

# Spacetime metric fluctuations and gravitational decoherence

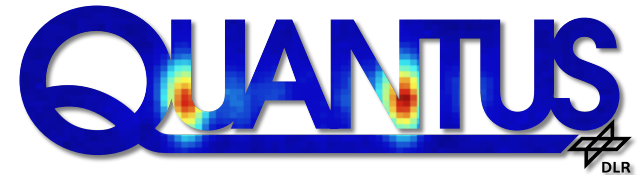
Albert Roura

Institut für Quantenphysik, Universität Ulm

Malta, 27 March 2017



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# Gravitational waves

- In **general relativity** gravitation is a manifestation of the **curvature** of the **spacetime** geometry.
- **Gravitational waves** → *distortions* of the spacetime geometry that propagate at the speed of light

$$ds^2 = (\eta_{\mu\nu} + h_{\mu\nu}) dx^\mu dx^\nu$$

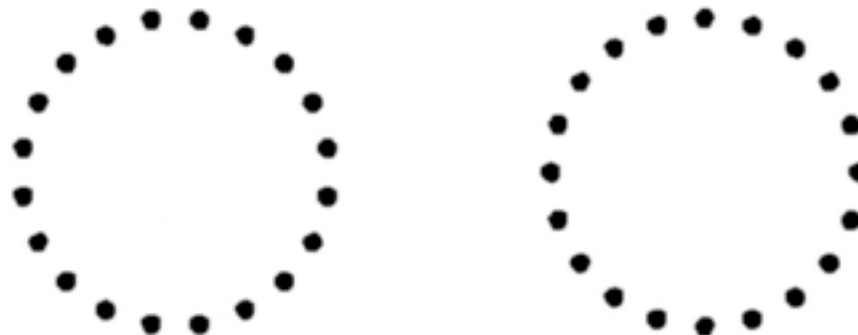
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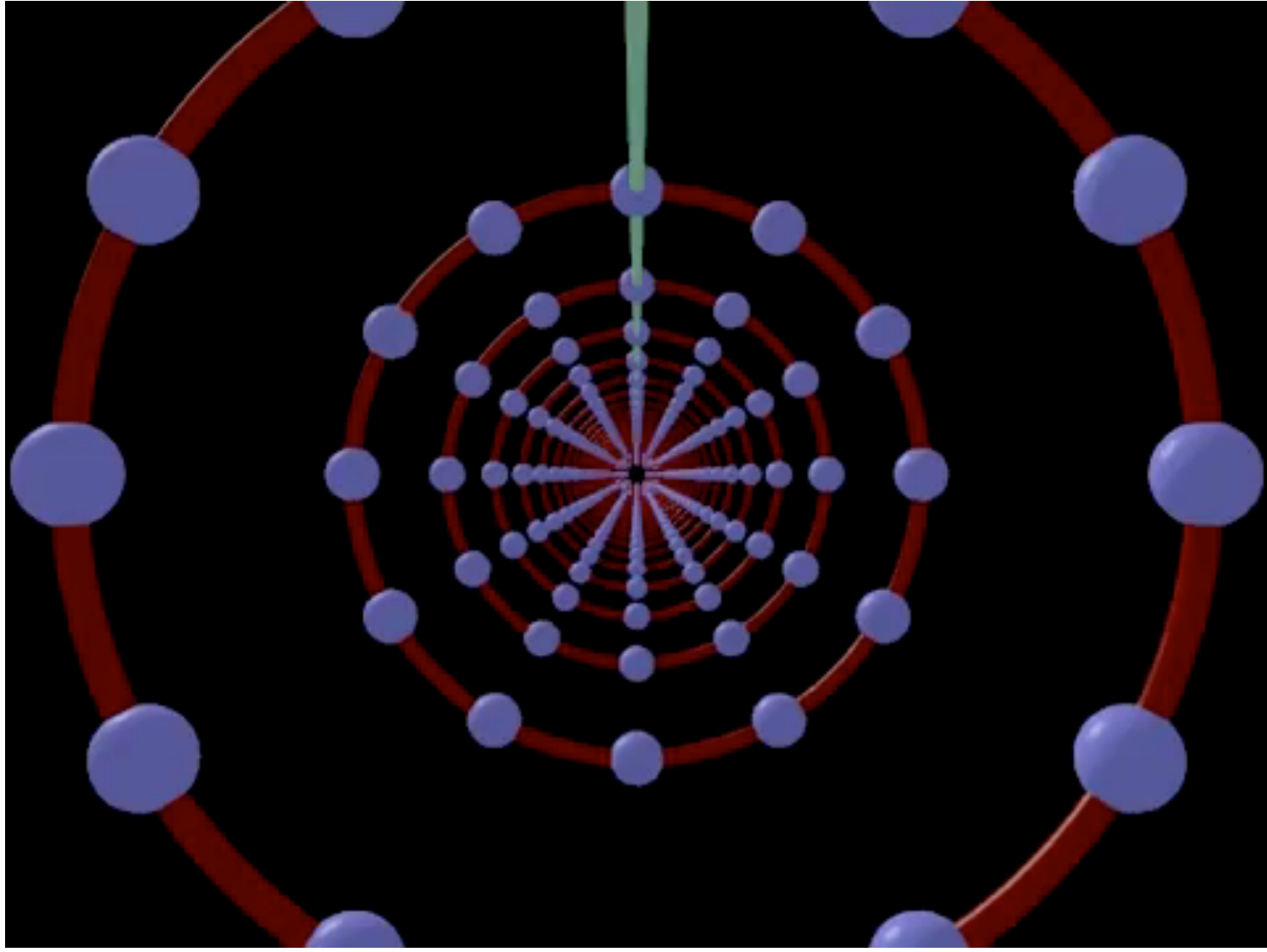


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- Dynamics of *linearized gravitational waves* (GWs):

