Cosmological (non)-Constant Problem: 
*The case for TeV scale quantum gravity*

Niayesh Afshordi
Punchline!

• Quantum Gravity is already in the Infrared!

• CC problem (in its various forms) is possibly the single most significant theoretical clue as to how to modify UV and IR physics
Hierarchy problem(s)

- neutrino mass
- dark energy

Higgs, Electroweak  
GUT...Planck

$10^{-3} \text{eV}$  
$10^{12} \text{eV}$  
$10^{28} \text{eV}$

$\rho_{DE} \sim \Lambda^4$  
$\delta m_H^2 \sim \Lambda^2$  
$\Lambda?$
Hierarchy problem(s)

old cosmological constant (CC) problem

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- dark energy
  - LHC

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$\Lambda?$
Can modifying gravity solve the old CC problem? 

\[ \zeta_4 \]

\[ \frac{G_s}{G_n} = (1 + \zeta_4)^{-1} \]

(Narimani, NA & Scott 2014)
Can modifying gravity solve the old CC problem?

*not quite yet!*
Outline

• **Prelude**: Cosmological Hierarchy Problems

• **Cosmological non-Constant (CnC) Problem** (*TeV scale QG!*)
  
  • *Argument 1*: Poisson Phase Space
  
  • *Argument 2*: Kallen-Lehmann representation
  
  • *Argument 3*: Holographic entropy bound

• **Epilogue**: The folly of the Effective Field Theory

  ➤ *Firewalls!*
Does Quantum Gravity matter in the IR?

• Quantum Fluctuations do fluctuate!

\[ \langle T_{\mu\nu} \rangle = 0 \not\iff \langle T_{\mu\nu} T_{\alpha\beta} \rangle = 0 \]

• What is the analog of CC for the covariance of stress fluctuations?

• Can these fluctuations have an observable gravitational signature on large scales?

with Elliot Nelson (Penn-State ➔ PI), 1504.00012
Vacuum Fluctuations in Linear Gravity

- Linearized Perturbations around FRW space-time

\[ ds^2 = a^2(\eta) \left[ -(1 + 2\phi)d\eta^2 + 2V_i dx_i d\eta + (1 - 2\psi)dx^2 \right] \]

- Einstein constraint sector: *scalars in longitudinal gauge and vectors*

\[ -k^2 \psi = 4\pi G \left( \delta T_{00} - \frac{3H}{k^2} ik^i \delta T_{i0} \right), \]

\[ -k^2 \phi = 4\pi G \left( \delta T_{00} - \frac{3H}{k^2} ik^i \delta T_{i0} + \left( \delta^{ij} - 3 \frac{k^i k^j}{k^2} \right) \delta T_{ij} \right), \]

\[ k^2 V_i = 16\pi G (\delta_{ij} - \hat{k}_i \hat{k}_j) \delta T_{j0}, \]
CnC: the upshot!
CnC: the upshot!

- Random stress fluctuations at cut-off scale $\Lambda$

\[ \langle T_{ij}^{(V)}(x)T_{kl}^{(V)}(y) \rangle \sim \delta^3(x - y)\Lambda^5 \]
CnC: the upshot!

- Random stress fluctuations at cut-off scale $\Lambda$

- Poisson eq. for anisotropic stress

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k^2\Phi \sim M_p^{-2} A^{ij}T_{ij}
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(\Delta_{(V)}^\Phi)^2 \sim \frac{\Lambda^5}{M_p^4 k}
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- A UV/IR Heisenberg uncertainty relation
  \[
  \Lambda_{IR} = \frac{\Lambda_{UV}^5}{M_p^4}
  \]

- Cosmology limits the UV scale
  \[
  \Lambda \lesssim (M_p^4 H_0)^{1/5} \approx 2 \text{ PeV}
  \]
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What is a cosmological non-constant?
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What is a cosmological non-constant?

