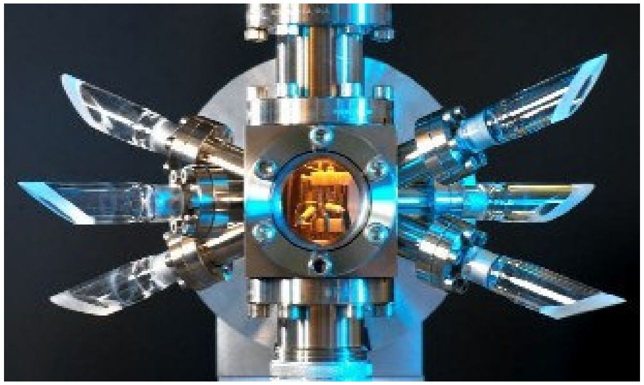
Opportunities for space-based experiments using optical clock and comb technology



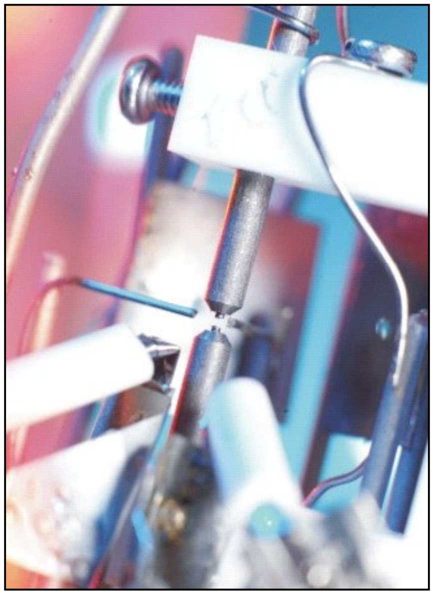
Patrick Gill

National Physical Laboratory, UK

Quantum to Cosmos, Virginia, 9th July 2008

Outline

- Background to ESA studies
- Technology: recent developments & state-of-the-art performance
  - Local oscillators
  - Trapped ion standards
  - Neutral atom standards
  - Femtosecond combs
  - Optical clock comparison
- Opportunities for space missions
- Development plan for optical clocks at suitable technology readiness to move to space qualification



$^{88}Sr^{+}$ ion trap (NPL)

ESA study 2006-07: optical frequency synthesizer for space-borne optical frequency metrology

Patrick Gill, Hugh Klein and Helen Margolis
National Physical Laboratory

Ronald Holzwarth, Marc Fischer and Theodor Hänsch
Menlo Systems GmbH

Stephan Schiller
Heinrich-Heine Universität Düsseldorf

Volker Klein
Kayser-Threde GmbH (KT)

ESTEC Contract No. 19595/06/NL/PM
ESA Technical Officer: Eamonn Murphy

Conclusions & Recommendations:

- Optical frequency combs now mature lab devices
- Ground-based optical clocks specs of 10^{-17} – 10^{-18} available in near future
- Significant advance on microwave frequency best capability
- Opportunities across a range of future space mission sectors

→ **High precision, high performance clocks,**
Need to work on high reliability for space

- A substantial ESA-sponsored development programme **to enable optical clock technology to be better prepared for future space missions**
- ESA-steer in the planning of a **future mission based on optical clocks**
- Focus the efforts of leading optical frequency metrology groups and companies **to achieve a space-based optical clock demonstrator within the next decade**

Development of Optical Atomic Clocks for Space

Patrick Gill, Helen Margolis & Hugh Klein
National Physical Laboratory

Remit:

Draw up a viable technology development plan for OACs for space

Timescale: May – September 2008

ESTEC Contract No. 21641/08/NL/PA
ESA Technical Officer: Eamonn Murphy

Technology development plan for OACs in space

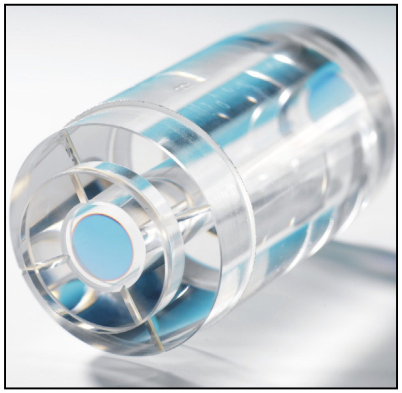
- Pointers to potential future missions and associated user requirements benefiting from OACs
- Aim for a fit between fundamental physics & other subsidiary science mission goals
- Identify necessary parallel development activities to progress OAC sub-unit technologies to TRL 5/6, ideally consistent with next CV timeframe
- Identify a co-ordinated activity plan (with costs) involving the ESA space research community that addresses the following sub-units:
  - Atomic reference (cold atom and single ion options)
  - Optical local oscillator
  - Frequency synthesis
  - Frequency comparison
- Integration of sub-unit development into advanced prototype (by 5 years)
- Identify systems providers and ball-park cost for next stage EM

Optical Clocks: What and Why?

instability $\sigma \propto \dfrac{\Delta f}{f}\,\dfrac{1}{(S/N)}$

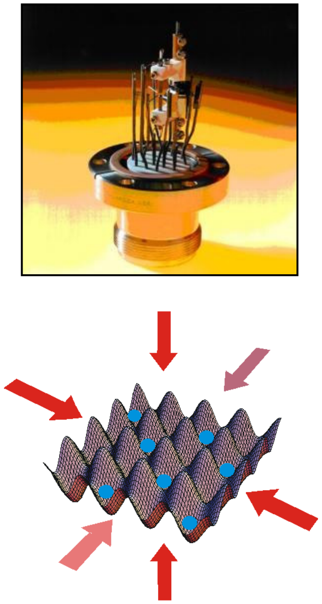
- Based on narrow optical transitions in atoms or ions
- Frequencies ~10^5 times higher than microwave frequencies
- Q-factor ~10^{15}
- Better time resolution
- Better stabilities than microwave clocks

$$\sigma(\tau) \sim \frac{1}{2\pi f\sqrt{N T_{\text{int}}\tau}}$$



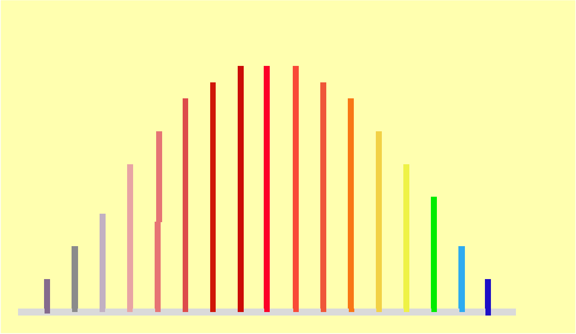
Cavity-stabilised Oscillator (Ultra-stable laser)

+



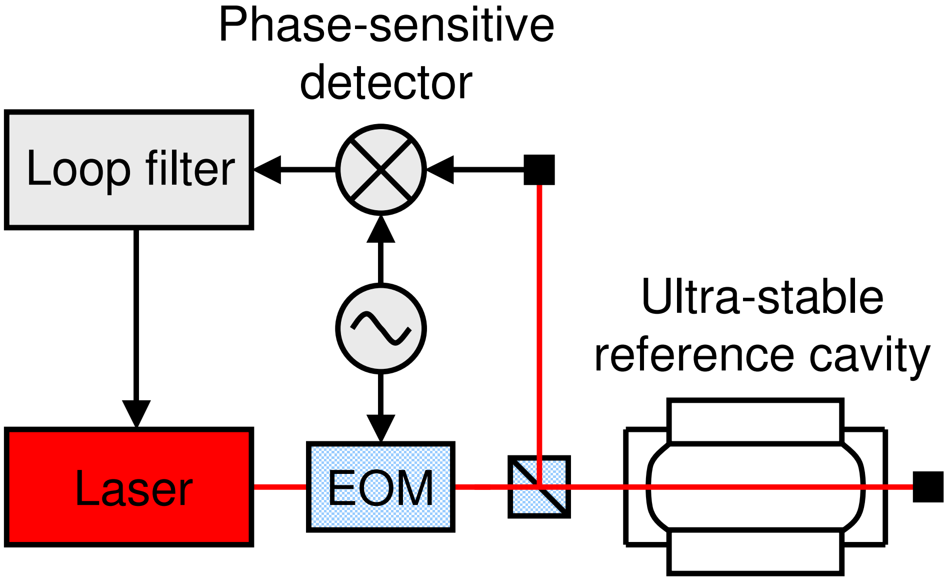
Reference (Narrow optical transition in an atom or ion)

+



Counter (Femtosecond comb)

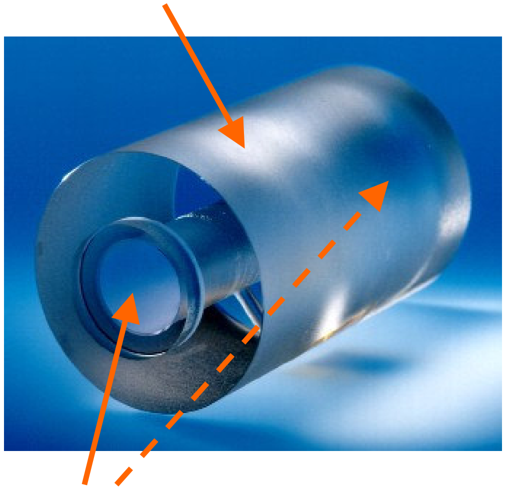
Optical local oscillators



Spacer:

Ultra-low-expansion (ULE) glass

Length ~10 cm → FSR ~ 1.5 GHz



Mirrors:

optically contacted to spacer

Refl. > 99.998%, finesse ~ 200,000

Cavity must be:

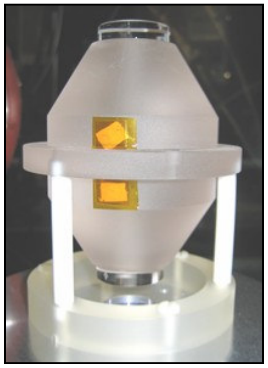
- Operated at a temperature where coefficient of thermal expansion α_{CTE} is close to zero;
- Isolated from sources of vibration.

State-of-the-art LO performance

Benchmark: ULE-cavity-stabilized dye laser at NIST
linewidth ~ 0.2 Hz, rel. frequency instability $3x10^{-16}$ at 1 s

Other systems:
Nd:YAG laser ~ 0.4 Hz (NPL, JILA, …)
Diode lasers ~ 0.4 – 1 Hz (PTB, NIST, NPL, …)
Ti:sapphire ~ 5 Hz (NPL)

Recent developments: Vibration-insensitive cavities

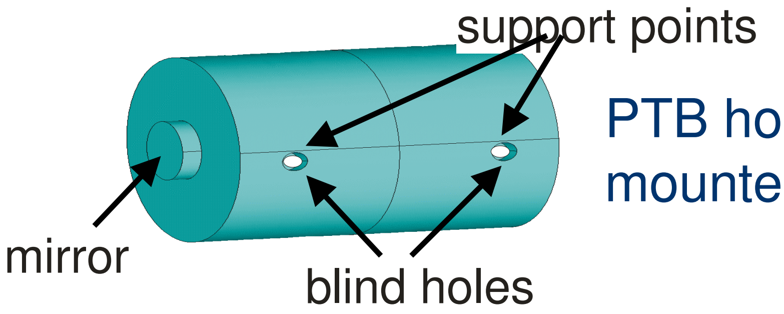


JILA vertical cavity

Ludlow et al.
Opt. Lett. 32, 641 (2007)

NPL cut-out cavity

Webster et al. PRA 75, 011801 (R) (2007)

