European strategy for astroparticle physics

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Outstanding problems in astro & particle physics

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The Standard Model of Nature

Almost 40 years ago physicists have formulated what we may call a Standard Model of Nature (SMN).
A triumph of reductionism, based on two pillars:

1. A Gauge Theory for the non-gravitational interactions

2. General Relativity for the gravitational interaction

Since then the SMN has been confirmed to higher and higher precision & confirmed modulo two "small" improvements...

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

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

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

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

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

Still to be confirmed

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

Breaking news: neutrinos are not massless!

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

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

Breaking news: cosmic acceleration (this year's Nobel prize)

The coupling to matter follows from the principle of general covariance

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 straightforward.

Is there a message that Nature wants to convey through the success of the SMN?

Why Gauge Theories?

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.

Message #1: Nature likes J=1 massless particles*) and is therefore well-described by a gauge theory.

*) At the simplest Lagrangian level: 3 different realizations of the gauge symmetry occur for the 3 int's

Why General Relativity?

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

Message#2: Nature likes J=2 massless particles and is therefore well-described by GR!

The question still remains:

Why does Nature like m=0, J=1, 2 particles?

Before attempting an answer...

... a short reminder of the successes (and puzzles) of our present SMN.

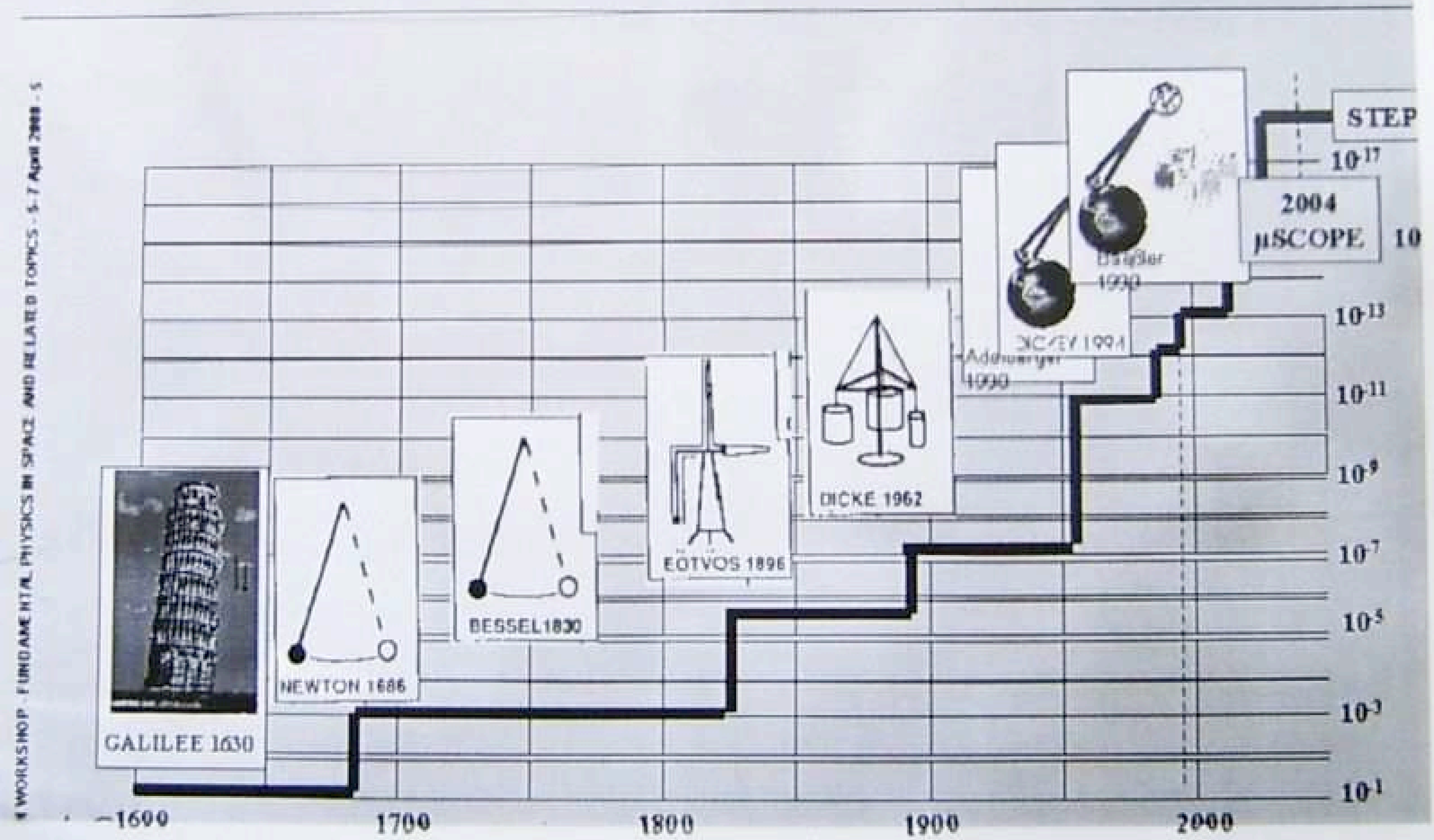
General Relativity

Its theoretical basis, the equivalence principle, has been tested to higher and higher precision*)

