Les Rencontres de Physique de la Vallée d’Aoste

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Space, time, matter: 90 years after

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~100 years ago: two revolutions

At the beginning of the XXth century two revolutions shook two sacred scientific beliefs:

1. The belief in absolute determinism when Max Planck, in 1900, introduced h and started the Quantum Revolution.
2. The belief in absolute time when Albert Einstein, in 1905, building on the invariance of the speed of light, c, formulated Special Relativity.

10 years later: a 3rd revolution!

3. In 1915, starting from the Galileian universality of free-fall, Einstein arrived at a geometric theory of gravity, General Relativity, in which even the concept of an absolute geometry of spacetime is abandoned.

The best physicists of the time were deeply impressed by these amazing revolutions and wrote vividly about them:

In 1918 Hermann Weyl wrote

"Raum-Zeit-Materie"

In 1950 he wrote a preface to the American printing of its 4th 1921 edition.

In 1921 Wolfgang Pauli wrote

"Relativitatstheorie"

In 1956 he reedited the original text adding several interesting notes...

Both Pauli and Weyl were expressing concern about the lack of a theory of matter exhibiting the same compelling and simple beauty as Maxwell's or Einstein's.

From H. Weyl's 1950 preface

- Importance of (a modified version of his original) gauge invariance principle.
- Need for a "unitary*) theory" encompassing electromagnetic, gravitational and "electronic" fields.
- "Ultimately fields for the other elementary particles should be also included unless quantum physics succeeds in interpreting them all as different quantum states of one particle".

*) read: unified

- Acknowledges success of Dirac's theory of the electron... but adds:

"Difficulties of the gravest kind turn up when one passes from one electron or photon to the interaction among an undetermined number of such particles."

- "Solution not yet in sight: may need deep modification of foundations of QM where the elementary electric charge e is accounted for in a fundamental way like c and h are in Relativity and Quantum Mechanics."

W. Pauli 1956 notes

Not so many on the SR and GR parts.

- Many on the last part (Chapt. 8) devoted to elementary particles.
- Very sharp and critical about most proposals including Einstein's. Classical theory doomed...
- Quite positive (and very clear!) about the Kaluza Klein idea. But conclude s:

"The question of whether the KK formalism will have a bearing on physics leads us to the more general and yet unresolved problem of realizing a synthesis between General Relativity and Quantum Mechanics".

Last sentence:

"New elements, estraneous to the concept of a field as a continuum, should be added in order to arrive at a satisfatory solution of the problem of matter".

While not much has happened since those days as far as Space and Time are concerned, giant steps along the lines advocated by HW and WP have been carried out in what concerns Matter.

The long road to Gauge Theories

- First attempts to combine Special Relativity and Quantum Mechanics in the 30s; Eventually (late 40's) these led to Quantum-Field-Theory and to QED.

- It took another 30-40 years of experimental and theoretical work before it was realized that all non-gravitational interactions can be described by a special class of QFT's.

- In spite of their obvious phenomenological differences, they are different manifestations of the same underlying structure, that of a gauge theory.

- They simply correspond to different realizations of one and the same deeper structure.

The Standard Model of Nature

By the mid 70's, physicists had formulated what we may call a Standard Model of Nature (one so far not contradicted by experiments). It is based on two pillars:

1. General Relativity for the gravitational interaction

2. A Gauge Theory for the non-gravitational interactions

Is there a message that Nature wants to convey?

Why Gauge Theories?

A gauge theory is the way to describe covariantly 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 the unphysical polarization of a J=1 massless particle while keeping Lorentz invariance explicit.

Conclusion: Nature likes J=1 massless particles and is therefore well-described by a gauge theory.

Similarly

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.

In other words: Nature likes J=2 massless particles and is therefore well-described by GR!

Furthermore, interactions mediated by a massless J=2 particle necessarily acquire a geometric meaning (in the classical limit).

The question still remains of why Nature likes m=0, J=1, 2 particles.

Before attempting an answer...

... a little reminder of the successes (and puzzles) of our present Standard Model of Nature.

