Disentangling genuine from matter-induced CP violation in neutrino oscillations

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The Concept

We prove that, in any flavor transition, neutrino oscillation CP asymmetries have two disentangled components:

a) A CPT-violating T-invariant term, non-vanishing due to matter effects.

b) A T-violating CPT-invariant term, non-vanishing only iff there is genuine CP violation.

These two terms are distinct L-even and L-odd observables to separately test (a) matter effects that violate CPT and (b) genuine CP violation in the neutrino sector.

Asymmetry Disentanglement Theorem

The behavior under symmetry transformations separates the observable CP asymmetry into L-even (CPT-violating) and L-odd (T-violating) functions,

$$\mathcal{A}^{\rm CP}_{\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar\nu_\alpha \to \bar\nu_\beta) =$$

$$-4\sum_{j<i}\left[\text{Re}\,\tilde J^{ij}_{\alpha\beta}\sin^2\tilde\Delta_{ij} - \text{Re}\,\tilde{\bar J}^{ij}_{\alpha\beta}\sin^2\tilde{\bar\Delta}_{ij}\right] \quad \rightsquigarrow \quad \mathcal{A}^{\rm CPT}_{\alpha\beta}$$

$$-2\sum_{j<i}\left[\text{Im}\,\tilde J^{ij}_{\alpha\beta}\sin 2\tilde\Delta_{ij} - \text{Im}\,\tilde{\bar J}^{ij}_{\alpha\beta}\sin 2\tilde{\bar\Delta}_{ij}\right] \quad \rightsquigarrow \quad \mathcal{A}^{\rm T}_{\alpha\beta}$$

where $\mathcal{A}^{\rm CPT}_{\alpha\beta}$ is invariant under T ($\tilde J \to \tilde J^*$, $\tilde{\bar J} \to \tilde{\bar J}^*$) and vanishes when $a = 0$, and $\mathcal{A}^{\rm T}_{\alpha\beta}$ is invariant under CPT ($\tilde J \leftrightarrow \tilde{\bar J}^*$, $\Delta\tilde m^2 \leftrightarrow \Delta\tilde{\bar m}^2$) and vanishes when $\sin\delta = 0$.

