GGI Tea Breaks, July 7, 2021

Reflections on 50+ years of success stories

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Preamble

Having graduated in 1967, I have been very lucky of having lived and worked through an exceptional era in the history of fundamental physics.

Looking back at > 50y spent on this fantastic adventure, I'd like to share with you some thoughts.

I apologize to the experts for those remarks that are too trivial and/or old-fashioned. If the remaining ones don't make much sense please let me know…

Outline

- The Standard Model (SM) of Nature, 2021
- The role of Quantum Mechanics
  - in the SM of Elementary Particles
  - in the SM of Gravity & Cosmology
- The role of Symmetries
- Quantum Corrections: the good & the bad
  - Wanted: an IUVC (to be explained...)
- Can it be Quantum String Theory?
  - Two welcome miracles
  - Two less(?) welcome ones
- Summary

The Standard Model of Nature

(after LHC, PLANCK, LIGO/VIRGO)

Two Pieces:

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

Throughout 5 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

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

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

Einstein 1917

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

confirmed?

new!

The SM of Elementary Particles

A quantum-relativistic theory (a QFT)

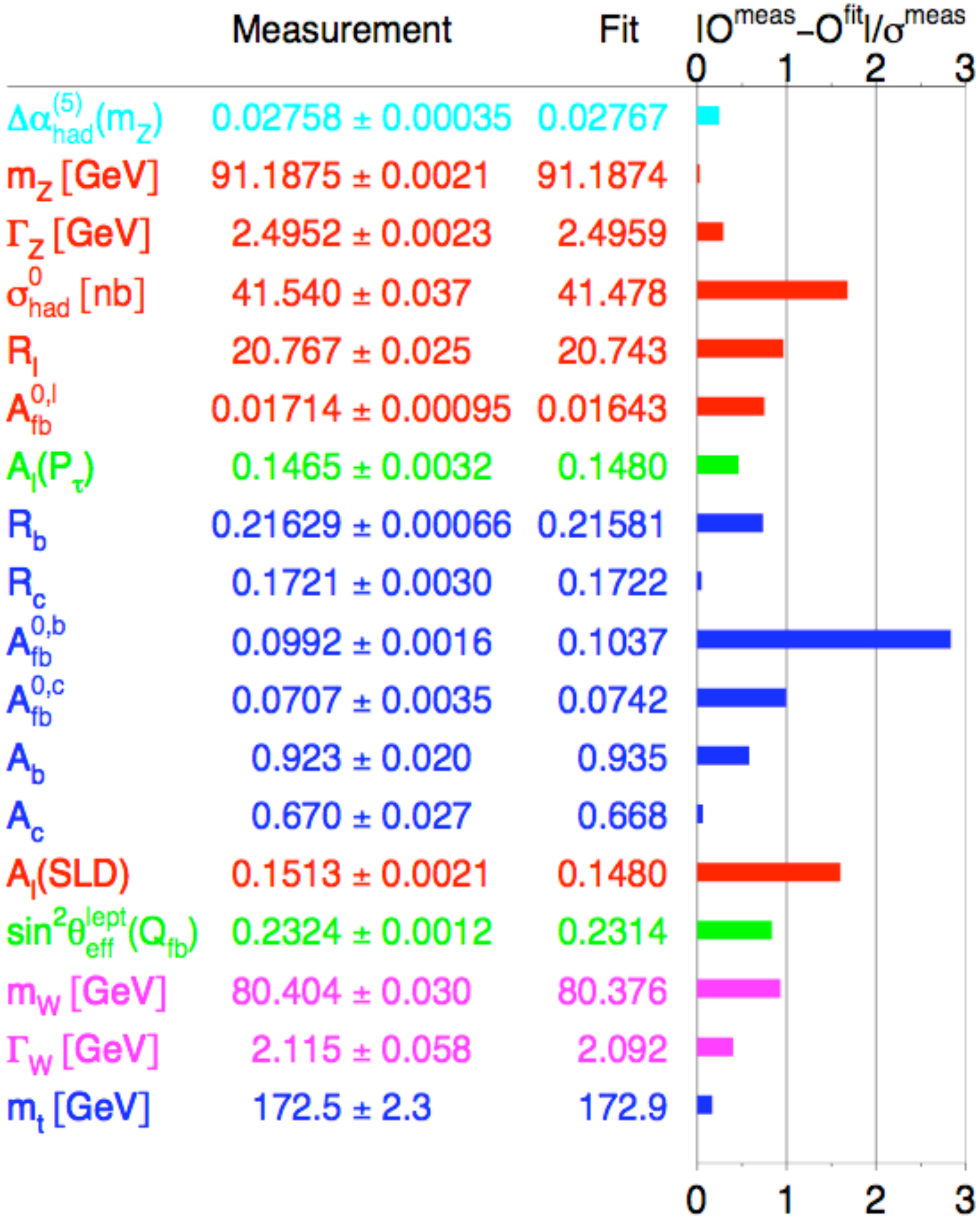
The quantum-relativistic nature of SMEP manifests itself through real and virtual particle production

