Уравнение состояния нейтронной материи в модели Составного кваркового мешка

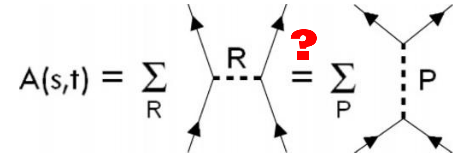
М.И. Криворученко
ИТЭФ, Москва

M.I.K., Phys. Rev. C, 82, 018201 (2010)
M.I.K., Phys. Rev. C, 84, 015206 (2011)
М.И.К., Письма в ЭЧАЯ (2017), в печати.

- Аналитичность и унитарность в модели СКМ
- КДД полюса, ассоциированные с примитивами Джаффе-Лоу
- Конверсия «примитив-резонанс» и узкие дибарионы
- Сверхпроводимость, EoS нейтронной материи

Семинар БЛТФ, ОИЯИ
Дубна, 14 июня 2017

INTRODUCTION



NN INTERACTION MODELS:

t-channel vs. s-channel

Exchange of $\bar{q}q$-mesons

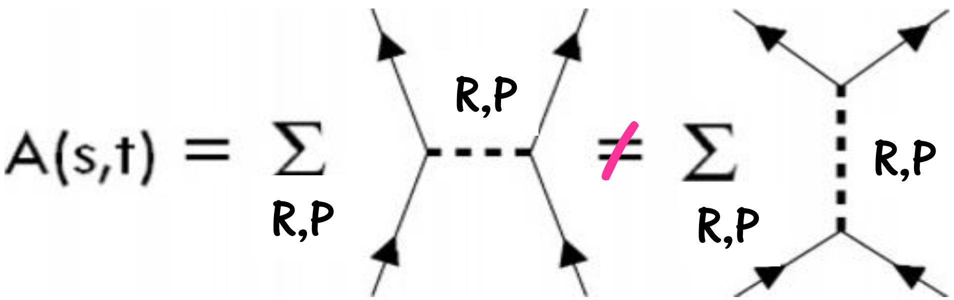
Yukawa mechanism

95% of the market

Lee-Dyson model,

QCB model:

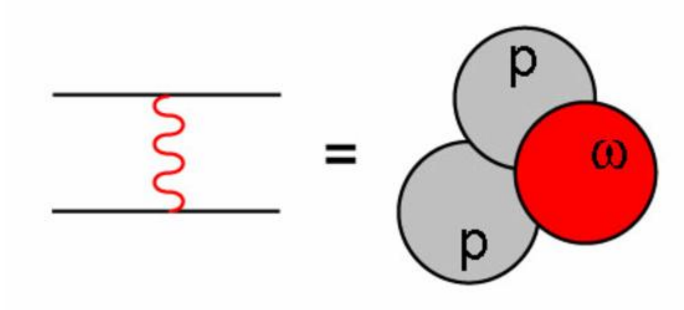
Exchange of 6q-primitives



These two mechanisms may appear **mutually exclusive** or **dual** to each other.

Motivation for an *s*-channel NN interaction model

NO FREE SPACE in nuclei
for *t*-channel meson exchange:



The sphere of radius *r* is empty, the nearest neighbor is located in $dV = 4\pi\, r^2 dr$

Poisson law:

$$p_k = \frac{\overline{n}^k}{k!} e^{-\overline{n}},$$
$$\overline{n} = \rho V.$$

HOLZMARK DISTRIBUTION:

$$dw = \exp(-\rho V)\,\rho dV$$

Motivation for an *s*-channel NN interaction model

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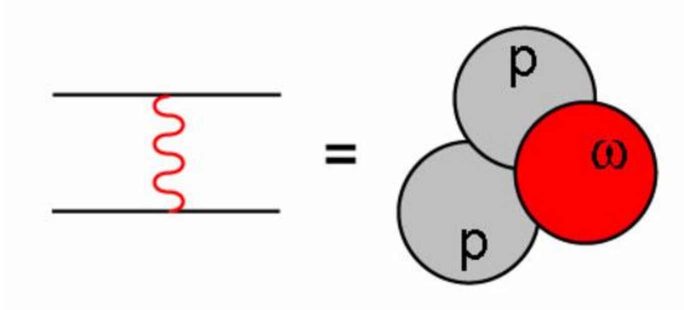

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$$\mathrm{E}[r] \pm (\mathrm{Var}[r])^{1/2} = \begin{cases} \mathbf{1.02 \pm 0.37}\ \mathrm{fm}, & \text{without correlations}, \\ \mathbf{1.18 \pm 0.31}\ \mathrm{fm}, & \text{with correlations}. \end{cases}$$

$$\langle r^2 \rangle_p^{1/2} = 0.8750 \pm 0.0068\,\mathrm{fm}, \quad \langle r^2 \rangle_\pi^{1/2} = 0.659 \pm 0.025\ \mathrm{fm}$$

Motivation for an *s*-channel NN interaction model

Neutron stars with mass $2M_\odot$ are observed

P. B. Demorest et al., Nature **467**, 1081 (2010).
J. Antoniadis et al., Science **340**, 448 (2013).

- Soft EoS of *t*-channel OBE models are excluded,

in particular

- pion/kaon condensate EoS
- Reid soft core model
  for NN interaction potential
- All earlier hyperon EoS

S. L. Shapiro and S. A. Teukolsky, Black Holes, White Dwarfs, and Neutron Stars, (Cornell U., N. Y., 1983)

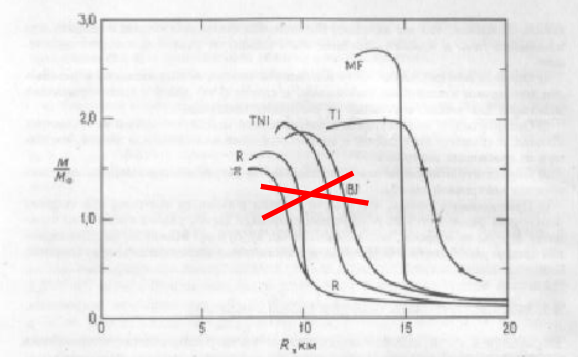


Рис. 9.3. Гравитационная масса как функция радиуса для тех же уравнений состояния, что и на рис. 9.2 [52].

HYPERONS EFFECT ON MASSES OF NEUTRON STARS

At high density the production of hyperons becomes energetically favorable:

V. A. Ambartsumyan and G. S. Saakyan, Astron. Zh. 37, 193 (1960).

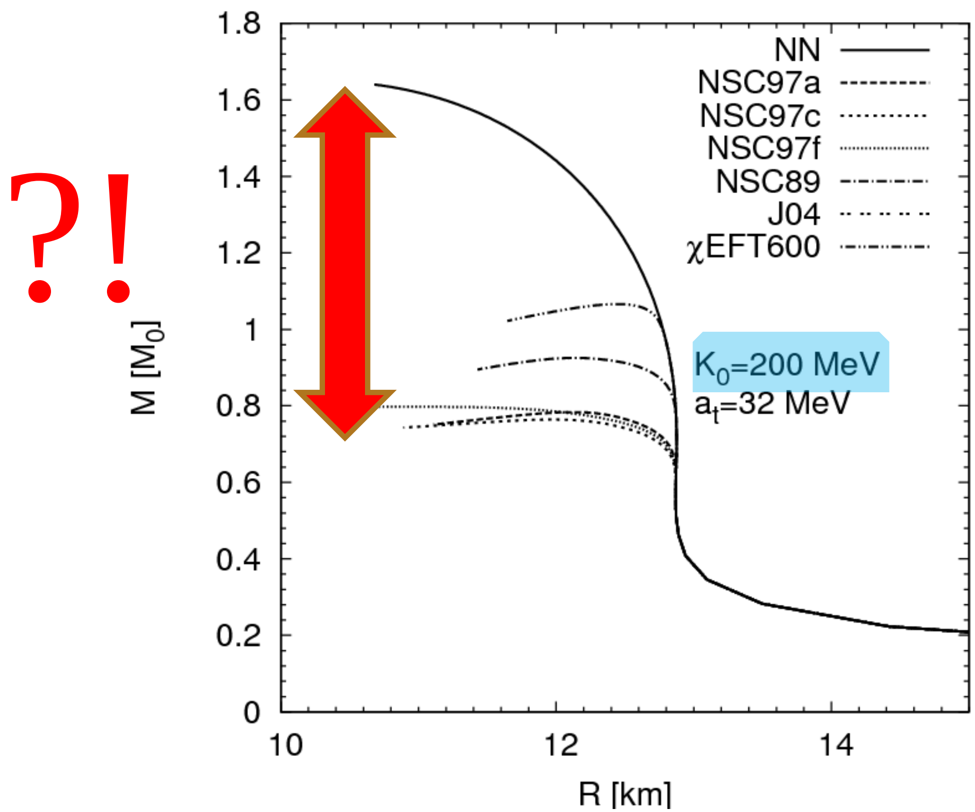
In the EoS based on the Reid soft core model, the inclusion of hyperons drops the maximum mass of neutron stars from 1.6 $M_\odot$ down to 1.4 $M_\odot$.

V. R. Pandharipande, R. A. Smith, Nucl. Phys. A237, 507 (1975).

HYPERONS EFFECT ON MASSES OF NEUTRON STARS

DBHF model with hyperons from:

H. Djapo, B.-J. Schaefer and J. Wambach, Phys. Rev. C81, 035803 (2010)

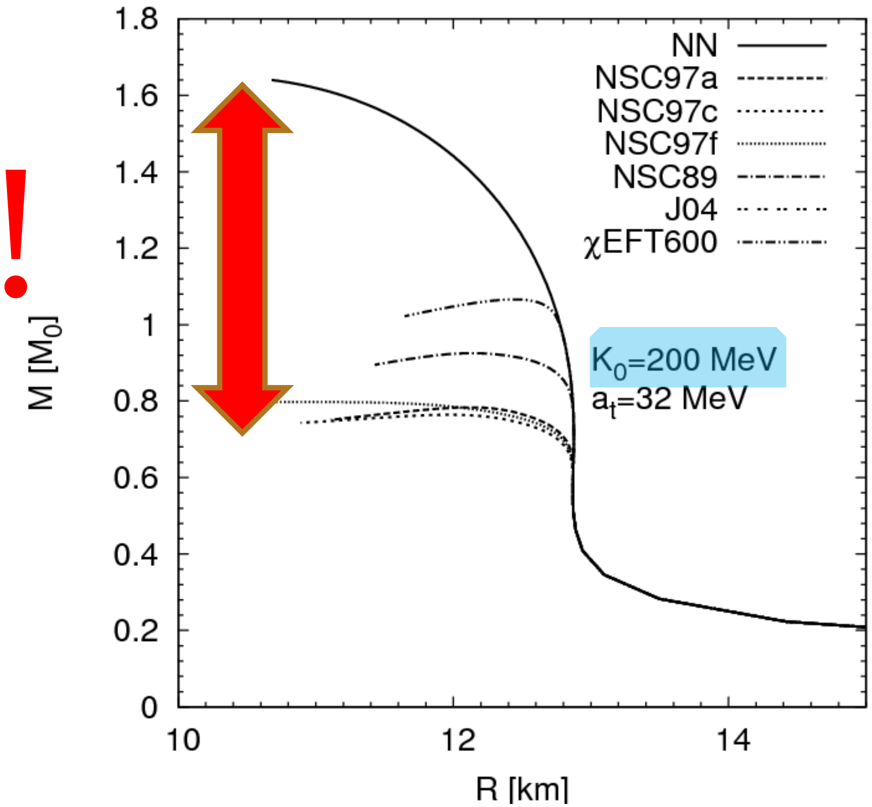


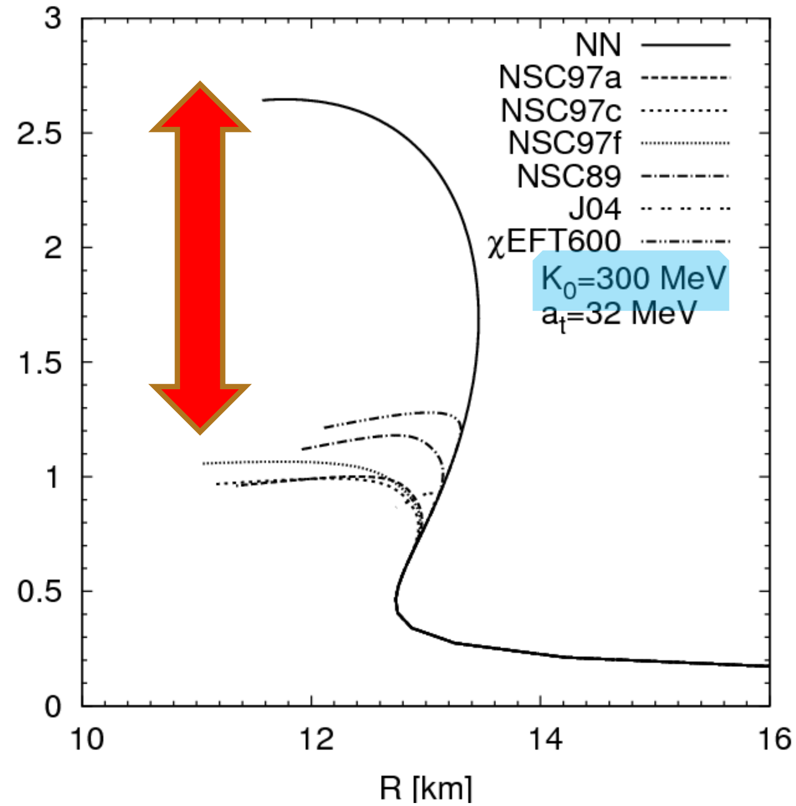
HYPERONS EFFECT ON MASSES OF NEUTRON STARS

DBHF model with hyperons from:

H. Djapo, B.-J. Schaefer and J. Wambach, Phys. Rev. C81, 035803 (2010)

?!





