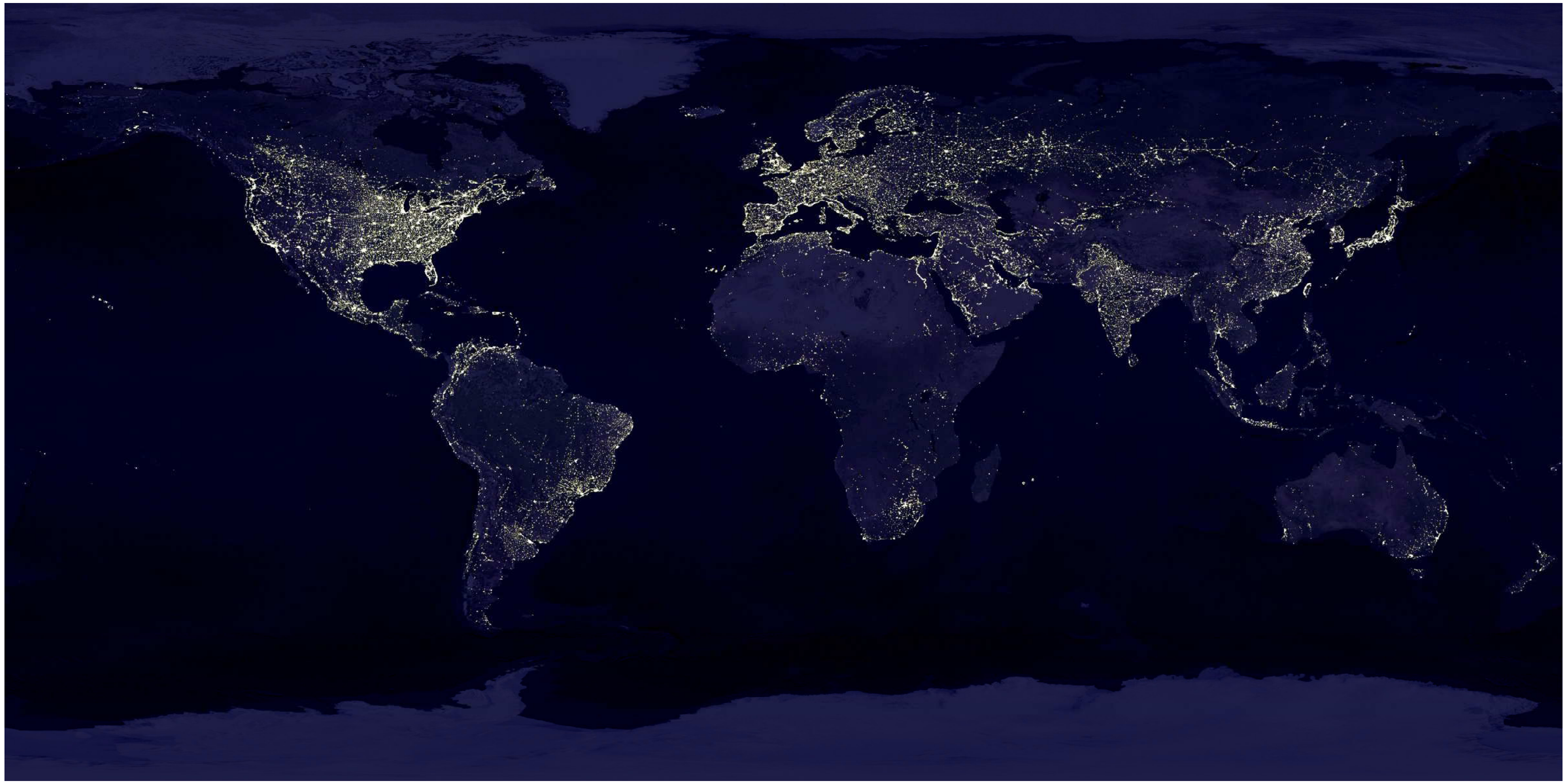
Observing the **material** universe



Using the *see-and-avoid* technique of “visual flight regulations” a Star Trek pilot would collide on the Ocean crust (direct detection).

Some of the current hottest scientific issues are on **matter**

Gravitational Waves: signals emitted by bulk masses through mechanisms that either do not involve electromagnetic radiation or, when they do have such a counterpart, this carries different information and has a completely different frequency content. In fact the portion of the spectrum that reaches us and is not absorbed or scattered by matter, only relates to the outermost layers of the astrophysical source.

