Title: Scenes From Polymer Quantization

Date: Jul 26, 2013 11:00 AM

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Abstract: A regime of "polymer quantum field theory on curved spacetime" should emerge in a low energy approximation of quantum gravity based on LQG ideas. This era should be characterized by a polymer scale, and give modifications to the usual semiclassical approximation. I will describe work on gravitational collapse, cosmology, and statistical mechanics in this setting. Results include models of horizon evaporation, inflation and graceful exit without an inflaton potential, and an indication of dimensional reduction from 4 to 2.5 dimensions.

Scenes from Polymer Quantization

Loops 13

[I. Brown, G. Hossain, A. Kreienbuehl, S. S. Seahra, B. Tippett, E. Webster]

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Motivation & Introduction

Scenes

1. Cosmology
2. Gravitational collapse
3. Propagator
4. Dimensional reduction?

LQG = Polymer Geometry + Polymer Matter

Expectations

- Low energy: QFT on curved spacetime.
- Intermediate energy: "Polymer QFT" on curved spacetime
- High energy: full QG

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In LQC – a hybrid approach:
polymer quantization of gravity + Schrodinger quantization of matter: Polymer scale from quantum gravity.

In PQFT on curved spacetime:
polymer scale from matter

Focus of this talk:

Are there polymer matter effects
in cosmology, black hole physics, etc.?

Scalar field (ϕ, P_ϕ)

Metric:

$$ds^2 = -dt^2 + q_{ab}dx^a dx^b$$

$$H = \int d^3x \left(\frac{1}{2\sqrt{q}} P_\phi^2 + \sqrt{q} q^{ab} \partial_a \phi \partial_b \phi \right).$$

Polymer variables (scalar field analog of holonomy flux algebra)

$$p_f(t) = \int_\Sigma d^3x \; f(x) P_\phi(x,t), \qquad h = e^{i\lambda\phi(x,t)}.$$

$$\{p_f, h\} = i\lambda f \; h.$$

(Thiemann; Ashtekar, Lewandowski, Sahlmann; Laddha, Varadarajan; Date)

Alternative polymer variables

$$\Phi_f = \int d^3x \, \sqrt{q} f(x) \phi(x,t), \qquad U_\lambda = e^{i\lambda P_\phi/\sqrt{q}}$$

$$\{\Phi_f(t), U_\lambda(x,t)\} = i\lambda f \; U(x,t).$$

We will use these.

- "dual" to variables from LQG
- useful to explore quantization on fixed background.

Polymer quantization

$\hat{U}_\lambda$: shift operator Φ_f: diagonal operator

Basis states: $|\mu_1, \mu_2, \cdots \mu_N\rangle_\Gamma$ Γ: "graph" $\{x_1, x_2 \cdots x_N\}$

Momentum operator

$$\hat{P}_\phi^\lambda := \frac{\sqrt{q}}{2i\lambda}(\hat{U}_\lambda - \hat{U}_\lambda^\dagger)$$

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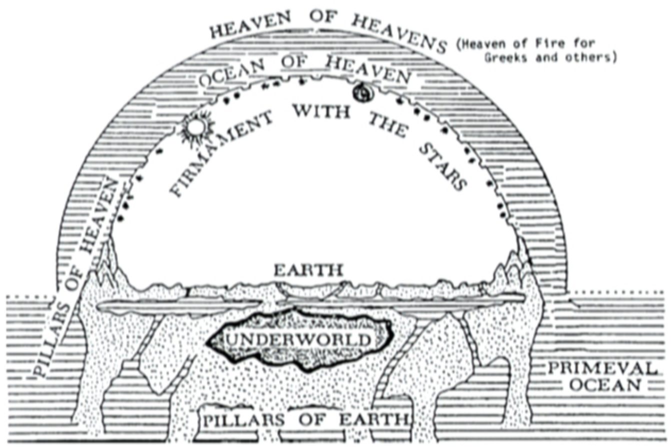
COSMOLOGY



G. Hossain, VH, S. Seahra, arXiv:0906.2798; PRD81 (2010) 024005

S. Seahra, I. Brown, G. Hossain, VH, arXiv:1207.6714; JCAP 1210 (2012) 041

Fix background:

$$ds^2 = -dt^2 + a^2(t)d\mathbf{x}^2$$

.

