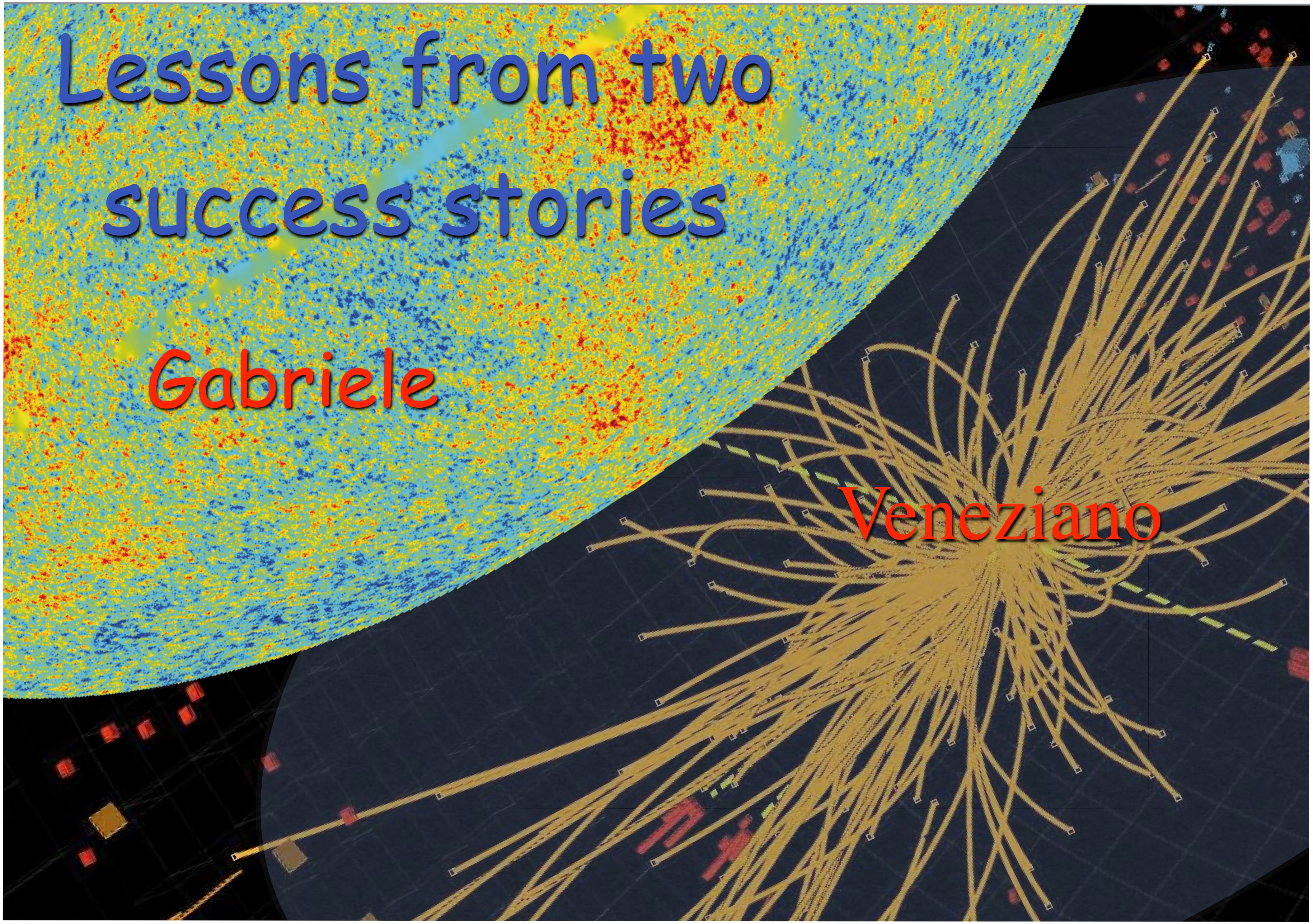
KICP, May 21, 2014



Lessons from two success stories

Gabriele Veneziano

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

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

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

$$
\begin{aligned}
L_{SMP} &= -\frac{1}{4}\sum_a F^a_{\mu\nu}F^a_{\mu\nu} + \sum_{i=1}^{3} i\bar{\Psi}_i\gamma^\mu D_\mu\Psi_i + D_\mu\Phi^* D^\mu\Phi \\
&- \sum_{i,j=1}^{3}\lambda^{(Y)}_{ij}\Phi\Psi_{\alpha i}\Psi^c_{\beta j}\epsilon_{\alpha\beta} + c.c. \\
&+ \mu^2\Phi^*\Phi - \lambda(\Phi^*\Phi)^2 \\
&- \frac{1}{2}\sum_{i,j=1}^{3} M_{ij}\;\nu^c_{\alpha i}\nu^c_{\beta j}\epsilon_{\alpha\beta} + c.c.
\end{aligned}
$$

new!

confirmed?

The SM of Elementary Particles

A quantum-relativistic theory incorporating the gauge-invariance principle

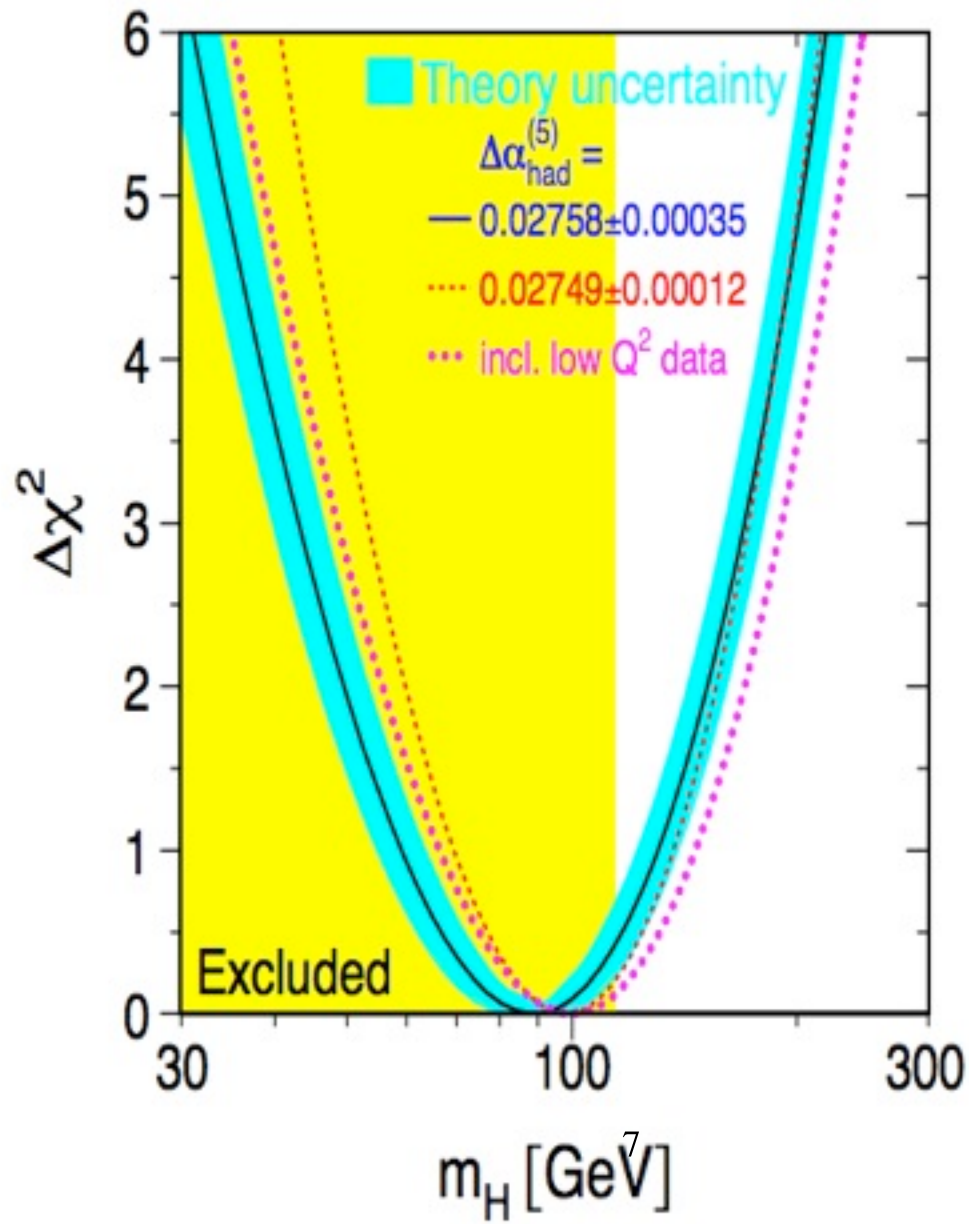
The quantum-relativistic nature of SMEP manifests itself through real and virtual particle production

