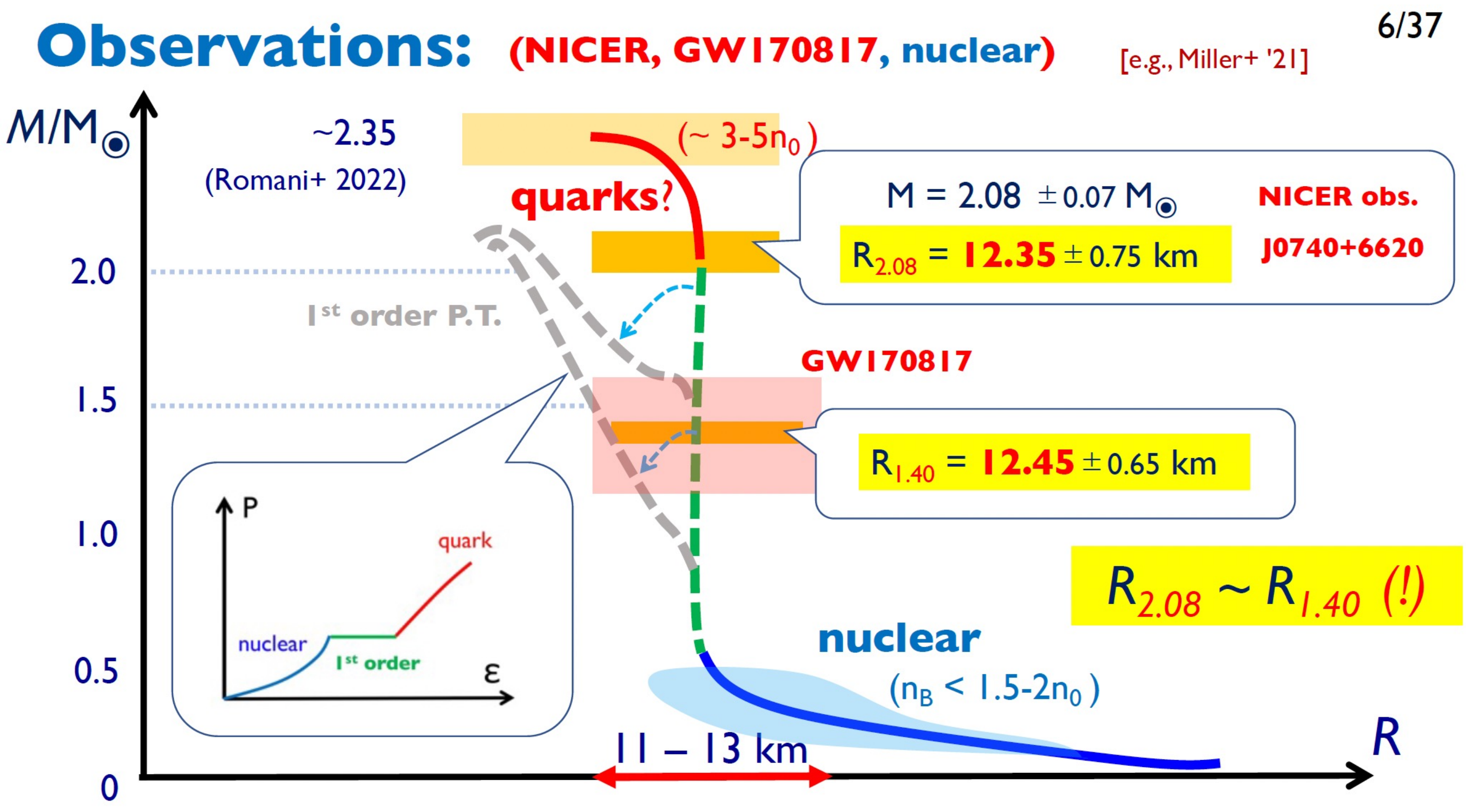
Brief review of sound velocity

Mamiya

Mass and radius relation in neutron star (from Kojo's slide)



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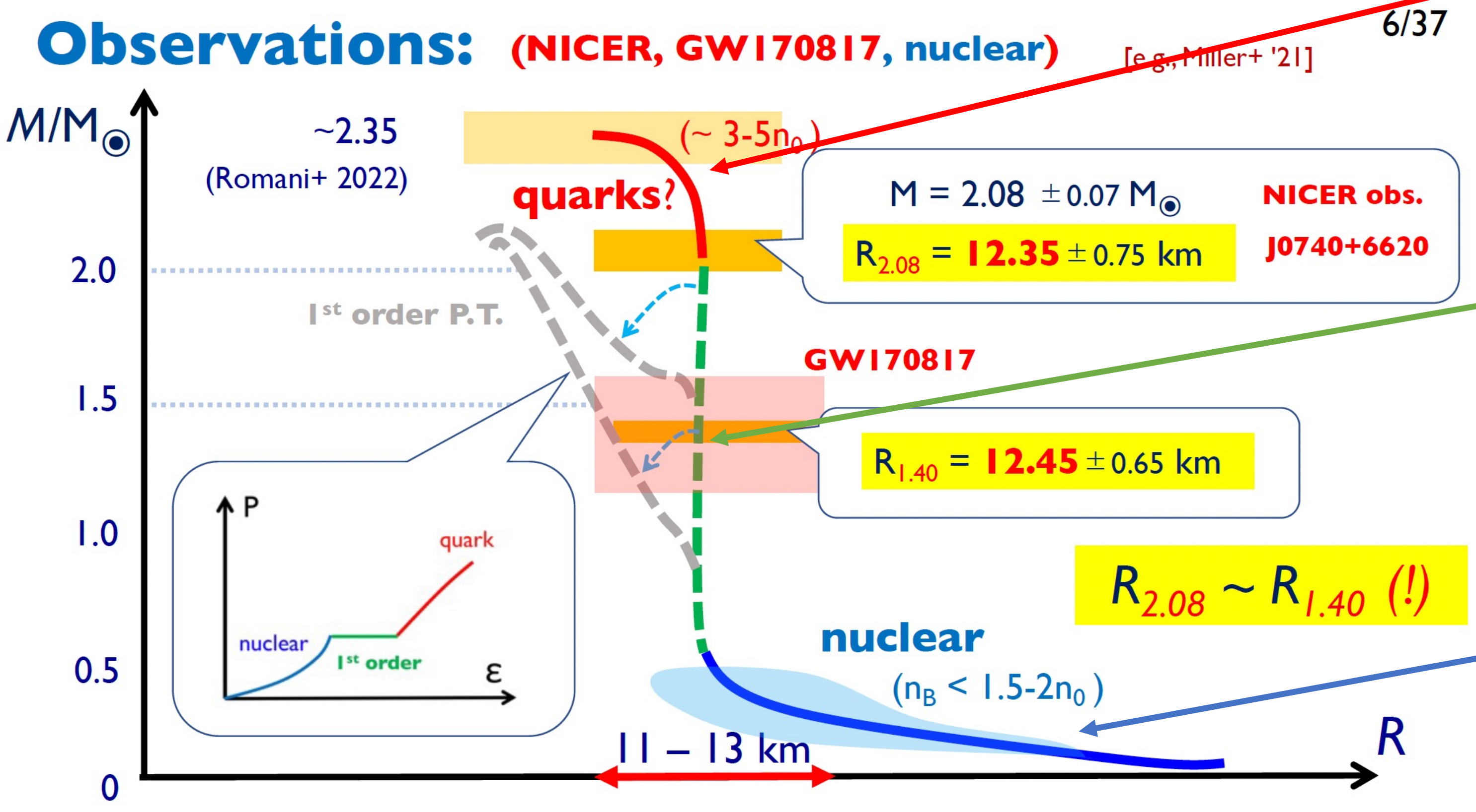

Quarks would be dominated in high density region.

