Continuity from neutron matter to color-superconducting quark matter with $^3P_2$ superfluidity

Yuki Fujimoto
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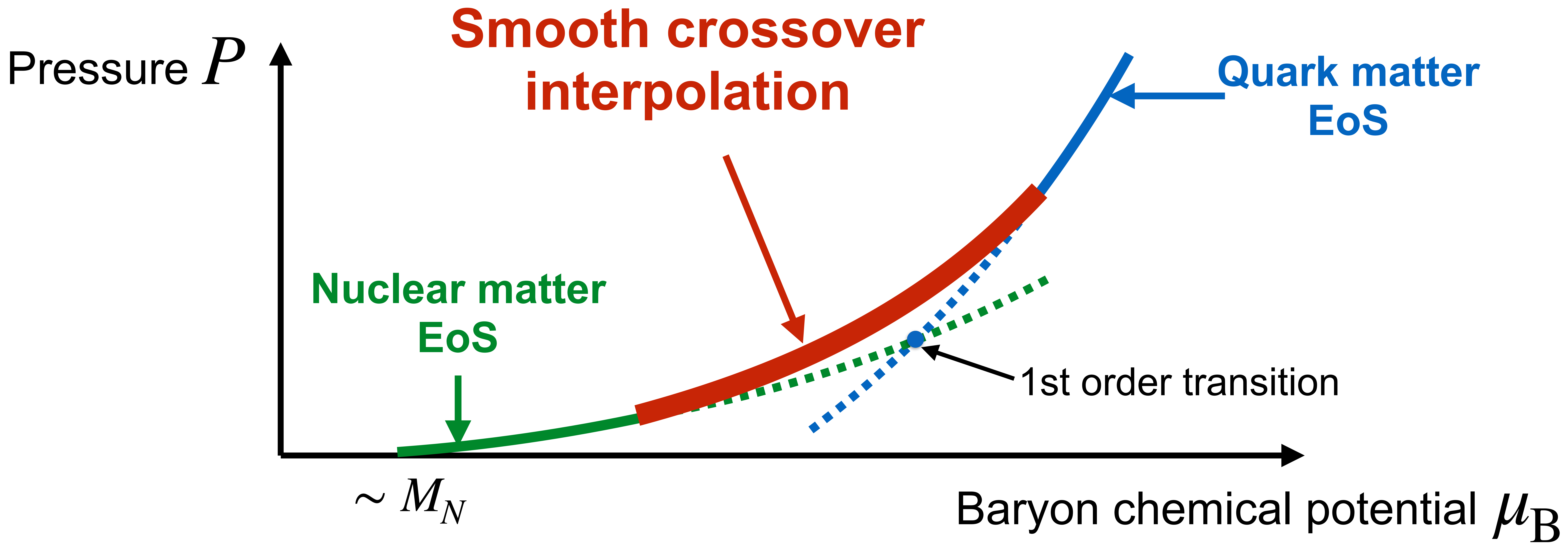
based on: **YF**, K. Fukushima, W. Weise, arXiv:1908.09360 [hep-ph]

6 Nov. 2019, Quark Matter 2019 @ Wuhan

Prelude: Dense Matter Equation of State (EoS)

Masuda,Hatsuda,Takatsuka (2012); Kojo,Powell,Song,Baym (2014)

Neutron star phenomenology implies…



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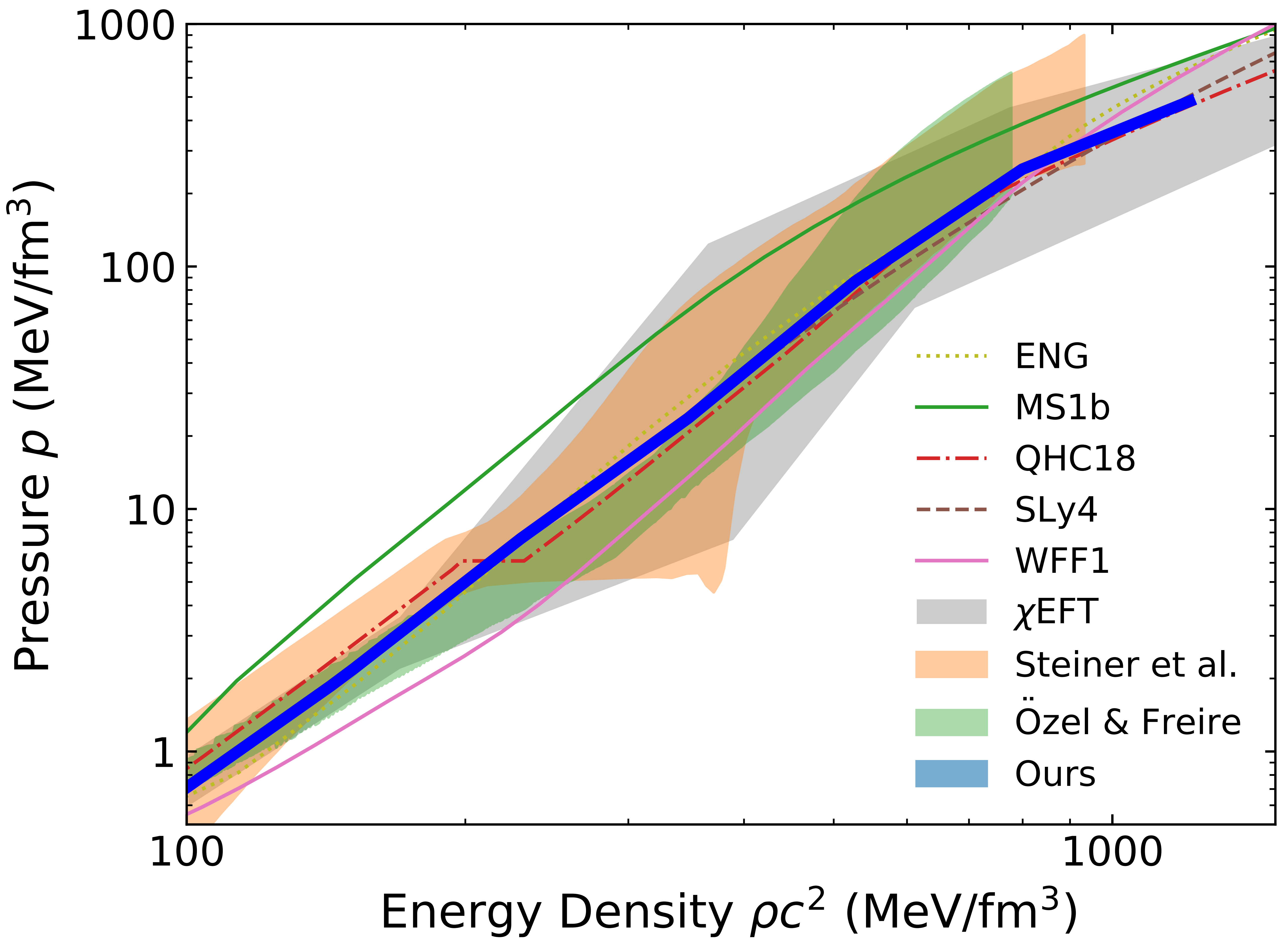
Fujimoto,Fukushima,Murase, arXiv:1903.03400

