Precision measurement with ultracold atoms & molecules

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Advances in Precision tests and Experimental Gravitation in Space
Firenze, September 28, 2006

$ Funding $

NIST, ONR, NSF, AFOSR, NASA, DOE

First, let there be light

Continuous wave laser: **< 1 Hz stability and accuracy**

Ultrafast pulse: **< 1 fs generation and control**

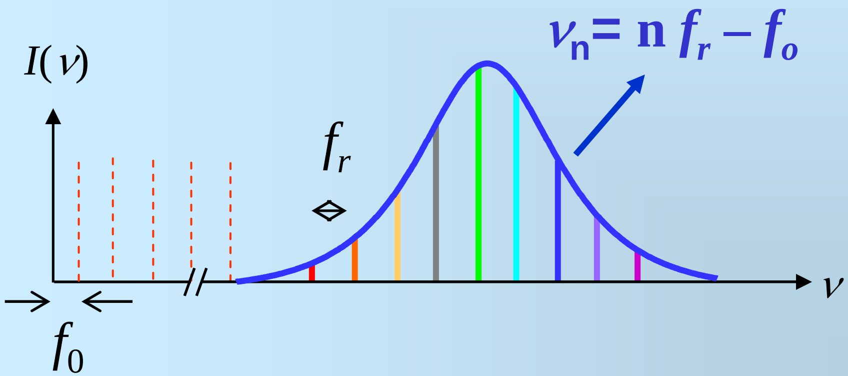
Figure of merit: 10^{-15}

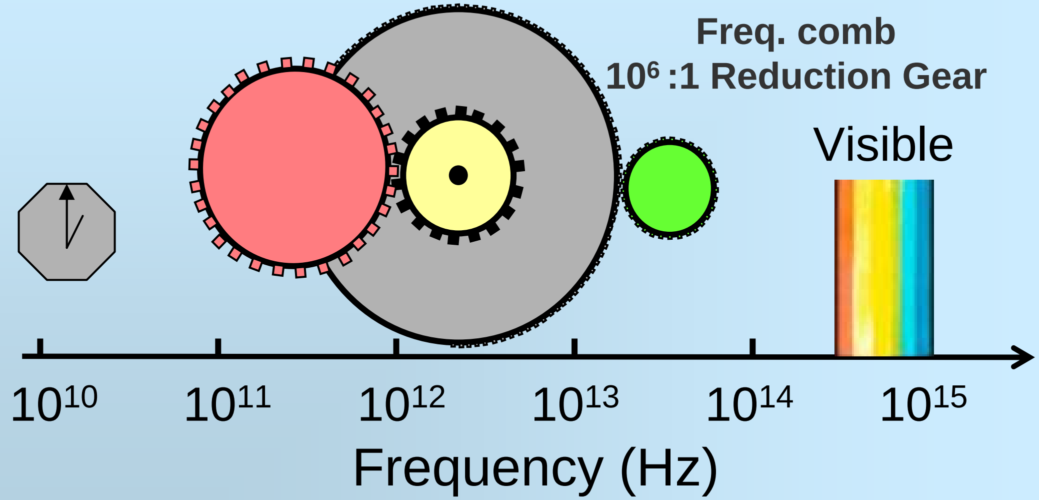
Phase coherence after 10^{15} optical cycles

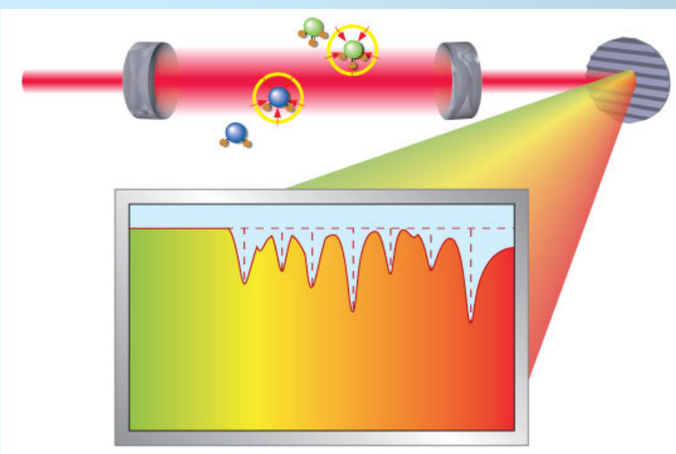
Precision spectroscopy and quantum control
at highest resolution over widest optical bandwidth

Frequency comb: state-of-the-art

- Optical Synthesizer

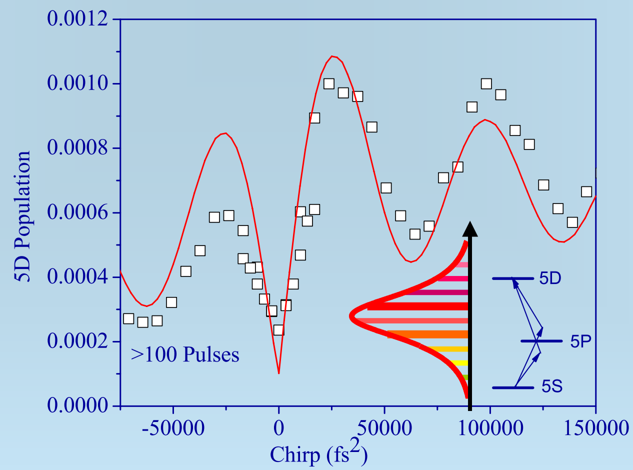






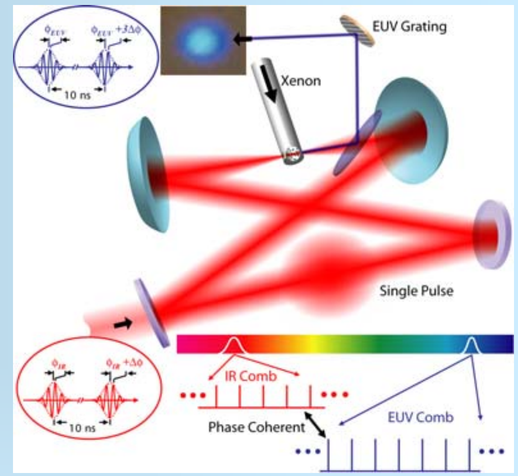
Molecular spectroscopy

Thorpe *et al.*,
Science **311**, 1595 (2006).



Quantum control

Stowe *et al.*,
PRL **96**, 153001(2006).

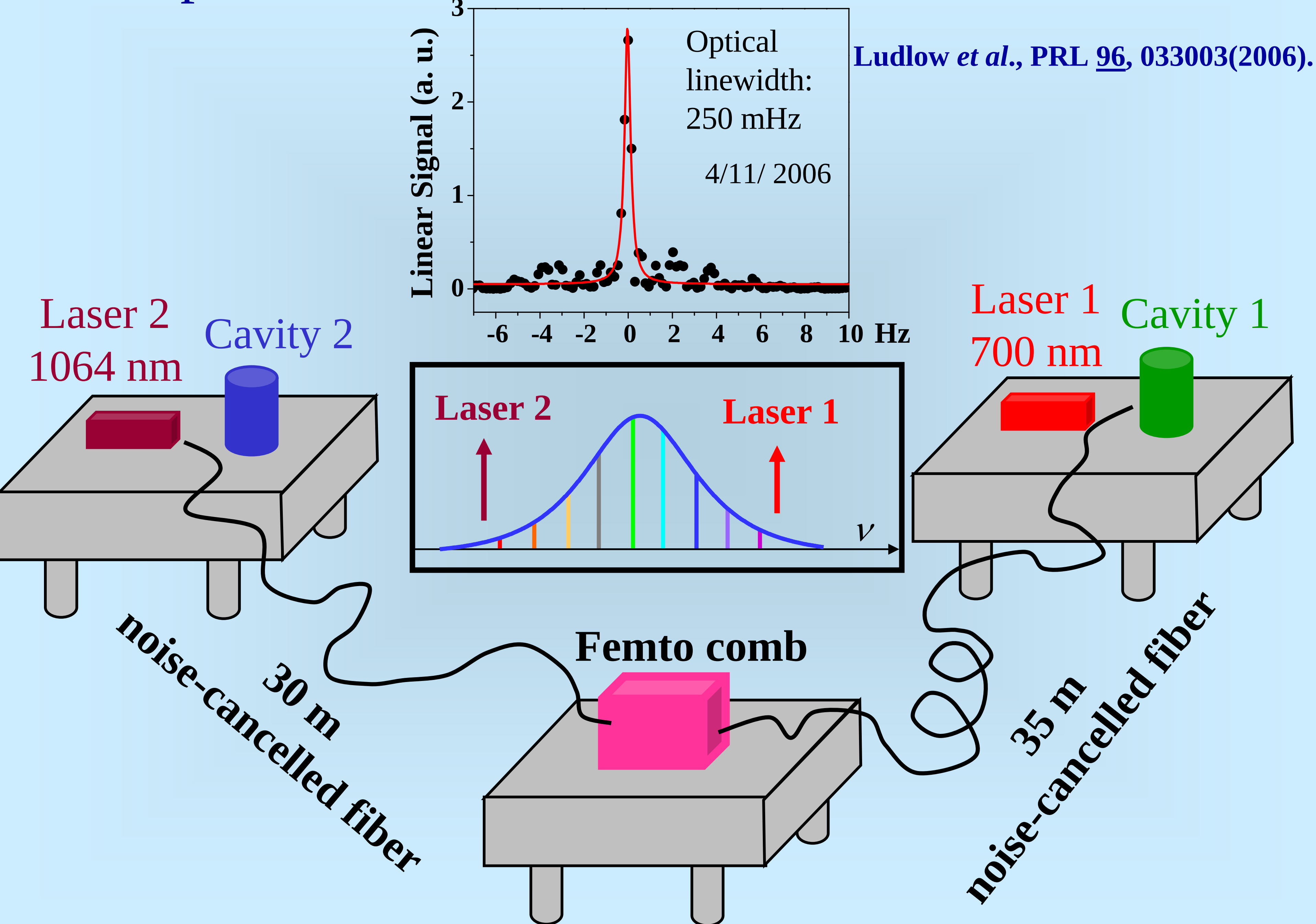


XUV comb

Jones *et al.*
PRL **94**, 193201 (2005).
C. Gohle *et al.*,
Nature 436, 234 (2005).

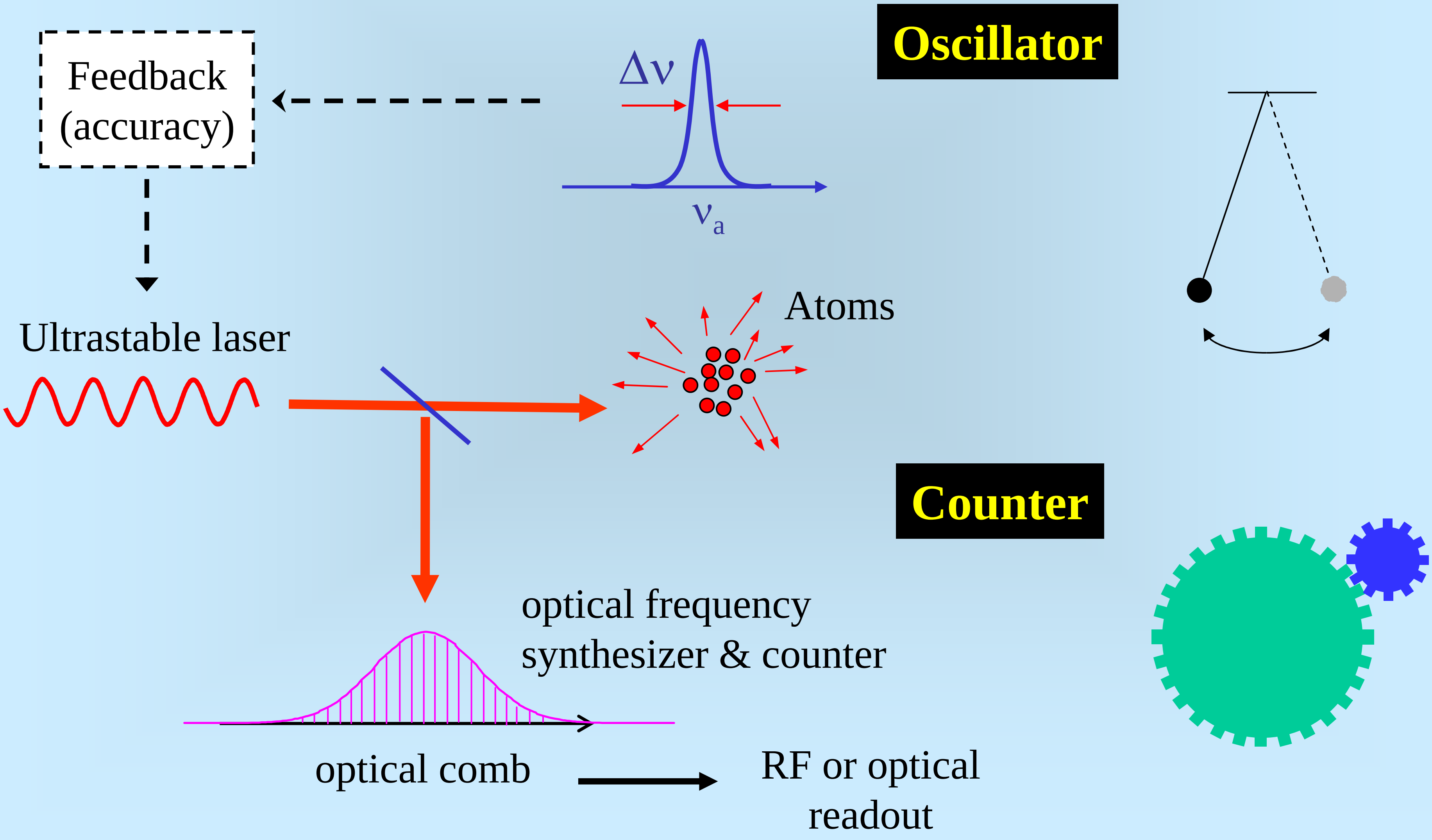
Optical coherence > 1 s, across entire visible

Ludlow *et al.*, PRL 96, 033003(2006).



