GGI, 28-30 September 2006

Advances in Precision Tests
and
Experimental Gravitation in Space

Alternative Theories of Gravity and Cosmology

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Outline

1. Why alternatives?
2. From quantum strings to classical "gravity"
3. Light scalars?
4. Large extra dimensions?
5. Conclusions

Why alternatives?

Einstein's General Relativity (GR) is a very successful framework for describing gravity in most physical situations: our Standard Model of gravitational interactions, tested by now to $O(10^{-3})$ accuracy

It seems to be applicable, equally well, to isolated systems, to waves in empty space, and to the Universe as a whole.

The universal attractive nature of gravity is responsible for the growth of small initial perturbations into the large-scale structure of our Universe.

There is no apparent reason for mistrusting GR in yet unexplored regimes…but

Experimental puzzles abund

1. What is dark matter?
2. What is dark energy?
3. What's the origin of the initial inhomogeneities?
4. What's the origin of baryon asymmetry?
5. What's the origin of HECR and GRB?
6. …

Theoretical puzzles too!

Gravitational attraction is also responsible for gravitational collapse, formation of black holes, and of singularities.

Theorems by Hawking & Penrose imply that, under mild assumptions, smooth «initial conditions» lead, inevitably, to space-time singularities, e.g.

1. The singularity behind a black-hole horizon
2. The cosmological (big bang) singularity

Q_1: What happens to singularities when we take quantum effects into account?
Answer not known: have you ever heard about QGD?

Q_2: Can we reconcile General Relativity & Quantum Mechanics?

At present, the leading candidate for reconciling GR and QM is (Super)String Theory

As such, it should provide answers to those hard questions

From quantum strings to classical “gravity”

- Classical strings (e.g. cosmic strings) do gravitate but that’s not what we are after. By contrast:

- Quantum (fundamental) strings induce gravity: how come?

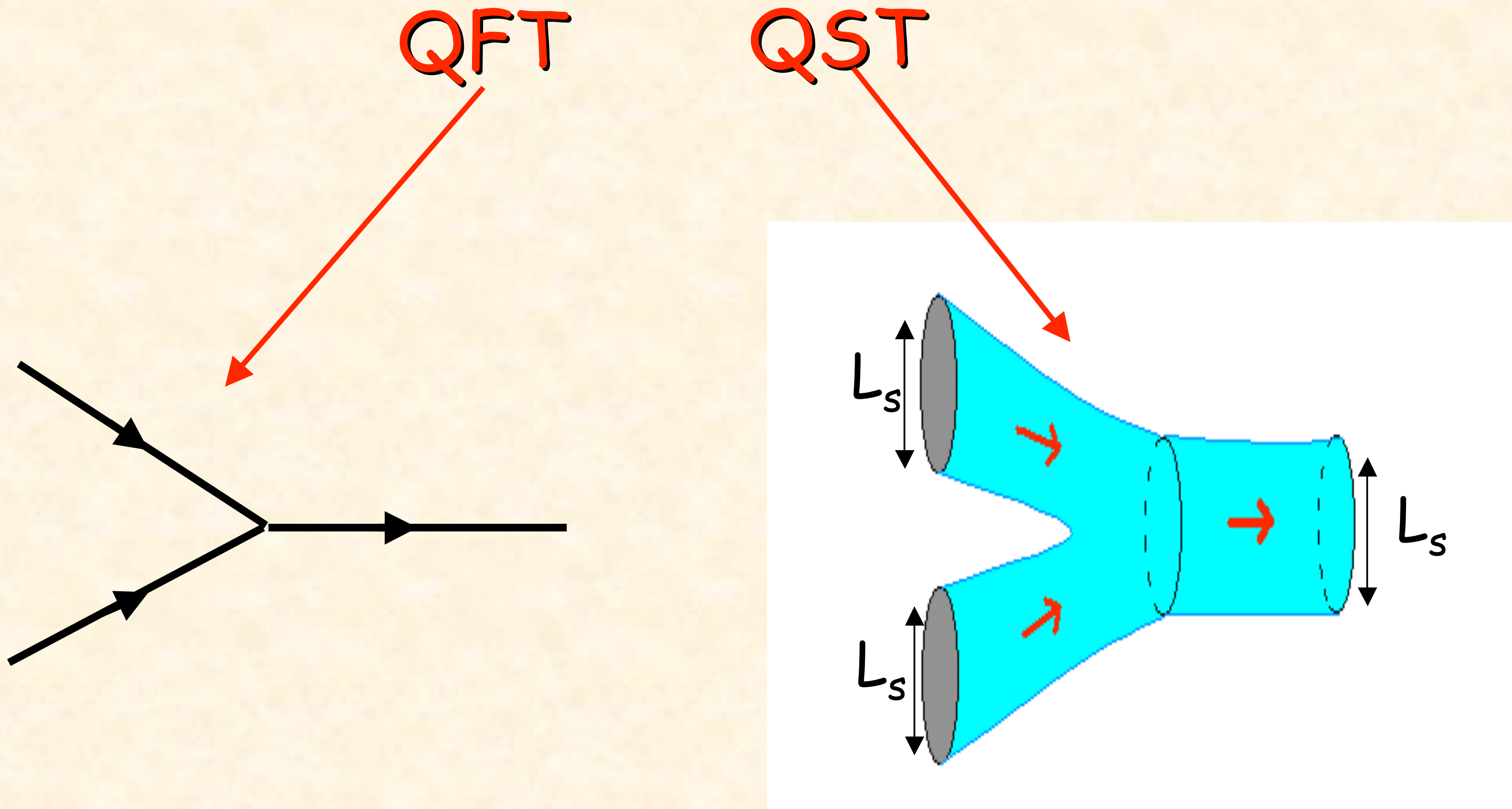
- It’s the consequence of some remarkable quantum miracles!

