

Probing the collapse models at high energy scale: New aspects?

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May 26, 2017

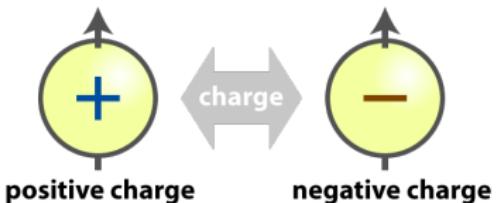


Der Wissenschaftsfonds.

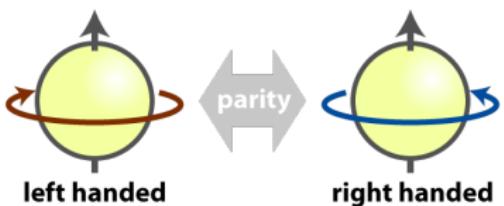
(Project FWF-P26783)

Discrete symmetries: \mathcal{C} , \mathcal{P} , \mathcal{T}

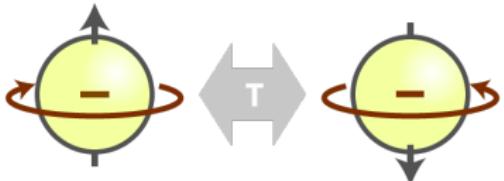
\mathcal{C} (charge conjugation): $\{q\} \rightarrow \{-q\}$



\mathcal{P} (parity inverse): $x \rightarrow -x, t \rightarrow t$



\mathcal{T} (time reversal) : $x \rightarrow x, t \rightarrow -t$



Neutral meson system: Kaons

Decay: $\mathbf{K^0}(\bar{s}d)$, $\bar{\mathbf{K}}^0(s\bar{d}) \rightarrow 2\pi$ ($\mathcal{CP} = +1$), 3π ($\mathcal{CP} = -1$).

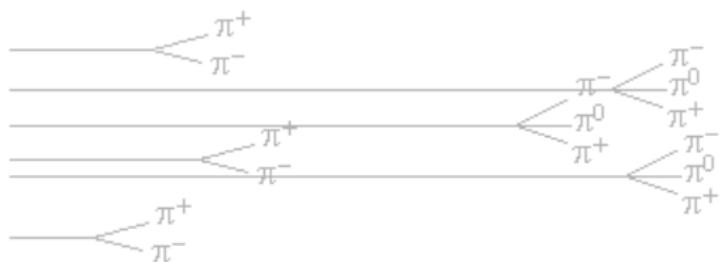
Flavour eigenstates:

$$\mathcal{S}|K^0/\bar{K}^0\rangle = \pm|K^0/\bar{K}^0\rangle.$$

Mass eigenstates:

$$|K_{L/S}\rangle \rightarrow m_{L/S}.$$

$$\Delta m = 5.29 \cdot 10^9 \text{ } \hbar s^{-1}$$



\mathcal{CP} eigenstates: $\hat{\mathcal{CP}}|K_{1/2}\rangle = \pm|K_{1/2}\rangle$.

When \mathcal{CP} symmetry is conserved, $|K_1\rangle = |K_S\rangle$, $|K_2\rangle = |K_L\rangle$.

Mass eigenstates: $|K_S\rangle \rightarrow 2\pi$, $|K_L\rangle \rightarrow 3\pi$.

Flavour eigenstates:

$$|K^0, \bar{K}^0\rangle = \frac{1}{\sqrt{2}}(|K_L\rangle \pm |K_S\rangle).$$

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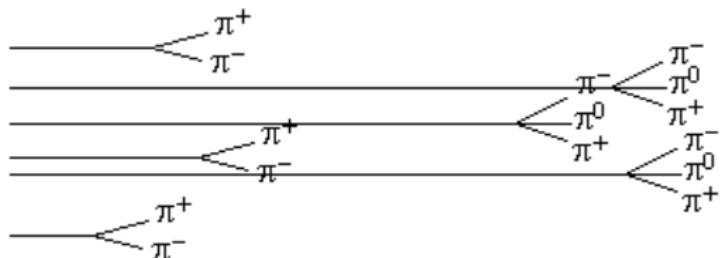
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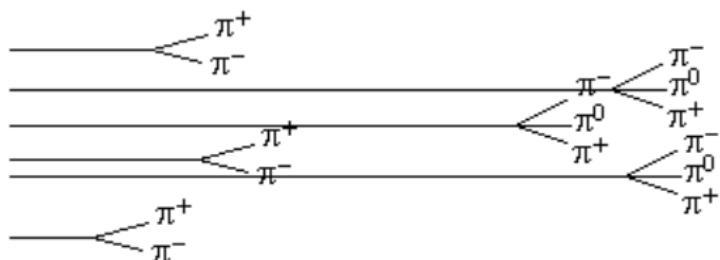
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Neutral meson system: Time evolution

Time evolution of the flavour states:

$$|\psi\rangle_t = a_t |M^0\rangle + b_t |\bar{M}^0\rangle$$

$$\hat{H} = \hat{m} + \frac{i}{2} \hat{\Gamma}$$

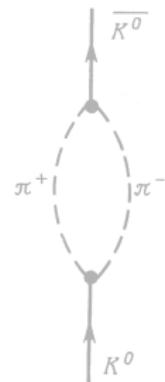
$$\hat{H}|M_i\rangle = \left(m_i + \frac{i}{2}\Gamma_i\right)|M_i\rangle$$

$i = H \dots \text{Heavy}, L \dots \text{Light}$

Kaons:

$$\Gamma_H \approx 1.95 \cdot 10^7 s^{-1}$$

$$\Gamma_L \approx 1.12 \cdot 10^{10} s^{-1}$$



$$|M^0(t)\rangle = \frac{1}{\sqrt{2}} \left(e^{-\frac{\Gamma_H}{2}t - im_H t} |M_H\rangle + e^{-\frac{\Gamma_L}{2}t - im_L t} |M_L\rangle \right),$$

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Transition probabilities:

$$P_{M^0 \rightarrow M^0/\bar{M}^0}(t) = \frac{1}{4} \left(e^{-\Gamma_H t} + e^{-\Gamma_L t} \underbrace{\pm 2e^{-\frac{\Gamma_H+\Gamma_L}{2}t} \cos [t\Delta m]}_{\text{interference term!}} \right).$$

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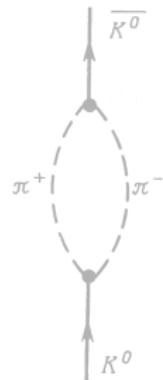
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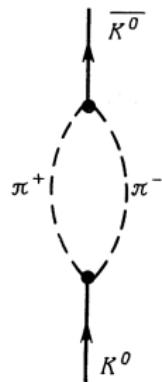
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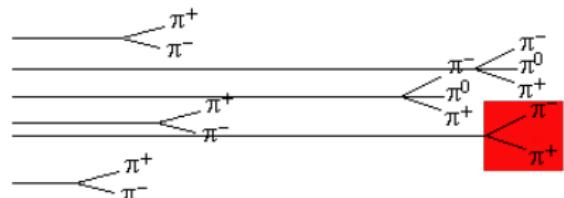
\mathcal{CP} violation

J. Cronin & V. Fitch (1964):

sometimes $K_L \rightarrow 2\pi$!