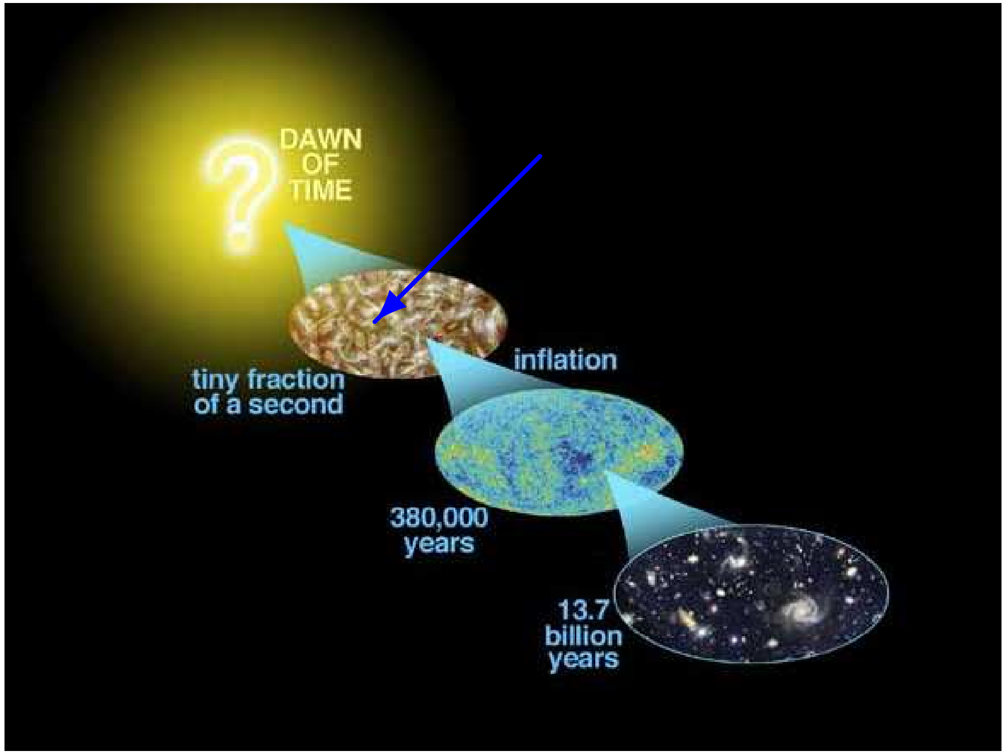
Dark Matter: density distribution inferred by the rotational velocity of galaxies, their orbits in clusters and the high temperature gas that populates these. Measurements based on gravitational lensing have also indicated extended dark matter halos.

Their influence has been indirecly “seen” electromagnetically

The formation of the universe is also shaped by **matter**

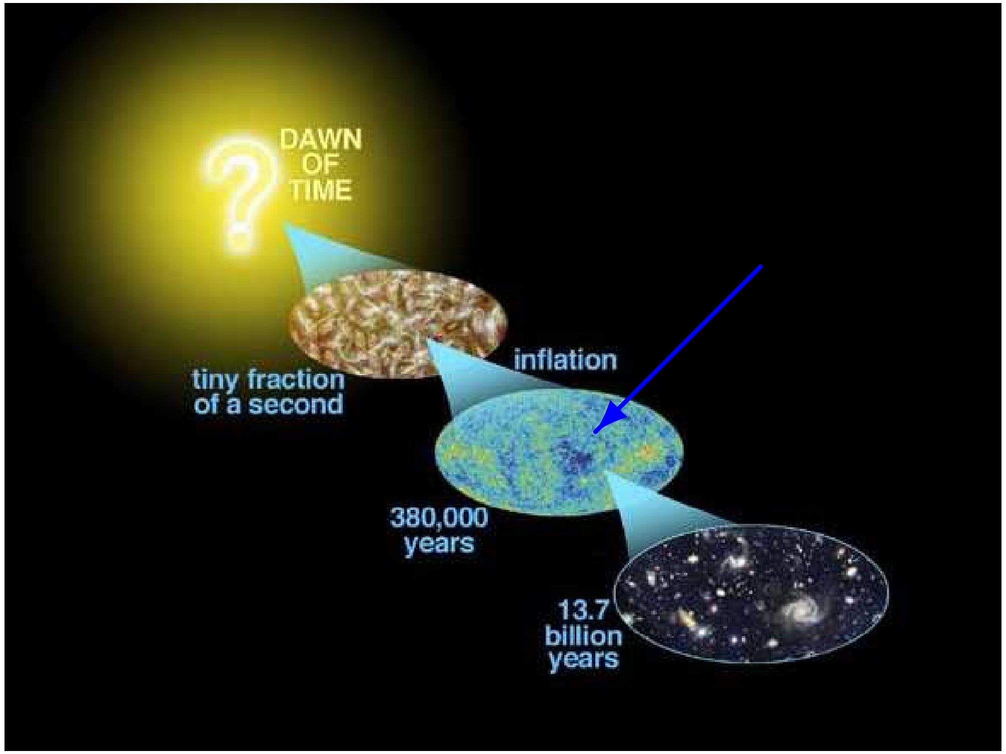
Gravitational Waves: data on their stochastic background are expected to distinguish among some the most credited models on the early stages:

- inflation with inhomogeneous initial conditions;
- quantum string dynamics (pre-big bang inflation).

