Precision Atomic Optics at the IQ - Perspectives in applied & fundamental sciences

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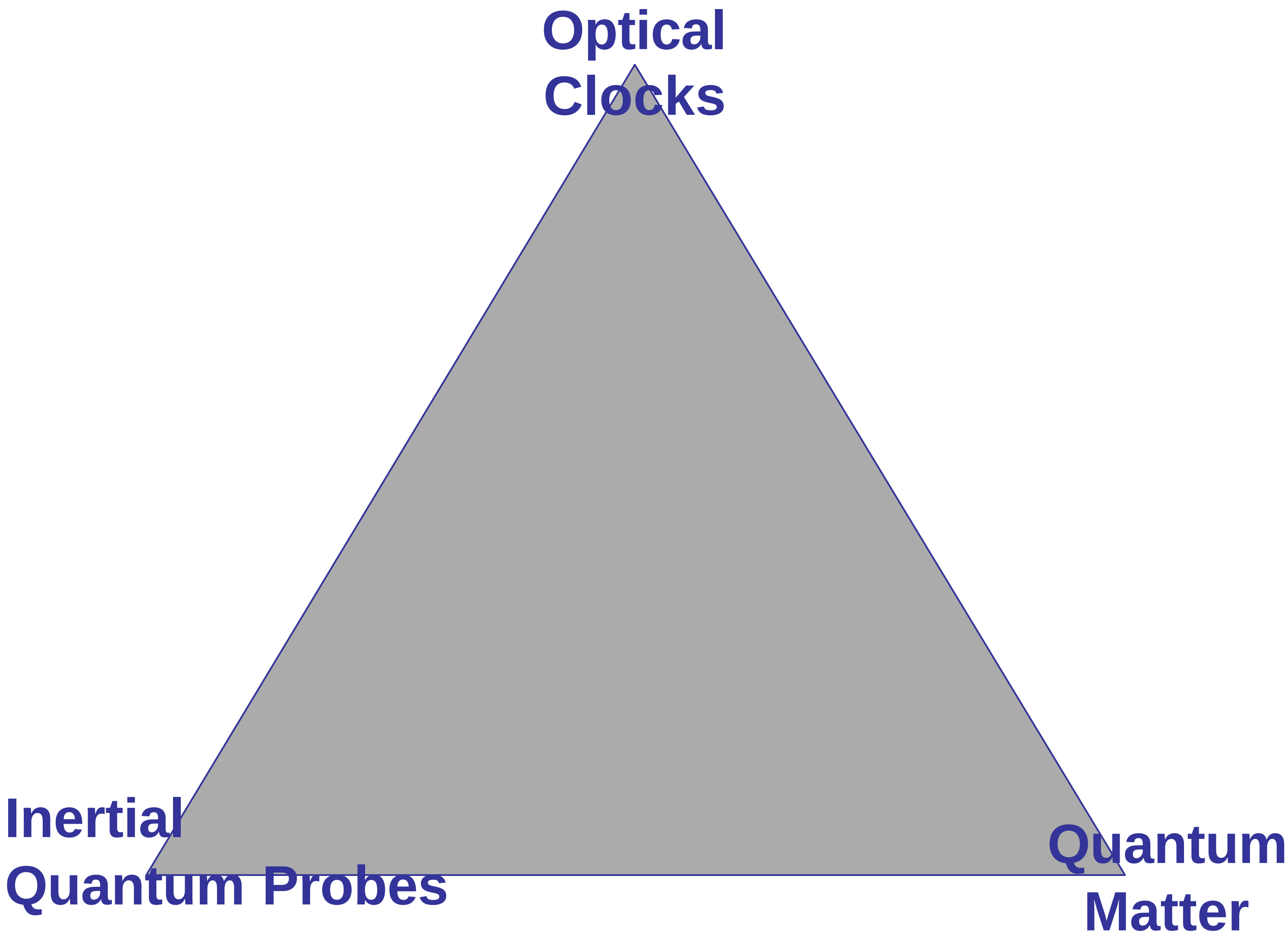
IInd generation atom optical experimen...

Heritage of PHARAO/ACES pr...

dedicated to ine...

- Lens...
- ...orks (1999/2000)
- ...clock (2001)


Optical Clocks
Inertial Quantum Probes
Quantum Matter

Magnesium Opt. Clock

From microwaves to optical frequencies

10^{10} Hz ® 10^{15}Hz

Mg frequency standard

$$\frac{\Delta n}{n} \approx 10^{18}$$

Instability $8 \cdot 10^{-14}$
Q =$2.3*10^{12}$

Sterr et al., Appl. Phys. B 54, 341 (1992)

J. Keupp, et al., High-resolution atom interferometry in the optical domain, E.J. Physics D, Highlight Paper (2002)

Candidates

H,

Ca,

Mg,

Sr,

Ag,

Yb,

Hg,

…

What will be the „best“ atom

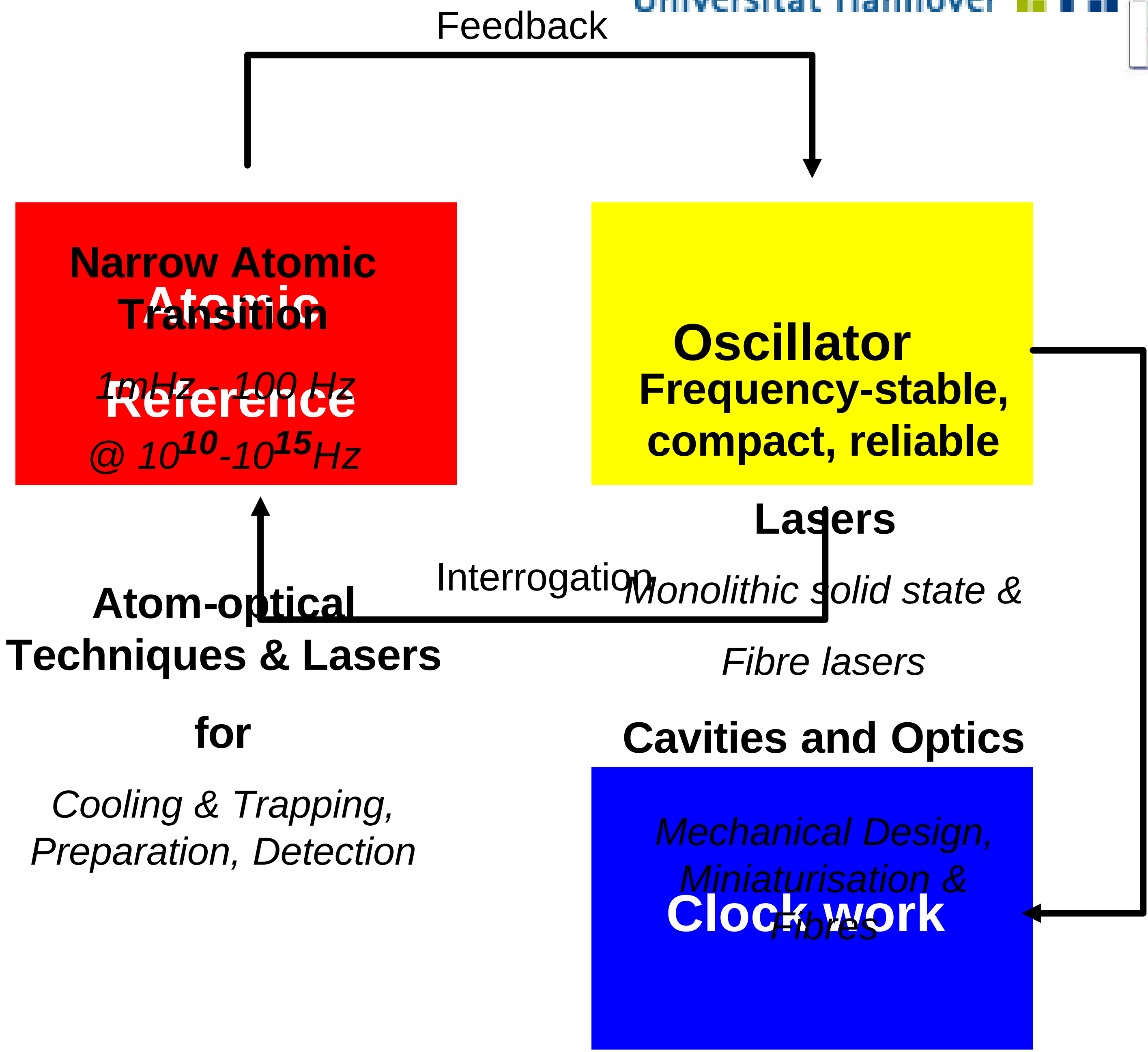
What will be the „best“ clock

Criteria ?

What to be tested ?

Diversity of Clocks

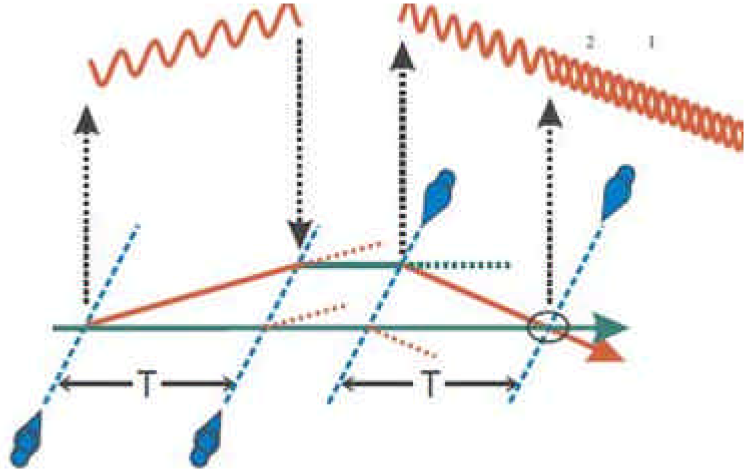
Clock Techniques



1st measurement of

the Mg frequency $^1S_0$®$^3P_1$

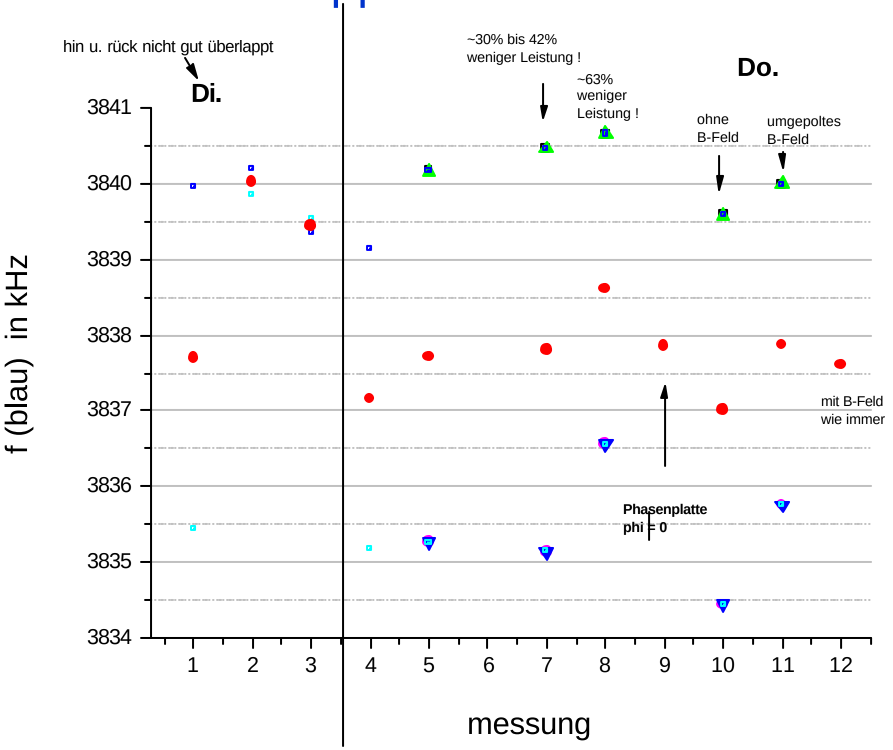
655.660.083.836 kHz +/- 3 kHz

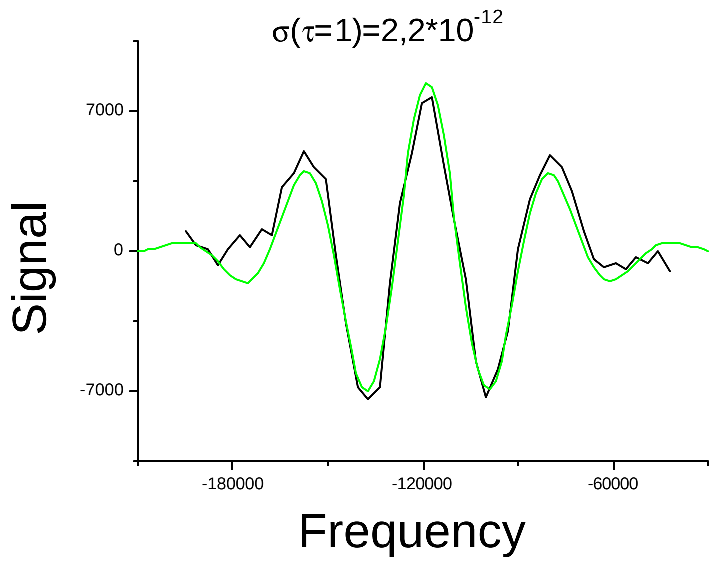


Precision £ 10^{-11}

Evaluation ongoing

2nd order Doppler shift ~1.5 kHz





Systematics

$$\frac{\Delta n}{n} \approx 10^{-18}$$

Table 1 | Systematic corrections and uncertainties for the Sr optical lattice clock