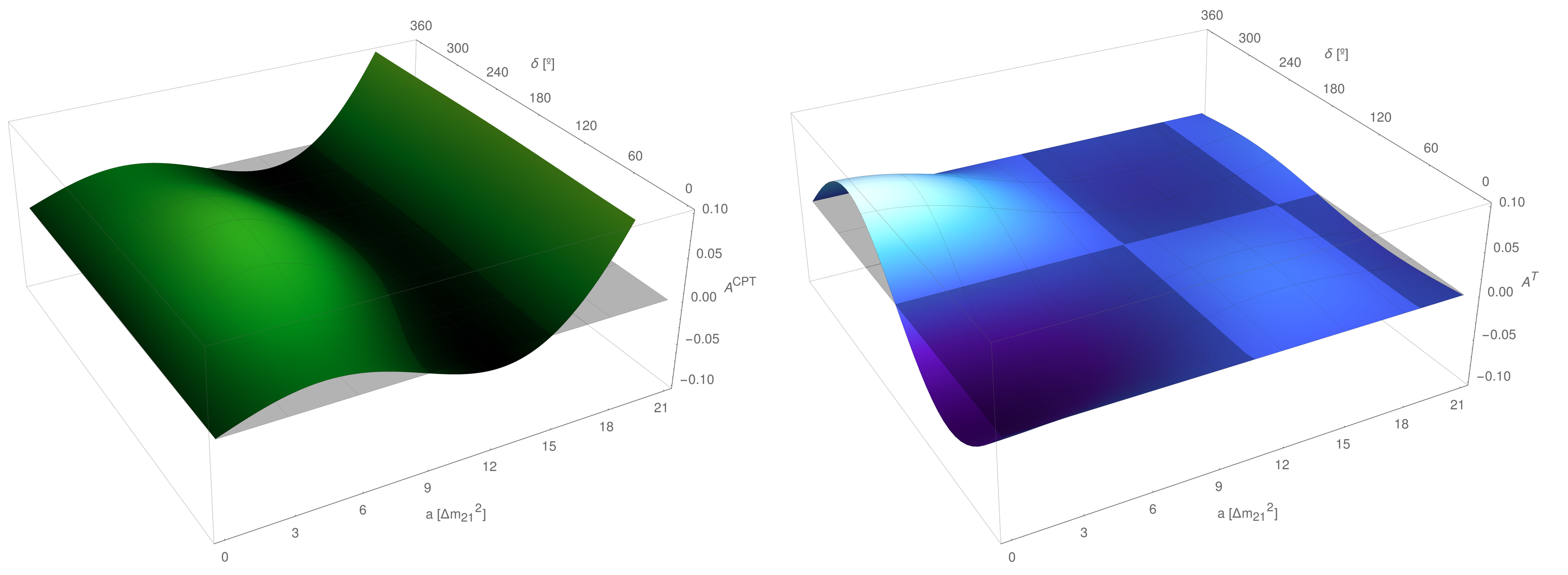


Figure 1: CPT (left) and T (right) asymmetries at $L = 1300$ km and $E = 0.7$ GeV as function of a and δ.

$\mathcal{A}^{\rm CPT}$ is even in $\sin\delta$ $\forall a$ and vanishes at $a = 0$ $\forall\delta$, whereas $\mathcal{A}^{\rm T}$ is odd in $\sin\delta$ $\forall a$, as requested by the theorem.

Framework

Neutrino oscillations in matter are described through the Hamiltonian

$$H = \frac{1}{2E}\left\{U\begin{bmatrix} m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{bmatrix}U^\dagger + \begin{bmatrix} a & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\right\} = \frac{1}{2E}\tilde U\tilde M^2\tilde U^\dagger$$

where the first term describes neutrino oscillations in vacuum and the second one accounts for matter effects. For antineutrinos, $U \to U^*$ and $a \to -a$. All neutrino masses ($\tilde M^2$) and mixings ($\tilde U$) in matter can be explicitly written in terms of the parameters in the vacuum Hamiltonian (M^2, U) and a (see for example [1]).

This Hamiltonian leads to the flavor oscillation probabilities

$$P_{\alpha\beta}(L) = \delta_{\alpha\beta} - 4\sum_{j<i}\text{Re}\,\tilde J^{ij}_{\alpha\beta}\sin^2\tilde\Delta_{ij} - 2\sum_{j<i}\text{Im}\,\tilde J^{ij}_{\alpha\beta}\sin 2\tilde\Delta_{ij}$$

where $\tilde J^{ij}_{\alpha\beta} \equiv \tilde U_{\alpha i}\tilde U^*_{\alpha j}\tilde U^*_{\beta i}\tilde U_{\beta j}$ and $\tilde\Delta_{ij} \equiv \frac{\Delta\tilde m^2_{ij}L}{4E}$. The unique rephasing-invariant associated to genuine CP violation $\tilde{\mathcal{J}}$ is related to its value in vacuum $\mathcal{J}$ [2] by

$$\tilde{\mathcal{J}} \equiv \text{Im}\,\tilde J^{12}_{e\mu} = \frac{\Delta m^2_{21}\Delta m^2_{31}\Delta m^2_{32}}{\Delta\tilde m^2_{21}\Delta\tilde m^2_{31}\Delta\tilde m^2_{32}}\mathcal{J} \approx \frac{\Delta m^2_{21}\Delta m^2_{31}}{(\Delta m^2_{31} - a)|a|\left[1 + \frac{2a\Delta m^2_{31}|U_{e3}|^2}{(\Delta m^2_{31} - a)^2}\right]}\mathcal{J}$$

The first equality [3] is due to the fact that the quantity characterizing CP violation in the flavor basis [4] remains invariant for any flavor-diagonal interaction. The proportionality of $\tilde{\mathcal{J}}$ with Δm^2_{21} explains the absence of genuine CP violation in the vanishing limit of this parameter, even if there are three non-degenerate neutrino masses in matter. The last approximation is valid in the energy region between the two MSW resonances, $\Delta m^2_{21} \ll a \ll |\Delta m^2_{31}|$, and $|U_{e3}|^2 \ll 1$.

The parameter a is convenient to discuss accelerator experiments, since at the Earth mantle $a \approx 3E\,[\text{GeV}]\,\Delta m^2_{21}$. Our analyses are illustrated for $\nu_\mu \to \nu_e$ at HK and DUNE experiments. All Figures are produced using the best-fit mixing parameters from [5] and assuming Normal Hierarchy, unless otherwise specified.

Energy Dependence

We study, at fixed L through the Earth mantle, the energy distribution of the two terms of the CP asymmetry looking for signatures of its separation.

