Title: Shock Therapy

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Abstract:

SHOCK THERAPY

Nemanja Kaloper
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Overview

- Changing gravity: Why Bother?

…

- DGP: headaches in perturbation theory
- Relativistic particles and shock waves
- Hiding the 5th dimension
- Future directions
- Summary

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Modifying Einstein?

- Einstein's GR offers a beautiful theoretical framework for the description of gravity, consistent with numerous experiments and observations:
  - Solar system tests of GR
  - Sub-millimeter (non) deviations from Newton's law
  - Agreement with much of cosmology at large scales
- But: how well do we REALLY know gravity?
  - Hands-on observational knowledge consistent with GR at scales between roughly ***0.1 mm*** and - say - about ***100 MPc;*** we can't be certain - yet - that the extrapolation of GR to *shorter* and *longer* distances is necessary
  - Problems with **Things Dark** (cosmological constant, missing mass): are we pushing GR too far?…
- In consistent top-down approaches – string theory – 4D gravity is certainly modified at short distances; at long distances?

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Dark thoughts

- Can we explain galaxy rotation curves by changing gravity instead of using dark matter? (e.g. covariant MOND?… (Bekenstein, 2004))
- Can we change the nature of the cosmological constant problem by changing gravity?
- Even if this fails - exploring modifications of gravity could teach us just how robust the framework of GR is…

Cosmological constant failure

- The situation with the cosmological constant is desperate (by at least 60 orders of magnitude!) $\rightarrow$ desperate measures required?
- Might changing gravity help? A (very!) heuristic argument:
  - **Legendre transforms:** adding $\int dx\, \Phi(x)\, J(x)$ to S trades an independent variable Φ for another independent variable J.
  - Reconstruction of $\Gamma(\Phi)$ from $W(J)$ yields a **family** of effective actions parameterized by an arbitrary J, where $J=0$ must be put in by hand!
  - Cosmological constant term $\int dx \sqrt{det(g)}\, \Lambda$ is a Legendre transform.
  - In GR, general covariance $\rightarrow$ $det(g)$ does not propagate!
  - So the Legendre transform $\int dx \sqrt{det(g)}\, \Lambda$ loses information about **only ONE** IR parameter - Λ. **Thus Λ is not calculable, but is an input!**
  - Could changing gravity alter this, circumventing no-go theorems?…

Headaches

- Changing gravity means adding new DOFs in the IR
- They could be problematic:
  - Too light and too strongly coupled → new long range forces
  - Negative mass squared or negative residue of the pole in the propagator for the new DOFs: ***tachyons*** and/or ***ghosts***

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DGP Braneworlds

- Use braneworlds as a playground to learn how to change gravity in the IR?
- Brane-induced gravity (Dvali, Gabadadze, Poratti, 2000):
  - Ricci terms BOTH in the bulk and on the end-of-the-world brane, arising from e.g. wave function renormalization of the graviton by brane loops
  - May appear on bosonic string theory D-branes (Corley, Lowe, Ramgoolam, 2001)

DGP Action

- Action:

$$S = \int d^5x\sqrt{g_5}\,\frac{M_5^3}{2}R_5 + \int d^4x\sqrt{g_4}\left(\frac{M_4^2}{2}R_4 - M_5^3 K^A{}_A - \lambda - \mathcal{L}_{\rm SM}\right)$$

- Assume ∞ bulk: 4D gravity has to be mimicked by the exchange of bulk DOFs!
- How do we then hide the $5^{\rm th}$ dimension???
- Gravitational perturbations: assume flat background & perturb; while perhaps dubious this is simple, builds up intuition…

Masses and filters

- **Propagator:**

$$G(p)|_{z=0} = \frac{1}{2M_5^3 p + M_4^2 p^2}\left(\frac{1}{2}\eta^{\mu\alpha}\eta^{\nu\beta} + \frac{1}{2}\eta^{\mu\beta}\eta^{\nu\alpha} - \frac{1}{3}\eta^{\mu\nu}\eta^{\alpha\beta}\right)$$

- **Gravitational filter**:
  - Terms $\sim M_5$ in the denominator of the propagator dominate at LOW p, suppressing the momentum transfer as $1/p$ at distances $r > M_4^2/2M_5^3$, making theory look 5D.
  - Brane-localized terms $\sim M_4$ dominate at HIGH p and render theory 4D, suppressing the momentum transfer as $1/p^2$ at distances shorter than $r_c < M_4^2/2M_5^3$.

vDVZ

- Terms ~ M_5 like a mass term; resonance is composed by bulk modes, which have 5 DOFs and so are massive from the 4D point of view. So the resonance has extra longitudinal gravitons; discontinuity when $M_5 \to 0$ similar to $m_g \to 0$ (van Dam, Veltman; Zakharov; 1970):
- Fourier expansion for the field of a source on the brane:

$$\tilde{h}_{\mu\nu}(p, z=0) = \frac{\tilde{T}_{\mu\nu} - \frac{1}{3}\eta_{\mu\nu}\tilde{T}^{\lambda}{}_{\lambda}}{2M_5^3\, p + M_4^2\, p^2}$$

