Hadron Structures toward dense matter

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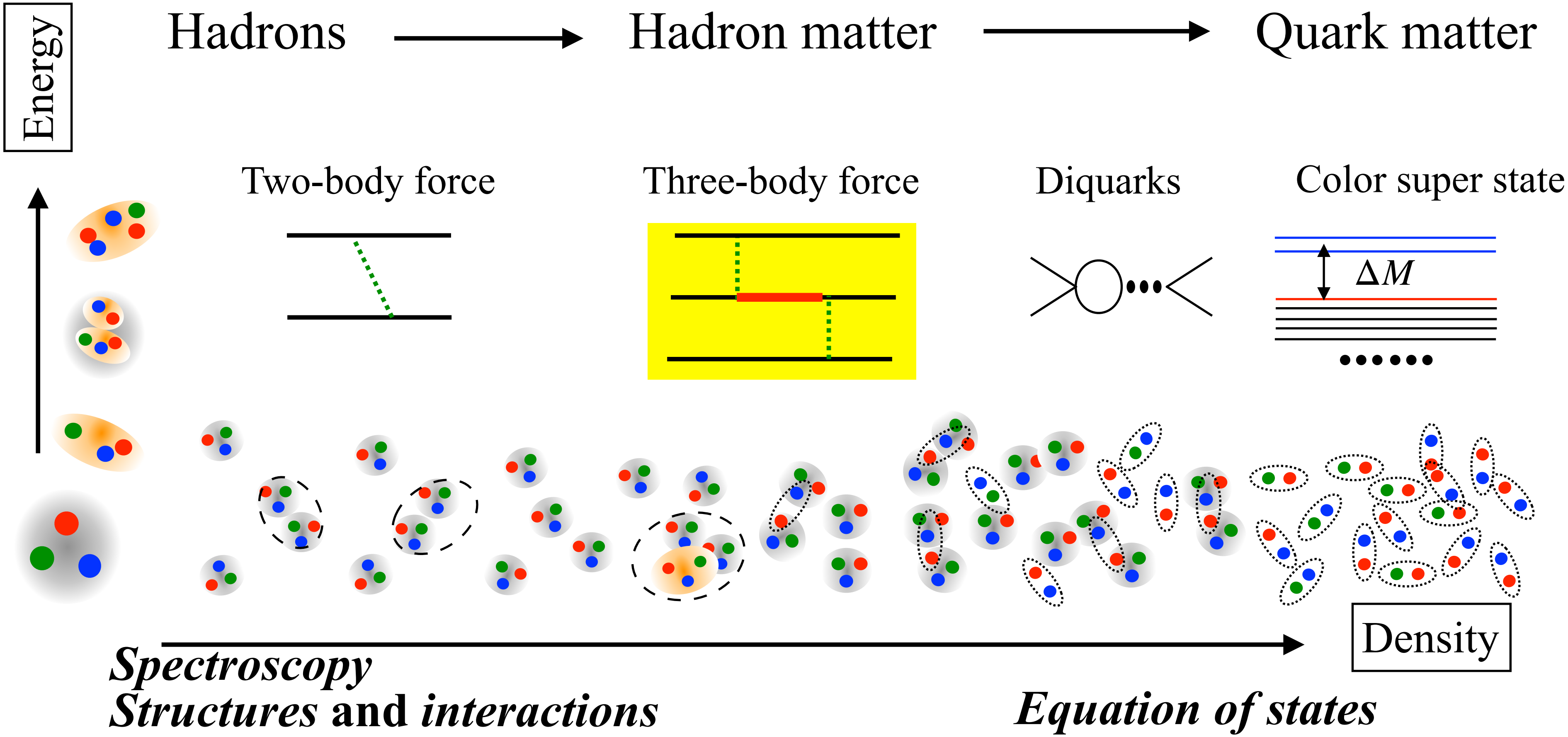
1. Introduction:
   Role of Resonances in finite density matter with various structures
2. ϕ meson and nucleon resonance N*
3. Chiral baryons for nuclear matter:
   Towards hints to mass generation

