Quantized Field with Excitations of Spacetime

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Time and Space Oscillation Symmetry

- A simple harmonic oscillator has oscillation in space but not in time.
- Following the spirit of relativity, can matter has oscillation in time?
- Line of thinking analogous to time crystal theory - Could there be a time crystal with a time-periodic ground state that breaks the time translational symmetry if a regular crystal has broken spatial translational symmetry?

Properties of a Proper Time Oscillator

- Properties of a harmonic oscillator in time (also called proper time oscillator)
  1. Spacetime around is the Schwarzschild field.
  2. Reconcile same properties of a quantum field (bosons and fermions).

- If a real particle is an excitation of the corresponding quantum field and its underlying spacetime, the proper time oscillation will allow a real particle to interact directly with spacetime, generating a gravitational field.

- Testing the theory:
  1. Decay rate of unstable particle.
  2. Uncertainty in neutrino arrival time.
  3. Rank 1 tensor gravitational wave.

References

[1] Yau, H. Y.: Quantized field with excitations of spacetime. Sci Rep 15, 30844 (2025).
[2] Yau, H. Y.: Matter, spacetime and proper time oscillator. To appear in (2024) Marcel Grossman Conference Proceeding
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[4] Yau, H. Y.: Schwarzschild field of a proper time oscillator. Symmetry 12(2), 312 (2020)
[5] Yau, H. Y.: Self-adjoint time operator in a quantum field. J. Quant. Info. 1941016 (2020)
[6] Yau, H. Y.: Thin shell with fictitious oscillations, in Spacetime Physics1907 – 2017, Chapter 6 (Minkowski Institute Press, Montreal, 2019)
[7] Yau, H. Y.: Time and space symmetry in a quantum field. J. Phys.: Conf. Ser. 1194, 012116 (2019)

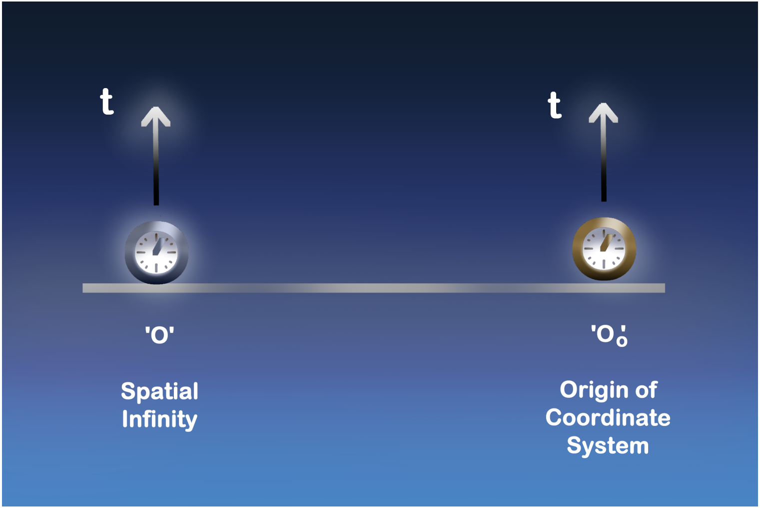
Oscillator in Space

Analogy as a particle traveling at average $\mathbf{v}$, but oscillate with angular frequency ω and amplitude $\mathring{\mathbf{X}}$,

$$\mathring{\mathbf{x}}_f = \mathbf{v}t - \mathring{\mathbf{X}} \sin(\omega t). \tag{1}$$