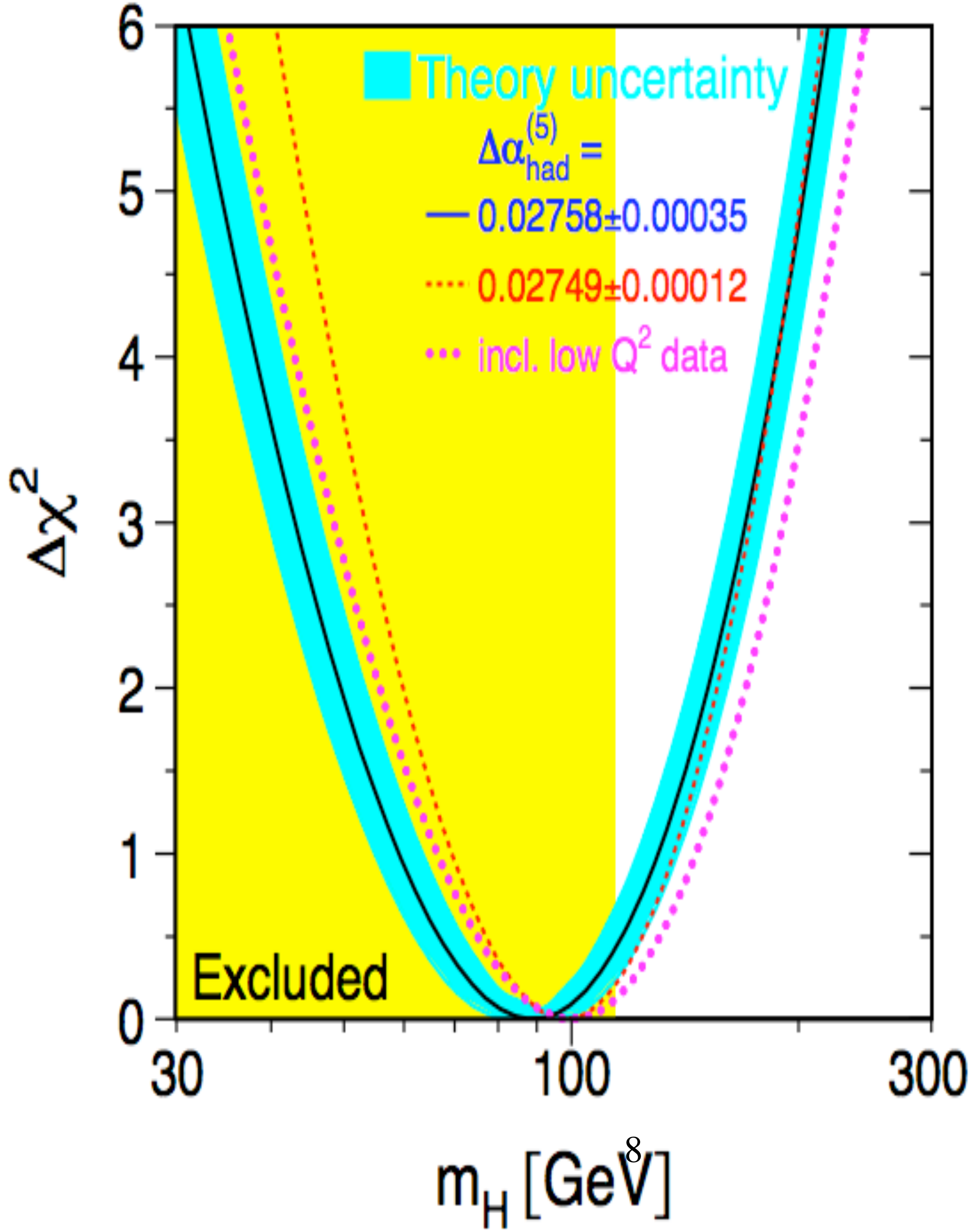
These are essential for agreement w/ experiment (tree-level predictions are off by many σ's)

Actually, virtual effects anticipated the experimental discoveries of the top quark and of the Higgs boson.

(and the absence of low-scale SUSY?)

Strong hints of a light Higgs after LEP





The SM of Gravity: General Relativity

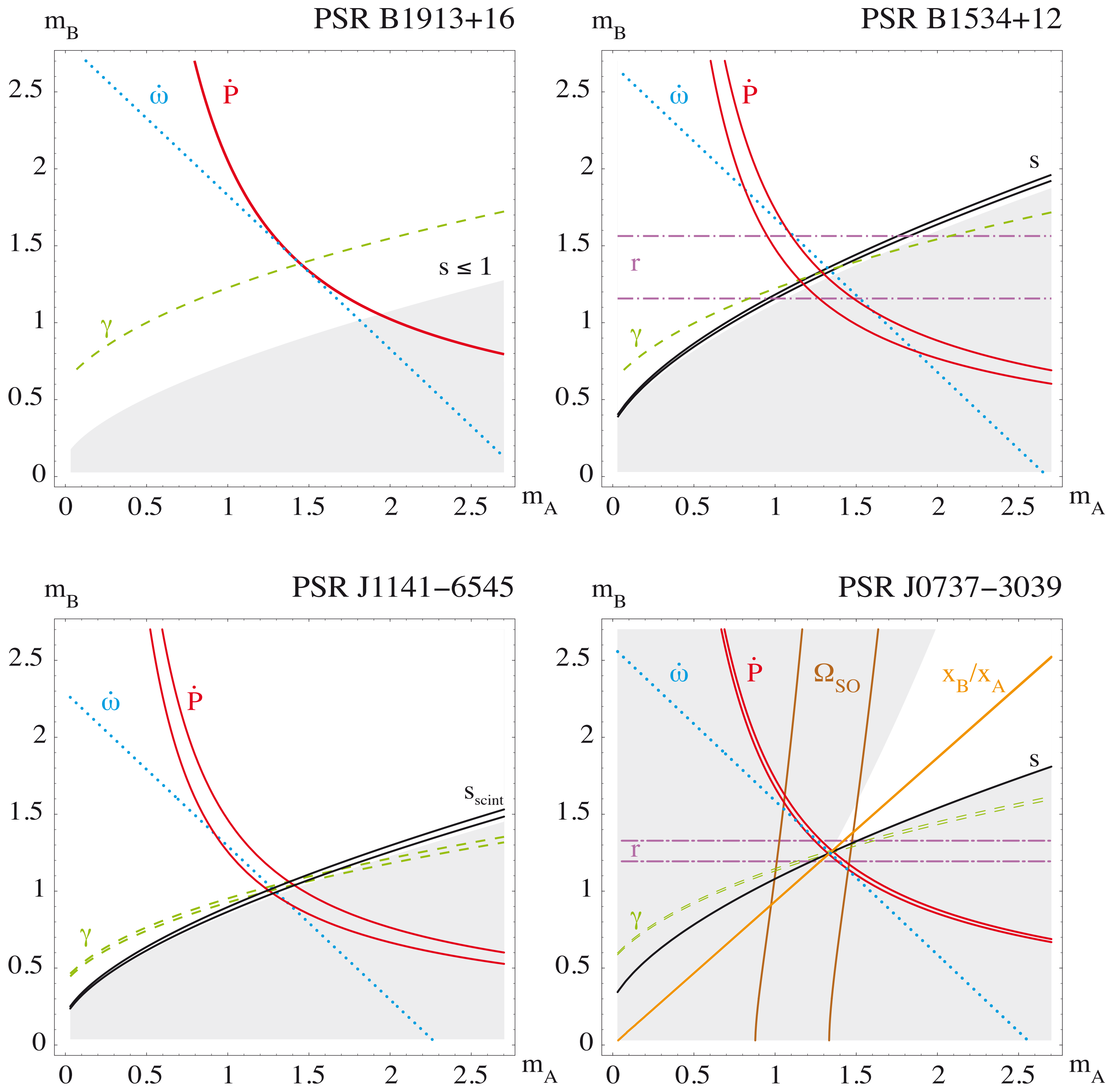
A classical theory incorporating the equivalence principle through general covariance

Free-fall Univ. tested with incredible precision

Deviations from Newtonian Gravity well tested

New GR predictions:

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



PSR B1913+16
s ≤ 1
PSR B1534+12
s
r
PSR J1141−6545
s_{scint}
PSR J0737−3039
Ω_{SO}
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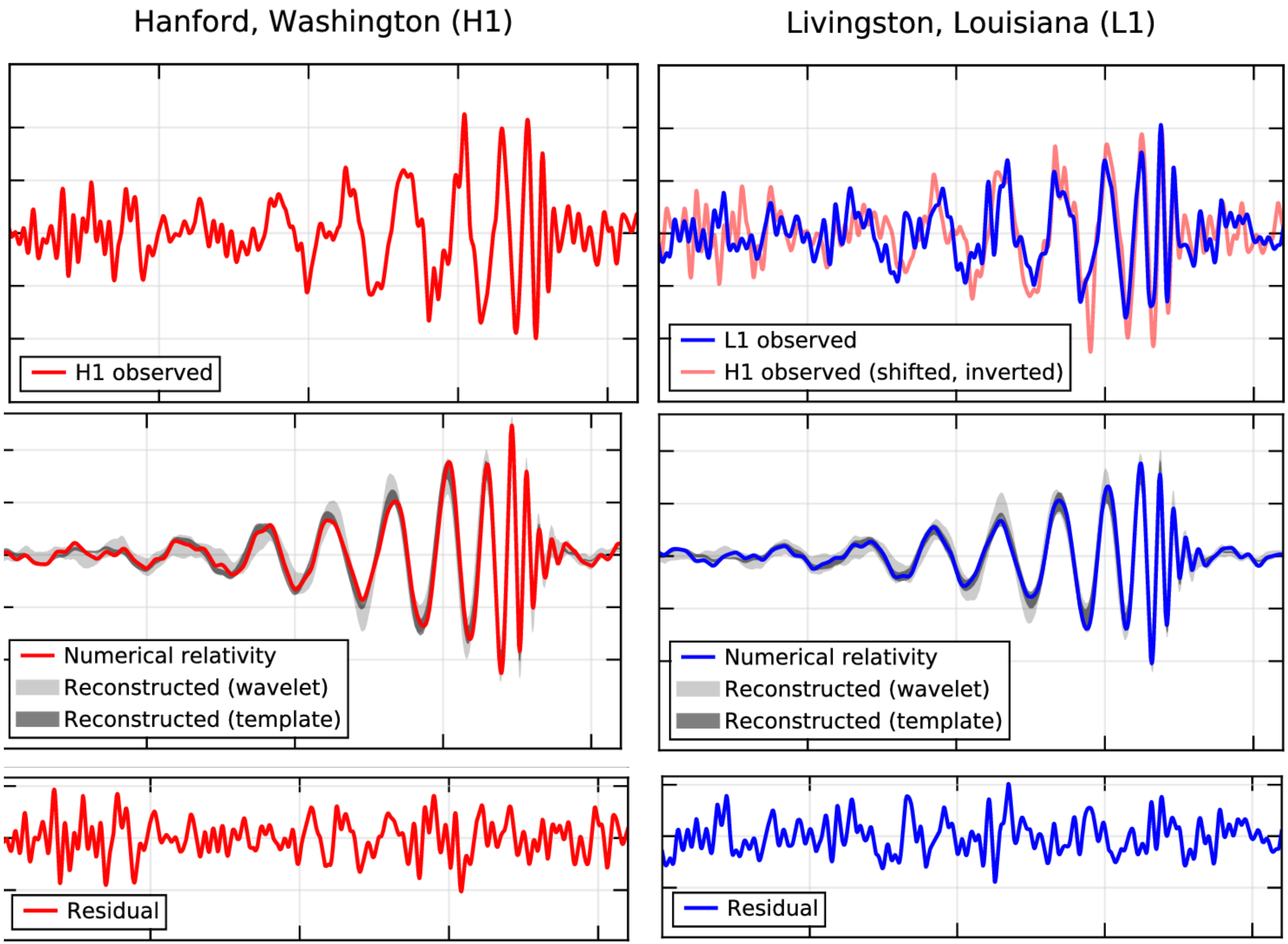
s
r
$\dot{\omega}$
$\dot{P}$
γ
m_B
m_A



LIGO, Sept. 14, 2015

While for the SMEP quantum mechanics is crucial it looks as if Classical GR can cope with Gravity

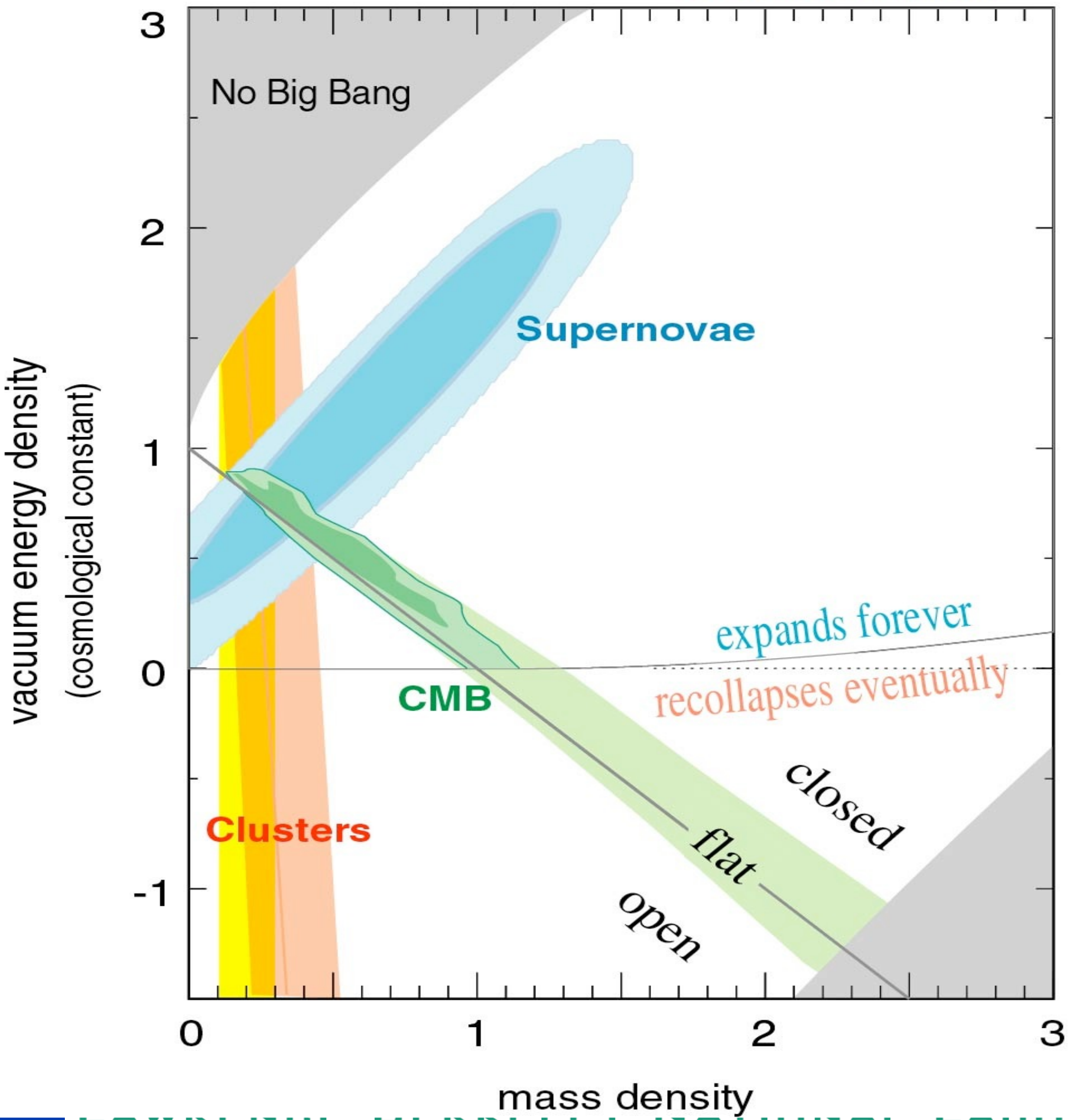
Things change, I claim, when we consider cosmology!

