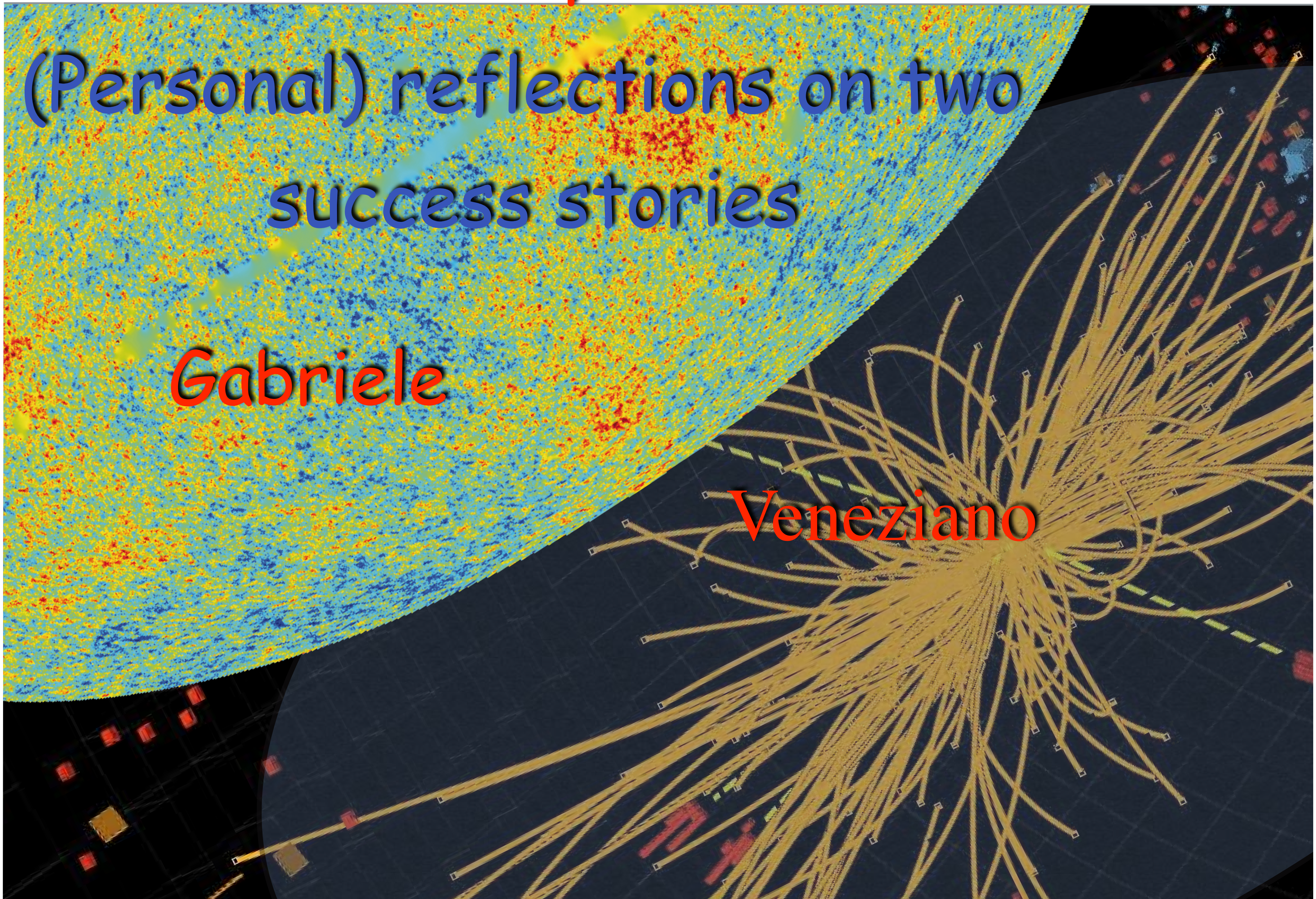
La Sapienza, 19.02.2015



(Personal) reflections on two success stories

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Outline

- The SM of Nature after LHC & PLANCK
  - The SM of Elementary Particles
  - The SM of Gravity & Cosmology
  - Two personal reflections
- Quantum corrections: the good & the bad
  - A third personal reflection
  - Wanted: an IUVC
- Can it be Quantum String Theory?
- Summary

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

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

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

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

new!

confirmed?

The SM of Elementary Particles

A quantum-relativistic theory incorporating the gauge-invariance principle

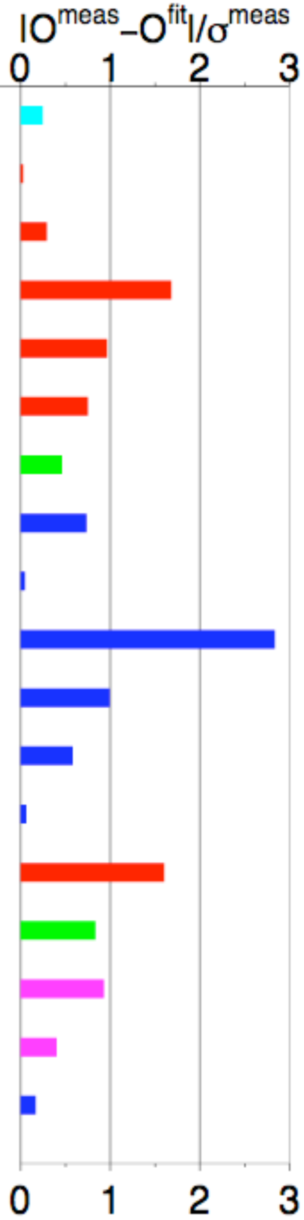
The quantum-relativistic nature of SMEP manifests itself through real and virtual particle production

