Memory effects in radiative spacetimes: A study in Eddington-inspired Born-Infeld gravity

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[Based on: Phys. Rev. D 105, 024063, arXiv: 2110.02295]

PLAN OF THE TALK

•Gravitational memory effects: brief introduction

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•Kundt wave geometries

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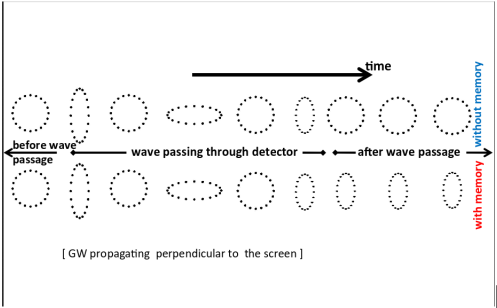
- Memory effects in Eddington-inspired Born-Infeld (EiBI) gravity

GRAVITATIONAL WAVE MEMORY

Net relative displacement and /or a net relative velocity caused by the passage of a gravitational wave pulse.



[Favata, ICTS]

Permanent distortion!

Memory in radiative spacetimes

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$u = const.$ **hypersurfaces are planar, wavefronts.**

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$u = const.$ **hypersurfaces are planar, wavefronts.**

$H_{,xx} + H_{,yy} = 0$ **(Wave eqn.)**

$$H(u,x,y) = \frac{1}{2}A_+(u)(x^2 - y^2) + A_\times(u)xy$$

$A_+, A_\times$: **polarizations of the wave**

Memory in radiative spacetimes (contd...)

Gaussian pulse profile

$$A_+(u) = e^{-u^2}, A_\times(u) = 0$$

Solved the geodesic equations numerically, arrived at memory effects.

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In our work we work with a slightly modified geometry, called Kundt wave spacetimes.

Kundt wave spacetimes

The metric

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•$u = const.$ **hypersurfaces are not planar (presence of matter/ cosmological constant).**

I. C. (PRD, 2021; arXiv:2110.02295)

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1. Examine Kundt wave geometry solutions in Eddington-inspired Born-Infeld (EiBI) theory of gravity.

2. Analyse memory effect using geodesic eqns and geodesic deviation eqns.

EiBI gravity (briefly)

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•**Action**

$$S_{EiBI}(g,\Gamma,\Psi)=\frac{2}{\kappa}\int d^4x\left[\sqrt{-|g_{\mu\nu}+\kappa R_{\mu\nu}(\Gamma)|}-(1+\kappa\Lambda)\sqrt{-|g_{\mu\nu}|}\right]+S_M(g,\Psi)$$

[Banados, Ferreira; Phys. Rev. Lett., 2010]

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•**Relevant field eqns (Bimetric theory).**

$$q_{\mu\nu} = g_{\mu\nu} + \kappa R_{\mu\nu}(\Gamma) \quad (1)$$

$$\sqrt{-|q_{\mu\nu}|}q^{\mu\nu} = (1+\kappa\Lambda)\sqrt{-|g_{\mu\nu}|}g^{\mu\nu} - \kappa\sqrt{-|g_{\mu\nu}|}T^{\mu\nu} \quad (2)$$

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•**EiBI**$\rightarrow$ **GR in vacuum** ($S_M = 0$) **and in regions having low curvature** ($g_{\mu\nu} >> \kappa R_{\mu\nu}$)

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•We try to understand how nature of memory effect behaves under different matter sources.

•How memory effect varies with κ (EiBI theory parameter)

Generalised matter source

(not derived from explicit matter Lagrangian)

Kundt wave metric with generalised matter source

Kundt wave metric with generalised matter source

Physical metric

$$ds_1^2 = -2dudv - H_1(u,x,y)du^2 + \frac{1}{P_1(x,y)^2}(dx^2 + dy^2)$$

Auxiliary metric

$$ds_2^2 = -2dudv - H_2(u,x,y)du^2 + \frac{1}{P_2(x,y)^2}(dx^2 + dy^2)$$

- **Use this metric ansatze in the field eqns. of EiBI gravity.**

Kundt wave metric with generalised matter source

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•**Use this metric ansatze in the field eqns. of EiBI gravity.**

Solutions

•$H_1 = H_2 = h(u)(x^2 - y^2)$.

