Short distance Modifications of Gravity

A curious coincidence: $p_{DE} \sim (\text{meV})^4$, gravity tests down to $\frac{1}{\text{meV}}$

Modify gravity above meV?

OK, but gravitons probing DE are ultrasoft, $\lambda \geq \frac{1}{H_0}$.

How can gravitons this soft get affected by new physics at meV?
$\text{SED (Burgess)}$

Extra dimensions (ED)

Imagine n extra dimensions

Consider 'effective' brane source combining bulk sing & brane tension

\[
T_b^{\text{eff}} = T_b - \frac{1}{16\pi G_{n+4}} \int d^n x \sqrt{g_n} \Delta R^\text{bulk}
\]

From Einstein Eqs \[\Delta G_{ab} = 8\pi G_{n+4} \left( -T_b \frac{\delta^n}{\sqrt{g_n}} g_{4\mu\nu} \delta^a \delta^b \right)\]

\[\Rightarrow \Delta R^\text{bulk} = 8\pi G_{n+4} \frac{8}{n+2} T_b \frac{\delta^n}{\sqrt{g_n}}\]

\[\Rightarrow T_b^{\text{eff}} = T_b \left( 1 - \frac{4}{n+2} \right) = T_b \left( \frac{n-2}{n+2} \right) \rightarrow 0 \text{ for } n=2\]

\(n=2\) is good!

(i) permits flat branes tension $\rightarrow$ defect $\times$

(ii) allows for large ED (see later)

\[G_{n+4} = G_4 l^n \text{ so large } l \rightarrow \text{large } G_{n+4}\]
Supersymmetric (S)

Flat brane soln guaranteed if

(i) brane stress energy vanishes in 8+4 brane directions
(ii) brane dilaton couplings absent

These criteria are generically broken by loops but if bulk SUSY low enough
effects are ‘small’

Large (L)

Explicit calc \( \rightarrow V_{eff}^{4D} \sim m_{kk}^4 \sim \frac{1}{q^4} \)

Bulk scale invariance also plays a role helping to suppress bulk \( \Lambda @ \) tree level.

... some suggestion that proposed solution may not be compatible with

Gauss' Law for dilaton
Fat Graviton (Sundrum)

Graviton width \( \sim \frac{1}{\text{meV}} \)

Soft SM - graviton couplings are pointlike, as in ER

Hard SM - graviton couplings are not pointlike, but global & suppressed

\[
\begin{align*}
\text{Soft} & \quad \implies \quad \text{Hard} \\
\text{(diagram)} & \quad \implies \quad \text{(diagram)}
\end{align*}
\]

No contribution to Vac. Energy
from heavy SM fields

Sundrum constructs EFT describing coupling of heavy SM fields to soft gravitons using HQET methods

Largest contribution to CC are vibrational modes of fat graviton \( \sim (\text{grav. width})^4 \)

But... hard to realize desired UV properties from a local th.

Why does this \( \text{loop, but } \) does not? By fiat
Large distance (Global?) Modifications of Gravity

DE probed by ultralight gravitons, wavelengths \( L \sim \frac{1}{H_0} \).

Idea: get gravity to "switch off" on large scales \( \gtrsim L \).
Fab Four

- Take general scalar-tensor th. given by Horndeski $S_H[g, \phi]$
- Couple matter to $g, \phi$ only
- Require that th. admits Minkowski soln. for ANY VACUUM ENERGY, even allowing for PTs

Then $S_H[g, \phi] \rightarrow S_{Fab4}[g, \phi]$

$$= \int d^4x \sqrt{g} \left[ V_g(\phi) G_{\mu\nu} \nabla^\mu \phi \nabla^\nu \phi + V_p(\phi) P_{\mu\nu\rho\sigma} \nabla^\mu \phi \nabla^\nu \phi \nabla^\rho \phi \nabla^\sigma \phi + V_g(\phi) R + V_r(\phi) R_{\mu\nu} \nabla^\mu \phi \nabla^\nu \phi \right]$$

