Cosmic Vision

Quests
for Cosmic Vision

- What is expected –“beyond the standard model“
- What is the state-of-the-art
- What has to be done in the next 20 years to make a leap forward

Motivation

Frame theories

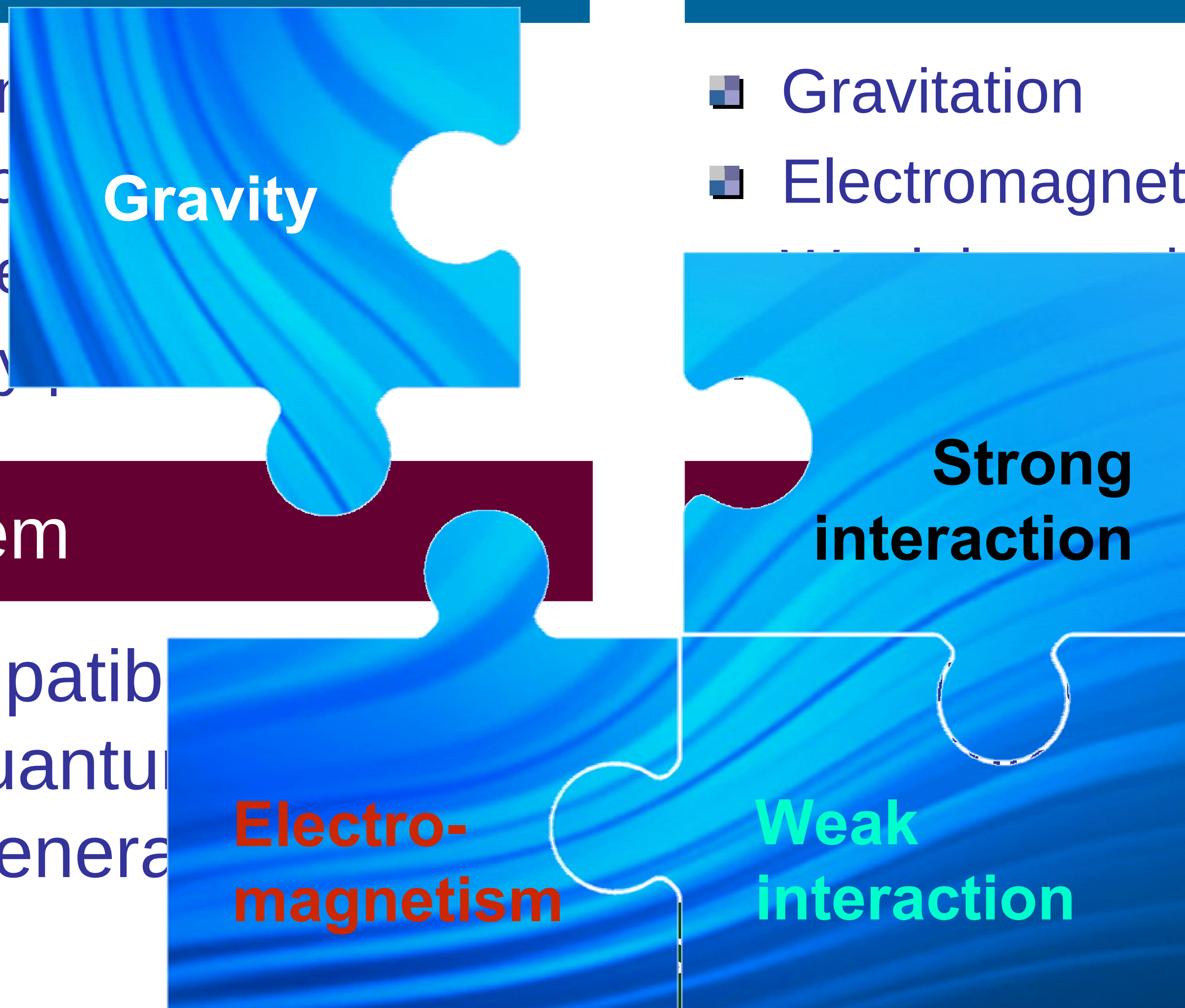
- Quar
- Spec
- Gene
- Many p

Interactions

- Gravitation
- Electromagnetisms
- ...on
- ...ion

Problem

Incompatib... ...of all
quantu... ...ions
Genera...



THEMES
for Cosmic Vision

Search for New Phenomena

- **Relativity and Gravity**
- **Constancy of Constants**
- Foundations of Quantum Mechanics
- **Quantum Matter**
- Quantum Gravity

Relativity and Gravity

Claims

- *WEP: trajectories of neutral freely falling bodies are independent of their structure and composition*

  Eötvös-type Tests

- *In any local freely falling reference frame, the result of a non gravitational measurement is independent of the velocity of the frame*

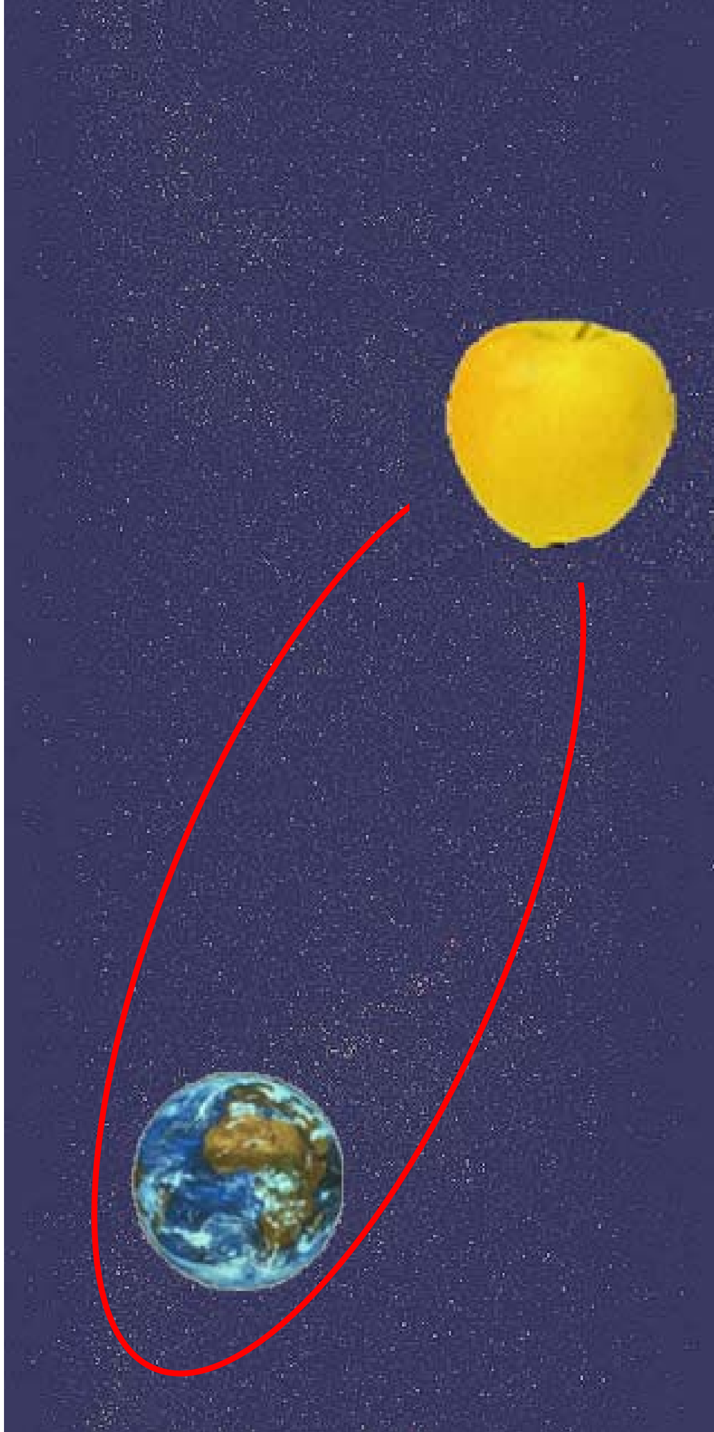
  Local Lorentz invariance (LLI), Kennedy-Thorndike, Michelson-Morley preferred frame expts

- *In any local freely falling reference frame, the result of a non gravitational measurement is independent of where and when it is performed.*

  Local position invariance (LPI),Null differential red-shift expts, stability of fundamental constants

Advantages of Space

- Large velocity differences
- Large gravitational potential differences
- Long distances
- Low noise
- Infinitely long free fall