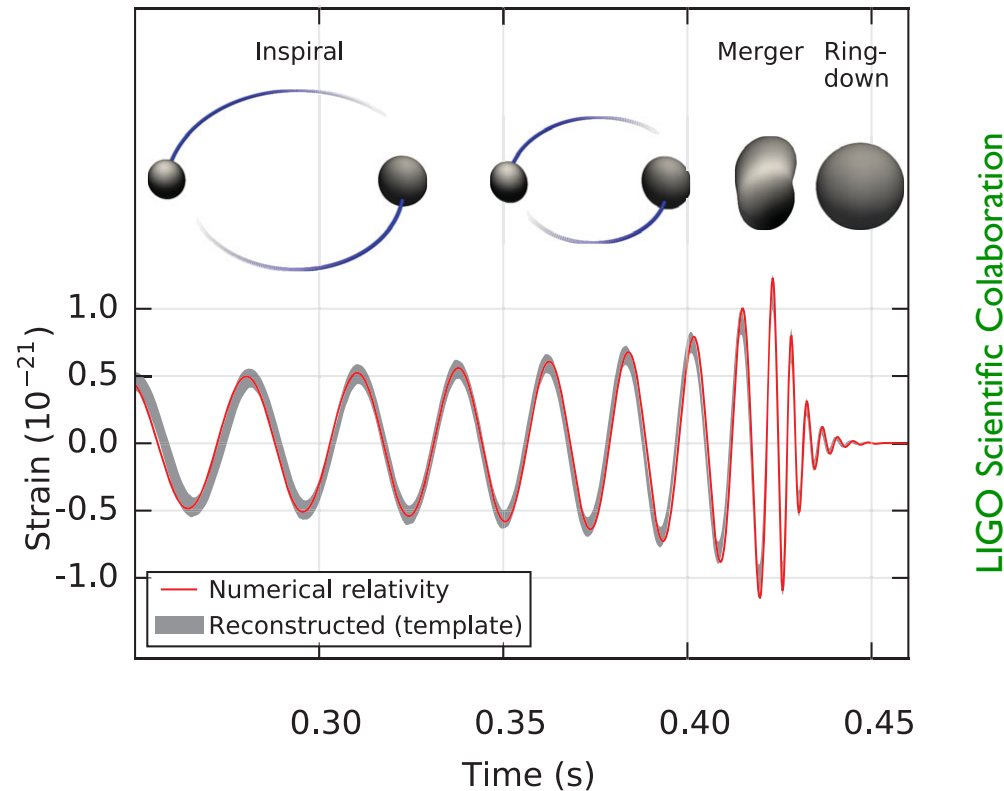
$$\square \bar{h}_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Analogous to *electromagnetic waves* (transverse but *dipolar*):

$$\square A^\mu = J^\mu$$

- I will *exploit this analogy* to introduce in a *non-technical* way some key concepts and ideas in connection with *gravitational decoherence* due to *spacetime metric fluctuations*.

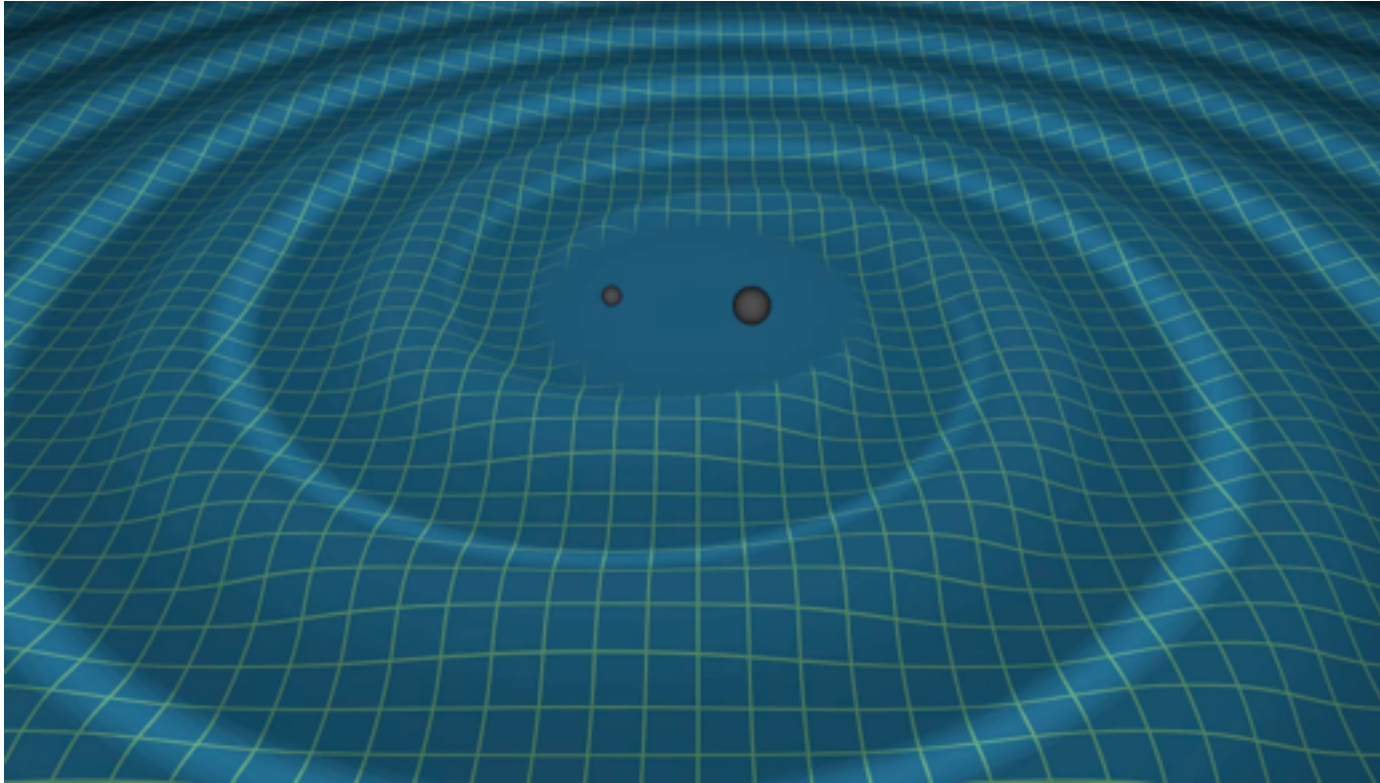
- First GW detection announced in February 2016:



- Spectacular example of mass-energy equivalence,  $E = mc^2$ :  
about 3 solar masses radiated in a fraction of a second!



