Mirrored Schrödinger’s cat

What CP-violating particles tell us about quantum collapse models

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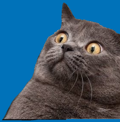
Standard quantum mechanics



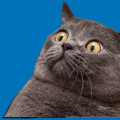
- linearity of Schrödinger equation allows superpositions:

$$\psi_1, \psi_2 \text{ are solutions} \Rightarrow \psi = c_1\psi_1 + c_2\psi_2 \text{ is also a solution}$$

- evolution of quantum system due to Schrödinger equation is deterministic
- measurement destroys superposition with outcomes distributed due to Born rule:

$$P_1 = |c_1|^2,\ P_2 = |c_2|^2\ (\langle\psi_1|\psi_2\rangle = 0).$$

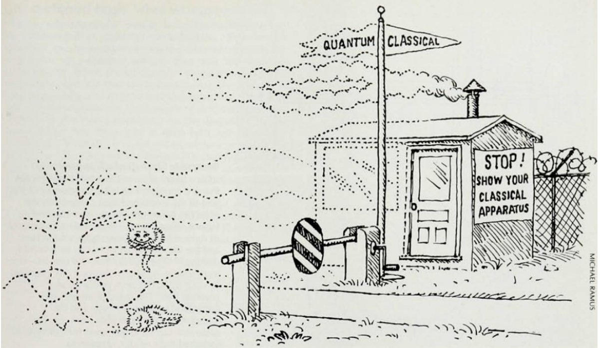
Troubles with standard QM



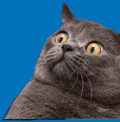
Standard quantum mechanics exposes two different regimes:

1. Schrödinger evolution: linear, deterministic and reversible.
2. Measurement: non-linear, stochastic and irreversible.

Question: Is there a border between quantum and classical worlds?



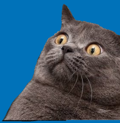
Solutions?



- Copenhagen interpretation (Bohr, 1928)
- Bohmian mechanics (Bohm, 1952)
- many-worlds interpretation (Everett, 1957)
- decoherence (Zeh, 1970)
- spontaneous collapse (Ghirardi, Rimini, and Weber, 1986)
- gravity induced collapse (Károlyházy, 1966; Diósi, 1984; Penrose, 1996)
- quantum Bayesianism (Caves, Fuchs, and Schack, 2002)
- quantum Darwinism (Zurek, 2003)
- coarse-grained measurements (Kofler and Brukner, 2007)

A. Bassi et al., Rev. Mod. Phys. **85**, 471 (2013).

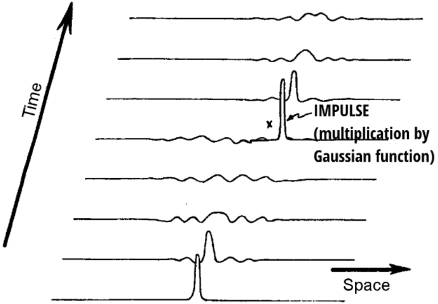
How does a collapse model work?



Universal dynamics should:

1. be **non-linear**
2. be **stochastic**
3. include **non-unitary evolution**
4. **not** allow for superluminal signaling

> **Proposition (GRW)**
> Each particle of a system of n particles experiences a sudden spontaneous localization process with defined rate, and in the time interval between two localizations system evolves due to Schrödinger equation.



