Why is a nucleon bound? *

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In a style of popular article, we discuss models of hadronic structure and their relation with models of the QCD vacuum and lattice simulations. Borrowing two main characters from G. Gamow, Mr. Thompson and Professor, we make a travel in the QCD vacuum. Instanton-generated interaction between quarks appear to be major player, they alone create quark condensate, constituent quark masses and their bound states with properties very close to those observed. Direct removal of perturbative and confining forces (possible on the lattice by “cooling”) result in very small modification of hadrons.

I. VARIOUS MODELS OF HADRONIC STRUCTURE

It is by now firmly established that strongly interacting particles are made of quarks, which do not exist individually due to color confinement. The question why quarks form hadrons with precisely the properties observed in experiments is far from being quantitatively answered. However recent development have significantly clarified the issue, some models seem to be qualitatively wrong and some are confirmed: the instanton-induced interaction between quarks has emerged as a major player, and existing models of vacuum and hadronic structure based on it claim accuracy at 10-20% level.

A brief introduction to old models of a nucleon structure is provided by Fig. 1. The first picture (a) shows the essence of the nonrelativistic quark model suggested in 60’s. It shows a family of three rather massive “constituent quarks” (with $M_{\text{eff}} = 300 - 400 \, \text{MeV}$) kept together by mutual attraction (described by the potential $V(r)$).

Fig. 1(b) represents the MIT bag [1], suggested in the mid-70’s, in the early days of QCD. It is a completely different picture: the objects are nearly massless “current” quarks. They are not specifically attracted to each other, and perturbative approach like Coulomb and magnetic spin-spin interactions are supposed to be used inside the bag. The object exists because quarks are unable to get out of a “bag”: they are simply not admitted in the “physical vacuum” outside it.

Fig. 1(c) corresponds to the so called Skyrmion, proposed in the early 60’s [2] but becoming fashionable in 80’s, after several puzzling questions have been clarified. The “hedgehog” is made out of the pion field, with its pins representing radially directed isospin $\vec{\pi} \sim \vec{r}$. If this objects rotates slowly (as it should, provided the number of colors $N_c \gg 1$ and baryons become parametrically heavy), it is the nucleon (spin and isospin $S=I=1/2$), if more rapidly, it becomes a $\Delta(S=I=3/2)$, etc. There are no quarks in this picture at all.

The last picture Fig. 1(d) shows a combination of the previous two: it is a chiral bag, surrounded by a hedgehog-shaped pion cloud. Gerry Brown and collaborators, who did the surgery, took care and ensure that at the boundary the pressure and other important quantities like “chiral current” are continuous, so the “scar” is hardly physical. A smile of the hedgehog should remind us about the so called “Cheshire Cat Principle”, according to which even the location of this “scar” should be irrelevant.

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Can all of those models be at least partially true at the same time? It is very unlikely. Looking at these models closer and trying to ignore differences in language, one is still puzzled by a completely different physics involved. For example, according to the MIT bag model, all hadronic properties directly follow from confinement physics, with masses (and other dimensional quantities) simply related to the bag constant B. The non-relativistic potential model ascribe most of the hadronic mass to the sum of “constituent quark” masses, with only a small part coming from an interaction. The Skyrmion picture implies that quark and antiquark always travel together, in a pion form: if so, there is simply no place for confinement left.

There are also many minor problems with those models, but one is a generic one, common to all of them. They do not follow the general wisdom which follows from the solution of multiple quantum mechanics problems: one should try to understand the ground state first, then properties of the excitations will follow naturally. Hadrons we know most about (and therefore, most care about) like pions or nucleons are low-lying collective excitations of the QCD vacuum, like phonons in solids and nuclei. So, we have to focus our attention on the underlying matter first.

At this point it is fair to recall one model which had actually followed this strategy closely. It is the Nambu-Jona-Lasinio (NJL) model [4], suggested in 1961, long before QCD and even before quarks. It was inspired by the BCS theory of superconductivity, and therefore also based on hypothetical attractive four-fermion interaction. It was shown that if it is strong enough, it can rearrange the vacuum into a chirally asymmetric (or “superconducting”) phase, with mesons analogous to the Cooper pairs and (unconfined) quarks with reasonably large effective masses.

