The findings of RHIC about quark gluon plasma from the TGD point of view

December 26, 2025

Matti Pitkänen

orcid:0000-0002-8051-4364.
email: matpitka6@gmail.com,
url: `http://tgdtheory.com/public_html/`,
address: Valtatie 8, as. 2, 03600, Karkkila, Finland.

Contents

Abstract

The study of quark gluon pasma at RHIC has revealed many surprises.

1. Jet quenching means that jets predicted by QCD lose energy much faster than expected. This would be due to the strong interactions with quark gluon plasma implying dissipation. In QCD, this interaction is modelled in terms of collisions of quarks with the quark gluon plasma formed by quarks and gluons.
2. The almost ideal perfect fluid behavior was totally unexpected. This hydrodynamic flow is known as elliptic flow. A further surprise was that heavy quarks also participate in the elliptic flow. This is like boulders flowing in a river.
3. Also light ions create the quark-gluon plasma. QGP, or whatever it is, is created even in the collisions of photons and heavy ions.
4. The basic questions concern the critical temperature and critical collision energy per nucleon at which the transition to QGP occurs. There is no consensus but the proposal is that 19.6 GeV collision energy could be a critical point. There is however a bumpy structure also below this critical point.

What can be said about these findings in the TGD framework?

1. The counterpart of quenching would be conformal dissipation or equivalently p-adic occurring for mass squared scale identifiable as conformal weight rather than energy. p-Adic temperature T_p which depends logarithmically on the p-adic mass scale has a discrete spectrum and would decrease in a stepwise manner in the p-adic cooling. T_p is naturally identifiable as the temperature of the counterpart of QGP and has also an interpretation as Hagedorn temperature.

2. p-Adic length scales hypothesis suggests that there is an entire discrete hierarchy of critical temperatures rather than only a single critical temperature. These temperatures would come as logarithms of p-adic mass squared scales proportional to 2^k.
3. In the TGD framework, the large values of h_{eff} associated with the quantum criticality and implying long scale quantum coherence could explain the perfect liquid behavior in terms of long term correlations, which are typical for hydrodynamics. Recall that at the classical level TGD is essentially a hydrodynamical theory since field equations reduce to conservation laws for the charges associated with the isometries of H.
4. The TGD based explanation for the boulders flowing in the river would be that for the TGD analog of QGP, the induced Dirac equation in X^4 implies that both leptons and quarks behave like massless particles. Masses emerge only in the hadronic initial and final states constructed as modes of the H Dirac equation.

1 Introduction

I encountered a highly interesting popular article in which the work at RHIC relating to a phase transition to quark gluon plasma (QGP) dominated phase was discussed. The title of the popular article (see this) is "Clear Sign that QGP Production 'Turns Off' at Low Energy". The title of the article (see this) published in Phys Rev Letters [C1] "Beam Energy Dependence of Fifth- and Sixth-Order Net-Proton Number Fluctuations in Au+Au Collisions at RHIC" is so technical that it does not tell much to a layman. However, since fluctuations characterize criticality, one can guess that criticality is studied.

1. Collisions of Gold ions have been studied at RHIC. The cm energy per nucleon has varied from 3 GeV to 200 GeV. At LHC the upper limit for energies is considerably higher, about 5 TeV and therefore 25 times higher. The research has shown that the behavior of the quark gluon plasma differs rather dramatically from the expectations.

2. What is the critical temperature for the transitions to quark gluon plasma? This has been one of the key questions. No definite answer has been found although $\sqrt{s_{NN}} = 19.6$ GeV is considered as a candidate for 19.6 GeV for the critical collision energy per nucleon. However, a bumpy structure is observed also below this energy down to 3 GeV. Therefore the existence of a single critical temperature can be challenged. It is also clear that a first order phase transition involving single discontinuities of various thermodynamic observables is not in question.

   A more technical way to say this is as follows. What is studied are higher order cumulants for proton number fluctuations around average. At quantum criticality they are expected to be large. At higher collision energies they deviate from those predicted by a first order phase transition. At low collision energies the "off" signal shows up as a sign change—from negative to positive—in data that describe "higher order" characteristics of the distribution of protons produced in these collisions. To sum up, a higher order statistical analysis of protons emitted from a wide range of gold-gold collision energies shows clear absence of a quark-gluon plasma (QGP) at the lowest collision energy.

Here is the abstract of the article "Beam Energy Dependence of Fifth- and Sixth-Order Net-Proton Number Fluctuations in Au+Au Collisions at RHIC" [C1] summarizing the findings at RHIC.