- Replace motions in space with motions in time. **Assume proper time of a stationary particle also oscillates**

$$\mathring{t}_f = t - \mathring{T}_0 \sin(\omega_0 t), \quad \mathring{T}_0 = 1/\omega_0. \tag{2}$$


t
t
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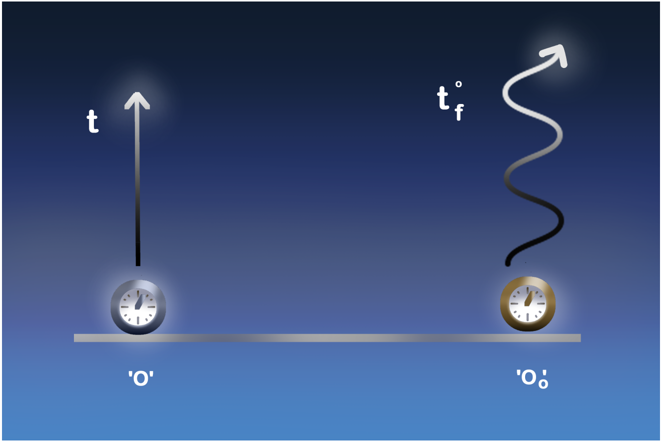
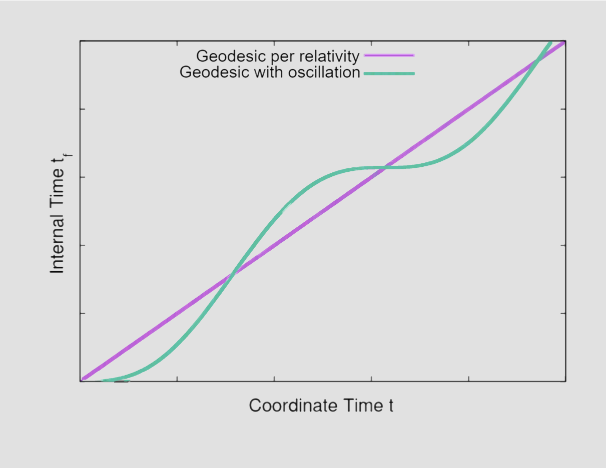
Spatial Infinity
Origin of Coordinate System

Oscillator in Time



$$\mathring{t}_f = t - \mathring{T}_0 \sin(\omega_0 t), \qquad \mathring{T}_0 = 1/\omega_0. \tag{3}$$



- Time at $\mathbf{x}_0$ flows forward along timelike geodesic if the instrument used not sensitive enough.
- **Time never travel backward**.
- **Time evolves closely with coordinate time.**.

Proper Time Oscillations

Proper time oscillation is an additional degree of freedom introduced beyond the properties of standard model.

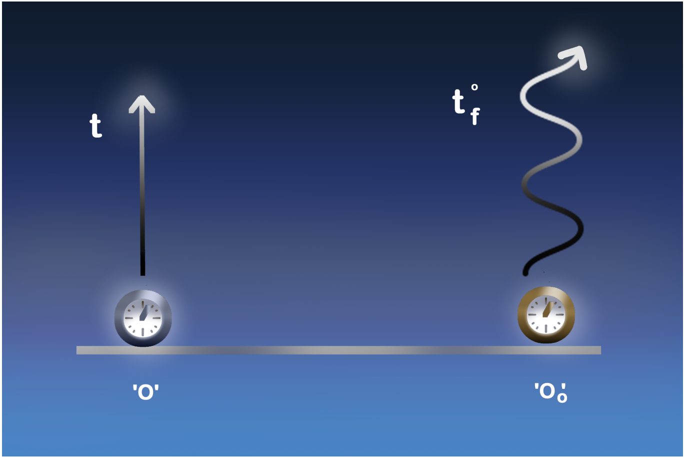
Proper time oscillation is not the results of:

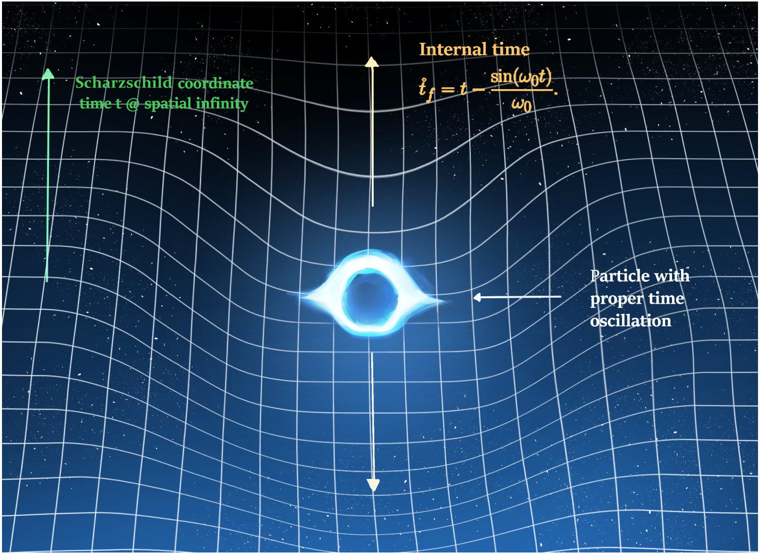
- Relative motion between observers. X
- External gravitational field. X

Total mass-energy is conserved.

Local spacetime provides the restoring action - analogy of a spring.

Oscillator in Time




Internal time
$\tilde{t}_f = t - \frac{\sin(\omega_0 t)}{\omega_0}$.
Scharzschild coordinate
time t @ spatial infinity
Particle with
proper time
oscillation

Curved Spacetime

- For a Minkowski spacetime, a clock stationary anywhere can be synchronized with a clock of spatial infinity.
- Instead of being flat, assume time at the origin flows forward but oscillates.

$$\mathring{t}_f = t - \mathring{T}_0 \sin(\omega_0 t), \quad \mathring{T}_0 = 1/\omega_0. \tag{4}$$

- As a part of the spacetime geometry, the fluctuating proper time has geometrical properties differ from spatial infinity.
- Difference in spacetime geometry implies spacetime between cannot be flat.
- Fluctuating proper time can curve its surrounding spacetime.

Schwarzschild Field

The vacuum space–time outside proper time oscillator is the Schwarzschild spacetime,

$$ds^2 = [1 - \frac{\breve{r}\breve{\Re}^2\omega_0^2}{r}]dt^2 - [1 - \frac{\breve{r}\breve{\Re}^2\omega_0^2}{r}]^{-1}dr^2 - r^2 d\Omega^2. \quad (5)$$

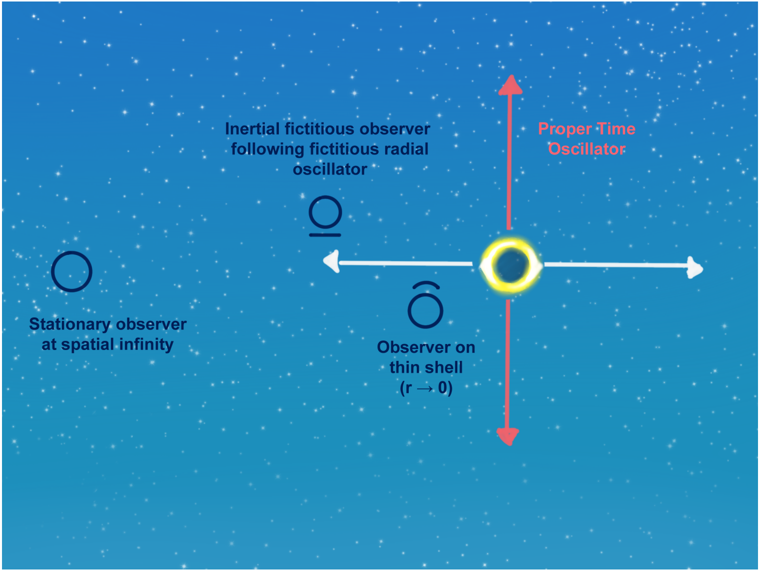
with

$$m = \frac{\breve{r}\breve{\Re}^2\omega_0^2}{2}. \quad (6)$$

Trace of the extrinsic curvature K for a timelike hypersurface at constant radius r:

$$K = \frac{2}{r}\left(1 - \frac{2m}{r}\right)^{1/2} + \frac{m}{r^2}\left(1 - \frac{2m}{r}\right)^{-1/2} = \frac{2}{r}\left(1 - \frac{2}{T_0 r}\right)^{1/2} + \frac{1}{T_0 r^2}\left(1 - \frac{2}{T_0 r}\right)^{-1/2}, \quad (7)$$

Oscillator in proper time can mimic a rest mass in relativity. Spacetime outside is Schwarzschild.