The main lesson we would like to discuss in this article is in fact the statement, that we now have convincing evidences that such kind of interaction actually exists in QCD, and that its exact form and nature can be quantitatively obtained from a semiclassical theory based on instantons.

Since we aim at readers which are not very familiar with these methods and jargon used, we invite them to a little travel through the QCD vacuum first, which will provide some general picture. Most of them surely are familiar with Gamow’s books, explaining relativity and quantum mechanics to “pedestrians” with unbeatable clarity1. Let me borrow his style for this travel, together with two main characters.

II. TRAVELLING THROUGH THE VACUUM WITH MR. STRANGE

1 They are also an excellent example of how much fun one may get in physics: I was told by several colleagues that these books directly influenced their professional choice. Unfortunately, I was not among those because Gamow’s books were not available in the part of the world where Gamow (and myself) come from. The explanations of why this is the case, as well as a lively description of some (failed) tunneling experiments he made himself, one can find in Gamow’s autobiography “My world line”.

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Mr. Thompson and Professor have found themselves in a very colorful country, see Fig.2. They were still looking around, when a car drove by. A fat short fellow opened the door and said: “I am Mr. Strange, and my job is to search this country. I was told you are interested in a tour, so please jump into the back seats”. The car started, moving in an erratic unpredictable way, avoiding larger bumps and jumping at many smaller ones. “Do you see any road here?” - asked Mr. Thompson. “We quarks do not need any, just take any path we like”, Mr. Strange replied proudly. Puzzled by that, Mr. Thompson thought for a moment and then tried a simpler question: “By the way, what color is your car?”, but was again taken back by a strange cool reply: “Come on, this is not even a gauge invariant question!”.

Mr. Thompson gave up the questions and decided to look around. Other cars were travelling here and there, either jeeps, marked ‘Up’, or low sport models marked ‘Down’. After a while, a larger car appeared, with a nice lady at the wheel, followed by a jeep with a tiny little fellow in it. Mr. Strange made a signal and waved his hand to greet the lady before they disappeared behind a little hill. “It is my first cousin Charm, with that little fellow Anti-Up. He spins around her all the time, but I do not trust him, though. Once I met him with another lady, known as Beauty, and he behaved in exactly the same way.” Professor remarked, with sudden enthusiasm: “Oh, yes, this is what we call the Heavy Quark Symmetry”.

In a valley something like a race took place. A little crowd watched bunches of cars, each time consisting of two “ups” and a “down” ones, starting in regular intervals and disappearing in about the same direction (see Fig.3). “It is the measurements of the proton mass”, - commented Mr. Strange, “they have done it for ages. A very dull job, I am glad I am not in the game.”

Some object looking like a flat cloud but bent in a complicated way happened to be close by. Professor became very agitated and asked whether it is possible to drive through it. “Well, put your belts on - replied Mr. Strange, - its the storm”. Indeed, the car was pulled in by a strong force, everybody’s hair jumped up, lightnings was all around, but in a second it was all over. “This cloud is known as a virtual string path”, said Professor, “They are as mysterious as the ball lightnings. In spite of all the efforts, nobody really understands what they are made of. Some say magnetic monopoles should be around, but I have not noticed any.”

A range of mountains blocked the way, but Mr. Strange did not slow down. “I do not like mountain driving”, said Mr. Thompson still frightened by the storm. “We will take the tunnel,” - replied Mr. Strange, “Besides, we are not going to wait this time: see those fellows over there.” He pointed toward the tunnel entrance, where two cars, “up” and “down” ones, were moving in funny little circles. “They are waiting for us. Due to the First Tunneling Law no tunneling is permitted unless for a complete set of quarks. By the way, I have seen much higher mountains, made of W,Z rocks, and nobody was able to tunnel through those ones.” “I can tell you why,” said Professor, “according to the same Tunneling Law one has to collect a company of 12 weakly interacting fermions, with a representative of

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2 Like coordinates in general relativity, in QCD one is allowed to take any definition of 3 basic quark charges, called colors, and change it at any point or moment.

3 Hydrogen atoms with a deuteron or triton instead of a proton have about the same chemical properties. Similarly, with any heavy quark (c,b or the recently discovered t) one has about the same hadron.

