Dirac Fields in Hybrid LQC

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Motivation

- Any fundamental theory includes **fermionic** fields.
- It is interesting to incorporate fermions in analyses of the **Early Universe** and of possible effects on the primordial perturbations.
- We want to extend the **hybrid LQC** formalism including Dirac fields. This will put to the **test** the very own consistency of the hybrid approach.
- We want to obtain a framework to discuss the effects of **quantum geometry** on realistic quantum matter fields.
- In this way we can explore issues such as the definition of a **vacuum**, the recovery of **QFT**, and **backreaction**.

Unperturbed model

- We start with a **FLRW model** with **flat** compact sections (three-tori).

$$ds^2=\frac{4\pi}{3}\left[-\left(\frac{4\pi e^{3\alpha(t)}}{3}\right)^2 N_0^2(t)\,dt^2+e^{2\alpha(t)}\ {}^0h_{ij}\,d\theta_i\,d\theta_j\right].$$

Euclidean

We include a scalar field (the **inflaton**) subject to a potential $W(\phi)$.

- The phase space can be described with **two canonical pairs**:

1) (ϕ,π_ϕ) for the inflaton.

Unperturbed model

2) (v, b) for the **FLRW geometry**, adopting the usual description in LQC, with $\{b, v\}=2$ and

$$e^{\alpha}=\left(\sqrt{\frac{27\Delta_g}{16\pi}}\gamma|v|\right)^{1/3}, \qquad \pi_{\alpha}=-\frac{3}{2}v\,b.$$

Area gap

Immirzi parameter

The sign of v determines the orientation of the triad.

The **volume** of the homogeneous sections is $V=2\pi\gamma\Delta_g^{1/2}|v|$.

- The system is subject to a (rescaled) **Hamiltonian constraint**:

$$\boldsymbol{H}_0=\frac{1}{2}\left(\pi_{\phi}^2-H_0^{(2)}\right), \qquad H_0^{(2)}=3\pi(vb)^2-2V^2W(\phi).$$

Non-fermionic perturbations

- We perturb the geometry and the inflaton, and **truncate the action at second perturbative order**.
- Using **spatial, vector, and tensor** harmonics, constructed from the Laplace-Beltrami operator on the spatial sections, we expand the perturbations in modes.
- **Zero-modes** are treated exactly at second perturbative order.
- In this perturbative scheme, the total system is a **constrained** system with a **canonical** structure.

Non-fermionic perturbations

- Linear perturbative constraints generate perturbative diffeomorphisms. Only perturbative quantities not affected by these transformations are physical:

  → **GAUGE INVARIANTS**.

- **Tensor perturbations** are gauge invariants.

- The **Mukhanov-Sasaki invariant** is related to the comoving curvature (*scalar*) perturbations. Its **momentum** can be chosen proportional to the time derivative.

- One can find **momenta** for the linear perturbative constraints, that commute with the gauge invariants.

Non-fermionic perturbations

- In all these considerations, the **background** variables (zero-modes) had been kept fixed. [Langlois]

↓

- The variables for the perturbations can be completed into a **canonical set for the whole system**. [Pinto-Neto]

- Zero-modes are corrected with a fixed quadratic contribution of the perturbations.

  The **corrected zero-modes** are the genuine free (*background*) variables.

Non-fermionic perturbations

- This correction of the zero-modes modifies the **quadratic perturbative contribution** to the global Hamiltonian constraint.

The resulting global Hamiltonian constraint is a gauge invariant.

- This **quadratic perturbative contribution**, additional to the Hamiltonian of the homogeneous sector, equals the Mukhanov-Sasaki Hamiltonian ${}^{MS}H_2$ plus the tensor one ${}^{T}H_2$.

- The rest of the total Hamiltonian is a sum of linear perturbative constraints, with redefined Lagrange multipliers.

The Dirac field

- We introduce a **massive Dirac field** Ψ:

$$S_D = \int d^4x \sqrt{|g|} \left[i M \Psi^\dagger \gamma^0 \Psi - \frac{1}{2} \left(i \Psi^\dagger \gamma^0 e_a^\mu \gamma^a \nabla_\mu^S \Psi + Hermitian \quad conj. \right) \right].$$

Connection

Mass

Tetrad

Dirac matrices

At our truncation order the Dirac field, regarded as a perturbation, couples directly with the (corrected) **FLRW geometry**.