Inertial fictitious observer
following fictitious radial
oscillator
Proper Time
Oscillator
Stationary observer
at spatial infinity
Observer on
thin shell
(r → 0)

Quantized Field with Proper Time oscillations

Plane Wave with Proper Time Oscillations

Apply proper time oscillations to all matters inside a plane wave

$$t_f(t,\mathbf{x}) = t + \mathrm{Re}[\zeta_{t0}(t,\mathbf{x})] = t - T_0 \sin(\omega_0 t), \tag{8}$$

where

$$\zeta_{t0}(t,\mathbf{x}) = -iT_0 e^{-i\omega_0 t}. \tag{9}$$

- Matters at rest have no spatial oscillation displacement.

Plane Wave Describing Oscillations in Space and Time

Oberved in another frame, the plane wave has oscillations in time and space:

$$t'_f = t' + t'_d = t' + \mathrm{Re}(\zeta_{t\mathbf{k}}) = t' + T_{\mathbf{k}} \sin(\mathbf{k} \cdot \mathbf{x}' - \omega t'), \tag{10}$$

$$\mathbf{x}'_f = \mathbf{x}' + \mathbf{x}'_d = \mathbf{x}' + \mathrm{Re}(\zeta_{\mathbf{x}\mathbf{k}}) = \mathbf{x}' + \mathbf{X}_{\mathbf{k}} \sin(\mathbf{k} \cdot \mathbf{x}' - \omega t'), \tag{11}$$

where

$$\zeta_{t\mathbf{k}} = -iT_{\mathbf{k}} e^{i(\mathbf{k}\cdot\mathbf{x}' - \omega t')}, \tag{12}$$

$$\zeta_{\mathbf{x}\mathbf{k}} = -i\mathbf{X}_{\mathbf{k}} e^{i(\mathbf{k}\cdot\mathbf{x}' - \omega t')}, \tag{13}$$

Plane Wave Describing Oscillations in Space and Time

- $\zeta_{t\mathbf{k}}$ and $\zeta_{\mathbf{xk}}$ form a Lorentz covariant plane wave

$$\begin{bmatrix} \zeta_{t\mathbf{k}} \\ \zeta_{\mathbf{xk}} \end{bmatrix} = -i \begin{bmatrix} T_{\mathbf{k}} \\ \mathbf{X}_{\mathbf{k}} \end{bmatrix} e^{i(\mathbf{k}\cdot\mathbf{x}' - \omega t')}. \tag{14}$$

- We apply plane waves to study a real scalar field $\zeta(x)$ matter field.
- Gravitational effects of the oscillations are negligible.
- Spacetime considered as flat.

Plane Wave Describing Oscillations in Space and Time

Define a plane wave,

$$\zeta_{\mathbf{k}} = \frac{T_{0\mathbf{k}}}{\omega_0} e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}. \tag{15}$$

Temporal and spatial oscillation displacements can be written as

$$\zeta_{t\mathbf{k}} = \partial_0 \zeta_{\mathbf{k}} = -iT_{\mathbf{k}} e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}, \tag{16}$$

$$\zeta_{\mathbf{xk}} = -\nabla \zeta_{\mathbf{k}} = -i\mathbf{X}_{\mathbf{k}} e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}. \tag{17}$$

$\zeta_{\mathbf{k}}$ satisfies the Klein Gordon equation:

$$\partial_u \partial^u \zeta_{\mathbf{k}} + \omega_0^2 \zeta_{\mathbf{k}} = 0. \tag{18}$$