Solutions (contd..)

•**Choosing** $T^{uv} = \sigma$ **we get,**

$$P_2 = 1 + \frac{\alpha}{4}(x^2 + y^2) \qquad P_1 = \sqrt{1 + \kappa(\Lambda + \sigma)}\left[1 + \frac{\alpha}{4}(x^2 + y^2)\right]$$

•$\alpha = \dfrac{\Lambda + \sigma}{1 + \kappa(\Lambda + \sigma)}$

•**Ricci scalar** $R = 2(\Lambda + \sigma)$

•**We will analyse positive** ($\Lambda > 0$) **and negative** ($\Lambda < 0$) **curvature scalar solutions having** $\sigma = 0$**.**

Memory effects

Geodesic eqns.

Geodesic deviation eqn.

Memory effects using geodesics (methodology)

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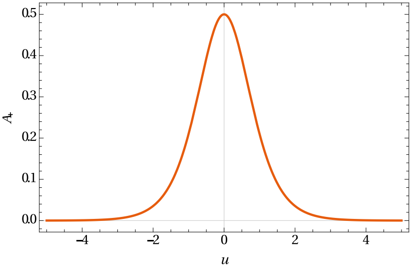
Differentiating the geodesic solutions Velocity memory effect



Sech-squared pulse

$$H(u,x,y) = \operatorname{sech}^2 u (x^2 - y^2)$$

Geodesic analysis

Kundt wave spacetimes (Physical metric)

$$ds^2 = -2dudv - H_1(u,x,y)du^2 + \frac{1}{P_1(x,y)^2}(dx^2 + dy^2)$$

Geodesic analysis

Kundt wave spacetimes (Physical metric)

$$ds^2 = -2dudv - H_1(u,x,y)du^2 + \frac{1}{P_1(x,y)^2}(dx^2 + dy^2)$$

•**Geodesic eqns:**

$$\ddot{x} + \frac{P_{1,x}}{P_1}(\dot{y}^2 - \dot{x}^2) - 2\dot{x}\dot{y}\frac{P_{1,y}}{P_1} + \frac{1}{2}H_{1,x}{P_1}^2 = 0$$

$$\ddot{y} + \frac{P_{1,y}}{P_1}(\dot{x}^2 - \dot{y}^2) - 2\dot{x}\dot{y}\frac{P_{1,x}}{P_1} + \frac{1}{2}H_{1,y}{P_1}^2 = 0$$

•$H_1 = \frac{1}{2}\operatorname{sech}^2 u(x^2 - y^2)$: **Pulse Profile**

Memory effects in negative scalar curvature

Scalar curvature: $R = -0.5, \Lambda = -0.25$.

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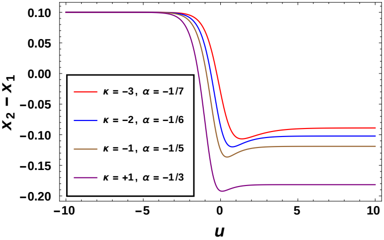
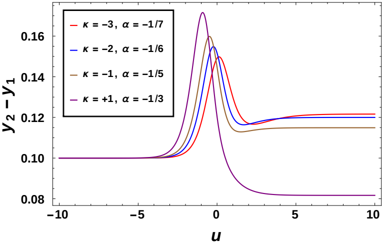


x-direction



y-direction

Memory effects in negative scalar curvature

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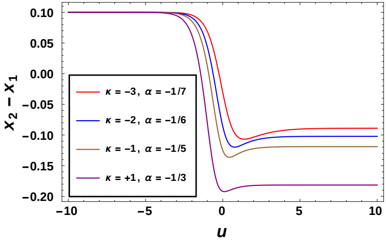

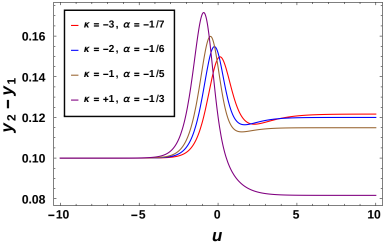

***x*-direction** ***y*-direction**

•**Constant shift displacement memory, no velocity memory.**

•**Higher value of** $|\alpha|$ **gives,**

i) Displacement of the separation from its initial value increases along x**.**
ii) The higher of the peak of the maxima along y**.**