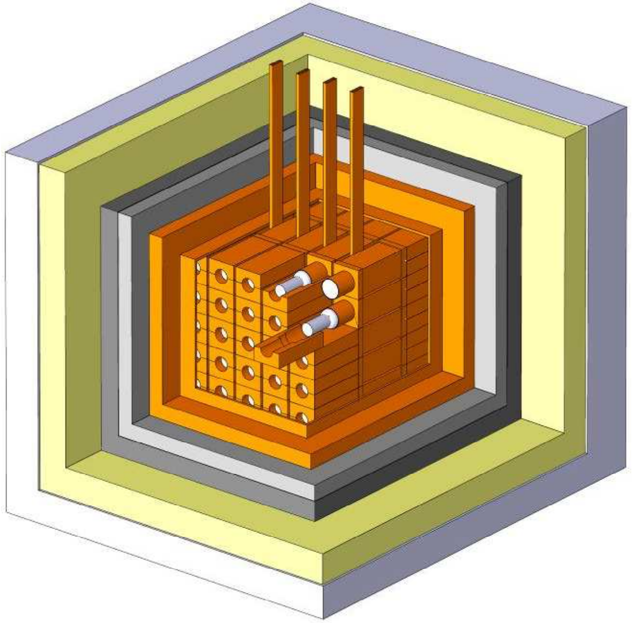


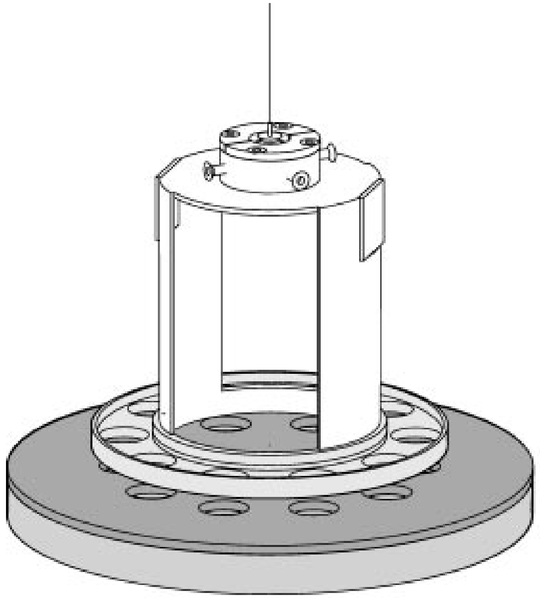
The formation of the universe is also shaped by **matter**

Dark Matter: it must be invoked for the amplification of the initial fluctuations into growing structures, which hierarchically generated the galaxies and galaxy clusters of our Universe, a process that would not have been started by the sole ordinary matter, until a much later time and with completely different results (rarefied uniformity).



Direct observation of new physics also involves **matter**





Gran Sasso National Laboratories

Looking for particles outside the Standard Model (one isolated recoil by any possible mechanism, at very low energy).