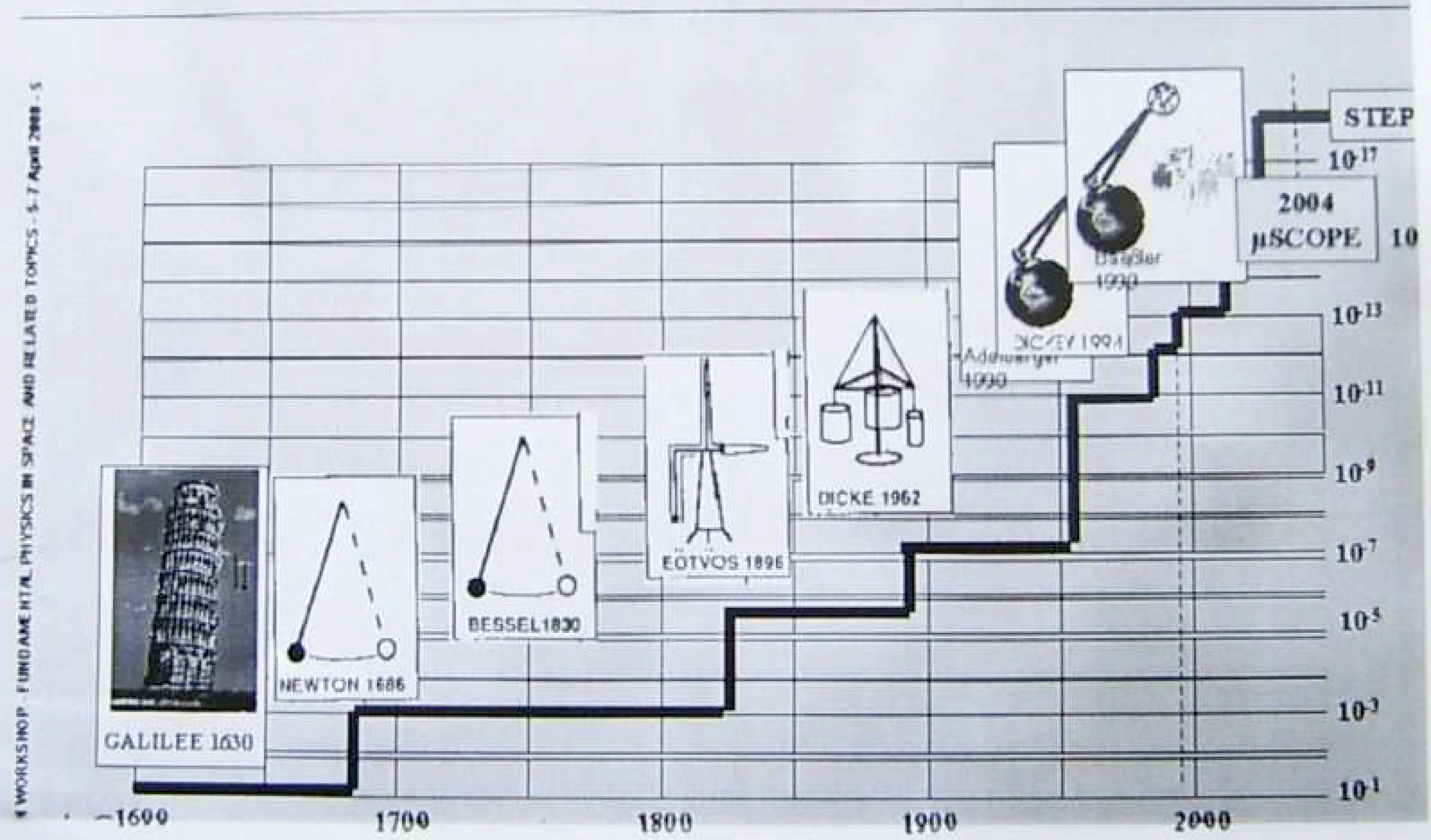
The successes: General Relativity

Newtonian Gravity + Special Relativity =

General Relativity

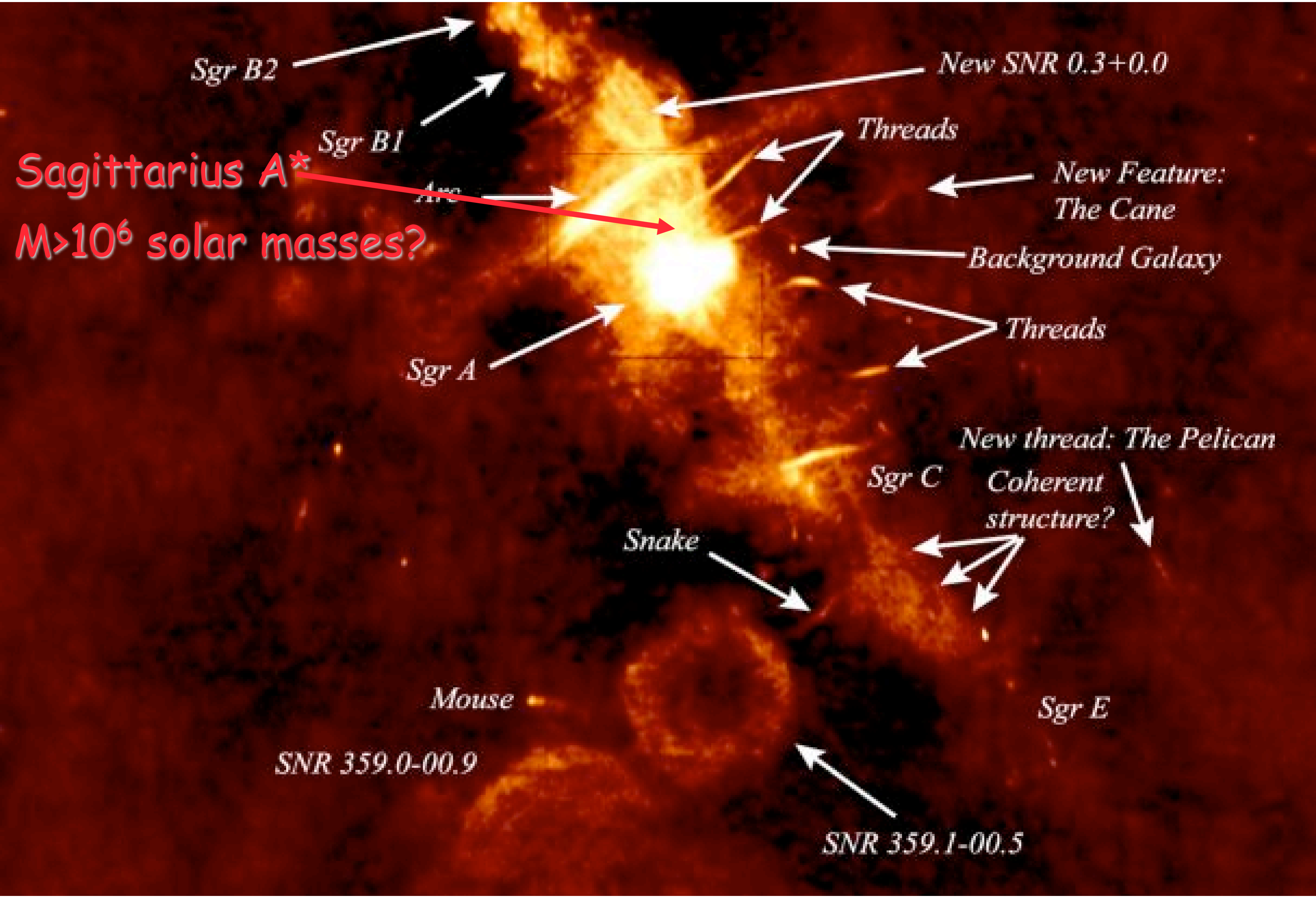
Corrections to NG better and better tested (precision 10^{-3} --10^{-13})

