Why could strangeon matter be "superluminal"?

——sound speed in compact star

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maximum mass of pulsar

- The maximum mass of a neutron star can hardly surpass $2M_{\odot}$ due to the "hyperon puzzle". (Schaffner-Bielich 2008)
- PSR J0715+1807, $1.97M_{\odot}$ (Demorest et al. 2010)
- PSR J0348+0432, $2.01M_{\odot}$ (Antoniadis et al. 2013)
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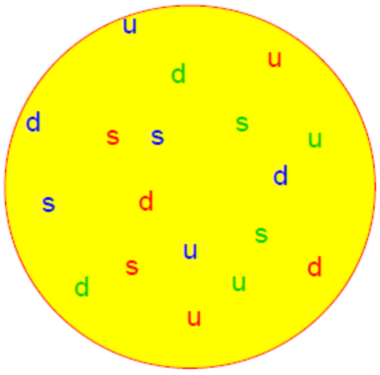
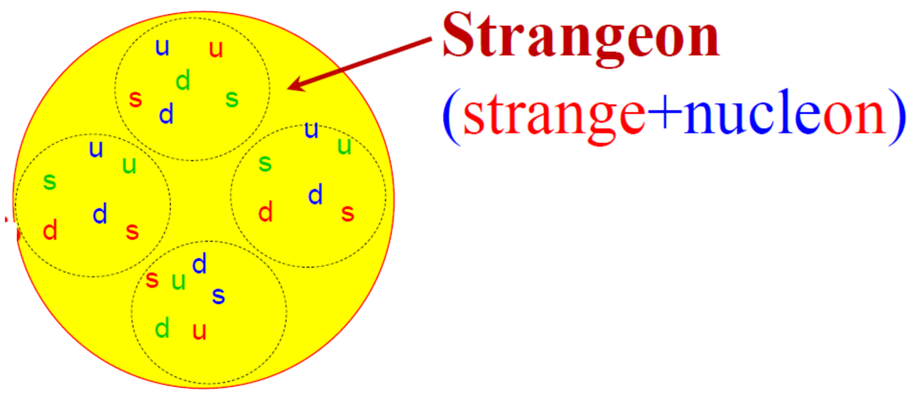
Strangeon matter!

What is a strangeon?

- speculated in generalized Witten's conjecture
- 3 flavor symmetry (u, d, s)
- Strangeons in bulk constitutes the true ground state of the strong-interaction at supra nuclear density.



Strange quark matter



Strangeon matter

What is the property of strangeon matter?

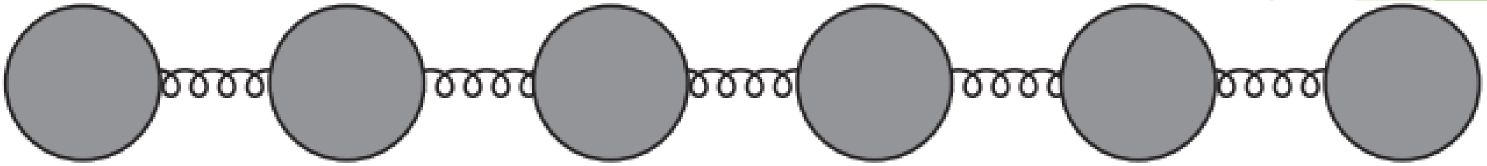
- A strangeon is much more massive than a nucleon. Thus the strangeon can be regarded as a traditional localized point particle rather than quantum wave.
- Strangeon matter should be much stiffer than neutron matter, which signifies a larger bulk modulus.
- $\sqrt{\frac{\partial P}{\partial \rho}} > c$ (superluminal sound speed**??**)

sound speed & causality

- There is no priori reason to believe the variational principle is physical, thus any result based on the Lagrangian may be invalid (Ellis, Maartens & MacCallum, 2007).
- Lorentz invariance per se does not prohibit macroscopic theories with superluminal sound, and superluminal propagation is not necessarily noncausal (Bruneton, 2007).
- Sound speed $c_s = \sqrt{\frac{\partial P}{\partial \rho}}$**??** Caporaso & Brecher (1979) pointed out that it is possible to construct lattice models with $P > \rho c^2$ and $\mathrm{d}P > c^2 \mathrm{d}\rho$, but sound speed remains subluminal.

