Precision measurement with ultracold atoms & molecules

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http://jilawww.colorado.edu/YeLabs

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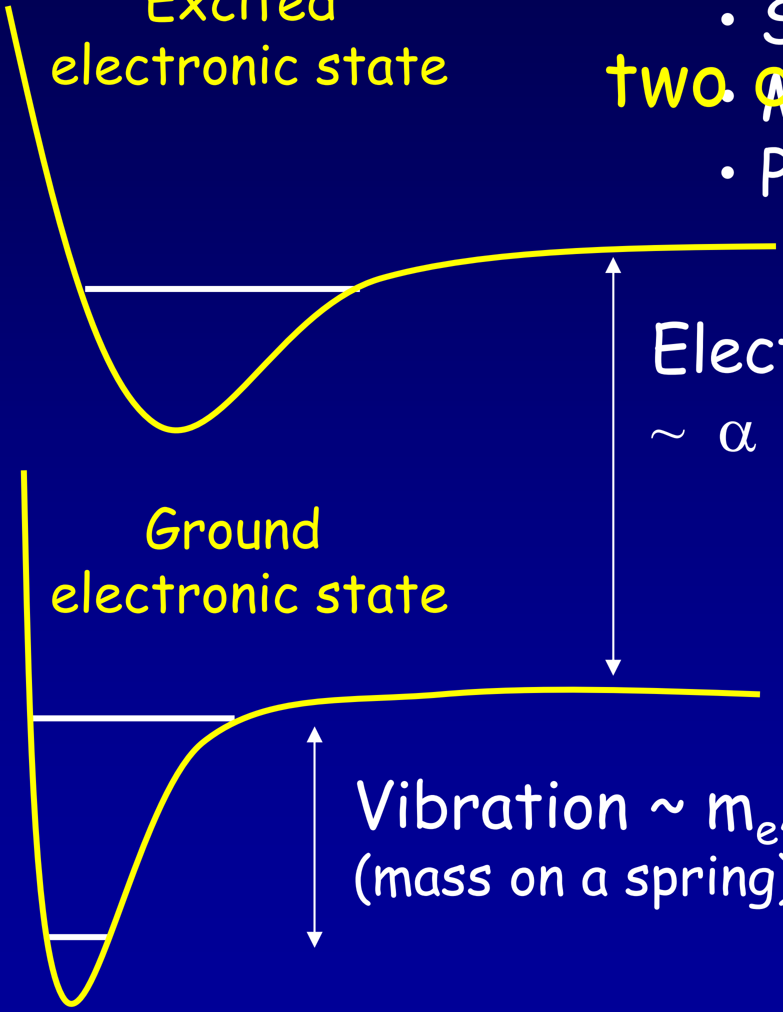
AFOSR, NASA, DOE

Ultracold molecules: Test fundamental principles

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

One system,
two different fundamental forces!



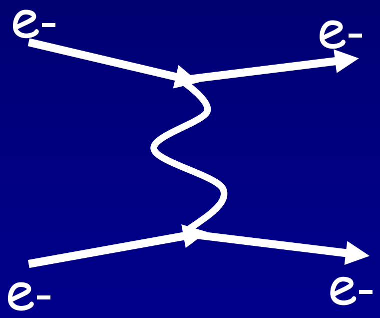
Excited electronic state

Ground electronic state

Electronic $\sim \alpha$

Vibration ~ m_e/m_p
(mass on a spring)

QED



Strong interactions

First, let there be light

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

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

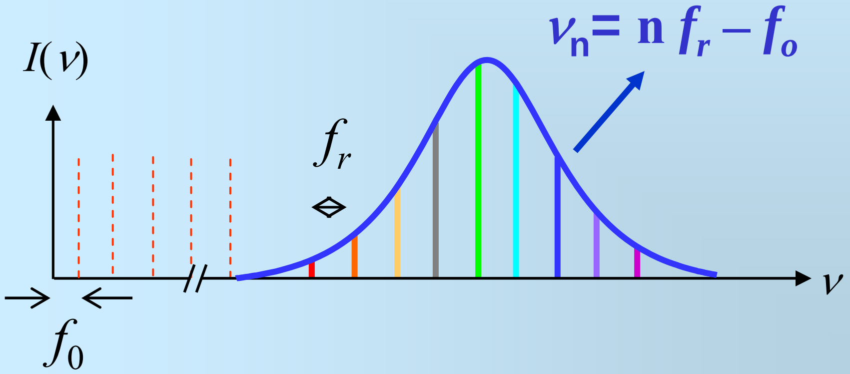
Figure of merit: 10^{-15}

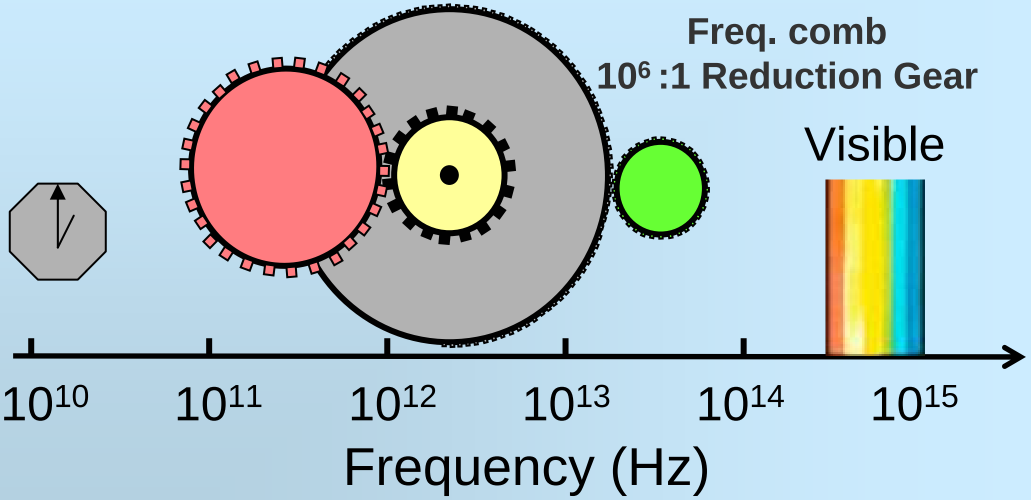
Phase coherence after 10^{15} optical cycles

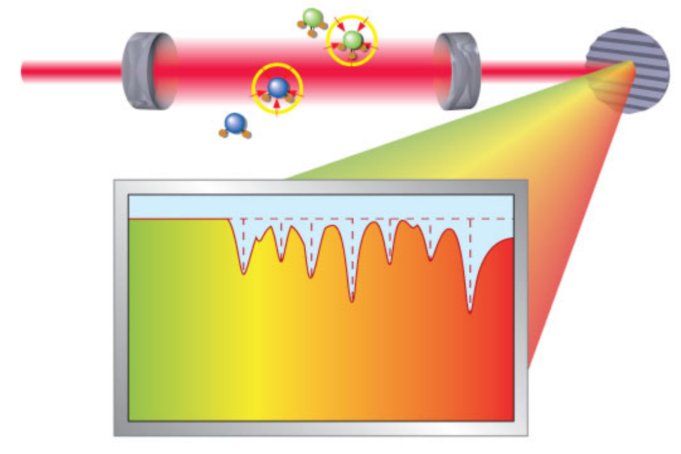
Precision spectroscopy and quantum control
at highest resolution over widest optical bandwidth

Frequency comb: state-of-the-art

- Optical Synthesizer

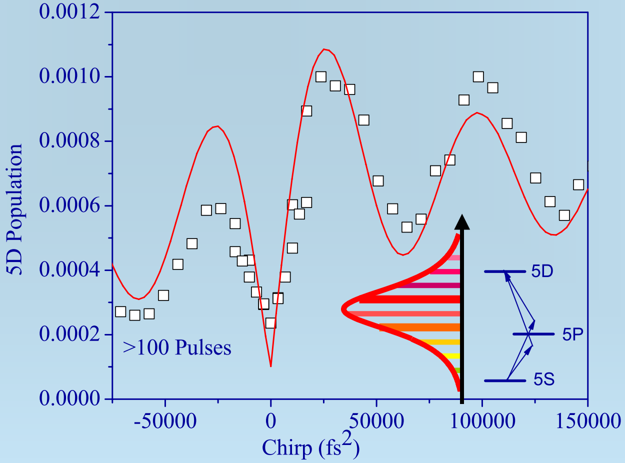






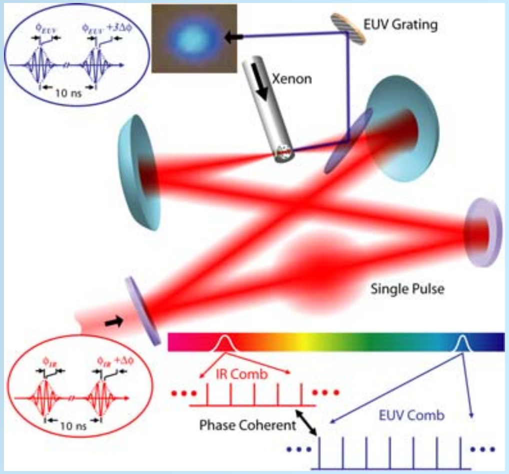
Molecular spectroscopy

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



Quantum control

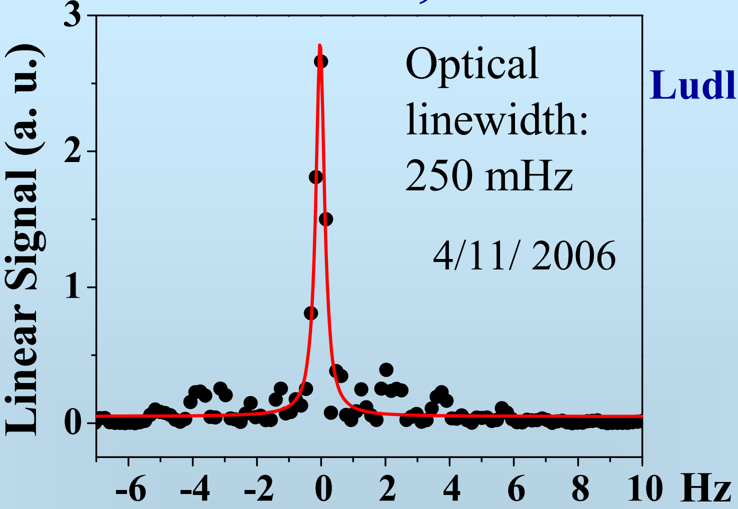
Stowe *et al.*,
PRL **96**, 153001(2006).