Increasing precision of UFF tests

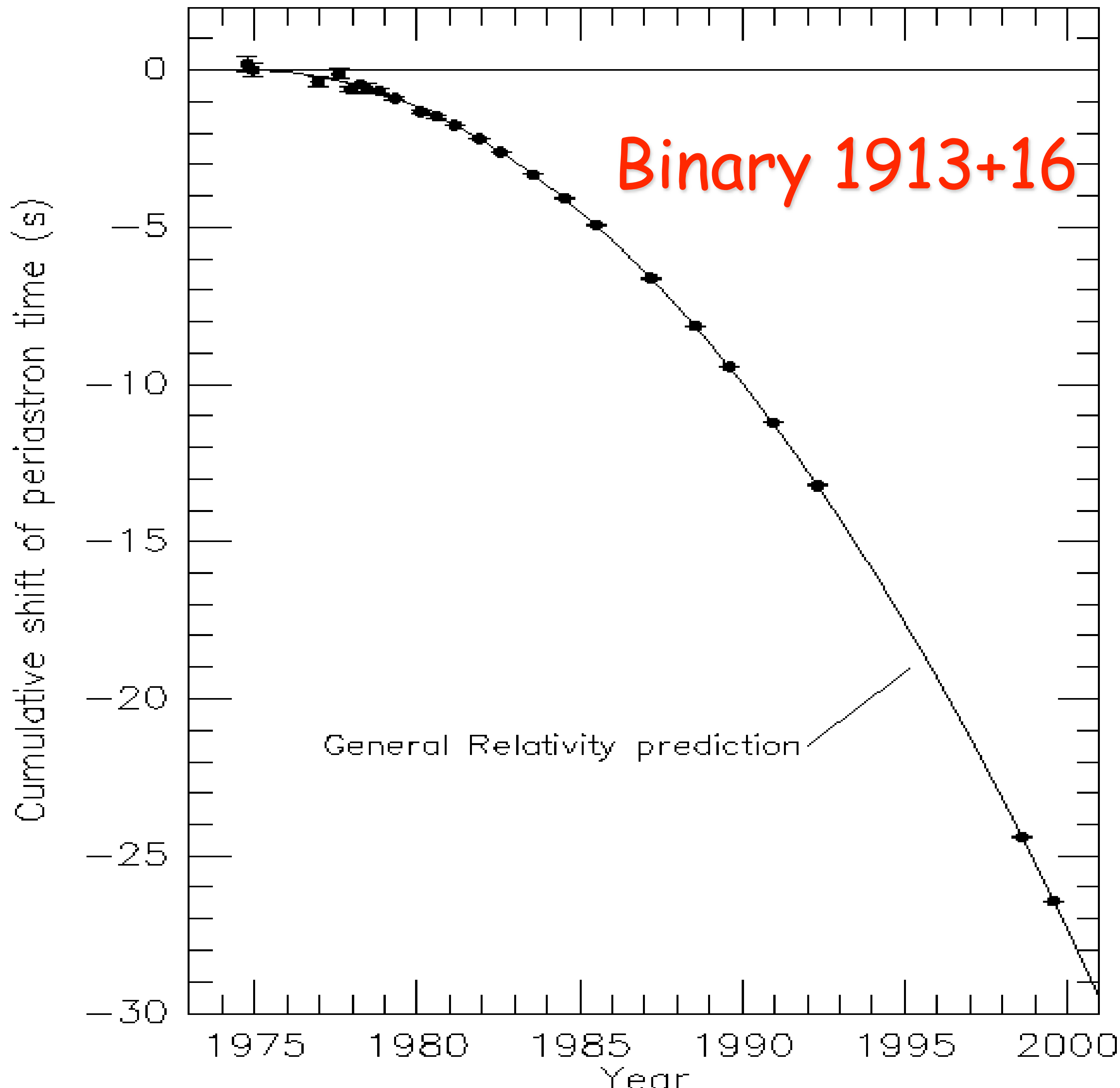


but also new predictions:

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



Sgr B2
Sgr B1
Sagittarius A*
M>10⁶ solar masses?
Arc
New SNR 0.3+0.0
Threads
New Feature:
The Cane
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent
structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5