Intermediate density region: phase transition would happen from nuclear phase to quark phase

QCD matter at low density regions should be described by nuclear.

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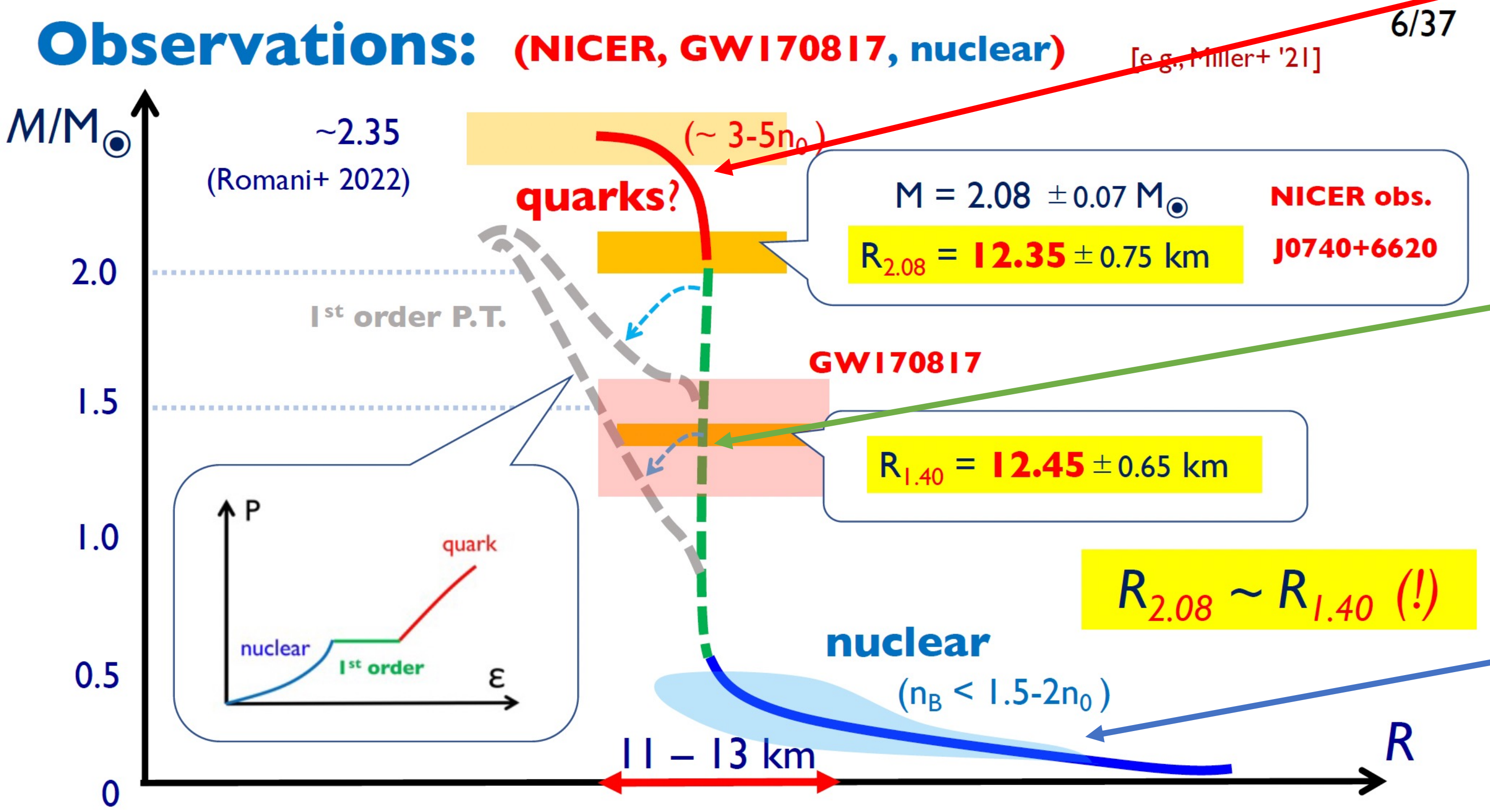

Quarks would be dominated in high density region.

→ NJL model would work well.

Intermediate density region: phase transition would happen from nuclear phase to quark phase

→ We do not know relevant model… Instead, interpolating functions are used.

QCD matter at low density regions should be described by nuclear.

→ Nuclear model (Walecka Model) works.

Intermediate density region is unclear: nobody knows a relevant physical picture.
→ it is closely related to the QCD phase transition at finite density: nonperturbative property of QCD.

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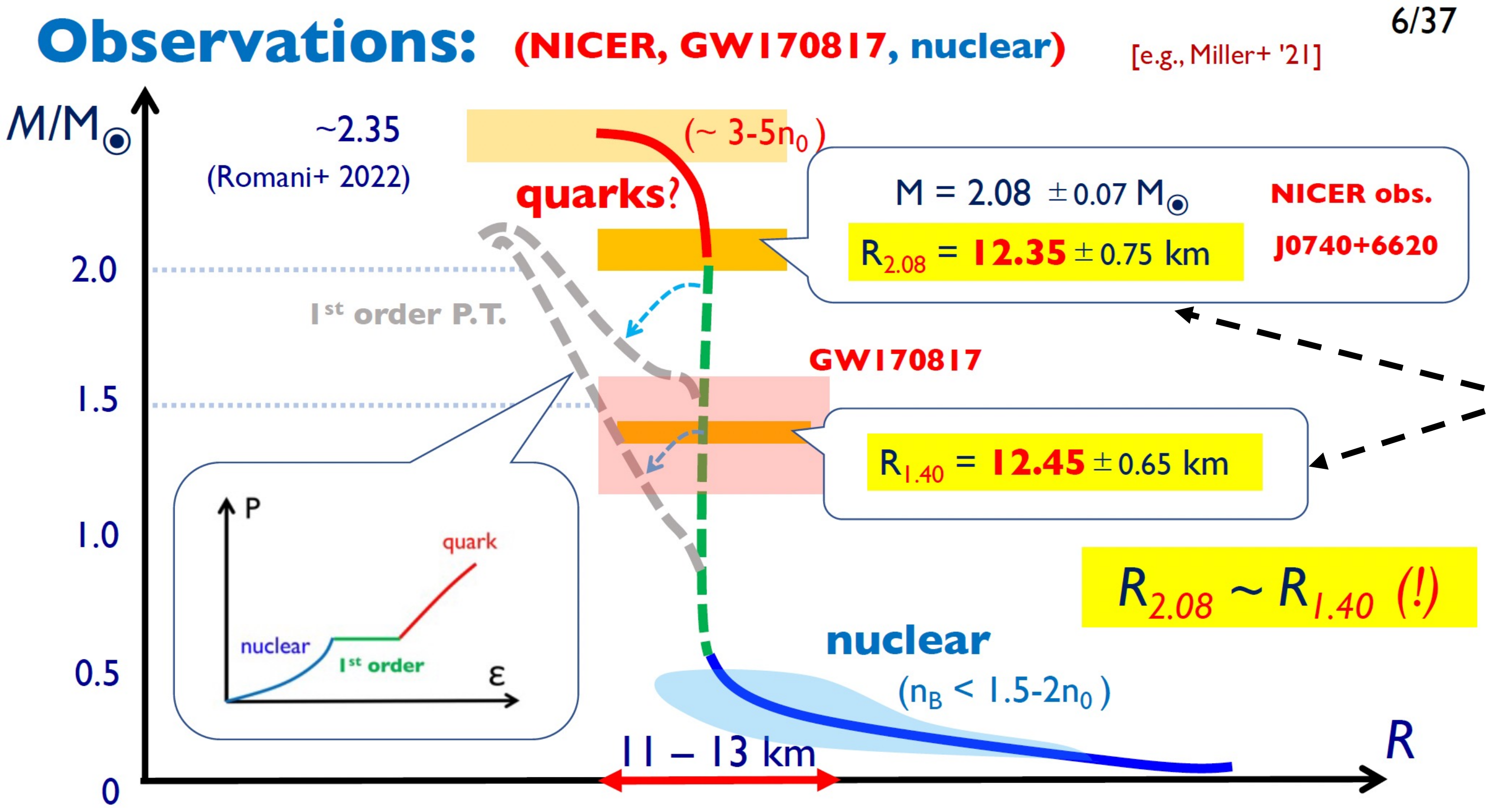

Intermediate density region:
phase transition would happen
from nuclear phase to quark phase

But...