Possible reasons of low masses of the hyperon stars:

1. Inadequacy of OBE models of nuclear matter at high densities
2. Poor knowledge of the interaction forces between hyperons
3. Missing contribution of new exotic particles - WILBs

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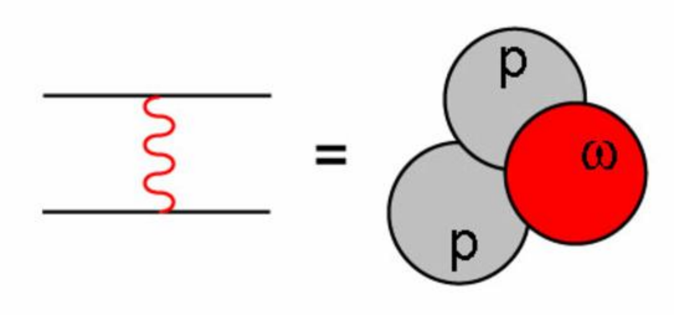

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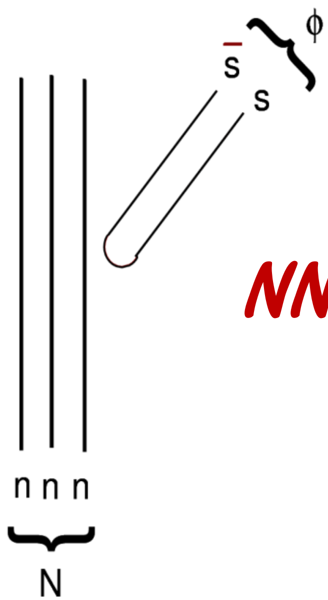
$\phi(1020)$-meson subjected to the OZI rule

is appropriate to make a stiff EoS



$NN\phi$ coupling is small

$HH\phi$ coupling is large

more repulsion

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A quantitative analysis of the $\phi(1020)$-meson role

R. Lastowiecki, D. Blaschke, H. Grigorian and S. Typel, Acta Phys. Polon. Supp. 5, 535 (2012)

S. Weissenborn, D. Chatterjee, and J. Schaffner-Bielich, Phys. Rev. C 85, 065802 (2012)

confirmed our conjecture about its influence on EoS

M.I.K., F. Simkovic, Amand Faessler, Phys. Rev. D 79, 125023 (2009).

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The effect of a vector boson on the energy density:

$$E_I = \frac{1}{2}\int d\mathbf{x}_1 d\mathbf{x}_2 \rho \frac{g^2}{4\pi r} e^{-\mu r} \rho = V \frac{g^2 \rho^2}{2\mu^2}.$$

Vector WILBs cf. ω-mesons

$$\frac{g^2}{\mu^2} \approx \frac{g_\omega^2}{\mu_\omega^2} \approx 200\,\mathrm{GeV}^{-2}.$$

Scalar WILBs cf. σ-mesons

$$\frac{g^2}{\mu^2} \approx \frac{g_\sigma^2}{\mu_\sigma^2} \approx 300\,\mathrm{GeV}^{-2}.$$

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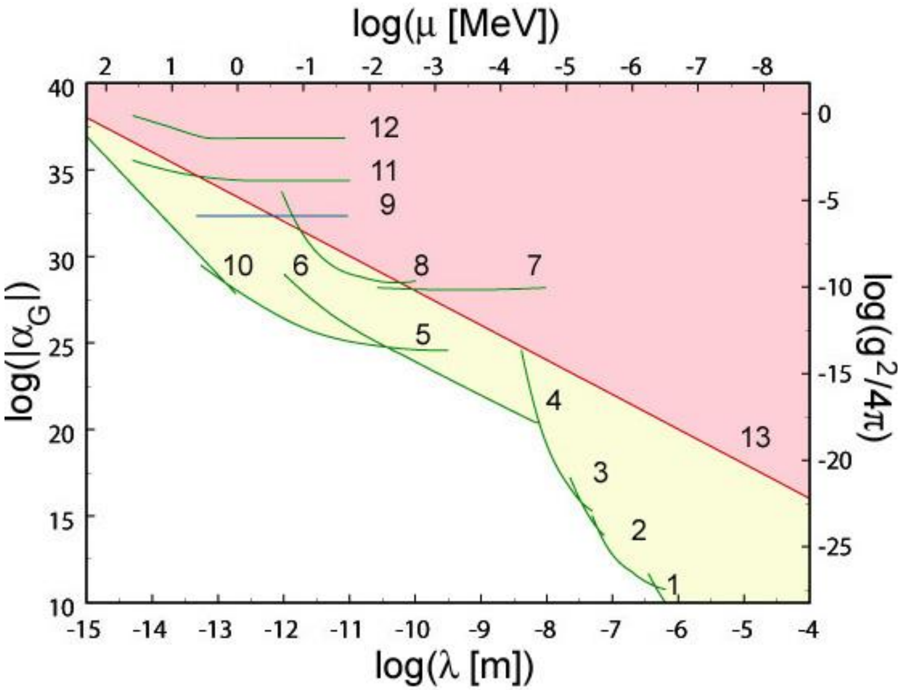
Constraints on the coupling strength with nucleons $g^2/(4\pi)$ and the mass μ (α_G and λ):



1 - S. K. Lamoreaux, Phys. Rev. Lett. 78, 5 (1997).

2 - R. S. Decca et al., Phys. Rev. Lett. 94, 240401 (2005).

3 - V. M. Mostepanenko et al., J. Phys. A41, 164054 (2008).

4 - M. Bordag et al., Phys. Lett. A187, 35 (1994).

5, 10 - Yu. N. Pokotilovski, Phys. Atom. Nucl. 69, 924 (2006), R. Barbieri, T. E. O. Ericson, Phys. Lett. B57, 270 (1975)

6 - V. V. Nesvizhevsky, G. Pignol, K. V. Protasov, Phys. Rev. D77, 034020 (2008).

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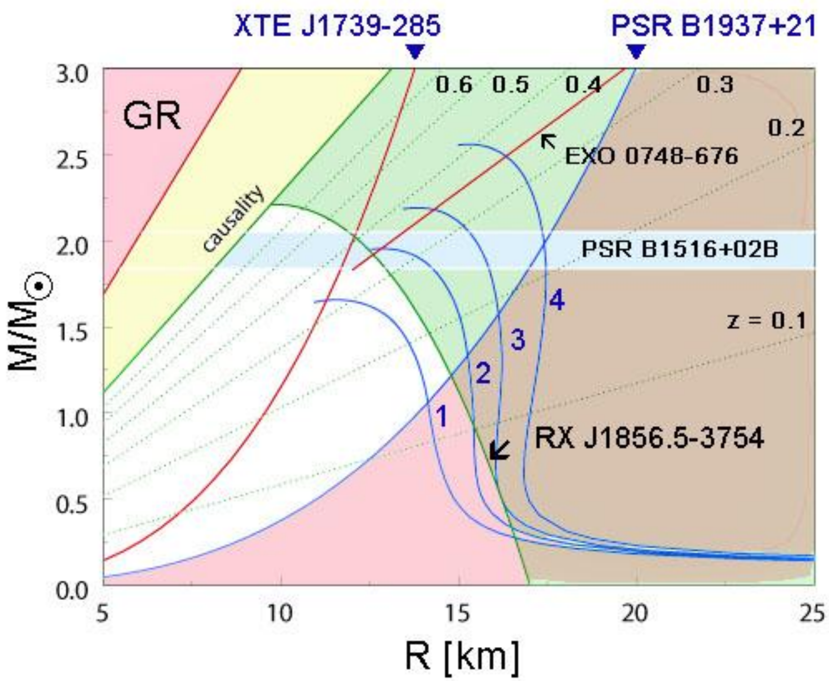

Neutron stars with WILBs:

D. H. Wen, B. A. Li, and L. W. Chen, PRL 103, 211102 (2009).

M.I.K., F. Simkovic, A. Faessler, PRD 79, 125023 (2009).

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What about EoS in *s*-channel exchange models?

Remark about exotic states of nuclear matter:

Vol 441|29 June 2006|doi:10.1038/nature04858 nature

LETTERS

Soft equations of state for neutron-star matter ruled out by EXO 0748−676

F. Özel[1]

precision[2]. Here I report a determination of the mass and radius of the neutron star EXO 0748−676 that appears to rule out all the soft equations of state of neutron-star matter. If this object is typical, then condensates[2] and unconfined quarks[1] do not exist in the centres of neutron stars.

In MF new degrees of freedom soften EoS

Beyond MF this is not true:

Amand Faessler, A.J. Buchmann, M.I.K., Phys. Rev. C 56, 1576 (1997)

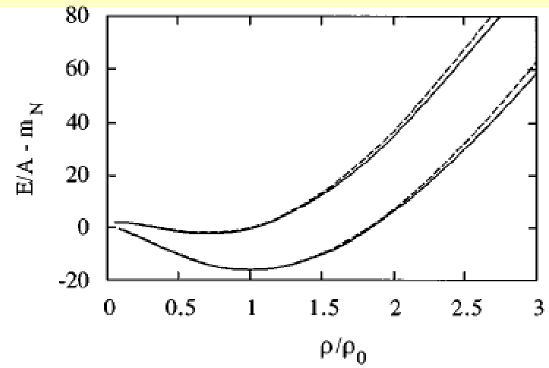
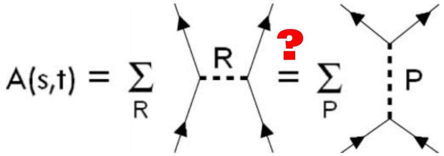


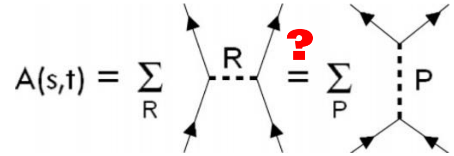
FIG. 2. Saturation curve for nuclear matter in the RHA: without dibaryons (solid line) and with the inclusion of H dibaryons (dashed line) for $h_\sigma/(2g_\sigma)=0.6$.

INTRODUCTION



What about EoS in *s*-channel exchange models?

INTRODUCTION - HISTORY



- Analyticity and unitarity for amplitudes lead to the Low scattering equation

  Low (1955)

- CDD poles as ambiguities in solutions to the Low scattering equation - Castillejo, Dalitz, Dyson (1956)

Д. В. ШИРКОВ, В. В. СЕРЕБРЯКОВ, В. А. МЕЩЕРЯКОВ

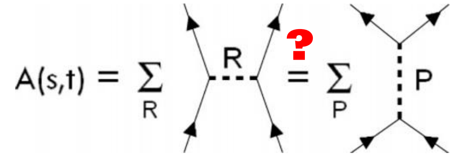
ДИСПЕРСИОННЫЕ ТЕОРИИ
СИЛЬНЫХ ВЗАИМОДЕЙСТВИЙ
ПРИ НИЗКИХ ЭНЕРГИЯХ

12.1. Модель Дайсона. Физический смысл членов КДД.

- To clarify the physical meaning of the CDD poles, Dyson constructed a model that demonstrates the relationship of the CDD poles to bound states and resonances

  Dyson (1957)

INTRODUCTION - HISTORY



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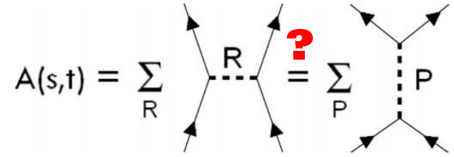

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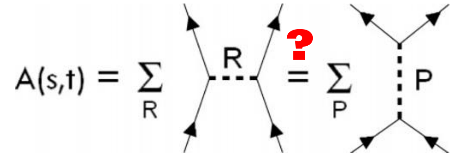
  Dyson (1957)

Lee-Dyson model
is a model for systems
with ATTRACTION

where is
REPULSION?

