Lessons from two success stories

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Outline

• The Standard Model of Nature & its 2 pillars
  • The SM of Elementary Particles
  • The SM of Gravity & Cosmology
• Two first lessons
• Good and bad quantum effects
  • A third lesson?
• Wanted: an intelligent UV completion
• Can it be Quantum String Theory?
• Conclusion
The Standard Model of Nature
(after LHC & PLANCK)

Resting on two pillars:

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 written on a slide.
\[ L_{SMN} = L_{SMG} + L_{SMP}^{(\text{gen. cov.})} \]

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

\[ L_{SMP} = - \frac{1}{4} \sum_a F^a_{\mu\nu} F^a_{\mu\nu} + \sum_{i=1}^{3} i\bar{\Psi}_i \gamma^\mu D_\mu \Psi_i + D_\mu \Phi^* D^\mu \Phi \]
\[ - \sum_{i,j=1}^{3} \lambda^{(Y)}_{ij} \Phi \Psi_{\alpha i} \Psi^c_{\beta j} \epsilon_{\alpha\beta} + c.c. \]
\[ + \mu^2 \Phi^* \Phi - \lambda (\Phi^* \Phi)^2 \]
\[ - \frac{1}{2} \sum_{i,j=1}^{3} M_{ij} \nu^c_{\alpha i} \nu^c_{\beta j} \epsilon_{\alpha\beta} + c.c. \]
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 effects are essential for agreement between theory and experiment

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

Actually they anticipated, theoretically, the experimental discovery of the Higgs boson.
Strong hints of a light Higgs after LEP
Understanding non-perturbative IR effects was also crucial within the strong interaction (QCD) sector of the SM (confinement of quarks, chiral symmetry breaking, anomalies...)
The SM of Gravity...

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

Universality of free-fall 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.
This graph shows the temperature fluctuations in the Cosmic Microwave Background detected by Planck at different angular scales on the sky, starting at ninety degrees on the left side of the graph, through to the smallest scales on the right hand side. The multipole moments corresponding to the various angular scales are indicated at the top of the graph.

The red dots are measurements made with Planck; these are shown with error bars that account for measurement errors as well as for an estimate of the uncertainty that is due to the limited number of points in the sky at which it is possible to perform measurements. This so-called cosmic variance is an unavoidable effect that becomes most significant at larger angular scales.

The green curve represents the best fit of the 'standard model of cosmology' – currently the most widely accepted scenario for the origin and evolution of the Universe – to the Planck data. The pale green area around the curve shows the predictions of all the variations of the standard model that best agree with the data.

While the observations on small and intermediate angular scales agree extremely well with the model predictions, the fluctuations detected on large angular scales on the sky – between 90° and six degrees – are about 10 per cent weaker than the best fit of the standard model to Planck data. At angular scales...
Cosmic acceleration

Type Ia Supernovae


- Supernova Cosmology Project
- High-Z Supernova Search
- Calan/Tololo Supernova Survey

Accelerating Universe

Decelerating Universe

Redshift

Magnitude

Relative brightness
Cosmic Concordance

Adding LSS & putting all together

- No Big Bang
- Supernovae
- CMB
- Clusters
- flat
- closed
- expands forever
- recollapses eventually

Vacuum energy density (cosmological constant) vs. mass density
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.
Nonlinear Spectrum:

\[ k_{UV} = 3.0 \, \text{h}^{-1} \text{Mpc} \Rightarrow \mu^M = 5 \log_{10} \left( \frac{2+z}{z^2} H_0 \right) \text{is \mu for Milne Universe} \]

\[ \Omega_\Lambda = 0.77, \quad \Omega_\Lambda = 0.75, \quad \Omega_\Lambda = 0.73, \quad \Omega_\Lambda = 0.71, \quad \Omega_\Lambda = 0.69 \]

\[ \langle \mu \rangle - \mu^M \text{ with } \Omega_\Lambda = 0.77, \quad \Omega_\Lambda = 0.75, \quad \Omega_\Lambda = 0.73, \quad \Omega_\Lambda = 0.71, \quad \Omega_\Lambda = 0.69 \]

Observations:

Negligible average at large \( z \l \sim 0.1 \), only a small average shift and big standard deviation at \( z \geq 0.1 \) Doppler.

BUT standard deviation due to lensing terms is \( \sim \nu \).

Reference:


Fabien Nugier (LPTENS) Structures & Dynamics in FLRW APC, 5 March 2013 37 / 42
The total effect is well fitted by Doppler ($z \leq 0.2$) + Lensing ($z > 0.5$), Doppler prediction is a bit bigger than in the literature, Lensing prediction is in great agreement with experiments so far.

