100$			R/km		
	$n_{1/2}=2.0$	$n_{1/2}=3.0$	$n_{1/2}=4.0$	$n_{1/2}=2.0$	$n_{1/2}=3.0$	$n_{1/2}=4.0$	$n_{1/2}=2.0$	$n_{1/2}=3.0$	$n_{1/2}=4.0$
1.40	2.02	2.30	2.30	7.85	6.52	6.52	13.0	12.8	12.8
1.60	2.61	2.54	2.54	2.85	2.90	2.90	12.8	12.8	12.8
1.80	3.11	2.84	2.81	1.21	1.30	1.30	12.8	12.8	12.8
2.00	4.50	3.60	3.21	0.37	0.55	0.55	11.5/12.2	12.6	12.7
2.20	—	—	4.00	—	—	0.20	—	—	12.3

Ma and Rho, arXiv:1811.07071

Summary and discussion

- Topology change + emergent symmetries inspired us to propose the PC structure of DM.
- In stark contrast to what was found in the literature, the PCM, which works well for normal nuclear matter density, gives $v_s \to 1/\sqrt{3}$ --- the conformal limit --- at a density $\geq n_{1/2}$ and accommodates massive neutron stars up to $2.23 M_{solar}$, which is consistent with the present observation.
- So far, our model has stood the test from both the nuclear physics and astrophysics.

Summary and discussion

Is this pseudo-conformal structure at odds with Nature?

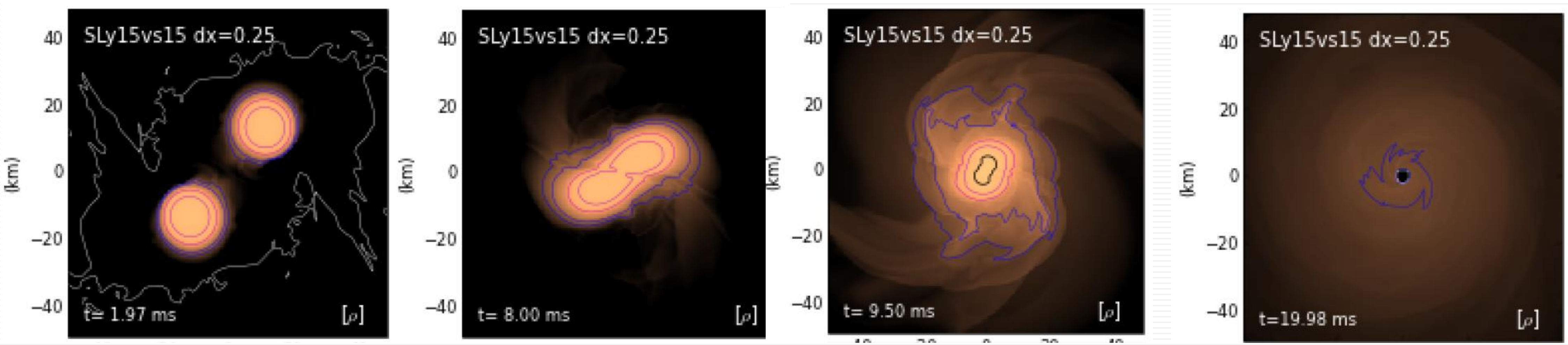
Not with what's measured (or known) up to now

Constraint to: $2.0 n_0 \leq n_{\frac{1}{2}} < 4.0\, n_0$

Thank you for your attention

Gravitational waves from Neutron star merger

A typical evolution can be divided in three (or four) phases:



The inspiral phase

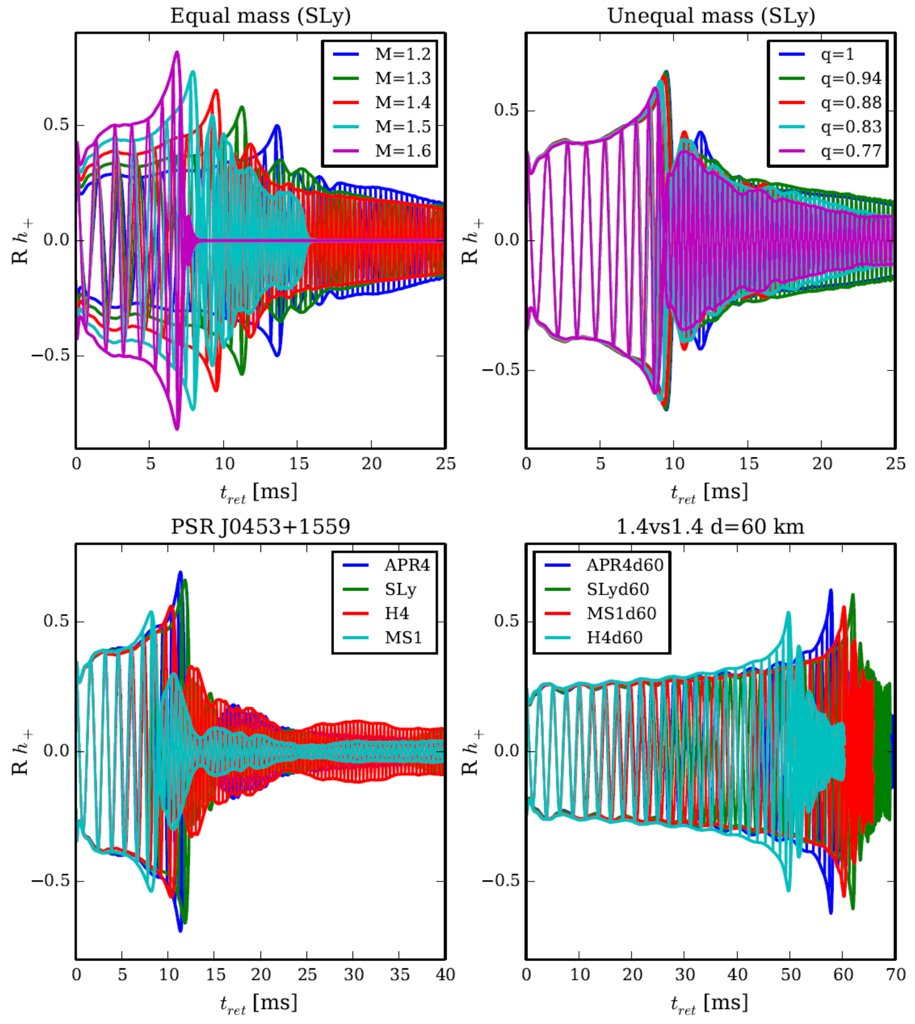
The merger phase:
The two stars come into contact, compressing their matter and giving rise to a complex hydrodynamical phen.

The post-merger phase:
The neutron star formed during the merger evolves, with a different phen. depending on its mass, EOS, and angular momentum distribution. The remnant star is bar-deformed, rotates differentially and emits gravitational waves with high

The collapse phase:
If the merger remnant has a mass greater than the limit for a non-rotating neutron star imposed by its EOS, the neutron star collapses to a black hole, when its rotation has slowed down enough.

Bauswein and Stergioulas 2015 PRD91 124056.

EoS effect on GWs



- In the first phase (the so called inspiral phase) the GWs progressively increase both their frequency and amplitude, generating a signal known as "chirp". The point of maximum amplitude is conventionally defined as the merger of the two stars.
- After the merger, the signal amplitude drops and then its amplitude raises again, at a higher frequency, which strongly depends on the EOS, for the GW emission due to the rotation of the bar-deformed neutron star remnant.
- The post merger GW emission amplitude decreases exponentially, due to the redistribution of angular momentum and the star approaching a more axisymmetric state, but it shows in some models interesting features, which will be analysed later.
- The models collapsing to black hole are clearly recognizable, because after collapse the GW amplitude drops immediately to negligible values.

K. Hotokezaka, et. al., PRD 87 044001

IV. Conclusion

Model of dense matter

General relativity

Star properties

Gravitational waves

Astrophysical Observation

Properties of Dense nuclear matter
QCD phase structure

New era of nuclear physics is coming

We are just at the very beginning of a trip