Deep learning: NS observations → EoS



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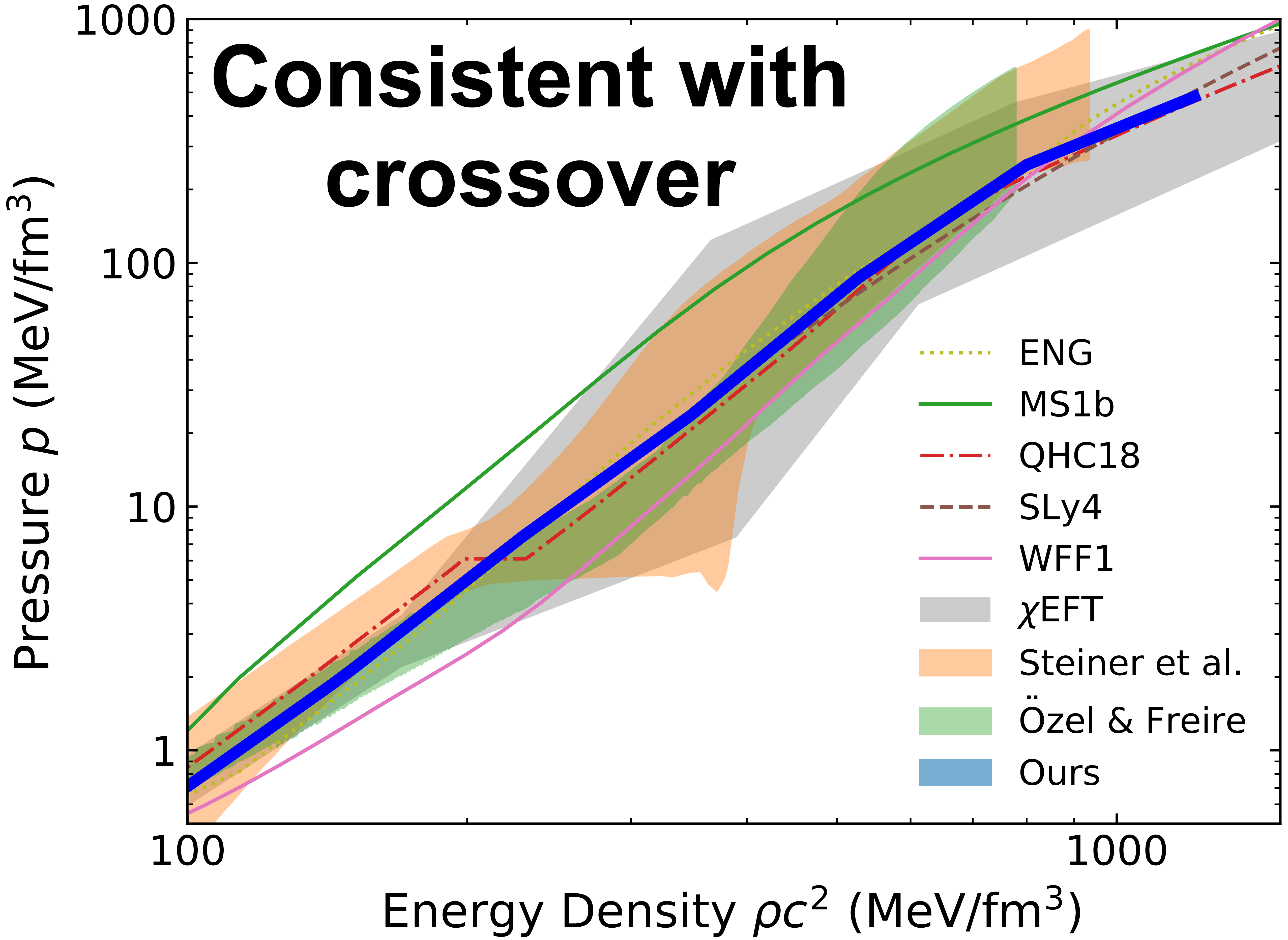


Theoretical Background of Crossover EoS

Schafer,Wilczek (1998)
Alford,Berges,Rajagopal (1999)

Quark-Hadron Continuity (3-flavor)

= Both phases are indistinguishable

i.e. **(1) symmetries are the same**;

(2) no order parameter

… Assumes **3-flavor symmetric** matter $m_u = m_d = m_s$

- In reality, nuclear matter is **2-flavor symmetric** rather than three:

$$m_s \gg m_u \simeq m_d$$

- Most nuclear EoS are for 2-flavor matter → **2-flavor matter continuity?**

No Quark-Hadron Continuity in Usual 2-flavor

Schafer,Wilczek (1998)
Alford,Berges,Rajagopal (1999)

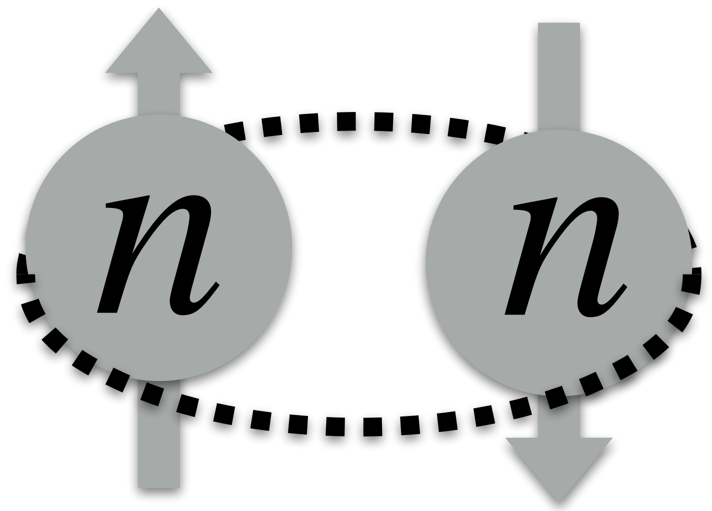
Quark-Hadron Continuity?? (2-flavor)

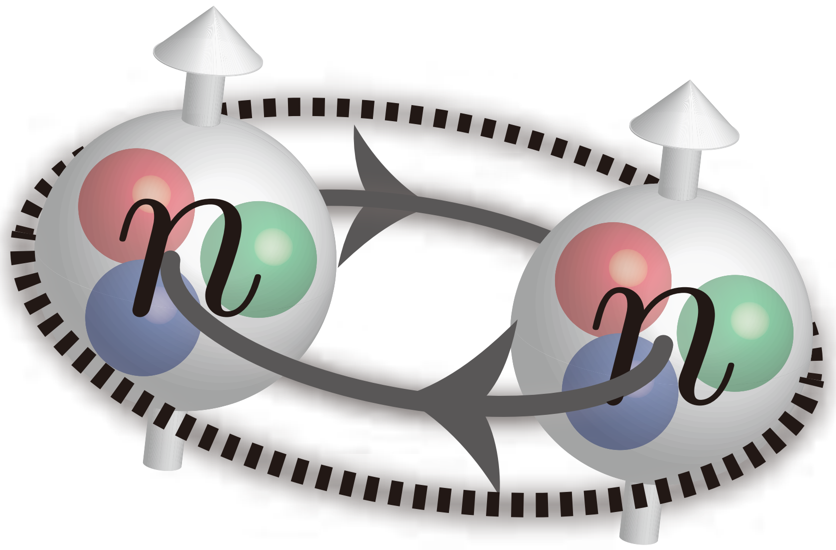
Conventional wisdom tells us…

- In **quark phase**, 2-flavor color-superconductivity (**2SC**) has: $\langle ud \rangle_{L/R}$