Signal in strangeon matter

- The particle (strangeon) is so massive that it has small wave-packet, thus, the strangeon can be regarded as a traditional localized point particle rather than quantum wave.
- **two-body short-range repulsive conservative** interaction between particles
- For simplification, the oscillation propagation in a 1-D discrete chain is considered.



frequency domain result of strangeon matter

- Assume a sine wave propagate in the chain, and the wave form is stable.

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- Sound speed $c_s = \frac{1}{\sqrt{\frac{1}{2}\left[\frac{1}{\frac{\partial P}{\partial \rho}} + \sqrt{\frac{1}{\left(\frac{\partial P}{\partial \rho}\right)^2} + \frac{1}{l^2 \omega^2 c^2}}\right]}}$
- **It could be superluminal!!**

frequency domain result of strangeon matter

- Assume a sine wave propagate in the domain, and the wave form is stable.
- Sound speed $c_s = \frac{1}{\sqrt{\frac{1}{2}\left[\frac{1}{\frac{\partial P}{\partial \rho}} + \sqrt{\frac{1}{\left(\frac{\partial P}{\partial \rho}\right)^2} + \frac{1}{l^2 \omega^2 c^2}}\right]}}$
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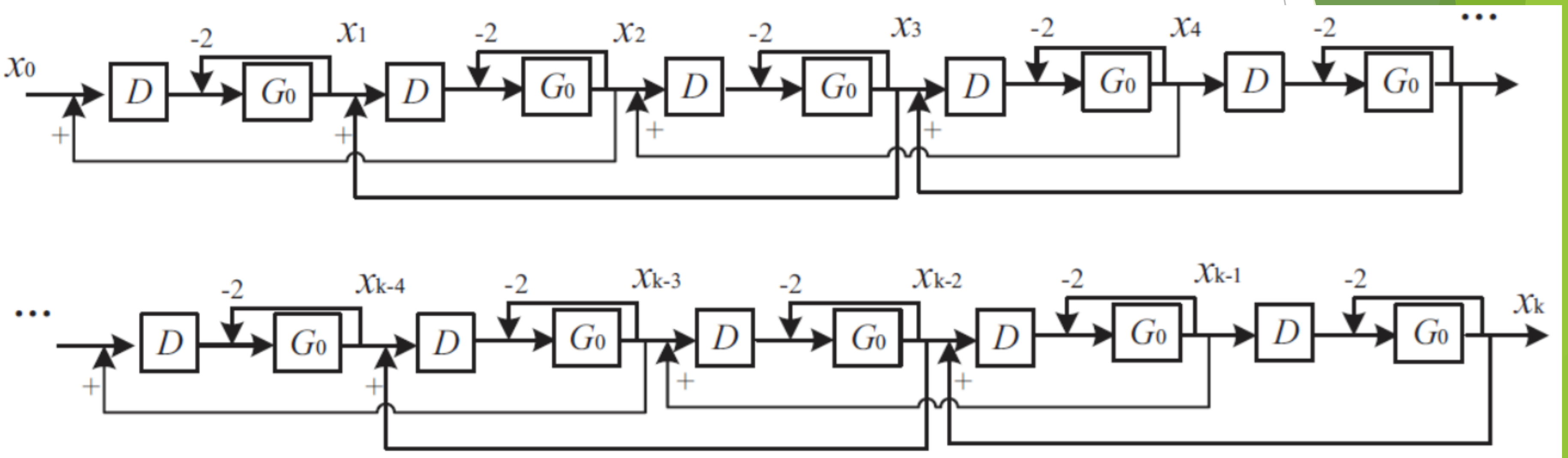
FALSE!

because of the reflected wave

time domain result of strangeon matter

- time domain response of an impulse input



$$D(s) = \exp\left(-\frac{ls}{c}\right) \qquad G_0(s) = -\frac{1}{ms^2}\frac{\partial F}{\partial x}\Big|_{x=l}$$