INTRODUCTION - HISTORY



- P matrix method for identifying exotic multiquark states with **PRIMITIVES** «элементарный»

that appear as poles of the P matrix

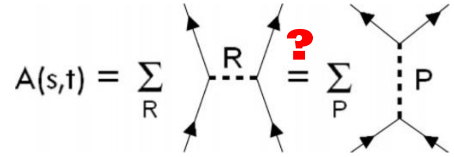
$$P = kb\cot[kb + \delta(s)]$$

rather than the S matrix:

$$S = e^{2i\delta(s)} = \frac{D(s - i0)}{D(s + i0)}$$

Jaffe and Low (1979)

INTRODUCTION - HISTORY



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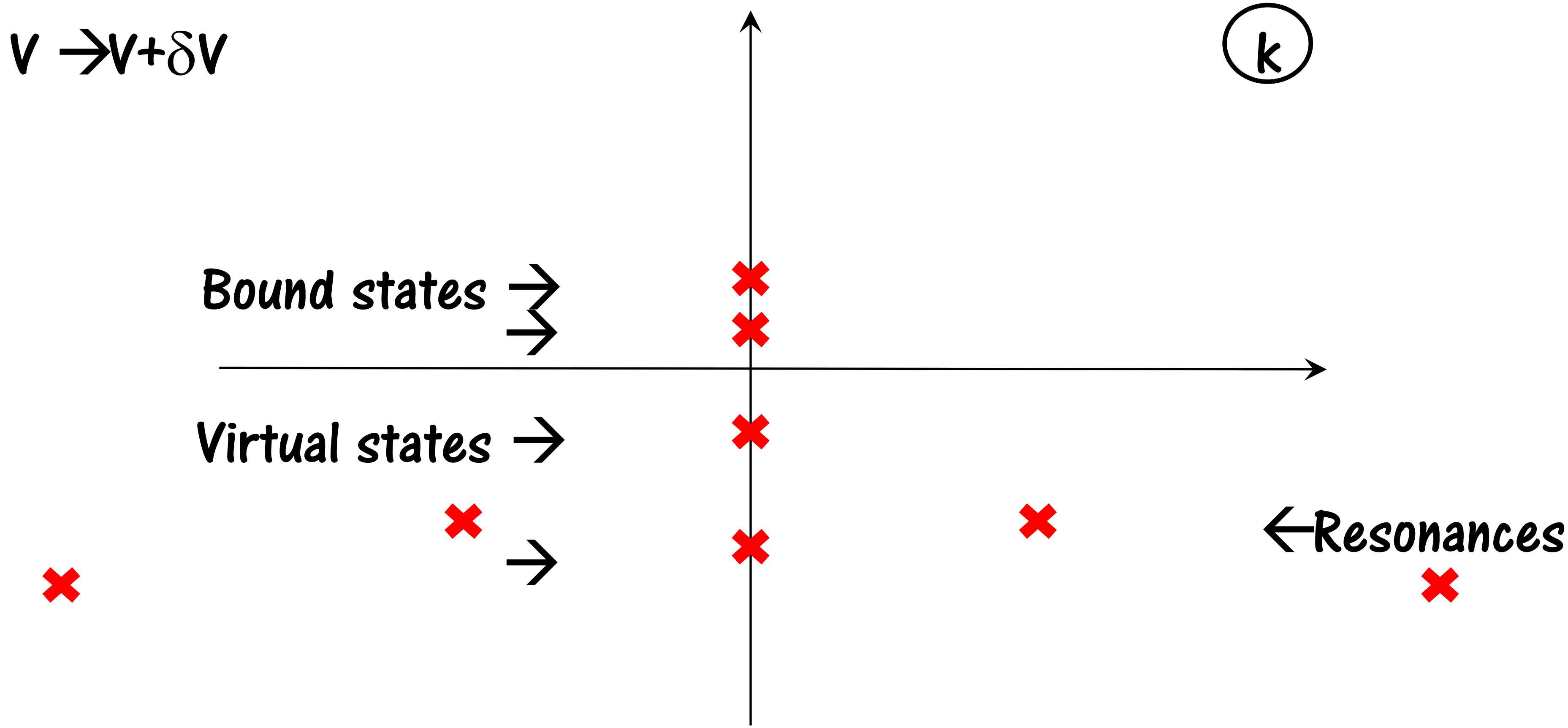
Physical meaning of primitives?

S-matrix poles in t- and s-channel exchange models

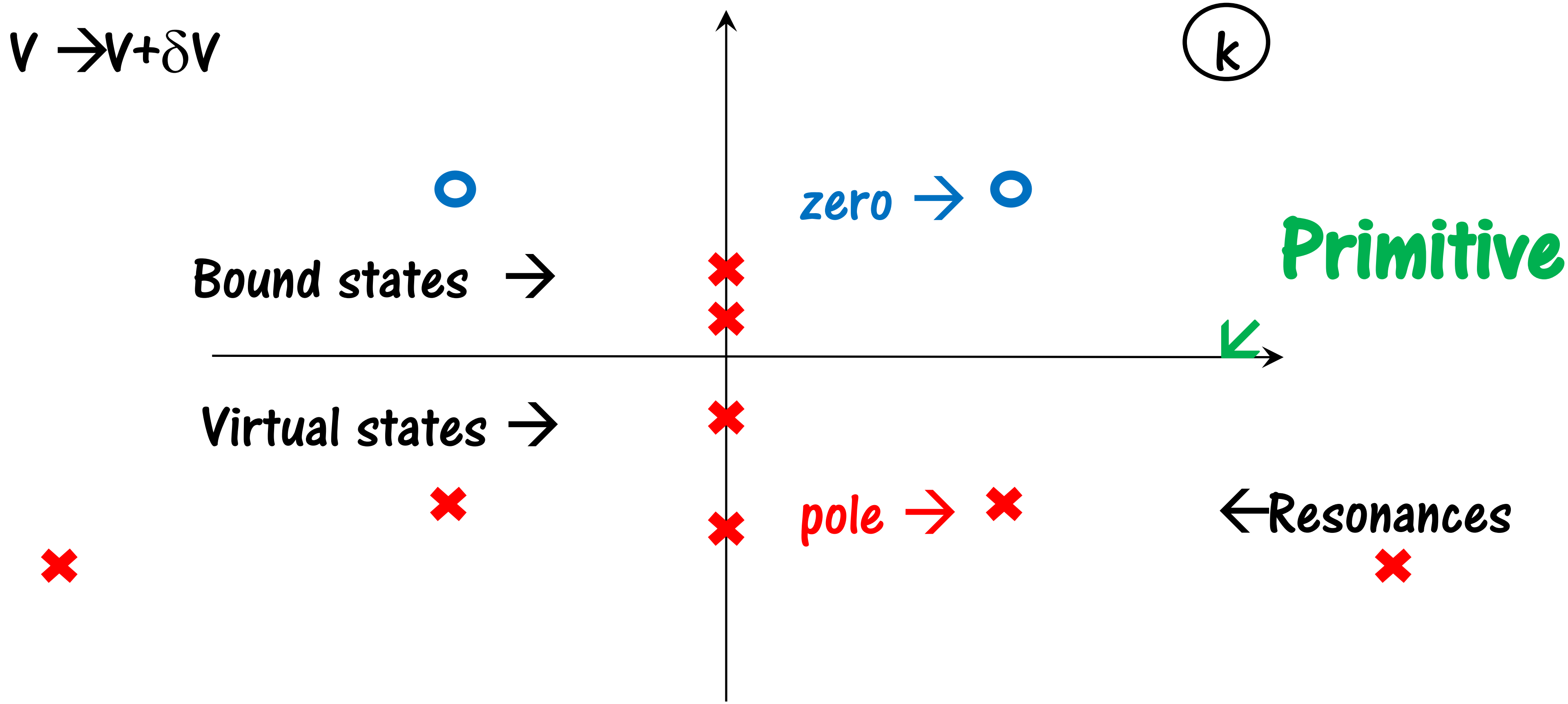


Bound states - Virtual states - Resonances conversion

e.g. Hydrogen atom in electric field

Increased $g_{\pi NN}$ in the pp $^1S_0$ channel

S-matrix poles and zeros in s-channel exchange model

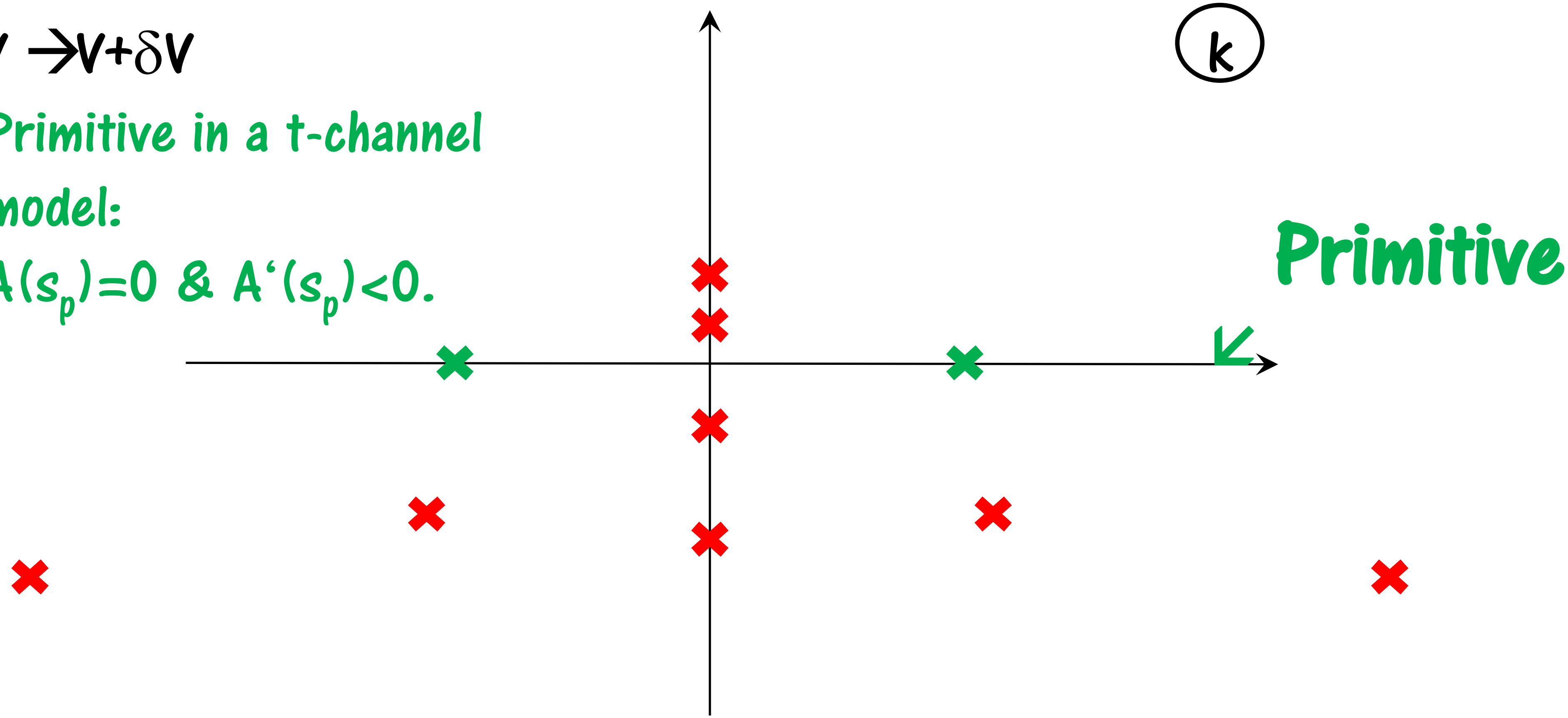


S-matrix poles, zeros and a primitive in a t-channel exchange model

$V \to V + \delta V$

Primitive in a t-channel model:

$A(s_p)=0$ & $A'(s_p)<0$.



The same old Bound states- Virtual states- Resonances conversion

but primitives do not mix ..