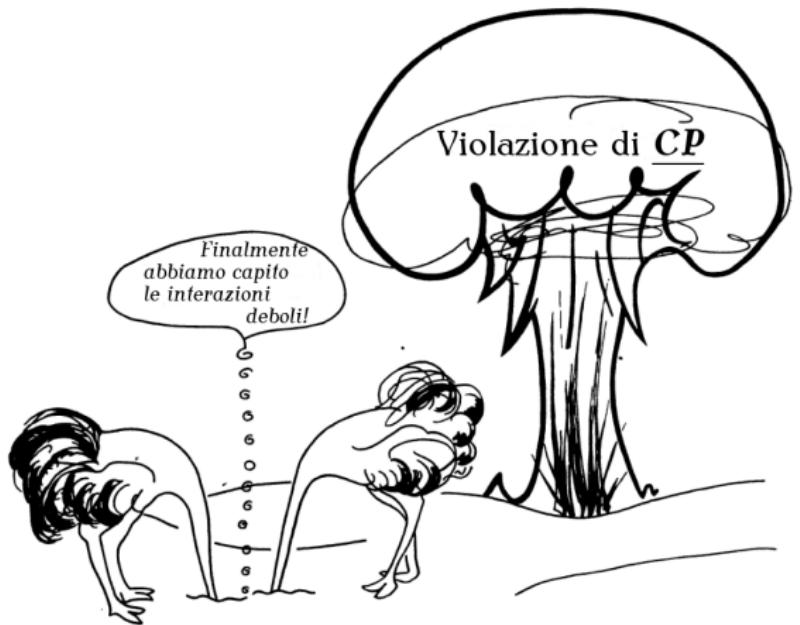
$$|K_S\rangle = \frac{1}{\sqrt{2(1+|\varepsilon|^2)}} (|K_1\rangle + \varepsilon |K_2\rangle),$$

$$|K_L\rangle = \frac{1}{\sqrt{2(1+|\varepsilon|^2)}} (\varepsilon |K_1\rangle + |K_2\rangle).$$



$|\varepsilon| \approx 10^{-3}$

rate of \mathcal{CP} violation



Collapse models: Crash course

The general stochastical differential equation of a collapse model:

$$d|\phi_t\rangle = \left[-i\hat{H}dt + \sqrt{\lambda} \sum_{i=1}^N (\hat{A}_i \underbrace{- \langle \hat{A}_i \rangle_t}_{\text{non-lin.}}) \underbrace{dW_{i,t}}_{\text{stoch.}} - \frac{\lambda}{2} \sum_{i=1}^N (\hat{A}_i \underbrace{- \langle \hat{A}_i \rangle_t}_{\text{non-lin.}})^2 dt \right] |\phi_t\rangle,$$

QMUP and CSL setups:

$$\hat{\mathbf{A}}_{QMUP} = \hat{\mathbf{q}} \otimes \left[\frac{m_H}{m_0} |M_H\rangle\langle M_H| + \frac{m_L}{m_0} |M_L\rangle\langle M_L| \right],$$

$$\hat{A}_{CSL}(\mathbf{x}) = \int d\mathbf{y} g(\mathbf{y} - \mathbf{x}) \left(\frac{m_H}{m_0} \hat{\psi}_H^\dagger(\mathbf{y}) \hat{\psi}_H(\mathbf{y}) + \frac{m_L}{m_0} \hat{\psi}_L^\dagger(\mathbf{y}) \hat{\psi}_L(\mathbf{y}) \right),$$

$$\text{where } g(\mathbf{y} - \mathbf{x}) = \frac{1}{(\sqrt{2\pi r_C})^d} e^{-\frac{|\mathbf{y}-\mathbf{x}|^2}{2r_C^2}}.$$

$$\lambda_{GRW} \approx 10^{-16} s^{-1}$$
$$\lambda_{Adler} \approx 10^{-(8\pm2)} s^{-1}$$

L. Diósi, Phys. Rev. A 40, 1165 (1989).

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Collapse models & neutral mesons: State of the art

Modified Hamiltonian via imaginary trick: $\hat{H} \rightarrow \hat{H} - \sqrt{\lambda} \sum_{i=1}^N \hat{A}_i w_{i,t}$
 $\qquad\qquad\qquad \underbrace{\qquad\qquad\qquad}_{:=N(t)}$

Probabilities of finding M^0 or \bar{M}^0 in beam:

$$|\langle M^0/\bar{M}^0 | M^0(t) \rangle|^2 \rightarrow \sum_{\mathbf{p}_f} \mathbb{E} \underbrace{|\langle M^0/\bar{M}^0; \mathbf{p}_f | U(t) | M^0; \mathbf{p}_i, (\sqrt{\alpha}) \rangle|^2}_{\text{includes collapse now!}}$$

$N(t) \rightarrow$ perturbation \Rightarrow Dyson expansion of $U(t)$.