UNIVERSITY OF WASHINGTON

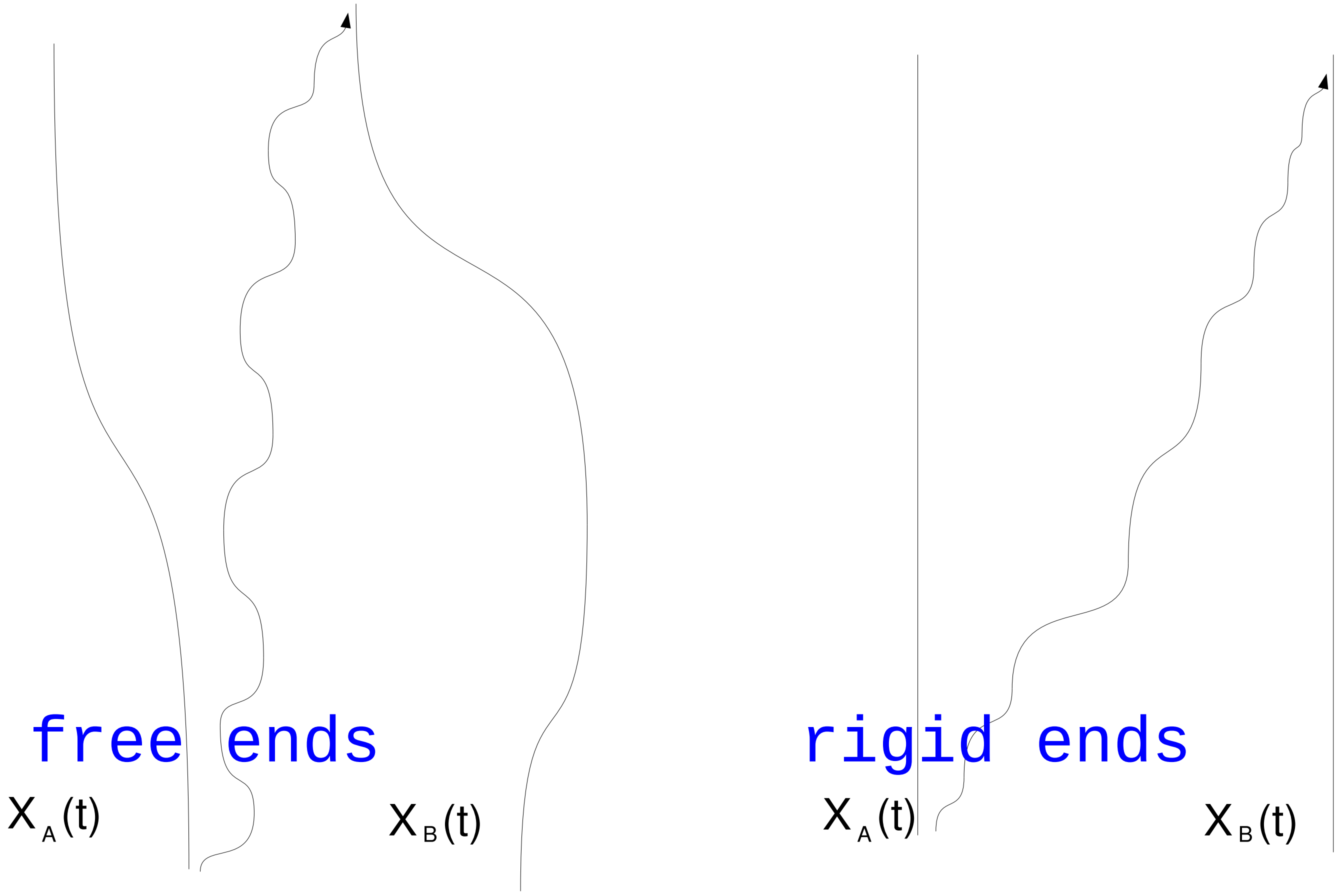
$$G(m), G(r), G(t), G(D)\ldots$$

$$G = G(1+\alpha e^{-r/\lambda}),\ \lambda(D)$$

$$G = G(\rho(Z,N))$$

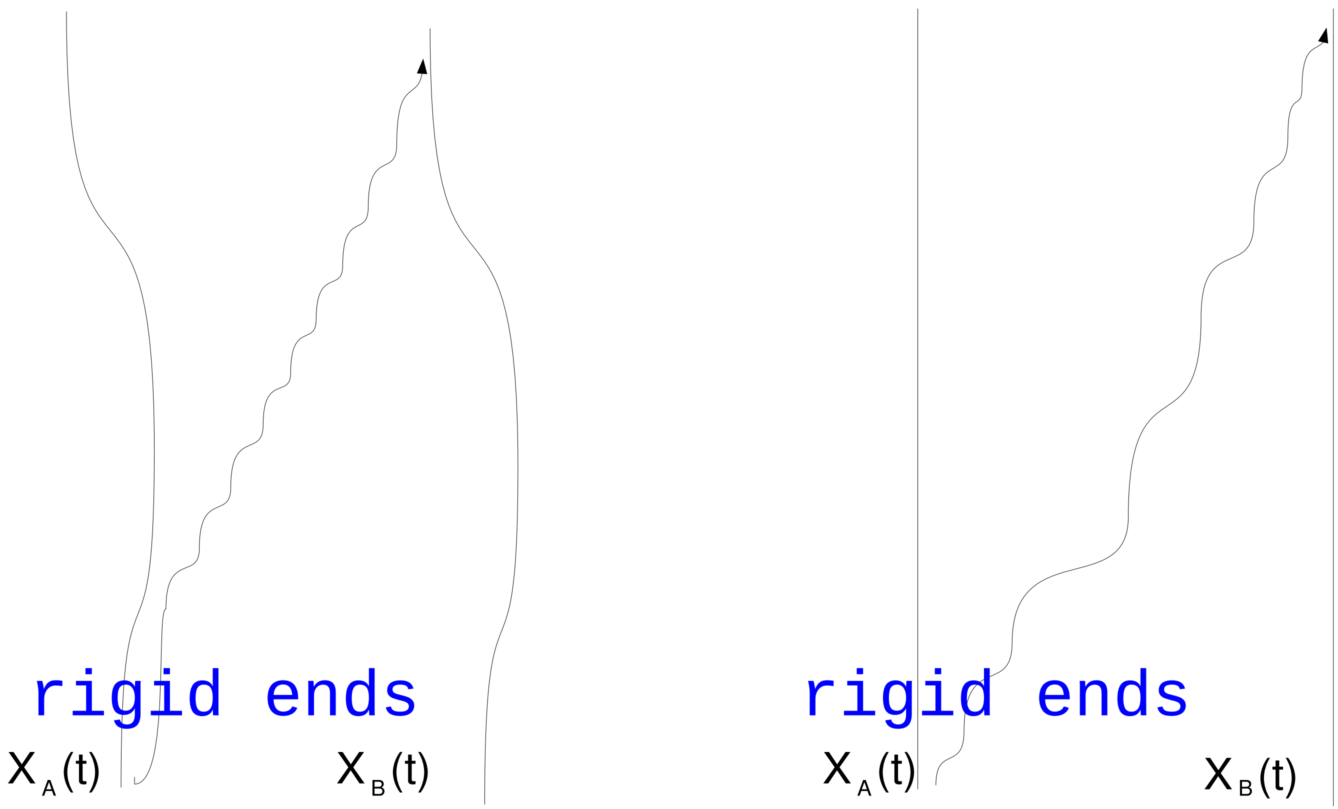
More in the presentation of Guglielmo Tino