Scalar EoM forces curvature $\rightarrow 0$

Evade Weinberg by breaking Poincaré $\phi \neq \text{const.}$

But... light scalar: can we maintain success of GR in SS? (Vainh, chans)
Radiative stability of Fab4 structure?
Does this ‘truncation’ make sense as an EFT?
Large distance MG & Causality

Take a gravity th. that shuts down at scales \( \geq L \)

Assume: locality & causality

Just after BB \( T_{\mu\nu} \) contains a long wavelength source to be ‘eaten’ by our MG

\[
T_{\mu\nu} = T_{\mu\nu}^{\text{long}} + T_{\mu\nu}^{\text{short}}
\]

\[
\downarrow
\]

looks constant

on scales \( \leq L \)

Need to wait until \( t \geq L \) to establish what lives in \( T_{\mu\nu}^{\text{long}} \) & what doesn’t

\[\rightarrow\] Theory cannot ‘decide’ which sources to degravitate until \( t \geq L \) !!
Ether (1) cannot cancel large $\Lambda$ until $t \geq L$ [violates obs – no weirdness after nucleosyn]

(2) th. isn’t choosy – cancels $\Lambda$ & plenty more beside

[danger! short dist gravity screwed?]

(3) Drop causality!!??!
Can we go with (3)?

Yes... give up causality GLOBALLY! (future b.c)

GLOBAL Modification of fraudly

λ is the GLOBAL contribution to $\tau_N$
Old Sequester
with Nemanja Kaloper

1309.6562
1406.0711
1409.7073

see also
1502.05296

with Kaloper, Stefanyszyn, Zahariade
1505.01492
\[ S = \int d^4 x \sqrt{-g} \left[ \frac{M_{pl}^2}{2} R - \Lambda - \mathcal{L}(g^{\mu\nu}, \Psi) \right] \]
Introduce global dynamical variables $\Lambda$

\[
S = \int d^4 x \sqrt{-g} \left[ \frac{M_{pl}^2}{2} R - \Lambda - \mathcal{L}(g^{\mu\nu}, \Psi) \right]
\]
Introduce global dynamical variables $\Lambda, \lambda$

\[ S = \int d^4 x \sqrt{-g} \left[ \frac{M^2_{pl}}{2} R - \Lambda - \lambda^4 \mathcal{L}(\lambda^{-2} g^\mu{}^\nu, \Psi) \right] \]

$\lambda$ sets the hierarchy between matter scales and $M_{pl}$

\[ \frac{m_{phys}}{M_{pl}} = \frac{\lambda m}{M_{pl}} \]
Introduce global dynamical variables $\Lambda$, $\lambda$

$$S = \int d^4x \sqrt{-g} \left[ \frac{M_{\text{pl}}^2}{2} R - \Lambda - \lambda^4 \mathcal{L}(\lambda^{-2} g^{\mu\nu}, \Psi) \right] + \sigma \left( \frac{\Lambda}{\lambda^4 \mu^4} \right)$$

$\lambda$ sets the hierarchy between matter scales and $M_{\text{pl}}$

$$\frac{m_{\text{phys}}}{M_{\text{pl}}} = \frac{\lambda m}{M_{\text{pl}}}$$
Equations of motion

\( \Lambda \) equation : \[ \frac{\sigma'}{\lambda^4 \mu^4} = \int d^4 x \sqrt{g} \]

\( \lambda \) equation : \[ 4\Lambda \frac{\sigma'}{\lambda^4 \mu^4} = \int d^4 x \sqrt{g} \lambda^4 \tilde{T}^\mu_{\mu} \]