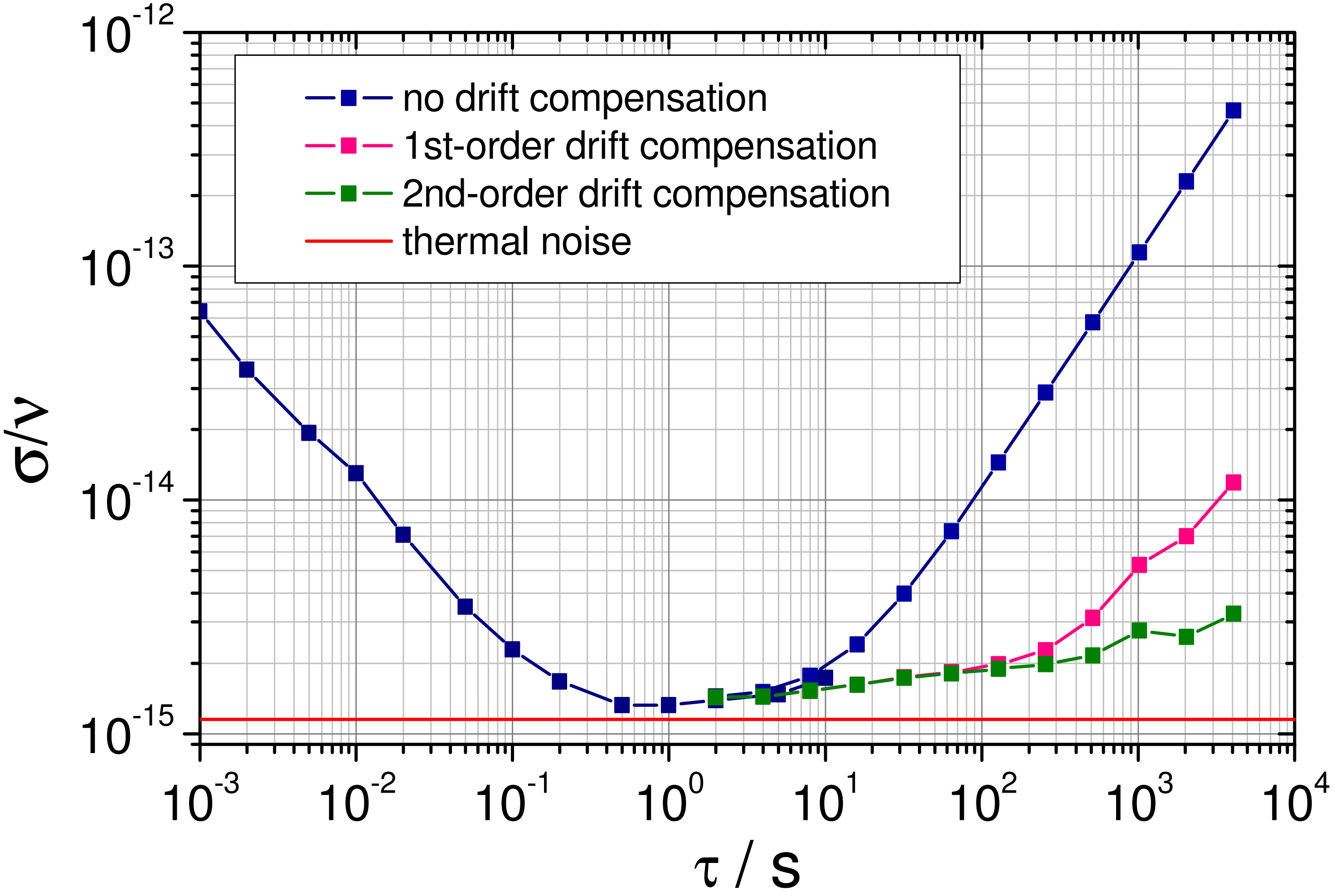


PTB horizontally-mounted cavity

Nazarova et al., Appl. Phys. B 83, 531 (2006)

Sensitivity to vertical vibrations up to 1000 times lower than standard cylindrical cavities

Thermal noise limit

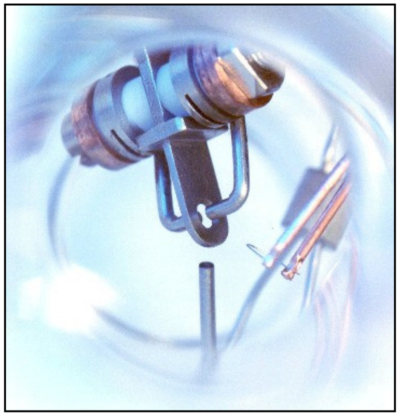


Experiment: Webster *et al*., PRA 77, 033847 (2008)

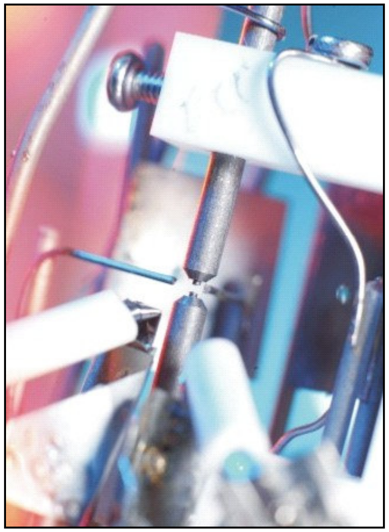
Theory: Numata *et al*., PRL 93, 250602 (2004)

Trapped ion optical clocks

- Laser-cooled single trapped ion
- High-*Q* optical clock transitions (10^{15} or higher)
- Long interrogation times possible
- Electron shelving scheme → high detection efficiency



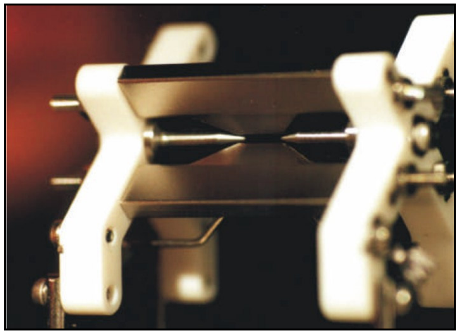
$^{171}Yb^{+}$ trap (PTB)



$^{88}Sr^{+}$ trap (NPL)

Low perturbation environment:

- No 1st-order Doppler shift (& minimum 2nd-order shift)
- Field perturbations minimised at trap centre
- Background collision rate low

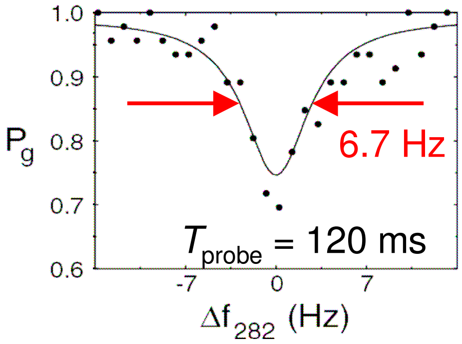


Ca^{+} trap (Innsbruck)

Ion clocks: candidate systems

Ion	Clock transition	λ / nm	Natural linewidth / Hz	Best experimental linewidth / Hz	Frequency measurement uncertainty / Hz	Laboratory
$^{199}Hg^+$	$^2S_{1/2}$–$^2D_{5/2}$	282	1.8	6.7	0.7	NIST
$^{171}Yb^+$	$^2S_{1/2}$–$^2D_{3/2}$	436	3.1	10	2.2	PTB, NPL
$^{88}Sr^+$	$^2S_{1/2}$–$^2D_{5/2}$	674	0.4	5	1.7	NPL, NRC
$^{40}Ca^+$	$^2S_{1/2}$–$^2D_{5/2}$	729	0.14	15	0.9	Innsbruck, CRL, Marseilles
$^{115}In^+$	$^1S_0$–$^3P_0$	237	0.8	170	230	MPQ / Erlangen
$^{27}Al^+$	$^1S_0$–$^3P_0$	266	8×10^{-3}	8.4	0.7	NIST
$^{171}Yb^+$	$^2S_{1/2}$–$^2F_{7/2}$	467	$\sim 10^{-9}$	40	11	NPL, PTB

Ion clocks: observed *Q*-factors & absolute frequency measurements



$^{199}Hg^+$ standard:

observed $Q \approx 1.6\times10^{14}$ ***Rafac et al., PRL 85, 2462 (2000)***

f = 1 064 721 609 899 145.30(69) Hz

(rel uncertainty 6.5 × 10^{-16})

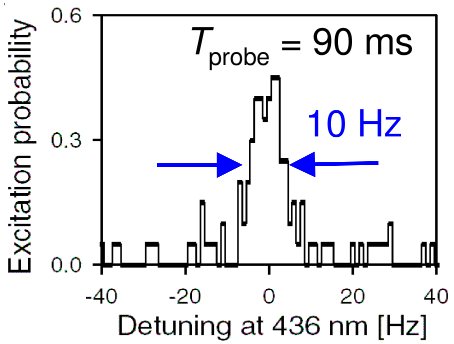
Stalnaker et al., Appl. Phys. B 89, 167 (2007)

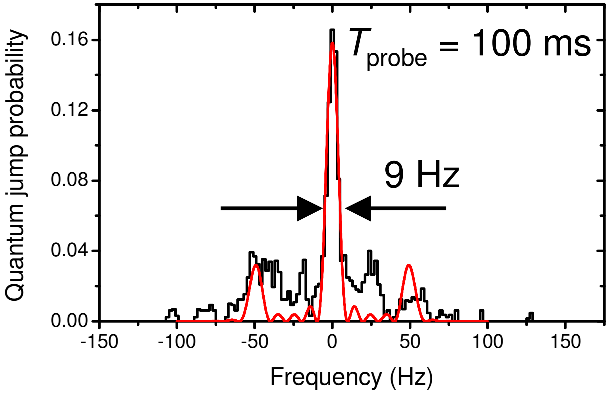
$^{171}Yb^+$ quadrupole standard:

observed $Q \approx 7\times10^{13}$ ***Peik et al., PRL 93, 170801 (2004)***

f = 688 358 979 309 307.6 (2.2) Hz

(rel uncertainty 3.2 × 10^{-15}) ***Tamm et al., IEEE TIM. 56, 601 (2007)***





$^{88}Sr^+$ standard:

observed $Q \approx 5\times10^{13}$ ***Barwood et al, IEEE TIM. 56, 226 (2007)***

f = 444 779 044 095 484.2 (1.7) Hz

(rel uncertainty 3.8 × 10^{-15})

Margolis et al., Science 306, 1355 (2004)

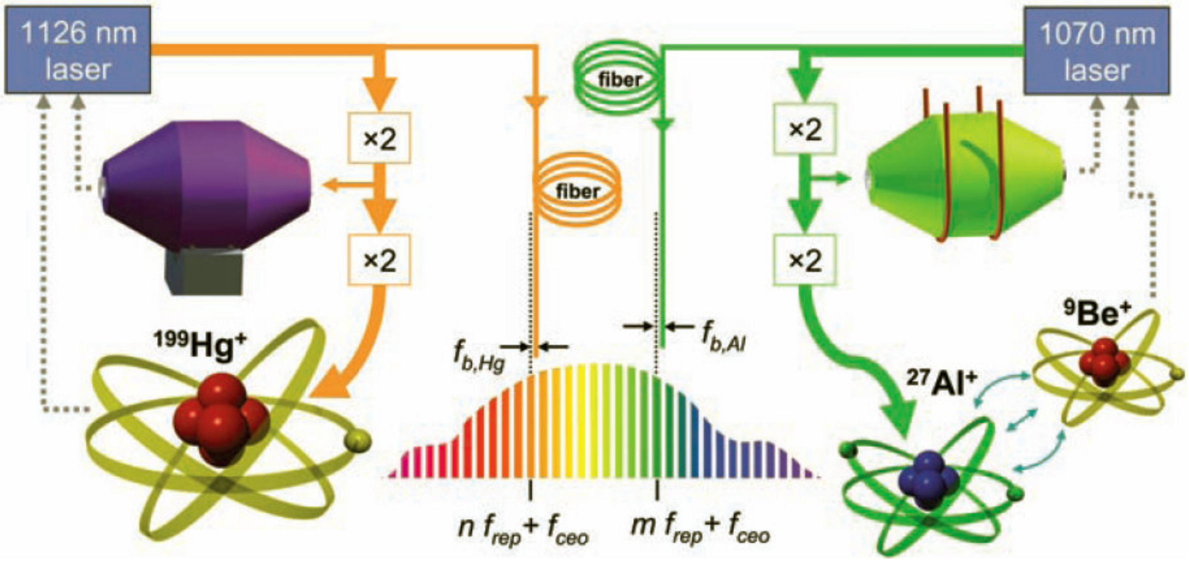
Ion clocks: frequency ratio measurements

Optical frequency ratios can be measured much more accurately.

$$\frac{f_{\mathrm{Al+}}}{f_{\mathrm{Hg+}}} = 1.052\ 871\ 833\ 148\ 990\ 438\ (55)$$