The "concordance model"

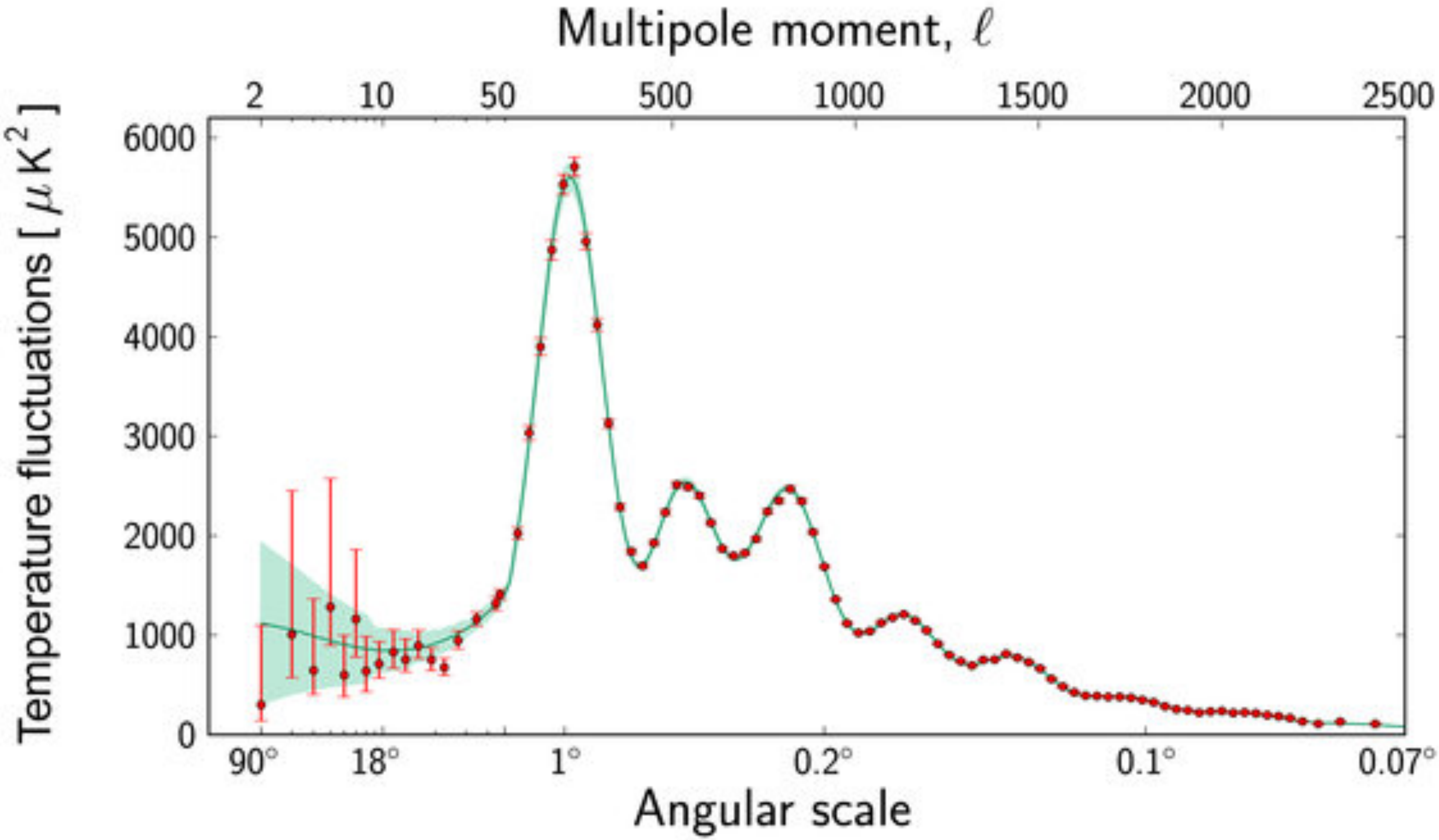
Since a few decades we have a good ("standard"?) cosmological model combining the inflationary paradigm with that of a "dark" sector in the energy budget of the Universe.

NB: Without inflation we need a huge fine-tuning of the properties of the hot big bang.