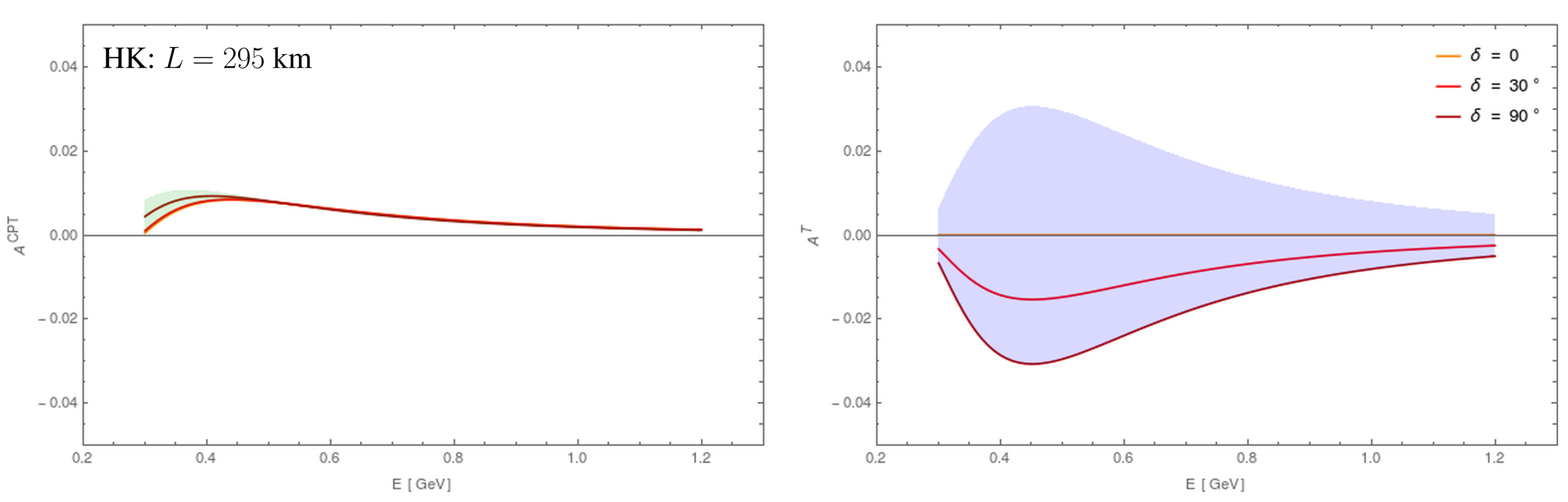
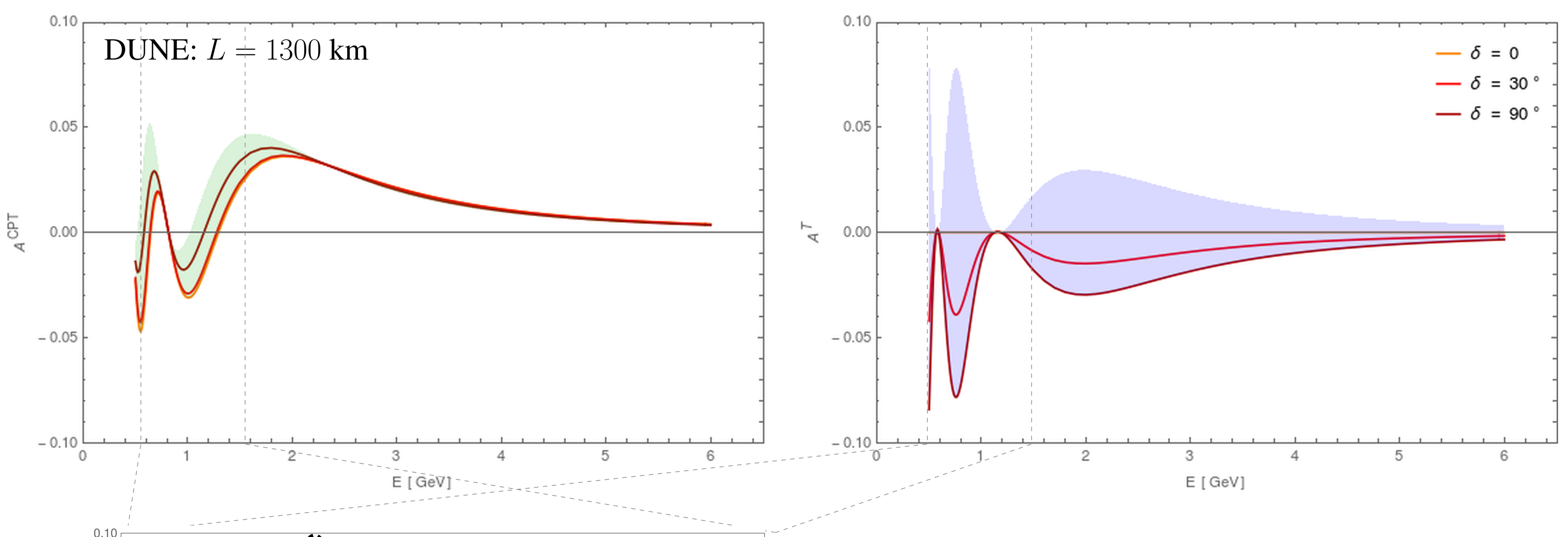
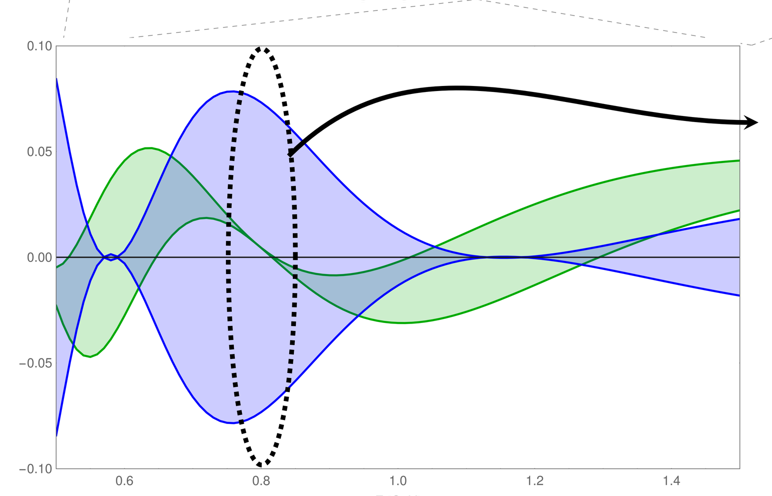