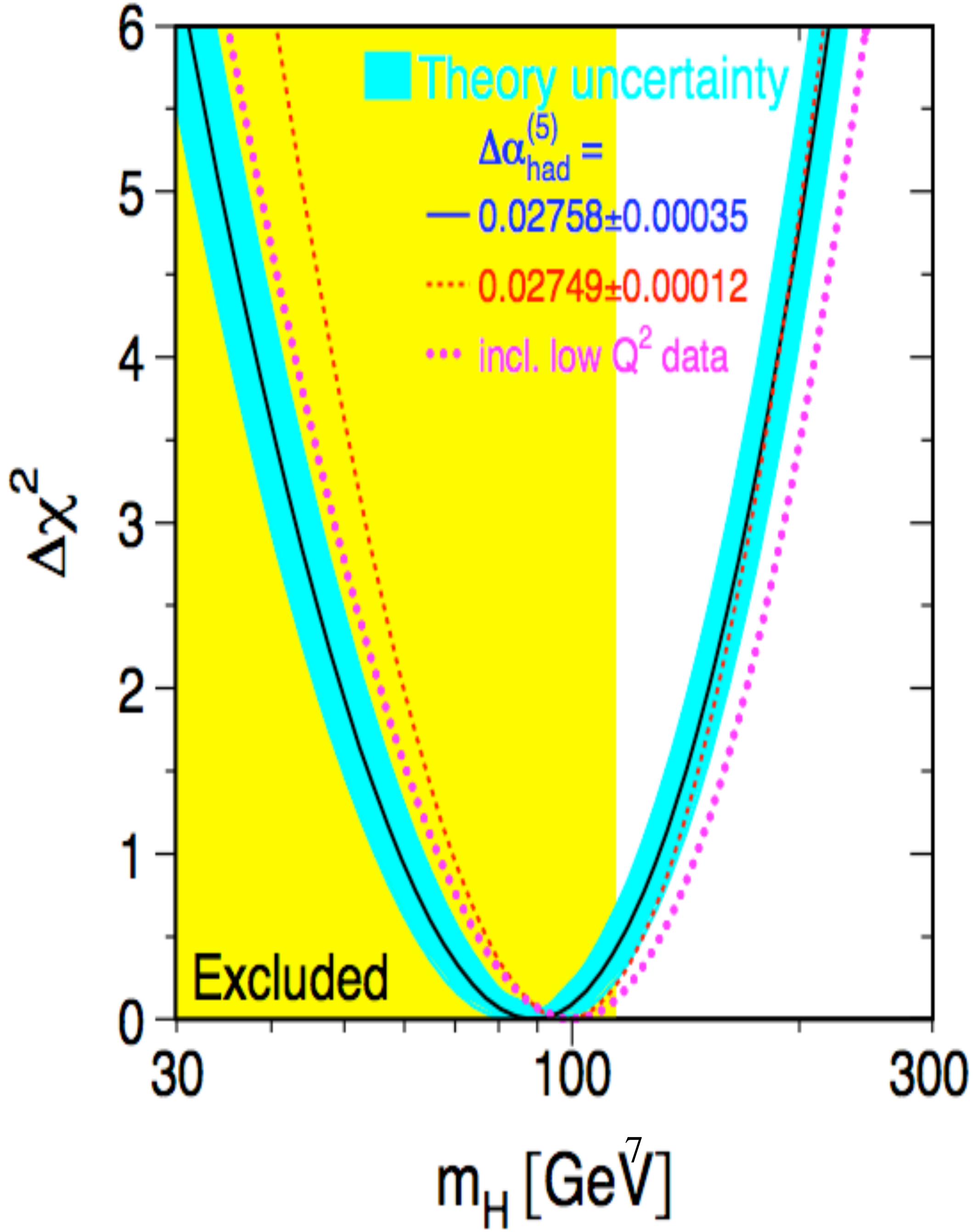
These are essential for agreement w/ experiment (tree-level predictions are off by many σ)

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

	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





Understanding non-perturbative (i.e. very quantum) IR effects was also crucial within the strong interaction (QCD) sector of the SM (quark confinement, chiral symmetry breaking, instantons,...)

The SM of Gravity…

General Relativity: a classical relativistic theory incorporating the equivalence principle

