Workshop on
"ADVANCES IN PRECISION TESTS AND EXPERIMENTAL GRAVITATION IN SPACE"
Arcetri, September 28-30, 2006

HEINRICH HEINE UNIVERSITÄT DÜSSELDORF

Proposal for a Gravity Explorer Satellite Mission

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Contents

- Overview
- Choice of optical clock types
- Some implementation considerations
- Progress on clocks and related topics in Düsseldorf

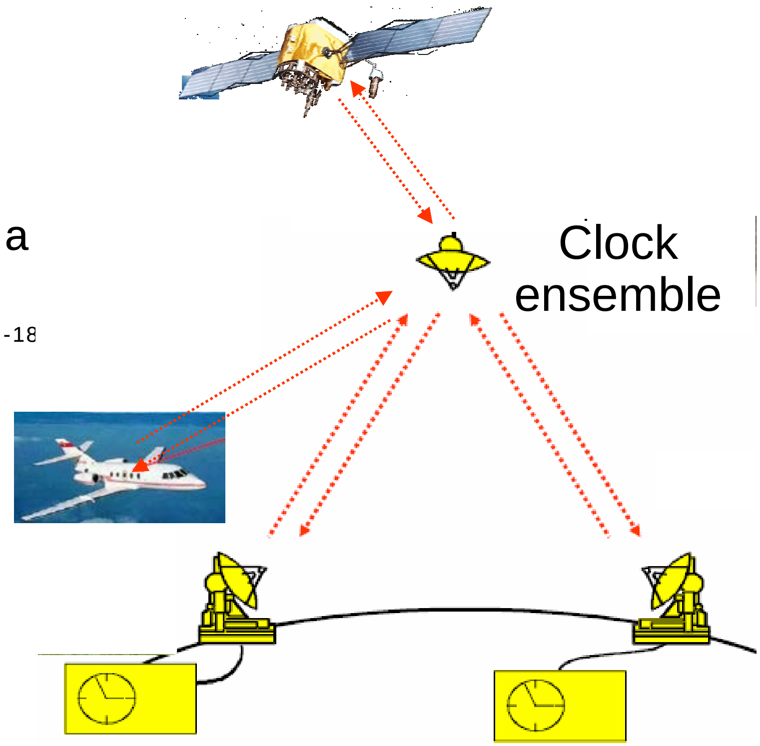
Introduction

Scope of a satellite mission:

- Explore Gravity:
  - Fundamental physics:
    - high precision test of fundamental aspects of General Relativity
    - search for new physics
  - Geophysics: Gravity field and elevation mapping
    - Clock comparison measures the difference in U
    - Map out U using movable clocks

- Time and frequency distribution on earth and in space („Master clock“):
  - Terrestrial use of future optical clocks requires a reference clock in a well-defined potential
    $\Delta U/U = 1 \cdot 10^{-9}$ (corresponds to $\Delta h = 1$ cm) results in $\Delta\nu/\nu = 1 \cdot 10^{-18}$
  - Precision navigation in space
  - Space-VLBI