\( g_{\mu\nu} \) equation : \[ M^2_{\text{pl}} G^\mu_{\nu} = -\Lambda \delta^\mu_{\nu} + \lambda^4 \tilde{T}^\mu_{\nu} \]

\[ \tilde{T}_{\mu\nu} = \frac{2}{\sqrt{-g}} \frac{\delta}{\delta \tilde{g}^{\mu\nu}} \int d^4 x \sqrt{-\tilde{g}} \mathcal{L}(\tilde{g}^{\mu\nu}, \Psi) \]
Equations of motion

\[ \Lambda \text{ equation} \quad \frac{\sigma'}{\lambda^4 \mu^4} = \int d^4 x \sqrt{g} \]

\[ \lambda \text{ equation} \quad 4\Lambda \frac{\sigma'}{\lambda^4 \mu^4} = \int d^4 x \sqrt{g} \lambda^4 \tilde{T}^\mu_\mu \]

\[ g_{\mu\nu} \text{ equation} \quad M_{\text{pl}}^2 G^\mu_\nu = -\Lambda \delta^\mu_\nu + \lambda^4 \tilde{T}^\mu_\nu \]

\[ \tilde{T}_{\mu\nu} = \frac{2}{\sqrt{-g} \delta g_{\mu\nu}} \int d^4 x \sqrt{-\tilde{g}} L(\tilde{g}^{\mu\nu}, \tilde{\Psi}) \]
Equations of motion

\[ \Lambda \text{ equation } : \quad \Lambda = \frac{1}{4} \langle T^\alpha_{\alpha} \rangle, \quad \langle Q \rangle = \frac{\int d^4 x Q \sqrt{g}}{\int d^4 x \sqrt{g}} \]

\[ \lambda \text{ equation } : \]

\[ g_{\mu\nu} \text{ equation } : \quad M^2_{pl} G^\mu_{\nu} = -\Lambda \delta^\mu_{\nu} + T^\mu_{\nu} \]
Equations of motion

\[ M_{\text{pl}}^2 G_{\mu \nu} = T_{\mu \nu} - \frac{1}{4} \delta_{\mu \nu} \langle T^{\alpha \alpha} \rangle \]
Equations of motion

\[ M_{pl}^2 G^\mu_\nu = T^\mu_\nu - \frac{1}{4} \delta^\mu_\nu \langle T^\alpha_\alpha \rangle \]

\[ T^\mu_\nu = -V_{vac} \delta^\mu_\nu + \tau^\mu_\nu \]
Equations of motion

\[ M^2_{pl} G_{\mu \nu} = \tau_{\mu \nu} - \frac{1}{4} \delta_{\mu \nu} \langle \tau^\alpha \alpha \rangle \]

\[ T^\mu_{\nu} = -V_{vac} \delta^\mu_{\nu} + \tau^\mu_{\nu} \]
\[ M_{pl}^4 G_{\mu}^\nu = -\frac{1}{4} \langle \tau_\alpha^\alpha \rangle \delta_{\nu}^\mu + \tau_{\nu}^\mu \]

Vacuum energy drops out at each and every loop order

No hidden equations — this is everything!

Residual cosmological constant  \[ \Lambda_{e.f.f} = \frac{1}{4} \langle \tau_\alpha^\alpha \rangle \]
\[ M_{pl}^4 G_{\mu \nu} = -\frac{1}{4} \langle \tau_\alpha^\alpha \rangle \delta_{\mu \nu} + \tau_{\mu \nu} \]

Vacuum energy drops out at each and every loop order

No hidden equations — this is everything!

Residual cosmological constant \[ \Lambda_{eff} = \frac{1}{4} \langle \tau_\alpha^\alpha \rangle \]

\( \Lambda_{eff} \) has nothing to do with vacuum energy

It is radiatively stable

OK to fix it empirically
How big is $\Lambda_{\text{eff}}$?