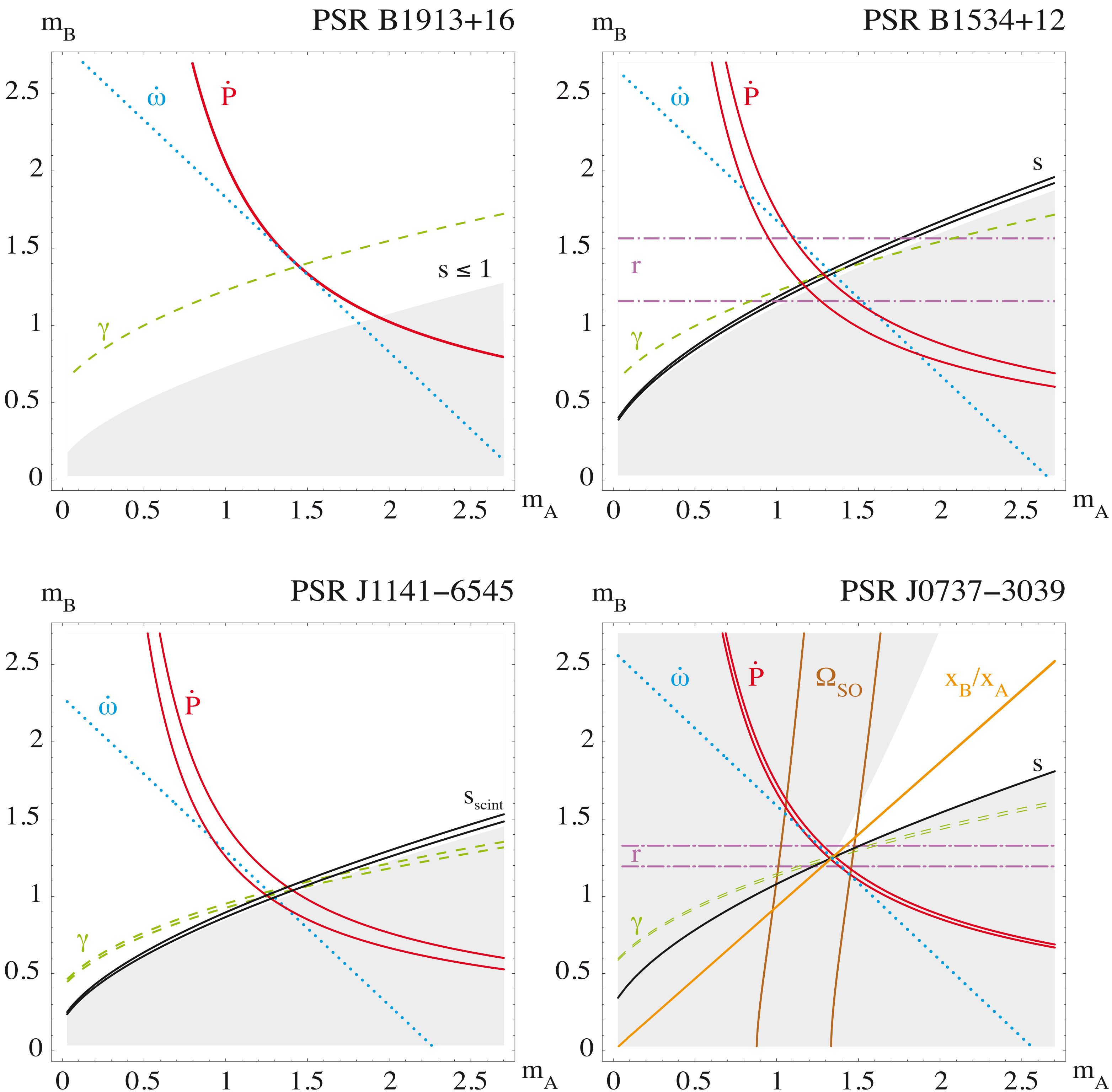
UFF tested with incredible precision

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!!


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
