Clocks and dynamics in Quantum Universe

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Quantum Universe

- **General relativity** cannot be trusted at extreme curvature regime, ultimately needs to be quantized (Singularity theorems by Hawking & Penrose). **Quantum corrections** are expected to resolve classical singularities.
- **Conceptual problem**: no background structure. One needs to pick up internal variables to play a role of internal coordinates. In particular, **no preferred internal clock** so one can have multiple Schrödinger equations.
- Universal question regarding quantum gravity: are **quantum dynamics based on different clocks** closely related? Is the singularity resolution a meaningful concept?

GR as a totally constrained system

- $\mathcal{M} = \Sigma \times \mathbb{R}$, $\Gamma = (q_{ab}, p^{ab})$:

$$H = \int_\Sigma \mathrm{d}^3x \ \left(NC_0 + N^i C_i\right)$$

where $C_\mu(x)[q_{ab}, p^{ab}]$ are first-class constraints. **What are all these dofs?**

- *Canonical transformation:*

$$(q_{ab}, p^{ab}) \mapsto (X^\mu, P_\mu, \phi^r, \pi_s)$$

such that $C_\mu \approx P_\mu + h_\mu(X, \phi, \pi)$.

- *Internal coordinates:* $X^0(x,t) := t$, $X^i(x,t) := x^i$,
- *Physical dynamics involves only physical DOFs:*

$$\frac{\mathrm{d}\phi^r}{\mathrm{d}t} = \{\phi^r, H_{true}\}_{phys}, \quad \frac{\mathrm{d}\pi_s}{\mathrm{d}t} = \{\pi_s, H_{true}\}_{phys}$$

where $H_{true}(t) = \int_\Sigma \mathrm{d}^3x \ h_0(t,x)[\phi, \pi]$

Clock transformations

Canonical transformations,
$(q^I, p_I) \mapsto (\bar{q}^I, \bar{p}_I)$:

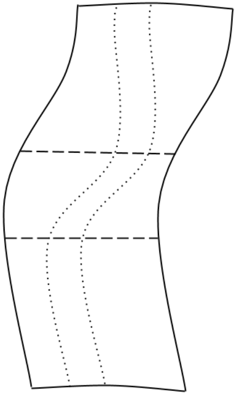
$$\omega = \mathrm{d}q^I \mathrm{d}p_I = \mathrm{d}\bar{q}^I \mathrm{d}\bar{p}_I$$

Contact transformations,
$(q^I, p_I, t) \mapsto (\bar{q}^I, \bar{p}_I)$:

$$\omega_{\mathcal{C}} = \mathrm{d}q^I \mathrm{d}p_I - \mathrm{d}t\mathrm{d}h = \mathrm{d}\bar{q}^I \mathrm{d}\bar{p}_I - \mathrm{d}t\mathrm{d}\bar{h}$$

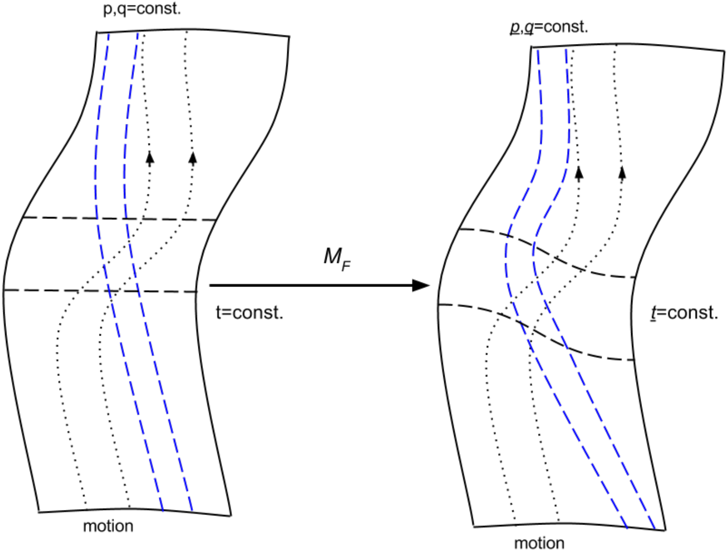
Clock transformations,
$(q^I, p_I, t) \mapsto (\bar{q}^I, \bar{p}_I, \bar{t})$:

$$\omega_{\mathcal{C}} = \mathrm{d}q^I \mathrm{d}p_I - \mathrm{d}t\mathrm{d}h = \mathrm{d}\bar{q}^I \mathrm{d}\bar{p}_I - \mathrm{d}\bar{t}\mathrm{d}\bar{h}$$



