

Closing talk

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We have been exposed to many talks and discussions,
reviewing many preexisting ideas and presenting new ones.

It is natural that each of us interprets new information
in the light of previously stored and digested data.

I will therefore begin by telling you how I have come to think of gravity,
and then how the material of this conference fits into that view.

Where is the group theory?

In the study of fundamental interactions, group theory plays an important role. In particle and in condensed matter physics we encounter both global and local (gauge) symmetries, and they can be unbroken, explicitly broken, spontaneously broken, broken by an anomaly.¹

Which of these situations occurs, determines to a large extent the properties of the theory, e.g. what states propagate, whether they are massive or massless etc.

In textbook GR we only encounter $\text{Diff}M$, which is an unbroken gauge group. This is a consequence of the use of natural (coordinate) frames.

In order to understand better the similarities (and differences) between gravity and the remaining interactions it is convenient to adopt Cartan's approach, which uses arbitrary frames, and an independent connection.

¹I will stick to the common usage and say that a gauge symmetry in Higgs phase is "spontaneously broken", even though gauge symmetries can never be broken.

Cartan's frame fields

Instead of the coordinate components $g_{\mu\nu} = g(\partial_\mu, \partial_\nu)$, one can use as independent variables the frame fields $\theta^a{}_\mu$ (with their dual coframes $\theta_a{}^\mu$) and the components of the metric in the frame: $\gamma_{ab} = g(\theta_a, \theta_b)$. Then

$$g_{\mu\nu}(x) = \theta^a{}_\mu(x) \theta^b{}_\nu(x) \gamma_{ab}(x)$$

In addition to the diffeomorphisms, that act on the greek indices, we now have the pointwise linear transformations of the frames, acting on the latin indices. In matrix form,

$$\begin{aligned}\theta &\mapsto \Lambda^{-1}\theta \\ \gamma &\mapsto \Lambda^T \gamma \Lambda\end{aligned}$$

These form a group of local $GL(4)$ transformations, analogous to the gauge transformations of the standard model.

Constraints

The frames and the metric satisfy some anholonomic constraints that force them to have values in coset spaces

- the metric must have signature $- , + , + , +$, $\Rightarrow \gamma_{ab} \in GL(4)/O(1, 3)$
- the frame must have $\det\theta \neq 0$, $\Rightarrow \theta^a{}_\mu \in GL(4)$

Thus they carry nonlinear realizations of $GL(4)$ and can be interpreted as Goldstone bosons.

Since there are two Goldstone bosons, there are also two “unitary” gauges for $GL(4)$, where one fixes the value of either of them:

- the gauge choice $\theta^a{}_\mu = \delta^a{}_\mu$ breaks $GL(4)$ to $\{\mathbf{1}\}$. It amounts to working in coordinate frames and leads to the usual metric formalism.
- the gauge choice $g_{ab} = \eta_{ab}$ breaks $GL(4)$ to $O(1, 3)$. It amounts to working with orthonormal frames, and leads to the vierbein formulation.

Note that there is not enough freedom to fix both gauge conditions simultaneously (except for flat space).

Connections

The components of a general connection are $A_\mu{}^a{}_b$ and its curvature is

$$F_{\mu\nu}{}^a{}_b = \partial_\mu A_\nu{}^a{}_b - \partial_\nu A_\mu{}^a{}_b + A_\mu{}^a{}_c A_\nu{}^c{}_b - A_\nu{}^a{}_c A_\mu{}^c{}_b$$

The covariant derivatives of the two Goldstone bosons are torsion and nonmetricity

$$\begin{aligned} T_\mu{}^a{}_\nu &= \partial_\mu \theta^a{}_\nu - \partial_\nu \theta^a{}_\mu + A_\mu{}^a{}_b \theta^b{}_\nu - A_\nu{}^a{}_b \theta^b{}_\mu \\ Q_{\lambda ab} &= -\partial_\lambda \gamma_{ab} + A_\lambda{}^c{}_a \gamma_{cb} + A_\lambda{}^c{}_b \gamma_{ac} \end{aligned}$$

