A GLIMPSE OF THE EARLY UNIVERSE
WITHOUT REAL LIGHT

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Transmission of information from the early Universe to the current era
THE RADIATION GREEN’S FUNCTION OF A MASSLESS SCALAR FIELD HAS SUPPORT ONLY ON THE LIGHT-CONE

\[ \Box G'(x, x') = -4\pi \delta_4(x, x') \]

\[ [\Phi(x), \Phi(x')] = \frac{i}{4\pi} G(x, x') \]

- True in 3+1 Flat spacetime

- Violated in general if there is curvature (unless there is conformal invariance)

[McLenaghan, Sonego, Faraoni, …]
VIOLATION OF THE STRONG HUYGENS PRINCIPLE: CONSEQUENCES ON RELATIVISTIC QUANTUM COMMUNICATION in COSMOLOGY

In curved spacetimes, communication through massless fields is not confined to the light-cone, but there can be a leakage of information towards the inside of the light-cone.

SPATIALLY FLAT, OPEN FRW SPACETIME 3+1D:

\[ ds^2 = a(\eta)^2 (-d\eta^2 + dr^2 + r^2 d\Omega^2) \]

This geometry will be generated by:

- a perfect fluid with a constant density-to-pressure ratio \( p = w \rho \), \( w > -1 \)

- the scale factor evolves as \( a \propto \eta^{\frac{2}{3w+1}} \propto t^{\frac{2}{3(w+1)}} \)

\( \eta \) : conformal time

\( a(\eta) \) : scale factor

\( t \) : cosmological time,

\( dt = a(\eta) d\eta \)

units: \( \hbar = c = 1 \)
SET UP: TEST FIELD

**COUPLED** TO THIS BACKGROUND GEOMETRY:

A TEST **MASSLESS SCALAR FIELD** QUANTIZED e.g. IN THE ADIABATIC VACUUM
SCALAR FIELD COUPLING TO GRAVITY

**KLEIN-GORDON EQUATION**

\[(\Box - m^2 + \xi R)\phi = 0\]

\[\Box = \frac{1}{\sqrt{|g|}} \partial_\mu (\sqrt{|g|} g^{\mu\nu} \partial_\nu)\]

**CONFORMAL COUPLING**

\[\xi = \frac{1}{6}\]

**MINIMAL COUPLING**

\[\xi = 0\]
Alice & Bob do not have direct access to the field.

Alice makes a local perturbation of the field (let’s model it with a particle detector)

Bob can perform measurements on the field indirectly by locally coupling ‘particle detectors’

Information is encoded in the quantum state of the field
Unruh-DeWitt DETECTOR

- Two-level system
  \(|e\rangle\ \ \ \ \ \ \ |g\rangle\)

- Energy gap ground-excited states:
  \(\Omega\)

- Monopole moment operator:
  \(\mu_\nu(t) = |e_\nu\rangle\langle g_\nu| e^{i\Omega_\nu t} + |g_\nu\rangle\langle e_\nu| e^{-i\Omega_\nu t}\)

- Spatially smeared:
  \(F(\vec{x}, t) = \frac{1}{\sigma^3 \sqrt{\pi^3}} e^{-a(t)^2 \vec{x}^2 / \sigma^2}\)

Detectors:
\(\nu = \{A, B\}\)
$$H_{I,\nu} = \lambda_{\nu} \chi_{\nu}(t) \mu_{\nu}(t) \int d^3x \ a(t)^3 F[x - x_{\nu}(t), t] \Phi[x, \eta(t)]$$
Hamiltonian
Detector-field interaction

$$H_{I,\nu} = \lambda_{\nu} \chi_{\nu}(t) \mu_{\nu}(t) \int d^3 x \ a(t)^3 F[\mathbf{x} - \mathbf{x}_{\nu}(t), t] \Phi[\mathbf{x}, \eta(t)]$$

Coupling strength
Monopole moment
Switching function
Detector's trajectory
Scale factor
Smearing function

Total Interaction Hamiltonian:

$$H_I = H_{I,A} + H_{I,B}$$
Influence of the presence of A on B ➔ SIGNALING ESTIMATOR, \( S \)

how much information can be sent? ➔ CHANNEL CAPACITY, \( C \)
How is B’s excitation probability modulated by the interaction of A with the field?