1. Introduction



Energy

Hadrons → Hadron matter → Quark matter

Two-body force

Three-body force

Diquarks

Color super state

Density

Spectroscopy

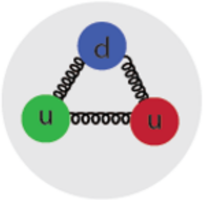
Structures* and *interactions

Equation of states

Hadrons are **Basis for** *Finite/High density matter*

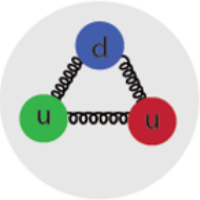
Various structures

Ground states



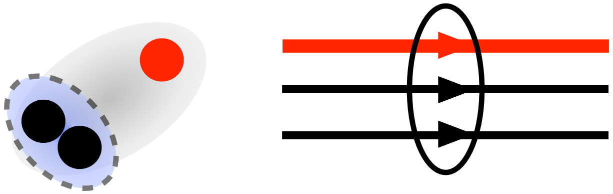
Various structures

Ground states

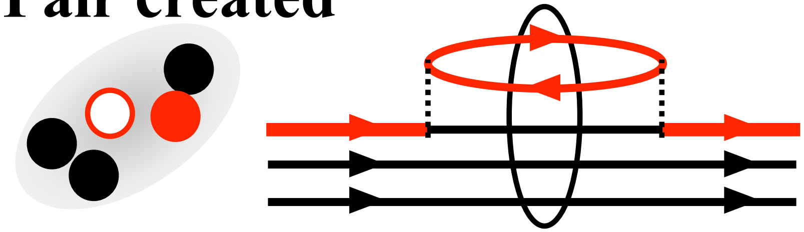


Resonances

Orbitally excited

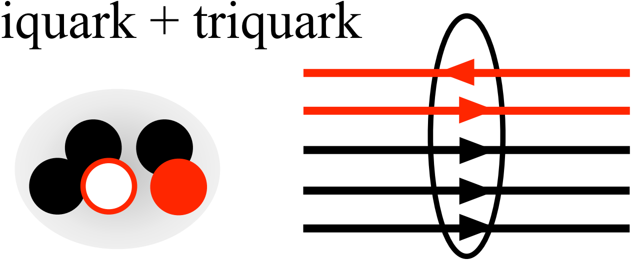


Pair created



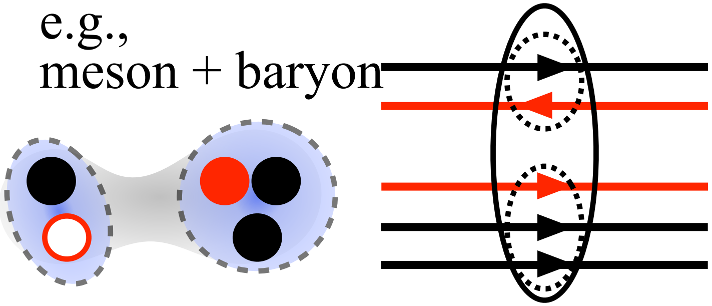
Compact quarks

e.g.,
diquark + triquark



Extended molecules

e.g.,
meson + baryon



For hadron structure

Mixing of Compact and Extended structure is interesting

X(3872), P_c, Ω(2012), …

- For X

  M. Takizawa and S. Takeuchi, Prog. Theor. Exp. Phys. 2013, 093D01
  Y. Yamaguchi, AH, S. Takeuchi and M. Takizawa, J.Phys.G 47 (2020) 5, 053001

- . For Pc

  Giachino, Yamaguchi, AH, Santopinto, Takeuchi, Takizawa, Yamaguchi, Phys.Rev.D 108 (2023) 7, 074012, Phys.Rev.D 101 (2020) 9, 091502, Phys.Rev.D 96 (2017) 11, 114031

- . For Ω(2012)

  QF. Lyu, H. Nagahiro, AH, hys.Rev.D 107 (2023) 1, 014025,
  N. Su, HX. Chen, P. Gubler, AH, hys.Rev.D 110 (2024) 3, 034007

But today, ϕ and related nucleon resonance N^* as molecules

2. ϕ meson and nucleon resonance N^*

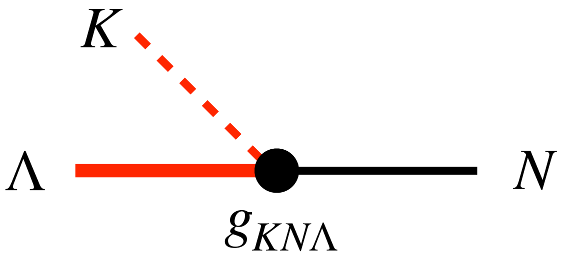
- $\phi(1020)$, $J^{PC} = 1^{--}$, almost $s\bar{s}$
- Narrow width 4.2 MeV, suited to a small mass shift
- Would be relevant for dense matter (with (anti)strangeness)

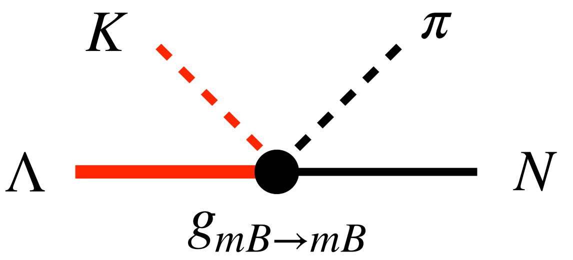
At first sight: $s\bar{s}$ does not play for *nuclear matter* (~ u, d quarks)

But **large link** between u, d and s quarks

- Yukawa coupling, $g_{KN\Lambda} \sim \sqrt{3} \sim g_{\pi NN} \sim 5/3$
- WT couplings

$S = 0$	$g_{mB\to mB}$	$I = \frac{1}{2}$				$I = \frac{3}{2}$	
		πN	ηN	$K\Lambda$	$K\Sigma$	πN	$K\Sigma$
$I = \frac{1}{2}$	πN	2	0	$\frac{3}{2}$	$\frac{1}{2}$		
	ηN		0	$-\frac{3}{2}$	$\frac{3}{2}$		
	$K\Lambda$			0	0		
	$K\Sigma$				2		
$I = \frac{3}{2}$	πN					-1	-1
	$K\Sigma$						-1





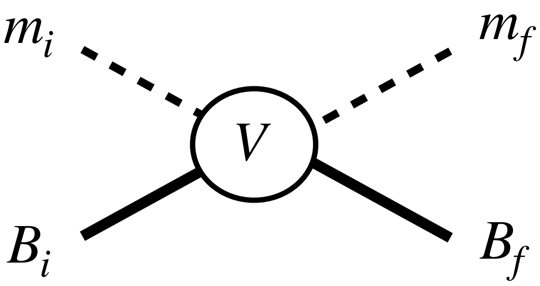
N* resonance around 2 GeV may be dressed by mesons with s-quark

mB molecules

Coupled channel model with PS and V mesons

Khemchandani, Kaneko, Nagahiro, AH, Phys.Rev.D 83 (2011) 114041
Khemchandani, Martinez, Kaneko, Nagahiro, AH, Phys.Rev.D 84 (2011) 094018
Khemchandani, Martinez, Nagahiro, AH, Phys.Rev.D 85 (2012) 114020,
Phys.Rev.D 88 (2013) 11, 114016, Phys.Rev.D 103 (2021) 1, 016015
Abreu, **Gubler**, Khemchandani, Martinez, AH, **Phys.Lett.B 860 (2025) 139175**