There are experimental observations in intermediate density region

Model analysis should satisfy these observations.
→Order of the phase transition is closely related to it.

Mass-Radius relation is crucially affected by order of the phase transition T. Kojo, arXiv:2011.10940

Order of phase transition is reflected to energy and pressure:
jump appears if first order phase transition happens. Otherwise smooth curve indicates the crossover

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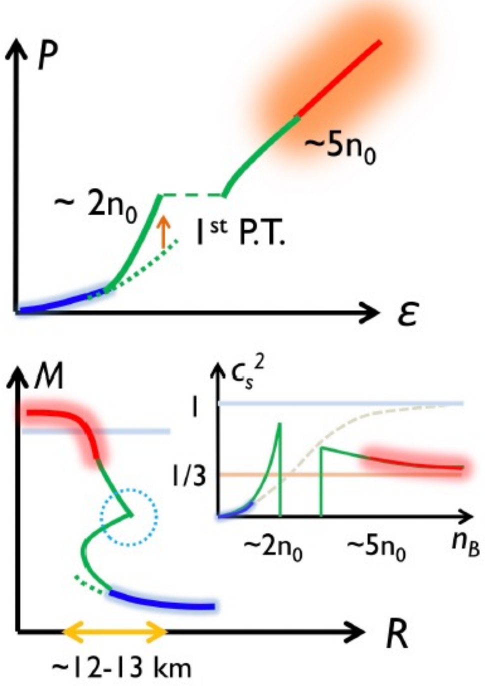
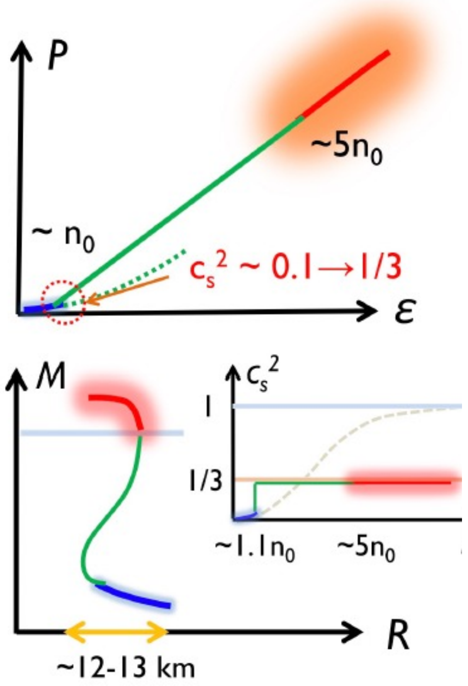
We can consider several cases.

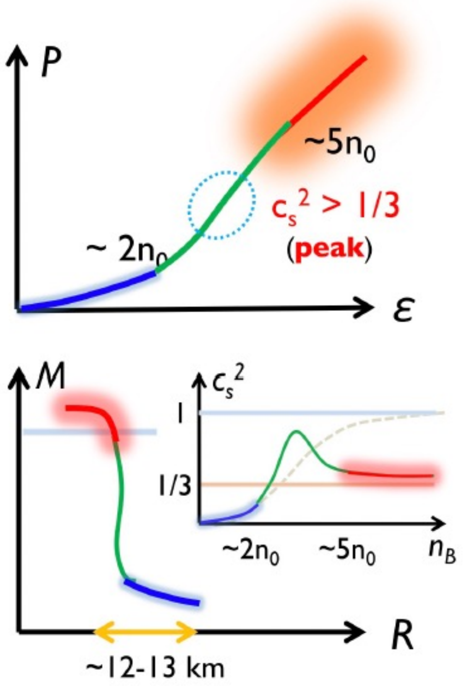
Case1: first order



Case2: Crossover



Case3: Crossover



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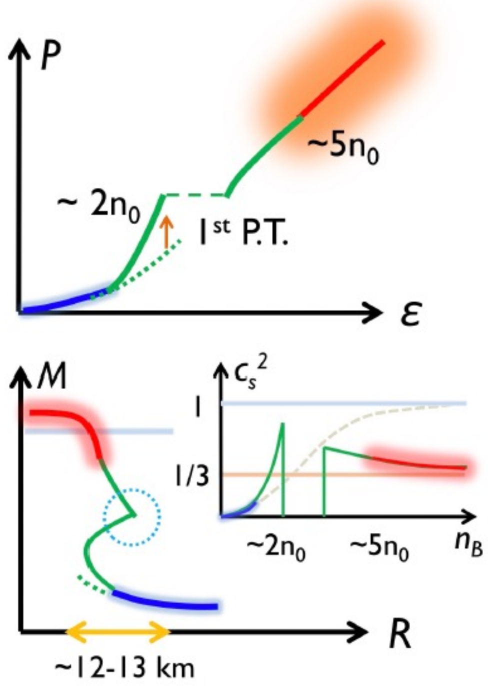

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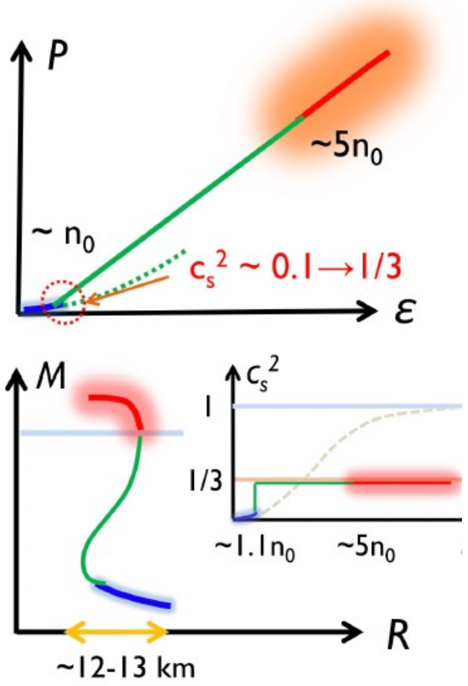

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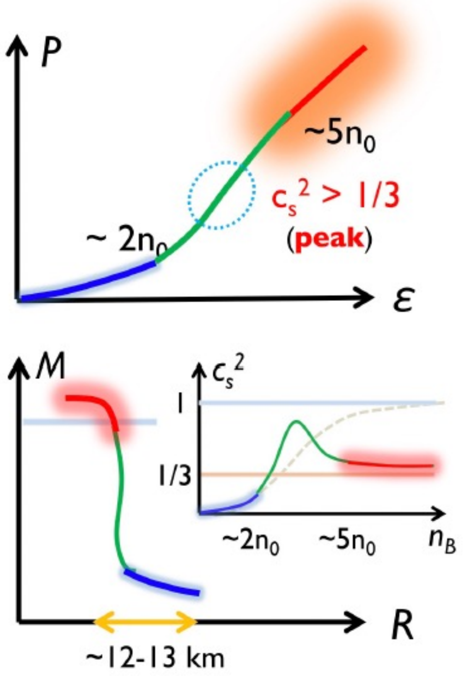