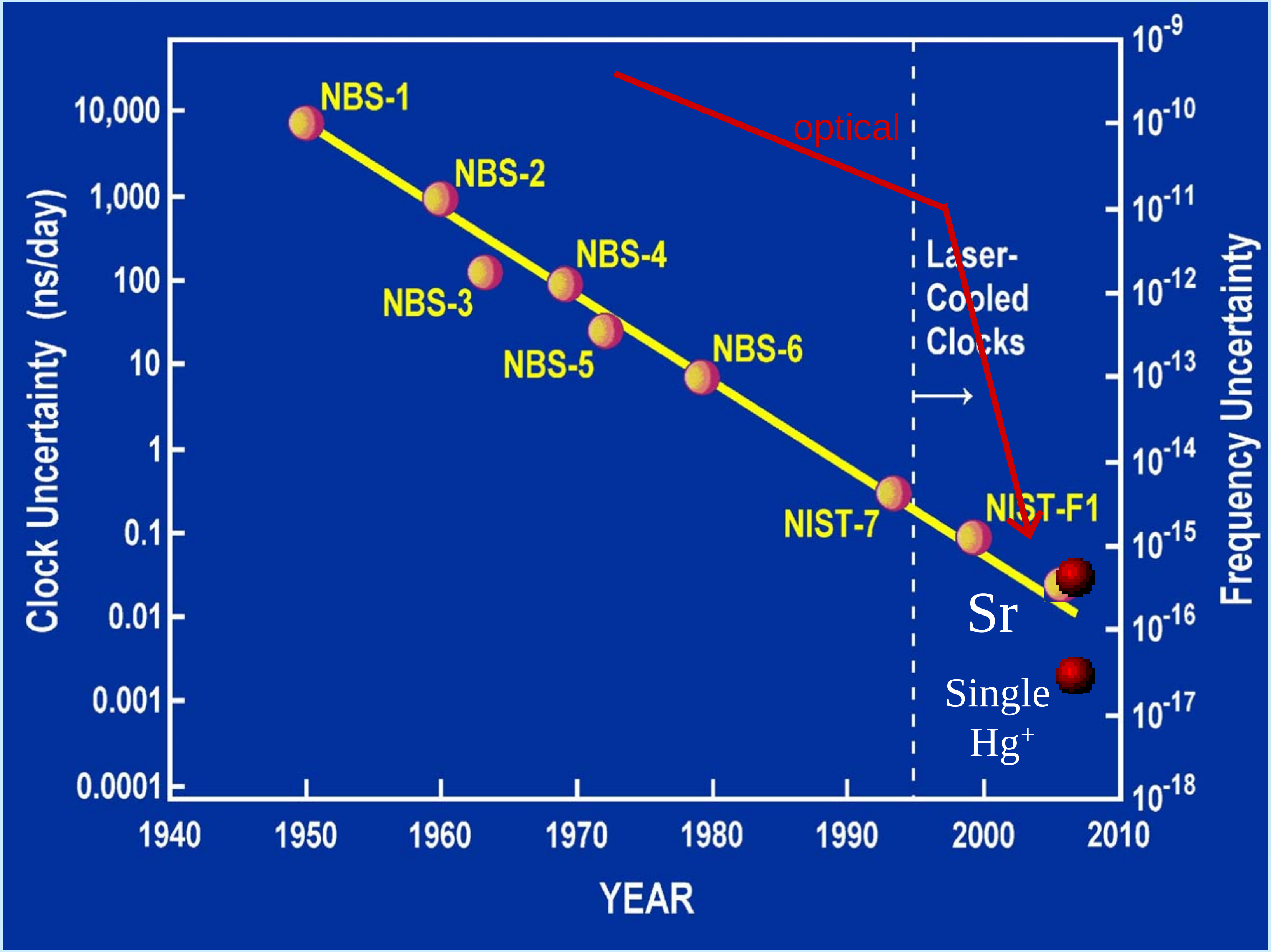
New era for optical atomic clocks

Diddams *et al*., Science 293, 825 (2001).
Ye *et al*, Phys. Rev. Lett. 87, 270801 (2001).



Accurate atomic clocks

Cs fountain: SYRTE, NIST, PTB, …



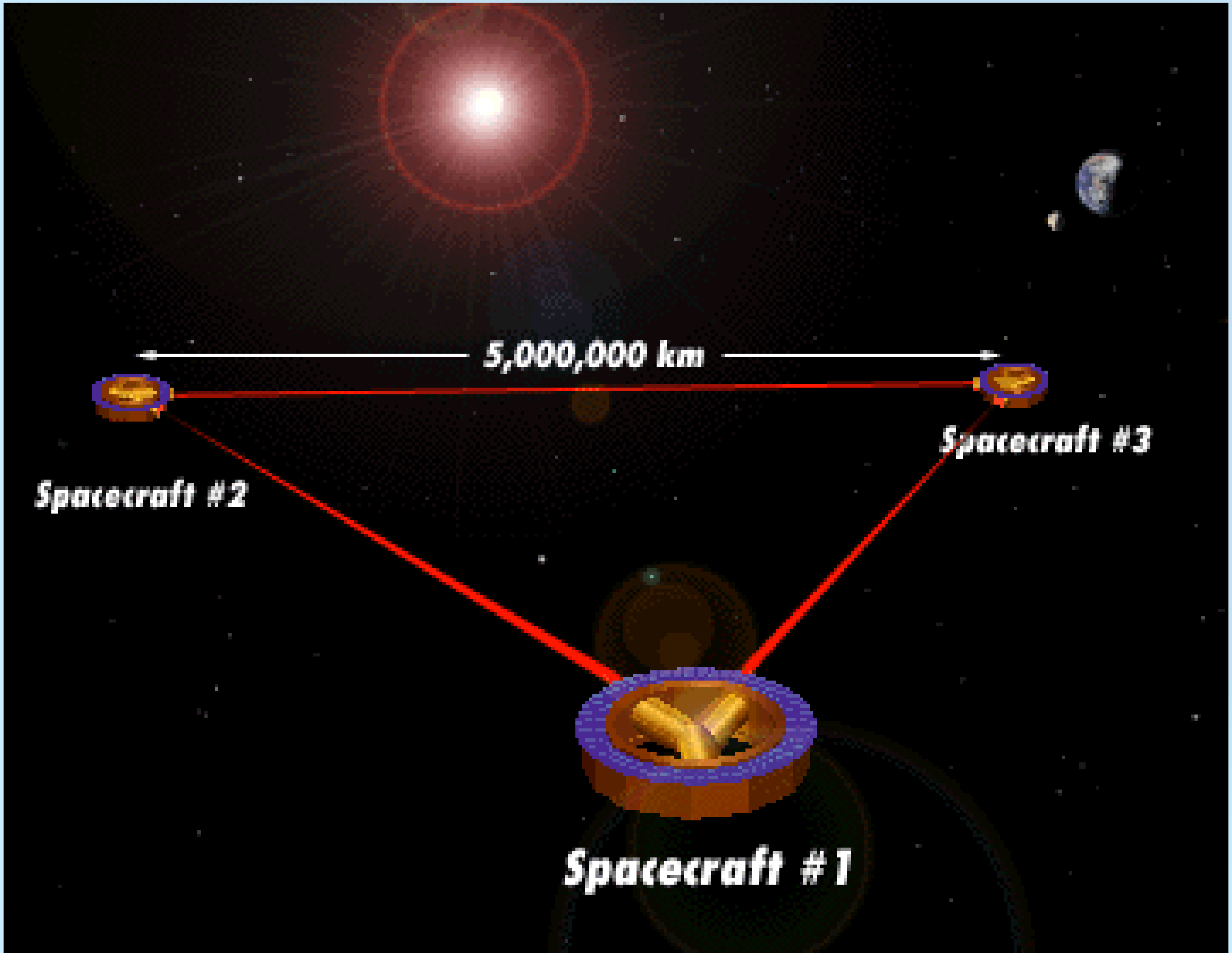
Yb^+, Sr^+, Al^+ …

All in one – Space Clock and Laser Ranging

Time meets length

Ye, Opt. Lett. 29, 1153 (2004).

Space based interferometer Courtesy of P. Bender



\+

Inertial
Sensor

Prof. G. Tino
PRL 2006

Control of matter
- Learning from ion trappers

Long - term quantum coherence:

Clean separation between internal & external degrees of freedom

Both in well defined quantum states

Magic wavelength dipole trap

Trapping of Single Atoms in Cavity QED

Ye, Vernooy & Kimble, Phys. Rev. Lett. 83, 4987 (1999).

that a judicious choice of λ_{FORT} can eliminate both of these problems by making $\Delta^{e}_{\mathrm{FORT}}(\vec{r}) = \Delta^{g}_{\mathrm{FORT}}(\vec{r}) < 0$, and hence $\Delta_{\mathrm{FORT}}(\vec{r}) = 0$ [24]. Alternatively, even for the

the capabilities presented in this Letter should allow us to achieve atomic confinement in the Lamb-Dicke regime (i.e., $\eta_x \equiv 2\pi\Delta x/\lambda \ll 1$) in a setting for which the trapping potential for the atomic center-of-mass motion is independent of internal atomic state, as has been so powerfully exploited with trapped ions [25]. Generally

For clocks:

Katori *et al.*, Katori et al., J. Phys. Soc. Jpn 68, 2429 (1999)
6th Symp. Freq. Standards & Metrology (2002);
Phys. Rev. Lett. 91, 173005 (2003).

Cool Alkaline Earth – Strontium

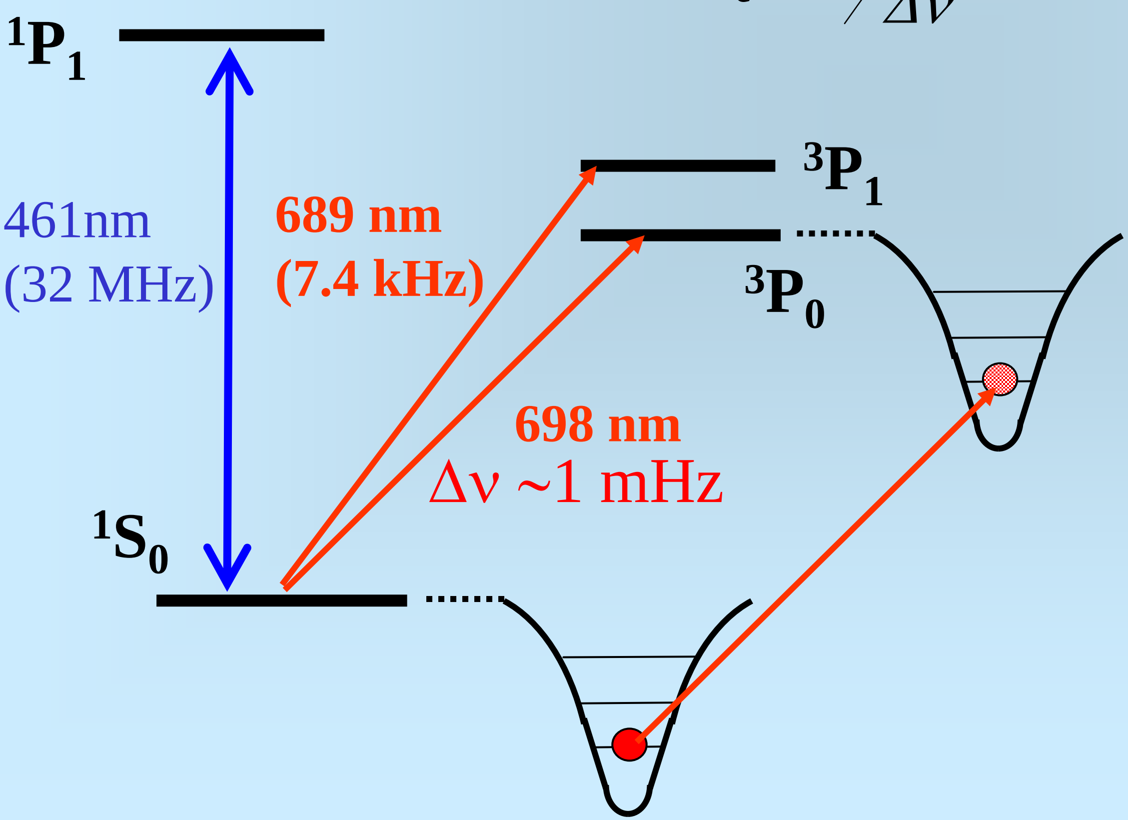
JILA work: Phys.Rev.Lett. <u>90</u>, 193002 (2003); Phys.Rev.Lett. <u>93</u>, 073003 (2004); Phys.Rev.Lett. <u>94</u>, 153001 (2005); Phys.Rev.Lett. <u>94</u>, 173002 (2005); Phys.Rev.Lett. <u>96</u>, 033003 (2006); Phys.Rev.Lett. <u>96</u>, 203201 (2006).