Binary 1913+16
Cumulative shift of periastron time (s)
0
−5
−10
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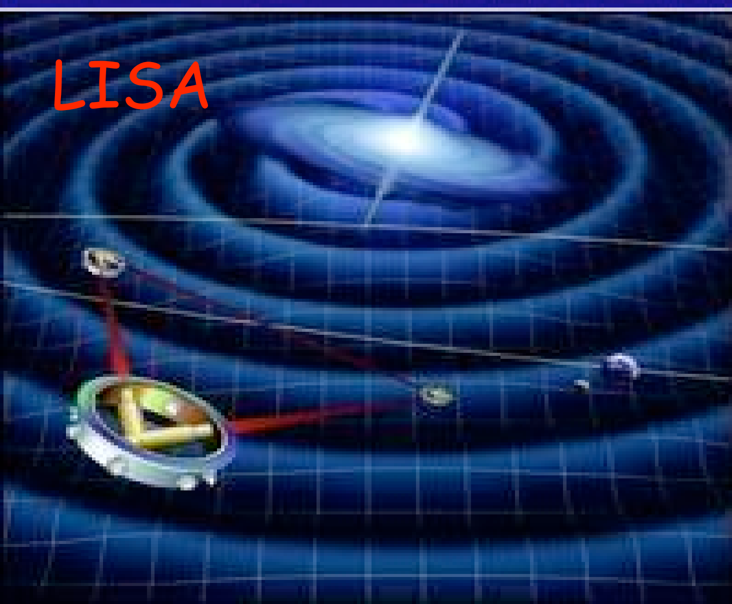
−30
1975
1980
1985
1990
1995
2000
Year
General Relativity prediction


LIGO (USA)


VIRGO(Cascina)


LISA


EXPLORER
Explorer(CERN)

The (extended) Standard Model of gravitational interactions in 2 lines

$$
\begin{aligned}
\boxed{L_{SMG} = L_{EH} + L_{CC}} \\
L_{EH} &= -\frac{1}{16\pi G_N}\sqrt{-g}\, R(g) \\
L_{CC} &= \frac{1}{8\pi G_N}\sqrt{-g}\,\Lambda
\end{aligned}
$$

The cosmological constant (dark energy) term, originally due to Einstein and abandoned for a long time, looks now necessary, albeit at very low level ($G_N\Lambda \sim 10^{-120}$), because of the observed cosmic acceleration.