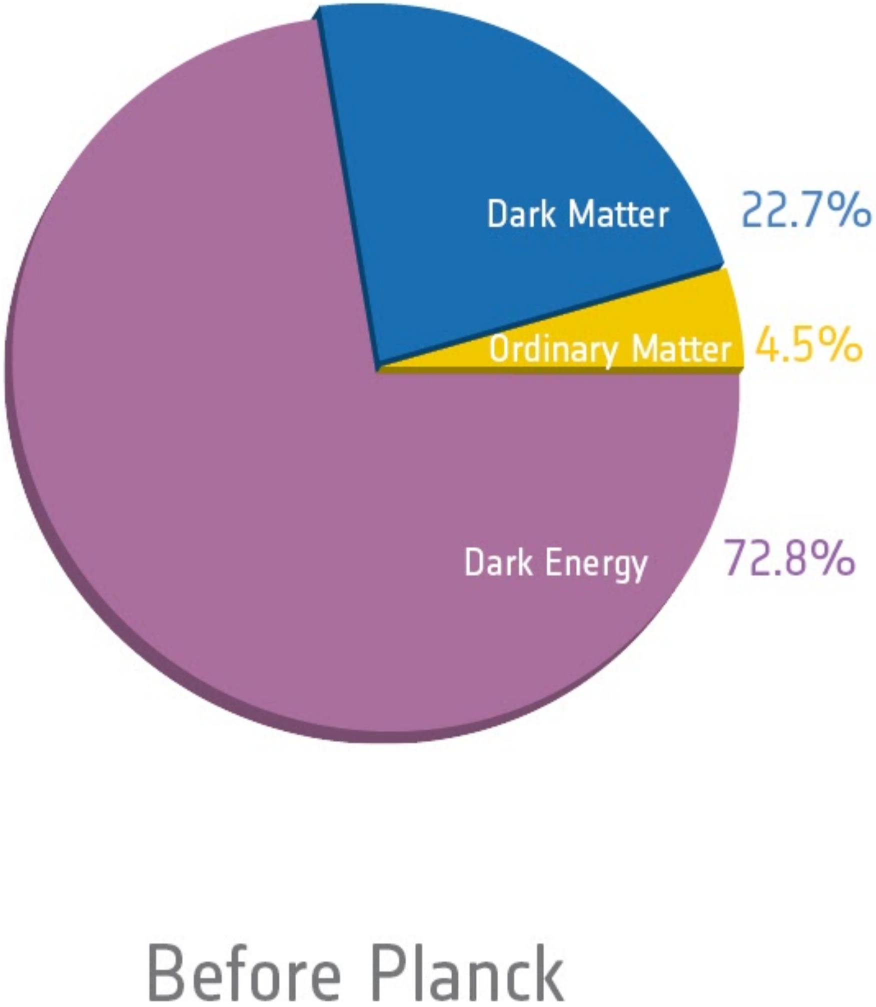
Cosmic Concordance

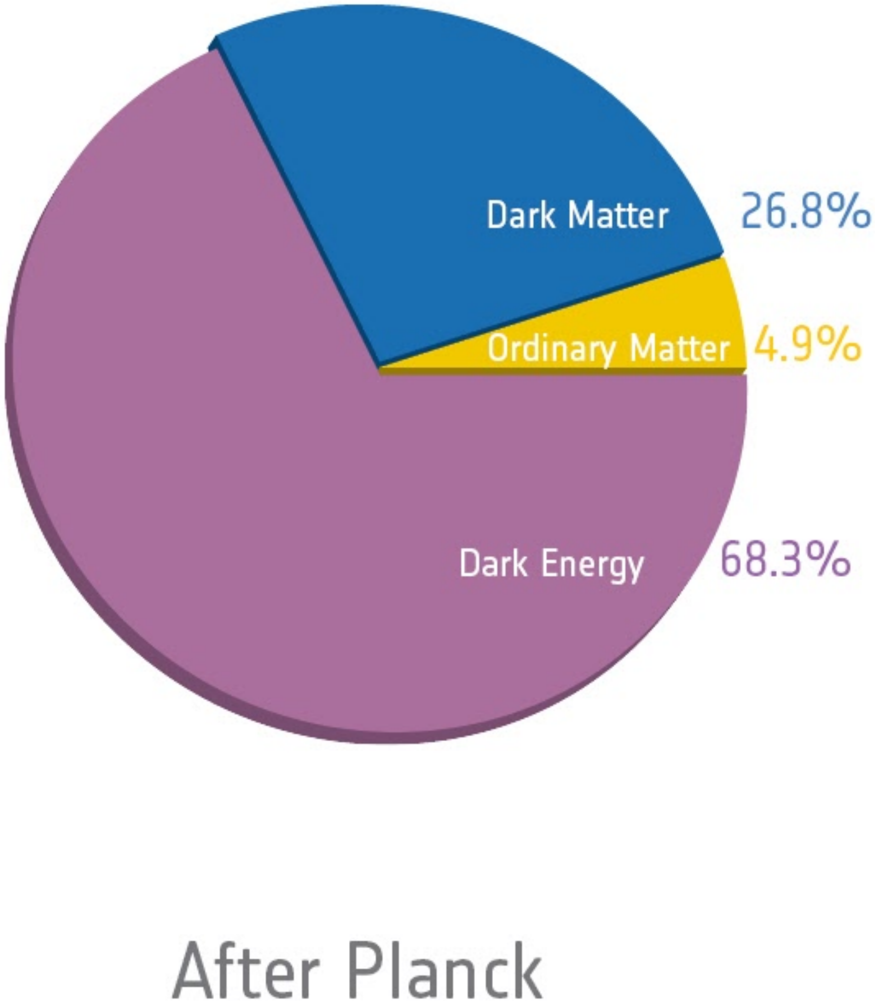


PLANCK POWER SPECTRUM



Portions in cosmic composition pie...
somewhat redistributed after PLANCK





Is the H_0 tension an alert?

R1: Modern cosmology needs QM
1. Origin of structure

Without QM: inflation produces a perfectly homogeneous Universe: initial inhomogeneities are completely erased, but then the structures we see in the sky could not have formed.

With QM: classical initial inhomogeneities are still erased, but are replaced by calculable quantum fluctuations produced, amplified and stretched throughout the inflationary epoch.

The CMB & LSS we observe today carry an imprint of those primordial quantum fluctuations.

(Semiclassical) quantization of geometry is part of the game explaining the large-scale structure of the Universe.

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

Unavoidable if primordial GW will be detected in the CBM (via B-mode polarization).