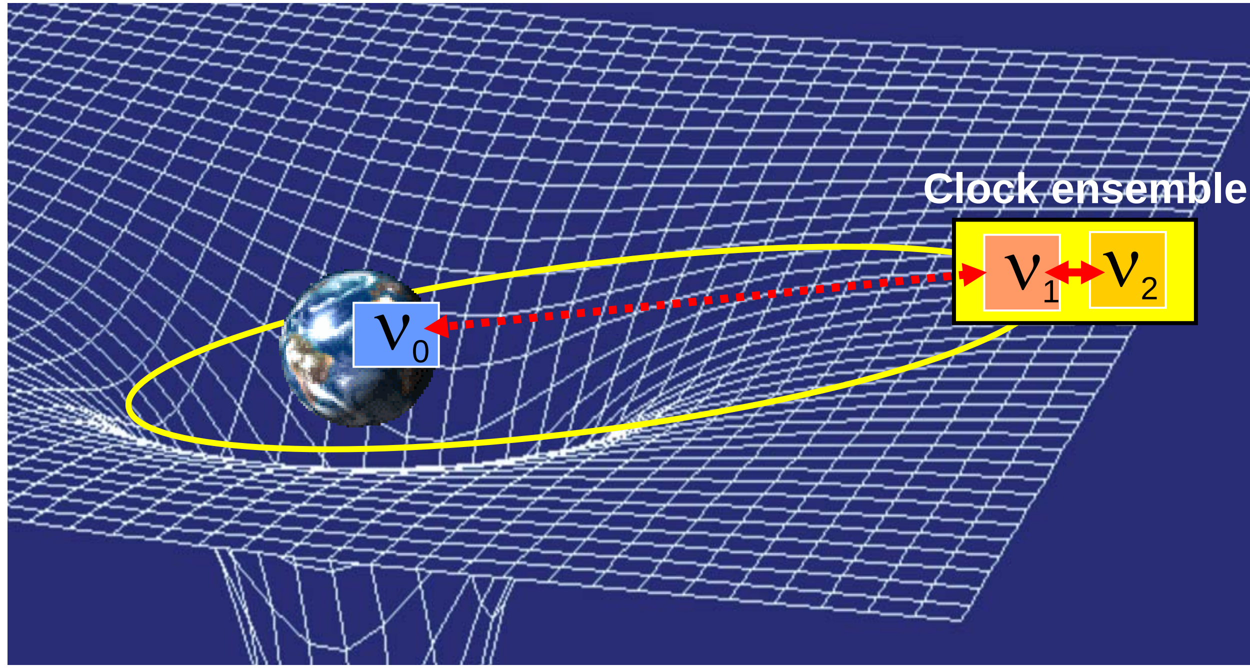
- Optical Link between distant clocks



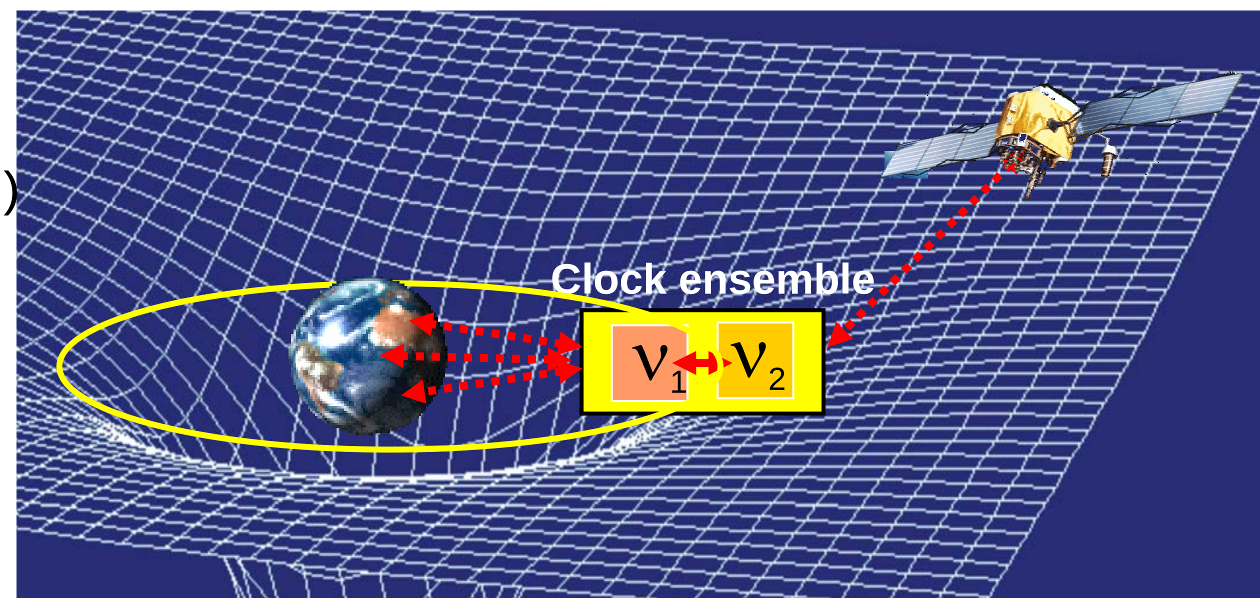
- Optical Clocks & Optical Metrology

Mission Scenario

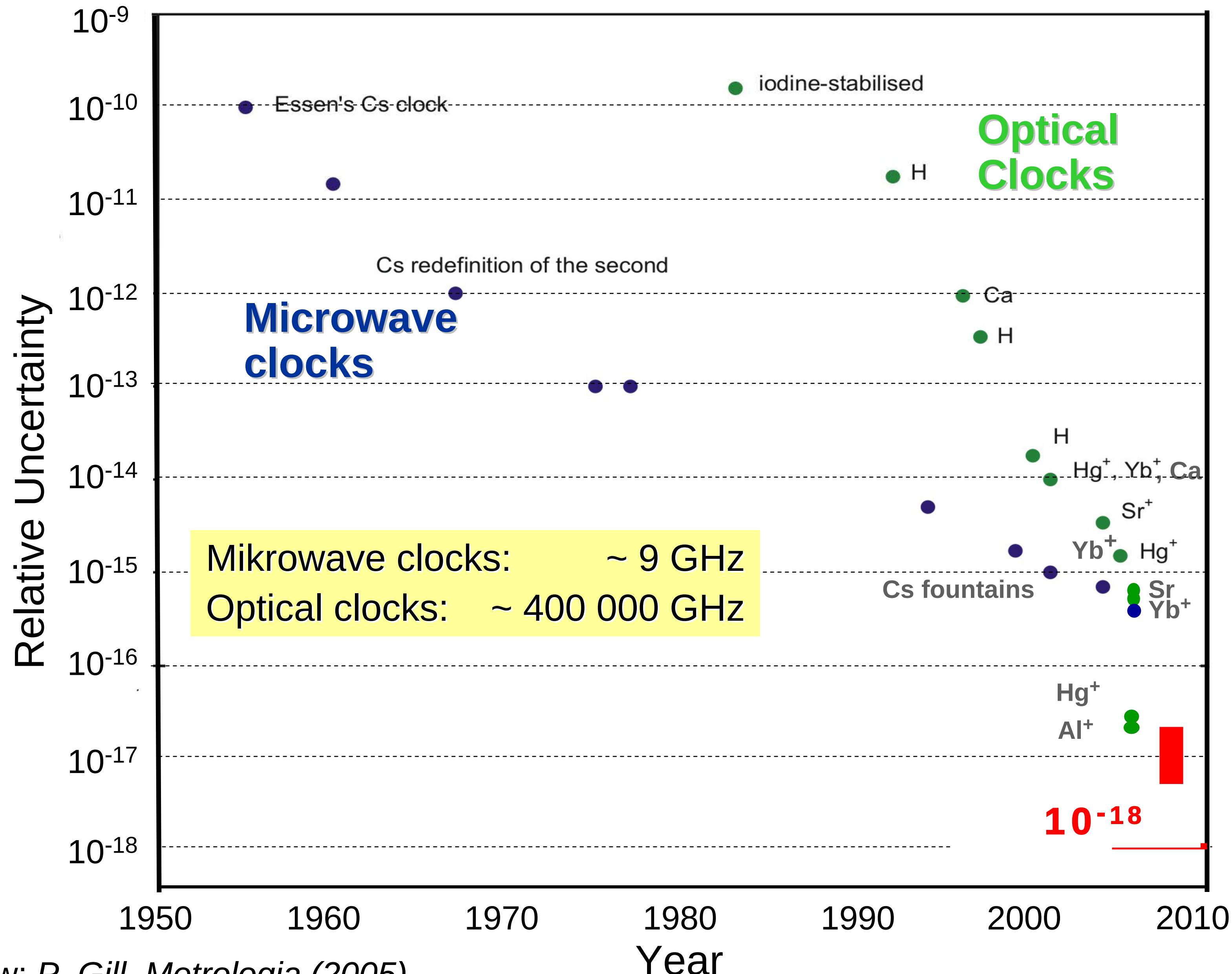
- Orbital phase I
  (~ 1 year duration,
  highly elliptic orbit)
  - Test of Local Position Invariance and of grav. redshift