Figure 2: CPT (left) and T (right) asymmetries at HK. The bands correspond to all possible values changing δ in (0, 360°). Notice a factor of 2 between the asymmetry scale in HK plots and DUNE plots.





We discover a **magic configuration** at $L = 1300$ km around $E \sim 0.8$ GeV in which $\mathcal{A}^{\rm CP}_{\mu e}$ **probes genuine CP violation!**

$\mathcal{A}^{\rm T}_{\mu e}$ has a maximum (proportional to $\sin\delta$) whereas at a symmetric energy interval $\mathcal{A}^{\rm CPT}_{\mu e}$ vanishes (independent of δ)

Figure 3: CPT (left) and T (right) asymmetries at DUNE. Zoom at low energies in the bottom panel. The bands correspond to all possible values changing δ in (0, 360°)

$\mathcal{A}^{\rm CPT}$ slightly dependent on δ at low E $\left[\mathcal{O}\left(\Delta m^2_{21}\right)\right]$ and $\mathcal{A}^{\rm T}$ changes its sign as $\sin\delta$

Hierarchy Discrimination

We study the changes induced in $\mathcal{A}^{\rm CPT}$ and $\mathcal{A}^{\rm T}$ for the Inverted Hierarchy case, looking for the discrimination of the two mass spectra.

