Holography and emergent gravity

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CPHT 61st Anniversary
Ecole Polytechnique, 25-03-2019

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- The ST group was hosted in the Levy Building (burned down in 2012), which looked a bit like this:

(not actual picture)

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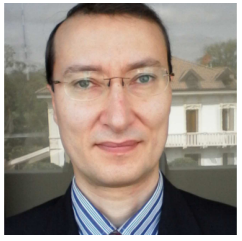

Around the same time, Damiano Anselmi happened to be visiting Università Statale di Milano...

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Damiano: *"sure, something something c-functions"*

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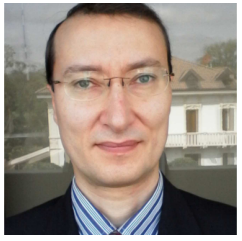

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Anselmi was a postdoc at CPHT. Hence, in June '98 I packed my notebooks and came to Paris for 2 weeks...

An Italian undergrad in CPHT (June 98)

I was staying with some friends, therefore my first contact with to Ecole Polytechnique was not CPHT, but this:

"the largest annual student event in the Paris region." Basically a huge party over the entire Ecole Polytechnique ground.

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(...which turned out to be a McDonald's)

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Typical conversations with Damiano:

- Damiano: *"You should do calculation X"*
- Me (after the whole day calculating): *"I'm done, the result is Y"*
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- Me: *"I redid it, however I found the result is Z' , not Z"*
- Damiano: *"No, it is Z as it should, I did it in 20 minutes on the train this morning"*
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Somehow, I managed to survive, write a thesis, and graduate.

Fast forward to 2005

After five uneventful PhD years in New York...

(my thesis advisor, Massimo Porrati, an old aquaintance here in Paris, and friend and collaborator of Luciano Girardello et c.)

...I received a postdoc offer from CPHT.

Fast forward to 2005

Aside: Typical conversation with Massimo during my PhD:

- Massimo: *"You should do calculation X"*
- Me (after several hours/days of calculation):
  "I'm done, the result is Y"
- Massimo: *"That can't be right. The result should be Z. Try again."*
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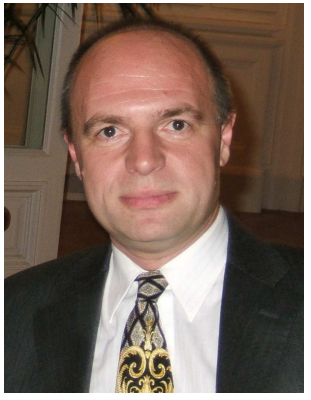
An Italian Postdoc in Paris, 2005-2008

In CPHT I stared working with Emilian Dudas and Elias Kiritsis,



and interacting with Marios, Hervé plus lots of postdocs and students, some of whom became good friends, including

Umut Gursoy, Angel Paredes, Roberto Casero, Alberto Romagnoni, Pablo Camara, Vasilis Niarchos, Liuba Mazzanti, Domenico Orlando, Tristan Maillard, Mike Lennek, Eran Palti, Georgios Michalogeorgakis ...

Thinking about emergent gravity at CPHT

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WHY would that even be 1) interesting 2) possible ?

1. Thinking of GR as being the fundamental theory of gravity leads to all sort of puzzles at the quantum level (non-renormalizability/non-unitarity, quantum space-time, etc). If gravity is an emergent low energy phenomenon, some of these puzzles go away
2. In the AdS/CFT correspondence, gravity is indeed emergent, but in the wrong number of dimensions: if the QFT is 4d, gravity is (at least) 5d. On the other hand, 4d QFT describes well all other interactions we know.

Can we have a 4d QFT in which *4d gravity* emerges at low energy?

Flashback to 1998

ANTI DE SITTER SPACE
AND HOLOGRAPHY

Edward Witten

School of Natural Sciences, Institute for Advanced Study
Olden Lane, Princeton, NJ 08540, USA

