Scale invariance in particle physics and cosmology

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Book of Abstracts

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Quantum Scale Symmetry

Quantum scale symmetry is the realization of scale invariance in a quantum field theory. No parameters with dimension of length or mass are present in the quantum effective action. Quantum scale symmetry is generated by quantum fluctuations via the presence of fixed points for running couplings. As for any global symmetry, the ground state or cosmological state may be scale invariant or not. Spontaneous breaking of scale symmetry leads to massive particles and predicts a massless Goldstone boson. A massless particle spectrum follows from scale symmetry of the effective action only if the ground state is scale symmetric. Approximate scale symmetry close to a fixed point leads to important consequences for observations in various areas of fundamental physics.
We review consequences of scale symmetry for particle physics, quantum gravity and cosmology. For particle physics, scale symmetry is closely linked to the tiny ratio between the Fermi scale of weak interactions and the Planck scale for gravity. For quantum gravity, scale symmetry is associated to the ultraviolet fixed point which allows for a non-perturbatively renormalizable quantum field theory for all known interactions. The interplay between gravity and particle physics at this fixed point permits to predict couplings of the standard model or other "effective low energy models" for momenta below the Planck mass. In particular, quantum gravity determines the ratio of Higgs boson mass and top quark mass. In cosmology, approximate scale symmetry explains the almost scale-invariant primordial fluctuation spectrum which is at the origin of all structures in the universe. The pseudo-Goldstone boson of spontaneously broken approximate scale symmetry may be responsible for dynamical dark energy and a solution of the cosmological constant problem.

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Scale Invariance and its Breaking in Cosmology

Holographic ideas are used to set-up cosmology along the Wilsonian paradigm. Cosmological solutions are investigated, and the connection between de Sitter and Anti de Sitter regimes in the supergravity landscape is probed.

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K(E10) and Standard Model Fermions

In this talk I will describe an attempt to understand the
fermion spectrum of the Standard Model (with three generations of quarks
and leptons, and no "extra baggage") from a more fundamental theory. One interesting possible consequence of this scheme is the emergence of new super-heavy dark matter candidates.

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Three Scale Invariant Tales

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Scale Invariance and Symmetries in Inflation

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Building a viable asymptotically safe SM

I report on recent work to embed the Standard Model within an asymptotically safe framework. This approach, which is based on gauge-Yukawa theories with interacting UV fixed points, focusses on providing a field theoretical UV completion to the SM along with radiative symmetry breaking. The framework yields several generic predictions.

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Towards a Scale Invariant Theory of Gravity

I will discuss some of the recent results obtained in ghost free infinite derivative theory of gravity, which suggests towards scale invariant, conformally flat for static and rotating non-singular metric solutions at both linear and non-linear level. From quantum perspective such class of theory provides a new scale in the infrared which points towards transmutation of scales from ultraviolet to infrared. Based on these results I will discuss further conjectures that astrophysical blackholes can be mimicked by non local stars puffed up slightly larger than the horizon scale, such that information loss paradox can be ameliorated.

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Dimensional Transmutation in Particle Physics and Cosmology

Models with classical scale invariance (CSI) provides us with a dynamical origin for all masses (via dimensional transmutation) and can account for all evidence of beyond the standard model physics. Furthermore, a general theory with CSI is renormalizable (even in the gravity sector) and can solve the hierarchy problem. The price to pay is a classical ghost. The theory, however, admits quantizations that preserve unitarity and a Hamiltonian bounded from below. The solution of the hierarchy problem implies that the theory can be tested through inflationary data (indeed it predicts a (gravitational) isocurvature mode that could be observed in the next future).

I will give an overview of CSI and introduce the subsequent talks on this subject.

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Gauge Assisted Quadratic Gravity

In work with Gabriel Menezes, we are exploring the use of quantum field theory for quantum gravity at all scales. Starting from a scale invariant action, our variant uses an extra Yang-Mills gauge interaction to induce the Einstein action in such a way that gravity is kept weakly coupled at all scales. We have explored the unusual field theoretic aspects of this theory, and so far have promising results.