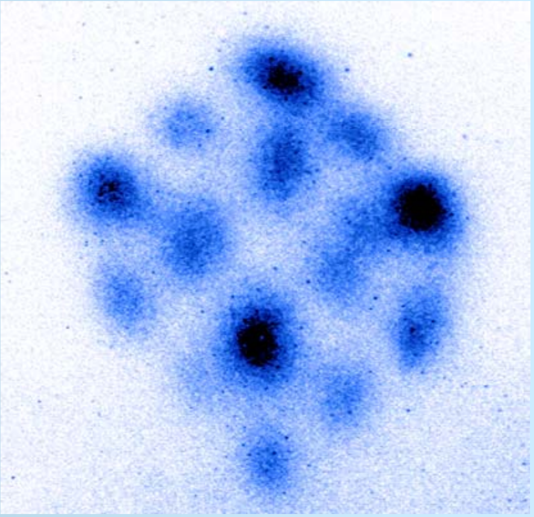
T ~ 0.5 photon recoil
~ 220 nK

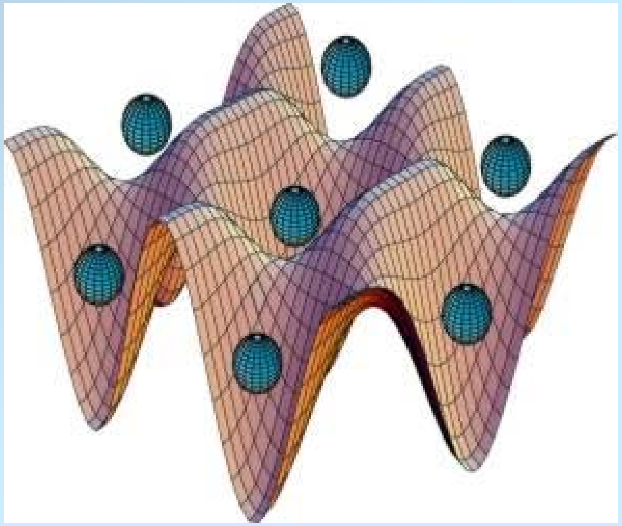
	$\Delta\nu$	$\delta\nu/\nu_0$ at 1s
$^{87}Sr\ ^1S_0$-$^3P_0$	~ 1 mHz	$\sim 10^{-18}$

$$\frac{\delta\nu_{noise}}{\nu_0} \approx \frac{1}{Q} \cdot \frac{1}{S/N} \cdot \frac{1}{\sqrt{\tau}}$$

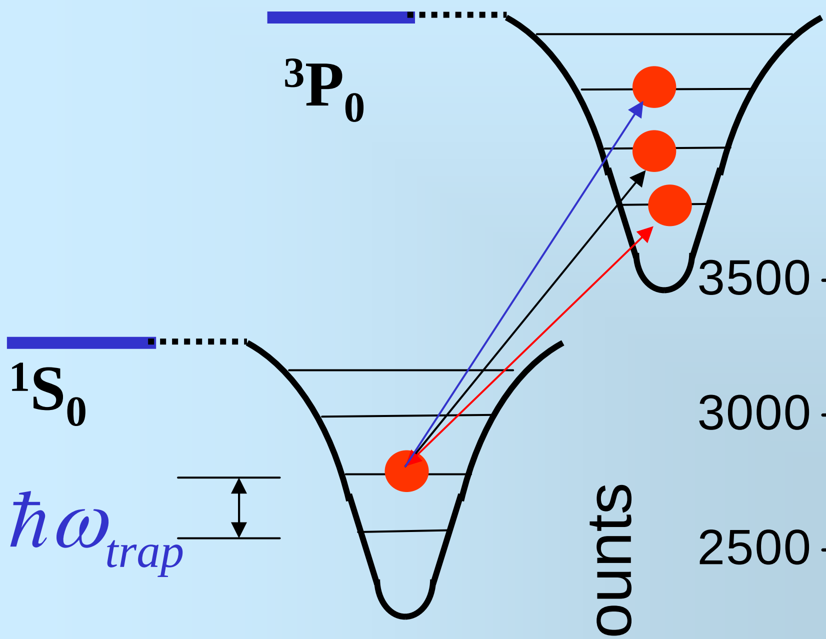
$$Q \approx \nu_0 / \Delta\nu$$





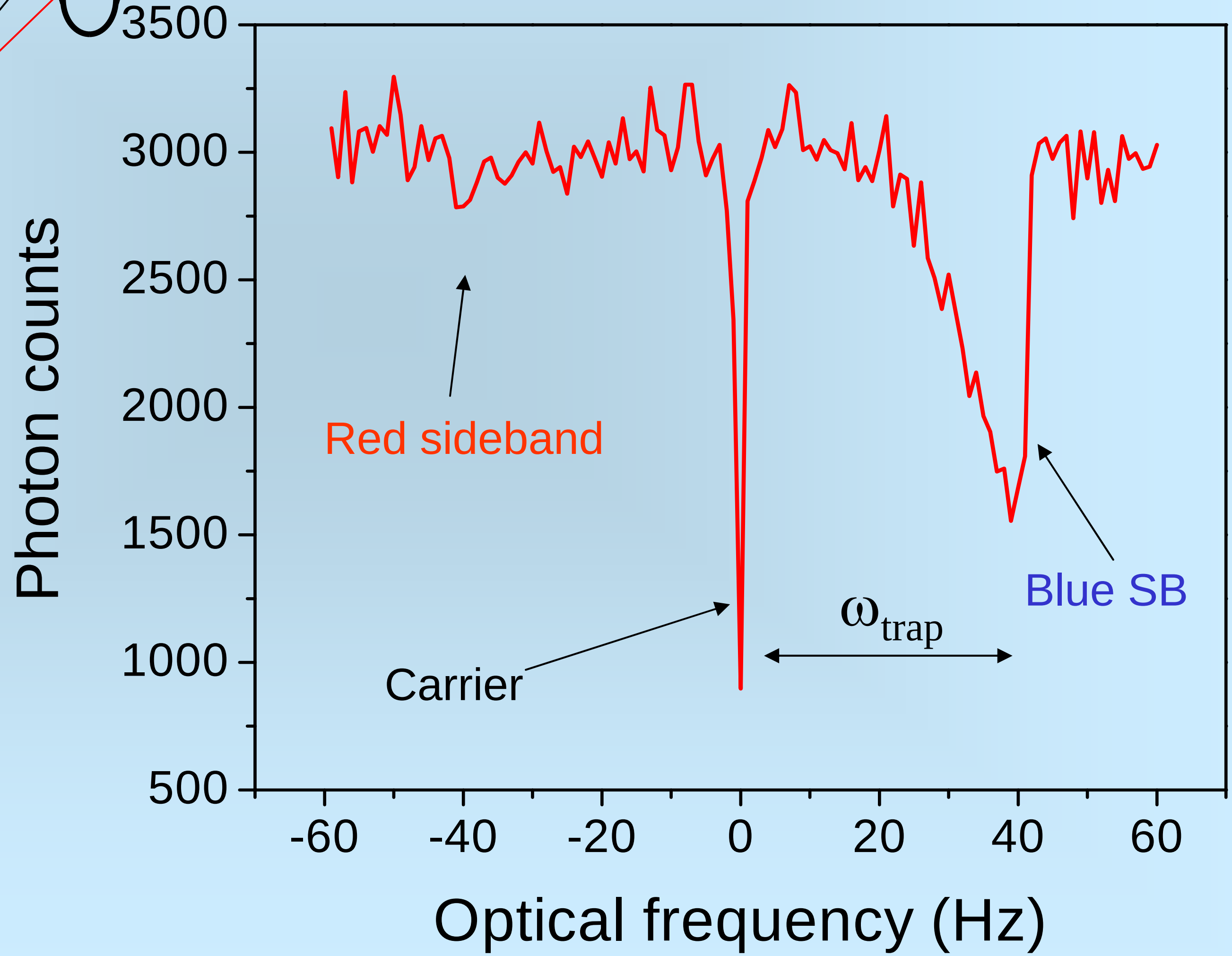


Spectroscopy at the magic wavelength



1-D Lamb-Dicke Regime

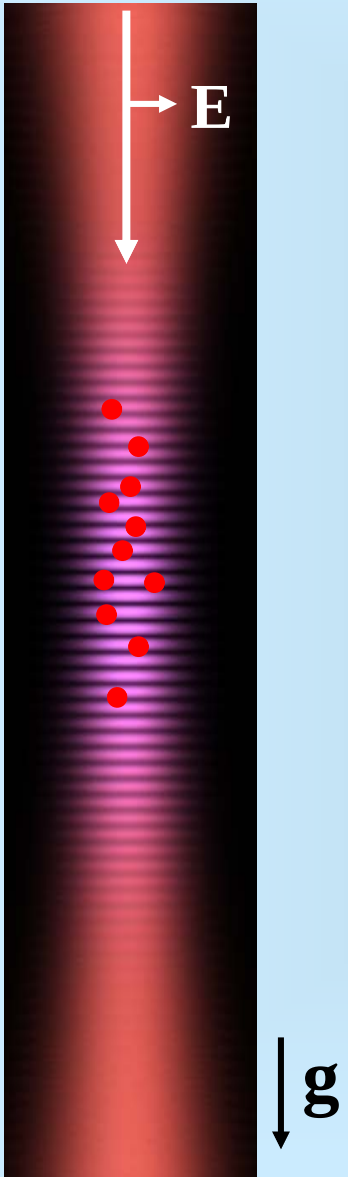
$\eta = kx_0 = (\omega_{recoil} / \omega_z)^{0.5} \sim 0.23$