Quantum miracles: I. Finite Size

- Classical relativistic strings with tension T may have any size L and any mass $M \sim T L c^{-2}$;
- Quantum strings have a minimal (optimal) size L_s (Cf. Bohr radius), given by $L_s^2 = hc/T$ *).
- This length appears naturally in the (dimensionless, quantum) action of a string:

$$S_{class.} = T(Area\ swept) \Rightarrow \frac{1}{\hbar} S_{class.} = \frac{1}{L_s^2}(Area\ swept)$$

*) Note analogy with $L_P^2 = hG/c^3$ (if $G \to c^4/T$)



This finite string size, L_s, is responsible for the smearing of interactions over finite regions of spacetime and for the consequent disappearance of UV divergences

Quantum miracles: II. Finite Spin

While classical string cannot have angular momentum without also having a finite size/mass, quantum strings may have up to 2 units of J without acquiring mass:

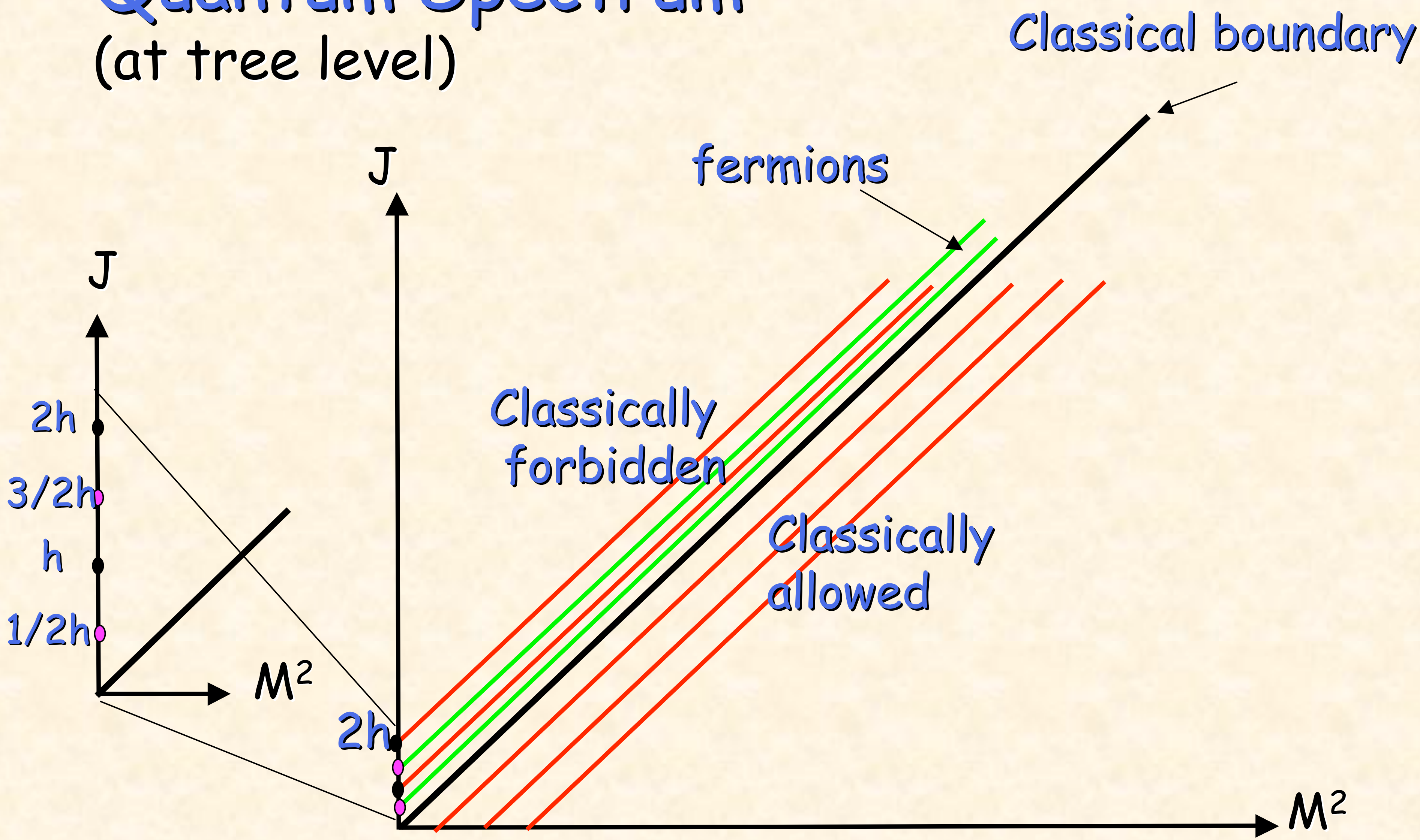
$$\frac{M^2}{T} \geq J + \hbar \sum_{1}^{\infty} \frac{n}{2} = J - \alpha_0 \hbar$$

$$\alpha_0 = 0, 1/2, 1, 3/2, 2.$$

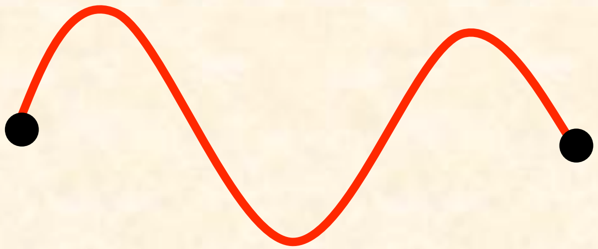
Cf. Casimir effect

Quantum Spectrum

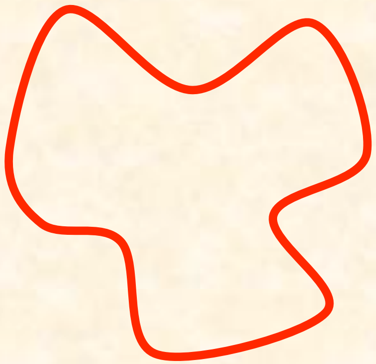
(at tree level)



In particular..