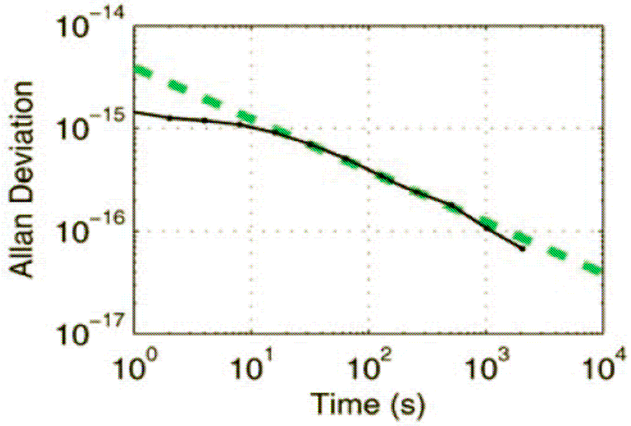
Relative uncertainty 5.2×10^{-17}

4.3×10^{-17} statistics
1.9×10^{-17} Hg^{+} systematics
2.3×10^{-17} Al^{+} systematics



Rosenband *et al*.,
Science 319, 1808 (2008)

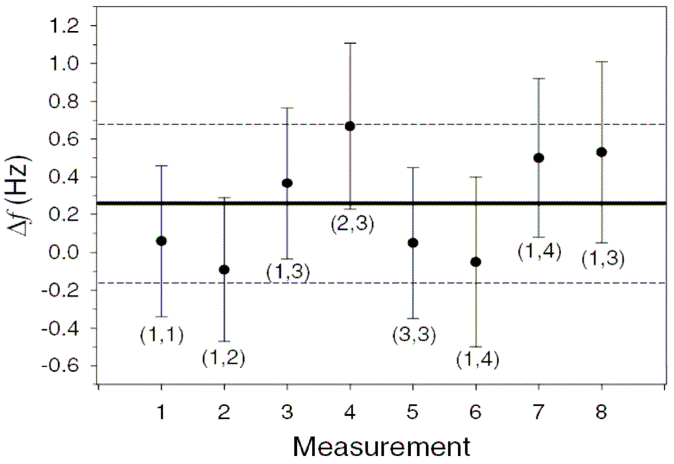
Ion clocks: stability and reproducibility



Comparison of ^{199}Hg$^+$ and ^{27}Al$^+$ standards:

instability $4 \times 10^{-15}\,\tau^{-1/2}$ for $20\text{ s} \le \tau \le 2\,000\text{ s}$

Rosenband *et al.*, Science 319, 1808 (2008)

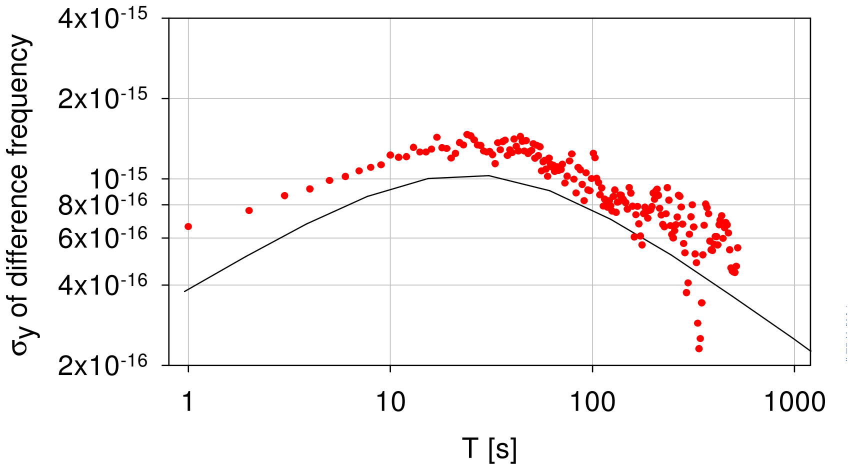


Comparison of two ^{171}Yb$^+$ standards:

fractional frequency difference $3.8(6.1) \times 10^{-16}$

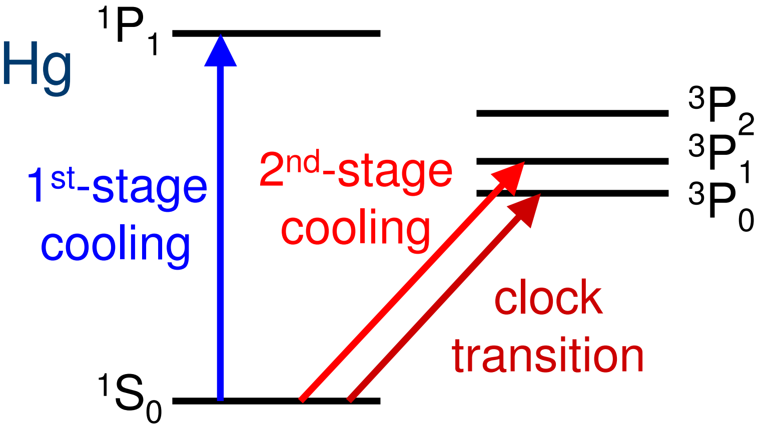
Schneider *et al.*, Phys. Rev. Lett. 94, 230801 (2005)

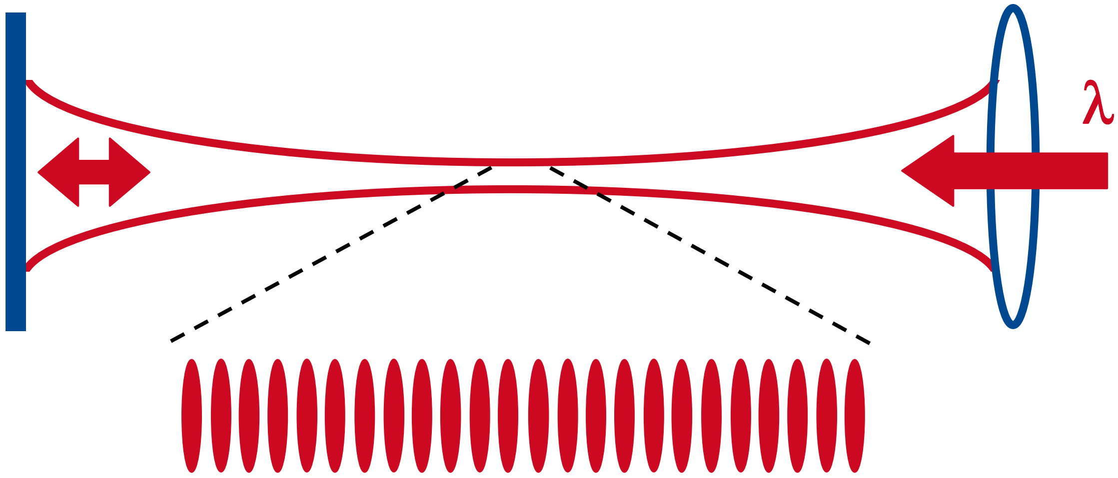
Peik et al, J. Phys. B: At.Mol.Opt. Phys 39,145 (2006)



Neutral atom lattice clocks

- $^1S_0 - ^3P_0$ clock transitions in eg Sr, Yb, Hg (mHz natural linewidth)
- Atoms confined in an optical lattice
- AC Stark shift eliminated by operating at “magic” wavelength
- N atoms, stability $\propto N^{1/2}$
- Ultimate goal: 3D lattice with 1 atom per site



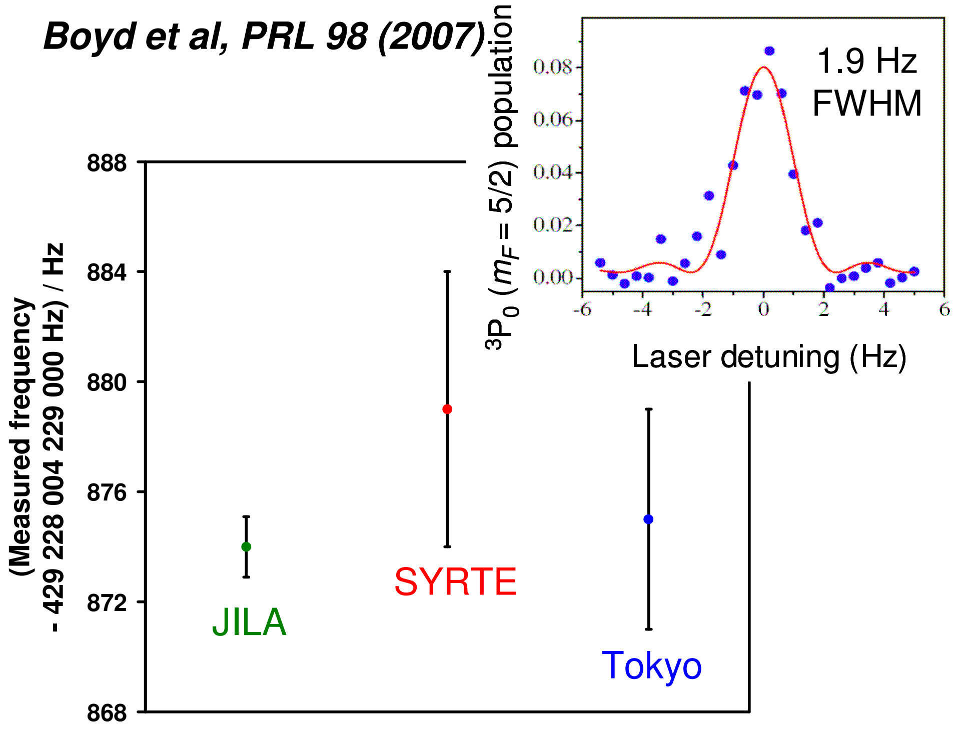


1D lattice, site spacing λ/2

Lattice clocks: absolute frequency measurements

^{87}Sr standard:

- Highest observed optical Q-factor (2x10^{14})
- Independent measurements from 3 groups now agree at the 10^{-15} level
- Secondary representation of the second

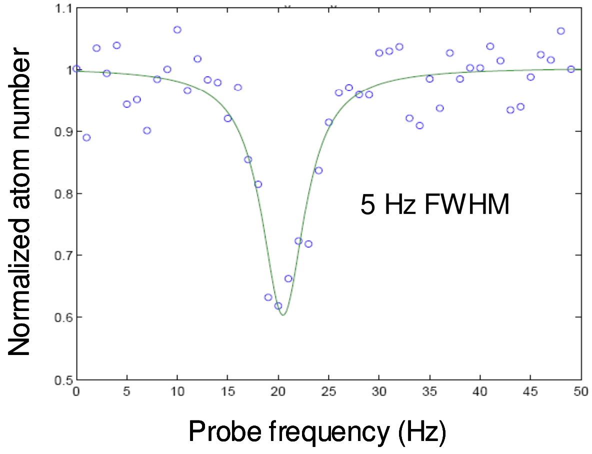


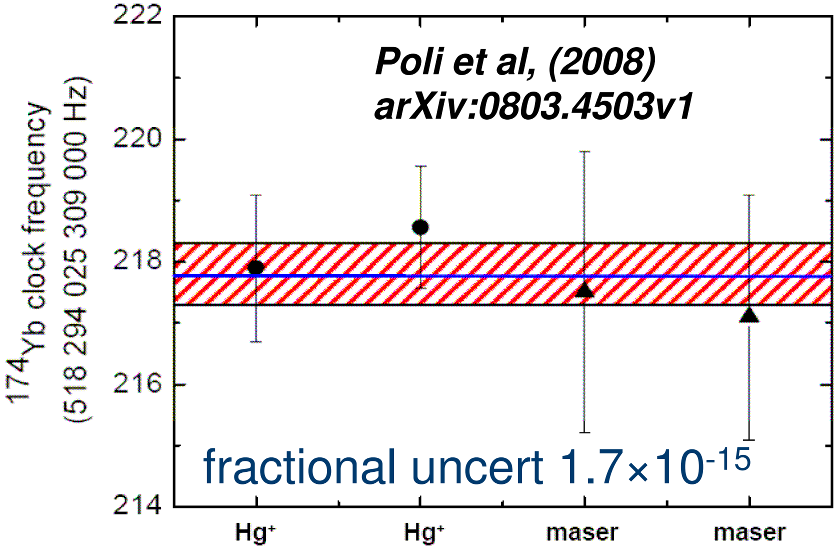
Boyd et al, PRL 98 (2007)

^{174}Yb standard:

- observed Q ~ 1x10^{14}

Barber et al, Proc. SPIE 6673, (2007)