- Take the limit $M_5 \to 0$ and compare with 4D GR:

$$\tilde{h}_{\mu\nu}(p) = \frac{\tilde{T}_{\mu\nu} - \frac{1}{2}\eta_{\mu\nu}\tilde{T}^{\lambda}{}_{\lambda}}{M_4^2\, p^2}$$

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Strongly coupled scalar gravitons

- However: naïve linear perturbation theory in massive gravity on a flat space breaks down → nonlinearities yield continuous limit (Vainshtein, 1972).
- There exist examples of the absence of vDVZ discontinuity in curved backgrounds (Kogan *et al*; Karch *et al*; 2000).
- The reason: the scalar graviton becomes strongly coupled at a scale much bigger than the gravitational radius. (Arkani-Hamed, Georgi, Schwartz, 2002):

Strong coupling in DGP

- EFT analysis of DGP (Luty, Porrati, Rattazzi, 2003) finds similar behavior. A nice back-of-the envelope argument: linearized expansion around masses in DGP breaks down when $G_N m/r \sim r^2/r_c^2$, where $r_c = M_4^2/2M_5^3$ is the scale where gravity is modified, or at distances $r \sim (G_N m\, r_c^2)^{1/3}$. For small masses with Planck scale horizon size, $r_* \sim (r_c^2/M_{Pl})^{1/3}$. One would expect strong ***QUANTUM*** effects there as well!
- Borne out by perturbative analysis – *on a flat background* – integrating out the bulk dynamics LPR find EFT for the pullback of the metric on the brane. The Goldstone mode analysis finds the scalar graviton is strongly coupled at $r_* \sim (r_c^2/M_{Pl})^{1/3}$. Plugging in $r_c \sim 1/H_0$ shows that $r_c \sim 1000\ km$.
- The theory loses predictivity at macroscopic scales???
- LPR also find that the scalar mode becomes a ghost on the self-inflating branch (to be defined below), in the regime where the gravity modifications dominate cosmology.

Curvature as a coupling controller?

- What if we include the curvature of the source itself? (Nicolis, Rattazzi, 2003)
- By including the effects of the source mass on the local geometry, via the local value of the extrinsic curvature K_{AB}, NR find that the strongly coupled scalar may in fact receive large 'renormalization' from the background fields:

$$\mathcal{L} = Z_{\mu\nu}\,\partial^\mu\phi\,\partial^\nu\phi$$

where

$$Z_{\mu\nu} = -3\eta_{\mu\nu} - 4r_c(K_{\mu\nu} - \eta_{\mu\nu}K)$$

- Near a source, where couplings would be strong: $Z \sim (G_N m r_c^2/r^3)^{1/2}$
- Substituting r_* yields $Z \sim (m/M_{Pl})^{1/2}$ – huge suppression for big masses! This could restore EFT down to much shorter distances than ***1000 km***! NR: EFT could remain valid down to scales $\sim$ ***1 cm***…
- But why only these counterterms?

Beyond naïve perturbation theory

- Construct first the realistic backgrounds; solve

$$M_5^3 G_5^A{}_B + M_4^2 G_4^\mu{}_\nu \delta_\mu^A \delta_B^\nu \delta(w) = -T^\mu{}_\nu \delta_\mu^A \delta_B^\nu \delta(w)$$

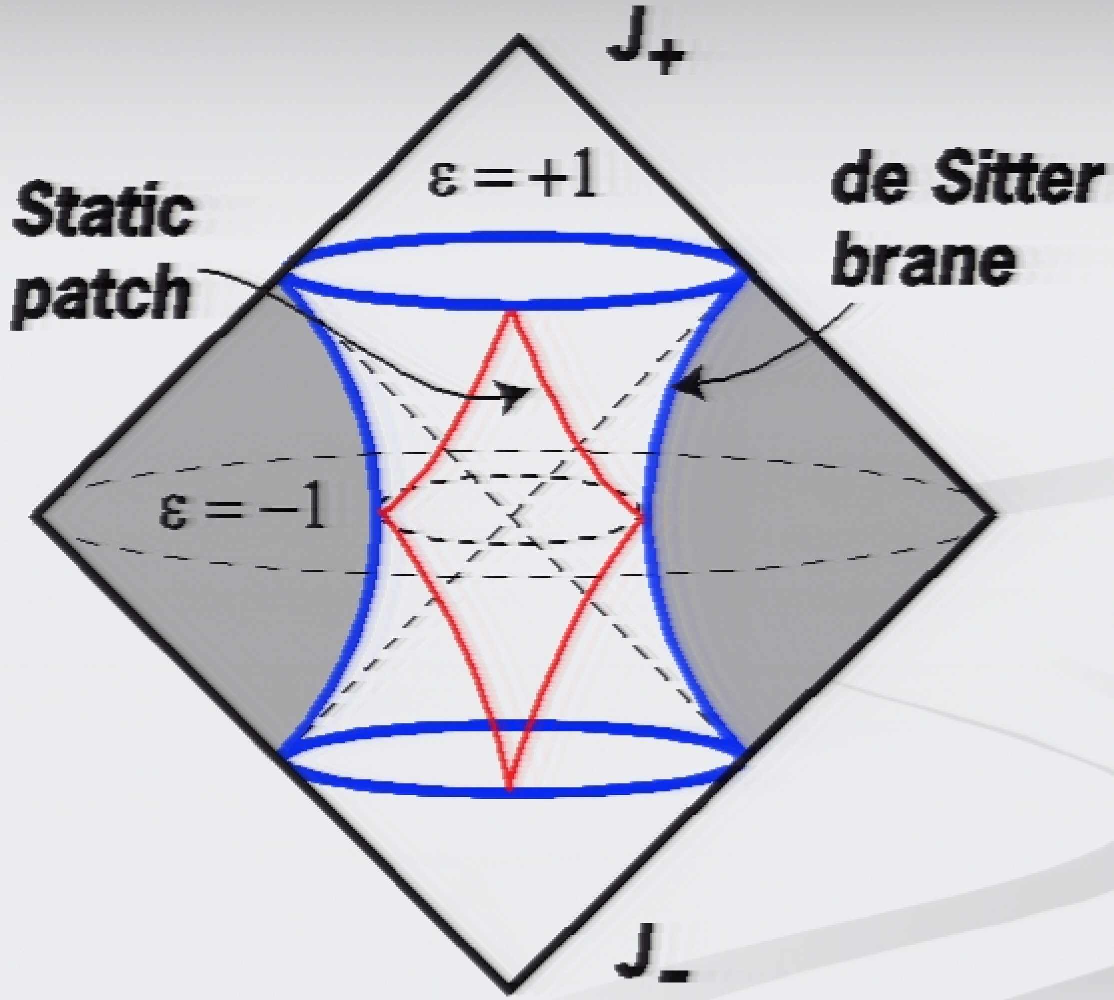
- Look at the vacua first: $T^\mu{}_\nu = -\lambda \delta^\mu{}_\nu$
- Symmetries require (see e.g. N.K, A. Linde, 1998):