=> m=0, J = 1 => photon and other gauge bosons



⇒m=0, J = 2 => graviton,

⇒ m=0, J = 0 => dilaton

Integer-J massless states => carriers of interactions;
1/2-integer-J massless (light)states => constituents of matter

Combining both miracles provides

A unified and finite theory of elementary particles, and of their gauge & gravitational interactions

…an old challenge as we know from CSI…

Episode 101 - “Blink”
Detective Mac Taylor discovers the body of a missing woman in Brooklyn Heights. When he discovers a second victim on a garbage barge, his investigation leads him to a serial killer who “imprisons” his victims.
Grappling with memories of his own wife, Taylor follows the killer’s trail to a live victim. A woman who cannot move, feel, or speak. A woman who stretches Veneziano’s theory of quantum physics to its outer limit, challenging Taylor to prove that “everything is connected.”

But there are other quantum news..

- Classical strings can move consistently in any ambient space-time; Quantum strings require particular background space-times in order to avoid lethal anomalies. E. g.: a Minkowskian space-time must have 1 time and 9 space dimensions. Six of them are presumably compact.

- No free parameters: replaced by scalar fields whose expectation values provide (dynamically?) the «Constants of Nature». For instance, the fine-structure constant α and $G_N T$ are fixed by the dilaton and by the various compactification radii.

- String theory goes one step further than GR by making everything, including microphysics, soft (T. Damour)

Light scalars?

- Some J=0 massless strings (at tree level) are there irrespectively of compactification: the dilaton ϕ and its SUSY (pseudoscalar) partner, the (KR) axion σ
- $<\phi>$ controls the importance of loops (analogue of gauge coupling in QFT) but ϕ itself is a bona-fide field associated with a spin 0 particle
- => Gauge and gravitational couplings can be, in principle, functions of space and time.
- As such, the dilaton is responsible for an extra attractive force between two bodies A and B whose strength (in units of G_N) is given by:

$$F_{A,B} \sim g_{\phi AA}\, g_{\phi BB}\ ;\ g_{\phi AA} = \frac{\partial log M_A}{\partial \phi}\Big|_{\phi=<\phi>}$$

This "5th force" violates the EP, universality of free fall

The compactification moduli

- Sizes and shapes of the extra dimensions are controlled by a bunch of (pseudo)scalar fields called moduli, usually also massless at tree level (or even to all orders in PT)
- They may acquire a mass from higher order (or non-perturbative) effects (only "protected" by SUSY)
- If they end up being "heavy" they are not so interesting
- If they end up being very light (or massless) we may distinguish two cases:
  1. They have been light and coupled $O(G_N)$ in the early universe, acquired a mass later => interesting for early cosmology, not for today's experiments
  2. They may be light and very weakly coupled ($< G_N$) even today => interesting for dark energy, violations of Equivalence Principle, variations of "constants"

1. Light, gravitationally coupled scalar fields in EU

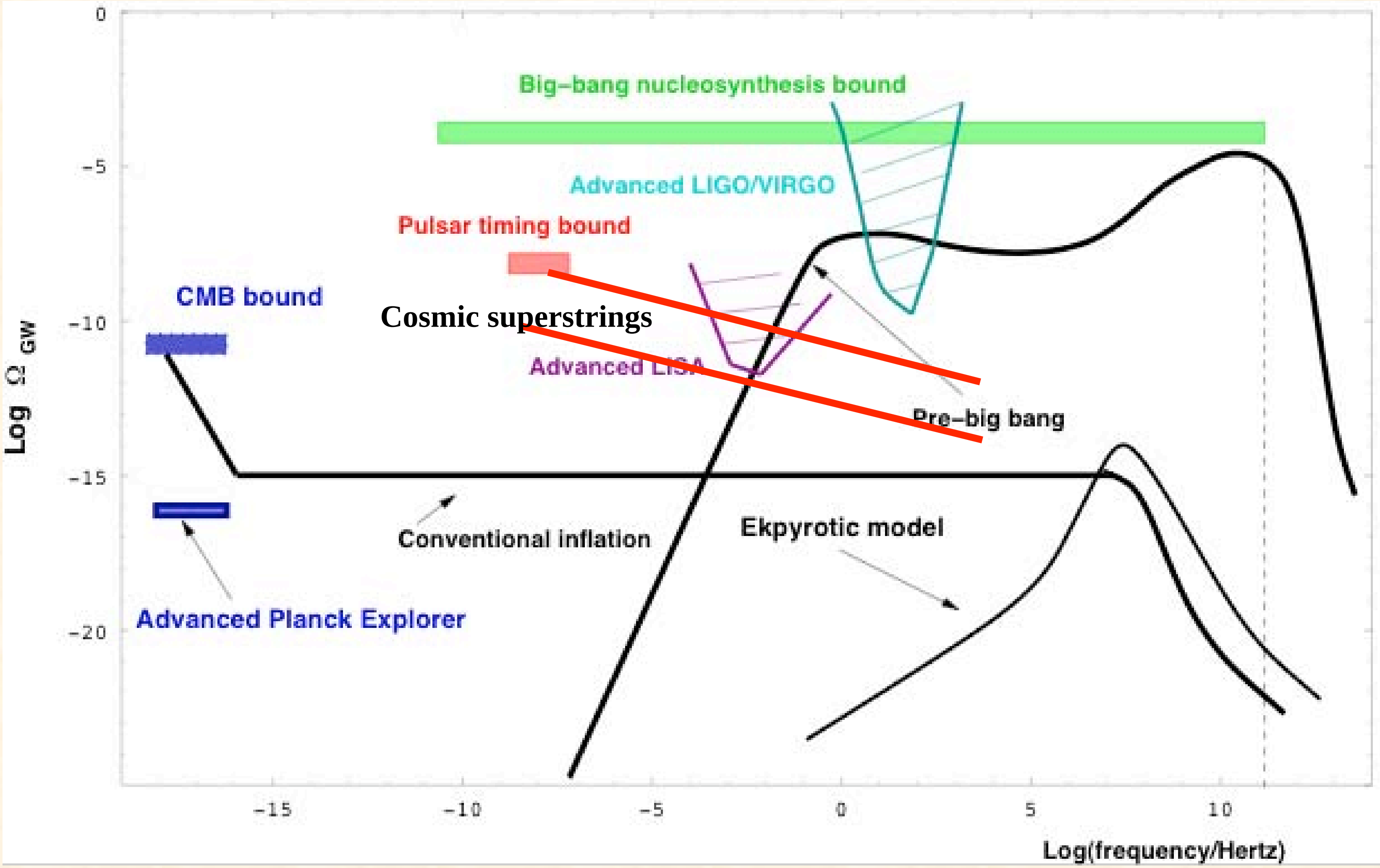
Early cosmology would not be described by GR, but by the appropriate (multidimensional) effective lagrangian of string theory, even in its classical regimes.