Jönsson et al. (2010) 

\[ \sigma_\mu^{\text{lens}} = (0.055^{+0.039}_{-0.041}) z \]

Kronborg et al. (2010) 

\[ \sigma_\mu^{\text{lens}} = (0.05 \pm 0.022) z \]
The SMEP and the SMGC nicely combined in inflationary cosmology. At this point CGR is no longer enough 

(Semiclassical) quantization of the geometry is part of the game explaining the large-scale structure of the Universe. This is 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...

Nonetheless let’s draw some first lessons from its remarkable successes
It’s the way to describe massless spin-1 particles, such as the photon.

A massless J=1 particle (an EM wave) has 2 physical polarizations, while a massive one has 3.

**Gauge invariance** is a (local) symmetry that allows to remove (“gauge away”) the unphysical polarization of a J=1 massless particle while keeping **Lorentz invariance** explicit.

**Lesson #1:** Nature likes J=1 massless particles and is therefore well-described by a gauge theory.
A massless J=2 particle has two physical polarizations, while a massive one has five.

**General covariance** is a (local) symmetry that allows to remove the unphysical polarizations of a J=2 massless particle while retaining explicit Lorentz invariance.

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

Lesson #2: **Nature likes J=2 massless particles and is therefore well-described by GR!**
The question still remains of why Nature likes $m=0, J=1, 2$ particles...
Theoretical puzzles

(fortunately there are still some!)
Particle physics puzzles

1. Why $G = SU(3) \times SU(2) \times U(1)$?
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 $\Omega_\Lambda \approx O(1)$ today?
8. What’s the origin of matter-antimatter asymmetry?
9. ...

Not many clues about all these puzzles from presently accessible length/energy scales.
Theoretical/conceptual problems

In spite of the common denominator of gauge and gravity the SMN is “limping”.

The two legs it is resting on are uneven.

In particular, the GR side should be elevated to a full quantum theory

At least two reasons to be unhappy about leaving gravity classical:

1. Avoid classical singularities;
2. Appeal of quantum origin of LSS.
Quantum Relativistic Problems

- QM was invented/introduced to solve a UV problem.
- Relativistic QM (i.e. QFT) reintroduces one!
- Virtual pair creation (allowed by SR + QM) leads to infinities since virtual particles of arbitrarily high energy are too copiously produced in a local QFT.
- Already true for Gauge Theories.
- Worse for quantum GR since the gravitational interaction grows with energy.
• A recipe, renormalization, handles UV infinities of gauge theories, gives a (partially) predictive theory.
• Attempts to do the same for GR have failed so far.
• The only way to make sense of quantum gravity seems to be to soften it below a certain short-distance scale.
• Like Fermi’s theory wrt the SM, GR would then just be a large-distance approximation to a better theory.
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)

• A couple of them (the “bad” ones) have not. Basically:
  • 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 all the expected quantum corrections to marginal and irrelevant operators but NOT those to relevant (low-dimensional) operators.

• It is well known (and almost obvious) that quantum contributions 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!
In the late sixties M. Gell Mann used to say:
Nature reads books in **free** field theory!
Then came QCD and asymptotic **freedom**.

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

Intelligent Ultraviolet Completion
Q: Is it Supersymmetry?
Theoretically appealing for solving some puzzles (hierarchy, dark matter, grand unification, ...)
It’s being explored at LHC up to some energy scale...wait and see...
Q: Is it String Theory?
A: Possibly, but certainly not Classical String Theory!
The (Nambu-Goto) action of a relativistic string:

\[ S_{\text{rel.string}} = T \int d(\text{area}) \]

is proportional to the area of the surface ("world-sheet") swept by the string, the tension \( T \) being the universal proportionality constant. \( T \) has dimensions energy/length. Leads immediately to some strong consequences...
A classical string cannot have angular momentum without having a finite length $L$, hence a finite mass, $T L$.

**Classical lower bound on $M$:** $M^2 \geq 2\pi T \ J$

The bound is saturated by a rotating rod with $v = c$ at ends.

\[ J = \frac{M^2}{2\pi T} = \alpha' M^2 , \quad \alpha' \equiv \frac{1}{2\pi T} \]

$\Rightarrow$ CST does not allow for the spinning massless states that the SMN badly needs!
II: Absence of a fundamental scale

• Classical string theory is scale free. Classical strings have no characteristic size.