Reduced classical variables:

$$\Phi_f = V_0 a^3 \phi, \quad U_\lambda = \exp\left(i\lambda P_\phi / a^3\right)$$

Now "momentum" operator is

$$\hat{P}_\phi^\lambda := \frac{a^3}{2i\lambda}(\hat{U}_\lambda - \hat{U}_\lambda^\dagger).$$

– depends on the metric; used in the $\hat{H}_\phi$ operator.

Semiclassical dynamics

Friedmann equation:

$$H_g(a, \dot{a}) + \langle\psi|\hat{H}_\phi|\psi\rangle = 0.$$

$\hat{H}_\phi = V_0(\hat{P}_\phi)^2/2a^3$

State: semiclassical

$$|\psi\rangle(\phi, P_\phi) = \frac{1}{\mathcal{N}} \sum_{k=-\infty}^{\infty} c_k|\mu_k\rangle, \quad c_k = e^{-(\phi_k-\phi)^2/2\sigma^2} e^{-iP_\phi\phi_k V_0}.$$

$(\phi_k = \mu_k/V_0 a^3.)$

$$\langle \hat{H}_\phi \rangle \equiv V_0 a^3 \rho_{\text{eff}}, \quad \rho_{\text{eff}} = \frac{1}{8\lambda^2}[2 - \langle \hat{U}_{2\lambda} \rangle - \langle \hat{U}^\dagger_{2\lambda} \rangle],$$

$$H^2 = \frac{\dot{a}^2}{a^2} = \frac{8\pi G}{3} \rho_{\text{eff}}(a, P_\phi; \sigma, \lambda)$$

$$\dot{P}_\phi = 0, \quad \dot{\phi} = \tfrac{1}{2} M^2 e^{-\Theta^2/\Sigma^2} \sin(2\Theta),$$

$$\Theta \equiv \lambda P_\phi a^{-3}, \quad \Sigma \equiv \sigma V_0 P_\phi.$$

(invariant under rescalings:

$$\mathbf{x} \to \ell \mathbf{x}, \quad a \to \ell^{-1} a, \quad V_0 \to \ell^3 V_0, \quad P_\phi \to \ell^{-3} P_\phi)$$

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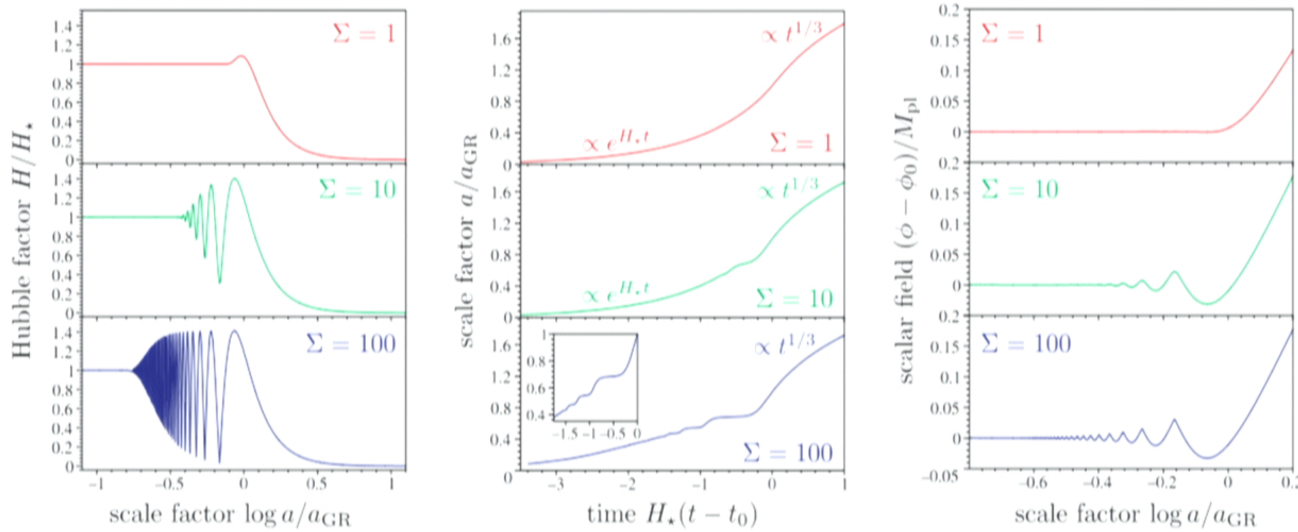
Numerical solution of semiclassical equations:



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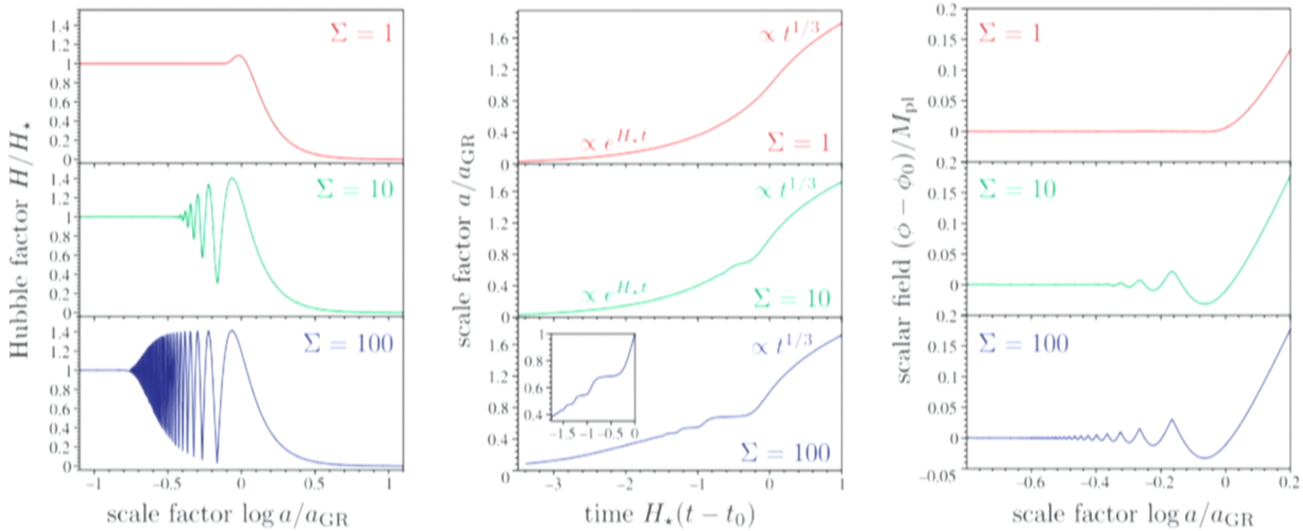

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– Early inflationary phase: sufficient e-foldings to solve horizon problem.

– A graceful exit from inflation.

– A classical universe at late times.