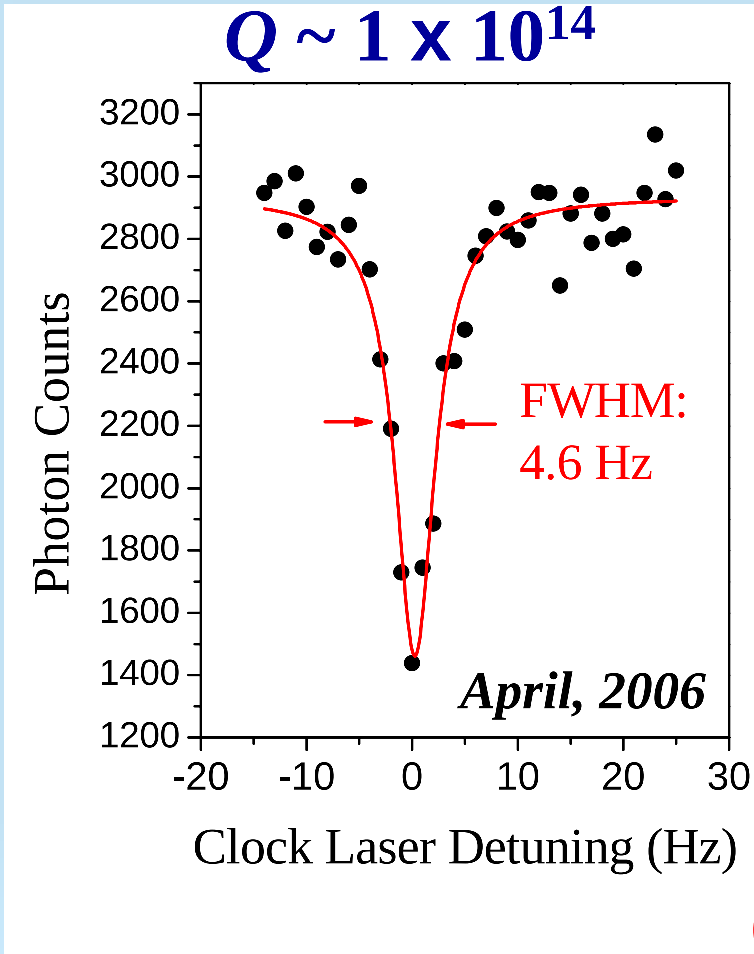


$\omega_{recoil} << \omega_{trap}$

$\Gamma_{clock} << \omega_{trap}$

Zoom into the carrier of ^{87}Sr $^1S_0 - {}^3P_0$





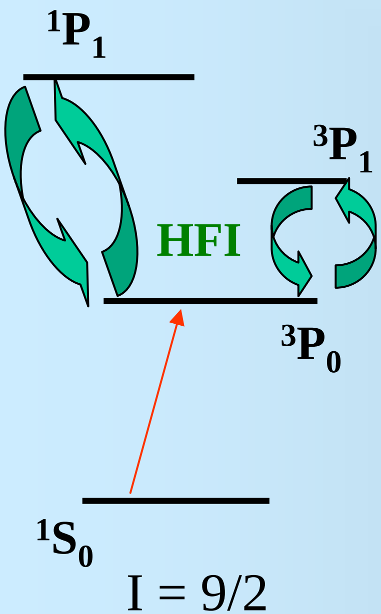
Single trace without averaging

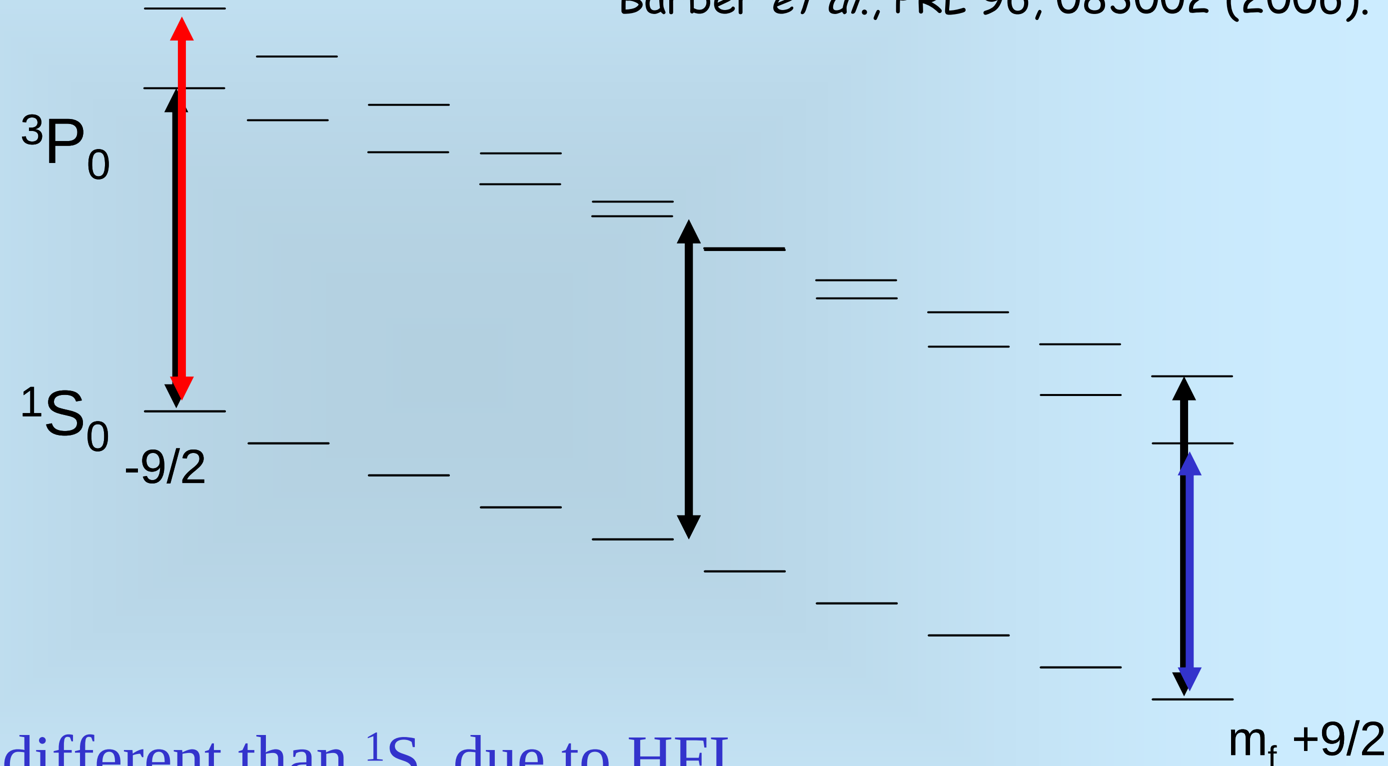
Projected stability $< 1 \times 10^{-15}$ at 1 s

Reproducibility $\sim 6 \times 10^{-16}$ (March – September, 2006)

Differential g-factor – Tensor polarizability

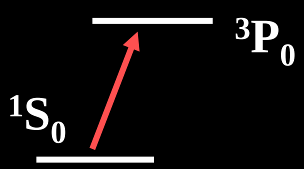
Proposals based on Bosons:
Santra *et al.*, PRL 94, 173002 (2005).
Hong *et al.*, PRL 94, 050801 (2005).
Barber *et al.*, PRL 96, 083002 (2006).





- $^3P_0$ g-factor different than $^1S_0$ due to HFI
- Shift of ~110 x m_F Hz/Gauss for Δm_F=0
- State preparation, field control
- HF structure introduces slight lattice polarization sensitivity

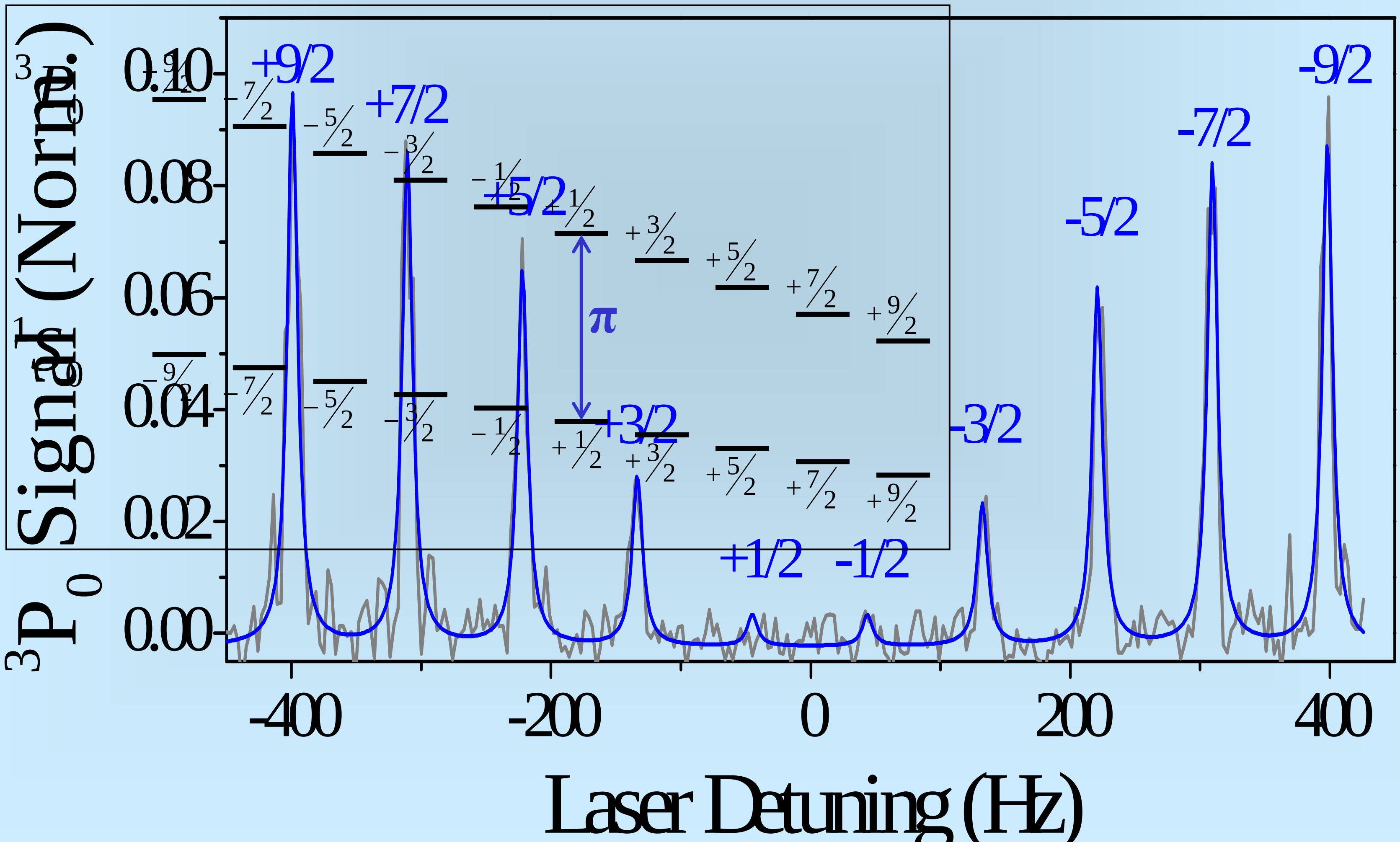
Optical Measurement of Nuclear *g*-factor



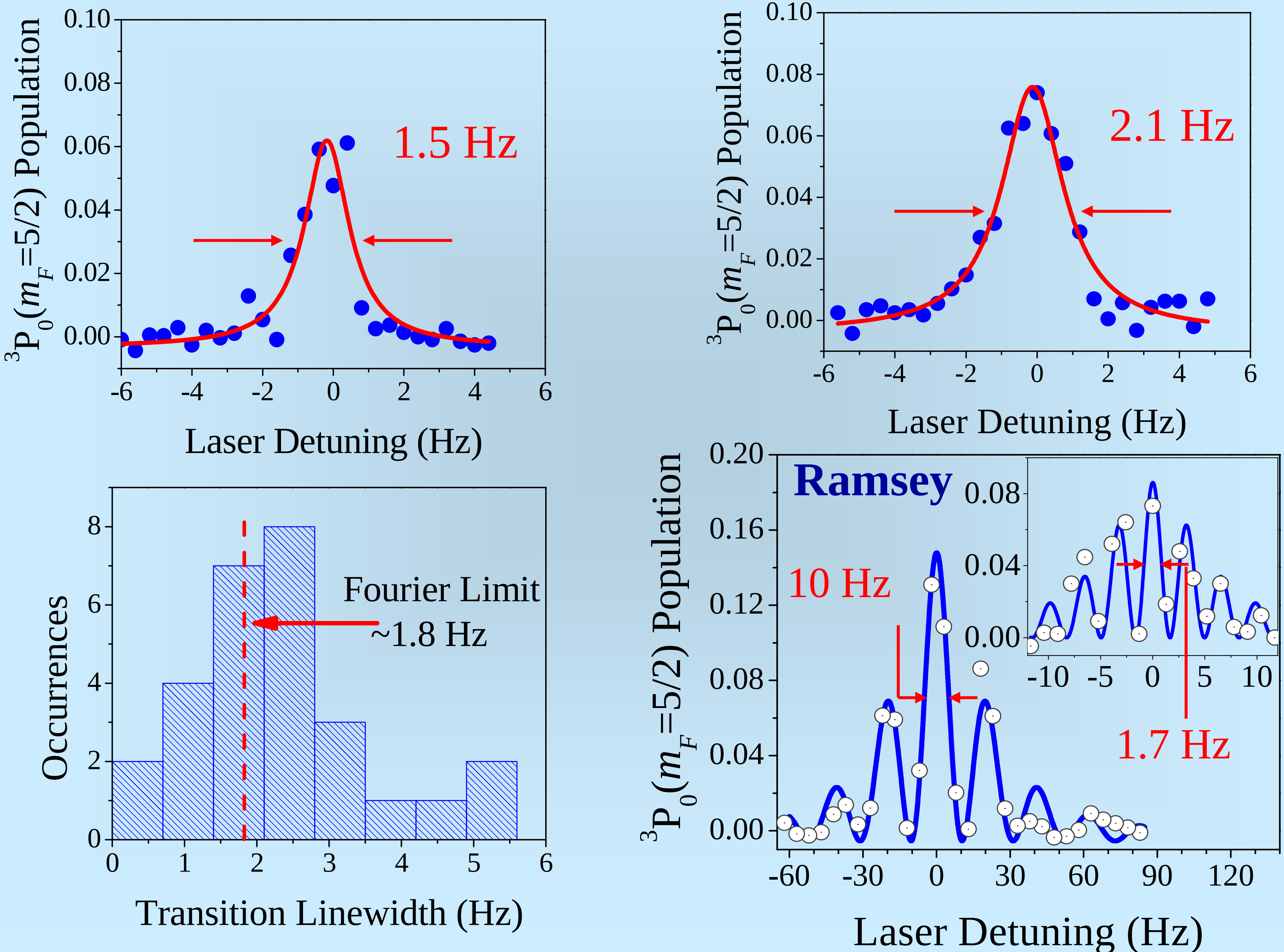
No net electronic angular momentum

Δg = -108.5(4) Hz/(G m_F)