  → **NO $\mathrm{U(1)_B}$ breaking** (i.e. no superfluidity)

- In **hadron phase**, neutron superfluid → **$\mathrm{U(1)_B}$ breaking**

$^1S_0$ pairing 

 $^3P_2$ pairing

n_B

$\sim 0.5\, n_0\, (= 0.08\ \mathrm{fm}^{-3})$

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No continuity?

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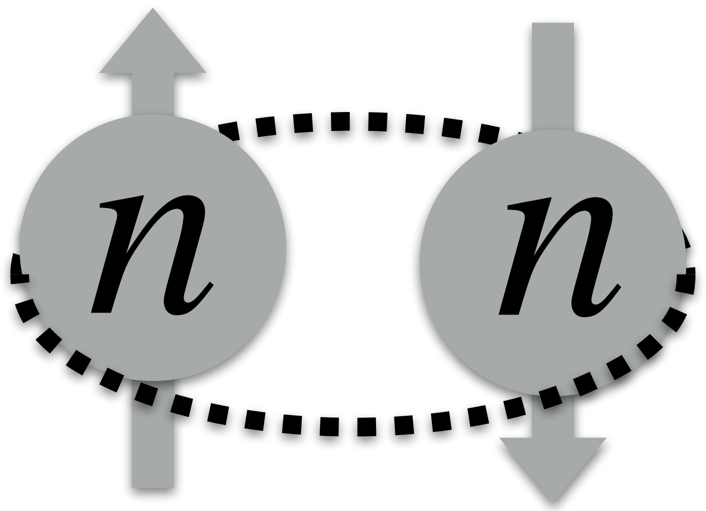
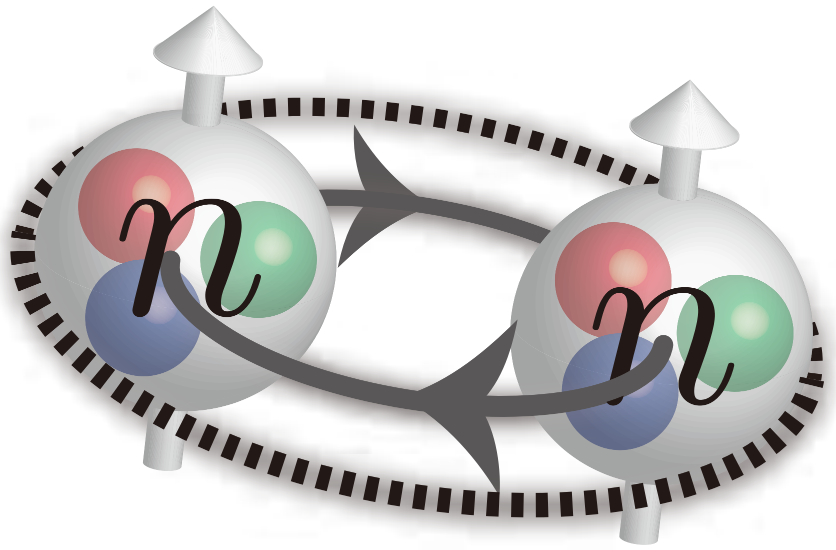
$^1S_0$ pairing 



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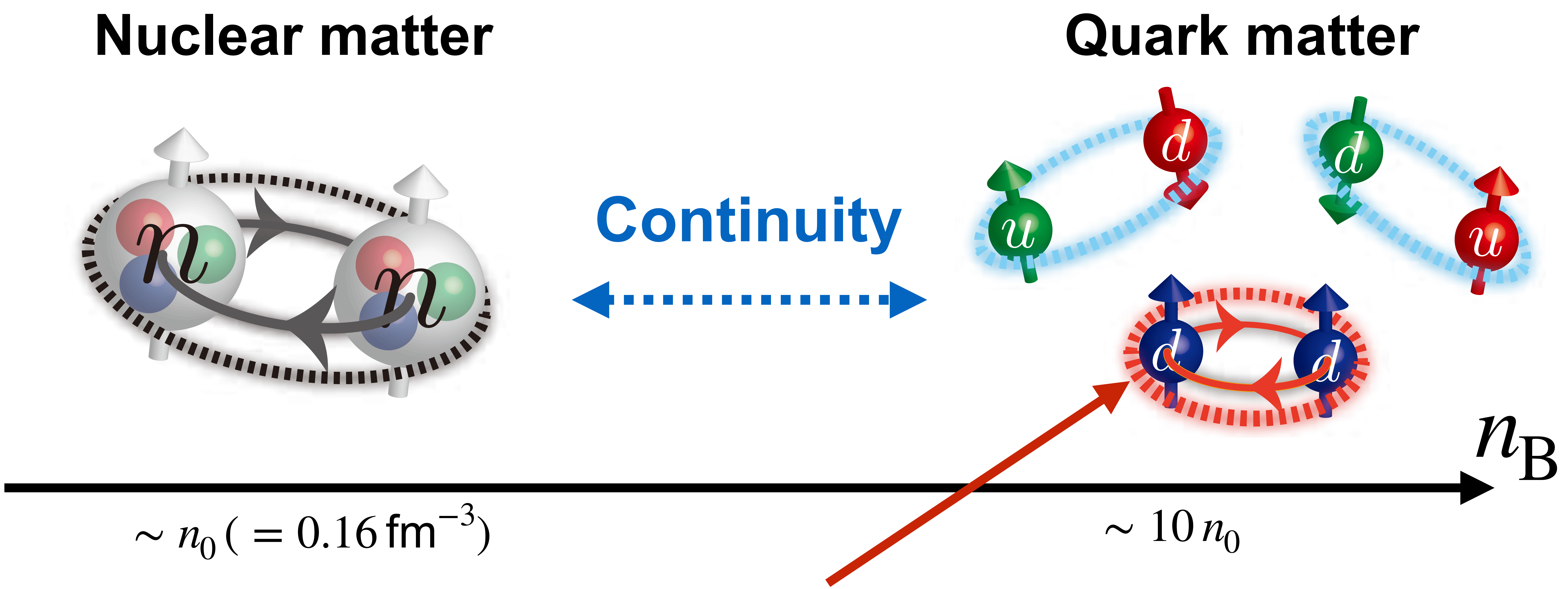
What We Found Here: 2-flavor Continuity