Effect	Correction (Hz)	Uncertainty (Hz)	
		Achieved	Attainable
First order Doppler*	0	3×10^{-2}	$<10^{-3}$
Second order Doppler	0	2×10^{-6}	$<2 \times 10^{-6}$
Recoil shift	0		
First order Zeeman	0	10	10^{-3}
Collision shift	0.6	2.4	10^{-3}†
Blackbody shift‡	2.4	0.1	3×10^{-3}
Probe laser light shift	0.1	0.01	10^{-3}
Scalar light shift	−3.8§	4	10^{-3}
Vector light shift‖	0	10^{-3}	10^{-3}
Tensor light shift	0	10^{-3}	10^{-3}
Fourth order light shift¶	0	10^{-3}	10^{-3}
Cs clock offset	−45	3	
Frequency measurement	0	9	
Systematic total	−45.7		
Total uncertainty $\delta\nu$		15	4×10^{-3}

M. Takamoto et al.. Nature. 435. 321 (2005)

Mg- optical clock

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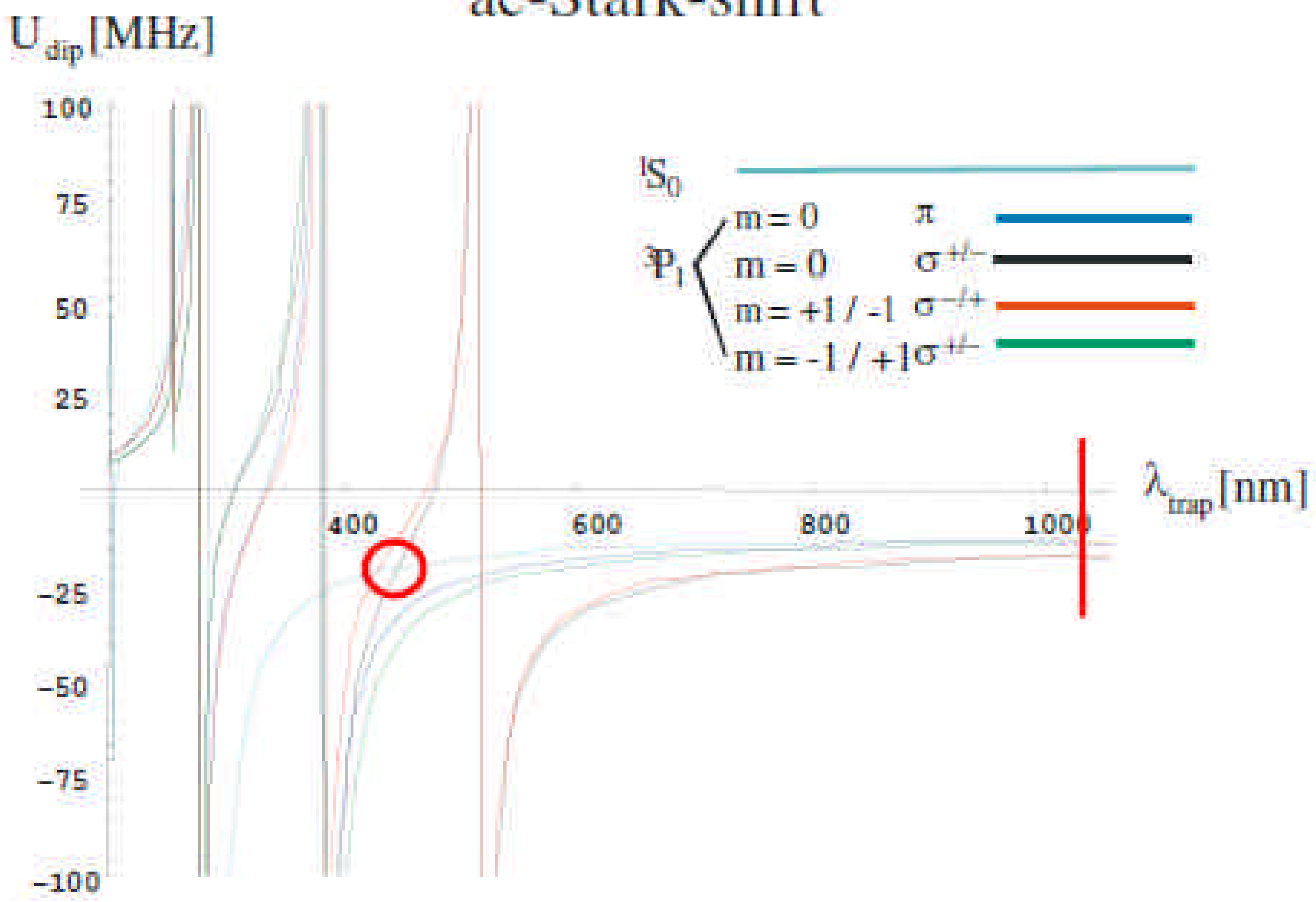
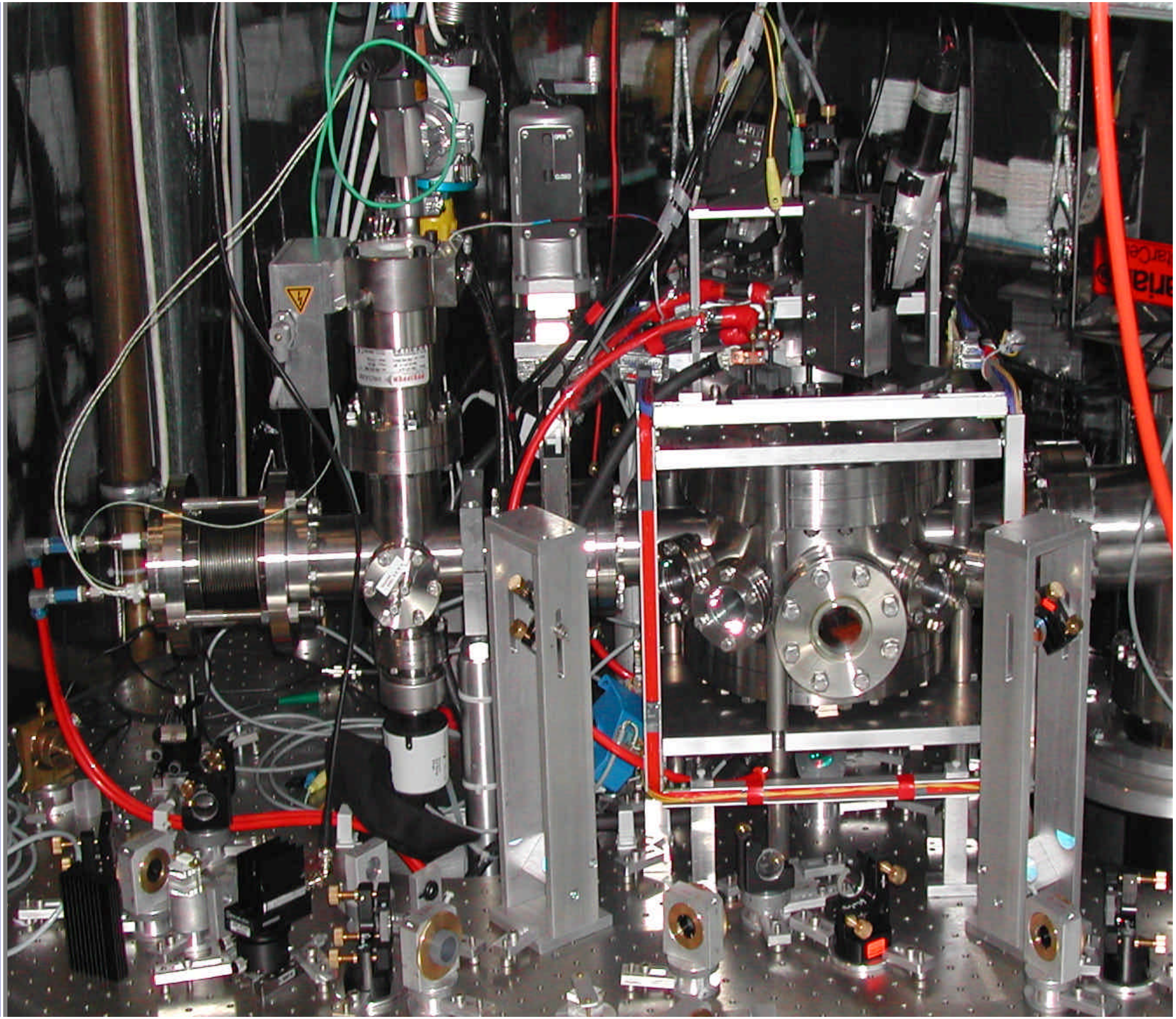
ac-Stark-shift



Mg- optical clock

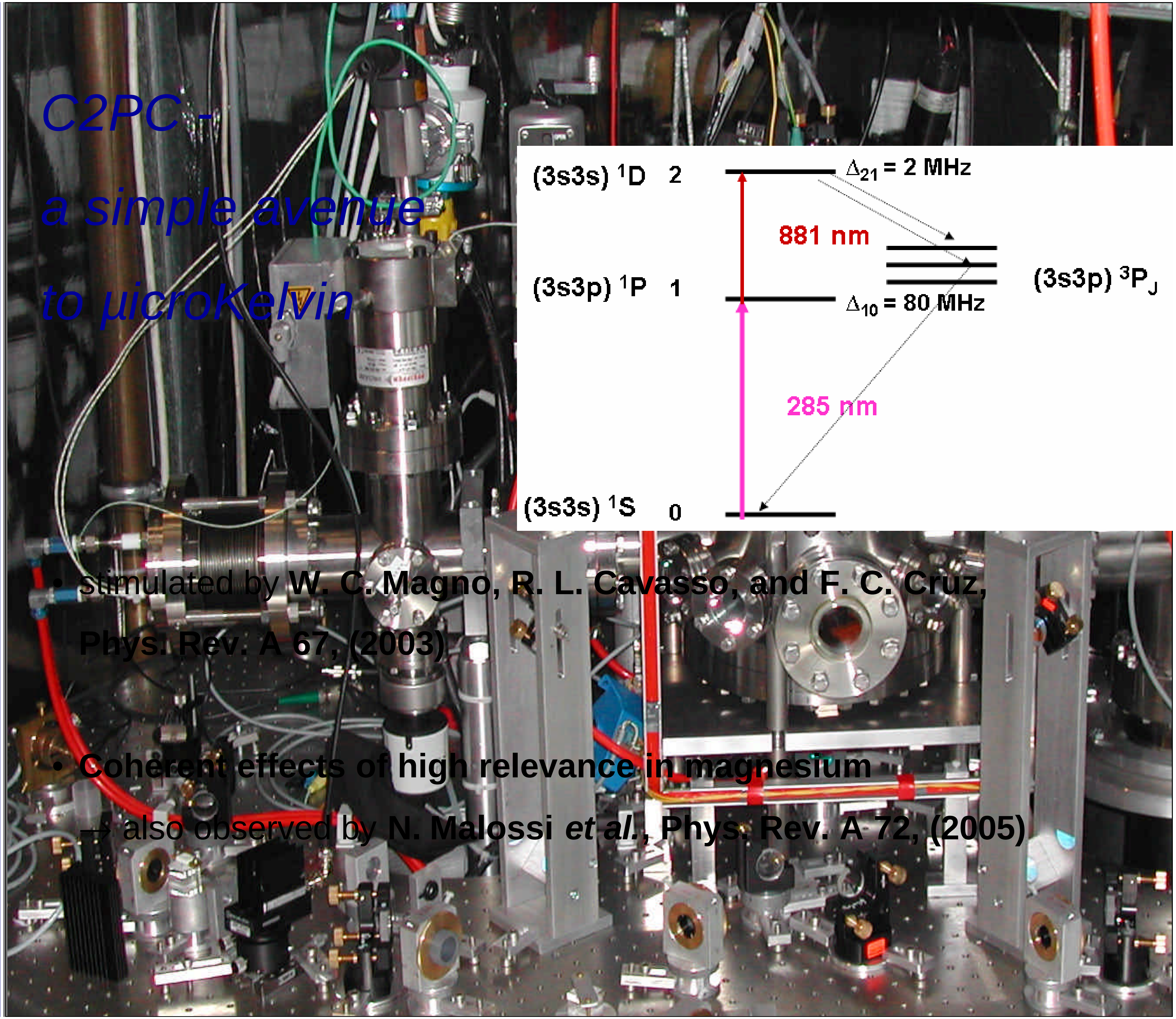
- ✔ Narrow to ultra-narrow transition
- ✔ "Magic" wave length dipole trap ($^1S_0 \rightarrow {}^3P_0$: 465 nm)
- Higher order effects ?
- ✔ Reasonable abundance of fermionic and bosonic isotopes ^{24,25,26}Mg
- ✔ Low black-body shift (10^{-16})
- ✔ Simple electronic structure- easy to model
- Semi-conductor laser + Frequency Doubling
- ✔ Fast and efficient laser cooling