• Vacuum fluctuations should be finite, Lorentz invariant, and conserved (i.e. satisfy Ward identities)

• UV fluctuations should be un-correlated in the IR

• Imagine particles of mass $m$, uniformly sprinkled in the phase space with density $\langle f_0 \rangle$

\[
\langle T^\mu_\nu(y, t') T^{\alpha \beta}(y + x, t' + t) \rangle = m^5 \langle f_0 \rangle \frac{x^\mu x^\nu x^\alpha x^\beta}{(-x_\gamma x^\gamma)^{7/2}} \Theta(-x_\gamma x^\gamma)
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What is a cosmological non-constant?

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• We shall see that this structure occurs in generic quantum field theories.
Gravity of Poisson vacuum

• Solving Einstein equations, we find the spectrum of metric perturbations: 
  \[ \Delta_\phi^2 \simeq \frac{m^5 \langle f_0 \rangle}{M_p^4 k} \]

• or 
  \[ \Delta_\phi^2 \simeq 4 \times 10^{-9} \left( \frac{m}{50 \text{ TeV}} \right)^5 \left( \frac{\langle f_0 \rangle}{1/2} \right) \left( \frac{k/a}{2 \times 10^{-4} \text{Mpc}^{-1}} \right)^{-1} \]

• spectrum of CMB anisotropies (Integrated Sachs-Wolfe, or ISW effect):

  \[ (\Delta_l^2)^{\text{ISW}} \equiv \frac{l(l+1)C_l^{\text{ISW}}}{2\pi} = \frac{49\pi}{720} \frac{m^5 t_0}{M_p^4} \langle f_0 \rangle \]

  \[ (t_0 = 13.7 \text{ billion years}) \]
power spectrum of CMB
power spectrum of CMB

$m < 14\ TeV!\ (<f_0> \sim 1)$
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Kallen-Lehmann spectral representation

- Most general expectation for stress correlators from **Unitarity** + **Lorentz symmetry**

\[
<T_{\mu\nu}(x)T_{\alpha\beta}(y)> = \int \frac{d^4k}{(2\pi)^4} e^{i\mathbf{k}\cdot(x-y)} \int_0^\infty d\mu \left[ \rho_0(\mu)P_{\mu\nu}P_{\alpha\beta} + \rho_2(\mu) \left( \frac{1}{2} P_{\mu\alpha}P_{\nu\beta} + \frac{1}{2} P_{\mu\beta}P_{\nu\alpha} - \frac{1}{3} P_{\mu\nu}P_{\alpha\beta} \right) \right] \theta(k^0)2\pi \delta(k^2 + \mu),
\]

- \(\rho\)'s must positive.

- **Cosmological** constraints will roughly translate to

\[
\int \frac{d\mu}{\sqrt{\mu}} \rho_2(\mu) \lesssim (10 \text{ TeV} - 1 \text{ PeV})^5
\]

- Metric fluctuations are **high frequency** but **blow up at long wavelength** —> **Observables??**
I: An offset in Hubble law

- Particle action
  \[ S_p = -m \int dt \sqrt{1 + 2\phi(x, t) - |\dot{x}|^2}, \]

- To 2nd order in \( \phi \)
  \[ S_p \approx m \int d\tau \left[ -1 + \frac{1}{2}|\dot{x}|^2 + \phi(0, t) - \phi(x, t) + \frac{1}{2}\phi(x, t)^2 - \frac{3}{2}\phi(0, t)^2 + \phi(x, t)\phi(0, t) \right]. \]

- Effective Newtonian potential
  \[ \Phi_N(x, t) \approx -\langle \phi(x, t)\phi(0, t) \rangle \]

- An offset in the Hubble law
  \[ v \approx Hr - \frac{1}{32\pi HM_p^4} \int \frac{d\mu}{\sqrt{\mu}} \rho_2(\mu) \]

- Planck cluster kSZ monopole
  \[ \langle v_r \rangle = 72 \pm 60 \text{ km/s}, \]
  \[ \left[ \frac{1}{2} \int \frac{d\mu}{\sqrt{\mu}} \rho_2(\mu) \right]^{1/5} < 1.1 \text{ PeV}, \]
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II: CMB anisotropies