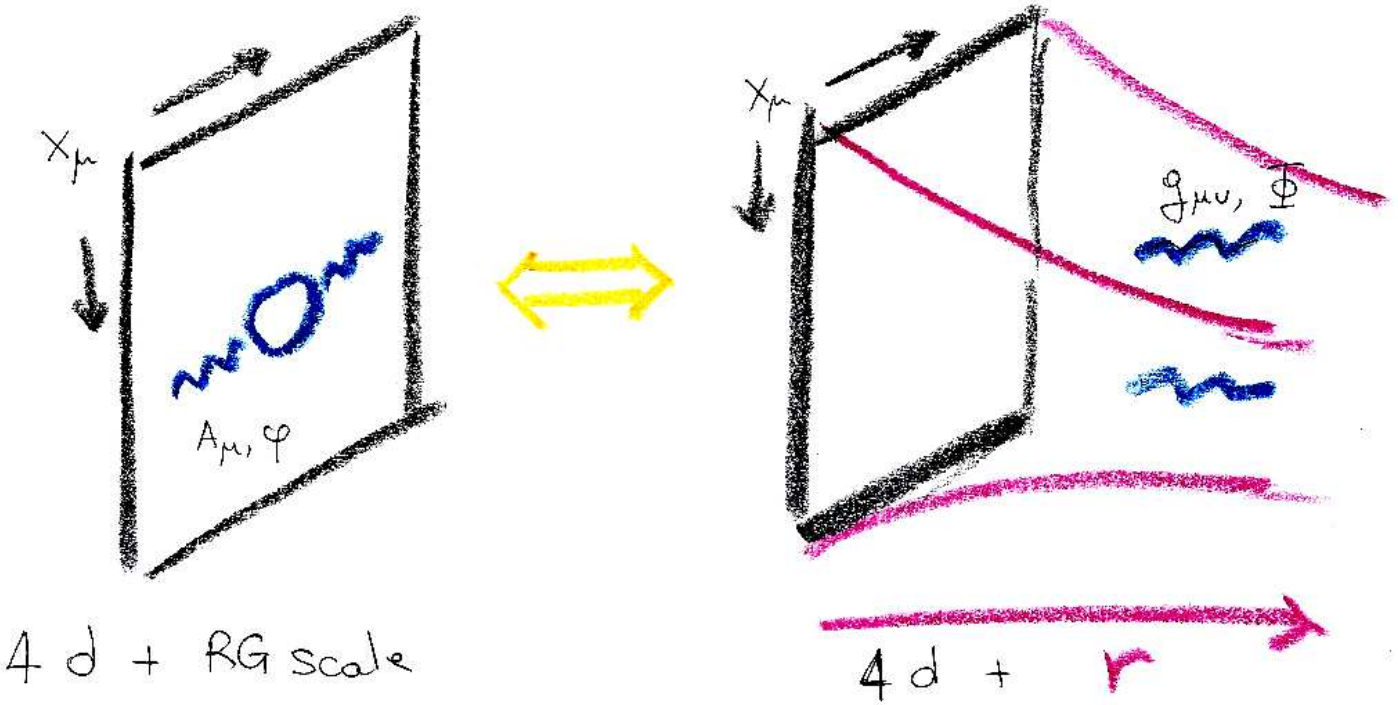
L. Giradello, handing me Witten's paper:

"this just came out, can you take a look at it? it might be interesting."

Me: *"???"*

The AdS/CFT correspondence

The AdS/CFT duality: conjecture that some quantum field theories are equivalent to theories of gravity (string) in higher dimensions (*holography*). Maldacena '97, Witten '98....