- Adopting the Weyl representation for the Dirac matrices, we can describe the Dirac field by a pair of two-component spinors of definite chirality $\varphi_A, \bar{\chi}_{A'} \, (A, A'=1,2)$, that are **Grassmann** variables.

- In the internal time gauge $e_0^a = 0 \ \ (a \neq 0)$, the gauge group reduces to SU(2).

The Dirac field

- We **expand** the spinors in eigenmodes of the Dirac operator on the spatial sections, with time-dependent anticommuting coefficients:

$$\phi_A(x) = e^{-\frac{3\alpha}{2}} \left(\frac{3}{4\pi}\right)^{3/4} \sum_{\vec{k},(\pm)} \left[m_{\vec{k}} w_A^{\vec{k},(+)} + \bar{r}_{\vec{k}} w_A^{\vec{k},(-)} \right],$$

$$\bar{\chi}_{A'}(x) = e^{-\frac{3\alpha}{2}} \left(\frac{3}{4\pi}\right)^{3/4} \sum_{\vec{k},(\pm)} \left[\bar{s}_{\vec{k}} \bar{w}_{A'}^{\vec{k},(+)} + t_{\vec{k}} \bar{w}_{A'}^{\vec{k},(-)} \right].$$

Left-handed chirality

Right-handed chirality

Eigenvalue $-\omega_k$

Complex conjugation

Constant anticommutation relations

$\vec{k} \in \mathbb{Z}^3$

Eigenvalue $+\omega_k$

- Dirac eigenspinors:

$$w_A^{\vec{k},(\pm)}(\vec{\theta}) = u_A^{\vec{k},(\pm)} e^{i 2\pi (\vec{k}+\vec{\tau})\cdot\vec{\theta}}.$$

Constant normalized spinors

Determines the spin structure

- $\vec{\tau}$ may be any of the vertices of the cube with side ½.

The Dirac field

- Eigenmode expansion:

$$\phi_A(x) = e^{-\frac{3\alpha}{2}} \left(\frac{3}{4\pi}\right)^{3/4} \sum_{\vec{k},(\pm)} \left[m_{\vec{k}} w_A^{\vec{k},(+)} + \bar{r}_{\vec{k}} w_A^{\vec{k},(-)} \right],$$

$$\bar{\chi}_{A'}(x) = e^{-\frac{3\alpha}{2}} \left(\frac{3}{4\pi}\right)^{3/4} \sum_{\vec{k},(\pm)} \left[\bar{s}_{\vec{k}} \bar{w}_{A'}^{\vec{k},(+)} + t_{\vec{k}} \bar{w}_{A'}^{\vec{k},(-)} \right].$$

Same helicity

Eigenvalues: $+\omega_k = 2\pi |\vec{k} + \vec{\tau}|$, each with **degeneracy** $g_k = O(\omega_k^2)$.

- Let us use the same annihilation and creation variables as **D'Eath & Halliwell**. For nonzero-modes, and $(x, y) = (m, s)$ o (t, r):

$$a_{\vec{k}}^{(x,y)} = \sqrt{\frac{\xi_k - \omega_k}{2\xi_k}} x_{\vec{k}} + \sqrt{\frac{\xi_k + \omega_k}{2\xi_k}} \bar{y}_{-\vec{k}}, \qquad \bar{b}_{\vec{k}}^{(x,y)} : \omega_k \to -\omega_k; \qquad \xi_k = \sqrt{\omega_k^2 + M^2 V^{2/3}}.$$

Particle annihilation

Antiparticle creation

The Dirac field

- Variables: $(x, y) = (m, s)$ or (t, r).

$$a_{\vec{k}}^{(x,y)} = \sqrt{\frac{\xi_k - \omega_k}{2\xi_k}}\, x_{\vec{k}} + \sqrt{\frac{\xi_k + \omega_k}{2\xi_k}}\, \bar{y}_{-\vec{k}}, \qquad \bar{b}_{\vec{k}}^{(x,y)} : \omega_k \to -\omega_k; \qquad \xi_k = \sqrt{\omega_k^2 + M^2 V^{2/3}}.$$

This choice provides an **instantaneous diagonalization** of the Dirac Hamiltonian.