The successes: Gauge Theories

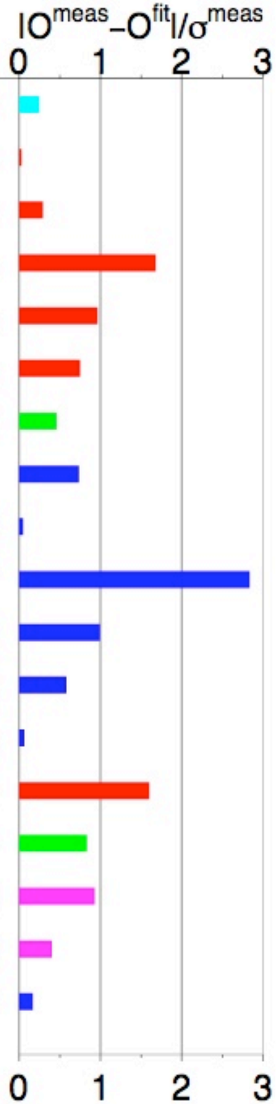
Special Relativity + Quantum Mechanics

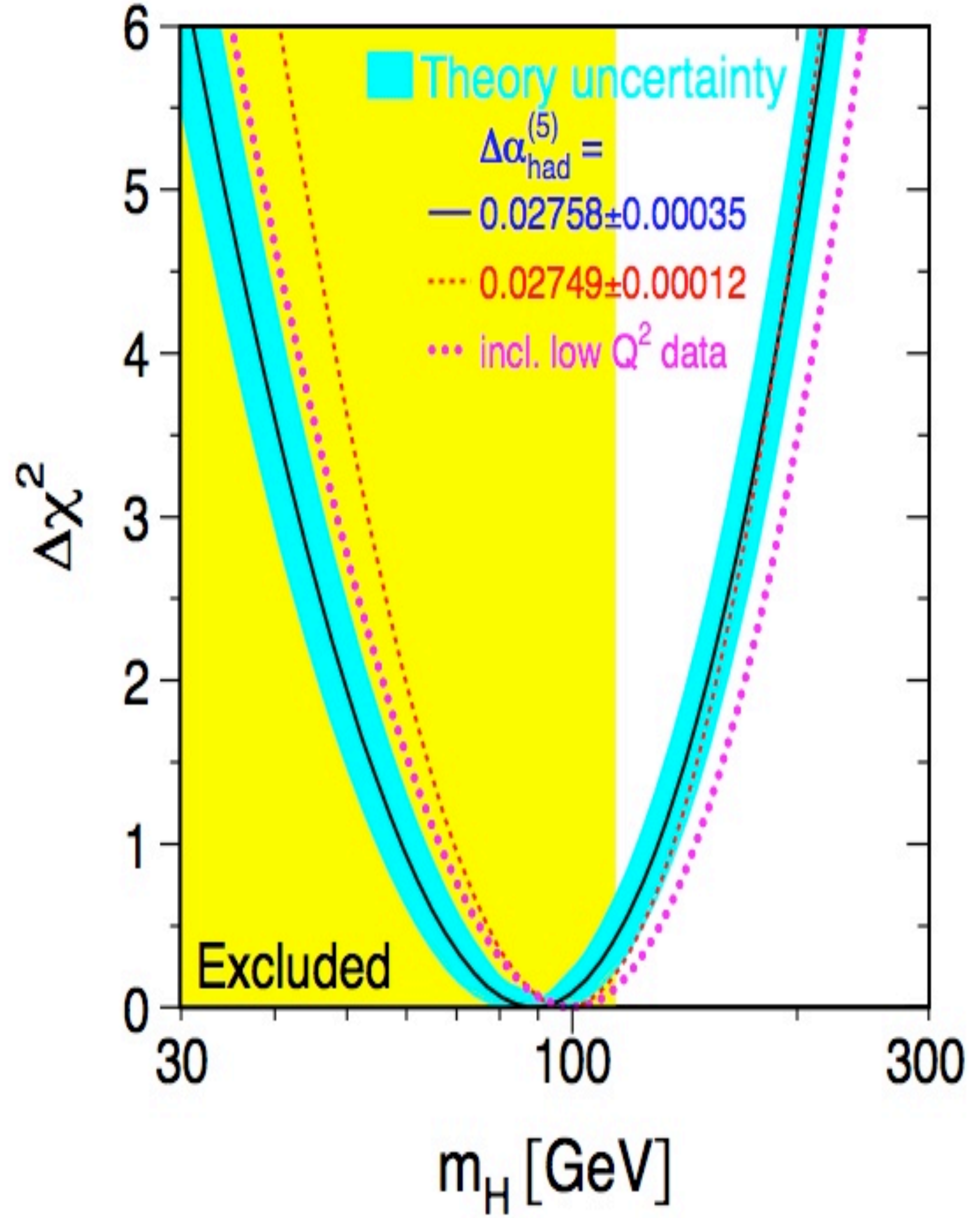
= Quantum Field Theory => gauge theory

The Standard Model of elementary particles
verified to high precision, e.g. @ LEP.

The quantum-relativistic nature of the SM manifests itself through real and virtual particle production
Taking these effects into account is essential for agreement between theory and experiment.

	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^0 [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.743
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01643
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21581
R_c	0.1721 ± 0.0030	0.1722
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.404 ± 0.030	80.376
Γ_W [GeV]	2.115 ± 0.058	2.092
m_t [GeV]	172.5 ± 2.3	172.9





The (extended) Standard Model of non-gravitational interactions in 4 lines

$$L_{SM} = L_{Gauge} + L_{Yukawa} + L_{Higgs} + L_{mass}$$

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

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

$$L_{Higgs} = -\mu^2\Phi^*\Phi - \lambda(\Phi^*\Phi)^2$$

$$L_{mass} = -\frac{1}{2}\sum_{i,j=1}^{3} M_{ij}\ \nu^c_{\alpha i}\nu^c_{\beta j}\epsilon_{\alpha\beta} + c.c.$$

Neutrinos are not massless!

The Standard Model of Nature?

$$L_{SMN} = L_{SMG} + L_{SMP}^{(\text{gen. cov.})}$$

Combining the two Standard Models at the Classical-Lagrangian level is thus straightforward.

Can we go home?

The puzzles: particle physics

1. Why G = SU(3)xSU(2)xU(1)?
2. Why do the fermions belong to such a bizzare, highly reducible representation of G?
3. Why 3 families? Who ordered them (I. Rabi)?
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 is the Higgs et al. mechanism: what keeps the Higgs-boson "light"?
8. If it is SUSY, why did we see no signs of it yet?
9. …

The puzzles:
Gravitation and Cosmology

D'où venons-nous?

- Has there been a big bang, a beginning of time?
- What provided the initial (non vanishing, yet small) entropy?
- Was the big-bang fine-tuned (homogeneity/flatness problem)?
- If inflation is the answer: Why was the inflaton initially displaced from its potential's minimum?
- Why was it already fairly homogeneous ?

Que sommes-nous?

- What is Dark Matter?
- What is Dark Energy?
- Why is the latter so small and yet non-zero?
- Why is there matter-antimatter asymmetry?

Où allons-nous?

Eternal expansion or a big crunch?

(Cosmological Constant or Quintessence?)

Theoretical headaches

Classical Headaches

- There is a UV catastrophe in classical black-body radiation (Cf. Max Planck's introduction of h).
- There is a problem with atomic stability.
- The electromagnetic energy of a point-like charge is infinite.
- On the gravity side: CGR implies that, under quite general conditions, perfectly smooth initial data lead to space-time singularities (Hawking & Penrose), like the cosmological singularity or the one hidden behind the back-hole horizon.

Quantum Headaches

- Non-relativistic QM overcomes most of the problems of the classical theory but…
- RQM (i.e. QFT) reintroduces an UV problem (one of H. Weyl's remarks…)
- The virtual pair creation allowed by SR + QM leads to infinities since virtual particles of arbitrarily high energy are copiously produced in a local QFT.
- This is already true for Gauge Theories.
- It is worse for quantum GR since the gravitational interaction grows with energy.

- Theorists have found a recipe, known as renormalization, for handling the UV infinities of gauge theories and get a predictive theory
- But many physicists (Dirac, Landau, ...) were convinced that local QFTs could not be the full story
- Attempts to do the same for GR have failed so far.
- The contradiction between GR and QM that Einstein was fighting with is still with us.
- The only way to make sense of quantum gravity would be to soften it above a certain energy scale.
- Like Fermi's theory wrt the SM, GR would then just be a low-energy/large-distance approximation to a better theory

The missing quantum corrections

- Radiative corrections to marginal and irrelevant operators in the SM have been seen in precision experiments (e.g. @ LEP):

- running of gauge couplings;
- effective 4-fermi interactions;
- anomalies.