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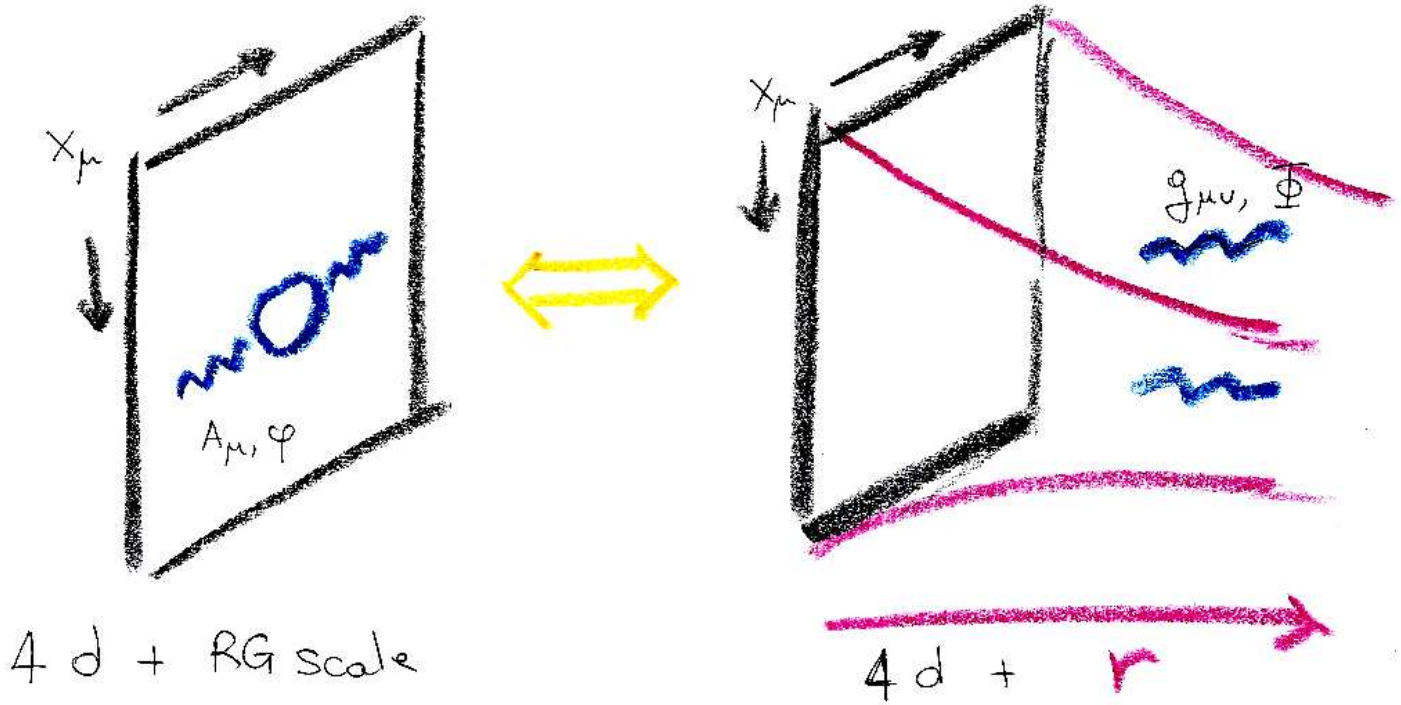
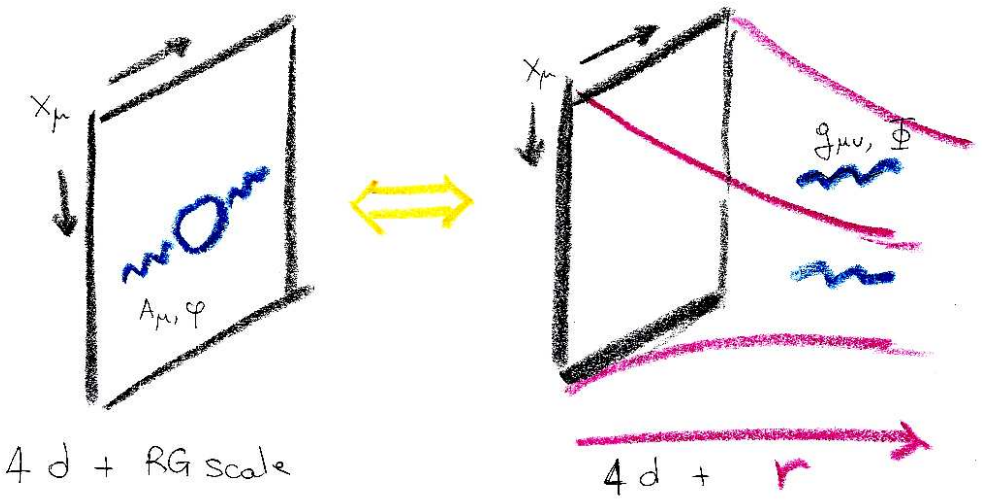


- The two sides describe the same physical system using two (very) different languages.
- When QFT side is strongly coupled, gravity side is classical (GR)

The AdS/CFT correspondence



- CFT : quantum field theory with conformal symmetry
- AdS: anti-de Sitter space (a maximally symmetric space with constant negative curvature) (same symmetry group as a CFT in 1d less)
- Normalisable modes inside AdS_{d+1} correspond to physical states in the dual d-dimensional QFT