$$ds_5^2 = (1 - \epsilon H|w|)^2 ds_{4dS}^2 + dw^2$$

where 4d metric is de Sitter; in static patch:

$$ds_{4dS}^2 = -(1 - H^2 r^2) dt^2 + \frac{dr^2}{(1 - H^2 r^2)} + r^2 d\Omega_2$$

Penrose diagram for a tensional brane in 5D locally Minkowski bulk



Normal and self-inflating branches

- The intrinsic curvature and the tension related by (N.K.; Deffayet,2000)

$$H^2 + \epsilon \frac{2M_5^3}{M_4^2} H = \frac{\lambda}{3M_4^2}$$

- $\varepsilon = \pm 1$ an integration constant; $\varepsilon = 1$ normal branch,

$$M_5 \gg M_4 \quad \rightarrow \quad \frac{2M_5^3}{M_4^2} H \simeq \lambda / M_4^2$$

i.e. this reduces to the usual inflating brane in 5D!

- $\varepsilon = -1$ self-inflating branch:

$$\lambda \ll 12 M_5^6 / M_4^2 \quad \rightarrow \quad H \sim 2M_5^3 / M_4^2$$

inflates even if tension vanishes!

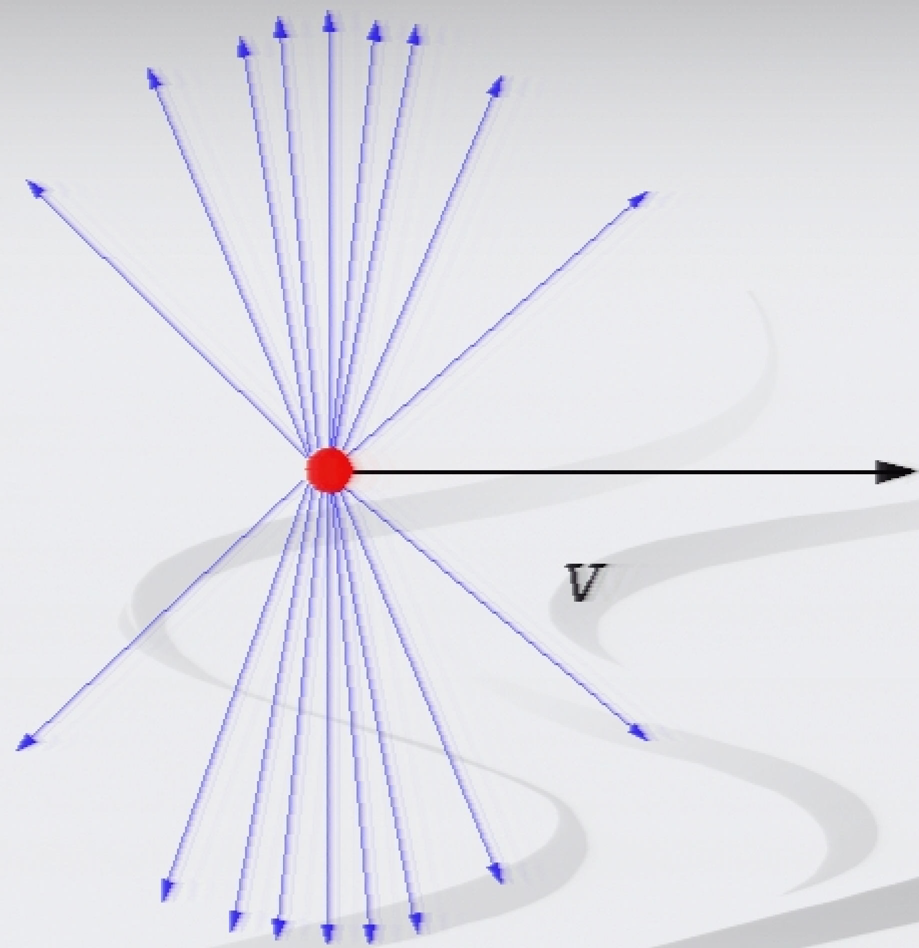
Fields of small energy lumps

- DGP equations are notoriously difficult to solve for compact matter sources
- However: using analyticity it is *always* possible to find a solution for compact ultra-relativistic sources!
- Consider a geometry of a mass point, which is a solution of some gravitational field equations, which obey
  - Analyticity in m
  - Principle of relativity (i.e. general covariance)
- Then pick an observer who moves VERY FAST relative to the mass source. In his frame the source is boosted relative to the observer. Take the limit of infinite boost.

Only the first term in the expansion of the metric in m survives, since $p = m \cosh\beta = const$. All other terms are $\sim m^n \cosh\beta$, for $n > 1$, and so in the extreme relativistic limit they vanish!

Shock waves

- Physically: because of Lorentz contraction in the direction of motion, the field lines are getting pushed towards the instantaneous plane orthogonal to ***V***.
- The field lines of a massless charge are confined to the instantaneous plane orthogonal to ***V***.
- The same intuition works for the gravitational fields.



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Aichelburg-Sexl shockwave