Also: corrections to Newtonian gravity better and better tested

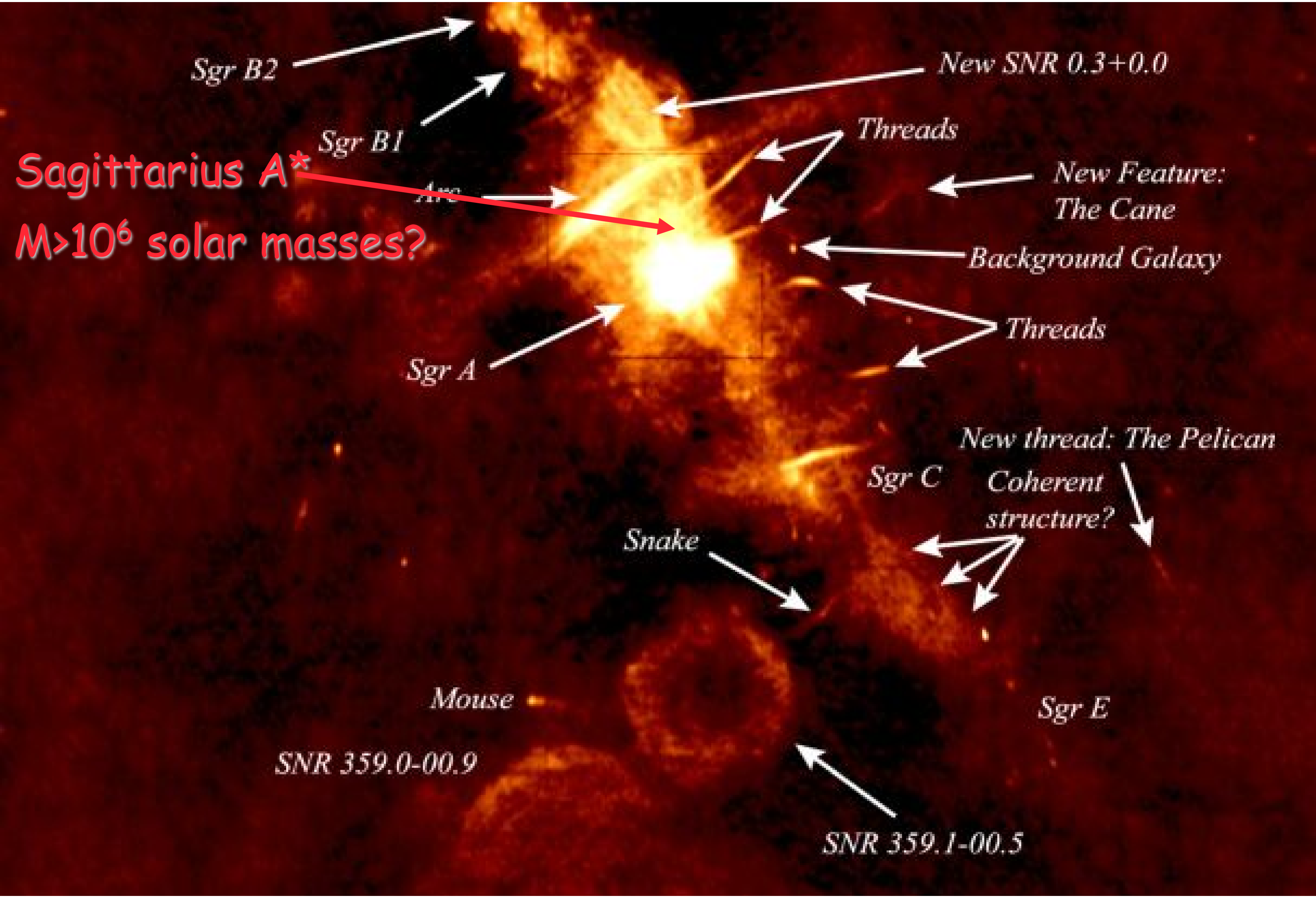
*) Unless the findings of OPERA are confirmed and special relativity has to be revised!