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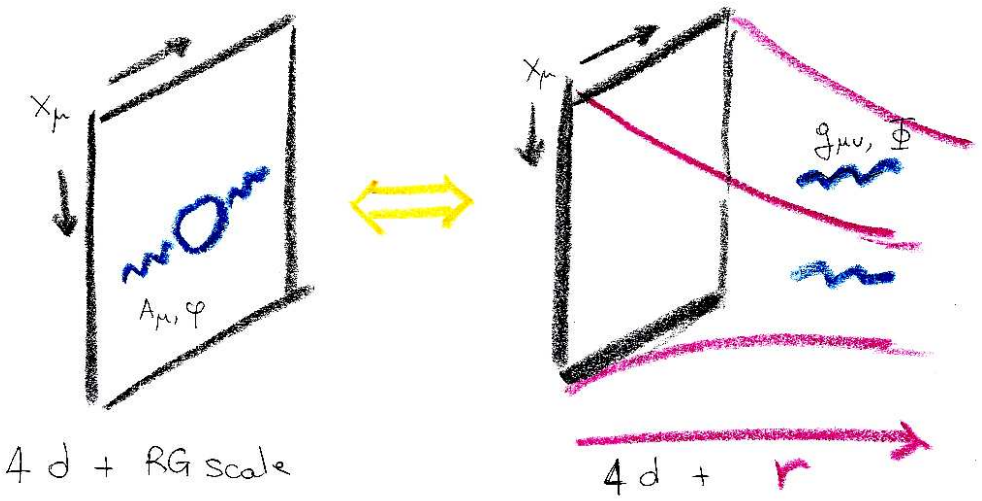

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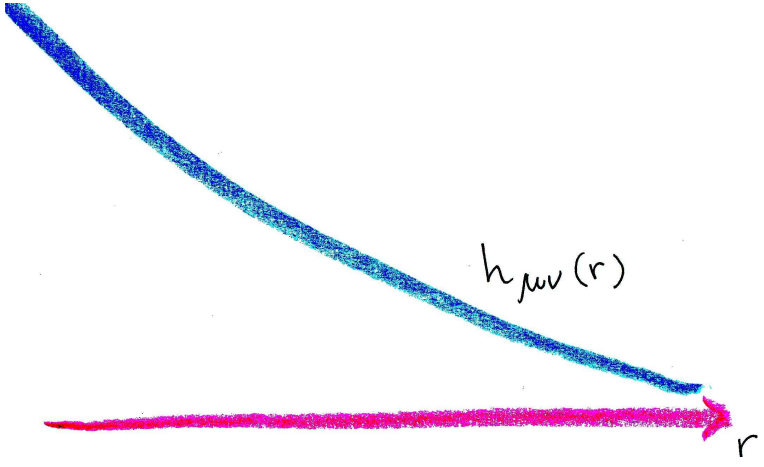
- Normalisable modes inside AdS_{d+1} correspond to physical states in the dual d-dimensional QFT
- Can one have normalisable spin-2 modes *(gravitons)* in AdS_5?
- If yes, in the dual picture gravity emerges from an ordinary (albeit strongly coupled) QFT.

Localized gravitons

Graviton wave-function in AdS_5 is non-normalizable:



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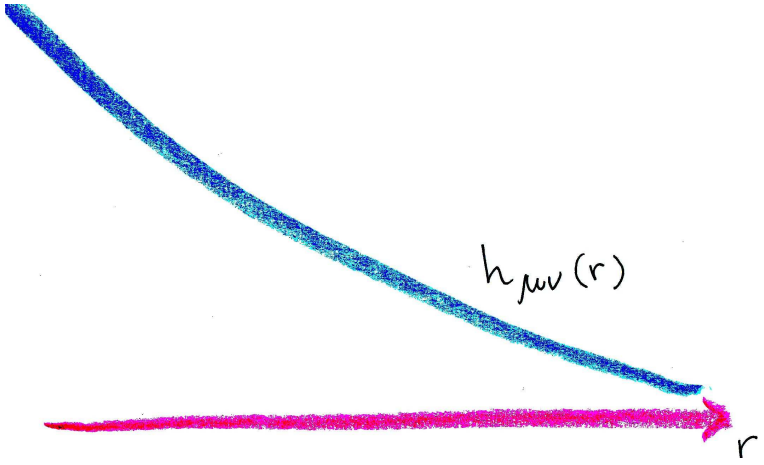
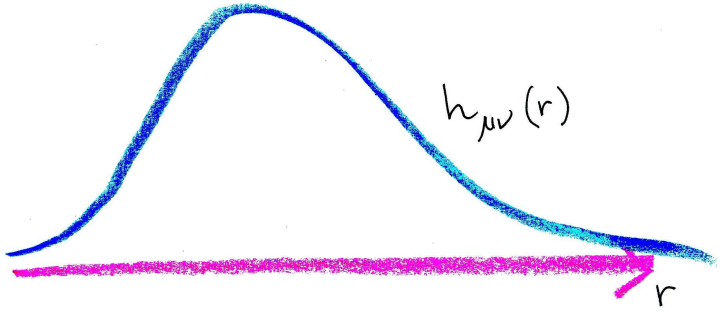