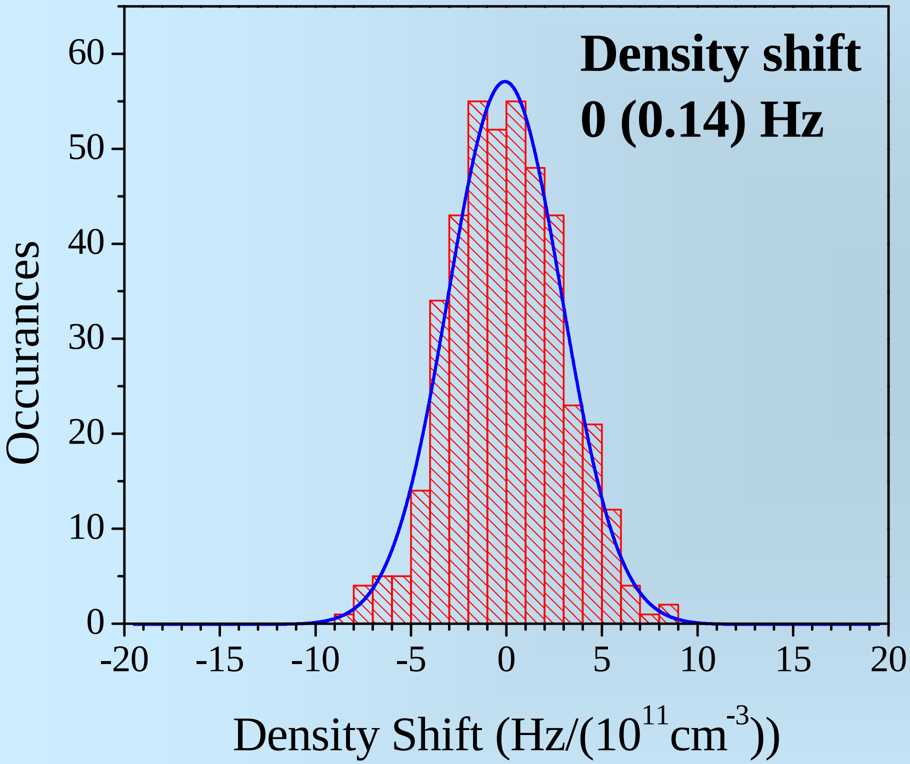
$^3P_0$ lifetime 140(40) s

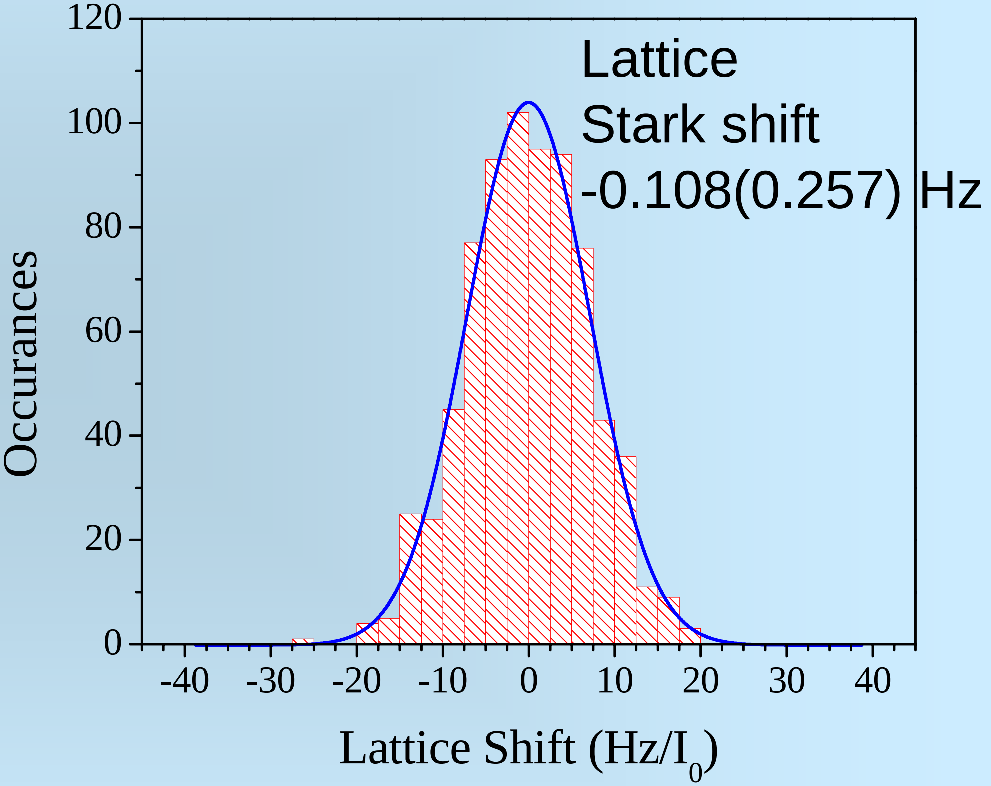


Coherent spectroscopy Q ~ 3 x 10^14



Understanding systematics: Collision shift and Lattice AC Stark shift





Total uncertainty 0.29 Hz → 6.7 x 10^{-16}

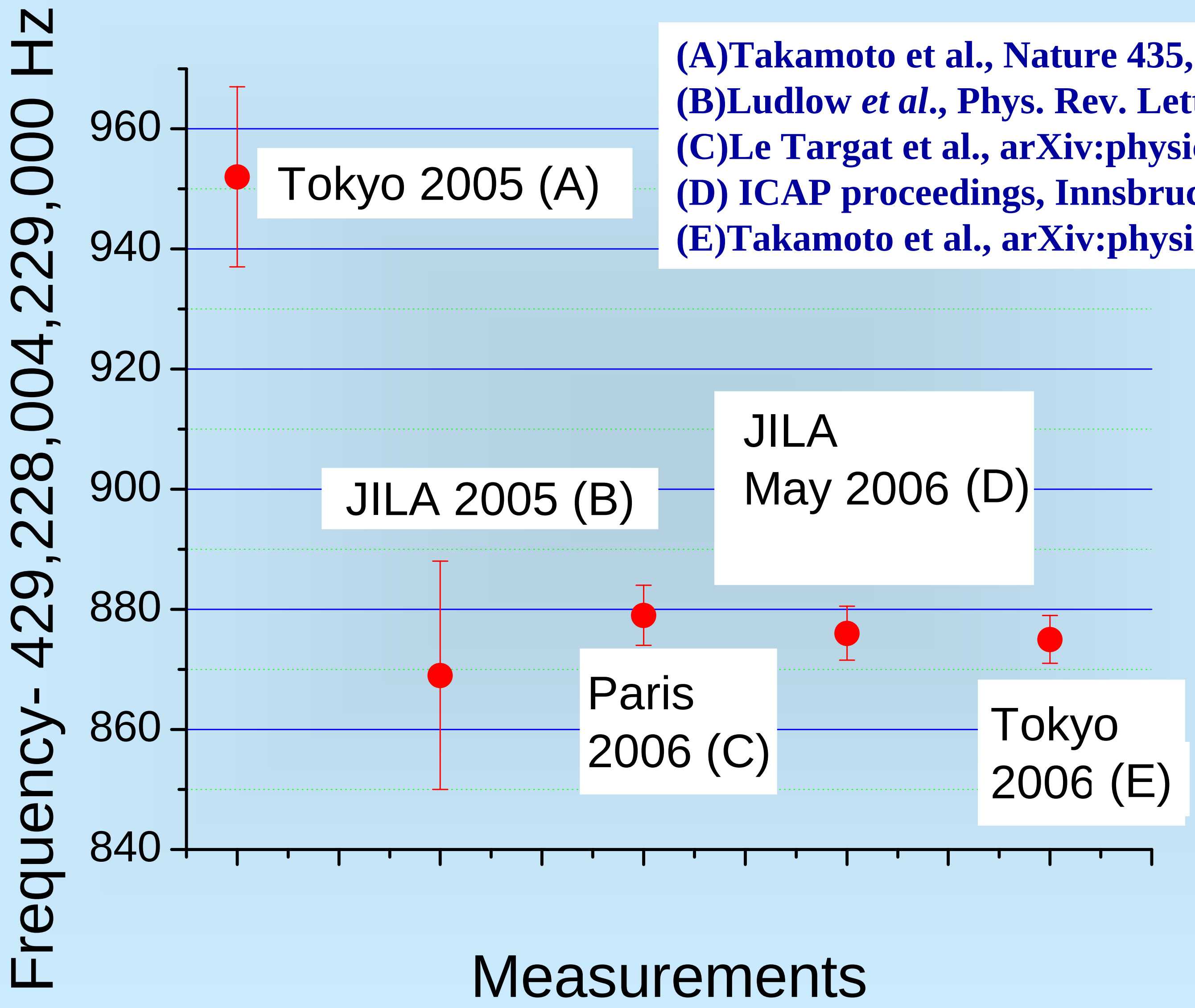
Systematic uncertainty evaluations

Zeeman shift,	0.10 Hz,	2.3 E-16
Lattice AC Stark,	0.26 Hz,	6.0 E-16
Atom density shift,	0.14 Hz,	3.3 E-16
Probe AC Stark,	0.05 Hz,	1.0 E-16
Blackbody	0.03 Hz	0.7 E-16
Systematic Total	***0.39 Hz***	***7.3 E-16***

For Absolute frequency measurement against Cs:

Gravitational shift	3.0 E-16
Counting statistics	6.0 E-16
NIST Maser calibration	2.0 E-15 ←
Measurement uncertainty Total	***2.2 E-15***

Agreement among Boulder, Paris, and Tokyo

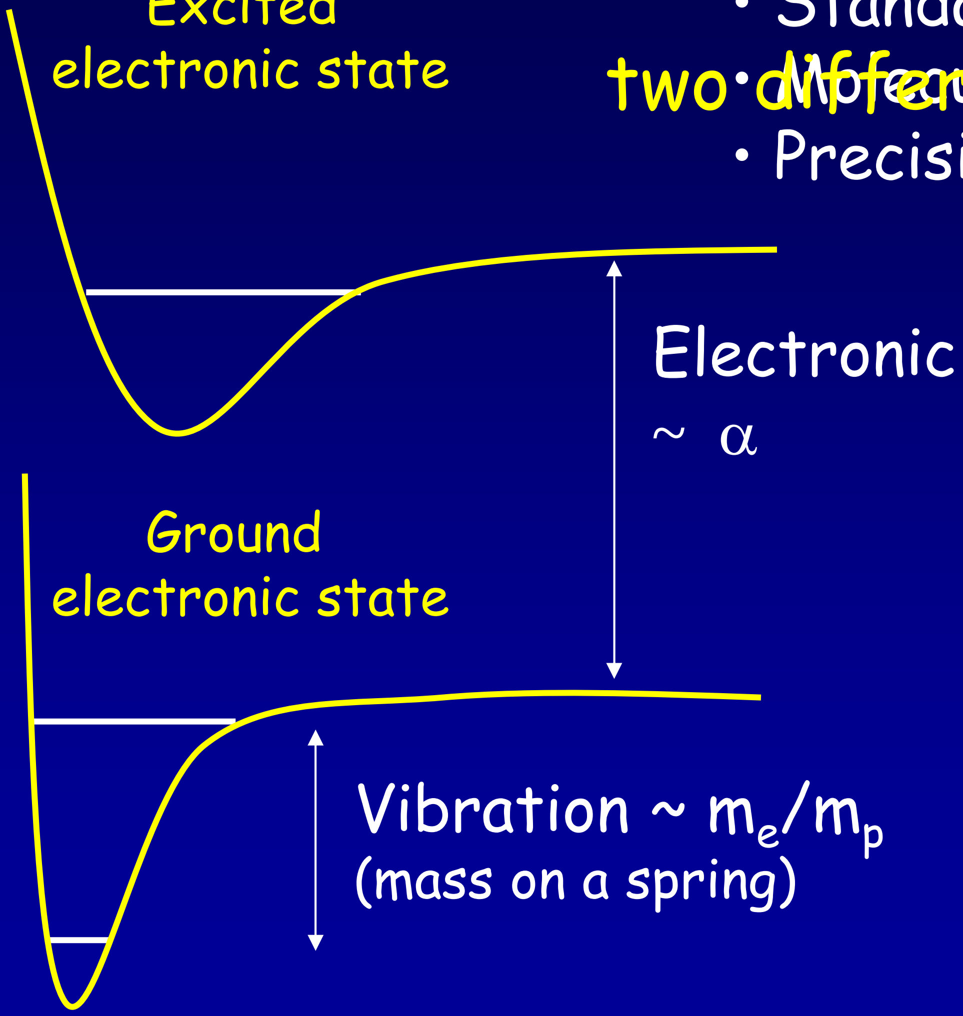


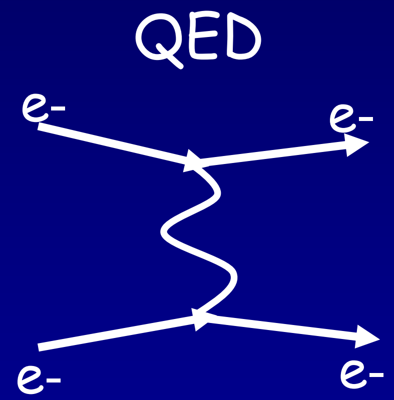
(A)Takamoto et al., Nature 435, 321 (2005).
(B)Ludlow *et al*., Phys. Rev. Lett. 96, 033003 (2006).
(C)Le Targat et al., arXiv:physics/0605200
(D) ICAP proceedings, Innsbruck, July 2006.
(E)Takamoto et al., arXiv:physics/0608212

Ultracold molecules: Test fundamental principles

- Ultrahigh resolution spectroscopy
- Standards in wide spectral ranges
- Molecular interferometry
- Precision measurement

One system,
two different fundamental forces!