- The choice is **unique** up to unitary transformations if:
  - The FLRW background is treated **classically**.
  - The dynamics of these variables must be **unitarily implementable** on Fock space.
  - The Fock vacuum must be invariant under the Killing isometries of the spatial sections and the spin rotations generated by the helicity.
  - The convention of particles and antiparticles must connect smoothly in the massless limit with the standard one.

Fermionic perturbations

- The D'Eath & Halliwell variables are volume dependent. Hence, the FLRW geometric momentum must be **corrected** to maintain the canonical structure:

$$b \to b + i\frac{M\omega_k V^{1/3}}{3\xi_k^2 v}\sum_{(x,y),\vec{k}}\left(a_{\vec{k}}^{(x,y)} b_{\vec{k}}^{(x,y)} + \bar{a}_{\vec{k}}^{(x,y)} \bar{b}_{\vec{k}}^{(x,y)}\right).$$

- Once this volume dependence is taken into account, the contribution of the fermionic nonzero-modes to the global **Hamiltonian constraint** becomes

$$\sum_{\vec{k}} H_D^{\vec{k}} = \sum_{(x,y),\vec{k}} \frac{\xi_k V^{2/3}}{2}\left(\bar{a}_{\vec{k}}^{(x,y)} a_{\vec{k}}^{(x,y)} - a_{\vec{k}}^{(x,y)} \bar{a}_{\vec{k}}^{(x,y)} + \bar{b}_{\vec{k}}^{(x,y)} b_{\vec{k}}^{(x,y)} - b_{\vec{k}}^{(x,y)} \bar{b}_{\vec{k}}^{(x,y)}\right)$$

$$+2\pi i \sum_{(x,y),\vec{k}} \frac{M\omega_k V^{1/3}}{2\xi_k^2} vb\left(a_{\vec{k}}^{(x,y)} b_{\vec{k}}^{(x,y)} + \bar{a}_{\vec{k}}^{(x,y)} \bar{b}_{\vec{k}}^{(x,y)}\right).$$

Instantaneous diagonalization

Particle production

Hybrid quantization

- For the geometry zero-modes (v, b) we adopt the **polymeric** representation of LQC, with **superselection** of volume states.

- For the inflaton, a conventional **Schrödinger** representation.

- For the Mukhanov-Sasaki field, the tensor perturbations, and the Dirac field, a **Fock** representation (*selected by unitarity criteria*).

- The linear perturbative constraints imply that **physical states** depend only on zero-modes and gauge invariants.

- Only one relevant constraint remains: the **global Hamiltonian** one.

$$\boldsymbol{H}_T = \boldsymbol{H}_0 + {}^{MS}H_2 + {}^{T}H_2 + \sum_{\vec{k}} H_D^{\vec{k}}.$$

Hybrid quantization: LQC

- In **Loop Quantum Cosmology,** the canonical variables can be chosen as the volume variable v, proportional to the cube of the scale factor, and the scaled **connection** $b \propto \dot{\alpha}$, with $\{b, v\} = 2$.

- Only **holonomies** of the connection are meaningful. Their elements can be expressed in terms of $e^{\pm i b/2}$.

- These holonomies shift the volume in a constant, unit step.

- We adopt a **volume** representation with **DISCRETE** measure. It is not continuous.

- The unperturbed Hamiltonian constraint leaves invariant **superselection sectors** with volume eigenvalues that differ in multiples of 4 units.

Hybrid quantization

- In particular: $\hat{\boldsymbol{H}}_0 = \frac{1}{2}\left(\hat{\pi}_\phi^2 - \hat{H}_0^{(2)}\right), \qquad \hat{H}_0^{(2)} = \frac{3}{4\pi\gamma^2}\hat{\Omega}_0^2 - 2\hat{V}^2 W(\hat{\phi}),$

$$2\pi\gamma vb \xrightarrow{\text{Even power}} \hat{\Omega}_0 = \frac{1}{2\sqrt{\Delta_g}}\hat{V}^{1/2}[\widehat{\mathrm{sign}(v)}\widehat{\sin(b)} + \widehat{\sin(b)}\widehat{\mathrm{sign}(v)}]\hat{V}^{1/2}.$$

- In the **fermionic part** of the global Hamiltonian:

- Products with the volume are symmetrized **algebraically**.
- We represent vb by an operator $\hat{\Lambda}_0$ like $\hat{\Omega}_0$, but with double angle.
- $\xi_k = \sqrt{\omega_k^2 + M^2 V^{2/3}}$ is represented in terms of the volume, using the spectral theorem.