We report the beam energy and collision centrality dependence of fifth and sixth order cumulants (C_5, C_6) and factorial cumulants (κ_5, κ_6) of net-proton and proton number distributions, from center-of-mass energy ($\sqrt{s_{NN}}$) 3 GeV to 200 GeV Au+Au collisions at RHIC. Cumulant ratios of net-proton (taken as proxy for net-baryon) distributions generally follow the hierarchy expected from QCD thermodynamics, except for the case of collisions at 3 GeV. The measured values of C_6/C_2 for 0%–40% centrality collisions show progressively negative trends with decreasing energy, while it is positive for the lowest energy studied. These observed negative signs are consistent with QCD calculations (for baryon chemical potential, $\mu_B leq 110 MeV$) which contains the crossover transition range. In addition, for energies above 7.7 GeV, the measured proton , within uncertainties, does not support the two-component (Poisson + binomial) shape of proton number distributions that would be *expected from a first-order phase transition. Taken in combination, the hyper order proton number fluctuations suggest that the structure of QCD matter at high baryon density,* $\mu_B \sim 750 MeV$ *at* $\sqrt{s_{NN}}$*=3GeV is starkly different from those at vanishing* $\mu_B \sim 24 MeV$ *at* $\sqrt{s_{NN}}$ *=200GeV and higher collision energies.*

1.1 A brief summary of the findings at RHIC

Consider first a brief summary of the unexpected RHIC findings (see this) concerning the creation of what is thought to be QGP. The study revealed many surprises.

1. Jet quenching means that jets predicted by QCD lose energy much faster than expected. This would be due to the strong interactions with quark gluon plasma implying dissipation. In QCD, this interaction is modelled in terms of collisions of quarks with the quark gluon plasma formed by quarks and gluons.
2. The almost ideal perfect fluid behavior was totally unexpected. This hydrodynamic flow is known as elliptic flow. A further surprise was that heavy quarks also participate in the elliptic flow. This is like boulders flowing in a river.
3. Also light ions create the quark-gluon plasma. QGP, or whatever it is, is created even in the collisions of photons and heavy ions.
4. The basic questions concern the critical temperature and critical collision energy per nucleon at which the transition to QGP occurs. There is no consensus but the proposal is that 19.6 GeV collision energy could be a critical point. There is however a bumpy structure also below this critical point.

1.2 TGD view briefly

What can be said about these findings in the TGD framework?

1. The counterpart of quenching would be conformal dissipation [L15] or equivalently p-adic occurring for mass squared scale identifiable as conformal weight rather than energy. p-Adic temperature T_p which depends logarithmically on the p-adic mass scale has a discrete spectrum and would decrease in a stepwise manner in the p-adic cooling. T_p is naturally identifiable as the temperature of the counterpart of QGP and has also an interpretation as Hagedorn temperature [B1].
2. p-Adic length scales hypothesis [L4] suggests that there is an entire discrete hierarchy of critical temperatures rather than only a single critical temperature. These temperatures would come as logarithms of p-adic mass squared scales proportional to 2^k.
3. In the TGD framework, the large values of h_{eff} associated with the quantum criticality and implying long scale quantum coherence could explain the perfect liquid behavior in terms of long term correlations, which are typical for hydrodynamics. Recall that at the classical level TGD [K1] is essentially a hydrodynamical theory since field equations reduce to conservation laws for the charges associated with the isometries of H.
4. The TGD based explanation for the boulders flowing in the river would be that for the TGD analog of QGP, the induced Dirac equation in X^4 [L14] implies that both leptons and quarks behave like massless particles. Masses emerge only in the hadronic initial and final states constructed as modes of the H Dirac equation.

2 The TGD view of the RHIC findings

2.1 The TGD view of the standard model

My personal interest is to relate the overall view about the findings of RHIC to the TGD view about standard model interactions [L17]. This view differs rather dramatically from the standard view. It is good to start with a general summary of the TGD view of standard model physics.

1. The basic difference between standard model and TGD is due to the realization of color symmetries. In TGD, space-times are 4-surfaces $X^4 \in H = M^4 \times CP_2$ and color is not a spin-like quantum number at the fundamental level and both quarks and leptons move in spinor color partial waves defined in CP_2 [L16, L14].