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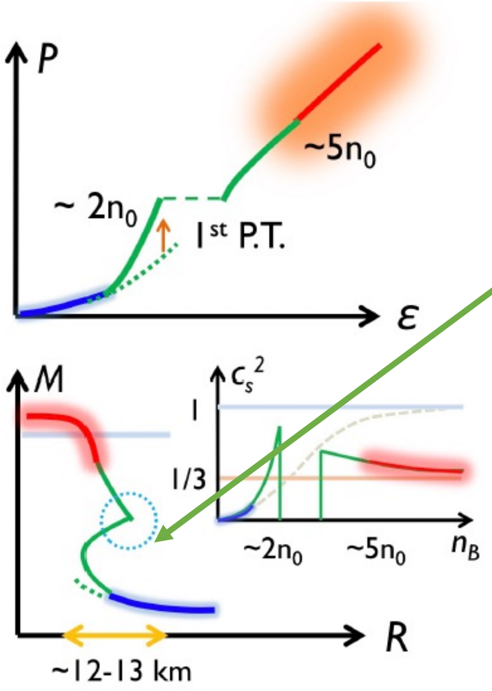
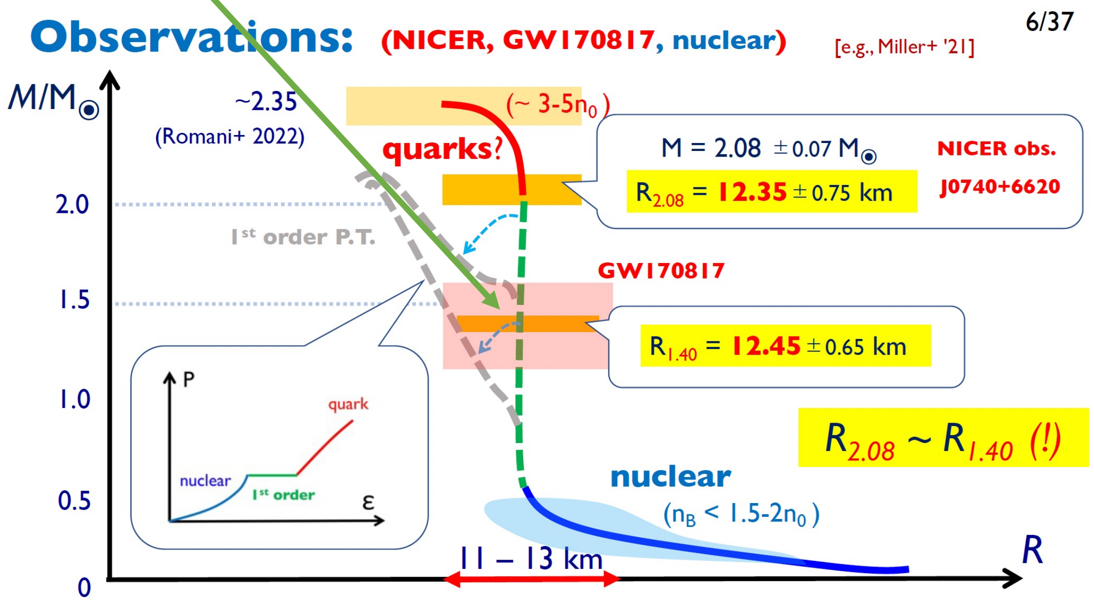


Due to first order, mass and radius relation in intermediate density region becomes complicated.

But… this complicated behavior is inconsistent with the experimental observations: straight line would be preferred.



Mass-Radius relation is crucially affected by order of the phase transition   T. Kojo, arXiv:2011.10940

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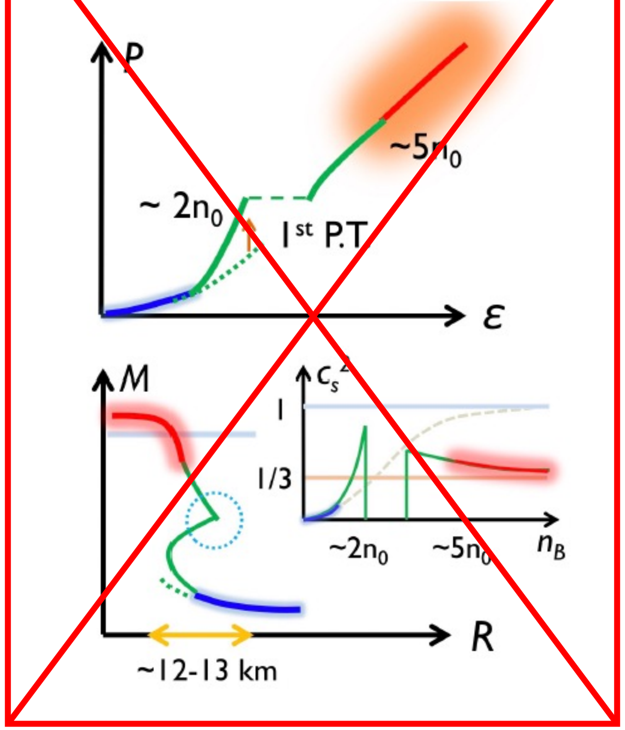

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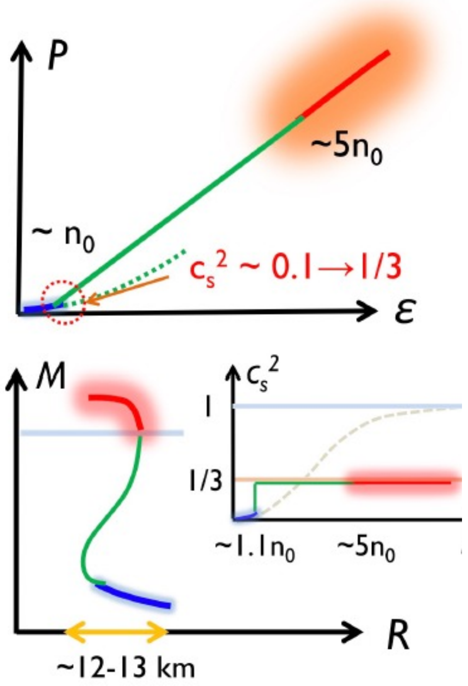

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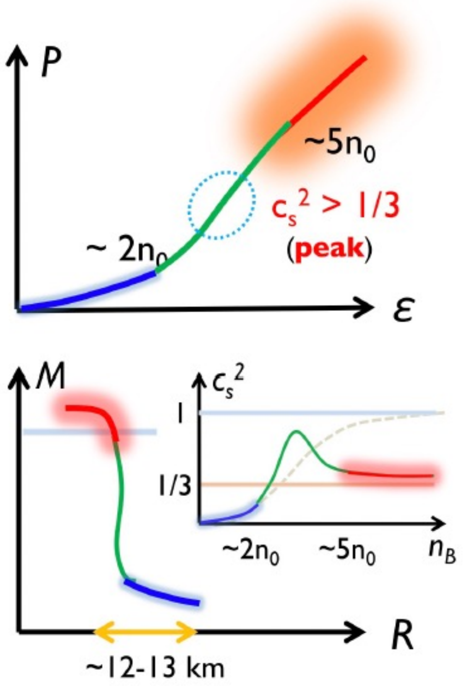

Case 1 would be discarded.