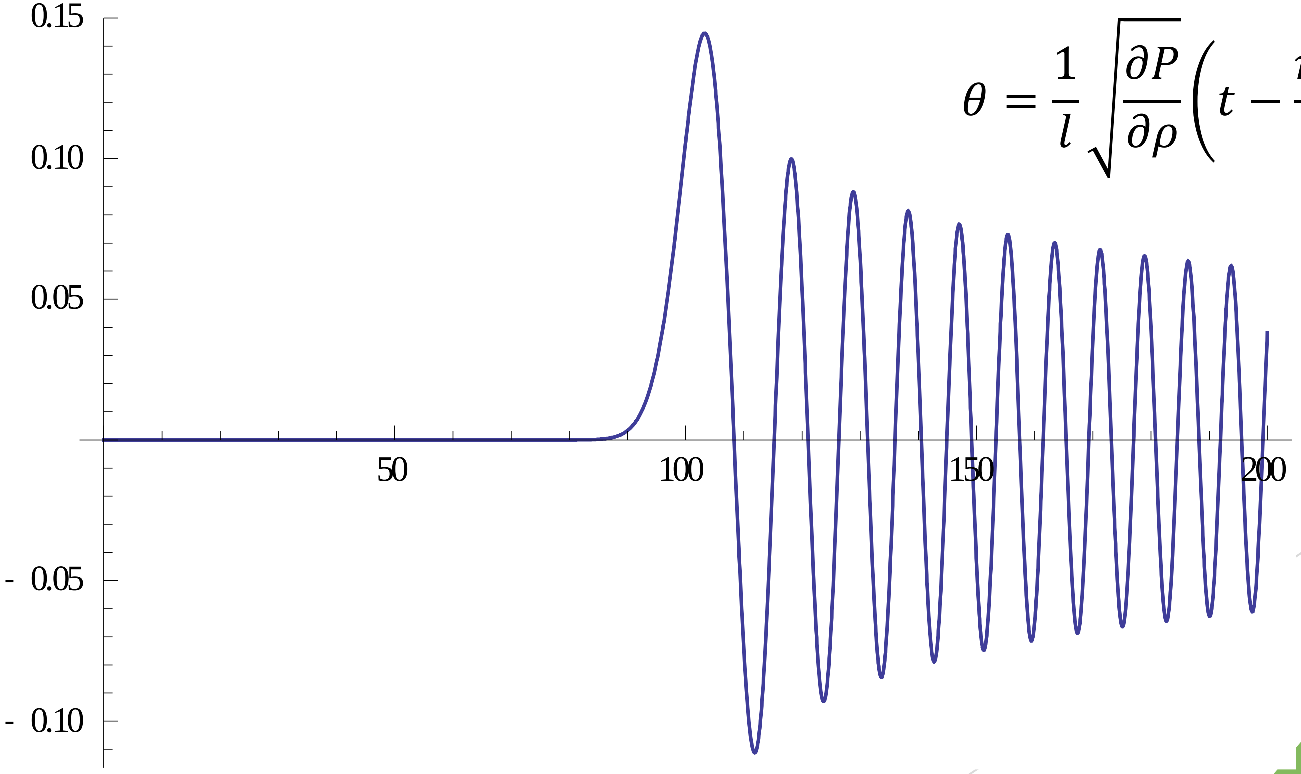
- With Meson's gain formula

$$G(s) = \frac{2^k G_1^k}{k+1} = \frac{1}{k+1}\left(\frac{\frac{\partial P}{\partial \rho}}{\frac{l^2 s^2}{2} + \frac{\partial P}{\partial \rho}}\right)^k \exp\left(-\frac{kls}{c}\right)$$

time domain result of strangeon matter

- time domain response of an impulse input

$$x_k(t) = \mathscr{L}^{-1}[\mathscr{L}[x_0(t)]G(s)] = \frac{2^{k-\frac{1}{2}}\sqrt{\pi}A}{(k+1)\Gamma(k)}\sqrt{\frac{2}{l^2}\frac{\partial P}{\partial \rho}}\theta^{k-\frac{1}{2}}J_{k-\frac{1}{2}}(\theta)$$



$$\theta = \frac{1}{l}\sqrt{\frac{\partial P}{\partial \rho}}\left(t - \frac{nl}{c}\right)$$