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

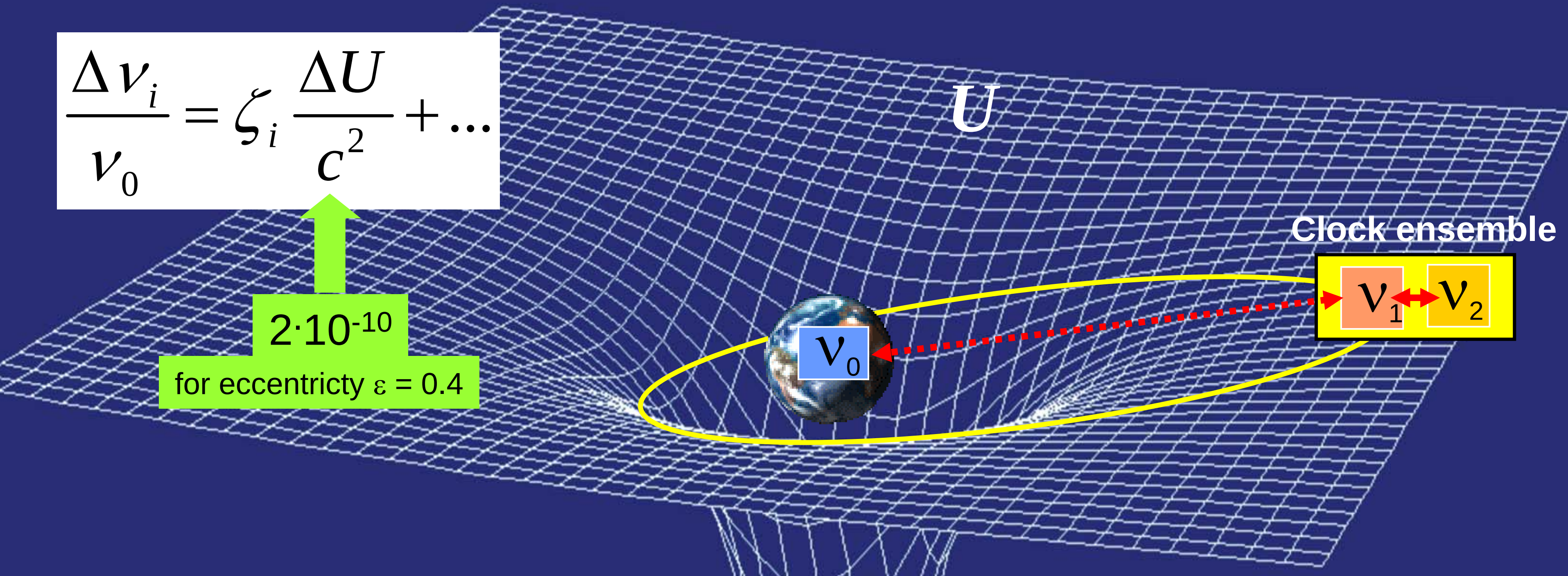


Optical Clocks



Review: *P. Gill, Metrologia (2005)*

Measurement of the Gravitational Redshift



- ➤ - **Absolute** gravitational redshift measurement
  - Test of higher-order relativistic corrections *(Linet & Teyssandier 2002, Blanchet et al 2001, Ashby 1998)*
  - Comparison with a ground clock *(via microwave/optical link)*
  - Requires precise orbit determination (laser ranging)

- ➤ - Gravitational redshift **universality** test: $\zeta_1 = \zeta_2$? (Test of Local Position Invariance)
  - Intercomparison of **dissimilar** on-board clocks

Gravity and its foundations

General Relativity

Gravitational redshift
Lense-Thirring effect
....

Metric theory of gravity

Einstein Equivalence Principle

Universality of Free Fall
(Weak equivalence princip.)

Local Position Invariance
(Universality of grav. Redshift constancy of constants)

Local Lorentz Invariance
(Special Relativity)

Fundamental Constants and Clocks

- Frequencies depend on fundamental constants

$$\nu_i = \nu_i(\alpha, m_e, m_N, g_N, \ldots)$$

- Gravitational redshift experiments test whether some of these constants β_j depend on the gravitational potential

$$\beta_j = \beta_j(U)? \quad \Rightarrow \quad \zeta_i = 1 + \sum_j \left(\nu_i^{-1} \frac{\Delta \nu_i}{\Delta \beta_j} \right) \left(\frac{d\beta_j}{d(U/c^2)} \right)$$

- The clock ensemble used for tests of LPI should contain clocks whose frequencies depend „strongly" on the fundamental constants

Fundamental Constants

- Some constants can be related to more fundamental constants:

$$m_p \propto \Lambda_{QCD} + corrections$$

Strong interaction

$$m_e \propto \langle \phi \rangle \quad = \quad Higgs\ vacuum\ \ field$$

Weak interaction

$$\frac{\Delta(m_N/m_p)}{m_N/m_p} = c_\alpha (\Delta\alpha/\alpha) + c_\phi \frac{\Delta(\langle\phi\rangle/\Lambda_{QCD})}{\langle\phi\rangle/\Lambda_{QCD}}$$

$$c_\alpha, c_\phi \ : \ O(10^{-3})$$

$$\frac{\Delta g_N}{g_N} = O(10^{-1}) \frac{\Delta(m_q/\Lambda_{QCD})}{m_q/\Lambda_{QCD}} + O(10^{-2}) \frac{\Delta(m_s/\Lambda_{QCD})}{m_s/\Lambda_{QCD}}$$

Flambaum and Tedesco 2006

Optical Clocks and Fundamental Constants

- Scaling of transition energies (in units of Rydberg energy)
  - Electronic energies (incl. relativistic effects) $G(\alpha)$ →

	$(\Delta\hat{\nu}/\hat{\nu})/(\Delta\alpha/\alpha)$
Yb:	0.31
Sr:	0.06
Yb$^+$:	(0.9, - 5.3)

  - Vibrational energies in molecules $\sqrt{m_e/m_N}$

    e.g. Hilico et al. 2000, S.S. and Korobov 2005

  - Hyperfine transition in hydrogenlike highly charged ions $Z^3 g_N \frac{m_e}{m_p} F(\alpha)$

    (S.S., TCP 2006)

  - Nuclear transition

    (Peik and Tamm 2003, Flambaum 2006)

$$\frac{\Delta\nu}{\nu} = O(10^5)\left(4\frac{\Delta\alpha}{\alpha} + \frac{\Delta(m_q/\Lambda_{QCD})}{m_q/\Lambda_{QCD}} - 10\frac{\Delta(m_s/\Lambda_{QCD})}{m_s/\Lambda_{QCD}}\right)$$

Clock choice

- A comparison of an atomic optical clock to a molecular optical clock is (within the Standard Model) sensitive to several fundamental constants:

$$\frac{\Delta(\nu_{at}/\nu_{vib})}{\nu_{at}/\nu_{vib}} = O(1)\frac{\Delta\alpha}{\alpha} + O(1)\frac{\Delta(m_e/\Lambda_{QCD})}{m_e/\Lambda_{QCD}} +$$

$$O(10^{-1})\frac{\Delta(m_q/\Lambda_{QCD})}{m_q/\Lambda_{QCD}} + O(10^{-2})\frac{\Delta(m_s/\Lambda_{QCD})}{m_s/\Lambda_{QCD}}$$

- In gauge unification theories the time variations of α and m_e/Λ_{QCD} are correlated *(Damour 1999, Langacker et al, Calmet & Fritzsch, 2002)*

$$\frac{\partial_t(m_e/\Lambda_{QCD})}{m_e/\Lambda_{QCD}} \sim 40\frac{\partial_t\alpha}{\alpha}$$

- Optimum clock choice may be different for the two proposed applications:
  - For LPI test and redshift measurement, stability on timescale of ~ 10 h is relevant
  - For Master Clock use, accuracy and long-term stability are also important

Ultracold Molecule Clocks

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Proposals: U. Fröhlich et al. Lect. N. Phys. ***648****, 297 (2004)*
S.S. and V. Korobov, PRA ***71****, 032505 (2005)*