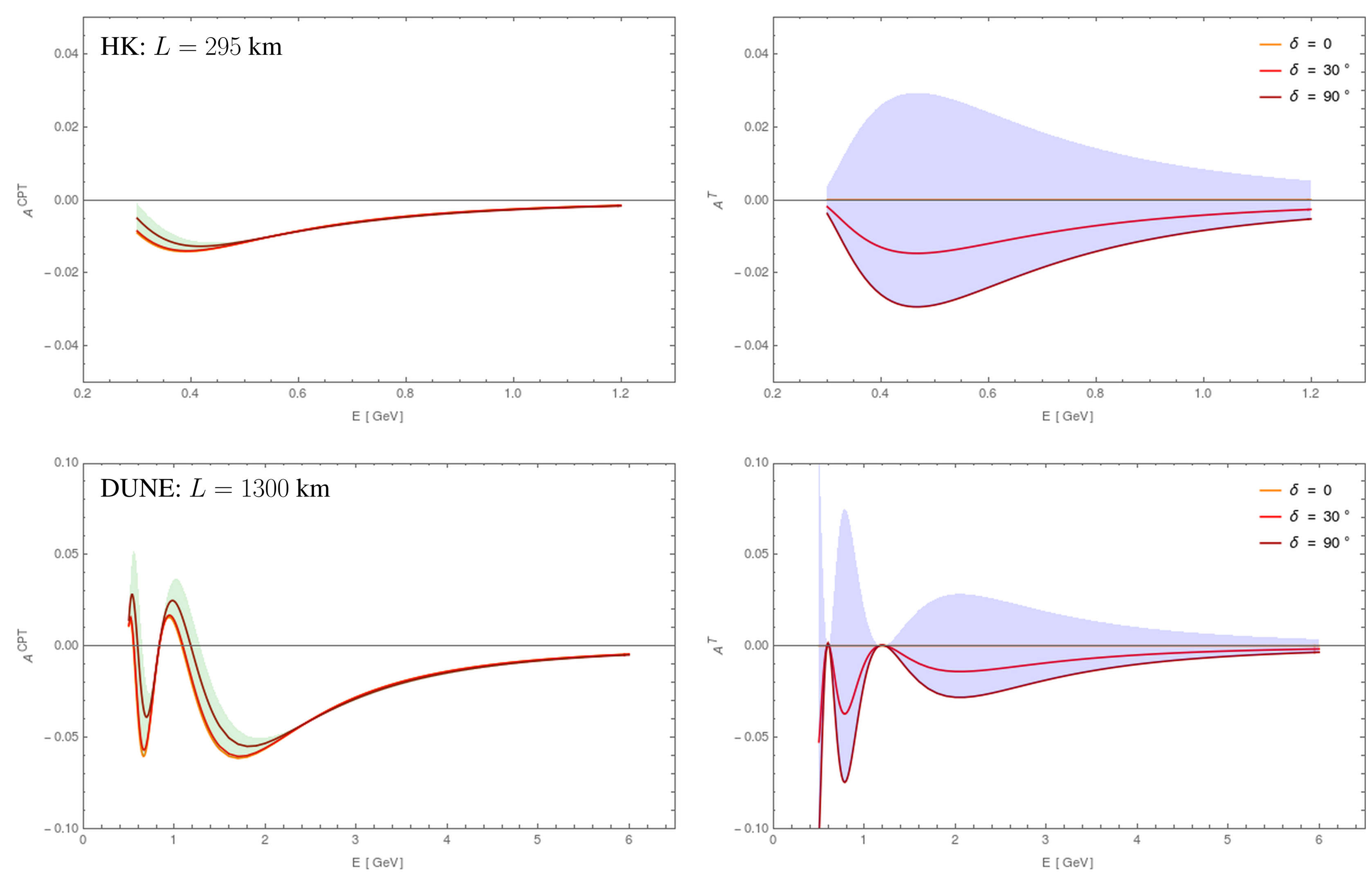


Figure 4: CPT (left) and T (right) asymmetries at HK (top) and DUNE (bottom), assuming Inverted Hierarchy. The bands correspond to all possible values changing δ in (0, 360°)

The important opposite behavior of $\mathcal{A}^{\rm CPT}$ and $\mathcal{A}^{\rm T}$ under a change of hierarchy is well understood at leading order in Δm^2_{21}: zero order for $\mathcal{A}^{\rm CPT}$, independent of δ, and first order for $\mathcal{A}^{\rm T}$. The mass spectrum in matter changes from neutrinos to antineutrinos as

$$\Delta\tilde m^2_{21} \leftrightarrow \Delta\tilde{\bar m}^2_{21}\,, \qquad \Delta\tilde m^2_{31} \leftrightarrow -\Delta\tilde{\bar m}^2_{32}\,, \qquad \Delta\tilde m^2_{32} \leftrightarrow -\Delta\tilde{\bar m}^2_{31}\,.$$

In this exchange of neutrinos by antineutrinos, the imaginary part of $\tilde J^{ij}_{\alpha\beta}$ (as that of $J^{ij}_{\alpha\beta}$) changes sign whereas the real parts do not. Being the CP asymmetries a difference between neutrino and antineutrino probabilities, we discover that $\mathcal{A}^{\rm CPT}$ is changing its sign whereas $\mathcal{A}^{\rm T}$ remains invariant.

The information to discriminate the hierarchy comes entirely from $\mathcal{A}^{\rm CPT}$

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