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The Standard Model of Nature and its legacy

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1530

Outline

- The Standard Model of Nature after 2012:
  - SM of elementary particles
  - SM of gravitation and cosmology
- Lessons from a success story.
- Puzzles & problems: what's their message?
- Classical String Theory can't help.
- Quantum String Theory can, but...

The Standard Model of Nature (after LHC & PLANCK)

based on two pillars:

1. A Gauge Theory, dating from the early seventies, for the electro-weak and strong interactions;
2. General Relativity, invented by Einstein in 1915, for gravity.

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 in a few lines

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

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

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

New!

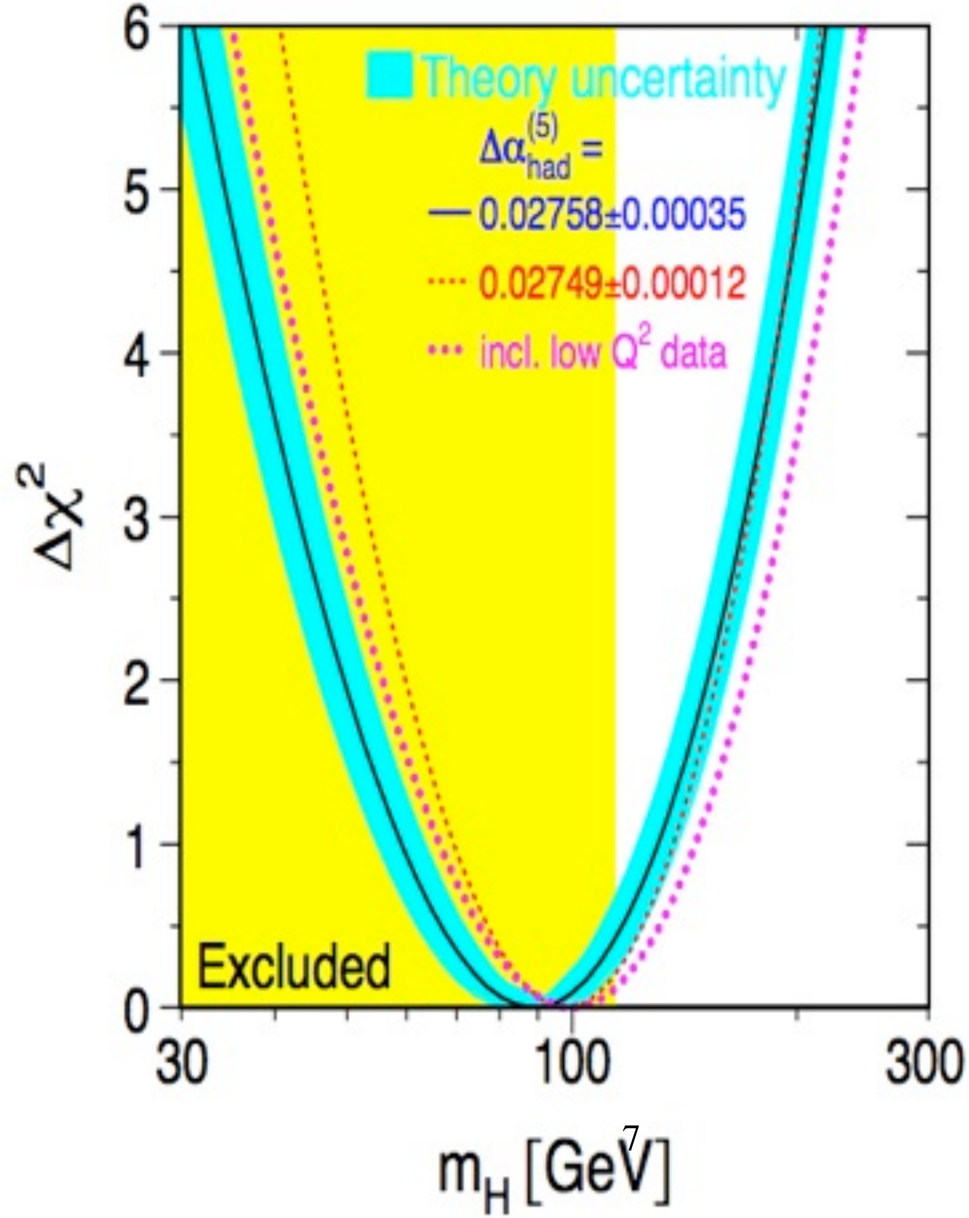
Successes of the SMEP (updated July 4th, 2012)

Very widely tested in accelerator experiments (... LEP, HERA, Tevatron, LHC)

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

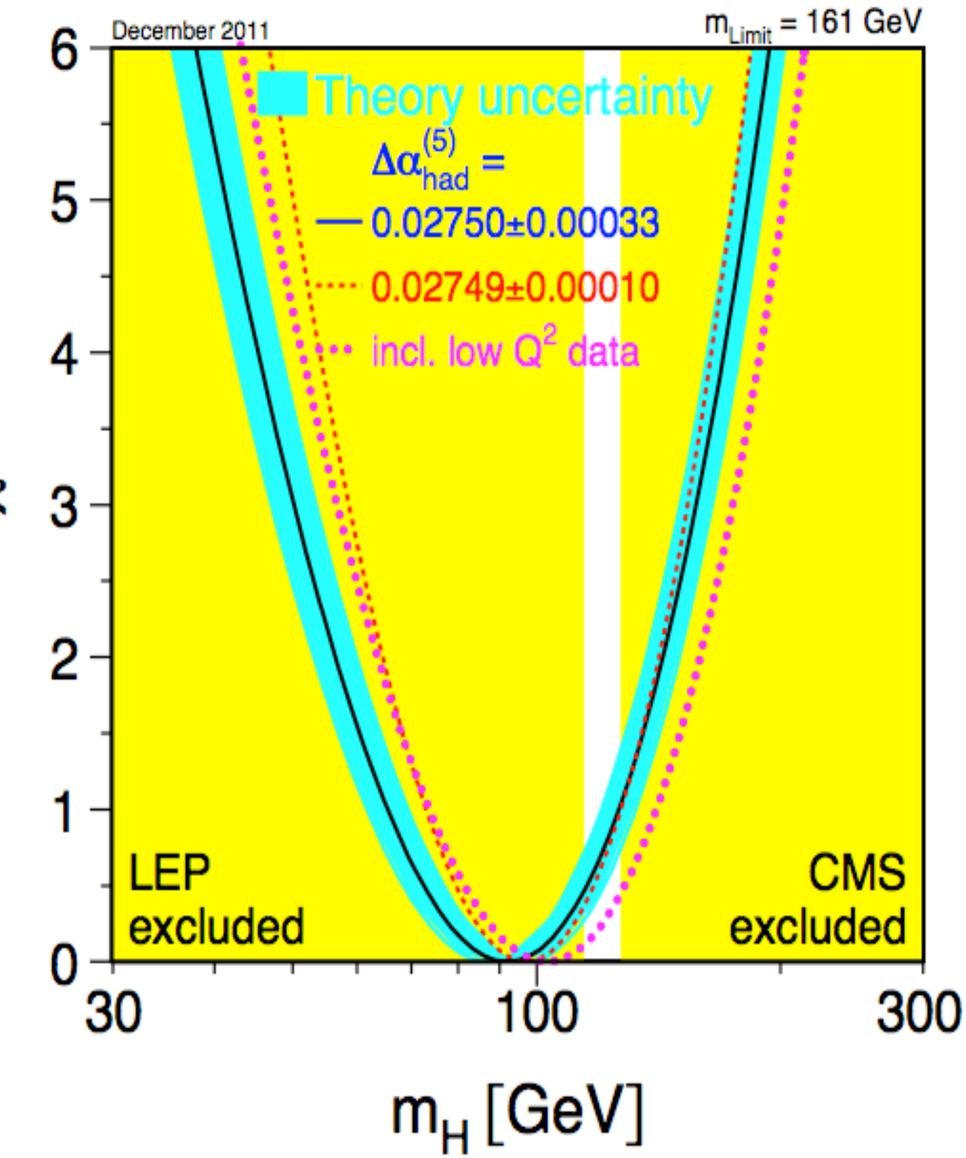
After LEP

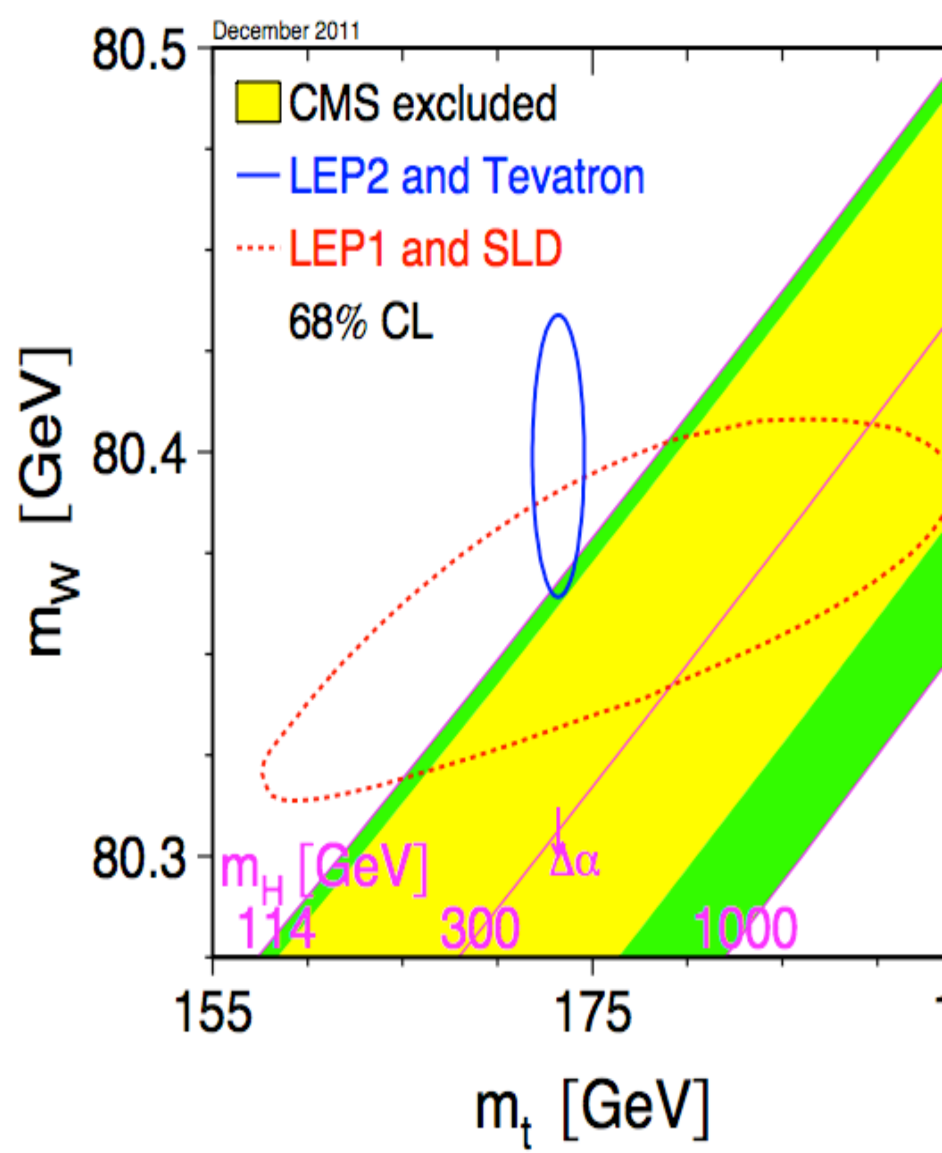
Measurement
Fit
|O^meas−O^fit|/σ^meas
0 1 2 3
Δα^(5)_had(m_Z) 0.02758 ± 0.00035 0.02767
m_Z [GeV] 91.1875 ± 0.0021 91.1874
Γ_Z [GeV] 2.4952 ± 0.0023 2.4959
σ^0_had [nb] 41.540 ± 0.037 41.478
R_l 20.767 ± 0.025 20.743
A^0,l_fb 0.01714 ± 0.00095 0.01643
A_l(P_τ) 0.1465 ± 0.0032 0.1480
R_b 0.21629 ± 0.00066 0.21581
R_c 0.1721 ± 0.0030 0.1722
A^0,b_fb 0.0992 ± 0.0016 0.1037
A^0,c_fb 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
sin²θ^lept_eff(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
0 1 2 3