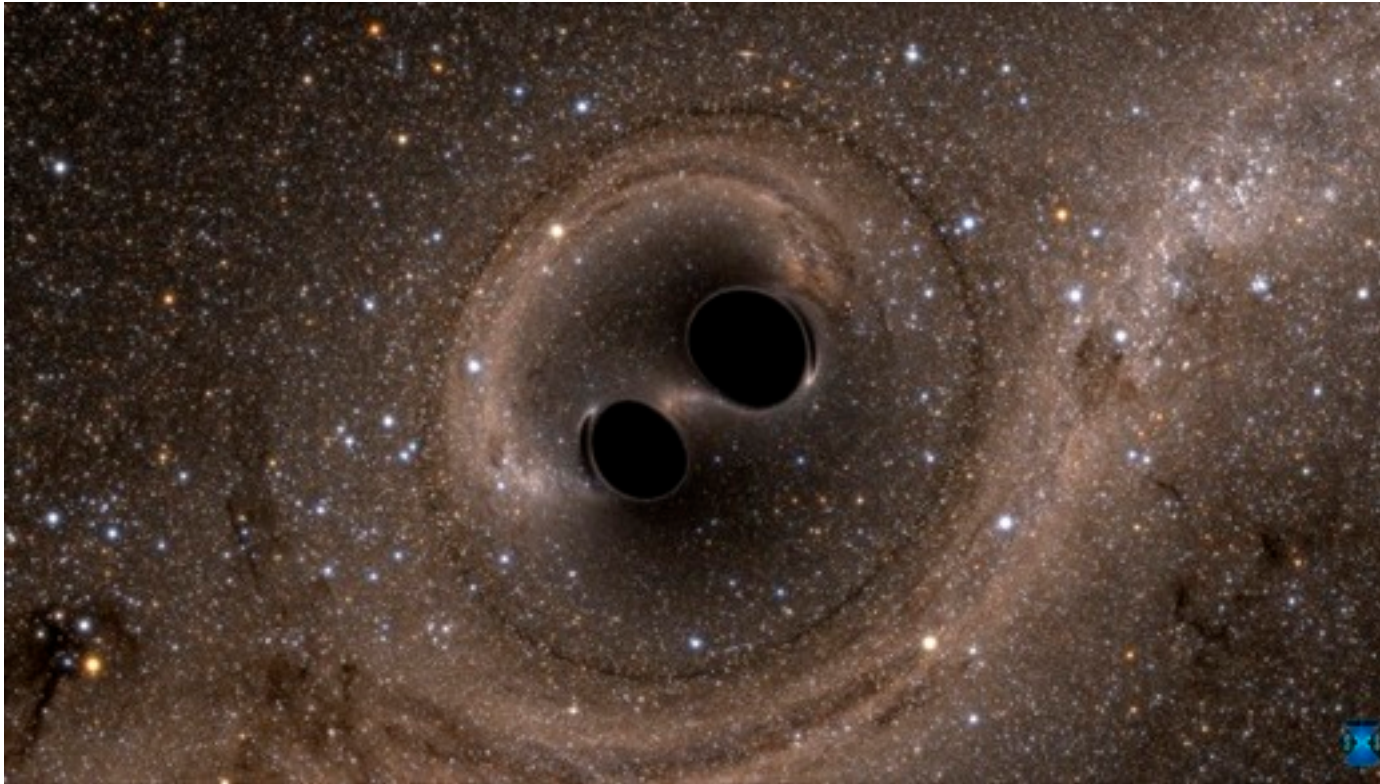
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LIGO / T. Pyle

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- New era of **gravitational-wave astronomy**.
- Opens a completely **new window** to the universe:
  - ▶ different frequency bands
  - ▶ completely different kind of radiation
- **“Listening”** to the universe:
  - ▶ *coherent* emission due to the motion of *macroscopic* masses rather than *incoherent* emission due to *microscopic* processes
  - ▶ analogous to *hearing* a violin rather than *seeing* it

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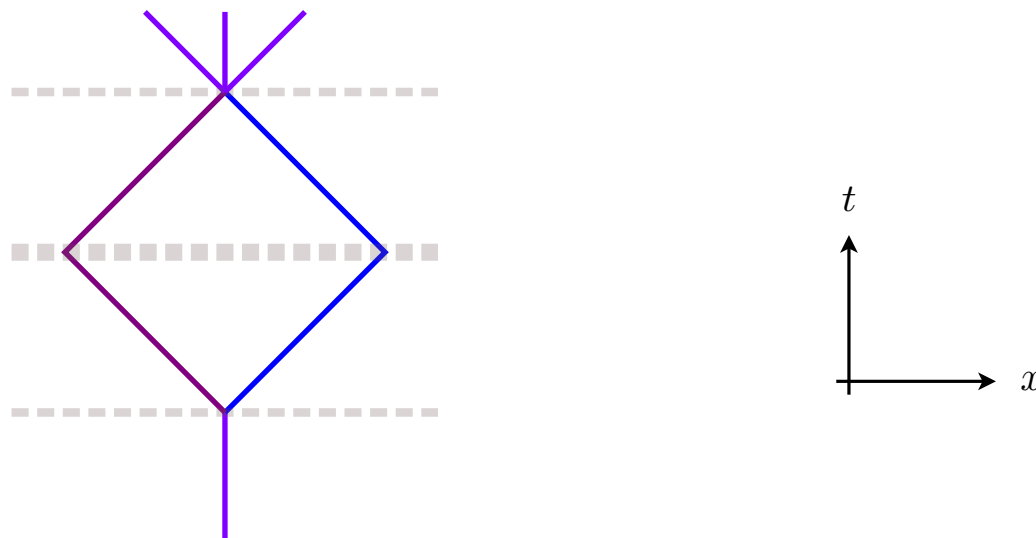
# Outline