sound speed in strangeon matter

- signal propagation time

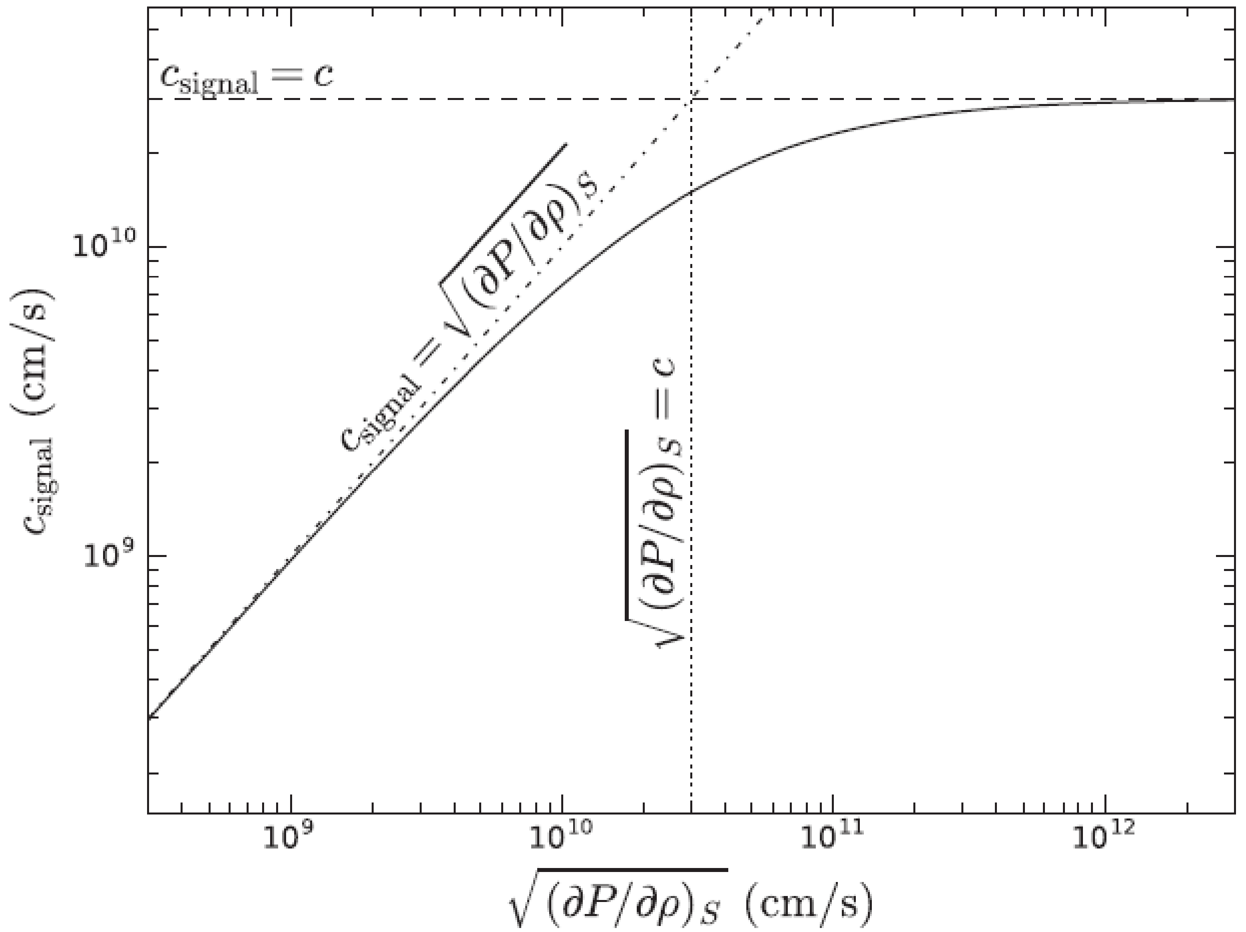
$$t_{\text{signal}} = \left[\frac{n - \frac{3}{2} + 1.855757\left(n - \frac{3}{2}\right)^{\frac{1}{3}} + O[1]}{\sqrt{\frac{\partial P}{\partial \rho}}} + \frac{n}{c} \right] l$$