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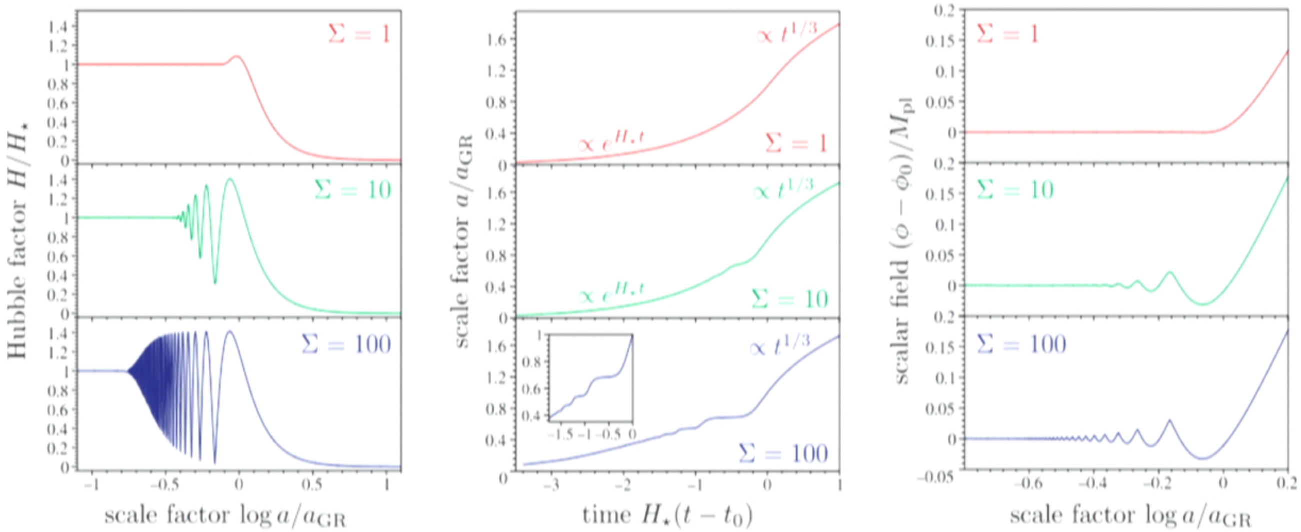


These figures show 3 important features:

– Early inflationary phase: sufficient e-foldings to solve horizon problem.

– A graceful exit from inflation.

– A classical universe at late times.

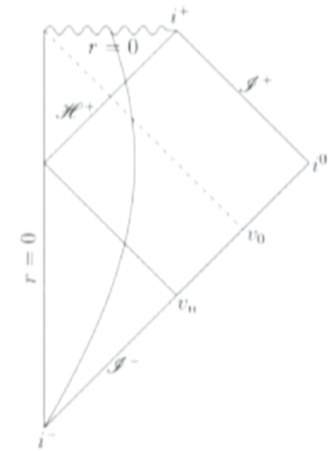
All without an inflaton mass, potential, or fine tuning – the only input is polymer quantization and semiclassical state.

Why does this work?

2 regimes for the scale factor:

$$\rho_{eff} \approx \begin{cases} M^4, & a < \left(\frac{P_\phi}{\Sigma M^2}\right)^{1/3}, \\ P_\phi^2/a^6, & a > \left(\frac{P_\phi}{M^2}\right)^{1/3} \end{cases}$$

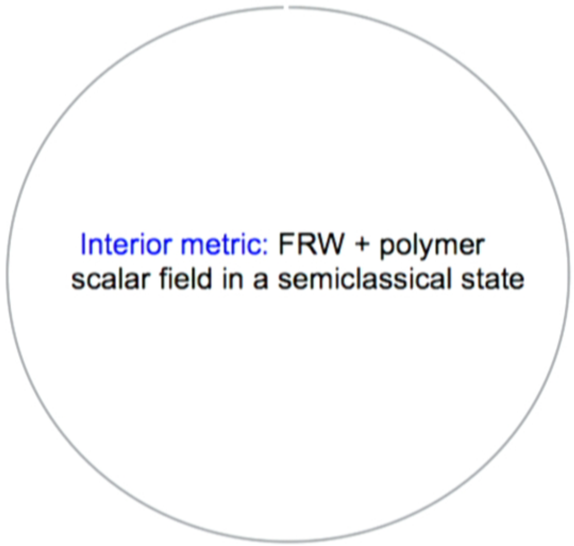
GRAVITATIONAL COLLAPSE



[VH, B. Tippett, arXiv:1106.1118; PRD 84 (2011) 104031.]