Cooling strategies



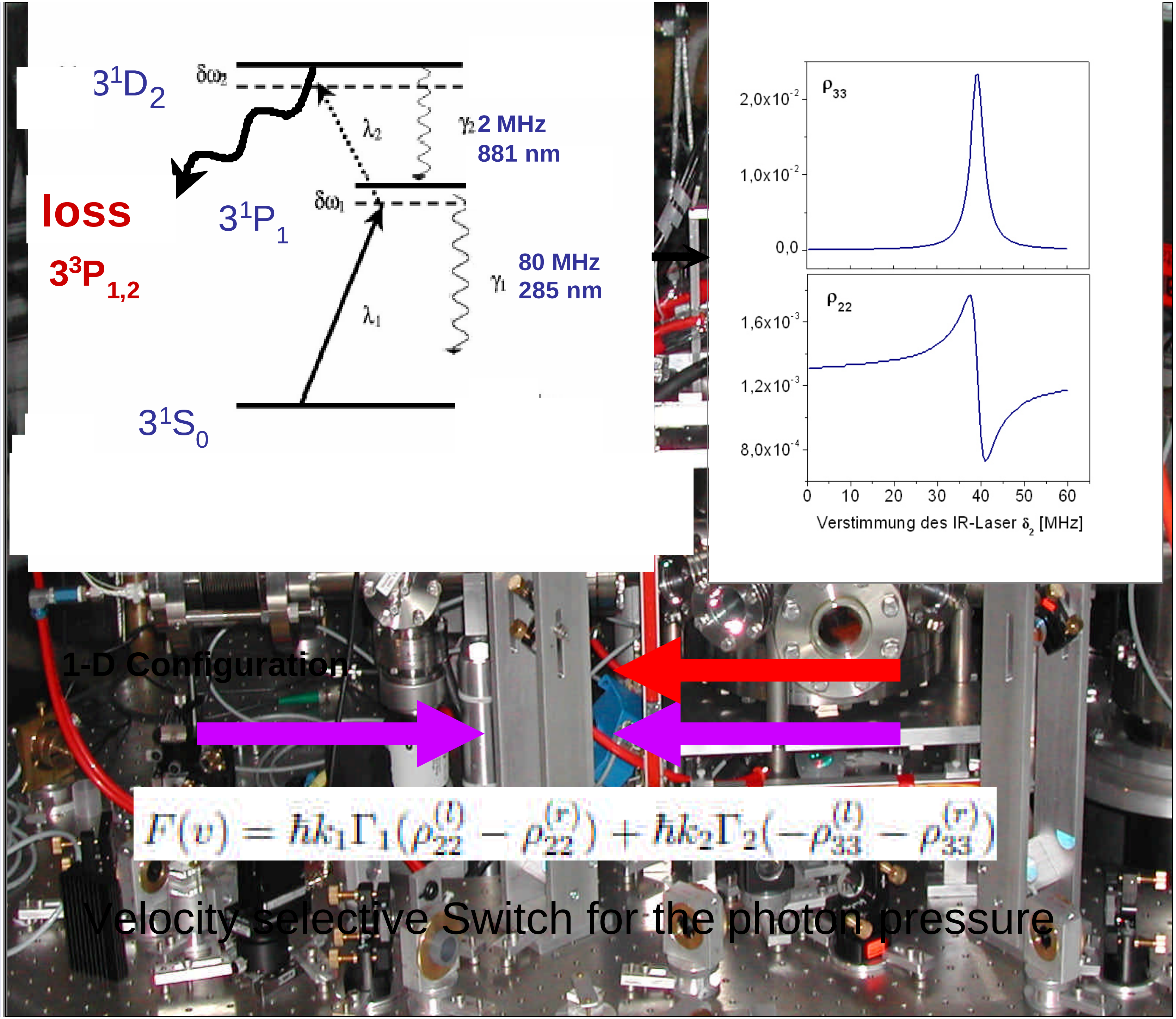
Coherent 2-Photon Cooling

C2PC - a simple avenue to µicroKelvin



- stimulated by **W. C. Magno, R. L. Cavasso, and F. C. Cruz, Phys. Rev. A 67, (2003)**
- **Coherent effects of high relevance in magnesium**
  → also observed by **N. Malossi *et al.*, Phys. Rev. A 72, (2005)**

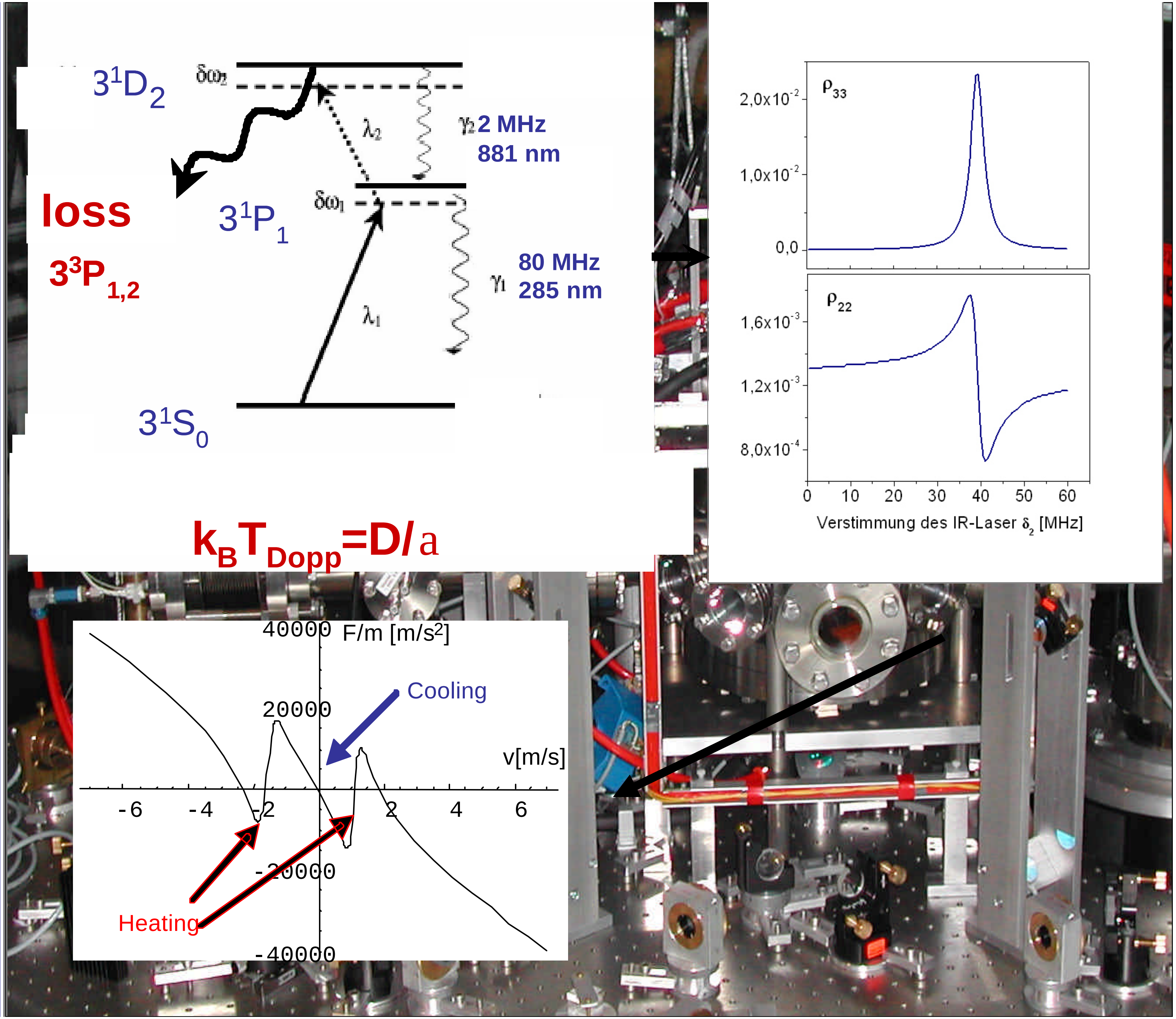
C2PC ctd.



$$F(v) = \hbar k_1 \Gamma_1 (\rho_{22}^{(l)} - \rho_{22}^{(r)}) + \hbar k_2 \Gamma_2 (-\rho_{33}^{(l)} - \rho_{33}^{(r)})$$

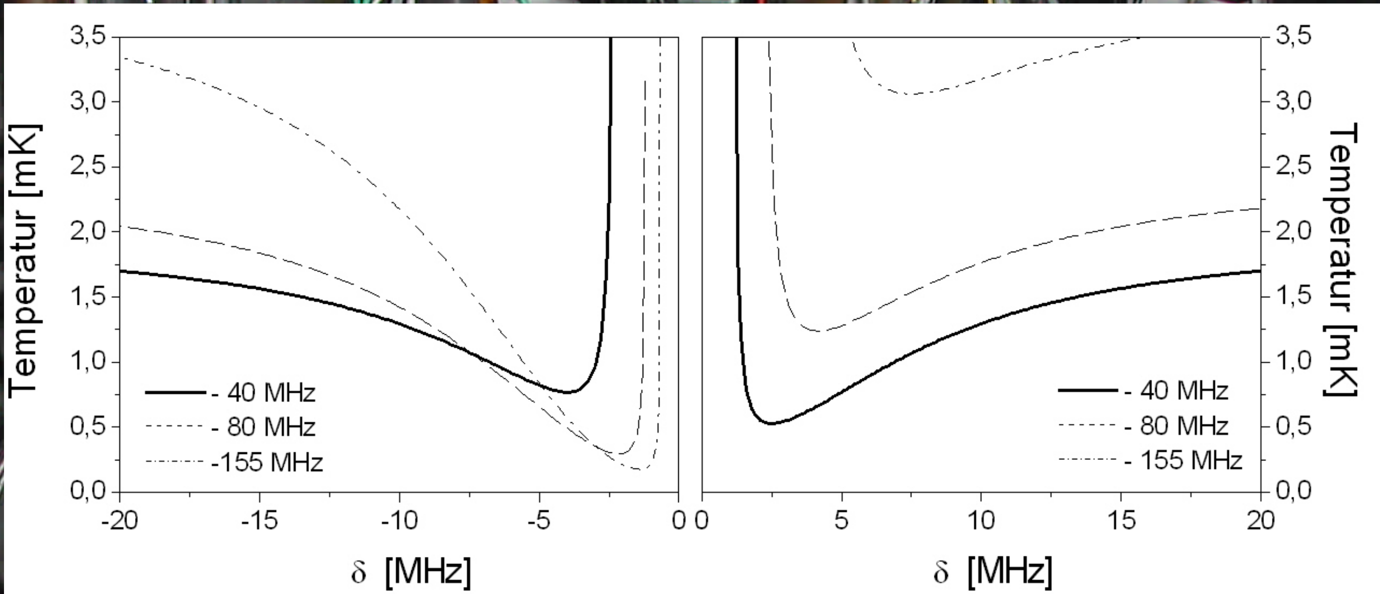
Velocity selective Switch for the photon pressure

C2PC ctd.