The effect of the CSL model calculated up to the first order:

$$P_{M^0 \rightarrow M^0/\bar{M}^0}^{(1)}(t) = \frac{1}{4} \left(e^{-\Gamma_H t} + e^{-\Gamma_L t} \pm 2e^{-\frac{\Gamma_H+\Gamma_L}{2}t} (1-\Lambda t) \cos[\Delta m t] \right),$$

where $\Lambda = \lambda_{CSL} \frac{(\Delta m)^2}{m_0^2}$, for kaons $\Lambda \propto 10^{-38} s^{-1}$.

S. Donadi, PhD Thesis (Università degli studi di Trieste, 2012).

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Going beyond: Effect of the QMUPL model

Mass eigenstates:

$$P_{M_\mu \rightarrow M_\nu}^{QMUPPL}(t) = \delta_{\mu\nu} \left(1 - \Lambda_\mu^{QMUPPL} \cdot t + \textcolor{red}{3} \cdot \frac{1}{2} (\Lambda_i^{QMUPPL})^2 \cdot t^2 \right) \cdot e^{-\Gamma_\mu t}.$$

Flavour eigenstates:

$$\begin{aligned} P_{M^0 \rightarrow M^0/\bar{M}^0}^{QMUPPL}(t) &= \frac{1}{4} \left\{ \sum_{i=H,L} e^{-\Gamma_i t} \left(1 - \Lambda_i^{QMUPPL} \cdot t + \textcolor{red}{3} \cdot \frac{1}{2} (\Lambda_i^{QMUPPL})^2 \cdot t^2 \right) \right. \\ &\quad \pm 2 \cos(\Delta m t) e^{-\frac{\Gamma_H + \Gamma_L}{2} t} \cdot \left(1 - \frac{\alpha \lambda}{2} \left[\frac{(\Delta m)^2}{2m_0^2} + \frac{\Lambda_H^{QMUPPL} + \Lambda_L^{QMUPPL}}{2} \right] \cdot t \right. \\ &\quad \left. \left. + \textcolor{red}{3} \cdot \frac{1}{2} \left(\frac{\alpha \lambda}{2} \left[\frac{(\Delta m)^2}{2m_0^2} + \frac{\Lambda_H^{QMUPPL} + \Lambda_L^{QMUPPL}}{2} \right] \right)^2 \cdot t^2 \right) \right\}, \end{aligned}$$

$$\text{where } \Lambda_\mu^{QMUPPL} = \frac{\alpha \lambda}{2} \cdot \frac{m_\mu^2}{m_0^2} \cdot (1 - 2\theta(0)).$$

K. Simonov, B. C. Hiesmayr, Phys. Lett. A 380, 1253 (2016).

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Flavour eigenstates:

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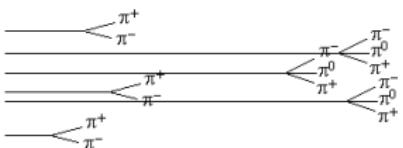
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Impact of the CSL model prediction: Masses



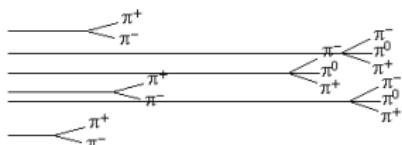
$$\frac{\Gamma_L^{CSL} - \Gamma_H^{CSL}}{\Gamma_L^{CSL} + \Gamma_H^{CSL}} = \frac{m_H^2 - m_L^2}{m_H^2 + m_L^2} = \pm \left(1 - \frac{m_L^2}{m_L^2 + m_L \Delta m + \frac{1}{2}(\Delta m)^2} \right),$$