- In flat 4D environment, the exact gravitational field of a photon found by boosting linearized Schwarzschild metric (Aichelburg, Sexl, 1971).

$$ds_4^2 = dudv - \delta(u) f du^2 + dy^2 + dz^2$$

- If f is a constant, it can be removed by a diffeomorphism – space flat! Here $u,v = (x \pm t)/\sqrt{2}$ are null coordinates of the photon.
- For a particle with a momentum p, f is

$$f_{4D}(\Omega) = \frac{p}{\pi M_4^2} \ln(\frac{\mathcal{R}}{\ell_0})$$

where $\mathcal{R} = (y^2 + z^2)^{1/2}$ is the distance from the particle in the direction orthogonal to the motion, and ℓ_0 an arbitrary integration parameter.

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Dray-'t Hooft trick

- Encode the shockwave behavior by introducing a discontinuity in the null direction of motion v using orthogonal coordinate u, controlled by the photon momentum. Field equations linearize, yield a single field eq. for the wave profile → in fact this is the Israel junction condition on a null surface. The technique has been generalized by K. Sfetsos to general 4D GR (string) bakcgrounds. Extends to DGP, and other brany setups! (NK, 2005)
- Idea: pick a spacetime and a set of null geodesics.
- Trick: substitute

$$v \to v + \Theta(u) f\,,$$

$$dv \to dv + \Theta(u) df$$

discontinuity

change to

$$\hat{v} = v + \Theta(u) f$$

$$dv \to d\hat{v} - \delta(u) f du$$

$$v, dv \to \hat{v}, d\hat{v} - \delta(u) f du$$

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DGP in a state of shock

- The starting point for shocking DGP is (NK, 2005)

$$ds_5^2 = e^{-2\epsilon H|z|}\{\frac{4dudv}{(1+H^2uv)^2} - \frac{4\delta(u)fdu^2}{(1+H^2uv)^2} + \\ + (\frac{1-H^2uv}{1+H^2uv})^2\frac{d\Omega_2}{H^2} + dz^2\}$$

- Term ~ f is the discontinuity in dv. Substitute this metric in the DGP field equations, where the new brane stress energy tensor includes photon momentum

$$T^\mu{}_\nu = -\lambda\delta^\mu{}_\nu + 2\frac{p}{\sqrt{g_5}}g_{4\,uv}\delta(\theta)\delta(\phi)\delta(u)\delta^\mu_v\delta^u_\nu$$

- Turn the crank!