P matrix method for identifying exotic multiquark states with

primitives

that appear as poles of the P matrix rather than the S matrix:

Jaffe and Low (1979)

Dyson-Lee model

CDD poles ⟷ resonances, bound states, primitives

resonances, bound states } attraction

primitives } repulsion

QCB model

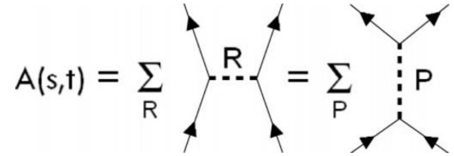
A dynamical model of the P matrix was developed and applied to the description of NN scattering

Simonov (1981)

CDD poles correspond to resonances, bound states, and primitives

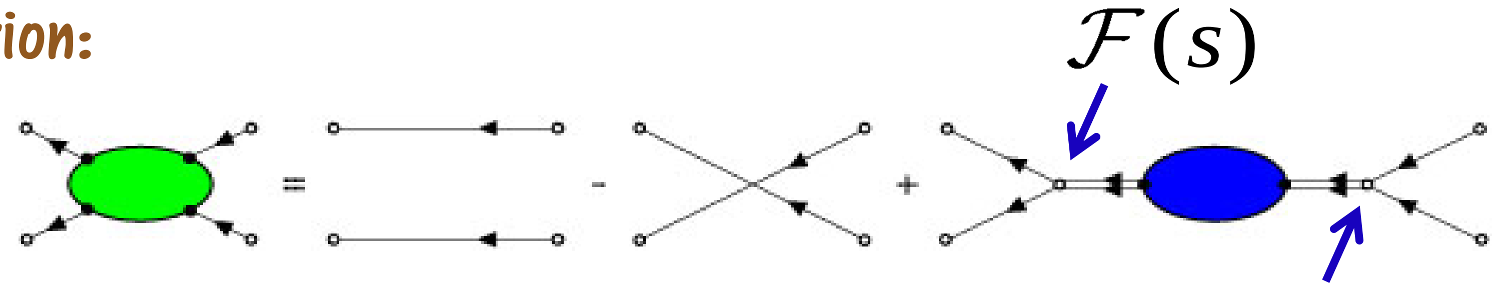
M.I.K. Phys. Rev. C 82, 018201 (2010)

QCB model through diagrams

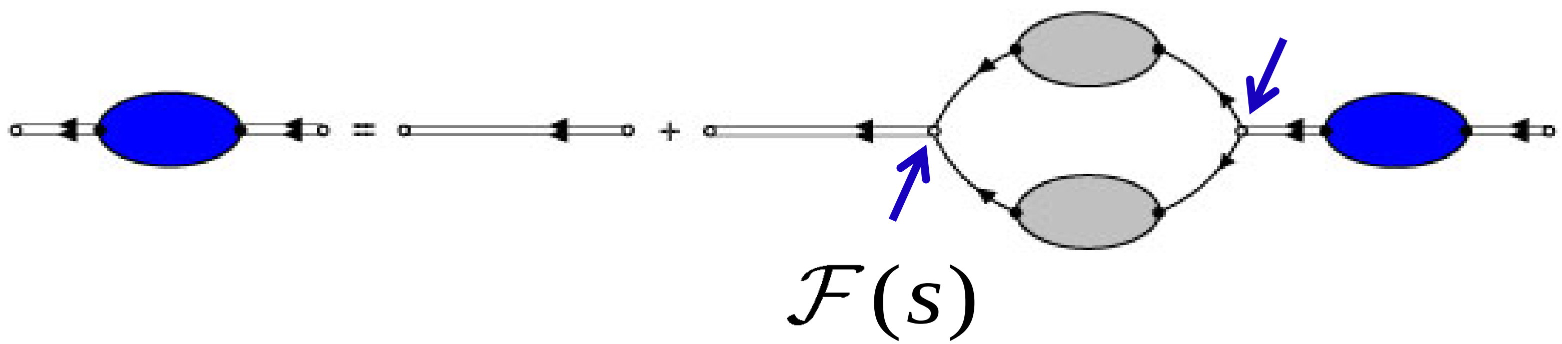


Two-body SCATTERING:

The 2-body Green's function:

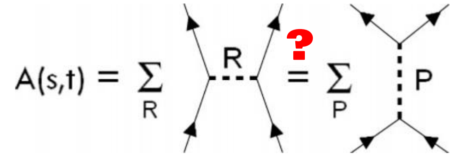


Compound state propagator:



Analyticity = Yes, elastic unitarity = Yes, crossing symmetry = No

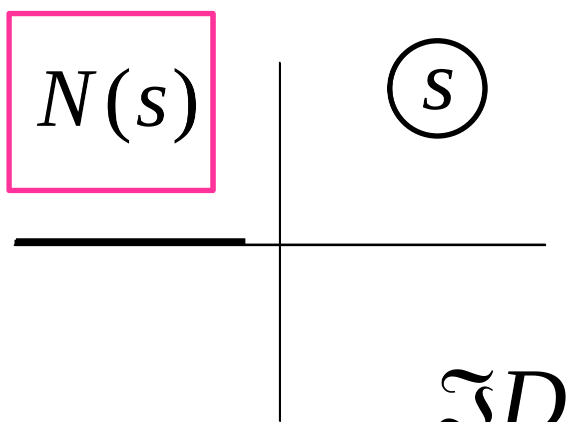
QCB model through diagrams

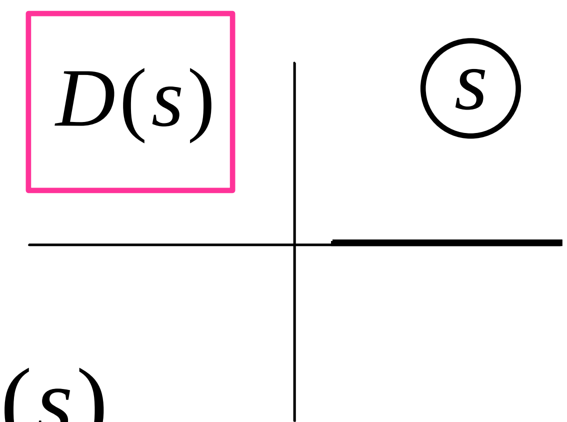


One starts from the scattering of two particles, e.g., a nucleon and a pion. A nucleon can absorb a pion and can turn into an excited compound state.

The scattering amplitude

$$A(s) \equiv e^{i\delta(s)} \sin\delta(s) = \frac{N(s)}{D(s)}.$$

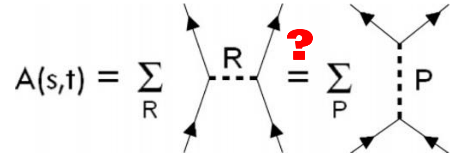




$$\Im D(s) = -N(s)$$

from unitarity

QCB model through diagrams



D function of the process: $\sim s - M^2 + iM\Gamma$

$$D(s) = \Lambda(s) - \Pi(s),$$

where, in the relativistic {tg} notations,

The poles of $\Lambda(s)$ are the CDD poles

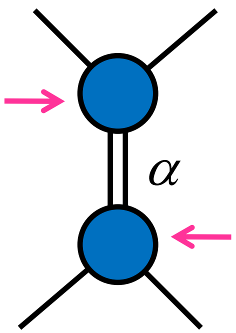
$$\Lambda^{-1}(s) = \sum_{\alpha} \frac{g_{\alpha}^{2}}{s - M_{\alpha}^{2}},$$

{ctg}

$\rightarrow$ **Masses of compound states**

$$\Pi(s) = \frac{1}{\pi} \int_{s_0}^{+\infty} \frac{N(s')}{s' - s} ds',$$

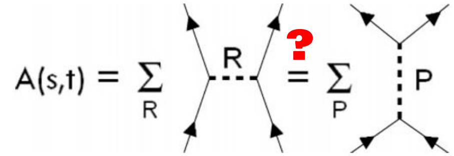
$\sim$ **form factor** $\rightarrow$



$$N(s) = -\Phi_2(s)\mathcal{F}^2(s).$$

$\sim$ **phase space**

QCB model through diagrams



The D function constructed in such a way is the generalized R function. The S matrix has the form

$$\boxed{S = e^{2i\delta(s)} = \frac{D(s-i0)}{D(s+i0)}.}$$

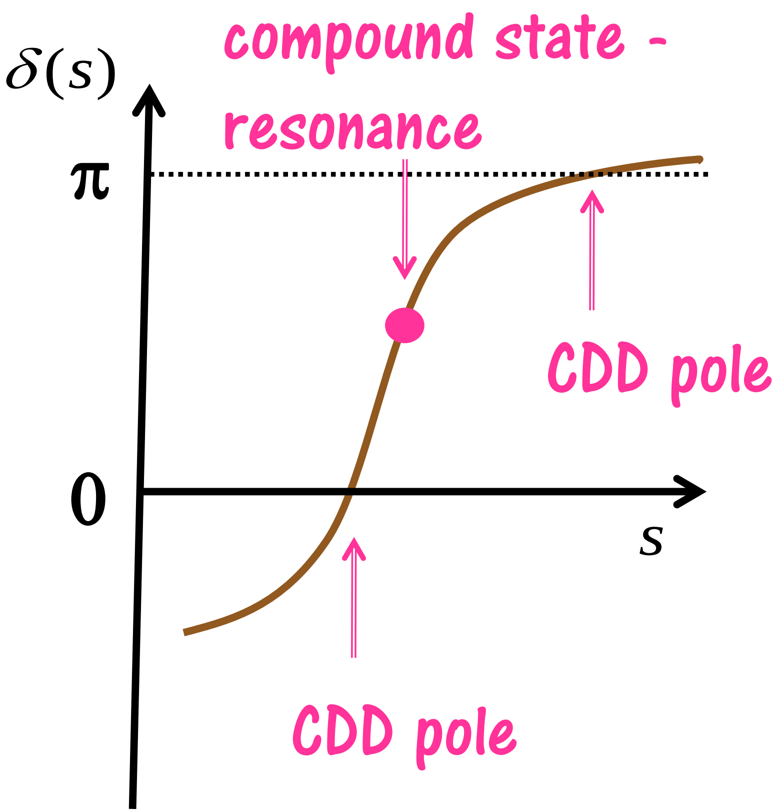
At the CDD poles $s = s_\gamma$

$$\delta(s) = 0 \bmod(\pi),$$

the slope of the phase is positive. By expanding the D function around $s = s_\gamma$, one finds

$$\delta(s_\gamma)' = \underbrace{-\Im D(s_\gamma)}_{>0}\overbrace{\Lambda^{-1}(s_\gamma)'}^{<0} > 0.$$

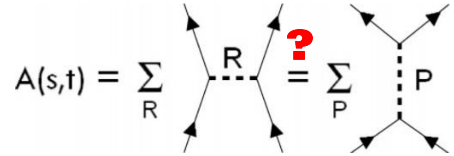
The Dyson model applies to systems with attraction where scattering phase shifts increase with increasing energy



Resonances drive the phase shift up

CDD pole = zero phase with a positive slope

QCB model through diagrams



The nucleon-nucleon phase shifts, conversely, decrease with increasing energy and provide evidence for a repulsion.