Fujimoto, Fukushima, Weise, arXiv:1908.09360



New element here; ensures continuity
"2SC + <dd>"

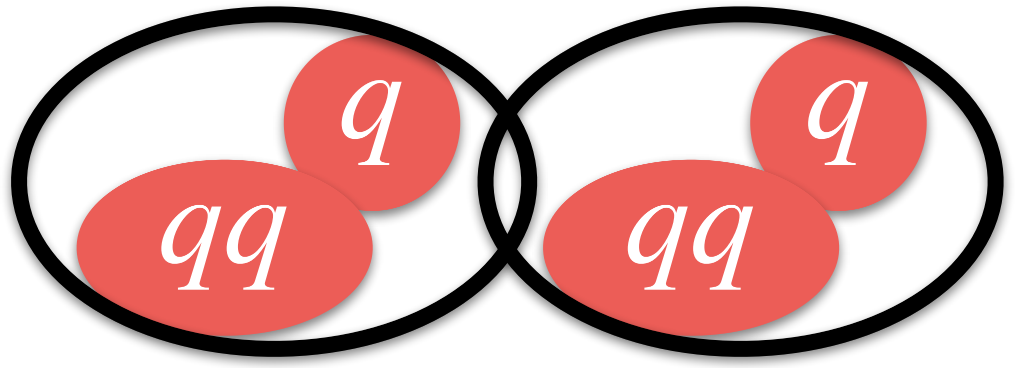
[Review] Quark-Hadron Continuity: 3-flavor

Alford,Baym,Fukushima,Hatsuda,Tachibana (2018)

- Here, define CFL diquark operator: qq (**gauge variant**; color $\bar{3}$)
- **Gauge invariant** order parameters with the same quark constituent:

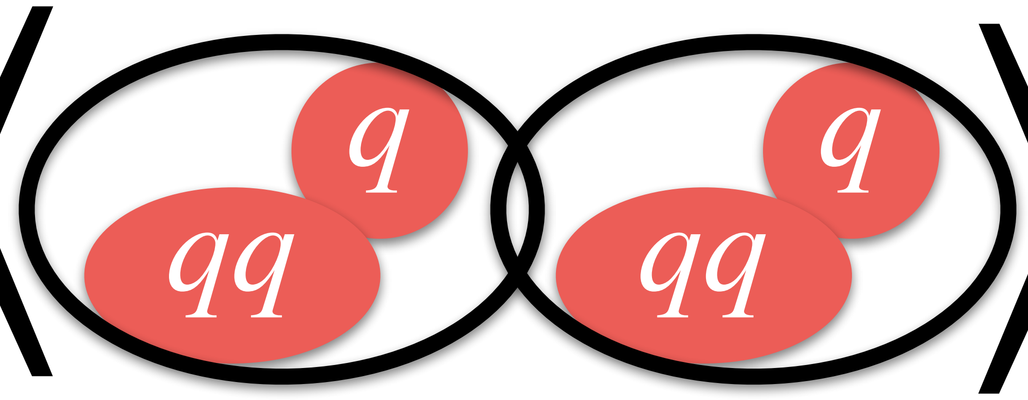
in the CFL phase

in the hadronic phase



- Compare the expectation value (in the mean field approx.):

H $\langle$ 

$\rangle \approx \langle$ 

$\rangle$ $\Lambda\Lambda$

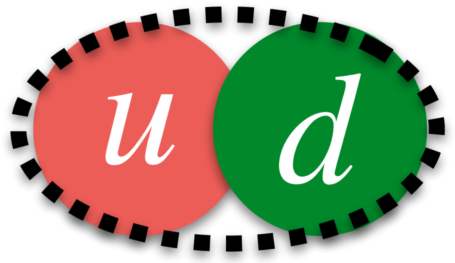
3 diquarks
~ 2 baryons

… **No gauge-invariant order parameter** to distinguish both phases

Quark-Hadron Continuity: 2-flavor Case

Fujimoto,Fukushima,Weise, arXiv:1908.09360

- Doing just the same as in 3-flavor case…

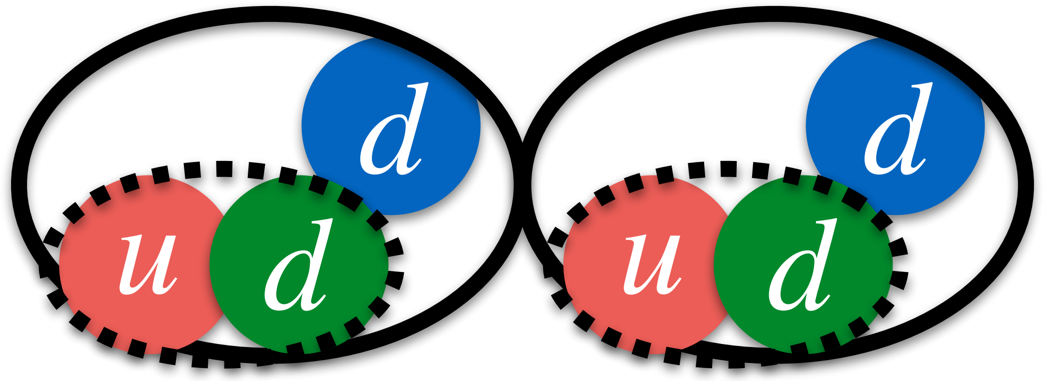
- We already know 2SC diquark operator: 

- **Gauge invariant** order parameters with the same quark constituent:

in the quark phase

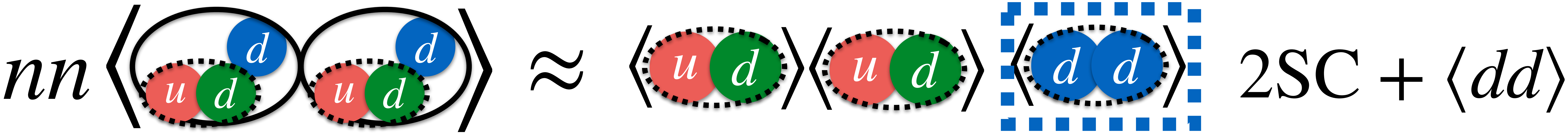
?

in the hadronic phase



nn

- Find the quark phase counterpart by rearrangement (in the mean field approx.):



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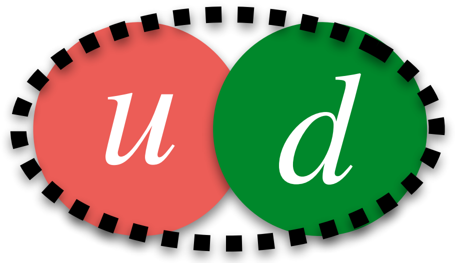
- We already know 2SC diquark operator: 