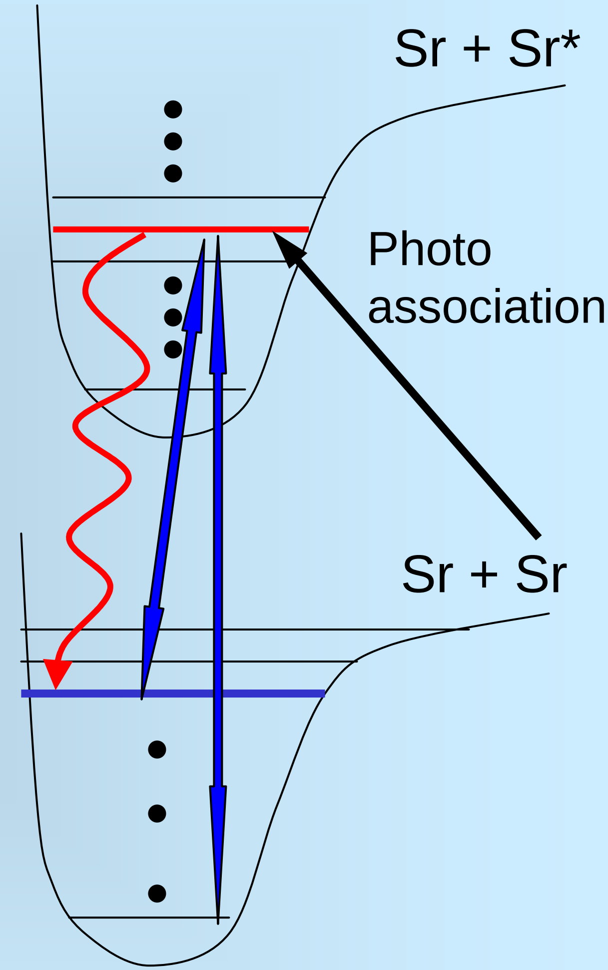




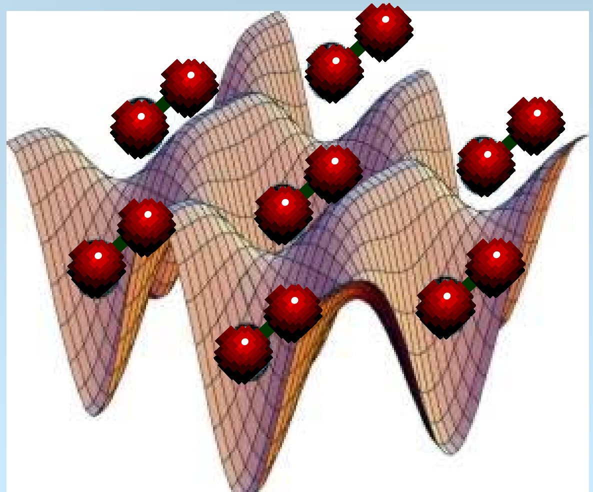
Ultracold Sr_2 Molecules in Lattice

- Narrow lines
  – Favorable decay to electronic ground state

- Structureless ground state
  – Small branching ratio losses

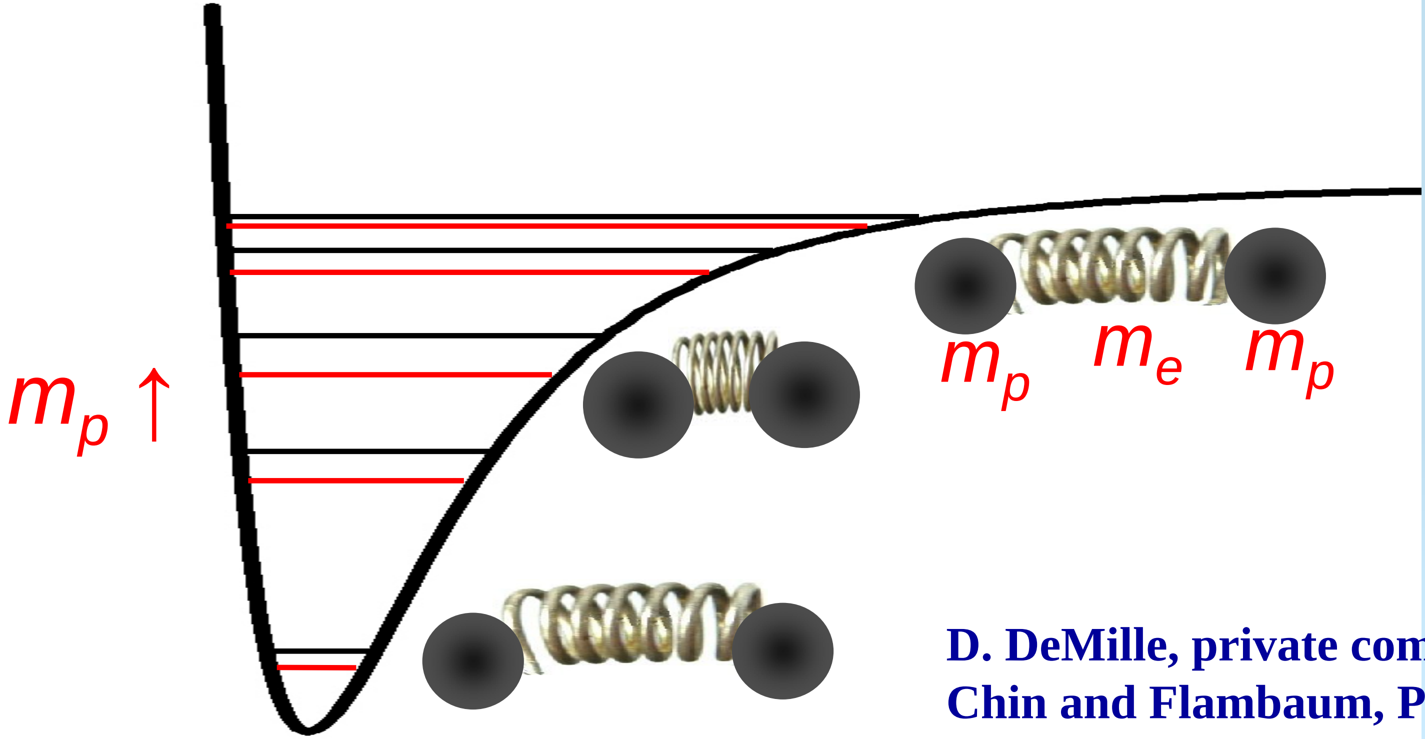


Raman transition for ground state production



Molecular Clock – Sensitivity to Mass Ratio

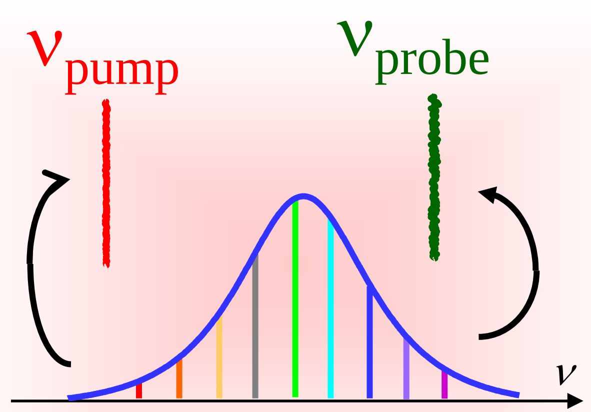
- Molecular potentials depend on electron mass, m_e
- Kinetic energy depends on proton mass, m_p
- Vibrational spacings depend on m_p / m_e
- **Precision tests of time variation of m_p / m_e?**



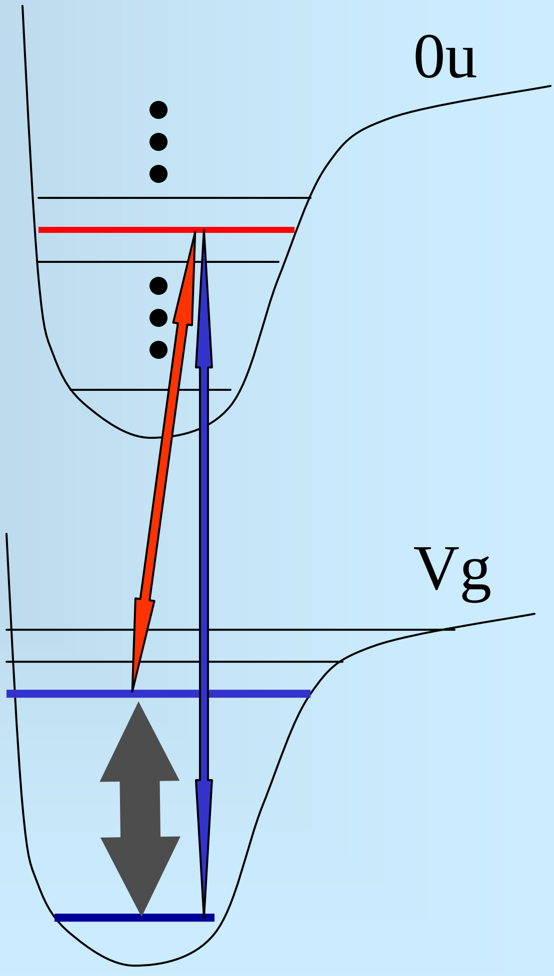
D. DeMille, private communications (2005).
Chin and Flambaum, PRL 96, 230801 (2006).
S. Schiller, molecular ions

Mass ratio tests

- Homonuclear molecules are best
- Relative Raman frequency measurement 0.3 Hz (fs comb), potential depth 3×10^{13} Hz → 1×10^{-14}
- Atomic clocks: 6×10^{-15} / year, but model-dependent, mainly QED effects

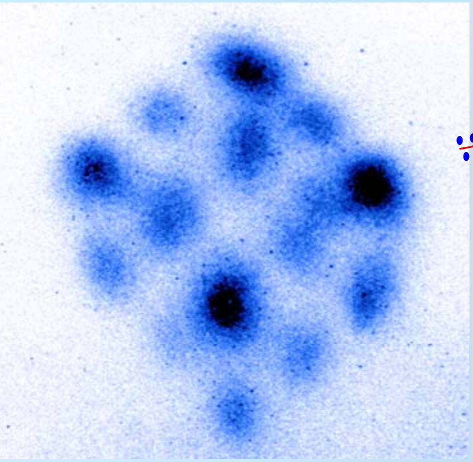


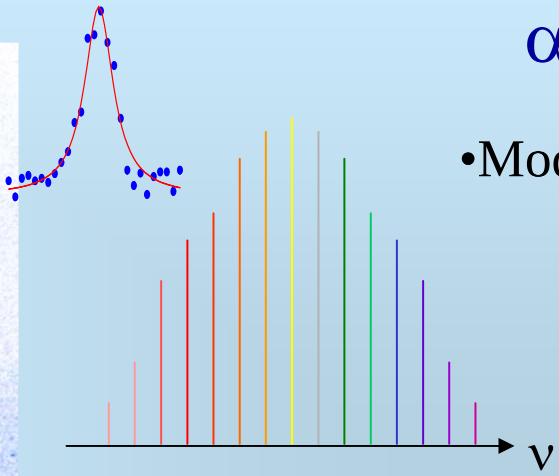
$\delta(\nu_{pump} - \nu_{probe}) < 0.5$ Hz



Test of fundamental constants

α: fine structure constant

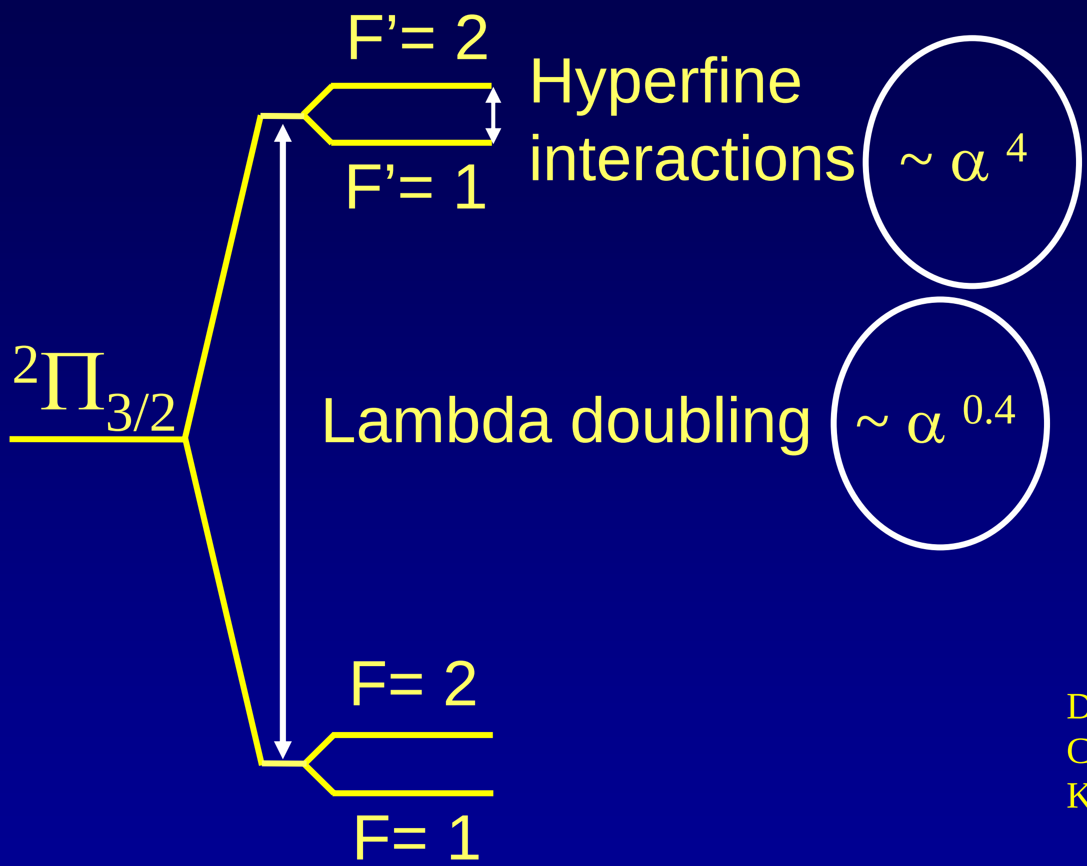




- Modern epoch
  - Atomic clock measurements are consistent with zero
    $\Delta\alpha/\alpha < 10^{-15}$/yr

- Early universe
  - Not so clear…
    Webb *et al*., PRL 87, 091301 (2001).
    Astron. Astrophys. 415, L7 (2004).
    – Conflicting results

Cold OH molecules to constrain $\dot{\alpha}$



OH megamasers

Darling, Phys. Rev. Lett **91**, 011301 (2003).
Chengalur *et al*., Phys. Rev. Lett. 91, 241302 (2003).
Kanekar *et al*., Phys. Rev. Lett. **93**, 051302 (2004).