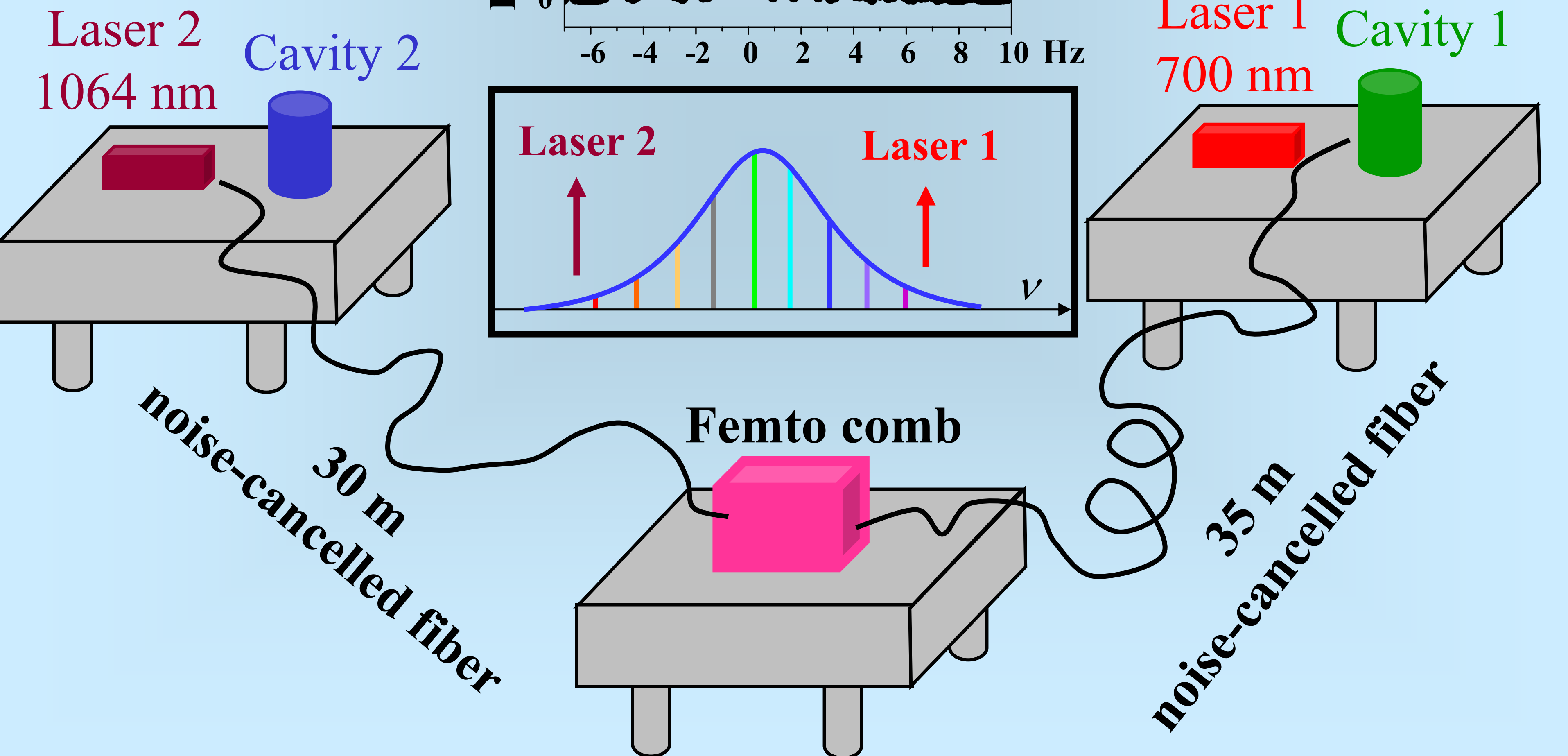
XUV comb

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).



Control of matter

Long - term quantum coherence:

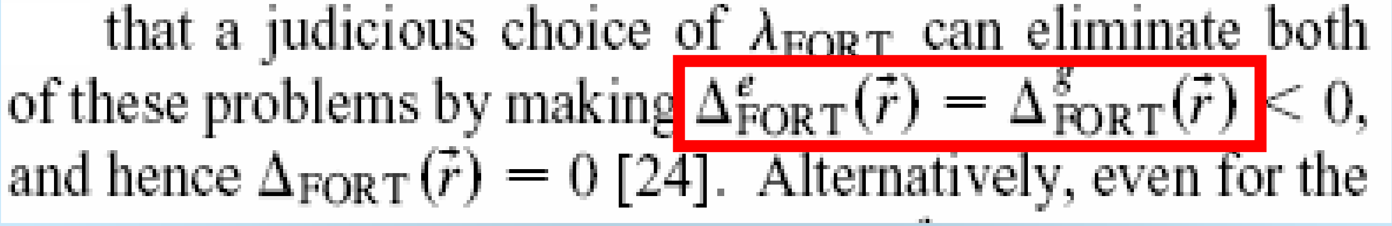
Clean separation between internal & external degrees of freedom

Both in well defined quantum states

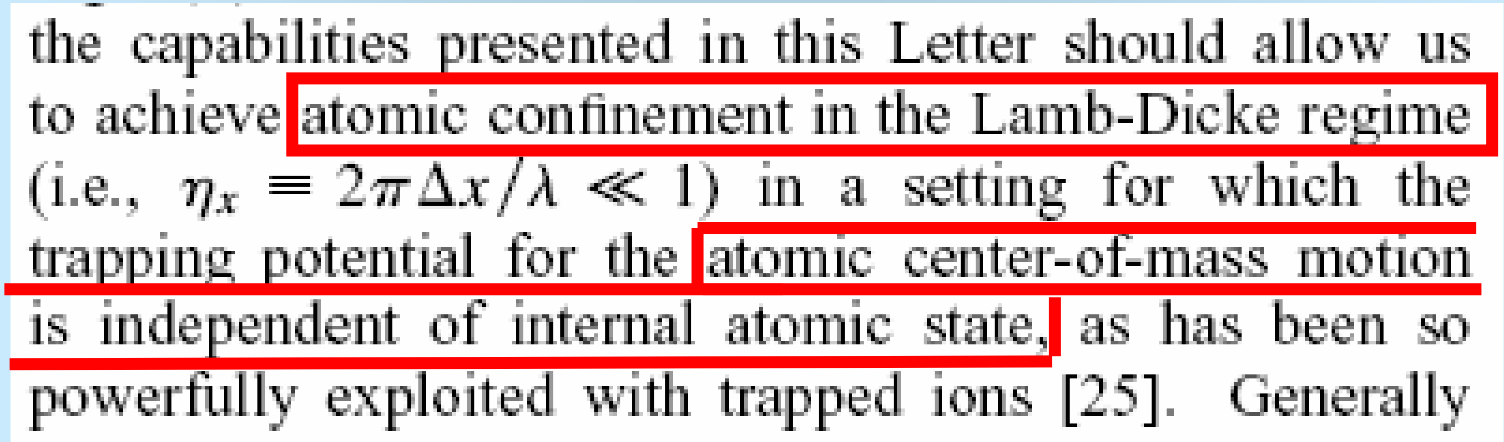
Magic wavelength dipole trap

Trapping of Single Atoms in Cavity QED

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



that a judicious choice of $\lambda_{\rm FORT}$ can eliminate both of these problems by making $\boxed{\Delta^{e}_{\rm FORT}(\vec{r}) = \Delta^{g}_{\rm FORT}(\vec{r})} < 0$, and hence $\Delta_{\rm FORT}(\vec{r}) = 0$ [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., $\eta_x = 2\pi\Delta x/\lambda \ll 1$) 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

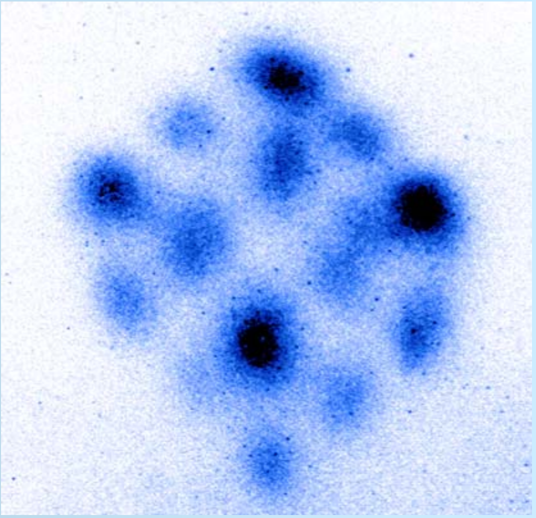
JILA work: Phys.Rev.Lett. 90, 193002 (2003); Phys.Rev.Lett. 93, 073003 (2004); Phys.Rev.Lett. 94, 153001 (2005); Phys.Rev.Lett. 94, 173002 (2005); Phys.Rev.Lett. 96, 033003 (2006); Phys.Rev.Lett. 96, 203201 (2006).

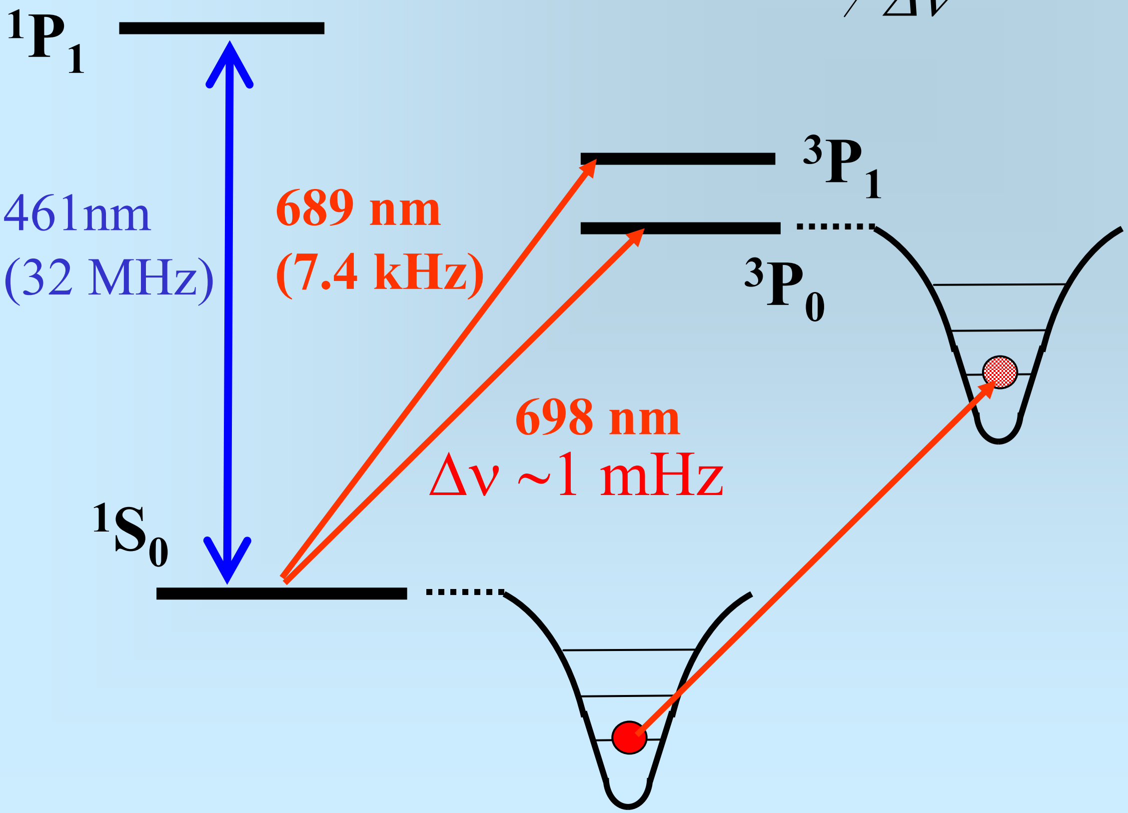
T ~ 0.5 photon recoil
~ 220 nK

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

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

$$Q \approx {}^{\nu_0}\!/_{\Delta\nu}$$





$^1P_1$

461nm
(32 MHz)

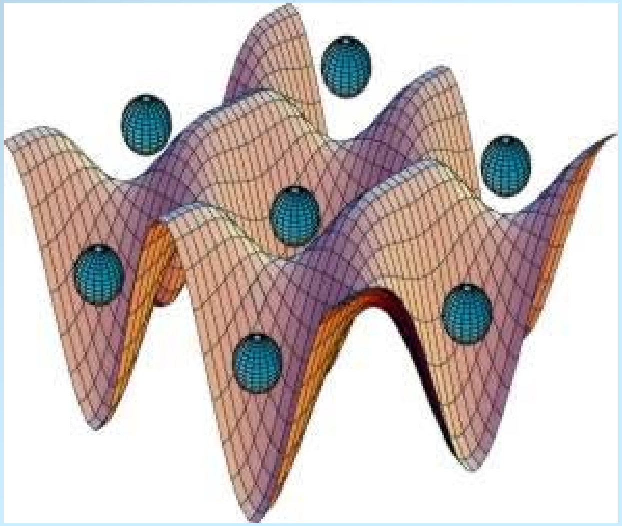
689 nm
(7.4 kHz)