General relativity tests using microscopic **matter**



The traveling wave propagates between the two ends of the interferometer arms. A displacement of those ends modifies the path and adds to the perturbation phase. *Phys. Rev. D 71, 084003*

Interferometer in “real” space with local ends of the arms



The coordinates are variables of the mass-energy which determines the curvature. *Phys. Rev. D 73, 084018*

Interferometer in “real” space with local ends of the arms

Original work of a variety of prominent groups, this formalism is illustrated in several articles and textbooks.

$$< q|\psi >= e^{\frac{iS(q)}{\hbar}}\psi$$

Schrödinger’s equation: $i\hbar\frac{\mathrm{d}|\psi>}{\mathrm{d}t} = \hat{H}|\psi >$

$$\frac{1}{2m}(\frac{\partial S}{\partial q})^2 + V(q) + \frac{\partial S}{\partial t} = 0$$

$$H(q_1, \ldots, q_N, \frac{\partial S}{\partial q_1}, \ldots, \frac{\partial S}{\partial q_N}) + \frac{\partial S}{\partial t} = 0$$

Solution of the Hamilton-Jacobi equation: $\mathrm{d}S = p\mathrm{d}q - H\mathrm{d}t$

Interferometer in “momentum” space: atomic quantum superposition

In analogy with the eikonal approximation I constructed a similar formalism and applied to atom interferometers.

$$< p|\psi >= e^{\frac{iF(p)}{\hbar}}\psi$$

Schrödinger’s equation: $i\hbar\frac{\mathrm{d}|\psi>}{\mathrm{d}t} = \hat{H}|\psi >$

$$\frac{p^2}{2m} + V(-\frac{\partial F}{\partial p}) + \frac{\partial F}{\partial t} = 0$$

$$H(-\frac{\partial F}{\partial p_1}, \ldots, -\frac{\partial F}{\partial p_N}, p_1, \ldots, p_N) + \frac{\partial F}{\partial t} = 0$$

Solution of the Hamilton-Jacobi equation: $\mathrm{d}F = -q\mathrm{d}p - H\mathrm{d}t$

More details in a paper of mine in preparation for PLA, quant-ph

General properties and applications of my formalism

Properties

Legendre transform: $\frac{\partial}{\partial q}(q\,\mathrm{d}p + H\,\mathrm{d}t) = 0$

Evolution in momentum space:

$|\psi >= c_e(p_e, t)|e, p_e > +c_g(p_g, t)|g, p_g >$

Distinguishing features: it describes systems based on momentum selection and momentum space “condensation”, rather than systems based on active control of local optical elements.

It expresses noise as disturbances of the momentum in $|\psi >$ **whereas** the sensitivity of real space interferometers is mainly limited by position and orientation variations of the local ends that identify the arms.

Momentum manipulations: they are naturally accounted for by the formalism and *constitute* the interferometer.

General properties and applications of my formalism

Properties

Atomic quantum state manipulation:

$$\begin{pmatrix} \cos\frac{\Omega_r\tau}{2} & -i\mathcal{U}^{-1}_{\bar{p}+\hbar k/2}(t)\mathcal{U}_{\bar{p}-\hbar k/2}(t)\sin\frac{\Omega_r\tau}{2} \\ -i\mathcal{U}^{-1}_{\bar{p}-\hbar k/2}(t)\mathcal{U}_{\bar{p}+\hbar k/2}(t)\sin\frac{\Omega_r\tau}{2} & \cos\frac{\Omega_r\tau}{2} \end{pmatrix}$$