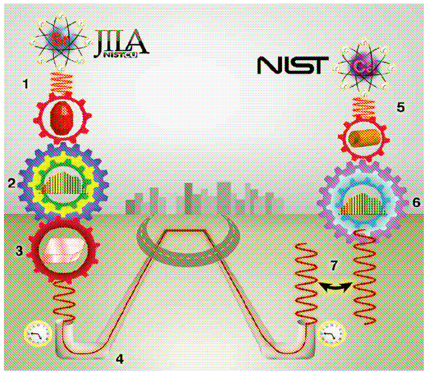


Poli et al, (2008)
arXiv:0803.4503v1

fractional uncert 1.7×10^{-15}

Both Qs limited by spectroscopic probe times

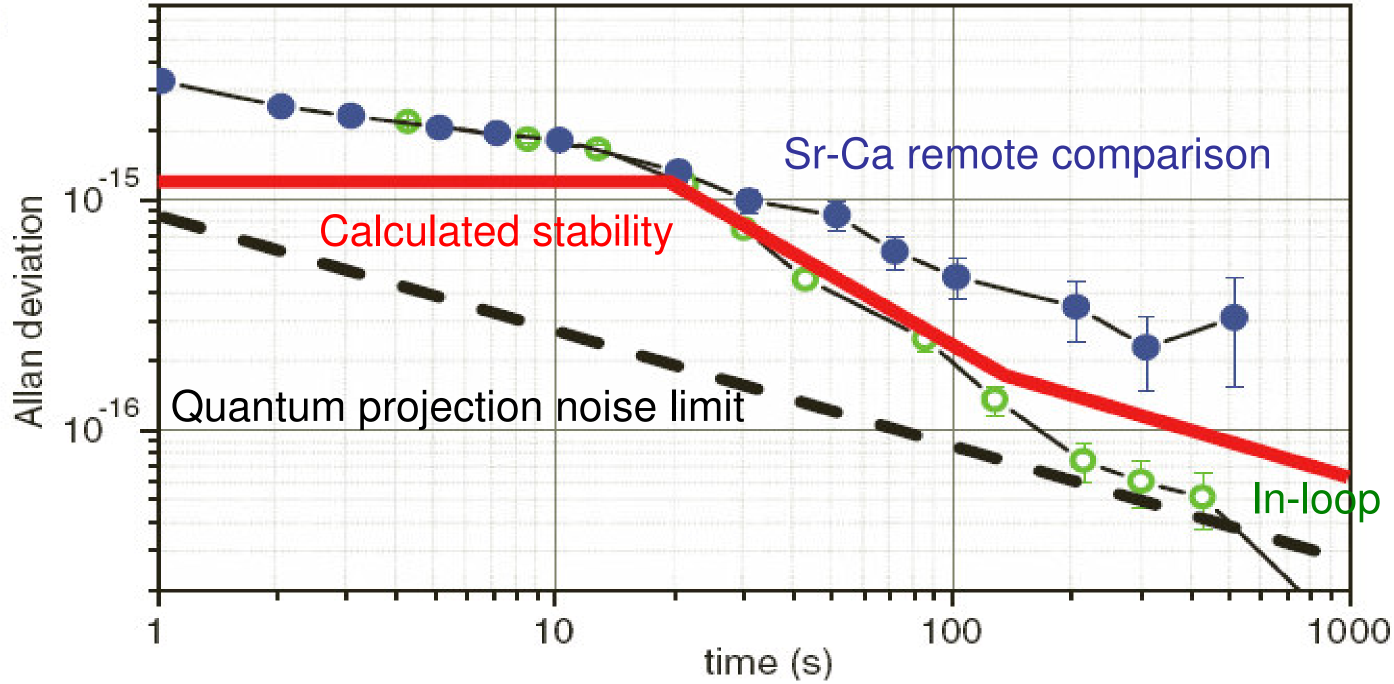
Lattice clocks: systematic uncertainty & stability



^{87}Sr standard:

Fractional frequency uncertainty of 10^{-16} demonstrated by remote optical comparison with a Ca standard.

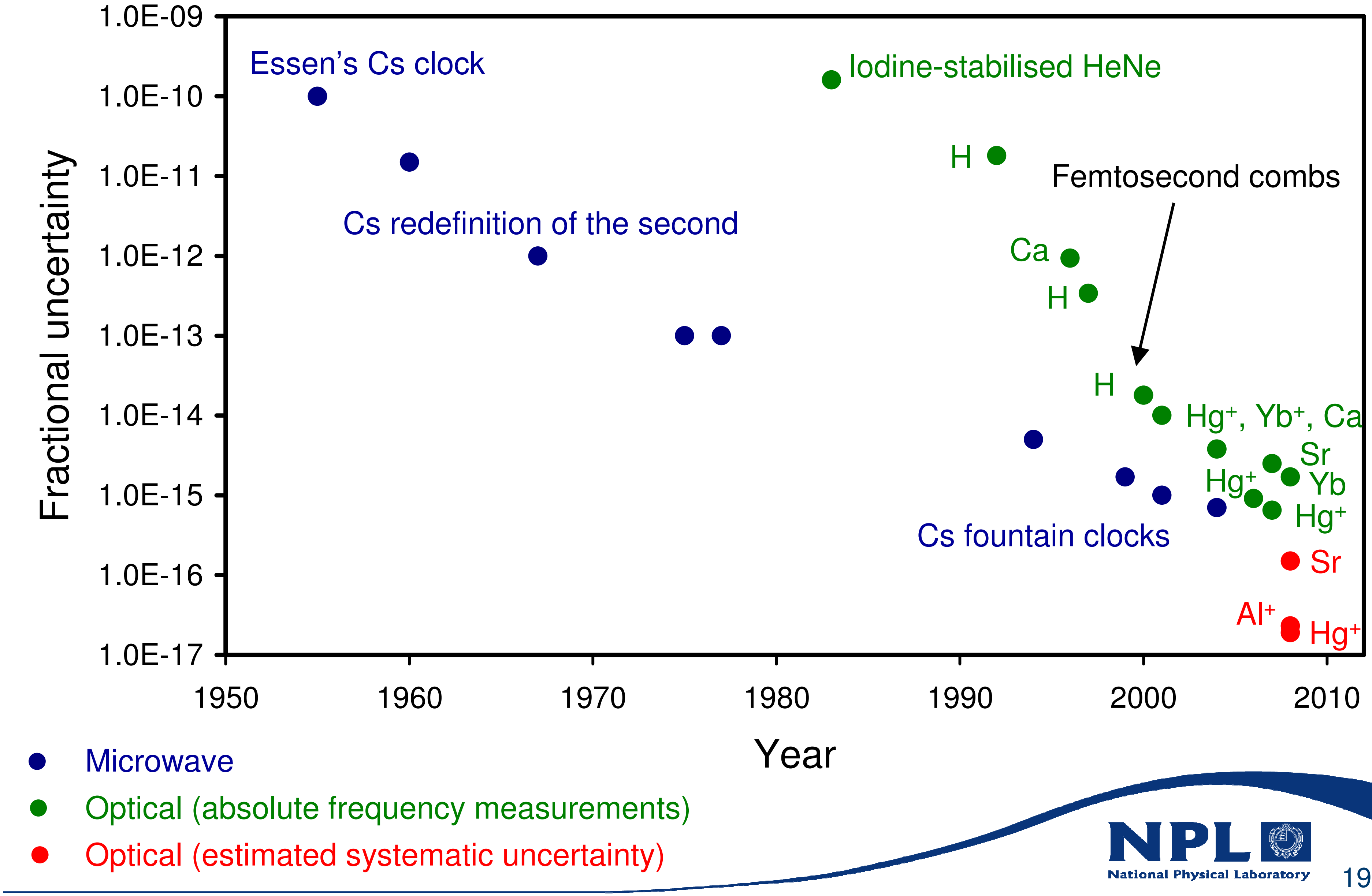
Ludlow et al., Science 319, 1805 (2008)



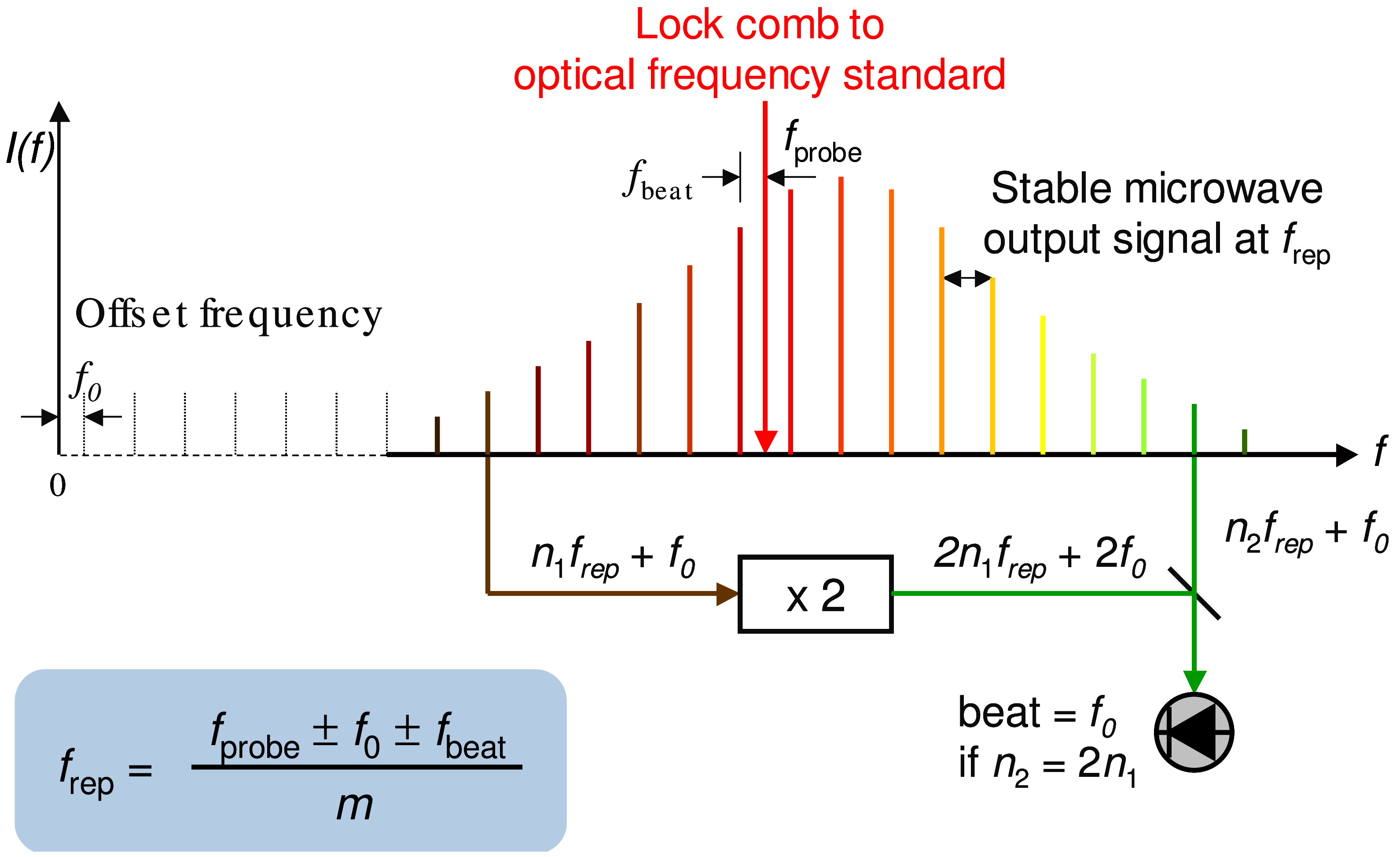
Similar stability demonstrated for ^{174}Yb (v. Hg$^+$)

Poli et al., arXiv:0803.4503v1 (2008)