For standard matter, space-time integrals dominated by time when universe is largest

$$\int d^4 x \sqrt{-g} \sim \frac{1}{H_{\text{age}}^4}$$

where lifetime $t_{\text{age}} \sim \frac{1}{H_{\text{age}}} \geq 13.7$ Gyrs

$$\langle \tau_\alpha^\alpha \rangle \sim \rho_{\text{age}} \sim \text{energy density at largest size} < \rho_c$$

$\Rightarrow \Lambda_{\text{eff}}$ is not dark energy … too small!
Observational consequences?
Universe has finite spacetime volume
Universe has finite spacetime volume

\[
\frac{\sigma'}{\lambda^4 \mu^4} = \int d^4 \sqrt{g}
\]

space-time volume must be finite or else \( \lambda \to 0 \)

\[
\frac{m_{phys}}{M_{pl}} = \frac{\lambda m}{M_{pl}}
\]

if \( \lambda \to 0 \) particle masses go to zero
Universe has finite spacetime volume

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if \( \lambda \to 0 \) particle masses go to zero

Ends in a crunch

\( w=-1 \) is transient

\( \Omega_k > 0 \)
Universe has finite spacetime volume

\[ \frac{\sigma'}{\lambda^4 \mu^4} = \int d^4 \sqrt{g} \]

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if \( \lambda \to 0 \) particle masses go to zero

*Ends in a crunch*  
*\( w=-1 \) is transient*  
*\( \Omega_k > 0 \)*  

circles in the sky?  
possible correlation  
between 1+w and \( \Omega_k \)
Worries?

Consistency with QM requires action to be additive

\[ S_{AC} = S_{AB} + S_{BC} \]

\[ A_{A-B} = \langle B, t_B | A, t_A \rangle = \int dx_1 \ldots dx_{N-1} \langle B, t_B | x_{N-1}, t_{N-1} \rangle \langle x_{N-1}, t_{N-1} | x_{N-2}, t_{N-2} \rangle \ldots \langle x_1, t_1 | A, t_A \rangle \]

\[ = \int dx_1 \ldots dx_{N-1} e^{\frac{i}{\hbar} \sum_i L_i \delta t} = \int Dxe^{\frac{i}{\hbar} S_{AB}[x]} \]
New Sequester
Old Sequester in “Jordan frame”

\[ S = \int d^4 x \sqrt{g} \left[ \frac{M_{Pl}^2}{2} R - \Lambda - \lambda^4 \mathcal{L}_m (\lambda^{-2} g^{\mu \nu}, \Phi) \right] + \sigma \left( \frac{\Lambda}{\lambda^4 \mu^4} \right) \]

\[ g_{\mu \nu} \rightarrow \frac{\kappa^2}{M_{Pl}^2} g_{\mu \nu}, \ \Lambda \rightarrow \Lambda \left( \frac{M_{Pl}}{\kappa} \right)^4, \ \kappa^2 = M_{Pl}^2 / \lambda^2 \]

\[ S = \int d^4 x \sqrt{g} \left[ \frac{\kappa^2}{2} R - \Lambda - \mathcal{L}_m (g^{\mu \nu}, \Phi) \right] + \sigma \left( \frac{\Lambda}{\mu^4} \right) \]
The sequestering path integral?

\[ \int d\kappa \int d\Lambda \int Dg_{\mu\nu} \int D\Phi e^{iS/\hbar} \]

where

\[ S = \int d^4x \sqrt{g} \left[ \frac{\kappa^2}{2} R - \Lambda - \mathcal{L}_m(g^{\mu\nu}, \Phi) \right] + \sigma \left( \frac{\Lambda}{\mu^4} \right) \]

sums over wormholes, string compactifications?
The sequestering path integral?

\[ \int d\kappa \int d\Lambda \int Dg_{\mu\nu} \int D\Phi e^{iS/\hbar} \]

where \( S = \int d^4x \sqrt{g} \left[ \frac{\kappa^2}{2} R - \Lambda - \mathcal{L}_m(g_{\mu\nu}, \Phi) \right] + \sigma \left( \frac{\Lambda}{\mu^4} \right) \)

sums over wormholes, string compactifications?