Hamiltonian Density

- A system in a volume V with multiple particles of mass m.
- Impose periodic boundary conditions at the box walls.
- The corresponding Hamiltonian density

$$\mathcal{H}_{\mathbf{k}} = \frac{m\omega_0^2}{2V}[(\partial_0\zeta_{\mathbf{k}}^*)(\partial_0\zeta_{\mathbf{k}}) + (\nabla\zeta_{\mathbf{k}}^*)\cdot(\nabla\zeta_{\mathbf{k}}) + \omega_0^2\zeta_{\mathbf{k}}^*\zeta_{\mathbf{k}}]. \tag{19}$$

Hamiltonian Density

To relate the spacetime oscillations of plane wave $\zeta_{\mathbf{k}}$ with a quantized field, we make an ansatz

$$K = m\omega_0^2. \tag{20}$$

- $m =$ mass of particles created in the system.
- $\omega_0 =$ de Broglie's angular frequency of the particle's rest mass-energy.
- ω_0^2 has the familiar form of the spring constant for a classical simple harmonic oscillator.

Quantized field with oscillations in time has same properties of a bosonic field

Bosonic Field

- A real scalar field by superposition of $\zeta_{\mathbf{k}}$ and $\zeta_{\mathbf{k}}^*$

$$\zeta(x) = \sum_{\mathbf{k}} (2\omega\omega_0)^{-1/2} [T_{0\mathbf{k}} e^{-ikx} + T_{0\mathbf{k}}^* e^{ikx}]. \tag{21}$$

- Transform into a quantized field through canonical quantization.
- Relate $\zeta(x)$ with the bosonic field $\varphi(x)$ in quantum theory

$$\varphi(x) = \zeta(x)\sqrt{\frac{\omega_0^3}{V}} = \sum_{\mathbf{k}} (2\omega V)^{-1/2} [a_{\mathbf{k}} e^{-ikx} + a_{\mathbf{k}}^\dagger e^{ikx}]. \tag{22}$$

- Annihilation and creation operators

$$a_{\mathbf{k}} = \omega_0 T_{0\mathbf{k}}, \quad a_{\mathbf{k}}^\dagger = \omega_0 T_{0\mathbf{k}}^\dagger. \tag{23}$$

- **Matter field with oscillations in time has same properties of a bosonic field**.

Bosonic Field

- $\zeta(x)$ and $\eta(x)$ satisfy the equal-time commutation relations,

$$[\zeta(t,\mathbf{x}),\eta(t,\mathbf{x}')] = i\delta(\mathbf{x}-\mathbf{x}'), \tag{24}$$

$$[\zeta(t,\mathbf{x}),\zeta(t,\mathbf{x}')] = [\eta(t,\mathbf{x}),\eta(t,\mathbf{x}')] = 0. \tag{25}$$

- $T_{0\mathbf{k}}$ and $T^{\dagger}_{0\mathbf{k}}$ satisfy the commutation relations:

$$[T_{0\mathbf{k}},\, T^{\dagger}_{0\mathbf{k}'}] = \frac{[a_{\mathbf{k}},\, a^{\dagger}_{\mathbf{k}'}]}{\omega_0^2} = \frac{\delta_{\mathbf{k}\mathbf{k}'}}{\omega_0^2}, \tag{26}$$

$$[T_{0\mathbf{k}},\, T_{0\mathbf{k}'}] = [T^{\dagger}_{0\mathbf{k}},\, T^{\dagger}_{0\mathbf{k}'}] = \frac{[a_{\mathbf{k}},\, a_{\mathbf{k}'}]}{\omega_0^2} = \frac{[a^{\dagger}_{\mathbf{k}},\, a^{\dagger}_{\mathbf{k}'}]}{\omega_0^2} = 0. \tag{27}$$

- the Hamiltonian of the field inside volume V is,

$$H = \sum_{\mathbf{k}} \omega(\omega_0^2 T^{\dagger}_{0\mathbf{k}} T_{0\mathbf{k}} + \frac{1}{2}) = \sum_{\mathbf{k}} \omega(a^{\dagger}_{\mathbf{k}} a_{\mathbf{k}} + \frac{1}{2}), \tag{28}$$