These effects are essential for agreement between theory and experiment

(tree-level predictions are off by many σs)

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.

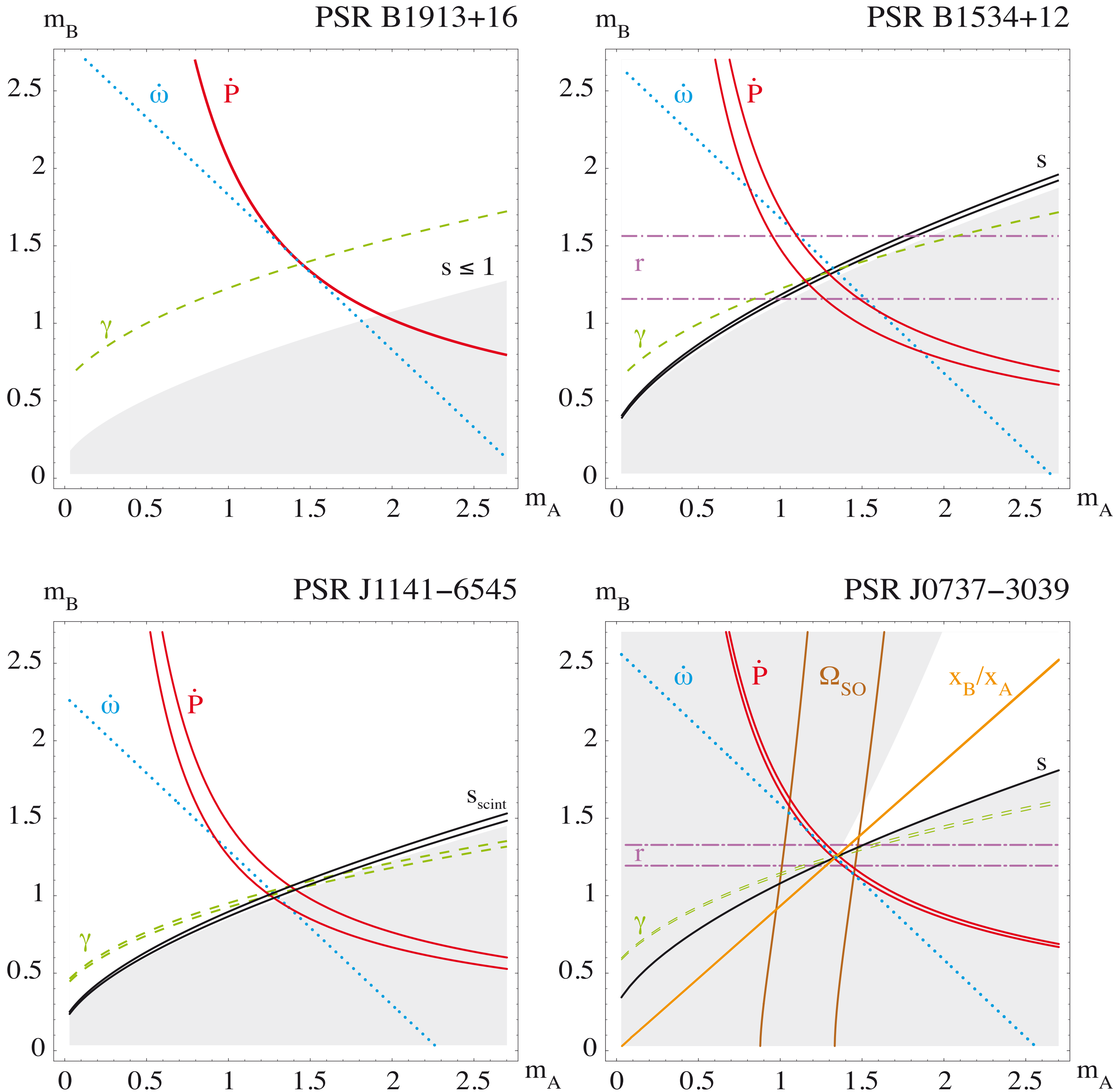
Universality of free-fall tested with incredible precision

Corrections to Newtonian Gravity well tested

New GR predictions:

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

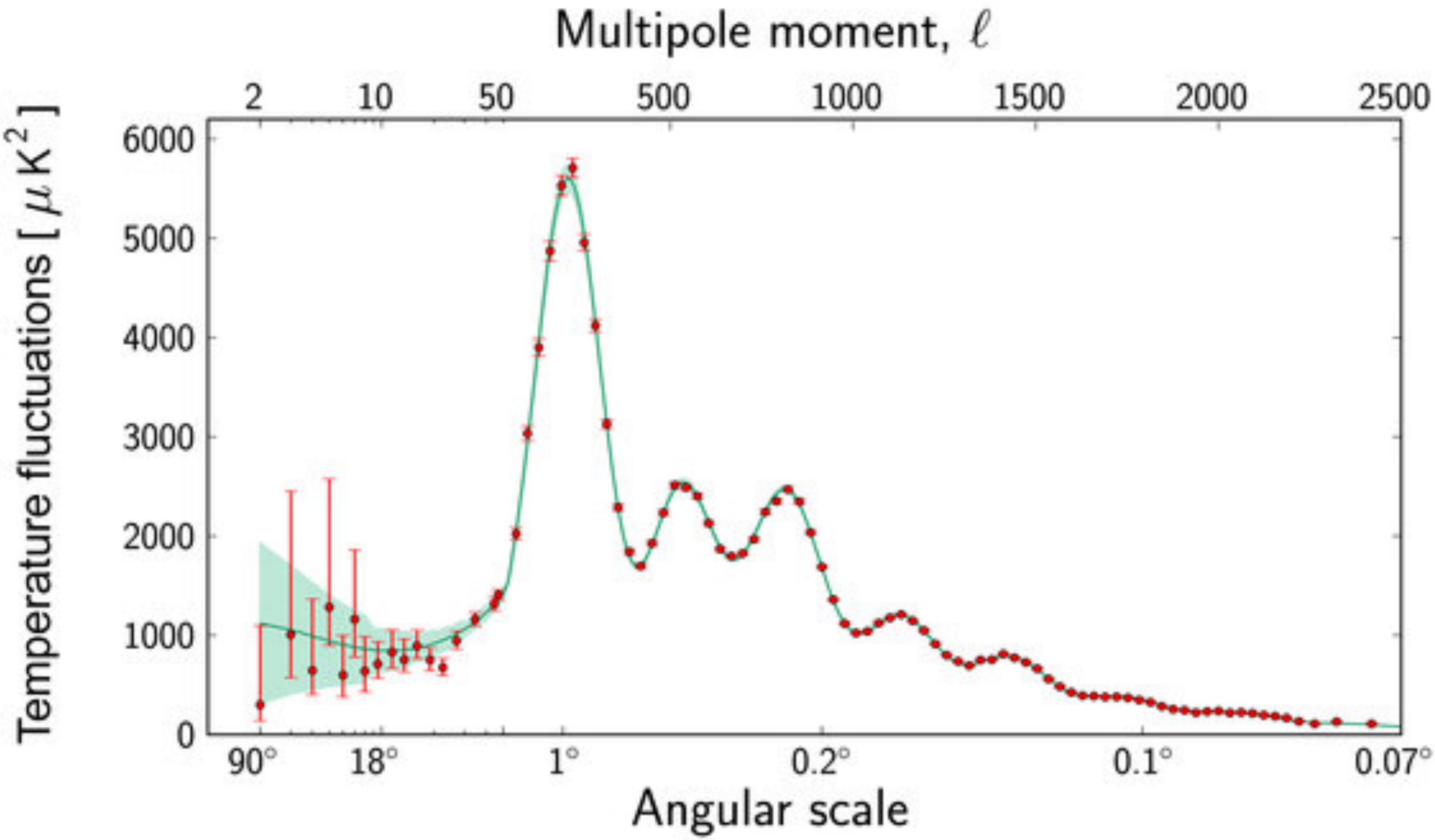
NB: All tests of Classical GR!!


PSR B1913+16
PSR B1534+12
PSR J1141−6545
PSR J0737−3039
m_B
m_A
$\dot{\omega}$
$\dot{P}$
γ
$s \leq 1$
s
r
s_{scint}
Ω_{SO}
x_B/x_A
0
0.5
1
1.5
2
2.5