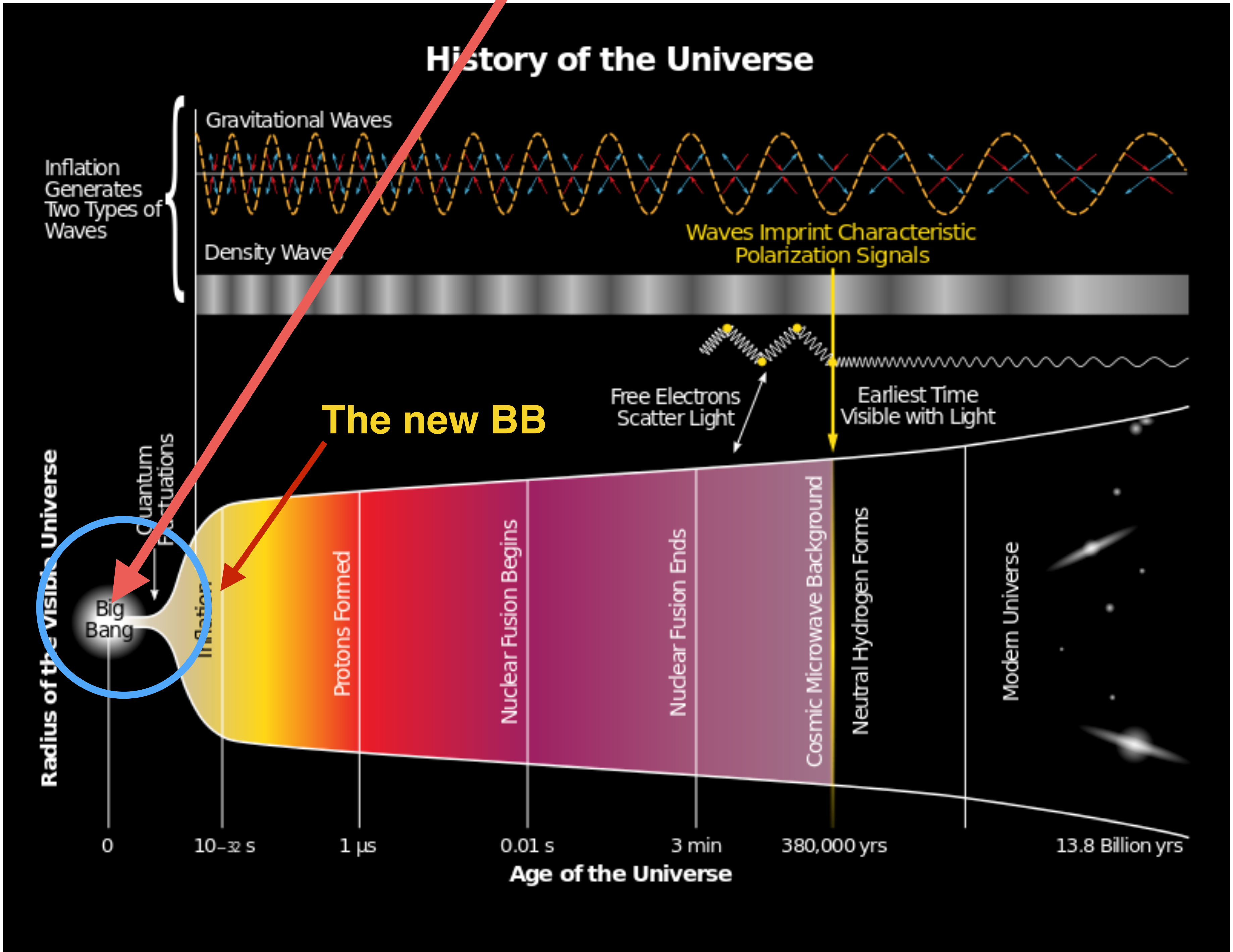
2. Reheating after inflation

Inflation cools the Universe to practically $T = 0$.
Can one generate a hot Universe after inflation?
If not, no CMB, BBN!
NB: after inflation the U is still expanding!
Second intervention of QM: reheating, i.e. the non-adiabatic conversion of potential energy into a hot thermal soup of elementary particles. R2:

Reheating replaces the old HBB!

...but: 1. It has no associated singularity;
2. It is certainly NOT the beginning of time!

An often shown (yet false) picture



In inflationary cosmology, we have to distinguish:

1. The "physical", non singular BB at the end of inflation with its measurable relics (CMB, BBN...)

2. A "theoretical" singular(?) BB (or a regular Big Bounce?), which <u>**may have**</u> preceded inflation (without leaving relics?).

In any case: the BB we know something about has nothing to do with a beginning of time.

Understanding the latter issue requires a quantum theory of gravity

Back to the SMN

The huge role of symmetries well known, appreciated, but distinguish:

1. Global symmetries (e.g. $SU(3)_F$, CP,..) together with their explicit or spontaneous breaking.
2. Local symmetries (e.g. gauge invariance, general covariance).

Local symmetry = redundancy

Allows to "gauge away" some degrees of freedom

A massless J=1 particle has two physical polarizations, a massive one has three.
Gauge invariance allows to remove the unphysical polarization of a J=1 massless particle.

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.

Some 50 years ago: a crucial breakthrough!

Also local symmetries can/do have

different realizations:

- Coulomb phase (EM, gravity)
- Brout-Englert-Higgs phase (weak interactions)
- Confining phase (strong interactions)

Two more reflections

R3: Nature appears to like J=1 massless particles.
That's why it's (partly) described by a gauge theory.

R4: Nature appears to like J=2 massless particles.
That's why it's (partly) described by Gen. Relativity!

Puzzles & Conceptual Problems

(fortunately there are still many!)

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. New physics in B-decays, $(g-2)_\mu$?
11. ….

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 (primordial cosmology?)

More general conceptual problems

Quantum-relativistic problems

- QM was introduced in 1900 to solve a UV problem in black-body radiation. Works fine in Non-Rel. QM.
- Rel. QM (a.k.a. QFT) reintroduces a UV problem!
- Virtual pair creation (allowed by a combination of SR + QM) leads to infinities since virtual particles of arbitrarily high energy are too copiously produced in a local QFT.
- A recipe, renormalization, handles UV infinities of *gauge* theories, gives a (partially) predictive theory: the SM!
- Ignorance about short distances can be lumped in a finite number of parameters that cannot be predicted, have to be taken from experiments. The rest is, in principle, predictable.

- Attempts to do the same for GR have failed so far since the gravitational interaction grows with energy.
- The price of UV ignorance becomes infinite. The same would be the case had we attempted to quantize Fermi's theory of weak interactions.
- The only way to make sense of quantum gravity seems to soften it below a length scale $L > l_P = (G\,h)^{1/2}$
- Like Fermi's theory wrt the SM, GR would then just be a large-distance approximation to a better theory.
- Q: Does Nature renormalize?
- R5: Nature (unlike us) cannot be ignorant about the UV.

The missing quantum corrections

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
  - welcome anomalies in global symmetries
  - effective 4-fermi interactions (neutral-K system)
  - quantum fluctuations during inflation
- A few (the "bad" ones) have not. Basically the 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
- We know that quantum corrections to (irrelevant) relevant operators in the IR are (in)sensitive to UV physics (diverge as powers of Λ_{UV})
- This may be telling us, once more, that the SM & GR are not the full story!

In the mid sixties Gell Mann used to say:
Strong interactions only read books in
free field theory!
Then came QCD and asymptotic freedom.

We can paraphrase GM today by saying:
Nature only reads books in dimensional
regularization (i.e. only knows about
logarithmic divergences)

R6

Intelligent **U**ltra-**V**iolet **C**ompletion

Is it Quantum String Theory?

Two Quantum Miracles speak for!