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2
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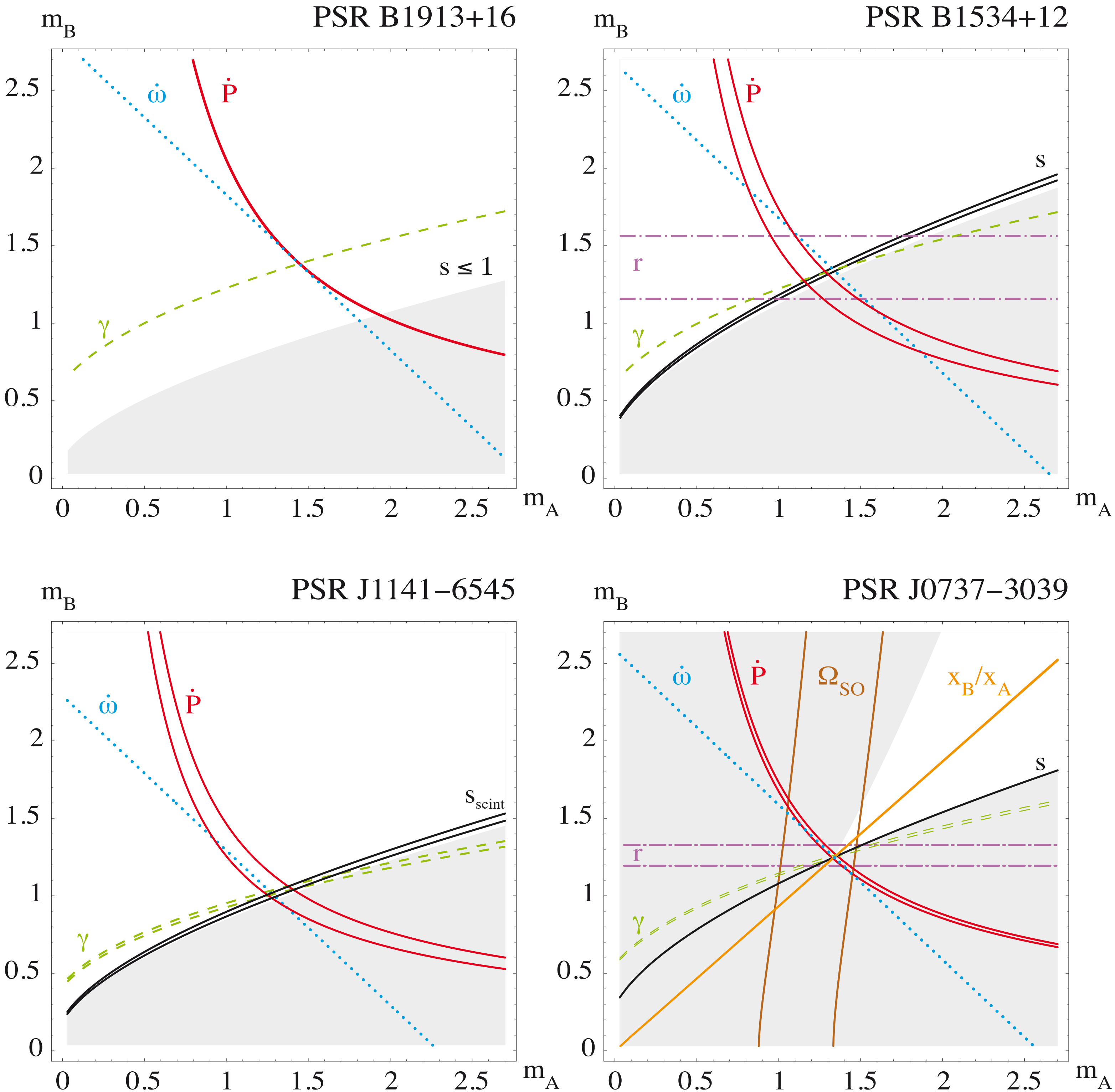