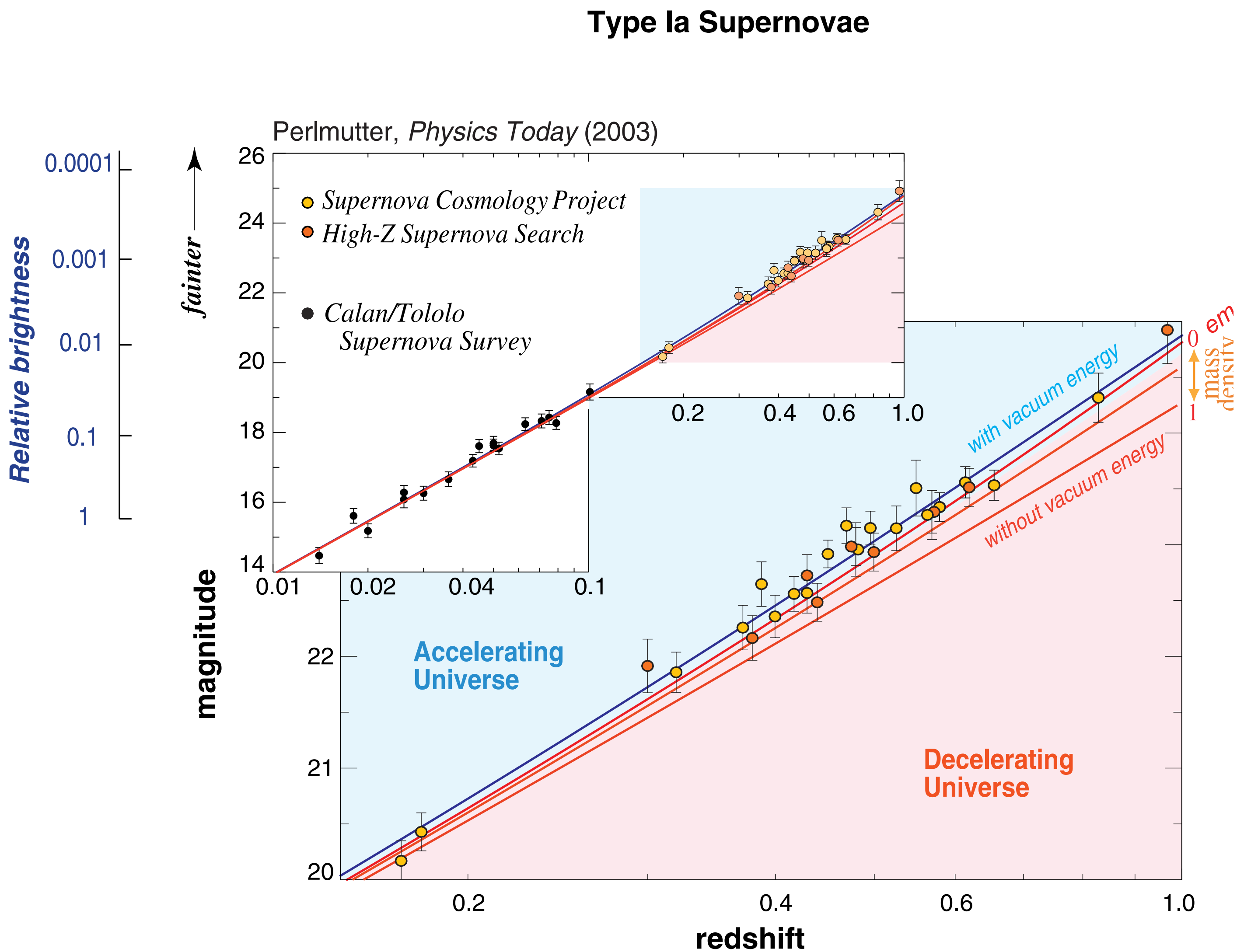
… and Cosmology

Various sets of data appear to converge towards the so-called concordance model

PLANCK POWER SPECTRUM

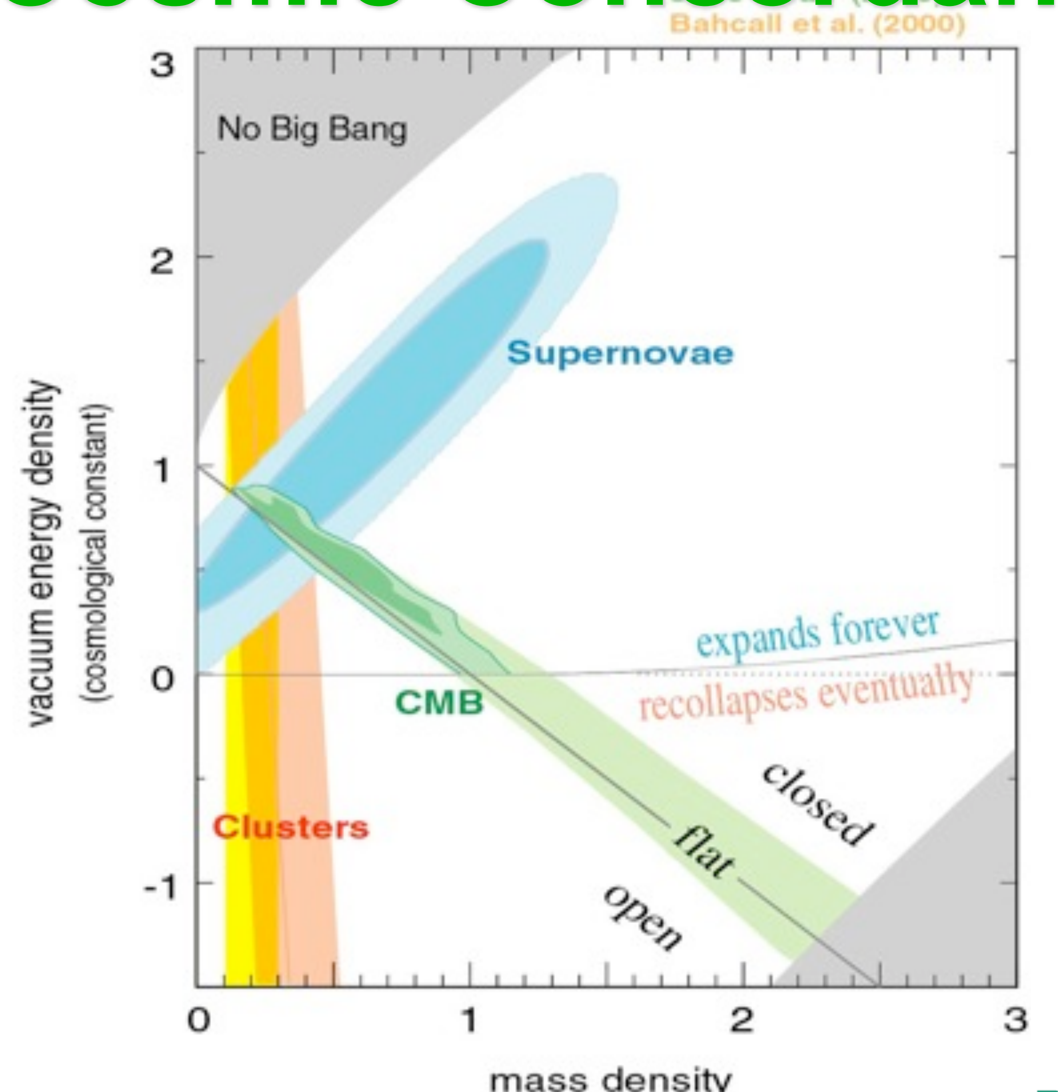


Cosmic acceleration

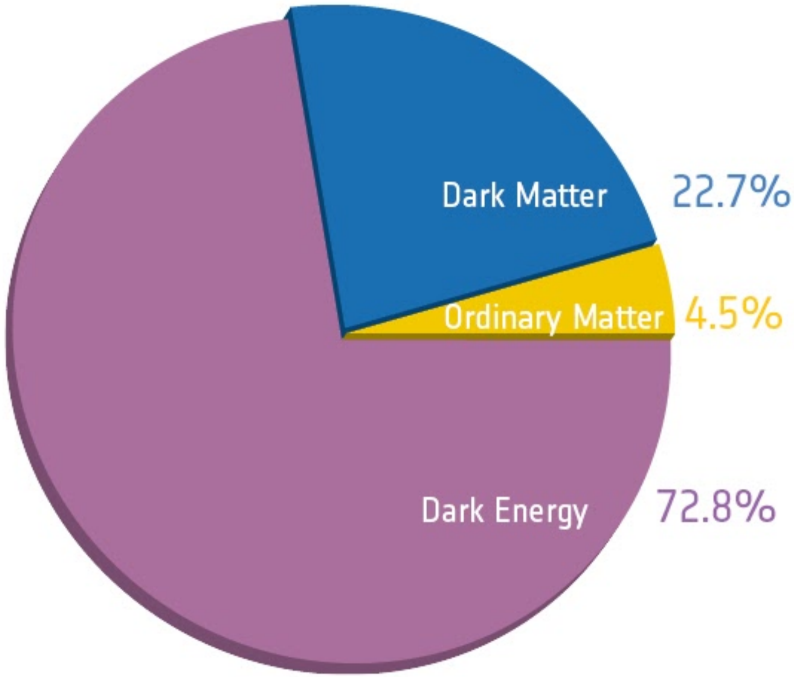


Adding LSS & putting all together

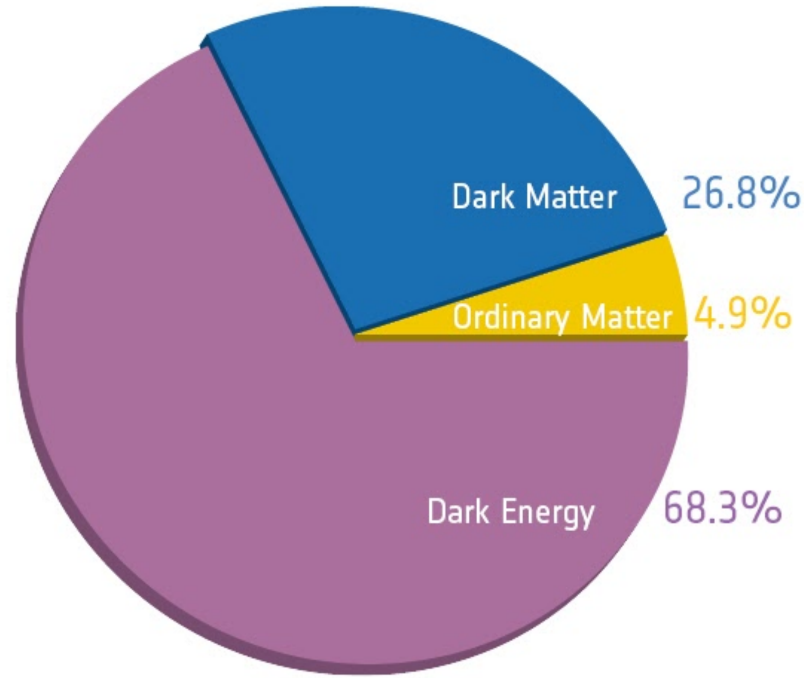
Cosmic Concordance



Portions in cosmic composition pie…
somewhat redistributed after PLANCK



Before Planck



After Planck

