A Mechanism of Baryogenesis for Causal Fermion Systems
(CQG. 39 (2022) 165005; arXiv: 2111.05556)

Prospects of deriving the matter/anti-matter asymmetry and the potential consequences of this mechanism for the cosmic evolution.

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joint work Felix Finster[‡] and Maximilian Jokel[‡].

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My Goal

The theory of Causal Fermion Systems (CFS) is a new attempt to unify gravity and the standard model of particle physics. My goals for this talk are:

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The theory of Causal Fermion Systems (CFS) is a new attempt to unify gravity and the standard model of particle physics. My goals for this talk are:

- Make you aware of all the claims that exist in the literature with respect to Causal Fermion Systems (most worked out by Felix Finster and a few collaborators).
- Convince you that it opens the gate to qualitatively new phenomenology that can be studied in the context of open problems.

Results from Theory of Causal Fermion Systems

- Standard Model gauge group and it's classical field equations in linear perturbation theory of Minkowski space. (Higgs open but expected to work out right).
- For that to work it requires at least three generations of fermions.
- Quantum Field Theory in non-linear perturbation theory of Minkowski space.
- Einstein equations can also be derived.
- Explains weakness of gravity as the Einstein equations appear as a third order effect.
- Euler Lagrange equations lead to the classical field equations on the light cone $\rightarrow$ insensitive to the cosmological constant.

The general definition

Definition (Causal fermion system)

Let $(\mathcal{H}, \langle .|. \rangle_{\mathcal{H}})$ be Hilbert space
Given parameter $n \in \mathbb{N}$ ("spin dimension")

$\mathcal{F} := \Big\{ x \in \mathrm{L}(\mathcal{H})$ with the properties:

- x is self-adjoint and has finite rank
- x has n positive and n negative eigenvalues $\Big\}$

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- $\mathcal{F}$ is an operator manifold $\rightarrow$ combines structures of GR and QT.
- Support of measure $\rho \rightarrow$ spacetime.
- Operator products $xy \rightarrow$ connection.
- EV's $\lambda_j^{xy} \rightarrow$ causality, lagrangian.

Causal action principle

$$\text{Lagrangian} \qquad \mathscr{L}[A_{xy}] = \frac{1}{4n} \sum_{i,j=1}^{2n} \left(|\lambda_i^{xy}| - |\lambda_j^{xy}| \right)^2 \;\geq\; 0$$

$$\text{Action} \qquad \mathscr{S} = \iint_{\mathcal{F}\times\mathcal{F}} \mathscr{L}[A_{xy}]\, d\rho(x)\, d\rho(y) \;\in\; [0, \infty]$$

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Minimize $\mathscr{S}$ under variations of ρ, with constraints

volume constraint: $$\rho(\mathcal{F}) = \text{const}$$

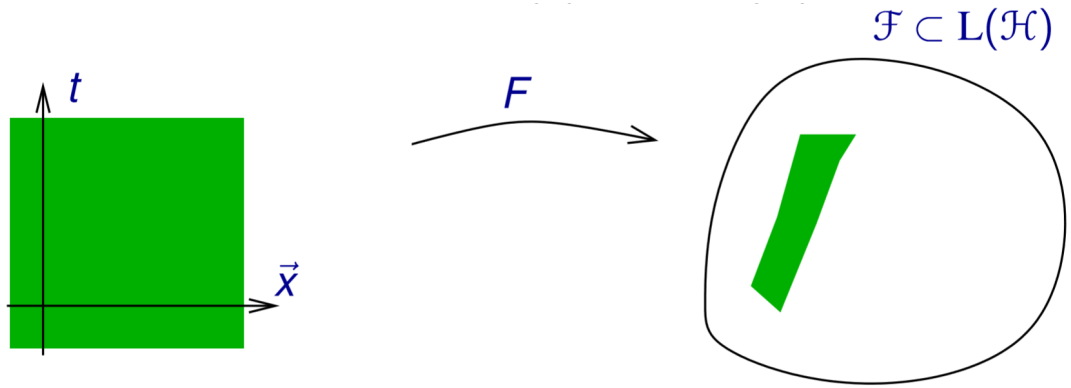
trace constraint: $$\int_{\mathcal{F}} \mathrm{tr}(x)\, d\rho(x) = \text{const}$$

boundedness constraint: $$\iint_{\mathcal{F}\times\mathcal{F}} \sum_{i=1}^{2n} |\lambda_i^{xy}|^2\, d\rho(x)\, d\rho(y) \leq C$$