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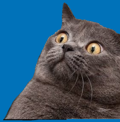

Quantum state equation:

$$d|\psi_t\rangle = [-i\hat{H}dt + \sqrt{\lambda}\sum_i(\hat{A}_i - \underbrace{\langle\hat{A}_i\rangle_t}_{nonlin})\underbrace{dW_{i,t}}_{stoch} - \frac{\lambda}{2}\sum_i(\hat{A}_i - \underbrace{\langle\hat{A}_i\rangle_t}_{nonlin})^2]|\psi_t\rangle,$$

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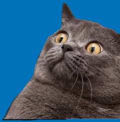

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Master equation for $\rho_t = \mathbb{E}[|\psi_t\rangle\langle\psi_t|]$**:**

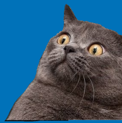
$$\frac{d\rho_t}{dt} = -i[\hat{H},\rho_t] - \underbrace{\frac{\lambda}{2}\sum_i\left[\hat{A}_i^2\rho + \rho\hat{A}_i^2 - 2\hat{A}_i\rho\hat{A}_i\right]}_{Lindblad\ evolution},$$

Mass-proportional CSL model

$$\hat{A} = \frac{1}{(\sqrt{2\pi}r_C)^3}\int d\mathbf{y}e^{-\frac{|\mathbf{x}-\mathbf{y}|^2}{2r_C^2}}\sum_i\frac{m_i}{m_0}\psi_i^\dagger(\mathbf{y})\psi_i(\mathbf{y}),$$

Neutral kaons

Neutral kaons



Dynamics

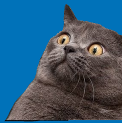
WWA Hamiltonian: $\hat{H}_{\mathrm{WWA}} = \underbrace{\hat{M}}_{\text{mass}} + \underbrace{\frac{i}{2}\hat{\Gamma}}_{\text{decay}}$

$$\begin{aligned} |\psi\rangle_t &= a_t|K^0\rangle + b_t|\bar{K}^0\rangle \\ \hat{H}|K_{L/S}\rangle &= \left(m_{L/S} + \frac{i}{2}\Gamma_{L/S}\right)|M_{L/S}\rangle \end{aligned}$$

$$\begin{aligned} \Gamma_L &\approx 1.95 \cdot 10^7 s^{-1} \\ \Gamma_S &\approx 1.12 \cdot 10^{10} s^{-1} \end{aligned}$$

Physical (flavor) states: $|K^0/\bar{K}^0\rangle = \frac{1}{\sqrt{2}}(|K_L\rangle \pm |K_S\rangle)$

Neutral kaons



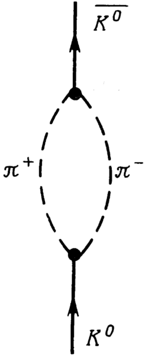
Single-particle evolution

$$P_{K^0\to K^0/\bar{K}^0}(t) = \frac{e^{-\Gamma t}}{2}\left(\cosh\left[\frac{\Delta\Gamma}{2}t\right] \pm \underbrace{\cos[t\Delta m]}_{\text{oscillations!}}\right).$$

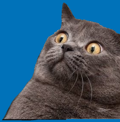
KLOE experiments

$$P_{I\to K^0\bar{K}^0/K^0\bar{K}^0}(t_1,t_2) = \frac{e^{-\Gamma t}}{4}\left(\cosh\left[\frac{\Delta\Gamma}{2}\Delta t\right] + \cos[\Delta t\Delta m]\right),$$

with $|I\rangle = \frac{1}{\sqrt{2}}(|K^0\bar{K}^0\rangle - |\bar{K}^0K^0\rangle)$



CSL collapse in flavor oscillations



Single particle:

$$P_{K^0\to K^0/\bar{K}^0}(t) = \frac{e^{-\Gamma t}}{2}\left[\cosh\left(\frac{\Delta\Gamma t}{2}\right) + e^{-\frac{\Lambda}{2}t}\cos(\Delta m t)\right],$$

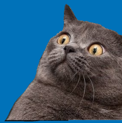
Two particles:

$$P_{I\to K^0\bar{K}^0/\bar{K}^0K^0}(t_1,t_2) = \frac{e^{-\Gamma(t_1+t_2)}}{4}\left[\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + e^{-\frac{\Lambda}{2}(t_1+t_2)}\cos(\Delta m\Delta t)\right],$$

Here $\Lambda = \lambda_{CSL}\frac{(\Delta m)^2}{m_0^2} \propto 10^{-38}s^{-1}$ is **too weak**!