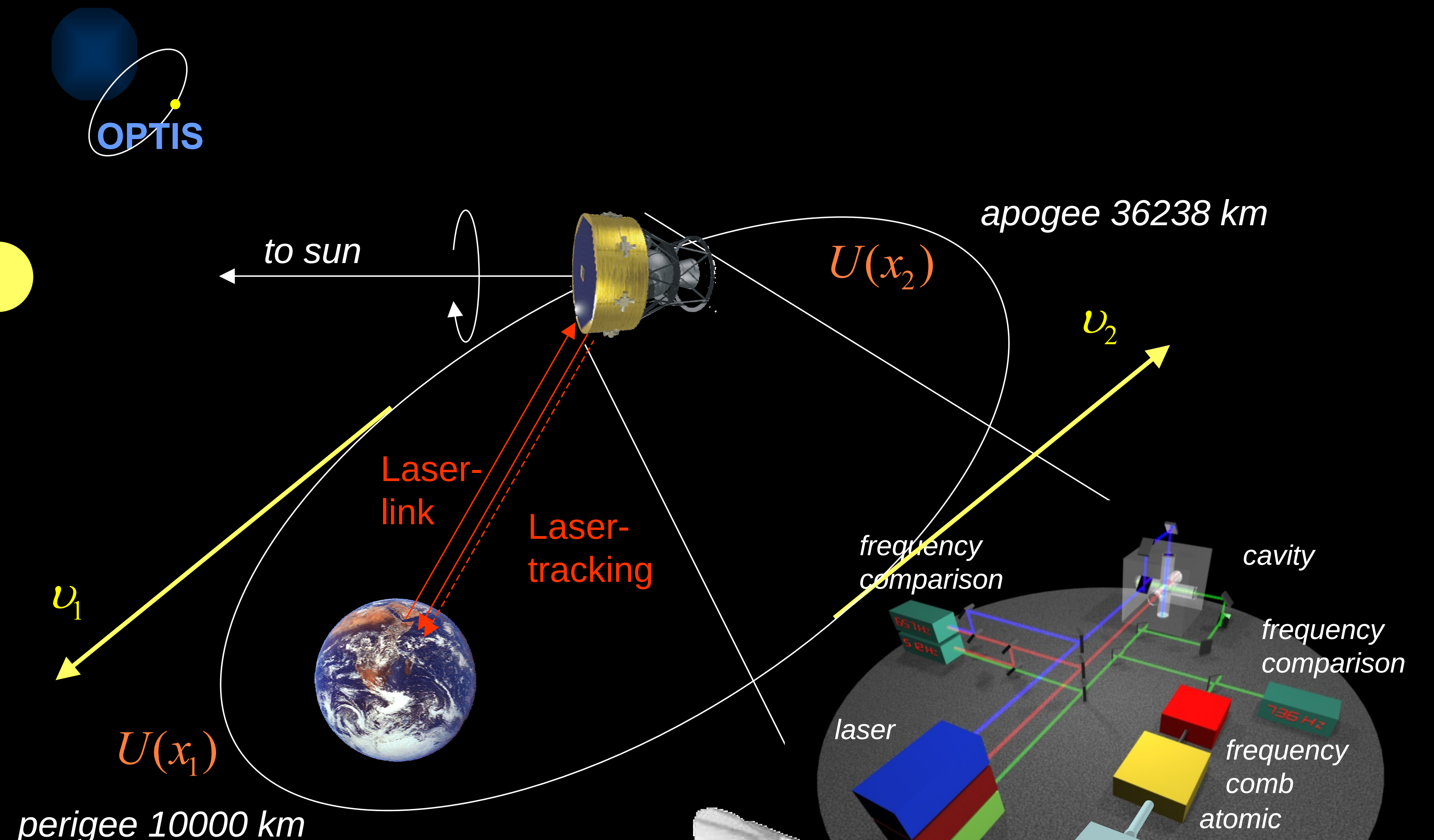


Investigating "c" -

Testing the Postulates of Relativity

$$c \stackrel{?}{=} c(v, \vartheta)$$

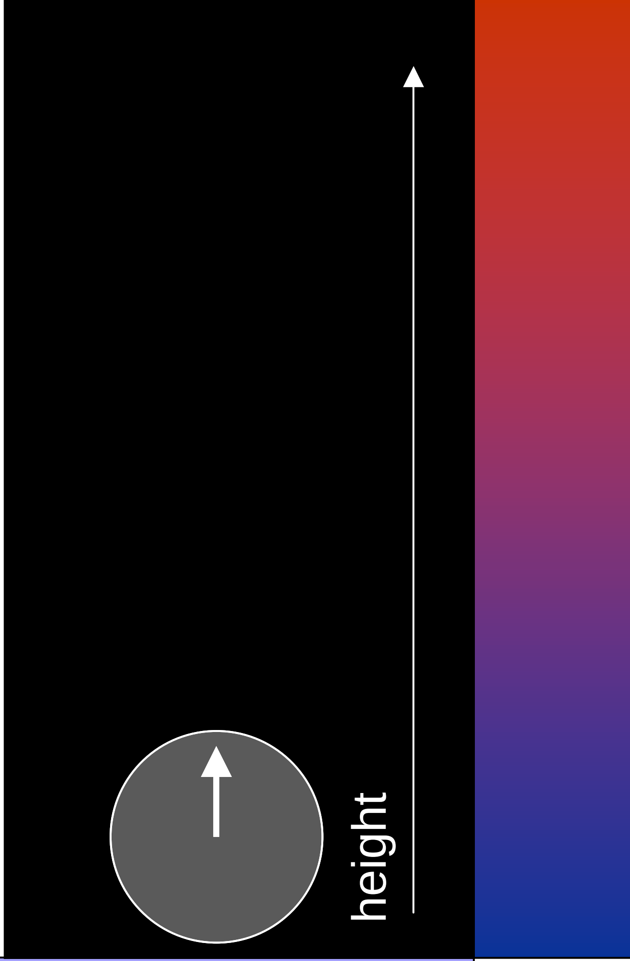
In any local freely falling reference frame, the result of a non gravitational measurement is independent of the velocity of the frame



- Michelson-Morley
- Kennedy-Thorndike
- Univ. grav. red-shift
- Abs. grav. red-shift, Doppler, rel. orbital effects

Gravitational **Red-** shift

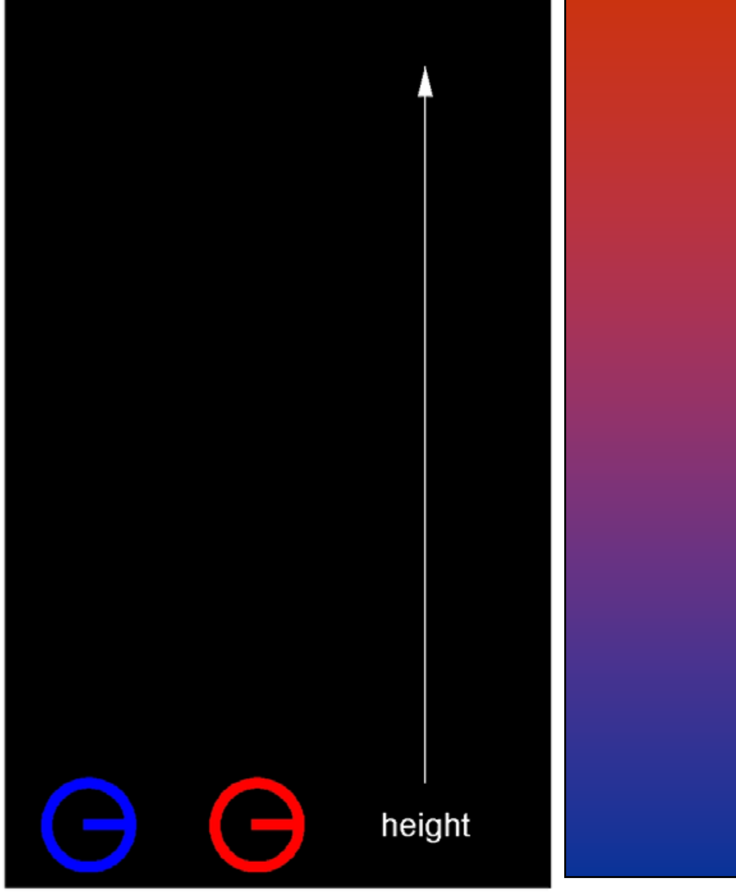
- Clock Comparisons on the ground and in space



$$\frac{\nu_S - \nu_E}{\nu_E} = \frac{\Delta\nu}{\nu_E} = (1+\varepsilon)\frac{\Delta U}{c^2} = (1+\varepsilon)\frac{gH}{c^2}$$

		State-of-the-art	projected for OPTIS
Gravitational Red Shift	$\frac{\delta c}{c}$	$7 \cdot 10^{-5}$	$7 \cdot 10^{-10}$

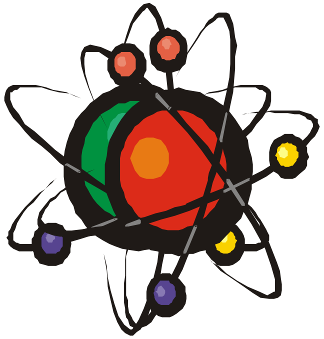
Universal Gravitational Red- shift



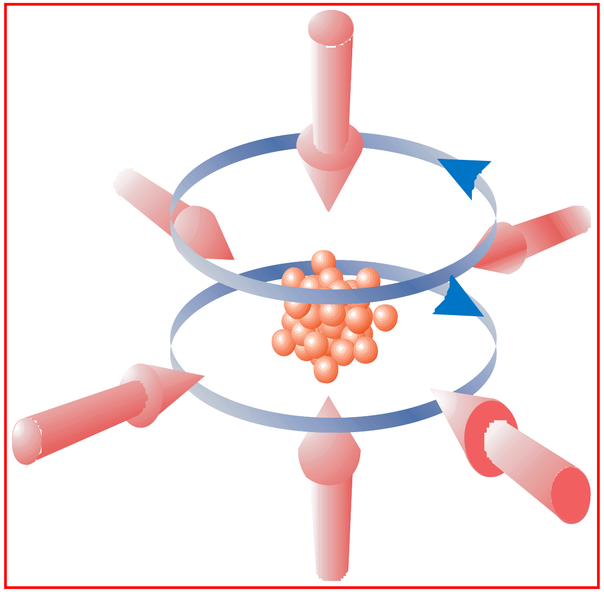
$$\nu(x_1) = \left(1 - (1 + \alpha_{clock})\frac{U(x_1) - U(x_0)}{c^2}\right)\nu(x_0)$$

Universal Gravitational Red Shift	$\frac{\delta c}{c}$	State-of-the-art	projected for OPTIS
		$2 \cdot 10^{-2}$	10^{-4}

Progress in atomic physics and quantum optics



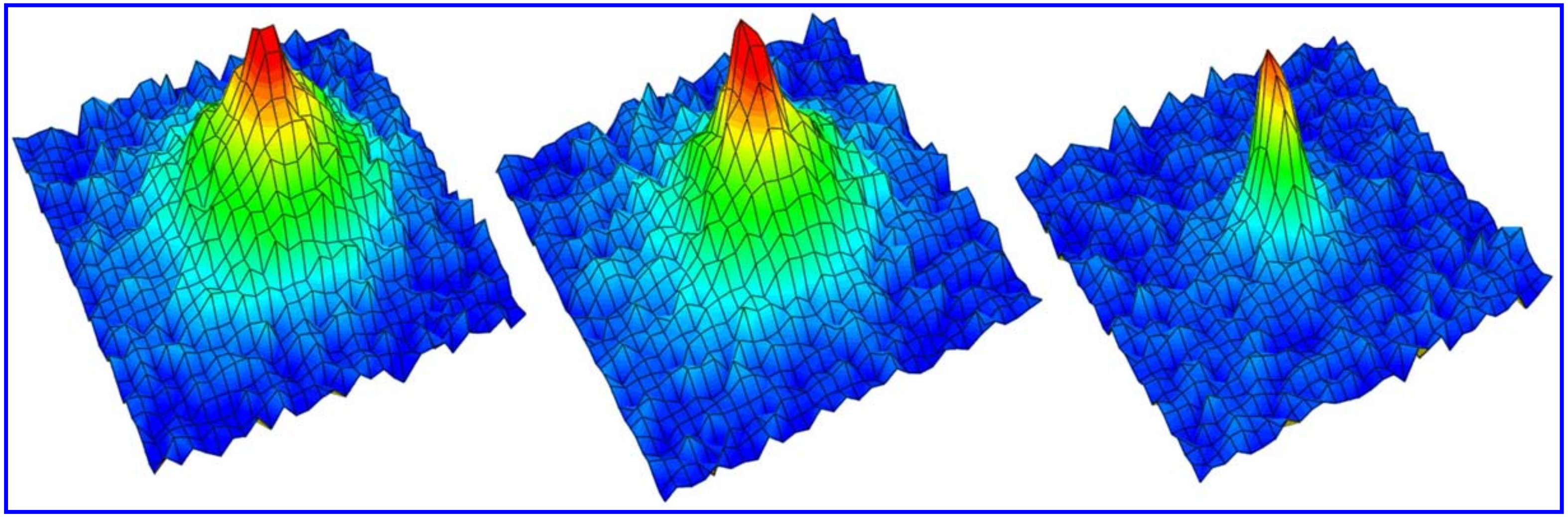
Laser-cooling and -trapping

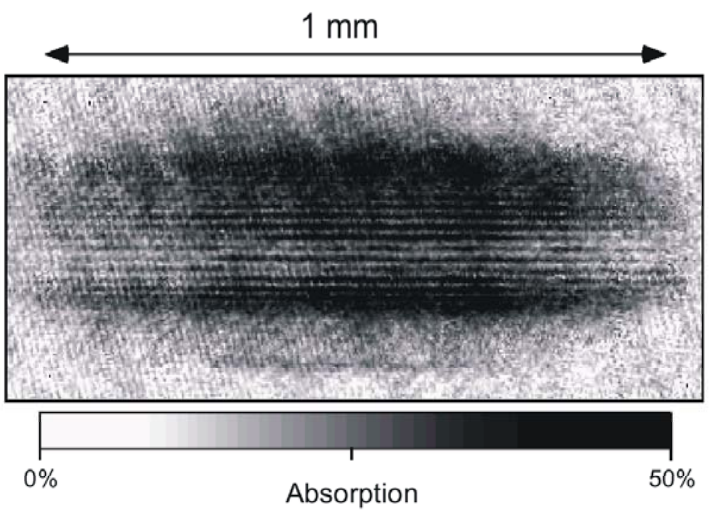


parameters:

- 10^{10} atoms in MOT
- density: $n \sim 10^{11}$ at/cm^3
- size: ~1mm
- temperature: few µK (molasses)
- trapping times: s…min (earth)
- control of external and internal degrees of freedom

Coherent matter wave ensembles



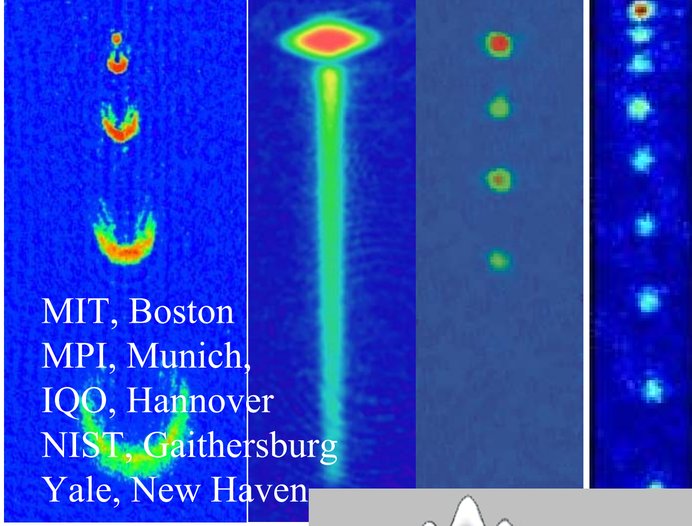


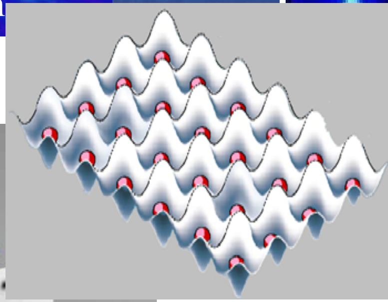
parameters:

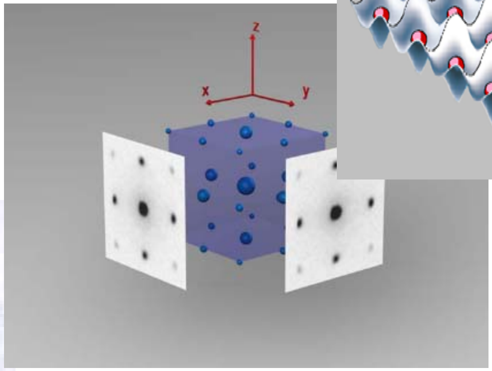
- few…10^8 atoms
- density: $n \sim 10^{14}$ at/cm^3
- size: ~10-100µm
- temperature: few nK

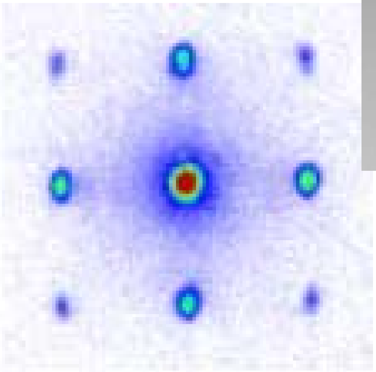
Quantum Engineering

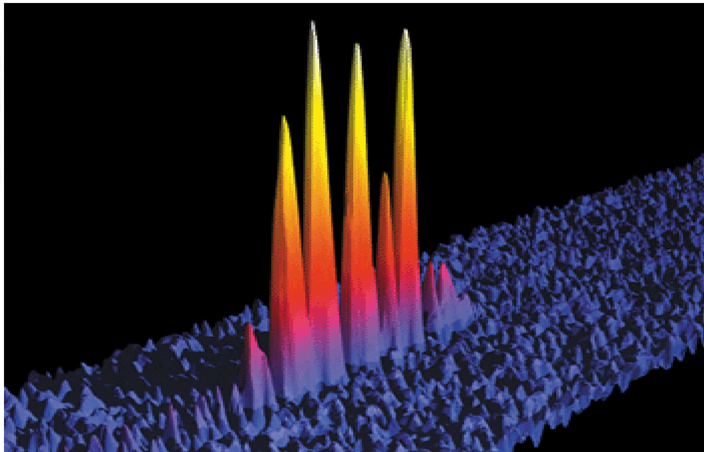
- Atom lasers
- Matter-Wave Amplification
- Thermodynamics
  (fermionic & bosonic mixtures)
- Solid State Physics
  (Light crystals)
- Low Dimensional Systems
  (Atomic Quantum Dots)
- Macroscopic Coherence
- Coherent Chemistry
- Molecular BEC
- Entanglement











COSMIC VISION

Experimental concepts …

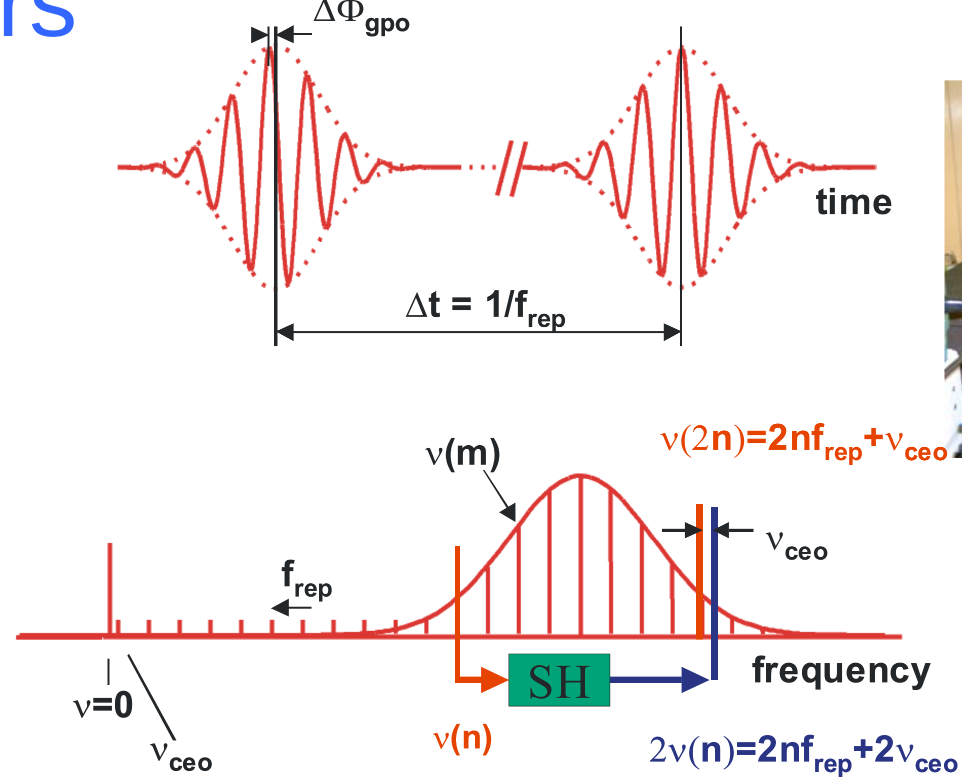
- Clock tests and comparisons
  beyond microwave-clocks
- Quantum Probes
  Novel Inertial sensors,
  Precision Spectroscopy
- Laser Interferometry and Ranging

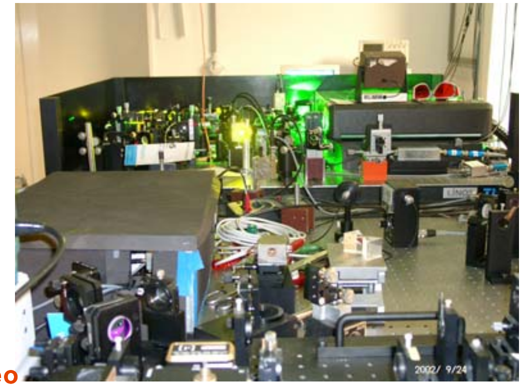
Towards Optical „Space-“ Clocks:

Development of Frequency Comb-generators

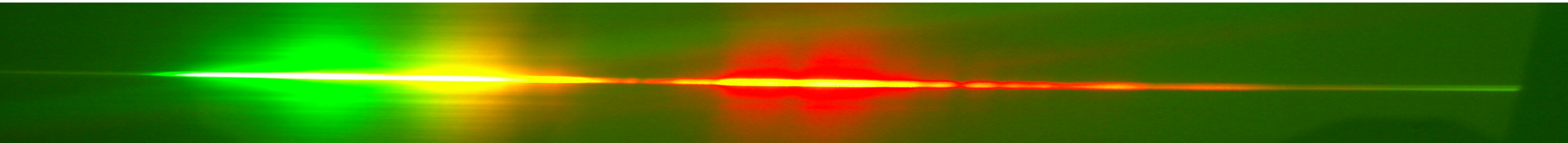
Time domain:

Frequency domain:

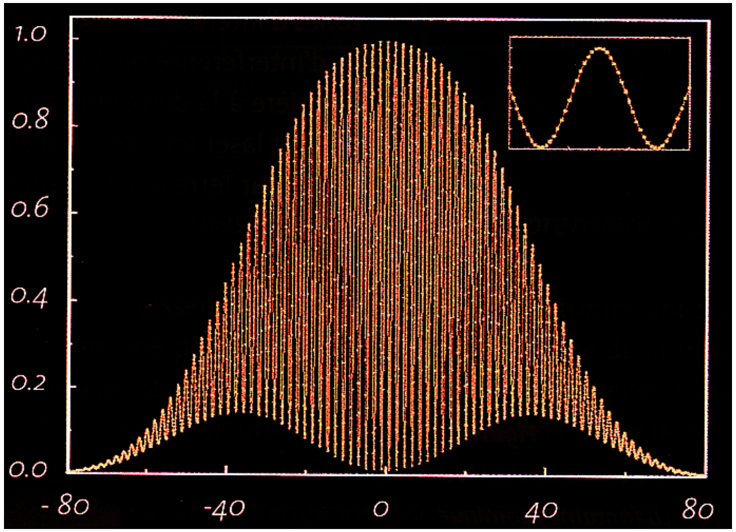


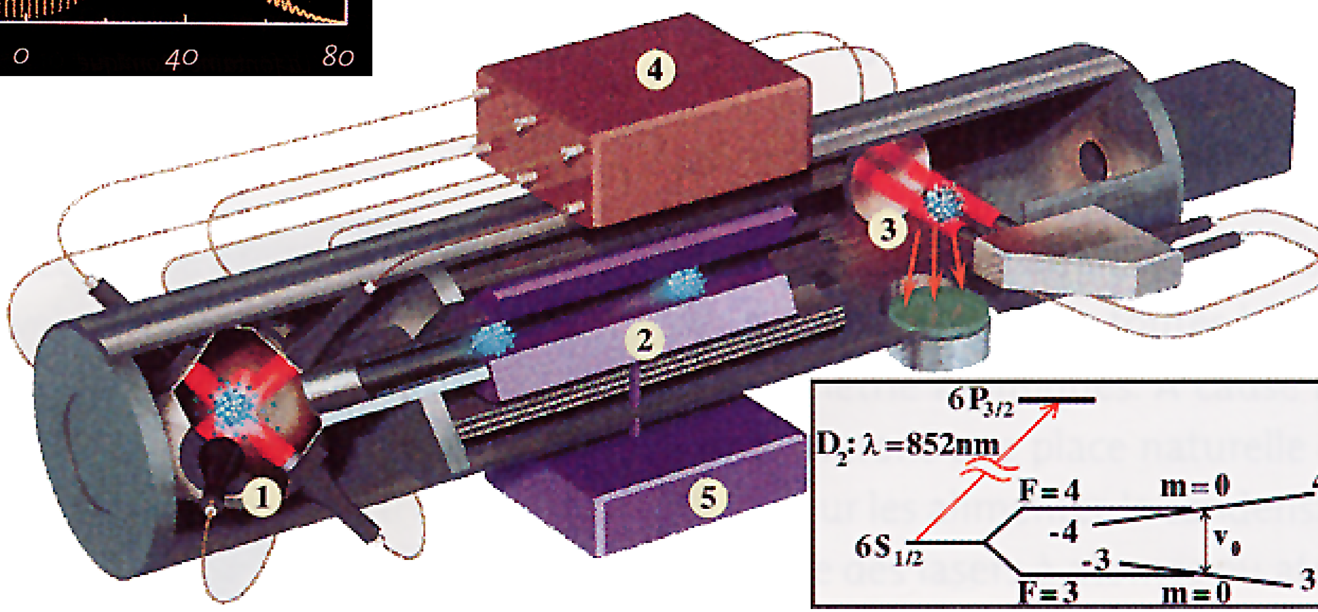


- State-of-the-art Fibre-laser „Combs“ operate 30 h without any interruption



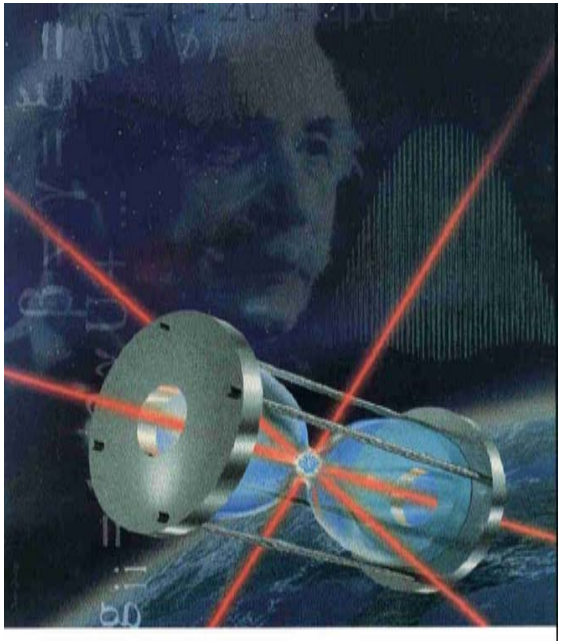
Microwave clocks



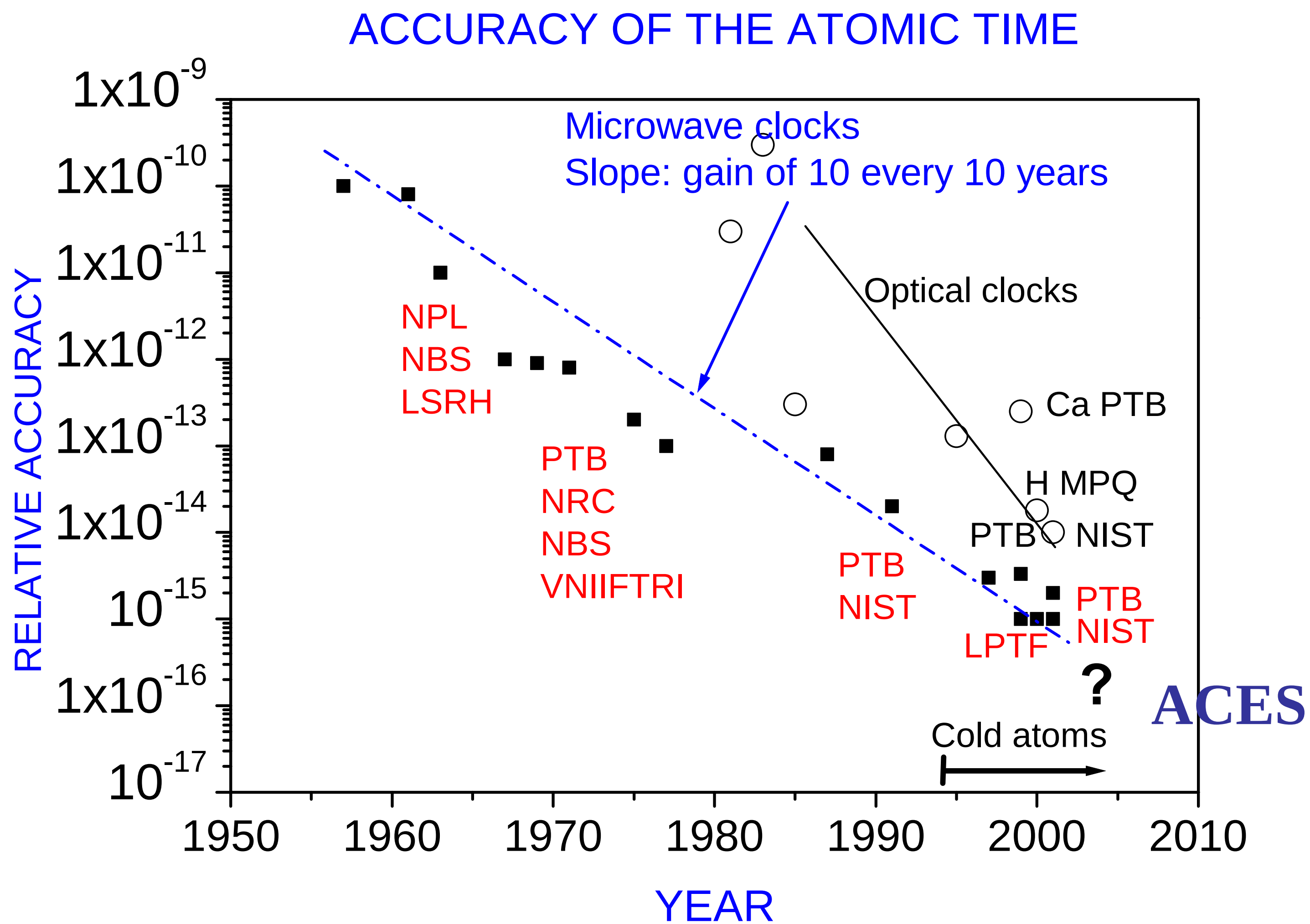


PHARAO

	Projected	Improvement
Isotropy of Space	10^{-16}	10
Gravitational Red Shift	10^{-7}	25
Variation of fine-structure Constants	$10^{-16}\,y^{-1}$	20

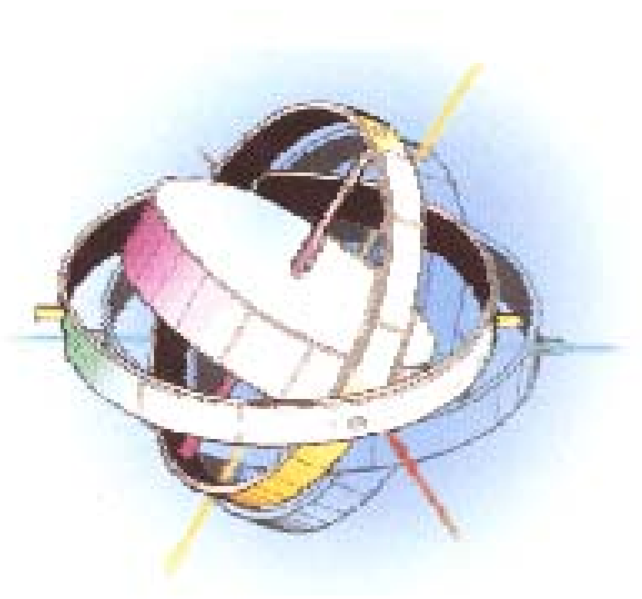


Accuracy of Atomic Time



Future Clocks

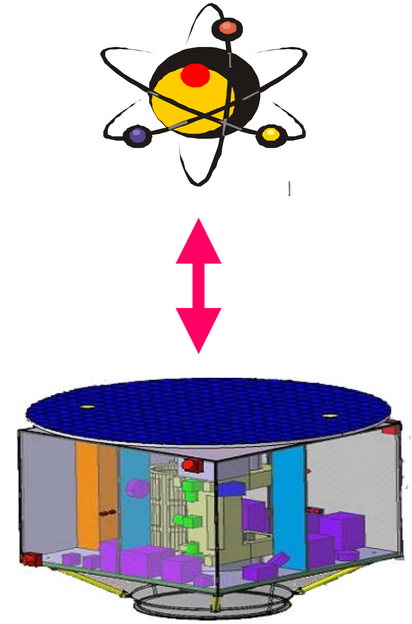
Performance / Clocks	Stability	Accuracy
State-of-the-art PHARAO 2007	100 mHz line width $\sigma_y(\tau) < 10^{-13}\ \tau^{-1/2}$	$\sim 10^{-16}$
Optical Clocks (Atoms/ Ions)	$\sigma_y(\tau) \longrightarrow 10^{-17}\ \tau^{-1/2}$	$\sim 10^{-18}$…
Cryogenic Resonators	$\sigma_y(\tau) \longrightarrow 8\text{x}10^{-16}\ \tau^{-1/2}$ @100 s	-