Spherically symmetric collapse model

-- a generalization of Oppenheimer-Schneider



Exterior metric: generalized Vaidya with P=kp

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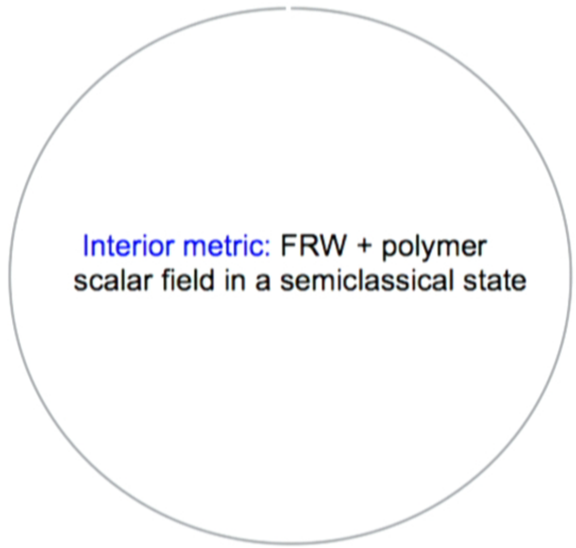

Exterior metric: generalized Vaidya with P=kp

Classical model

Model use an old idea (Oppenheimer-Snyder) with some twists.

OS model: patch an FRW metric with a static exterior

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OS model: patch an FRW metric with a static exterior

New ingredients:

- dynamical exterior
- polymer quantum matter as a source for FRW in interior

Interior solution

interior metric

$$ds_-^2 = -dt^2 + \frac{a^2(t)}{(1 + r^2/4)^2}(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2),$$

Exterior solution

$$ds_+^2 = -\left(1 - \frac{2M(R,v)}{R}\right) dv^2 + 2\ dvdR + R^2\left(d\theta^2 + \sin^2\theta d\phi^2\right).$$

exterior source: null fluid a generalization of Vaidya
[VH, PRD 53 (1996) 1759]

$$T_{ab} = \frac{1}{2\pi R^2}\frac{\partial M}{\partial v}\, v_a v_b + \rho(v,R) w_{(a}v_{b)} + P(v,R)\left(g_{ab} + w_{(a}v_{b)}\right).$$

pressure $P(v,R)$ and energy density $\rho(v,R)$ are

$$P = k\frac{g(v)}{4\pi r^{2k+2}} = k\rho,$$

$$M(R,v) = m(v) - \frac{g(v)}{2(2k-1)R^{2k-1}},$$

$$v_a = (1,0,0,0), \quad w_a = (f/2,-1,0,0),$$

future pointing null vectors; f coefficient of dv^2; k real parameter.

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junction conditions

Matching surface is timelike: $r = r_0$.

- $a(t)$ from FRW matter content.
- induced metrics on surface continuous: $a(t)r_0 = R(t)$ & $v = v(t)$.
- extrinsic curvatures on surface continuous.

$\longrightarrow$ $R(v)$: the star surface trajectory – exterior view.

$\longrightarrow$ $f(R, v)$: the exterior metric function.

k=2 fluid classical matter interior

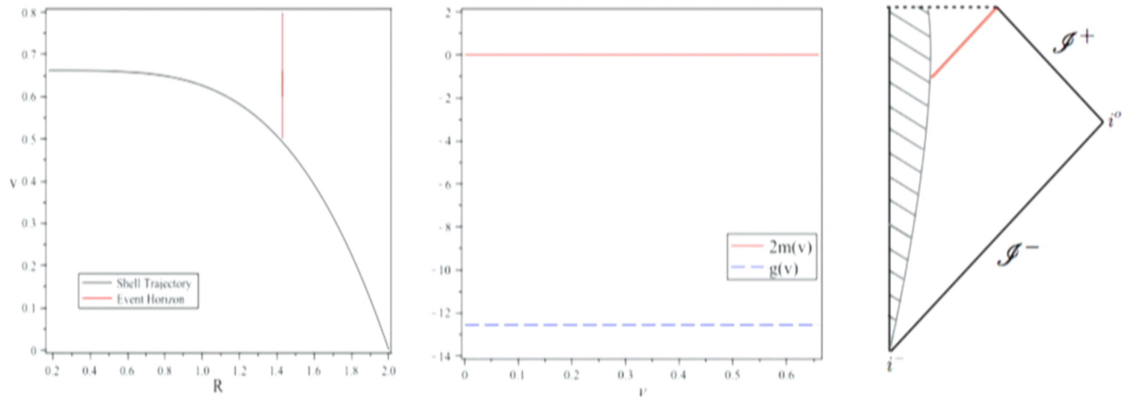


Figure: $k = 2$ exterior with classical scalar field interior: the only solution is a static exterior (constant $m(v)$ and $g(v)$). This is qualitatively similar to the Oppenheimer-Snyder solution.