   The states observable below CP_2 mass scale are color singlets consisting of color triplet counterparts of fundamental quarks and color singlet counterparts of fundamental leptons. Weak interactions can be regarded as color interactions in the "spin" degrees of freedom for CP_2 and this means unification of electroweak and color interactions [L17].

   At the space-time level spinor fields corresponding to the induced spinors are induced from second quantized H spinors, which behave like massless spinor fields. By holography= holomorphy principle the induced Dirac equation can be solved. One can also consider the possibility of Dirac equation inside causal diamond (CD). TheDirac equation in CD would involve a coupling to the Kähler structure of M^4 associated with its Hamilton-Jacobi structure [L6, L14].

2. p-Adic length scale hypothesis is a key prediction of the number theoretical vision, which in the TGD view is dual to the geometric vision of physics [L9, L13]. An entire hierarchy of standard model physics proposed to be labelled by Mersenne primes defining p-adic mass scales characterized the hadrons and also quarks. These standard model physics correspond to the hierarchy of irreducible representations of CP_2 and the multipletes for quarks and leptons are in 1-1 correspondence. Light many fermion states are color singlets [L14], which involve tachyonic fermions also allowed by the H Dirac equation. In the simplest model the tachyonic conformal weights would be associated with neutrinos. Free colored single particle states are possible only in CP_2 mass scales. Only right-handed neutrino can be color singlet.

3. A process that I call p-adic cooling [K4, K5] [L15] would characterize cosmic time evolution and mean a process in which hadrons with CP_2 mass scale decay in a cascade like matter to hadrons of light hadron physics. Needless to say that this view would revolutionize the views of cosmic evolution and astrophysics [L10, L7, L8].

4. Quantum criticality is a basic aspect of the TGD Universe and means that there are no continuously running coupling constants in the usual sense. Space-time surfaces obey holography = holomorphy principle [L11] and there is no path integral. All particles are bound states of fermions and the Feynman diagrammatics involves only fermionic 2-vertices so radiative corrections are absent [L15]. There is an analogy with Brownian motion and fermion pair creation is possible due to the existence of exotic smooth structures, possible only in the space-time dimension $D = 4$. Number theoretic vision predicts that coupling constant evolution is discrete and labelled by the p-adic length scales and possible other number theoretic parameters.

   Quantum criticality involves long range quantum fluctuations. In the number theoretic vision, they would correspond to large values of effective Planck constant h_{eff} having number theoretic interpretation either as the dimension of an algebraic extension characterizing the space-time surface or as the degree of the polynomial characterizing it.

   At quantum criticality for a phase transition changing the Mersenne prime characterizing the standard model physics large values of h_{eff} are possible and an interesting hypothesis is that there is a length scale resonance, the value of h_{eff}/h for the hadrons of the new hadron physics is such that the Compton scales for the ordinary hadrons and the hadrons of new hadron physics are the same.

5. p-Adic thermodynamics [L4] for mass squared, identified as a conformal weight, involves p-adic temperature T_p which is proportional to the inverse of the logarithm of the p-adic mass squared scale. The discreteness of the temperature conforms with the interpretation as a Hagedorn temperature [B1] (see this) characterizing extended objects with infinite number of degrees of freedom. In TGD, these objects would correspond to monopole flux tubes characterizing particles and also hadrons as 3-D geometric objects. A hierarchy of Hagedorn temperatures is predicted.

The p-adic length scale hypothesis states that primes near to some powers $p \simeq 2^k$ of 2 are physically preferred and this hypothesis has no number theoretical justification based on the naturally emerging generalization of p-adic number fields to function fields. This would suggest that the ratios of the Hagedorn temperatures are rational numbers $T_k/T_l \in \{l/k\}$.

If the Hagedorn temperatures correspond to the temperature assigned with the high-energy collisions of nuclei, this temperature is piecewise constant and the feed of energy creates entropy but does not affect temperature. This is indeed the case: the plasma temperature assigned with the collision increases very slowly with the collision energy.

This view leads to the notions of p-adic cooling occuring after the collision as the QGP expands and p-adic heating during which the QGP is formed [K4, K5] [L17].

6. Ordinary hadron physics would correspond to Mersenne prime M_{107} and there are indications for M_{89} hadron physics at LHC and from cosmic ray physics [K4, K5]. The proposal is that M_{89} hadron physics could play a central role in the physics of the Sun [L12].