4 Mr. Strange hints that studies of strange baryons, or hyperons, in which he could participate, did not get much attention.
all quarks and all lepton families, electron, muon and tau. But even then, it is very unlikely to happen.\footnote{The probability of tunneling in electroweak theory is very small, $\exp(-\frac{16\pi^2}{g^2}) \sim 10^{-170}$, where $g_c$ is the weak gauge coupling. It maybe happened once in the visible part of the Universe. if it did, the baryon number was changed.}

The tunneling itself took little time: a strong force pushed the car to another valley. But during it something very bizarre had happened: although Mr.Strange continued driving, he was sitting on the other side of the front seat! Mr.Thompson looked at departing “up” and “down” cars: the same thing has happened to them as well. Mr.Strange noticed puzzled expression on his face in the mirror and smiled: “Well, that is the Second Tunneling Law: anyone who was right-handed becomes left-handed, and vice versa. Even cars do that.” Professor nodded and made notes in his notebook (with a pen in his left hand, of course). He said he had studied this curious phenomenon, known as “chiral anomaly”, for years going through multiple unclear papers, and how happy he is to see how the thing really works. Mr.Thompson remarked: ”Now I have an idea: how about putting such a tunnel between Britain and France?”

The rest of the journey was full of other adventures: it happen to be rather long. One of the reason for that was the Third Tunneling Law, demanding that not a single mountain should remain untunneled. Finally the car returned to the spot they had started from. Mr.Strange took a notebook and wrote down numbers from a device, which looked like a taxi meter. “My job is to evaluate how passable this country is: it will appear in the next edition of the maps. Would you care for another trip?”, said Mr.Strange. Mr.Thompson tried to escape, but Mr.Strange has said that it would be a very easy one, in the desert, and so they went along.

And indeed, in was a completely different landscape (Fig.3). Gone were all the large hills and little bumps: the country was basically a flat desert, with only a few mountains. Those had also changed: they all now had the same rounded shape, looking like a set of domes. The tunnels could be well seen from a distance, and now, when they became used to them, Professor and Mr.Thompson enjoyed them, as rides in Disneyland. Finally, after Mr.Strange wrote down another set of numbers, they thanked him once more and said goodbye to a strange colorful world.

### III. WHAT CAN ONE LEARN FROM THIS TRAVEL?

At this point, the reader is probably confused by details, or even by the very goals of this travel. Well, some explanations are coming.

First of all, the “landscapes” described above represent the set of configurations of the “colored” gauge field $A_\mu(x)$ in 4-dimensional space-time. Furthermore, in order to simplify calculations one usually rotates time into its imaginary axis, going into the so called Euclidean space-time, with the same metrics for all 4 coordinates: so there is no difference between them. Ensemble of “landscapes” represents the wave function of the QCD ground state. Of course, one should include them with the proper weight:

$$Weight = \exp(-S_g(A))\Pi_{q=u,d,s}det[i\gamma_\mu(\partial_\mu + igA_\mu) - m_q]$$

The first factor contains (Euclidean) gauge field action $S_g = \frac{1}{4} \int d^4x (\vec{E}^2 + \vec{B}^2)$ containing gluoelectric and gluomagnetic fields, while the second factor is a product of very complicated quantities, the “fermionic determinants”, one for each kind of light quarks. It appears because we have chosen to integrate away all fermionic degrees of freedom. The aim of Mr.Strange’s travels is precisely the evaluation of one of those determinants. For example, if he dislikes a particular field configuration, he can simply veto it by giving it the zero value: then the configuration will be dropped from the ensemble.

One may find it surprising, that during our travel with Mr.Strange no direct interaction between different quarks was seen. However, it does not contradict to hadronic models discussed in the beginning because the averaging over the gauge fields has not been done yet. As all quarks (i) avoid the same “bumps”, (ii) suffer the same “storms”, and (iii) tunnel through the same “mountains”. Their common adventures take them on similar path, or take them closer together. In a more conventional language, when one integrate over gauge field first, these are described as (i) the Coulomb-type, (ii) confinement-related and (iii) instanton-induced forces, respectively.

Now, suppose a proper set of field histories is collected: how can we connect it to mesons and baryons? In the same way as we study “elementary excitations” of any matter: by observing the propagation of small perturbations. Say, to study “phonons”, one person can speak and another listen. Similarly, one can inject to the vacuum few quarks at one point and extract them back at another: in this way one gets the so called “point-to-point correlation function”.