for now we will take a different approach......make it local
Hint: UMG a la Henneaux & Teitelboim

\[ S_{UMG} = \int d^4 x \sqrt{g} \left[ \frac{M_{pl}^2}{2} R - \mathcal{L}_m(g^{\mu\nu}, \Phi) \right] - \int d^4 x \Lambda(x) (\sqrt{g} - 1) \]

non-gravitating but breaks diffs

\[ S_{HT} = \int d^4 x \sqrt{g} \left[ \frac{M_{pl}^2}{2} R - \mathcal{L}_m(g^{\mu\nu}, \Phi) \right] - \int \Lambda(x) (\sqrt{g} d^4 x - F_4) \]

alternative measure: the 4 form

retains diffs
does not gravitate

exact 4 form \( F_4 = dA_3 \) forces constant \( \Lambda \)
New Sequester

\[ S = \int d^4x \sqrt{g} \left[ \frac{\kappa^2(x)}{2} R - \Lambda(x) - \mathcal{L}_m(g^{\mu\nu}, \Phi) \right] \]

\[ + \int \sigma \left( \frac{\Lambda(x)}{\mu^4} \right) F_4 + \hat{\sigma} \left( \frac{\kappa^2(x)}{M_{Pl}^2} \right) \hat{F}_4. \]
\( \kappa^2 G^\mu_\nu = (\nabla^\mu \nabla_\nu - \delta^\mu_\nu \nabla^2) \kappa^2 + T^\mu_\nu - \Lambda(x) \delta^\mu_\nu \)

\begin{align*}
\frac{\sigma'}{\mu^4} F_4 &= \sqrt{g} d^4 x, \\
\frac{\hat{\sigma}'}{M_{Pl}^2} \hat{F}_4 &= -\frac{1}{2} R \sqrt{g} d^4 x, \\
\frac{\sigma'}{\mu^4} \partial_\mu \Lambda &= 0, \\
\frac{\hat{\sigma}'}{M_{Pl}^2} \partial_\mu \kappa^2 &= 0.
\end{align*}
\[ \kappa^2 G^\mu_\nu = (\nabla^\mu \nabla_\nu - \delta^\mu_\nu \nabla^2) \kappa^2 + T^\mu_\nu - \Lambda(x) \delta^\mu_\nu \]

\[ \frac{\sigma'}{\mu^4} F_4 = \sqrt{g} d^4 x, \quad \frac{\hat{\sigma}'}{M_{Pl}^2} \hat{F}_4 = -\frac{1}{2} R \sqrt{g} d^4 x, \]

\[ \frac{\sigma'}{\mu^4} \partial_\mu \Lambda = 0, \quad \frac{\hat{\sigma}'}{M_{Pl}^2} \partial_\mu \kappa^2 = 0. \]

\[ \implies \kappa^2 G^\mu_\nu = T^\mu_\nu - \frac{1}{4} \delta^\mu_\nu \langle T^\alpha_\alpha \rangle - \Delta \Lambda \delta^\mu_\nu \]
\[ \kappa^2 G_{\mu \nu} = (\nabla^\mu \nabla_\nu - \delta_{\mu \nu} \nabla^2) \kappa^2 + T_{\mu \nu} - \Lambda(x) \delta_{\mu \nu} \]

\[ \frac{\sigma'}{\mu^4} F_4 = \sqrt{g} d^4 x, \quad \frac{\hat{\sigma}'}{M^2_{Pl}} \hat{F}_4 = -\frac{1}{2} R \sqrt{g} d^4 x, \]

\[ \frac{\sigma'}{\mu^4} \partial_{\mu} \Lambda = 0, \quad \frac{\hat{\sigma}'}{M^2_{Pl}} \partial_{\mu} \kappa^2 = 0. \]

\[ \implies \kappa^2 G_{\mu \nu} = \left( T_{\mu \nu} - \frac{1}{4} \delta_{\mu \nu} \langle T^\alpha_{\alpha} \rangle \right) - \Delta \Lambda \delta_{\mu \nu} \]

\[ \Delta \Lambda = -\frac{\mu^4}{2} \frac{\kappa^2 \hat{\sigma}'}{M^2_{Pl} \sigma'} \int \hat{F}_4 / F_4 \]
Is \( \Delta \Lambda = -\frac{\mu^4}{2} \frac{\kappa^2 \hat{\sigma}'}{M_{Pl}^2 \sigma'} \int \hat{F}_4 \) radiatively stable?
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**Effect of vacuum loops:**

\[
\Lambda \rightarrow \Lambda + M_{UV}^4 \quad \Rightarrow \quad \sigma' \rightarrow \mathcal{O}(1) \sigma'
\]

\[
\kappa^2 \rightarrow \kappa^2 + M_{UV}^2 \quad \Rightarrow \quad \hat{\sigma}' \rightarrow \mathcal{O}(1) \hat{\sigma}'
\]

smooth functions

\( \mu > M_{UV} \)