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Spontaneous Breaking of Restricted Weyl Symmetry in Pure Rˆ2 Gravity

Recent work has shown that pure Rˆ2 gravity (i.e. Rˆ2 gravity with no extra R term) has a symmetry that is larger than scale symmetry and smaller than full Weyl symmetry. This has been dubbed restricted Weyl symmetry as it involves a Weyl transformation where the conformal factor has a constraint. Most importantly, this symmetry is spontaneously broken when the vacuum (background spacetime) has a non-zero Ricci scalar. In this case, the theory can be shown to be equivalent to Einstein gravity with non-zero cosmological constant and a massless scalar field. The massless scalar field is identified as the Goldstone boson of the broken sector. In spontaneously broken theories, the original symmetry of the Lagrangian is realized as a shift symmetry of the Goldstone bosons. We show that this is the case also here. The unbroken R=0 sector is completely different and has no connection to Einstein gravity.

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Fakeons, quantum gravity and the classical limit

A new quantization prescription is able to endow quantum field theory with a new type of "particle", the fakeon (fake particle), which mediates interactions, but cannot be observed. A massive fakeon of spin 2 (together with a scalar field) allows us to build a theory of quantum gravity that is both renormalizable and unitary, and to some extent unique. After presenting the general properties of this theory, I discuss its classical limit, which carries important remnants of the fakeon quantization prescription.

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Conformal extensions of the Standard Model

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A ghost and a naked singularity: facing our demons

We encounter these demons on the path towards a UV complete QFT of gravity and a horizonless replacement for black holes. The fate of the ghost and related issues are discussed in the strong coupling version of classically scale invariant quadratic gravity. We compare this story to QCD. The 2-2-hole solutions appearing in a classical approximation of the gravity theory are then discussed, along with some new results. The timelike singularity is shrouded by a fireball and thorny issues of black hole horizons are avoided. Observable consequences might even lurk in present LIGO data.

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Scale invariance: super-cooling and Dark Matter (talk shared with S.Iso)

If the electroweak sector of the Standard Model is described by classically conformal dynamics, the early Universe evolution can be substantially altered. In particular, one generically has a significant period of super-cooling, often ended when quark condensates form at the QCD phase transition. This scenario is potentially rich in cosmological consequences, such as renewed possibilities for electroweak baryogenesis and gravitational-wave production. In the second part of the talk we will focus on Super-cool Dark Matter, a new mechanism of generation of the cosmological Dark-Matter relic density: super-cooling can easily suppress the amount of Dark Matter down to the desired level. This mechanism generically takes place in old and new scale-invariant models.

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On the preheating in a scale invariant UV extension of Higgs inflation

Higgs inflation with the nonminimal coupling to gravity \xi Hˆ2 R is the unique model
to realize inflation driven by the Standard Model Higgs field in a classically scale invariant way.
However, the reheating in that model is not understood well yet.
In particular, in the so-called "non-critical"regime, it turned out that there are violent instabilities
in the longitudinal mode at very high energy scales.
Since they lie beyond the cutoff scale of the theory, it is not clear if they are really physical,
and how they affect the process of reheating if ever.
In this talk, I will point out that by extending the model by adding the classically
scale invariant Rˆ2 term, the model is UV extended so that it becomes possible to analyze the instabilities
within the validity of the theory. For stronger Rˆ2 term, I show that the instability gradually disappear.
I will clarify if there are some parameter spaces where the instabilities still remain below the cutoff scale
and the instabilities are really physical. I also discuss how the reheating will proceed.

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Scale symmetry, the Higgs and the cosmos

I will review a scale-invariant extension of the Standard Model and gravity able to support inflation and dark energy and containing just an additional degree of freedom on top of the Standard Model content. This scenario has some interesting features such as i) the existence of a conserved current that effectively forbids the generation of isocurvature perturbations ii) an alpha-attractor-like solution for the spectral tilt and the tensor-to-scalar ratio, iii) the absence of fifth-force effects and iv) a set of consistency relations between the inflationary and dark energy observables that can be tested with future cosmological observations.

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What do we know about quantum corrections to Higgs Inflation?

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Quantum Scale Invariance and Weyl Conformal Gravity

Recent results in (quantum) scale invariance and its spontaneous breaking are presented. In flat spacetime, for a scale invariant theory the scalar potential is presented at three loops while keeping manifest scale symmetry. This is possible in a scale-invariant regularization (in $d = 4 - 2\epsilon$) in which the Goldstone (dilaton) of this symmetry generates (spontaneously) the subtraction scale (μ). Although non-polynomial (effective) operators are generated at the quantum level, suppressed by the (large) dilaton vev, a classical hierarchy of vev's (Higgs vs dilaton vev) is quantum stable. In curved spacetime, conformal symmetry and consistency (no ghosts) demands one introduce the Weyl gauge field ω_μ (and Weyl conformal geometry). In the {\it absence} of matter, Weyl's (conformal) quadratic gravity has spontaneous breaking (Stueckelberg mechanism) to Einstein action which is a "low-energy" effective theory below the mass of ω_μ (where the geometry becomes Riemannian). In the {\it presence} of matter (Higgs) with non-minimal coupling to Weyl gravity, the breaking of Weyl conformal symmetry triggers EW symmetry breaking. (arXiv:1812.08613, 1809.09174, 1712.06024)