Low (1955)

Castillejo, Dalitz, Dyson (1956)

Dyson (1957)

$$\Im D(s) > 0$$

attraction

Simonov (1981)

$$\Im D(s) \geq 0$$

attraction & repulsion

$$\exists s_p : \quad \mathcal{F}(s_p) = 0$$

$$\Im D(s) = \Phi_2(s) \mathcal{F}^2(s)$$

If $D(s_p) = 0$ for real $s_p \in (s_0, +\infty)$, the phase crosses the level

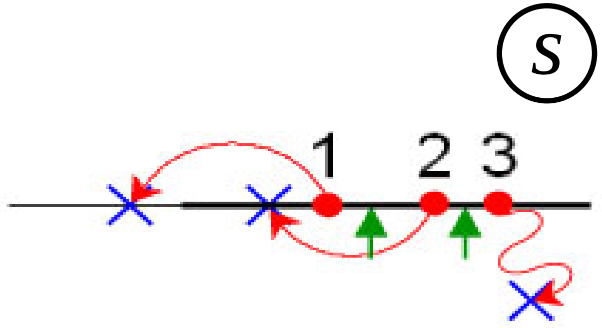
$$\delta(s) = 0 \bmod(\pi),$$

with a negative slope. This can be verified by expanding $D(s)$ around s_p:

$$\delta(s_p)' = -\frac{\Im D(s_p)''}{2\Re D(s_p)'} < 0.$$

In potential scattering, a negative slope of the phase shift is associated with a repulsion

D-FUNCTION ZEROS IN THE COMPLEX s-PLANE

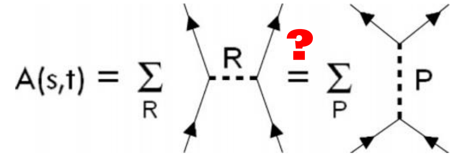


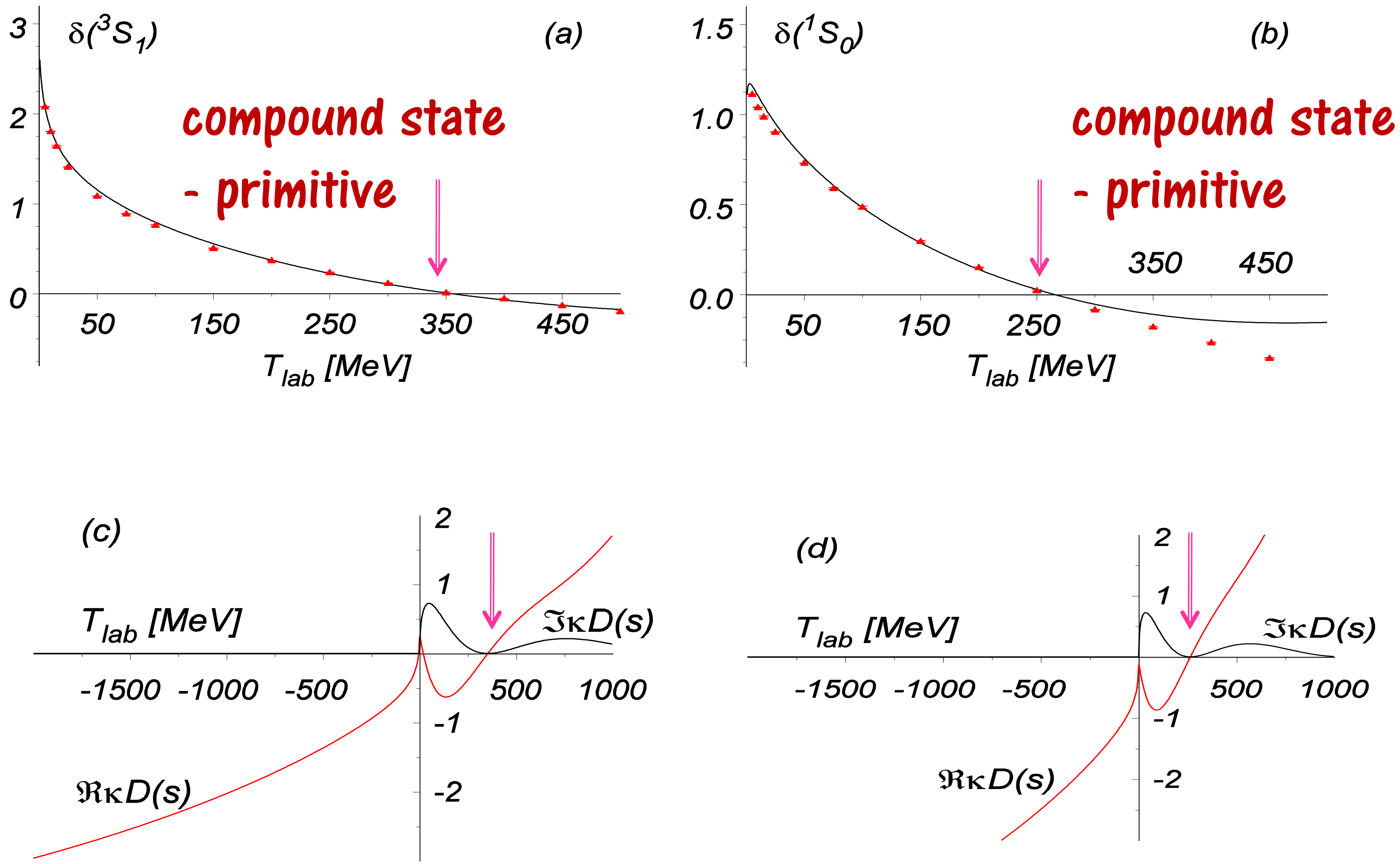
Compound states 1, 2, and 3 move to new positions:
bound state, primitive, and resonance.

A pair of the CDD poles that squeezes compound state 2 of the primitive type is shown by arrows.

QCB model applies to systems with attraction and repulsion

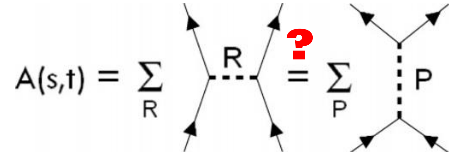
NN scattering S-wave phase shifts and D functions versus the proton kinetic energy

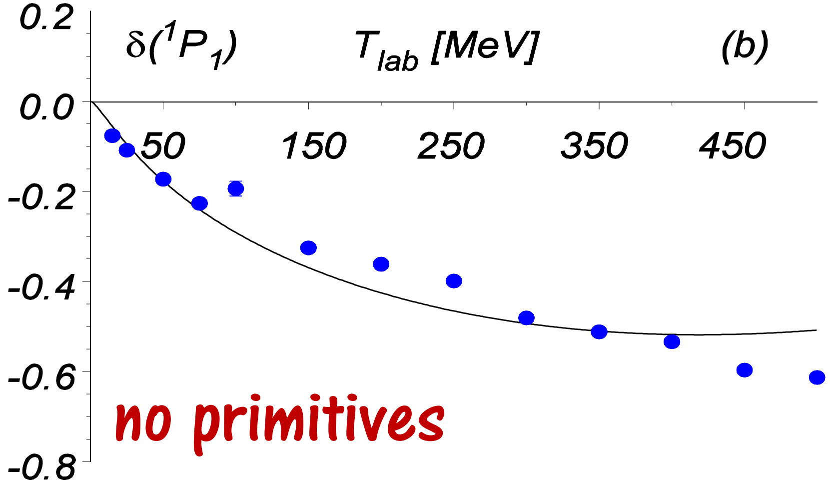


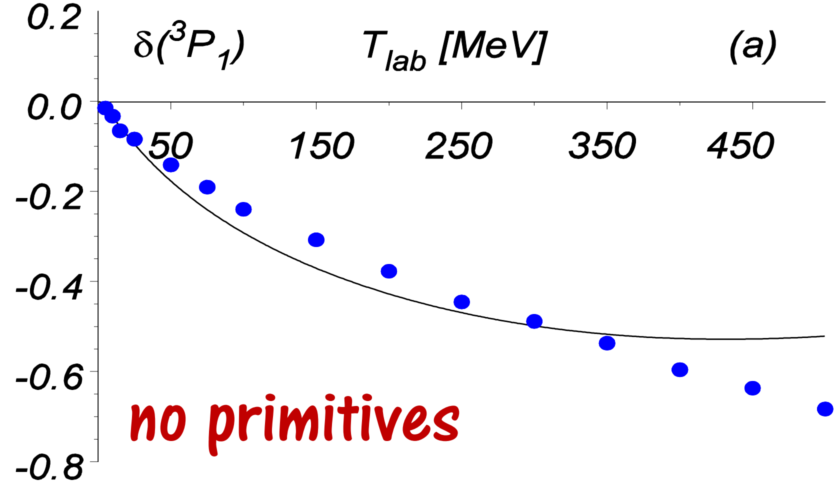


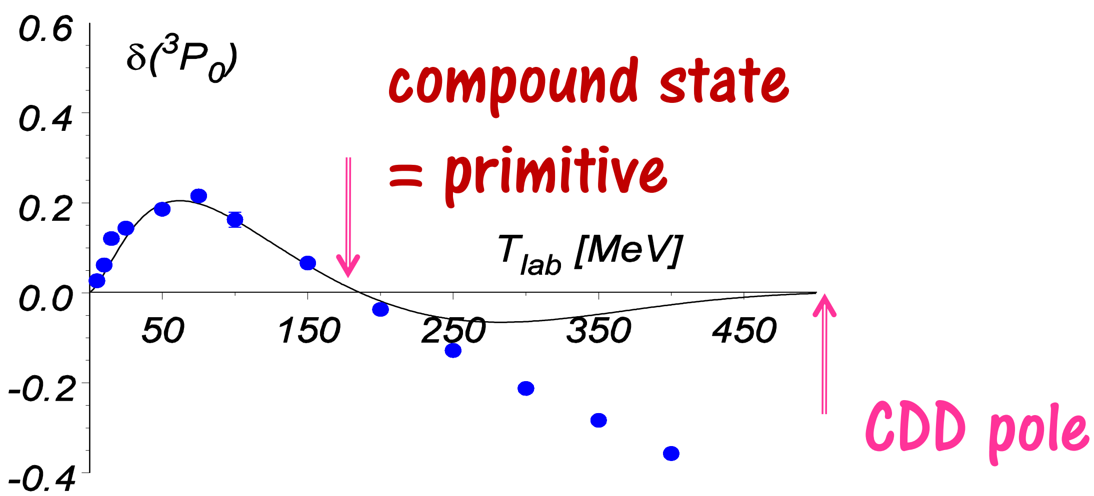
M.I.K., Phys. Rev. C 82, 018201 (2010)

NN scattering P-wave phase shifts versus the proton kinetic energy



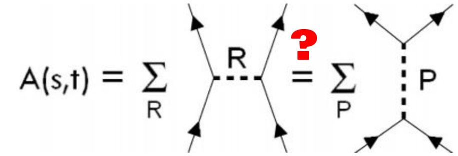






M.I.K., D.K. Nadyozhin, T.L. Rasinkova, Yu.A. Simonov, M.A. Trusov, and A.V. Yudin, Phys. At. Nucl. 74, 371 (2011)

The generalized Low scattering equation



The scattering amplitude

$$A(s) \equiv e^{i\delta(s)} \sin\delta(s) = -\frac{\Phi_2(s)\mathcal{F}^2(s)}{D(s)}$$

obeys the generalized Low scattering equation

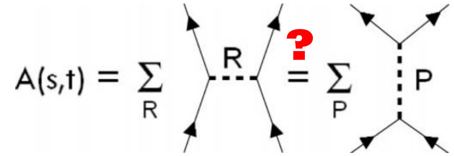
$$\frac{A(s)}{\Phi_2(s)\mathcal{F}^2(s)} = \frac{1}{\pi}\int_{s_0}^{+\infty} \frac{|A(s')|^2}{\Phi_2(s')\mathcal{F}^2(s')} \frac{ds'}{s'-s}$$

$$-\sum_b \frac{C_b}{s-s_b} - \sum_p \frac{C_p}{s-s_p} - C$$

NEW

$s_b < s_0 < s_p$

(Intermediate) Summary



- The CDD poles are related to **bound states**, **resonances**, and **primitives**.

- New primitive-type CDD poles occur

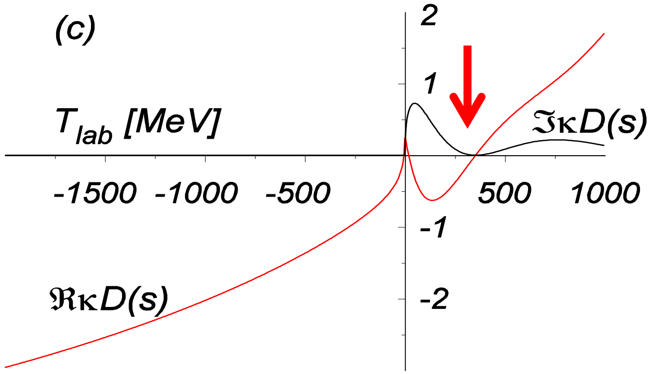
- In the $^3S_1$, $^1S_0$ and $^3P_0$ NN channels,

the CDD poles at M = 3203, 2916, and 2650 MeV are associated with the **primitives** at 2047, 2006, and 1969 MeV, respectively.

of our interest -- **how to detect it?**

QCB model for strong & electromagnetic interactions

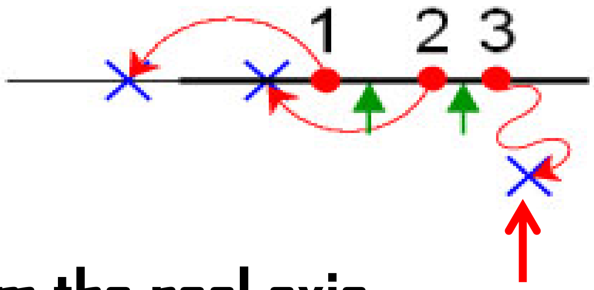
ASSUMING THAT IN THE BARE STRONG INTERACTION
i.e. FOR $\alpha = 1/137 \rightarrow 0$ THE ROOT OF EQUATION



$$D(s) = 0$$

LIES ON THE REAL AXIS:

FIND THE EFFECT OF $\alpha = 1/137 \neq 0$



The root of D(s) will move away from the real axis,

TURNING PRIMITIVE TO A RESONANCE

QCB model for strong & electromagnetic interactions

D function

A(s) = N(s)/D(s) & ImD(s) = - N(s)

$$D(s) = \Lambda(s) - \Pi(s),$$

with

$$\Lambda^{-1}(s) = \sum_{\beta} \frac{g_{\beta}^{2}}{s - M_{\beta}^{2}} + f,$$

→ 4-fermion interaction

$$\Pi(s) = -\frac{1}{\pi}\int_{s_0}^{+\infty} \Phi_2(s') \frac{\mathcal{F}^2(s')}{s' - s} ds'.$$

In the pp channel the form factor is modified:

$$\mathcal{F}(s) = \left(\frac{s}{s_0}\right)^{1/4} \frac{\sin(kb)}{kb} C_0(s),$$

where $C_0(s)$ is the Gamow-Sommerfeld factor

$$C_0^2(k) = \frac{2\pi\eta}{\exp(2\pi\eta) - 1}, \quad \text{with} \quad \eta = \frac{\alpha\mu}{k}.$$

QCB model for strong & electromagnetic interactions

The dispersion integral can be evaluated to give

$$\kappa\Pi(s) = \frac{1}{2k^2b}\Big(2\mathrm{Si}(2kb)\sin(2kb)+(\mathrm{Ci}(2kb)+\mathrm{Ci}(-2kb))\cos(2kb)-2C-\ln(-4k^2b^2)\Big)$$
$$-\frac{\sin(kb)}{kb}e^{ikb}\left(C_0^2(k)+\frac{\pi}{k}\right)+\sum_{n=1}^{\infty}\frac{\sinh(b/n)}{b/n}e^{-b/n}\frac{2}{1+k^2n^2},$$

where $\kappa = 2mb/\pi$ in units $\alpha\mu = 1$.