Basis of unconventional cosmologies such as the pre-big bang or expyrotic/cyclic scenarios

Typically, a classical (but not GR) pre-bang phase gets connected to a standard (GR) post-bang cosmology through a "quantum bridge", a high-curvature phase in which an effective field theory (let alone GR) description makes no sense

These cosmologies do not (seem to) give the right spectrum of adiabatic density perturbations that slow-roll inflation provides: blue, rather than nearly scale-invariant.

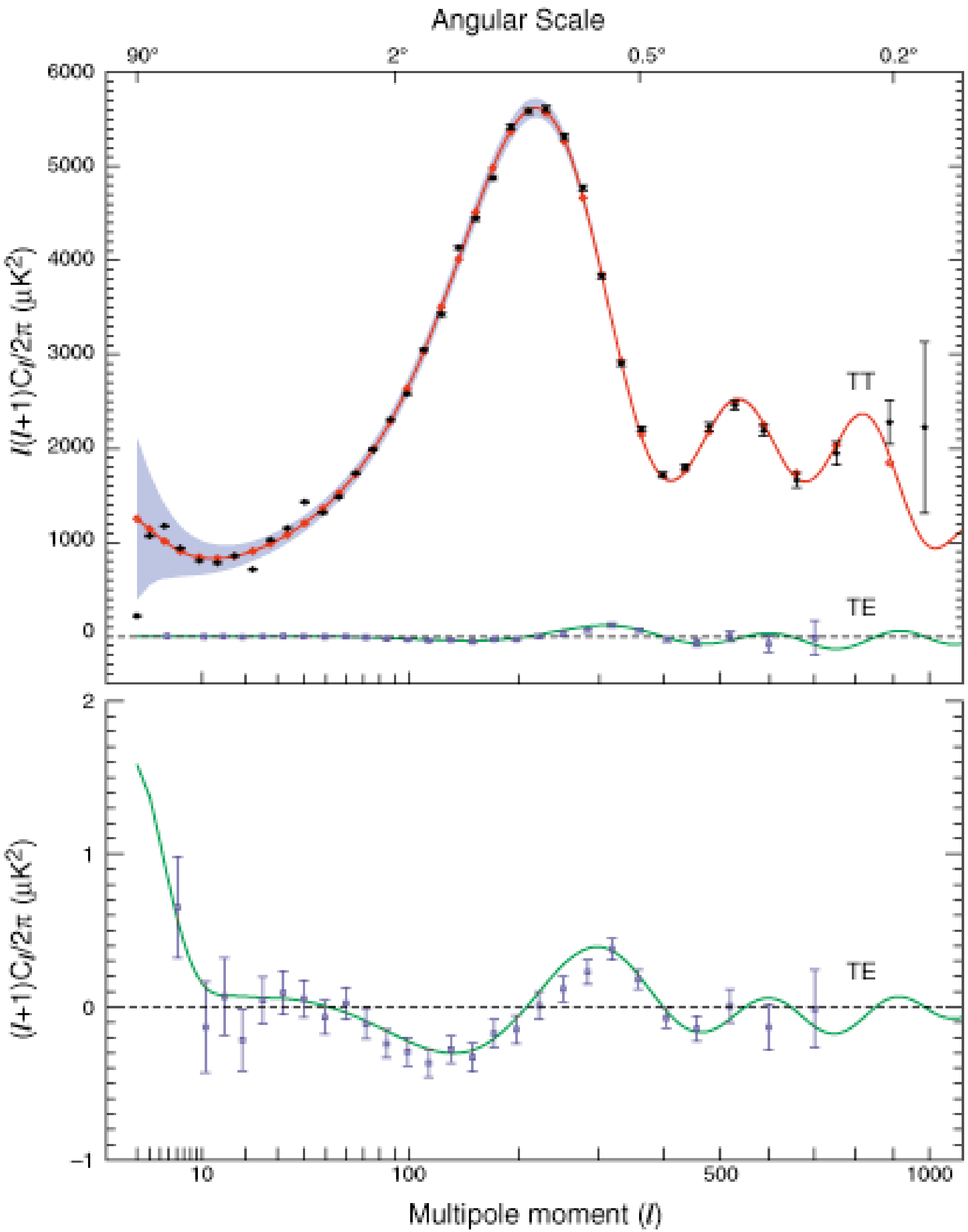
Example of tensor perturbations (GW)


Big–bang nucleosynthesis bound
Advanced LIGO/VIRGO
Pulsar timing bound
CMB bound
Cosmic superstrings
Advanced LISA
Pre–big bang
Conventional inflation
Ekpyrotic model
Advanced Planck Explorer
Log Ω GW
Log(frequency/Hertz)
0
-5
-10
-15
-20
-15
-10
-5
0
5
10

Can the axion save the day?

- The (KR) axion σ can have a scale-invariant spectrum. Its tilt, (n_σ -1), depends on evolution of the internal dimensions in pre-bang phase: SI spectrum corresponds to a "symmetric" evolution of all nine spatial-dimensions
- Unfortunately, axion perturbations do not talk, to first order, to metric perturbations (entropic, isocurvature fluctuations) => bad predictions for acoustic peaks
- The way to rescue these cosmologies is to have the axion play the role of the "curvaton" by first becoming a relevant fraction of the total energy density, and by then decaying (before Nucleosynthesis)
- Gives agreement with present CMB data and specific expectations on T-perturbations, non-gaussianity.