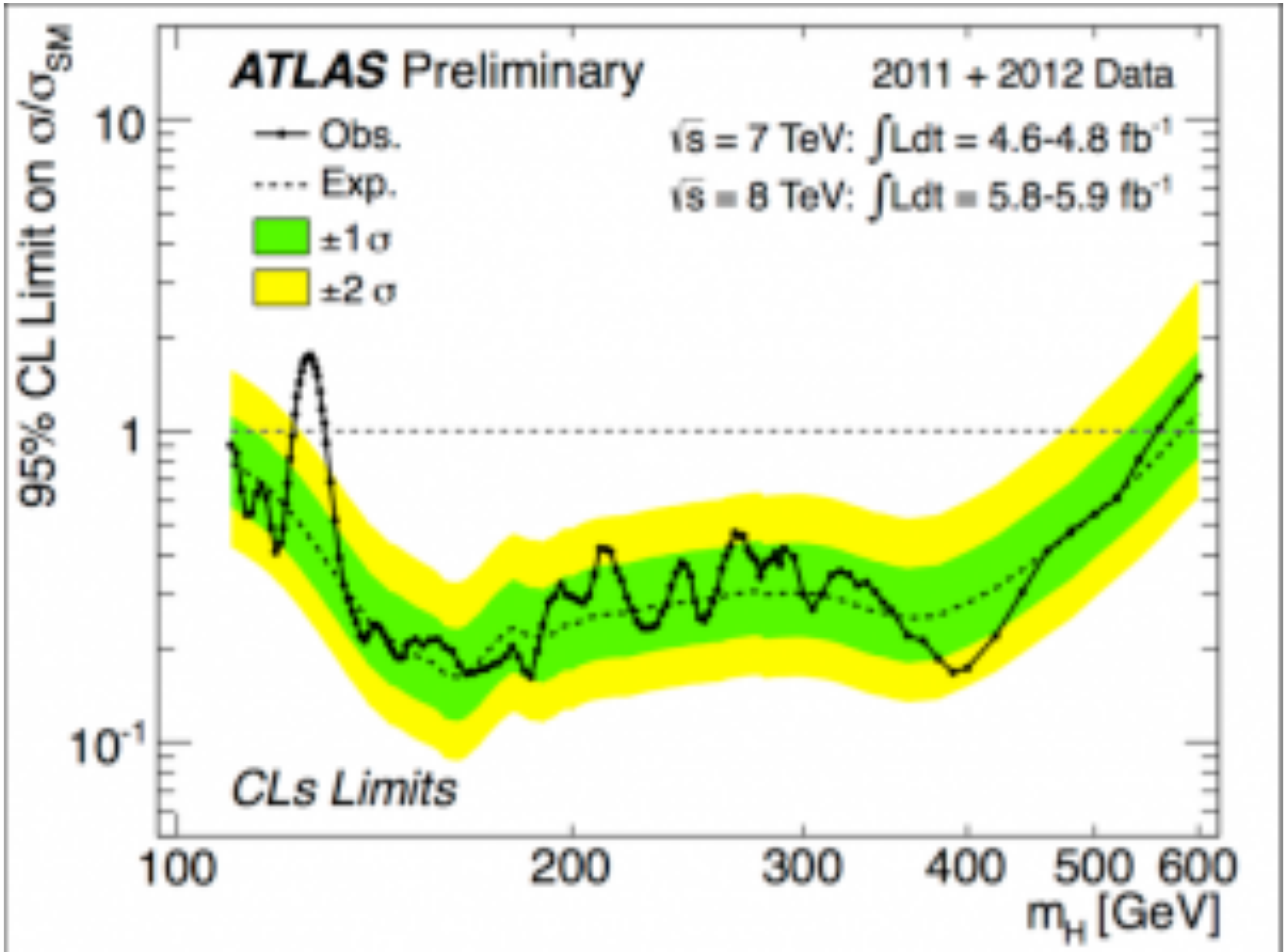
Theory uncertainty
Δα^(5)_had =
0.02758±0.00035
0.02749±0.00012
incl. low Q² data
Excluded
Δχ²
0 1 2 3 4 5 6
30 100 300
m_H [GeV]

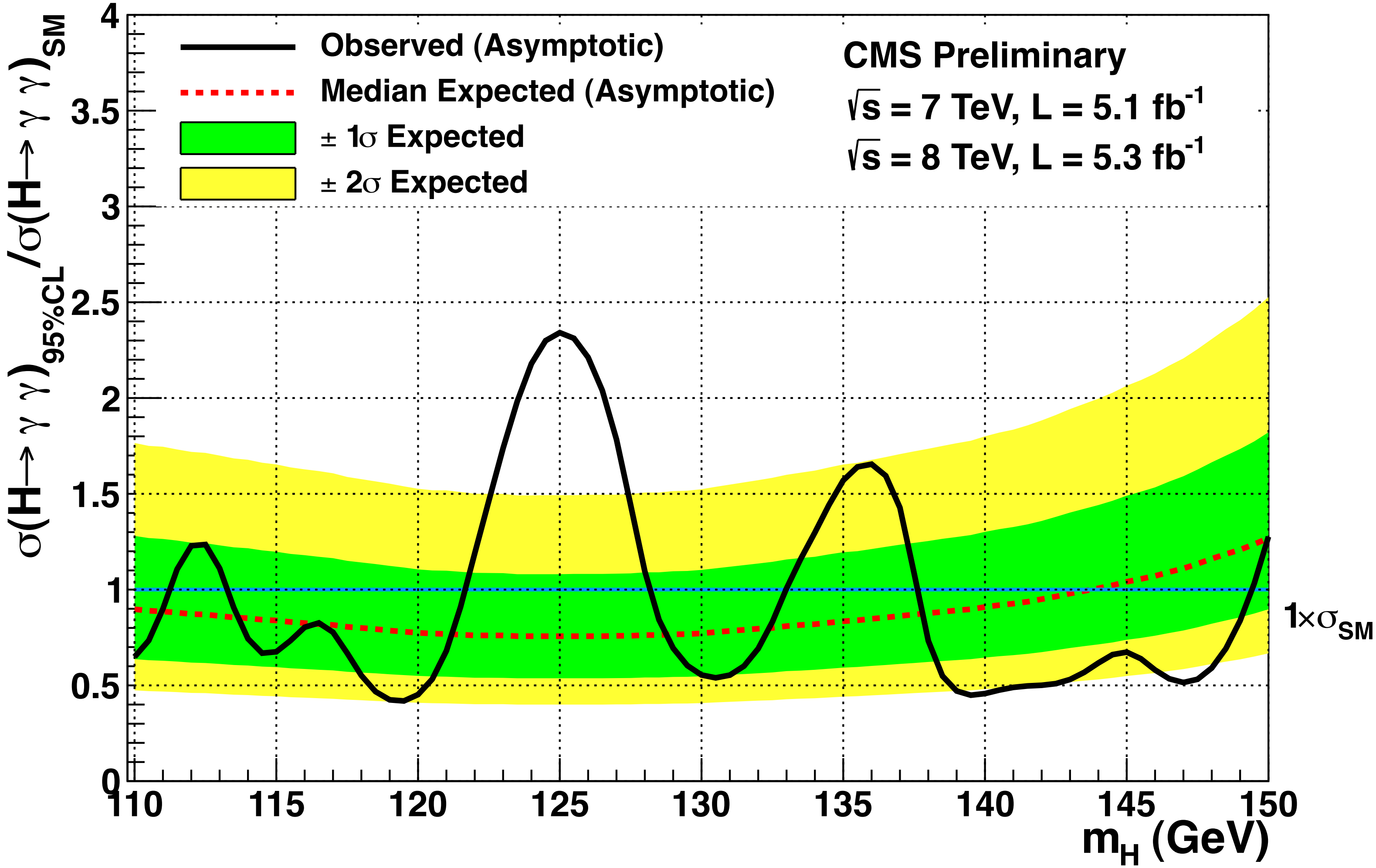
After 5 fb^{-1} @ LHC (end 2011)





After ~ 6 fb^{-1} more (2012 run @ 8 TeV)





(a) mass-fit MVA.

Successes of the SMG

EP tested with incredible precision
(universality of free-fall)

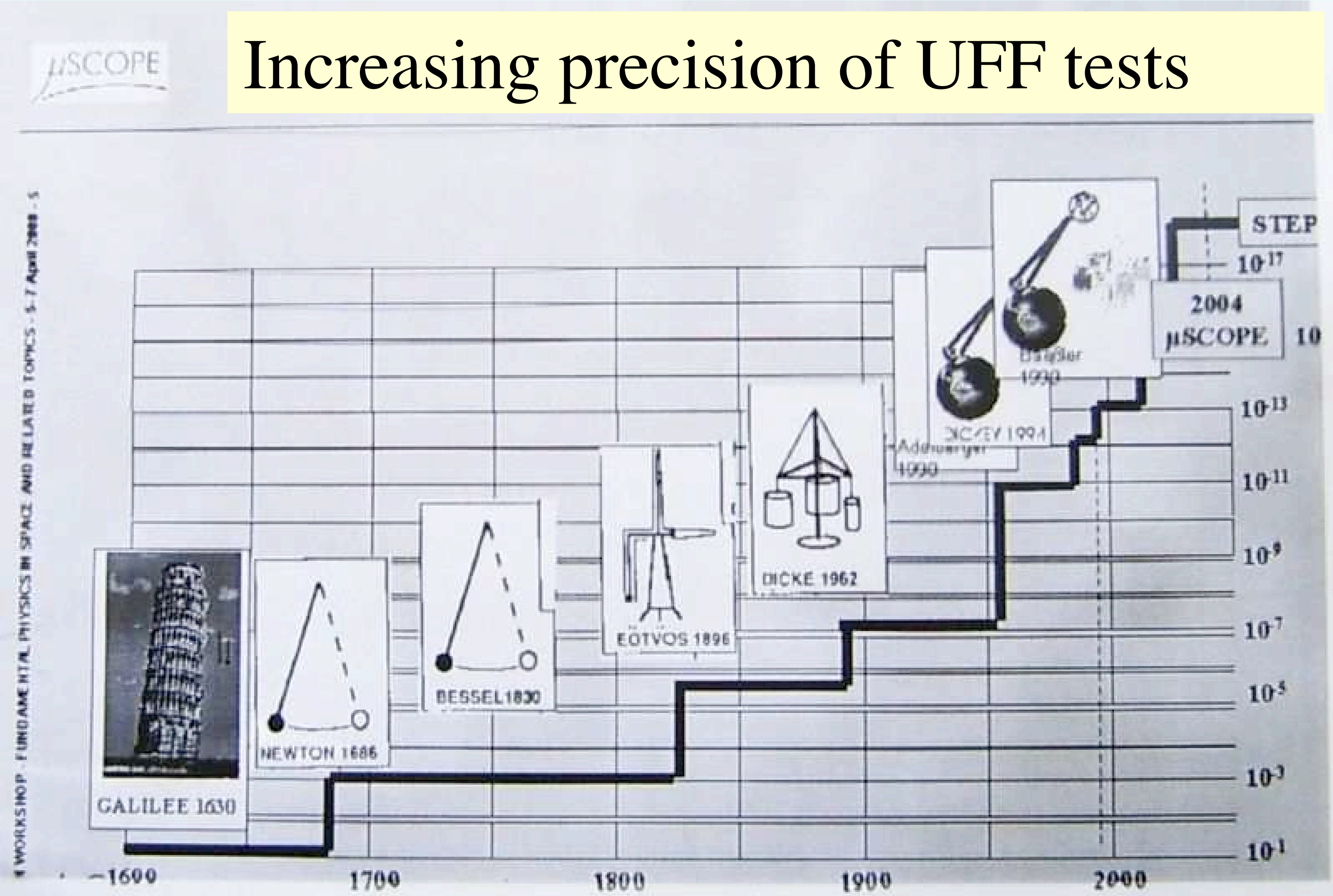
Corrections to NG better and better tested