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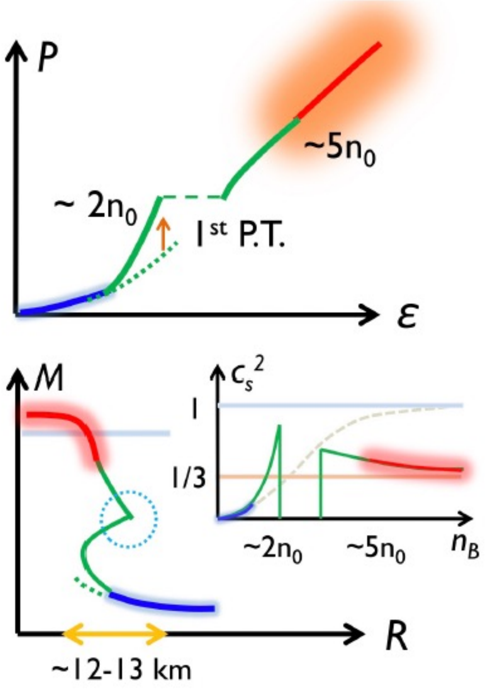

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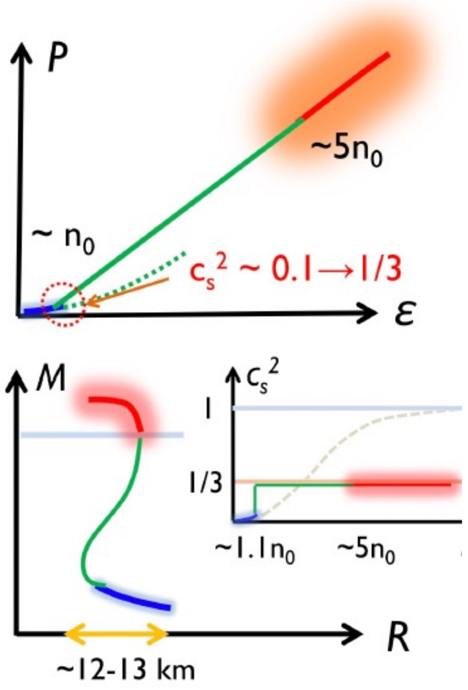

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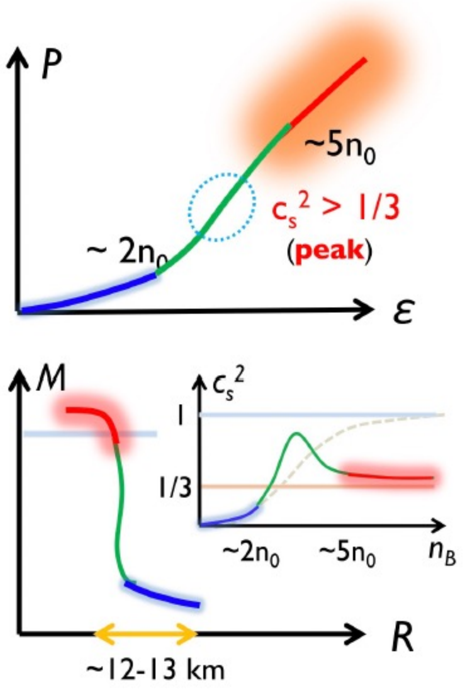
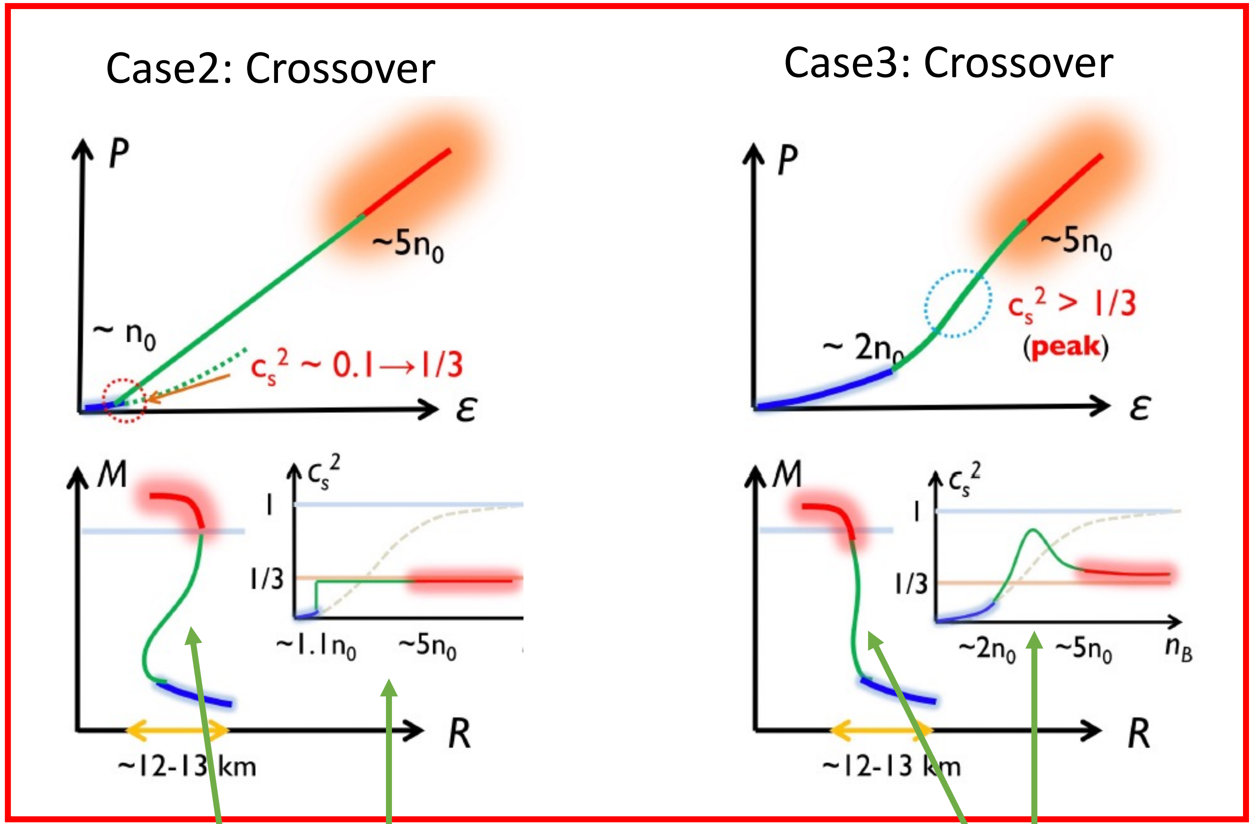
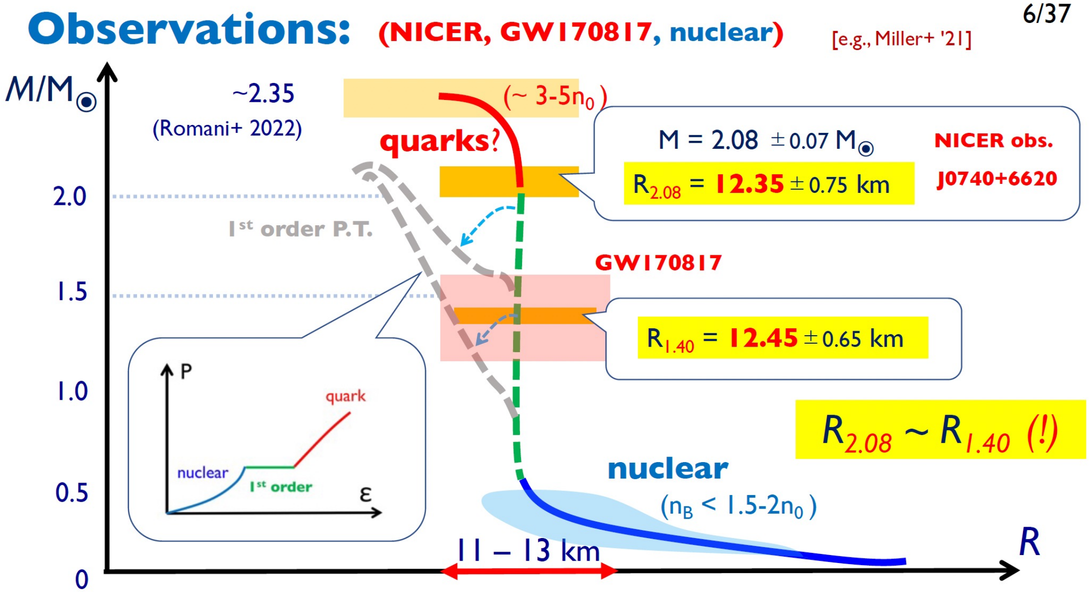


The difference comes from the behavior of the speed of sound.