Contains s, t, u, and c terms



4 PS and 5 V channels

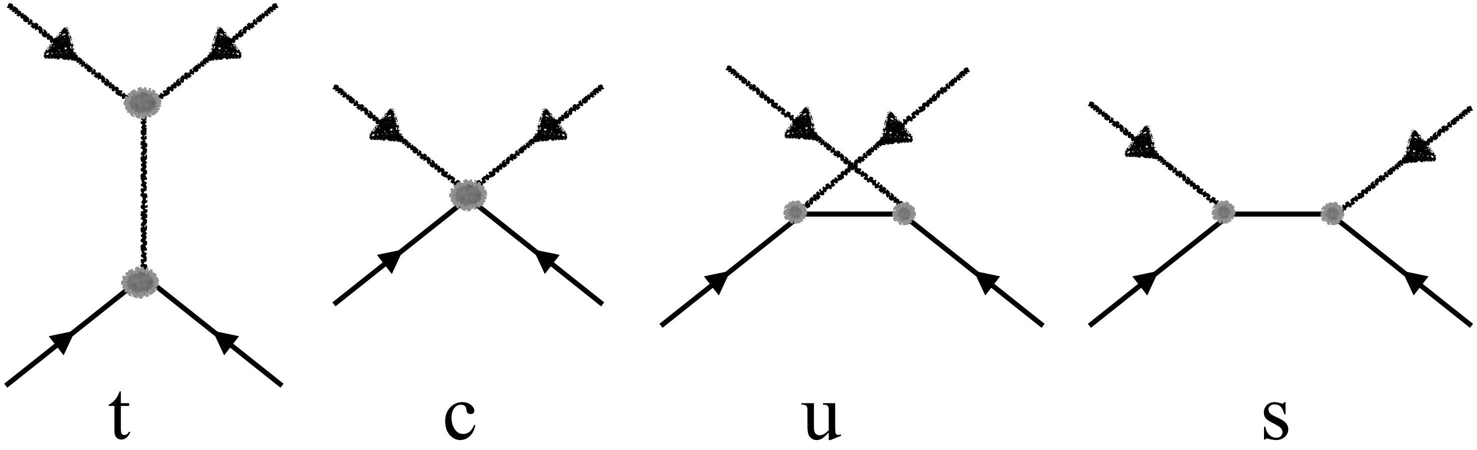
PS: πN, ηN, $K\Lambda$, $K\Sigma$
V: ρN, ωN, ϕN, $K^*\Lambda$, $K^*\Sigma$,

Interactions are dictated by low energy theorems of chiral symmetry

Amplitudes are obtained by LS equation

$$T = \frac{V}{1 - VG} = V + VGV + VGVGV + \cdots$$

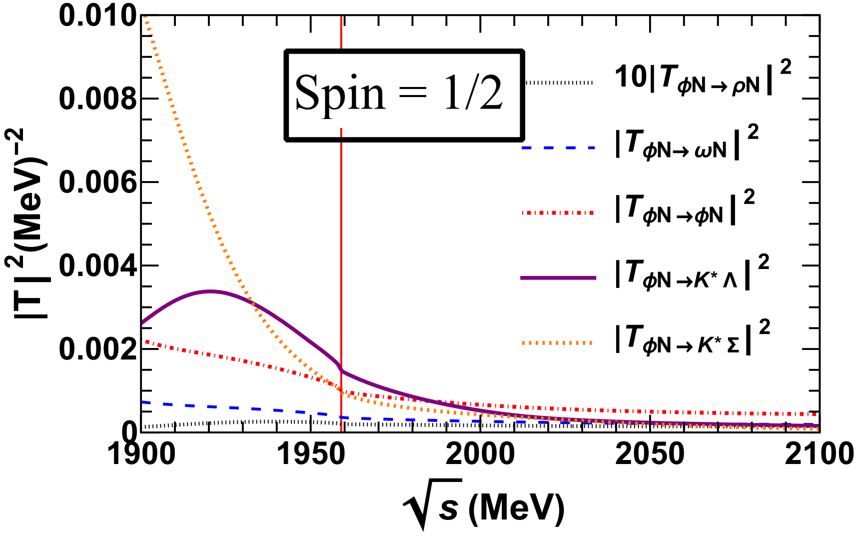
Some details

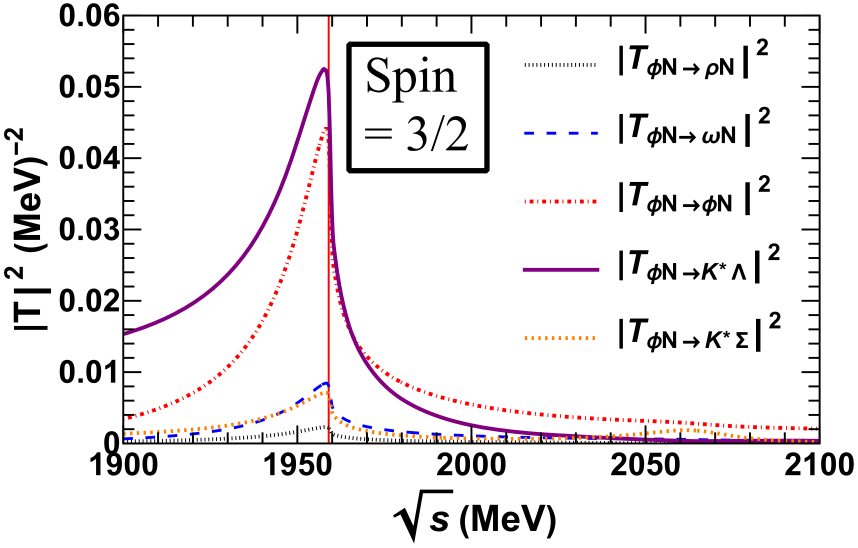


$$\mathcal{L}_{\mathrm{V}B} = -g\left\{ \langle \bar{B}\gamma_{\mu}\left[V_8^{\mu}, B\right]\rangle + \langle \bar{B}\gamma_{\mu}B\rangle\langle V_8^{\mu}\rangle + \frac{1}{4M}\left(F\langle \bar{B}\sigma_{\mu\nu}\left[V_8^{\mu\nu}, B\right]\rangle \right.\right.$$