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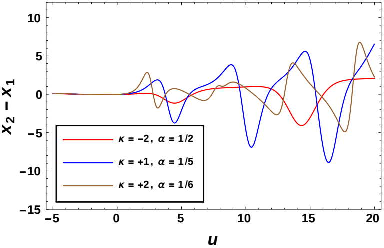
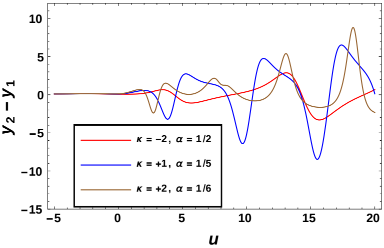


x-**direction**



y-**direction**

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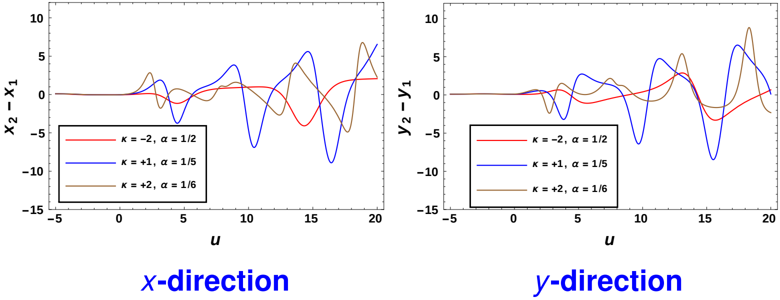

•**Frequency memory effect**

•**Formation of beats.**

•**Lower the value of α, more is the frequency of oscillation.**

Memory effects

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Geodesic deviation eqn.

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•Geodesic eqn. $\equiv$ Non-linear, decomposition not possible

•Geodesic deviation eqn. $\equiv$ **Linear**, decomposition is achievable.

Formalism (methodology) [Chu, Koyama; PRD, 2019]

Devn. vector → Fermi basis

$$\xi^\mu = Z^i e^\mu{}_i$$

$\Downarrow$

Devn. in Fermi basis

$$\frac{d^2 Z^i}{dt^2} = -R^i{}_{0j0} Z^j$$

$\Downarrow$

$$Z^i = Z^i_B + Z^i_W$$

$\Downarrow$

Riem. tensor splitting

$$R^i{}_{0j0} = (R^i{}_{0j0})_B + (R^i{}_{0j0})_W$$

$\Downarrow$

$$(R^i{}_{0j0})_W \propto \{H(u,x,y), H'(u,x,y)\}$$

Evolution eqn.

$$\frac{d^2 Z^i_B}{dt^2} = -(R^i{}_{0j0})_B Z^j_B \quad \text{(no wave pulse)}$$

$$\frac{d^2 Z^i_W}{dt^2} = -[(R^i{}_{0j0})_B + (R^i{}_{0j0})_W] Z^j_W - (R^i{}_{0j0})_W Z^j_B$$

$\Downarrow$

Fermi basis → Coo. basis

$\Downarrow$

Separate devn. → ξ^μ_B **and** ξ^μ_W

$\Downarrow$

Total devn. → $\xi^\mu_B + \xi^\mu_W$

$\Downarrow$

Match → geodesic analysis

Deviation analysis

Kundt wave spacetimes

- **Orthonormal tetrads**

$$e_0{}^{\mu} = [1, \dot{v}, \dot{x}, \dot{y}] \qquad e_1{}^{\mu} = \left[0, -\frac{\dot{x}}{P_1}, -P_1, 0\right]$$

$$e_2{}^{\mu} = \left[0, -\frac{\dot{y}}{P_1}, 0, -P_1\right] \qquad e_3{}^{\mu} = [-1, 1 - \dot{v}, -\dot{x}, -\dot{y}]$$

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•$e_1{}^{\mu}, e_2{}^{\mu}$ **parallel transport when they are rotated by an angle** θ_p.