$^3P_1$

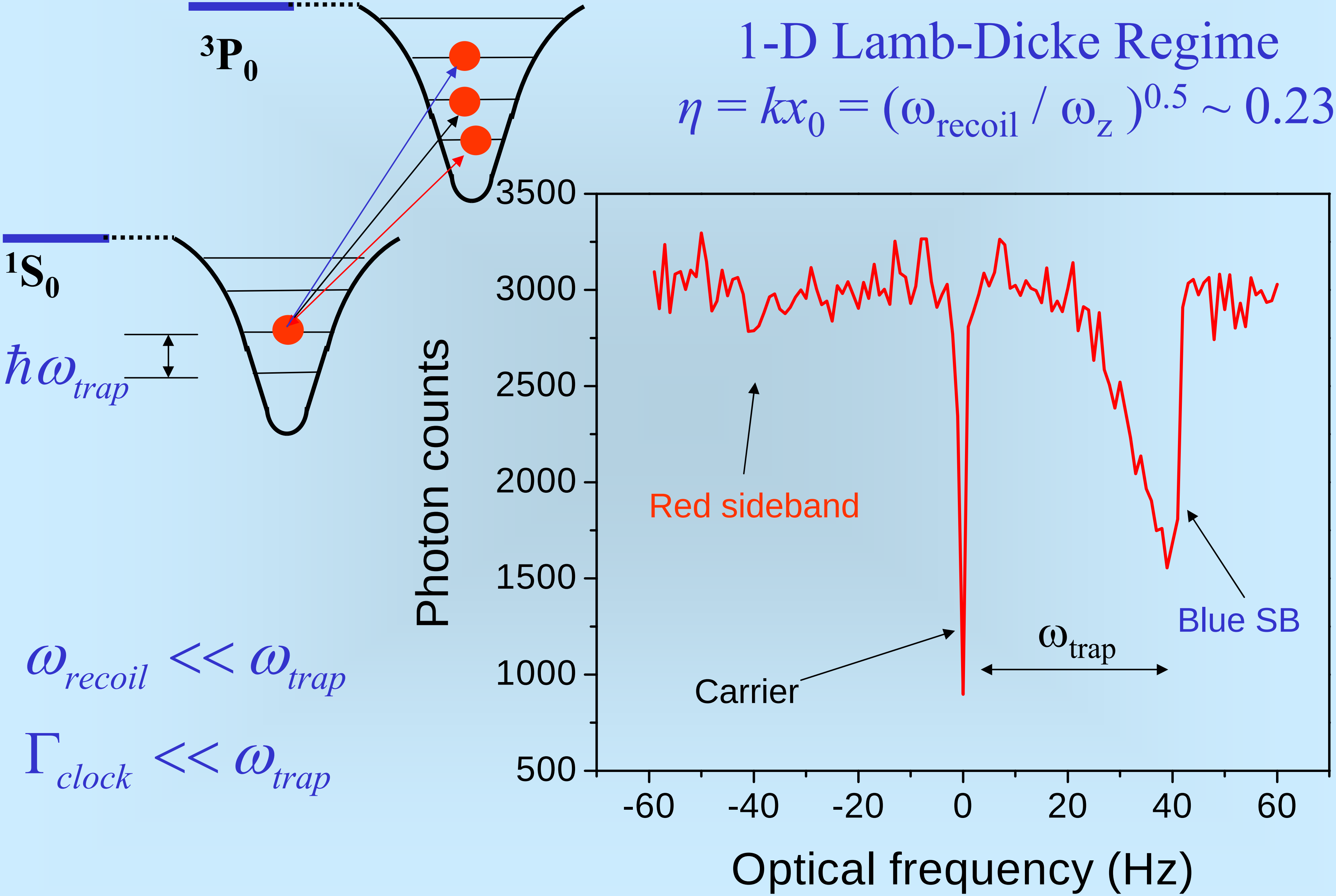
$^3P_0$

698 nm
$\Delta\nu$ ~1 mHz

$^1S_0$



Spectroscopy at the magic wavelength



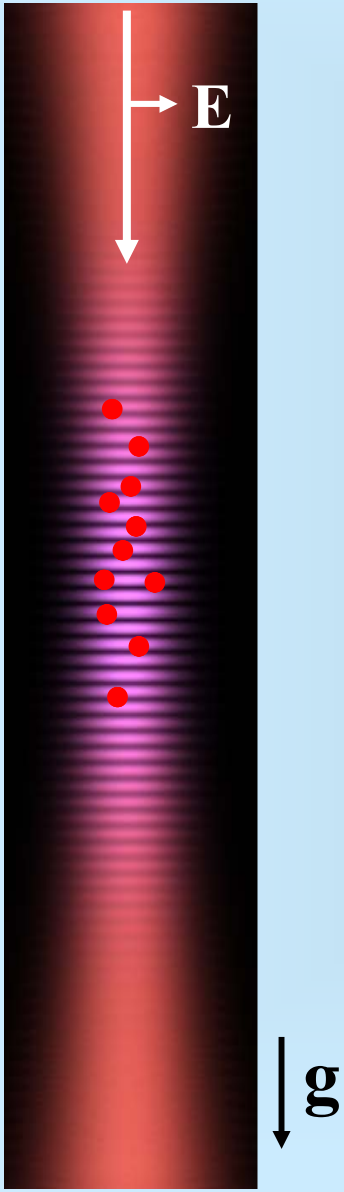
1-D Lamb-Dicke Regime

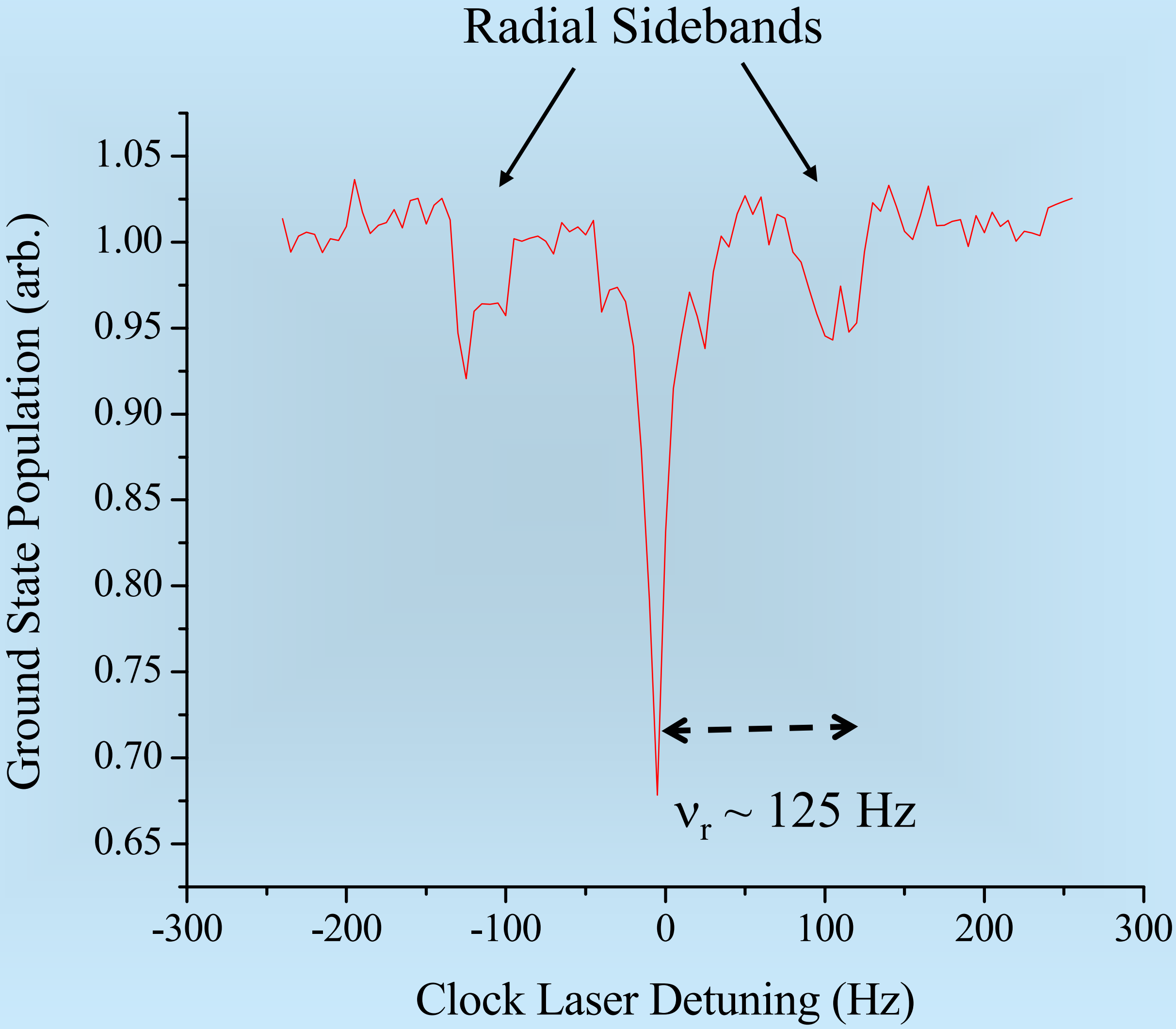
$$\eta = kx_0 = (\omega_{recoil} / \omega_z)^{0.5} \sim 0.23$$

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

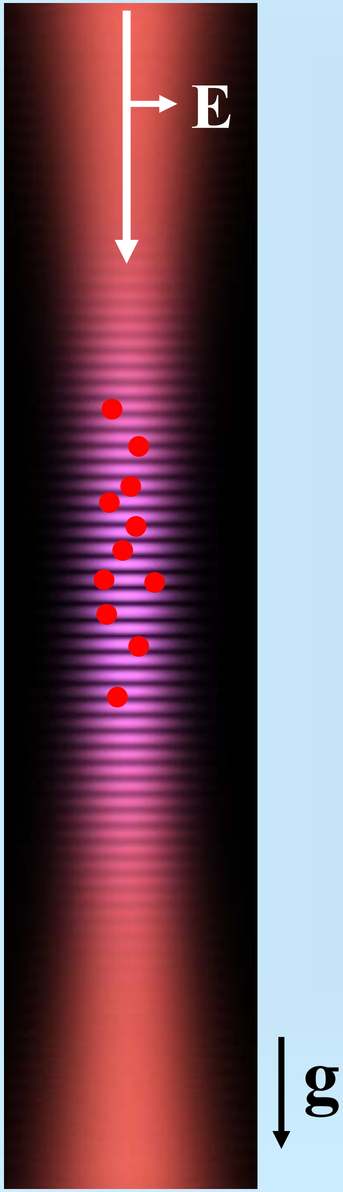
$$\Gamma_{clock} << \omega_{trap}$$

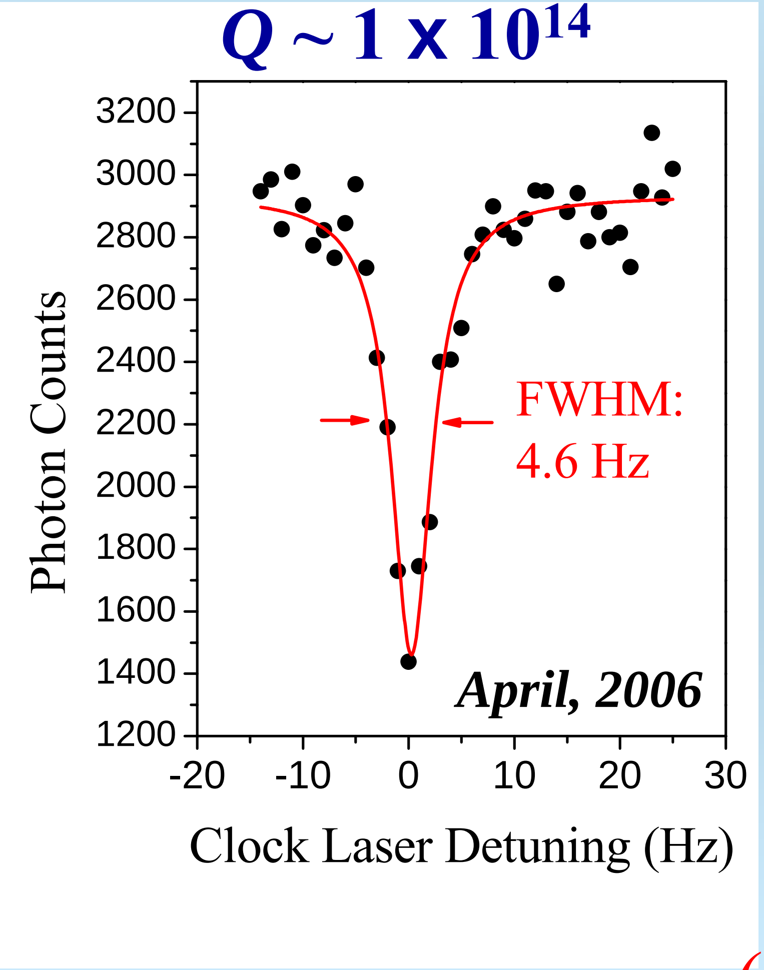
Zoom into the carrier of ^{87}Sr $^1S_0 - {}^3P_0$





