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Personal reflections on two success stories

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Outline

• The SM of Nature after LHC & PLANCK
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• Quantum corrections: the good and the bad
  • A 3rd personal reflection
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• Can it be Quantum String Theory?
The Standard Model of Nature (after LHC & PLANCK)

Its two components:

1. The SM of Elementary Particles and their non-gravitational interactions based on a Gauge Theory
2. The SM of Gravity and Cosmology based on General Relativity
Through many decades this SMN has been thoroughly tested and only slightly amended/extended.

It represents an unprecedented Triumph of Reductionism.

The theory of all known particles and forces can be written on one slide.
\[ L_{SMN} = L_{SMG} + L_{SMP} \]

\[ L_{SMG} = -\frac{1}{16\pi G_N} \sqrt{-g} \, R(g) + \frac{1}{8\pi G_N} \sqrt{-g} \, \Lambda \]

\[ L_{SMP} = -\frac{1}{4} \sum_a F^a_{\mu\nu} F^a_{\mu\nu} + \sum_{i=1}^{3} i\bar{\Psi}_i \gamma^\mu D_\mu \Psi_i + D_\mu \Phi^* D^\mu \Phi \]

\[ -\sum_{i,j=1}^{3} \lambda^{(Y)}_{ij} \Phi \Psi_{\alpha i} \Psi^c_{\beta j} \epsilon_{\alpha\beta} + c.c. \]

\[ + \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 \]

\[ -\frac{1}{2} \sum_{i,j=1}^{3} M_{ij} \nu^c_{\alpha i} \nu^c_{\beta j} \epsilon_{\alpha\beta} + c.c. \]
The SM of Elementary Particles

A quantum-relativistic theory incorporating the gauge-invariance principle.

The quantum-relativistic nature of SMEP manifests itself through real and virtual particle production.

These are essential for agreement experiment.

(tree-level predictions are off by many $\sigma$)

Actually virtual effects anticipated, theoretically, the experimental discoveries of the top quark and of the Higgs boson.
Strong hints of a light Higgs after LEP
Understanding non-perturbative (i.e. very quantum) IR effects was also crucial within the strong interaction (QCD) sector of the SM (confinement of quarks, chiral symmetry breaking, instantons,...)
The SM of Gravity...

General Relativity: a classical relativistic theory incorporating the equivalence principle.

UFF tested with incredible precision

Corrections to Newtonian Gravity well tested

New GR predictions:

1. Black holes (overwhelming evidence)
2. Gravitational waves (indirect evidence)

NB: All tests of Classical GR!!
... and Cosmology

Various sets of data appear to converge towards the so-called concordance model
Cosmic Concordance
Portions in cosmic composition pie... somewhat redistributed after PLANCK

Before Planck

- Dark Energy: 72.8%
- Ordinary Matter: 4.5%
- Dark Matter: 22.7%

After Planck

- Dark Energy: 68.3%
- Ordinary Matter: 4.9%
- Dark Matter: 26.8%
Two arguments for DE (CMB & LSS) are based on inhomogeneities.

The 3rd one (SNIa) ignores them completely.

Q: How do inhomogeneities affect the determination of DE parameters via SN? Studied in a series of papers: (GMNV, 1104.1167, BGMNV, 1202.1247, 1207.1286, 1302.0740; BGNV, 1209.4326, F. Nugier 1309.6542)

Bottom line: stochastically homogeneous & isotropic inhomogeneities do not change the naive conclusions about DE, but induce an intrinsic scatter limiting attainable precision for limited statistics.
The SMEP and the SMGC nicely combined in inflationary cosmology. At this point CGR is no longer enough for (Semiclassical) quantization of the geometry is part of the game explaining the large-scale structure of the Universe. This will be even more true if the recently claimed detection of primordial GW is confirmed.
Cosmic pie gives strong evidence that our SMN cannot be the full story: no dark matter!

Nonetheless let me draw two observations from its remarkable successes.
The way to describe massless spin-1 particles, and their interactions

A massless $J=1$ particle has two physical polarizations, a massive one has three.

Gauge invariance allows to remove ("gauge away") the unphysical polarization of a $J=1$ massless particle.

Observation #1: Nature appears to like $J=1$ massless particles. That’s why it is partly described by a gauge theory.
A massless J=2 particle has two physical polarizations, while a massive one has five.

General covariance allows to remove the unphysical polarizations of a J=2 massless particle.

Interactions mediated by a massless J=2 particle necessarily acquire a geometric meaning: curved space-time as an emergent phenomenon.

Observation #2: Nature apperas to like J=2 massless particles. That’s why it is partly described by GR!
But why does Nature like $J=1, 2$ massless particles?
Theoretical puzzles

(fortunately there are still some!)
1. Why $G = \text{SU}(3) \times \text{SU}(2) \times \text{U}(1)$?
2. Why do the fermions belong to such a bizarre, highly reducible representation of $G$?
3. Why 3 families? Who ordered them? (Cf. I. Rabi about $\mu$)
4. Why such an enormous hierarchy of fermion masses?
5. Can we understand the mixings in the quark and lepton (neutrino) sectors? Why are they so different?
6. What’s the true mechanism for the breaking of $G$?
7. If it’s the Higgs mechanism: what keeps the boson “light”?
8. If it is SUSY, why did we see no signs of it yet?
9. Why no strong CP violation? If PQSB where is the axion?
10. ...
Puzzles in Gravitation & Cosmology

1. Has there been a big bang, a beginning of time?
2. What provided the initial (non vanishing, yet small) entropy?
3. Was the big-bang fine-tuned (homogeneity/flatness problems)?
4. If inflation is the answer: Why was the inflaton initially displaced from its potential’s minimum?
5. Why was it already fairly homogeneous?
6. What’s Dark Matter?
7. What’s Dark Energy? Why is $\Omega_\Lambda \sim O(1)$ today?
8. What’s the origin of matter-antimatter asymmetry?
9. ...