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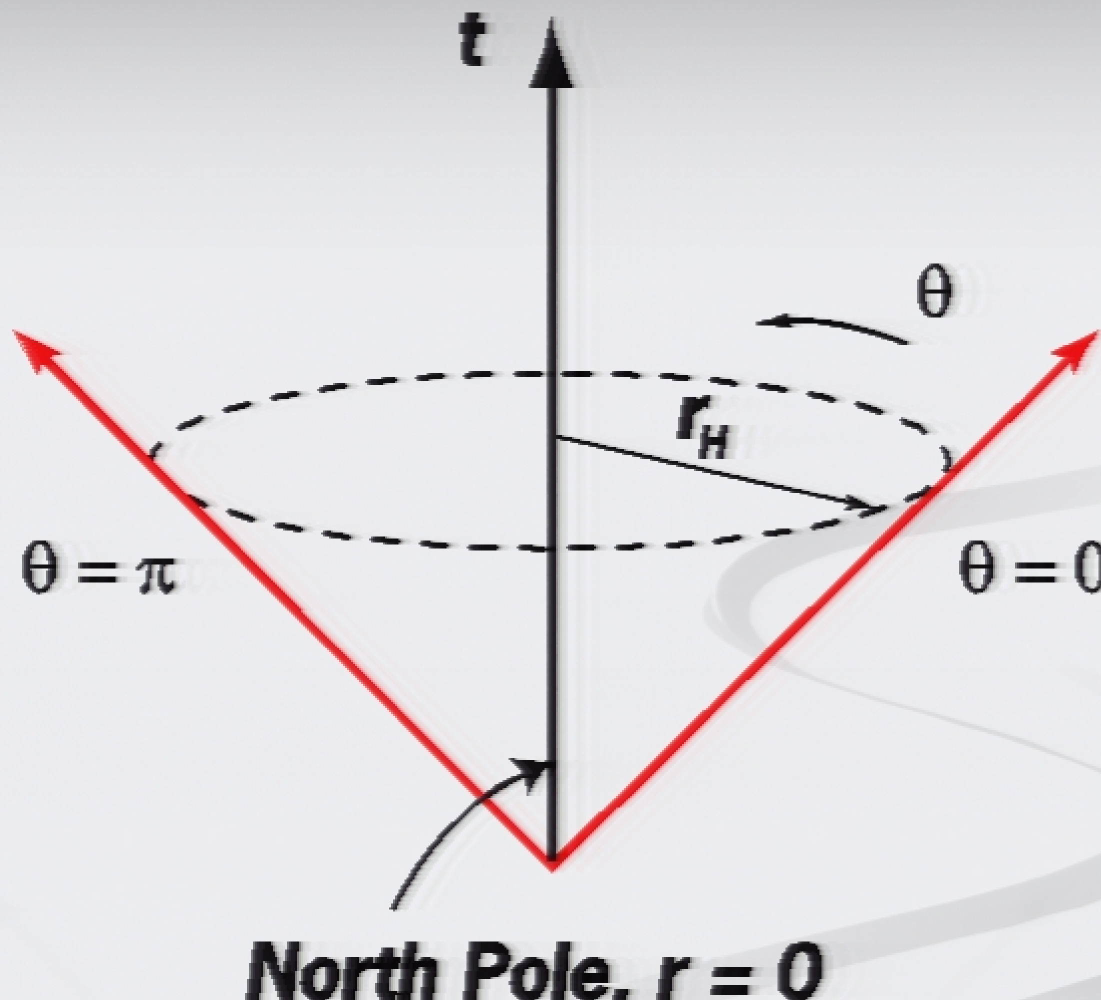
Shockwave field equation

- In fact it is convenient to work with two 'antipodal' photons, that graze along the past horizon in opposite directions. This avoids problems with spurious singularities on compact spaces. It is also the correct infinite boost limit of Schwarzschild-dS solution in 4D (Hotta, Tanaka, 1993) . The field equation is (NK, 2005)

$$\frac{M_5^3}{M_4^2 H^2}(\partial_z^2 f - 3\epsilon H \partial_{|z|} f + H^2(\Delta_2 f + 2f)) +$$

$$+(\Delta_2 f + 2f)\delta(z) = \frac{2p}{M_4^2}(\delta(\Omega) + \delta(\Omega'))\delta(z)$$

"Antipodal" photons in the static patch on the de Sitter brane



Shockwave solutions I

- Using the symmmetries of the problem, this equation can be solved by the expansion (NK, 2005)

$$f = 2\sum_{l=0}^{\infty} f_{2l}(z) P_{2l}(\cos\theta)$$

- The solution is (using ***τ=exp(-H|z|), x = cos θ, g=2M$_5^3$/M$_4^2$H=1/r$_c$H***)

$$f(\Omega, z) = -\frac{[3-(1+\epsilon)\mathrm{g}]\,p}{(3-\epsilon\mathrm{g})\,\pi M_4^2}\sum_{l=0}^{\infty}\frac{\tau^{2l+(1-3\epsilon)/2}}{2l-1+\frac{(1+\epsilon)\mathrm{g}}{2}}P_{2l}(x)$$

$$-\frac{[3+(1-\epsilon)\mathrm{g}]\,p}{2(3-\epsilon\mathrm{g})\pi M_4^2}\sum_{l=0}^{\infty}\frac{\tau^{2l+(1-3\epsilon)/2}}{l+1+\frac{(1-\epsilon)\mathrm{g}}{4}}P_{2l}(x)$$

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Shockwave solutions II

- The series can be rewritten as an integral, analogous to the Poisson integral (NK, 2005),

$$f(\Omega, z) = \frac{p}{2\pi M_4^2} \frac{\tau^{\frac{1-3\epsilon}{2}}}{1 - \frac{1+3\epsilon}{4}\mathrm{g}} - \frac{p}{2(3-\epsilon\mathrm{g})\pi M_4^2} \times$$

$$\times \int_0^\tau d\vartheta \left(\frac{1}{\sqrt{1 - 2x\vartheta + \vartheta^2}} + \frac{1}{\sqrt{1 + 2x\vartheta + \vartheta^2}} - 2 \right)$$