Local Correlation Map

We can define a mapping

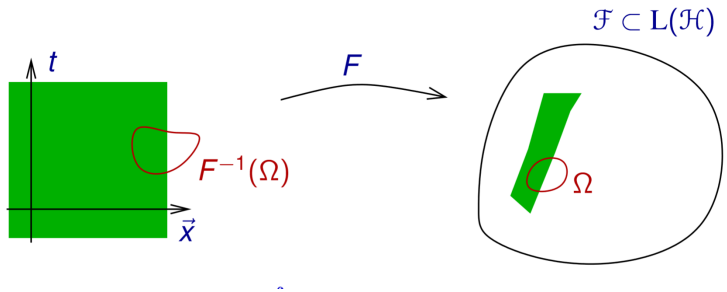
$$\begin{aligned} \mathscr{M} &\mapsto \mathcal{F} \qquad \subset \mathrm{L}(\mathcal{H}) \\ x &\mapsto F(x) \end{aligned}$$



Concept:

- left side is an (approximate) effective description of the right side
- objects on the right represent the ”true” nature of the physical system.
- the map allows us to work with familiar structures on the left.

Local Correlation Map



$$\rho(\Omega) := \int_{F^{-1}(\Omega)} d^4x = \mu\big(F^{-1}(\Omega)\big)$$

- push-forward measure, is measure on $\mathcal{F}$.
- image of F recovered as the support of the measure,

$$M := \operatorname{supp} \rho = \big\{ F \in \mathcal{F} \mid \rho(\Omega) \neq 0 \text{ for every open neighborhood } \Omega \text{ of } x \big\}$$

- Define representation of Hilbertspace in terms of ”physical wave functions” $\psi(x) = \pi_x \psi$ with $\psi \in \mathcal{H}$.

Minkowski space as a CFS

- Choose $\mathcal{H}$ as the space of all negative-energy solutions, hence "Dirac sea"
- Introduce regularization with length scale ε.
- Take limit $\varepsilon \to 0$.
  $\longrightarrow$ Minkowski space with the "Dirac sea" as a Hilbertspace is a minimizer to the causal action principle.
  $\longrightarrow$ Only perturbations to the Dirac sea can be observed as matter and physical fields.

Sakharov's Criteria

- The second criteria is trivially satisfied as the fundamental description treats particle and anti-particle states differently (while preserving the symmetries in the effective description in the continuum limit).
- In our recent paper (arXiv: 2111.05556) we showed that the first criterion can indeed be satisfied in the CFS setup in the form of a fermion number violation.
- It is not entirely clear how the third criteria is satisfied in the context of our new mechanism. Note however that we require deviations from FLRW for the effect to exist. This can be interpreted as a form of non-thermality.

The Mechanism - The Ingredients

- Finite regularization ε with associated regularizing vector field.
- Deviation from Dirac dynamics on cosmological scales implied by the rigid regularization.

The locally rigid regularization (i.e. cut of at a certain energy with respect to the regularizing vector field) is motivated by detailed studies of the causal action principle.

The Mechanism - The Effect

- Dynamics in the regularization lead to a change in the ”sea-level” of the Dirac sea (technically we prove a spectral flow across the zero energy level).
- Effect is identical across all three generations, across all charged fermionic sectors (i.e. the matter created is neutral w.r.t. all charges).
- Non-Riemannian measures are required. The dynamics of the measure compensates for the non-conservation of the matter stress energy.

The Timeline

- Small ε vacuum state
- Baryogenesis
- Reheating (decay of the third generation fermions)
- FLRW evolution
- Large ε vacuum state

Novel Phenomenology

- If DM is Fermionic and weakly coupled it could survive reheating in the Fermi ground state.
- Different dynamics during the matter dominated era of the universe due to the degeneracy pressure from DM.
- Dynamics become dust like after structure formation when the gravitational potential wells get deep enough and the fermi gas localizes around galaxies and clusters.
- Fermionic DM in ground state could solve the DM cusp problem in galaxies.

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applications:

- describes fundamental forces of nature
- approach for unification of gravitation and the standard model.
- gives rise to new mechanism for fermiogenesis.

Thank You

Thank you for your attention.

For a more in depth introduction see the website
causal-fermion-system.com