- sound speed

$$c_{\text{signal}} = \frac{nl}{t_{\text{signal}}} \approx \frac{1}{\frac{1}{\sqrt{\frac{\partial P}{\partial \rho}}} + \frac{1}{c}} < c$$

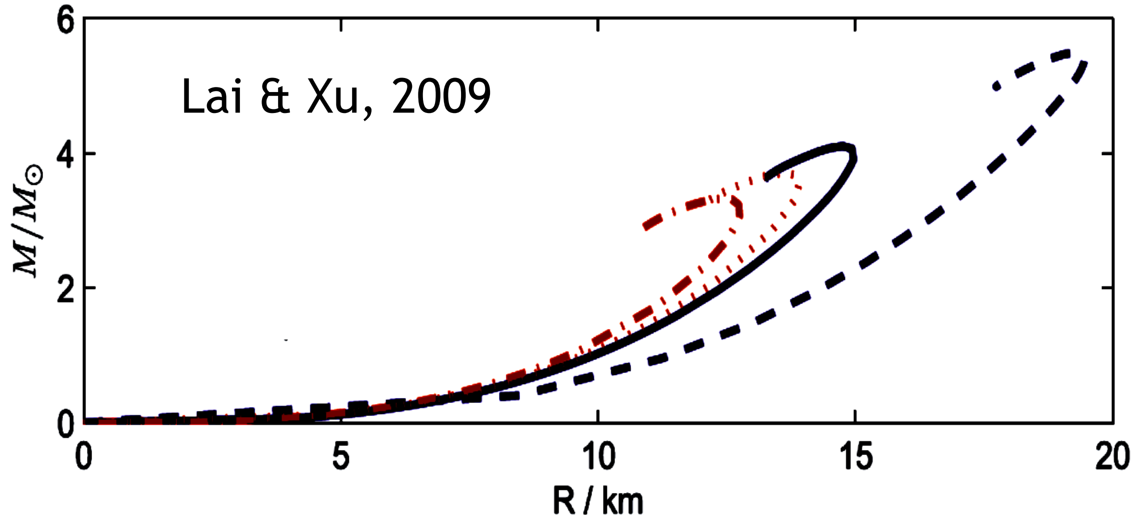
The signal speed would never be superluminal!!

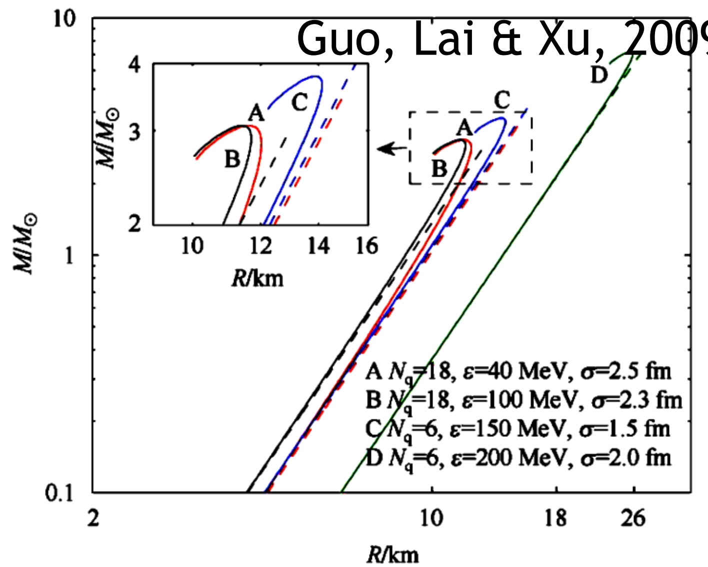
sound speed in strangeon matter



sound speed and the maximum mass of pulsar

- $\frac{\partial P}{\partial \rho} < c^2 \Rightarrow M_{\max} \approx 3.2 M_\odot$ (Rhoades & Ruffini, 1972), is often given the status of a rigorous upper limit in astrophysical literature.





SUMMARY

- The sound speed in strangeon matter is still subluminal.
- The large mass compact star could be the evidence for strangeon star.

Thanks!