\footnote{Thus, it is more accurate to call them histories of the field evolution. The time running during the travel (such as shown by Mr.Thompson’s watch) just parameterizes the points on the quark path, and in fact it is unphysical.}
If this set of quarks forms a bound state\(^1\) they would travel together, and the behavior of the correlation function will reflect it. Furthermore, one can extract masses, wave functions, form-factors and other parameters which can be directly compared to the experimental data.

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\(^1\)For example, the “races” observed during the travel above, was done for u,u,d quarks, a set with quantum numbers of the nucleon.

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**IV. THE INSTANTON STORY**

It is usual for popular-style articles to jump over years of hard work of many people, proceeding directly to final conclusions. Only few of them mention what was actually done, and even those are usually related with only a couple of most recent works. Alas, we have to follow the same well trotted path, with a brief sketch of history.

Let us start with conclusions. Above we have mentioned 3 types of forces between quarks. Somewhat unexpectedly, quite different ones bind different quarks together, depending mostly on their mass. Heavy b quarks make bound states, dominated by the Coulomb-type forces. The “charmed” \( \bar{c}c \) pair forms mesons of the \( J/\psi \) family, using mainly the confining potential. However, a nucleon (and other hadrons made of light quarks) are mostly bound by forces induced by tunneling.\(^2\)

As usual, realization of that came gradually, due to a chain of seemingly unrelated works. In 1975 Weinberg\(^3\) has pointed out that one particular meson, called \( \eta' \), is about twice heavier than it should be due to strange quark mass.\(^4\) At the same year, A.M.Polyakov with collaborators\(^5\) have found enigmatic solution of Yang-Mills equations (QCD analog of Maxwell’s ones). Only later it was realized that it is a path describing the tunneling process. G. ’t Hooft\(^6\) found the Tunneling Laws mentioned by Mr.Strange and related it to “anomalies”. Among other things, it was found that this interaction violates Weinberg’s \( U(1) \) symmetry. Its effect in the \( \eta' \) channel is repulsive, as needed, but in order to explain the puzzle in should be extremely strong.\(^7\) Gradually it was realized, that if it is that strong in one channel, it cannot probably be unimportant in many others as well. Although multiple attempts to derive properties of the instanton ensemble from first principles failed, but simple phenomenological model called the “instanton liquid”\(^8\) has simultaneously explained large \( \eta' \) mass, properties of the pion and few other vacuum parameters.\(^9\) Its basic assumption was that, for whatever reason, in QCD vacuum there are many small-size instantons, \( \rho \approx 1/3 fm \), with very strong field and therefore semiclassical.

Recently breakthrough is due to simultaneous attack on the problem by two teams, moving toward each other from opposite directions. The Stony Brook group work out numerical methods capable to follow quark propagation (and correlators) in a “instanton liquid” up to rather large distances \( x \sim 1.5 – 2 fm \). Hadronic masses, wave functions and

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\(^2\)The reader should also be warned at this point, that this statement is far from being the universally accepted.

\(^3\)For example, its close relative \( \eta \) meson contains larger share of strangeness, but it is lighter. By the way, none of models mentioned at the beginning can explain this phenomenon.

\(^4\)For example, counting powers of the number of colors one can find that the \( \eta' \) mass is \( O(N_c^{-1}) \) and the nucleon one is \( O(N_c) \). Naively for \( N_c = 3 \) the former should be an order of magnitude smaller, but experimentally both masses are about the same.

\(^5\) It corresponds to a “desert” picture of vacuum fields, shown in Fig.\(^3\)
other hadronic parameters were calculated in this model, with results in good agreement with data. Among other things, a nucleon was found to be deeply bound state of constituent quarks, with the right mass $960 \pm 30$ MeV. (And this is in the model without confinement!) Furthermore, large mass splitting between the nucleon and $\Delta$ isobar was found (in the model without perturbative one-gluon exchange!). In Fig. we show the results for the nucleon and $\Delta$ correlation function from (dots) (lattice data which are not shown are in good agreement with them). Both are normalized in such a way that unit value correspond to free propagation of massless quarks, and the argument $\tau$ is length of the quark travel in femtometers. An attrative interaction (the correlator rizes above 1) is clearly seen in the nucleon case, but is absent for $\Delta$. The reason is (spin-0) u-d quark pair can tunnel together, and thus are strongly attracted to each other: such pairs exist in the nucleon but are absent in $\Delta$. For comparison, the dotted line show independent motion of three constituent quarks, and the dashed on an independent motion of quark and bound scalar u-d diquark. None of those is close to the data points, which can be well fitted by existence of the bound states.