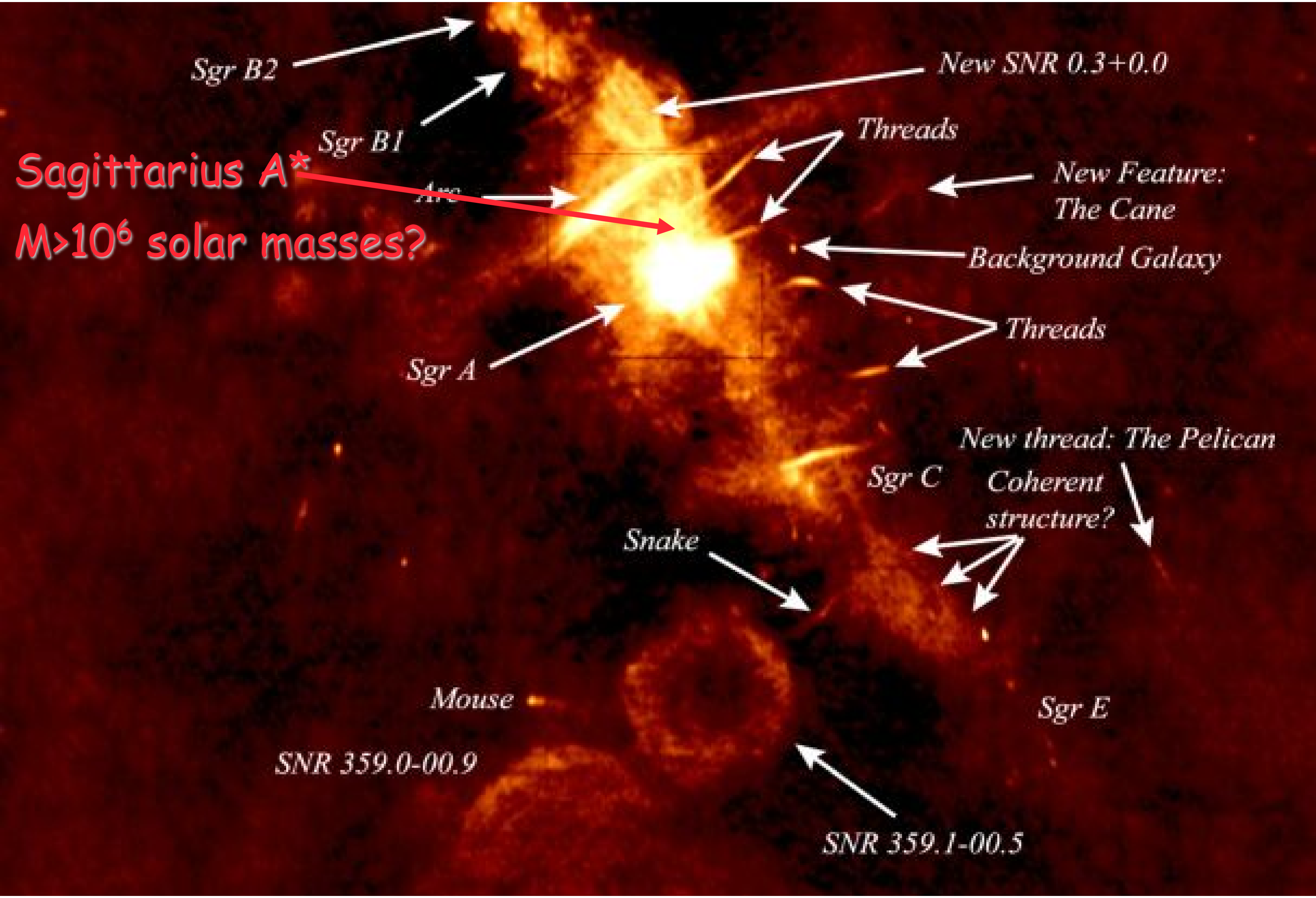
New predictions:

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

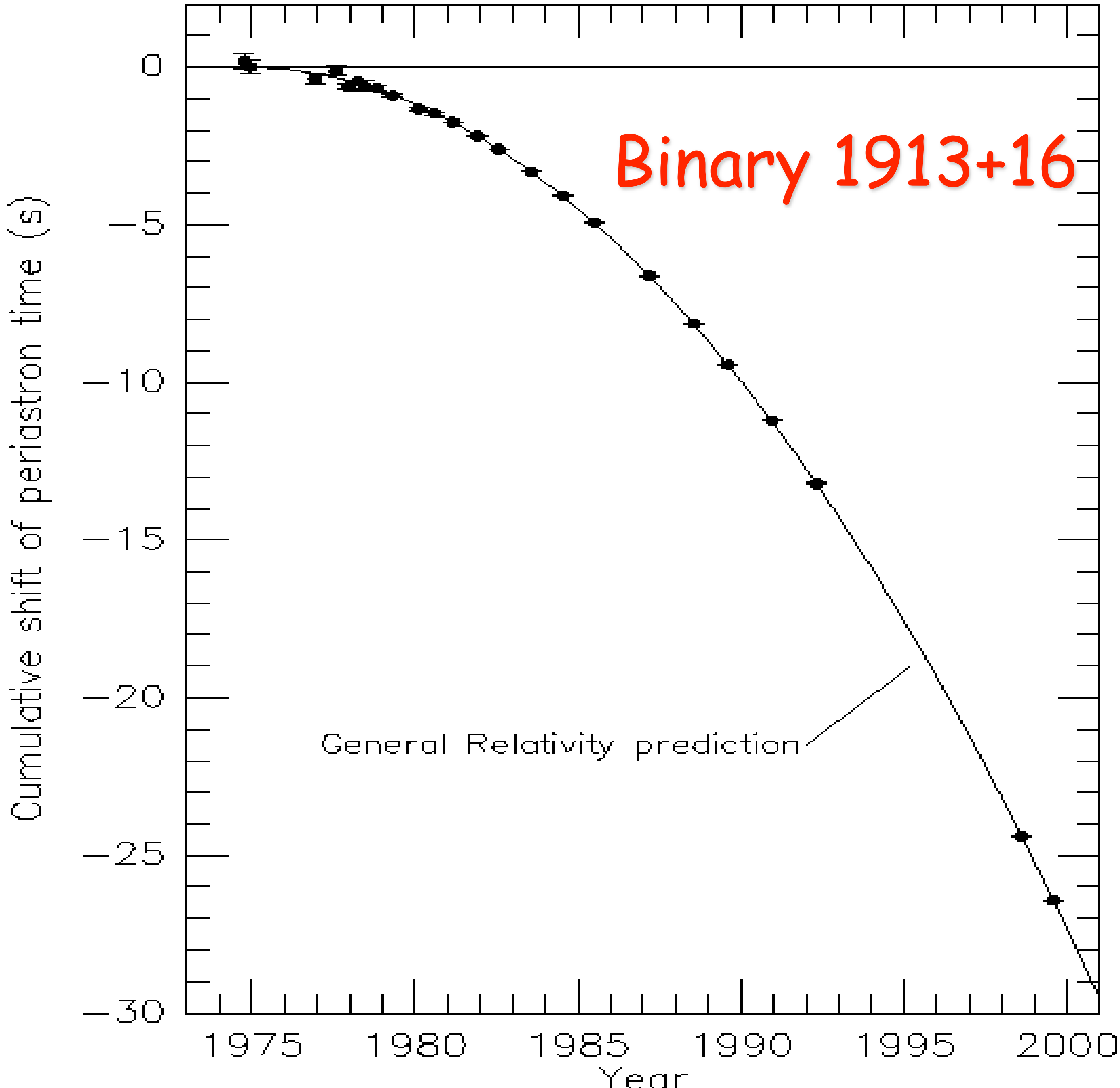
NB: This are all tests of Classical GR!!