1. Classical gravitational waves
2. Metric fluctuations and gravitational decoherence
3. Quantum vacuum fluctuations in the early universe and cosmological large-scale structure

# Metric fluctuations and gravitational decoherence

# Analogy with electromagnetism

- Example: *interferometry* with **charged** particles

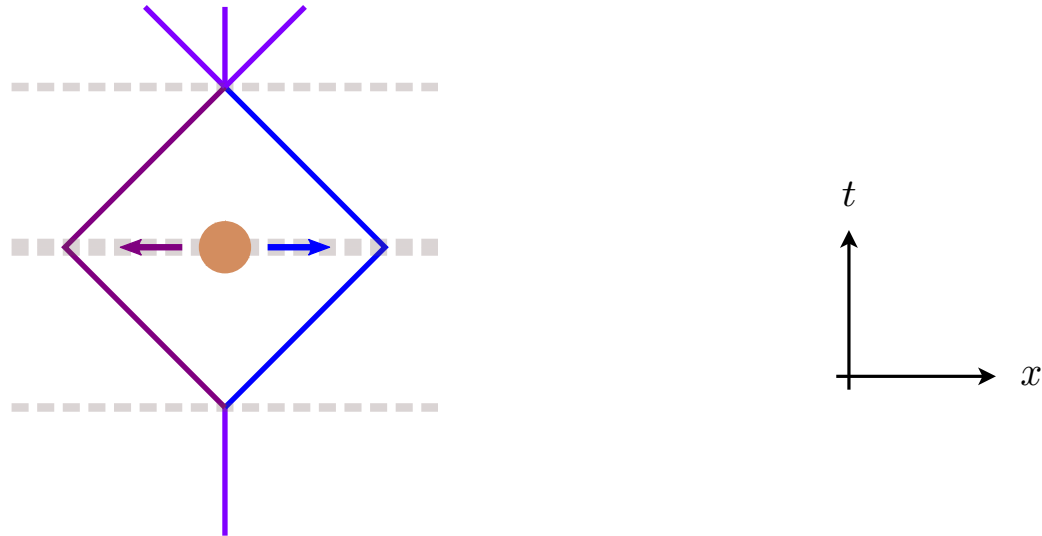


- Sources of **decoherence** (*Coulomb gauge*):
  - ▶ *potential*  $\rightarrow$  entanglement with other test charges
  - ▶ *transverse radiation*  $\rightarrow$  entanglement, dephasing



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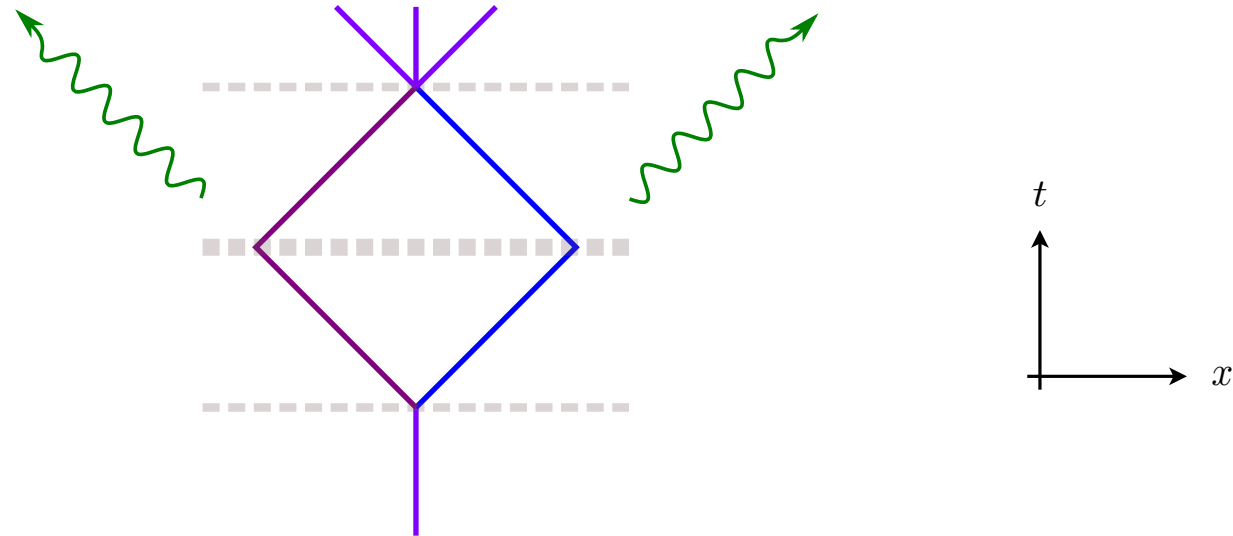
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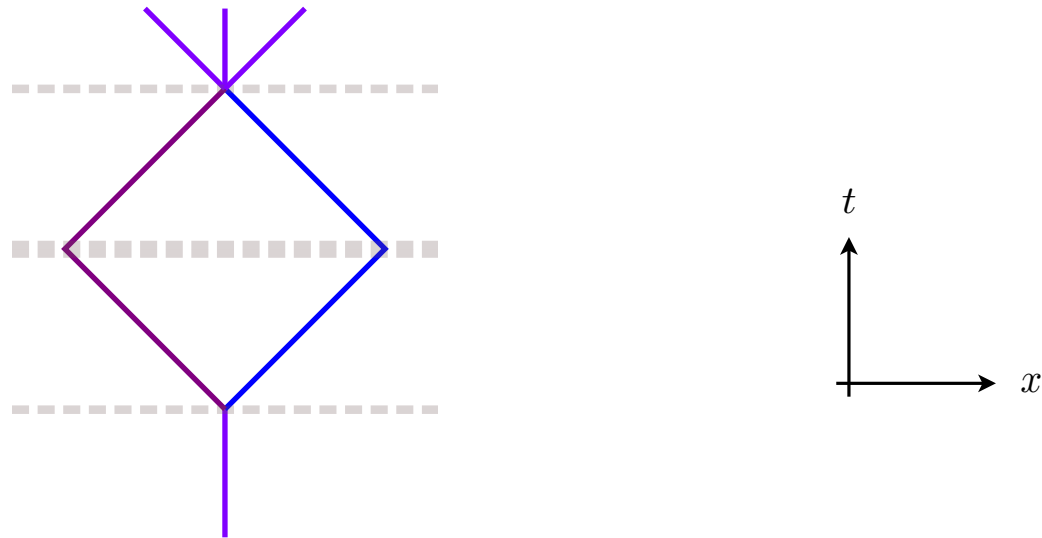
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being prepared for publication.