Increasing precision of UFF tests

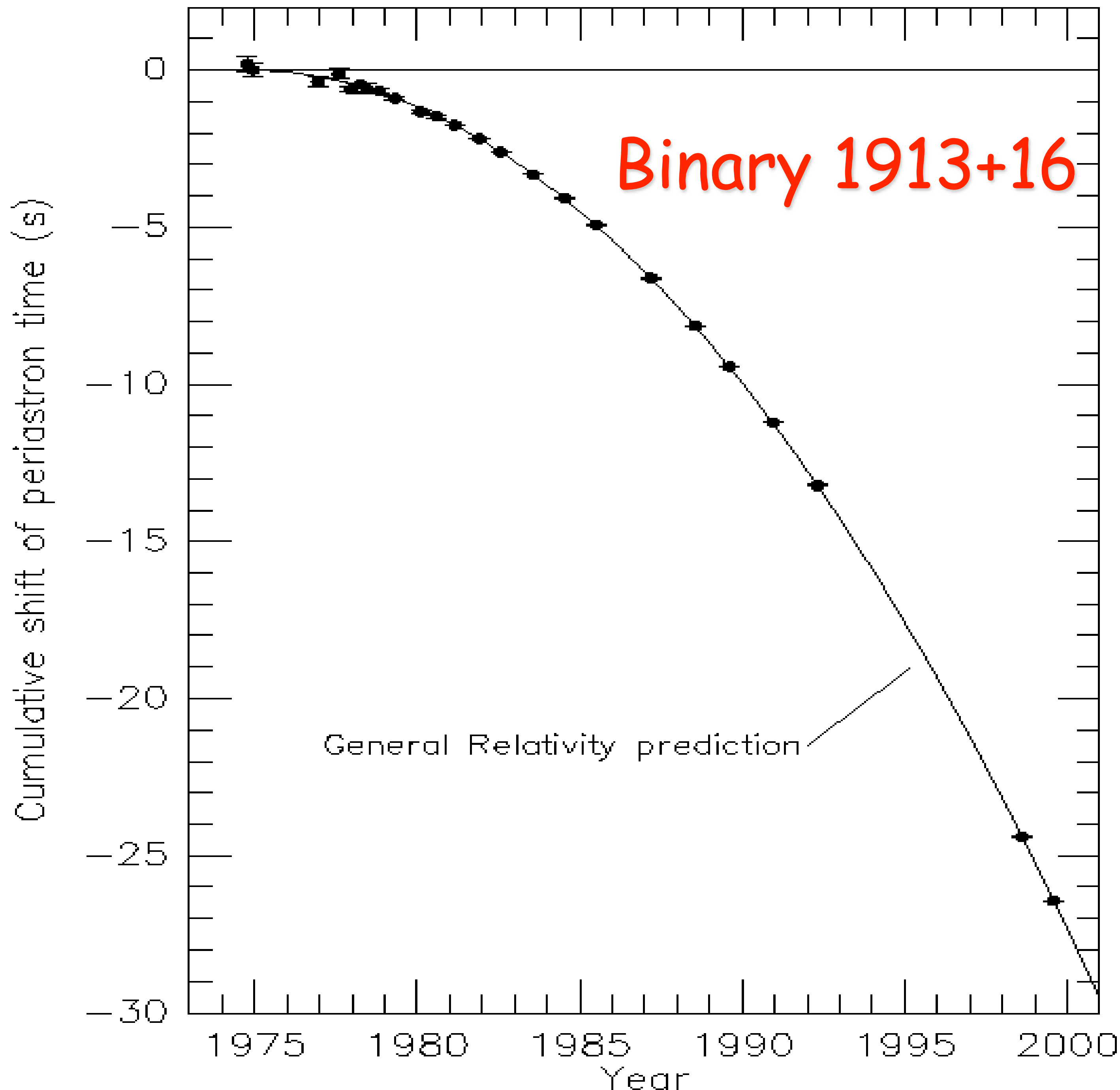


GR's new predictions:

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

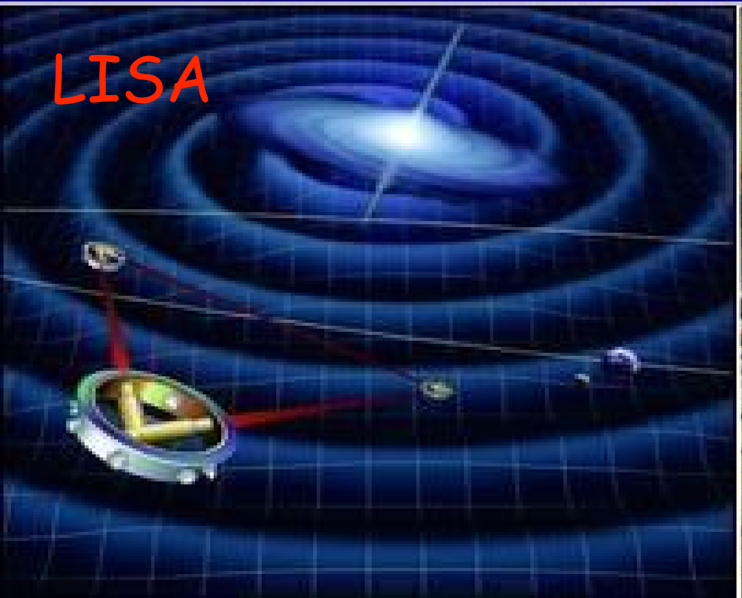


Sagittarius A*
M>10^6 solar masses?
Sgr B2
Sgr B1
Arc
Sgr A
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
SNR 359.0-00.9
Sgr E
SNR 359.1-00.5


Binary 1913+16
Cumulative shift of periastron time (s)
0
−5
−10
−15
−20
−25
−30
General Relativity prediction
1975
1980
1985
1990
1995
2000
Year


LIGO (USA)


VIRGO(Cascina)


LISA


Explorer(CERN)

It seems that we only have to find what dark matter is made of...