- We adopt **normal** ordering for creation and annihilation operators.

Born-Oppenheimer

- We adopt a **Born-oppenheimer ansatz**, with the inflaton playing the role of internal time:

$$\Phi=\chi_0\psi=\chi_0(V,\phi)\psi_s(N_s,\phi)\psi_T(N_T,\phi)\psi_D(N_D,\phi),$$

$$\chi_0(V,\phi)=\hat{U}_0(V,\phi)\chi(V).$$

Fock representation

χ_0: Solution at the considered perturbative order.

$\hat{U}_0$: Evolution operator, with positive $\hat{\tilde{H}}_0=[\hat{\pi}_\phi,\hat{U}_0]\hat{U}_0^{-1}.$

- **Approximation**:

No change of FLRW geometry is mediated by the constraint.

⬇

The diagonal element in the FLRW geometry encodes all relevant information about the constraint.

Born-Oppenheimer

- With the ansatz $\Phi=\chi_0(V,\phi)\psi$ and our approximation, we obtain a quadratic **master constraint** for the perturbations, in which the quantum effects on the FLRW geometry are incorporated, and the homogeneous inflaton appears as an **internal time**.

  Neglecting some ignorable terms for the scalar perturbations:

Possible FLRW contribution

$$\|\chi_0\|^2\,\hat{\pi}_\phi^2\psi+\langle(\hat{\tilde{H}}_0)^2-\hat{H}_0^{(2)}\rangle_{\chi_0}\psi$$

$$+2\langle\hat{\tilde{H}}_0\rangle_{\chi_0}\hat{\pi}_\phi\psi=-2\langle{}^{MS}\hat{H}_2+{}^{T}\hat{H}_2\rangle_{\chi_0}\psi-2\langle\textstyle\sum_{\vec{k}}\hat{H}_D^{\vec{k}}\rangle_{\chi_0}\psi.$$

LQC inner product

Schrödinger equation

Born-Oppenheimer

- If the perturbations have a negligible contribution to the inflaton momentum compared to the average of the FLRW part, we arrive at **Schrödinger** equations for the different perturbations.

In particular:

$$\hat{\pi}_\phi \psi_D = -\frac{\langle \sum_{\vec{k}} \hat{H}_D^{\vec{k}} \rangle_{\chi_0}}{\langle \hat{\tilde{H}}_0 \rangle_{\chi_0}} \psi_D - \frac{C_D^{(\chi)}(\phi)}{2\langle \hat{\tilde{H}}_0 \rangle_{\chi_0}} \psi_D .$$

Expectation values of the geometry

- The constraint allows for a **backreaction**, which can add to zero:

$$C_s^{(\chi)}(\phi) + C_T^{(\chi)}(\phi) + C_D^{(\chi)}(\phi) = \langle (\hat{\tilde{H}}_0)^2 - \hat{H}_0^{(2)} \rangle_{\chi_0} .$$

- One can **derive equations** of motions for the perturbations directly from the master constraint, even without the above approximation.

Fermionic dynamics

- From the master constraint, the fermionic operators satisfy the **Heisenberg** equations:

$$d_\eta \hat{a}_{\vec{k}}^{(x,y)}(\eta) = -iF_k^{(\chi)} \hat{a}_{\vec{k}}^{(x,y)}(\eta) + G_k^{(\chi)} \hat{b}_{\vec{k}}^{(x,y)\dagger}(\eta),$$
$$d_\eta \hat{b}_{\vec{k}}^{(x,y)\dagger}(\eta,\eta_0) = iF_k^{(\chi)} \hat{b}_{\vec{k}}^{(x,y)\dagger}(\eta) - G_k^{(\chi)} \hat{a}_{\vec{k}}^{(x,y)}(\eta).$$

where the evolution is described in terms of a well-defined **conformal time** that depends on the state of the FLRW geometry

$$d\eta = \frac{\langle \hat{V}^{2/3} \rangle_{\chi_0}}{\langle \hat{\tilde{H}}_0 \rangle_{\chi_0}} d\phi .$$