Improvements in optical frequency standards



Femtosecond combs: optical clock operation

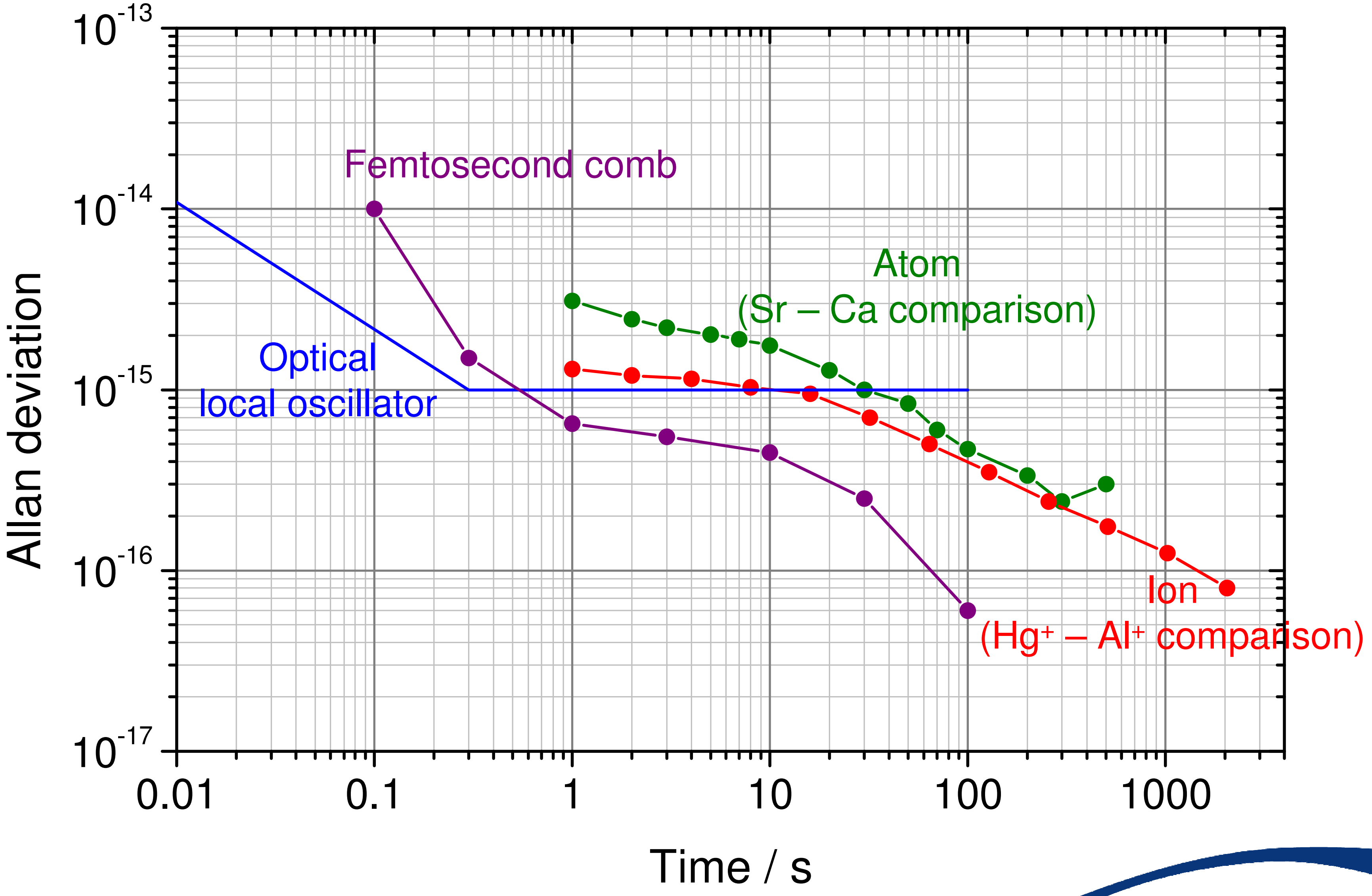


$$f_{\text{rep}} = \frac{f_{\text{probe}} \pm f_0 \pm f_{\text{beat}}}{m}$$

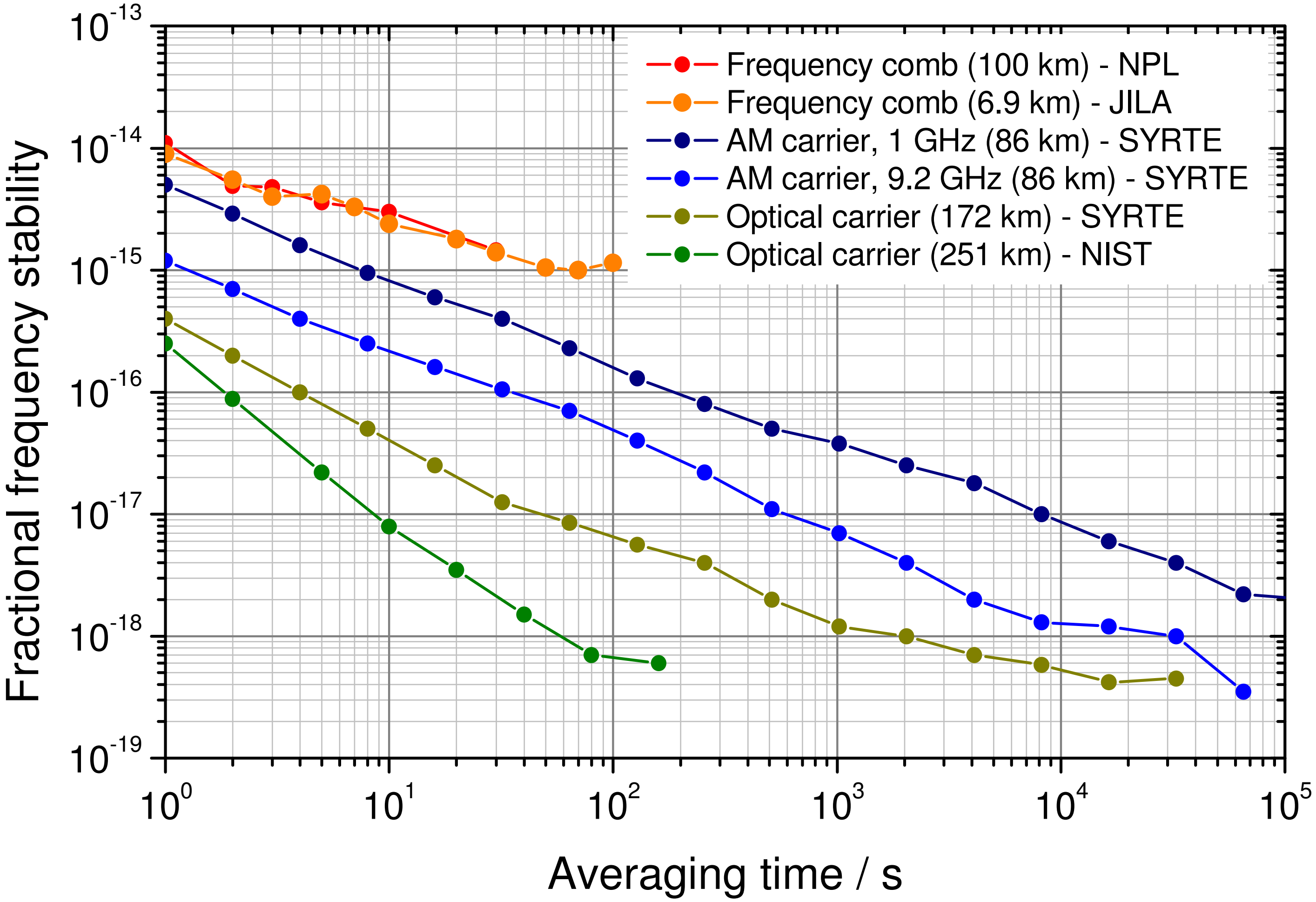
→ millions of modes across visible/IR with known frequency

- Uncertainty between combs locked to the same optical ref: ~1.4 x 10^{-19} *(Ma et al, Science 2004)*
- Comb hardware: fs laser (eg TiS, Fibre laser ….) + microstructure fibre

Overall system performance



Optical clock comparison by fibre: state of the art



Compare frequency transfer by fibre with satellite MWL between high performance remote clocks to validate MWL for transportable ground clocks

Opportunities for OAC space missions in fundamental physics

Development of quantum theory of gravity implies violations of standard General Relativity principles such as the Einstein Equivalence Principle:

GR effects small, but space environment offers variable gravity, large distances, high velocities and low accelerations and freedom from Earth seismic noise. Optical clocks most sensitive to gravitational effect through effect on frequency

$$\frac{\nu_1 - \nu_2}{\nu} = \frac{U(r_1) - U(r_2)}{c^2}$$

Tests of Local Position Invariance (LPI)

→ Absolute gravitational redshift (GRS) measurements due to $\Delta U/c^2$ orbit change in Earth potential

→ Absolute GRS measurements of solar potential

→ Null GRS tests between dissimilar clocks in changing potential

$$\frac{\nu_A}{\nu_B} = const.$$

Tests of Local Lorentz Invariance (LII)

→Test of time dilation between ground & space clock (Ives-Stilwell)

→ Cavity / OAC freq comparison in orbiting arrangement (Kennedy-Thorndike)

Measurement of space-time curvature

(Shapiro time delay)

EGE (Einstein Gravity Explorer)

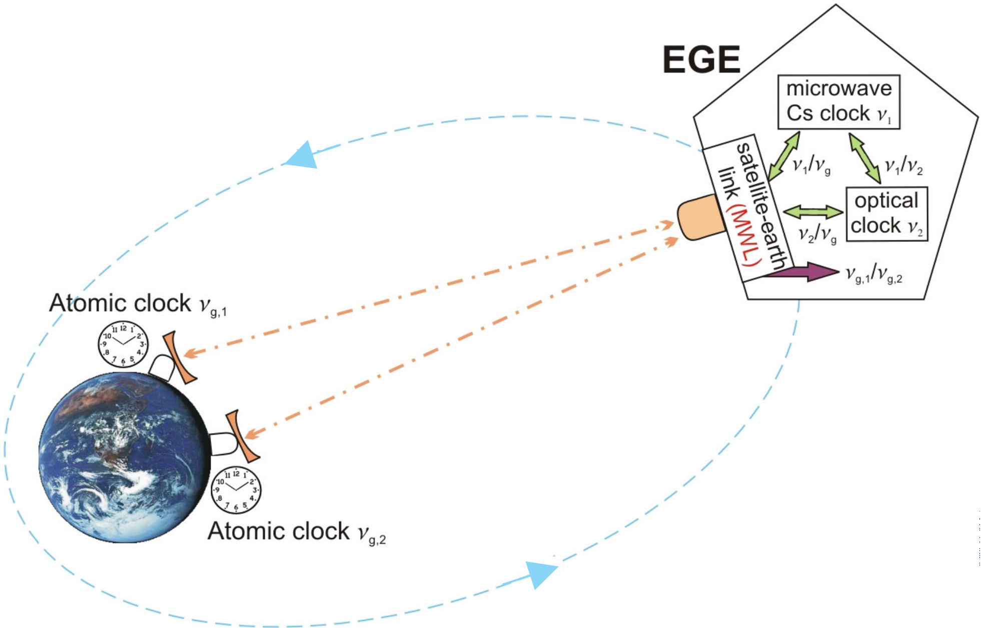
Class M Cosmic Vision proposal: Schiller, Tino, Gill, Salomon *et al.* (2007)

Scientific goals:

- Tests of fundamental physics (gravitation)
  (Gravitational redshift, variation of fundamental constants, Lorentz invariance + + + +)
- Spin-off to other fields
  (Determination of earth's geopotential, comparison of distant terrestrial clocks at the 10^{-18} level, technology demonstration)

Payload:

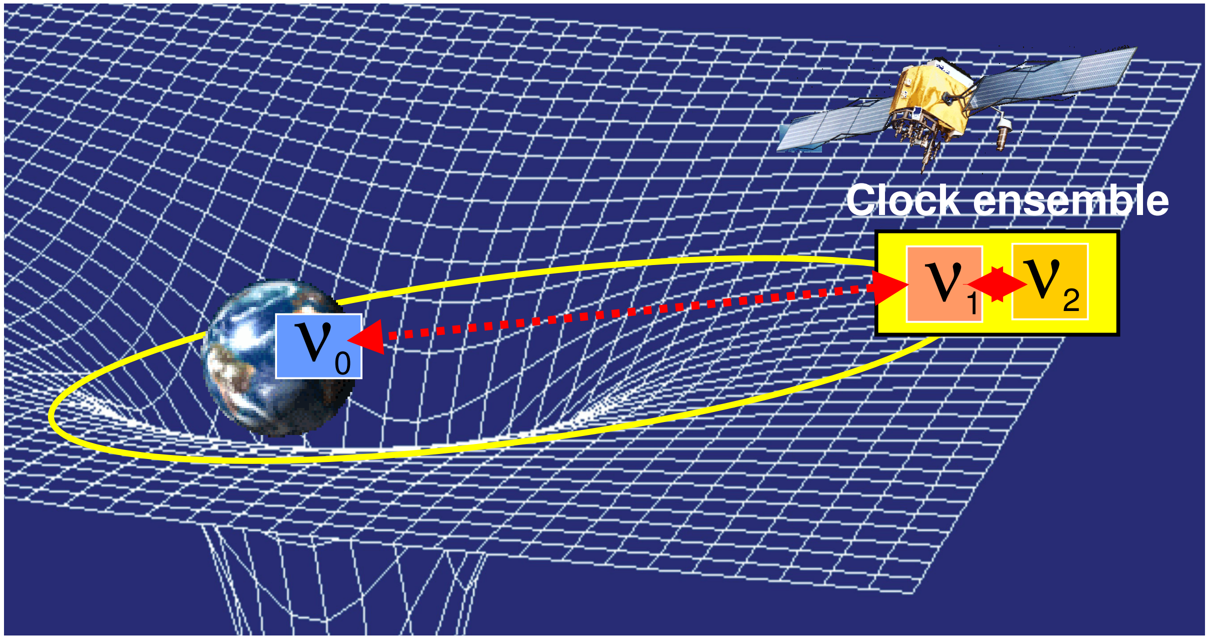
- Two atomic clocks
  (one optical, one microwave)
- Optical frequency comb
- Microwave link to earth