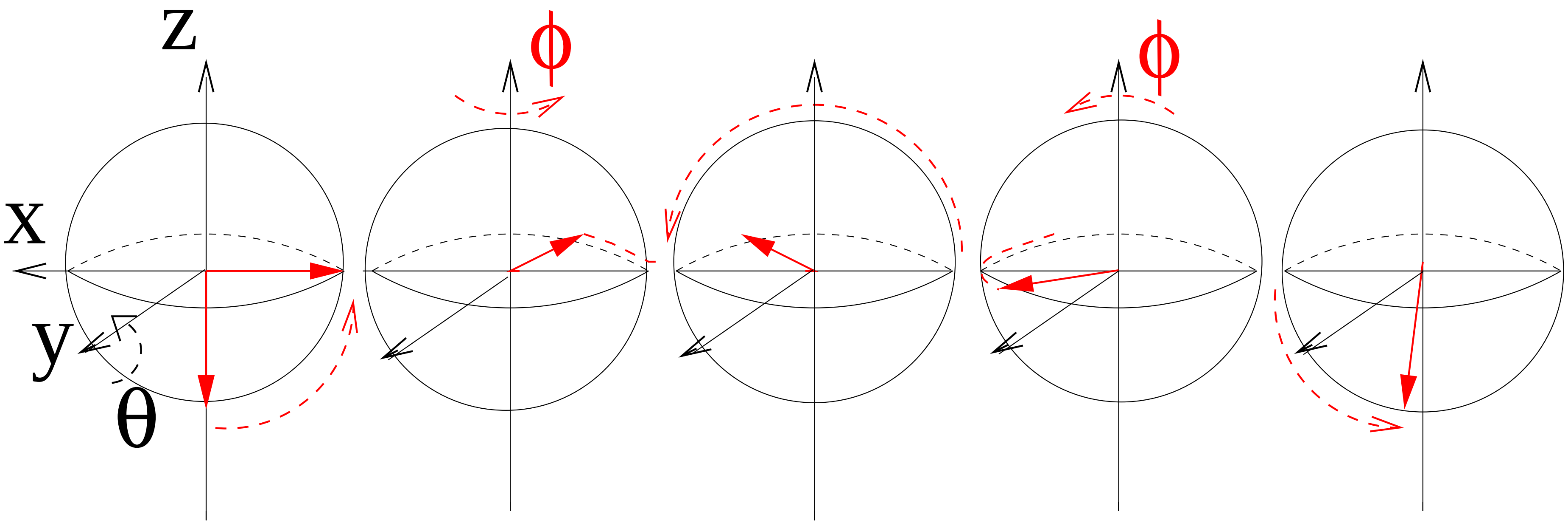
where Ω_r is the generalized Rabi frequency and $\tau \longrightarrow 0$ is the duration of the irradiation.

The transition between the discrete internal energy levels and the variation of momentum are “mutually contingent”.

The difference between τ and the free evolution time-scale in $\mathcal{U}(t)$ enables a complete separation of the impulsive interaction from the propagation. Phys. Rev. A 45, 342

General properties and applications of my formalism

Properties

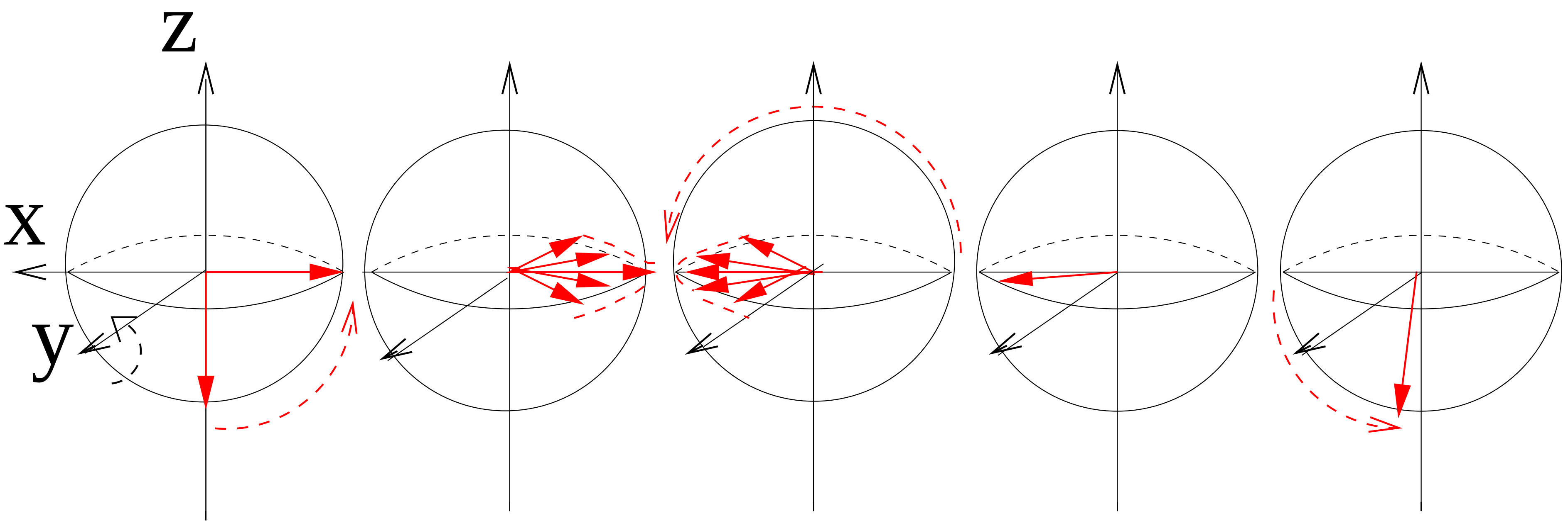


$$\theta_{t-T}=\pi/2 \quad \phi(t)-\phi(t-T) \quad \theta_t=\pi \quad \phi(t+T)-\phi(t) \quad \theta_{t+T}=\pi/2$$

$$\{x,y,z\} \equiv \sqrt{\frac{1-z}{2}}|g,\bar{p}-\frac{\hbar k}{2}> + \sqrt{\frac{1+z}{2}}\frac{x+iy}{\sqrt{1-z^2}}|e,\bar{p}+\frac{\hbar k}{2}> \quad x^2+y^2+z^2=1$$

General properties and applications of my formalism

Properties



The choerence of the emitted signal of a collection of atoms is lost during the progression of the relative evolving phase and is then recovered after an equal amount of regression. This is obtained by population inversion and the number of progression and regression intervals can be any, only the sum of their durations must be the same.