- For a weakly coupled scalar field

\[ \rho_2(\mu) = \frac{1}{16\pi^2} \sqrt{\frac{1}{4} - \frac{m^2}{\mu}} \left[ \frac{11}{40} \mu^2 + \frac{14}{15} m^2 \mu + m^4 \right] \Theta(\mu - 4m^2) \]

- For large scale, real-space correlations, one can deform the contour to get

\[ \rho_{2,\text{eff}}(\mu) = \frac{m^5}{16\pi^2 \sqrt{-\mu}} \Theta(-\mu) \]

- This is identical to Poisson model, with \( \langle f_0 \rangle = 15/(2\pi)^3 \).
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  ➡ *Firewalls!*
Interaction entropy

Imagine a system with Hamiltonian $H_0$, in its ground state $|0\rangle_0$, and zero energy.

Now, turn on $H_{\text{int}}$; to 1st order, new eigenstates are $|n\rangle_0 \simeq -\frac{\langle n|H_{\text{int}}|0\rangle}{E_n}$.

Time-Averaged density matrix:

$$\rho_{\text{int}} = \sum_n |\langle n|0\rangle_0|^2 |n\rangle\langle n| = \sum_n \frac{\langle n|H_{\text{int}}|0\rangle|^2}{E_n^2} |n\rangle\langle n|,$$

Entropy of a 2-state system:

$$S_{\text{qubit}} = -tr(\rho_{\text{int}} \ln \rho_{\text{int}}) \simeq \alpha [1 - \ln(\alpha)] + O(\alpha^2),$$

Fine structure constant:

$$\alpha \equiv \frac{\langle 1|H_{\text{int}}|0\rangle^2}{E_1^2},$$
A Holographic Bound!

- Gravitational fine structure constant $\alpha_G \sim \frac{E^2}{M_p^2}$
- Number of qubits in a Dirac field
- Holographic Bound

\[ \# = 2 \times 2 \times \text{Volume} \times \int_{2\pi}^{\Lambda} \frac{d^3k}{(2\pi)^3} = \frac{2\Lambda^3}{3\pi^2} \times \text{Volume}, \]

\[ S_{BH} = 2\pi M_p^2 \times \text{Area} > S = \# \times \alpha_G \left[ 1 - \ln(\alpha_G) \right] \sim \frac{2\Lambda^5 \left[ 1 + \ln(M_p^2/\Lambda^2) \right]}{3\pi^2 M_p^2} \times \text{Volume}. \]

- An IR cut-off for gravity

\[ R \lesssim R_{\text{max}} \sim \frac{3\pi^3 M_p^4}{\Lambda^5 \left[ 1 + \ln(M_p^2/\Lambda^2) \right]}, \]

\[ \Lambda_{IR} \sim \frac{\pi}{R_{\text{max}}} \sim \frac{\Lambda^5 \left[ 1 + \ln(M_p^2/\Lambda^2) \right]}{3\pi^2 M_p^4}. \]

\[ \Lambda_{IR} < H_0 \simeq 9.5 \times 10^{-33}\text{eV} \]

$\Rightarrow \Lambda \lesssim 2.4 \text{ PeV.}$
Cosmological Non-Constant (CnC) problem
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- Vacuum energy-momentum fluctuations can also source gravity
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- They change the gravitational constraint sector in the IR, thru equal-time correlators
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• Vacuum energy-momentum *fluctuations* can also source gravity

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• Heisenberg Uncertainty principle for UV/IR observables
Cosmological Non-Constant (CnC) problem

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- CnC problem is more severe than the old CC problem, due to the positivity of the spectral functions or entropy, i.e. fine-tuning doesn’t work
Cosmological Non-Constant (CnC) problem

- Vacuum energy-momentum fluctuations can also source gravity
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- Heisenberg Uncertainty principle for UV/IR observables
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- What about Effective Field Theory?
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On the folly of EFT
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• When it comes to gravity, EFT doesn’t have a good track record!
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• CC problem
On the folly of EFT

- When it comes to gravity, EFT doesn’t have a good track record!
- CC problem
- CnC problem
On the folly of EFT

• When it comes to gravity, EFT doesn’t have a good track record!