$$\left.\left. + D\langle \bar{B}\sigma_{\mu\nu}\left\{V_8^{\mu\nu}, B\right\}\rangle \right) + \langle \bar{B}\gamma_{\mu}B\rangle\langle V_0^{\mu}\rangle + \frac{C_0}{4M}\langle \bar{B}\sigma_{\mu\nu}V_0^{\mu\nu}B\rangle \right\},$$

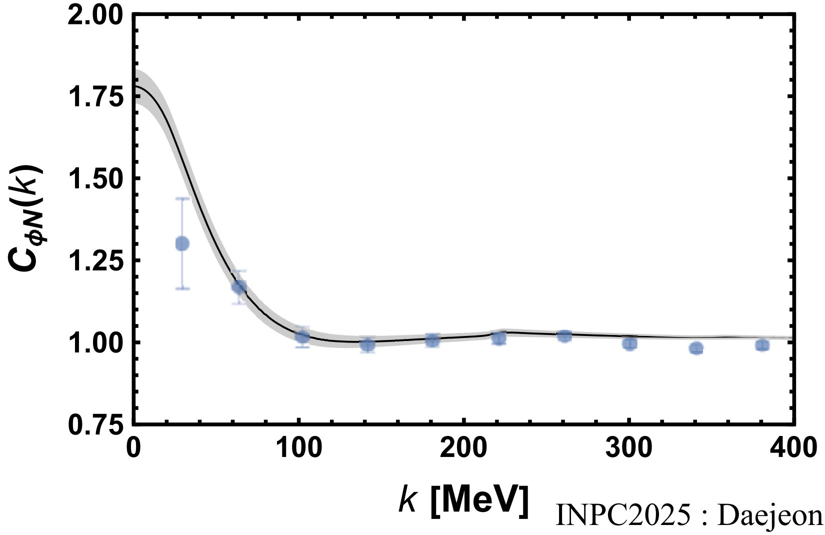
Amplitudes show strong attraction for ϕN channels