3¹D₂
δω₂
γ₂ 2 MHz
881 nm
λ₂
loss
3³P₁,₂
3¹P₁
δω₁
80 MHz
285 nm
γ₁
λ₁
3¹S₀
k_B T_Dopp=D/a
ρ₃₃
2,0x10⁻²
1,0x10⁻²
0,0
ρ₂₂
1,6x10⁻³
1,2x10⁻³
8,0x10⁻⁴
0 10 20 30 40 50 60
Verstimmung des IR-Laser δ₂ [MHz]
40000
F/m [m/s²]
20000
Cooling
v[m/s]
-6 -4 -2 2 4 6
-20000
Heating
-40000

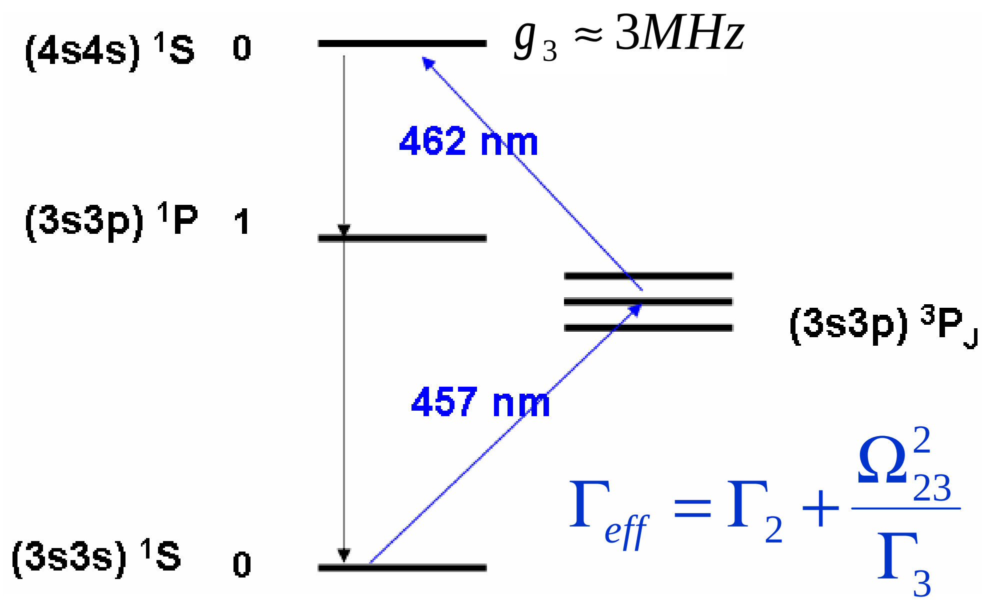
C2PC ctd.



- C2PC - a simple extension of Doppler cooling
- Accessible temperatures ~200 µK
- Fast cooling scheme: 1-2 ms
- Technical heating of UV-MOT influences also C2PC
- Bridges temperature gap for Quench cooling

K. M
Univ
temperatures in magnesium, in prep. for subm. to PRL

Avenue below µK



$$\Gamma_{eff} = \Gamma_2 + \frac{\Omega_{23}^2}{\Gamma_3}$$

- Quench Cooling –only efficient for cold atoms below the Doppler temperature
- Laser Cooling in dipole traps operated at magic wavelength

N. Rehbein et al., "Quenching metastable magnesium" sub. to Phys. Rev. A
T. Binnewies, G. Wilpers, U. Sterr, F. Riehle, J. Helmcke, PTB;
T. E. Mehlstäubler, E. M. Rasel, W. Ertmer, IQ, Leibniz Universität Hannover, "Doppler cooling and trapping on forbidden transitions", Phys. Rev. Lett. 87, p. 123002, 2001.
T.E. Mehlstäubler, J. Keupp, A. Doulliet, N. Rehbein, E.M.Rasel and W. Ertmer, J.O.B 5, p.183 (2003)

IQ - Quantum Sensors

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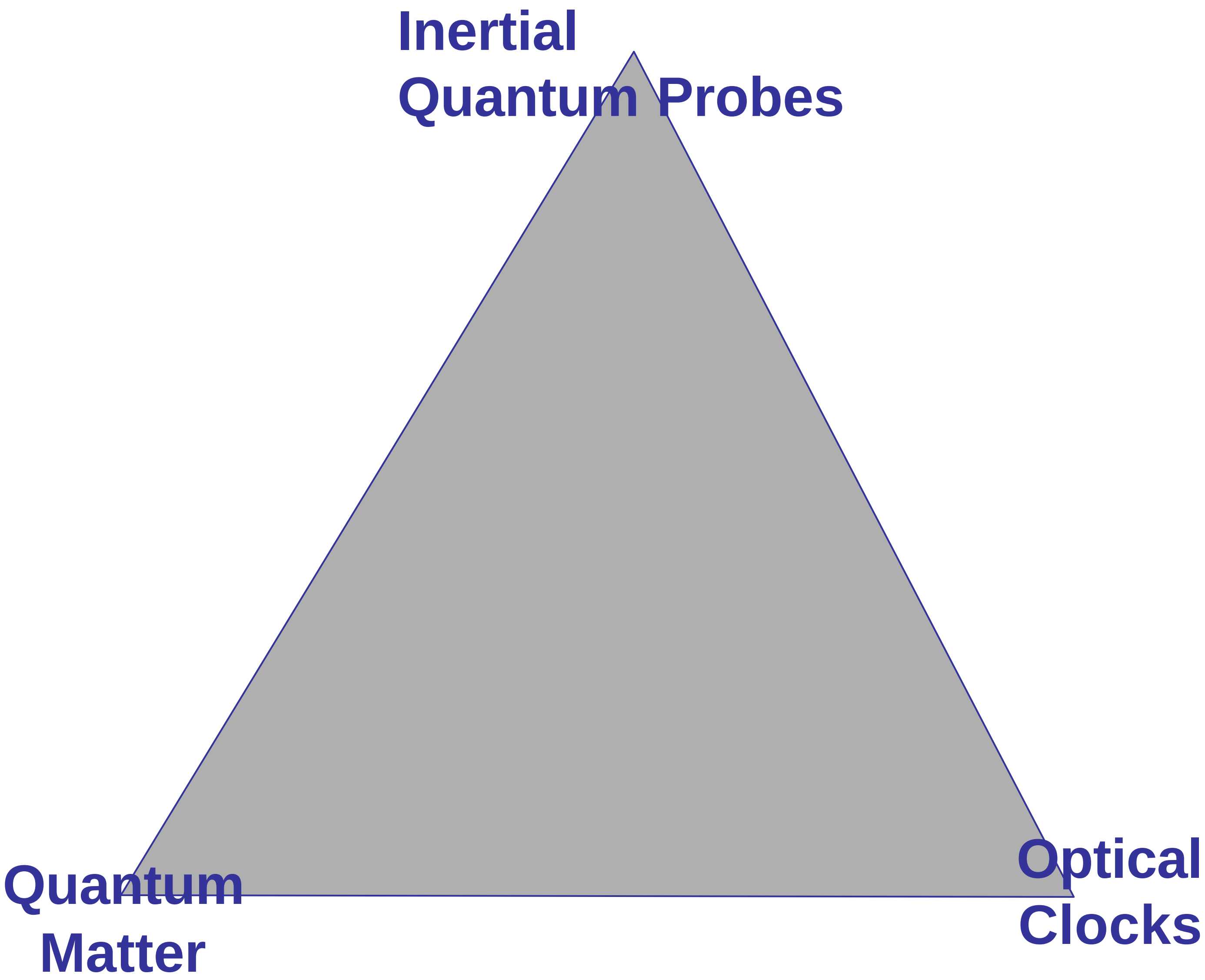
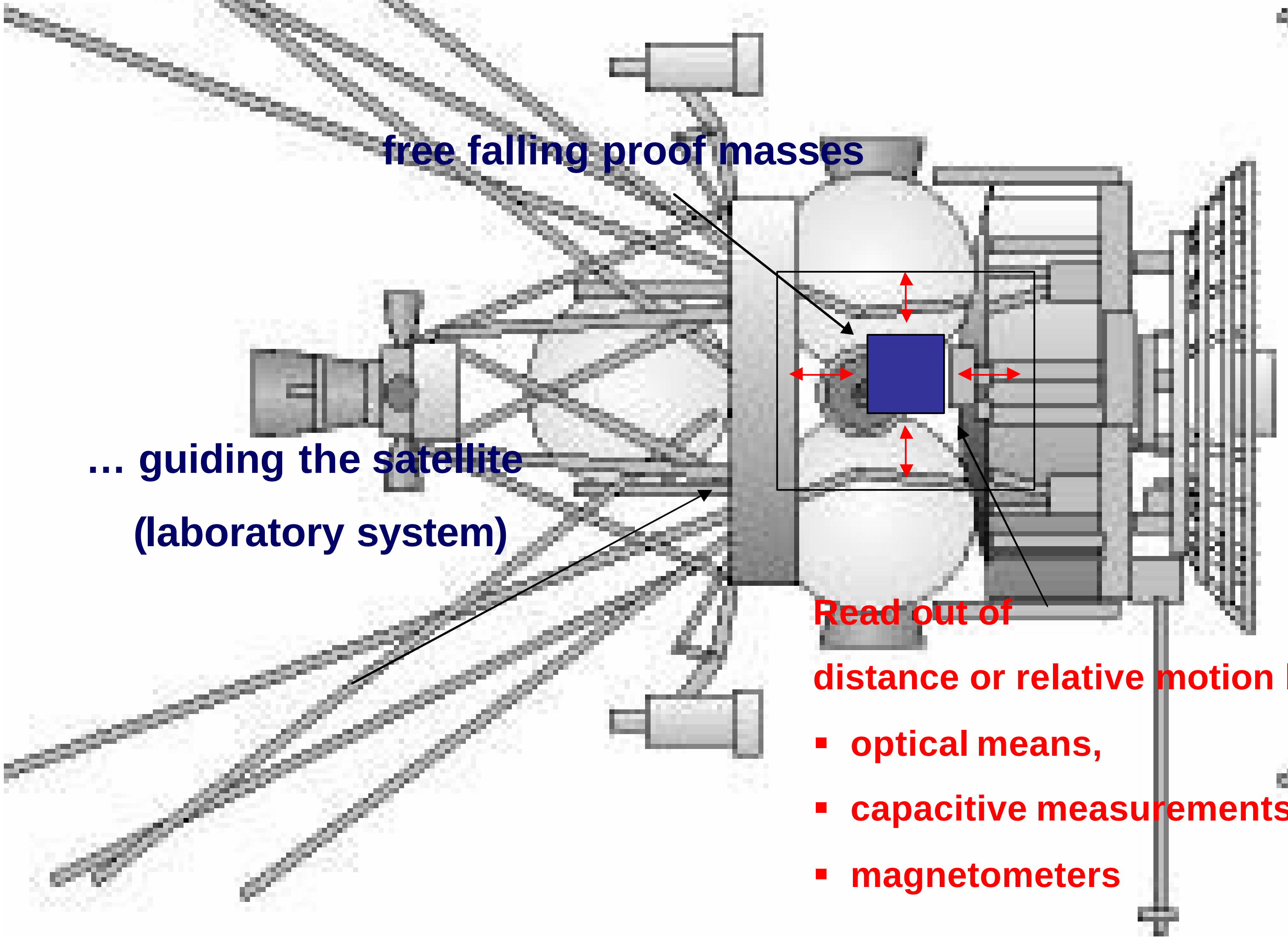


Inertial sensing

Using atoms as microscopic perfect test masses



Atomic Quantum Sensors

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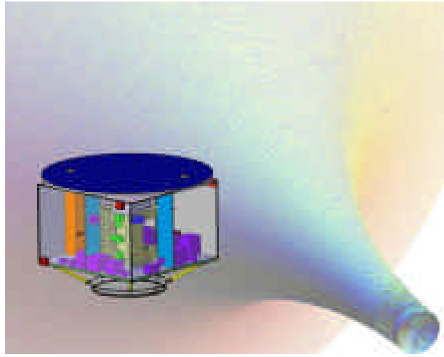
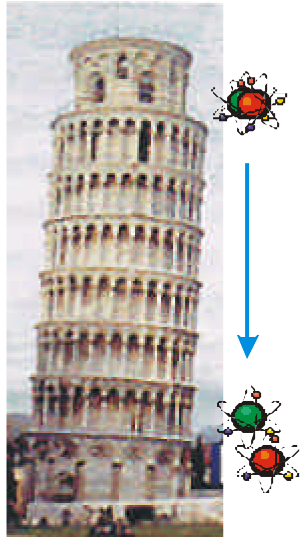
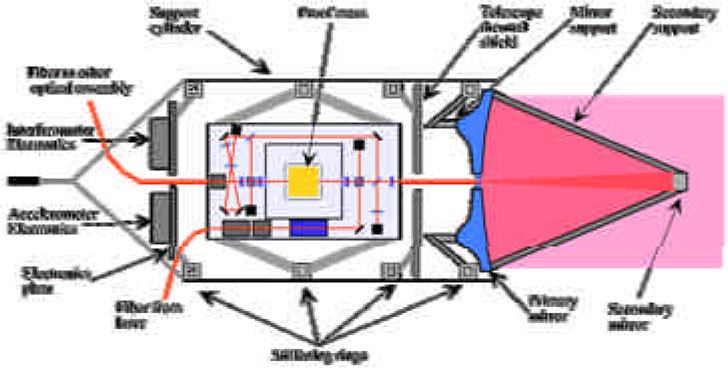
Fields of Interest:



- Inertial standards/references
- Earth Observation
- Measurement of relativistic effects & gravity
- Pioneer anomaly
- Testing the Weak Equivalence Principle
- Drag-free sensors

  perhaps in gravitational wave detectors ?