It can be made normalizable by deforming the geometry (aka breaking conformal symmetry).



Possible at the cost of having a badly singular interior (Kiritsis, FN, '05)

Fast FWD to 2017: Holographic self-tuning

- Around 2017: Elias Kiritsis, Christos Charmousis and I revisited the emergent gravity idea, by relaxing it a bit: instead of a localized graviton, allow for a *metastable*, quasi-localized graviton.

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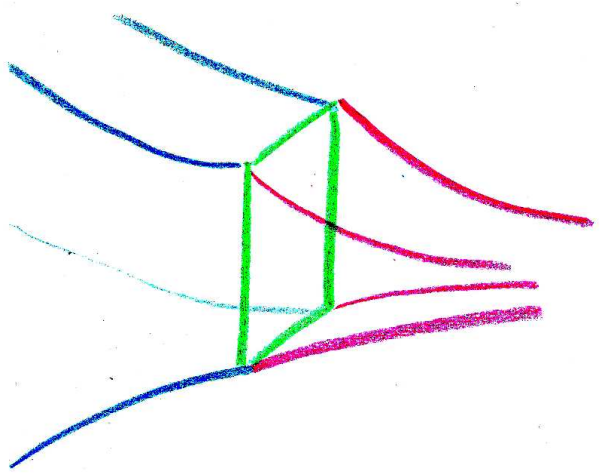
- Construction and motivation were slightly different: we were looking for a mechanism of *self-tuning of the cosmological constant* within holography.
- Cosmological Constant problem: The QFT vacuum energy is expected to be of order $(UV cutoff)^4$. If it couples to gravity, why is the observed curvature of the universe so small (corresponding to a vacuum energy of $(10^{-3}eV)^4$?

Living in a brane-world

- Model can be described in terms of a *branerorld*: The observed particles and fields (except gravity) are localized on a 4d defect (*brane*) embedded in a 5d spacetime (*bulk*)
- Connection to holography: interaction between a strongly coupled (the bulk) and a weakly coupled sector (the brane).



$$S = M^3 \int d^4x \int du \sqrt{-g} \left[R - \frac{1}{2} g^{ab} \partial_a \varphi \partial_b \varphi - V(\varphi) \right]$$

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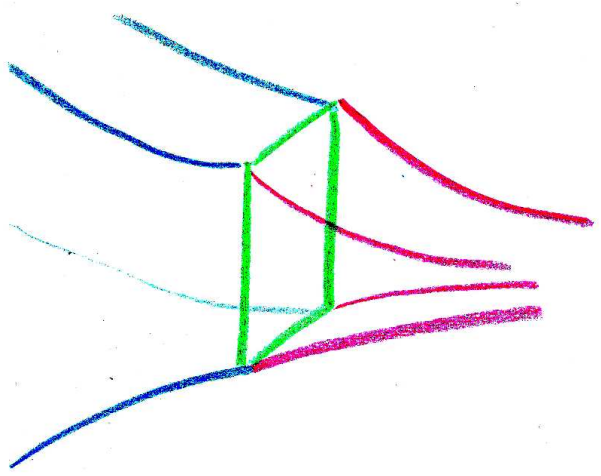

$$S = M^3 \int d^4x \int du \sqrt{-g} \left[R - \frac{1}{2} g^{ab} \partial_a \varphi \partial_b \varphi - V(\varphi) \right]$$
$$+ M^3 \int_{\Sigma_0} d^4\sigma \sqrt{-\gamma} \left[-W_B(\varphi) - \frac{1}{2} Z(\varphi) \gamma^{\mu\nu} \partial_\mu \varphi \partial_\nu \varphi + U(\varphi) R^{(\gamma)} + \dots \right]$$