To be included in a later version.

# Gravitational decoherence

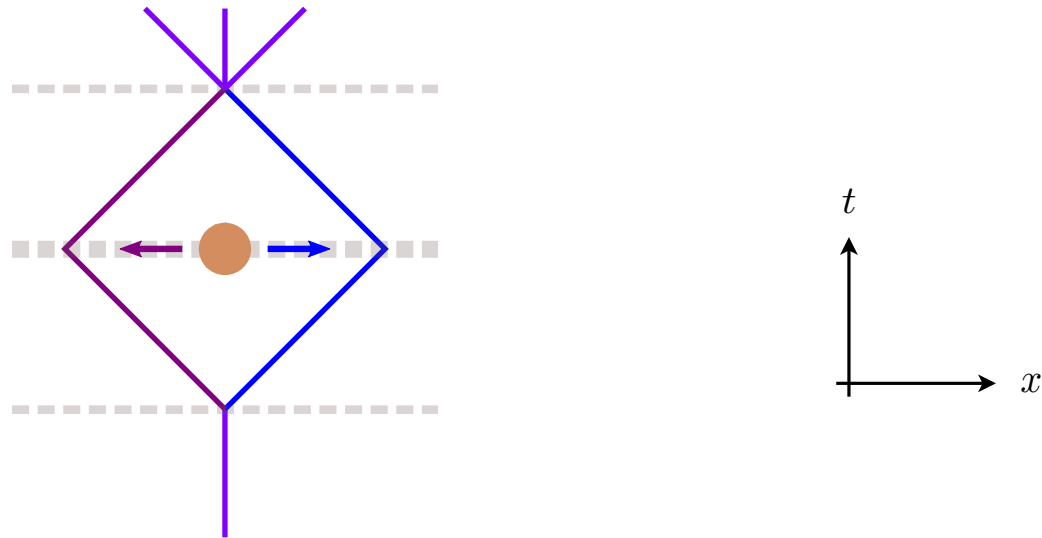
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- Sources of **decoherence** ( $TT$  gauge):
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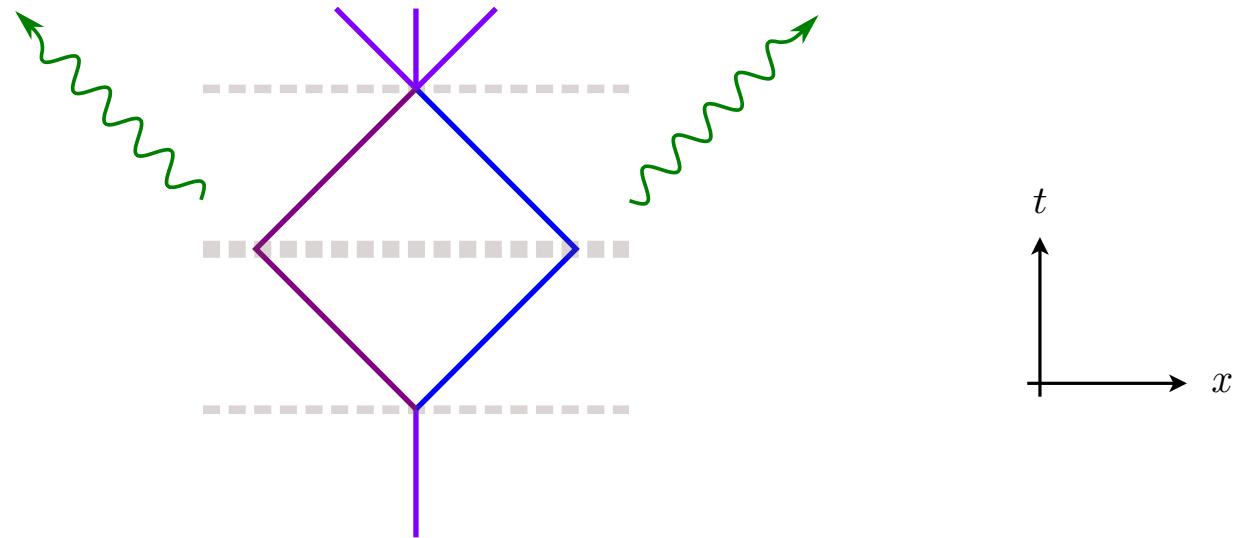
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- **Weakness** of gravitational interaction
  - difficult to *produce* and *detect* GWs
  - no shielding/absorption, undisturbed radiation from early universe ( $10^{-35}$  s)
- Negligible *decoherence* **in vacuum** ← extremely low emission rate (average *graviton number*  $\ll 1$ )

$$\frac{P_{\text{GW}}}{P_{\text{em}}} \sim \frac{1}{\alpha} \left( \frac{m}{m_{\text{pl}}} \right)^2 \left( \frac{L \omega}{c} \right)^2 \quad m_{\text{pl}} \approx 22 \mu\text{g} \sim 10^{19} \text{ GeV}$$

- What about *dephasing* due to **stochastic background** of **classical GWs** generated by astrophysical sources?