   For the transition from M_{107} hadron physics to M_{89} hadrons physics quantum criticality, assuming that Compton lengths are same, implies $h_{eff}/h = 512$ as ration of p-adic mass scales. Interestingly, if the scaling by h_{eff}/h can occur also for the hadrons of ordinary hadron physics, the Compton length of the ordinary proton is scaled up to about 4 times Compton length of electron. This kind of scaling is assumed to occur in the TGD based model for the "cold" fusion [L1, L2, L3] as dark fusion. In the TGD based model for the Sun [L12] dark fusion would take place also at the surface of the Sun and replace the ordinary hot fusion in the solar core. It would occur after the transformation of M_{89} hadrons to ordinary hadrons by p-adic cooling at the surface of the Sun.

2.2 General TGD view of particle reactions

The general TGD based view of particle reactions generalizes the QCD view of hadronic reactions.

1. Interactions in H are contact interactions determined by the intersections of the space-time surfaces. Without additional assumptions the intersection consists in the generic case of discrete points. If the Hamilton-Jacobi structures are the same, the intersection consists of 2-D string world sheets whose dynamics is strongly restricted by the hypercomplex structure, meaning that only a second coordinate with light-like coordinate lines is dynamical. This is the case also in string models. By $M^8 - H$ duality a similar picture holds true also at the level of M^8 which corresponds to momentum space description for particles identified as Bohr orbits of 3-surfaces.

2. There would be two phases: X^4-phase as the counterpart of QGP but involving only free quarks and H-phase as counterpart of hadron phase. Hadronization leading from QGP the final state and the generation of the analog of QGP phase from hadronic initial state generalize to all standard model interactions and are universal mechanisms [L17].

3. The role of ZEO is essential. ZEO involves two kinds of state function reductions (SFRs). "Big" SFRs (BSFRs) and "small" SFRs (SSFRs). SSFRs are self measurements in the non-deterministic degrees of freedom assignable to the space-time surfaces $X^4 \subset H$ obeying holography = holomorphy principle and therefore being analogous to Bohr orbits for particles as 3-surfaces. Sequence of SSFRs defines a conscious entity, self. Slight classical non-determinism of holography= holomorphy vision accompanied by quantum non-determinism essential also for the particle reactions.

   In BSFR which is the TGD counterpart for the ordinary measurement reducing the entanglement between observer and the systems, the arrow of time changes. In a hadronic reaction two BSFRs take place. In the first BSFR a p-adic cooling in a reversed time direction occurs. For an external observer it looks like heating of the system. After the second BSFR p-adic cooling in standard time direction takes place. Conformal dissipation is involved with the cooling.

2.3 Conformal dissipation, p-adic length scale hypothesis and quantum ciriticality

Could quantum quantum criticality involving conformal invariance and quantum coherence play a central role in jet quenching. M^8-H duality inspires the notion of conformal dissipation [L15] as a dissipation in which energy is replaced with conformal weight, which is essentially mass squared. Could conformal dissipation interpreted as p-adic cooling help in the attempts to understand quenching?

1. Conformal dissipation [L15] is suggested by the M^8-H duality and would be described in terms of 4-surface Y^4 in M^8 as dual of space-time surface and defining the analog of momentum space defining dispersion relation. The time evolution at space-time level would correspond to p-adic momentum space evolution as a decrease of the mass scale and ending up to an evolution at mass shells of final state particles identifiable as ordinary dissipation. This could correspond to p-adic cooling. p-Adic heating can be considered would correspond to p-adic cooling with a reversed arrow of time and occur after the first BSFR. The p-adic cooling could be synonymous to a conformal dissipation.

2. Two kinds of number theoretic phase transitions and their combination are possible. The decrease of the p-adic mass scale of hadrons and quarks can take place as the collision energy increases. Quantum criticality in turn induces the increase of h_{eff}. A physically attractive proposal is that the increase of h_{eff} compensates the decrease of the Compton scales due to the shortening of the p-adic length scale. Frequency and wavelength resonance between initial and final states would become possible.

3. The TGD based proposal is that the Nature is theoretician friendly [K3] [L5]: when interactions get so strong that perturbation series fails to converse, a phase transition increasing the value of h_{eff} takes place implying the reduction of α_s. This allows converging perturbation series but the states are changed. Also the interaction range as a scale of quantum coherence increases. This could lead to the formation of perfect liquid.

   Also the Compton scales of quarks could increase. For 4 MeV quark the Compton scale for $h_{eff}/h = 512$ corresponding to M_{89} and scaling by $h_{eff} = 512h$ would be proton Compton length.