Increasing precision of UFF tests



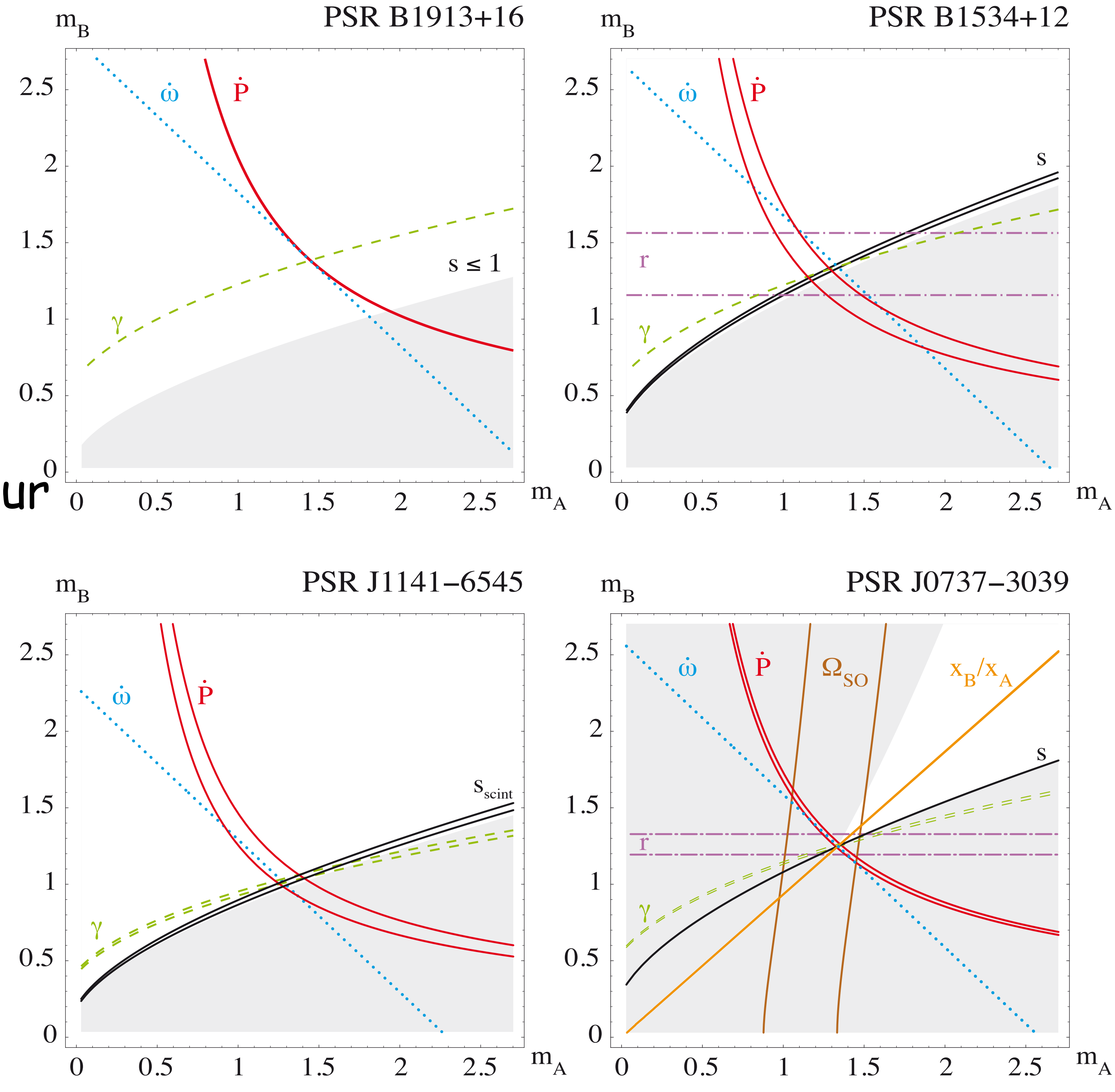


Sagittarius A*
M>10⁶ solar masses?
Sgr B2
Sgr B1
Arc
New SNR 0.3+0.0
Threads
New Feature: The Cane
Background Galaxy
Threads
Sgr A
New thread: The Pelican
Sgr C
Coherent structure?
Snake
Mouse
Sgr E
SNR 359.0-00.9
SNR 359.1-00.5



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

Courtesy of Thibault Damour (review for particle data group)




LIGO (USA)


VIRGO (Cascina)


LISA

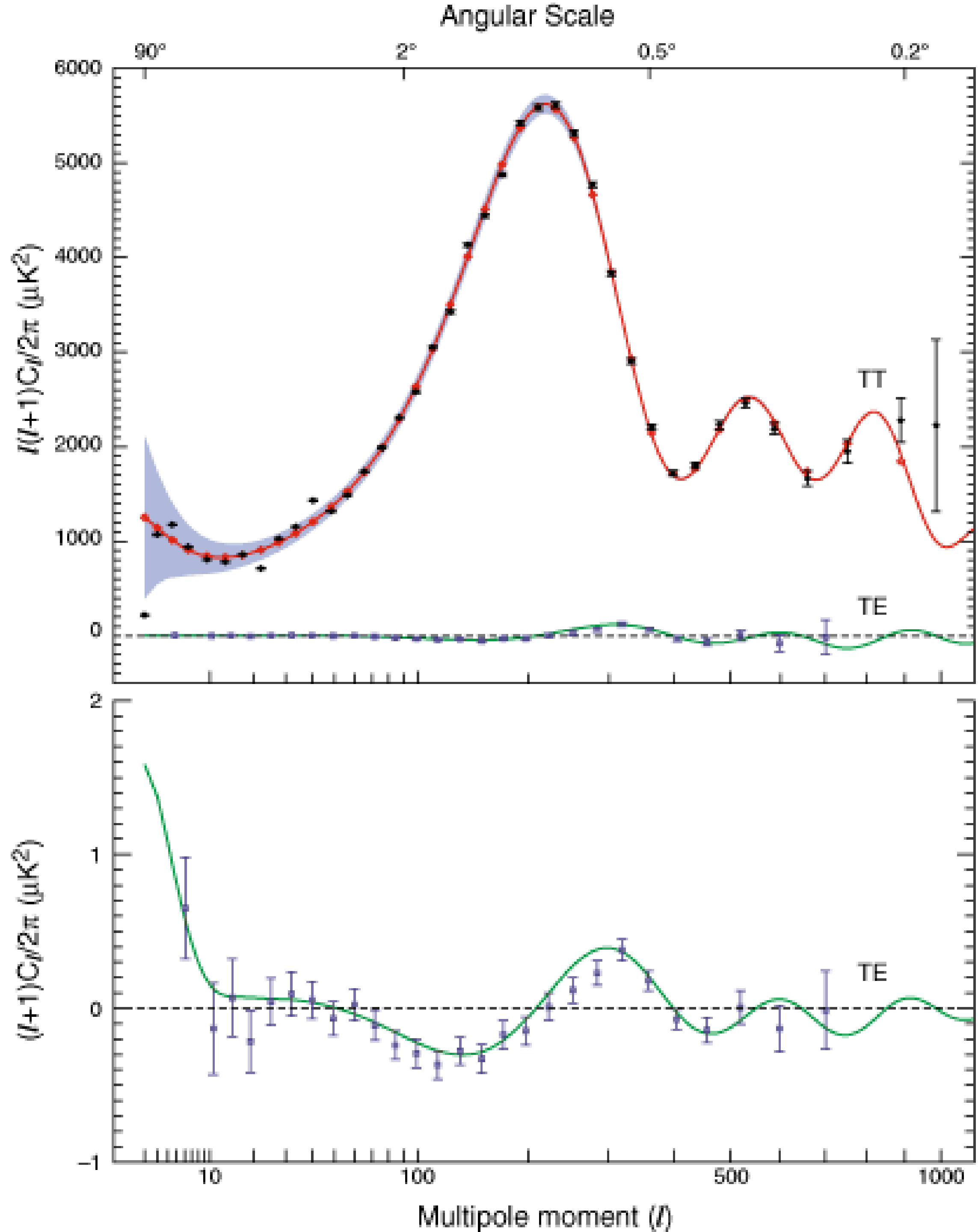

EXPLORE
Explorer(CERN)

… and of the "Standard Model of Cosmology" (after March 21st 2013)

The SMEP and the SMG nicely combined in inflationary cosmology. (Semiclassical) quantization of the geometry is part of the game explaining the large-scale structure of the Universe