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





$Q \sim 1 \times 10^{14}$

FWHM: 4.6 Hz

April, 2006

Single trace without averaging

Projected stability

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

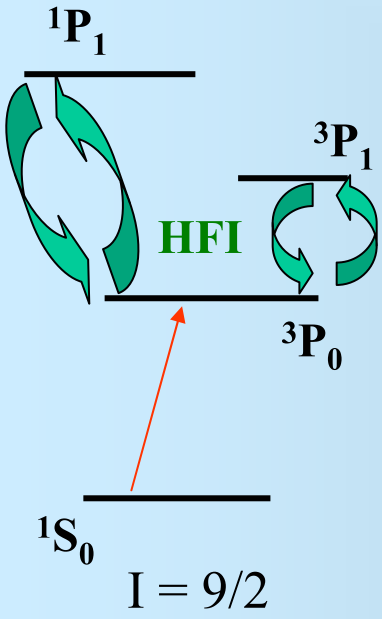
Reproducibility

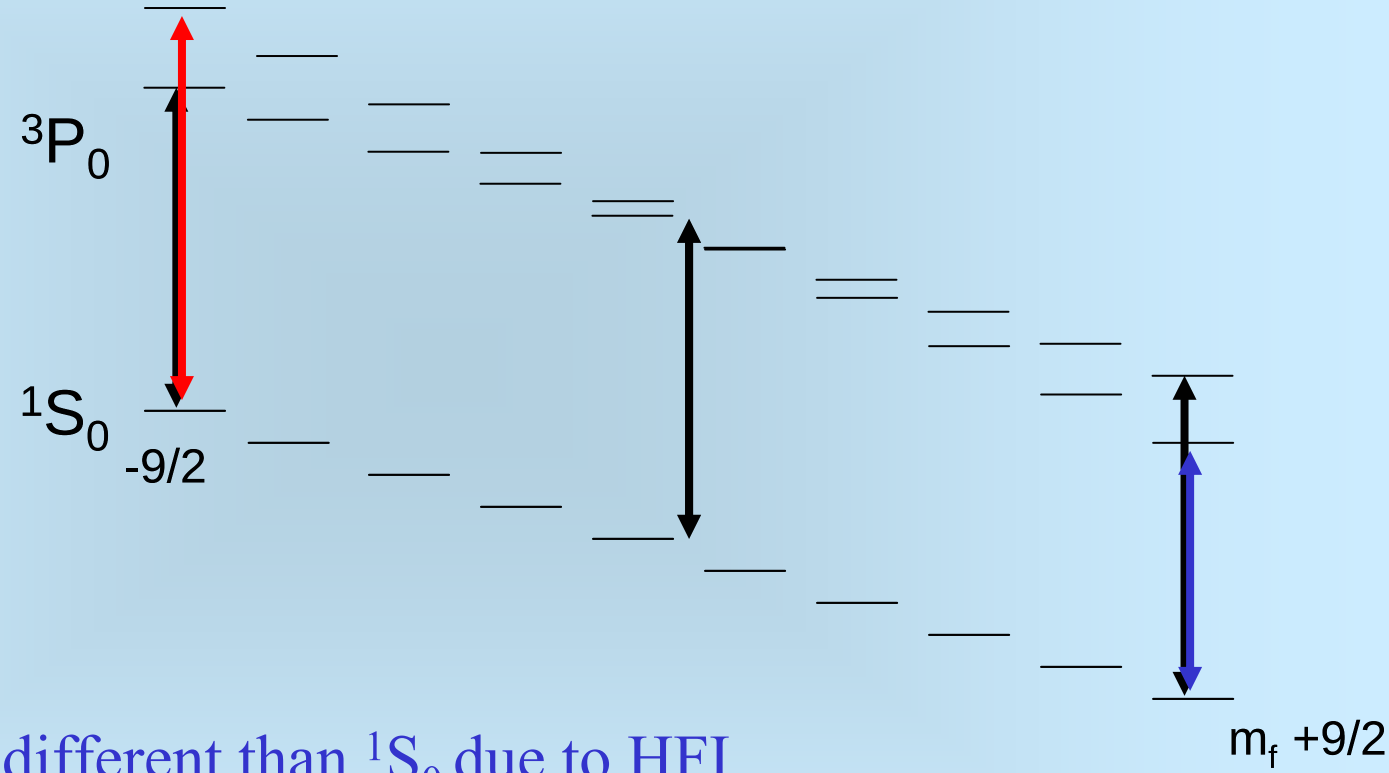
$\sim 1 \times 10^{-15}$

(March – June, 2006)

Differential g-factor – Tensor polarizability

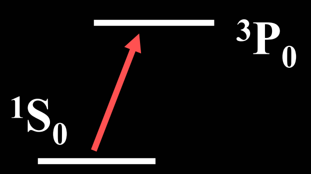
Santra *et al.*, Phys. Rev. Lett. 94, 173002 (2005).
Hong *et al.*, Phys. Rev. Lett. 94, 050801 (2005).
Barber *et al.*, Phys. Rev. Lett. 96, 083002 (2006).





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

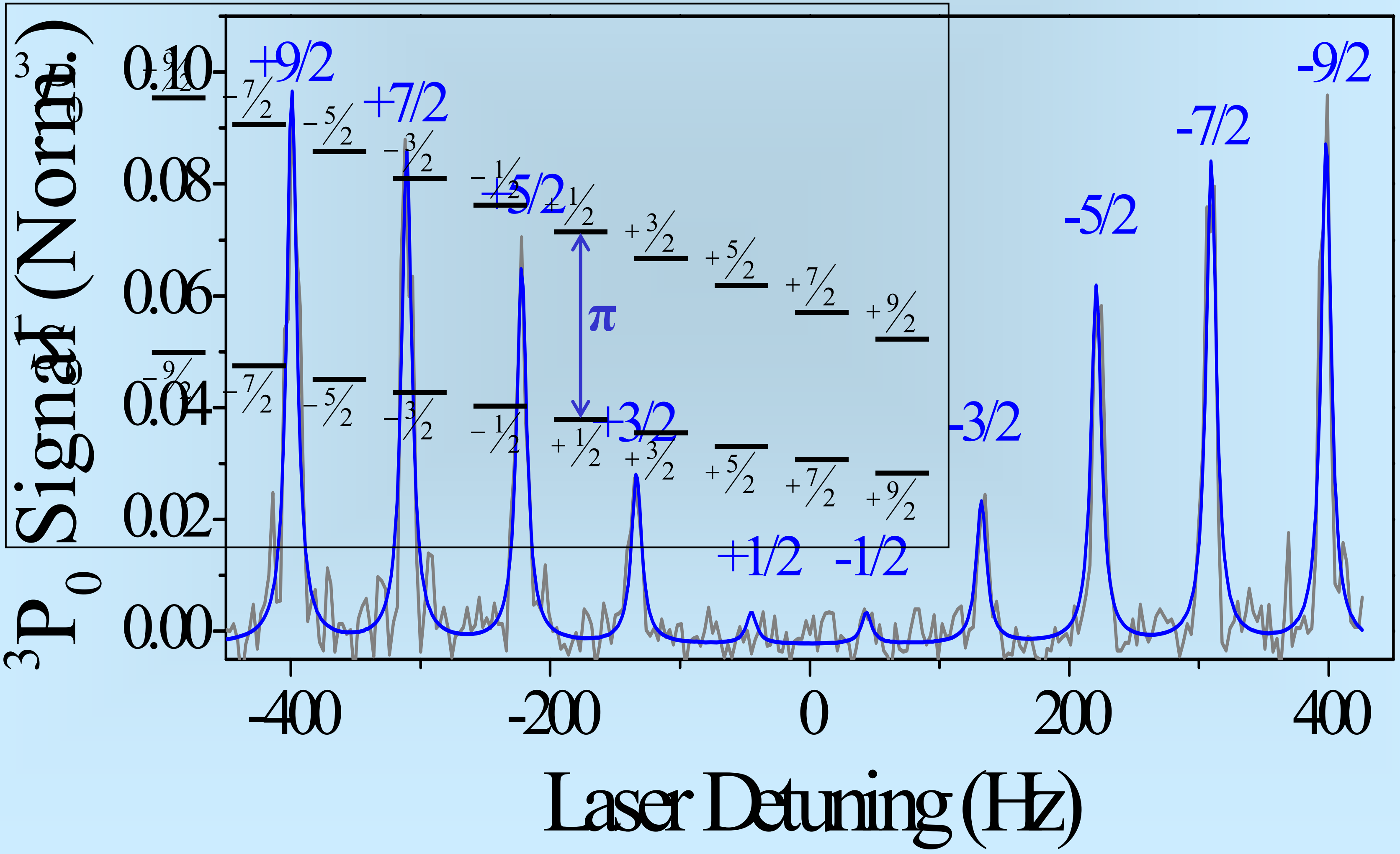
Optical Measurement of Nuclear *g*-factor



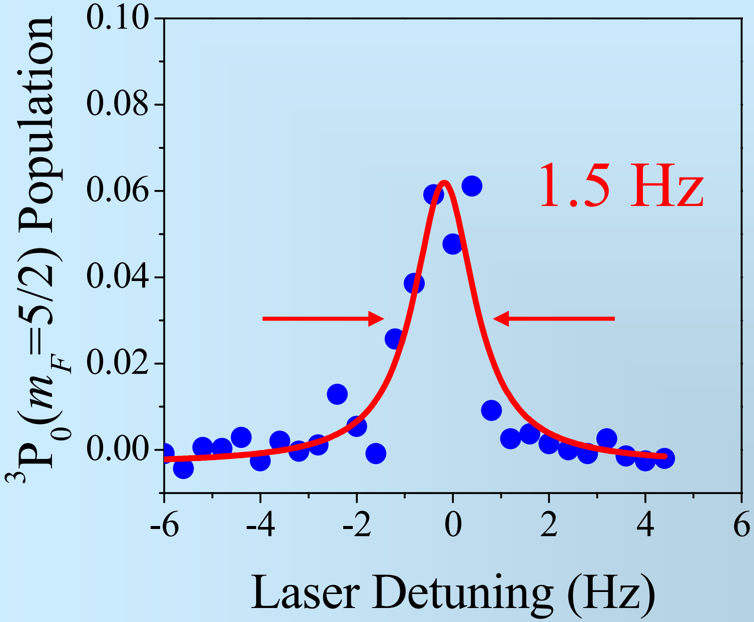
No net electronic angular momentum

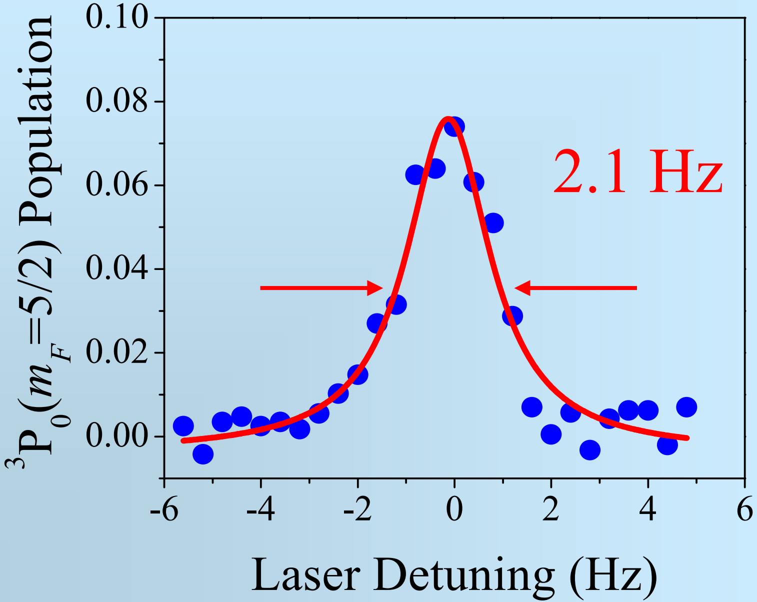
Δg = -108.5(4) Hz/(G m_F)