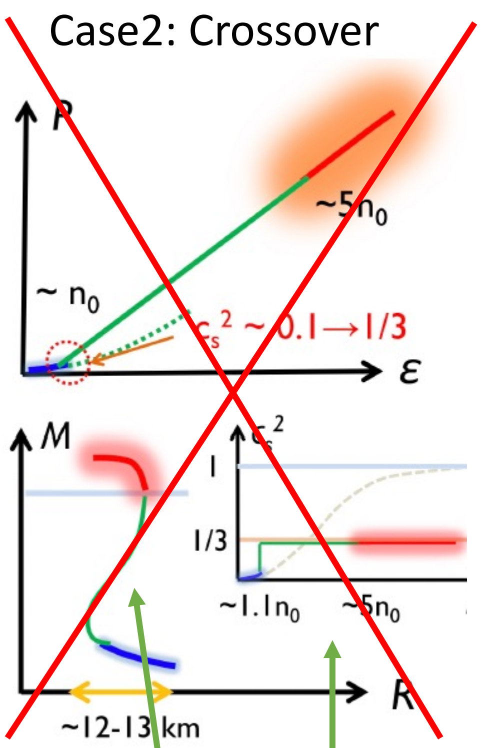
Sound velocity does not have peak.

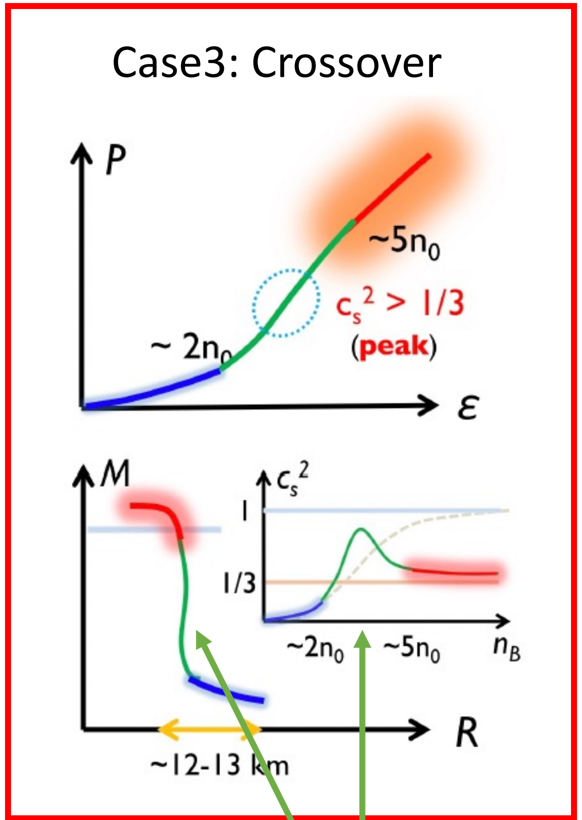
Absence of peak makes it curve.

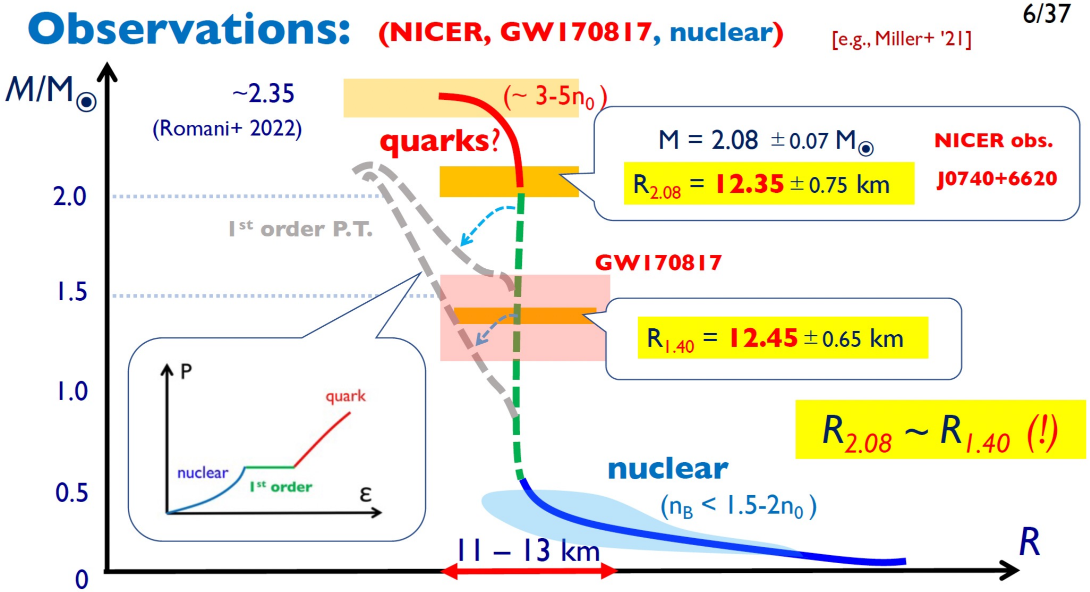
Sound velocity has peak.

Peak provides straight line

Experimental observations indicate that straight line would be preferred.







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It is preferred that …

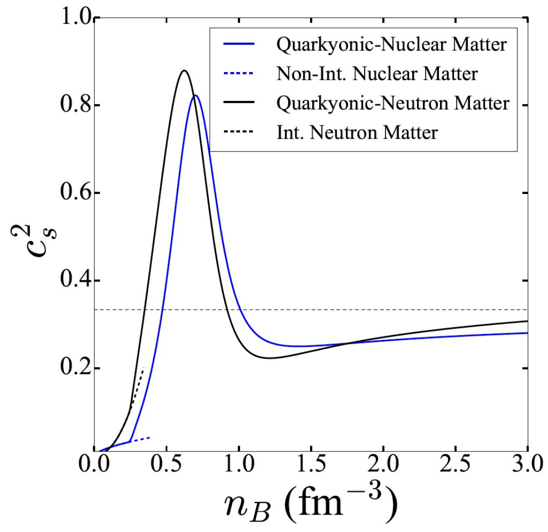
- Energy and pressure is smooth (crossover).
- Sound velocity has peak structure.

*Note that this is one of possible scenarios.
Maybe, there is a way for first order scenario to survive.

Sound velocity peak predicted by effective models

- K. Masuda, T. Hatsuda and T. Takatsuka, PTEP 2013, no.7, 073D01 (2013) (first study for sound velocity in neutron star)
  - They used the NJL model with vector interaction (three flavor analysis).
  - They discuss the correlation between the quark-hadron crossover picture observed neutron stars (M-R relation).
  - They have shown that the vector meson interaction enhances the peak structure of the sound velocity.

- L. McLerran and S. Reddy, PRL. 122, no.12, 122701 (2019)
  - They employed quarkyonic matter model.
  - Quarkyonic matter model also provides the peak.
  - Asymptotic behavior at high density has been pointed out:
    "It reaches a maximum at relatively low density,
    decreases, and then increases again to its asymptotic value of 1/3."