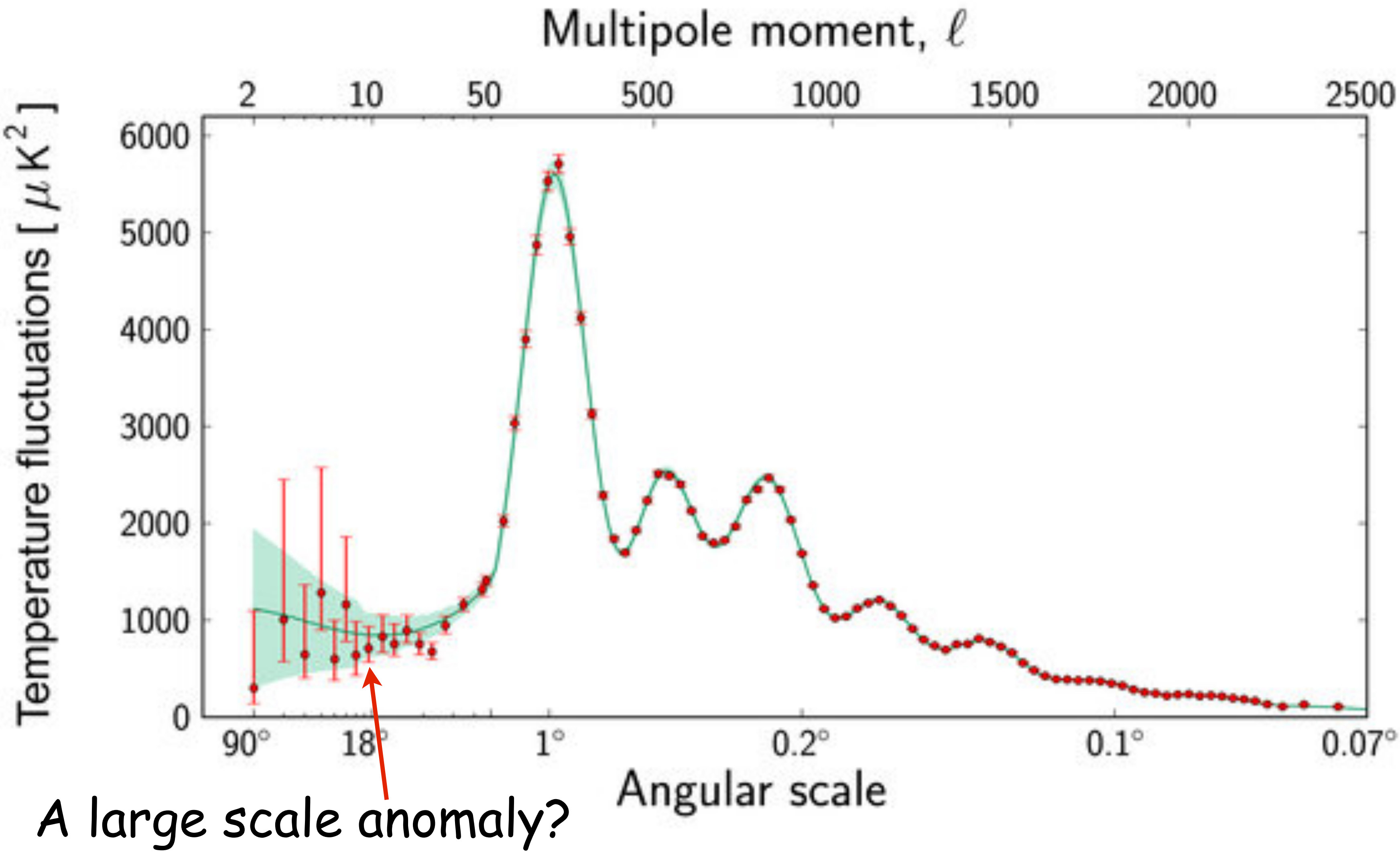
CMB after WMAP

TT and TE correlations from WMAP
Peak position favors spatially flat U



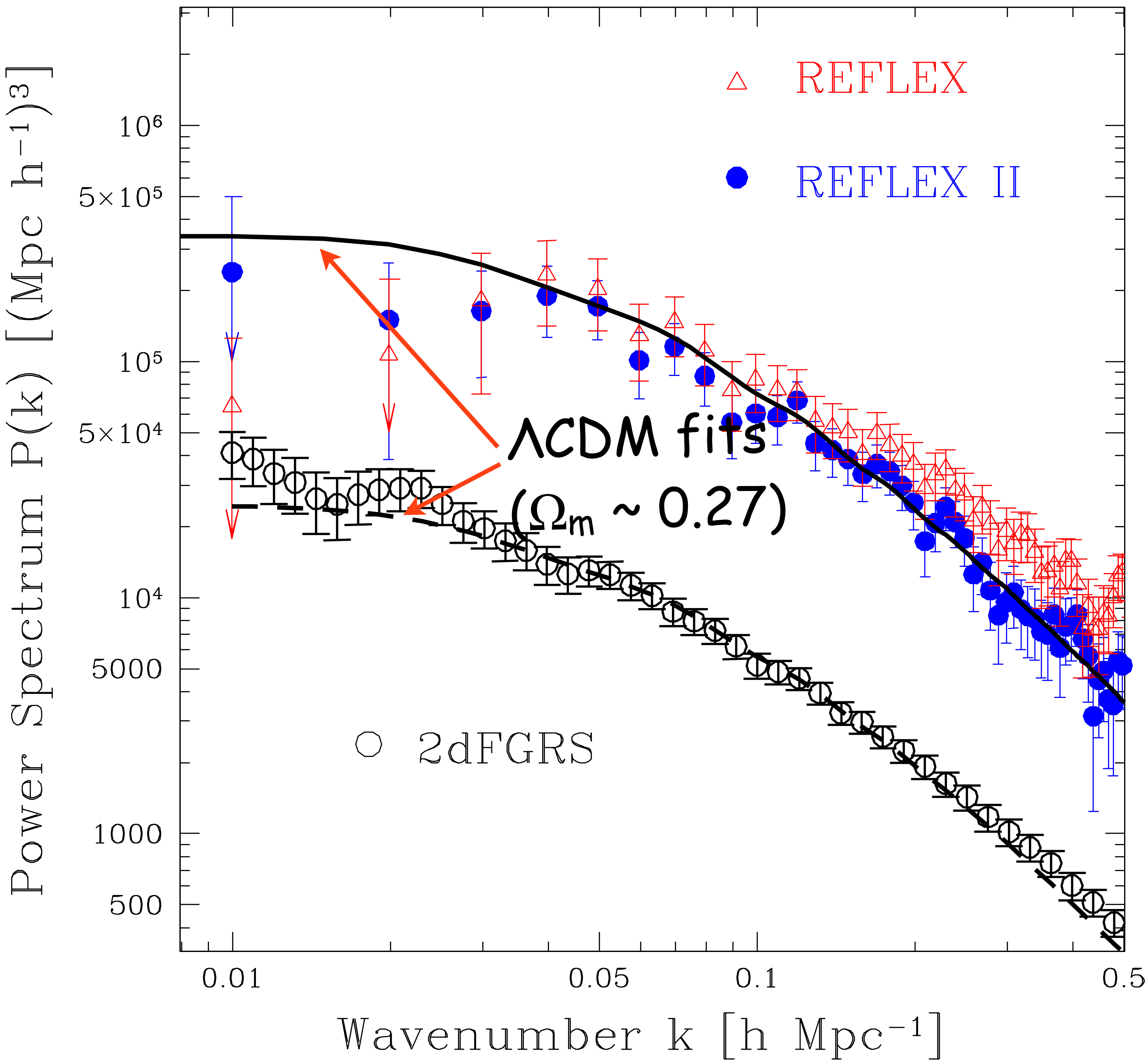
PLANCK POWER SPECTRUM

and after PLANCK

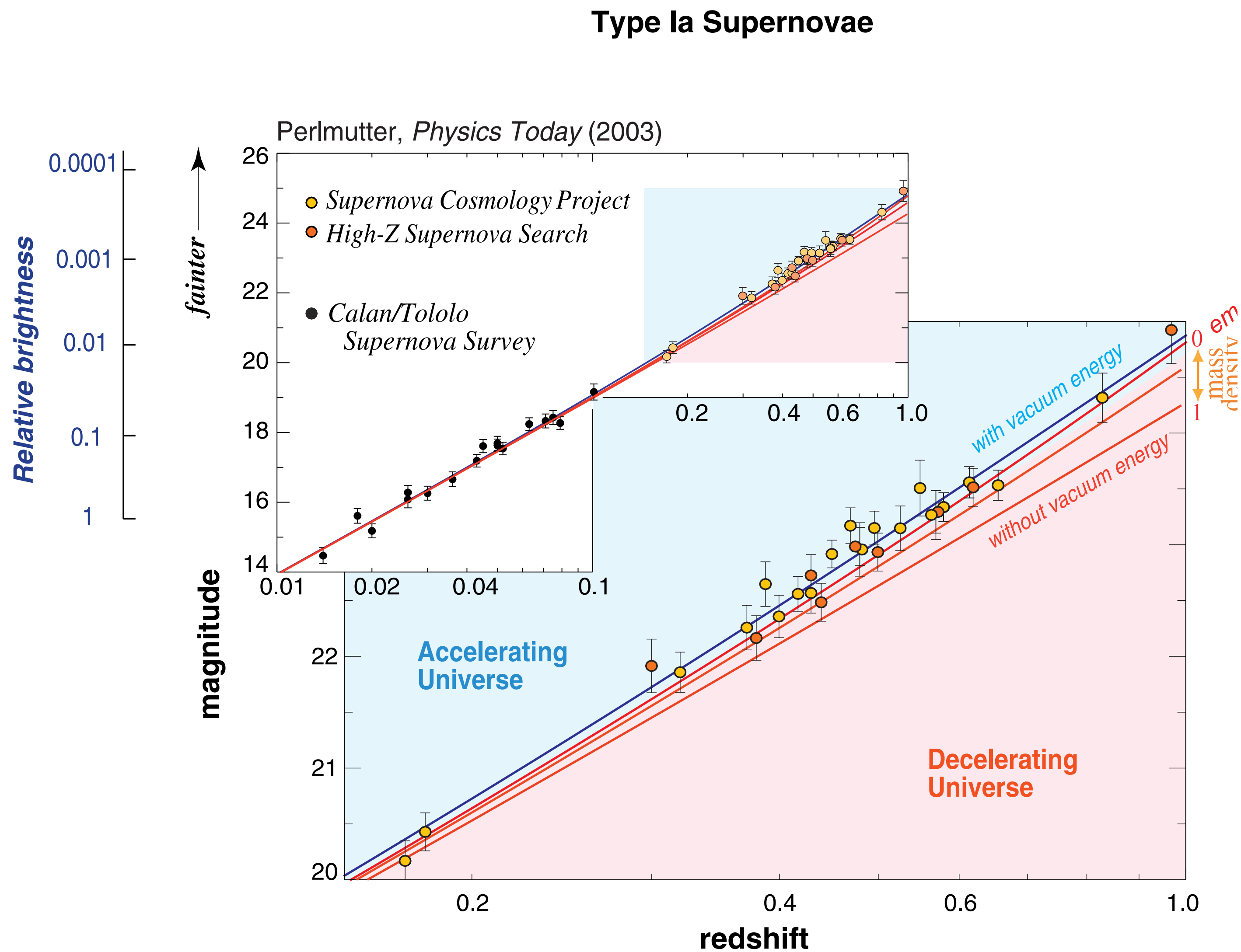


LSS

Balaguera-Antolínez et al. Astro-ph.10.12.1322

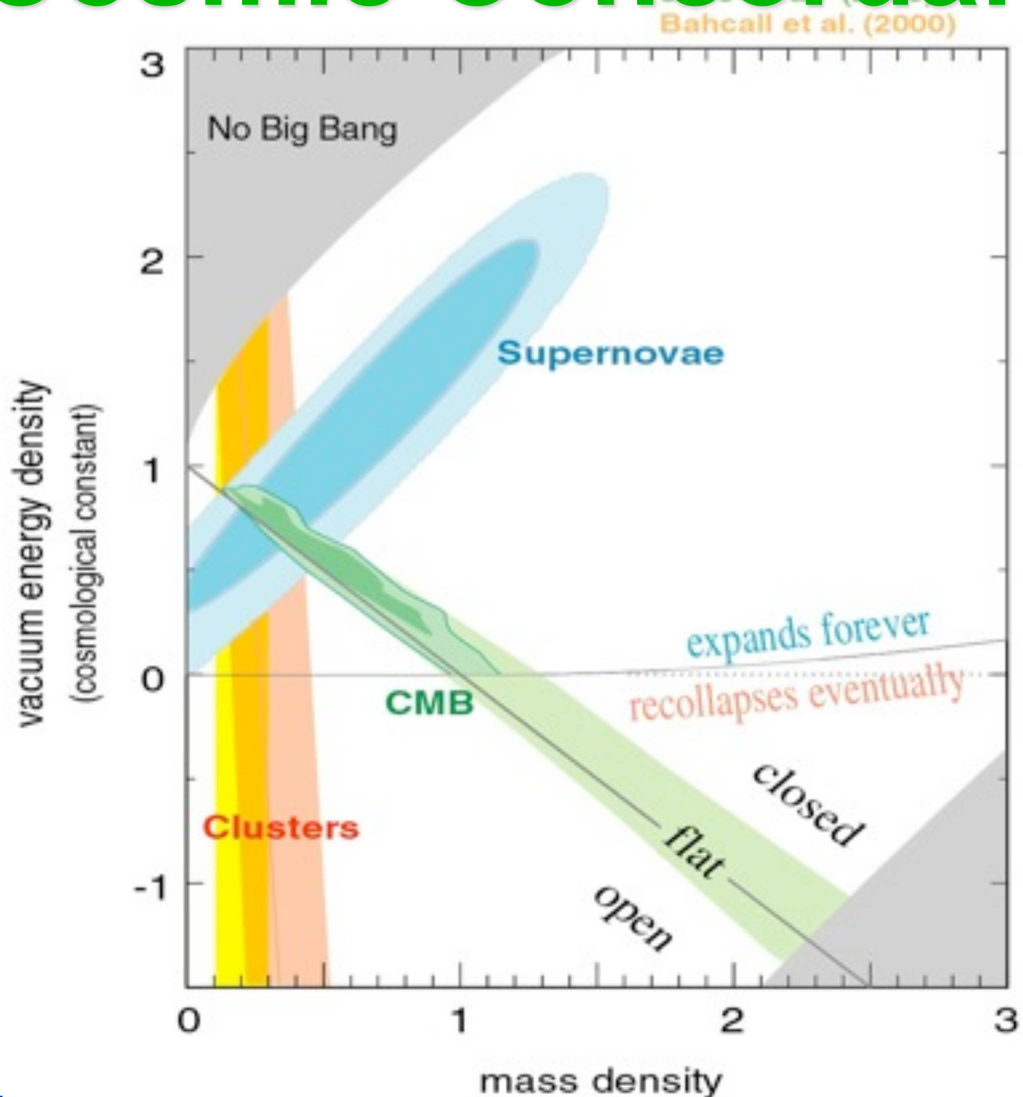


Cosmic acceleration

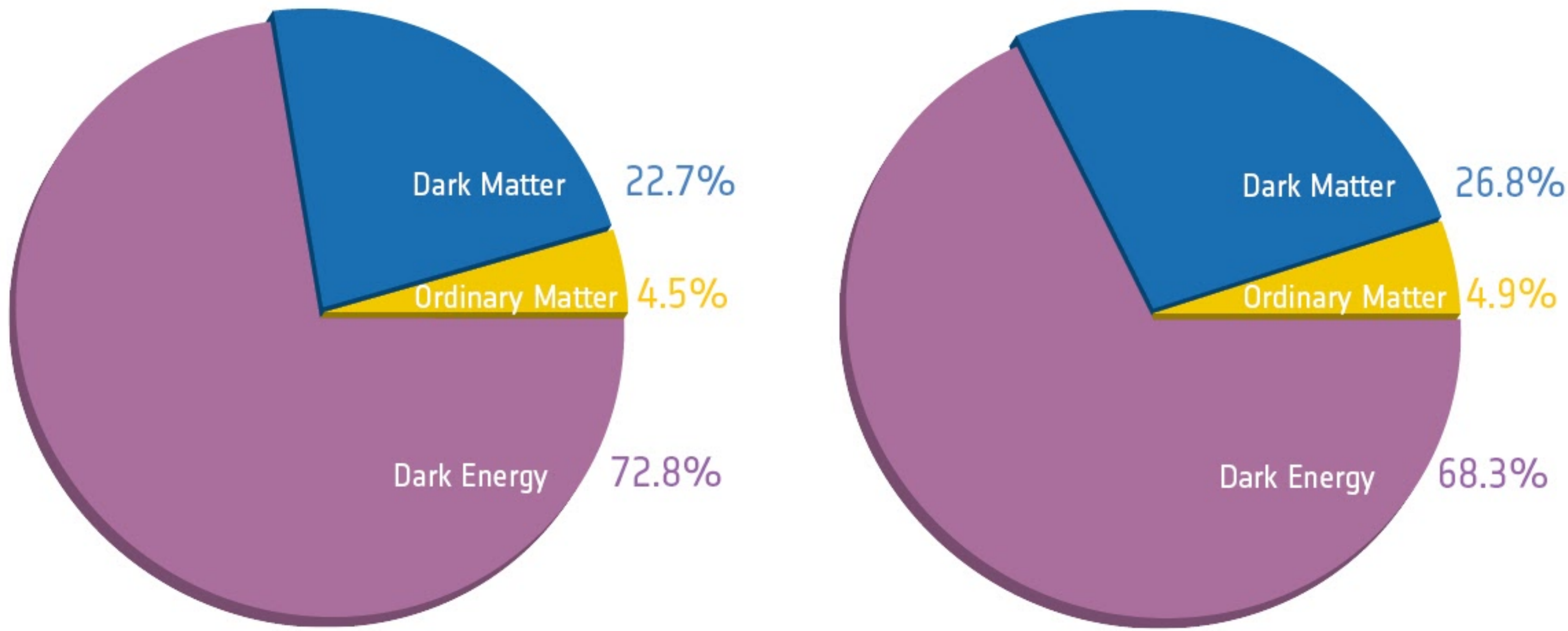


Putting all together

Cosmic Concordance



Portions in cosmic composition pie...



Also H_0 went down a bit

Before Planck After Planck

somewhat redistributed after PLANCK

Strong evidence that our SMN cannot be the full story...
Nonetheless let's draw some:

Lessons from 2 success stories based on a Gauge Theory + General Relativity

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.

Message #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

Message#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

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 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 would 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.

Missing quantum corrections?

- Most radiative corrections have been "seen" in precision experiments:
    - running of gauge couplings, anomalous dimensions
    - anomalies in global symmetries (U(1)-problem)
    - effective 4-fermi interactions (neutral-K system)
- A couple of them have not. Basically:
    - the Higgs mass (hierarchy problem)
    - the cosmological constant (120 orders off?)
- Latter(former) (in)sensitive to short-distance physics.