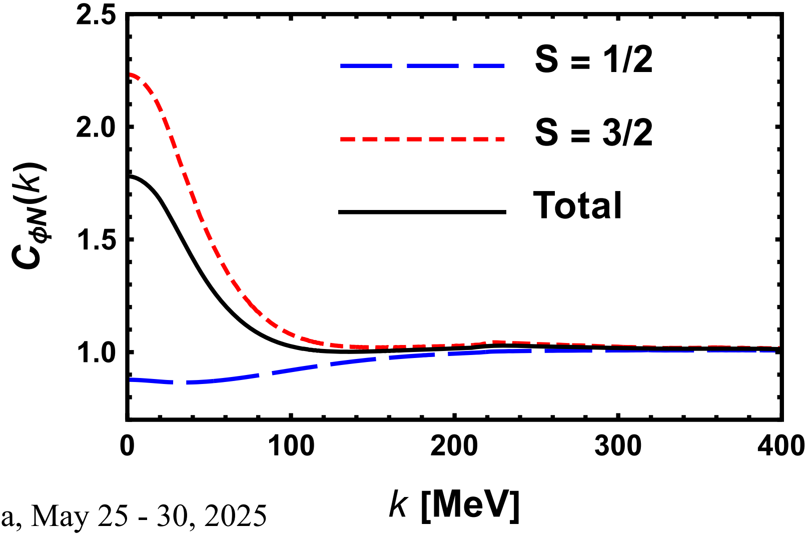




(Spin averaged) correlation agrees well with data

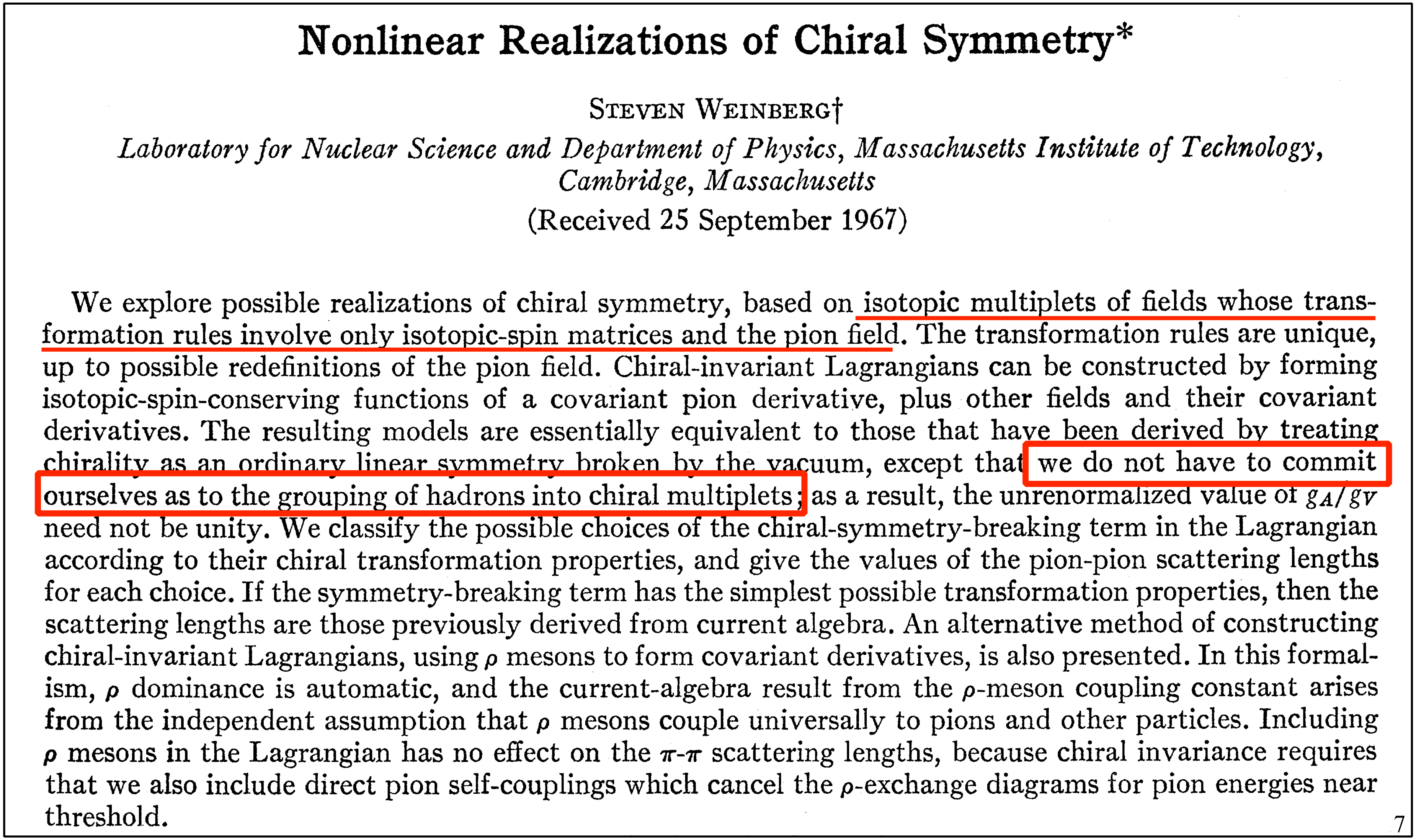
ALIS, S. Acharya, et al., Phys. Rev.Lett. 127 (17) (2021) 172301





3. Chiral baryons for nuclear matter

We can trace back to 1970’th, S. Weinberg



Nonlinear Realizations of Chiral Symmetry*

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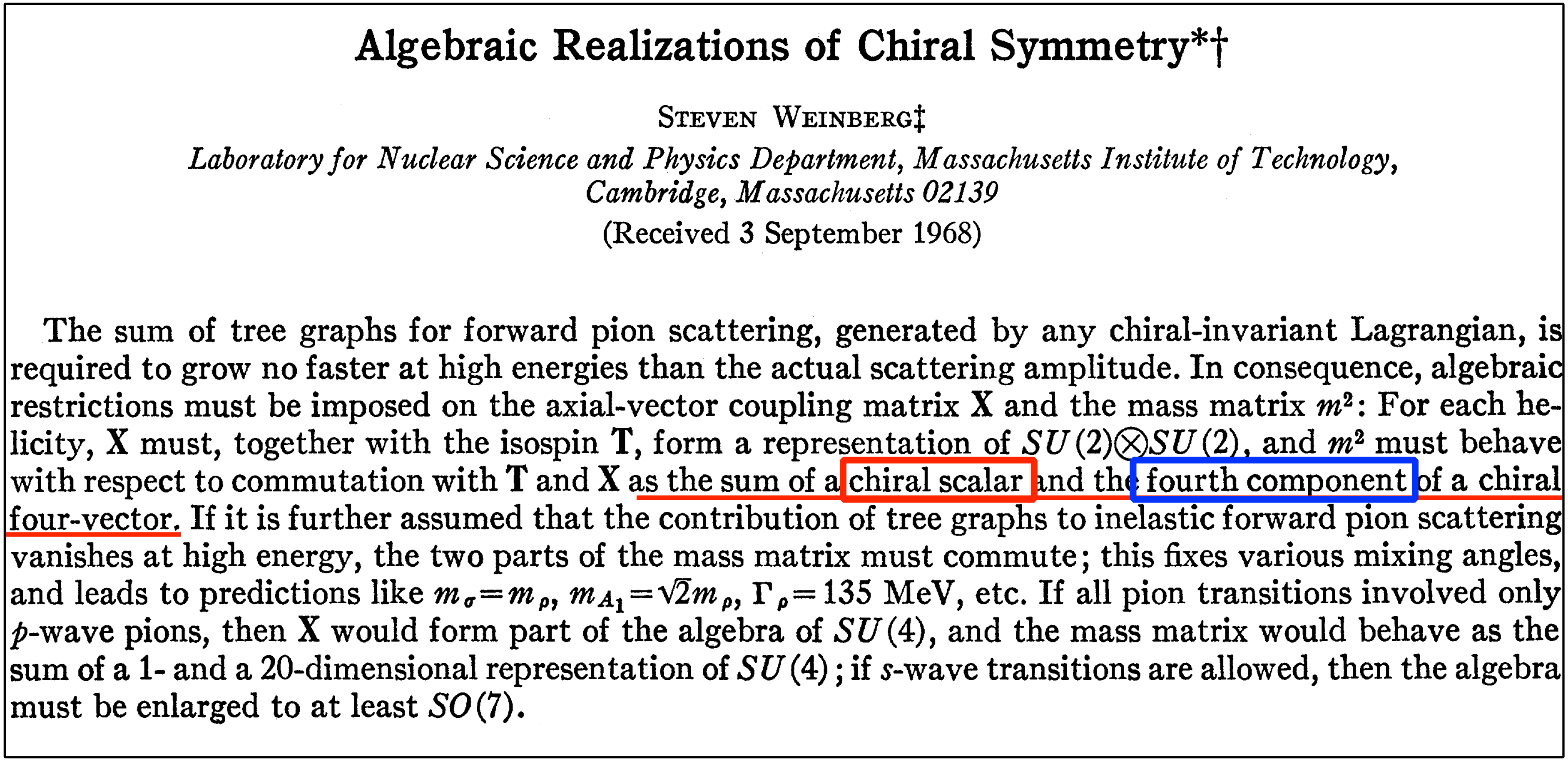
Cambridge, Massachusetts