Given $\theta^a{}_\mu$ and γ_{ab} , the Levi-Civita connection is the unique connection with zero torsion and nonmetricity

$$\Gamma_{abc} = \frac{1}{2}(E_{cab} + E_{abc} - E_{bac}) + \frac{1}{2}(C_{abc} + C_{bac} - C_{cab})$$

where $E_{cab} = \theta^{-1}{}_c{}^\lambda \partial_\lambda \gamma_{ab}$ and

$$C_{abc} = g_{ad} \theta^d{}_\lambda (\theta^{-1}{}_b{}^\mu \partial_\mu \theta^{-1}{}_c{}^\lambda - \theta^{-1}{}_c{}^\mu \partial_\mu \theta^{-1}{}_b{}^\lambda)$$

Gravitational Higgs mechanism

The action is a functional $S(\theta, \gamma, A)$, invariant under *Diff* and local $GL(4)$. It will contain kinetic terms for the Goldstone bosons, of the form

$$S_G(\theta, \gamma, A) = m^2 \int d^4x \sqrt{|g|} [T_{\dots} T^{\dots} + Q_{\dots} Q^{\dots} + T_{\dots} Q^{\dots}]$$

where we do not spell out all possible contractions of the indices.

Assume that the ground state on the theory is flat spacetime.

There is a gauge choice where it is represented by $\theta^a_{\mu} = \delta^a_{\mu}$, $\gamma_{ab} = \eta_{ab}$.

Expanding around the flat background:

$$T_{\mu}^a{}_{\nu} = A_{\mu}^a{}_{\nu} - A_{\nu}^a{}_{\mu}, \quad Q_{\mu ab} = A_{\mu ab} + A_{\mu ba}$$

and the kinetic term of Goldstone bosons becomes a mass for the connection

$$S_G = m^2 \int d^4x \sqrt{|g|} A_{\dots} A^{\dots}$$

This is a gravitational version of the Higgs phenomenon.

A more general statement

Decompose

$$A_{abc} = \Gamma_{abc} + \Phi_{abc}$$

where the tensor Φ is given by

$$\Phi_{abc} = \frac{1}{2}(T_{abc} + T_{bac} - T_{acb} + Q_{abc} + Q_{cba} - Q_{bac})$$

or conversely

$$T_{\mu}{}^a{}_{\nu} = \Phi_{\mu}{}^a{}_{\nu} - \Phi_{\nu}{}^a{}_{\mu}, \quad Q_{\mu ab} = \Phi_{\mu ab} + \Phi_{\mu ba}$$

If we can change variables from A to Φ , the action becomes

$$S(\theta, \gamma, A) = S(\theta, \gamma, \Gamma(\theta, \gamma) + \Phi) = S'(\theta, \gamma, \Phi)$$

Applying to S_G , we find that it is a mass term for Φ :

$$S'_G(\theta, \gamma, \Phi) = m^2 \int d^4x \sqrt{|g|} \Phi \dots \Phi \dots$$

Thus, without having to assume any specific form for the action, nor that the ground state is flat, we see that the deviation of the dynamical connection A from the Levi-Civita connection Γ is massive.

The Cartan/Palatini term

Note that the "Palatini" term

$$S_P(g, \theta, A) = \frac{m_P^2}{2} \int d^4x \sqrt{|g|} F(A)_{ab}{}^{ab}$$

also contributes

$$\frac{m_P^2}{2} \int d^4x \sqrt{|g|} \left(\Phi_a{}^{ac} \Phi_{bc}{}^b - \Phi_{bac} \Phi^{acb} \right)$$

(a degenerate quadratic form).

So it is natural to assume that the mass of Φ is at the Planck scale.

At energies much below this mass scale we can assume

$$\Phi = 0 \iff T = Q = 0 \iff A = \Gamma(\theta, g)$$

independently of the detailed form of the action.

So this formulation of gravity has a greater explanatory power than the standard one, since it explains why, at low energy, the connection can be identified with the Levi-Civita one, a fact that normally has to be postulated.

Similarity to electroweak and strong interactions

We also recognize that gravity looks exactly like the low energy limit of a theory in the Higgs phase.

It is similar to the low energy limit of the Landau-Ginzburg theory of superconductivity, or to the so-called "electroweak chiral perturbation theory", that describes electroweak theory below the Higgs mass.²

Unlike these two theories, where the Goldstone boson disappears when one fixes the unitary gauge, in the case of gravity one of the two Goldstone bosons remains, and then plays a role that is very similar to that of the pion fields in the low energy theory of the strong interactions.

²It differs from the full Weinberg-Salam theory, whose Higgs doublet carries a linear representation.