- This may be telling us, once more, that the SM & GR are not the full story!

The SMN's puzzles & problems appear to be related to our ignorance about short-distance physics!

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 action of a relativistic particle:

$$S_{rel.part.} = mc \int d(length)$$

is proportional to the length of the "world-line" described by the particle's motion, with mc the proportionality constant. By analogy (hereafter c=1):

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

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 E/l: it gives the energy/length of string.

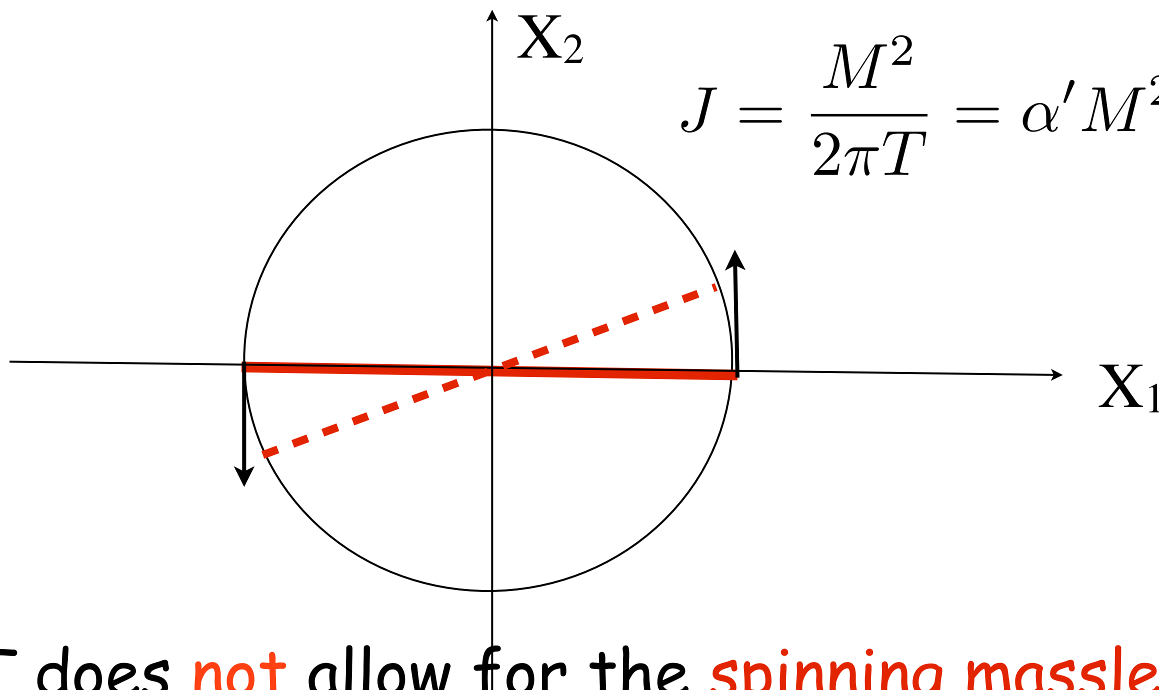
Leads immediately to some strong consequences...

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 CGR: GE = length.

➡ 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?

- In the quantum theory a relevant quantity is the dimensionless action, S/h:

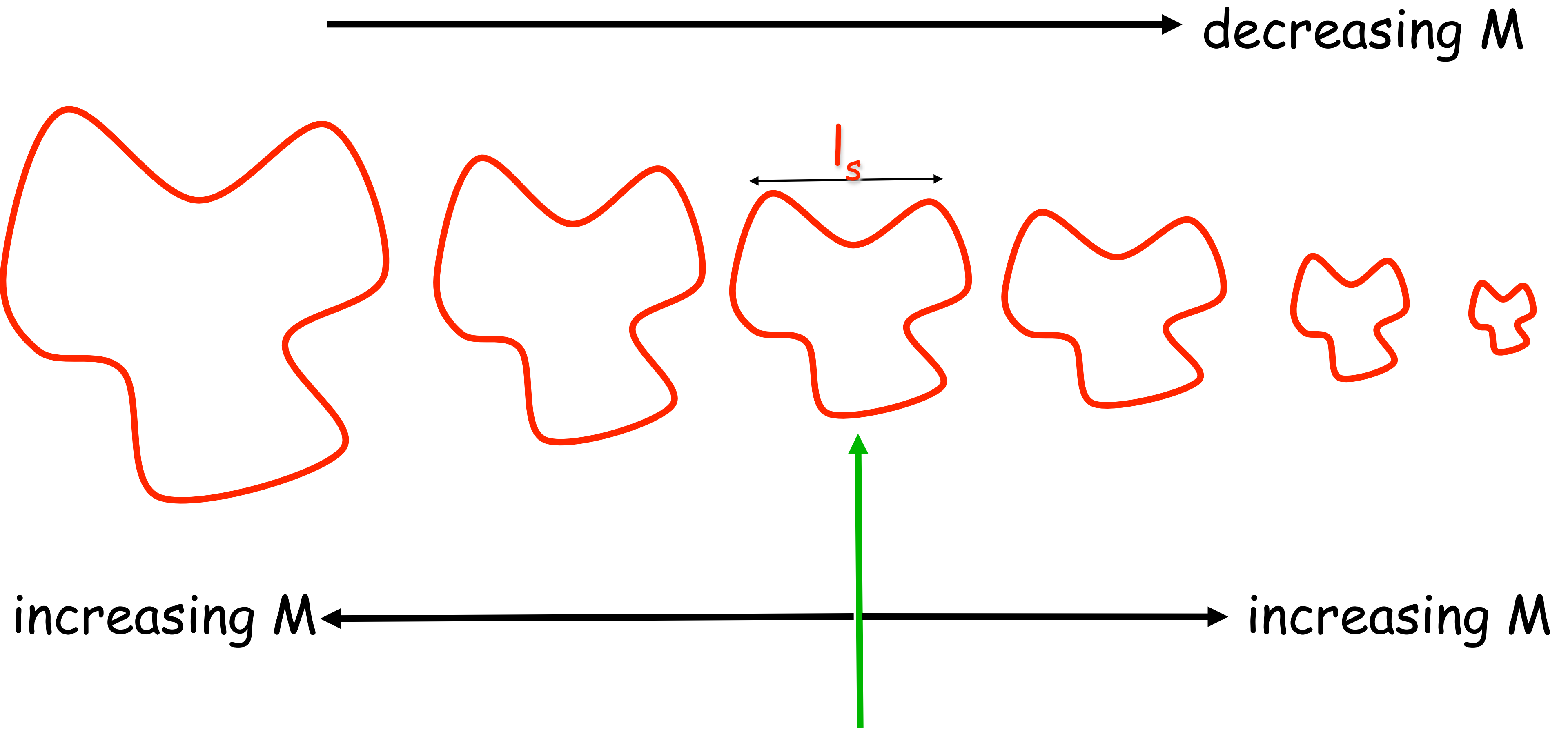
$$\frac{1}{\hbar}S_{string} = \frac{T}{\hbar}(\text{Area swept}) \equiv \frac{\text{Area swept}}{\pi l_s^2} \quad ; \quad l_s \equiv \sqrt{\frac{\hbar}{\pi T}} \equiv \sqrt{2\alpha' \hbar}$$

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

Quantization has introduced a length scale, l_s (and an associated energy scale M_s). The ratio L/l_s is a relevant dimensionless parameter.

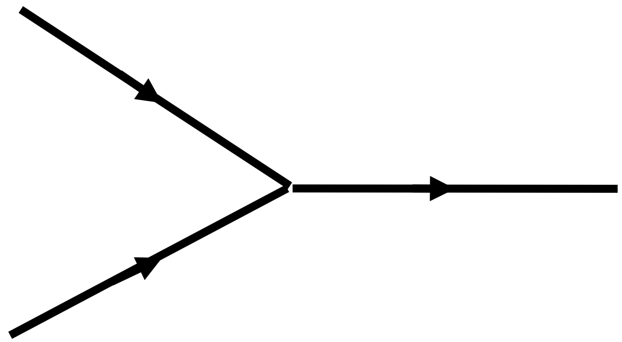
- l_s enters string theory in many important ways. It is the characteristic size of a (minimal-mass) string (cf. ground state of harmonic oscillator).