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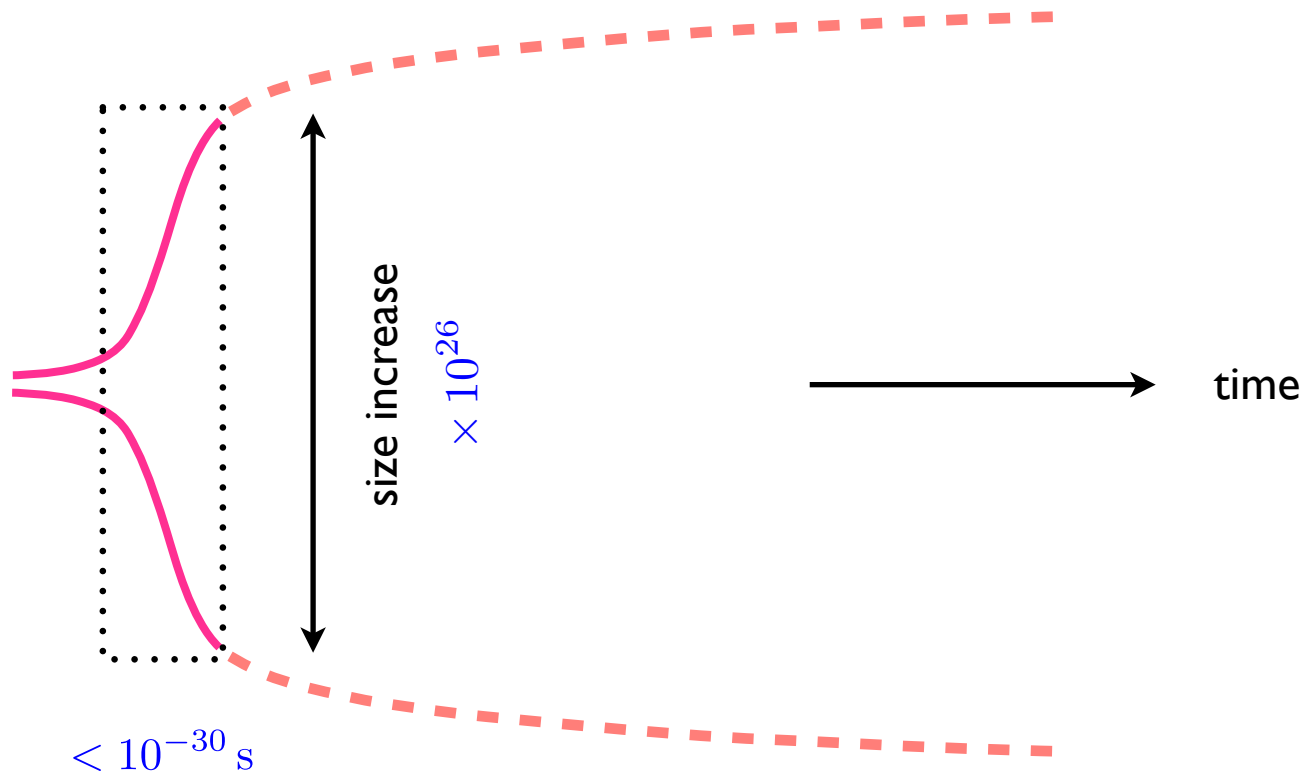
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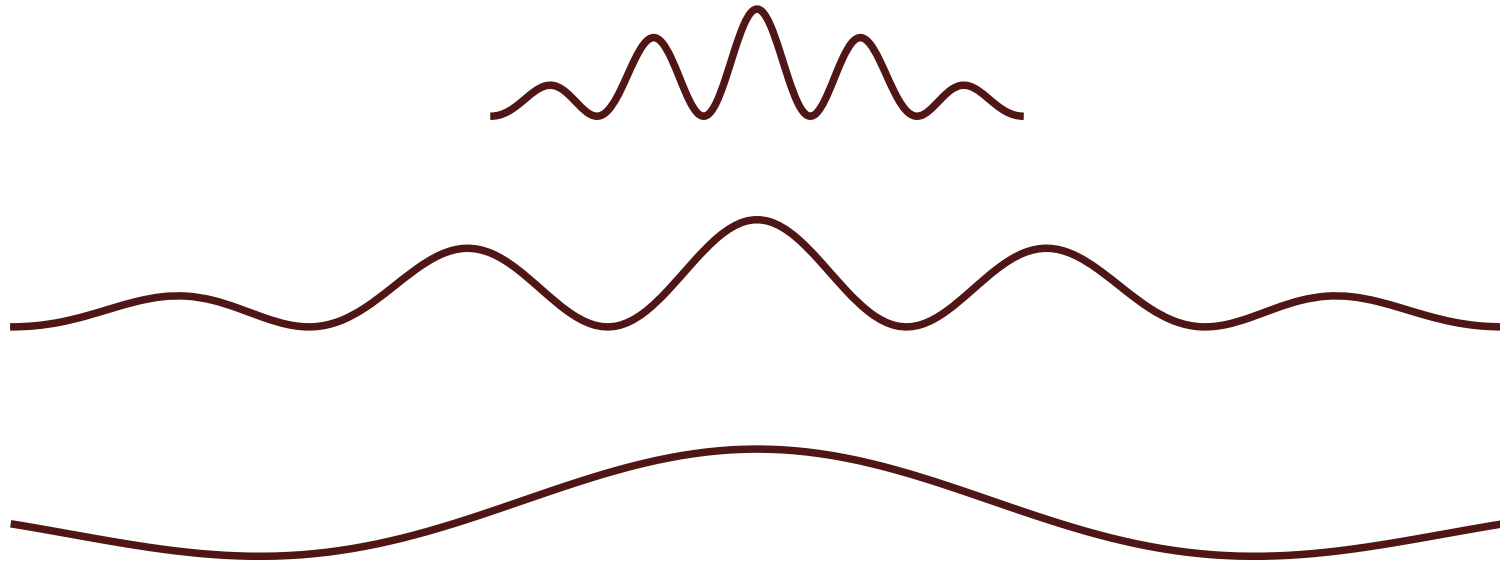
# Quantum vacuum fluctuations in the early universe