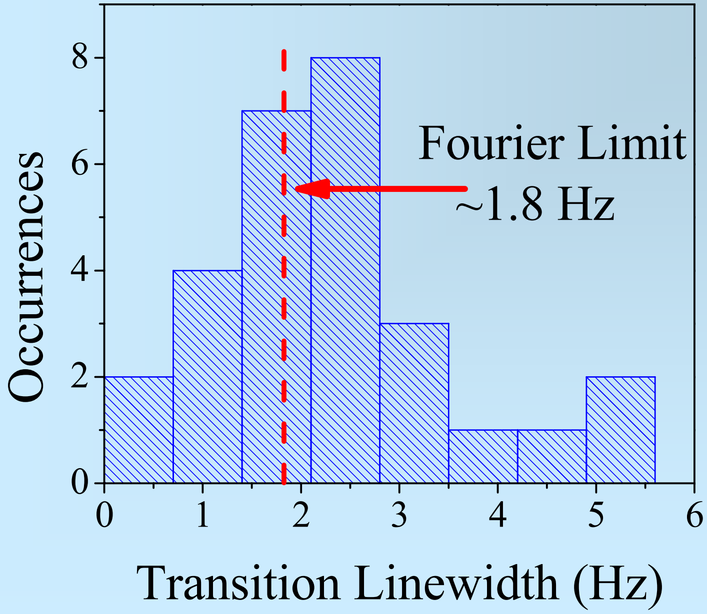
$^3P_0$ lifetime 140(40) s

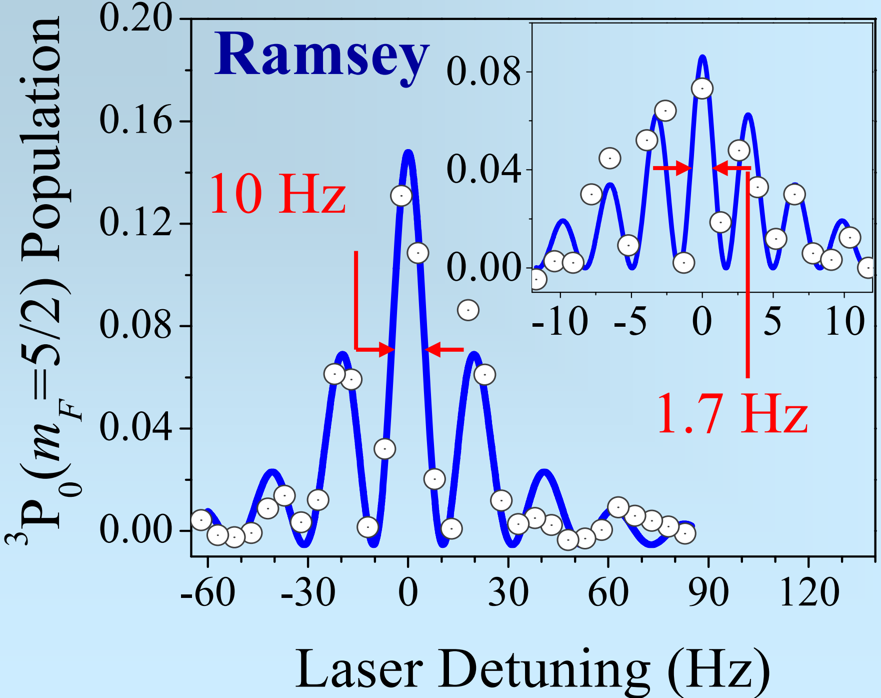


Coherent spectroscopy Q ~ 3 x 10^{14}

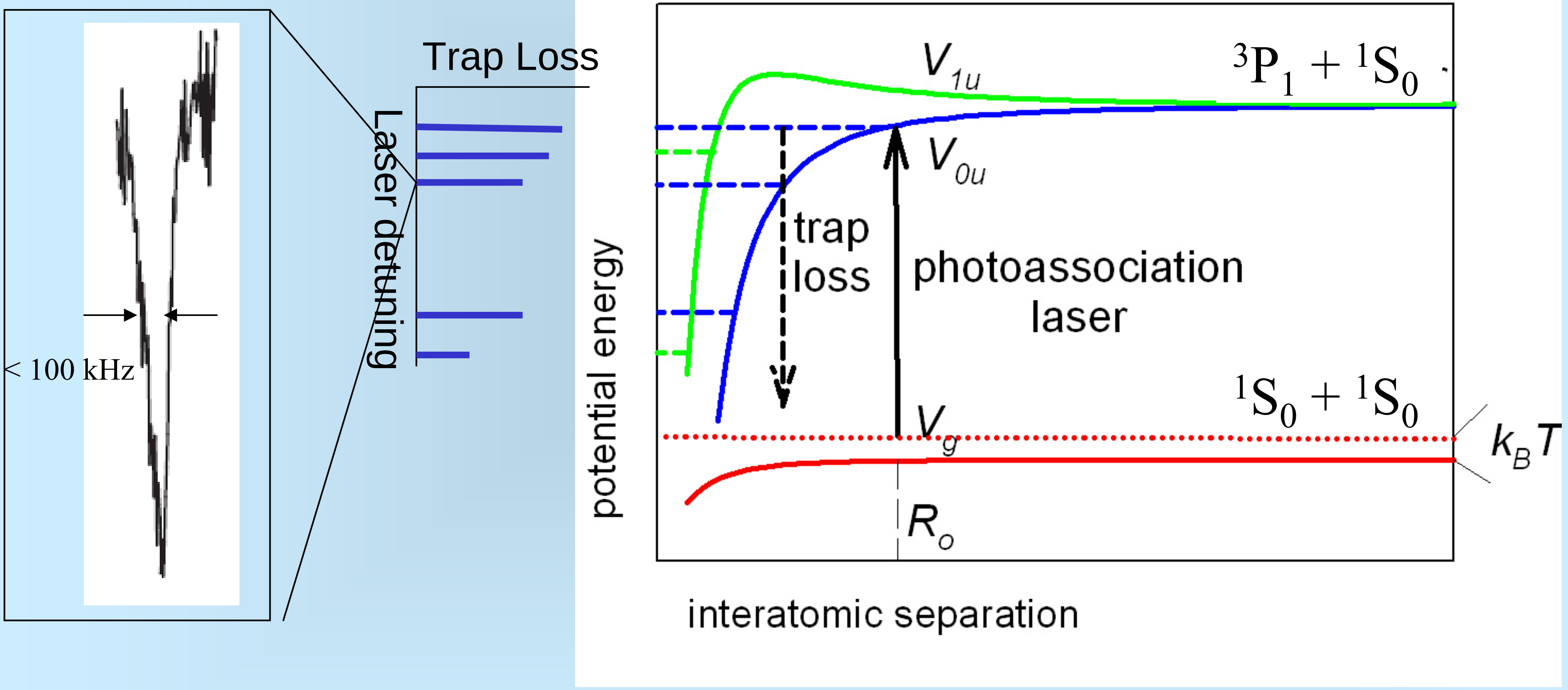








Ultracold Sr_2 molecules via narrow-line Photoassociation



Zelevinsky et al., Phys. Rev. Lett. 96, 203201 (2006).

Narrow-line Photo-association Spectroscopy

Theory: Paul Julienne

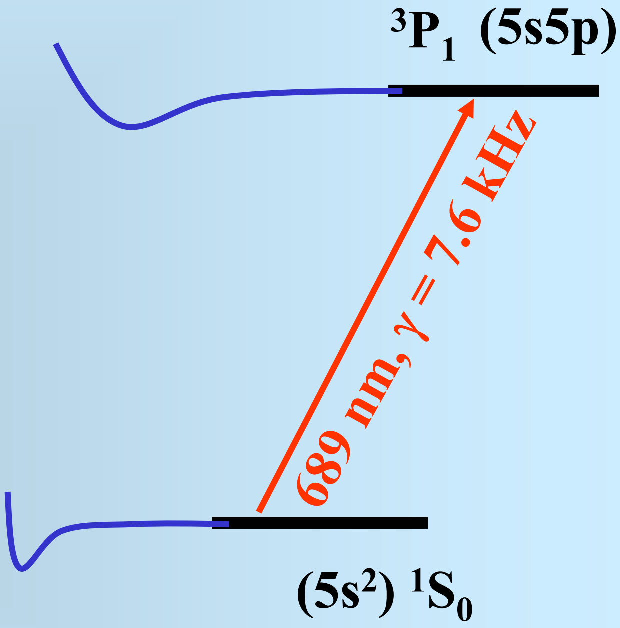
- New Territory for PAS

  All bound states are resolved by the narrow line

- Interesting regime, $C_3 \rightarrow C_6$ crossover

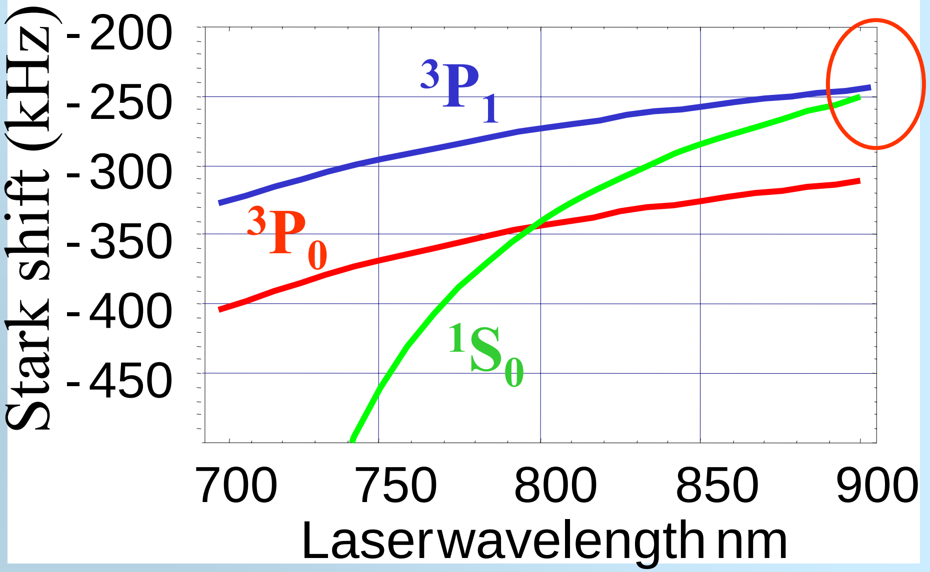
$$\boxed{\frac{C_3}{R^3} \approx \frac{C_6}{R^6} \qquad \text{at } \Delta\sim 500 \text{ MHz}}$$