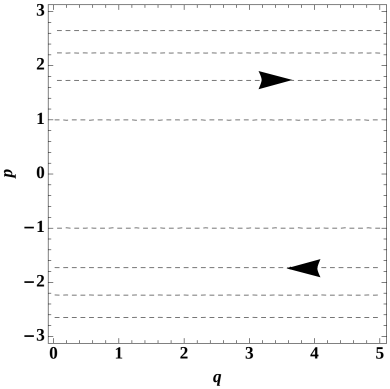
$\mathbf{R}^1$ x Phase Space

Matching different canonical frameworks together



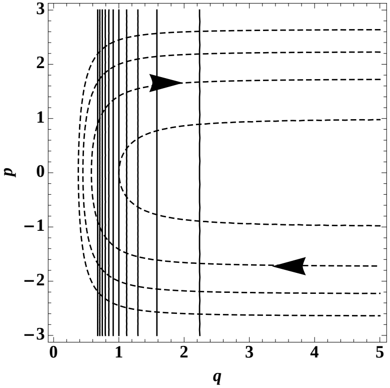
Isotropic singularity model

$$H = p^2, \quad q > 0$$

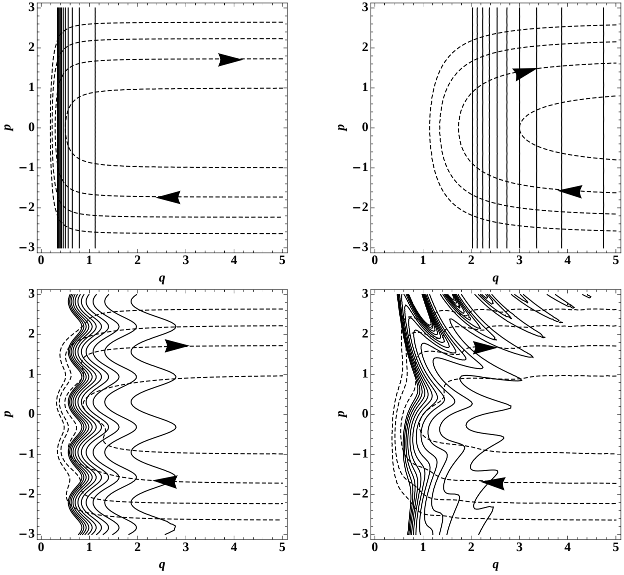


Isotropic singularity resolution

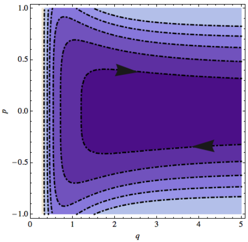
$$H_{sem} = p^2 + Kq^{-2}$$

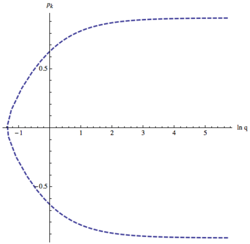


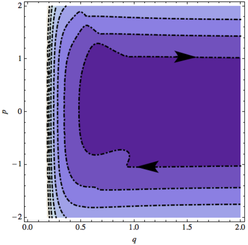
Clock effect

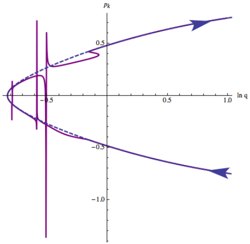


Anisotropic singularity resolution









Conclusions

1. Not all dynamical features of quantized gravity models are meaningful (e.g. Planck scale, number of bounces, . . .).
2. Dynamical observables in quantum gravity models are only the asymptotic states. In this restricted sense, the dynamics in quantum gravity is deterministic (and the singularity resolution meaningful).
3. This could be reconciled with lab systems: the total system contains both quantum and classical (**classical environment**) variables. Any clock redefinition involving only the classical variables do not alter the dynamics of the quantum variables. A unique Schrödinger equation holds.
4. Expectation: the early Universe lacks classical environments...