Rotation sensing

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The Earth's rotation:
$\Omega_E \sim 7{,}2 \cdot 10^{-5}$ rad/s

$\Delta\Omega_E / \Omega_E$

- 10^{-0} - earth rotation
- 10^{-1}
- 10^{-2} ← GOM SYRTE
- 10^{-3}
- 10^{-4} - seismics
- 10^{-5} ◄ our goal (single shot) ← Kasevich Gyro
- 10^{-6}
- 10^{-7} - tide forces
- 10^{-8} - variation of earth rotation ← $10^{-10} – 10^{-11}$ rad/s √Hz^{-1}
- 10^{-9}
- 10^{-10} - relativistic effects
- 10^{-11} - galactic rotation ←
- 10^{-12}

$10^{-8} – 10^{-9}$ rad in 24 h

10^{-9} rad / 1 year

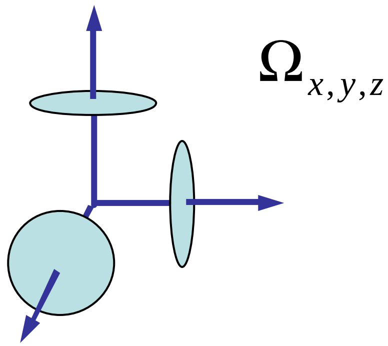
Comparison

	Wettzell (light)	Stanford (thermal Cs-atoms)	CASI (cold Rb-atoms)
length [cm]	400	200	15
area	$16m^2$	$26mm^2$	$25mm^2$
sensitivity $[rad.s^{-1}Hz^{-1/2}]$	$9x10^{-11}$	$6x10^{-10}$	$2x10^{-9}$

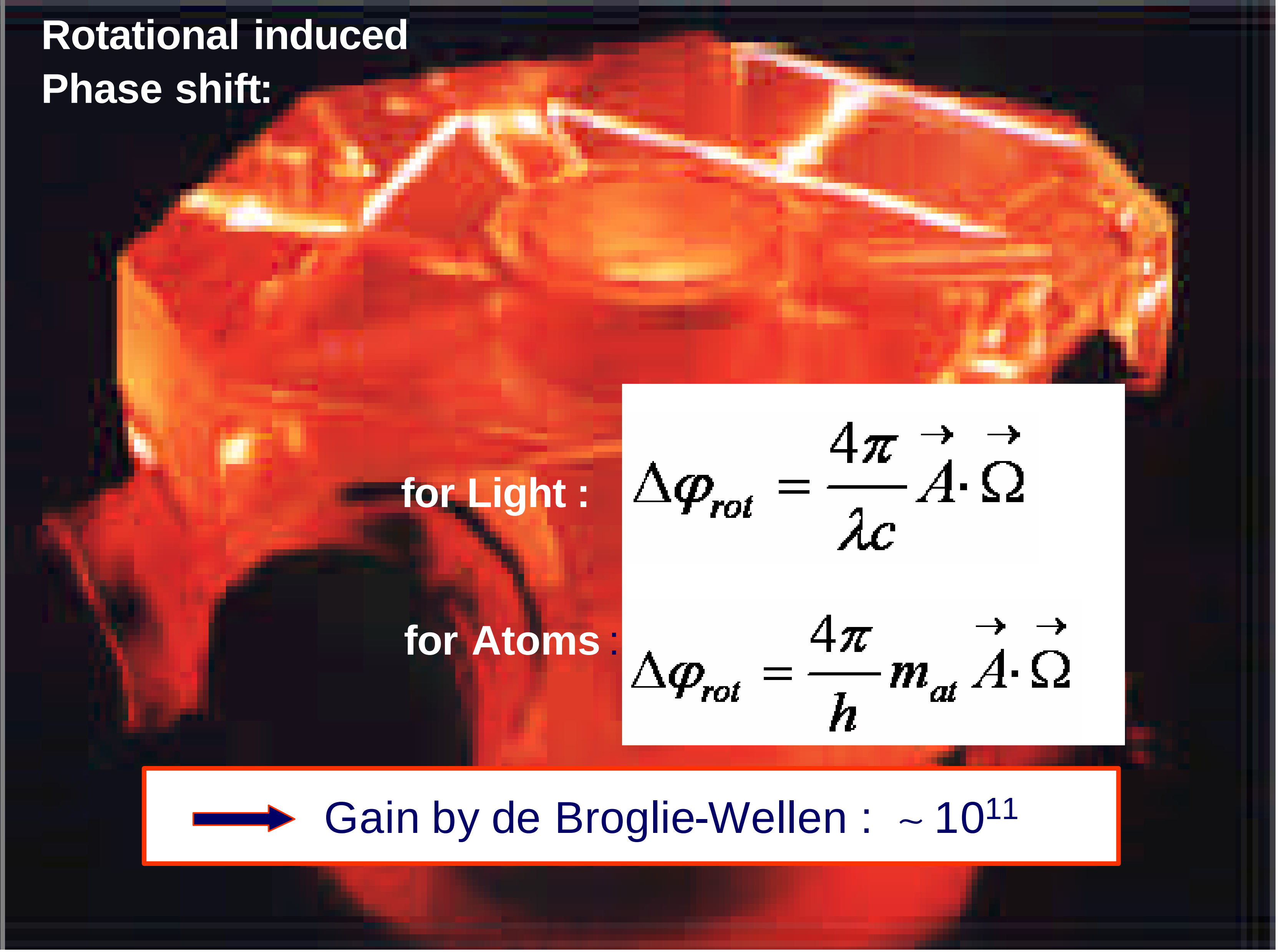
→ different application for interferometer using atoms:

• small device → portable sensor

• inertial sensitivity in 3 dimensions
[B. Canuel, F. Leduc, A. Clairon, Ch.Bordé and A. Landragin, Phys.Rev.Lett. **97,** 010402 (2006)]



Sagnac Effect



Rotational induced Phase shift:

for Light :

$$\Delta\varphi_{rot} = \frac{4\pi}{\lambda c}\vec{A}\cdot\vec{\Omega}$$

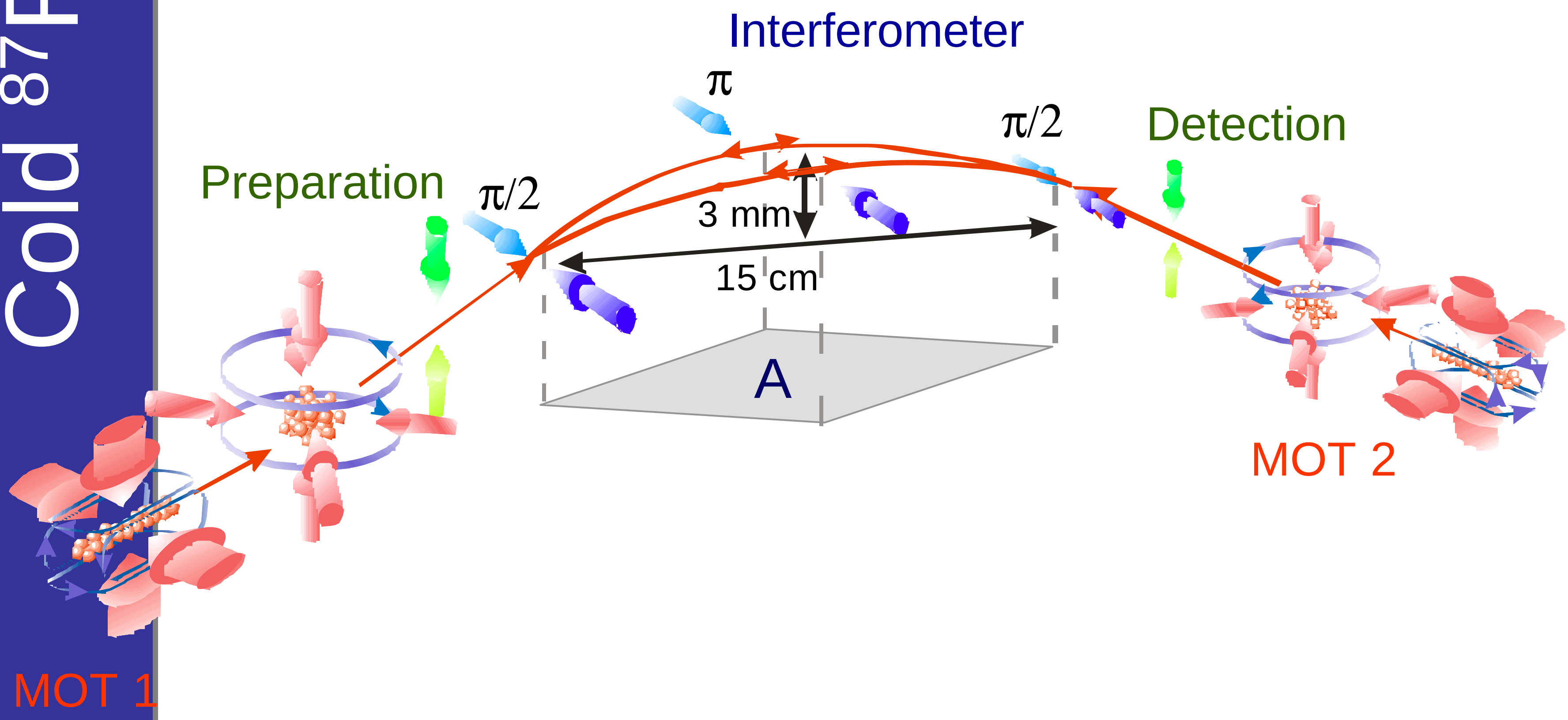
for Atoms :