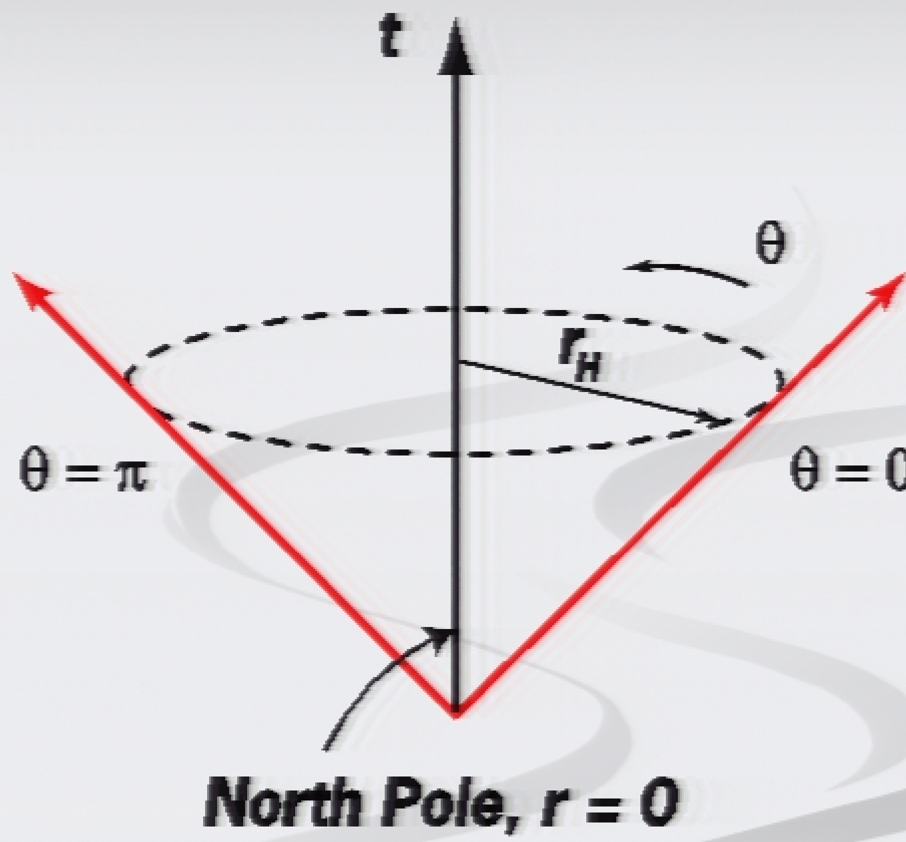
$$\times \left(\frac{[3 - (1+\epsilon)\mathrm{g}]\vartheta^{\frac{\mathrm{g}(1+\epsilon)-4}{2}}}{\tau^{\frac{(\mathrm{g}+3)(1+\epsilon)-6}{2}}} + \frac{[3 + (1-\epsilon)\mathrm{g}]\vartheta^{\frac{\mathrm{g}(1-\epsilon)+2}{2}}}{\tau^{\frac{(\mathrm{g}-3)(1-\epsilon)+6}{2}}} \right)$$

- OK, but where is the physics???

Arc lengths

- The horizon is at $r_H = 1/H$. So the distance between the photon at $\theta=0$ and an event at a small θ is

$$\mathcal{R} = \theta/H$$



Short distance properties I

- Consider first the limit g *= 0;* on the brane at *z=0,* the integral yields

$$f_{4D}(\Omega) = \frac{p}{2\pi M_4^2}(2 - x \ln[\frac{1+x}{1-x}])$$

- Identical to the 4D GR shockwave in de Sitter background, found by Hotta & Tanaka in 1993. Using arc length $\mathcal{R} = \theta/H$, the 4D profile in dS reduces to the flat Aichelburg-Sexl at short distances ($x=1-H^2\mathcal{R}^2/2$):

$$f_{4D}(\Omega) = \frac{p}{\pi M_4^2} + \frac{p}{\pi M_4^2}\ln(\frac{\mathcal{R}}{2H^{-1}})$$

- What about the short distance properties when g $\neq 0$? …

Short distance properties II

- In general: the solution is a Green's function for the two source problem and can only contain the physical short distance singularities. For ANY finite value of **g** those yield

$$f(\Omega) = \frac{p}{\pi M_4^2}((1 + a_1 H^2\mathcal{R}^2 + \ldots)\ln(\frac{\mathcal{R}}{2H^{-1}}) + \text{const} + b_1 H\mathcal{R} + b_2 H^2\mathcal{R}^2 + \ldots)$$

- The only singular term is logarithmic – just like in the 4D GR wave profile. Thus at short distances the shockwave looks precisely the same as in 4D! The corrections appear only as the terms linear in $\mathcal{R}$, and are suppressed by ***1/H* g = *1/r$_c$***. (NK, 2005)

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Recovering 5th D

- We can take the limit $\mathbf{g} \to \infty$ ($r_c \to 0$) on the normal branch while keeping positive tension; we find 5D + 4D contributions:

$$f_{5D}(\Omega) = \frac{p}{2\pi M_5^3 \mathcal{R}} + \frac{3pH}{4\pi M_5^3} \ln\left(\frac{\mathcal{R}}{2H^{-1}}\right)$$

(NK, 2005)

- So only in the limit $r_c \to 0$ will we find no filter; whenever r_c is finite, the filter will work preventing singularities worse than logarithms in the Green's function, and thus screening X-dims!