	$\Gamma_L^{\text{exp}} [s^{-1}]$	$\Gamma_H^{\text{exp}} [s^{-1}]$	$\Delta m^{\text{exp}} [hs^{-1}]$	$m_L [hs^{-1}]$	$m_H [hs^{-1}]$
K -mesons	$1.117 \cdot 10^{10}$	$1.955 \cdot 10^7$	$0.529 \cdot 10^{10}$	$2.311 \cdot 10^8$	$5.524 \cdot 10^9$
D -mesons	$2.454 \cdot 10^{12}$	$2.423 \cdot 10^{12}$	$0.950 \cdot 10^{10}$	$1.468 \cdot 10^{12}$	$1.477 \cdot 10^{12}$
B_d -mesons	$6.582 \cdot 10^{11}$	$6.576 \cdot 10^{11}$	$0.510 \cdot 10^{12}$	$1.020 \cdot 10^{15}$	$1.020 \cdot 10^{15}$
B_s -mesons	$7.072 \cdot 10^{11}$	$6.158 \cdot 10^{11}$	$1.776 \cdot 10^{13}$	$2.477 \cdot 10^{14}$	$2.655 \cdot 10^{14}$

Impact of the CSL model prediction: Masses



$$\frac{m_\mu}{m_0} \longleftrightarrow \frac{m_0}{m_\mu}$$



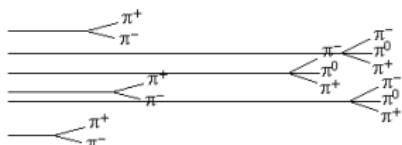
$$\frac{\Gamma_L^{CSL} - \Gamma_H^{CSL}}{\Gamma_L^{CSL} + \Gamma_H^{CSL}} = \frac{m_H^2 - m_L^2}{m_H^2 + m_L^2} = \pm \left(1 - \frac{m_L^2}{m_L^2 + m_L \Delta m + \frac{1}{2}(\Delta m)^2} \right),$$

	$\Gamma_L^{\text{exp}} [s^{-1}]$	$\Gamma_H^{\text{exp}} [s^{-1}]$	$\Delta m^{\text{exp}} [hs^{-1}]$	$m_L [hs^{-1}]$	$m_H [hs^{-1}]$
K -mesons	$1.117 \cdot 10^{10}$	$1.955 \cdot 10^7$	$0.529 \cdot 10^{10}$	$2.311 \cdot 10^8$	$5.524 \cdot 10^9$
D -mesons	$2.454 \cdot 10^{12}$	$2.423 \cdot 10^{12}$	$0.950 \cdot 10^{10}$	$1.468 \cdot 10^{12}$	$1.477 \cdot 10^{12}$
B_d -mesons	$6.582 \cdot 10^{11}$	$6.576 \cdot 10^{11}$	$0.510 \cdot 10^{12}$	$1.020 \cdot 10^{15}$	$1.020 \cdot 10^{15}$
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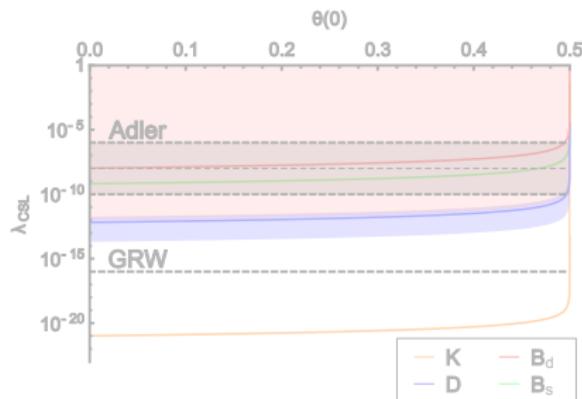
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Impact of the CSL model prediction: Collapse rate

$$\Gamma_\mu^{exp} = \lambda_{CSL} \frac{m_0^2}{m_\mu^2} \left(1 - 2\theta(0)\right),$$

$$\lambda_{CSL}^{estimated} = \frac{1}{\left(\sqrt{\Gamma_L^{-1}} - \sqrt{\Gamma_H^{-1}}\right)^2} \frac{(\Delta m)^2}{m_0^2} \frac{1}{1 - 2\theta(0)},$$