$$\Delta\varphi_{rot} = \frac{4\pi}{h} m_{at}\vec{A}\cdot\vec{\Omega}$$

→ Gain by de Broglie-Wellen : $\sim 10^{11}$

Cold ^{87}Rb

Sagnac Interferometer



C. Jentsch, T. Müller, E. Rasel, and W. Ertmer, Gen. Rel. Grav, 36, 2197 (2004)
& Adv. At. Mol. Physics

Cold Atom Sagnac Interferometer

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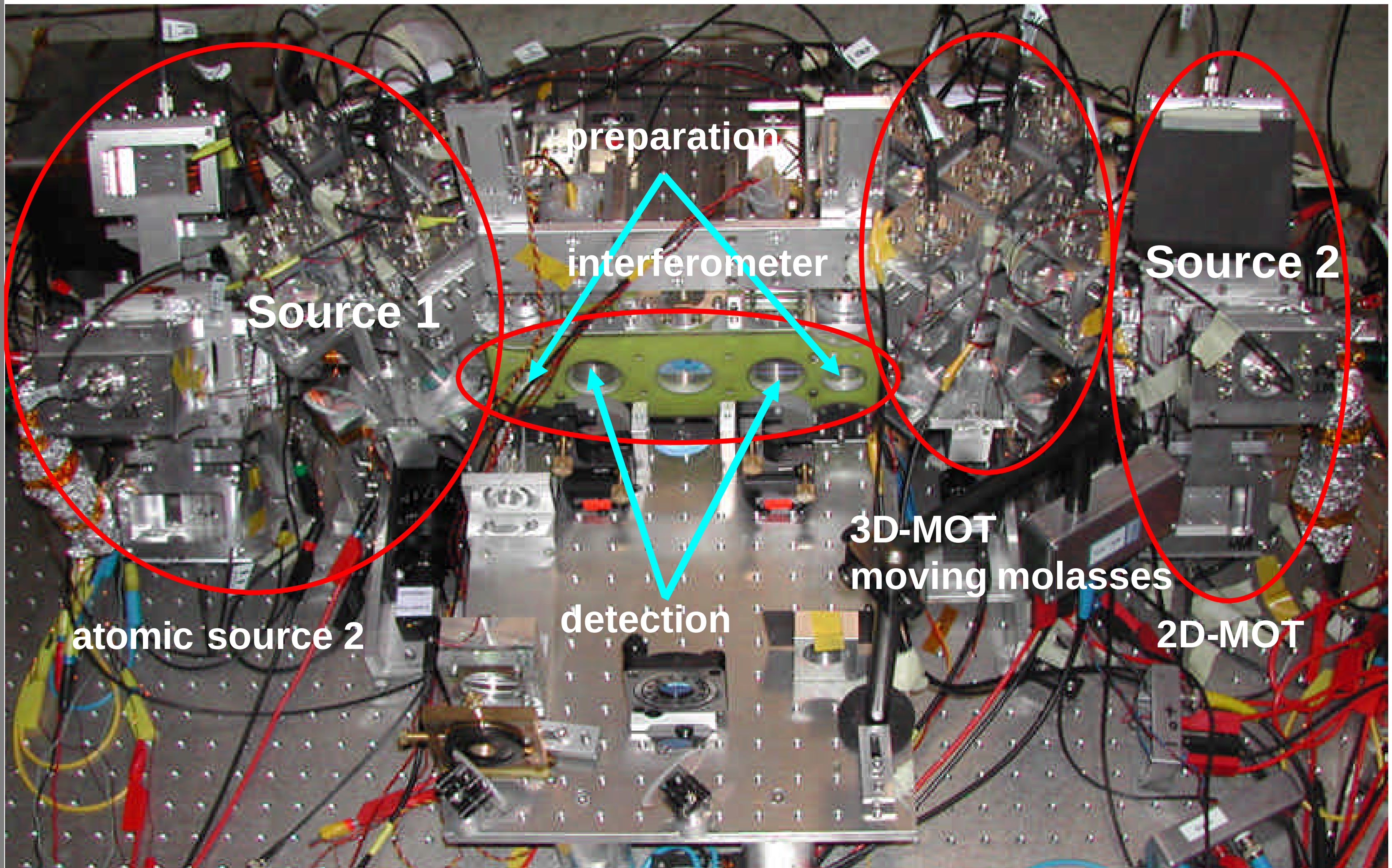
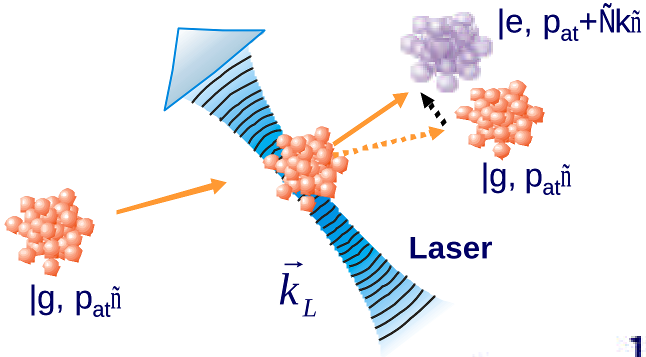
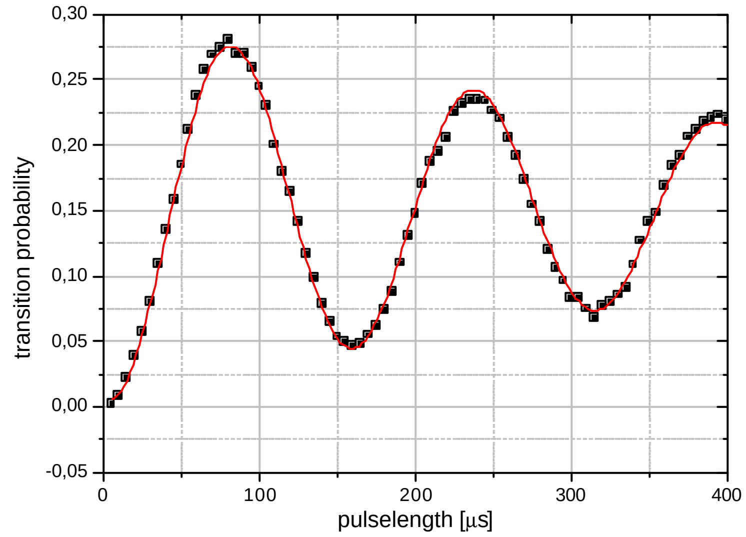
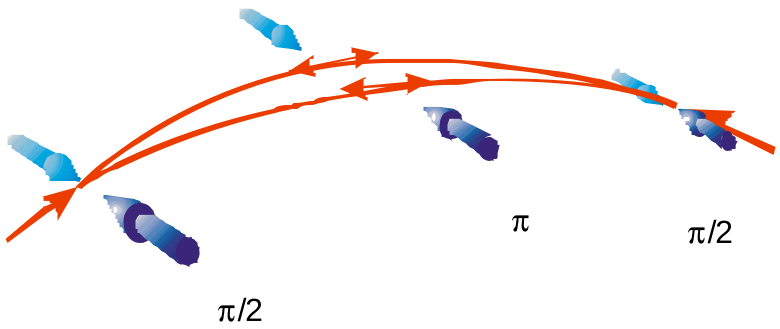


Dual interferometer



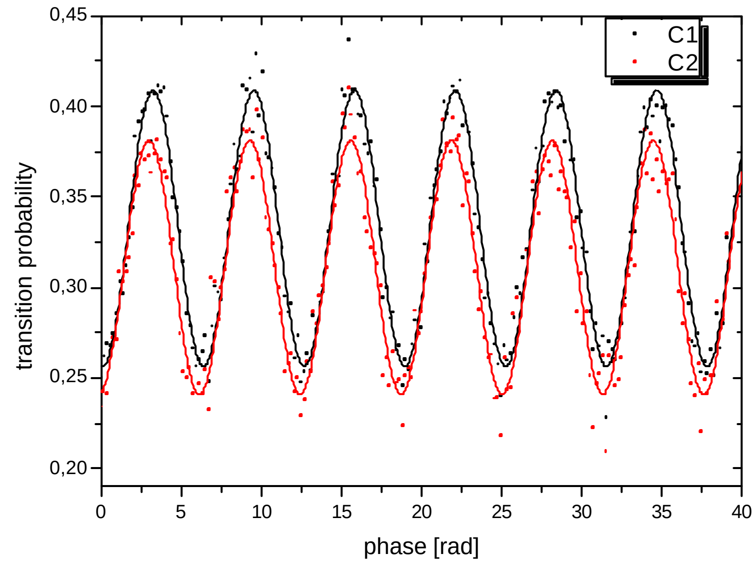
$$\vec{v}_{rec} = \frac{1}{m_{atom}} \hbar \vec{k}_L$$