Main questions

Since the metric is the order parameter that determines whether the theory is in the "broken" (Higgsed) or unbroken phase, the most important questions for quantum gravity would be

- Is the metric a fundamental variable?
- What generates the VEV for the metric, and why is it Minkowski space?

A theory that addresses these questions will be called a *quantum theory of spacetime*

There are also other classes of questions that we expect a quantum theory of gravity to address, namely those related to gravitational scattering and to cosmology.

I will now review the main approaches to Quantum Gravity (QG) discussed in this conference and comment on the extent to which they address these questions.

A difficulty

In the continuum quantum field theory (QFT) description of a broken symmetry $G \rightarrow H$ (à la Landau–Ginzburg) the order parameter is a linear field and its VEV is determined by the minima of a G –invariant potential.

This is not possible in gravity because, as we have seen, the embedding of the coset in a linear space is defined by anholonomic constraints.

In practice, in gravity *Diff*–invariance means that the potential must be a function of $g^{\mu\nu}g_{\mu\nu}$, i.e. a constant. One needs two metrics to write a potential for the metric, as in massive gravity.

Theories of spacetime cannot be so simple.

Discrete models

Causal Dynamical Triangulations (CDT), as discussed by **Loll**, is a rather successful theory of spacetime based on glueing standard 4-simplexes with a suitable weight inspired by the Hilbert action.

It can be in various phases, among which

- the crumpled phase, where every simplex is attached to every other, can be identified with the "unbroken" phase with vanishing VEV for the metric
- an extended 4-dimensional phase, approximating in some sense a De Sitter geometry, can be identified with the Higgs phase.

CDT can also be viewed as a tool to explore the transitions between these phases, possible associated continuum limits and their relation to continuum theories such as Hořava gravity and asymptotic safety.

Causal set theory is the most minimalistic of all approaches to QG, assuming only a discrete set of points and their causal relations. Nevertheless, as recalled by **Dowker**, Sorkin could derive from this theory a rather striking prediction for the value of the cosmological constant.

Loop Quantum Gravity

LQG was initially formulated as a continuum, Hamiltonian quantization of GR, based mainly on quantum mechanical, rather than QFT methods.

It is close in spirit to Cartan's description of gravity:

the connection (or a discrete version of it) is an independent variable and group theory plays an important role.

One striking aspect of this is that gravity can be seen as a constrained version of an $SU(2)$ Yang-Mills theory, as recalled by **Sahlmann**.

Later developments of the theory (the spin foams, discussed by **Sahlmann**, **Dittrich** and Group Field Theory, discussed by **Gielen**) look much more like statistical models.

The connection of these theories to macroscopic gravity is still tenuous. In particular, attempts to generate a continuum 4-dimensional spacetime have met with success only in simplified settings.

AdS/CFT, holography etc

String theory in its original formulation was a perturbative theory in 10 flat dimensions, certainly not a theory of spacetime. However, it has spawned several ideas that could fall in this category.

We heard about AdS/CFT and holography from **Raclarou**. They give us a particular notion of emergence, although only one space dimension would be emergent. Assuming that the AdS/CFT duality holds, as much evidence leads us to believe, it gives a nonperturbative, UV complete theory of gravity, albeit not on a realistic spacetime.

Matrix theory has also been mentioned a few times. Even though in general it has little to do with string theory, some particular models (BFSS, IKKT) can be viewed as nonperturbative formulations of string theory and do give rise, to various degrees, to an emergent space/spacetime.

The most striking development along these lines is the conjecture that the spacetime structure could be dictated by the entanglement between some basic quantum mechanical degrees of freedom. This would certainly be the most beautiful incarnation of a quantum theory of spacetime.

Noncommutative Geometry (NCG)

This is perhaps the only theory, among those discussed here, that uses genuinely new mathematics, at least compared to standard GR and QFT.

As reviewed by [Lizzi](#), the Connes version of NCG replaces the classical notion of manifold by that of spectral triple (A, H, D) , where A is an algebra, H a Hilbert space ("space of spinors") and D an operator on H ("Dirac operator"), all satisfying suitable axioms.

Continuum spacetimes are special cases when A is commutative, and there are rigorous ways to define when a spectral triples "approximates" a continuum manifold.

As an action, NCG uses the spectral action (which is in some ways reminiscent of Sakharov's "induced gravity"). Thus the dynamics of the boson fields, including gravity, can be seen as "emerging" from the more basic dynamics of the spinors.