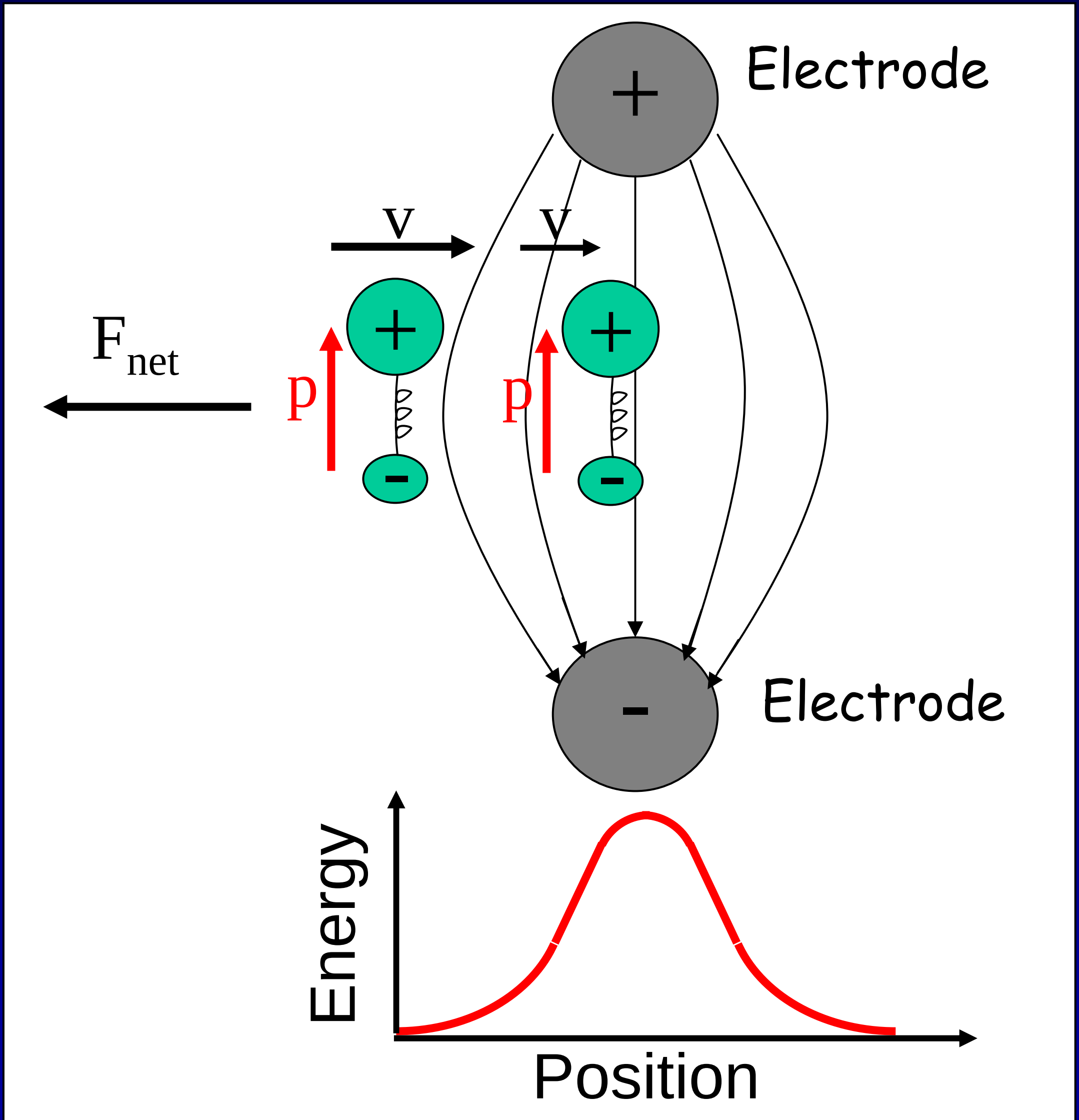
Multiple transitions from the same gas cloud (different dependences on α)
(Self check on systematics)

Current uncertainly in laboratory based experiments is 100 Hz, leading to $\Delta\alpha/\alpha \sim 10^{-5}$

ter Meulen & Dymanus, Astrophys. J. **172**, L21(1972).

Stark deceleration

Direct manipulation of ground state molecules



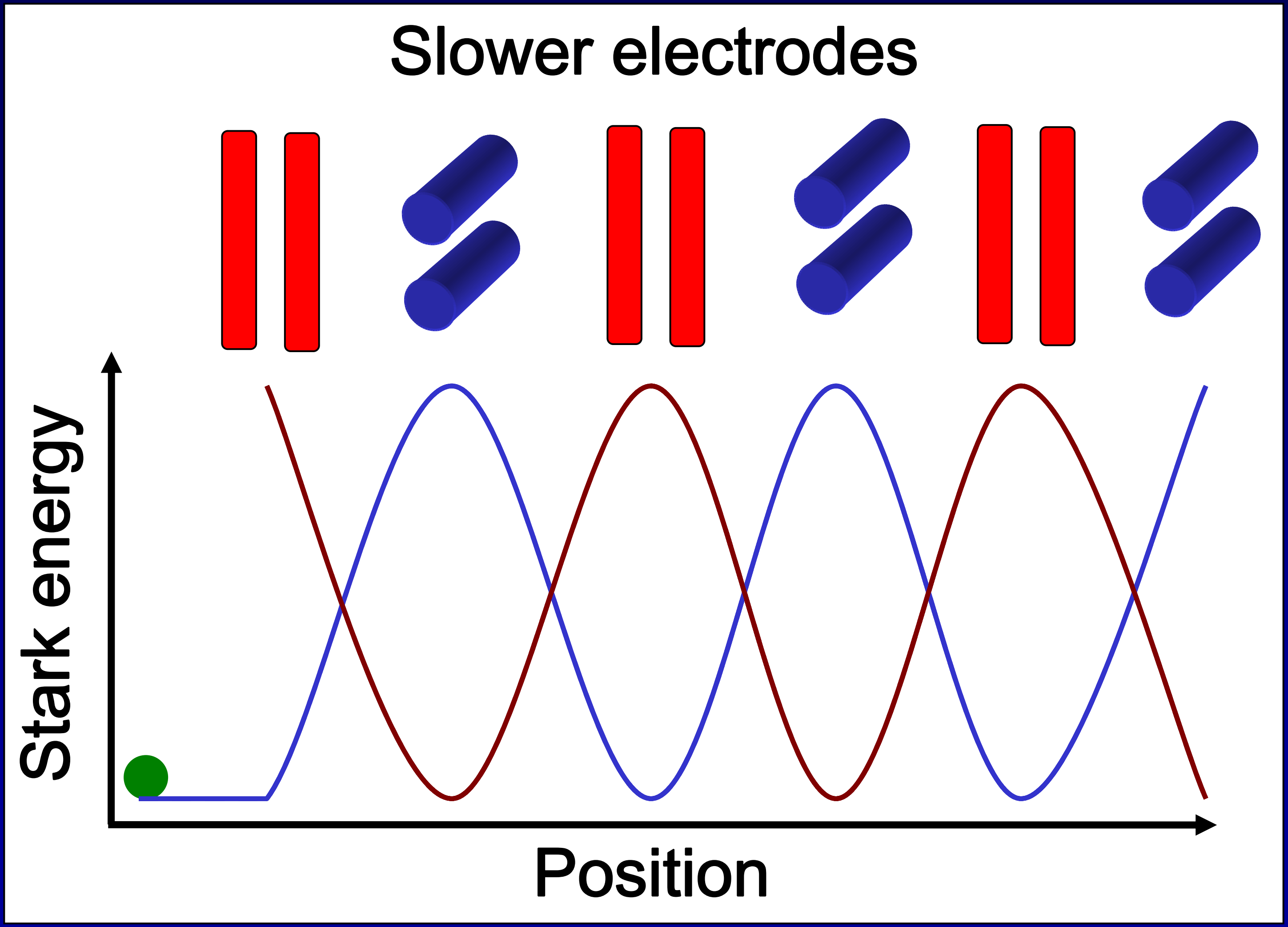
Initial cooling important (supersonic jets: single internal quantum state; external temp. ~ 1 K in a moving frame)

Phase space selection (~ 10 mK)

Applicable to a large variety of polar molecules

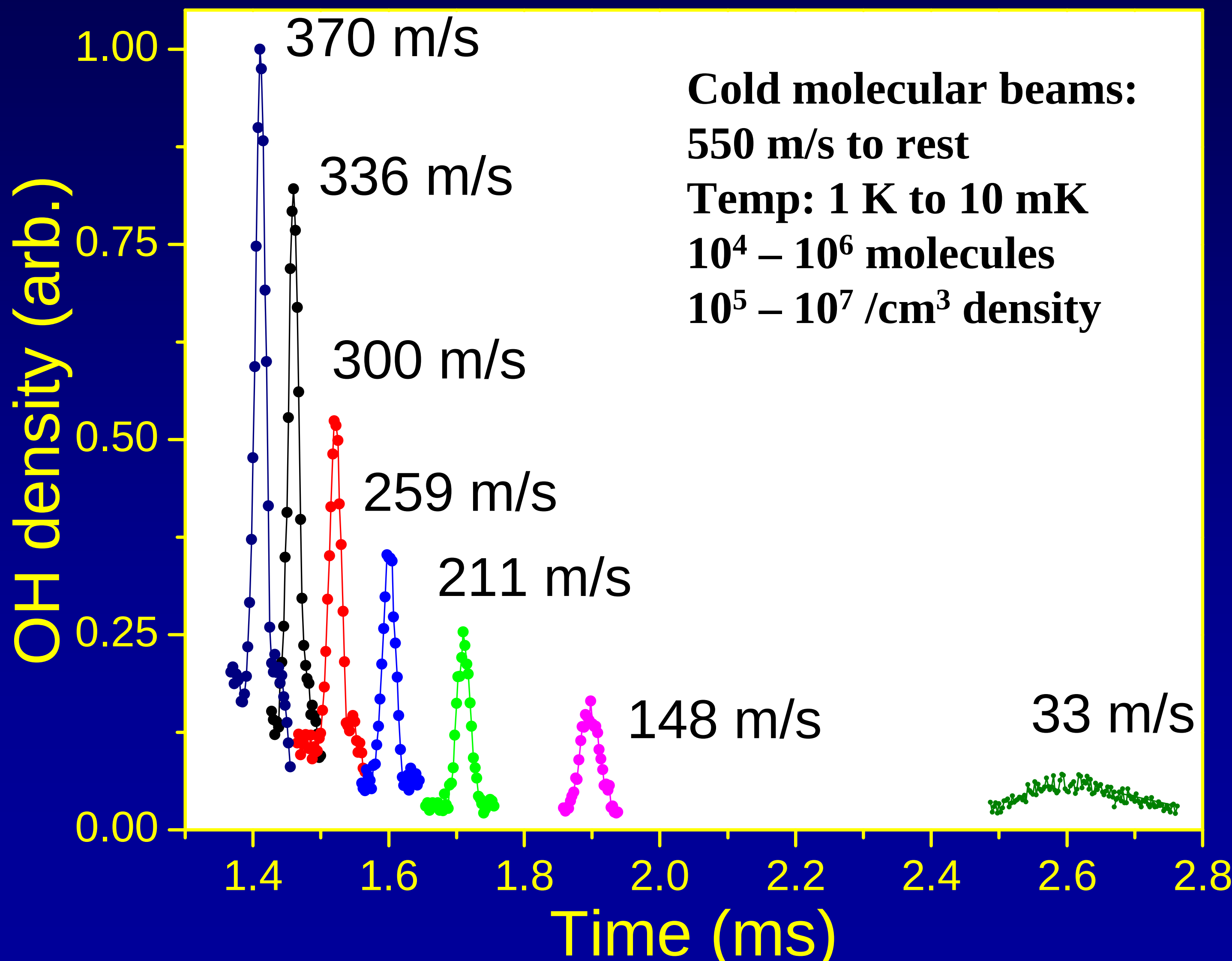
Bethlem, Berden, Meijer, Phys. Rev. Lett. **83** 1558 (1999).

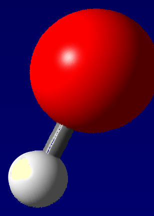
Stark Decelerator



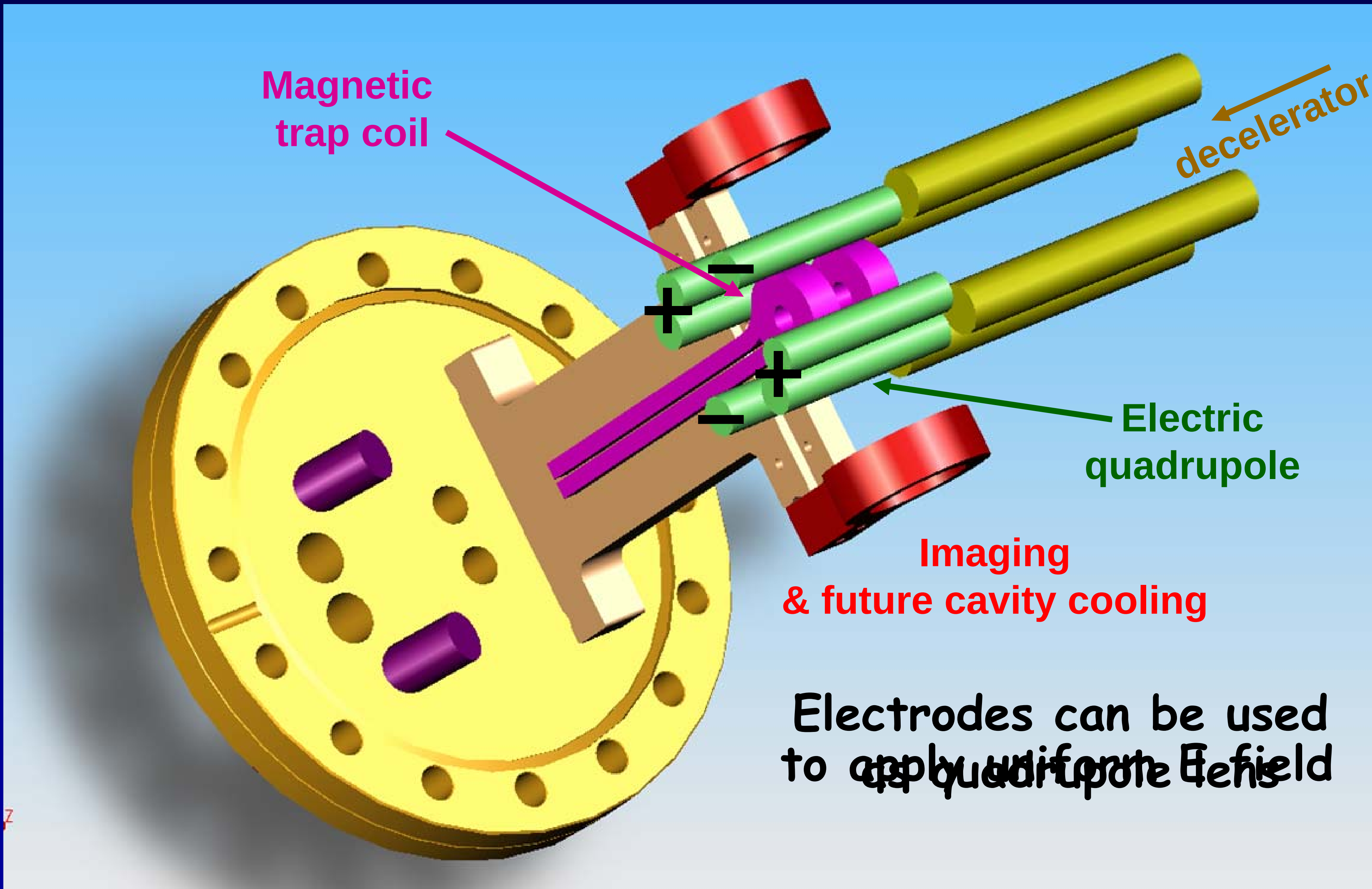
Cold OH molecules

Bochinski *et al.*, Phys. Rev. Lett. **91**, 243001 (2003).
Bochinski *et al*, Phys. Rev. A **70**, 043410 (2004).