TT and TE
(E-mode of polarization) correlations from WMAP
B-mode needed to test different theories



2. Some scalar fields are light even today (and coupled « G_N)

Interesting for:

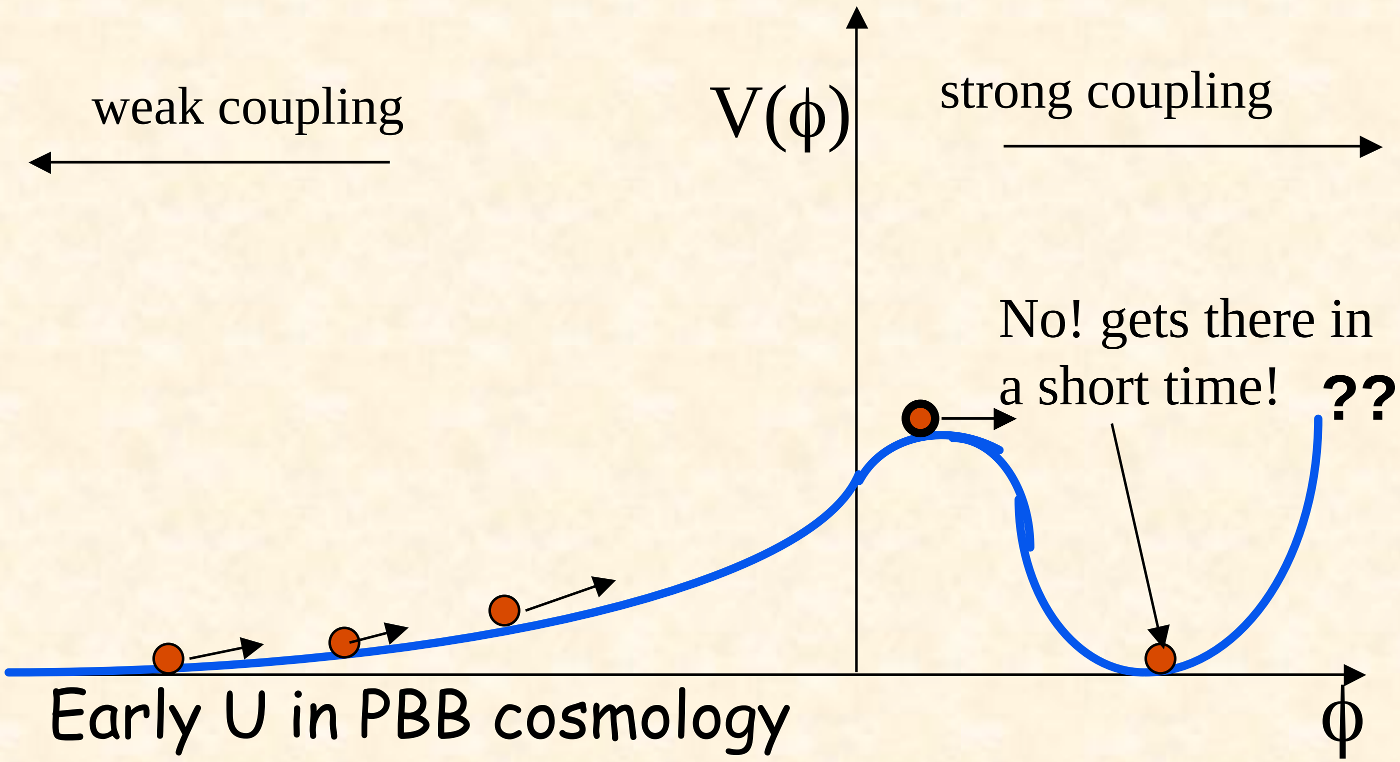
Dark energy,
Violations of EP,
Variations of "constants"

Dilaton as dark energy?

- We have to settle first the question of its coupling to matter and of possible EP-violations
  - By supersymmetry, ϕ is massless to all orders in perturbation theory
  - Its perturbative coupling to matter is larger than gravity and non-universal

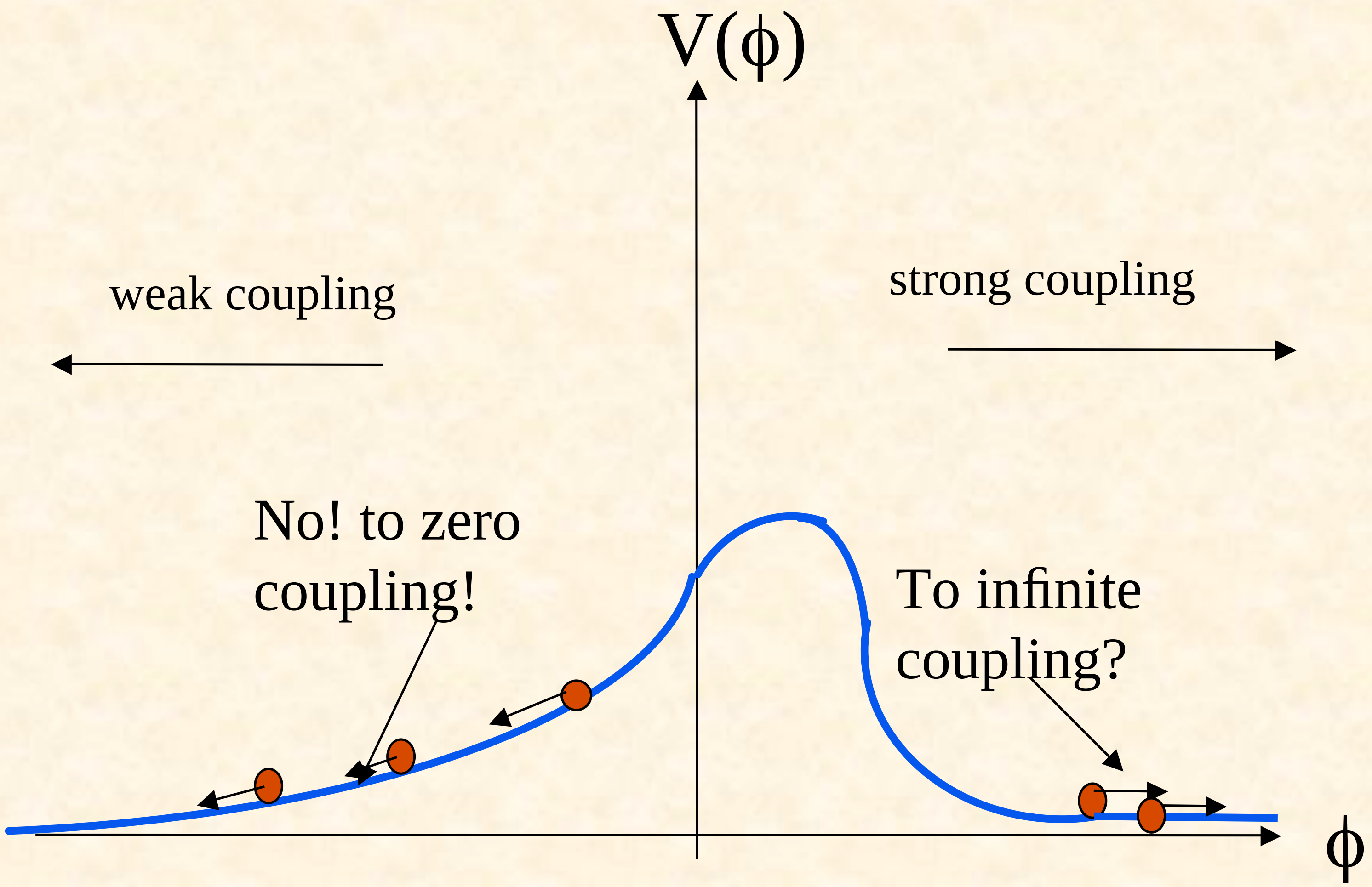
This problem goes under the name of the "Dilaton (moduli) Stabilization Problem" in String Theory