Not many clues about all these puzzles from presently accessible length/energy scales
Quantum corrections: the good and the bad

- Most radiative corrections (the “good” ones) have been “seen” in precision experiments:
  - running of gauge couplings, scaling violations
  - anomalies in global symmetries (U(1)-problem)
  - effective 4-fermi interactions (neutral-K system)
  - quantum fluctuations during inflation
- A few (the “bad” ones) have not. Basically corrections
  - to the Higgs mass (hierarchy problem)
  - to the cosmological constant (120 orders off?)
The IR-UV connection

- From the point of view of an effective “low-energy” theory we have seen the expected quantum corrections to marginal and irrelevant operators but **NOT** those to relevant (low-dimensional) operators.

- It is well known that quantum corrections to (irrelevant) relevant operators are (in)sensitive to short-distance physics. The opposite is true for sensitivity to long-distance physics.

- This may be telling us, once more, that the SM & GR are **not** the full story!
Other than that, local QFT appears to work fine up to very high energy (cf. triviality bound on Higgs mass).

In the late sixties M. Gell Mann used to say: Nature only reads books in free field theory! Then came QCD and asymptotic freedom.

We can paraphrase it today by saying: Nature only reads books in dimensional regularization (i.e. only knows about logarithmic divergences).
Lesson # 3

Intelligent Ultra-Violet Completion
How about an IR completion?

• For gravity an interesting alternative (or addition?) to an IUV could possibly be an IR modifying GR at cosmologically large distances.

• Examples are the much studied massive-gravity theories on which much progress has been made in recent years.

• It seems that a BD-ghost-free massive gravity theory exhibiting the Vainshtein mechanism (i.e. reducing to GR at moderate distances) does exist and provides a possible degravitation mechanism for vacuum energy at very large scales. Yet it looks rather complicated...
Going back to the IUVC

Q: Is it SUSY?
Theoretically appealing for solving some puzzles (hierarchy, dark matter, grand unification, ...)
Will be explored at LHC14 up to some energy scale: wait and see...

Q: Is SUSY necessary?
Q: Is it sufficient?
Is it **Loop Quantum Gravity**?
(if so, quantum GR is already UV-complete without adding new physics. Not what happened to Fermi’s theory...)

Is it **Quantum String Theory**?
Some properties of QST point in that direction!
I. QST provides a new UV scale

\[ \frac{1}{\hbar} S_{\text{string}} = \frac{T}{\hbar} \text{(Area swept)} \equiv \frac{\text{Area swept}}{\pi l_s^2} ; \quad l_s \equiv \sqrt{\frac{\hbar}{\pi T}} \equiv \sqrt{2\alpha' \hbar} \]

Note analogy with:

\[ G_N \sim T^{-1} \quad l_P = \sqrt{G_N \hbar} \]

\( l_s \) is ST’s Planck constant! Enters in many crucial ways

- **Characteristic size** of a (minimal-mass) string.
- T-duality, mirror symmetry etc.
- Physical reason behind QST’s good UV behavior
- ...

\[ S_{\text{string}}/\hbar \text{ introduces a fundamental length scale:} \]
Interactions smeared over regions of order $l_s$ 
$\Rightarrow$ Quantum corrections down to arbitrarily small distances are under control.
II. J without M

Quantum strings can have up to two units of angular momentum without gaining mass. Consequence of zero-point energy, classically impossible.

\[
\frac{M^2}{2\pi T} \geq J + \hbar \sum_{n=1}^{\infty} \frac{n}{2} = J - \alpha_0 \hbar
\]

\[
\alpha_0 = 0, \frac{1}{2}, 1, \frac{3}{2}, 2.
\]
Classical ST has nothing to do with Classical FT!
QST appears to answer our 2 questions:

Why does Nature like J=1 massless particles?
Why does Nature like J=2 massless particles?

and thus to explain why it is well described by

Gauge Theories + General Relativity

- Together with the smearing of interactions it leads to a **unified and finite** theory of elementary particles, and of their gauge and gravitational interactions, **not just compatible with, but based on**, Quantum Mechanics!
Having a UV-finite theory does not mean having no radiative corrections.

Q₁: Did QST learn our 3rd lesson? (absence of rad. corrections to relevant operators)

All consistent QSTs are supersymmetric and, as such, do satisfy that requirement... in perturbation theory.

But at that level SUSY is unbroken...

Q₂: Is QST able to provide mechanisms of (spontaneous) SUSY breaking that preserves that particular virtue of its perturbation theory? A₂ lies in deep UV, but does not look like a no-go... a selection principle for acceptable string theories/vacua?

Or should we just play, as a last resort, an anthropic game based on the huge landscape of string vacua?
Thank You!