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Gravity, Scale Invariance and the Hierarchy Problem

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Combining the quantum scale invariance with the absence of new degrees of freedom above the electroweak scale leads to stability of the latter against perturbative quantum corrections. Nevertheless, the hierarchy between the weak and the Planck scales remains unexplained. We argue that this

hierarchy can be generated by a non-perturbative effect relating the low energy and the Planck-scale physics. The effect is manifested in the existence of an instanton configuration contributing to the vacuum expectation value of the Higgs field. We analyze such configurations in several toy models and in a phenomenologically
viable theory encompassing the Standard Model and General Relativity in a scale-invariant way. Dynamical gravity and a non-minimal coupling of it to the Higgs field play a crucial role in the mechanism.

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Conformal symmetry as an exact symmetry with Higgs mechanism (TH colloquium)

In theories such as asymptotically safe gravity, conformal symmetry is treated as a symmetry for the ultra-violet limit of quantum gravity. However, gravity can be formulated as a theory where conformal symmetry is exact, but broken in the same way as in the Brout-Englert-Higgs-Kibble formalism, where local gauge symmetry is still exactly valid but realised in an apparently asymmetric manner. This formally turns gravity into a renormalizable theory, except for the fact that a physically dubious particle emerges, a heavy excitation of the graviton with spin 2 but negative metric. It is not understood what exactly the role of such a particle would be, but it can be pointed out that, leaving this mystery as it is, does produce a scheme that is worth further study. It generates a system without any tuneable parameters, so it may be worth-while to investigate what the coupling parameters of such a theory would be, and check whether anything physically realistic can be produced. We must have matter added to the system, and the algebra will have to meet with rigorous constraints.

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Inertial Weyl Symmetry Breaking, Dilaton, and Weyl Photon

Globally Weyl invariant theories have a conserved current that is generally the derivative of a scalar. In general expansion, this scalar flows to a constant, K, that serves as the order parameter of symmetry breaking, eg, the decay constant of the dilaton is proportional to \sqrt{K}. If we introduce the Weyl photon the dilaton is eaten and the photon acquires a mass proportional to K. The divergence of the Weyl current is the trace anomaly, and connected to the renormalization group (RG). If the RG is interpreted as flow of coupling constants in Weyl invariant ratios, such as $VEV(phi_i)^2/K$, then the Weyl symmetry is maintained at the quantum level.

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Quantum Scale Invariance, Hierarchy generation and Inflation

Global and local Weyl invariant theories of scalars and gravity can generate all mass scales spontaneously, initiated by a dynamical process of "inertial spontaneous symmetry breaking"that does not involve a potential. We discuss how inflation readily occurs and how an hierarchy of mass scales may be generated and consider its stability against quantum corrections.

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Status and Perspectives of Asymptotic Safety

I will review the key idea underlying the asymptotic-safety programme both in particle physics as well as quantum gravity. I will discuss mechanisms that can generate asymptotic safety and will provide an overview of models that could exhibit these mechanisms. After reviewing recent developments I will give a short outlook on future perspectives.

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Fundamental Interactions

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Phenomenological and cosmological implications of hidden scale invariance

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I discuss a class of effective low-energy theories that incorporate nonlinearly realised scale invariance through the dilaton field. Radiatively stable mass hierarchies are realised in a natural (without fine-tuning) way in this class of models, with a generic prediction of a light dilaton field. The cosmological electroweak phase transition in this scenario is triggered by the QCD phase transition. This has significant implications for potential gravitational wave signals, solar masses black holes and generation of matter-antimatter asymmetry at the QCD scale.

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Scale Invariant Theories of Gravity and the Meaning of the Planck Mass

I will review metric-affine theories of gravity and the occurrence of a Higgs mechanism that gives mass to the gravitational connection. I will then discuss the possibility of achieving quantum scale invariance at high energy in such theories.