NCG has also been used to construct models for particle physics. In this role, it implies stronger constraints, compared to a generic QFT.

Quantum theories of gravity but not necessarily of spacetime

This concludes the list of the quantum theories of spacetime.
From now on we assume all the usual geometrical machinery of GR (to be read from the bottom up):

metric
causal structure connection
differentiable structure
topological structure
set

Except for string theory, the following are all QFTs.

EFT of gravity

For a long time it was assumed that nonrenormalizable theories should not even be taken into consideration: they contain an infinite number of divergent terms, and were therefore considered to be completely devoid of predictivity.

It was later understood that some low energy effects are contained in nonlocal terms that are not affected by the divergences.

Thus, even nonrenormalizable theories are predictive, to some extent.

Weinberg proved some theorems that paved the way to the development of Effective Field Theories (EFT). This technique was first applied successfully to the low energy description of strong interactions ("chiral perturbation theory"), and later took over most of model building.

The proof that pure GR is nonrenormalizable came only in 1985, but the result was widely anticipated.

The notion of EFT slowly percolated to gravity around the mid '90s through the work of Donoghue.

Applications of the EFT

Bjerrum-Bohr recalled that the first successful application of the EFT logic to gravity was the calculation of the quantum correction to the Newtonian scattering potential

$$V(r) = -\frac{Gm_1m_2}{r} \left[1 + \frac{41}{10\pi} \frac{G\hbar}{r^2c^3} + \dots \right]$$

The coefficient $41/10\pi$ is not affected by UV divergences and is completely unambiguous.

This is because the correction comes from non-local terms in the effective action, of the form

$$\int dx \sqrt{g} [c_1 R \log(\Box) R + c_2 R_{\mu\nu} \log(\Box) R^{\mu\nu}]$$

Such terms are calculable, whereas local terms are affected by the divergences and cannot be calculated.

Beyond perturbations around flat spacetime, nowadays the EFT also plays an important role in cosmology, as we heard in the talk by **Salvio**.

Lessons

The main conclusion to be drawn from this calculation is that the EFT describing gravitons that propagate and interact in Minkowski space, is a quantum theory of gravity that can make unambiguous predictions, as long as one stays well below the Planck scale.

Remarkably, loop effects also generate the general relativistic corrections to the potential. In fact, these and other techniques are being used to compute gravitational wave signatures of black hole mergers (Bjerrum-Bohr).

At the currently available accelerator energies, the gravitational coupling constant is of order $GE^2 \approx 10^{-32}$, so this is the most perturbative of all known QFTs. As a result, the loop corrections are entirely negligible and the EFT is practically indistinguishable from its tree level approximation, which is GR. This is a mixed blessing, because it seems that we will never be able to see the genuine quantum effects.

This makes it extremely important to find situations where this conclusion can be avoided. This could happen near certain black hole horizons, as we heard in the talks by Gneccchi, Emparan and could also be the case for the cosmological constant or quantum noise, as discussed by Friedel.

Beyond the EFT: general requirements

Before coming to actual candidate UV completions, we should recall that one can derive nonperturbative constraints on scattering amplitudes from general principles such as crossing symmetry, unitarity, causality etc. These are modern incarnations of the old S -matrix bootstrap program of the '60s and have been discussed in the talks by Tokareva, Tourkine.

In a somewhat similar vein, there are many attempts to derive constraints on the EFT from assumed properties of its UV completion (swampland). These have been mentioned multiple times. In particular, it has been stressed that different UV completions could give rise to different constraints, and that one should therefore distinguish between different notions of swampland.

These are important research lines that can help us rule out some unpromising models. However, one has to keep in mind that a conclusion can only be as true as the hypotheses it is based on, and one should not underestimate the capacity of Nature to surprise us with unexpected effects.

Higher derivative gravity (HDG)

As recalled by **Salvio**, the first nontrivial step beyond GR was the theory of gravity with action quadratic in curvature. Neglecting total derivatives,

$$S = \int d^4x \sqrt{-g} \left[\frac{1}{2\kappa^2} R - \frac{1}{2\lambda} C^2 - \frac{1}{\xi} R^2 \right],$$

where $\kappa^{-2} = (8\pi G)^{-1} = m_P^2$. This theory is renormalizable.