4. The basic steps of the process would be p-adic heating as a cooling with a reversed arrow of time initiated by the first BSFR followed by p-adic cooling initiated by the second BSFR. Cooling would be a stepwise process and there would be a hierarchy of criticalities. Are p-adically scaled up variants of hadron physics with $p \simeq 2^k$ for all values of k be involved as intermediate states in the cooling and heating. Or are only those values of k which can be assigned with quarks involved?

   Sequence of critical temperatures depending logarithmically on the p-adic mass scale increasing as powers of 2. The fact that T_p has logarithmic dependences of the discrete p-adic mass scale would explain the bumpiness at low energies.

5. What p-adic temperature does the mass scale 19.6 GeV correspond to? p-Adic length scale hypothesis predices $T = log((M/m_p)^2/log(2)$. This predicts $T(19.6GeV) = 214.5$ MeV, which is surprisingly near to the estimate for QCD Λ. p-Adic cooling suggests that the bumpiness between 3.6 GeV and 20 GeV could correspond to sequence of phase transition temperatures $T(127-k)$, $k = 4, 5, 6, 7, 8$. For 200 GeV energy one would have $T \sim 379.36$ MeV. Note that M_{89} hadron physics corresponds to a considerably lower temperature $T = 285.39$ MeV.

   It should be also noticed that quite recently 20 GeV gamma rays have been reported (see this). This is discussed in [K2]. In TGD they could correspond to decay products of a pion-like state with mass of 40 GeV about 286 pion masses.

2.4 Heavy ion collision as a p-adic heating followed by p-adic cooling

enumerate

p-Adic mass scale as octaves or half octaves 2^k. The most general option is that all values of k are possible. p-Adic length scales come as powers of 2 for odd k and of $\sqrt{2}$ in the general case! The strongest restriction is that the p-adic primes correspond to Mersenne primes for stable hadrons and leptons. The transitions between these M_{89} hadron physics and M_{107} hadron physics could occur via p-adic cooling via unstable intermediate states as cascades in with k decreases in a stepwise manner.

The p-adic temperature T_p appearing in p-adic mass calculations corresponds to the integer valued inverse temperature of p-adic thermodynamics for mass squared identified as conformal weight is naturally identifiable Hagedorn temperature. Since Boltzman weights as exponential $e^{-E/T}$ are for number theoretical existence reasons replaced by powers p^{m^2/T_p}, $T_p = 1/n$, the real counterpart of $1/T_p$ $k/log(p)$ meaning that it depends logarithmically on mass squared scale. For fermions $k = 1$ is realized.

Conformal invariance motivates the guess that T_p corresponds to the hadronic temperature T. p-Adic temperature is not the same thing as the ordinary temperature. T_p scales like $1/log(p) \propto 1/k$ if the p-adic length scale hypothesis $p \simeq 2^k$ and supported by the function field generalization of p-adic numbers holds true.

$1/p$ scales like mass squared and p-adic temperature T_p scales like logarithm of the mass squared scale and is discrete. If the p-adic length scale hypothesis is true, the ratio of p-adic temperatures equals to $T_k/T_l = l/k$. The piecewise constancy justifies the interpretation as Hagedorn temperature. For instance, $T_{89}/T_{127} = 127/89 = 1.42$ so that the scaling is very slow. M_{89} corresponds to 284 MeV if M_{107} corresponds to 200 MeV.

Quantum criticality is associated with the transition changing the p-adic length scales Compton lengths for the scaled up hadron physics would be the same as for the M_{107} hadron physics at quantum criticality. Critical points could correspond to the temperatures of quark gluon plasmas characterized by the p-adic temperature depending logarithmically on the p-adic mass scale. This predicts that critical collision energies $\sqrt{s_{NN}}$ come as powers of 2.

REFERENCES

Theoretical Physics

[B1] Rafelski J Ericson T. The tale of the Hagedorn temperature. *Cern Courier*, 43(7), 2002. Available at: `https://www.cerncourier.com/main/toc/43/7`.

Particle and Nuclear Physics

[C1] Aboone BE et al. RHIC. Beam Energy Dependence of Fifth- and Sixth-Order Net-Proton Number Fluctuations in Au+Au Collisions at RHIC. *PRL*, 130(082301), 2023. `https://arxiv.org/pdf/2207.09837`. See also Erratum PRL 134,139901 (2025). `https://doi.org/10.1103/PhysRevLett.130.082301`.