- For precision spectroscopy, ultracold, trapped molecules are necessary

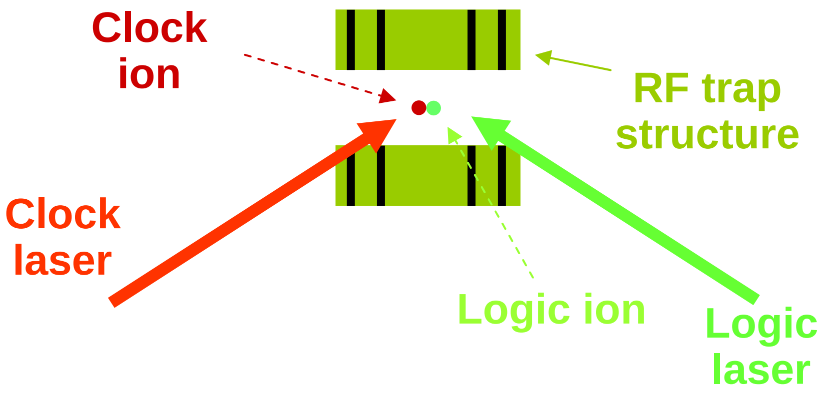
  - reduces various line broadening mechanisms
  - allows best control over and characterization of systematic effects

- Rapid progress of the field *(e.g. Special Issue J. Phys. B 2006)*
  - Ultracold neutral diatomic molecules produced by photoassociation from ultracold atoms
  - Trapping in an optical lattice demonstrated *(e.g. Rom et al. 2004)*
  - Molecular ions have been cooled and trapped by sympathetic cooling *(Aarhus/Düsseldorf)*
  - Cold Neutral dipolar molecules have been trapped in electric/magnetic traps *(Rhinhuizen/Berlin/München/Boulder)*
- Cold molecular clock performance could reach levels similar to atomic clocks
  - Their development will profit from optical atomic clock developments

Quantum logic ion clocks

P. Schmidt et al. (2005)

- Uses a laser-coolable „logic“ ion and a „clock“ ion, a few µm apart
- Clock ion is sympathetically cooled
- No laser cooling of clock ion is required, therefore greatly extends variety of usable clock ions
- Spectroscopy uses coherence - no fluorescence of clock ion occurs
- Should be applicable to molecular ions as well



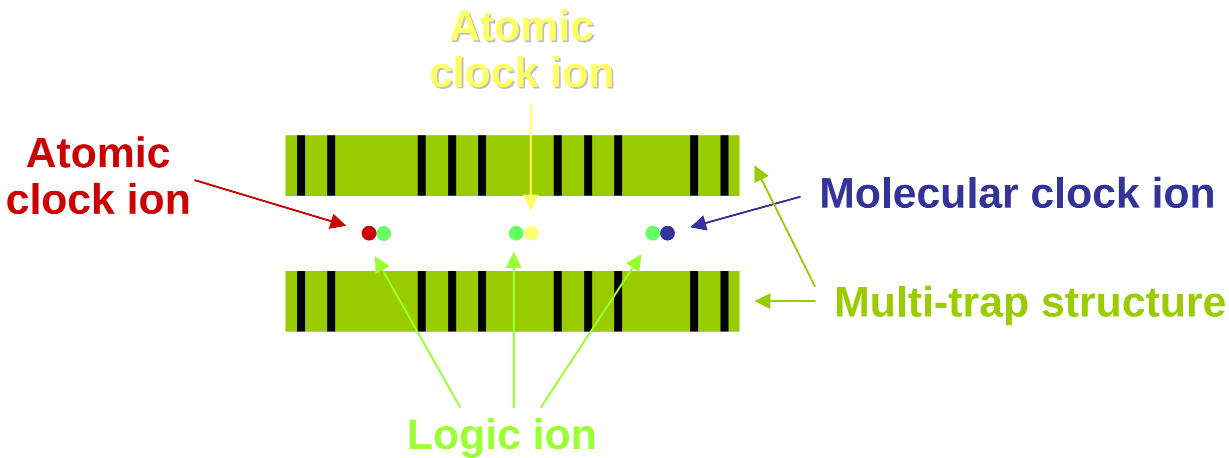
NIST Be^+ / Al^+ clock status (TCP 2006)

Inaccuracy: $2.3 \cdot 10^{-17}$

Instability: $7 \cdot 10^{-15}\, \tau^{-1/2}$ $(1 < \tau < 10^4$ s$)$

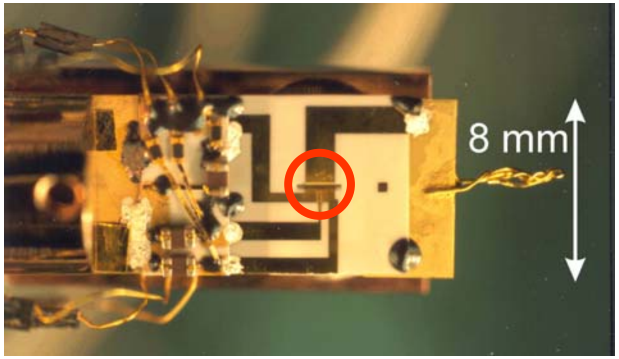
A multispecies ion trap clock for a satellite experiment

- Double/Triple ion trap clock



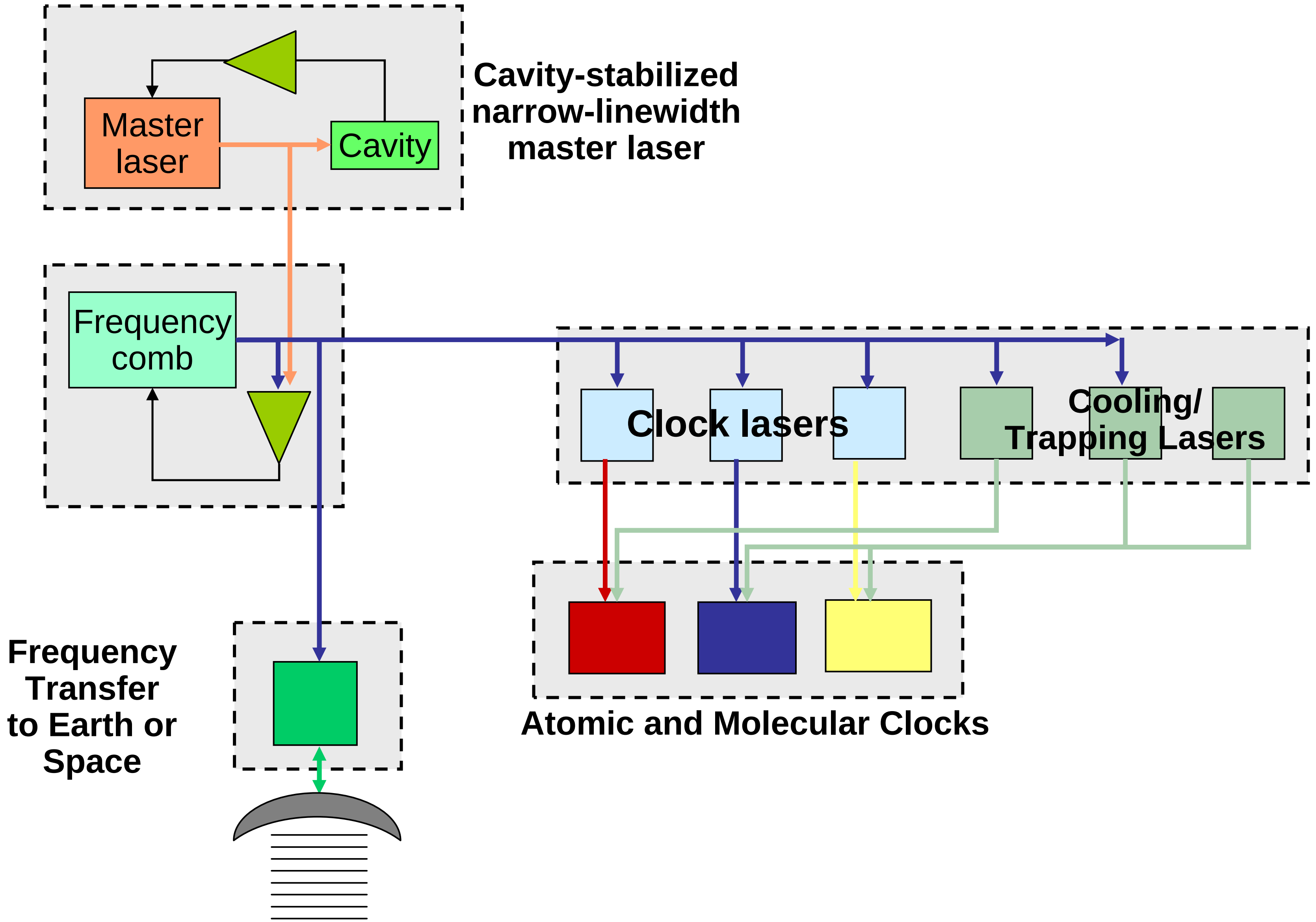
- Suitable logic ions: Be^+, Mg^+ , Yb^+, Ca^+
- Clock ions: e.g. Al^+ , Yb^+, suitable molecular ions