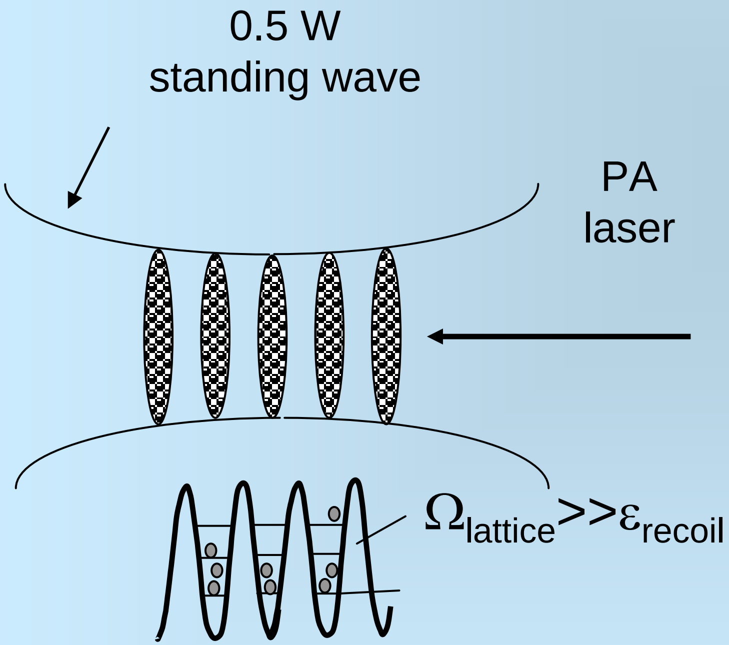
- Ground/Excited state similar for large detunings
- Hyperfine-free for bosonic isotopes
- Useful for precision tests
- Optical control of cold collisions with low loss



Photoassociation inside a Magic wavelength lattice

Doppler- and recoil-free

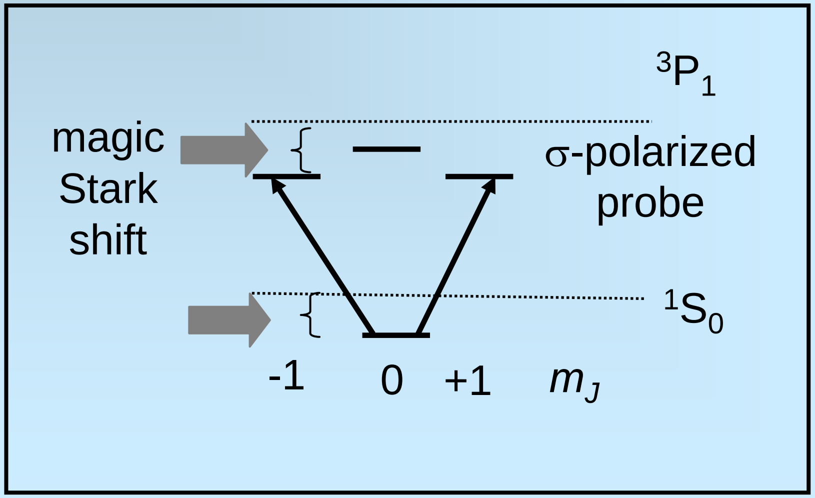




0.5 W
standing wave

PA
laser

$\Omega_{lattice} >> \varepsilon_{recoil}$



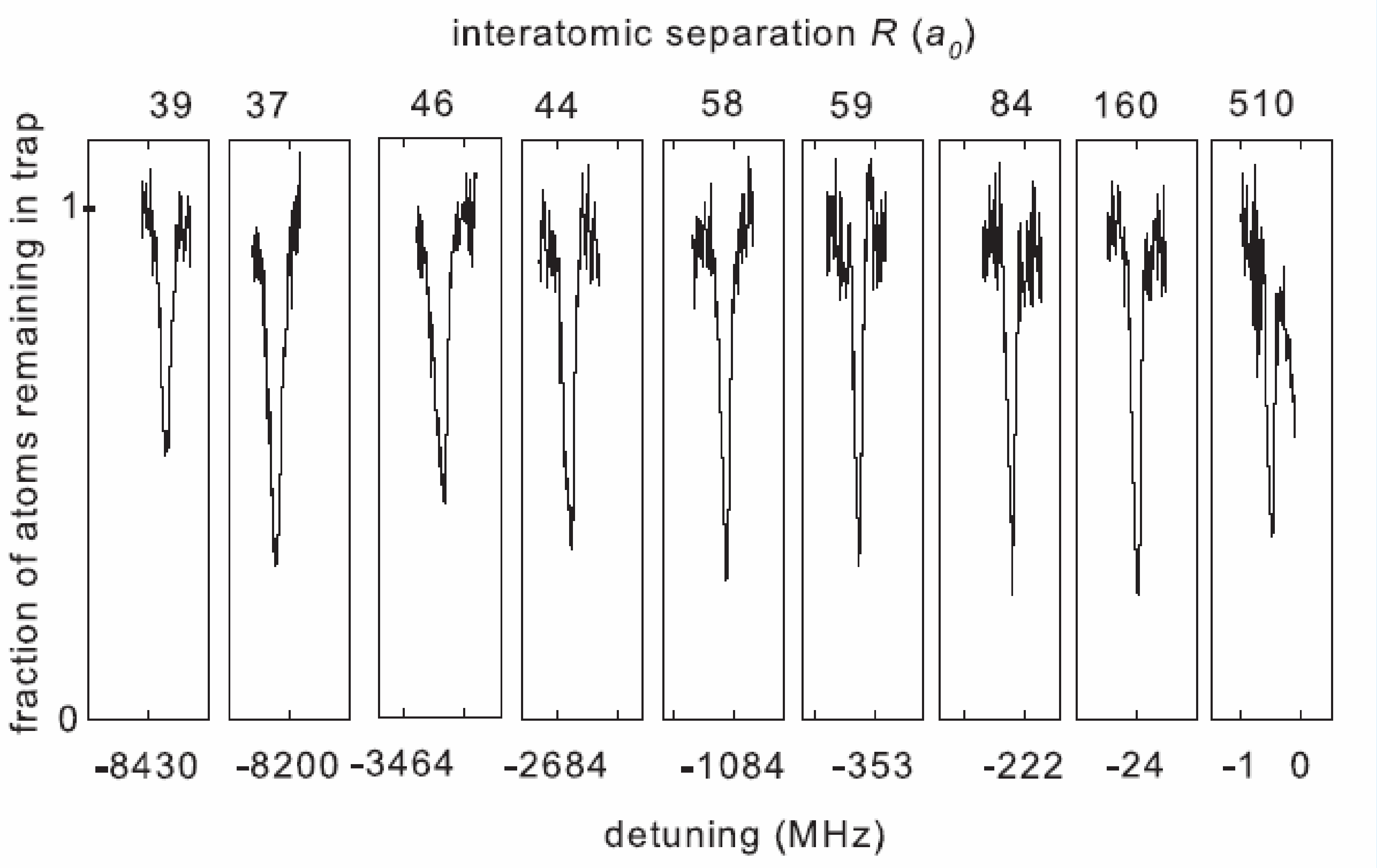
magic
Stark
shift

σ-polarized
probe

Photoassociation: Experiment vs. theory

10^{-5} agreement for near detuning,

0.1-1% agreement deeper in the potential curve

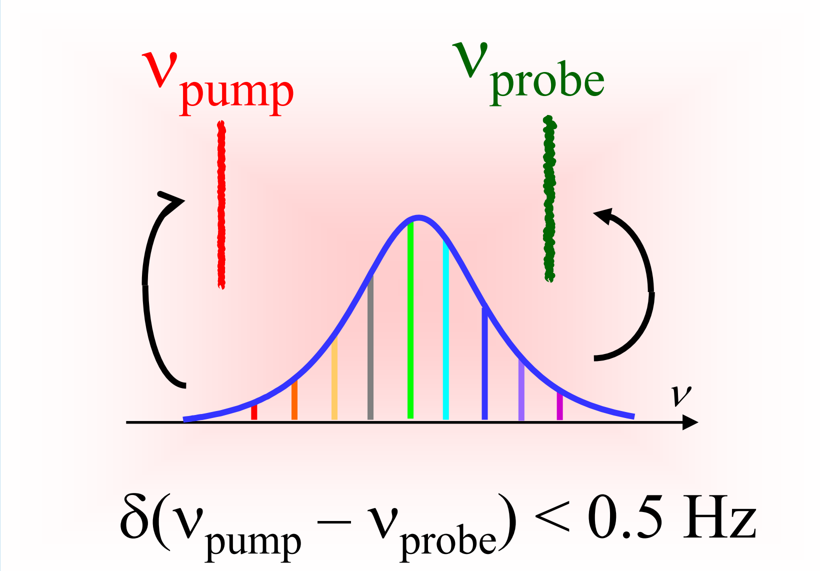


Nine least bound states measured

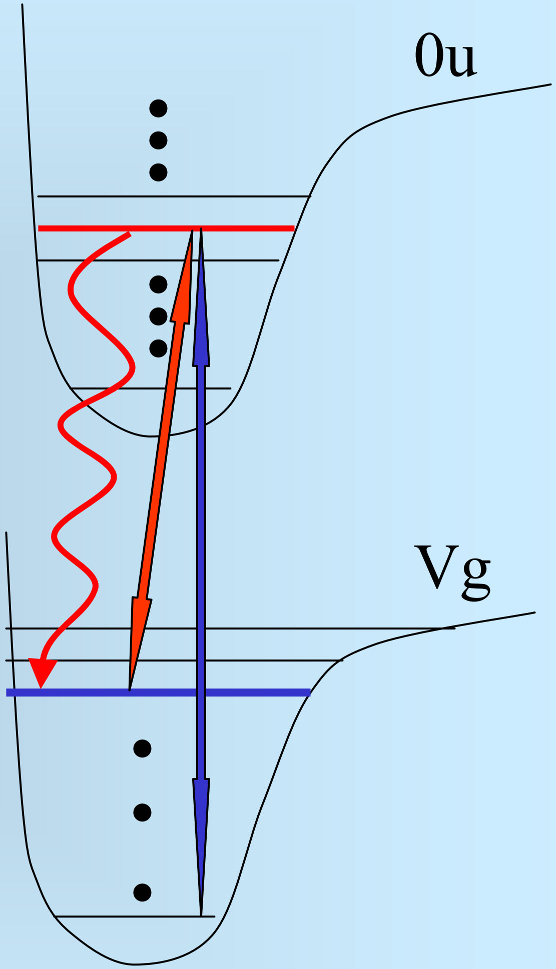
Ground State Molecules

Similar excited and ground state wavefunctions
~90% of molecules in 8.4 GHz state decay to single g.s.

Should be possible to drive Molecules to deepest g.s.



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



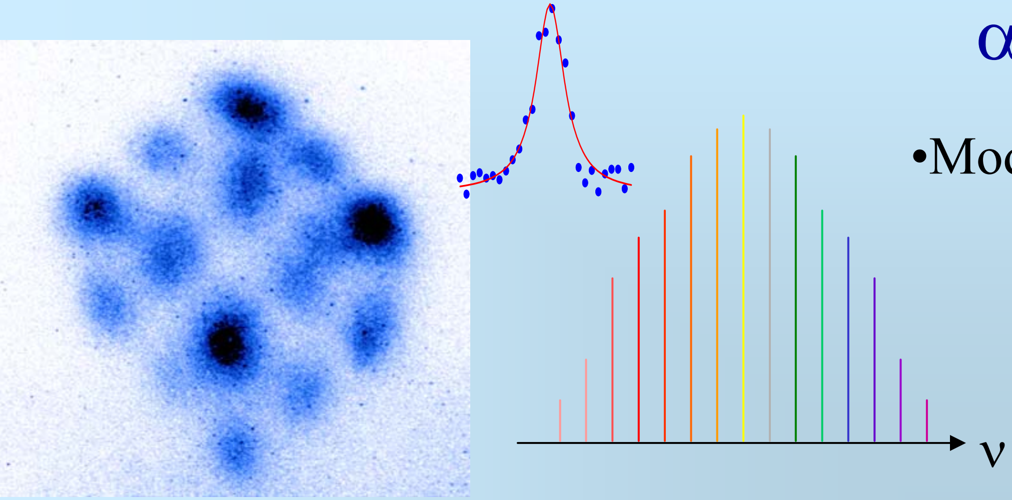
Magic wavelength trap for molecules?
Theory: P. Julienne and A. Derevianko

Time-variation of electron-proton mass ratio?