The propagator in the spin-2 sector is

$$-\frac{4\lambda}{p^4 + \frac{1}{2}\lambda m_P^2 p^2} = \frac{8}{m_P^2} \left(\frac{1}{-p^2} - \frac{1}{-p^2 - \frac{1}{2}\lambda m_P^2} \right)$$

and shows, in addition to the massless graviton, a massive ghost, that is also tachyonic when $\lambda < 0$. The spin-0 sector has propagator

$$\frac{\xi/3}{p^4 + \frac{1}{12}\xi m_P^2 p^2} = \frac{4}{m_P^2} \left(-\frac{1}{-p^2} + \frac{1}{-p^2 + \frac{1}{12}\xi m_P^2} \right)$$

The massless pole is pure gauge, as in GR, and the massive spin-0 (called curvaton in cosmology) is a tachyon for $\xi > 0$.

Asymptotic freedom?

The beta functions, derived in the '80s, are

$$\beta_\lambda = -\frac{1}{(4\pi)^2} \frac{133}{10} \lambda^2$$
$$\beta_\xi = -\frac{1}{(4\pi)^2} \frac{5(72\lambda^2 - 36\lambda\xi + \xi^2)}{36}$$

and the theory seems to be Asymptotically Free (AF) in a subset of the first quadrant (where the spin 0 particle is a tachyon).

Apparently, then, perturbation theory is applicable, the tree level analysis of propagating degrees of freedom should be correct and the presence of ghosts seems unavoidable.

However, asymptotic freedom may be only apparent:
the derivative interactions overwhelm the log behavior of the coupling,
making the theory strongly coupled in the UV.

But then, what are its asymptotic states?

What would one really see in a scattering experiment?

These are open questions, that remain under current investigation.

Remarks on Metric-Affine Gravity (MAG)

A symmetric tensor h_{ab} can be split in the following representations of $O(3)$:

TT	$2_4^+, 0_5^+$
TL	1_7^-
LL	0_6^+

and the analogous decomposition for a generic 3-tensor A_{abc} is

	ts	hs	ha	ta
TTT	$3_1^-, 1_1^-$	$2_1^-, 1_2^-$	$2_2^-, 1_3^-$	0^-
$TTL + TLT + LTT$	$2_1^+, 0_1^+$	-	-	1_3^+
$\frac{3}{2}LTT$	-	$2_2^+, 0_2^+$	1_2^+	-
$TTL + TLT - \frac{1}{2}LTT$	-	1_1^+	$2_3^+, 0_3^+$	-
$TLL + LTL + LLT$	1_4^-	1_5^-	1_6^-	-
LLL	0_4^+	-	-	-

Here T and L stand for "transverse" and "longitudinal", and the four columns refer to totally symmetric, hook symmetric, hook antisymmetric and totally antisymmetric.

General MAG in Cartan form

The general Lagrangian for such fields, including terms of dimension 2 and 4, can be written schematically

$$\begin{aligned}
 \mathcal{L}_C = & a^F F + a^{TT} TT + a^{TQ} TQ + a^{QQ} QQ \\
 & + c^{FF} FF + c^{FT} FDT + c^{FQ} FDQ \\
 & + c^{TT} (DT)^2 + c^{TQ} DTDQ + c^{QQ} (DQ)^2 \\
 & + c^{FTT} FTT + c^{FTQ} FTQ + c^{FQQ} FQQ \\
 & + c^{TTT} TTD T + \dots + c^{QQQ} QQDQ \\
 & + c^{TTTT} TTTT + \dots + c^{QQQQ} QQQQ,
 \end{aligned}$$

where D is the A -covariant derivative and F its curvature. Depending on the values of the coefficients a and c , there will be propagating particles with any spin from 0 to 3. Demanding that there are no ghosts and tachyons imposes very strong restrictions, and consistent interactions even more.

In particular we heard from **Francia** about the status of higher spin theories, and their relation to string theory. In view of those results, it is interesting to ask whether a MAG including spin 3 fields could be consistent.