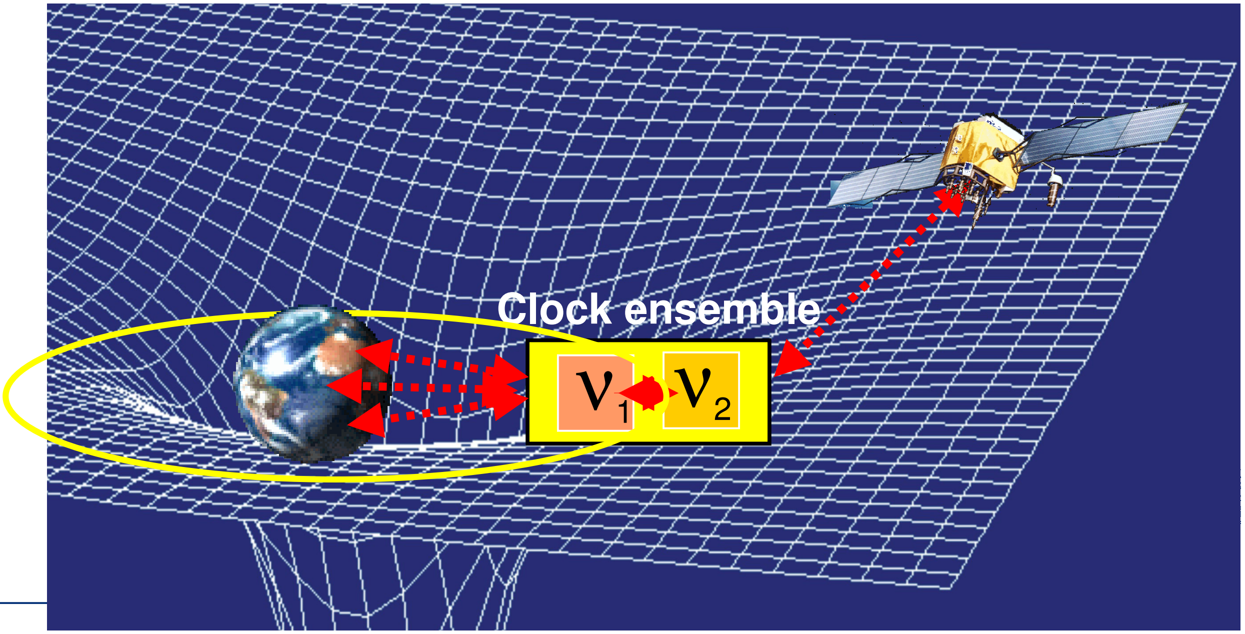
Possible EGE Mission Scenario

Schiller 2007

- Orbital phase I
  (~ 1 year duration,
  highly elliptic orbit)
  - Test of Local Position Invariance and of grav. redshift



- Orbital phase II
  (geostationary,
  several years duration)
  - Master clock for earth and space users
  - Geophysics



SAGAS (Search for Anomalous Gravitation using Atomic Sensors)

Class L Cosmic Vision proposal:
Wolf *et al*. (2007)

Scientific goals:

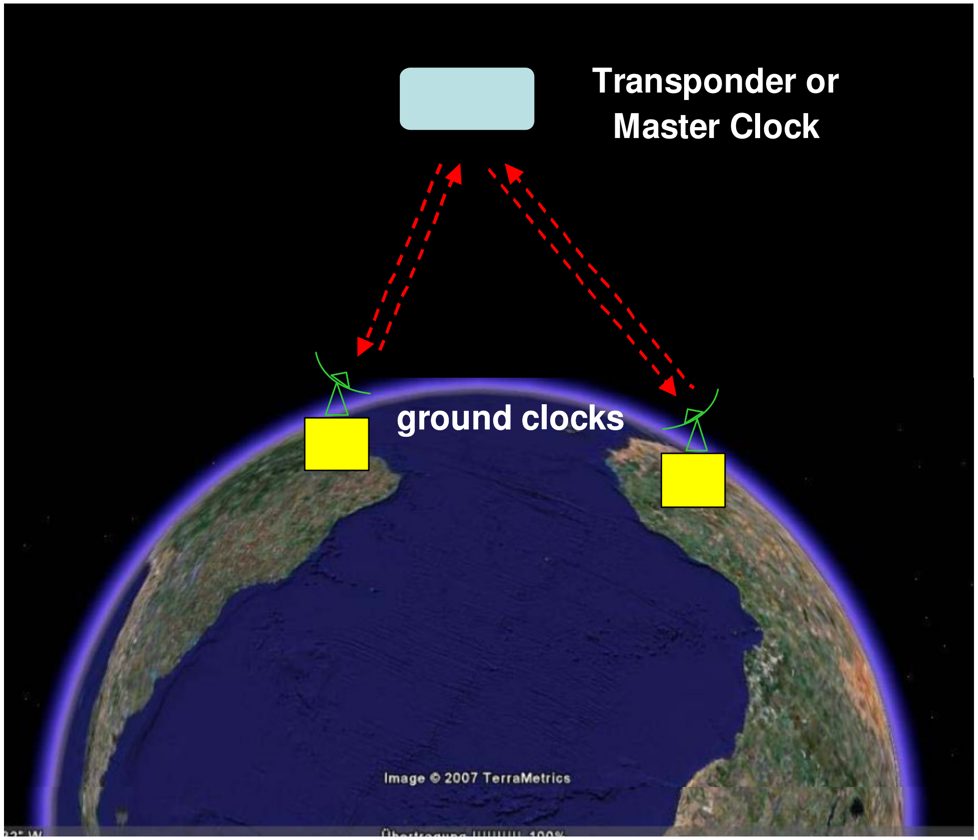
- Tests of fundamental physics (gravitation) in deep space
  (universality of gravitational redshift, local position invariance,
  parameterised post-Newtonian gravity, Pioneer anomaly,
  low frequency gravitational waves, variation of fundamental constants)
- Exploring the outer solar system
  (Kuiper belt mass distribution and total mass, planetary gravitational
  constant for Jupiter)

Payload:

- Trapped ion optical frequency standard
- Cold atom accelerometer
- Laser link for ranging, communication & frequency comparison

OAC benefits for Geoscience

Direct measurement of the earth’s geopotential with high resolution by using the gravitational redshift.



Comparison of ground clocks with 10^{-18} accuracy

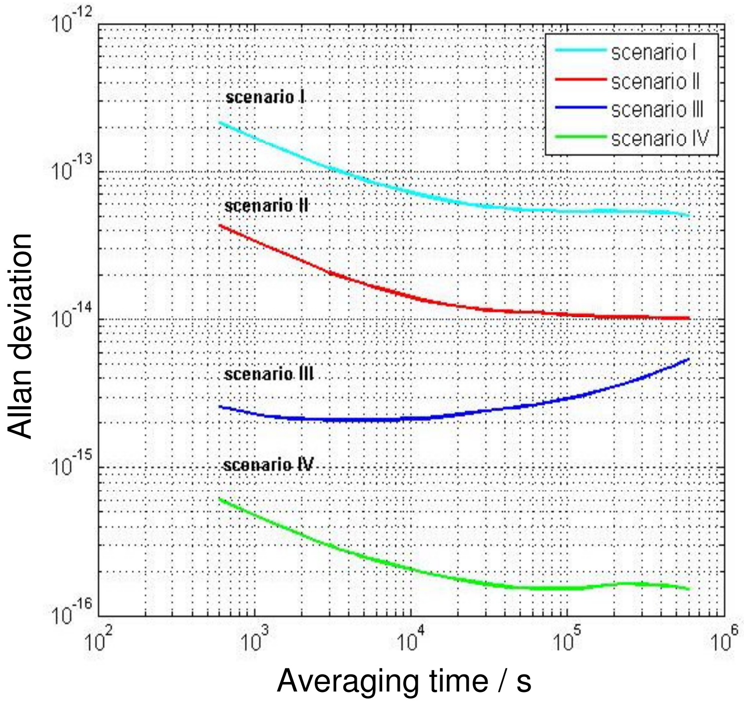
Measurement of potential differences with equivalent height resolution of 1 cm

Use of airborne clocks referenced to master should allow improved spatial resolution & faster data acquisition

Navigation: optical clocks for future GNSS

Benefits of using optical clocks in both satellite & ground segments:

- Improved timing / location resolution
- Improved integrity / autonomy of satellite segment
- Better correction for atmospheric and multi-path effects
- Improved time transfer

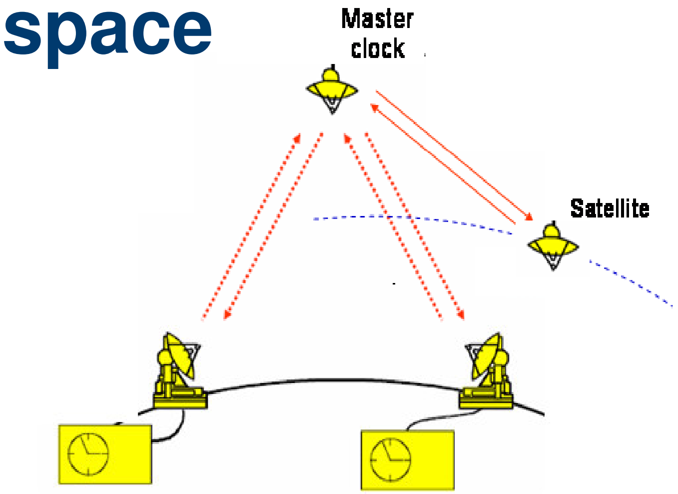


Scenario	Satellite time	System time	Theoretical error over 2 hours / ns
I	Rubidium clock	Optical clock	0.59
II	Passive maser	Optical clock	0.11
III	Optical clock	Active maser	0.14
IV	Optical clock	Optical clock	0.002

Simulations by Institute of Communications & Navigation (DLR)