$\Lambda^{-1}(s)$ has a single pole corresponding to a 6q-compound state

$$\kappa^{-1}\Lambda^{-1}(s) = c_p\left(\frac{r_p}{s-M^2}-\frac{r_p}{s_0-M^2}\right)-\frac{1}{\gamma},$$

with

$$\kappa c_p r_p = g_1^2, \quad r_p = 8\pi^2/b^2, \quad c_p r_p = \xi\frac{M^2-s_0}{\gamma}, \quad \xi \in (0,1).$$

coupling with continuum   residue of the free P matrix   analyticity of D funct.

QCB model for strong & electromagnetic interactions

In the pp channel, we use the series expansion around k = 0

Bethe (1949)

$$kC_0^2(s)\cot\delta(k) + 2h(k) = \frac{1}{a} + \frac{r}{2}k^2 + \ldots,$$

where h(k) is defined by

$$2\psi(1+\frac{i}{k}) + ik + \ln(-k^2) = 2h(k) + ikC_0^2(s).$$

γ is determined by the scattering length, the effective range is predicted:

$$\gamma = 1 \quad + \quad \frac{b}{a} + \left(\ln\left(4b^2\right) + 4C - 3\right)b - \sum_{m=2}^{\infty}(-1)^m \frac{2^{m+1}}{(m+1)!} b^m \zeta(m),$$

$$r = \frac{2}{3}(1+\gamma)b - \frac{8\gamma\xi}{b\left(M^2 - 4m^2\right)} - \frac{7}{9}b^2 + \sum_{m=2}^{\infty}(-1)^m \frac{2^{m+2}(m-1)(m+6)}{3(m+3)!} b^{m+1}\zeta(m).$$

In the $^1S_0$ np channel, we obtain r = 2.1 fm versus 2.8 fm in OBE models

The zeros of Im D(s) are the zeros of the phase shift and the zeros of the form factor

$$\mathcal{F}(s) = \left(\frac{s}{s_0}\right)^{1/4} \frac{\sin(kb)}{kb} C_0(s).$$

We thus find $k^*_0 = \pi/b_0$ and the primitive mass

$$M_0 = 2\sqrt{\pi^2 / b_0^2 + m_0^2}.$$

In the strong interaction + QED, the zero of D(s) is shifted due to:

1. $m_0 \rightarrow m = m_0 + \Delta m$ EM shift of the nucleon mass
2. $M_0 \rightarrow M = M_0 + \Delta M$ EM shift of the primitive mass
3. $b_0 \rightarrow b = b_0 + \Delta b$ EM shift of the interaction radius
4. The Coulomb interaction of the protons
5. The scattering length
6. g_1 is hard to control, $\Delta g_1 \rightarrow 0$.

Electromagnetic mass shifts (# 1,2)

Electromagnetic mass splitting of hadrons is attributed to
Coulomb interaction
& spin-spin interaction of quarks

$$\Delta\mathcal{M} = c < \sum_{i<j} e_i e_j > + h < \sum_{i<j} e_i e_j \sigma_i \sigma_j > .$$

In octet-baryon isomultiplets, accounting for the fixed mass difference of nonstrange quarks,

$c = 3.06$ MeV, $h = -1.35$ MeV,

according to J. L. Rosner, Phys. Rev. D 57, 4310 (1998).

1. $m_0 \to m = m_0 + \Delta m$
2. $M_0 \to M = M_0 + \Delta M$
3. $b_0 \to b = b_0 + \Delta b$
4. The Coulomb interaction of the protons
5. The scattering length
6. g_1 is hard to control, $\Delta g_1 \to 0$.

Average values of the spin-isospin operators and electromagnetic mass shifts of the proton, the neutron, and the 6q-compound states d*(2000) with isospin projections I = +1, 0, -1 (in MeV).

Hadron	I_3	$\langle \sum_{i<j} e_i e_j \rangle$	$\langle \sum_{i<j} e_i e_j \sigma_i \sigma_j \rangle$	$\Delta \mathcal{M}$	
p	$\frac{1}{2}$	0	$\frac{4}{3}$	-1.8	
n	$-\frac{1}{2}$	$-\frac{1}{3}$	1	-2.4	
d^{*++}	1	1	$-\frac{7}{5}$	5.0	pp
d^{*+}	0	$-\frac{1}{3}$	$\frac{19}{5}$	-6.2	np
d^{*0}	-1	$\frac{2}{3}$	$-\frac{2}{5}$	-1.5	nn

1. $m_0 \rightarrow m = m_0 + \Delta m$
2. $M_0 \rightarrow M = M_0 + \Delta M$
3. $b_0 \rightarrow b = b_0 + \Delta b$
4. The Coulomb interaction of the protons
5. The scattering length
6. g_1 is hard to control, $\Delta g_1 \rightarrow 0$.

Electromagnetic shift of the interaction radius (# 3)

The MIT bag model gives $b \sim R$ and $M \sim R^3$, where R is the radius of the 6-quark bag

$$\frac{\Delta b}{b} = \frac{\Delta M}{3M}.$$

1. $m_0 \rightarrow m = m_0 + \Delta m$
2. $M_0 \rightarrow M = M_0 + \Delta M$
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4. The Coulomb interaction of the protons
5. The scattering length
6. g_1 is hard to control, $\Delta g_1 \rightarrow 0$.

Scattering length (# 5) using heuristic arguments:

In the Born approximation,

$$f(\boldsymbol{q}) = -\frac{\mu}{2\pi}\int d\boldsymbol{x}e^{-i\boldsymbol{q}\boldsymbol{x}}U(\boldsymbol{x}).$$

The scattering length is proportional to the averaged interaction potential:

$$a = \lim_{\boldsymbol{q}\to 0} f(\boldsymbol{q}) = -\frac{\mu}{2\pi}\int d\boldsymbol{x}U(\boldsymbol{x}).$$

Isospin-dependent part of U(x) leads to a difference of scattering lengths in different isospin channels.

Isospin-dependent mass splitting of hadrons is also determined by averaging the electromagnetic potential, although of quarks rather than nucleons.

In any case, the equation

$$a = a_0 + C_2 \Delta M,$$

with $a_0 = 14.45$ fm and $C_2 = -1.45$ fm/MeV, gives scattering lengths

7.3 fm, 23.4 fm, and 16.6 fm

in the $I = +1, 0, -1$ channels, which agrees well with the empirical data.

1. $m_0 \rightarrow m = m_0 + \Delta m$
2. $M_0 \rightarrow M = M_0 + \Delta M$
3. $b_0 \rightarrow b = b_0 + \Delta b$
4. The Coulomb interaction of the protons
5. The scattering length
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$$7.3 \text{ fm}, 23.4 \text{ fm}, \text{and } 16.6 \text{ fm}$$

in the $I = +1, 0, -1$ channels, which agrees well with the empirical data.

#6: Coupling with the continuum

$$\Delta g_1 = 0 \text{ (not modified)}$$

1. $m_0 \rightarrow m = m_0 + \Delta m$
2. $M_0 \rightarrow M = M_0 + \Delta M$
3. $b_0 \rightarrow b = b_0 + \Delta b$
4. The Coulomb interaction of the protons
5. The scattering length
6. g_1 is hard to control, $\Delta g_1 \rightarrow 0$.

How to fix PARAMETERS:

The proton kinetic energy T_δ = 244 MeV → a vanishing phase shift. In the center-of-mass frame, the momentum of the protons

$$k_\delta = \sqrt{mT_\delta / 2}$$

and their total energy

$$M_\delta = \sqrt{2mT_\delta + 4m^2} = 1995 \text{ MeV}.$$

The phase shift vanishes provided that the imaginary part of the D function vanishes $k_\delta b = \pi$, so the interaction radius b is fixed.

The masses of the compound state M_0 and $M = M_0 + \Delta M \approx M_\delta$ are known, so we find the interaction radius b_0 with the electromagnetic interaction switched off with accuracy $O(\Delta M)$.

Summary TABLE

	Scattering length	Effective range	Interaction radius	Proton mass	Compound state mass	Prim/Resonance mass	Prim/Reso. width
α	a	r	b	m	M	M_*	Γ_*
0	14.45	2.22	1.829	940.1	1998.6	1998.6	0
1/137	6.50	0.84	1.831	938.3	2003.5	2000.5	0.260

The narrow resonance is associated with the complex root of the equation

$$D(M_*^2 - iM_*\Gamma_*) = 0.$$

A primitive root corresponding to $\Gamma_* = 0$ $\rightarrow$ bare strong interaction

A resonance with $\Gamma_* \neq 0$ occurs in the neighborhood of the primitive

$\rightarrow$ strong interaction + QED

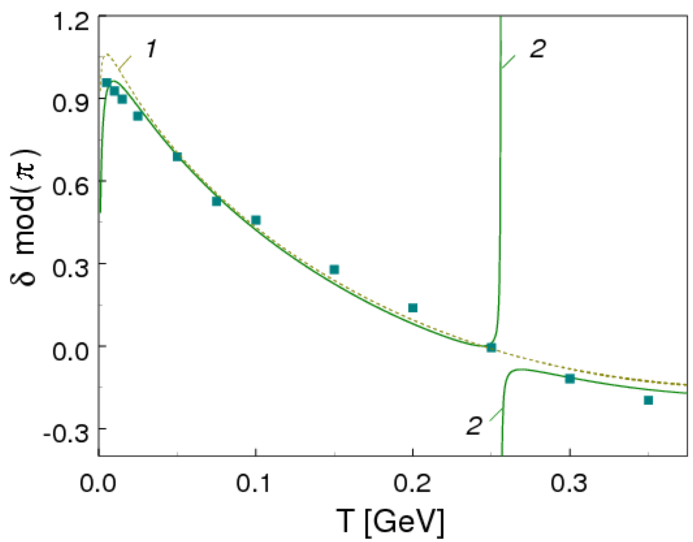
PRIMITIVE-TO-RESONANCE CONVERSION IN THE $^1S_0$ pp CHANNEL

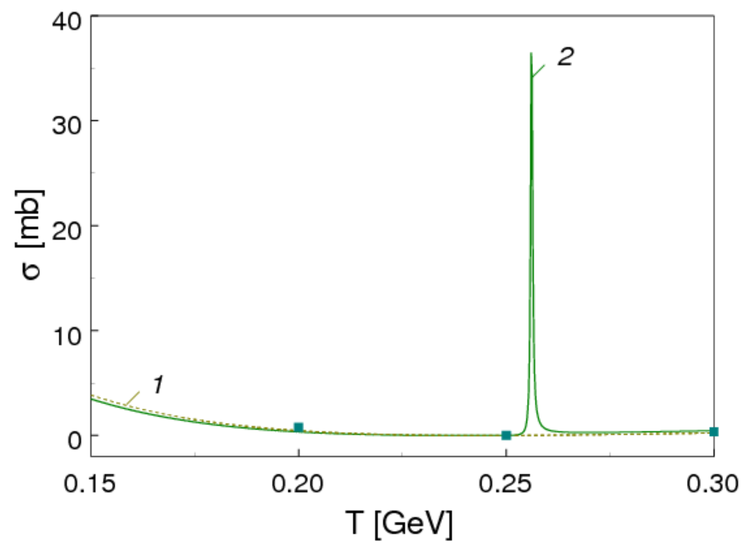
The narrow resonance is associated with the complex root of the equation

$$D(M_*^2 - iM_*\Gamma_*) = 0.$$

A primitive-type root corresponding to $\Gamma_* = 0$ → bare strong interaction

A resonance with $\Gamma_* \neq 0$ occurs in the neighborhood of the primitive → strong interaction + QED





M.I.K. Phys. Rev. C 84, 015206 (2011)

For an experimental search for narrow dibaryon resonances, **one should have a BEAM OF PROTONS**

- with a kinetic energy of $T \approx 250$ MeV and
- an energy spread below 100 keV

+ HYDROGEN TARGET

The energy resolution of the detector is not important, so one can use cheap scintillation detectors.