• \( T \) is NOT a fundamental energy or length scale; it is more like a conversion factor allowing to speak equivalently of the mass or length of a string.

• Note analogy with GR: \( G_{\text{NE}} = \text{length} \) (\( c=1 \)).

\[ \Rightarrow \text{CST cannot provide the scale needed for an UV completion of the SMN!} \]

\[ \Rightarrow \text{CST is useless for providing an interesting theory of classical and quantum fields} \]
Can QM save the day?
Has QST already learned our 3 lessons?
I. Appearance of a scale

• In the quantum theory the relevant quantity is the dimensionless action, $S/h$:

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

Note again an analogy with:

$$l_P = \sqrt{G_N\hbar}$$

Quantization has introduced a length scale, $l_s$ (and an associated energy scale $M_s$) needed for UV completion.

• $l_s$ enters string theory in many important ways. It's the characteristic size of a (minimal-mass) string (cf. ground state of an harmonic oscillator).
Interactions are smeared over regions of order $l_s$. 

Field Theory

String Theory
From Fermi (1934) to SMEP (~1973)

The interaction is smeared over a finite region of space-time making it a better theory in UV

The interaction takes place at a single point in space-time

An interesting analogy
II. J without M

A quantum string can have up to two units of angular momentum without gaining mass. The effect comes from zero-point energies...

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

\[ \alpha_0 = 0, \frac{1}{2}, 1, \frac{3}{2}, 2. \]

after consistent regularization
Classical ST has nothing to do with Classical FT!
Unification of all interactions

graviton, and other carriers of gravity-like interactions

\[ m=0, J=1 \]
\[ \Rightarrow \text{photon and other carriers of non-gravitational interactions} \]

\[ m=0, J=0, 2 \]
\[ \Rightarrow \text{graviton, and other carriers of gravity-like interactions} \]
QST appears to have an answer to the 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 this 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 not broken...

Q2: Is QST able to provide a mechanism of (spontaneous) SUSY breaking that preserves that particular virtue of its perturbation theory?

Does not look a priori impossible.
Some less desirable quantum effects
Quantum strings don’t like $D=4$!

Classical strings can move in any ambient space-time, flat, curved, and with an arbitrary number of dimensions.

Quantum strings require suitable space-times (more generally backgrounds) in order to avoid lethal anomalies.

In the case of weakly coupled superstring theories space-time, if nearly flat, must have 9 space and 1 time dimension.

In order to reconcile this constraint with observations we have to assume that the extra dimensions of space are compact (e.g. a 6-torus of small radius $R$)

QM pushes String Theory into a Kaluza-Klein scenario (or the waste basket?) to which it adds interesting twists...
Massless/light scalar fields: Achille’s heel of QST?
• QFT's parameters are replaced by fields whose values provide the «Constants of Nature», e.g. the overall strength $g_s$ of string interactions including $\alpha$

• Are they dynamically determined? Computing $\alpha$ has been a long-time theorist's dream...

• While today these «constants» look to be space-time-independent, their variations may have played a role in early cosmology (e.g. in PBB cosmology).

• If particles associated with above fields are too light, they induce long-range forces that threaten the EP (UFF).

• Very active field of experimental and theoretical research

• No need for Planck-scale experiments for testing string theory. True also for the old hadronic string!

• Tree-level QST is already ruled out! But so is the SMEP!
„Fifth Force” strengths now excluded at small distances

from ST
CONCLUSION

Our present Standard Model of Nature appears to be deceptively simple and successful.

- Its basic underlying principles (gauge invariance and general covariance) can be reduced to the existence of massless spin 1 & spin 2 particles; The evil is in the details:

  - For the SMEP in the matter content, the Yukawa couplings, the Higgs potential etc.
  - For the SMGC in the existence of a dark sector and of a mysterious inflaton.
  - Quantization of both looks more than ever a must
  - But QM brings in problems with its (in)famous UV divergences and its “bad” radiative corrections.
  - An intelligent UV completion appears to be needed
• Quantum String Theory could be such a sought-for completion, but:
  • QST is a package, you can’t just use the part you like about it (you can go from the SM to the SSM, you can’t go to the StSM so easily)
  • QST comes already equipped with SUSY, but also with extra dimensions, with dangerous massless scalars and with a whole landscape of possible vacua.
  • It is already ruled out at the perturbative level, but so is QCD...

• It may take a while before we can solve QST non-perturbatively (both in coupling and derivatives) and find out whether it will survive or go down the drain like its hadronic predecessor.
Thank You!