D. DeMille, private communications (2005).
Chin and Flambaum, Phys. Rev. Lett. 96, 230801 (2006).

Test of fundamental constants

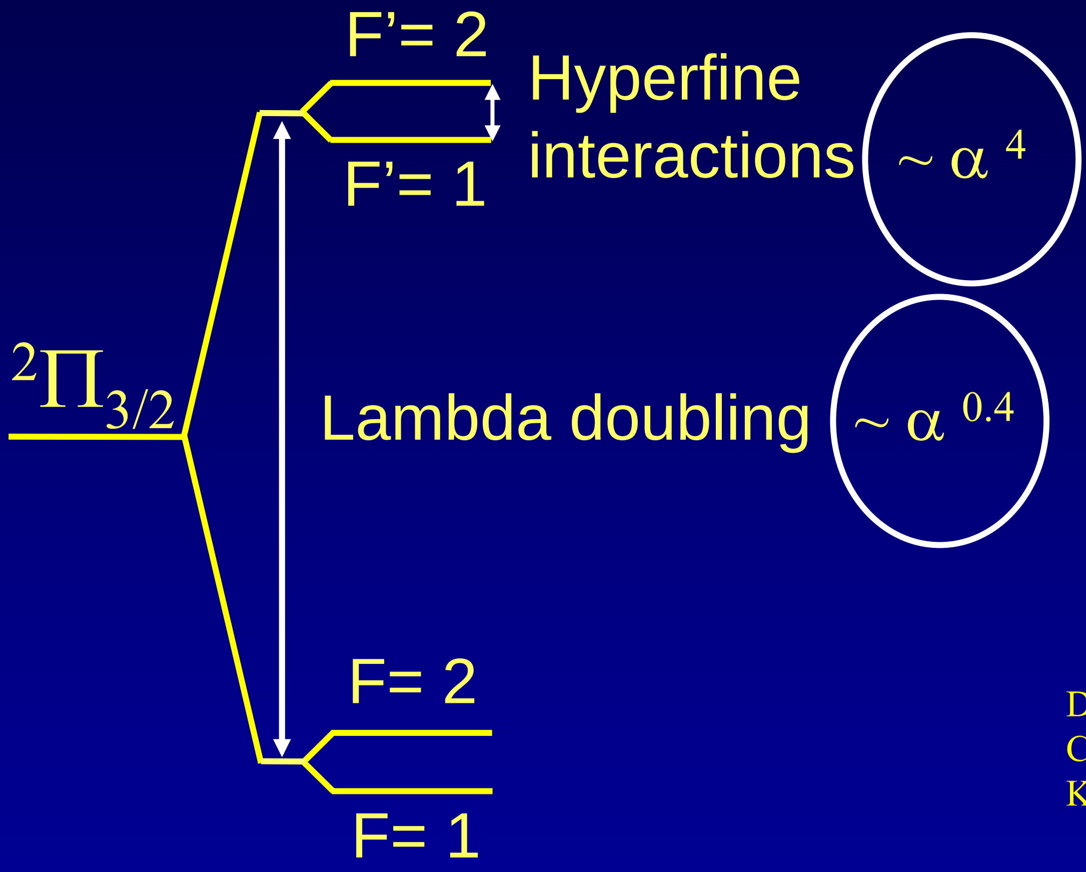
α: fine structure constant



- 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 $\dot{\alpha}$



F'= 2

Hyperfine interactions $\sim \alpha^{4}$

F'= 1

$^{2}\Pi_{3/2}$

Lambda doubling $\sim \alpha^{0.4}$

F= 2

F= 1

OH megamasers

High redshift *z* > 1

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).

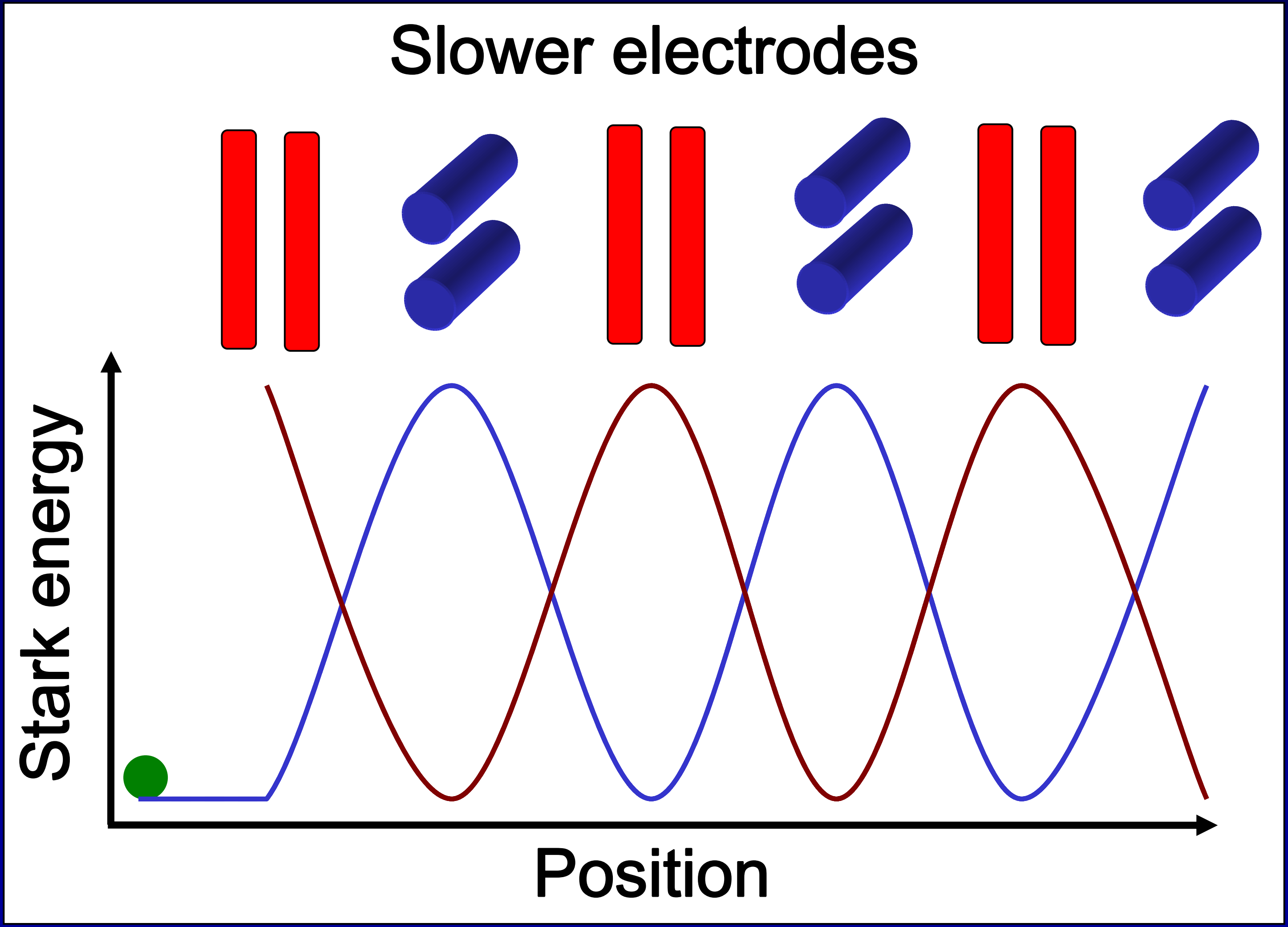
Multiple transitions from the same gas cloud (different dependences on α)
(Self check on systematics)

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).