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r
s_{scint}
Ω_{SO}
x_B/x_A
0
0.5
1
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2
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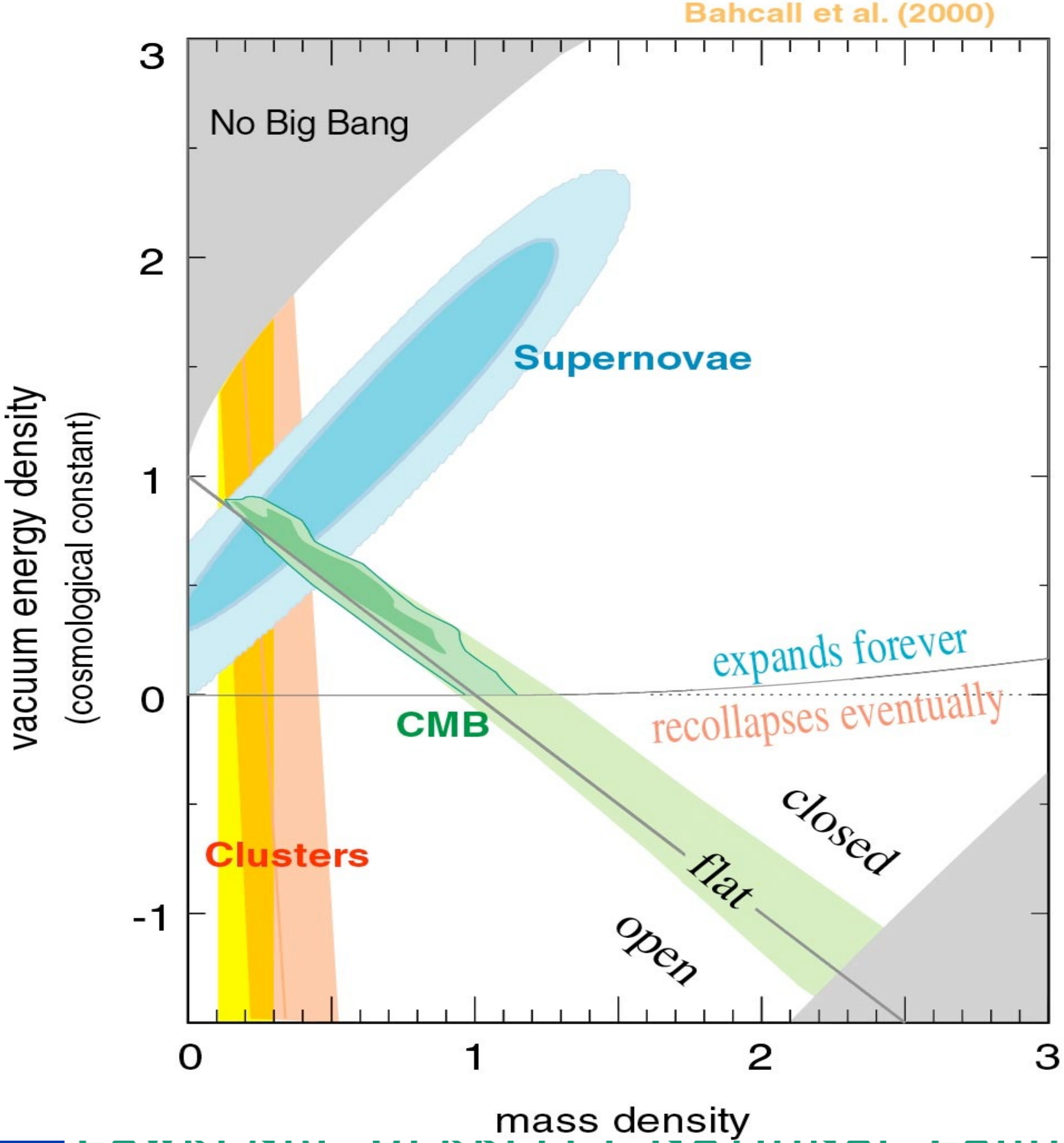
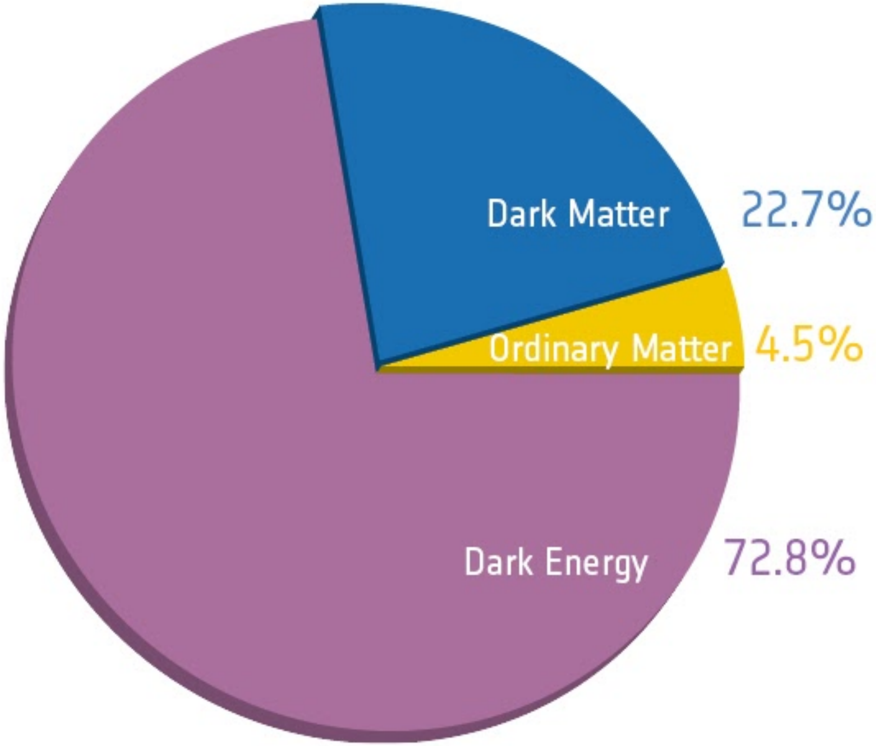
… and Cosmology