In the CELSIUS accelerator at Uppsala,

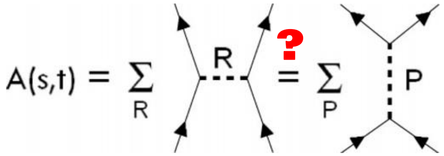
the beam momentum spread was a few times 10^{-3} before electron cooling

and a few times 10^{-5} after electron cooling.

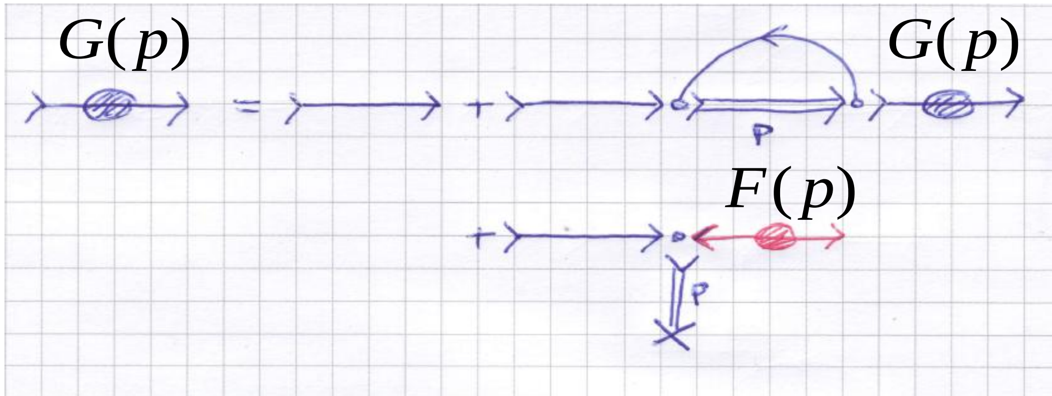
Under such conditions, it is possible to measure M with an accuracy of 10 keV or better.

- The narrow width of d*(2000) $\Gamma_* = 260$ keV is not an obstacle for its experimental search.

Neutrons pairing in QCB model

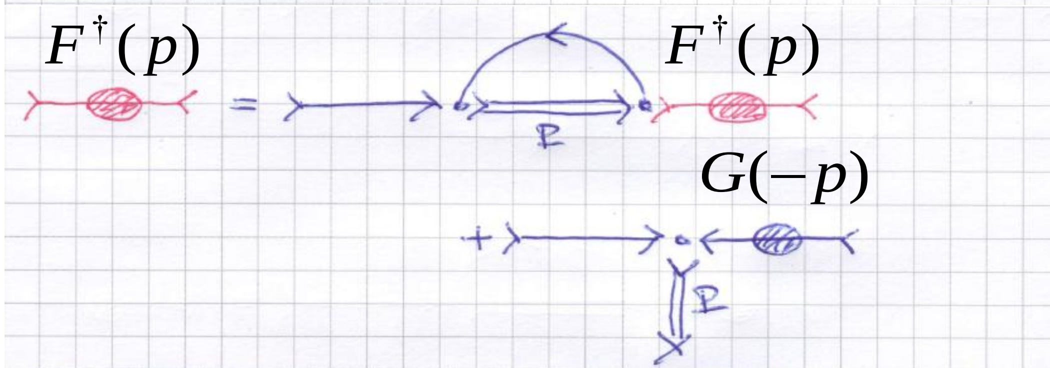


Уравнения Горькова-Элиашберга



⇒ **Green function**

NB: **очевидное сходство**
с сепарабельными моделями
NN **взаимодействий**



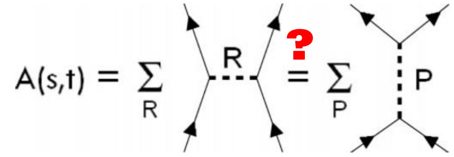
⇒ **anomalous**

Green function

GAP Equation:

$$1 = -\int \frac{d\boldsymbol{p}}{(2\pi)^3}\frac{2\pi^2}{E^2(\boldsymbol{p})}\mathcal{F}(\boldsymbol{p}^2)\Lambda^{-1}(s)\mathcal{F}(\boldsymbol{p}^2)\frac{1}{2\sqrt{(E(\boldsymbol{p})-\mu)^2+\Delta^2(s,\boldsymbol{p})}}\Bigg|_{s=4\mu^2}.$$

Neutrons pairing in QCB model



Gap

$$\Delta(4\mu^2, \boldsymbol{p}) = \frac{\sqrt{2\pi}}{E(\boldsymbol{p})} \mathcal{F}(\boldsymbol{p}^2) \Lambda^{-1}(4\mu^2) \, | \, \Xi \, | \, .$$

Condensate

$$i\Xi^* = \int \frac{d^4 p}{(2\pi)^4} \frac{\sqrt{2\pi}}{E(\boldsymbol{p})} \mathcal{F}(\boldsymbol{p}^2) F^{\dagger}(p),$$

- **Green function:**

$$\boxed{G(p) = \frac{u_{\boldsymbol{p}}^2}{\omega - \varepsilon(\boldsymbol{p}) + i0} + \frac{v_{\boldsymbol{p}}^2}{\omega + \varepsilon(\boldsymbol{p}) - i0},}$$

$$\begin{pmatrix} u_{\boldsymbol{p}}^2 \\ v_{\boldsymbol{p}}^2 \end{pmatrix} = \frac{1}{2}\left(1 \pm \frac{\eta_{\boldsymbol{p}}}{\varepsilon(\boldsymbol{p})}\right),$$

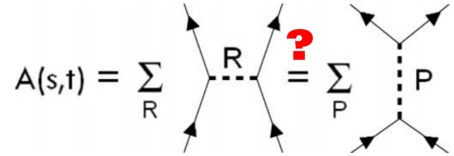
$$\varepsilon(\boldsymbol{p}) = \sqrt{\eta_{\boldsymbol{p}}^2 + \Delta^2(4\mu^2, \boldsymbol{p})}$$

$$\eta_{\boldsymbol{p}} = E(\boldsymbol{p}) - \mu$$

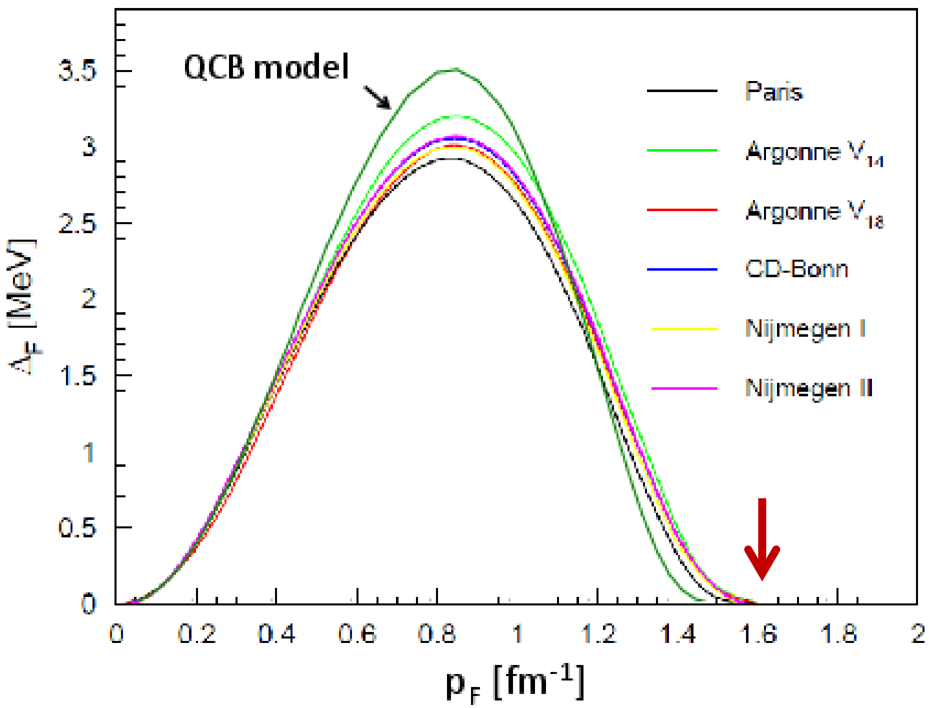
- **Anomalous Green function:**

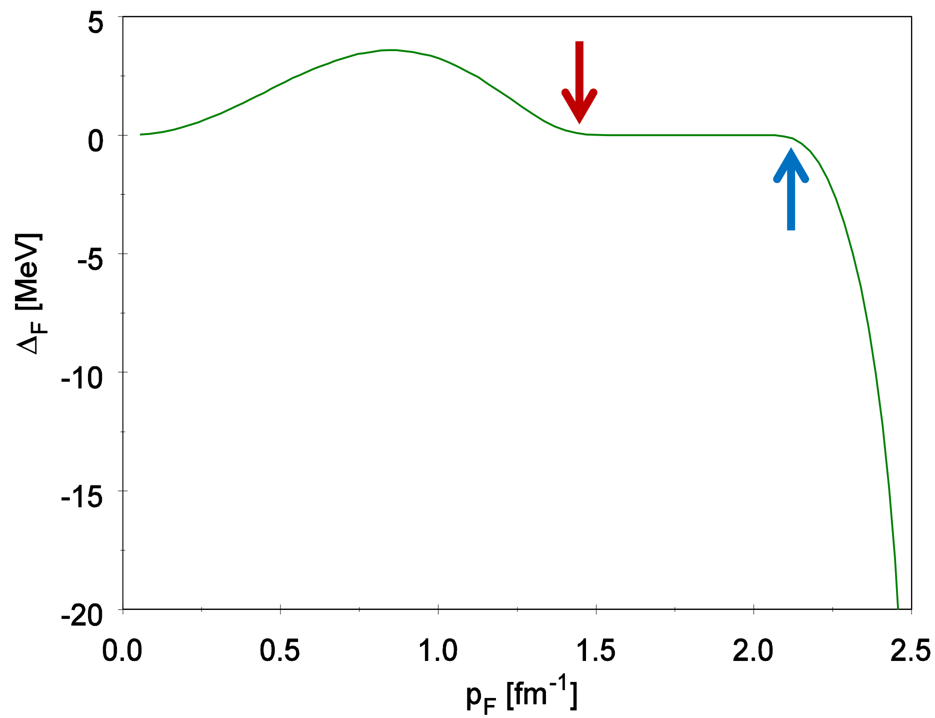
$$\boxed{F^{\dagger}(p) = -\frac{\sqrt{2\pi}}{E(\boldsymbol{p})} \mathcal{F}(\boldsymbol{p}^2) \Lambda^{-1}(4\mu^2) \frac{\Xi^*}{(\omega - \varepsilon(\boldsymbol{p}) + i0)(\omega + \varepsilon(\boldsymbol{p}) - i0)}}$$

Neutrons pairing in QCB model



Gap vs. p_F in QCB model





Plotted also are predictions
of *t*-channel exchange OBE models
Paris, Argonne (2), CD-Bonn, Nijmegen (2)

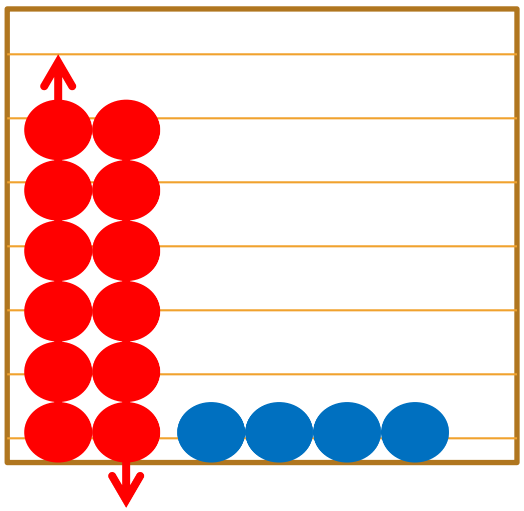
NB: New superconducting phase
of neutron matter
occurs at $p_F > 2\ \mathrm{fm}^{-1}$ (!?)