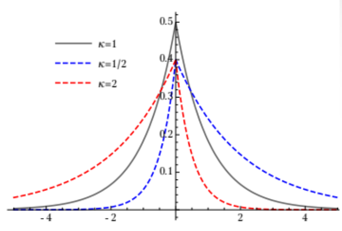
S. Donadi, A. Bassi, C. Curceanu, A. Di Domenico, and B. C. Hiesmayr, , Found. Phys. **43**, 813 (2013).
M. Bahrami, S. Donadi, L. Ferialdi, A. Bassi, C. Curceanu, A. Di Domenico, and B. C. Hiesmayr, Sci. Rep. **3**, 1952 (2013).

CSL collapse with time-asymmetric noise



Time-asymmetric noise

$$\int_0^t dt_1 \int_0^{t_1} dt_2 \mathbb{E}[dW_{t_1} dW_{t_2}] = (1-\beta)t$$



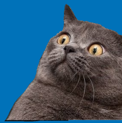
Neutral kaon dynamics under time-asymmetric noise

$$P_{K^0 \to K^0/\bar{K}^0}(t) = \frac{e^{-\tilde{\Gamma} t}}{2}\left[\cosh\left(\frac{\Delta\tilde{\Gamma} t}{2}\right) \pm e^{-\frac{\Lambda}{2}t}\cos(\Delta m t)\right],$$

with decay rates $\tilde{\Gamma}_i = \lambda_{CSL}(2\beta - 1)\frac{m_i^2}{m_0^2}$.

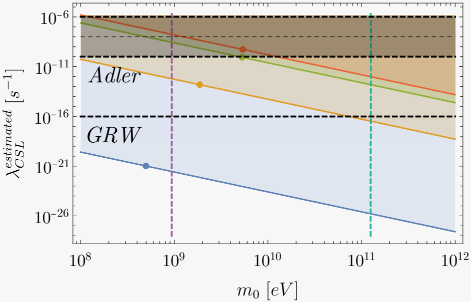
K. Simonov and B. C. Hiesmayr, Phys. Rev. A **94**, 052128 (2016).

CSL collapse with time-asymmetric noise



Collapse rate from the decay dynamics

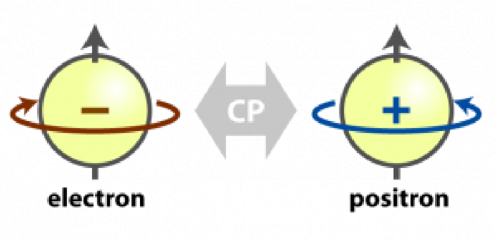
$$\lambda_{CSL} \geq \left(\frac{\Delta m}{m_0 \left(\sqrt{\Gamma_L^{-1}} - \sqrt{\Gamma_H^{-1}} \right)} \right)^2 .$$

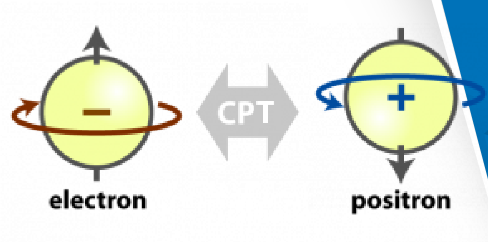


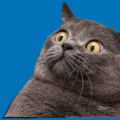
Time asymmetry in CSL noise allows one to recover decay mechanism and absolute masses of neutral kaons!