Proper time uncertainty relation analogous to position-momentum uncertainty relation

Proper Time Field

Consider a real scalar field that has oscillations of matter in proper time only

$$\zeta' = \frac{1}{\sqrt{2}}[\zeta_0 + \zeta_0^\dagger] = \frac{1}{\sqrt{2}\omega_0}[T_0 e^{-i\omega_0 t} + T_0^\dagger e^{i\omega_0 t}]. \tag{29}$$

- Displaced time t'_d and displaced time rate u'_d are,

$$t'_d = \frac{-i}{\sqrt{2}}[T_0 e^{-i\omega_0 t} - T_0^\dagger e^{i\omega_0 t}] = \frac{-i}{\sqrt{2}\omega_0}[a e^{-i\omega_0 t} - a^\dagger e^{i\omega_0 t}], \tag{30}$$

$$u'_d = \partial_0 t'_d = \frac{-\omega_0}{\sqrt{2}}[T_0 e^{-i\omega_0 t} + T_0^\dagger e^{i\omega_0 t}] = \frac{-1}{\sqrt{2}}[a e^{-i\omega_0 t} + a^\dagger e^{i\omega_0 t}]. \tag{31}$$

- The Hamiltonian density is

$$H' = \frac{1}{2}(m\omega_0^2 {t'_d}^2 + \frac{{P'_d}^2}{m}) = \omega_0(a^\dagger a + \frac{1}{2}), \tag{32}$$

where

$$P'_d = m u'_d. \tag{33}$$

Uncertainty Relations Comparison

Table 1		
	Proper Time Oscillator	**Quantum Harmonic Oscillator**
Hamiltonian	$H' = \omega_0(a^\dagger a + \frac{1}{2})$	$H = \omega(a^\dagger a + \frac{1}{2})$
Commutation Relation	$[t'_d, P'_d] = i$	[x,p]=i
Uncertainty Relation	$\Delta t'_d \Delta P'_d \geq \frac{1}{2}$	$\Delta x \Delta p \geq \frac{1}{2}$

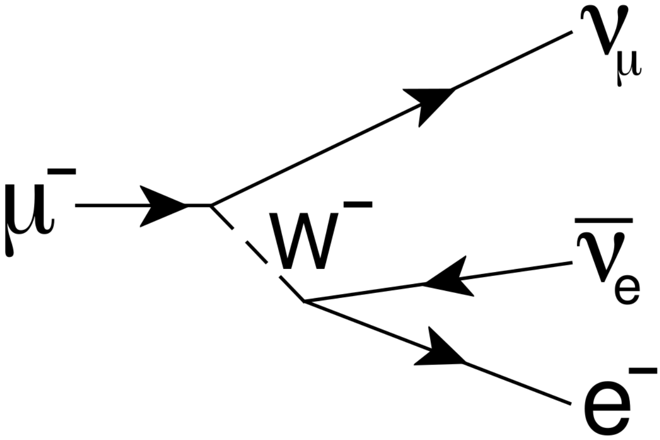
Creation and annihilation operators for bosonic field and quantum harmonic oscillator have similar formulation. Can there be a hidden symmetry?

If a real particle is an excitation of the corresponding quantum field and its underlying spacetime, the proper time oscillation will allow a real particle to interact directly with spacetime, generating a gravitational field.

A potential link between quantum theory and gravity.

Consistent with the predictions of quantum theory and general relativity

Muon Decay Time



Muon Decay Time

The uncertainty of decay time measurement.

$$\Delta t' = \sqrt{\frac{\omega}{2\omega_0^3}} = \hbar\sqrt{\frac{E}{2m^3}}. \tag{34}$$

- Muon mass-energy $m_\mu = 105.6583744 \times 10^6$ eV.
- Assume projected energy $E = 1$TeV.
- Uncertainty $\Delta t' = 4.3 \times 10^{-22}$s.
- Mean life time of muon decay $\Delta t_\mu = 2.1969811(22) \times 10^{-6}$s