Einstein form

Using the decomposition $A_{abc} = \Gamma_{abc} + \Phi_{abc}$ introduced earlier, with $\Phi \sim T + Q$, the Lagrangian can be rewritten

$$\begin{aligned} \mathcal{L}_E = & a^R R + a^{TT} TT + a^{TQ} TQ + a^{QQ} QQ \\ & + b^{RR} RR + b^{RT} R \nabla T + b^{RQ} R \nabla Q \\ & + b^{TT} (\nabla T)^2 + b^{TQ} \nabla T \nabla Q + b^{QQ} (\nabla Q)^2 \\ & + b^{RTT} RTT + b^{RTQ} RTQ + b^{RQQ} RQQ \\ & + b^{TTT} TT \nabla T + \dots + b^{QQQ} QQ \nabla Q \\ & + b^{TTTT} TTTT + \dots + b^{QQQQ} QQQQ, \end{aligned}$$

where ∇ is the Levi-Civita covariant derivative and R its curvature.

Quantum MAG

Notice the presence of the terms R and RR , showing that a general MAG can be viewed as HDG coupled to some particular matter, represented by the fields T and Q . There are known examples where the theory has no ghosts or tachyons, in spite of the presence of the RR terms.

Specializing the form of the tensors T or Q , this reduces to HDG coupled to spin 0, 1, 2, 3 fields. It is a huge class of scalar-vector-tensor modified gravity theories, of the type that is used in the cosmological models discussed by [Davis](#).

One would expect these theories to have quantum properties similar to those of HDG, for suitable choices of the coefficients a and b .

3 different directions

Returning to the issue of UV completion of the gravitational EFT, there are 3 main directions:

- Hořava gravity
- SUGRA/Superstrings
- asymptotic safety

that we shall now consider in turn.

Hořava gravity

This has been mentioned a few times during the conference.

It is based on the assumption that space and time have different scaling dimensions $x^i \rightarrow bx^i$, $t \rightarrow b^3t$.

Then, the Lagrangian in ADM variables is assumed to have the form

$$\mathcal{L} = \sqrt{q}N \left[\frac{2}{\kappa^2} (K_{ij}K^{ij} - \lambda K^2) - V(R_{ij}) \right]$$

where V is up to cubic in the Ricci tensor of the 3-metric.

Because it contains only two time derivatives of the field, the theory has no ghosts, and the (higher-space-derivative) interactions make it renormalizable. Recently, some version of this theory has been shown to be AF.

Of course, the price one has to pay is giving up (local) Lorentz invariance.

Also, due to the reduced invariance, calculations are much more complicated.

Supergravity (SUGRA)

One of the main ideas brought by particle physics to QG is that perhaps gravity in isolation is inconsistent, but that it becomes consistent when coupled to a suitable set of matter fields.

To guarantee that the good properties are preserved in the loop expansion, one has to postulate suitable symmetries, and the best candidate is supersymmetry (SUSY).

The current status of SUGRA has been reviewed by [Dall'Agata](#).

It was understood early on that local SUSY removes the two-loop divergence of GR, and that a R^4 divergence could appear at three loops (as far as I know, it has not yet been determined whether it appears or not).

It was shown by direct calculations that extended $N = 8$ SUGRA is finite up to four loops, Later, symmetry arguments indicated that divergences are suppressed up to 6 loops, but a divergence of the form $\nabla^8 R^4$ could appear at 7 loops. Will it? Probably yes, although some authors keep claiming that the theory seems better behaved than expected.

Nowadays SUGRA is viewed as the low energy limit of superstring theories.

Superstrings

Among approaches to QG, superstring theory is at the opposite extreme of causal sets, being the one that postulates the existence of the largest number of structures. These are put to good use: some superstring theories on certain backgrounds are UV finite to all orders of perturbation theory, and scattering amplitudes are very well behaved in some (though not all) regimes.

String theory has been less successful as a predictive unified theory of all interactions, partly because of the large number of possible vacua (compactifications, moduli etc). **Dall'Agata** has reviewed progress in the solution of hierarchy problems using compactifications on flat spaces.

A side benefit of string theory has been the development of powerful techniques to compute amplitudes in QFT (KLT, double copy etc). These were used to obtain the SUGRA results mentioned in the previous slide, and also in the aforementioned calculations of gravitational wave forms (**Bjerrum-Bohr**)

Asymptotic safety (AS)

Unlike the other UV completions mentioned so far, AS is nonperturbative: the (dimensionless) couplings are assumed to have a finite UV limit, unlike in AF.

It may work for pure gravity, but AS of gravity by itself would not be enough: we want AS for gravity and all other interactions. Gravity affects matter: it must cure the UV issues of the SM. Conversely, matter affects gravity: fixed point may not exist if there are too many fields of certain types.