Here:

$$F_k^{(\chi)} = \frac{\langle \xi_k(\hat{V}) \hat{V}^{2/3} \rangle_{\chi_0}}{\langle \hat{V}^{2/3} \rangle_{\chi_0}}, \quad G_k^{(\chi)} = M\omega_k \frac{\langle \xi_k^{-1}(\hat{V}) \hat{V}^{1/6} \hat{\Lambda}_0 \hat{V}^{1/6} \xi_k^{-1}(\hat{V}) \rangle_{\chi_0}}{2\gamma \langle \hat{V}^{2/3} \rangle_{\chi_0}}.$$

Fermionic dynamics

- $$d_\eta \hat{a}_{\vec{k}}^{(x,y)}(\eta) = -iF_k^{(\chi)} \hat{a}_{\vec{k}}^{(x,y)}(\eta) + G_k^{(\chi)} \hat{b}_{\vec{k}}^{(x,y)\dagger}(\eta),$$
$$d_\eta \hat{b}_{\vec{k}}^{(x,y)\dagger}(\eta,\eta_0) = iF_k^{(\chi)} \hat{b}_{\vec{k}}^{(x,y)\dagger}(\eta) - G_k^{(\chi)} \hat{a}_{\vec{k}}^{(x,y)}(\eta).$$

$$F_k^{(\chi)} = \frac{\langle \xi_k(\hat{V}) \hat{V}^{2/3} \rangle_{\chi_0}}{\langle \hat{V}^{2/3} \rangle_{\chi_0}},$$
$$G_k^{(\chi)} = M\,\omega_k \frac{\langle \xi_k^{-1}(\hat{V}) \hat{V}^{1/6} \hat{\Lambda}_0 \hat{V}^{1/6} \xi_k^{-1}(\hat{V}) \rangle_{\chi_0}}{2\gamma \langle \hat{V}^{2/3} \rangle_{\chi_0}}.$$

- Recall that $\xi_k(\hat{V}) = \sqrt{\omega_k^2 + M^2 \hat{V}^{2/3}}$. Therefore, fermions couple with an **infinite** sequence of expectation values on the geometry.

- The solution to the Heisenberg equations provides a **Bogoliubov transformation** from the initial operators.

There is no guarantee that it reproduces a transformation in an effective background.

Quantum evolution

- Let (α_k, β_k) be the coefficients of the Bogoliubov transformation. We must have $|\alpha_k|^2+|\beta_k|^2=1$. We use the **parametrization:**

$$e^{i\omega_k(\eta-\eta_0)}\alpha_k=\cos A_k+i\rho_k\frac{\sin A_k}{A_k}, \qquad \rho_k\in\mathbb{R}, \quad \Gamma_k\in\mathbb{C}.$$

$$e^{-i\omega_k(\eta-\eta_0)}\beta_k=-\Gamma_k\frac{\sin A_k}{A_k}, \qquad A_k=\sqrt{|\Gamma_k|^2+\rho_k^2}.$$

- Zero-modes aside, $\hat{U}_D=\hat{U}_B\hat{U}_F$ solves the fermionic evolution. $\hat{U}_F$ **rotates** the phase of the operators by $\omega_k(\eta-\eta_0)$ and $\hat{U}_B=e^{-\hat{T}_B}$:

$$\hat{T}_B=\sum\left[\Gamma_k\hat{a}_{\vec{k}}^{(x,y)\dagger}\hat{b}_{\vec{k}}^{(x,y)\dagger}-\bar{\Gamma}_k\hat{b}_{\vec{k}}^{(x,y)}\hat{a}_{\vec{k}}^{(x,y)}-i\rho_k\left(\hat{a}_{\vec{k}}^{(x,y)\dagger}\hat{a}_{\vec{k}}^{(x,y)}+\hat{b}_{\vec{k}}^{(x,y)\dagger}\hat{b}_{\vec{k}}^{(x,y)}\right)+ic_k^{(x,y)}\right].$$

$\vec{k}\neq\vec{0}$ *if* $\vec{\tau}=\vec{0}$; $(x,y)\in\{(m,s),(r,t)\}$.