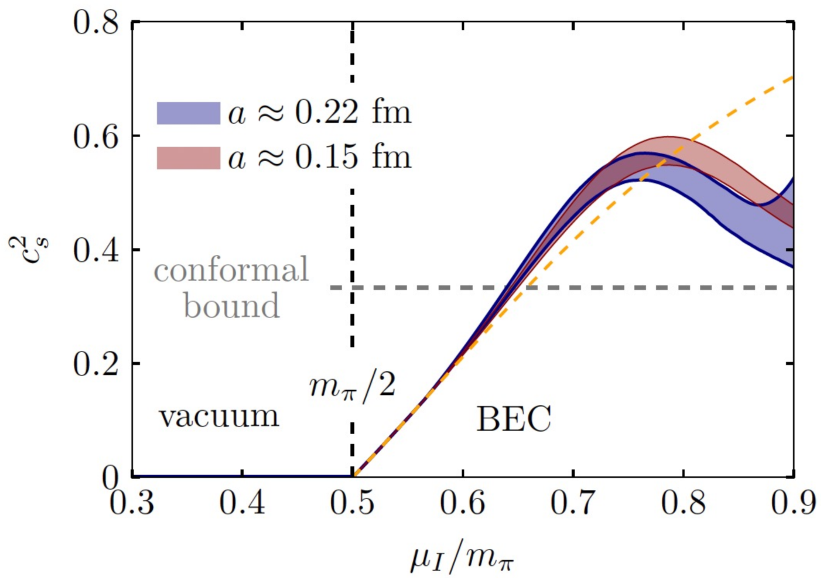
- T. Kojo and D. Suenaga, PRD 105, no.7, 076001 (2022)
  - Microscopic interpretation on the peak structure is given:
    distribution of quark saturation is related to peak structure.

Almost analyses for the peak structure
have been investigated by effective models based on quark pictures.
→This indicates that hadron picture is irrelevant to the peak structure???
(still unclear)

Sound velocity in lattice QCD simulations (Recent hot topic)

- B. B. Brandt, F. Cuteri and G. Endrodi, JHEP 07, 055 (2023)
  3-color QCD at finite isospin chemical potential

  ➡ Peak appears.



- K. Iida and E. Itou, PTEP 2022, no.11, 111B01 (2022)
  2-color QCD at finite baryon chemical potential

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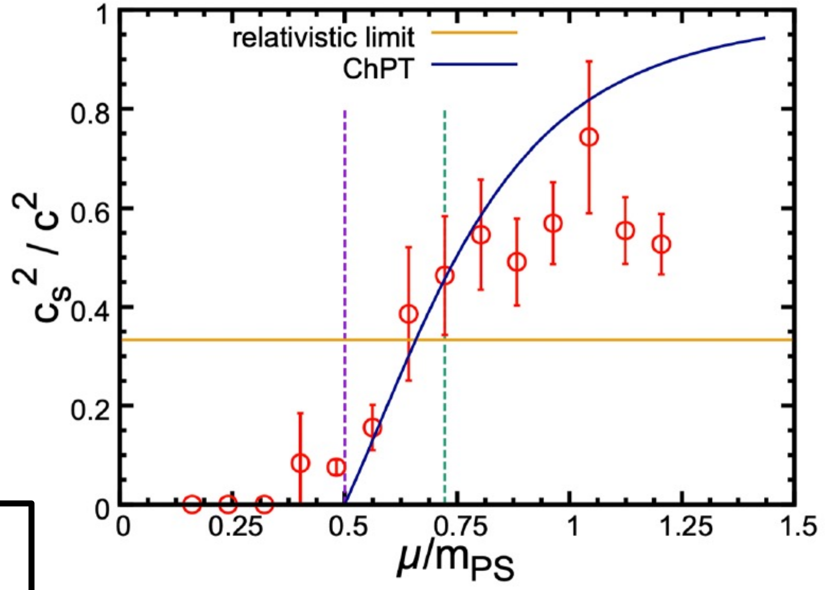
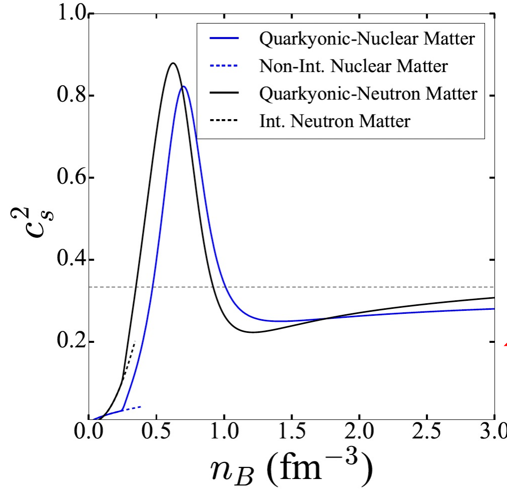


These results lead us to the following expectations:
3 color QCD at finite baryon chemical potential would have peak.

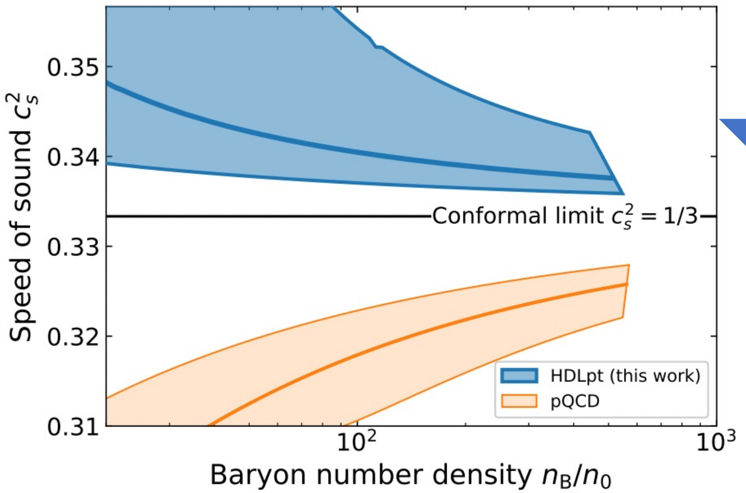
High density behavior of sound velocity (Recent hot topic)

It is expected that the sound velocity approaches 1/3.
Recently the detail of high density behavior has been extensively studied.

- L. McLerran and S. Reddy, PRL. 122, no.12, 122701 (2019)
  In quarkyonic matter model,
  the sound velocity approaches 1/3 from below.

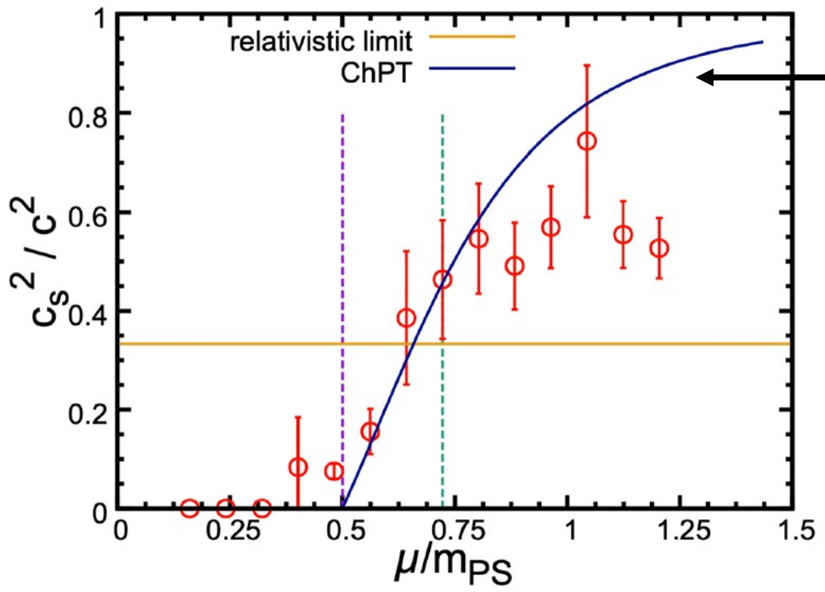


- Y. Fujimoto and K. Fukushima, PRD 105, no.1, 014025 (2022)
  In hard Dense Loop resummation,
  the sound velocity approaches 1/3 from above.



My recent work in Riken

I focus on the two color QCD system



ChPT provides the benchmark line: $c_s^2 = \dfrac{1-\mu_c^4/\mu^4}{1+3\mu_c^4/\mu^4}$ $\mu_c = m_\pi^{\mathrm{vac}}/2$

Expression is independent on model parameter.