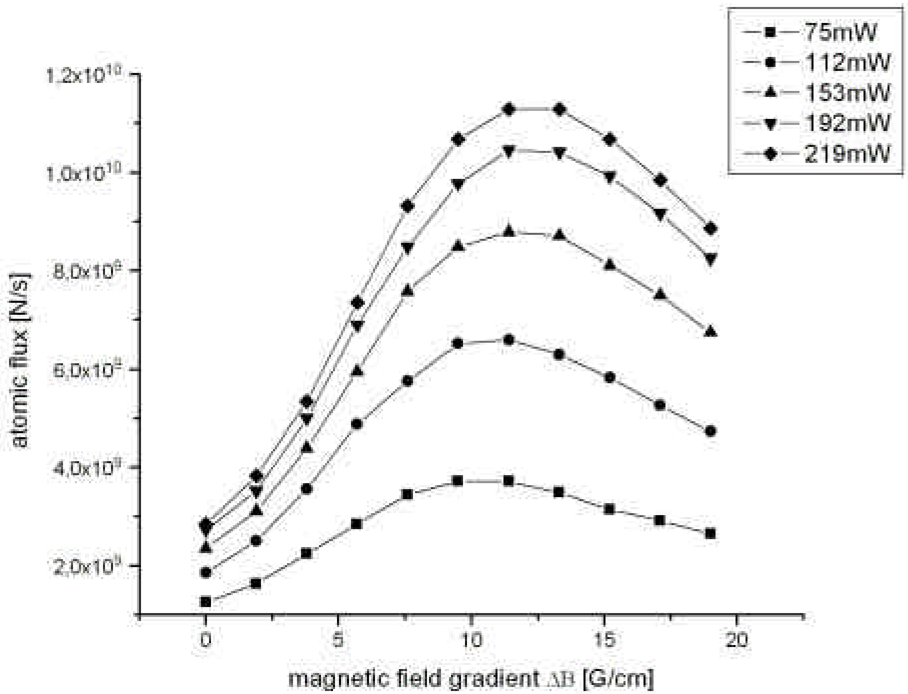


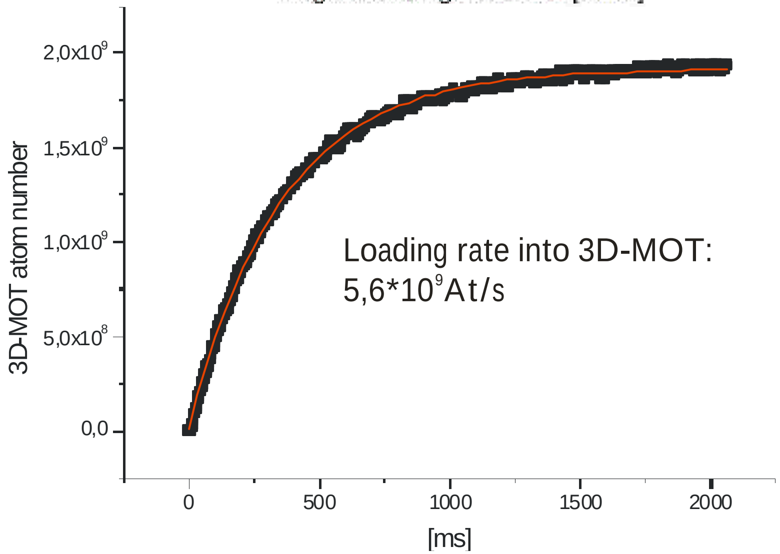
$C_1 = 24\%$ $C_2 = 22\%$

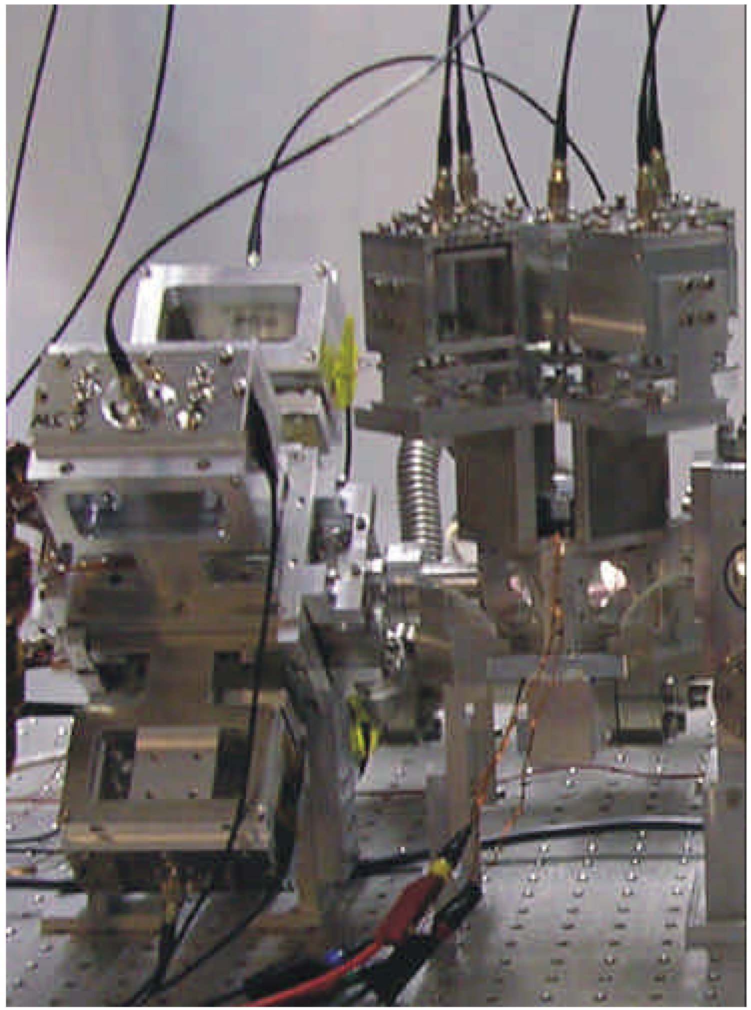
$T = 1ms$, $\tau = 7{,}5\mu s$



Intense Atomic Sources



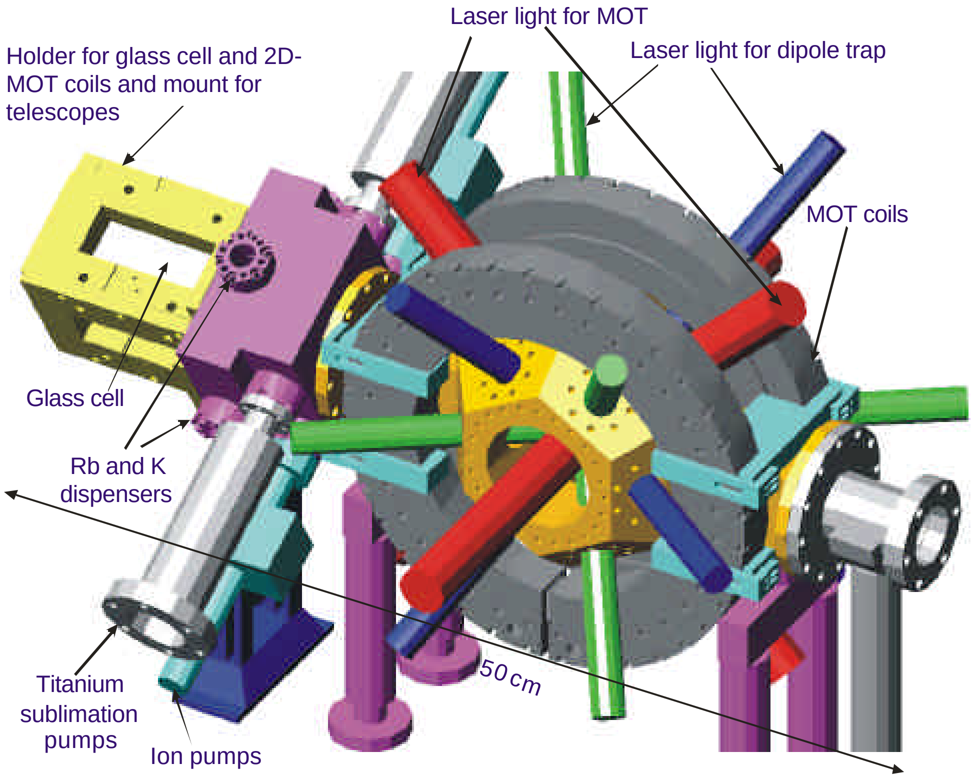


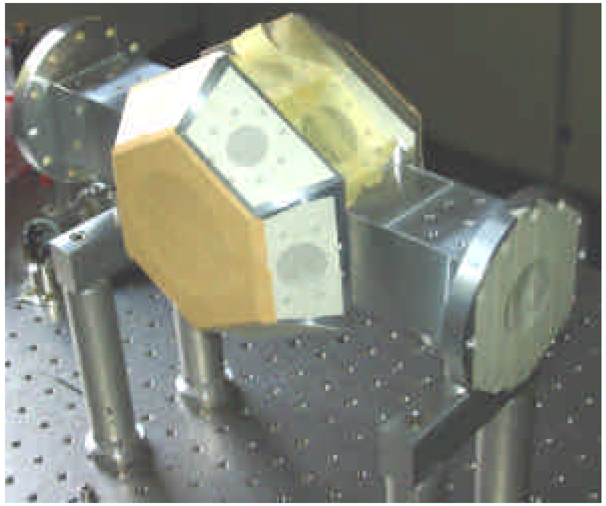


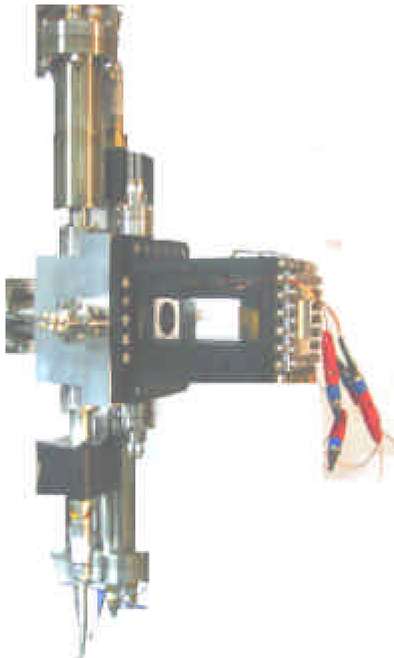
T. Müller, T. Wendrich, M. Gilowski, C. Jentsch, E.M.Rasel and W. Ertmer, "
"Versatile compact sources for high resolution dual atom interferometry" in prep. for Phys. Rev. A

All-optical source

for degenerate matter







C. Klempt, T. van Zoest, T. Henninger, O. Topic, E. Rasel, J. Arlt, W. Ertmer; Phys Rev A **73**, 013410, (2006)

Advantages of µ-gravity

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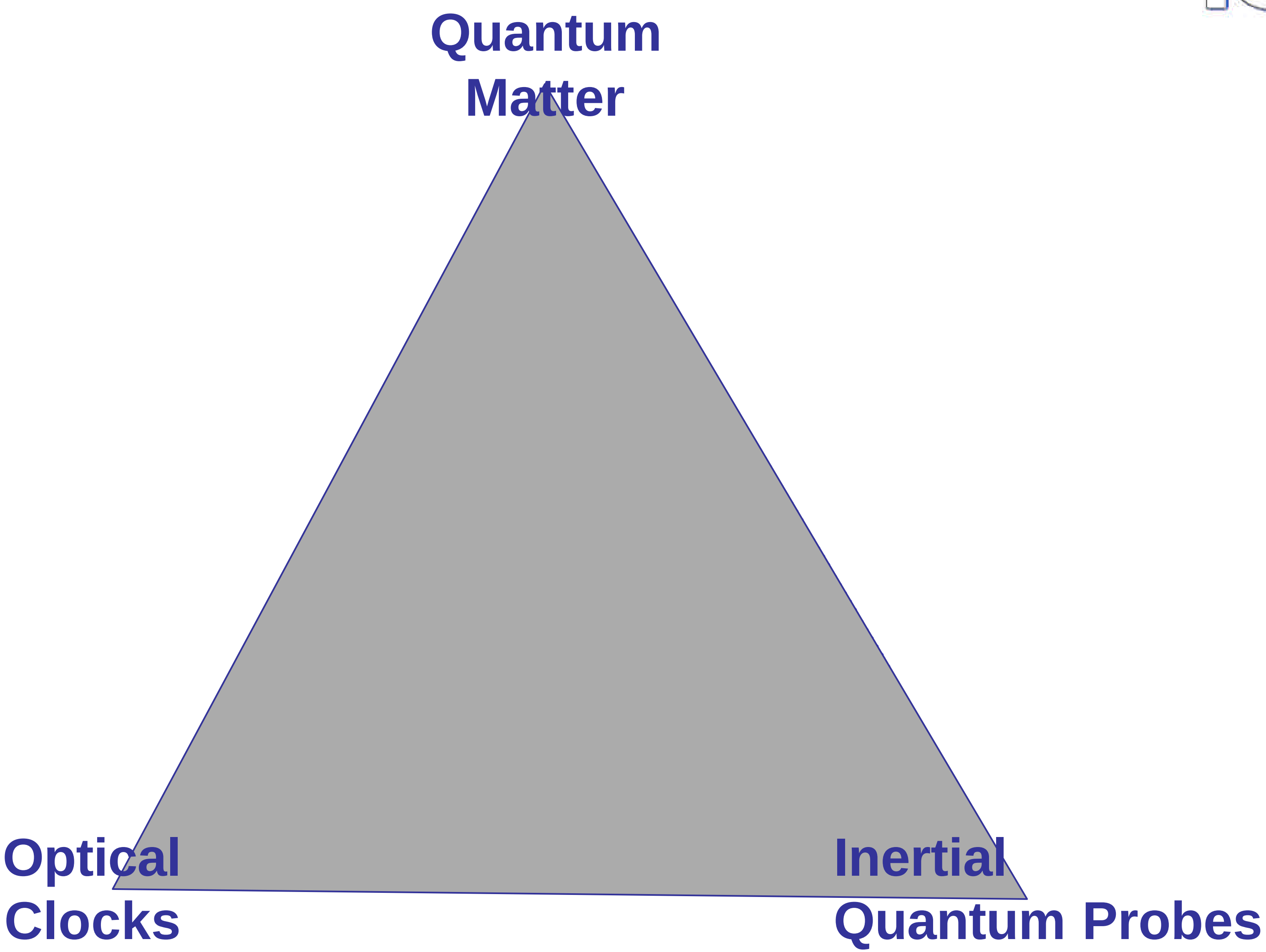
- **Extended Time of Evolution**
- **Perturbation-free Evolution**
- **No need to compensate gravity / to levitate the atoms**

EXTENDED
PARAMETER RANGE


Quantum
Matter
Optical
Clocks
Inertial
Quantum Probes

DLR

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IQ

Pilotproject QUANTUS

Inertial Sensors

Ultra-cold atoms
~ T^2

Atomic clocks

atom optic components for space

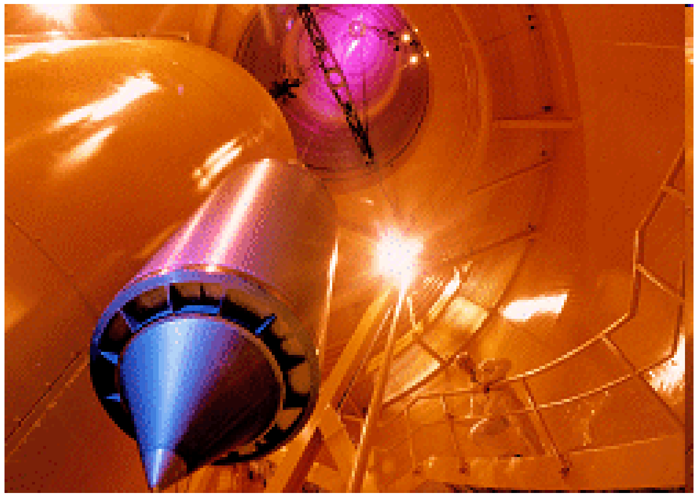
Atom Lasers & Quantum matter

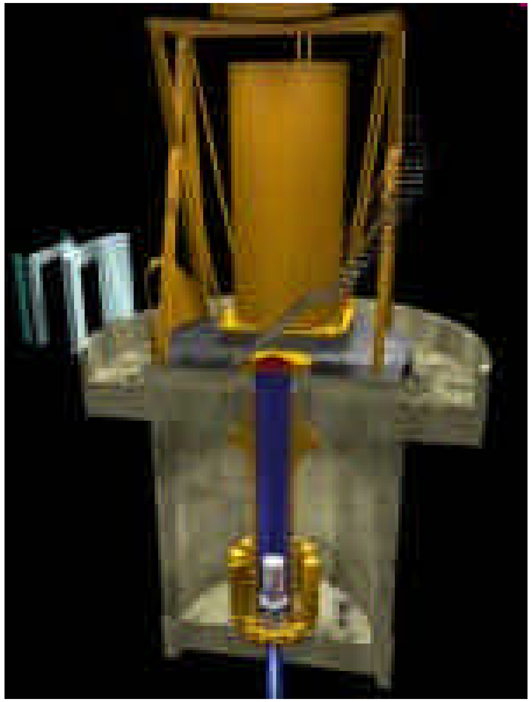
- large, shallow traps
- giant de Broglie waves
- de Broglie resonators
- constant de Broglie waves