- Standard way out assumes that ϕ acquires a NP mass and is frozen today at the bottom of its V.
- Solves EPV problem but cannot provide acceleration



Another possibility: vacuum at infinity

Can provide dark energy but what about EPV problem?



Induced gravity in String Theory?

- Is an infinite bare coupling ruled out in ST?
- So-called compositeness limit: kinetic terms of gauge and gravity fields generated by loops (Cf. induced gravity idea of Sakharov...)
- In some toy models one can argue that such limit exists and is even interesting if there are many matter fields (M_s/M_P lowered tow M_{GUT}?)
- Assuming this to be the case, we can have dilaton induced acceleration & dilatonic couplings turning off as the dilaton slowly rolls to infinity

Two cases

❶ If infinite bare coupling limit is same for ordinary matter and for non-baryonic dark matter, we fall into a rather conventional quintessence(Q)-model

❷ If the infinite bare coupling limit is not as smooth for non-baryonic dark matter then, at the cost of large EPV in the DM sector, we get a non conventional (so-called coupled-Q) model:

Attractor towards $\Omega_{DE} \sim \Omega_{DM}$ at equality followed by Acceleration with $\Omega_{DE} / \Omega_{DM} \sim$ constant

Solving coincidence problem?
Not quite: scale of V put in by hand!

EP violations & varying α

- Can we efficiently send the dilaton towards large values and get small enough -but perhaps measurable- EPV and/or variations of α?
- This question was addressed and answered affirmatively a few years ago:

(Damour, Piazza & GV, gr-qc/0204094,

hep-th/0205111, Damour, gr-qc 0210059, 0306023)

- It is necessary to couple the dilaton to an inflaton χ through a potential $V(\chi,\phi)$ taken for simplicity of the form

$$V(\chi,\phi) = \lambda(\phi)\chi^n$$

Using standard chaotic-inflation results we can relate ϕ at the end of inflation to the initial value of χ and, eventually, to the amount δ of primordial density fluctuations generated during inflation.

One gets:

$$e^{\phi_{end}} = O(10)(\delta)^{-\frac{4}{n+2}}$$

($\delta \sim 5 \times 10^{-5}$ from CMB data)

At this point we can compute EPV, $d\alpha/dt$

EP violations

Instead of PT result, $g_{\phi NN}/g_{grNN} \sim 40$, we get

$$\frac{g_{\phi NN}}{g_{gNN}} \sim 40\, e^{-\phi_{end}} \sim 4\,(\delta)^{\frac{4}{n+2}}$$

for the composition-independent part of the new force, denoted by α_{had}. As such it is quite safe

More interesting to look at the composition-dependent part, i.e. at violations of the universality of free fall (UFF).

- For two different bodies, A and B:

$$\left(\frac{\Delta a}{a}\right)_{AB} \equiv 2\frac{a_A - a_B}{a_A + a_B} \sim \alpha_{had}(\alpha_A - \alpha_B)$$

- The small quantity (α_A - α_B) can be argued to be linear in baryon number, neutron excess and Coulomb energy. For pairs such as Be-Cu or Pt-Ti one finds

$$\frac{\Delta a}{a} \sim 5 \cdot 10^{-5} \alpha_{had}^2 \sim 5 \cdot 10^{-4} (\delta)^{\frac{8}{n+2}}$$

- For n=2 (simplest chaotic inflation) this is compatible w/(but close to) present limits (10^{-12}) while n =4 looks already in trouble

MICROSCOPE, STEP aim at 10^{-14} , 10^{-18} resp.

A varying α?

In general we expect a time-variation of α given by

$$\frac{dln\alpha}{Hdt} = e^{-\phi_{end}} \frac{d\phi}{dlna} \sim 2.5 \cdot 10^{-2} \alpha_{had} \frac{d\phi}{dlna}$$

The last factor is the main uncertainty. It depends on the coupling of the dilaton to DM and on its possible role as quintessence

If ϕ has small coupling to DM, no role as Q, that factor kills any chance of appreciable variations of α.

In scenarios of the Q type $d\phi/d\ln a$ can easily be O(1) and we get a relation between $d\ln\alpha/Hdt$ and UFFV

$$\frac{d\,ln\alpha}{Hdt} \sim 3.5 \cdot 10^{-6}(1+q_0-1.5\Omega_m)^{1/2}\left(\frac{10^{12}\Delta a}{a}\right)^{1/2}$$

i.e. $d\ln\alpha/dt$ $\sim 10^{-16}\ \mathrm{yr}^{-1}$ for $\Delta a/a \sim 10^{-12}$

..below present sensitivity ($10^{-14}\ \mathrm{yr}^{-1}$) but close to planned sensitivity of cold-atom clocks.