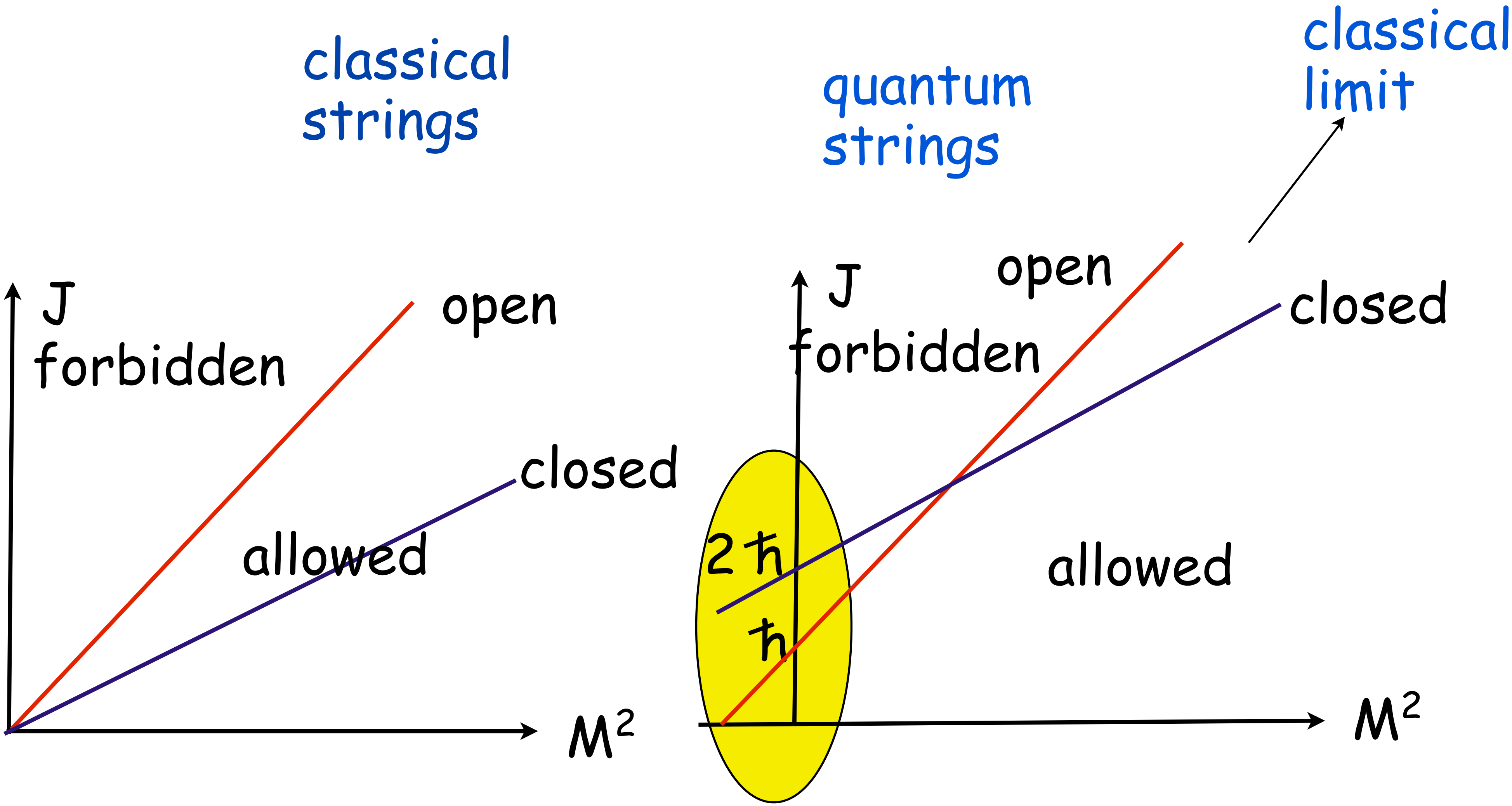
Quantum String Magic I: J without M

Quantum strings can have up to two units of angular momentum without gaining mass. Classically impossible, needed at quantum level (Virasoro's breakthrough, 1969).

after consistent regularization

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

T = classical string tension



Classical ST has nothing to do with Classical FT!

Quantum String Magic II: a length scale

QM introduces a fundamental length scale:

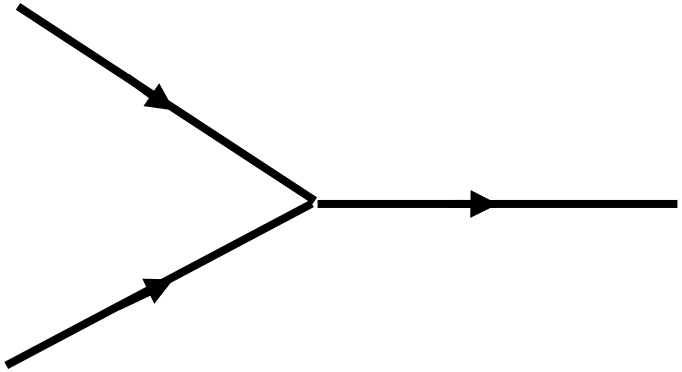
$$\frac{1}{\hbar}S_{string} = -\frac{T}{\hbar}(\text{Area swept}) \equiv -\frac{1}{\pi l_s^2}(\text{Area swept}) \quad ; \quad l_s \equiv \sqrt{\frac{\hbar}{\pi T}}$$

Note analogy w/: $l_P = \sqrt{G_N \hbar}$ Indeed: $G_N T \sim \alpha_{GUT}$

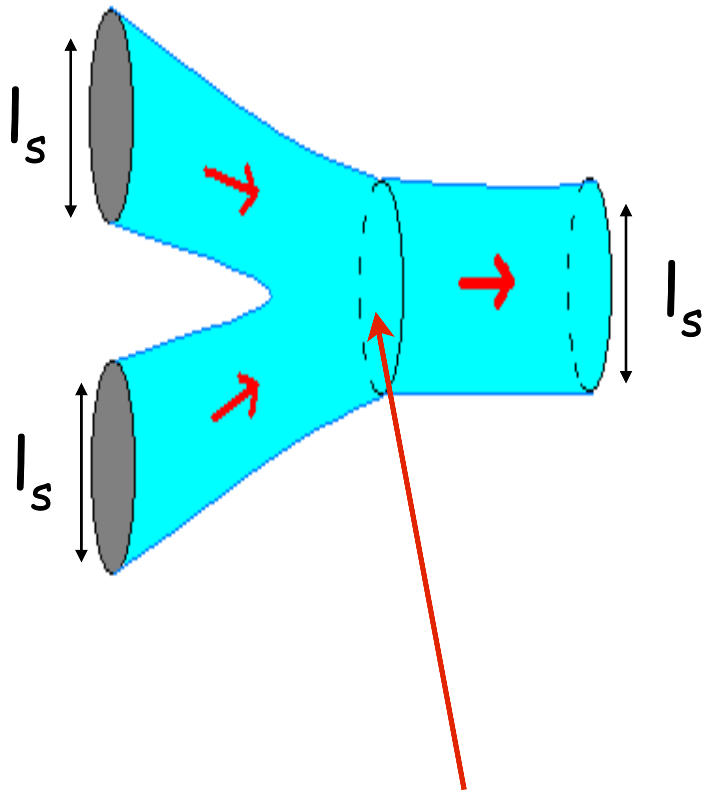
l_s enters QST in many crucial ways:

- Characteristic size of (lightest) strings
- T-duality, mirror symmetry etc.
- Maximal (Hagedorn) temperature
- Physical reason behind its good UV behavior
- ...