Moving Oscillator

- Consider a normalized plane wave

$$\tilde{\zeta} = \frac{e^{i(\mathbf{k}\cdot\mathbf{x}-\omega t)}}{\sqrt{\omega\omega_0^3}}. \tag{35}$$

- Hamiltonian density is

$$\tilde{\mathcal{H}} = \omega/V. \tag{36}$$

- Observed particle travels at an average velocity of $\mathbf{v} = \mathbf{k}/\omega$.
- As the particle propagates, it oscillates with amplitudes

$$\mathring{T} = \sqrt{\frac{\omega}{\omega_0^3}}, \quad \mathring{\mathbf{X}} = \frac{\mathbf{k}}{\sqrt{\omega_0^3\omega}}. \tag{37}$$

- **At a higher energy level, the effects of the particle's oscillations will be easier to detect.**

Even for a π^+ particle with an energy 1 TeV, detecting the oscillations is still beyond the reach of our experiments.

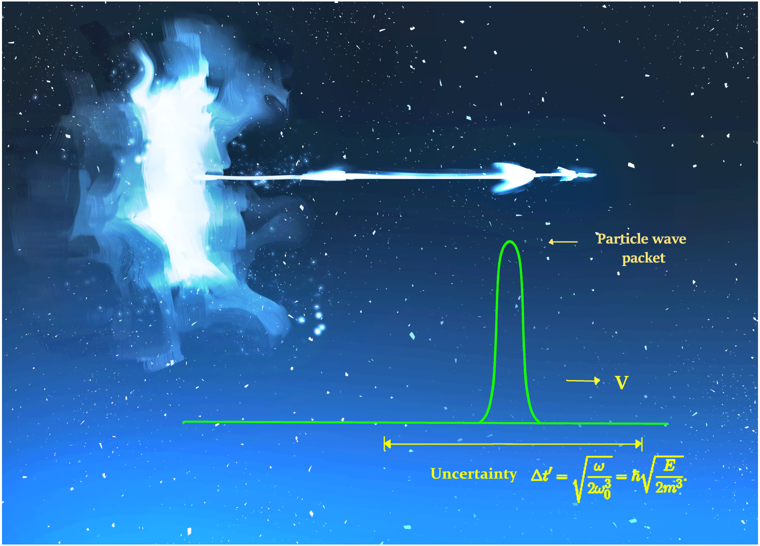
Table 1 Oscillation amplitudes of a π^+ with different projected energies.

$E(GeV)$	$\mathring{T}(s)$	$\mathring{X}(m)$
1	1.3×10^{-23}	3.5×10^{-15}
10	4.0×10^{-23}	1.2×10^{-14}
100	1.3×10^{-22}	3.8×10^{-14}
1000	4.0×10^{-22}	1.2×10^{-13}

Consistancy with Standard Theory

Poperties of a proper time oscillator stay consistent with the predictions of quantum theory until we reach a very high energy level, where the oscillations of matter in time and space become significant. However, the oscillations are small and cannot be detected by experiments yet.

Neutrino's arrival time


Particle wave packet
V
Uncertainty $\Delta t' = \sqrt{\frac{\omega}{2\omega_0^3}} = \hbar\sqrt{\frac{E}{2m^3}}$.

Particle's Arrival Time

Neutrino has extreme small mass and much larger amplitudes of oscillations.

$E(GeV)$	$\mathring{T}(s)$	$\mathring{X}(cm)$	$\omega_p(s^{-1})$
1	7.4×10^{-12}	0.22	6.1×10^6
10	2.3×10^{-11}	0.70	6.1×10^5
100	7.4×10^{-11}	2.20	6.1×10^4
1000	2.3×10^{-10}	7.00	6.1×10^3

Note: The assumed mass of the particle is $m = 2eV$.