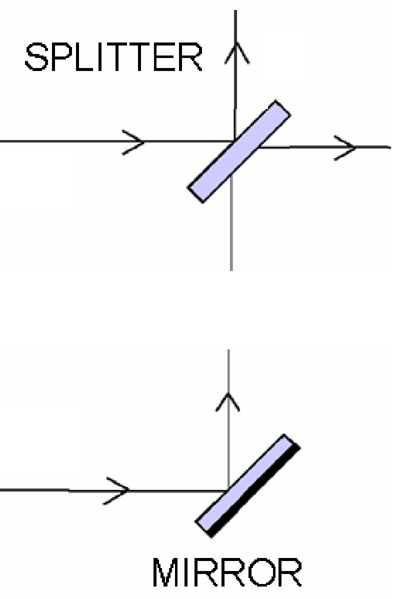
Quantum Probes

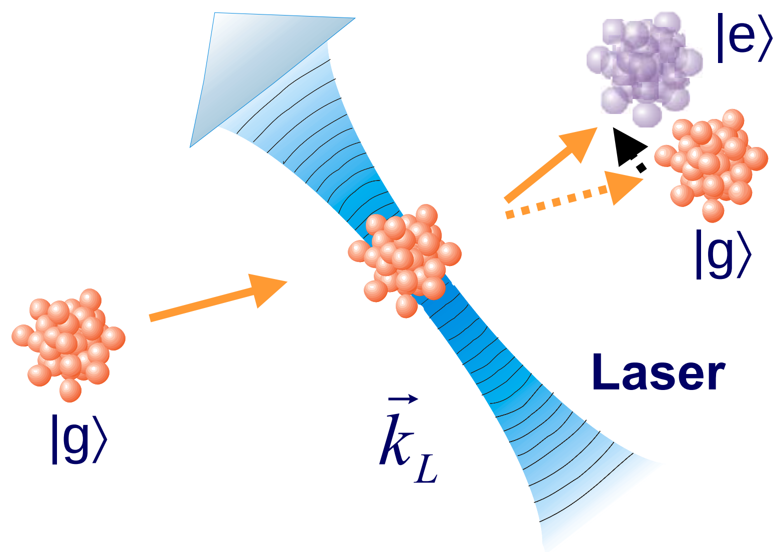
Inertial Matter-Wave Sensors

- Inertial Reference:
  freely falling atoms
  serve as
  “absolute” reference
  for the motion of the
  Laboratory/Satellite
  System



The mechanical effect of light

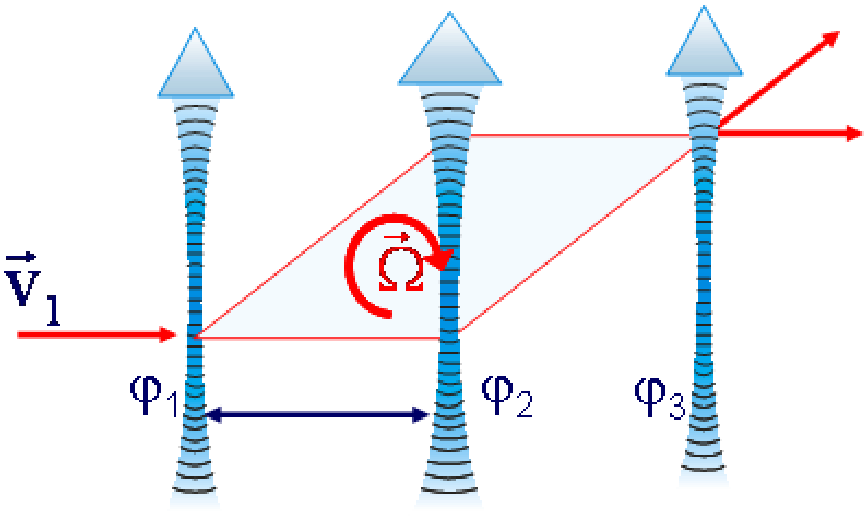




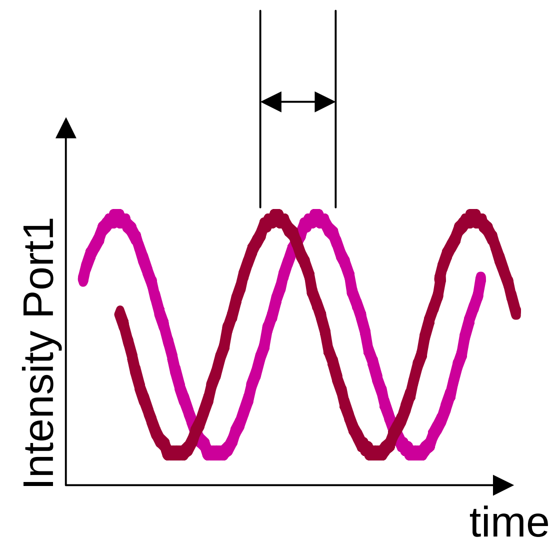
$$\vec{v}_{rec} = \frac{1}{m_{atom}} \hbar \vec{k}_L$$

Inertial phase shifts

constant rotations:



$$\Delta\varphi_{rot} = \frac{2\, m_{Atom}}{\hbar} \vec{A} \cdot \vec{\Omega}$$



T: drift time

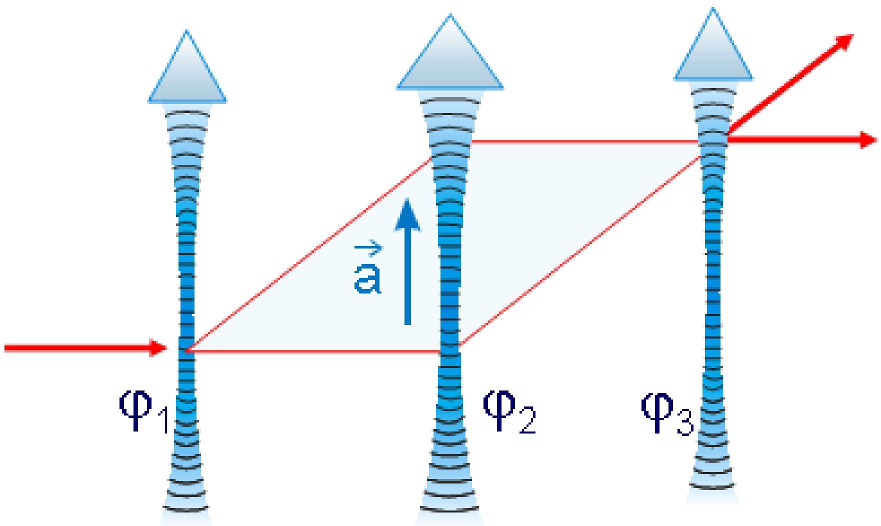
v_1: atomic forward drift

resolution: $\Delta\Omega \propto \frac{1}{T} \approx 10^{-12}\, rad/s\sqrt{Hz}$

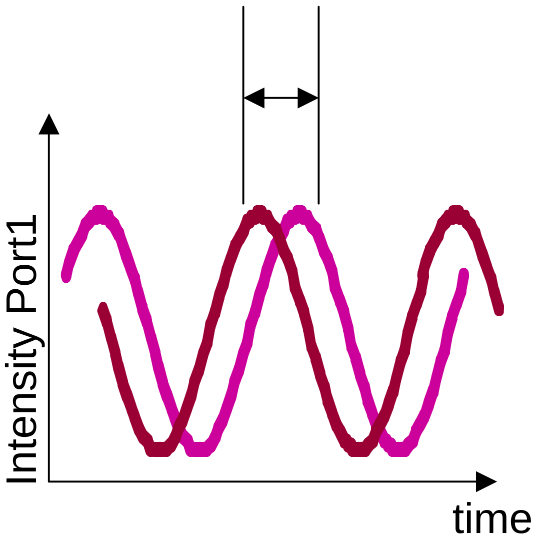
(space based)

Inertial phase shifts

constant accelerations:



$$\Delta\varphi_{acc} = T^2 \vec{k} \cdot \vec{a}$$



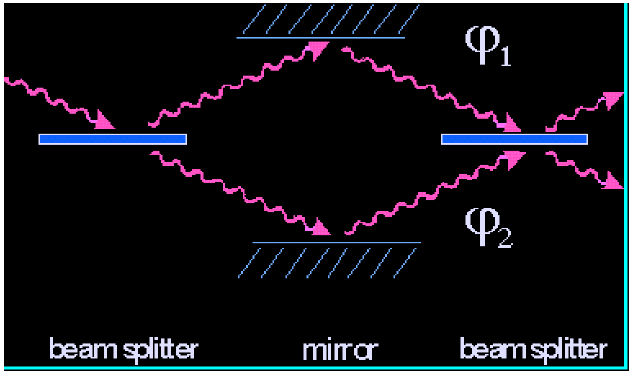
resolution:
(space based)

$$\Delta a \propto \frac{1}{T^2} \approx 10^{-13} g / \sqrt{Hz}$$

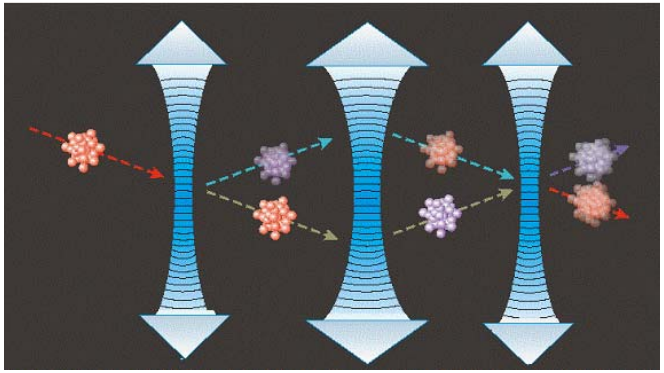
Interferometry: Light or Matter ?