- Initial state: \( \rho_0 = \rho_A^0 \otimes \rho_B^0 \otimes |0\rangle \langle 0| \)
  \( \rho_{\nu 0} = |\psi_{\nu 0}\rangle \langle \psi_{\nu 0}| \)
  \( |\psi_{\nu 0}\rangle = \alpha_{\nu} |e_{\nu}\rangle + \beta_{\nu} |g_{\nu}\rangle \)

- At time \( T \): \( \rho(T) = U_T \rho_0 U_T^\dagger \)

Taking \( \lambda_{\nu} \) small, perturbative expansion: \( U_T = \mathbb{I} + U_T^{(1)} + U_T^{(2)} \)

\[ \rho_B(T) \approx \text{Tr}_{A,\Phi} \left[ \rho_0 + U_T^{(1)} \rho_0 + \rho_0 U_T^{(1)\dagger} + U_T^{(1)} \rho_0 U_T^{(1)\dagger} + U_T^{(2)} \rho_0 + \rho_0 U_T^{(2)\dagger} \right] \]
How is B’s excitation probability modulated by the interaction of A with the field?

-Initial state: \( \rho_0 = \rho_A 0 \otimes \rho_B 0 \otimes |0\rangle \langle 0| \)  
  \( \rho_{\nu 0} = |\psi_{\nu 0}\rangle \langle \psi_{\nu 0}| \)

\[ |\psi_{\nu 0}\rangle = \alpha_{\nu} |e_{\nu}\rangle + \beta_{\nu} |g_{\nu}\rangle \]

-At time \( T \): \( \rho(T) = U_T \rho_0 U_T^\dagger \)

Taking \( \lambda_{\nu} \) small, perturbative expansion: \( U_T = \mathbb{I} + U_T^{(1)} + U_T^{(2)} \)

\( \rho_B(T) \simeq \rho_B 0 + \lambda_B^2 \underbrace{\cdots \cdots}_{\text{S}2} + \lambda_A \lambda_B \underbrace{\cdots \cdots}_{\text{S}2} + O(\lambda_{\nu}^4) \)

\[ S = \lambda_A \lambda_B S_2 + O(\lambda_{\nu}^4) \]
\[ S = \lambda_A \lambda_B S_2 + O(\lambda_{\nu}^4) \]

\[ S_2 = 4 \int dt \int dt' \chi_A(t) \chi_B(t') \text{Re}(\alpha_A^* \beta_A e^{i\Omega_A t}) \text{Re}(\alpha_B^* \beta_B e^{i\Omega_B t'}) [\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] \]
\[ S = \lambda_A \lambda_B S_2 + \mathcal{O}(\lambda^4) \]  

(INDEPENDENT OF STATE OF \( \Phi \))

\[ S_2 = 4 \int dt \int dt' \chi_A(t) \chi_B(t') \text{Re}(\alpha_A^* \beta_A e^{i\Omega_A t}) \text{Re}(\alpha_B^* \beta_B e^{i\Omega_B t'}) \left[ \Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t') \right] \]

CONFORMAL COUPLING

\[ \left[ \Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t') \right] = \frac{i}{4\pi} \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t) a(t') R} \]

\[ \Delta \eta = \eta(t) - \eta(t') \]

\[ R = \| \vec{x}_A - \vec{x}_B \| \]
Conformal coupling

\[ [\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{4\pi} \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t)a(t')R} \]

Support on the light cone

Decay with spatial separation

Conformal invariance
No violation of strong Huygens principle
Conformal Coupling

Decay with Spatial separation

Commutator

\[
[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{4\pi} \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t)a(t')R}
\]