Gauge Theories

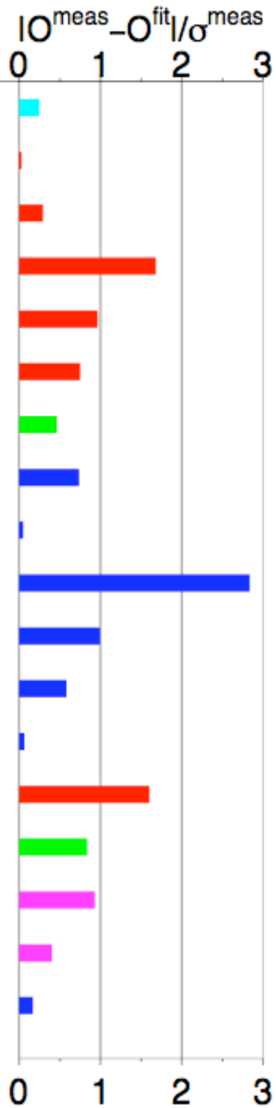
The SMP has been verified to (very) high precision (QED tests, LEP, Tevatron, LHC...)

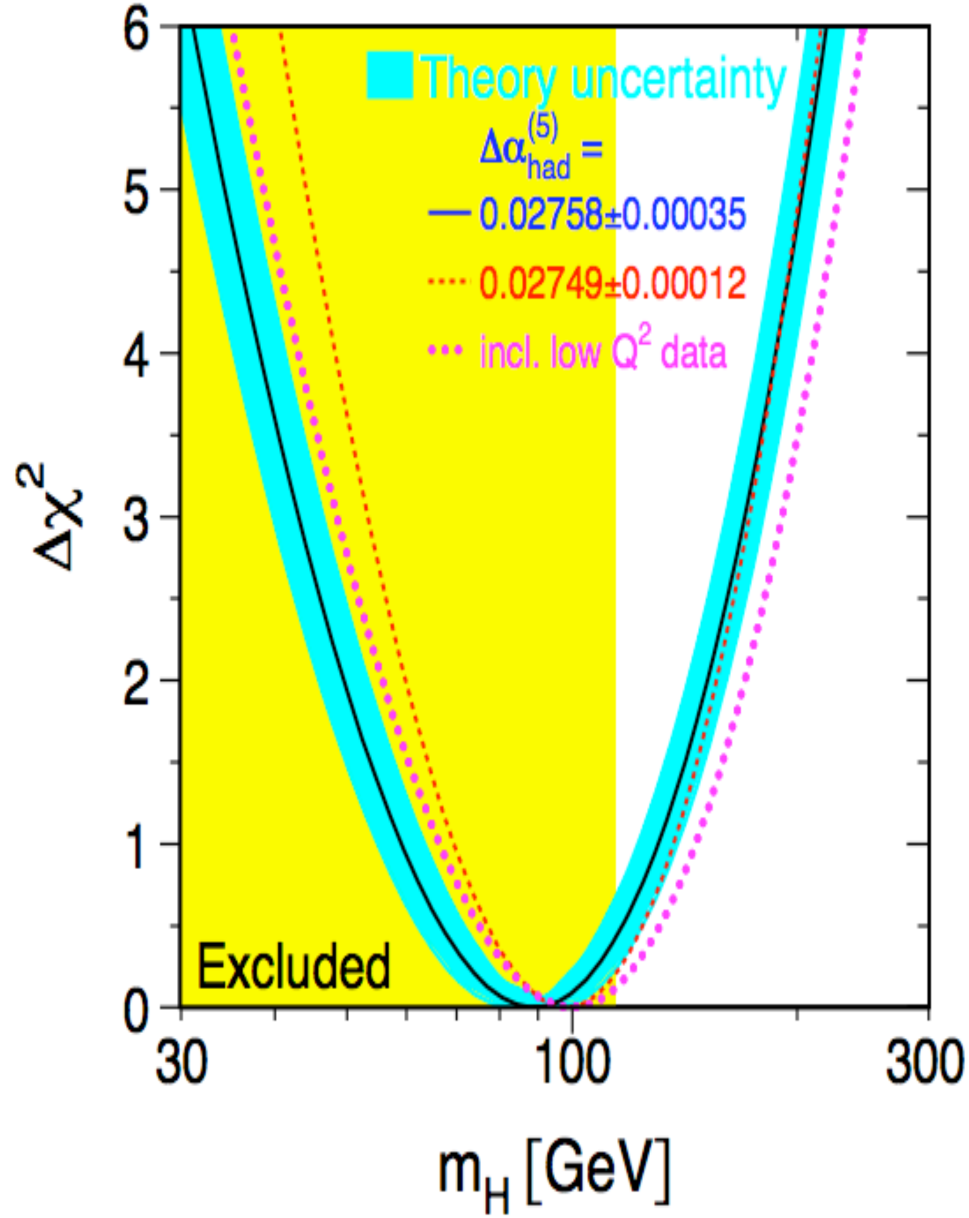
Recall: Special Relativity + Quantum Mechanics