K. Simonov and B. C. Hiesmayr, Phys. Rev. A **94**, 052128 (2016).
K. Simonov, Phys. Rev. A **102**, 022226 (2020).

Discrete symmetries







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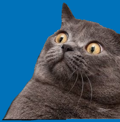
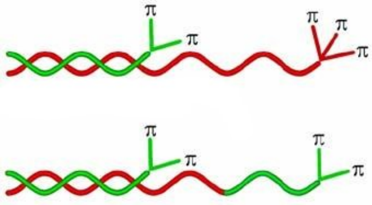


WWA Hamiltonian

$$\hat{H}_{\mathrm{WWA}} = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix}$$



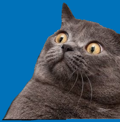
Violation of the $\mathcal{CP}$ symmetry

Non-orthogonality: $|H_{12}| \neq |H_{21}| \Rightarrow [\hat{M}, \hat{\Gamma}] \neq 0 \Rightarrow \langle K_L | K_S \rangle = \delta \neq 0$,

Violation of the $\mathcal{CPT}$ symmetry

Asymmetry: $H_{11} - H_{22} \propto z \neq 0 \Rightarrow \mathbb{A}_{QM}(t) = \frac{P_{K^0 \to K^0}(t) - P_{\bar{K}^0 \to \bar{K}^0}(t)}{P_{K^0 \to K^0}(t) + P_{\bar{K}^0 \to \bar{K}^0}(t)} \neq 0.$

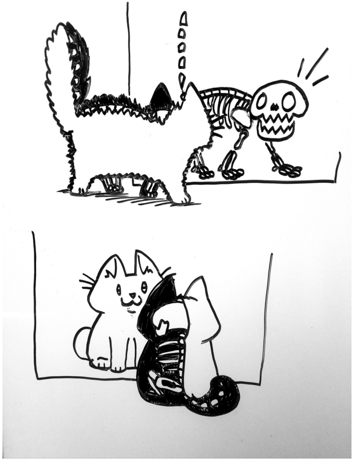
Asymmetry term for two particles

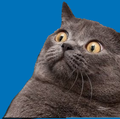


$$\mathbb{A}(t_1, t_2) = \frac{P_{I\to K^0\bar{K}^0}(t_1,t_2) - P_{I\to \bar{K}^0 K^0}(t_1,t_2)}{P_{I\to K^0\bar{K}^0}(t_1,t_2) + P_{I\to \bar{K}^0 K^0}(t_1,t_2)}.$$

In standard quantum mechanics:

$$\mathbb{A}_{QM}(\Delta t) = \frac{2\Re z \sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + 2\Im z \sin(\Delta m \Delta t)}{(1+|z|^2)\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + (1-|z|^2)\cos(\Delta m\Delta t)},$$





Asymmetry term for two particles:

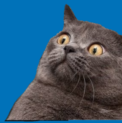
$$\mathbb{A}(t_1, t_2) = \frac{P_{I\to K^0\bar{K}^0}(t_1,t_2) - P_{I\to \bar{K}^0 K^0}(t_1,t_2)}{P_{I\to K^0\bar{K}^0}(t_1,t_2) + P_{I\to \bar{K}^0 K^0}(t_1,t_2)}.$$

Standard quantum mechanics

$$\frac{2\Re z \sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + 2\Im z \sin(\Delta m \Delta t)}{(1+|z|^2)\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + (1-|z|^2)\cos(\Delta m\Delta t)}.$$

This coincides with the single-particle case!