Light vs. **Matter**

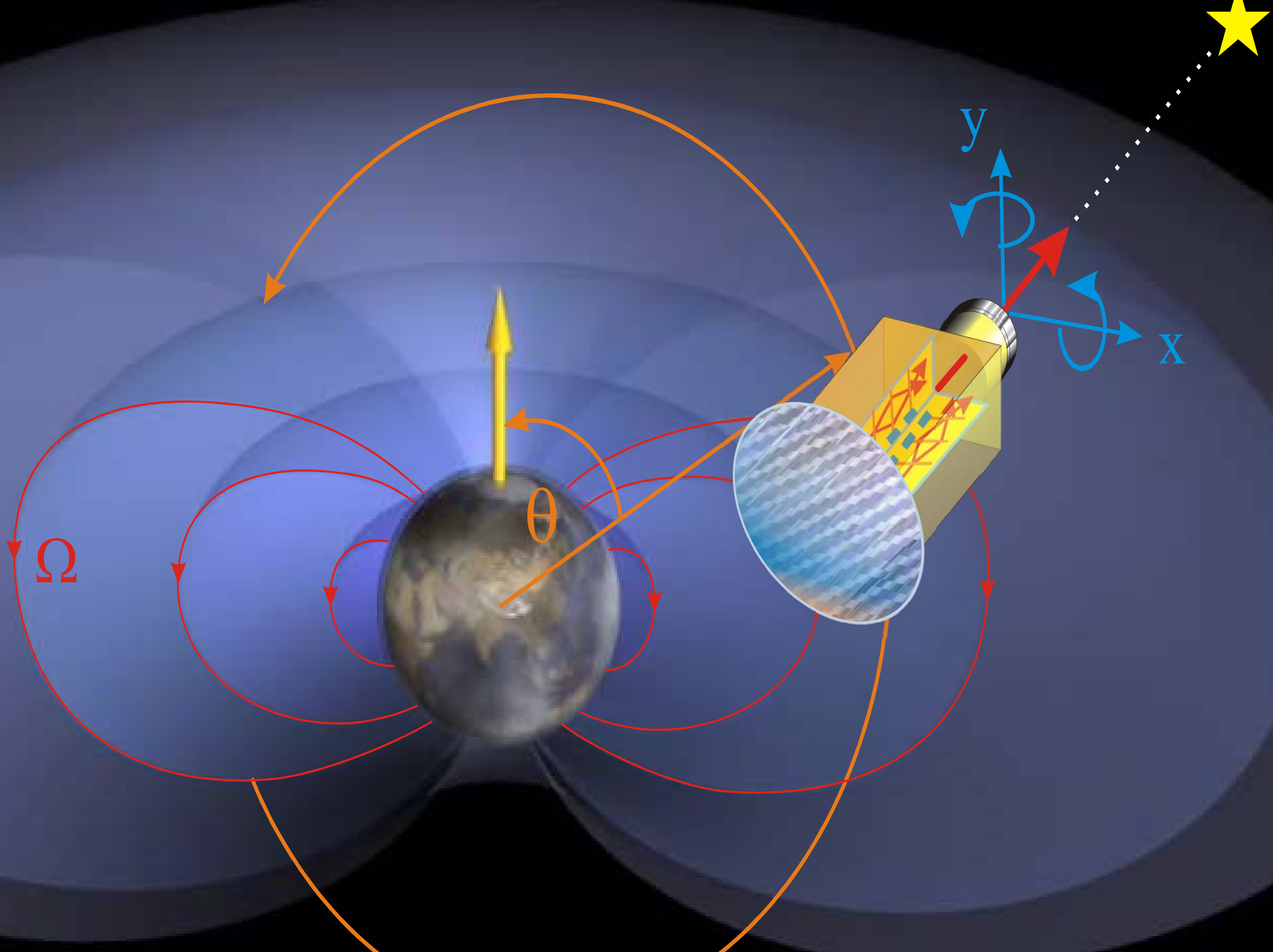
$$\Delta\Phi^{light}_{Sagnac} = 2\pi \frac{2}{\lambda\, c} A \cdot \Omega$$



$$\Delta\Phi^{atoms}_{Sagnac} = 2\pi \frac{2\, m_{at}}{h} A \cdot \Omega$$

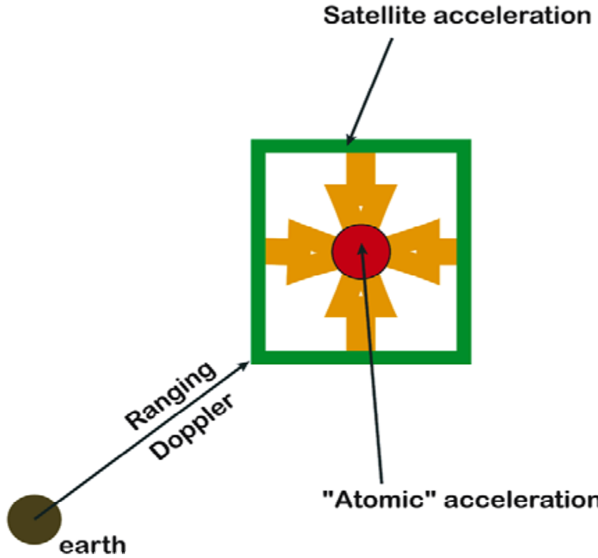


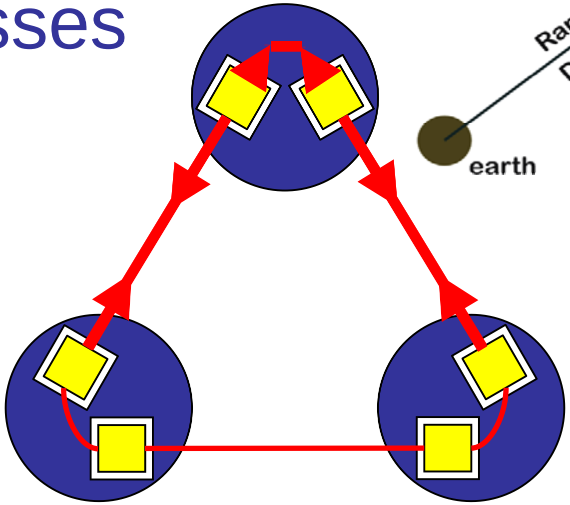
$$\frac{\Delta\Phi^{atoms}_{Sagnac}}{\Delta\Phi^{light}_{Sagnac}} = \frac{m_{at} \cdot c^2}{h \cdot \nu} \approx 10^{11}$$

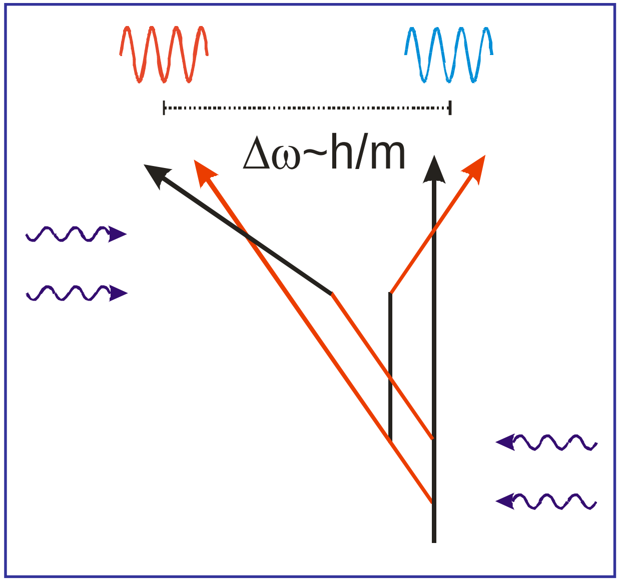

y
x
θ
Ω

Applications

- Mapping Gravity
- Weak Equivalence Principle
- Earth Gravity-Potential Monitoring
- Deep-Space Navigation
- Microscopic Proof-Masses







Constancy of the fine structure constant

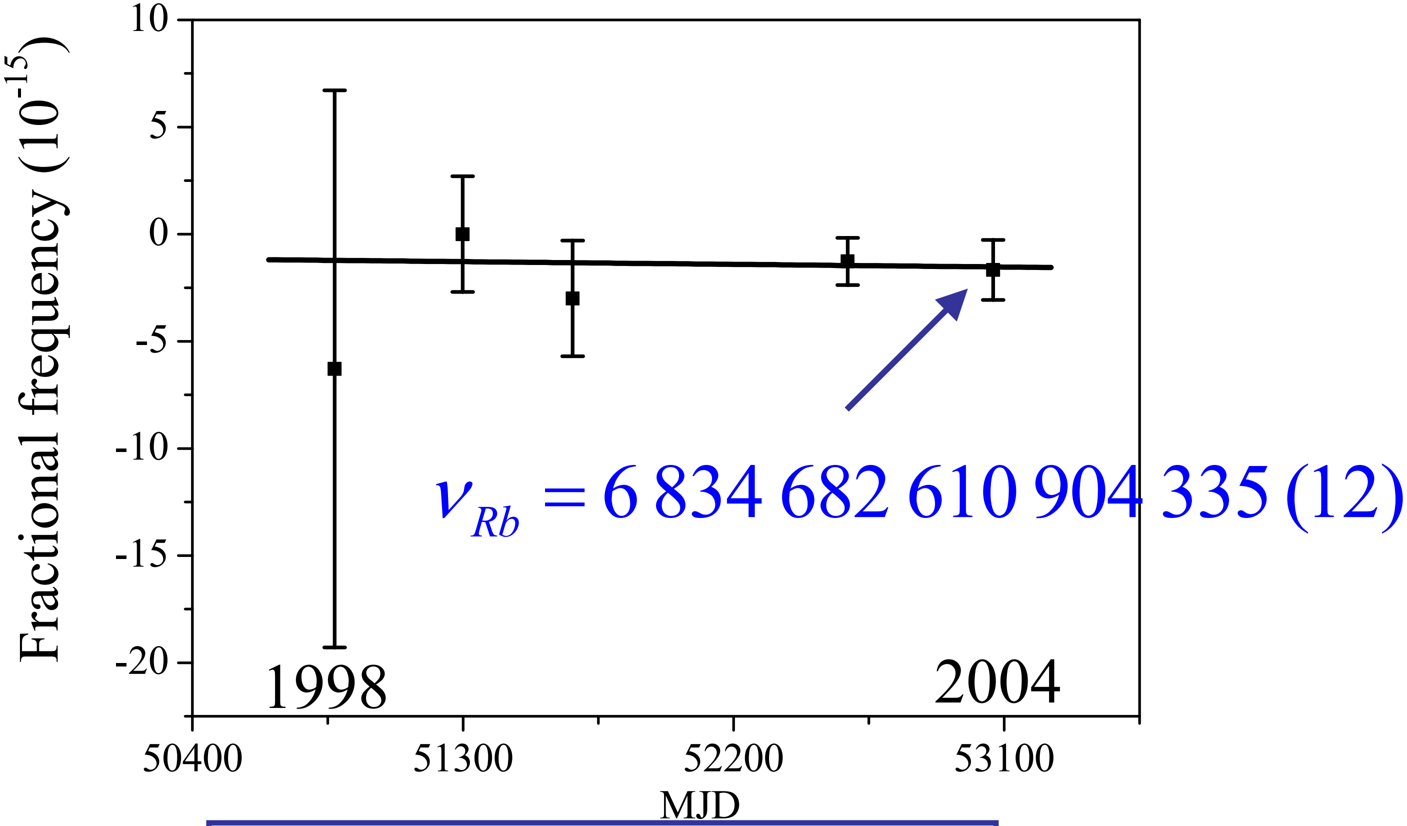
Einstein Equivalence Principle and the stability of fundamental constants

EEP ensures the universality of the definition of the second and is revisited by modern theories: $g_{\mu\nu} \Rightarrow g_{\mu\nu}, \varphi, \ldots$ Fundamental constants depend upon local value of φ : $\alpha(\varphi)$, $m(\varphi), \ldots$

- implies the stability of fundamental constants: $\alpha = e^2/hc$, m_e, $m_p, \ldots$
- the ratio of the transition frequencies in different atoms and molecules should not vary with space and time
- The EEP can be tested by high resolution frequency measurements regardless of any theoretical assumption

Violations of EEP are expected at some level !!