Phase

Unitarity

- **The quantum evolution is unitary iff** the β-coefficients are square-summable. A careful **asymptotic** analysis proves that:

$$\beta_k(\eta)=i\frac{M}{4\omega_k^2}\left[\lambda_0^{(\chi)}(\eta_0)e^{-i\omega_k(\eta-\eta_0)}-\lambda_0^{(\chi)}(\eta)e^{i\omega_k(\eta-\eta_0)}\right]+O(\omega_k^{-3}).$$

- Since the degeneracy goes like $g_k=O(\omega_k^2)$: ⬎

The quantum evolution is indeed well-defined and **unitary**.

- For large frequency, the β-coefficients are proportional to the fermion mass: **negligible production of particles**.

- $$\lambda_0^{(\chi)}=\frac{\langle\hat{V}^{1/6}\hat{\Lambda}_0\hat{V}^{1/6}\rangle_{\chi_0}}{\gamma\langle\hat{V}^{2/3}\rangle_{\chi_0}}$$ → It vanishes "at the bounce", reducing the particle production

Vacuum evolution

- The **evolved vacuum** is

$$\hat{U}_D|0\rangle_D=\prod_{(x,y),\vec{k}} e^{i\left[\rho_k-c_k^{(x,y)}-\omega_k(\eta-\eta_0)\right]}\,\bar{\alpha}_k\left[1+\frac{\beta_k}{\bar{\alpha}_k}\,\hat{a}_{\vec{k}}^{(x,y)\dagger}\,\hat{b}_{\vec{k}}^{(x,y)\dagger}\right]|0\rangle_D .$$

Particle creation

c-number phase

Rotating phase

- It is an exact solution to the Schrödinger equation if the **backreaction** is

$$C_D^{(\chi)}(\phi)=2\langle\hat{V}^{2/3}\rangle_{\chi_0}\sum_{(x,y),\vec{k}}\left[G_k^{(\chi)}\,\Im(\Gamma_k)+\left(c_k^{(x,y)}\right)'\right].$$

Phase

β-coefficient

Recall that $$G_k^{(\chi)}=M\,\omega_k\,\frac{\langle\xi_k^{-1}(\hat{V})\,\hat{V}^{1/6}\,\hat{\Lambda}_0\,\hat{V}^{1/6}\,\xi_k^{-1}(\hat{V})\rangle_{\chi_0}}{2\gamma\langle\hat{V}^{2/3}\rangle_{\chi_0}}.$$

Vacuum evolution

- **Backreaction:** $C_D^{(\chi)}(\phi)=2\langle\hat{V}^{2/3}\rangle_{\chi_0}\sum_{(x,y),\vec{k}}\left[G_k^{(\chi)}\Im(\Gamma_k)+\left(c_k^{(x,y)}\right)'\right].$

- Our asymptotic analysis gives:

$$G_k^{(\chi)}\Im(\Delta_k)=\frac{M^2}{8\omega_k^3}\lambda_0^{(\chi)}(\eta)\left[\lambda_0^{(\chi)}(\eta)-\lambda_0^{(\chi)}(\eta_0)\cos[2\omega_k(\eta-\eta_0)]\right]+O(\omega_k^{-4}).$$

- Recalling that the degeneracy is $g_k=O(\omega_k^2)$, **regularization** of the backreaction, absorbing the divergent part in the phase, is *(barely)* needed.

- This considerably improves the situation found by D'Eath & Halliwell, who got, for each fermionic mode, a contibution $O(\omega_k)$.

Conclusions

- We have completed the hybrid loop quantization of a perturbed FLRW cosmology with scalar and **Dirac fields**.
- We have deduced a master constraint for the perturbations using a Born-Oppenheimer approximation.
- In the resulting quantum dynamics, the fermions couple with the geometry through an **infinite** number of expectation values.
- We have solved this fermionic quantum dynamics and proven that it is **unitary**, even if the geometry is a quantum entity.

Conclusions

- We have shown that the unitarily **evolved vacuum** for the Dirac field is a **solution** to the associated Schrödinger equation.
- Since the dynamics is unitary, the **production of particles** is finite. Furthermore, it is negligible for modes of large frequency.
- **Backreaction** effects in our vacuum require regularization, but the situation is much better than in traditional studies.
- Finally, there exists the possibility of choosing **another vacuum**, in the same unitary family, which improves the behaviour of the backreaction in such a way that regularization **may not be needed**.