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Asymptotic Safety and Conformal Standard Model

There are many proposals to extend the Standard Model designed to deal with its fundamental inconsistencies. Since no new particles have been detected experimentally so far, the models which add only one more scalar particle and possibly right-chiral neutrinos are favored. One of them is the Conformal Standard Model, which proposes a coherent solution to the Standard Model drawbacks including the hierarchy problem and a dark matter candidate. On the other hand there are signs that gravity is asymptotically safe. If there are no intermediate scales between electroweak and Planck scale then the Conformal Standard Model supplemented with asymptotically safe gravity can be valid up to arbitrarily high energies and give a complete description of particle physics phenomena. Moreover asymptotic safety hypothesis restricts the mass of the second scalar particle to 300 ± 28 GeV, for a_{\lambda_3} <0. The masses of heavy neutrinos can also be estimated as 683 ± 83 GeV so these predictions can be explicitly tested in the nearby future.

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Scale invariance and strong dynamics as the origin of inflation and the Planck mass

Classical scale invariance represents a promising framework for model building beyond the Standard Model. However, once coupled to gravity, any scale-invariant microscopic model requires an explanation for the origin of the Planck scale. In this talk, I will present a minimal example for such a mechanism and show how the Planck mass can be dynamically generated in a strongly coupled gauge sector. I will consider the case of hidden SU(N) gauge interactions that link the Planck scale to the condensation of a scalar bilinear operator that is nonminimally coupled to curvature. The effective theory at energies below the Planck mass contains two scalar fields: the pseudo-Nambu-Goldstone boson of spontaneously broken scale invariance (the dilaton) and a gravitational scalar degree of freedom that originates from the Rˆ2 term in the effective action (the scalaron). I will discuss the effective potential for the coupled dilaton-scalaron system at one-loop order and demonstrate that it can be used to successfully realize a stage of slow-roll inflation in the early Universe. Remarkably enough, our predictions for the primordial scalar and tensor power spectra interpolate between those of standard Rˆ2 inflation and linear chaotic inflation. For comparatively small gravitational couplings, one thus obtains a spectral index n_s ˜= 0.97 and a tensor-to-scalar ratio as large as r ˜= 0.08.

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Conformal Realization of the Neutrino Option and its Gravitational Wave Signature

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It was recently proposed that the electroweak hierarchy problem is absent if the generation of the Higgs potential stems exclusively from quantum effects of heavy right-handed neutrinos which can also generate active neutrino masses via the type-I seesaw mechanism. Hence, in this framework dubbed the "neutrino option", the tree-level scalar potential is assumed to vanish at high energies. Such a scenario therefore lends itself particularly well to be embedded in a classically scale-invariant theory. In this talk we demonstrate that the minimal scale-invariant framework compatible with the "neutrino option" requires the Standard Model to be extended by two real scalar singlet fields in addition to right-handed neutrinos. We present the parameter space of the model for which a phenomenologically viable Higgs potential and neutrino masses are generated, and for which all coupling constants remain in the perturbative regime up to the Planck scale. In addition, we show that the phase transition connected with radiative scale symmetry breaking is of strong first order with a substantial amount of supercooling. This yields a sizable gravitational wave signal, so that the model can be fully tested by future gravitational wave observatories. In particular, most of the parameter space can already be probed by the upcoming LIGO science run starting in early 2019.

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A generalized multiple-point (criticality) principle and inflation

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Scale invariant extension of the SM with strongly interacting hidden sector and dark pion DM (WIMP vs. SIMP)

Scale invariant extension of the SM with QCD-like strongly interacting hidden (dark) sector is interesting, since the dimensional transmutation and chiral symmetry breaking in the hidden sector could be the origin of electroweak symmetry breaking (EWSB), and all the masses of the SM particles as well as dark pions and dark baryons that could be good cold dark matter candidates. In this talk I discuss dark pion DM as WIMP vs. SIMP. Ignoring the West-Zumio-Witten (WZW) interaction, I first discuss dark pion as a WIMP using two different approaches, the chiral perturbation theory (ChPT) and AdS/QCD. Then I include the WZW interaction and discuss dark pion within SIMP scenario. However, the analysis based on ChPT indicates that the viable parameter space for SIMP seems to be outside the validity region of ChPT. I show that this problem can be resolved if we include dark vector mesons, and the SIMP idea can be realized in the dark pion sector.