Without QM strings become lighter and lighter as they shrink

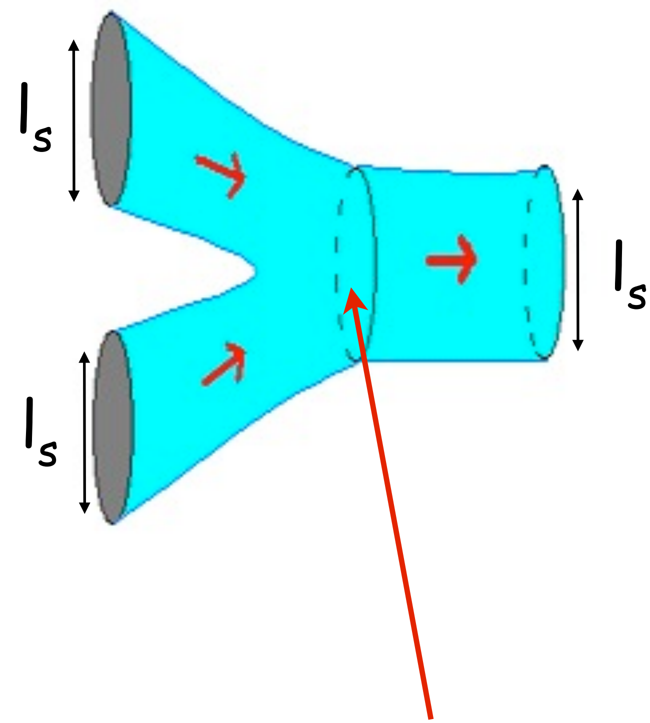


With QM strings are lightest when their size is l_s

Field Theory



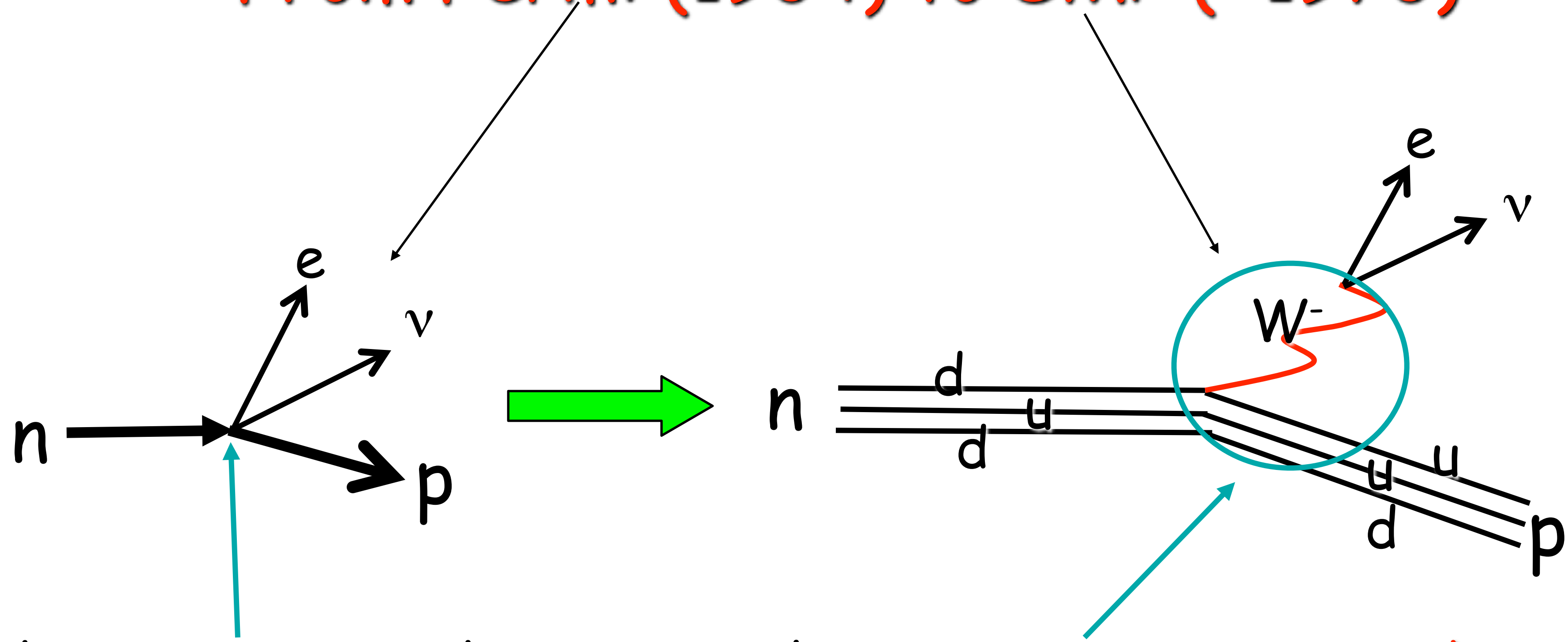
String Theory



Interactions are smeared over regions of order l_s

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 making it a better theory in UV

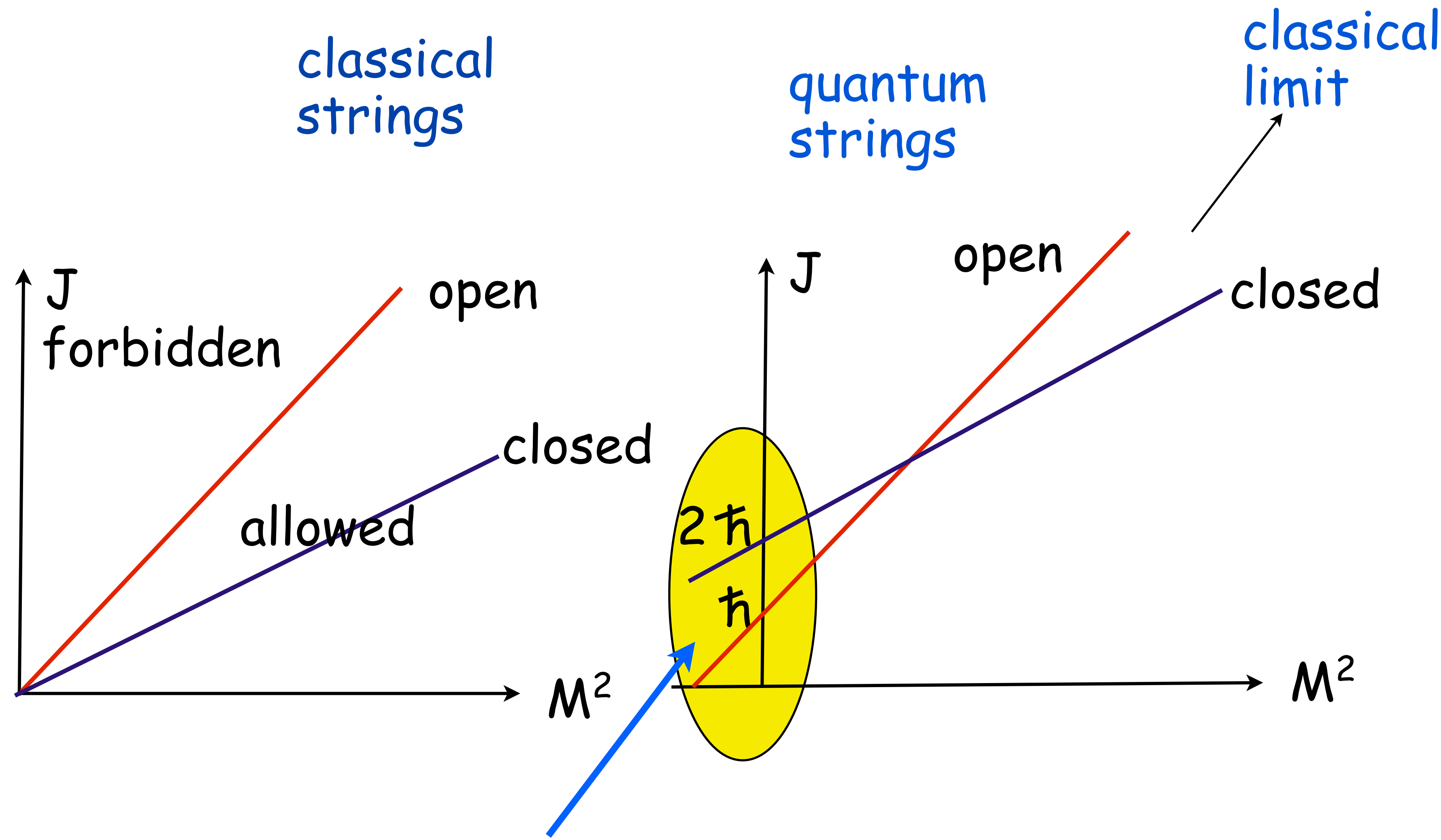
I. J without M

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

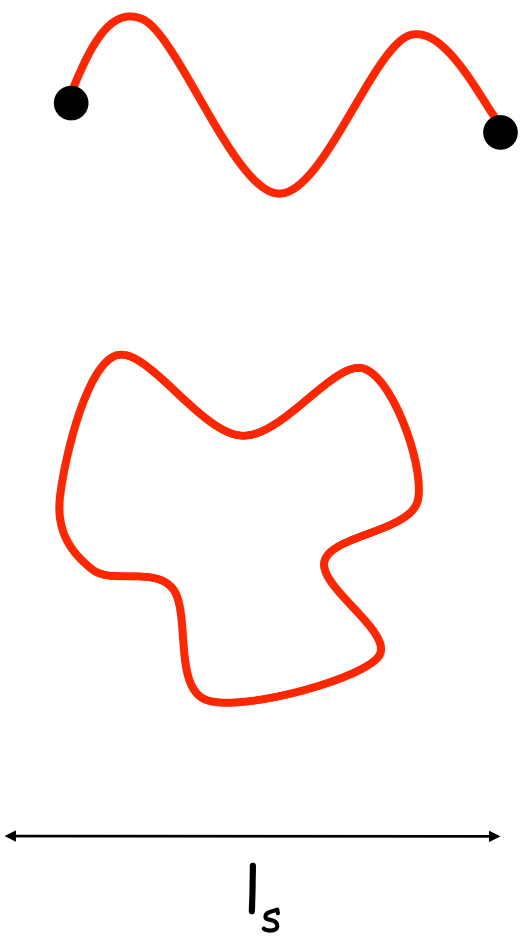
$$\frac{M^2}{2\pi T} \geq J + \hbar \sum_1^\infty \frac{n}{2} = J - \alpha_0 \hbar$$

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



Relevant limit for QFT/CFT opposite of CST limit!

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

The above properties of quantum strings may well provide answers to:

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

and thus 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!