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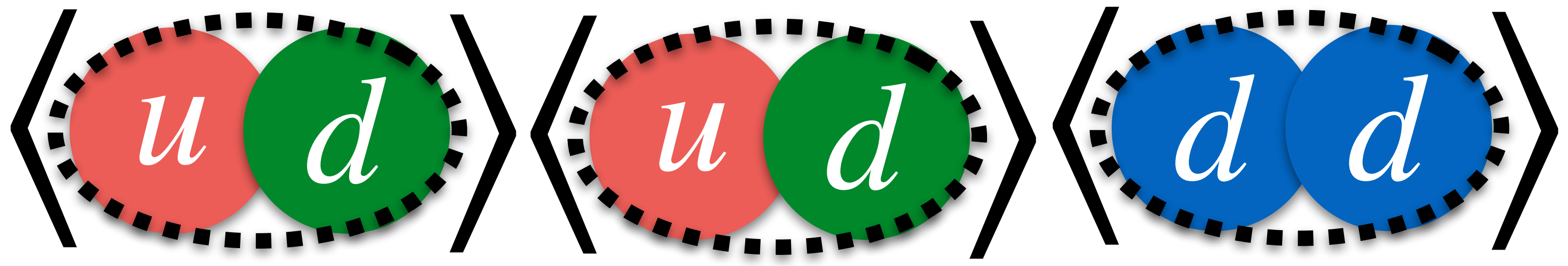
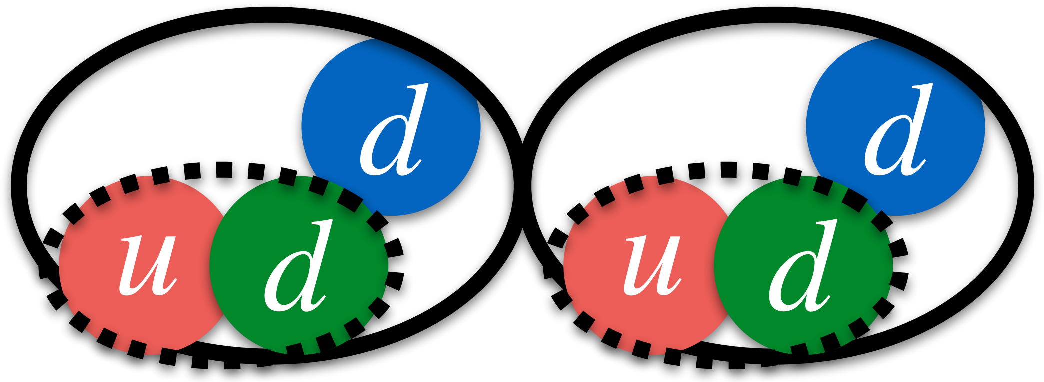


$$2\mathrm{SC} + \langle dd \rangle$$

in the hadronic phase



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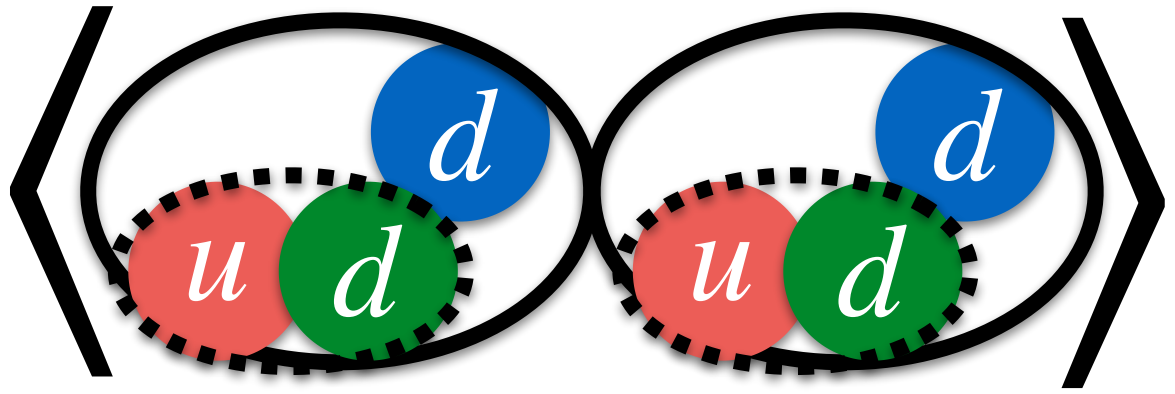
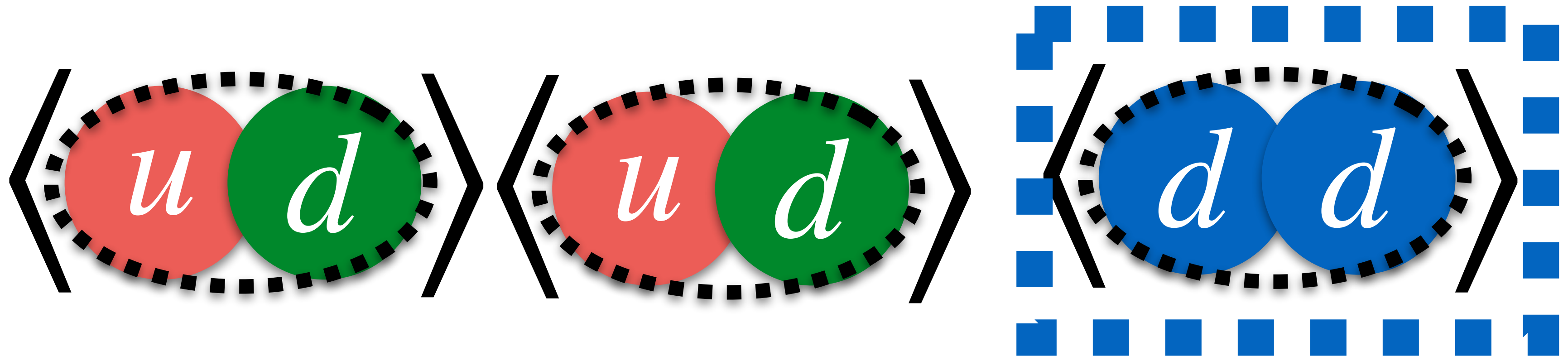
nn 

$\approx$ 

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Quark-Hadron Continuity: 2-flavor Case

Fujimoto, Fukushima, Weise, arXiv:1908.09360

- We have **2SC+<dd>**:

$$\langle ud \rangle_{L/R} + \langle \hat{d}^{\top} C \gamma^i \nabla^j \hat{d} \rangle$$

… <**dd**> breaks $\mathrm{U(1)_B}$

→ **matter is superfluid, the same as hadronic phase** → **Continuity!**

- $\langle \hat{d}_\alpha^{\top} C \gamma^i \nabla^j \hat{d}_\beta \rangle$ → Color should be **symmetric** (in sextet channel $\mathbf{6}$)

One-gluon exchange (i.e. short-range) between dd **repulsive!?**

→ **No Cooper pair formation?**

Repulsive interaction between *dd* ?