$$\dot{\theta}_p = \frac{1}{P_1}(P_{1,y}\,\dot{x} - P_{1,x}\,\dot{y})$$

Kundt wave spacetimes

•Riemann tensor in tetrad frame $\longrightarrow$

Background

$$(R^1{}_{010})_B = -\frac{1}{P_1^2}(\dot{y}\cos\theta_p + \dot{x}\sin\theta_p)^2[P_{1,x}^2 + P_{1,y}^2 - P_1(P_{1,xx} + P_{1,yy})]$$

$$(R^1{}_{020})_B = \frac{1}{2P_1^2}[2\dot{x}\dot{y}\cos(2\theta_p) + (\dot{x}^2 - \dot{y}^2)\sin(2\theta_p)][P_{1,x}^2 + P_{1,y}^2 - P_1(P_{1,xx} + P_{1,yy})] = (R^2{}_{010})_B$$

$$(R^2{}_{020})_B = -\frac{1}{P_1^2}(\dot{x}\cos\theta_p - \dot{y}\sin\theta_p)^2[P_{1,x}^2 + P_{1,y}^2 - P_1(P_{1,xx} + P_{1,yy})]$$

Gravitational wave

$$(R^1{}_{010})_W = h(u)P_1[P_1\cos(2\theta_p) + (x\cos(2\theta_p) + y\sin(2\theta_p))P_{1,x} + (y\cos(2\theta_p) - x\sin(2\theta_p))P_{1,y}]$$

$$(R^1{}_{020})_W = h(u)P_1[P_1\sin(2\theta_p) + (x\sin(2\theta_p) - y\cos(2\theta_p))P_{1,x} + (x\cos(2\theta_p) + y\sin(2\theta_p))P_{1,y}] = (R^2{}_{010})_W$$

$$(R^2{}_{020})_W = -h(u)P_1[P_1\cos(2\theta_p) + (x\cos(2\theta_p) + y\sin(2\theta_p))P_{1,x} + (y\cos(2\theta_p) - x\sin(2\theta_p))P_{1,y}]$$

Note terms are prop. to $h(u)$

Deviation analysis (negative curvature)

Reverting back to coordinate basis the results $\longrightarrow$

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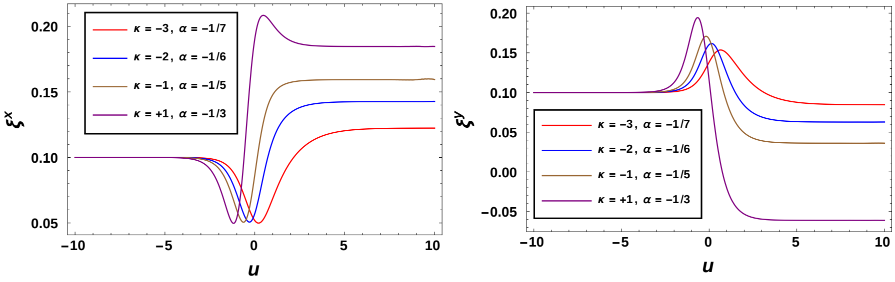
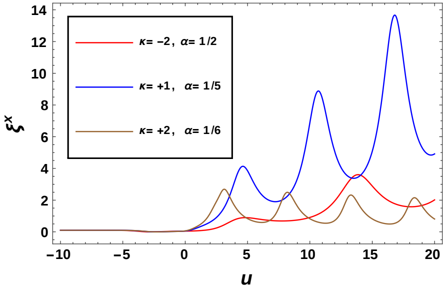


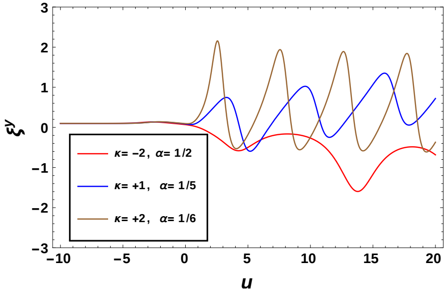
X-direction **Y-direction**

•**Constant shift displacement memory, no velocity memory**

NUMERICAL RESULTS !!

Deviation analysis (positive curvature)





x-direction

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- **Frequency memory effect along both *x* and *y* directions.**

NUMERICAL RESULTS !!