Upper limit from Oklo data ($5\times10^{-17}\ \mathrm{yr}^{-1}$) would correspond to $\Delta a/a \sim 10^{-13}$

Instead, difficult to get

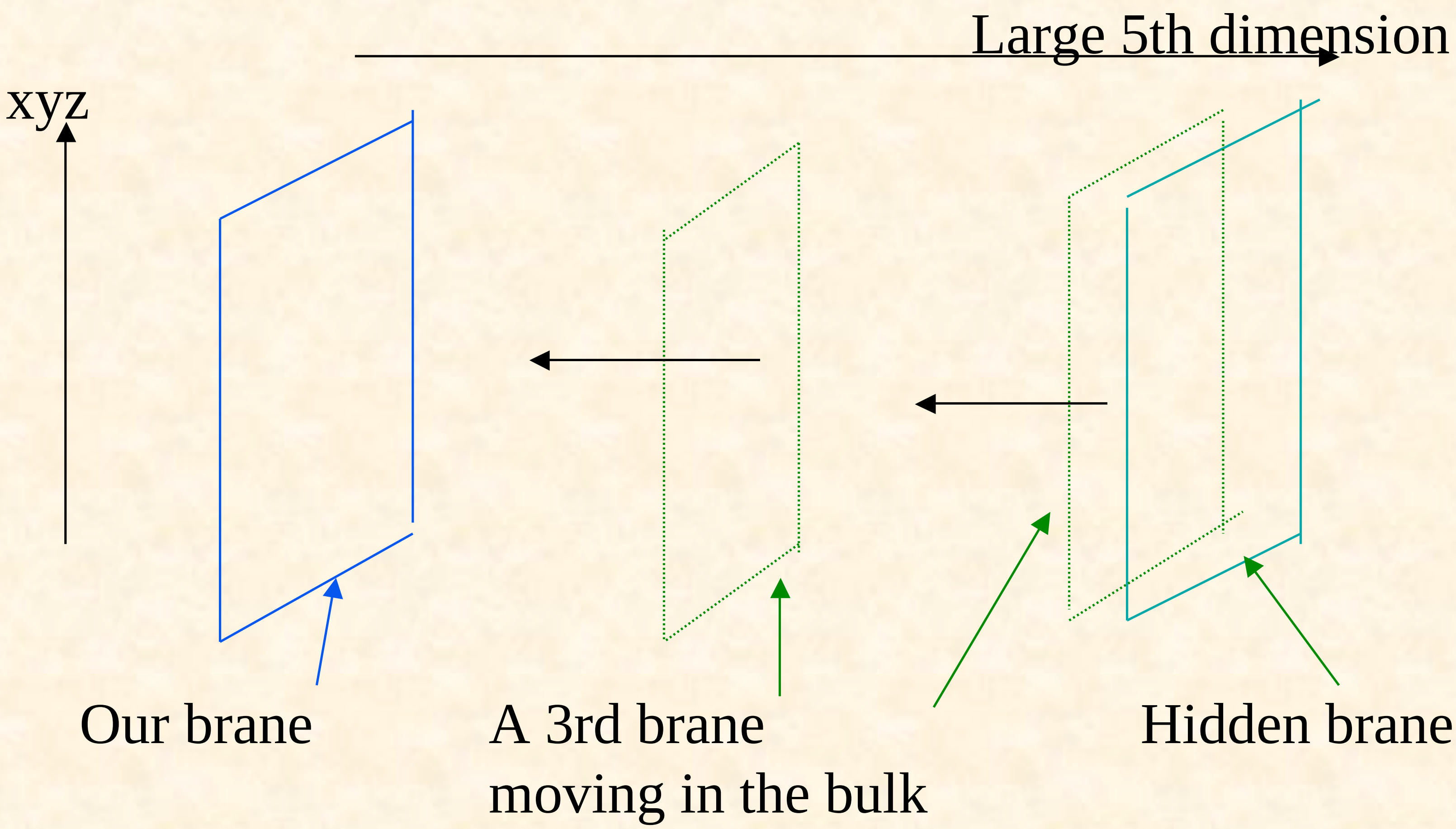
$\Delta\alpha/\alpha \sim 10^{-6}$ at $z \sim 0.5\text{-}3.5$

as claimed by Webb et al.

Large extra dimensions?

- The VEVs of the moduli determine sizes and shapes of the internal dimensions
- If these are of string scale and frozen, we can only "see" them indirectly (e.g. gauge fields generated a la KK)
- If they are large and/or dynamical, we can distinguish again two cases:
  1. They were large/dynamical in the EU but not now
  2. They are large/dynamical even today