=> QFT (e.g. gauge theories of SMP)

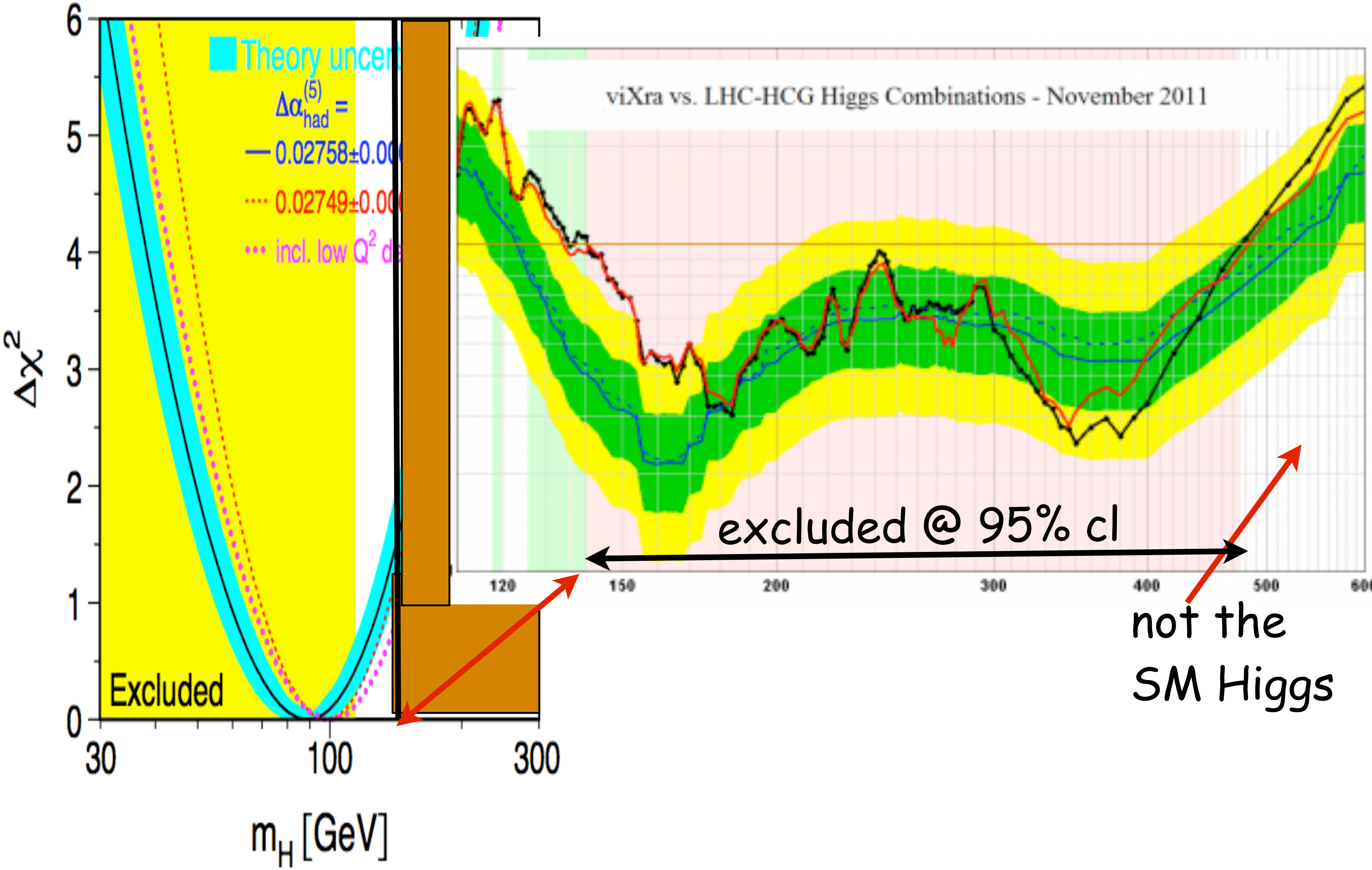
The quantum-relativistic nature of the SM manifests itself through real and virtual particle production
Taking these effects into account is essential for agreement between theory and experiment.

	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





Combining ~ 1/3 of LHC data @ ATLAS & CMS
(G. Rolandi, HCP conference, last week)



It seems that we only have to find the Higgs boson and check its properties...

The puzzles: particle physics

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 (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. Why no strong CP violation?
10. ...