Fujimoto,Fukushima,Weise, arXiv:1908.09360

- Repulsive nature is not harmful, rather **useful…**

S-wave Cooper pairing $(L=0)$ **P-wave pairing $(L=1)$**

- Due to <dd> structure: $\langle d^\top C \gamma^i \nabla^j \hat{d} \rangle$ spin & angular momentum ≠ 0

- Prototype example: **neutron $^3P_2$ pairing**

$^3P_2$ Neutron Superfluidity

Hoffberg *et al.* (1970); Tamagaki (1970)

- Inside neutron star, $^3P_2$ **neutron superfluid** is presumed

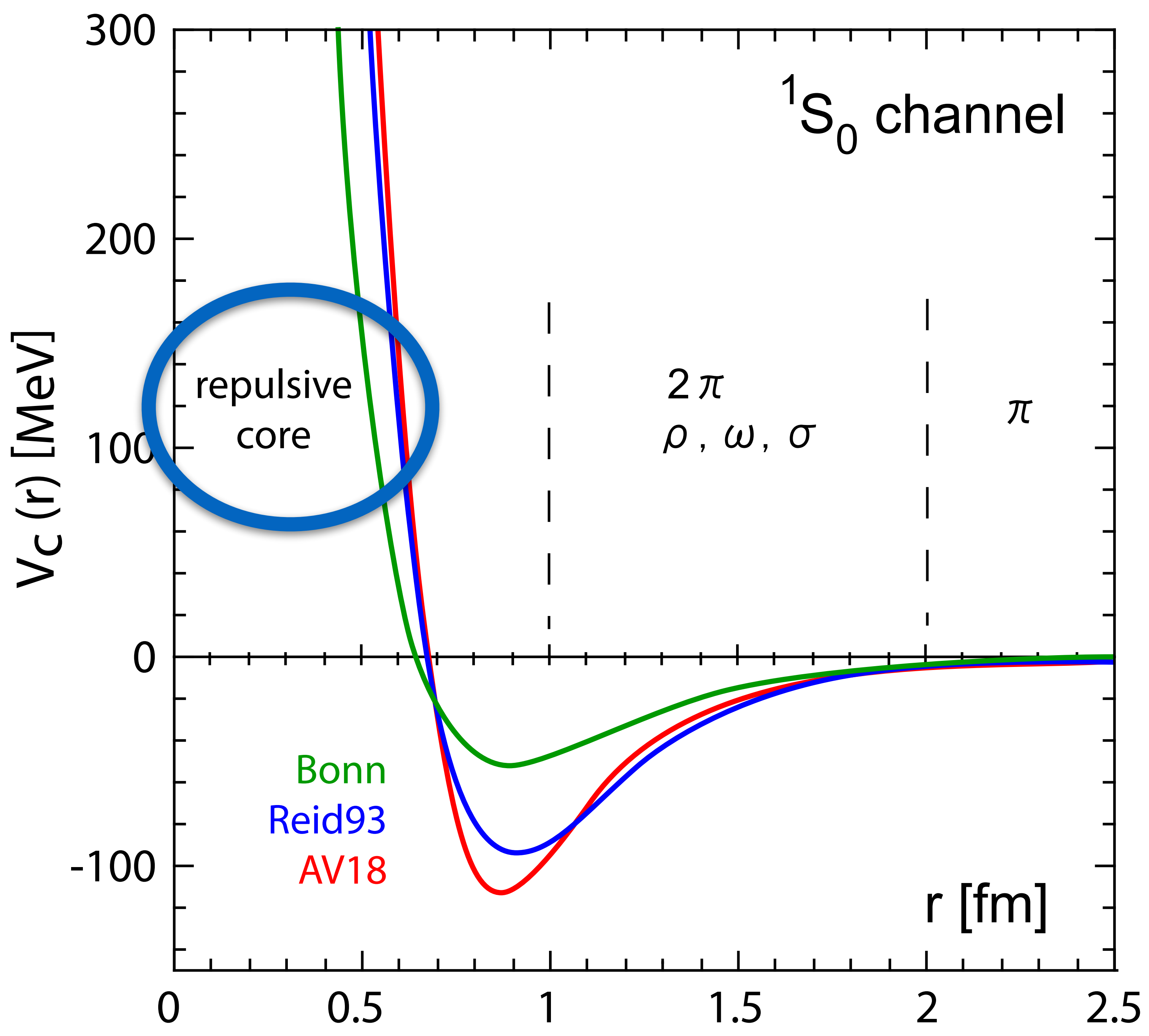
- Increasing densities, NN interaction becomes repulsive due to the **repulsive core**

  → - S-wave ($L = 0$) superfluidity suppressed

  - **P-wave** ($L = 1$) **takes over**

- **Spin triplet** ($S = 1$): fixed by anti-symmetry

Aoki (2011)



$^3P_2$ Neutron Superfluidity

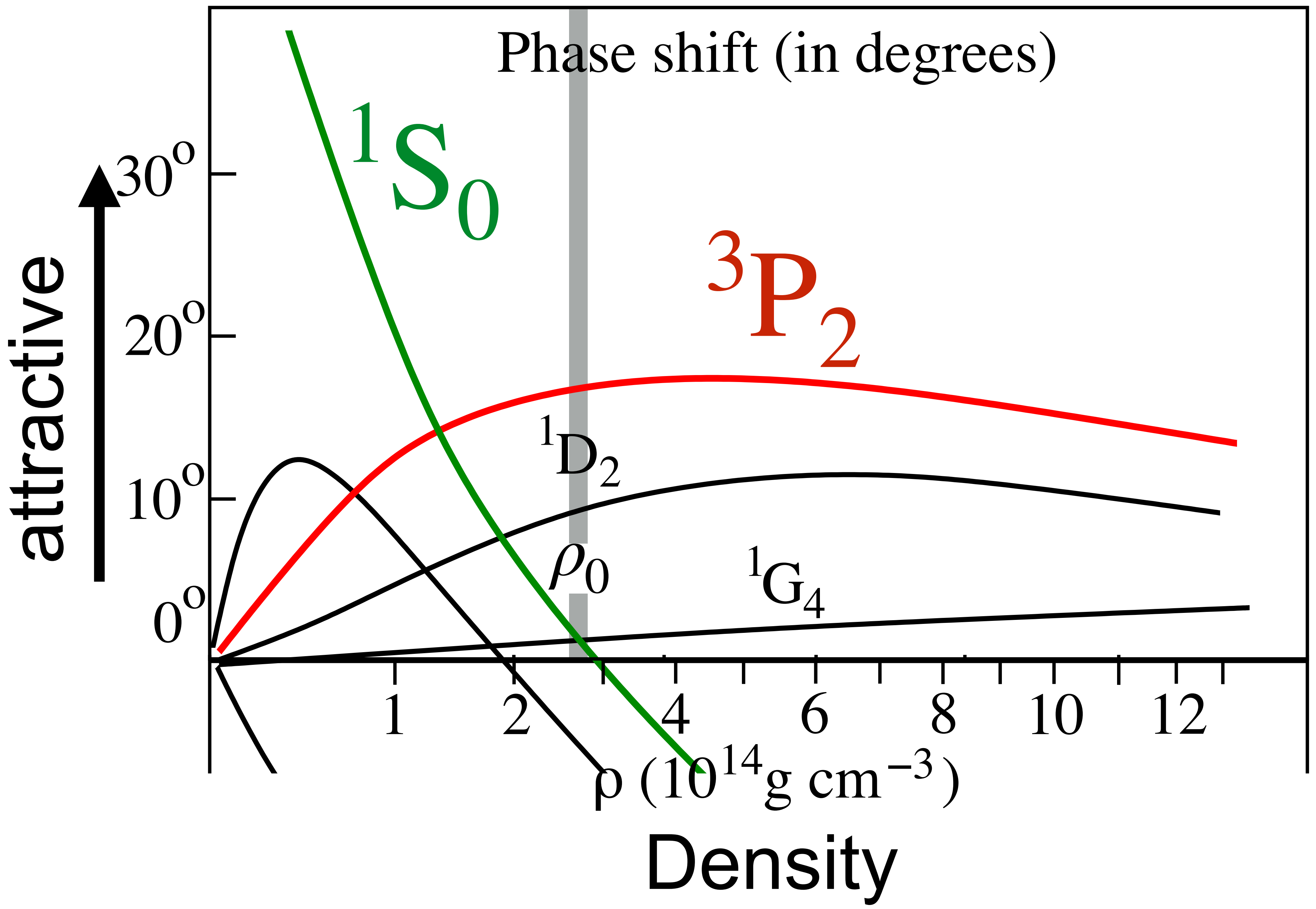
Hoffberg *et al.* (1970); Tamagaki (1970)