General properties and applications of my formalism

Properties

Thermal noise: collisions within the collection of atoms launched in free fall.
Instrumental noise: deviations from the resonance condition of the manipulation technique.

Interferometer in "real" space. Deformations of local ends of the interferometer arms (expansion, $\frac{dn}{dT}$, vibrational modes, charging effects, thermo-optic distortions).

Shot noise: the ultimate sensitivity is dominated by the standard quantum limit **for both**.

$$N_{atom} = N_{photon} \left(\frac{\lambda_{atom}}{\lambda_{photon}} \right)^2 \Rightarrow \text{design requirements}$$

Classical and Quantum Gravity 24, 2167-2178

General properties and applications of my formalism

Applications

$$< \delta\Phi^*(t)\delta\Phi(t') > \;=\; C(t'-t) = \text{correlation function} = \int_{-\infty}^{+\infty} S(\omega) e^{-i\omega(t'-t)} \frac{\mathrm{d}\omega}{2\pi}$$

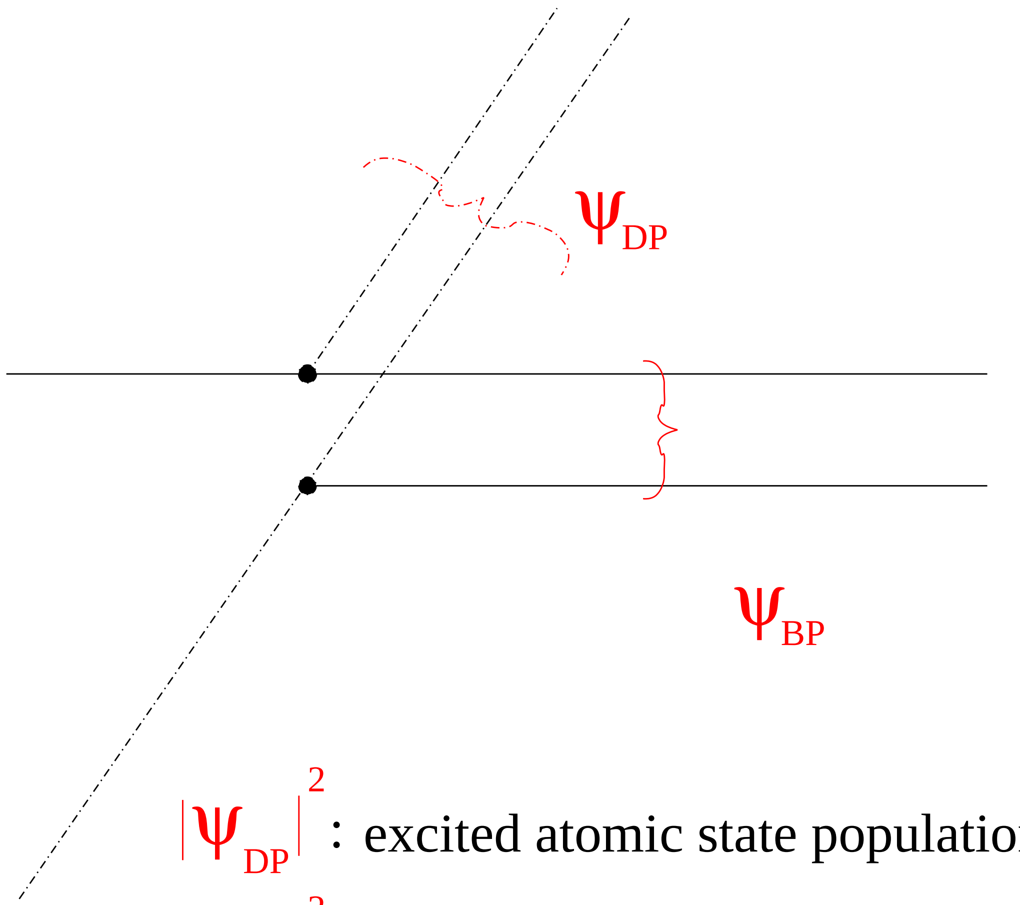
$$< \delta\Phi^*(\omega)\delta\Phi(\omega') > \;=\; \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} C(t'-t) e^{i\omega' t'} e^{-i\omega t} \mathrm{d}t\mathrm{d}t' = 2\pi\delta(\omega-\omega')S(\omega')$$

$$\sqrt{< \tilde{h}^2(\omega) >_{\mathrm{PSD}}} = \frac{1}{2\vec{k}\cdot\vec{p}/mT f(\omega)} \times \frac{1}{\sqrt{\dot{N}}}$$

Different formalisms result in different transfer functions $f(\omega)$.
Optical squeezing $\delta\Phi_{min} \propto 1/N$ is also analysed in different frameworks.