k=2 fluid quantum matter interior

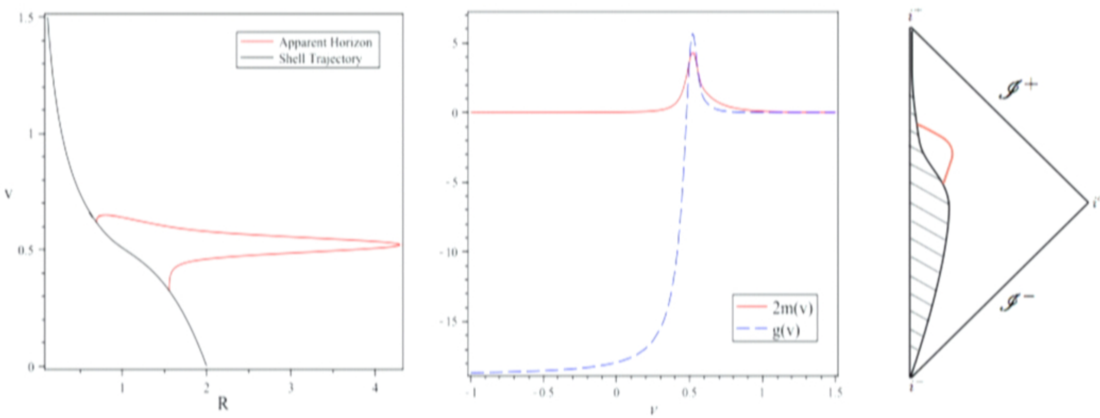
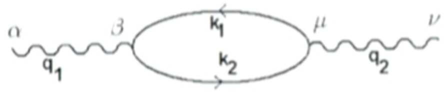


Figure: $k = 2$ exterior with quantum scalar field interior: the shell trajectory exponentially approaches $r = 0$ and there is no curvature singularity. The apparent horizon forms and evaporates in finite time.

PROPAGATOR



[G. Hossain, VH, S. Seahra, arXiv:1007.5500; PRD 82.124032 (2010)]

Write classical Hamiltonian in Fourier space → do polymer quantization in k space → compute propagator using oscillator matrix elements.

$$H_\phi = \sum_{\mathbf{k}} H_{\mathbf{k}} = \sum_{\mathbf{k}} \left[\frac{\pi_{\mathbf{k}}^2}{2} + \frac{1}{2}|\mathbf{k}|^2 \phi_{\mathbf{k}}^2 \right],$$

$$\hat{H}_{\mathbf{k}} = \frac{1}{8\lambda^2}\left[2 - \hat{U}_{2\lambda\mathbf{k}} - \hat{U}_{2\lambda\mathbf{k}}^\dagger\right] + \frac{1}{2}\mathbf{k}^2\phi_{\mathbf{k}}^2,$$

$$U_{\lambda\mathbf{k}} = e^{i\lambda\pi_{\mathbf{k}}}$$

.

$$\langle 0|\hat{\phi}(\mathbf{x},t)\hat{\phi}(\mathbf{x}',t')|0\rangle \equiv \frac{1}{V}\sum_{\mathbf{k}} e^{i\mathbf{k}\cdot(\mathbf{x}-\mathbf{x}')} D_{\mathbf{k}}(t-t'),$$

$$\begin{aligned} D_{\mathbf{k}}(t-t') &= \langle 0_{\mathbf{k}}|e^{i\hat{H}_{\mathbf{k}}t}\hat{\phi}_{\mathbf{k}}e^{-i\hat{H}_{\mathbf{k}}t}e^{i\hat{H}_{\mathbf{k}}t'}\hat{\phi}_{\mathbf{k}}e^{-i\hat{H}_{\mathbf{k}}t'}|0_{\mathbf{k}}\rangle \\ &\equiv \int \frac{d\omega}{2\pi}\, D(\omega,k)\; e^{-i\omega(t-t')} \end{aligned}$$

$$D(\omega,k) = \sum_{n=1}^{\infty} \frac{2i\Delta E_n |c_n|^2}{-\omega^2+\Delta E_n^2 - i\epsilon},$$

$$c_n = \langle n_{\mathbf{k}}|\phi_{\mathbf{k}}|0_{\mathbf{k}}\rangle \qquad \Delta E_n = E_n^{\mathbf{k}} - E_0^{\mathbf{k}}$$