(Received 25 September 1967)

We explore possible realizations of chiral symmetry, based on isotopic multiplets of fields whose transformation rules involve only isotopic-spin matrices and the pion field. The transformation rules are unique, up to possible redefinitions of the pion field. Chiral-invariant Lagrangians can be constructed by forming isotopic-spin-conserving functions of a covariant pion derivative, plus other fields and their covariant derivatives. The resulting models are essentially equivalent to those that have been derived by treating chirality as an ordinary linear symmetry broken by the vacuum, except that we do not have to commit ourselves as to the grouping of hadrons into chiral multiplets; as a result, the unrenormalized value of g_A/g_V need not be unity. We classify the possible choices of the chiral-symmetry-breaking term in the Lagrangian according to their chiral transformation properties, and give the values of the pion-pion scattering lengths for each choice. If the symmetry-breaking term has the simplest possible transformation properties, then the scattering lengths are those previously derived from current algebra. An alternative method of constructing chiral-invariant Lagrangians, using ρ mesons to form covariant derivatives, is also presented. In this formalism, ρ dominance is automatic, and the current-algebra result from the ρ-meson coupling constant arises from the independent assumption that ρ mesons couple universally to pions and other particles. Including ρ mesons in the Lagrangian has no effect on the π-π scattering lengths, because chiral invariance requires that we also include direct pion self-couplings which cancel the ρ-exchange diagrams for pion energies near threshold.

3. Chiral baryons for nuclear matter

We can trace back to 1970’th, S. Weinberg



Algebraic Realizations of Chiral Symmetry[*][†]

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(Received 3 September 1968)

The sum of tree graphs for forward pion scattering, generated by any chiral-invariant Lagrangian, is required to grow no faster at high energies than the actual scattering amplitude. In consequence, algebraic restrictions must be imposed on the axial-vector coupling matrix **X** and the mass matrix m^2: For each helicity, **X** must, together with the isospin **T**, form a representation of $SU(2)\otimes SU(2)$, and m^2 must behave with respect to commutation with **T** and **X** as the sum of a chiral scalar and the fourth component of a chiral four-vector. If it is further assumed that the contribution of tree graphs to inelastic forward pion scattering vanishes at high energy, the two parts of the mass matrix must commute; this fixes various mixing angles, and leads to predictions like $m_\sigma = m_\rho$, $m_{A_1} = \sqrt{2} m_\rho$, $\Gamma_\rho = 135$ MeV, etc. If all pion transitions involved only p-wave pions, then **X** would form part of the algebra of $SU(4)$, and the mass matrix would behave as the sum of a 1- and a 20-dimensional representation of $SU(4)$; if s-wave transitions are allowed, then the algebra must be enlarged to at least $SO(7)$.

Hadrons classified by chiral multiplets

Strategy

- Chiral symmetry is spontaneously broken, but not very badly.
- Baryons are classified by chiral multiplets.
- Broken symmetry is taken care of by their mixing.

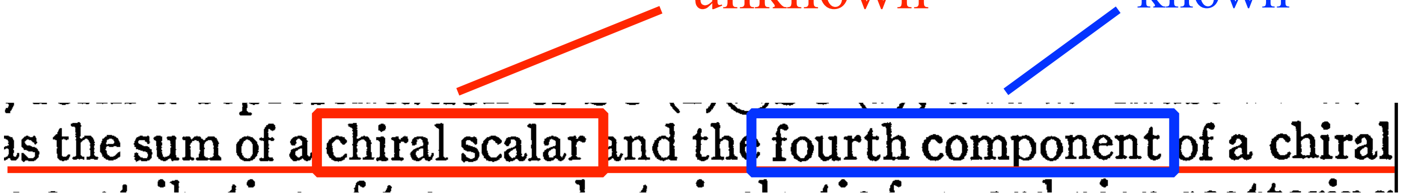
Models of chiral baryons

B. W. Lee, Chiral Dynamics (Gordon and Breach, New York, 1972)
C. DeTar and T. Kunihiro, Phys. Rev. D 39 (1989), 2805
D. Jido, M. Oka and A. Hosaka, Prog. Theor. Phys. 106 (2001), 873

→ For N and N^* of mirror baryons

Two mass generation mechanisms; $m_0 \sim \langle G^2 \rangle$ and $f_\pi \sim \langle \bar{q}q \rangle$

unknown known



as the sum of a chiral scalar and the fourth component of a chiral

Chiral multiplets/representations

Various structures encoded in (higher) dimension $SU(2)_L \times SU(2)_R$

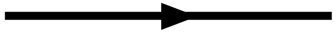
$(d_L, d_R) \sim$ dimension of $SU(2)_{L,R}$; isospin group for u, d quarks

Elementary spin 1/2 fermion:

$\psi = \psi_l + \psi_r$ left (l) and right (r) helicity components

$= (2,0) + (0,2)$ 2 corresponds to isospin ↑, ↓

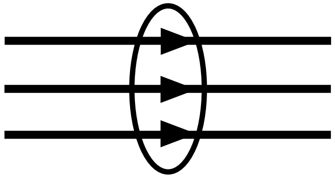
This applies to the elementary quarks



Composite spin 1/2 fermion
qqq baryons:

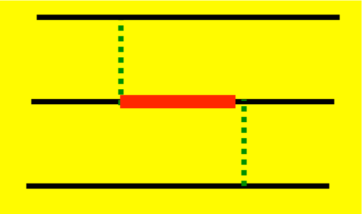
$$[(2,0) + (0,2)]^3$$

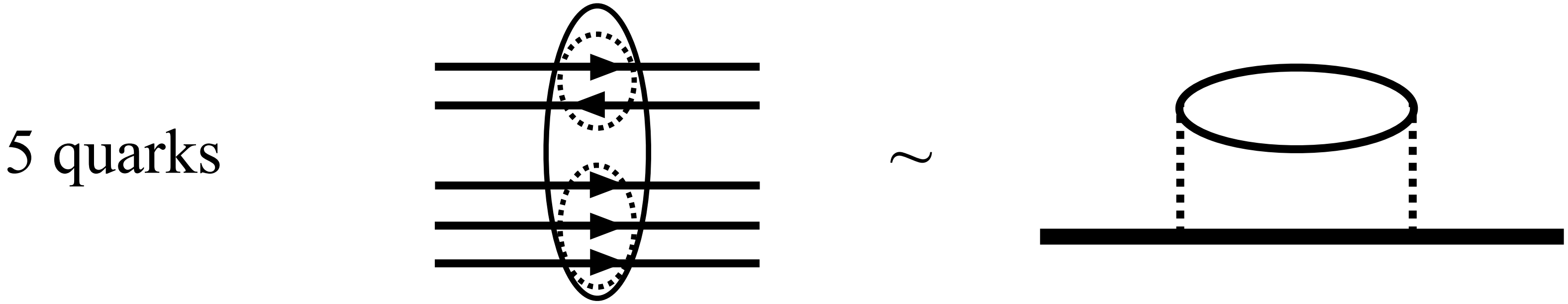
$$\sim \underbrace{[(2,0) + (0,2)]}_{N} + \underbrace{[(3,2) + (2,3)]}_{\Delta} + [(4,1) + (1,4)]$$



Resonances ~ **Composite spin 1/2 fermion**

Multiquarks; $qqqq\bar{q}$ or qqq+ meson clouds





$$[(2,0)+(0,2)]^{5} \sim qqqq\bar{q}$$

$$[(2,0)+(0,2)]^{3} + (1/2,1/2) \sim qqq + \text{meson}$$

$$\sim \underset{N}{[(2,0)+(0,2)]} + \underset{\substack{\text{Mirror}\\ N^*}}{[(0,2)+(2,0)]} + \underset{\Delta}{[(3,2),(2,3)]} + \underset{\substack{\text{Mirror}\\ \Delta^*}}{[(2,3),(3,3)]} + \cdots$$

With meson cloud, or multi quark components, higher dimensional multiplets are possible => Chiral baryon models.

Application to neutron stars for m_0

Motohiro, Kim, Harada, PRC92, 025201 (2015)
Minamikawa, Kojo, Harada, PRC103, 045205 (2021)
Gao, Yuan, Harada, Ma, PRC110, 045802 (2024)

Hybrid model of chiral mesons, baryons and NJL type quarks

N, N^*, π, σ, ρ, ω q, d(diquark)

Hadrons

$$\begin{aligned}
\mathcal{L}_N =& \bar\psi_{1r} i\gamma^\mu D_\mu \psi_{1r} + \bar\psi_{1l} i\gamma^\mu D_\mu \psi_{1l} \\
&+ \bar\psi_{2r} i\gamma^\mu D_\mu \psi_{2r} + \bar\psi_{2l} i\gamma^\mu D_\mu \psi_{2l} \\
&- m_0[\bar\psi_{1l}\psi_{2r} - \bar\psi_{1r}\psi_{2l} - \bar\psi_{2l}\psi_{1r} + \bar\psi_{2r}\psi_{1l}] \\
&- g_1\sigma[\bar\psi_{1r} U^\dagger \psi_{1l} + \bar\psi_{1l} U \psi_{1r}] \\
&- g_2\sigma[\bar\psi_{2r} U \psi_{2l} + \bar\psi_{2l} U^\dagger \psi_{2r}] \\
&- a_{\rho NN}[\bar\psi_{1l}\gamma^\mu(\xi_L^\dagger \hat\alpha_{\parallel\mu}\xi_L)\psi_{1l} + \bar\psi_{1r}\gamma^\mu(\xi_R^\dagger \hat\alpha_{\parallel\mu}\xi_R)\psi_{1r}] \\
&- a_{\rho NN}[\bar\psi_{2l}\gamma^\mu(\xi_R^\dagger \hat\alpha_{\parallel\mu}\xi_R)\psi_{2l} + \bar\psi_{2r}\gamma^\mu(\xi_L^\dagger \hat\alpha_{\parallel\mu}\xi_L)\psi_{2r}] \\
&- a_{0NN}\,\mathrm{tr}[\hat\alpha_{\parallel\mu}]\,(\bar\psi_{1l}\gamma^\mu\psi_{1l} + \bar\psi_{1r}\gamma^\mu\psi_{1r} \\
&+ \bar\psi_{2l}\gamma^\mu\psi_{2l} + \bar\psi_{2r}\gamma^\mu\psi_{2r}). \qquad (2.22)
\end{aligned}$$