Search for drift of fundamental constants
^{87}Rb - ^{133}Cs comparison over 6 years



Within Prestage *et al.* theoretical framework :

$$\frac{d}{dt}\ln\left(\frac{\upsilon_{Rb}}{\upsilon_{Cs}}\right) = (-0.5 \pm 5.3)\times 10^{-16} \,/\, year$$

$$\frac{\dot{\alpha}}{\alpha} = (+1 \pm 11)\times 10^{-16} \,/\, year$$

H. Marion et al., SYRTE

S. Bize et al., NIST, PRL **90**, (2003)

The fine-structure constant

$$\alpha^2 = 2 \cdot \frac{R_\infty}{c} \cdot \frac{h}{m_{e^-}}$$

cross link between

R_∞ : Rydberg constant

c : speed of light

h/m_{e^-}: ratio of the Planck constant to the electron mass

most precise determination today:

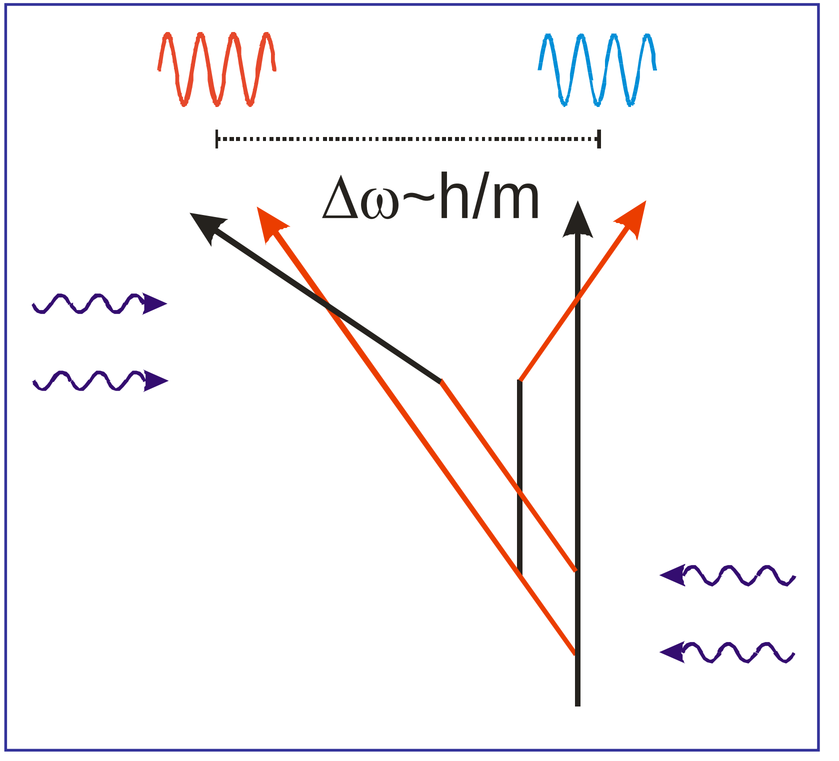
anomalous magnetic moment of the electron

α^{-1} = 137. 035 999 58(52) [3.8·10^{-9}]

The fine-structure constant

$$\alpha^2 = \frac{2R_\infty}{c} \frac{h}{m_{e^-}}$$

$$= \frac{2R_\infty}{c} \frac{m_p}{m_{e^-}} \frac{m_{at}}{m_p} \frac{h}{m_{at}}$$



most precise determination today:

anomalous magnetic moment of the electron

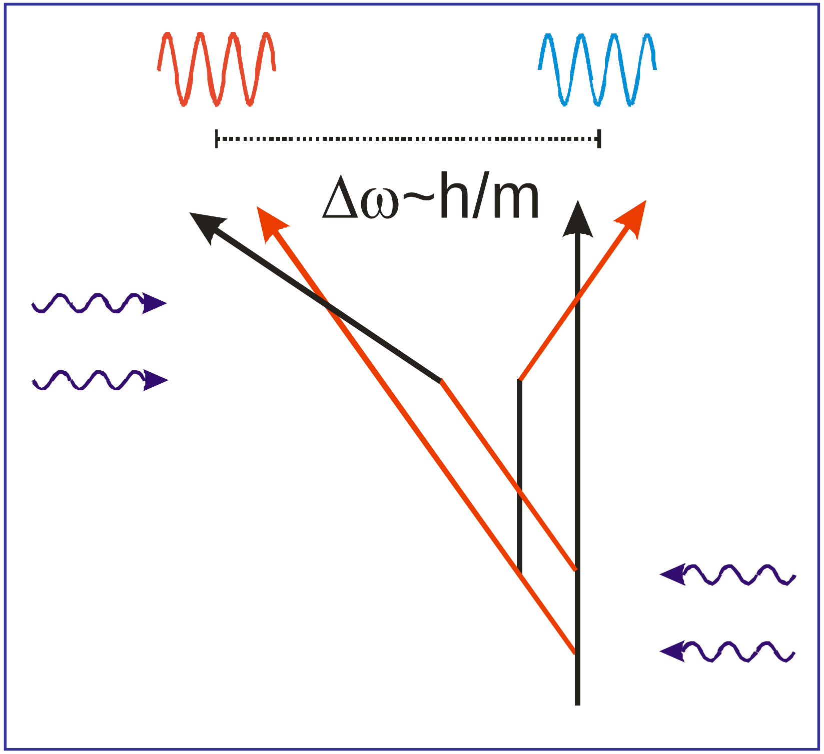
α^{-1} = 137. 035 999 58(52) [3.8·10^{-9}]

$$\Delta\omega = \frac{1}{2}k^2 \cdot \frac{\hbar}{m_{at}}$$

The fine-structure constant

$$\Delta\omega = \frac{1}{2}k^2 \cdot \frac{\hbar}{m_{at}}$$

$$\alpha^2 = \frac{2R_\infty}{c}\,\frac{m_p}{m_{e^-}}\,\frac{m_{at}}{m_p}\,\frac{h}{m_{at}}$$



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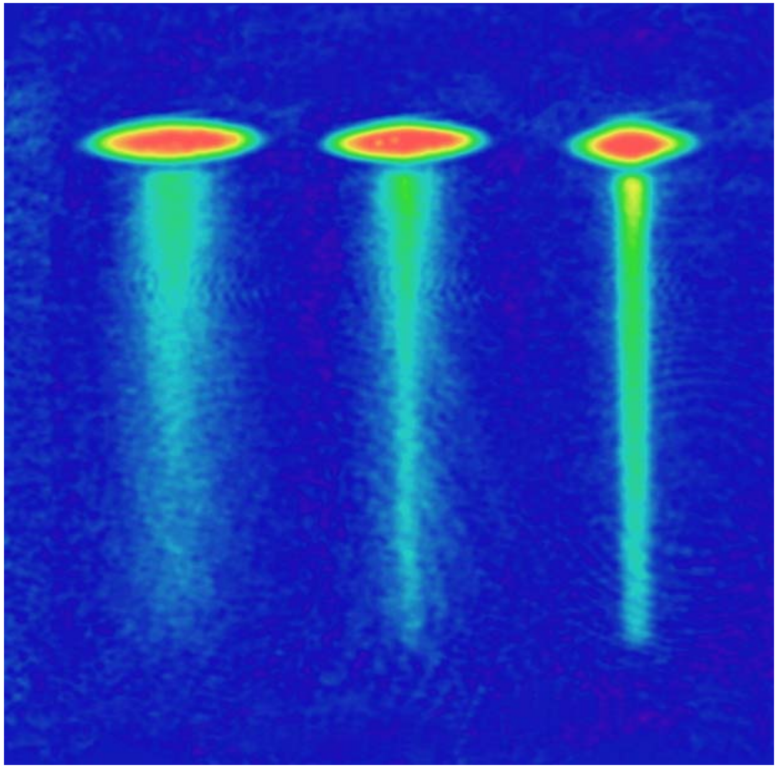
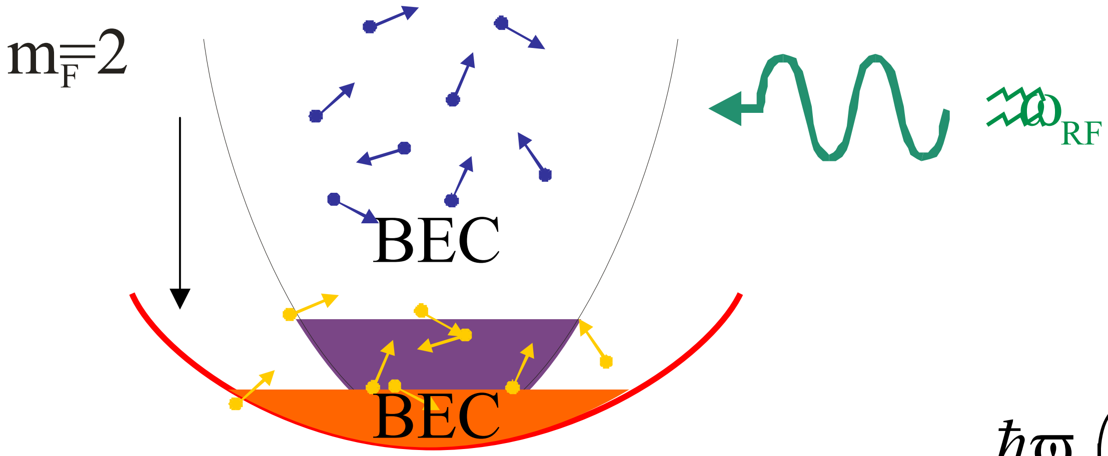