\( M_{Pl} > M_{UV} \)
Is $\Delta \Lambda = -\frac{\mu^4}{2} \frac{\kappa^2 \hat{\sigma}'}{M_{Pl}^2 \sigma'} \int \hat{F}_4$ radiatively stable?

Effect of vacuum loops:

\[ \Lambda \rightarrow \Lambda + M_{UV}^4 \quad \implies \quad \sigma' \rightarrow O(1) \sigma' \]
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$\mu > M_{UV}$

$M_{Pl} > M_{UV}$

\[ \int F_4, \quad \int \hat{F}_4 \quad \text{geometric, IR quantities, not UV sensitive} \]
Is $\Delta \Lambda = -\frac{\mu^4}{2} \frac{\kappa^2 \hat{\sigma}'}{M_{Pl}^2 \sigma'} \int \hat{F}_4$ radiatively stable?

**Effect of vacuum loops:**

- $\Lambda \rightarrow \Lambda + M_{UV}^4 \implies \sigma' \rightarrow \mathcal{O}(1) \sigma'$
- $\kappa^2 \rightarrow \kappa^2 + M_{UV}^2 \implies \hat{\sigma}' \rightarrow \mathcal{O}(1) \hat{\sigma}'$

\[
\int F_4, \quad \int \hat{F}_4 \quad \text{geometric, IR quantities, not UV sensitive}
\]

$\implies \Delta \Lambda \rightarrow \mathcal{O}(1) \Delta \Lambda$

- Smooth functions
- $\mu > M_{UV}$
- $M_{pl} > M_{UV}$
Global trace equations

\[
\frac{\sigma'}{\mu^4} \langle \ast F_4 \rangle = 1 \quad \frac{\kappa^2 \hat{\sigma}'}{2M_{Pl}^2} \langle \ast \hat{F}_4 \rangle = -\frac{1}{4} \kappa^2 \langle R \rangle
\]

\[
4\Lambda + 4V_{vac} = \langle \tau^\alpha_\alpha \rangle + \kappa^2 \langle R \rangle
\]
Global trace equations

\[ \frac{\sigma'}{\mu^4} \langle \ast F_4 \rangle = 1 \]

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GR

\[ 4\Lambda + 4V_{vac} = \langle \tau^\alpha_\alpha \rangle + \kappa^2 \langle R \rangle \]
Global trace equations

\[
\frac{\sigma'}{\mu^4} \langle * F_4 \rangle = 1 \quad \frac{\kappa^2 \sigma'}{2 \mathcal{M}_{Pl}^2} \langle * \hat{F}_4 \rangle = -\frac{1}{4} \kappa^2 \langle R \rangle
\]

GR fixed by assumption

\[
4 \Lambda + 4 V_{vac} = \langle \tau^\alpha_\alpha \rangle + \kappa^2 \langle R \rangle
\]
Global trace equations

\[
\frac{\sigma'}{\mu^4} \langle \ast F_4 \rangle = 1 \quad \frac{\kappa^2 \delta'}{2 M_{Pl}^2} \langle \ast \hat{F}_4 \rangle = -\frac{1}{4} \kappa^2 \langle R \rangle
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Sequester
Global trace equations

\[ \frac{\sigma'}{\mu^4} \langle \ast F_4 \rangle = 1 \]

\[ \frac{\kappa^2 \hat{\sigma}'}{2M_P^2} \langle \ast \hat{F}_4 \rangle = -\frac{1}{4} \kappa^2 \langle R \rangle \]