- $J=2$ is favored among $J=0,1,2$
  by **attractive LS potential** V_{LS}:

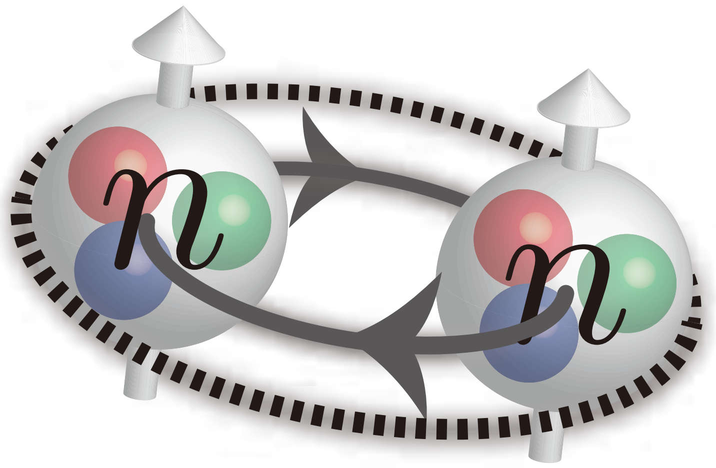
$$V_{LS} \propto -\boldsymbol{L}\cdot\boldsymbol{S} = \begin{cases} +2 & (J=0) \text{ Repulsive} \\ +1 & (J=1) \text{ Repulsive} \\ -1 & (J=2) \text{ Attractive} \end{cases}$$

Page,Prakash,Lattimer,Steiner (2011)

NN Scattering



- Phase shift (effective NN interaction):
  $^3P_2$ channel is dominantly attractive above ρ_0
  → **$^3P_2$ superfluidity**



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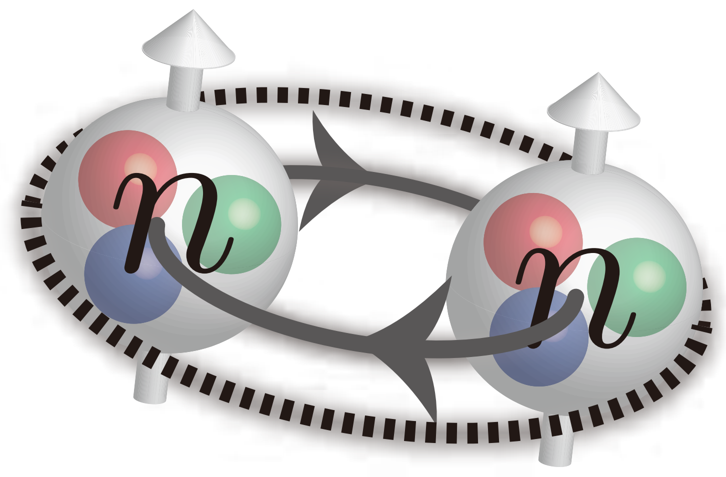

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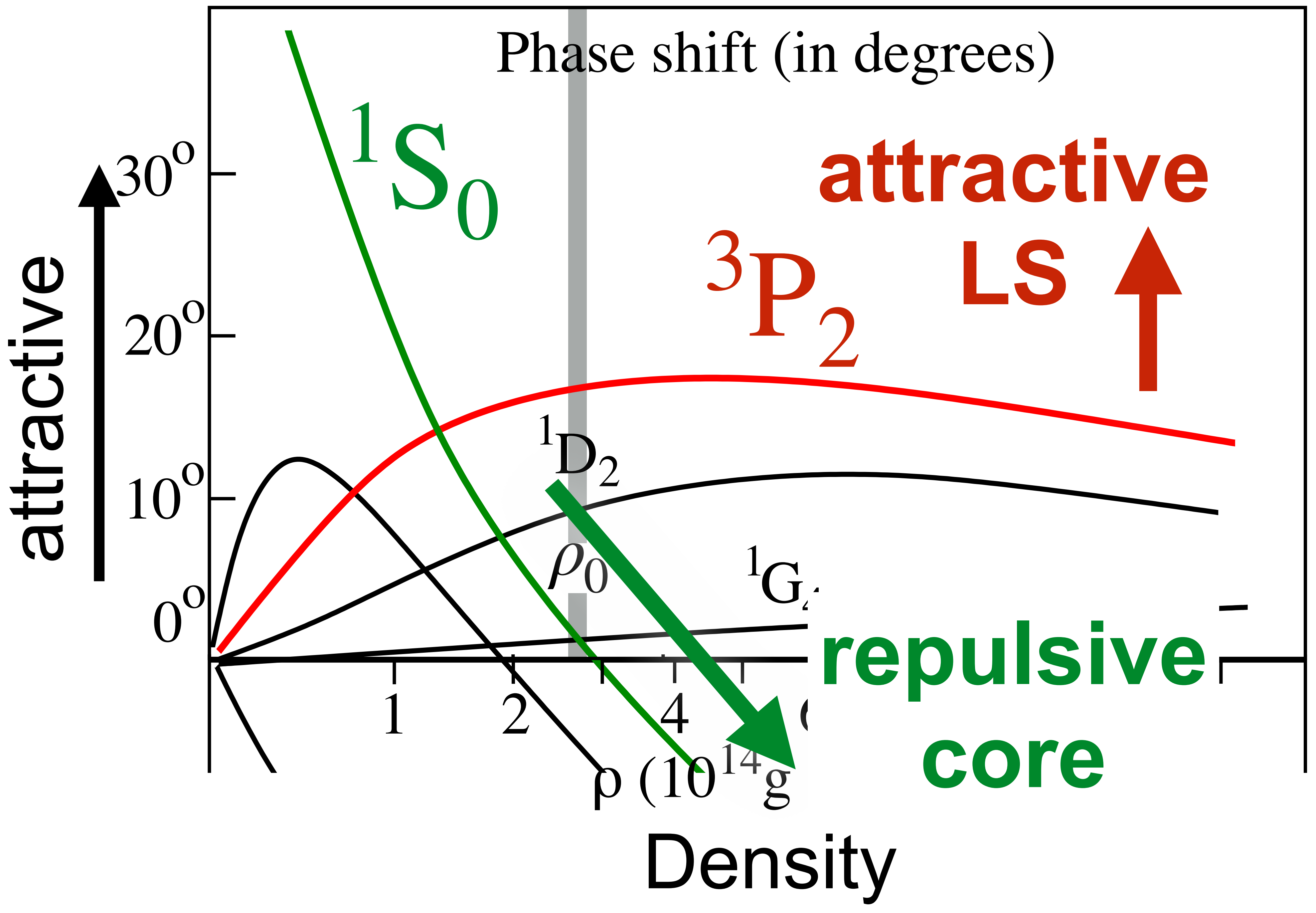