Gravitational filter beyond perturbation theory

- How does the filter work? The key is that in the Green's function expanded as a sum over 5D modes, the coefficients are suppressed by ℓ of $P_{2\ell}(x)$; their momentum is $q = \ell/H$; hence the effective coupling for momenta $q > 1/r_c$ is

$$G_{N\,eff}(q) \sim \frac{1}{M_4^2}\frac{H}{q}$$

- Rewrite this as (NK, 2005)

$$G_{N\,eff}(q) \sim \frac{1}{2M_5^3}\frac{1}{g r_c}\frac{1}{r_c q}$$

4D Graviton resonance

- In the 4D language, the structure of the singularity of the Green's function shows that the sum of the bulk modes behaves exactly as a 4D resonance.
- At short distance it's effective coupling to the brane matter is

$$G_N \sim \sum_{q \geq 1/b} G_{N\,eff}(q) \sim \frac{1}{M_4^2} \int_{1/b}^{\Lambda} \frac{dq}{q} \sim \frac{1}{M_4^2}$$

i.e. it mimics 4D gravity!

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Where is the scalar graviton?

- A very peculiar feature of the shockwave solution is that the scalar graviton has NOT been turned on: if f is viewed as a perturbation, $h_{\mu\nu} \sim f$, then $h^{\mu}{}_{\mu} = 0$.
- At first, that seems trivial; $\varphi = h^{\mu}{}_{\mu}$ is sourced by $T^{\mu}{}_{\mu}$, which vanishes in the ultrarelativistic limit. So it is OK to have $\varphi = 0$…

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- … as long as we are in a weak coupling limit where we can trust the perturbative effective action! However…
- … this survives for DGP sources with a lot of momentum in spite of the issues with strong coupling! This suggests that the nonlinearities may improve the theory.

Future directions

- **A new perturbative expansion?**
  - Test EFT; reconsider a mass at rest.
  - But let a fast moving observer probe it.
  - Let her move a little bit more slowly than c.
  - In her rest frame the source is fast. So it can be approximated by a shockwave; corrections controlled by $m/p = (1/v^2-1)^{1/2}$.
  - She can use m/p as a small expansion parameter and compute the field, then boost the result back to an observer at rest relative to the mass.
  - ***Analyticity suggests that perturbation theory may be under control; check it!***

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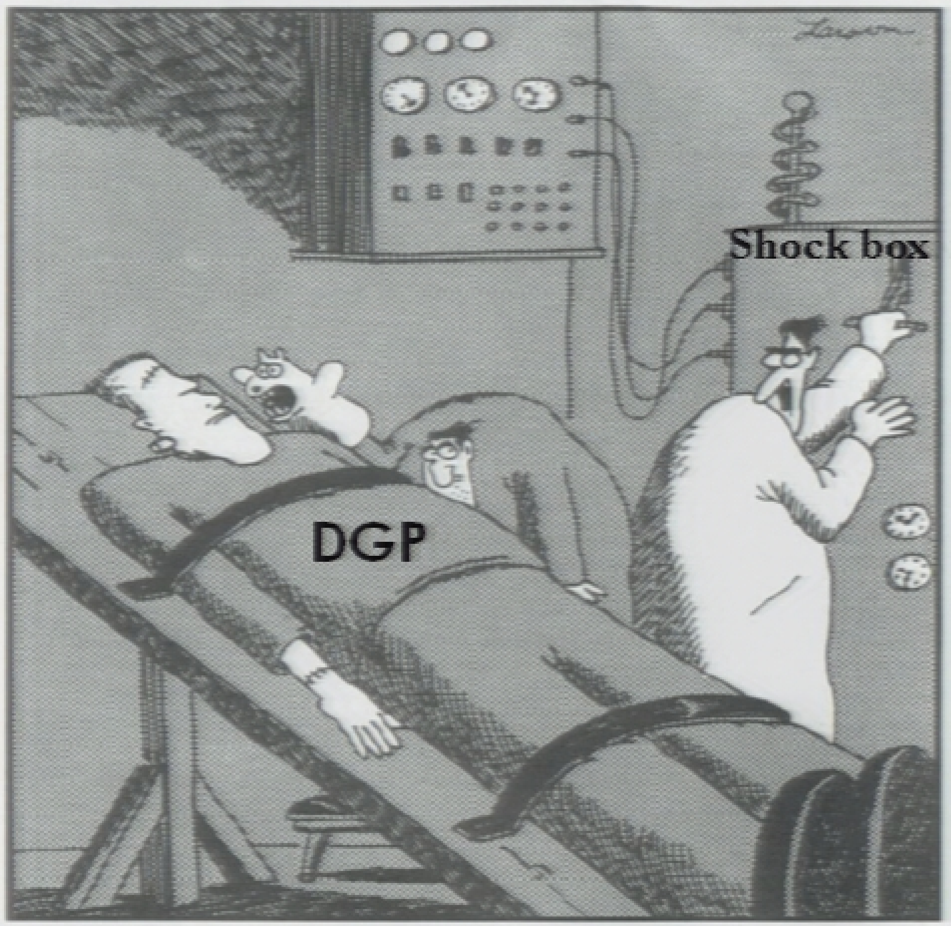
Summary

- The cornerstone of the DGP setup is the **gravitational filter** which hides the extra dimension.
- This entails extra DOFs in perturbation theory, including a strongly coupled scalar graviton which is **dangerous**!
- Shockwaves are the first example of exact DGP backgrounds for compact sources and a new arena to study perturbation theory.
- Shock therapy may thus yield new insights into the filter *(but it won't rid us of ghosts on the self-inflating branch…)*
- More work: we may reveal interesting new realms of gravity!