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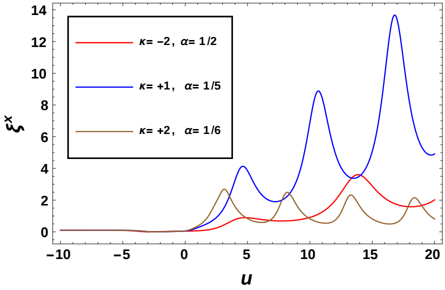

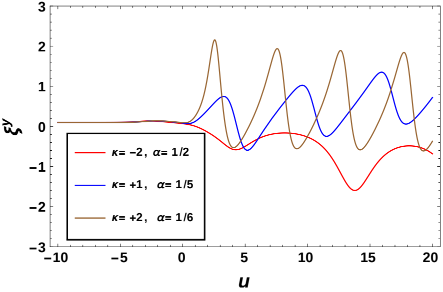

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NUMERICAL RESULTS !!

GEODESIC ANALYSIS ≡ TOTAL DEVIATION

EM matter source

Kundt wave metric with an EM field source

$$T^{\mu\nu} = F^{\mu}{}_{\sigma} F^{\nu\sigma} - \frac{1}{4} g^{\mu\nu} F_{\alpha\beta} F^{\alpha\beta}.$$

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Solutions

• $H_1 = H_2 = h(u)(x^2 - y^2)$

• **But now, from field eqns. we have $\Lambda \geq 0$.**

$$\beta = \frac{2\Lambda}{1 + 2\kappa\Lambda} \qquad P_2(x) = \cosh(\sqrt{\beta}x) \qquad P_1(x) = \sqrt{1 + 2\kappa\Lambda}\cosh(\sqrt{\beta}x)$$

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•**The Ricci scalar is 4Λ.**

•**Only positive curvature scalar solutions.**

•**Different from the case having generalised matter source.**

Maxwell field

Field eqns. of EiBI gravity $\rightarrow F_{uv}, F_{xy} \neq 0$

Maxwell field

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Bianchi identity $\rightarrow F_{uv} \equiv F_{uv}(u), F_{xy} \equiv F_{xy}(x)$

Maxwell field

Field eqns. of EiBI gravity $\rightarrow F_{uv}, F_{xy} \neq 0$

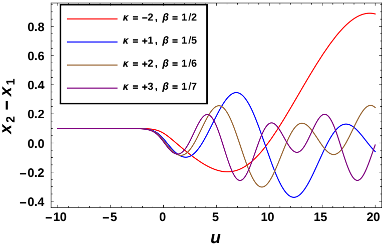
Bianchi identity $\rightarrow F_{uv} \equiv F_{uv}(u), F_{xy} \equiv F_{xy}(x)$

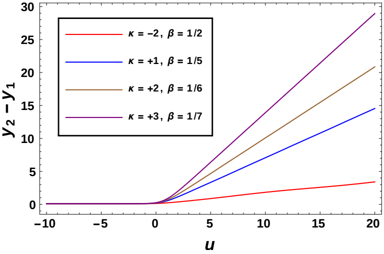
Consistent solution $\rightarrow$

$$A_\mu = [0, A_v(u), 0, A_y(x)] \qquad J^\mu = [0, J^v(u), 0, 0]$$

$$\frac{d^2 A_v}{du^2} = \frac{dF_{uv}}{du} = J^v \qquad \frac{dA_y}{dx} = F_{xy} = \frac{B}{P_1^2}$$

Geodesic analysis

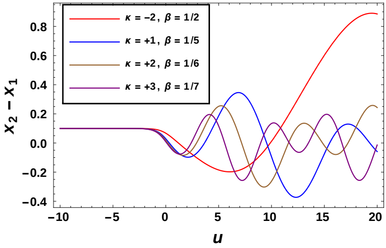


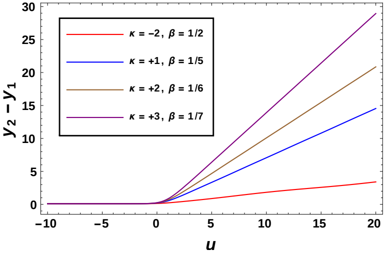


x-direction

y-direction

Geodesic analysis





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•Frequency memory is only observed along x, monotonically increasing displacement memory along y.