A short commercial break

Two arguments for DE (CMB & LSS) are based on inhomogeneities

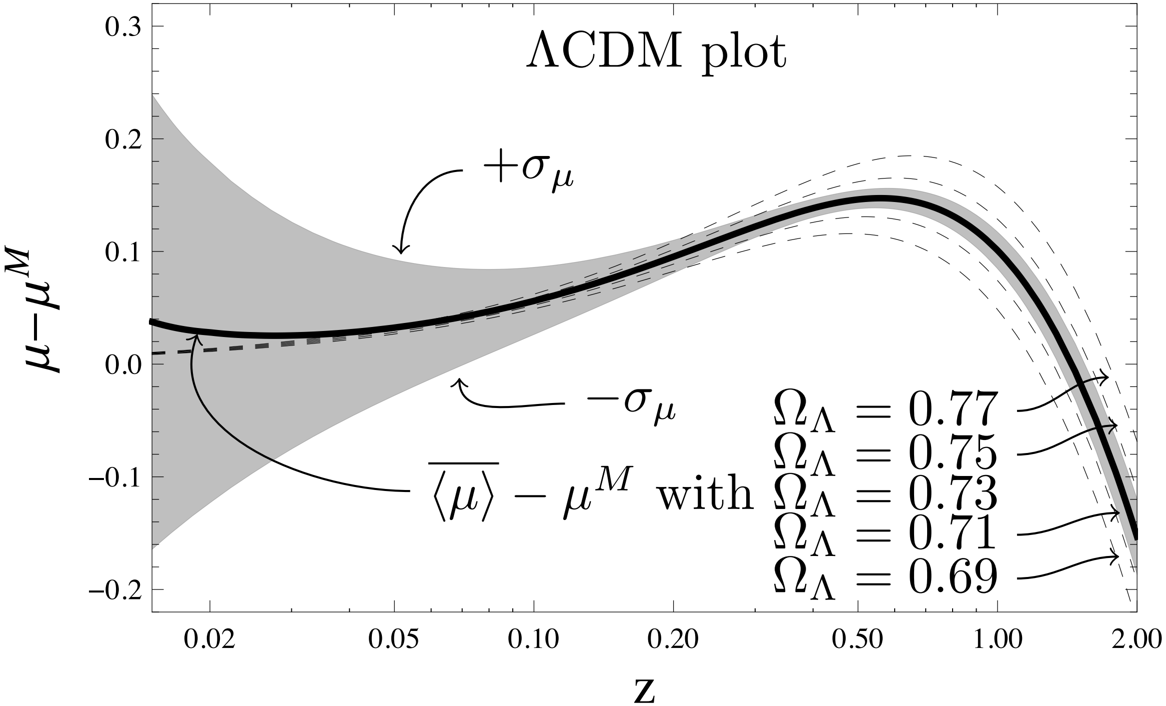
The 3rd one (SNIa) ignores them completely

Q: How do inhomogeneities affect the determination of DE parameters via SN? Studied in a series of papers:

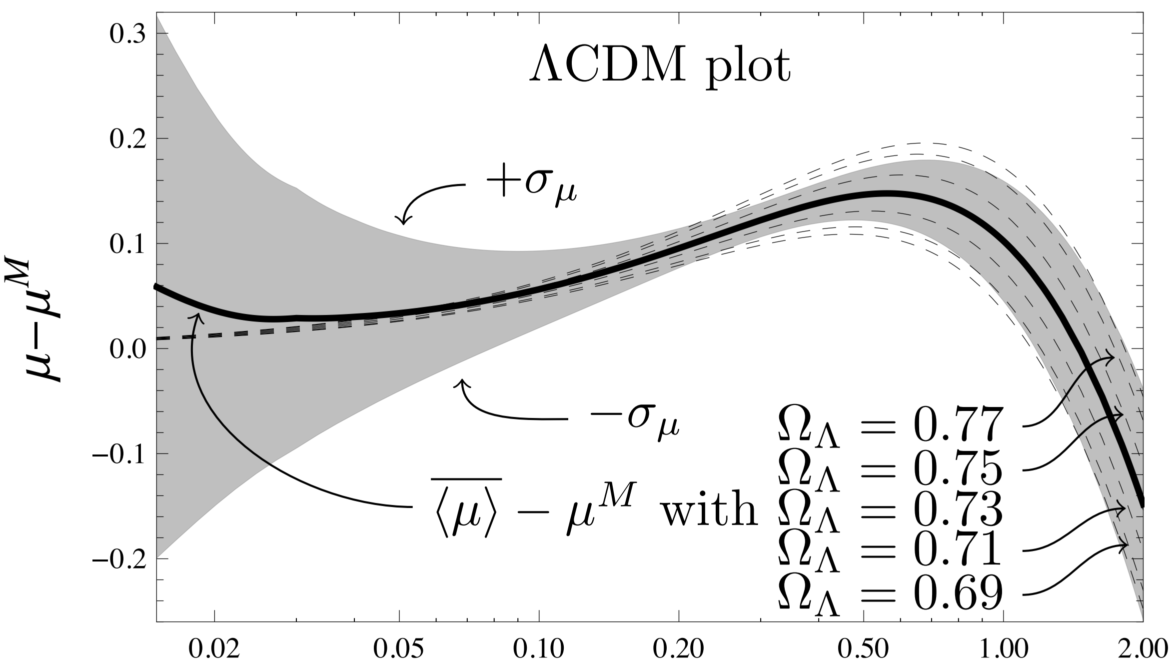
(GMNV, 1104.1167, BGMNV, 1202.1247, 1207.1286, 1302.0740; BGNV,1209.4326, F. Nugier 1309.6542)

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.