As emphasized by **Eichhorn**, one can use both arguments to make predictions. This logic could lead to the determination of some of the parameters that are free in the SM, such as mass ratios, mixing angles etc.

Predictions

AS is a direct extension of the EFT towards higher energy, and it correctly reproduces results of the EFT in the IR, as discussed by **Assant**.

What is missing so far is a clean, unambiguous prediction of the outcome of a measurement in some (thought)-experiment, analogous to the $41/10\pi$ of the EFT, but in the Planckian regime.

The main reason for this is the need to make approximations in the Functional Renormalization Group. The two main forms of expansion are the derivative expansion and the vertex expansion. In the beginning, most of the work has used the former, and calculations focused mostly on the running of coefficients of field monomials in the Lagrangian, which are not by themselves measurable, resulting in large systematic uncertainties.

The focus of the community is shifting gradually towards the vertex expansion, which is better suited to discussions of scattering processes, and where one can compute directly amplitudes, rather than Lagrangian couplings.

HDG and AS

Notice that AF is a special case of AS.

In particular, the AF fixed point of HDG can be seen very well in the theory space explored in the search of AS. This fixed point is better understood because it can be studied in perturbation theory, but I have already mentioned that the underlying physics remains somewhat mysterious.

For this reason I believe that understanding scattering in HDG is a very useful preliminary step to understanding scattering in AS.

Observables I

The structure of the theory is strongly influenced by what we want to compute, and vice versa.

In what I called theories of spacetime, it is quite hard to define observables beyond dimension, volume, average curvature, and a few others (Loll).

This should be contrasted to the large number of observables that are implicit in a scattering experiment.

Essentially all we know about subnuclear physics comes from scattering experiments, and one would expect this to be the case also for quantum gravity. Such calculations require many a priori assumptions, and constrain the theoretical framework to asymptotically flat (or AdS) spacetimes.

Leaving momentarily aside the practical feasibility issues, an unambiguous prediction of what one would see if the energy of the accelerators could be pushed up to the Planck scale, would give us a lot of confidence in the theory.

Observables II

Einstein sometimes complained that in classical GR, rods and clocks have to be treated as external entities, and are not described by the theory itself. As long as one thinks of laboratory measurements, this is a reasonable procedure. However, when the object under study is the whole universe, the measuring apparatus must be part of the system. One is then led to consider relational observables (**Gielen**), and this adds a whole new layer of conceptual complications.

Space, time and quantum mechanics

Here I want to mention two rather far fetched possibilities, that however cannot be excluded a priori.

In quantum mechanics, time is treated very differently from space (the position of a particle in space is an operator, its position in time is not). In QFT they can again be treated on the same basis, because it is the field that becomes an operator. It is generally expected that this situation will persist in QG.

However, we should be open to the possibility that time is really different, as in quantum mechanics, and that Lorentz invariance could be a property of low energy physics, as happens in Hořava theory or the BFSS matrix model.

Conversely the formulation of a quantum theory of cosmology, where the observers are necessarily internal to the system, may possibly require some modification of quantum mechanics.

If either of these possibilities was realized, it would require a significant revision of our ideas.

Conclusions

Let us stop saying: "we do not yet have a quantum theory of gravity".
By any reasonable definition, the EFT is a quantum theory of gravity.
Nobody ever dreams of saying that "we do not yet have a quantum theory of the electroweak interactions" because the SM is UV-incomplete.

Correct statements would be
"we do not yet have a quantum theory of spacetime"
or "we do not yet have a UV complete quantum theory of gravity".

We actually do have several candidates for both, and I am quite confident that some of them are at least on the right track. In fact it is quite possible that different approaches are simultaneously "correct", in the sense that they probe different aspects of reality.

Conclusions

I have made a broad distinction between theories of spacetime, whose main aim is to explain the existence of an extended spacetime with a smooth metric, and UV completions of the gravitational EFT.

- The former are mostly nonperturbative and the latter mostly perturbative (except for AS).
- They make widely different assumptions, from the fewest of causal sets to the most of superstrings.
- They strive to compute very different observables.

For these reasons, I think that they should also be judged by different criteria, and that direct comparisons are misleading.

From the way things stand at the moment, it would seem unlikely that all our goals can be achieved by a single theory.

But, *hic sunt leones....*