- Ion trap technology will be pushed strongly by quantum computing applications



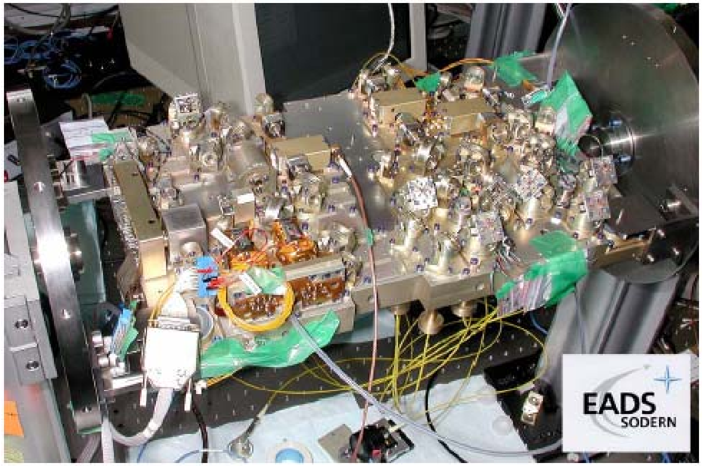
NIST

Satellite payload concept



Space suitability

- **Important optical clock components are already space-qualified**
  - Single-frequency diode lasers (PHARAO)
  - Ultracold atom sources (PHARAO)
  - Opto-electronic components
  - Solid-state lasers and amplifiers (TESAT Spacecom)
  - Optical resonators (TESAT Spacecom)
  - Phase-locking (TESAT Spacecom)



Mass 22 kg, power 65 W

- **PHARAO, LISA to be flown ca. 2009**
- **Studies toward space qualification and space uses of frequency combs are under way** (DLR, ESA)
- **High-precision time transfer between satellites and earth to be tested in upcoming missions** (ACES on ISS, T2L2 on JASON 2)
- **Optical link experiments** (LCT TerraSAR, LOLA,...)
- **Necessary developments:**
  - Ultrastable lasers (cavities + sources), atomic sources
  - Transportable cold atom optical clocks
  - Earth-Ground Time/Frequency transfer with strongly improved performance

Yb lattice optical clock

A. Görlitz, A. Nevsky, A. Wicht, S. S.
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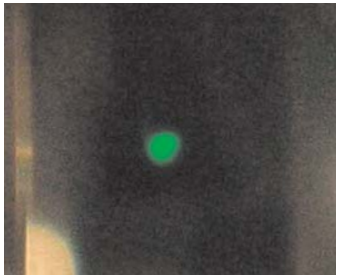
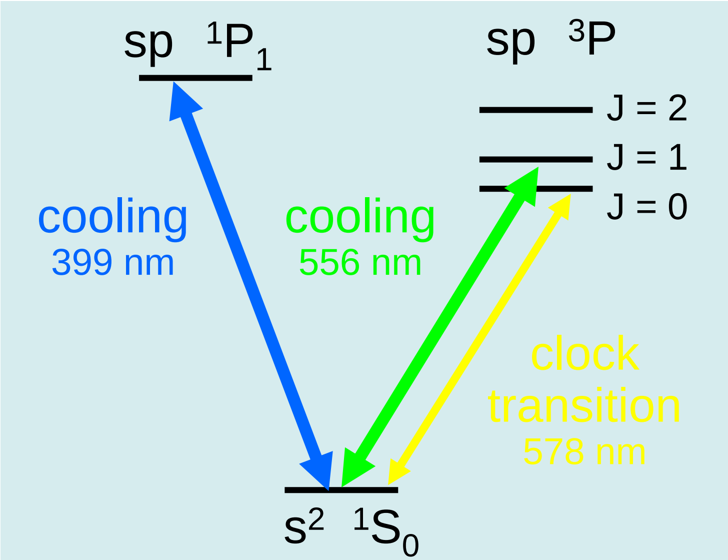
- **First stage cooling to ~ 2 mK**
- **Second stage cooling on weak transition**