Quantum Matter

Lowering the temperature
adiabatic expansion



$$T_c = \frac{\hbar\varpi}{k_B}\left(\frac{N}{\zeta(3)}\right)^{1/3} \approx 0.94\,\hbar\varpi N^{1/3}$$

F. Dalfovo, S. Giorgini, L. P. Pitaeskii, S. Stringari,

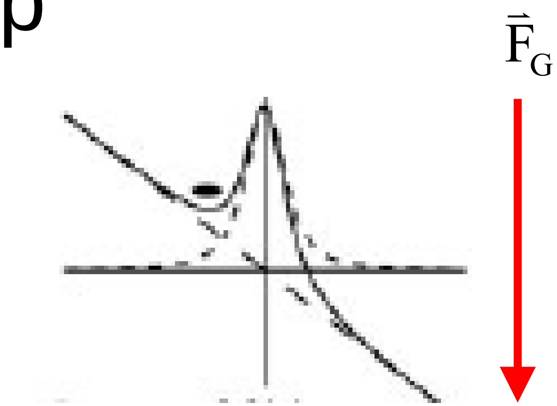
Rev.Mod. Phys. **71**, 463 (1999)

Gravity

- Hindrance for lowering the trap frequency
- Compensation required
- Desirable: long time scales

  for adiabaticity

  $\varpi \sim 1/10$ s $\leftrightarrow$ required time 100 s



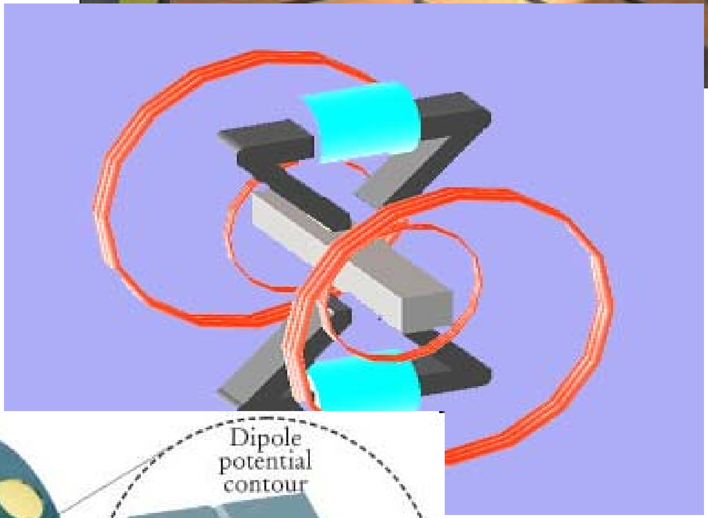
$\vec{F}_G = mg, U_G = mg * h$

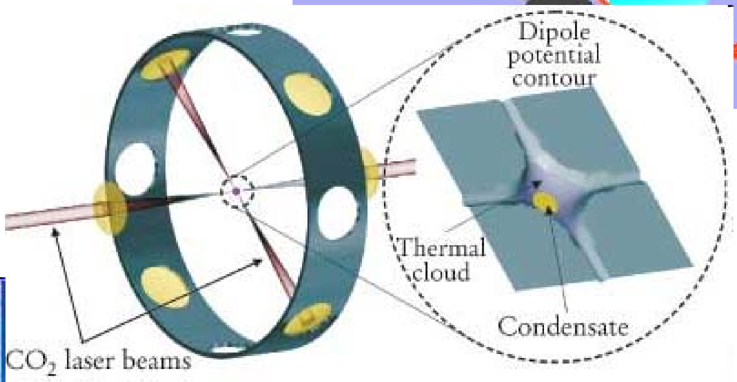
The Potential of Microgravity for BEC

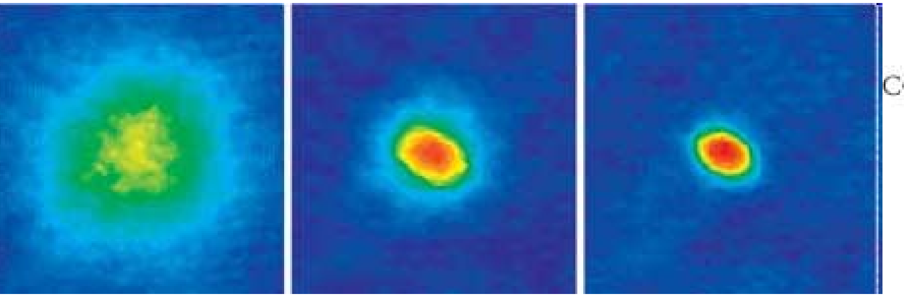
Parameter	Present experiments on ground	Experiments in μ-gravity environment
Free evolution	Time: 10 ms < *t* < 80 ms free fall	5s < *t* < 100 s (at the drop tower, parabolic flights, or orbital platforms)
Measurement time	Time: 10 ms < *t* < 100 ms	up to 100 s
Temperature	typically: 1 nK record: 500 pK	pK to fK (at the droptower, parabolic flights or orbital platforms)
Dynamics	Trap frequencies: *f* > 1Hz	0.01 Hz (orbital platform) < *f* < 1 Hz (drop tower
Size of the trapped condensate	*L*: up to several 100 μm	100μm < *L* < 10 mm
Matter-wave dimensions	Diameter: *d* < 1 mm	Diameter: 1mm < *d* < 100 mm
Healing length (scales with inverse trap frequency)	*L*: < 1 μm	1μm < *L* < 100 μm

Progress in BEC

- Chip-Traps
- Low-power magnetic traps
- All-optical Generation (Light Traps)
- Atom lasers

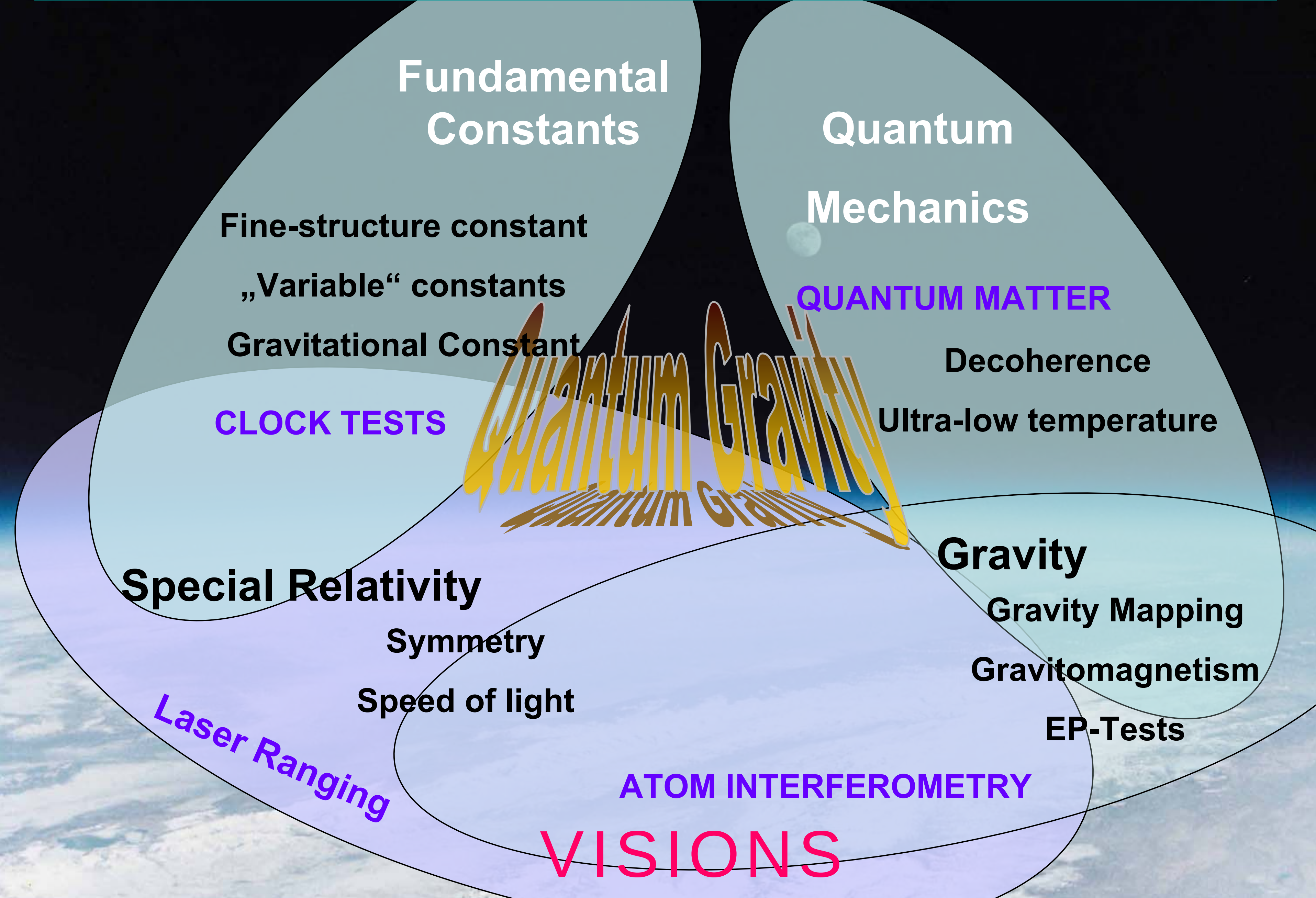






Missions

Proposed Themes



Roger Longstaff	NEWTON B" - Value of the Universal Gravitational Constant (G)
Claus Laemmerzahl	Testing the Pioneer Anomaly"
	Significance of the pioneer anomaly
	Laser Interferometric Test of Relativity"
Clive Speake	An artificial Moon
C.Trenkel	Search for New Short-Range Forces
	Search for Lorentz Symmetry Violation and Spin Spin coupling Forces
Hansjoerg Dittus	Testing General Relativity with Long-Term Satellite Tracking
	Deep Space Laser Ranging
	Observation of the Gravitomagnetic Clock-Effect
Wolfgang Ertmer	Exploring Bose-Einstein Condensates in Space
Axel Görlitz	Ultracold atomic gases
Philippe Bouyer	ICE
	NAO
E.M. Rasel	Exploring Gravity in the Quantum Domain
	Testing General Relativity by Mapping the

The teams of Fundamental Physics themes

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LGCR (*P. Tourrenc, P. Teyssandier, Paris*)
LPL (*C. Bordé, Paris & Hannover*)
PTB (*J. Helmcke, U. Sterr, Braunschweig*)
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Universität Trento (*S. Vitale, Trento*)
Universität Ulm (*W. Schleich, Ulm*)
Zarm (Hj. Dittus, *C.Lämmerzahl* Bremen)


ENOUGH SPACE FOR
EXCITING EXPERIMENTS