# Inflation

- **Exponential** expansion in the very early universe:  
 $10^{26}$ -fold size increase in less than  $10^{-30}$  seconds



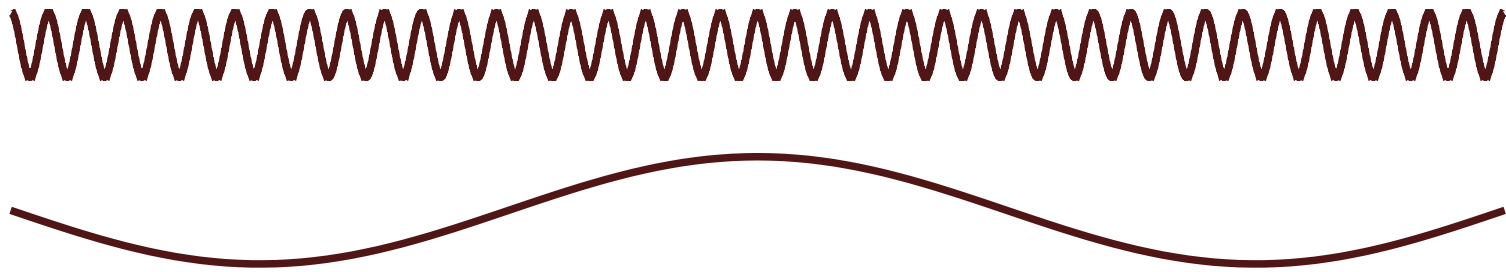
- Extreme **dilution**: almost no particles left in the whole observable universe, *nearly perfect vacuum*



- **Erases** any **previous features** → generic *initial conditions*
  - ▶ *classical vacuum* → vanishing field amplitudes
  - ▶ but there are **quantum fluctuations!**

# Quantum vacuum fluctuations

- Effects of the **exponential** expansion:
  - ▶ **wavelength** of the fluctuations **stretched** to cosmological scales  
(*redshift*)

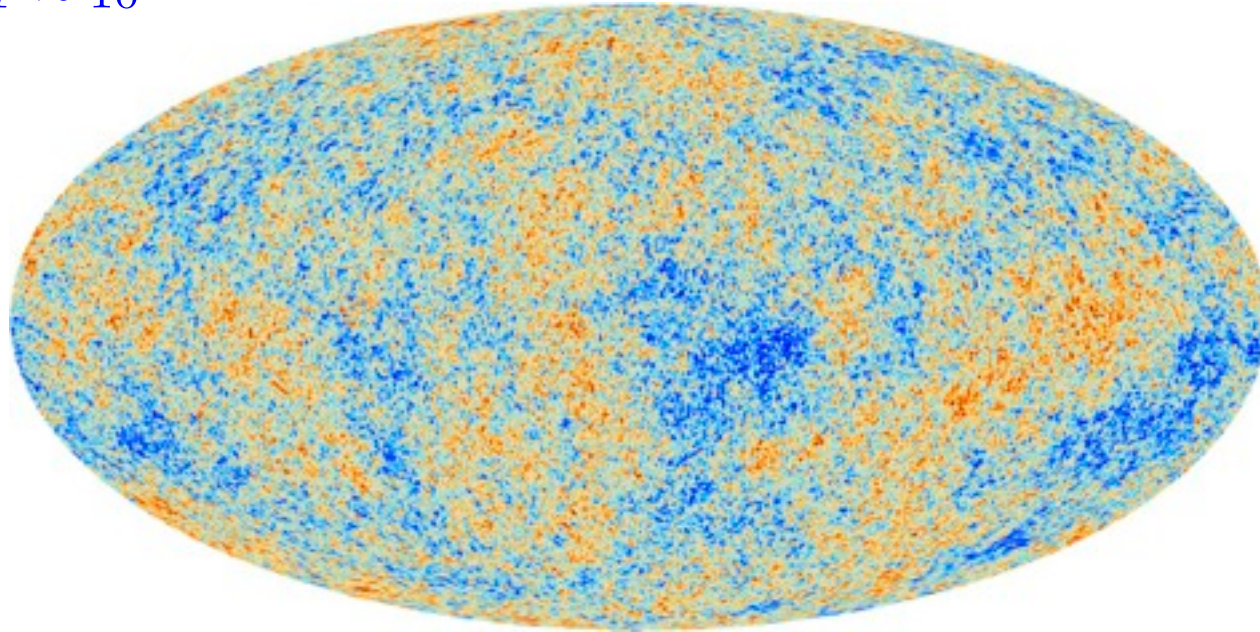


- ▶ **amplification** of their **amplitude**

*primordial inhomogeneities* → result of amplified  
*quantum vacuum fluctuations*