Pilotproject „QUANTUS“

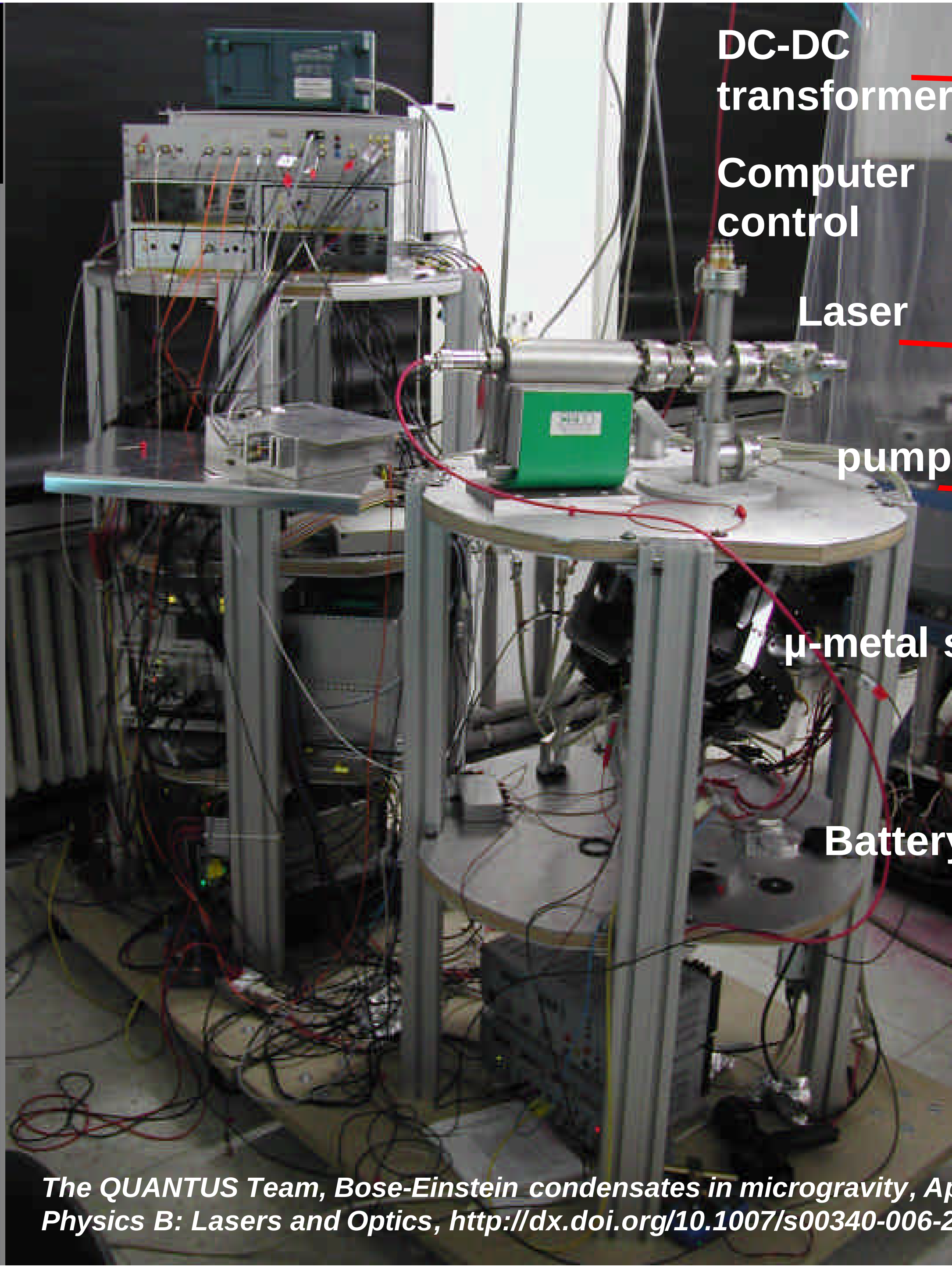
Implementation

- Free Fall: up to 9 sec
- Duration > 1 BEC-Experiment
- 3 flights per day
- Test of a robust BEC Facilities
  Dimensions < 0.6 ∅ x 1.5 m
  < 234 kg
- Height 110 m





QUANTUS



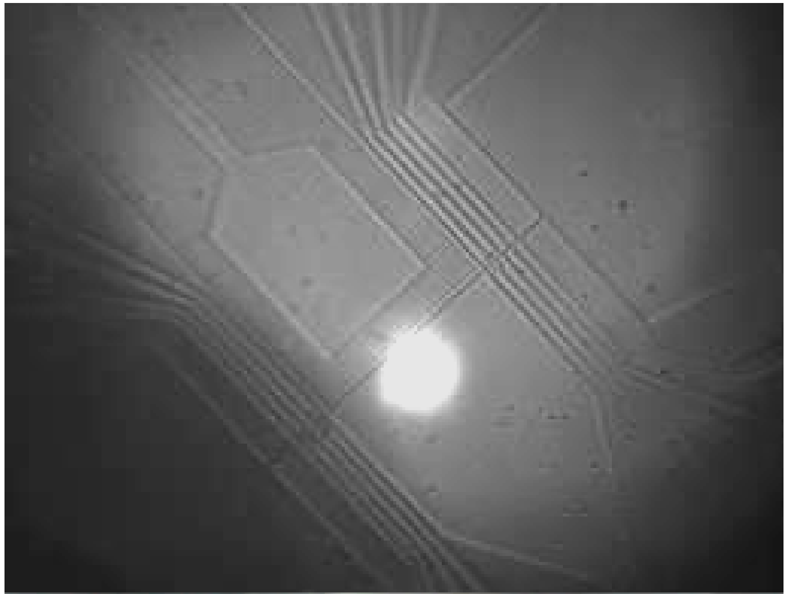
The QUANTUS Team, Bose-Einstein condensates in microgravity, Applied Physics B: Lasers and Optics, http://dx.doi.org/10.1007/s00340-006-2359-y

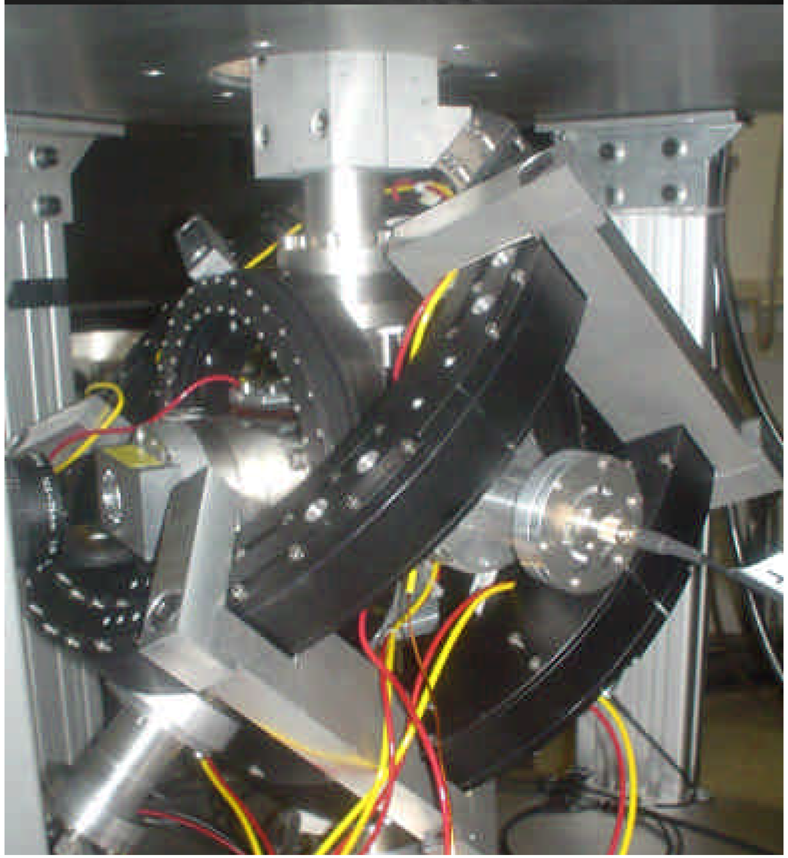
Status

- molasses T~15 µK
- ~3·10^6 atoms on the Chip magnetic trap
- lifetime 2.5 s
- evaporation works

- first drops this year
- interferometry
- mesoscopic trap

→ talk by A. Peters

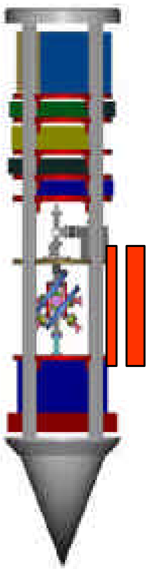


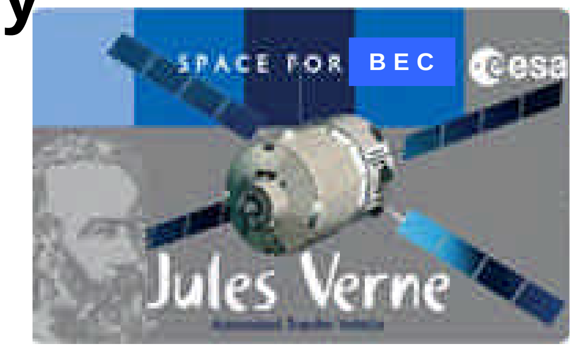


Perspectives

Perspectives

- **Maiden Flight: 2006- annual flights**
- **BEC apparatus 25% of 1 ATV rack**
- **µg-quality <10^{-6}g**
- **Weight < 100 kg / power << 1000 W**
- **Drop tower experiment is a big step in space qualification**
- **Early Flight opportunity**





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Perspectives

Dual Atomic Accelerometer

2 atomic species of 10^8 atoms < 1µK

combined with a drag free proof mass
(Pathfinder or ONERA-type / optical read out)

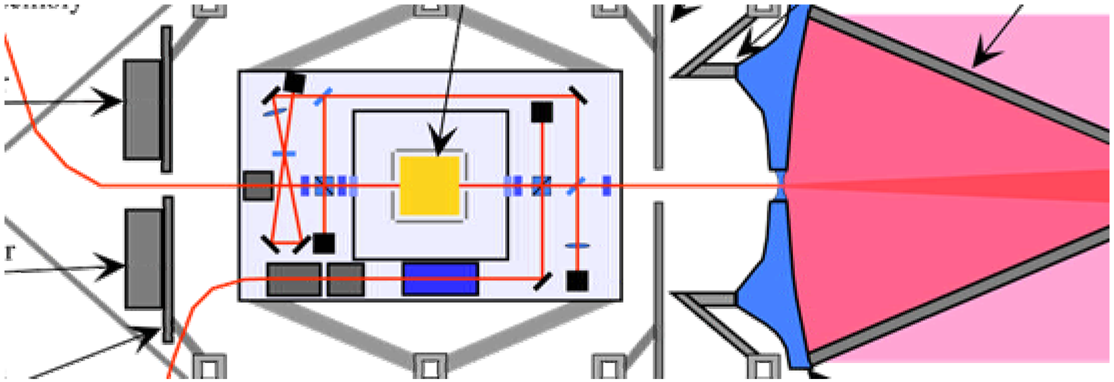
HYPER orbit

Accelerational Sensitivity with 10^8 ats:

Gravity Matter-Wave Explorer

GMWEX

Space 10^{-12} g/√Hz @ Expansion Time 3 s



The BEC-µg Team

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Ronald Mairose
Gerrit Nandi
Achim Peters
Peter Prengel
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Jakob Reichel
Wolfgang Schleich
Malte Schmidt
Tilo Schuldt
Klaus Sengstock
Thilo Steinmetz
Christian Stenzel
Anika Vogel
Reinhold Walser
Tim van Zoest

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The Mg-Team

Leibniz Universität Hannover

Optical Clock based on Magnesium

Present team

C. Moldenhauer

J. Friebe

M. Riedmann

Former team members
A. Douillet
J. Keupp
T. Mehlstäubler ® SYRTE (Paris)
N. Rehbein
H. Stöhr

Cooperation with

H. Schnatz

B. Lipphardt

G. Grosche

PTB

SFB 407

The CASI Team

Leibniz Universität Hannover

Inertial Quantum Probes

Present team

M. Gilovski

T. Müller

T. Wendrich

Former team members

C. Jentsch

Cooperation with

SYRTE & Univ. Florence

SFB 407

The CASI Team

Leibniz Universität Hannover IQ

Quantum Matter

Present team

T.v. Zoest (QUANTUS)

M. Zaiser (ATLAS)

Cooperation with

ZARM-Bremen

Humbolt Universität Berlin

MPQ/ENS

Universität Hamburg

Universität Ulm

SYRTE Paris

IOTA

Univ. Florence

DLR

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ENOUGH SPACE FOR
EXCITING EXPERIMENTS

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