$W_B(\varphi)$ includes the brane fields vacuum energy

Self-tuning

Charmousis, Kiritsis, Nitti, '17

- This model allows solutions with *flat space* as the 4d geometry, for *generic* potentials W_B of order (UV cut-off)^4.
- $\Rightarrow$ *large 4d vacuum energy does not imply large 4d curvature !*

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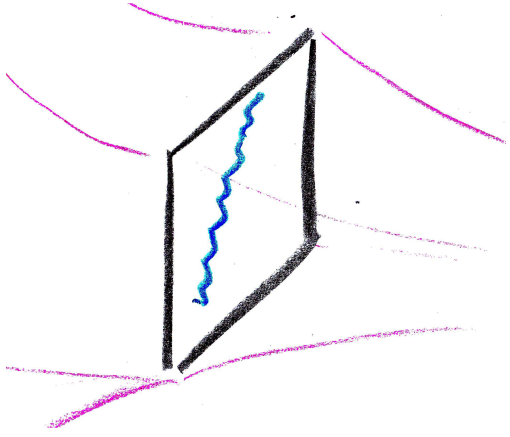
Explored before (2000-2002) but:

- IR geometry not fully understood (IR singularity)
- 4d gravity regime seemed incompatible with self-tuning (partly because models were not general enough)
- Holographic picture clarifies how to organize the space of solutions: what integrations constants are fixed, which are dinamically determied, and what IR geometries are acceptable.

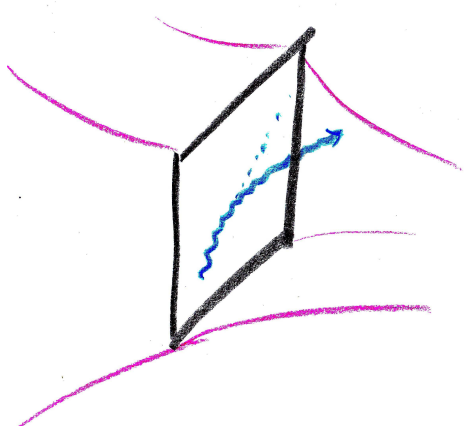
Quasi-localized gravity on the brane

- There is no localized graviton, like in AdS bulk.
- However, graviton propagation is effectively 4d over a certain distance, then it "leaks" into the fifth dimension (thanks to the 4d Einstein term in the brane action: DGP Mechanism

  Dvali-Gabadadze-Porrati, NYU around '00-'01



localized



quasi-localized

- Gravity is emergent: it comes from the bulk sector, which has the dual interpretation of a strongly coupled QFT.

Conclusion

- The 3 years I spent at CPHT was one of the most stimulating and of my career (among other things, it was the time where I was finally getting calculations right on the first take).
- Great atmosphere, real collective environment, tons of exchanges and discussions, lots of guests, seminars, etc

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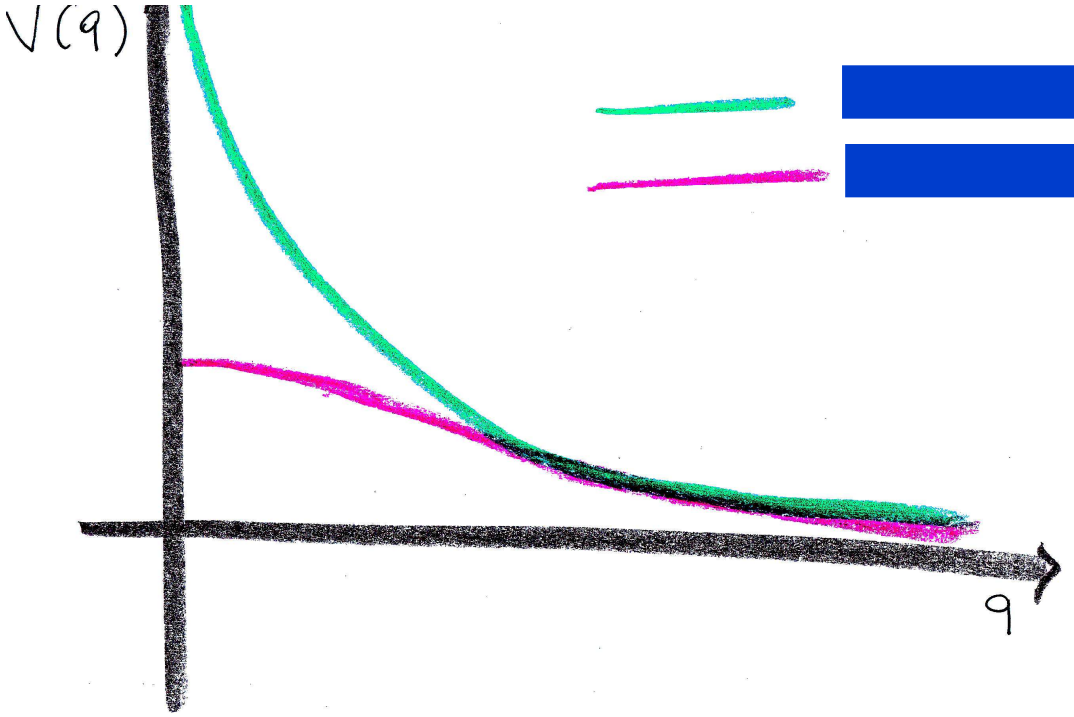
- Grateful for having been a part of this!