• CC problem

• CnC problem

• and firewalls!
On the folly of EFT

• Gravitational Path Integral

$$\int DgD\varphi \times \text{Diff}^{-1}[g,\varphi] \times \exp \left( i \int d^4x \sqrt{-g} \{ R[g] + \mathcal{L}_m[\varphi, g] \} \right).$$

• Naive Effective Action

$$\exp(iS_{\text{eff, naive}}[g]) \equiv \exp(iS_{\text{GR}}[g]) \times \int D\varphi \exp \left( i \int d^4x \sqrt{-g} \mathcal{L}_m[\varphi, g] \right).$$

• Ignores GR Constraints :-(

$$\text{Diff}^{-1}[g, 0] \exp(iS_{\text{eff, naive}}[g]) \neq \exp(iS_{\text{GR}}[g]) \times \int D\varphi \times \text{Diff}^{-1}[g, \varphi] \times \exp \left( i \int d^4x \sqrt{-g} \mathcal{L}_m[\varphi, g] \right).$$
On the folly of EFT

- Low energy scattering CANNOT produce massive particles of mass $\Lambda \rightarrow$ Effective Field Theory
- This is NOT the case for macroscopic systems
- Nearly all macroscopic systems have a fluid description in the IR; UV actions strongly coupled
- Separation of scales is not guaranteed, e.g. turbulent cascade, inverse cascade
Open Questions

• Should we take CnC problem seriously?!  
• What about the early universe/inflation?  
• Is there a gauge-invariant description of this effect?  
• What happens beyond linear order?  
• Nature of IR cut-off? massive gravity, Dark Energy?  
• What will a 100 TeV collider see?
Final Thoughts
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- **CC problem**: Possible to solve in a scientific framework; change how pressure gravitates
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  - A definite target for particle colliders (*e.g.* 100 TeV collider)
Final Thoughts

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- **EFT:** Just think outside the box!
why EFT fails at “horizon”

• **Information paradox:** unitary black hole evaporation, not consistent with local physics + smooth horizon *(Hawking … AMPS 2013)*

• **Quantum Tunnelling:** $\exp(-S_E) \times \exp(\text{entropy}) \sim 1$

• **Fuzzballs:** *(a la Mathur):* classical horizon-less spacetimes, that account for BH entropy

• **Dark Energy:** pressure eq. with stellar BH firewalls, $\rightarrow$ scale of dark energy *(Presocd-Weinstein, NA, Balogh 2009)*
How to form a Black Hole

How to form a Firewall?!
Firewall entropy & Lorentz violation

• Assume space-time ends at stretched horizon

• Israel Junction condition+$\mathbb{Z}_2$ symmetry:
  - membrane has vanishing surface density ($c_s \to \infty$)
  - integrated (surface) pressure: $= \text{Unruh Temperature/4}$
  - Entropy per unit area $= 1/4$ (Bekenstein-Hawking)

Saravani, NA, Mann 2012
Firewall entropy & Lorentz violation

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  ➡ membrane has vanishing surface density ($c_s \rightarrow \infty$)

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  ➡ Entropy per unit area $= 1/4$ (Bekenstein-Hawking)!

Saravani, NA, Mann 2012
Can we see firewalls?!

- If firewalls have a dense atmosphere, it could be opaque to photons but transparent to neutrinos.
- Similar to core-collapse supernovae.
- A fraction of accreted energy into the firewall/BH horizon can be re-radiated as neutrinos.
Possibly! (NA & Yazdi 2015)

IceCube constraints on firewall neutrino spectrum

Spectrum of High Energy Neutrinos

dN/dE \sim E^{-p}

Fraction of accreted energy re-radiated as neutrinos

spectral index

\frac{dN}{dE}$
What if Newton knew quantum field theory (and special relativity)?! 

\[ \nabla^2 \phi = 4\pi G(\rho) \]
What if Newton knew quantum field theory (and special relativity)?! 

\[ \nabla^2 \phi = 4\pi G (\rho + p/c^2) \]
How to do it covariantly?