Additional quantum effects

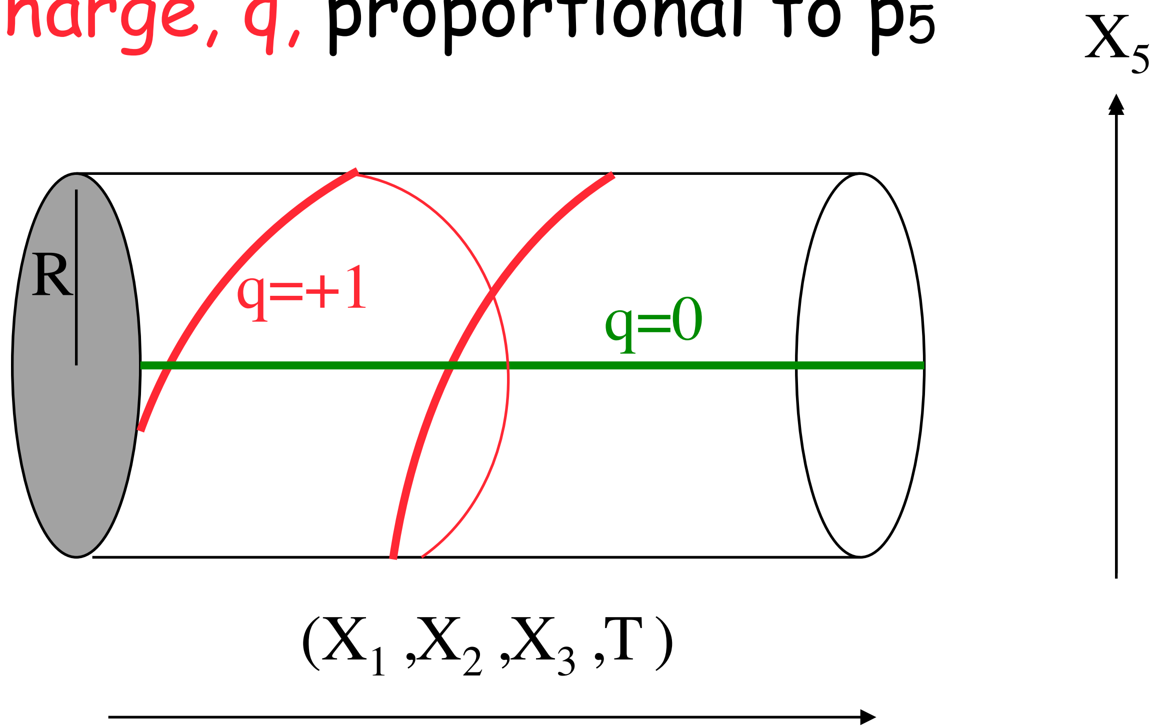
Quantum strings don't like D=4!

- 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 weakly curved, 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 into the waste basket.

A quick reminder of KK theory

- Kaluza (1921) and Klein (1926) managed to reformulate electromagnetism + gravity as just GR in a space containing one extra spatial dimension, a small circle, for instance.
- The e.m. potential A_μ (U(1) gauge field) becomes the component $g_{\mu 5}$ of the 5-dimensional metric, while g_{55} is a scalar field associated with the (physical) radius R of the circle.

Electric charge, q, proportional to p_5



p_5 is quantized in units of h/R (QM!)

$q = p_5/M_P = n\, l_P/R$, $n = 0, \pm 1, \pm 2, ..$

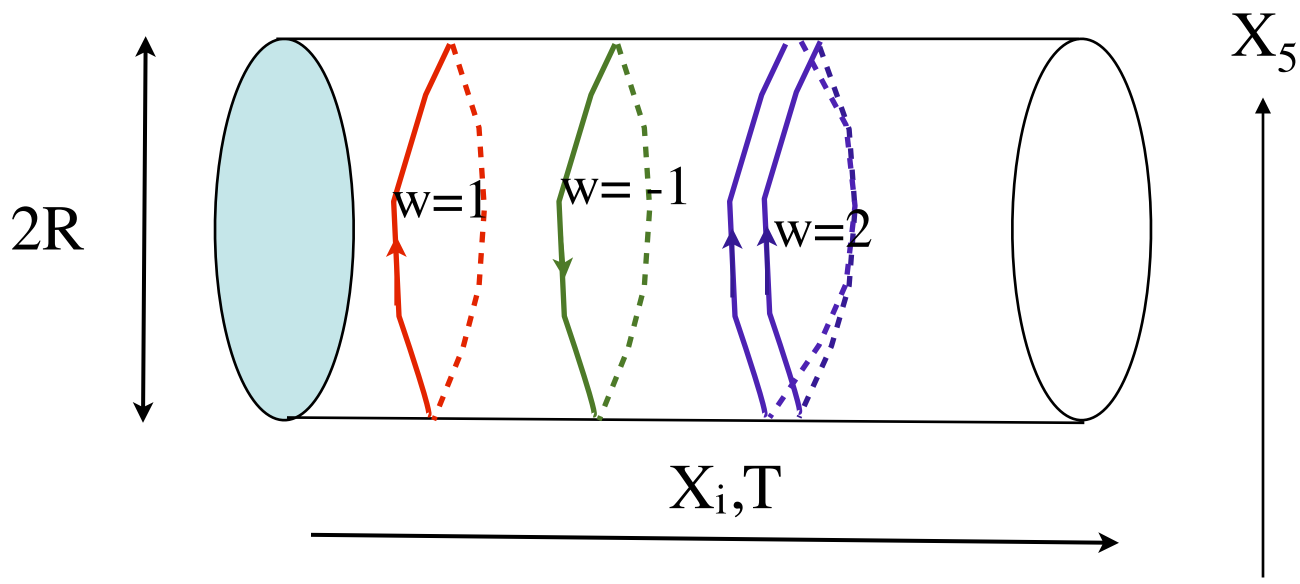
Quantization of electric charge is automatic!

No reason why R should take any special value.

QST's version of KK

In string theory, for a generic value of R, the gauge symmetry is actually U(1)xU(1). The reason for the second U(1) is that closed strings can wind around the circle.

NB: point particles (and open strings?) cannot wind!



The "charge" for one U(1) is p_5!

The "charge" for the second U(1) is w_5!

T-duality

- A symmetry, called T-duality, implies that closed strings can't tell the difference between R and l_s^2/R.
- This is a quantum string symmetry. Indeed, under the interchange R <--> l_s^2/R, one is supposed to swap momentum and winding modes. The latter are classically quantized, the former are only quantized because of QM.
- T-duality effectively introduces a minimal radius, $R = l_s$, a natural late-time attractor for R, the other being 0 (or ∞)
- For $R = l_s$ new non abelian gauge interactions emerge:

$$U(1)xU(1) \dashrightarrow SU(2)xSU(2)$$

- When applied to open strings T-duality is at the heart of the so-called 2nd string revolution: D-branes.

Massless scalar fields: Achilles' heel of QST?

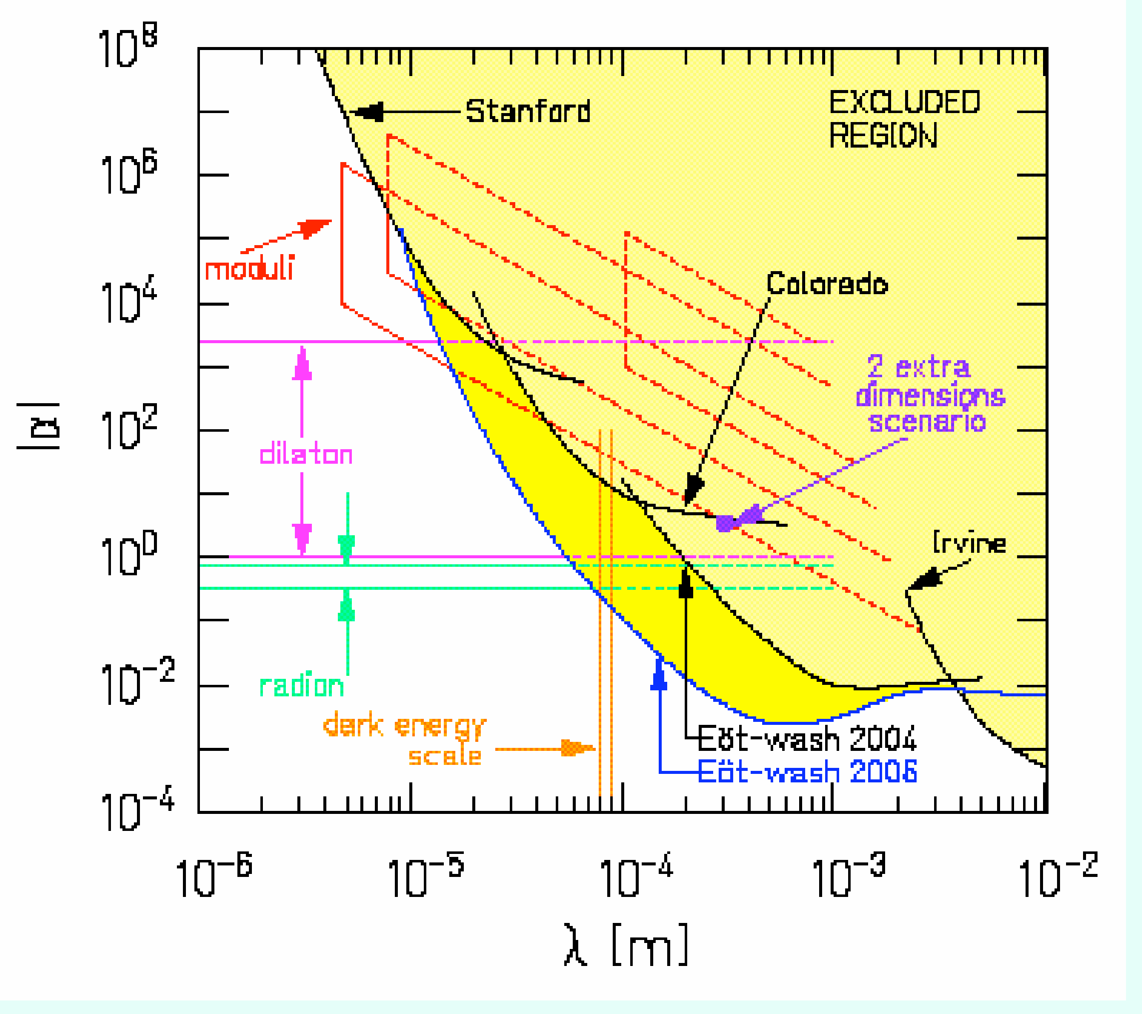
Absence of parameters

- 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
- 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!

„Fifth Force" strengths now excluded at small distances



QST: Successes and challenges

Besides its already mentioned virtues ST can claim a number of interesting specific results:

- A Stat. Mech. interpretation of black-hole thermodynamic entropy in favorable situations.

- Arguments, through the AdS/CFT correspondence, in favor of no-Q-information-loss in BH formation + evaporation processes

- New handles on gauge theories at strong coupling. Could be relevant for the physics of a strongly interacting quark-gluon plasma (RHIC, ALICE) and perhaps even in Condensed-Matter-Physics.

- New cosmological scenarios where strings and/or branes play a crucial role. Cosmology may turn out to be, eventually, our best handle for testing string theory...

But there are also many outstanding challenges:

- QST still unable to tell us what, if any, replaces the ubiquitous singularities of CGR? The Big Bang singularity and the one inside a BH horizon particularly challenging;
- Sheds no light, so far, on DM and DE;
- Has too many solutions, particularly in connection with the compactification of extra dimensions;
- The moduli stabilization problem. Moduli are free in PT, correspond to dangerous massless scalar fields.
- Old and new non-perturbative effects may give mass to moduli and pin down one good string vacuum.
- It would be wonderful to be able to construct at least one StMN (String Model of Nature) that provides a consistent UV-completion of the SMN!

Thank You!