Effective graviton potential

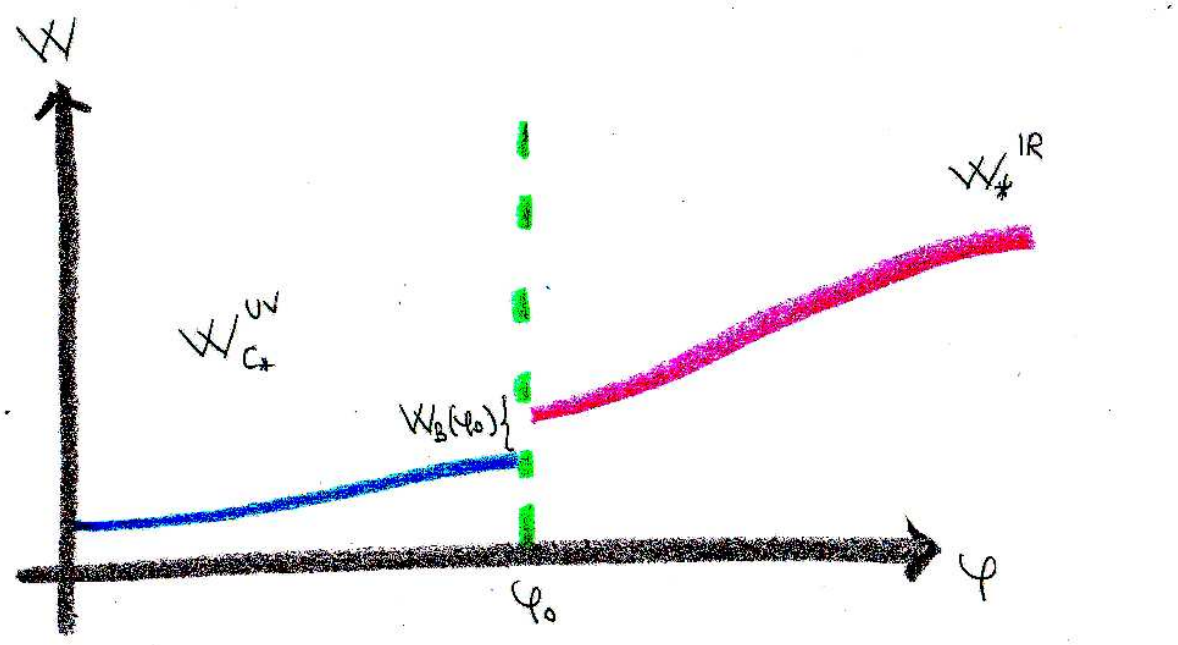
- The gravitatonal potential is 4d-like ($\sim 1/r$) at short distances (large q)
- The effect of the bulk curvature is to mimic a 4d massive graviton at *very* large distances (small q).



$$V(q) = \int d^3x V(|\vec{x}|) e^{-i\vec{q}\cdot\vec{x}}$$

Equilibrium solution

- The model generically allows *one* flat self-tuning vacuum solution with a good interior geometry and a stabilized brane position.



- No competion between flat and curved vacuum solutions (e.g. de Sitter geometries are not allowed in the same sector of the theory).