**GR**

Sequester

fixed by assumption

\[ 4\Lambda + 4V_{vac} = \langle \tau^\alpha{}_\alpha \rangle + \kappa^2 \langle R \rangle \]

fixed by ratio of fluxes
Global trace equations

\[
\frac{\sigma'}{\mu^4} \langle \ast F_4 \rangle = 1
\]

\[
\frac{\kappa^2 \sigma'}{2M_P^2} \langle \ast \hat{F}_4 \rangle = -\frac{1}{4} \kappa^2 \langle R \rangle
\]

GR fixed by assumption

Sequester fixed by ratio of fluxes

\[
4 \Lambda + 4V_{vac} = \langle \tau^\alpha_\alpha \rangle + \kappa^2 \langle R \rangle
\]
Key points
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Λ is sink for vacuum energy, channelled there by non-gravitating 4 forms
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Works to any order in matter loops
— gravity loops on the other hand....
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Equivalence Principle violated GLOBALLY
— local theory is GR, Weinberg no go evaded
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Infinite Universes allowed in new sequester, but not old.
Key points

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Infinite Universes allowed in new sequester, but not old.

Residual CC is radiatively stable
— like any relevant coupling, should be measured.
“...and that's why the whole universe eats the gravity!”
Stuff I probably won't talk about

Symmetries
Phase transitions
Inflation
Particle Physics Phenomenology
Corrections to Planck mass
Why now?

and plenty more.......
Colemania

What effect do small wormholes have on Euclidean path integral?

Smaller than some scale $\mu^{-1}$

Bigger than $M_p^{-1}$

$\Rightarrow$ Modifies coupling constants, $\lambda$

Provides prob function for the $\lambda$

\[ \lambda + \rho + \cdots \]
No Wormholes

\[ \langle 0 \rangle_x = \frac{\int Dg \, O \, e^{-I_{g,x}}}{\int Dg \, e^{-I_{g,x}}} \]

Insert wormhole connecting \( x, x' \) (then integrate over \( x, x' \))

\[ \int Dg \, O \, e^{-I_{g,x}} \int d^x \int d^x' \sum_{ij} \frac{1}{2} C_{ij} \phi_i(x) \phi_j(x') \]

\( \phi_i(x) \) are a basis of local operators

\( C_{ij} \) are "constant" above wormhole scale
Sum over any \( \ast \) of WTs

\[
\rightarrow \int Dg \int_0 e^{-I[g,\lambda]} e^{\frac{i}{2} \int d^4x d^4x' \sum_{ij} C_{ij} \Phi_i(x) \Phi_j(x')}
\]

Use \( e^{\pm C_{ij} \Phi_i(x)} = \int d\lambda \ e^{-\frac{i}{2} D_{ij} \Phi_i} - \alpha_i \Phi_i \quad D_{ij} = C_{ij}^{-1} \)

\( V_i = \int d^4x \Phi_i(x) \)

\[
\rightarrow \int Dg \int_0 e^{-\left[ I[g,\lambda] + \frac{1}{2} D_{ij} \Phi_i \Phi_j + \int d^4x \alpha_i \Phi_i(x) \right]}
\]

Let \( \alpha_i \) be the coeff of \( \Phi_i \) in the Lagrangian

\[
\rightarrow \int Dg \int_0 e^{-\left[ I[g,\lambda+\alpha] + \frac{1}{2} D_{ij} \Phi_i \Phi_j \right]}
\]
Now include extra closed $U$'s

New factors of $\int Dg \ e^{-I_g(x,x+\alpha)} = Z(x+\alpha)$

$\Rightarrow \langle 0 \rangle = \frac{1}{N} \int Dg \int d\alpha \ 0 \ e^{-\left[I_g(x,x+\alpha) + \frac{1}{2} D_{ij} \alpha_i \alpha_j \right]} e^{Z(x+\alpha)}$

$= \frac{1}{N} \int Dg \int d\alpha \ e^{-I_{eff}}$

where $I_{eff} = I_{g(x,x+\alpha)} + \frac{1}{2} D_{ij} \alpha_i \alpha_j - Z(x+\alpha)$

(looks a bit like a sequester action)
Colemaria continued...