General properties and applications of my formalism

Applications



$|\psi_{DP}|^2$: excited atomic state population

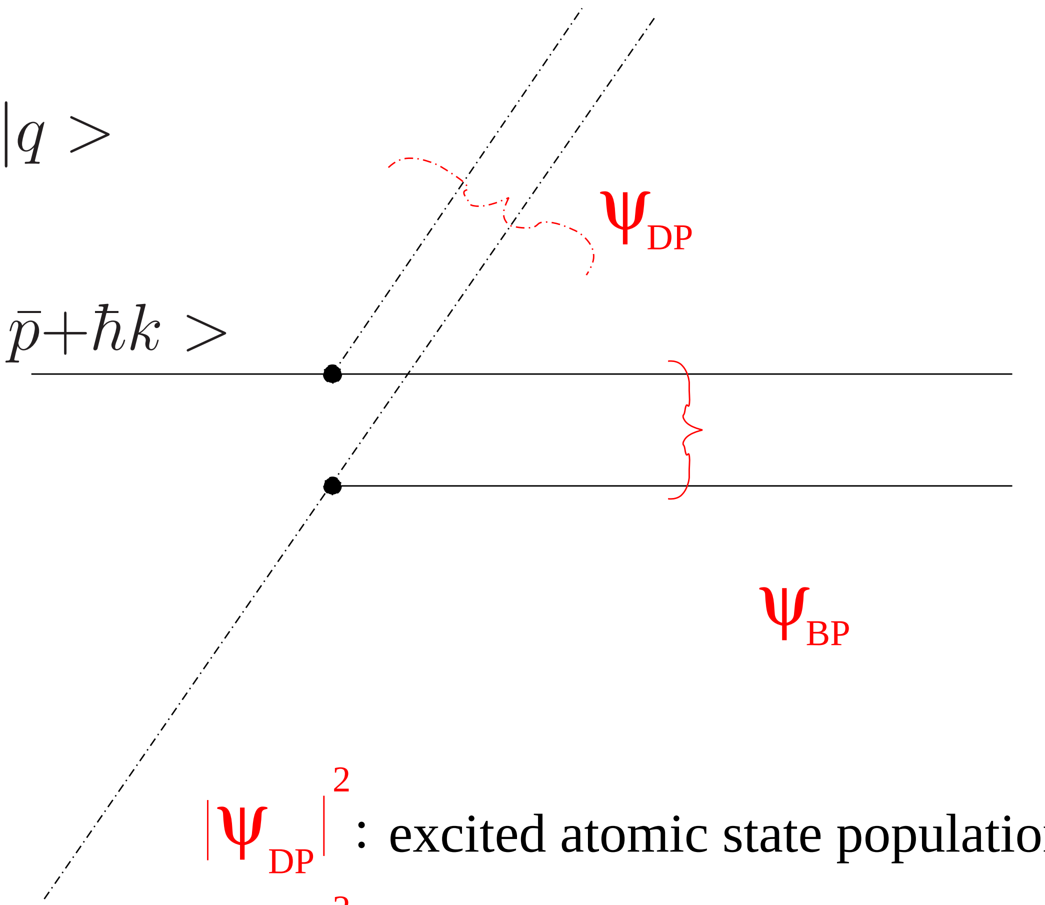
$|\psi_{BP}|^2$: ground atomic state population

General properties and applications of my formalism

Applications

$$e^{-ikr}|q>= e^{-ikq}|q>$$

$$e^{-ikr}|\bar{p}-\hbar k>= |\bar{p}+\hbar k>$$



$|\Psi_{DP}|^2$: excited atomic state population

$|\Psi_{BP}|^2$: ground atomic state population

General properties and applications of my formalism

Applications

The interferometer phase shift manifests itself as a modulation of the fraction of atoms in the excited and ground state of the superposition. Using a different formalism from the momentum space description we propose, that is relying on the “real” space mathematical framework:

$$|\Psi_{BP}|^2 = |\Psi_{BP}(t)|^2 \qquad |\Psi_{DP}|^2 = |\Psi_{DP}(t')|^2$$

$$|\Psi_{DP}(t)|^2 + |\Psi_{BP}(t')|^2 \neq 1 \qquad \text{even for } t = t'$$

- Standard fluorescence techniques involving normalized atom counting require two steps $\{t, t'\}$ for the detection.
- The assumption of different input points for the two initial arms or ’mid-point’ detection are the remedies found in literature (in those articles that do not neglect the problem only because it is beyond current sensitivity).
- These though neutralize the relation between ports underlying quantum squeezing.

Motivations

My conclusion is that the motivation of pursuing atom interferometer analytical investigations is **two-fold**: not only these detectors constitute inertial sensors and are ideal instruments to observe the **material** universe, but can even play an important role in understanding the mesh between general relativity and quantum mechanics, for the **difference in the predictions** of different formalisms will be soon within sensitivity reach.

1. There is disagreement in published papers and the experimental development will anticipate the theoretical breakthroughs and identify the correct analysis.

2. This two-fold achievement requires a quiescent space-based environment to neutralize most terrestrial noise sources. The longer integration times that can only be implemented in space are critical in improving the accuracy.