- Observation of the resulting *primordial inhomogeneities* through temperature *anisotropies* of *cosmic microwave background* (CMB):

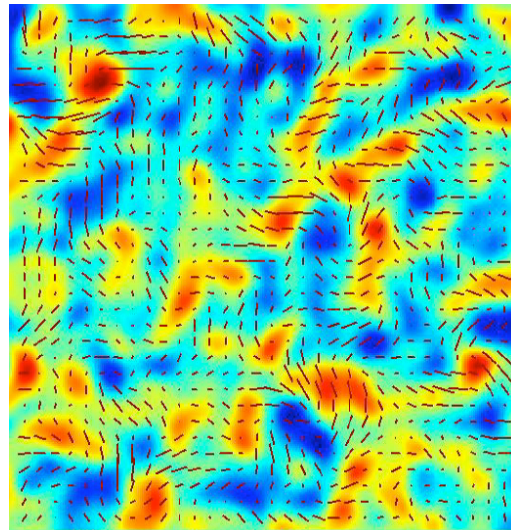
$$\Delta T/T \sim 10^{-5}$$



ESA / Planck collaboration

- *Seeds* for the formation of *cosmological large-scale structure* due to *instability* under *gravitational collapse*.

- They correspond to the analog of the *Coulomb part* of the gravitational interaction (*Newtonian potential*).
- Similar effect for the transverse part (*gravitational waves*). Besides *direct detection*, they can be observed through *polarization anisotropies* of the *CMB*:



Seljak & Zaldarriaga

- Observation of such a *stochastic GW background* would provide strong evidence for *inflation* and a *quantum gravity* effect:  
the *squeezing* of the *graviton vacuum*.

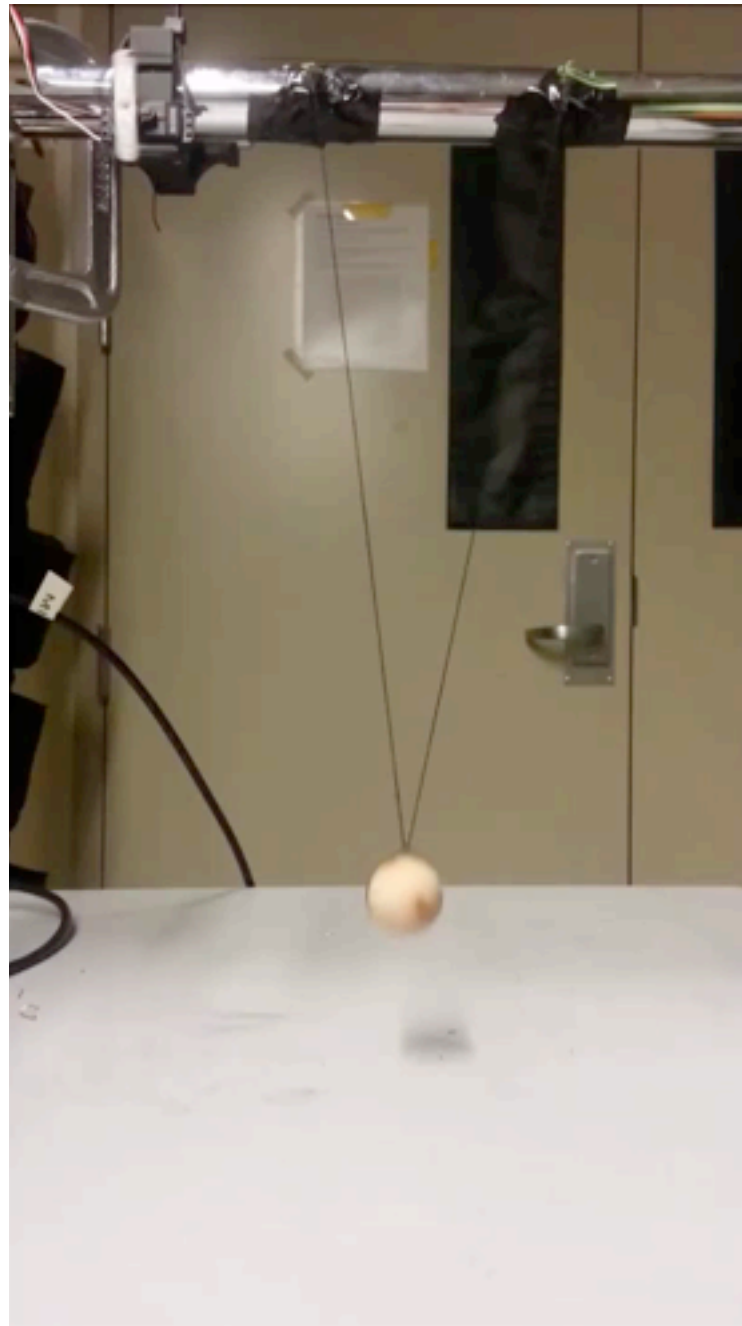
# Amplification of quantum vacuum fluctuations

- Accelerated *quasi-exponential expansion* during early *inflationary* period  $\rightarrow$  *amplification* of quantum vacuum fluctuations and *stretching* to cosmological scales.
- Each *normal mode*  $\rightarrow$  *harmonic oscillator* with *time-dependent frequency*:

$$\frac{d^2 \bar{\phi}_{\mathbf{k}}}{d\eta^2} + \Omega_{\mathbf{k}}^2(\eta) \bar{\phi}_{\mathbf{k}} = 0 \qquad \Omega_{\mathbf{k}}^2(\eta) = c^2 \mathbf{k}^2 - a''(\eta)/a(\eta)$$

- *Parametric amplification*: crucial role of *zero-point fluctuations* of the *ground state* for each normal mode.

Example of *parametric amplification* with a classical pendulum:





# Thank you for your attention.

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646. Wilhelm und Else Heraeus-Seminar

# Gravitational decoherence



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