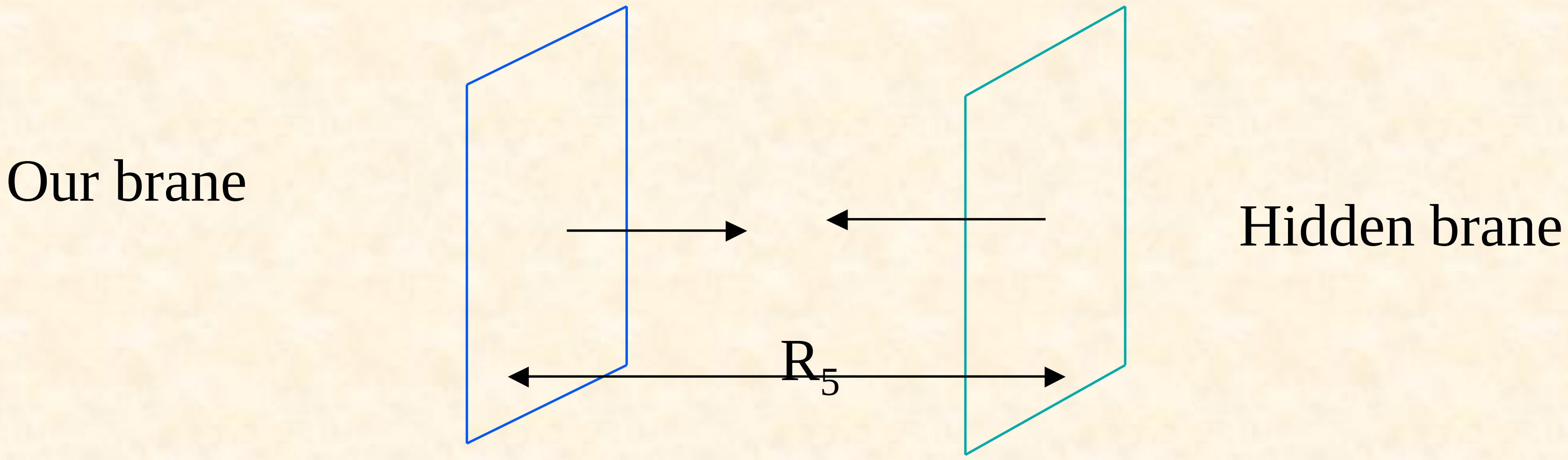
The first case is the one we have already discussed of some unconventional cosmologies of the pre-bang type. We may still distinguish the case of a multi-dimensional early universe (PBB) and that of an early brane-universe (EKP).



BB as result of impact of 3rd brane on ours

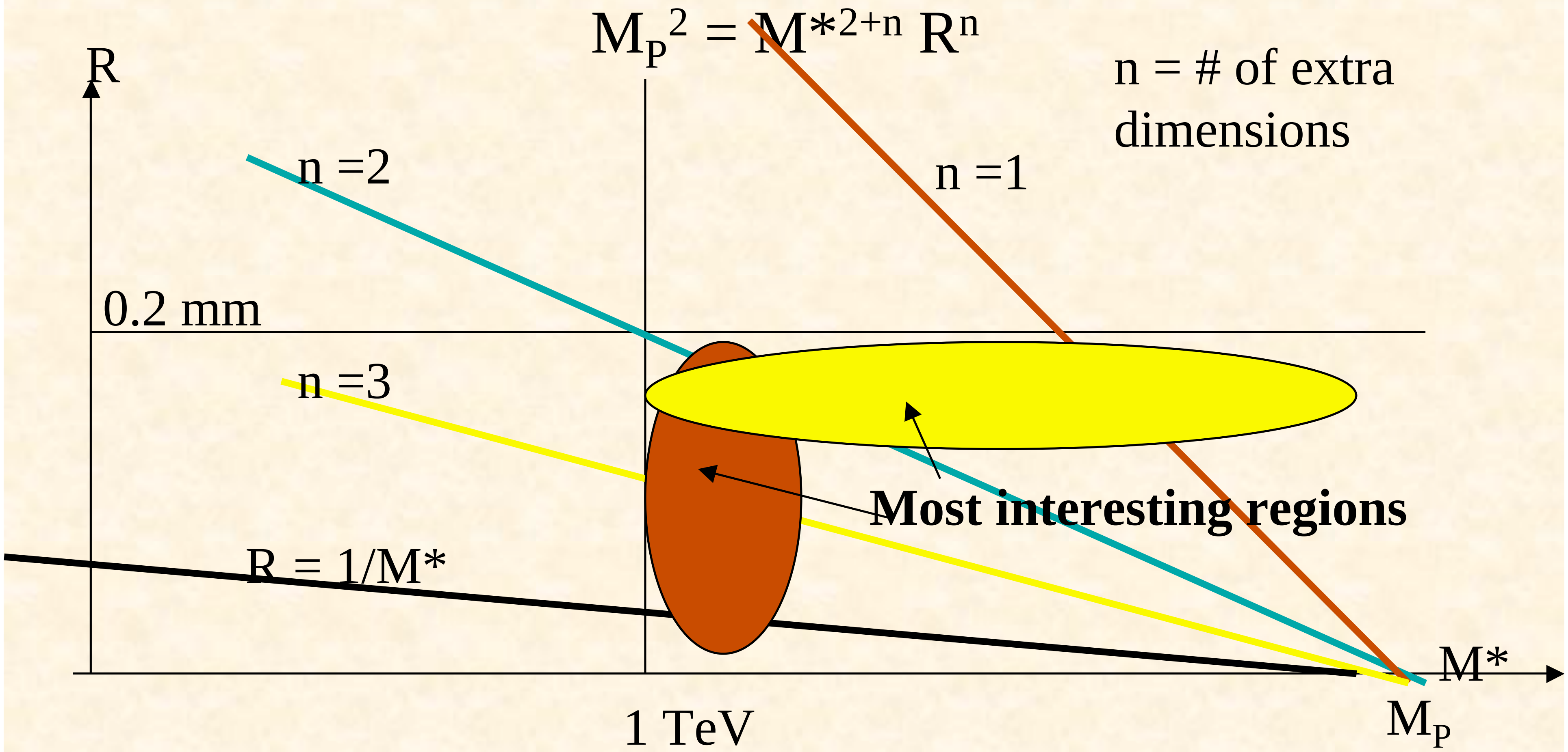
Alternatively:

Before the BB



BB is the collapse of the 5th dimension to zero size.

In the second case the extra dimensions can be small (but not infinitesimal) and may be seen through modifications of the $1/r^2$ law at short distance, or via new strong-gravity phenomena that should occur at high energy accelerators (mini black holes etc.)



Or they are really macroscopic, even infinite today. In this case we have to accept that we (the SM) are (is) confined to a brane…

Conclusions

Interesting new phenomena are usually expected in alternative theories of gravity and cosmology. Examples of BSGR physics:

1. Unconventional cosmic perturbations & dark energy
2. Violations of EP, UFF;
3. Modifications of Newton's law;
4. Strong gravity at accelerator energies;
5. Spacetime variations of "constants"

As with BSM physics, the obvious question making many theorists so nervous these days is:

Why have we not found any evidence so far for physics beyond the SM & GR?

Hopefully the answer will not be:
because there isn't!