Estimate for Neutrio Mass

The deviations will result in an uncertainty of arrival time when we measure a large collection of particles with the same average velocity, i.e.

$$\Delta t' = \sqrt{\frac{\omega}{2\omega_0^3}} = \hbar\sqrt{\frac{E}{2m^3}}. \tag{38}$$

With the arrival time uncertainty obtained from experiments, the mass of a neutrino can be reconciled,

$$m = [\frac{\hbar^2 E}{2(\Delta t')^2}]^{1/3}. \tag{39}$$

Fluctuation of Neutrino's Arrival Time

- The experiments (e.g. IceCube) on neutrinos' speed could provide some hints.
- Study in lightcone fluctuation evaluated the accumulated uncertainty effects of a neutrino's travel time and distance in fluctuating spacetime.
- Suggested uncertainty follows a power-law depending on the neutrino's energy, i.e., $\Delta t' \propto l^m E^n$. , where m and n are factors to be established by experiments or theoretical predictions.
- **Uncertainty derived from temporal oscillation is $\Delta t' \propto E^{1/2}$ akin to the power-law in quantum spacetime.**
- Assuming $m = 2eV$ and $E = 1TeV$, uncertainty is in the order of $10^{-10}s$.

	OPERA	MINOS
Baseline distance (km)	~ 731	~ 734
Timing resolution (ns)	Final $\sim$ 1, initial $\sim$ 60	$\sim$ 2–3 (systematic), $<$ 1 (statistical)
Speed deviation sensitivity $\left(\frac{v-c}{c}\right)$	$\lesssim 2 \times 10^{-6}$ (final)	$(1.0 \pm 1.1) \times 10^{-6}$
Typical neutrino energy (GeV)	Mean $\sim$ 17 (range $\sim$ 1–20)	Mean $\sim$ 3 (extends up to $\sim$ 50)

Table 3. Comparison of MINOS and OPERA neutrino time-of-flight measurements.[33,34].

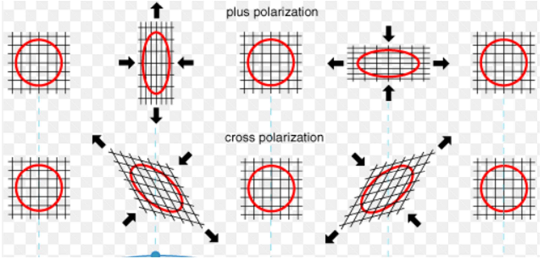
Dark Matter

Dark Matter

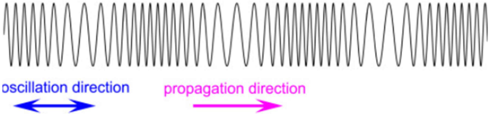
- Suppose a pure form (without non-gravitational properties) of proper time oscillations exists; it will not interact with ordinary baryonic matter and radiation except through gravity.

- **A scalar field with pure gravitational effects could be a potential candidate as dark matter.**

Rank 2 Tensor Wave



Rank 1 Tensor Wave



Rank 1 Tensor Wave

- A Lorentz covariant plane wave is a rank-1 tensor,

$$\begin{bmatrix} \zeta_{t\mathbf{k}} \\ \zeta_{\mathbf{xk}} \end{bmatrix} = -i \begin{bmatrix} T_{\mathbf{k}} \\ \mathbf{X}_{\mathbf{k}} \end{bmatrix} e^{i(\mathbf{k}\cdot\mathbf{x}' - \omega t')}. \tag{40}$$

- Object or particle can be induced to oscillate in the propagation direction of the plane wave contrast a gravitational wave's transverse distortions.
- Unlike scalar induced gravitational wave in modified theory without the 'cross' and 'plus' modes.

Conclusion

Assuming matter can oscillate in proper time:

- Reconcile basic properties of a quantum field.
- Spacetime around has the Schwarzschild solution.
- Neutrino time of arrival may provide hints.
- Rank 1 tensor gravitational wave may exist.

If a real particle is an excitation of the corresponding quantum field and its underlying spacetime, the proper time oscillation will allow a real particle to interact directly with spacetime, generating a gravitational field.

A potential link between quantum theory and gravity.

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