But…

ChPT result does not provide the peak structure.

→ ChPT line is inconsistent with lattice observation.

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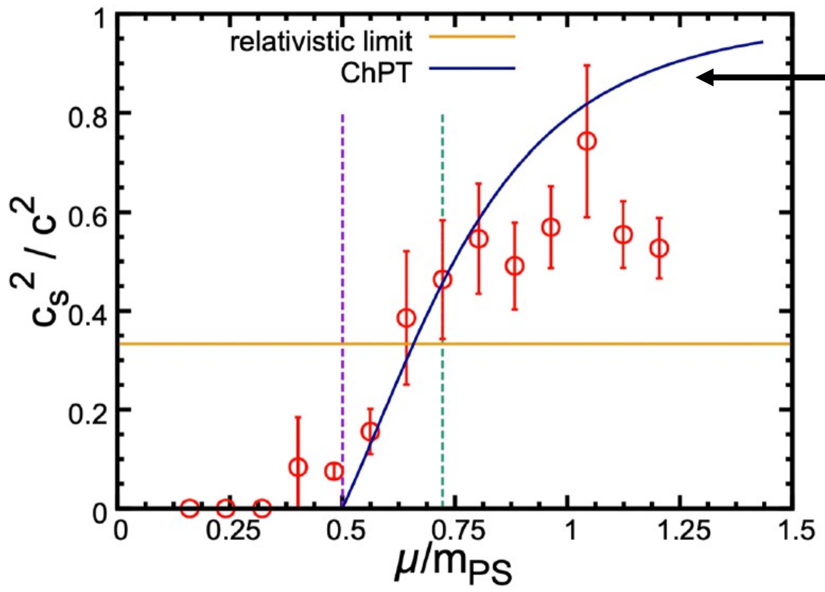

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Expression is independent on model parameter.

But…

ChPT result does not provide the peak structure.

→ ChPT line is inconsistent with lattice observation.

In my work, I have found a new expression based on the linear sigma model.

$$\left(c_s^{\rm LSM}\right)^2 = \frac{n_{\rm ChPT} + \delta n}{\mu_q(\chi_{\rm ChPT} + \delta\chi)} = \frac{(1-1/\bar{\mu}^4) + 8(\bar{\mu}^2 - 1)/\delta\bar{m}^2_{\sigma-\pi}}{(1+3/\bar{\mu}^4) + 8(3\bar{\mu}^2-1)/\delta\bar{m}^2_{\sigma-\pi}},$$

$$\delta\bar{m}^2_{\sigma-\pi} = \left\{(m_\sigma^{\rm vac})^2 - (m_\pi^{\rm vac})^2\right\}/(\mu_q^{\rm cr})^2$$

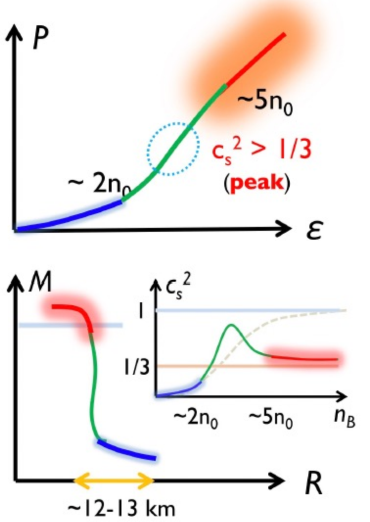
$$\bar{\mu} = \mu_q/\mu_q^{\rm cr}.$$

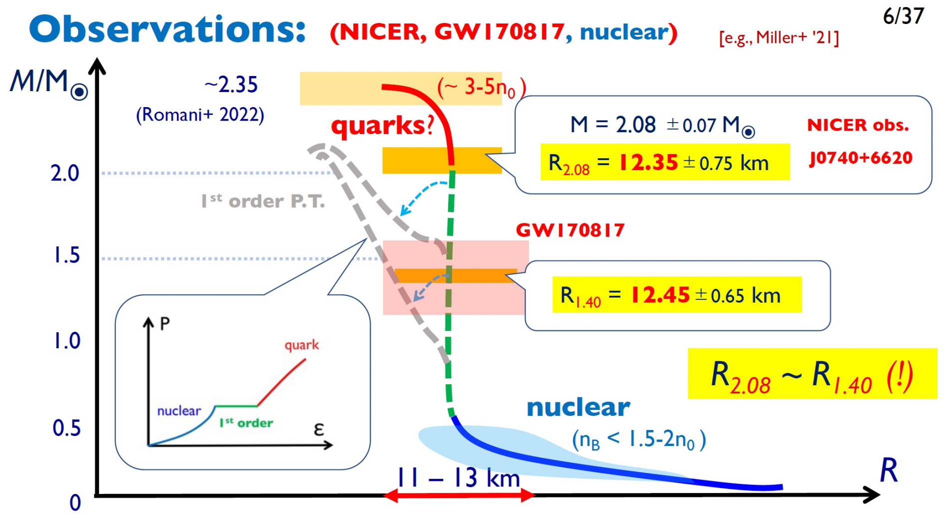
This is an expression extended from the ChPT: sigma meson mass is included.
This is independent on the model parameters.
Provides the peak: peak is driven by the sigma meson mass → peak is related to chiral structure.

M.K. and D. Suenaga in preparation

Summary

- Peak structure of sound velocity is necessary to explain the experimental observations:



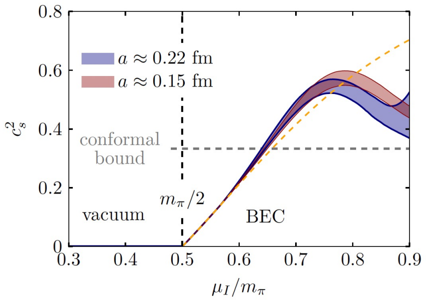


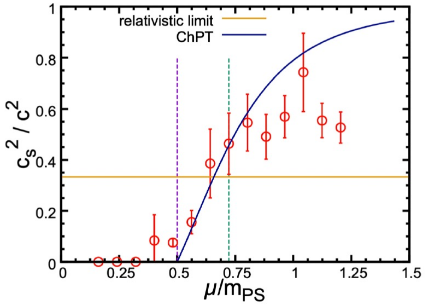
Its detail is still unclear, owing to the phase transition (non-perturbative property).

- Peak has been observed in lattices:

- 3-color QCD at finite isospin chemical potential
- 2-color QCD at finite baryon chemical potential

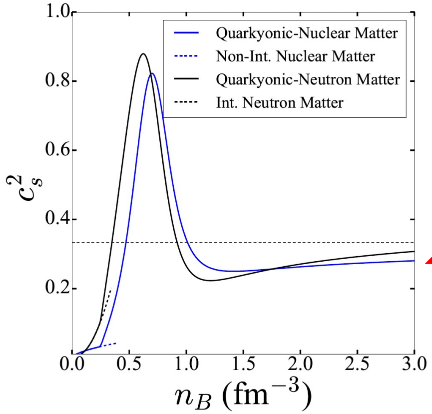
(I focus on the 2-color QCD.)

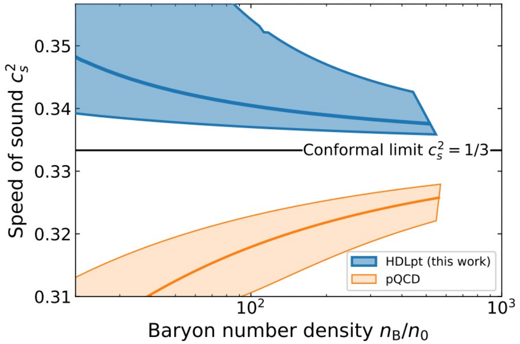




- High density behavior of sound velocity

The sound velocity approaches 1/3 from below or above.
(Fate of sound velocity is unknown.)





Thank you