The puzzles: 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 Ω_Λ O(1) today?
8. What's the origin of matter-antimatter asymmetry? LHCb new results may help if confirmed...
9. ...

Conceptual headaches

The SMN is limping: it stands on two unequal legs...

- A quantum leg for the SMP
- A classical leg for the SMG
- Yet Einstein's equations, $G_{\mu\nu} \sim T_{\mu\nu}$, connect them!
- Besides: our present understanding of the origin of large-scale-structure uses in crucial way the quantum fluctuations of space-time...

Quantum Headaches

- Relativistic QM (i.e. QFT) reintroduces an UV problem that had been solved by NRQM.
- 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 a recipe, known as renormalization, for handling the UV infinities of gauge theories and get a predictive theory.
- Attempts to do the same for GR have failed so far (I'm not convinced that loop gravity does it).
- The only way to make sense of quantum gravity appears to be to soften GR below a certain length scale.
- Like Fermi's theory w.r.t. the SM, GR would then just be a large-distance approximation to a better theory.

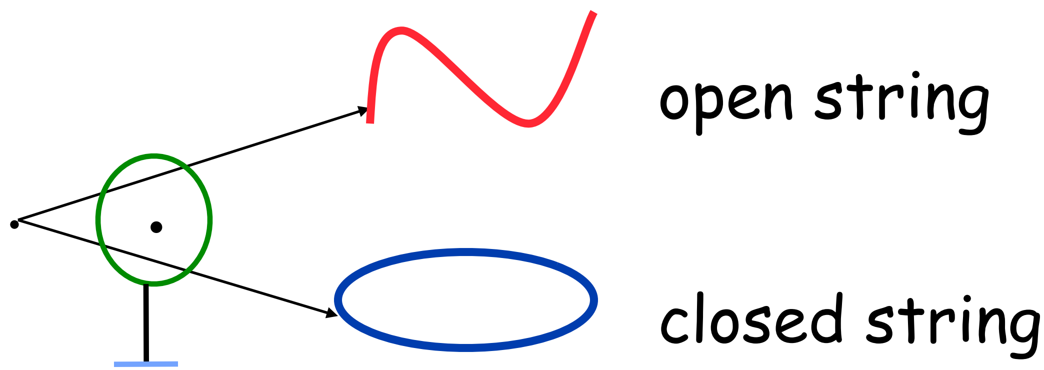
The missing quantum corrections

- Radiative corrections to marginal & irrelevant (in IR) operators have been seen in precision experiments:
  - running of gauge couplings;
  - effective 4-fermi interactions;
  - flavour anomalies.
- Radiative corrections to relevant operators have not been seen. Best known examples:
  - scalar masses (what keeps the Higgs light?);
  - cosmological constant (what keeps Λ small?) .
- IR-UV connection may be telling us that the SM & GR are not the full story: they are just effective theories in search of an ultraviolet completion that might explain away the huge fine-tunings needed in QFT.

Is it String Theory?

String Theory in a nutshell

- 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 major miracles of quantum strings
(leaving out minor ones…)

I. Finite Size

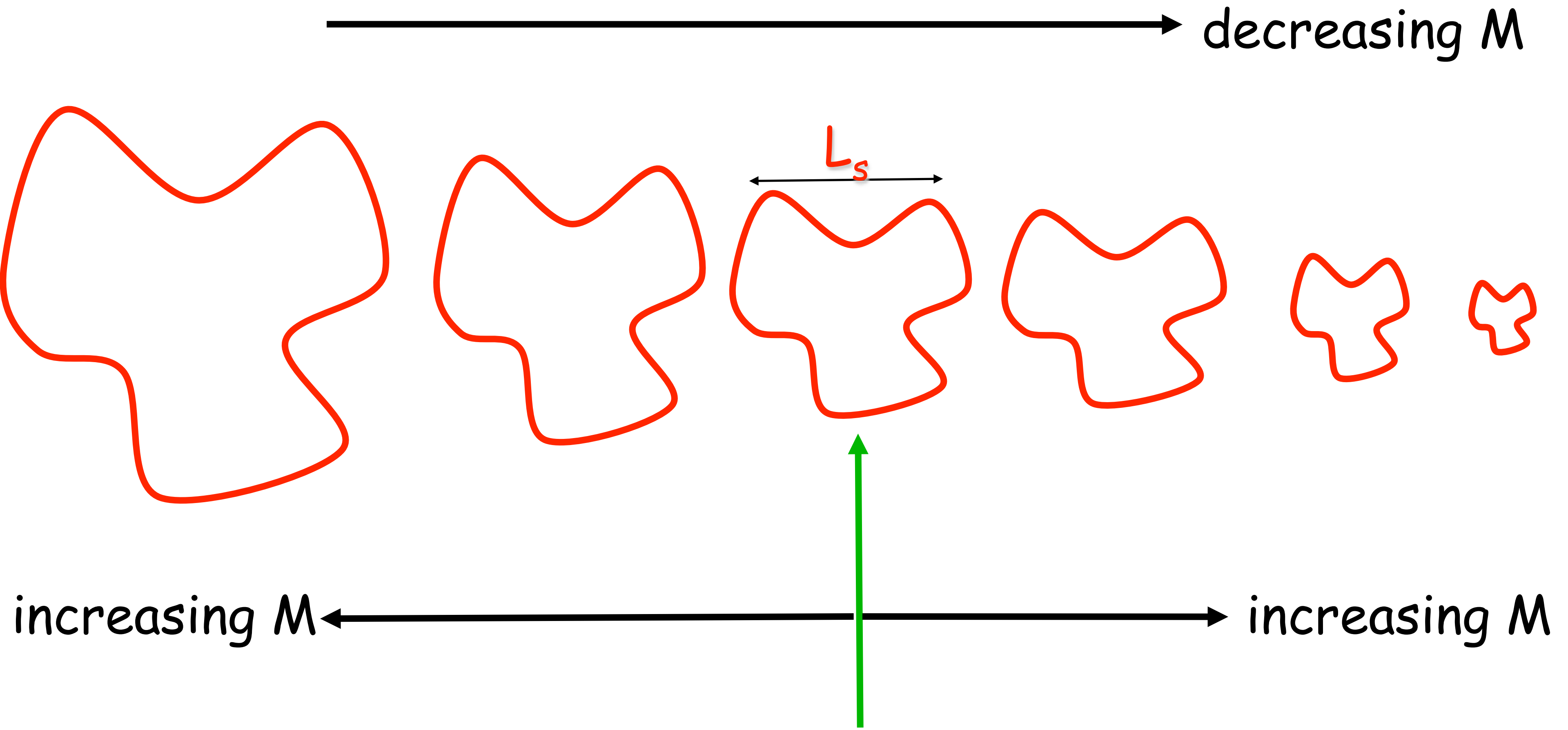
Classical string theory is scale free. Classical strings have no characteristic size.