10^7
^{174}Yb Atoms
at 60 µK in MOT

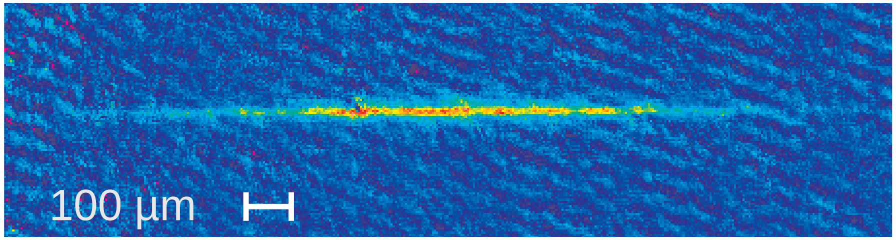




- **Reliable cooling of fermion (^{173}Yb) and boson (^{174}Yb) isotopes**

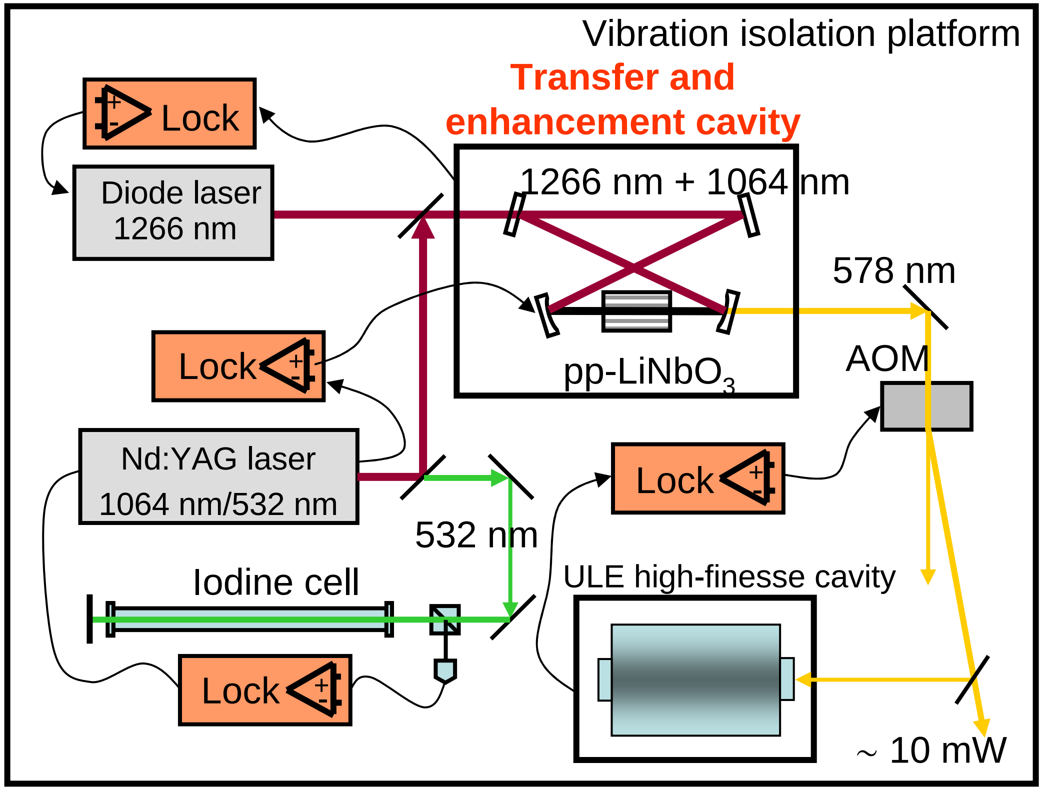
- **Optical trapping**
  - **Uses 532 nm laser so far (later: magic wavelength)**
  - **2 % transfer efficiency from MOT to optical trap, 1 s cycle time**
  - **Initial temperature ~ 100 µK**
  - **100 s life time of atoms in trap**
  - **Evaporation leads to 30 µK within a few seconds**
  - **Forced evaporation leads to ~ 1 µK at 10^4 atoms**

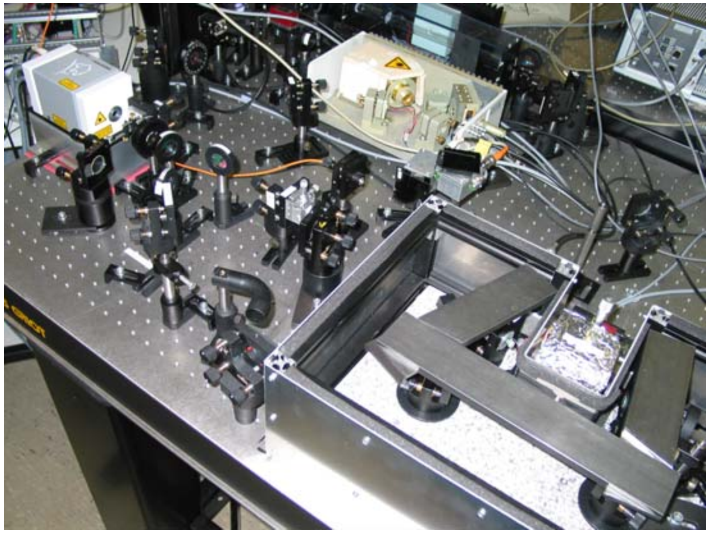
2.10^5
^{174}Yb atoms
at 40 µK
in optical trap

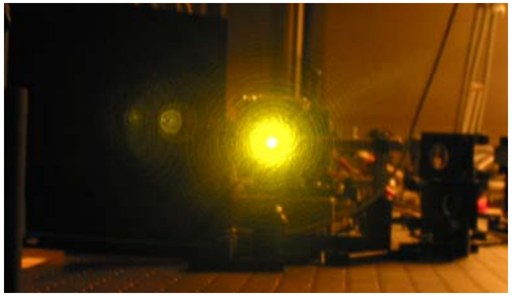


578 nm Yb clock laser development

- Based on cw sum-frequency generation
- Nd:YAG laser and diode laser stabilized to I_2 with kHz-level instability
- 10 mW power
- Transportable setup
- Further stabilization to ULE cavity is planned