Books related to TGD

[K1] Pitkänen M. About Preferred Extremals of Kähler Action. In *Physics in Many-Sheeted Space-Time: Part I. https://tgdtheory.fi/tgdhtml/Btgdclass1.html*. Available at: `https://tgdtheory.fi/pdfpool/prext.pdf`, 2023.

[K2] Pitkänen M. Dark Nuclear Physics and Condensed Matter. In *TGD and Nuclear Physics. https://tgdtheory.fi/tgdhtml/Bnucl.html*. Available at: `https://tgdtheory.fi/pdfpool/exonuclear.pdf`, 2023.

[K3] Pitkänen M. Does TGD Predict a Spectrum of Planck Constants? In *Dark Matter and TGD: https://tgdtheory.fi/tgdhtml/Bdark.html*. Available at: `https://tgdtheory.fi/pdfpool/Planck`, 2023.

[K4] Pitkänen M. New Physics Predicted by TGD: Part I. In *p-Adic Physics.* *https://tgdtheory.fi/tgdhtml/Bpadphys.html*. Available at: https://tgdtheory.fi/pdfpool/TGDnewphys1.pdf, 2023.

[K5] Pitkänen M. New Physics Predicted by TGD: Part II. In *p-Adic Physics.* *https://tgdtheory.fi/tgdhtml/Bpadphys.html*. Available at: https://tgdtheory.fi/pdfpool/TGDnewphys2.pdf, 2023.

Articles about TGD

[L1] Pitkänen M. Cold Fusion Again . Available at: https://tgdtheory.fi/public_html/articles/cfagain.pdf., 2015.

[L2] Pitkänen M. Cold fusion, low energy nuclear reactions, or dark nuclear synthesis? Available at: https://tgdtheory.fi/public_html/articles/krivit.pdf., 2017.

[L3] Pitkänen M. Could TGD provide new solutions to the energy problem? Available at: https://tgdtheory.fi/public_html/articles/proposal.pdf., 2020.

[L4] Pitkänen M. Two objections against p-adic thermodynamics and their resolution. https://tgdtheory.fi/public_html/articles/padmass2022.pdf., 2022.

[L5] Pitkänen M. About the TGD based views of family replication phenomenon and color confinement. https://tgdtheory.fi/public_html/articles/emuanomaly.pdf., 2023.

[L6] Pitkänen M. Holography and Hamilton-Jacobi Structure as 4-D generalization of 2-D complex structure. https://tgdtheory.fi/public_html/articles/HJ.pdf., 2023.

[L7] Pitkänen M. Magnetic Bubbles in TGD Universe: Part I. https://tgdtheory.fi/public_html/articles/magnbubble1.pdf., 2023.

[L8] Pitkänen M. Magnetic Bubbles in TGD Universe: Part II. https://tgdtheory.fi/public_html/articles/magnbubble2.pdf., 2023.

[L9] Pitkänen M. About Langlands correspondence in the TGD framework. https://tgdtheory.fi/public_html/articles/Frenkel.pdf., 2024.

[L10] Pitkänen M. About the Recent TGD Based View Concerning Cosmology and Astrophysics. https://tgdtheory.fi/public_html/articles/3pieces.pdf., 2024.

[L11] Pitkänen M. Holography=holomorphy vision in relation to quantum criticality, hierarchy of Planck constants, and M^8-H duality. https://tgdtheory.fi/public_html/articles/holoholonumber.pdf., 2024.

[L12] Pitkänen M. Some solar mysteries. https://tgdtheory.fi/public_html/articles/Haramein.pdf., 2024.

[L13] Pitkänen M. A more detailed view about the TGD counterpart of Langlands correspondence. https://tgdtheory.fi/public_html/articles/Langlands2025.pdf., 2025.

[L14] Pitkänen M. About Dirac equation in $H=M^4\times CP_2$ assuming Kähler structure for M^4 . https://tgdtheory.fi/public_html/articles/HJdireq.pdf., 2025.

[L15] Pitkänen M. About the construction of the scattering amplitudes using M^8-H duality. https://tgdtheory.fi/public_html/articles/M8Hample.pdf., 2025.

[L16] Pitkänen M. About the structure of Dirac propagator in TGD. https://tgdtheory.fi/public_html/articles/dirprop.pdf., 2025.

[L17] Pitkänen M. Comparing the S-matrix descriptions of fundamental interactions provided by standard model and TGD. https://tgdtheory.fi/public_html/articles/hadroQCDTGD.pdf., 2025.