- Radiative corrections to relevant operators have not been seen:

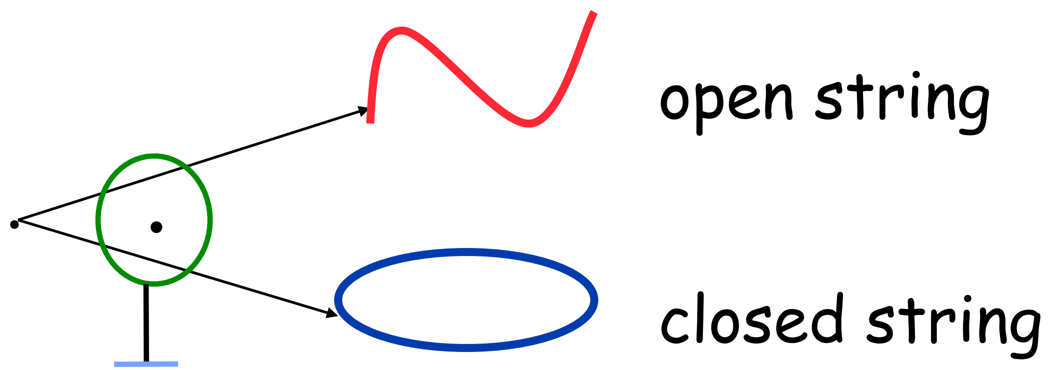
- scalar masses;
- cosmological constant.

- Because of a (well-known?) IR-UV connection this may be telling us that the SM & GR are not the full story: they are just effective theories in search of an ultraviolet completion!

Is it String Theory?

The paradigm

- Every elementary particle, previously seen as pointlike, is nothing but a vibrating string satisfying the laws of special relativity and quantum mechanics.



Strings + SR + QM = Grand Synthesis

A magic cocktail!

Two miracles of quantum strings

I. Finite Size

Classical string theory is scale free. Classical strings have no characteristic size.
The characteristic size of quantum strings is determined by Quantum Mechanics:

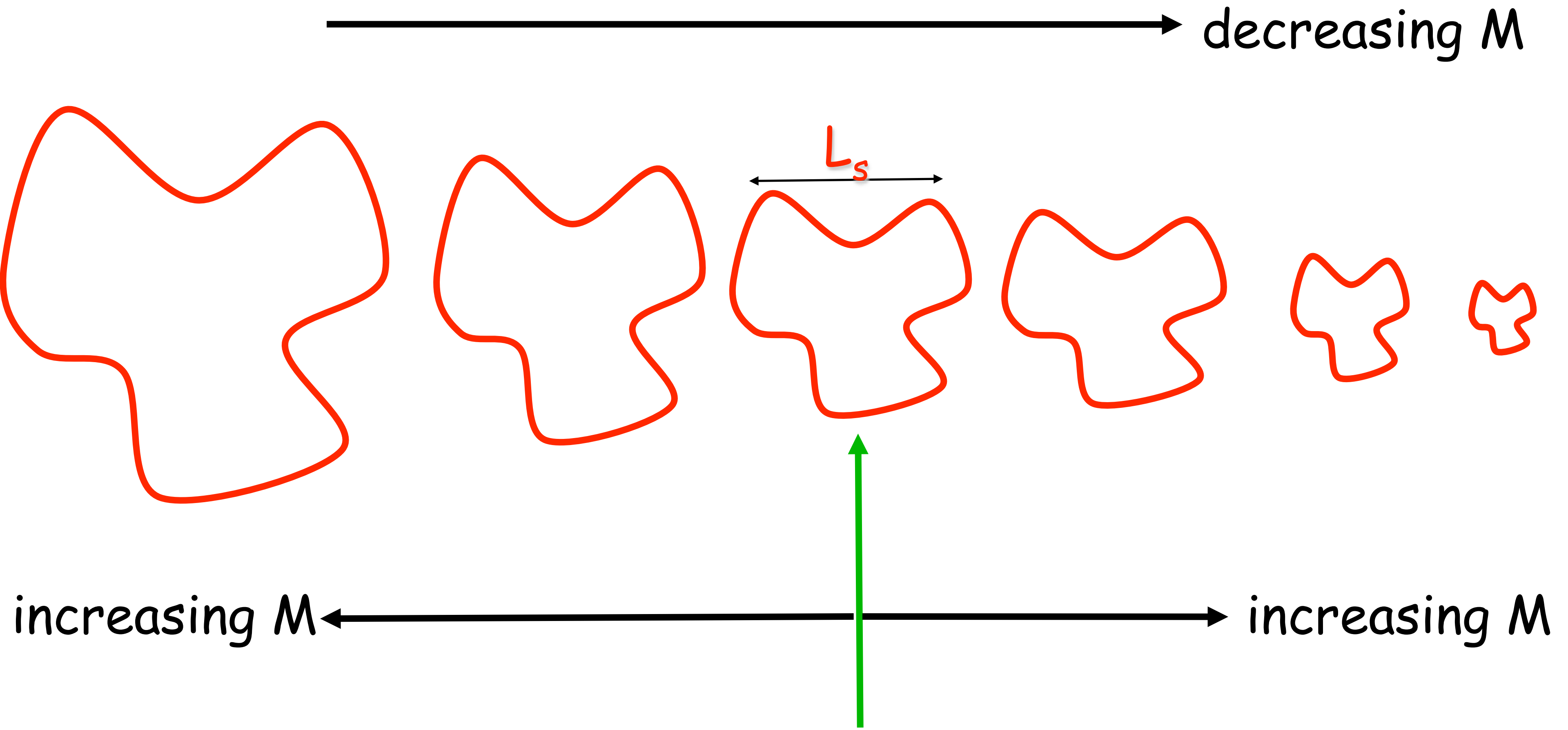
$$L_s = \sqrt{\frac{\hbar c}{T}}$$

T = string tension

Note analogy (in D=4) with:

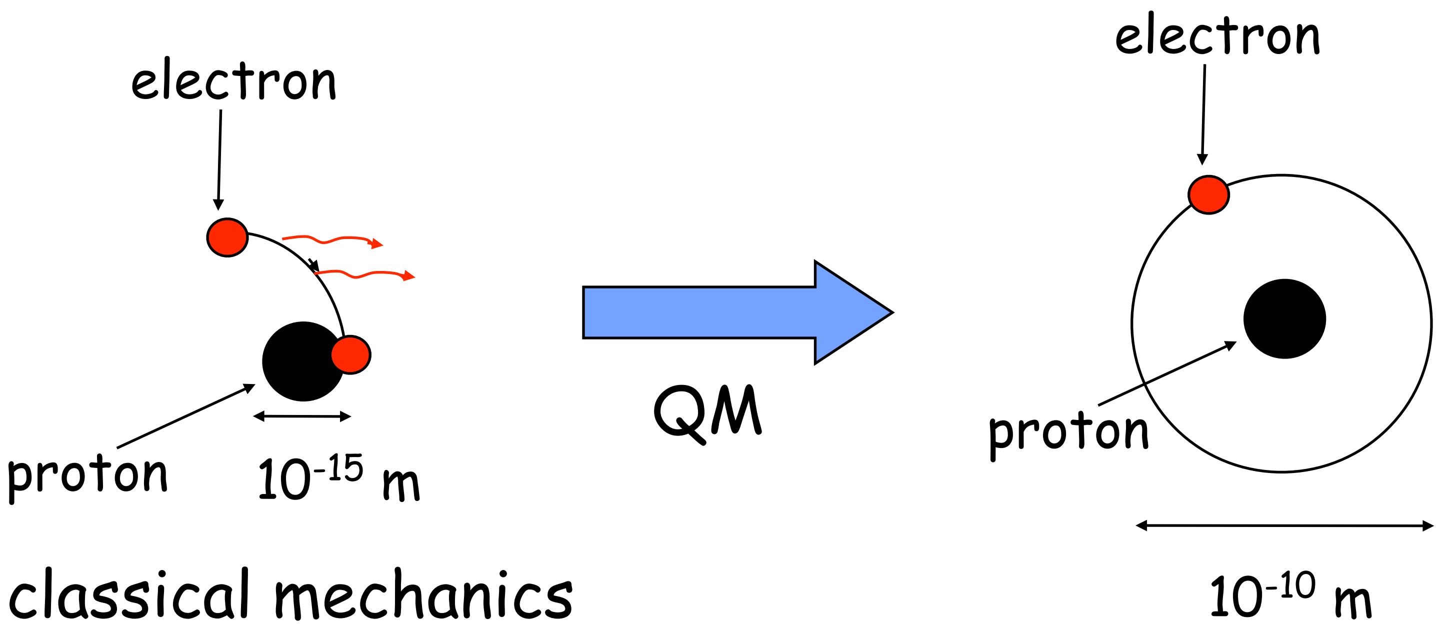
$$L_P = \sqrt{\frac{\hbar G_N}{c^3}}$$

Without QM strings become lighter and lighter as they shrink

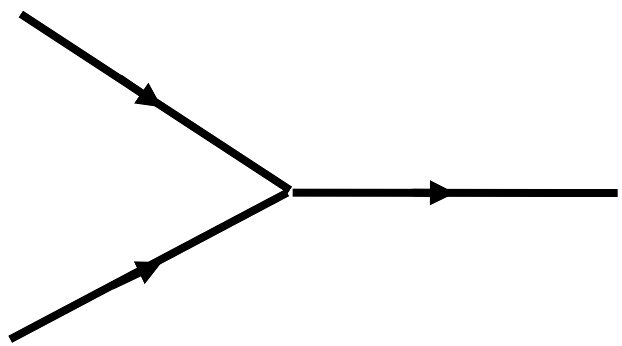


With QM strings are lightest when their size is L_s

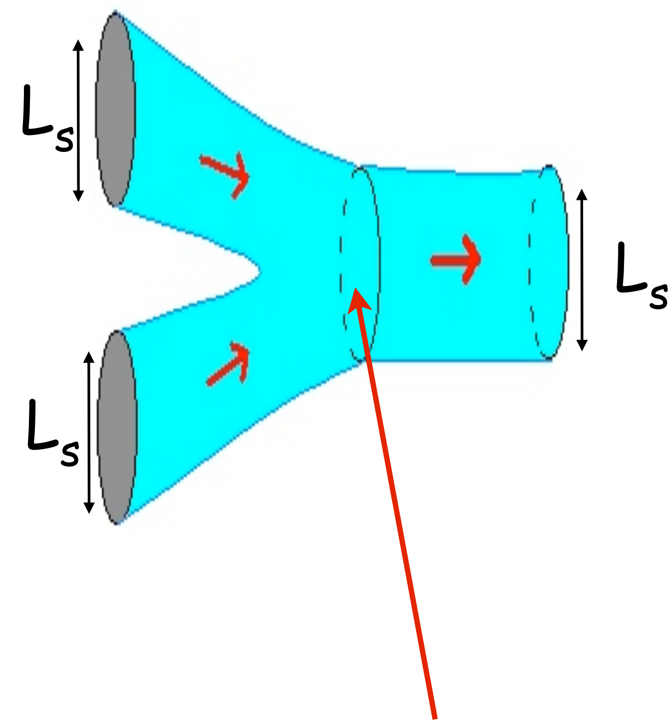
Analogy with atoms



Field Theory



String Theory



Interactions are smeared over regions of order L_s

II. J without M

A classical string cannot have angular momentum without having a finite length, hence a finite mass. A quantum string, instead, can have up to two units of angular momentum without gaining mass.