But...what happens if we consider minimal coupling?
MINIMAL COUPLING

\[
[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = i \theta(-\Delta \eta) - \theta(\Delta \eta) \int_0^\infty dk \sin(kR) g_\alpha(\eta(t), \eta(t'), k)
\]

\[
g_\alpha(\eta, \eta', k) = \sqrt{\frac{\eta}{\eta'} Y_\alpha(k \eta') \left[ J_{\alpha-1}(k \eta') - J_{\alpha+1}(k \eta') \right] - J_\alpha(k \eta') \left[ Y_{\alpha-1}(k \eta') - Y_{\alpha+1}(k \eta') \right]}
\]

\[
J_\alpha, Y_\alpha \quad \text{BESSEL FUNCTIONS} \quad \alpha = \frac{3 - 3w}{6w + 2}
\]
MINIMAL COUPLING

\[ [\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{\pi^2 a(t)a(t')R} \int_0^\infty dk \sin(kR)g_\alpha(\eta(t), \eta(t'), k) \]

\[ g_\alpha(\eta, \eta', k) = \sqrt{\frac{\eta}{\eta'}} \frac{J_\alpha(k\eta)Y_\alpha(k\eta') - Y_\alpha(k\eta)J_\alpha(k\eta')}{Y_\alpha(k\eta') [J_{\alpha-1}(k\eta') - J_{\alpha+1}(k\eta')] - J_\alpha(k\eta') [Y_{\alpha-1}(k\eta') - Y_{\alpha+1}(k\eta')] } \]

\( J_\alpha, Y_\alpha \) BESSEL FUNCTIONS \quad \alpha = \frac{3 - 3w}{6w + 2}

MATTER DOMINATED UNIVERSE

\[ [\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{4\pi} \left[ \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t)a(t')R} + \frac{\theta(-\Delta \eta - R) - \theta(\Delta \eta - R)}{a(t)a(t')\eta(t)\eta(t')} \right] \]

\( w = 0 \quad \alpha = 3/2 \quad a \propto \eta^2 \propto t^{2/3} \)
**CONFORMAL COUPLING**

\[
[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{4\pi} \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t)a(t') R}
\]

**MINIMAL COUPLING**

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[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{4\pi} \left[ \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t)a(t') R} + \frac{\theta(-\Delta \eta - R) - \theta(\Delta \eta - R)}{a(t)a(t') \eta(t) \eta(t')} \right]
\]

- Support on the light cone
- Decay with Spatial separation
**CONFORMAL COUPLING**

\[
[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{4\pi} \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t)a(t') R}
\]

**MINIMAL COUPLING**

\[
[\Phi(\vec{x}_A, t), \Phi(\vec{x}_B, t')] = \frac{i}{4\pi} \left[ \frac{\delta(\Delta \eta + R) - \delta(\Delta \eta - R)}{a(t)a(t') R} + \frac{\theta(-\Delta \eta - R) - \theta(\Delta \eta - R)}{a(t)a(t') \eta(t) \eta(t')} \right]
\]

**COMMENTS**

- Support on the light cone
- Decay with spatial separation
- Violation of Strong Huygens Principle
- Does NOT decay with spatial separation
- Timelike-leakage
To obtain a lower bound to the channel capacity, we use a simple **COMMUNICATION PROTOCOL:**

- **Alice** encodes “1” by coupling her detector A to the field, and “0” by not coupling it.

- Later **Bob** switches on B and measures its energy. If B is excited, Bob interprets a “1”, and a “0” otherwise.

\[
C \simeq \lambda_A^2 \lambda_B^2 \frac{2}{\ln 2} \left( \frac{S_2}{4|\alpha_B||\beta_B|} \right)^2 + \mathcal{O}(\lambda_{\nu}^6)
\]

(noisy asymmetric binary channel)
A&B CAUSAL RELATIONSHIPS

\[ \eta_{i\nu} \equiv \eta(T_{i\nu}) \]

\[ \eta_{f\nu} \equiv \eta(T_{f\nu}) \]
VARIATION WITH THE **SPATIAL SEPARATION** BETWEEN ALICE AND BOB

\[ \left| \psi_{\nu 0} \right> = \alpha_{\nu} |e_{\nu} \rangle + \beta_{\nu} |g_{\nu} \rangle \]

\[ |\alpha_A| = |\beta_A| = 1/\sqrt{2} \]

\[ \arg(\alpha_A) - \arg(\beta_A) = \pi \]

\[ \arg(\alpha_B) - \arg(\beta_B) = \pi/2 \]

\[ T_{fA} - T_{iA} = T_{fB} - T_{iB} = \Delta \]

\[ T_{iA} = \Delta/30 \quad T_{iB} = 10\Delta \]
VARIATION WITH THE **SPATIAL SEPARATION** BETWEEN ALICE AND BOB

\[ \psi_{\nu 0} = \alpha_{\nu} |e_{\nu}\rangle + \beta_{\nu} |g_{\nu}\rangle \]

\[ |\alpha_A| = |\beta_A| = 1/\sqrt{2} \]

\[ \arg(\alpha_A) - \arg(\beta_A) = \pi \]