The characteristic size of quantum strings is determined by Quantum Mechanics:

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

T = string tension ~ dE/dl

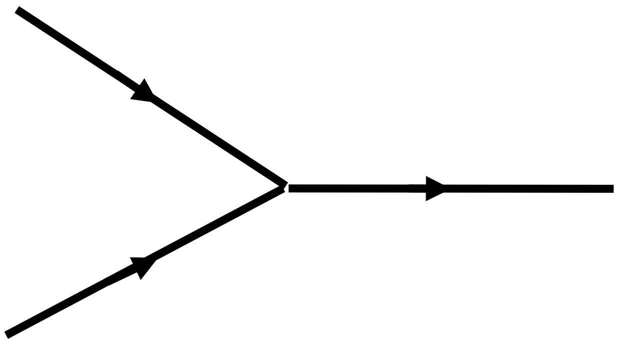
Without QM strings become lighter and lighter as they shrink



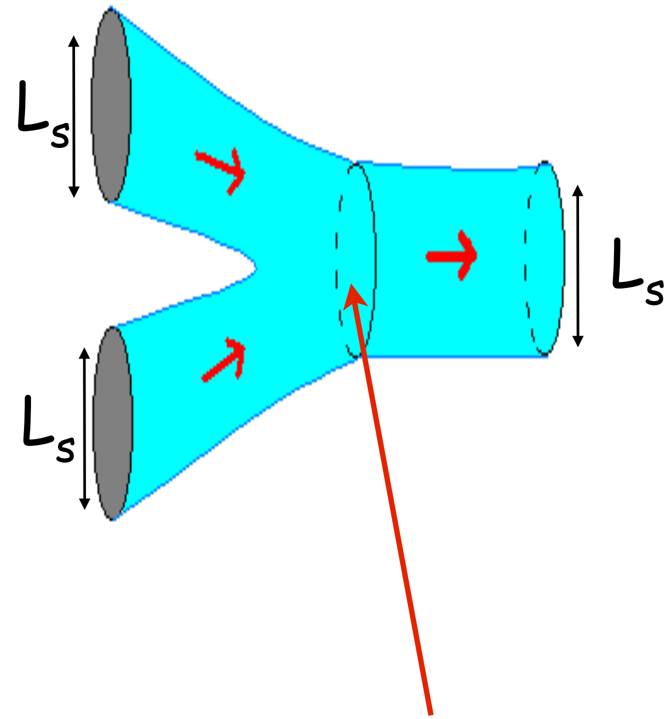
With QM strings are lightest when their size is L_s