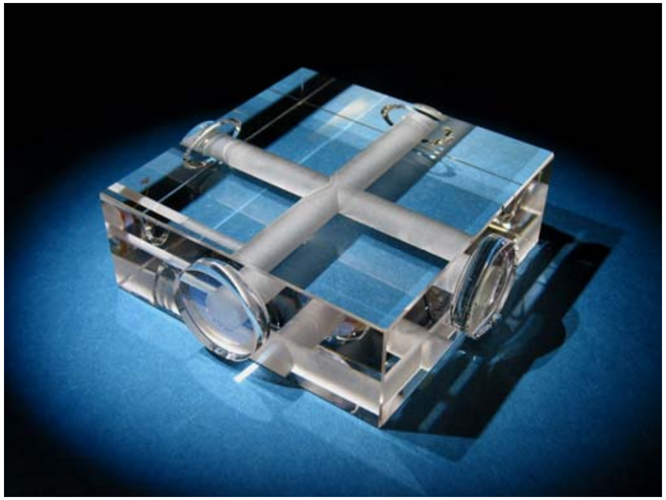




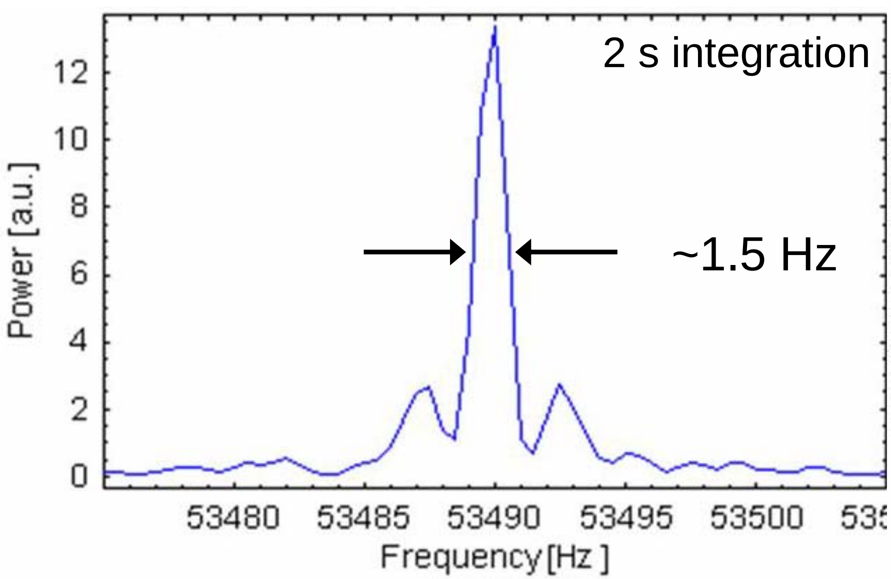


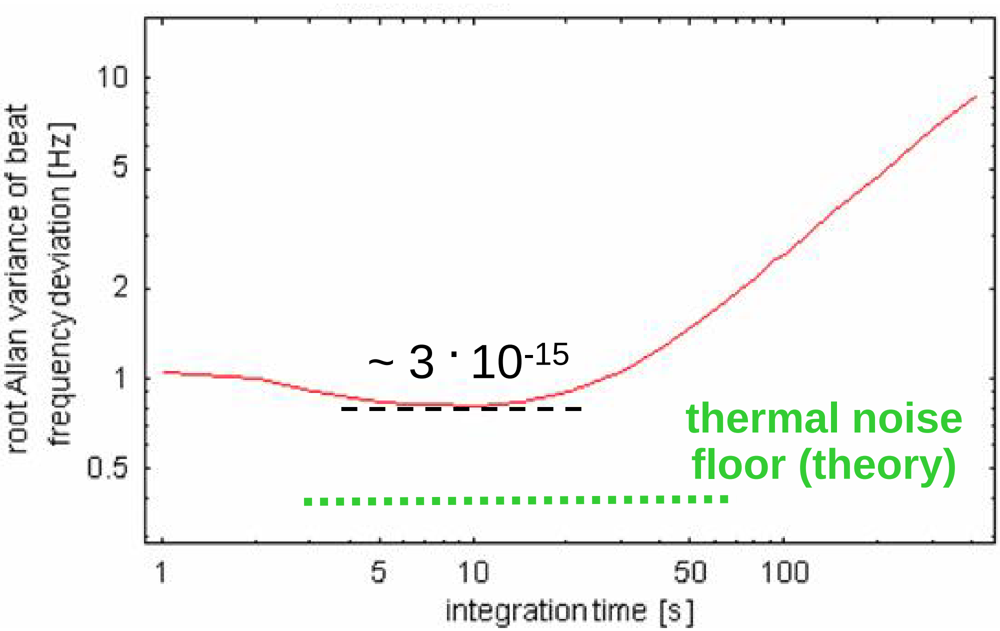
Laser stabilization techniques

- Technology development:
  - Nd:YAG laser (1064 nm)
  - ULE dual-cavity block
  - Low-frequency FM lock
  - Towards transportability
  - Uses active vibration isolation



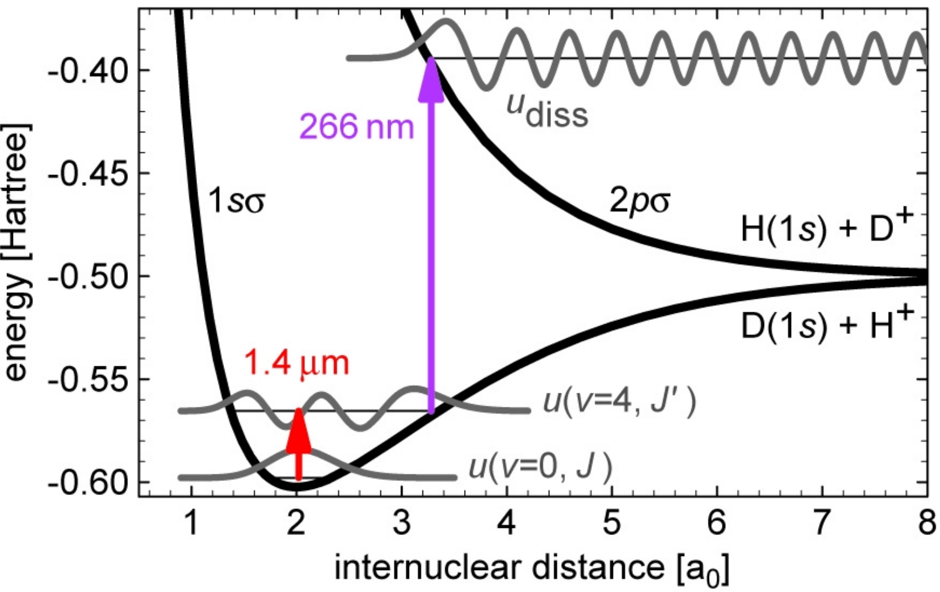
S. S. et al, 2005





Ro-vibrational spectroscopy of HD^+

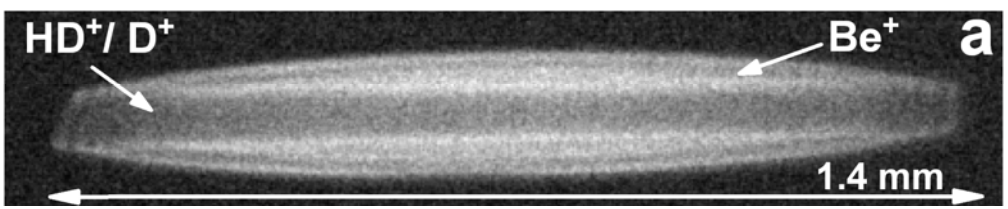
*Blythe et al., PRL **95**,183002 (2005); B. Roth et al., to appear in Phys. Rev. A*



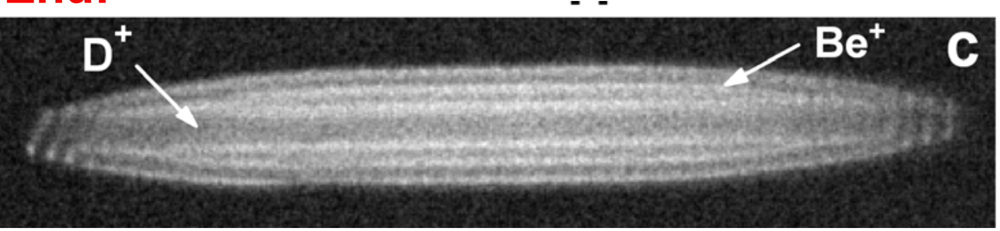
- **Dipole-allowed transitions**
- ***v* = 0 to *v* = 4 overtone transition is accessible to diode laser**
- **Long lifetime ~ 10 ms**
- **No detectable fluorescence**