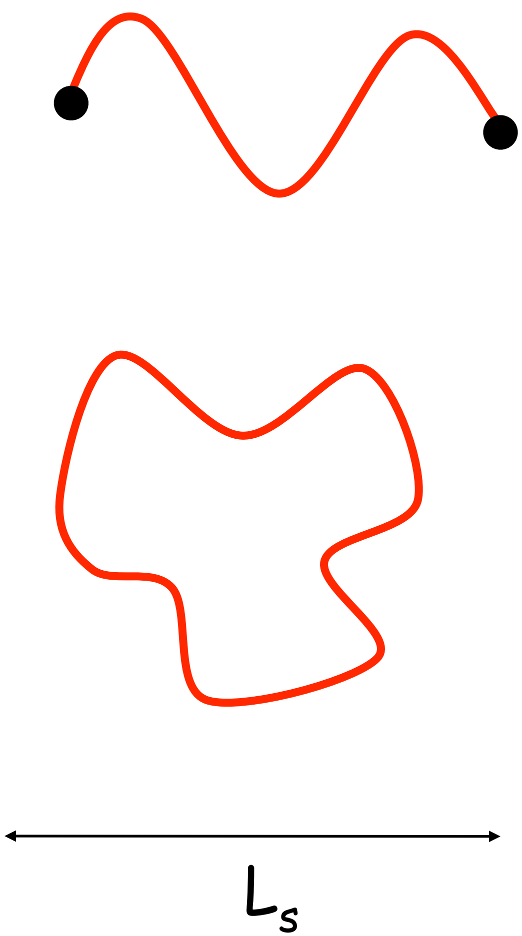
after consistent regularization

$$\frac{M^2}{2\pi T} \geq J + \hbar \sum_1^\infty \frac{n}{2} = J - \alpha_0 \hbar \qquad \alpha_0 = 0, \frac{1}{2}, 1, \frac{3}{2}, 2.$$

NB: The inevitability of massless spinning states was one reason for abandoning the old string theory in favour of QCD.

=>String theory CAN be falsified by large-distance experiments!

Unification of all interactions



m=0, J=1

⇒ photon and other carriers of non-gravitational interactions

m=0, J= 0, 2

⇒ graviton, and other carriers of gravity-like interactions

This amazing property of quantum strings may well provide answers to the two questions we asked at the beginning:

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

and explain why it is well described by
Gauge Theories + General Relativity

- A unified and finite theory of elementary particles, and of their gauge and gravitational interactions, not just compatible with, but based on, Quantum Mechanics!

The common stringy nature of gauge bosons and gravitons implies a quantitative unification of all forces at high energies. The energy scale associated with L_s is:

$$E_s \equiv \frac{\hbar c}{L_s} = c\sqrt{\hbar T}$$

At these energies gravitational and electromagnetic interactions become comparable. In turn this implies that:

$$L_s^2 \sim \frac{1}{\alpha} L_P^2 \Rightarrow L_s \sim 10 L_P \sim 10^{-32} cm$$ or $$E_s \sim E_P/10 \sim 10^{17} GeV$$

Does it mean that string theory will never be tested?
My answer is a definite NO!
First of all such energies have existed, most likely, in the very early Universe => cosmological consequences (Cf. inflation)

A generic prediction of string theory is the existence of (6?) extra dimensions of space which must be tiny but could nevertheless be felt through their "zero-modes" (gauge bosons, fermions...)

The sizes of these extra dimensions are arbitrary in perturbation theory .

Models can be conceived where such sizes are as large as a fraction of mm (provided the SM particles cannot move in them) leading to interesting experimental consequences (e.g. modifications of gravity, LHC events).

We do not have so far tests of string theory simply because of our present inability to solve it.

If taken at tree-level, string theory is already ruled out!

String theory's challenges

String theory comes with its own puzzles.

• One theory but too many solutions, particularly in connection with the compactification of the extra dimensions of space in which quantum strings like to move.

• The moduli stabilization problem. Often free in PT <=> massless fields. In best case they could answer Weyl's question about e, in worst case they give dangerous:

• Violations of the EP (UFF)

• Space-time dependence of physical "constants"

New (stringy) non-perturbative effects may remove those flat directions and help pinning down a good string vacuum. It would be already great to have even ONE:

<u>ST-based Standard Model of Nature</u>

Conclusion

90 years after Hermann Weyl's book, we have made enormous progress in describing matter.
Since the mid seventies we have a "Standard Model" of elementary particles, an achievement second only to the discoveries of relativity and quantum mechanics 100 years ago.

The SM unifies conceptually 3 of the 4 known interactions.
They are all described by a quantum-relativistic theory of the gauge type.

Much less has happened to our theory of gravity, still based on Einstein's general relativity. Simply its experimental confirmations have become sharper and sharper.
But the task of unifying GR and the SM in a fully quantum setup has proven tougher than anticipated.

Since the mid eighties there are hopes that, finally, a fully consistent unified quantum framework for describing all particles and interactions can be found in string theory.

Meanwhile a number of phenomenological puzzles have been uncovered as experiental data in astrophysics and cosmology have caught up in precision with those coming from accelerators.

It is still too early to say whether string theory will be able to successfully address the many remaining puzzles in particle physics, astrophysics and cosmology or whether it will make the unhappy end of its hadronic predecessor.

Even if so it had many spinoffs:

- In many branches of mathematics;
- In providing examples of Black Holes whose entropy can be given a Stat. Mech. interpretation;
- In providing new techniques to perform perturbative calculations in gauge theories;
- In giving new handles on gauge theories at strong coupling through a dual weak-coupling gravity description (Cf. AdS/CFT calculation of shear viscosity and other transport coefficients useful in heavy ion collisions).
- In providing a dual description of solid state problems?
- ...

I wonder what Hermann Weyl, Wolfgang Pauli (and Albert Einstein) would have thought of it...