Write \( \langle 0 \rangle = \int d\alpha \ p(\alpha) \langle 0 \rangle_{\lambda+\alpha} \)

\[
p(\alpha) = \frac{1}{N} e^{-\frac{1}{2} D_{\alpha} x_{\alpha}} e^{Z(\lambda+\alpha)}
\]

Expectation value of \( 0 \) is weighted average of exp value of \( 0 \) in weightless \( U \)'s.

Work with EFT \( p<\mu < WH \) scale. Integrate out heavy flows.

\[
Z(\lambda+\alpha) = \int Dg_{<\mu} e^{-I_{\text{eff}}[g_{<\mu}, \lambda(\mu) + \alpha]}
\]

\[
e^{-I_{\text{eff}}} = \int Dg_{>\mu} e^{-I[g_{>\mu}, g_{>\mu}, \lambda + \alpha]}
\]
For gravity \( I_{\text{eff}} = -\int d^4x \sqrt{g} \left[ \frac{R}{16\pi G(\mu)} - \Lambda(\mu) + \xi(\mu) \, R_{\text{iem}}^2 \right] \)

\( \Lambda(\mu), \text{etc are functions of WH shifted params } \xi(\mu) + \alpha \)

Assume Einstein gravity is good approx \( \Rightarrow R_{\mu\nu} - 8\pi G\Lambda g_{\mu\nu} \Rightarrow R = 2\cdot16\pi G \Lambda \)

\( \Rightarrow I_{\text{eff}} \sim -\int d^4x \sqrt{g} \left[ \Lambda + \xi \, o(8\pi G \Lambda)^2 \right] \)
Further assume that large 4-sphere dominates (Euclidean ds)

\[ \int d^4x \sqrt{g} \sim \frac{8\pi}{3} r^4 \quad r^4 = \frac{3}{8\pi G\Lambda} \]

\[ \Rightarrow I_{\text{eff}} \sim -\left[ (\frac{3}{8}) \frac{1}{G\Lambda} + \xi O(1) \right] \]

\[ Z \sim e^{-I_{\text{eff}}} \sim e^{\left[ \frac{3}{8G\Lambda} + \xi O(1) \right]} \]

\[ P(x) \sim \frac{1}{N} e^{-\frac{i}{N} \text{Dij} \phi_j} e^Z \Rightarrow P \text{ is peaked near } G^2 \Lambda = 0^+ \]

But...

Wittenberg points out that \( P(x) \) also peaked near \( |x| \to \infty \)

\[ \Rightarrow \text{violates unitarity} \]

\[ \Rightarrow \text{impose unitarity bound } \xi < \frac{1}{G\mu^2} \]
Wormhole Catastrophe (Fischler, Susskind, Kaplunovsky)

New change cut-off $\mu \rightarrow \mu' < \mu$

Not enough just to integrate out fluct in $g$, also need to integrate out WHs in range $[\mu', \mu]$

Their effect is to add in new auxiliary params

$$\int Dg_{<\mu'} \int d\alpha \int dp \ e^{-\int d\alpha \left[ g_{<\mu'}((\alpha + \mu)(\mu',\mu') + \beta) + \frac{1}{2} Dij(\mu)\alpha_i\alpha_j 
+ \frac{1}{2} Dij(\mu)\beta_i\beta_j - Z((\alpha + \mu)(\mu',\mu') + \beta) \right]}$$

Now $\mathcal{G}$ satisfies a weaker unitarity bound $\mathcal{G} \leq \frac{1}{G \mu^2}$

$\Rightarrow$ WH contribution $h \mathcal{G}$ increase at large dists! WH CATASTROPHE!

$F \& S$ also show that density of WHs at scale $\mu$ goes as $\frac{1}{\mu^4}$

$\Rightarrow$ Density of large WHs is high (large WHs increase vol of space on which to attach more WHs)
The End
(of the talk)