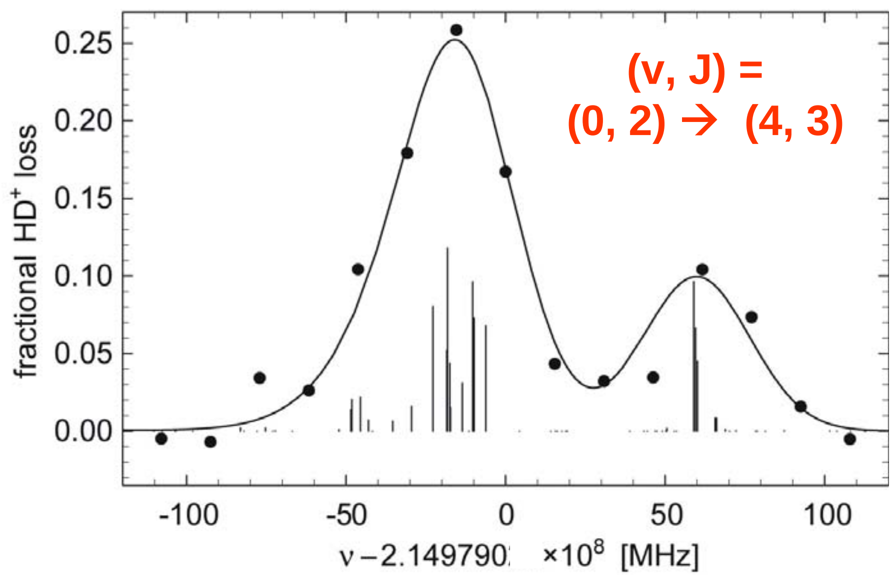
→ **uses state-selective photodissociation and measurement number of remaining HD^+ ions**

Beginning:



End:





Frequency measurements

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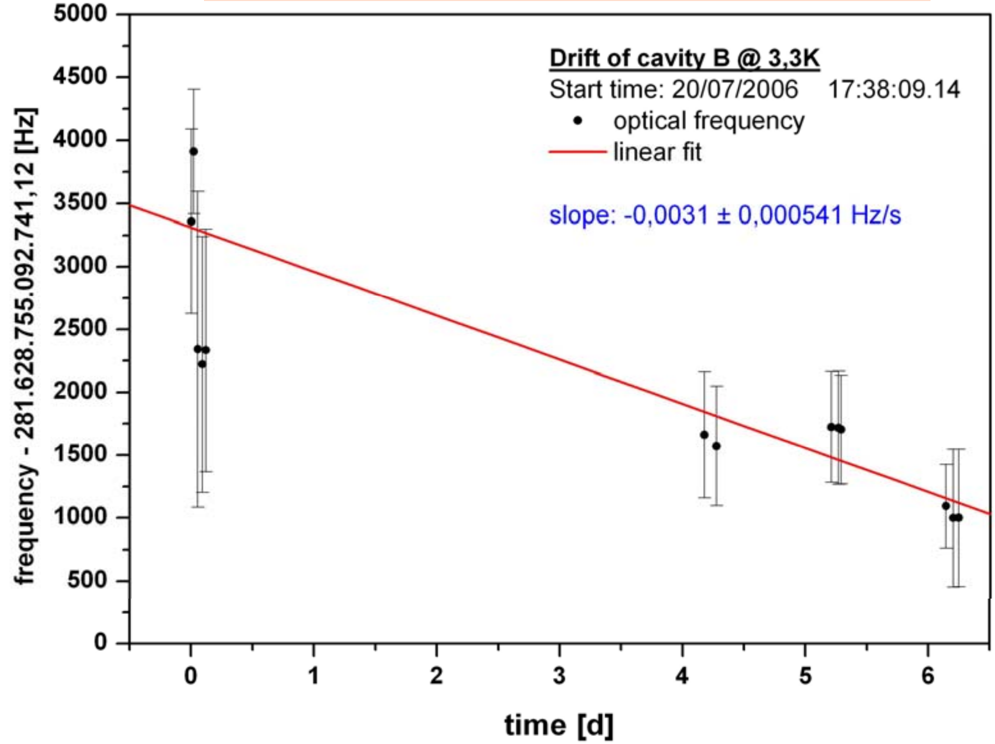
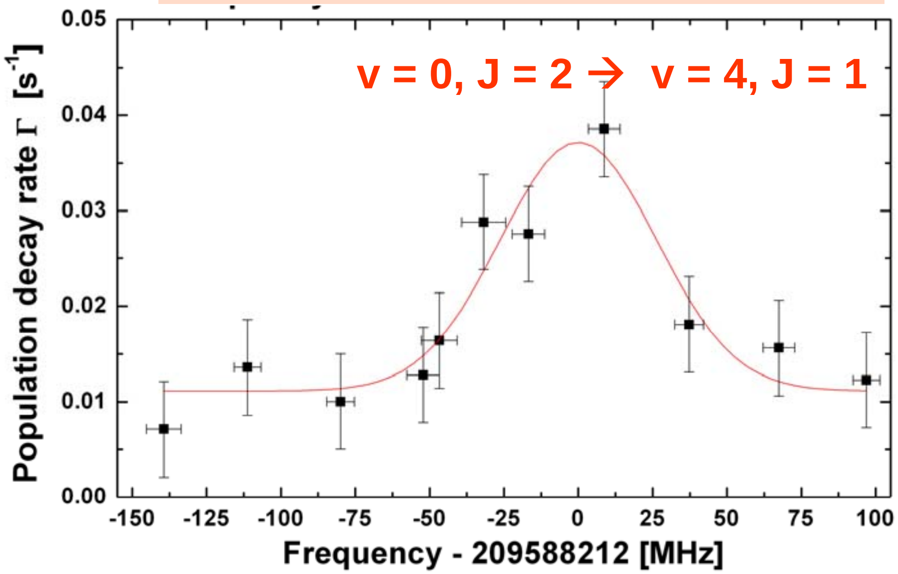
- Ti:Sapphire frequency comb, referenced to H-maser and GPS
- Fiber for extension to 1.4 µm range (measurements on cold molecules)

Cryogenic optical cavity vs. H - maser



HD^+ absolute frequency



Summary

S.S. et al. arxiv:gr-qc/0608081

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- **Fundamental physics goals:**
  (using clocks/links with 10^{-18} instability/accuracy)
  - Measure gravitational redshift with ~ 10^4 higher accuracy
  - Test higher-order relativistic effects in frequency comparison
  - Measure 2nd order Doppler effect with ~ 10^2 higher accuracy
  - Test independence of fine structure constant α on U with 10^2 higher accuracy*
  - Test independence of m_e/m_p on U with 10^2 higher accuracy*
  - **Additional possibilities**
    - With drag-free satellite, measure Lense-Thirring effect and perigee advance, ~10 times more accurately
    - Contribution to tests of time-independence of fundamental constants
    - Test of isotropy of speed of light (requires rotating satellite)
    - Other Local Lorentz Invariance tests
- **Gravity mapping**
  - Enable gravitational potential measurements at 2.10^{-10} resol4t56n (1 mm equiv.); requires clocks of 10^{-19} accuracy
- **Master clock for earth and space applications**
- **Enable distant ground clock comparisons**
- **Technology demonstration and validation**

*compared to future terrestrial experiments