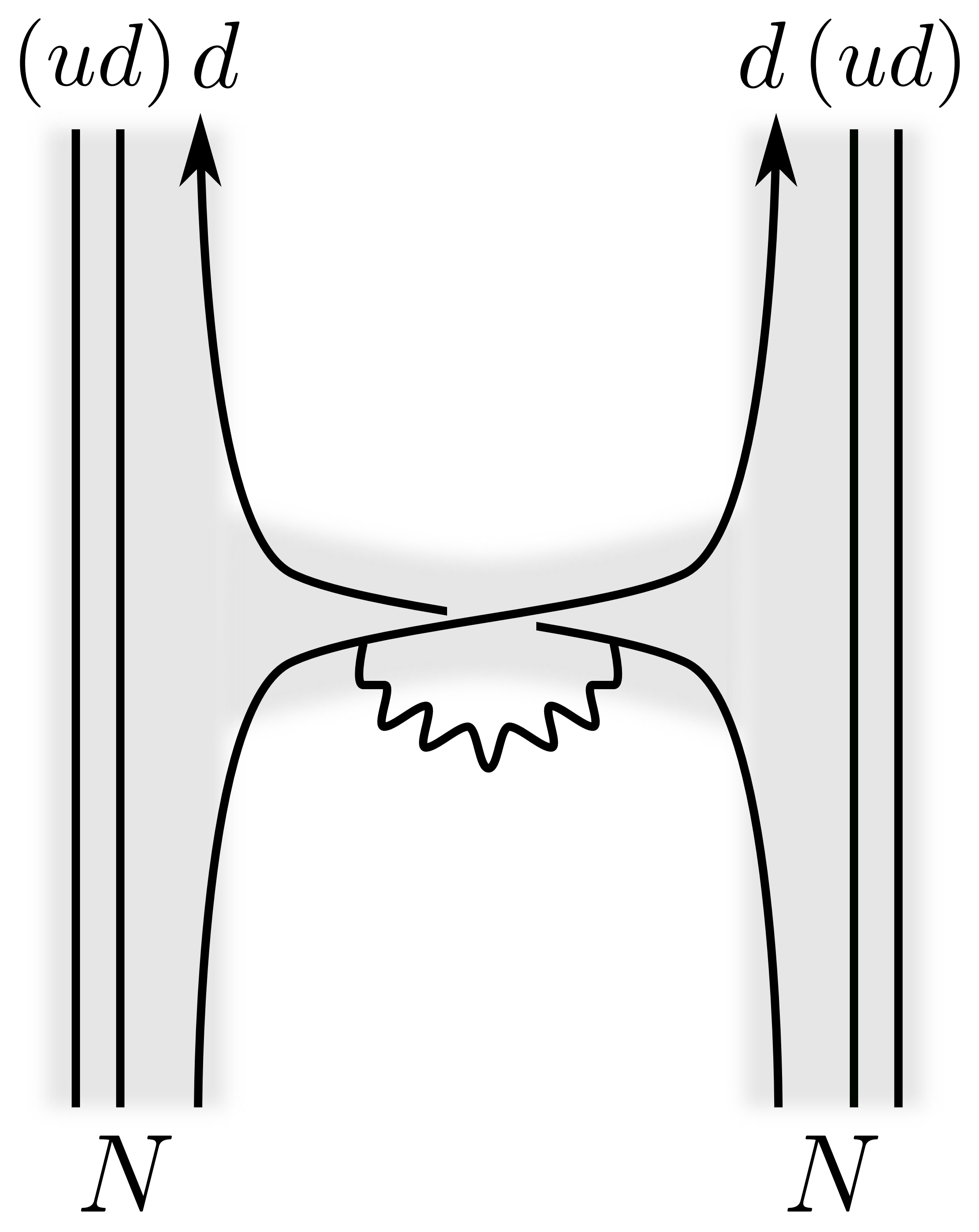
Quark-Hadron Continuity: 2-flavor Case

Fujimoto,Fukushima,Weise, arXiv:1908.09360

Physics mechanism that favors 2SC+<dd>

- Universal mechanism favoring ${}^3P_2$ superfluidity

- Short-range repulsion between dd disfavors S-wave:
  derived from dd quark exchange
  [cf. Repulsive core of NN force: Oka,Yazaki (1980)
  derived from **quark exchange between NNs**]



- $J = 2$ state is favored:
  confirmed this behavior employing NJL-type model with vector coupling

Coupling to Energy-Momentum Tensor (EMT)

Fujimoto, Fukushima, Weise, arXiv:1908.09360

- Gauge invariant order parameter for <dd>:

$$\hat{\mathscr{I}} = (\bar{\psi}_d \gamma^i \nabla^j C \bar{\psi}_d^\top)(\psi_d^\top C \gamma_i \nabla_j \psi_d)$$

Fierz transformation

EMT: $T^{\mu\nu} = \bar{\psi}_d i\gamma^\mu \partial^\nu \psi_d$

In equilibrium: $T^{\mu\nu} = \mathrm{diag}[\mathscr{E}, P, P, P]$

$$\langle \hat{\mathscr{I}} \rangle \approx \frac{3}{4} P^2$$

Macroscopic value related to EoS

Summary and Outlooks

- Established 2-flavor quark-hadron continuity with **2SC+<dd>** phase
  [**Fujimoto,**Fukushima,Weise, arXiv:1908.09360]

- Consistent with real data deduced from deep learning analysis
  [**Fujimoto,**Fukushima,Murase, arXiv:1903.03400]

- Implication to NS physics:
    - Theoretical background for smooth crossover EoS construction
    - NS cooling — 2SC+X scenario [Grigorian,Blaschke,Voskresensky (2005)]

- Outlooks:
    - Dynamical calculation of <dd> gap matrix
    - Vortex continuity of 2SC+<dd> — relation with glitch phenomena?
      [Alford,Baym,Fukushima,Hatsuda,Tachibana (2018)]