ESA study contract 19837/06/F/VS

Optical “master” clock (OMC) in space

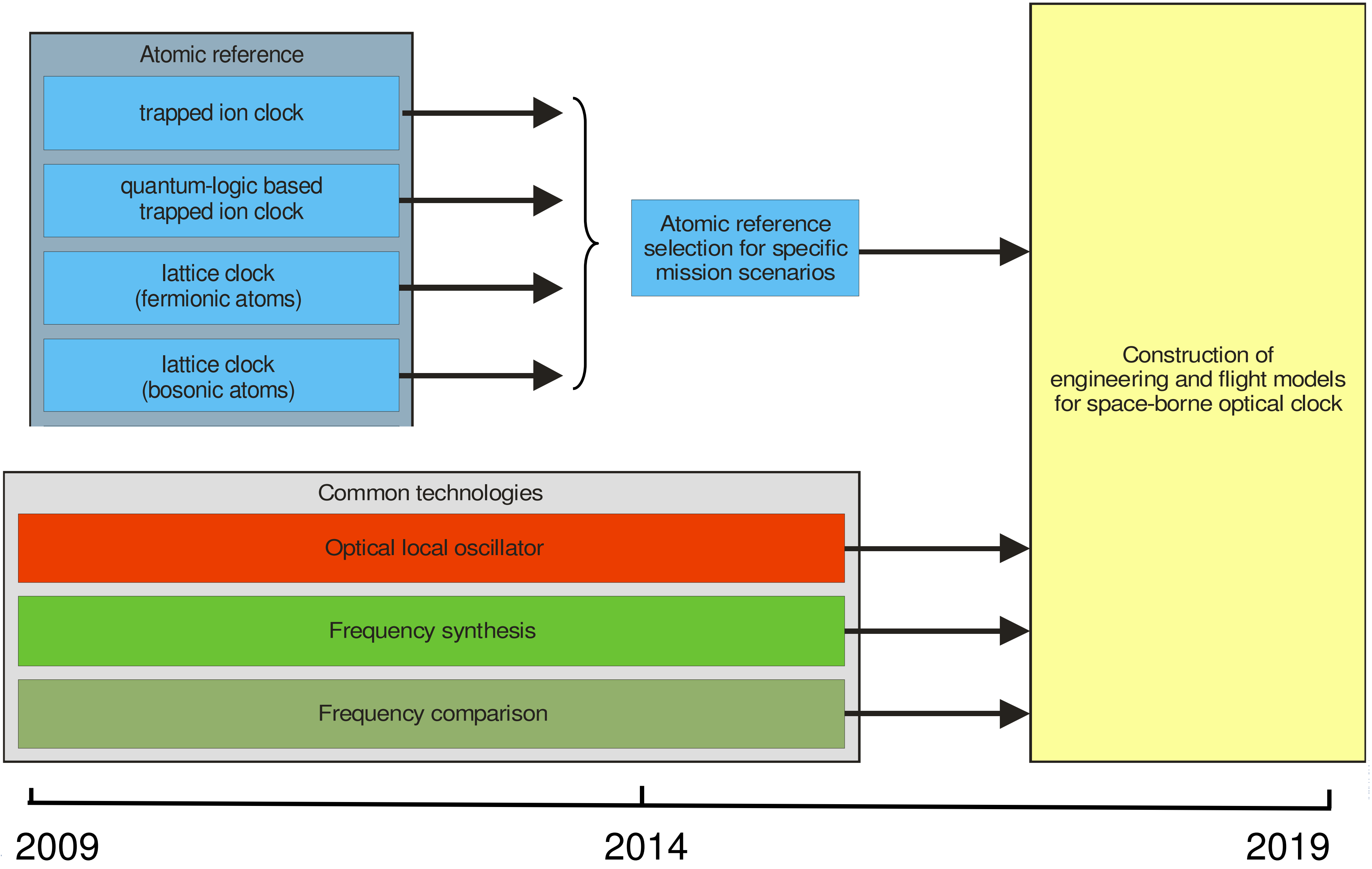


- Requirement for high accuracy (10^{-18} level) intercomparison of remote ground-based optical clocks
- ACES MWL target to approach 10^{-17} @ several days takes time
- Common-view comparison via optical master clock
- Geostationary orbit for ease of orbit determination and reduction of tracking requirements
- Altitude determination of master clock to 40 cm required for 10^{-18} accuracy (laser ranging sufficient)
- Also available as a clock reference for satellites in lower orbits

→ **OAC mission blueprint:**

Primary goal → Fundamental physics (Tests of GR eg EGE)
2nd ary goals → Geoscience (high spatial resn of geopotential)
→ GNSS (input to future GNSS architectures)
→ Optical master clock (high acc remote clock comparison)

Optical clock parallel-path technology development to reach TRL 5/6 by next CV call + 3 years



Atomic reference

trapped ion clock

quantum-logic based trapped ion clock

lattice clock (fermionic atoms)

lattice clock (bosonic atoms)

Atomic reference selection for specific mission scenarios

Common technologies

Optical local oscillator

Frequency synthesis

Frequency comparison

Construction of engineering and flight models for space-borne optical clock

2009

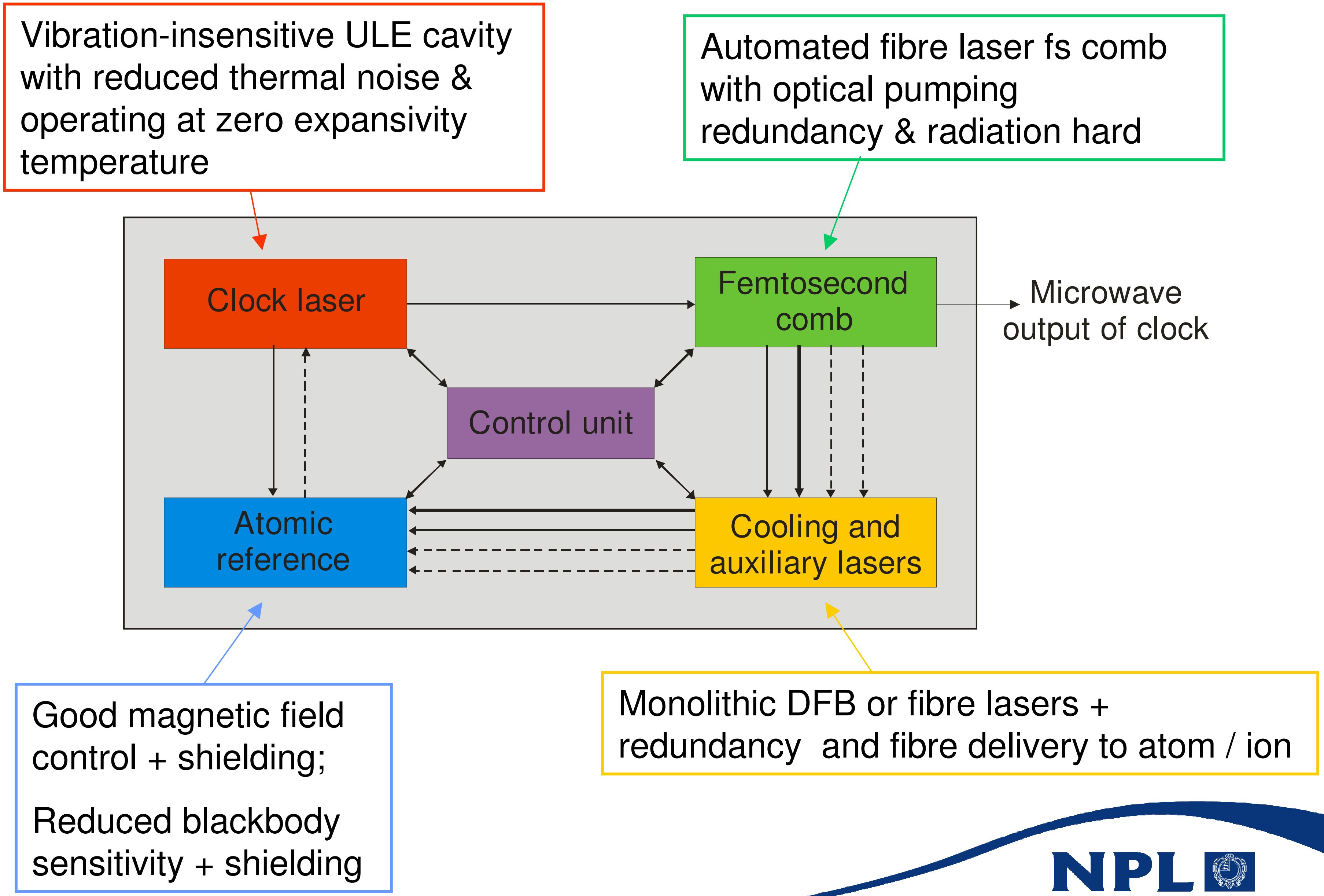
2014

2019

Benefits of a parallel track development

- Choice of particular clock may be mission dependent
- Better readiness for future Cosmic Vision calls
- Reduced time and improved efficiency to reach EM /FM
- Continuous improvement, benefiting technology development needed for missions
- Common technical sub-packages capable of wide application
- Spin-off to high profile ground-based science (eg time variation of fine structure constant; m_e/m_p)

Optical clock sub-unit technology requirements



Vibration-insensitive ULE cavity with reduced thermal noise & operating at zero expansivity temperature

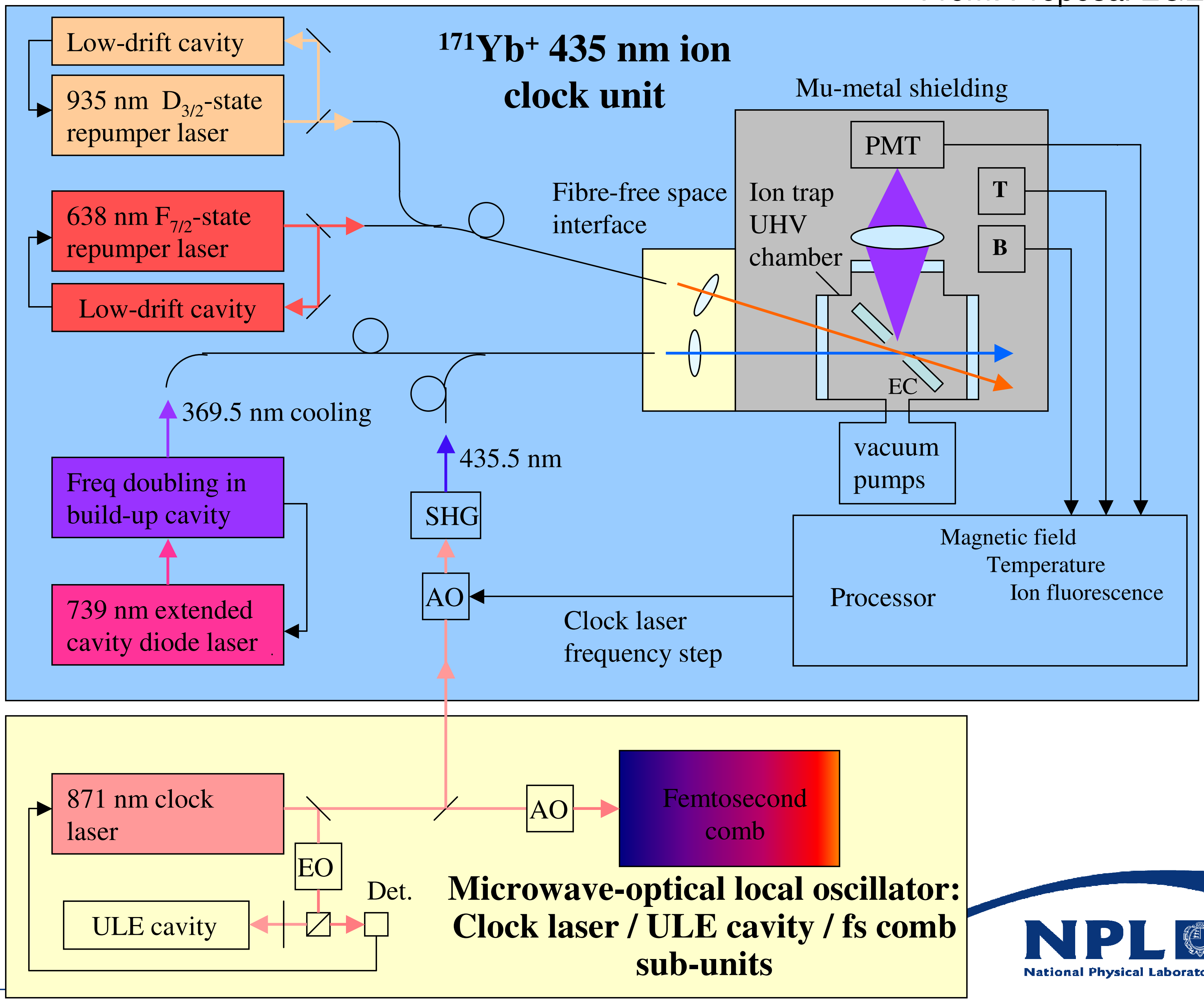
Automated fibre laser fs comb with optical pumping redundancy & radiation hard

Good magnetic field control + shielding;

Reduced blackbody sensitivity + shielding

Monolithic DFB or fibre lasers + redundancy and fibre delivery to atom / ion

From: Proposal EGE (2007)



^{171}Yb^{+} 435 nm ion clock unit

Low-drift cavity

935 nm $D_{3/2}$-state repumper laser

638 nm $F_{7/2}$-state repumper laser

Low-drift cavity

Fibre-free space interface

Mu-metal shielding

PMT

T

B

Ion trap UHV chamber

EC

vacuum pumps

369.5 nm cooling

Freq doubling in build-up cavity

739 nm extended cavity diode laser

435.5 nm

SHG

AO

Clock laser frequency step

Processor

Magnetic field

Temperature

Ion fluorescence

871 nm clock laser

EO

ULE cavity

Det.