If the primitive in high-density nuclear matter turns to a resonance, a dibaryon Bose condensation occurs, which makes neutron stars unstable

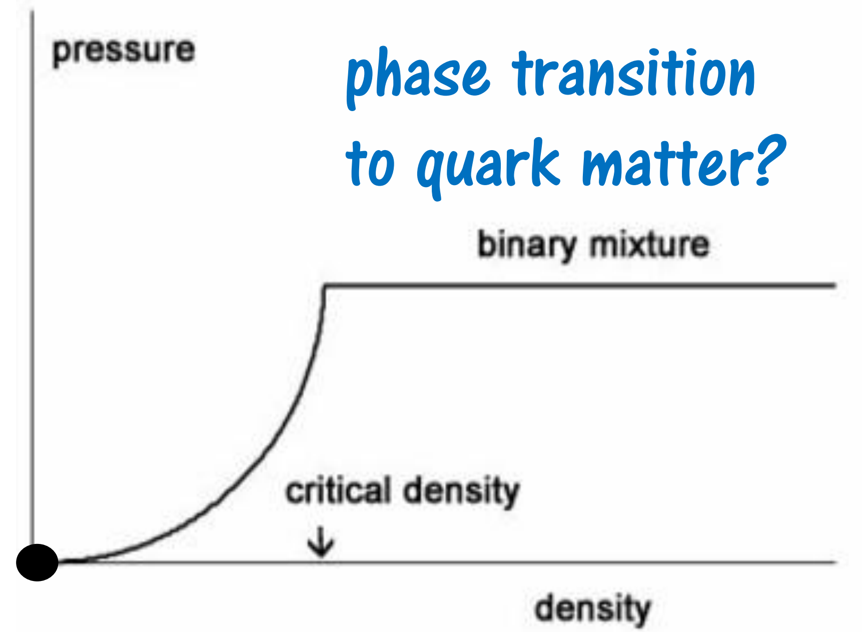
А. М. Балдин и др., Доклады Академии Наук СССР 279, 602 (1984).
А. С. Шумовский и В. И. Юкалов, ЭЧАЯ 16, 1274 (1985).
A. V. Chizhov, R. G. Nazmitdinov, A. S. Shumovsky, and V. I. Yukalov, Nucl. Phys. A 449, 660 (1986).

Fermi Energy
$E_F = m_D/2$ →

Dibaryon
condensate →



phase transition
to quark matter?



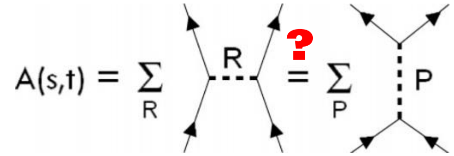
Euler's equation:

М.И.К., Письма ЖЭТФ 46, 5 (1987).

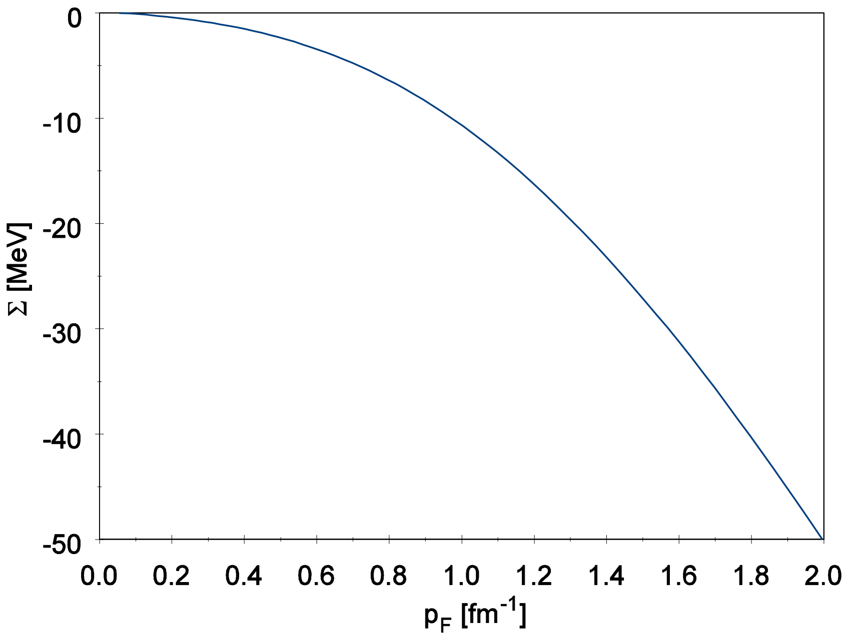
$$\rho \frac{\partial \mathbf{v}}{\partial t} + \rho(\mathbf{v} \cdot \boldsymbol{\nabla})\mathbf{v} = -\boldsymbol{\nabla} P - \rho \boldsymbol{\nabla} \Phi,$$

There are no static solutions above the critical density.

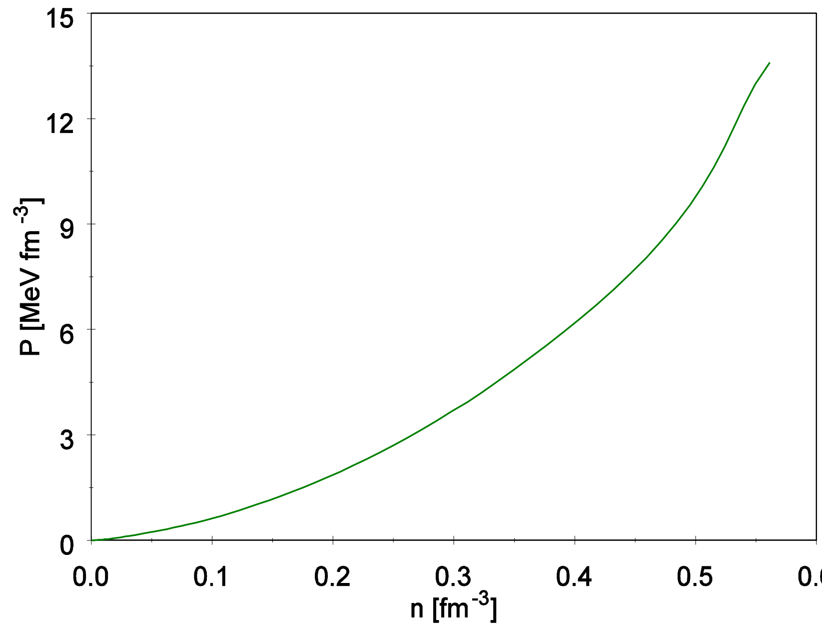
EoS in QCB model



Neutron self-energy vs. p_F



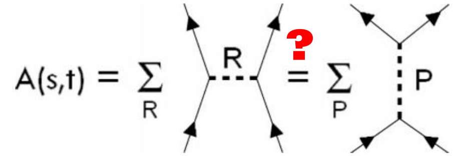
Pressure vs. number density



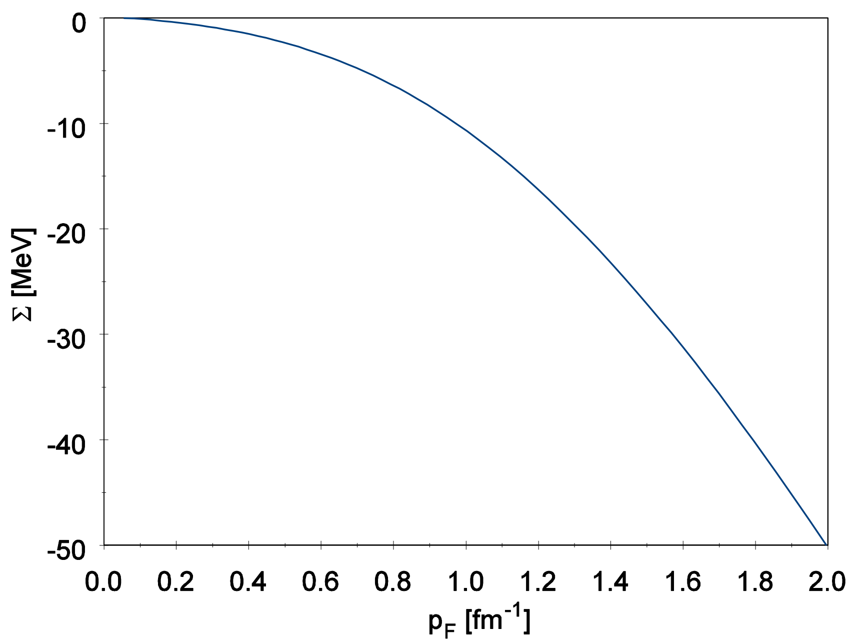
NB: ∑ is much smaller than in MF models and comparable with OBE models

NB: EoS is much softer than in MF models and in OBE models

EoS in QCB model

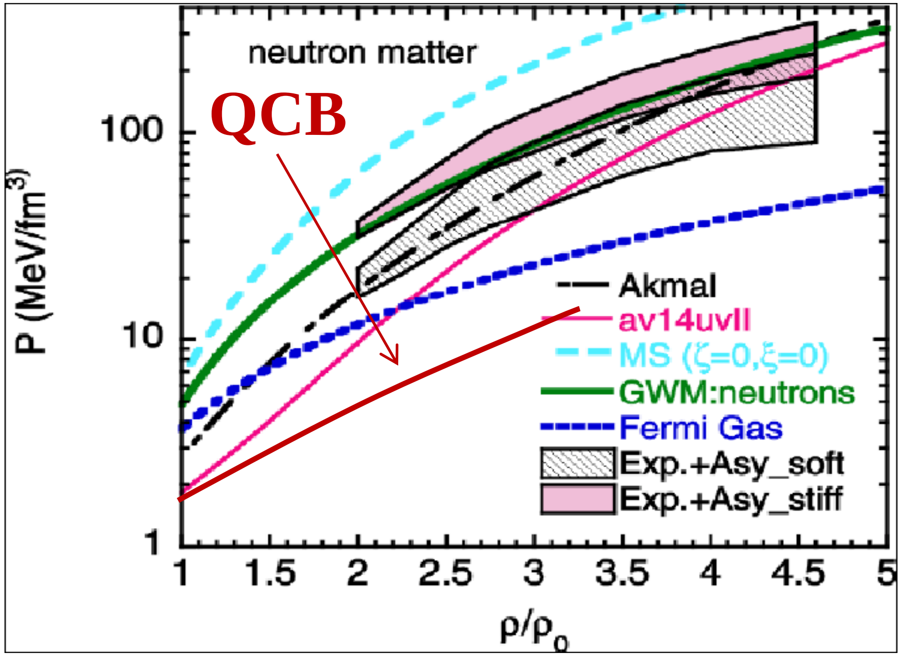


Neutron self-energy vs. p_F



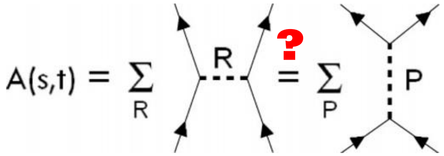
NB: ∑ is much smaller than in MF models and comparable with OBE models

Pressure vs. number density



EOS for neutron matter in OBE models.
The dashed regions correspond to the pressure consistent with the experimental flow data in heavy-ion collisions after inclusion of the stiffest and softest asymmetry terms.

EoS in QCB model

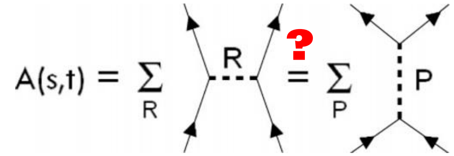


WHAT ELSE COULD BE DONE?

1. Include data on the NN scattering phases up to T_{lab} = 500 MeV

2. Include NN channels with *p*- and *d*-waves
3. Include NN* and NΔ channels (not a problem for separable-like potentials)
4. *Exact solution of Eliasberg equations for the pairing*
5. Symmetric nuclear matter at saturation
6. Do primitives stay always on the unitary cut? Duality?
7. A VERY HIGH-DENSITY EOS

SUMMARY



First calculation of EoS of nuclear matter in an *s*-channel exchange NN interaction model

- The CDD poles are related to **bound states, resonances**

  and PRIMITIVES
- **Primities are identified reliably in the $^3S_1$, $^1S_0$ and $^3P_0$ NN scattering channels**
- **Narrow dibaryon resonances Γ ~ 260 keV**

  in the $^3S_1$, $^1S_0$ and $^3P_0$ NN scattering channels due to possible primitive-to-resonance conversion
- Neutrons pairing in QCB model is well described
- **EoS of neutron matter in the considered version of QCB model appears to be soft**