![Graph](image)

**FIG. 5.** Comparison of correlation functions for the nucleon and $\Delta$ channels: see text for explanation.

The MIT team started with the complete vacuum, generated in lattice computer simulations, and moved toward instanton physics gradually. As a first step, the correlation function were measured: those were fund to be in stunning agreement with instanton-based calculations. The second step was application of the so called “cooling” algorithm, which makes lattice configuration smooth. Basically, only classical instanton field remained (see Fig), while perturbative and confining forces were strongly suppressed.

Their first major result is that all parameters of the “instanton liquid” are reproduced, literally inside the error bars. Moreover, even the size distribution was recently measured, and it happens to be peaked at $\rho \approx 1/3 \text{fm}$.

But even more striking was an observation that detailed behavior of the correlation functions measured after cooling have not significantly changed. In other words, the (lightest) hadrons have survived “cooling”? It has explicitly demonstrated, that by sacrificing Coulomb and confinement forces, one still can get about the same hadrons.

Let us now come back to models of hadronic structure mentioned at the beginning of the paper and try to connect them with these new results. We have already commented in the Introduction that NJL model is qualitatively correct, although its original Lagrangian should be substituted by (much more complicated and non-local) instanton-induced Lagrangian derived by ‘t Hooft. The similarity in fact goes even further: the BCS model is so successful because the range of the interaction in superconductors is indeed much smaller than the size of the Cooper pair. Similarly, QCD instantons are relatively small compared to sizes of most hadrons, therefore this effective interaction can also be approximated by a local one. Furthermore, results for mesons can be approximately reproduced by summing the same “fish-type” diagrams (or solving Bethe-Salpeter equation). Unfortunately, it is impossible to sum all of them analytically, so the major tool remain computer simulations.

These finding strongly contradict to some hadronic models mentioned above. The strongest case is against the MIT bag model: neither hadrons are “empty inside” (true non-perturbative vacuum energy density is huge compared to the MIT bag constant), nor are quarks light or bound mainly by confinement. Even spin splittings seem to be not due to dipole spin-spin interaction!

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6 About the largest deviation, at 20% level, is observed in the shape and size of the pion wave function (Bethe-Salpeter amplitude), in which perturbative effects produced a characteristic cusp at small distances and confinement produces some extra suppression at large ones.
The chiral bag model, with its large “pion cloud” around a small “quark core”, remains a reasonable picture (provided the core is not “empty” but rather the place where non-perturbative fields are the strongest).

Of course, the story of hadronic structure is still far from being finished: understanding and quantitative incorporation of confinement remains the long-standing challenging problem. Meanwhile experiments generate new puzzles: “spin crisis” in the polarized nucleon, large and polarized “strange sea”, strong isospin asymmetry of the “u,d sea”, etc. There are hints that instantons may explain these puzzles as well, but this remains to be calculated.

V. WEIGHTING AND MELTING THE VACUUM

In this last section let us consider an important question about the QCD ground state energy of QCD. As we will see, it is not so philosophical question as it sounds, but rather a practical one.

Still, let us start with a historical perspective. An ancient philosopher would say, that the weight of an empty bottle is nothing else but the weight of the bottle itself. A 16-th century physicist would be more careful: he would point out the difference between an open bottle, with air, and the “truly empty” one, with air pumped out of it. A 20-th century theorist would comment that such “truly empty” bottle still contains zero-point perturbative fluctuations of all fields.

In QED, after infinities are subtracted, the so called Casimir energy remains. In QCD this subtraction leads to a finite difference $\Delta \epsilon = \epsilon_{\text{physical}} - \epsilon_{\text{perturbative}}$. By analogy say to a superconductor, which has lower energy compared to a normal metal, one expects that the physical vacuum has lower energy than the perturbative one, $\Delta \epsilon < 0$.