AO

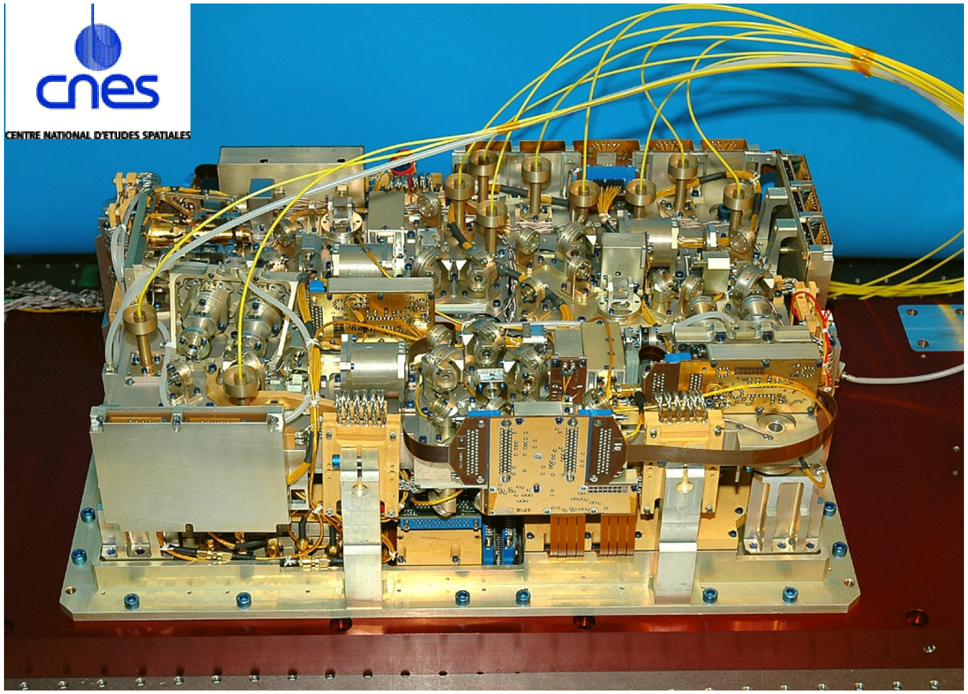
Femtosecond comb

Microwave-optical local oscillator: Clock laser / ULE cavity / fs comb sub-units

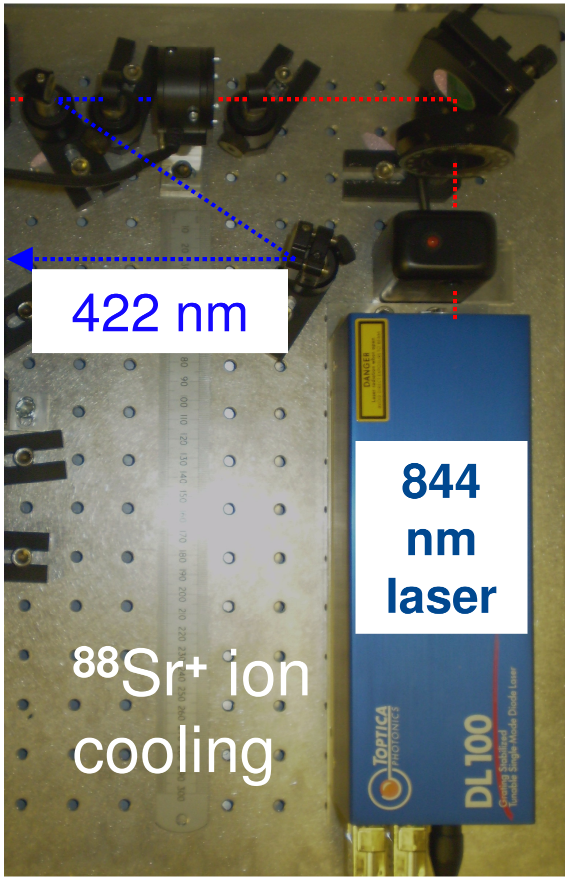
Laser cooling package

Potential for reduced package for ion clock: eg 1 ECDL + single pass doubling + aux DFBs + redundancy units

cf ACES development:
20 kg, 36 W, 30 liters
Air/vac operation, 10-35 ^{o}C

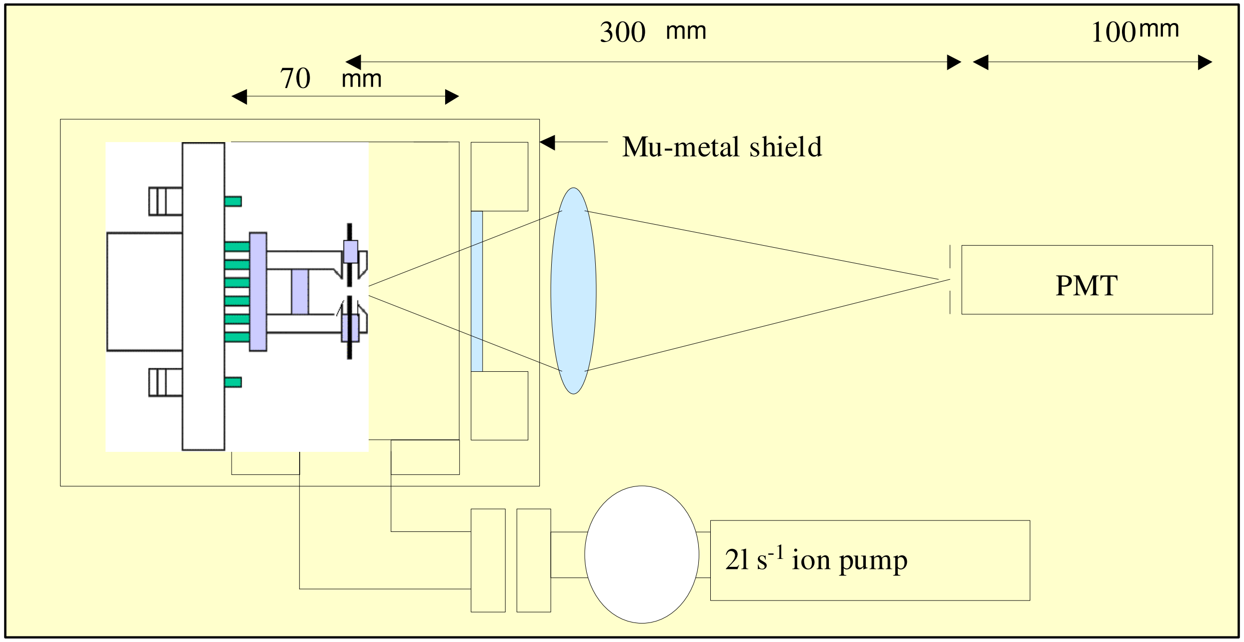


4 ECDL, 4 DL, 6 AOM, 30 PZT
11 motors, 6 photodiodes
8 peltier coolers



Single pass doubling in PPKTP
150 mW 844 nm diode →
0.5 mW of Sr^{+} 422 nm cooling light

Ion clock physics package

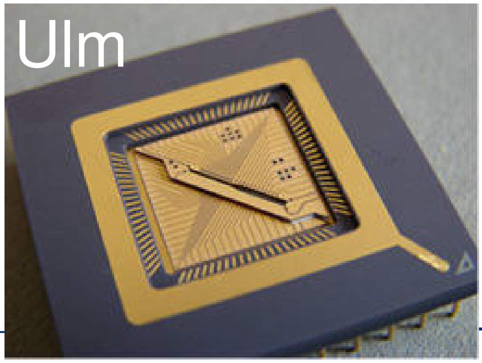


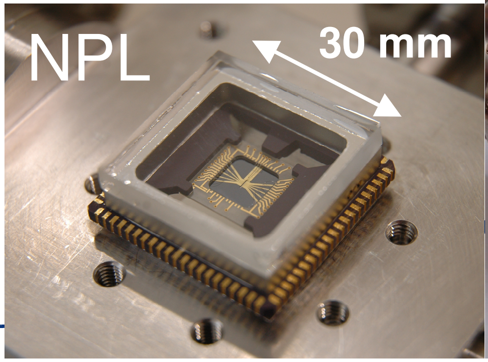
$^{88}Sr^{+}$ ion trap lab development ~ 10 litre volume

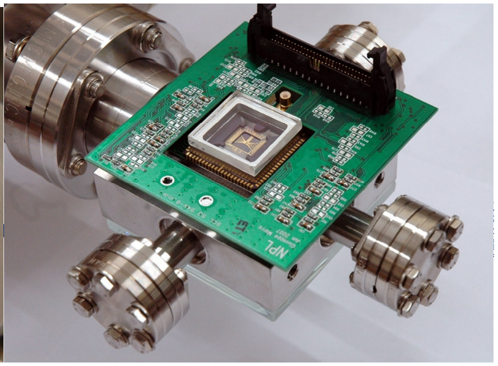
Microtrap development based on gold-coated ceramic wafers (Ulm) or gold-coated single silica-on-silicon wafer (NPL)

Microtrap

Information Society Technologies

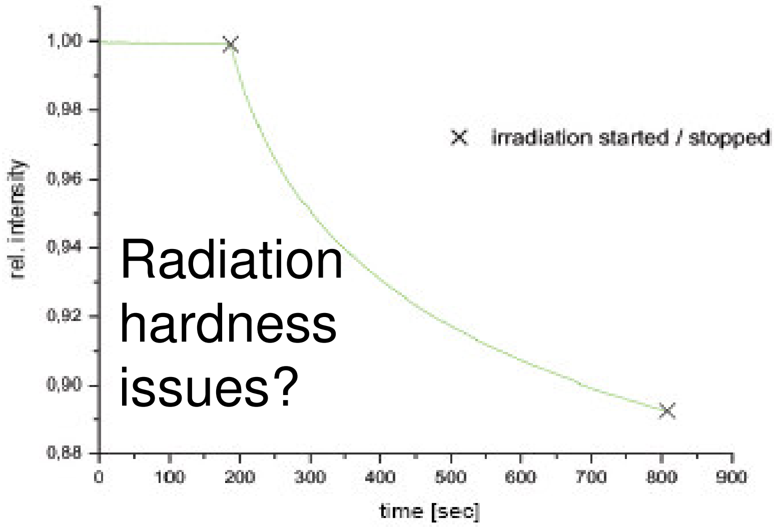






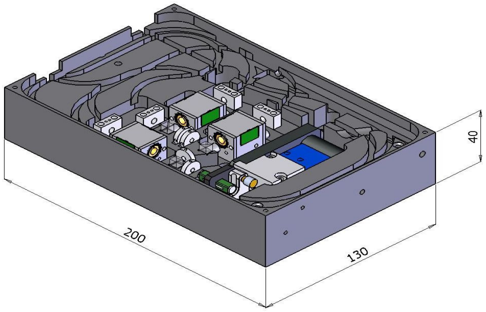
Femtosecond comb package

Transmissivity of an Er doped fibre (25 mm) irradiated with 2.6 MeV protons of a flux of 1.9 10^{11} protons / cm^2 s (from Predehl 2006).



Radiation hardness issues?

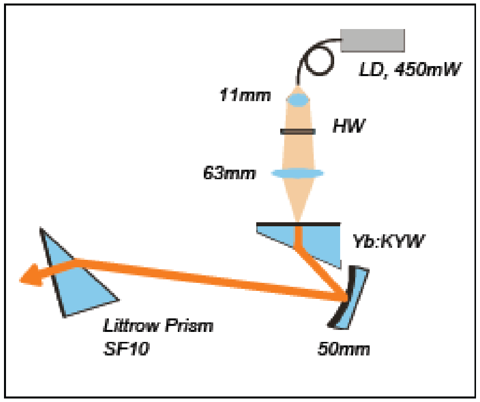
Commercial fibre-laser based comb



Space version: target vol 1 litre (200x130x40 mm), 5W power

Alternative high efficiency fs laser sources

A.A. Lagatsky et al, Opt. Express 12, 3928 (2004)



- Transform-limited 100fs over 1042-1075nm
- Average mode-locked power of 230mW at 294MHz
- *Optical-to-optical conversion efficiency is 53%*

OAC space clock issues

- Acceleration dependencies
- Influence of cosmic radiation
- Prolonged unattended & maintenance-free operation
- Mass, volume & power
- Operation in vacuum
- Internal spacecraft environment
- External perturbations

Type of optical clock	power (W)	Physics volume (litres)	Physics package mass	Support structure mass	Electronics mass	Total mass
Ion clock	60	50	50 kg	20 kg	30 kg	100 kg

Conclusion

- Proposal for a technology development programme
- managed through ESA TEC-MME Directorate
- involving development activities across the ESA research community in a co-ordinated way

→ Input to FPAG road-map construction

→ added resource (if successful) for ESA Science / Fundamental Physics strategy for optical clock-based future mission scenarios