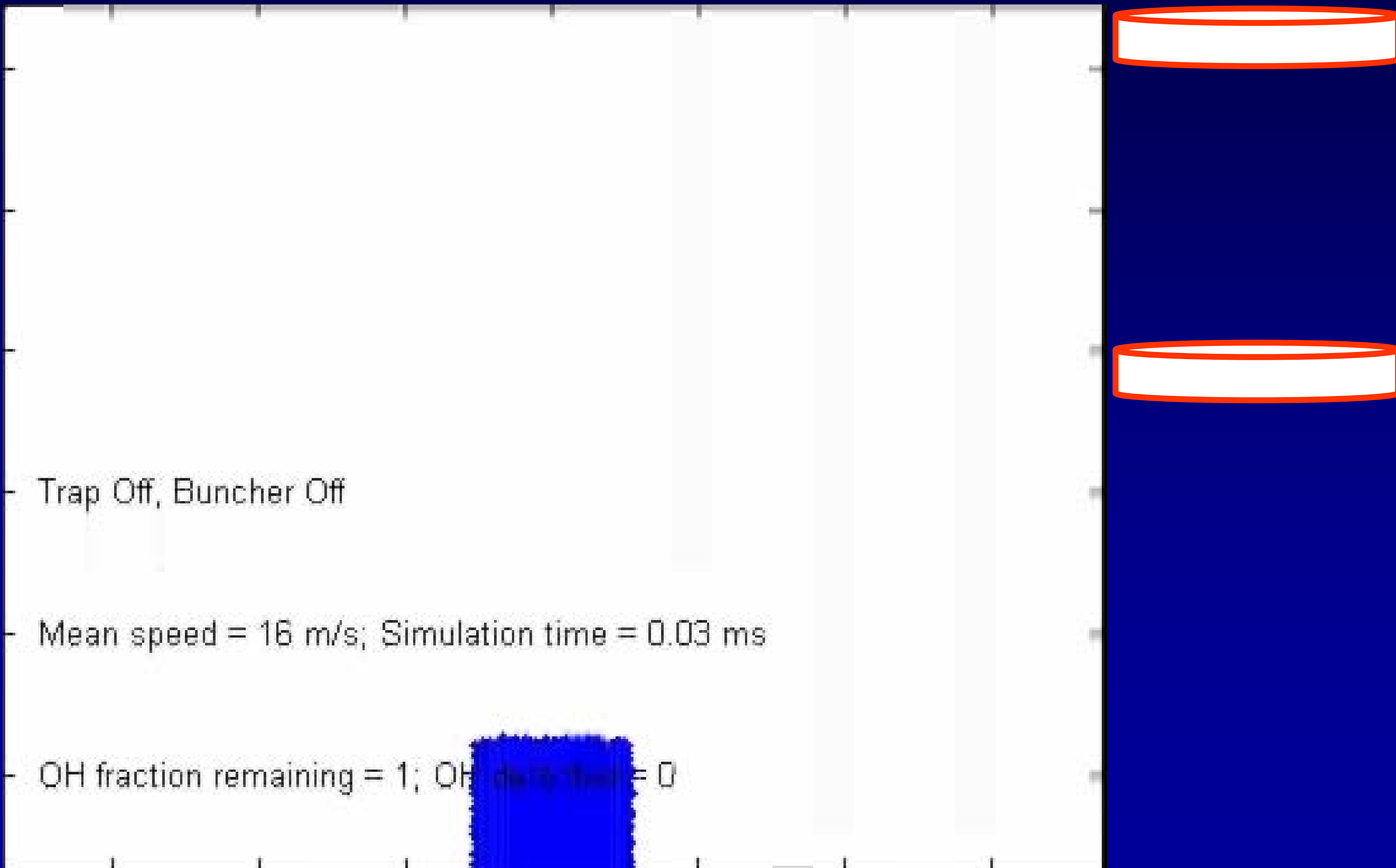




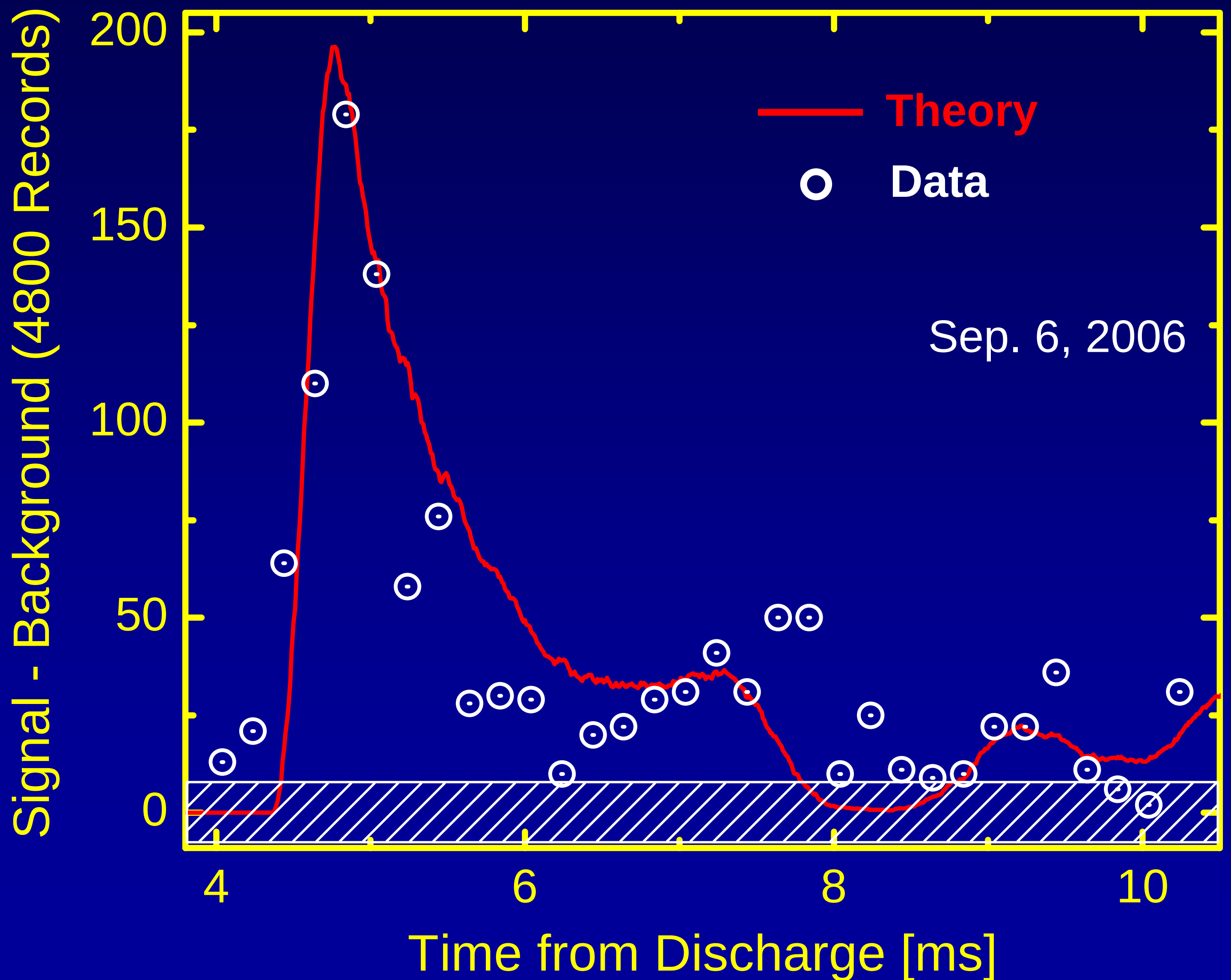
Magnetic trapping of OH



Magnetic trapping of OH



Magnetic trapping of OH



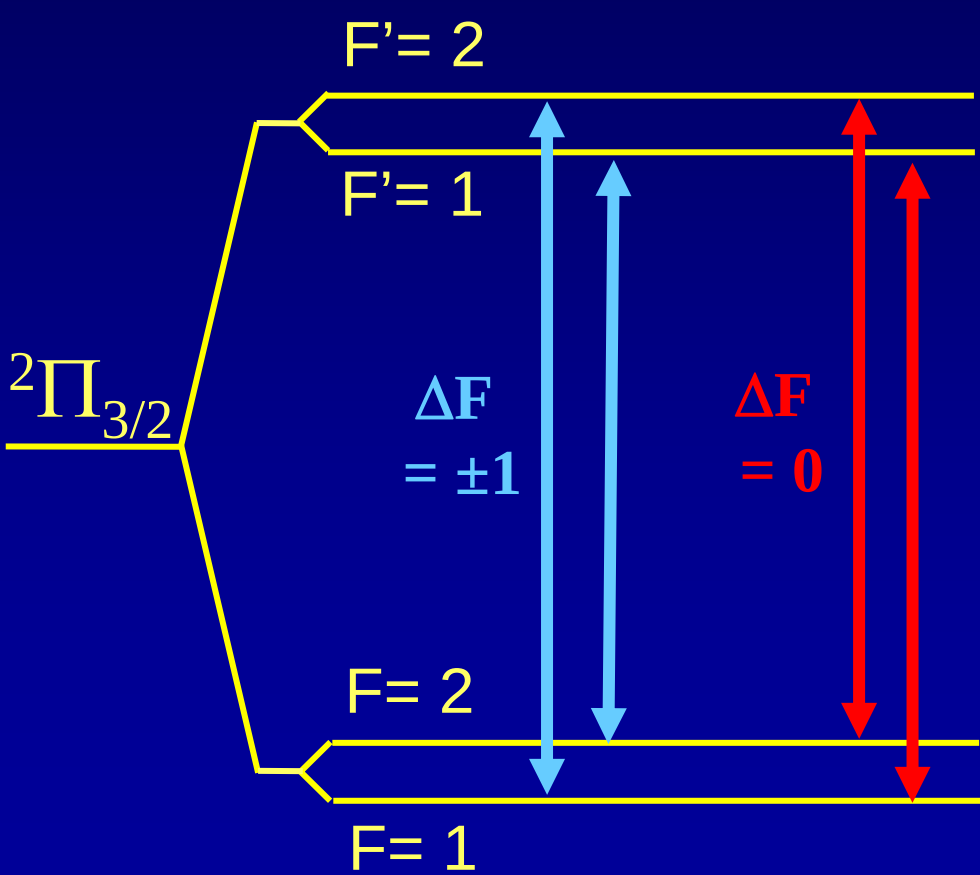
Precision measurement of OH ground structure

Measurement accuracy for all four lines: 4 – 10 Hz (x10 improvement)

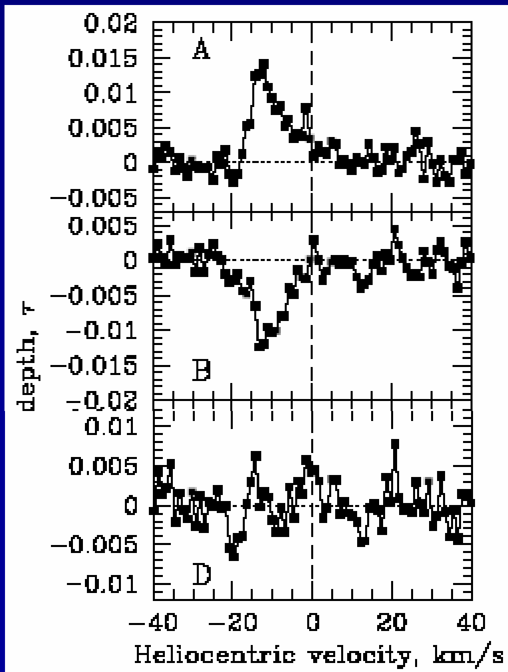
Hudson *et al.*, Phys. Rev. Lett. 96, 143004 (2006).

Lev *et al.*, arXiv:physics/0608194, August 2006.

- SUM (2 satellites) = SUM (2 main lines)
- Satellites calibrate B
- Observed satellites conjugate



Kanekar *et al.*, PRL 93, 051302 (2004).



What about space?

Possible sources of error:

- EM fields in space
- Varying Doppler effects for different lines

Solutions:

Main lines versus satellite lines

Emission and conjugate absorption

OH sum rule

Astrophysical measurements coming under 100 Hz accuracy.

Deep surveys of OH megamasers are active from the local Universe to red shift z ~ 4.

Tests on $\Delta\alpha / \alpha$ and $\Delta\beta / \beta$ ($\beta = m_e/m_p$) at 1 ppm over 10^{10} yr.

Special thanks

http://jilawww.colorado.edu/YeLabs

Ultracold Sr & Sr_2

M. Boyd
A. Ludlow
S. Blatt
Dr. T. Zelevinsky
Dr. T. Zanon
Dr. T. Ido (Tokyo)

Cold Polar Molecules

B. Sawyer
B. Stuhl
Dr. B. Lev
E. Hudson (Yale)

Femtosecond comb & Quantum control

S. Foreman
M. Thorpe
D. Hudson
M. Stowe
Dr. A. Pe’er
Dr. R. J. Jones (Arizona)
Dr. K. Moll (Precision Ph)

<u>Collaborators</u>

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E. Eyler (UConn), F. Krausz (MPQ)