Theoretical expression, known as trace anomaly, relates $\Delta \epsilon$ to the so called gluon condensate. In spite of intensive lattice simulations, we still know this quantity only very approximately. However, instantons alone produce a surprisingly large energy density, $\Delta \epsilon \approx -1 \text{GeV}/\text{fm}^3$. It is about 20 times larger than the MIT bag constant value, and about 6 times larger than the mass density of nuclear matter! Can one measure this vacuum energy in experiment? As we do not know how one can “pump the non-perturbative fields out”, we can at least pump in a comparable amount of energy into some volume and see what happens. It is predicted that the QCD vacuum becomes the so called quark-gluon plasma at $T > T_c \sim 150 \text{MeV}$. At higher $T$, its energy density is believed to be $\epsilon_{\text{QGP}} \sim T^4$, same as the “black body radiation” (modulo a different number of degrees of freedom). This energy is counted from the perturbative vacuum (the non-perturbative phenomena are believed to be suppressed at high $T$), so comparing the two one may find out the ground state energy of QCD.

Because this energy density is so large, in order to “melt the vacuum” and produce the new phase, one needs high energy colliders of heavy ions, such as the Relativistic Heavy Ion Collider (RHIC), now under construction in Brookhaven National Laboratory, or even the Large Hadron Collider to be built at CERN, Switzerland. These experiments look also how “melting” of hadronic states takes place at the phase transition. If this is observed, it clearly sheds some extra light at hadronic structure as well. (For example, if the MIT bag model would be right, hadrons would melt very easily, at rather low energies such as Berkeley BEVALAC.) If the Skyrmion picture is correct, no trace of the nucleon above chiral restoration point $T_c \approx 150 \text{MeV}$ is expected, where the quark condensate and pion clouds are supposed to disappear.

G.Brown and V.Koch [14] have analyzed lattice data describing the QCD phase transition, they have concluded that in fact only about half of the gluon condensate can “melt”. How this other half (a “hard glue” or “epoxy”, as Gerry Brown called it) looks like? Why it does not create quark condensate?

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7 Since it depends on the size of the bottle and what it is made of, it can hardly be ascribed to the QED vacuum itself, though.
FIG. 6. Typical instanton configurations for \( T = 75 \), and 158 MeV. The plots show projections of a four dimensional \((3\Lambda^{-1})^3 \times T^{-1}\) box into the 3-4 (z axis-imaginary time) plane. Instantons and antiinstanton positions are indicated by + and - symbols. The lines correspond to strongest fermionic “bonds”.

The instanton-based theory makes quite specific predictions here as well (not yet directly tested on the lattice). It was found \[15\] that at \( T = T_c \approx 150 \text{MeV} \) relatively random instanton liquid undergo rapid transition into a new phase, made of instanton-anti-instanton molecules. In a series of recent numerical simulations \[16\] it was found that this transition is indeed there, and its many features and thermodynamics is consistent with available lattice data. In Fig.6 we show a sample of configurations from this work, at different temperatures: one can see how these molecules appear around critical temperature. These molecules are the “epoxy”, and the reason they do not create a condensate is because they trap quarks inside them. Also, they create interaction \[15\] between quarks (being even more similar to the original NJL one) even at \( T > T_c \). This seems to lead to existence of some hadronic states (especially pions and its chiral partner sigma) surviving the phase transition! One more extension of those studies is QCD with larger number of flavors: when it exceed some critical value chiral symmetry is restored at \( T=0 \) (see Fig.7). Spectroscopy of this strange world with many flavors is predicted to be entirely dependent on these molecules: it is exciting topic for future lattice investigations.

\(^{1}\text{Note a similarity to Kosterlitz-Thouless transition in O(2) spin model in 2 dimensions: again one has paired topological objects, vortices, in one phase and random liquid in another. The high and low-temperature phase exchange places, though.}\)
FIG. 7. Schematic phase diagram of the instanton liquid for different numbers of quark flavors, $N_f = 2, 3$ and 5. We show the state of chiral symmetry in the temperature-quark mass planes. In the figure for $N_f = 2$, open squares indicate points where we found large fluctuations of the chiral condensate, the cross indicates the approximate location of the singularity. In two other figures the open squares correspond to non-zero chiral condensate, while at solid it is absent. The dashed lines connecting them show the approximate location of the discontinuity line.

Summarizing the main point of this last section: traditional studies of hadrons, as small perturbations of the QCD vacuum, can be supplemented by experiments with the matter which is so hot and dense, that it will have rather different (or even completely different, at $T > T_c$) excitations. Another way to perhaps similar world, in which chiral symmetry is restored, is to add more quarks to the QCD Lagrangian.

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