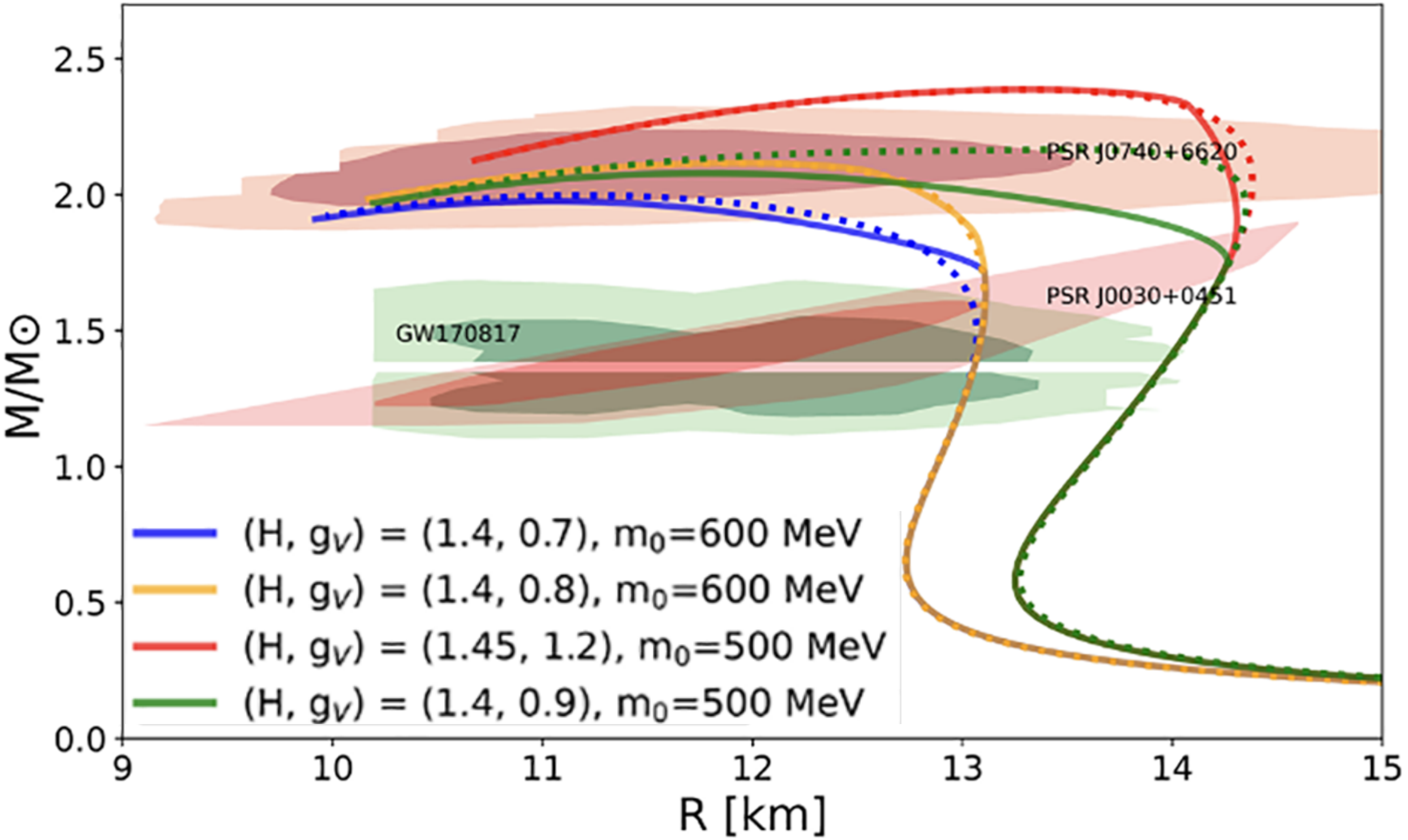
+

Quarks

$$\mathcal{L}_{\mathrm{CSC}} = \mathcal{L}_0 + \mathcal{L}_\sigma + \mathcal{L}_{\mathrm{d}} + \mathcal{L}_{\mathrm{KMT}} + \mathcal{L}_{\mathrm{vec}}$$

$$\begin{aligned}
\mathcal{L}_0 &= \bar q(i\gamma^\mu\partial_\mu - \hat m_q + \gamma_\mu \hat A^\mu)q, \\
\mathcal{L}_\sigma &= G\sum_{A=0}^{8}[(\bar q\tau_A q)^2 + (\bar q i\gamma_5\tau_A q)^2], \\
\mathcal{L}_{\mathrm{d}} &= H\sum_{A,B=2,5,7}[(\bar q\tau_A\lambda_B C\bar q^t)(q^t C\tau_A\lambda_B q) \\
&\quad + (\bar q i\gamma_5\tau_A\lambda_B C\bar q^t)(q^t C i\gamma_5\tau_A\lambda_B q)], \\
\mathcal{L}_{\mathrm{KMT}} &= -K[\det_f \bar q(1-\gamma_5)q + \det_f \bar q(1+\gamma_5)q] \\
\mathcal{L}_{\mathrm{vec}} &= -g_V(\bar q\gamma^\mu q)(\bar q\gamma_\mu q),
\end{aligned}$$

MR plot


2.5
2.0
1.5
1.0
0.5
0.0
M/M⊙
9
10
11
12
13
14
15
R [km]
PSR J0740+6620
PSR J0030+0451
GW170817
(H, g_V) = (1.4, 0.7), m_0=600 MeV
(H, g_V) = (1.4, 0.8), m_0=600 MeV
(H, g_V) = (1.45, 1.2), m_0=500 MeV
(H, g_V) = (1.4, 0.9), m_0=500 MeV

Summary

- Hadrons (resonances) show various structures

  Quark (compact) originated
  Hadron (extended) originated ~ would affect more matter properties

- Resonances are relevant for dense matter ~ origin of many-body force

•. ϕ meson couples to nucleon resonance around 2 GeV

- Chiral symmetry restoration can be studied by chiral multiplets
- Higher dimensional multiplets ~ resonances with multi quarks

  would-be degenerate set

- Chiral baryon scheme → Another mass generation mechanism m_0
- Neutron stars may shed light on elementary questions of QCD