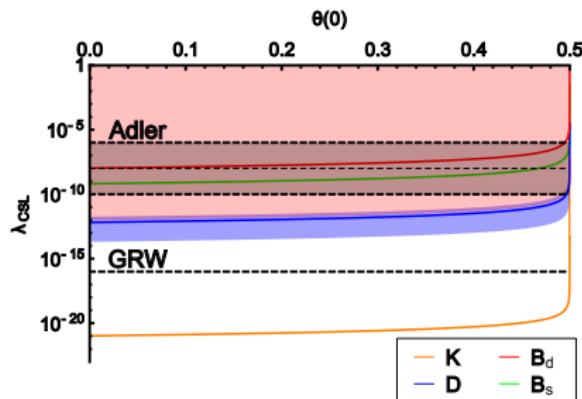
K. Simonov, B. C. Hiesmayr, Phys. Rev. A 94, 052128 (2016).

K. Simonov, B. C. Hiesmayr, arXiv:1705.00913 (2017).

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Conclusions

- The effect of the collapse models shows a dependence on the nature of the noise and its correlation functions through the choice of the value of the Heaviside function in zero $\theta(0)$.
- Any value $\theta(0) \neq \frac{1}{2}$ leads to a dependence on the absolute masses which does not show up in the standard quantum mechanics.
- The CSL collapse can be considered as the only source of the decay in neutral meson dynamics.
- In turn it is possible to deduce the absolute masses m_H , m_L of the neutral mesons and predict the value of the collapse rate λ .

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Further reading

Reviews of collapse models and their testing:

- A. Bassi *et al.*, Rev. Mod. Phys. **85**, 471 (2013).
- A. Bassi, H. Ulbricht, arXiv:1401.6314 (2014).

QMUPL model:

- L. Diósi, Phys. Rev. A **40**, 1165 (1989).

CSL model:

- P. Pearle, Phys. Rev. A **39**, 2277 (1989).
- G. C. Ghirardi, P. Pearle, A. Rimini, Phys. Rev. A **42**, 78 (1990).
- P. Pearle, E. Squires, Phys. Rev. Lett. **73**, 1 (1994).
- G. C. Ghirardi, R. Grassi, F. Benatti, Found. Phys. **25**, 5 (1995).

Testing collapse models via oscillating systems:

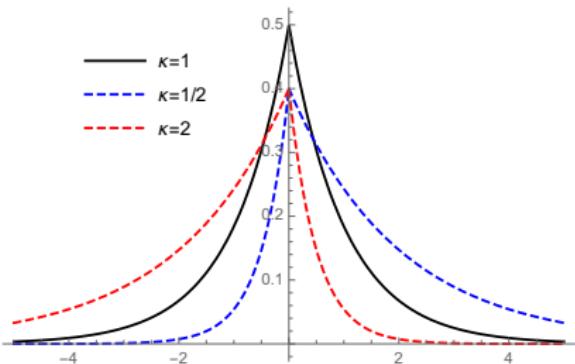
- M. Bahrami *et al.*, Nature Sci. Rep. **3**, 1952 (2013).
- S. Donadi *et al.*, Found. Phys. **43**, 813 (2013).
- K. Simonov, B. C. Hiesmayr, Phys. Lett. A **380**, 1253 (2016).
- K. Simonov, B. C. Hiesmayr, Phys. Rev. A **94**, 052128 (2016).
- K. Simonov, B. C. Hiesmayr, arXiv:1705.00913 (2017).

THANK YOU FOR YOUR ATTENTION!