Distance modulus

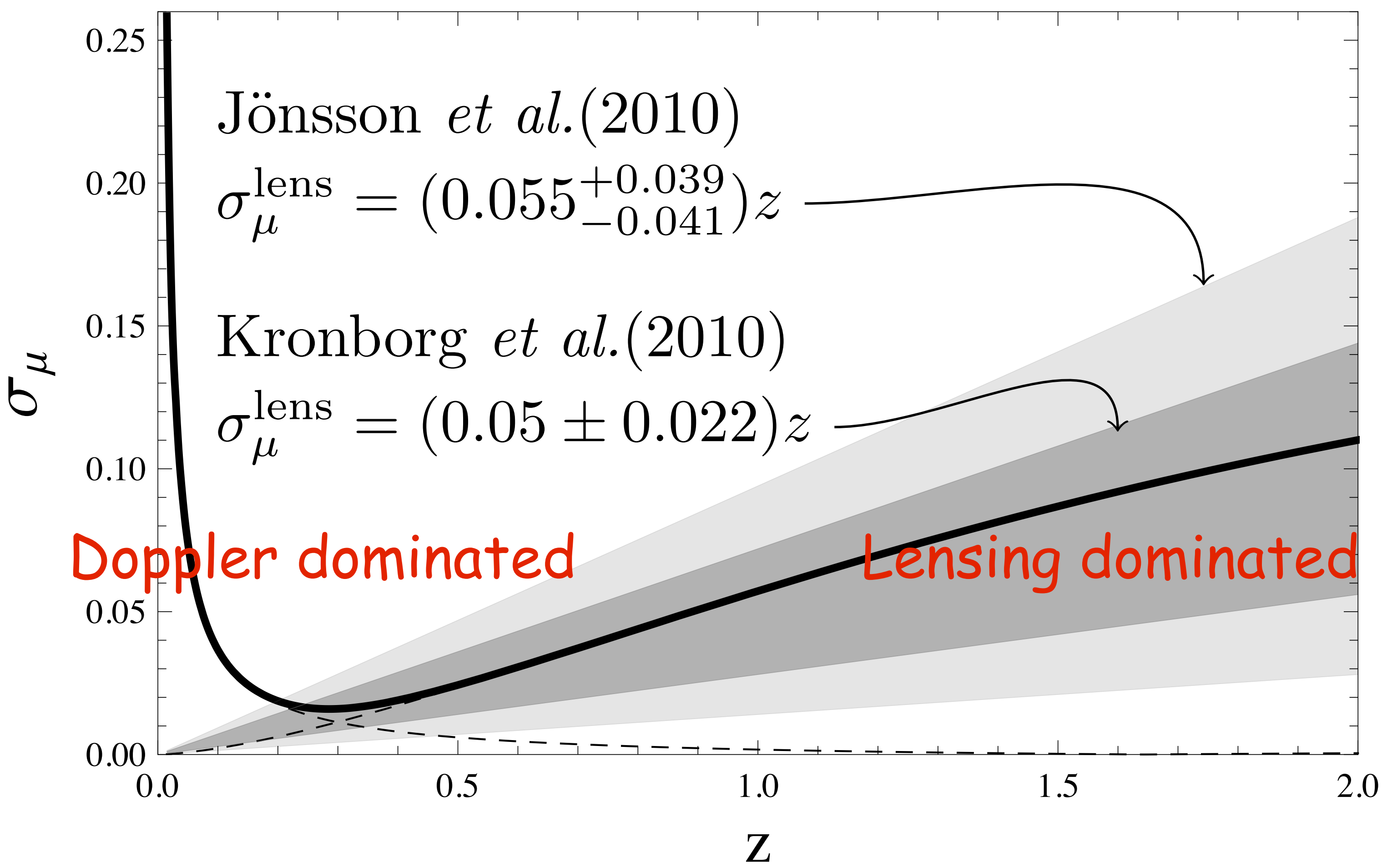


linear PS



non-linear PS

$$(\sigma_\mu^{\rm obs})^2 = (\sigma_\mu^{\rm fit})^2 + (\sigma_\mu^{z})^2 + \left[(\widehat{\sigma_\mu^{\rm int}})^2 + (\sigma_\mu^{\rm lens})^2\right]$$



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

Why a Gauge Theory?

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.

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.

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 μ)
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 Ω_Λ 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

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!

Classical Strings

The (Nambu-Goto) action of a relativistic string:

$$S_{rel.string} = T \int d(area)$$

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.

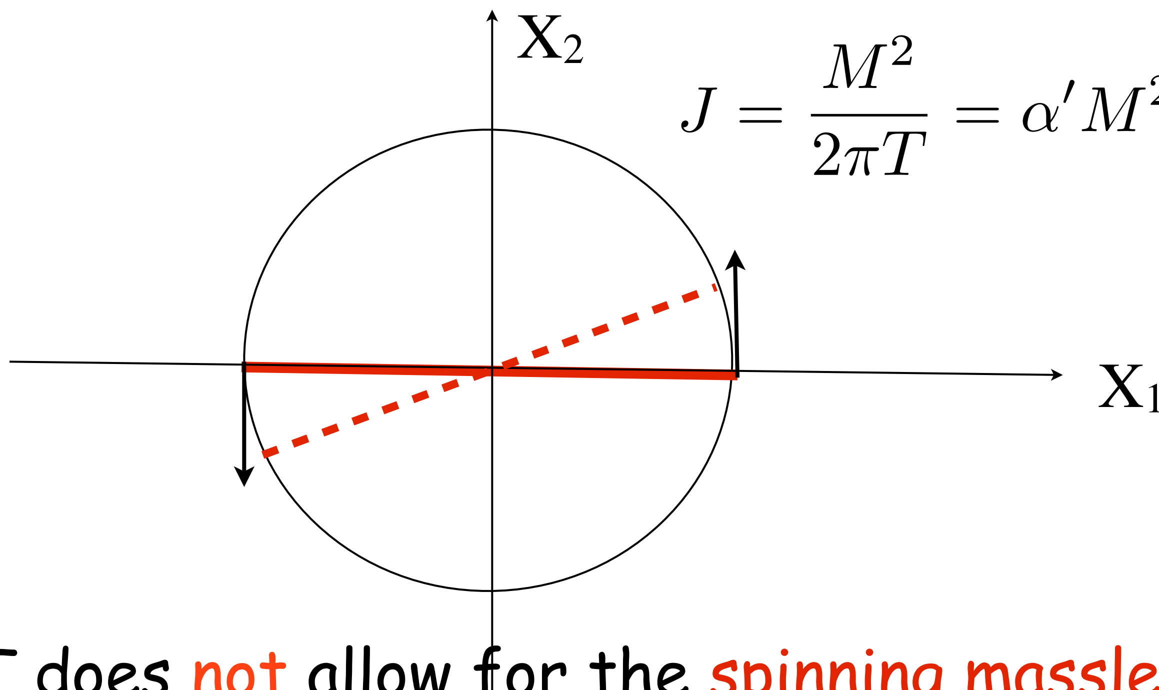
Leads immediately to some strong consequences...

I: No J without M!

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



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

➡ 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: $G_N E$ = length ($c=1$).

➡ CST cannot provide the scale needed for an UV completion of the SMN!