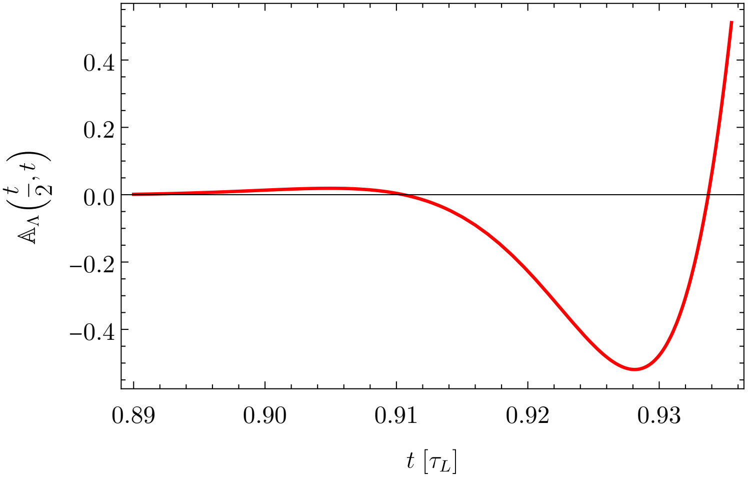
CSL collapse with CP violation



$$
\begin{aligned}
\mathbb{A}_\Lambda(t_1, t_2) \;\approx\; & \frac{2\delta \frac{\Lambda}{\Delta m} \sin(\phi)}{\cosh\left(\frac{\Delta\Gamma\Delta t}{2}\right) + \cos(\Delta m \Delta t)} \Bigg[\sin(\phi) \Bigg(\sinh\left(\frac{\Delta\Gamma\Delta t}{2}\right) \\
& - \sinh\left(\frac{\Delta\Gamma}{2} t_2\right) \cos(\Delta m t_1) + \sinh\left(\frac{\Delta\Gamma}{2} t_1\right) \cos(\Delta m t_2) \Bigg) \\
& + \cos(\phi) \Bigg(\sin(\Delta m \Delta t) + \cosh\left(\frac{\Delta\Gamma}{2} t_2\right) \sin(\Delta m t_1) \\
& - \cosh\left(\frac{\Delta\Gamma}{2} t_1\right) \sin(\Delta m t_2) \Bigg) \Bigg].
\end{aligned}
$$

K. Simonov, Phys. Lett. A **452**, 128413 (2022).

CSL collapse with CP violation



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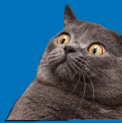
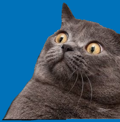


Conclusions and outlook



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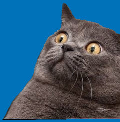
Conclusions and outlook



- Even tiny violation of the $\mathcal{CP}$ symmetry can significantly change the dynamics of neutral kaons under spontaneous collapse.
- When the $\mathcal{CP}$ symmetry is broken, the CSL dynamics affects an asymmetry term witnessing $\mathcal{CPT}$ violation in standard quantum mechanics: this allows one to distinguish in principle between the effects of $\mathcal{CPT}$ violation and spontaneous collapse.

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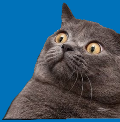

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- When the $\mathcal{CP}$ symmetry is broken, the CSL dynamics affects an asymmetry term witnessing $\mathcal{CPT}$ violation in standard quantum mechanics: this allows one to distinguish in principle between the effects of $\mathcal{CPT}$ violation and spontaneous collapse.
- While increasing the difference $\Delta\Gamma$ between the decay widths, spontaneous collapse effect on a neutral kaon system becomes stronger: hence, neutral kaons could provide a suitable setup to observe spontaneous collapse effect.

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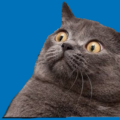

- Even tiny violation of the $\mathcal{CP}$ symmetry can significantly change the dynamics of neutral kaons under spontaneous collapse.
- When the $\mathcal{CP}$ symmetry is broken, the CSL dynamics affects an asymmetry term witnessing $\mathcal{CPT}$ violation in standard quantum mechanics: this allows one to distinguish in principle between the effects of $\mathcal{CPT}$ violation and spontaneous collapse.
- While increasing the difference $\Delta\Gamma$ between the decay widths, spontaneous collapse effect on a neutral kaon system becomes stronger: hence, neutral kaons could provide a suitable setup to observe spontaneous collapse effect.
- This suggests a further research of spontaneous collapse in a $\mathcal{CP}$-violating flavor oscillating system, in particular, how the effect of other types of collapse models such as gravity-related ones.

Thank you for your attention!