It remains to see if this is a playground for Victor or for Igor…



"Igor! Get that Wolfman doll out of his face! … Boy, sometimes you really are bizarre."

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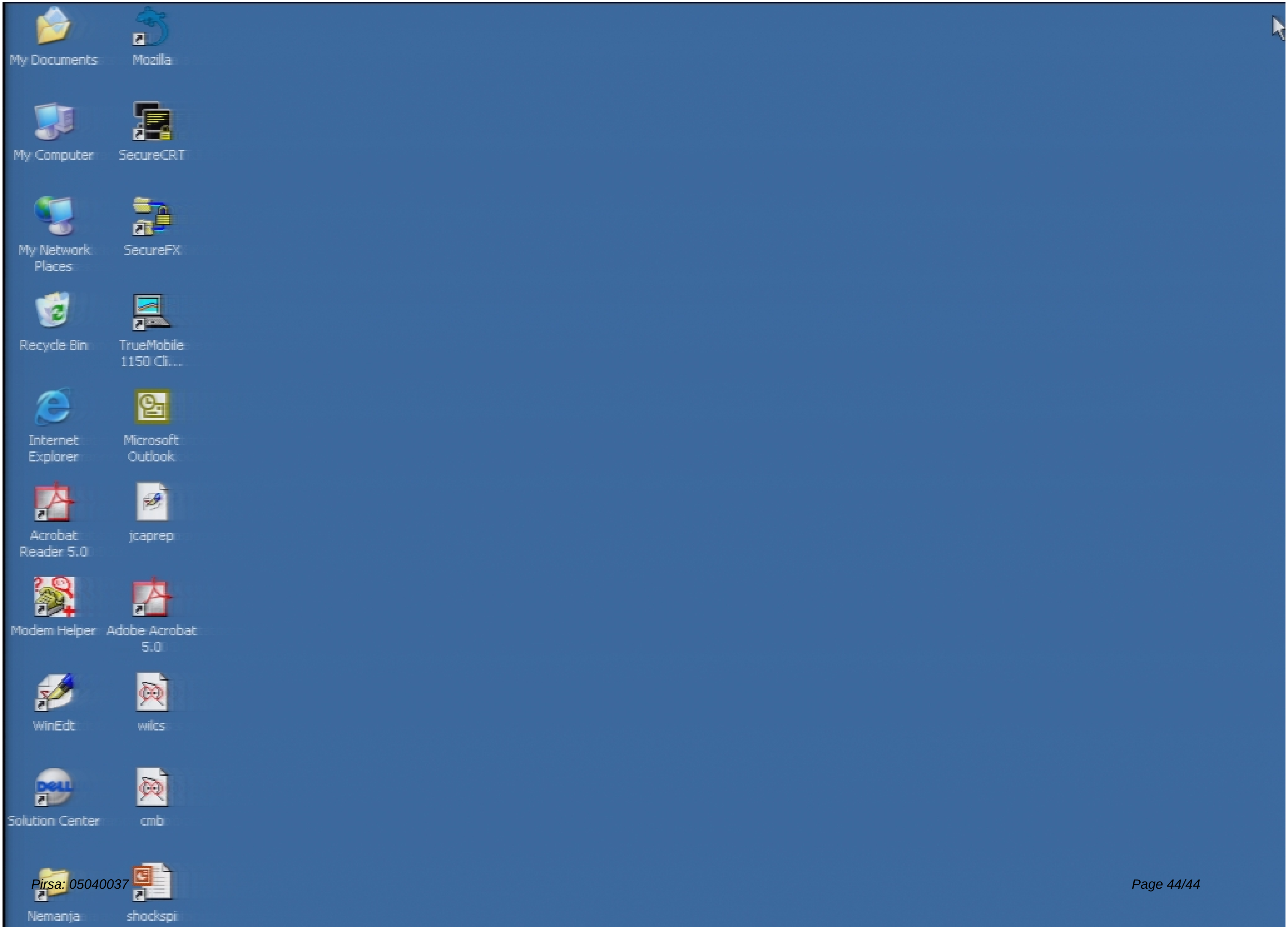
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Mozilla
My Computer
SecureCRT
My Network Places
SecureFX
Recycle Bin
TrueMobile 1150 Cli...
Internet Explorer
Microsoft Outlook
Acrobat Reader 5.0
jcaprep
Modem Helper
Adobe Acrobat 5.0
WinEdt
wilcs
Solution Center
cmb
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