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\[ T_fA - T_iA = T_fB - T_iB = \Delta \]

\[ T_iA = \Delta/30 \quad T_iB = 10\Delta \]
VARIATION WITH THE **TEMPORAL SEPARATION** BETWEEN ALICE AND BOB

\[
|\psi_{\nu 0}\rangle = \alpha_\nu |e_\nu\rangle + \beta_\nu |g_\nu\rangle \\
|\alpha_A| = |\beta_A| = 1/\sqrt{2} \\
\arg(\alpha_A) - \arg(\beta_A) = \pi \\
\arg(\alpha_B) - \arg(\beta_B) = \pi/2
\]

\[
T_fA - T_iA = T_fB - T_iB = \Delta \\
T_iA = \Delta/30 \\
R = \Delta/10
\]
VARIATION WITH THE **TEMPORAL SEPARATION** BETWEEN ALICE AND BOB

\[ |\psi_{\nu 0}\rangle = \alpha_{\nu}|e_{\nu}\rangle + \beta_{\nu}|g_{\nu}\rangle \]

\[ |\alpha_A| = |\beta_A| = 1/\sqrt{2} \]

\[ \arg(\alpha_A) - \arg(\beta_A) = \pi \]

\[ \arg(\alpha_B) - \arg(\beta_B) = \pi/2 \]

\[ T_{fA} - T_{iA} = T_{fB} - T_{iB} = \Delta \]

\[ T_{iA} = \Delta/30 \quad R = \Delta/10 \]

**DECAY, could we compensate it?**

**VIOLATION OF STRONG HUYGENS PRINCIPLE !!!!**
COMPENSATE DECAY WITH DISTRIBUTED DETECTORS

\[ S_2 \propto \ln \left( \frac{\eta f_A}{\eta i_A} \right) \ln \left( \frac{\eta f_B}{\eta i_B} \right) \]

\[ \eta i_B = \eta(T_{iB}) \]

\[ \eta \]

\[ \ln \]

\[ (\lambda A^2 \lambda B)^2 \]
THE ELECTROMAGNETIC TENSOR $F_{\mu\nu}$ IS CONFORMALLY INARIANT

→ IT DOES NOT VIOLATE STRONG HUYGENS PRINCIPLE
THE ELECTROMAGNETIC TENSOR \( F_{\mu\nu} \)

IS CONFORMALLY INVARIANT

\[ \rightarrow \quad \text{IT DOES NOT VIOLATE STRONG HUYGENS PRINCIPLE} \]

\[ \quad \text{BUT} \]

THE ELECTROMAGNETIC POTENTIAL \( A_\mu \) DOES VIOLATE IT

Charged currents couple to \( A_\mu \). Electromagnetic antennas will see the strong Huygens principle violation (in the same fashion they see e.g. the Aharonov-Bohm effect or Casimir forces.)
Conclusions

All events that generate light signals also generate timelike signals (not mediated by massless quanta exchange), that decay slower.

For a matter dominated universe we find that these signals do not decay with the spatial separation to the source. Temporal decay can be compensated by deploying a network of receivers inside the light-cone.

We particularize the discussion to a concrete channel as a mere example to illustrate the non-decaying behaviour of the information capacity.

Inflationary phenomena, early universe physics, primordial decouplings, etc, will also leave a timeline echo on top of the light signals that we receive from them.

OUR RESULTS MAY PERHAPS INSPIRE NOVEL WAYS TO LOOK AT THE EARLY UNIVERSE VIA THE TIMELIKE SIGNALS
NAME THAT EXOPLANET
The rush to go down in astronomical history

NewScientist

Ancient echoes speak to us from the big bang
NAME THAT EXOPLANET
The rush to go down in astronomical history

Thank you