- Let us propose (NA 2008):
  \[(8\pi G')^{-1} G_{\mu\nu} = T_{\mu\nu} - \frac{1}{4} T_{\alpha}^{\alpha} g_{\mu\nu} + \ldots\]

- The metric is now blind to vacuum energy
  \[T_{\mu\nu} = \rho_{\text{vac}} g_{\mu\nu} + \text{excitations}\]

- In order to satisfy Bianchi identity:
  \[(8\pi G')^{-1} G_{\mu\nu} = T_{\mu\nu} - \frac{1}{4} T_{\alpha}^{\alpha} g_{\mu\nu} + T_{\mu\nu}', \quad T_{\nu;\mu}' = \frac{1}{4} T_{\alpha,\nu}^{\alpha}\]

- Further assume an incompressible fluid (or gravitational aether)
  \[T_{\mu\nu}' = p'(u'_{\mu} u'_{\nu} - g_{\mu\nu})\]

- **Disclaimer**: The field equations do not follow from an Action principle
Deviations from GR sourced by **Pressure** or **Vorticity**

(Kamiab & NA, 2011)
(Aslanbeigi, Robbers, Foster, Kohri & NA, 2011)
(Narimani, NA & Scott, 2014)

- Neutron Star Structure (e.g. Adv LIGO)
- Cosmology (CMB, Big Bang Nucleosynthesis)
- *Intrinsic Gravitomagnetic Effect* (LAGEOS, GPB)
- **Vacuum gravity identical to GR**
How does pressure gravitate?

\( G_n/G_\ast = (1 + \zeta_4)^{-1} \)  
(Narimani, NA & Scott 2014)
What now?

• Original Gravitational Aether proposal (NA 2008) is ruled out at 3-4σ (still better than $10^{60}$-$10^{120}\sigma$!)

• But, vacuum is smooth

• Does that make a difference?

• The theory *must* have a cut-off/coarse-graining scale
neutron stars and aether

- Deviations from Einstein gravity are sourced by pressure
- Neutron Stars
- Aether EOS
- Uncertainty in nuclear equation of state
- Can test with Gravitational Wave detection from NS-NS mergers

Kamiab & NA 2011
Cosmology ($G_N/G_R = 0.75$ or $1$?)

(Aslanbeigi, Robbers, Foster, Kohri, NA, 2011)

Cosmic Microwave Background  Big Bang Nucleosynthesis
aether and black holes

- We can solve for the black hole spacetime in this theory

$$ds^2 = \left(1 - \frac{2m}{r}\right) \left[1 + 4\pi p_0 f(r)\right]^2 dt^2 - \left(1 - \frac{2m}{r}\right)^{-1} dr^2 - r^2 d\Omega^2$$

- $p_0$ is the aether pressure at infinity

- $f(r)$ is an analytic function of $r$ that diverges at $r \approx 2m$ & $r \to \infty$

- **UV-IR coupling thru aether pres:**

- **Finite redshift at $r=2m$**

- **No Horizon** (similar to Fuzzball r.)
... and dark energy!

- Let us propose that maximum redshift at “horizon” is set to Planck Temperature/Hawking Temperature by quantum gravity effects:

\[ p_0 = -\frac{1}{256\pi^2m^3} \approx \left( \frac{m}{74 M_\odot} \right)^{-3} p_{DE,obs}!! \]

- Aether pressure has the same sign and magnitude as Dark Energy for stellar mass black holes!

- ➤Conjecture: Formation of stellar black holes causes cosmic acceleration

- ➤Conjecture: Evolution of Astrophysical black holes leads to dynamical Dark Energy
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- ➤\textbf{Conjecture:} Evolution of Astrophysical dynamical Dark Energy
"a glorious historical accident!"

• **Barbour:** Mach suggested that Physics only depends on the change in observables. Relativity (and Lorentz Invariance) emerges as a consistency condition.

• **Horava:** A transition to Lifshitz symmetry makes gravity power-counting renormalizable.
A lesson from perihelion precession of Mercury
A lesson from perihelion precession of Mercury

- Newtonian Gravity has a symmetry between angular and radial coord’s: \( r \leftrightarrow \theta, \Omega_r = \Omega_\theta \)
A lesson from perihelion precession of Mercury

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• \textbf{Cosmologist:} \textit{Universe has already done this!}