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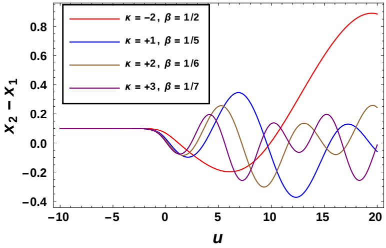

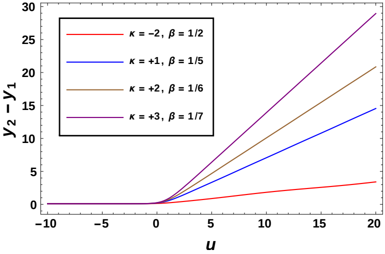

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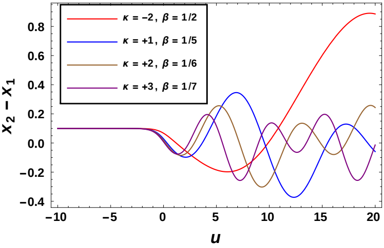

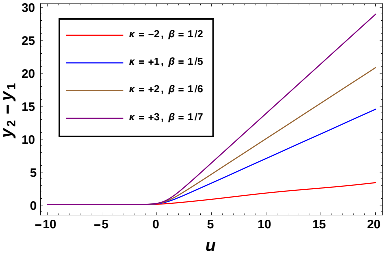

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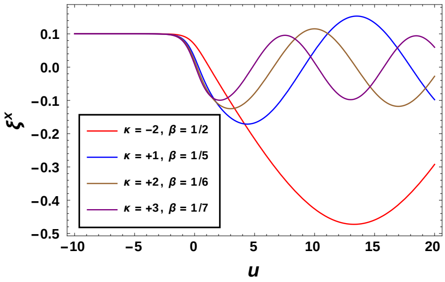
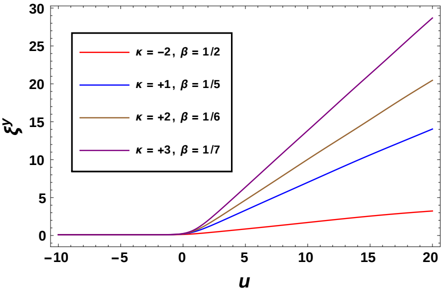
- Frequency memory is only observed along x, monotonically increasing displacement memory along y.
- Reason: $P_1 \equiv P_1(x)$, hence, nature of memory depends on the explicit functional dependence of P_1 on x and y.
- Increasing β decreases frequency of oscillation along x and also reduces the displacement memory along y.

Deviation analysis





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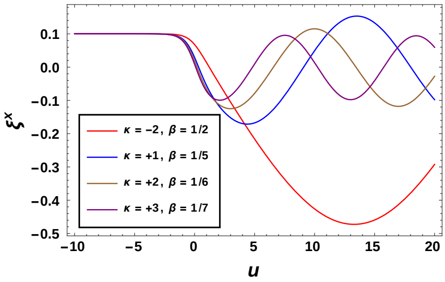

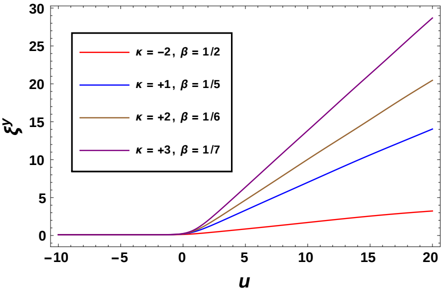

x-direction

y-direction

- **Frequency memory effect along x-direction**
- **Monotonically increasing displacement memory, presence of velocity memory along *y*.**

NUMERICAL RESULTS !!

FLOWCHART

Kundt wave spacetime

⇓

Generalised matter source

⇓

Negative and positive curvature scalar solns.

⇓

Memory effects
Geodesic eqns.
geodesic deviation equation.

Kundt wave spacetime

⇓

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•For positive curvature spacetimes, we get frequency memory in EiBI.

THANK YOU

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Fermi basis

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