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

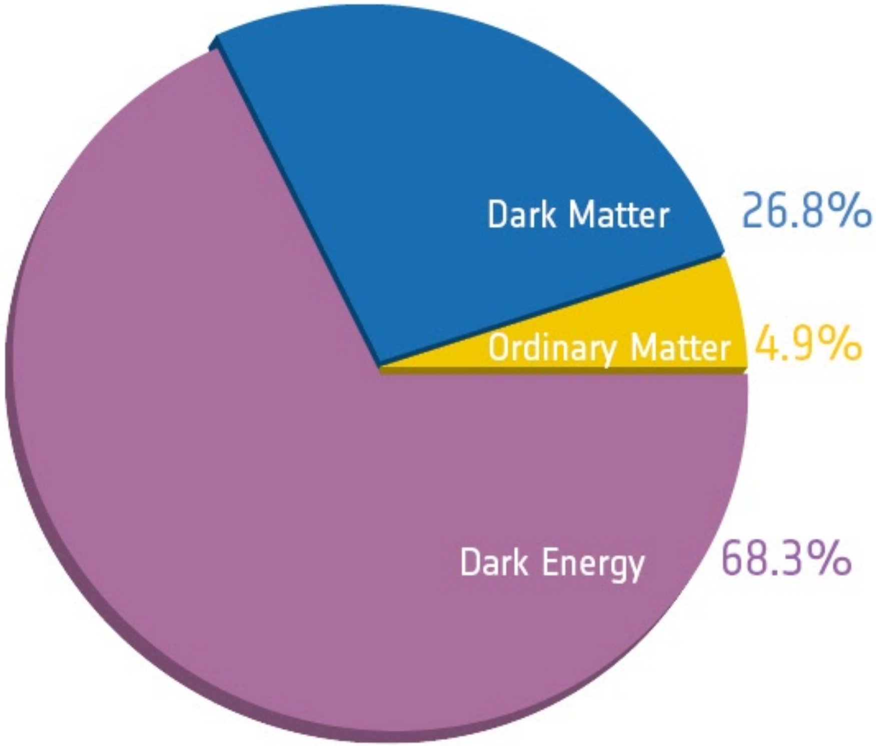
Cosmic Concordance



Portions in cosmic composition pie…
somewhat redistributed after PLANCK



Before Planck



After Planck

A short commercial break

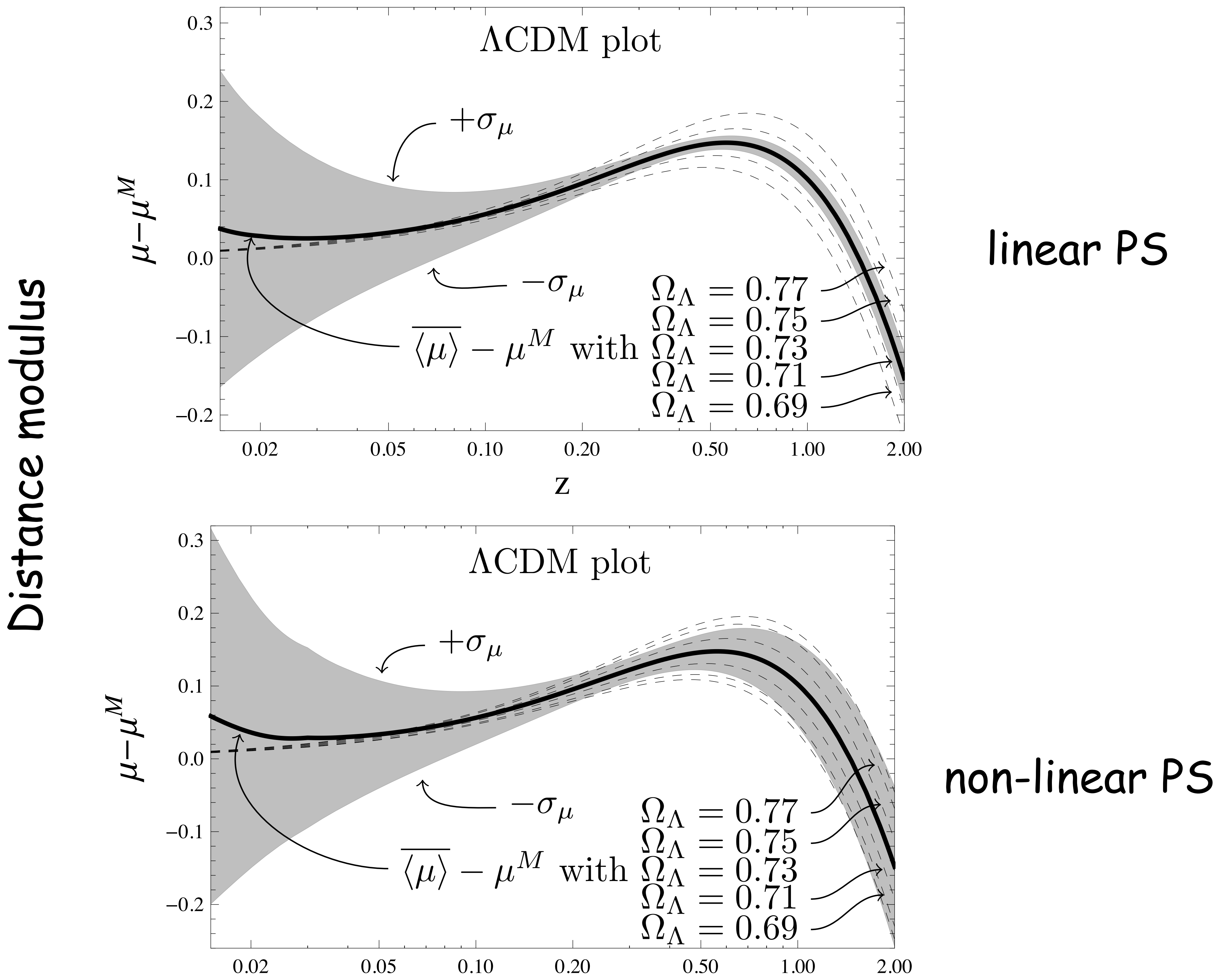
Two arguments for DE (CMB & LSS) are based on inhomogeneities

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 including:

GMNV, 1104.1167, BGMNV, 1202.1247, 1207.1286, 1302.0740; BGNV,1209.4326, FMGV, 1308.4935 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
ΛCDM plot
$+\sigma_\mu$
$-\sigma_\mu$
$\overline{\langle\mu\rangle} - \mu^M$ with
$\Omega_\Lambda = 0.77$
$\Omega_\Lambda = 0.75$
$\Omega_\Lambda = 0.73$
$\Omega_\Lambda = 0.71$
$\Omega_\Lambda = 0.69$
$\mu - \mu^M$
z
linear PS
non-linear PS

The SMEP and the SMGC get nicely combined in inflationary cosmology

However, classical GR no longer enough: (Semiclassical) quantization of the geometry is part of the game explaining the large-scale structure of the Universe

Already true for (observed) scalar perturbations: separation of matter and metric perturbations is gauge-dependent

Unavoidable if primordial GW will be found

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

Why a Gauge Theory?

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.

Why General Relativity?

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 appears 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?

Before trying to give an answer…

Theoretical puzzles

(fortunately there are still some!)