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For Fock quantization:

$$\Delta E_n = nk, \qquad c_n = \frac{\delta_{n,1}}{\sqrt{2k}}$$

$\longrightarrow$

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For polymer quantization:

Need ΔE_n and c_n for polymer oscillator.
[Ashtekar, Fairhurst , Willis calculated E_n.]

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dimensionless parameter:

$$g = \lambda^2 |\mathbf{k}|$$

$$D(\omega, k, g) = \frac{i(1-2g)}{-\omega^2 + \mathbf{k}^2 - g|\mathbf{k}|^2 - i\epsilon} + \mathcal{O}(g^2), \qquad g \ll 1.$$

$$D(\omega, k, g) = \frac{i/8g^2}{-\omega^2 + \mathbf{k}^2 + 4g^2|\mathbf{k}|^2 - i\epsilon} + \mathcal{O}\left(\frac{1}{g^6}\right), \qquad g \gg 1.$$

Comments on propagator calculation

– Asymptotic results are exact.

– Lorentz invariance recovered at low energy.

– Propagation suppressed at high energy

– Effective mass: $m_{eff}(g, \mathbf{k}) = \lambda^2 |\mathbf{k}|^3$ for $g \ll 1$

[further recent work by Barbero, Prieto, Villasenor 2013]

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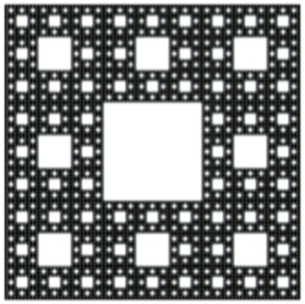
DIMENSIONAL REDUCTION



VH, S. Seahra, E. Webster, arXiv:1305.2814; PRD 88, 024014 (2013)

For blackbody radiation in $d + 1$ spatial dimensions, the Stefan-Boltzmann law is

$$\mathcal{U} \propto T^{1+d}$$

What happens for a polymer photon gas in 3+1 dimensions?

Basic input:

oscillator spectrum is modified by polymer quantization

[related work: Morales-Tecotl et.al.]

Partition function of mode k:

$$Z_{\mathbf{k}}(\beta) = \sum_{n=0}^{\infty} e^{-\beta(E_{n,k} - E_{0,k})}$$

Average energy in mode k:

$$\bar{E}_{\mathbf{k}}(\beta) = -\frac{d}{d\beta} \ln Z_{\mathbf{k}}(\beta).$$

Total energy:

$$\mathcal{U} = \frac{V}{\pi^2} \int_0^{\infty} dk\, k^2 \bar{E}_{\mathbf{k}}(\beta).$$

Polymer oscillator:

$$\Delta\varepsilon_n \approx \begin{cases} gn, & g \ll 1, \\ g^2 f_n, & g \gg 1. \end{cases}$$

$g = k/M$

This behaviour gives high energy modifications of black body spectrum.

Result: smooth transition from

$$U \sim T^4, \qquad k_B T \ll M.$$

to

$$U \sim T^{5/2}, \qquad k_B T \gg M.$$

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Evidence of dimensional reduction from 4 to 2.5?

Semiclassical — so we are not yet down to 2!

Equation of state changes from

$$P = \frac{1}{3}\rho, \qquad kT \ll M$$

to

$$P = \frac{2}{3}\rho, \qquad kT \gg M$$

SUMMARY

- Hints of interesting physics with polymer QFT on curved spacetime.
- May provide evidence of LQG methods at lower energy scales.

Many questions to explore:

– Semiclassical gravitational collapse.

– Modifications of black hole physics.