➡ 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:

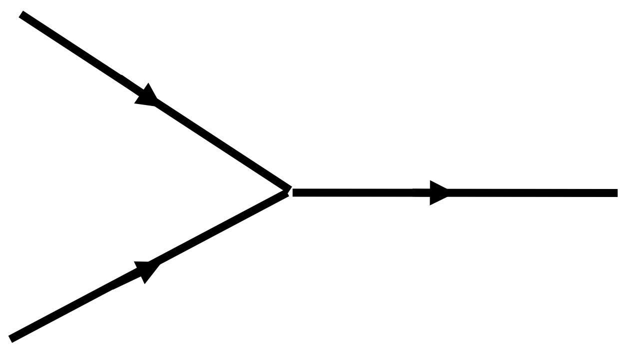
$$\frac{1}{\hbar} S_{string} = \frac{T}{\hbar} (\text{Area swept}) \equiv \frac{\text{Area swept}}{\pi l_s^2} \quad ; \quad l_s \equiv \sqrt{\frac{\hbar}{\pi T}} \equiv \sqrt{2\alpha' \hbar}$$

Note again an analogy with: $l_P = \sqrt{G_N \hbar}$

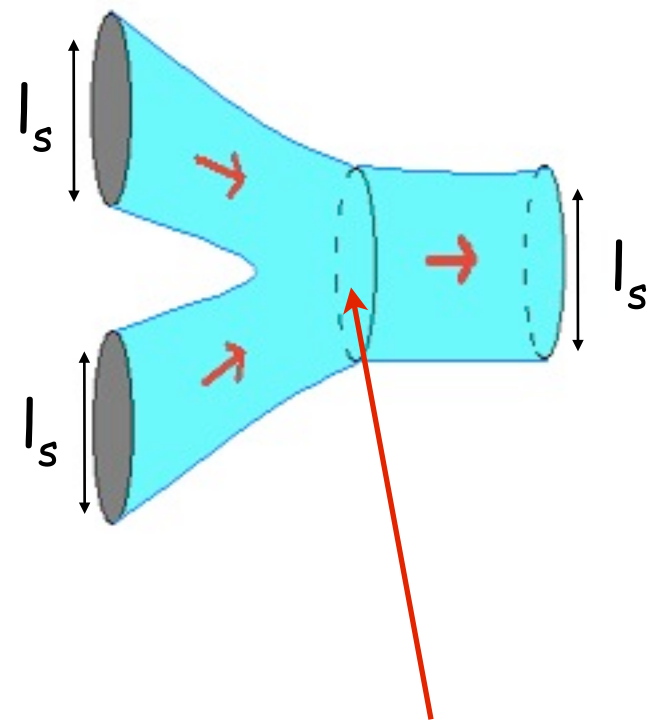
Quantization has introduced a length scale, l_s (and an associated energy scale M_s) needed for UV completion

- 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).

Field Theory



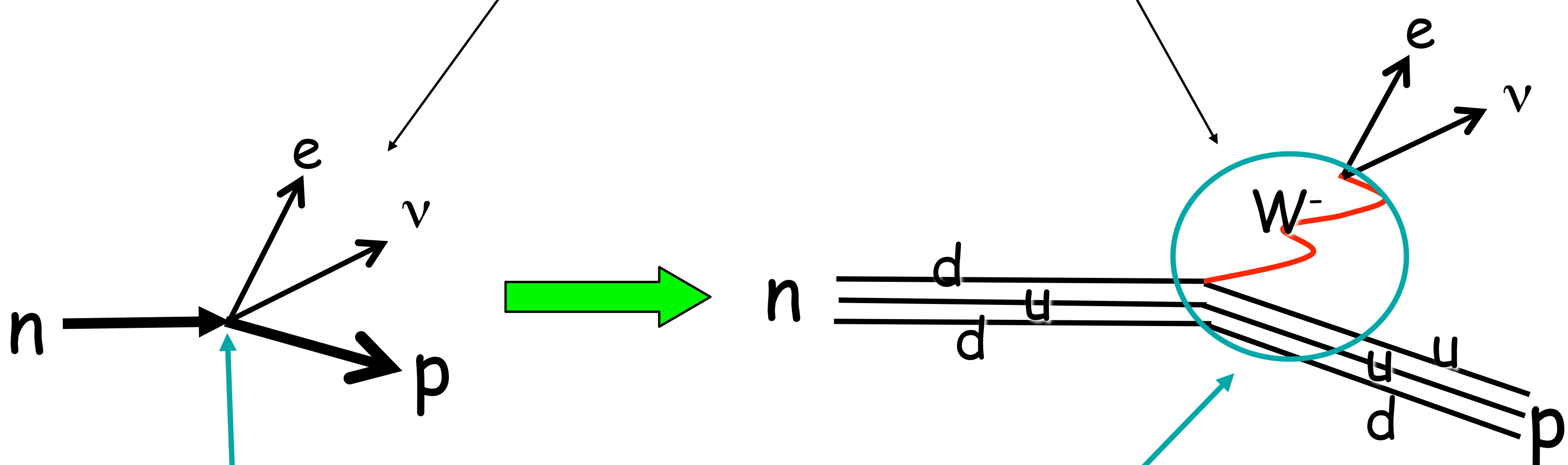
String Theory



Interactions are smeared over regions of order l_s

An interesting analogy

From Fermi (1934) to SMEP (~1973)



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

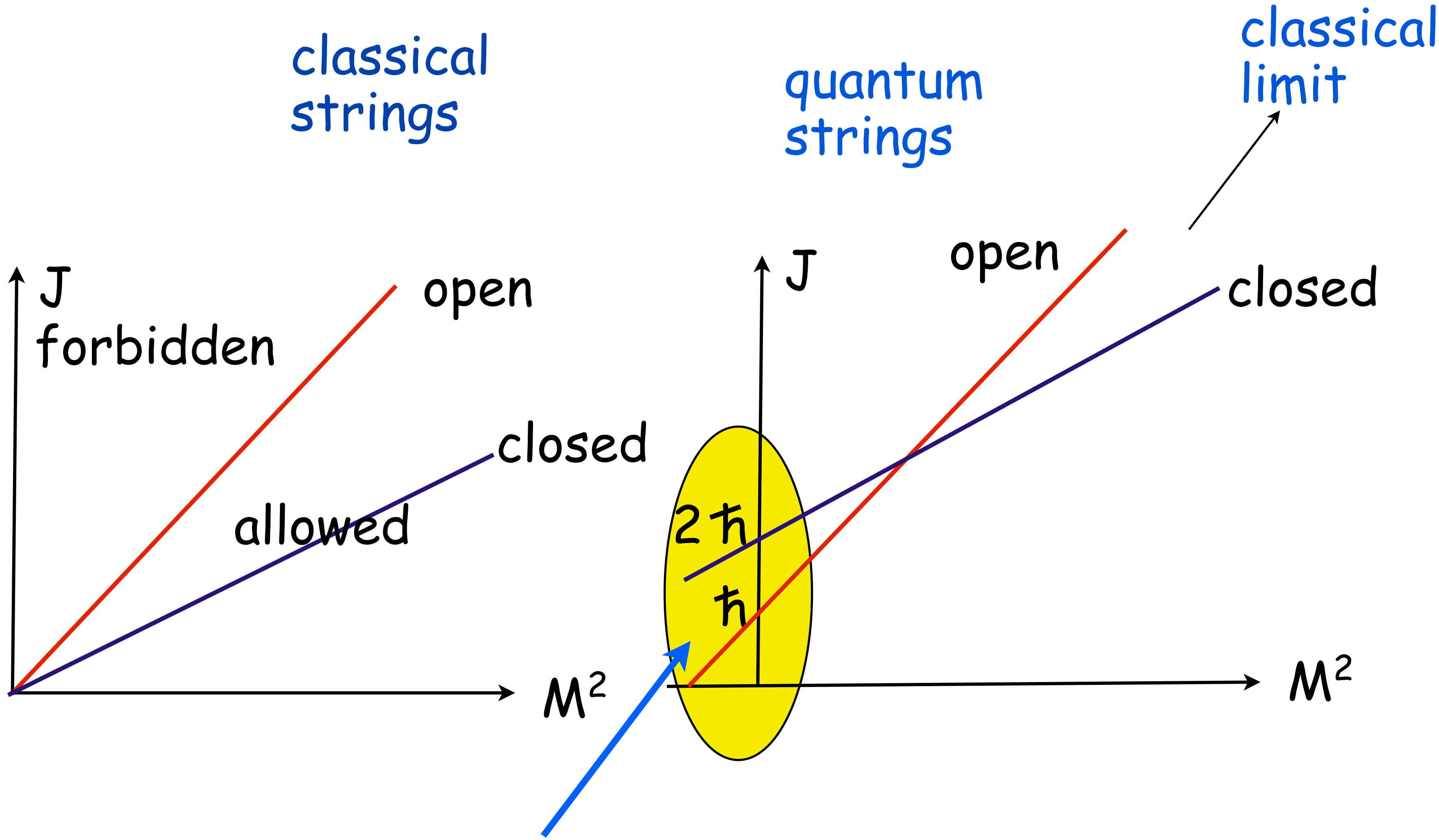
The interaction is **smeared** over a **finite region** of space-time making it a better theory in UV