Field Theory



String Theory



Interactions smeared over regions of order l_s

QST appears to have answered 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!
- 1st Quantization makes 2nd Q. UV finite!

Having a UV-finite theory does not mean absence of radiative corrections. Only that they are finite and, in principle, calculable!

Q_1: Does QST read the right books? (absence of rad. corrections to relevant operators)

A_1:All consistent QSTs are supersymmetric and, as such, do satisfy that requirement... in perturbation theory.

But, at that same level, SUSY is unbroken...

Q_2: Can QST provide mechanisms of (spontaneous) SUSY breaking preserving that particular feature of its perturbation theory?

A_2 lies in deep UV details. A selection principle for acceptable string theories/vacua? Or perhaps the sign of some subtle IR-UV connection/mixing?

Otherwise, just play an anthropic game based on the huge landscape of string vacua?

But can we find among them (at least) one that resembles the real world?

This is the (non-trivial) string-phenomenology program.

Two less(?) desirable QST miracles

I: 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 dimensions.
- In order to reconcile this constraint with observations we have to assume that the extra dimensions of space are compact and small (e.g. a 6-torus of radius $R \sim l_s$)
- QM pushes String Theory into a Kaluza-Klein scenario to which it adds interesting twists, such as T-duality…

II: 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»
- Are they dynamically determined? In perturbation they are not because the associated scalar fields ("moduli") are strictly massless.
- If they remain massless non-perturbatively, QST is very likely falsified by predicting additional long-range forces. This is the so-called "moduli stabilization problem".
- If they do acquire a mass, their vevs will fix the SM's constants, e.g. α or m_p/m_P (a win-win lose-lose game!)

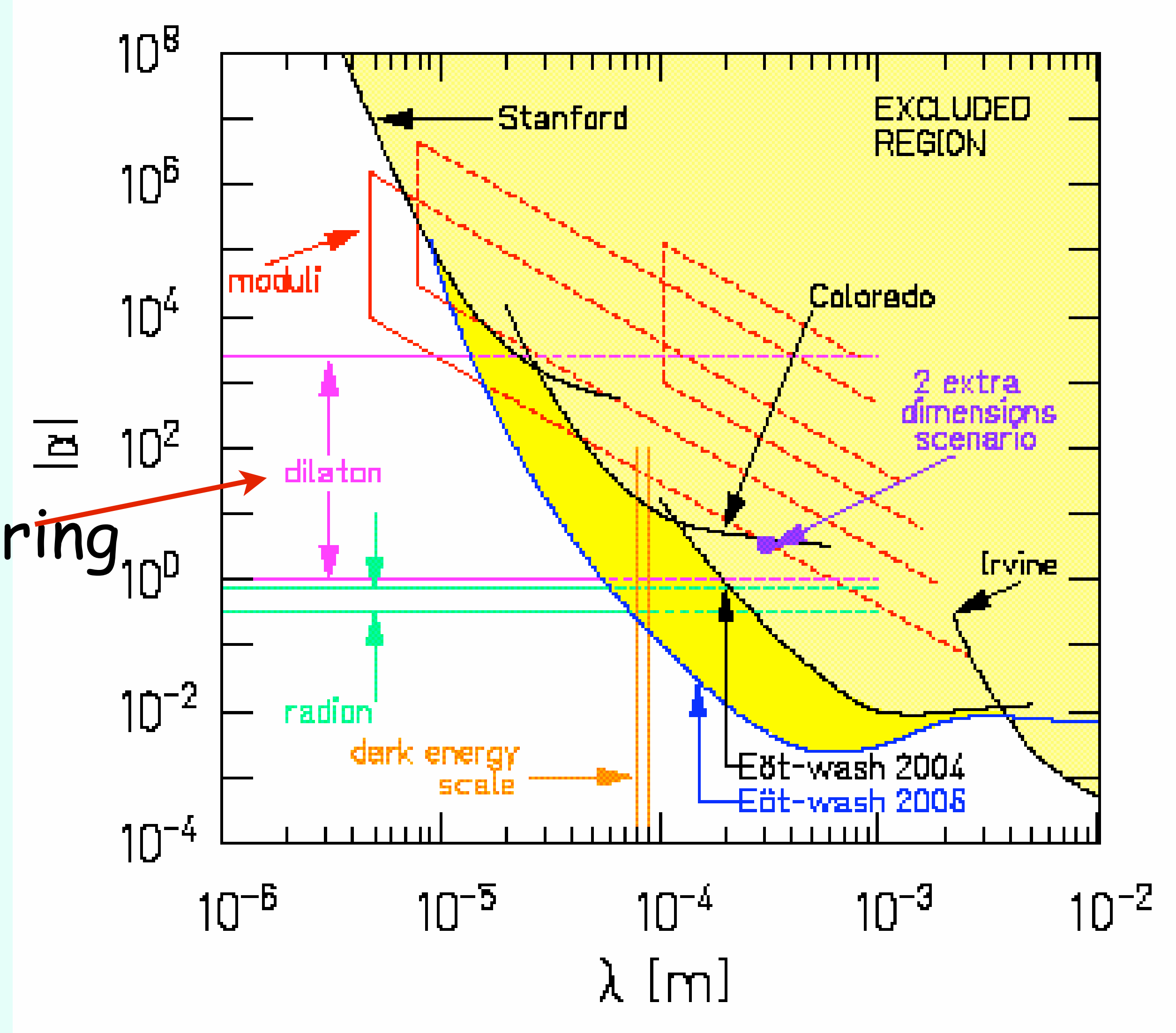
- While today these «constants» look to be space-time-independent, their variations may have played a role in early cosmology.

➪ An active field of experimental and theoretical research

- No need for Planck-scale experiments for testing string theory (true also for the old hadronic string)
- Perturbative QST is already ruled out! But so is QCD!

Not updated!

„Fifth Force" strengths now excluded at small distances



from string theory

SUMMARY

Our present SMN is 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 dark matter, of dark energy, and of a mysterious inflaton.

- Quantization of both looks more than ever a must

- QM crucial for modern cosmology. BB redefined

- 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 (QST), with its magic, could be such a sought-for completion, but:
- QST is a package, you can't just use what you like about it and throw the rest.
- 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 and find out whether it will survive or go down the drain like its hadronic predecessor. And, not to repeat the old mistake:
- Two Q^s: To which "elementary particles" should we apply string theory? Is it reasonable to assume no more sub-structures till the string/Planck scale?

Thank You!