Particle physics puzzles

1. Why G = SU(3)xSU(2)xU(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)
  - 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

In the mid 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

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

S_{string}/h introduces a fundamental length scale:

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

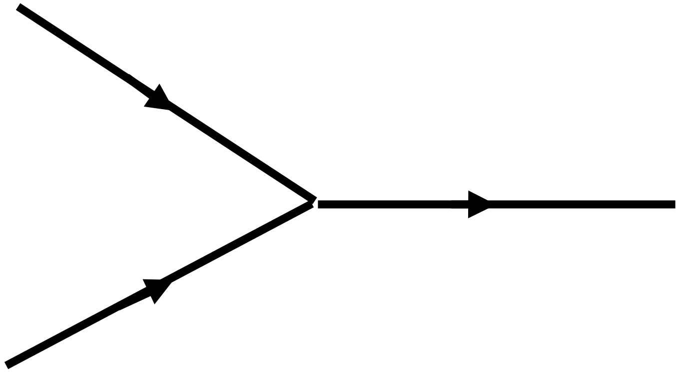
Note analogy with:

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

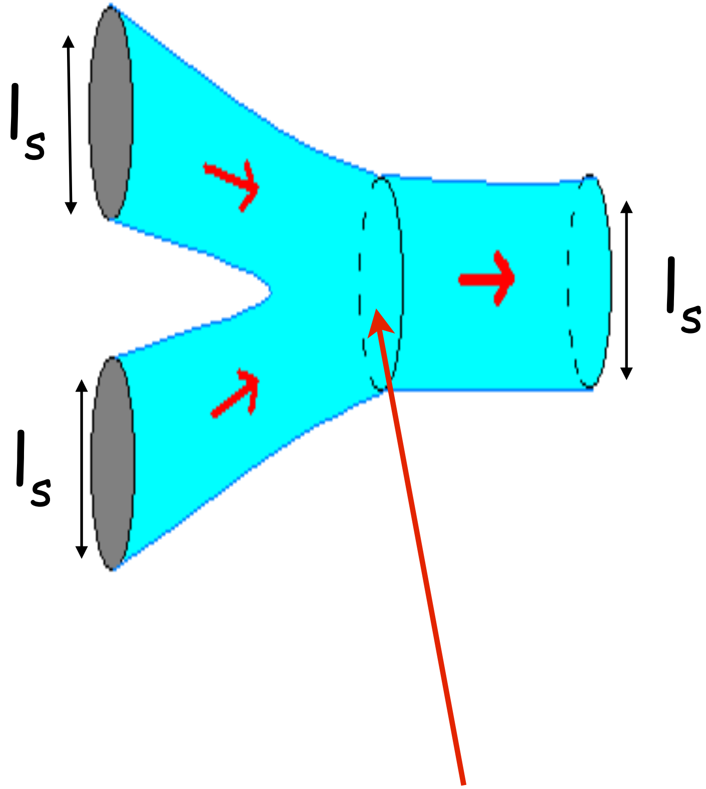
l_s is ST's Planck constant! Enters in many crucial ways

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

Field Theory



String Theory



Interactions smeared over regions of order l_s

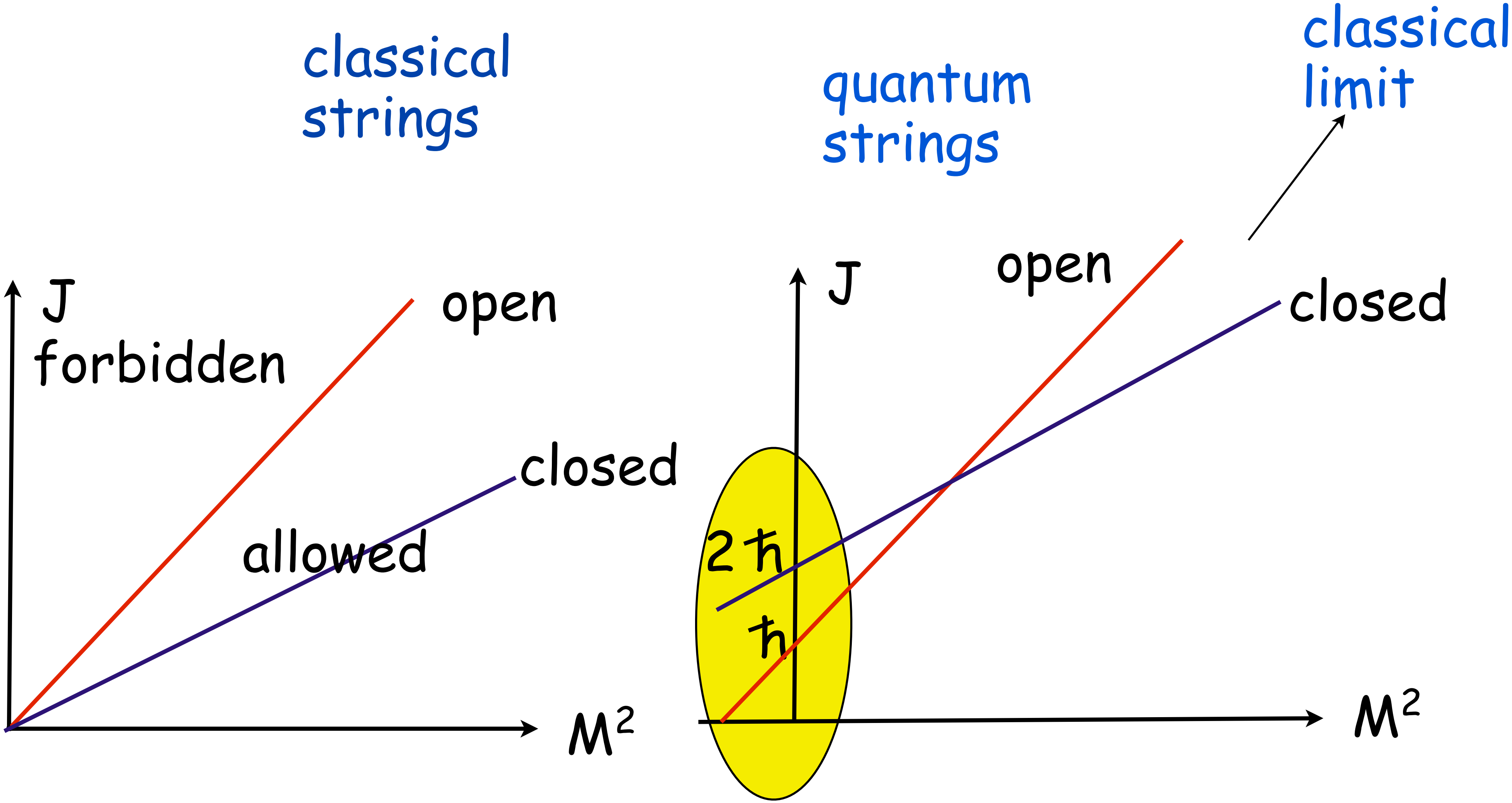
=> Quantum corrections down to arbitrarily small distances are under control.