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...

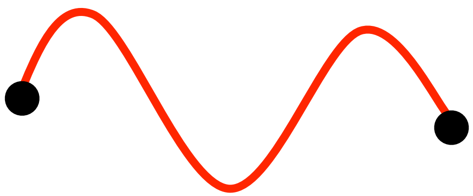
after consistent regularization

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



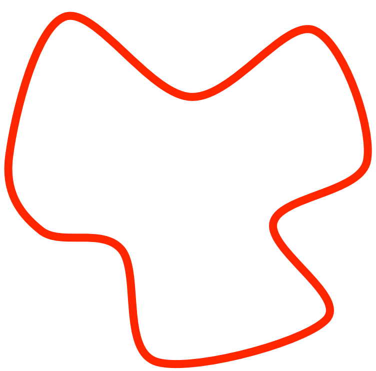
Classical ST has nothing to do with Classical FT!

Unification of all interactions



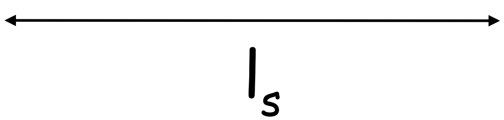
m=0, J=1

⇒ photon and other carriers of non-gravitational interactions



m=0, J= 0, 2

⇒ graviton, and other carriers of gravity-like interactions



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...

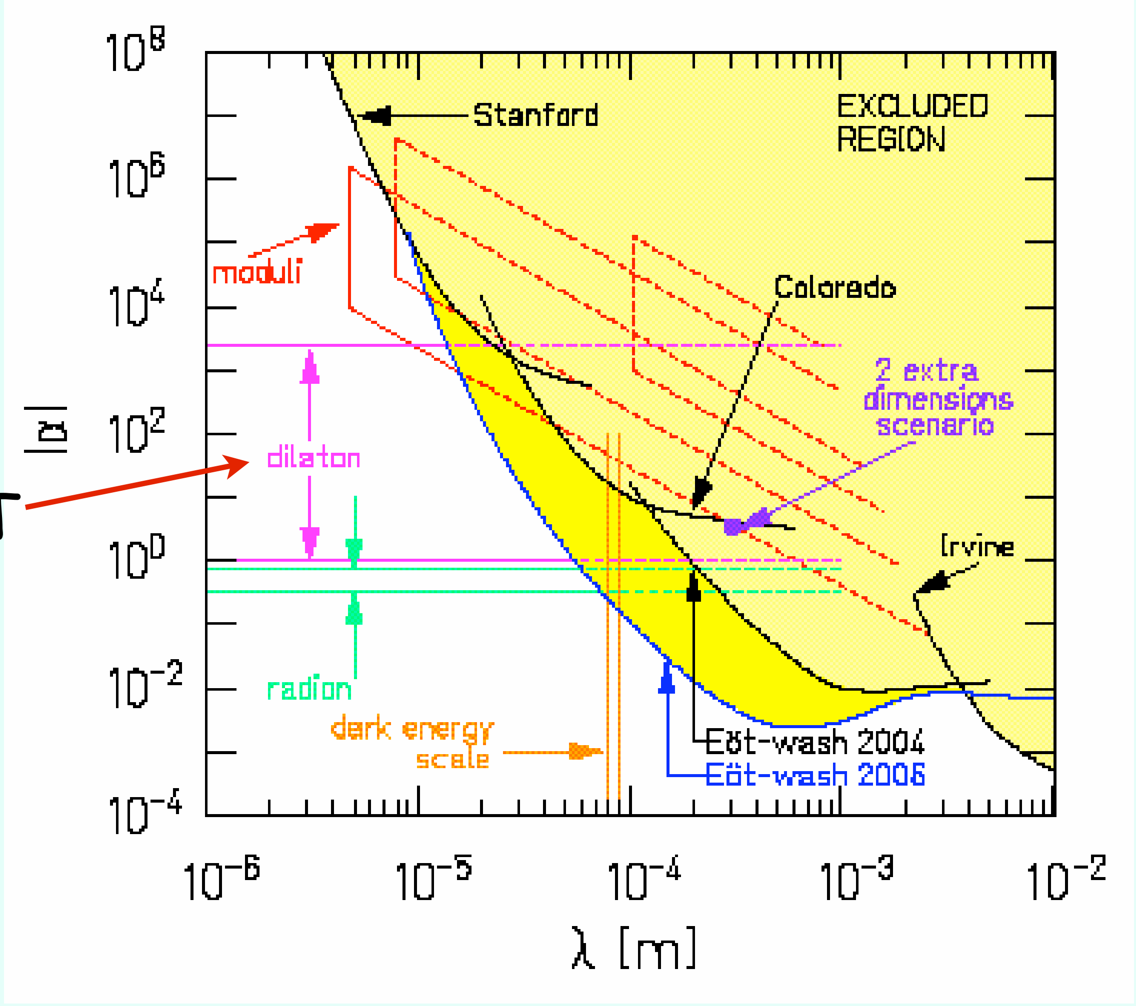
Massless/light scalar fields: Achille's heel of QST?

- 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 α
- Are they dynamically determined? Computing α 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!