Cf. harmonic oscillator's symmetry between x and p

Field Theory



String Theory

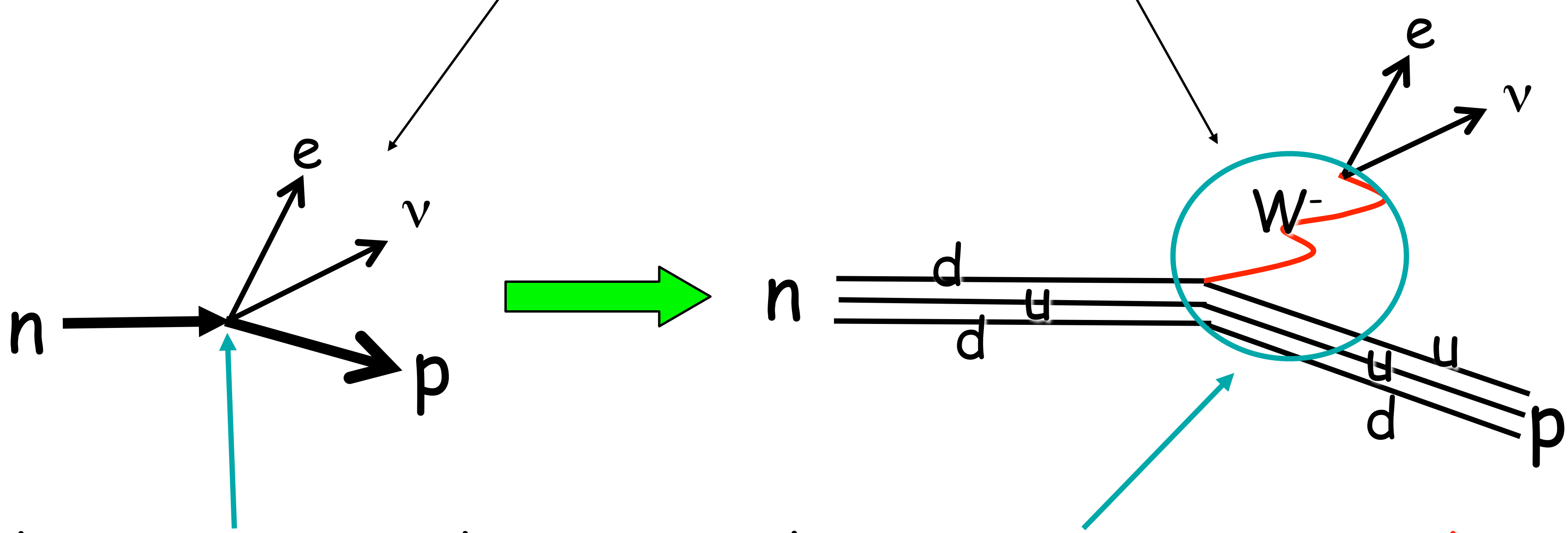


Interactions are smeared over regions of order L_s

=> elimination of UV divergences!

An interesting analogy

From Fermi (1934) to SMP (~1973)



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

The interaction is smeared over a finite region of space-time

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 (hadronic) string theory for QCD.
=>String theory CAN be falsified by large-distance experiments!

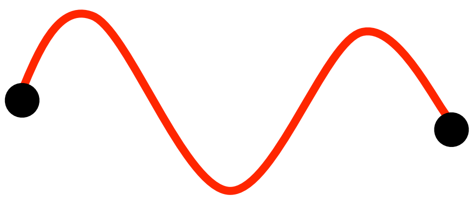
This property of quantum strings provides an answer to the two questions:

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

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

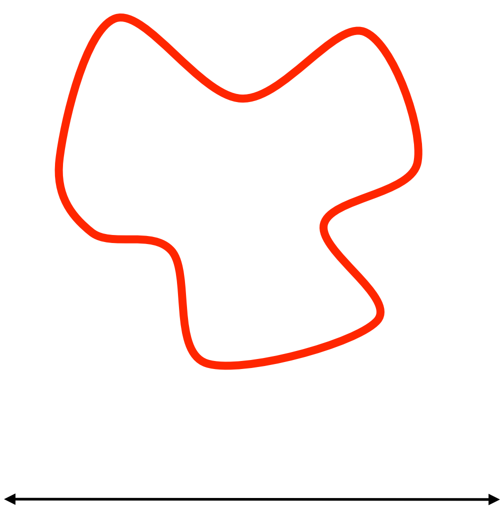
- A unified and finite theory of elementary particles, and of their gauge and gravitational interactions, not just compatible with, but based on, Quantum Mechanics!

Unification of all interactions at the string scale (~ 10^{17} GeV)



m=0, J=1

⇒ photon and other carriers of non-gravitational interactions



L_s

m=0, J= 0, 2

⇒ graviton, and other carriers of gravity-like interactions

String theory's own challenges

- One theory with many solutions
- Constants of Nature given by scalar fields. Often free in perturbation theory <=> massless scalars.
- Violations of the EP (UFF)
- Space-time dependence of physical "constants"

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>UV-complete Standard Model of Nature</u>

Conclusion

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 (mediated, at the basis, by J=1, m=0 quanta)

Much less has happened to our theory of gravity, still based on 1915's 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 a fully consistent quantum framework for describing all particles and interactions can be provided by quantum string theory, a theory that has, automatically, gauge and gravitational interactions (and their supersymmetric extensions)

Meanwhile, a number of phenomenological puzzles have been uncovered as experimental 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.

Thank You!