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.

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!

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.

Q_1: 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...

Q_2: Is QST able to provide mechanisms of (spontaneous) SUSY breaking that preserves that particular virtue of its perturbation theory? A_2 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?

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...

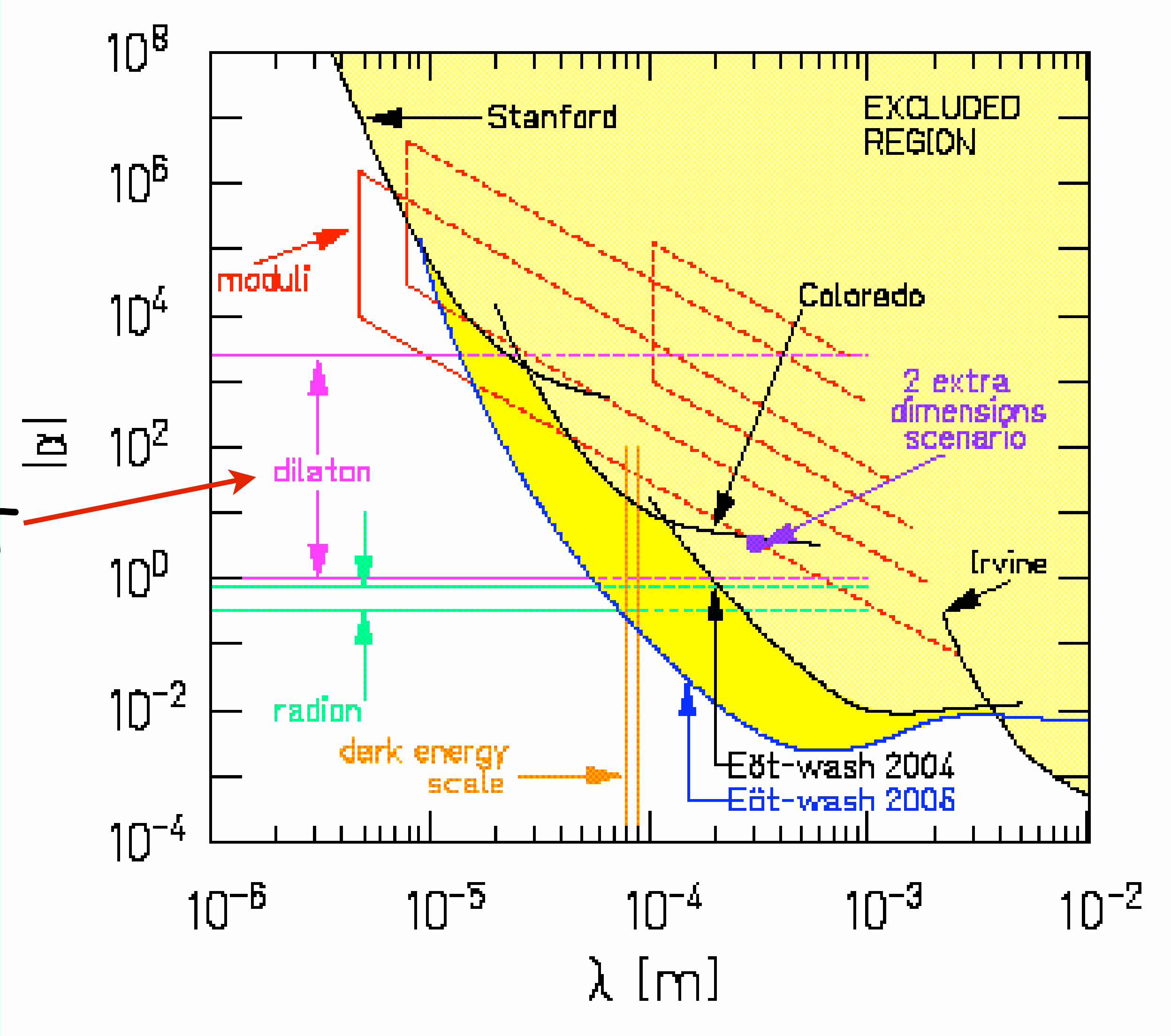
Massless/light scalar fields: Achille's heel of QST?

- QFT's parameters are replaced by (typically scalar) 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

SUMMARY

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 devil 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!