Mathematics: Correlation functions and asymmetry

$$\mathbb{E}[w(t_1)w(t_2)] = f(t_1 - t_2; \kappa, \nu) \equiv$$

$$\frac{1}{\nu} \frac{1}{1+\kappa^2} e^{-\frac{|t_1-t_2|}{\nu}} \cdot \kappa \operatorname{sgn}(t_1 - t_2)$$



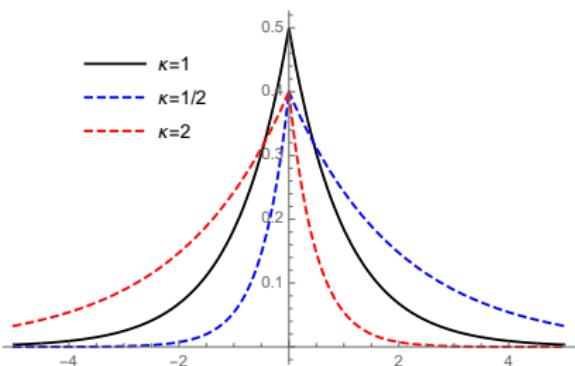
Correlation integral	Symmetric approximation	Asymmetric approximation
$\int\limits_0^t dt_1 \int\limits_0^t dt_2 f(t_1 - t_2; \kappa, \nu)$	$t - \nu [1 - e^{-\frac{t}{\nu}}]$	$t - \frac{\nu}{\kappa + \kappa^3} [1 - e^{-\frac{\kappa t}{\nu}}] + (1 - e^{-\frac{t}{\kappa \nu}}) \kappa^4$
$\int\limits_0^t dt_1 \int\limits_0^{t_1} dt_2 f(t_1 - t_2; \kappa, \nu)$	$\frac{1}{2}t - \frac{\nu}{2} [1 - e^{-\frac{t}{\nu}}]$	$\frac{1}{1+\kappa^2}t - \frac{\nu}{\kappa + \kappa^3} [1 - e^{-\frac{\kappa t}{\nu}}]$

The value of $\theta(0)$ is defined by asymmetry: $\theta(0) = \frac{\kappa^2}{1+\kappa^2}$.

Mathematics: Correlation functions and asymmetry

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$\int_0^t dt_1 \int_0^{t_1} dt_2 f(t_1 - t_2; \kappa, \nu)$	$\frac{1}{2} t - \frac{\nu}{2} [1 - e^{-\frac{t}{\nu}}]$	$\frac{1}{1+\kappa^2} t - \frac{\nu}{\kappa + \nu^3} [1 - e^{-\frac{\kappa t}{\nu}}]$

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CSL: neutrinos, neutral mesons, chiral molecules

NEUTRINOS			
Types of neutrinos	Energy (eV)	Time of Flight (s)	CSL damping ($\lambda_{ij} t$)
Cosmogenic neutrino	10^{19}	3×10^{18}	2×10^{-55}
Solar neutrino	10^6	5×10^2	4×10^{-45}
Laboratory neutrino	10^{10}	2×10^{-2}	2×10^{-57}
Decoherence effect			$\lambda_{DEC} t \sim 10^{-18} - 10^{-5}$
NEUTRAL MESONS			
Types of mesons			CSL collapse rate λ_{CSL} (Hz)
K-meson			1.5×10^{-38}
B-meson			1.4×10^{-34}
B _s -meson			1.7×10^{-31}
D-meson			3.2×10^{-37}
Decoherence effect			$\lambda_{DEC} \leq 8 \times 10^7$
CHIRAL MOLECULES			
Type of molecule			CSL collapse rate λ_{CSL} (Hz)
SOCH ₃ (p-CH ₃ C ₆ H ₄)			6.3×10^{-10}
SOCH ₃ (C ₆ H ₅)			7.9×10^{-10}
SOCH ₃ (CH ₂ CH ₂ - α -C ₁₀ H ₇)			2.5×10^{-9}
SOCH ₃ (1-pyrenyl)			5×10^{-9}
Decoherence effect			$\lambda_{DEC} \sim 10^{-11} - 10^{-9}$