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Making sense of the Nambu-Jona-Lasinio model via scale invariance

The status of the chiral-invariant Nambu-Jona-Lasinio (NJL) four-fermi model is quite equivocal. It serves as the paradigm for dynamical symmetry breaking and yet it is not renormalizable. NJL only studied one loop graphs with point vertices, and needed to use an ultraviolet cutoff. We propose to dress the point vertices with scale invariant vertices with anomalous dimensions. We show that if the dimension of the $\bar{\psi}\psi$ fermion mass operator is reduced from a canonical three to a dynamical two, the four fermion interaction becomes renormalizable to all orders in the four-fermion coupling constant. Additionally, we find that dynamical symmetry breaking then occurs with the fermion becoming massive, and we obtain a dynamical massless pseudoscalar Goldstone boson and a dynamical scalar Higgs boson. The Higgs boson mass is automatically of order the dynamical fermion mass, with there thus being no hierarchy problem. The Higgs boson automatically has a width, and the width could serve as a diagnostic to distinguish a dynamical Higgs from an elementary one. We extend the scale invariance to local conformal invariance as then coupled to a gravity theory, conformal gravity, that is conformal too. With Bender and Mannheim having shown that conformal gravity is a ghost-free, unitary theory, it can serve as a consistent theory of quantum gravity. We show that all of the achievements of supersymmetry can be achieved by conformal symmetry and conformal gravity instead, with there then being no need for any new particles at the LHC.

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Very light dilaton and naturally light Higgs boson

We study very light dilaton, arising from a scale-invariant ultraviolet theory of the Higgs sector in the standard model of particle physics. Imposing the scale symmetry below the ultraviolet scale of the Higgs sector, we alleviate the fine-tuning problem associated with the Higgs mass. When the electroweak symmetry is spontaneously broken radiatively à la Coleman-Weinberg, the dilaton develops a vacuum expectation value away from the origin to give an extra contribution to the Higgs potential so that the Higgs mass becomes naturally around the electroweak scale. The ultraviolet scale of the Higgs sector can be therefore much higher than the electroweak scale, as the dilaton drives the Higgs mass to the electroweak scale. We also show that the light dilaton in this scenario is a good candidate for dark matter of mass mD~1 eV−10 keV, if the ultraviolet scale is about 10−100 TeV. Finally we propose a dilaton-assisted composite Higgs model to realize our scenario. In addition to the light dilaton the model predicts a heavy U(1) axial vector boson and two massive, oppositely charged, pseudo Nambu-Goldstone bosons, which might be accessible at LHC.

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Continuum clockwork and classical scale invariance

The clockwork mechanism provides a useful picture to understand extra dimensions via continuum limit of the scheme (continuum clockwork). The continuum clockwork can find its concrete realization in the general linear dilaton model (GLD). GLD can be defined by classical scale invariance in the presence of supersymmetry, which implies a non-trivial selection rule for radiative corrections to dilaton potential. Known examples of GLD are heterotic M-theory, type II little string theory and non-critical string theories. Previously unexplored Kaluza-Klein spectra and couplings can be captured in GLD, which will be shown to be actually present in heterotic M-theory.

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Black Holes in Higher Derivative Gravity

Including quadratic curvature terms in the gravitational action yields a renormalizable theory at the apparent cost of instability in the radiation field. One also
needs to consider the effects upon classical solutions such as black holes. All vacuum solutions to Einstein's theory remain good solutions to the higher derivative theory, so the Schwarzschild family carries over to the generalized theory. There are in addition non-Schwarzschild solutions, however, crossing the Schwarzschild family at a point governed by the Gross-Perry-Yaffe Lichnerowicz eigenvalue. This crossing point also appears to be a changeover point
for classical stability between the Schwarzschild and non-Schwarzschild black hole families.

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Scale invariance: super-cooling and Dark Matter

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If the electroweak sector of the Standard Model is described by classically conformal dynamics, the early Universe evolution can be substantially altered. In particular, one generically has a significant period of super-cooling, often ended when quark condensates form at the QCD phase transition. This scenario is potentially rich in cosmological consequences, such as renewed possibilities for electroweak baryogenesis and gravitational-wave production. In the second part of the talk we will focus on Super-cool Dark Matter, a new mechanism of generation of the cosmological Dark-Matter relic density: super-cooling can easily suppress the amount of Dark Matter down to the desired level. This mechanism generically takes place in old and new scale-invariant models.

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Conformal Realization of the Neutrino Option and its Gravitational Wave Signature (talk shared with A. Helmboldt)

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