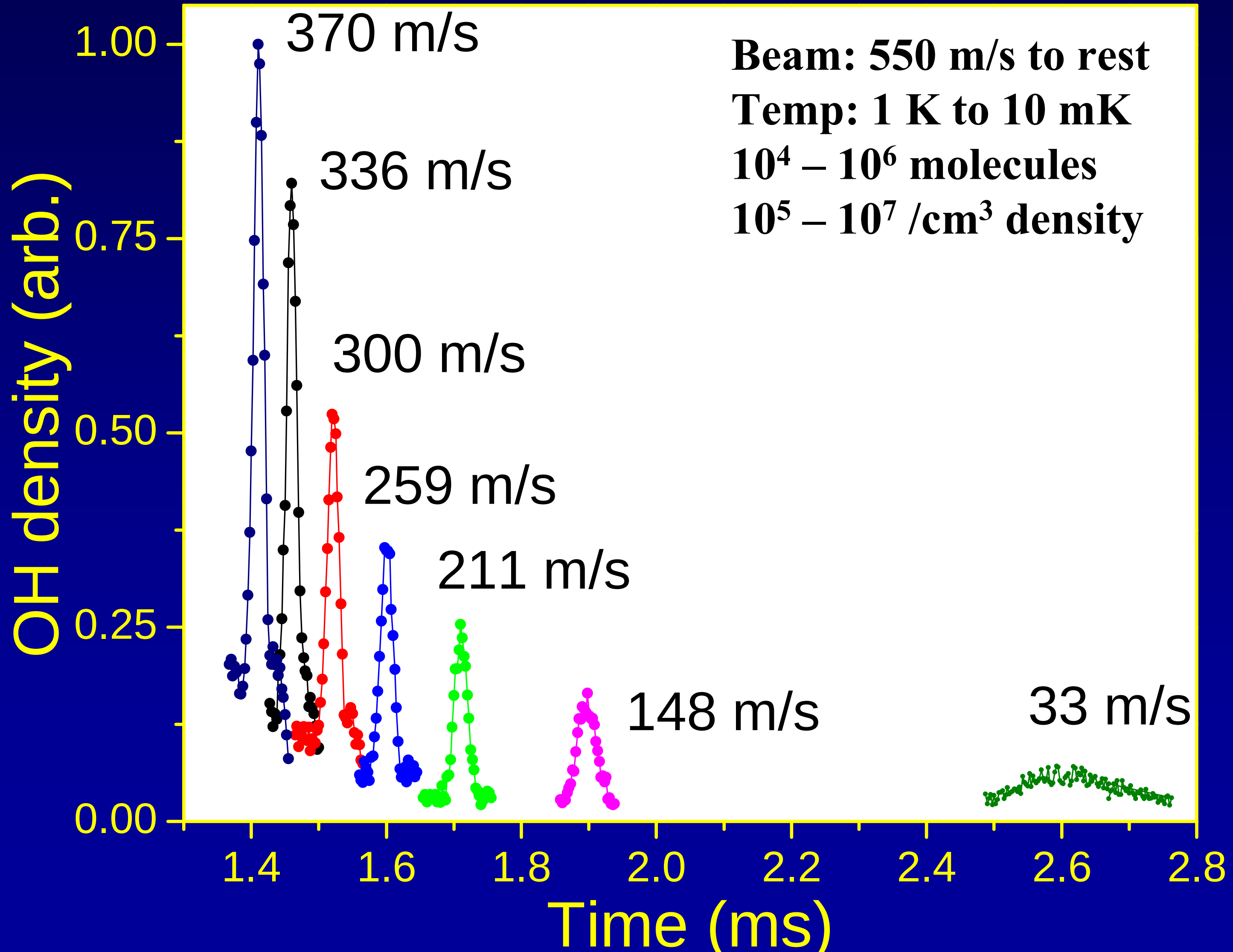
Stark Decelerator

G. Meijer



OH after the Stark-decelerator

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



Beam: 550 m/s to rest

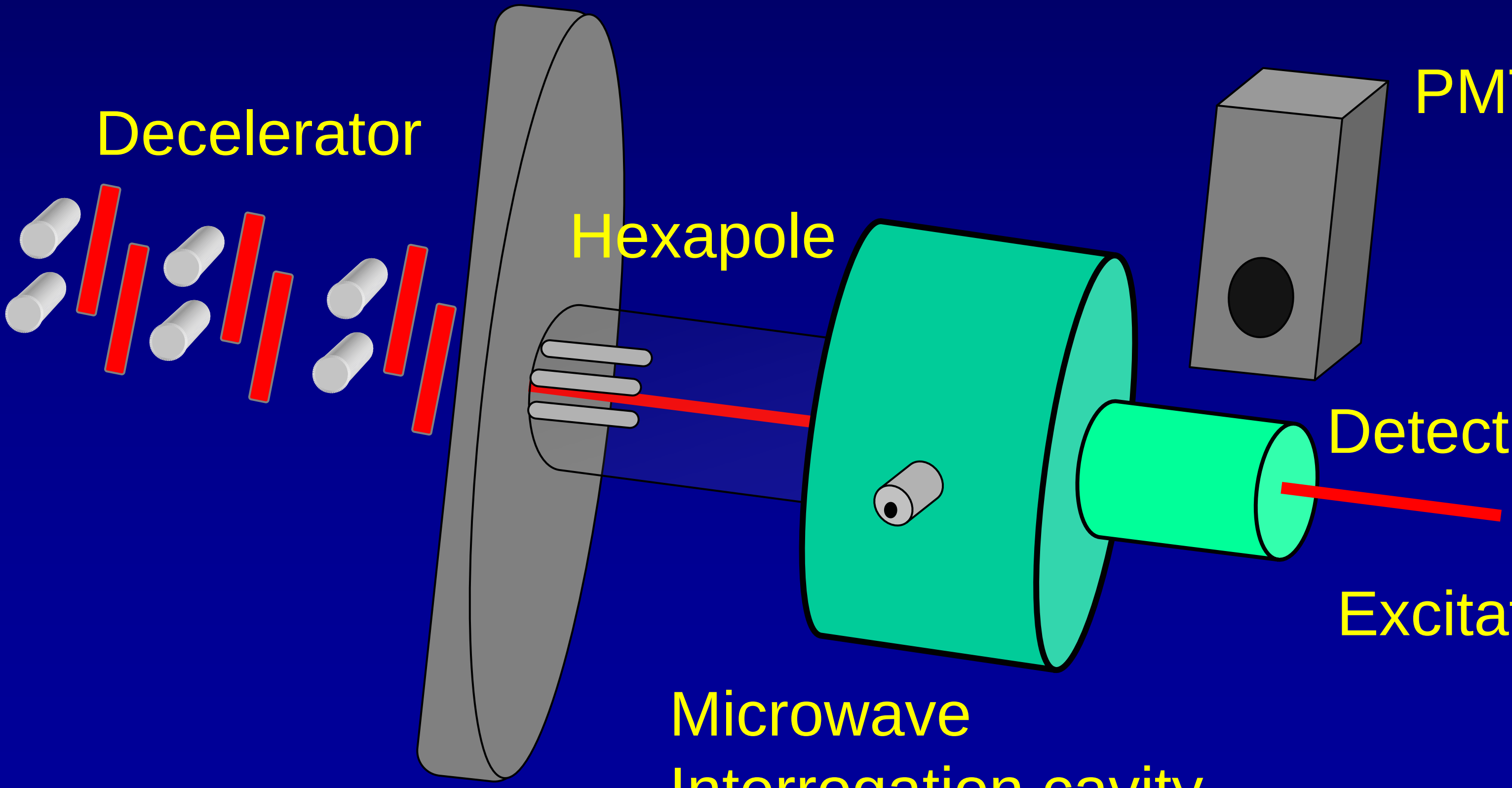
Temp: 1 K to 10 mK

$10^4 – 10^6$ molecules

$10^5 – 10^7$ /cm^3 density

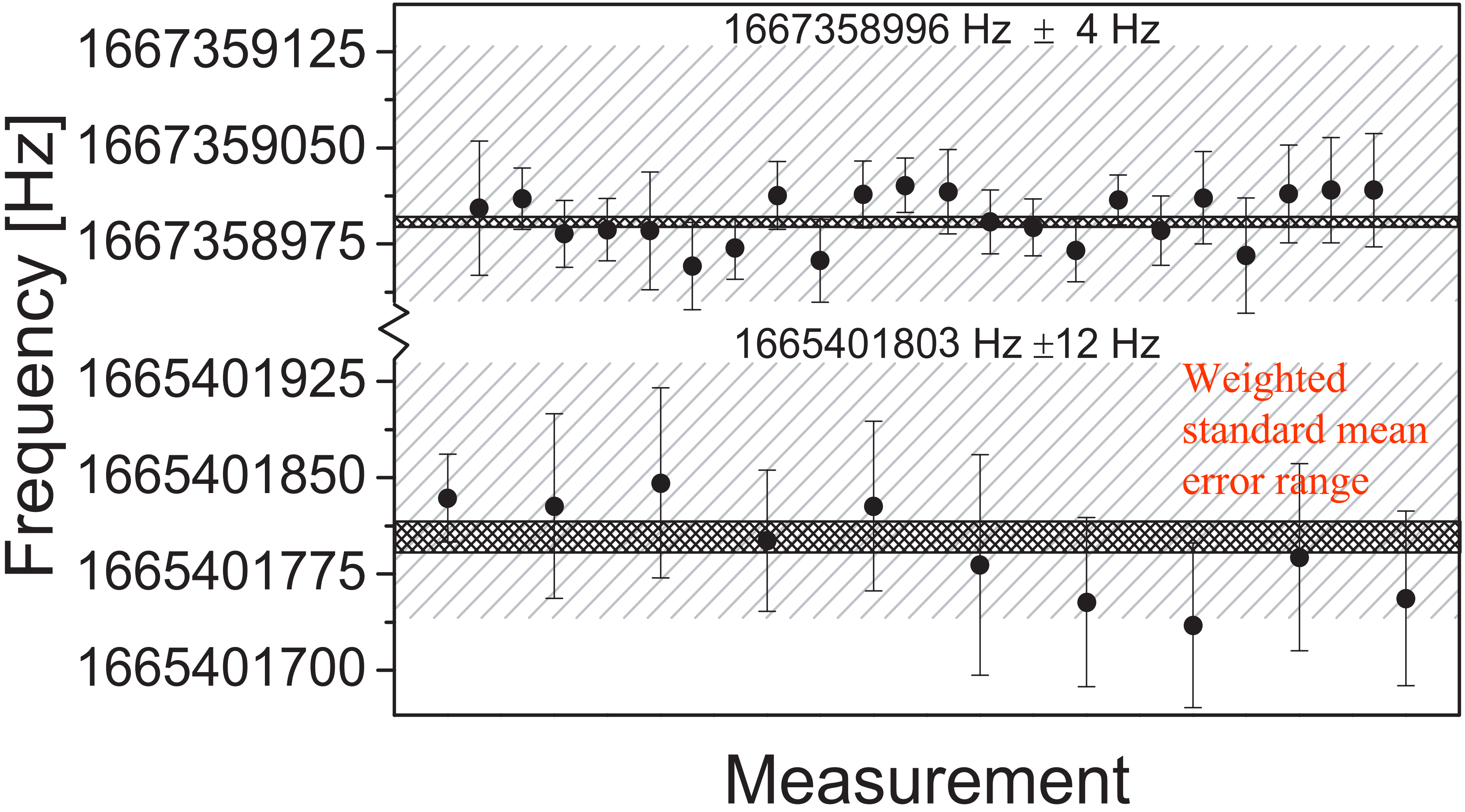
Cold molecule based precision spectroscopy

- Rabi or Ramsey interrogation on slowed OH beam
- High resolution and precision
- Systematic checks on beam (velocity) effects

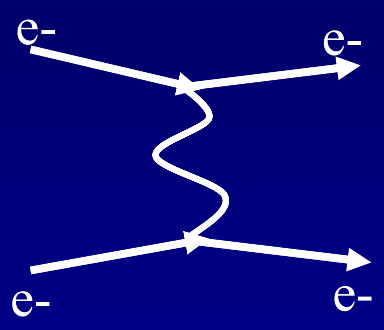


Precision measurement of OH structure

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



$\Delta\alpha/\alpha$ measurement status



- $\Delta\alpha / \alpha = 1$ ppm (and better) is now possible to measure over ~10 Gyr. Linear drift model → 10^{-16}/yr.
- Astrophysical measurements later this year plan better than 100 Hz accuracy.
- Deep surveys of OH megamasers are active from the local Universe to red shift $z \sim 4$.
- Optical clock comparisons ongoing, but test only modern epoch.
- Tests on $\Delta(m_e/m_p) / (m_e/m_p)$ is possible (W. Ubach, PRL <u>92</u>, 101302 (2004); PRL <u>96</u>, 151101 (2006).)

Special thanks

http://jilawww.colorado.edu/YeLabs

Ultracold Sr & Sr_2

M. Boyd
A. Ludlow
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Dr. T. Zanon
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Cold Polar Molecules

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

Femtosecond comb & cold atoms

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

Collaborators

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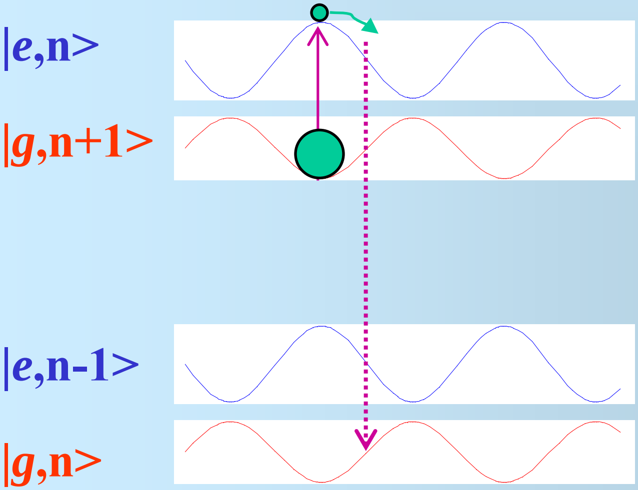
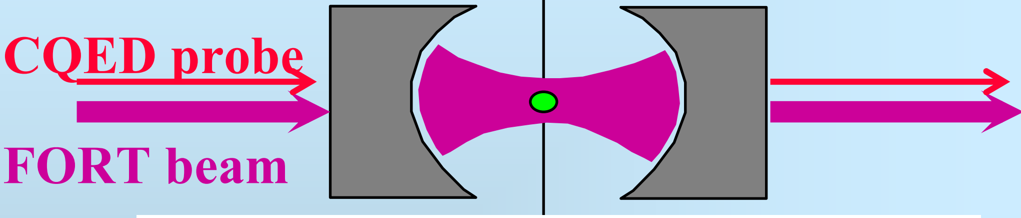
P. Julienne, S. Diddams, J. Bergquist, L. Hollberg, T. Parker (NIST)
E. Eyler (UConn), F. Krausz (MPQ)

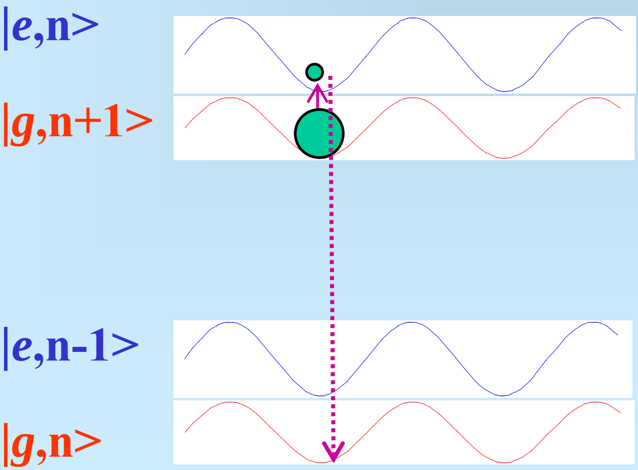
Problems in the neutral atom land





Caltech cavity QED lesson
Kimble group, 1999

Dipole force fluctuations:
Heating and position
-dependent decoherence



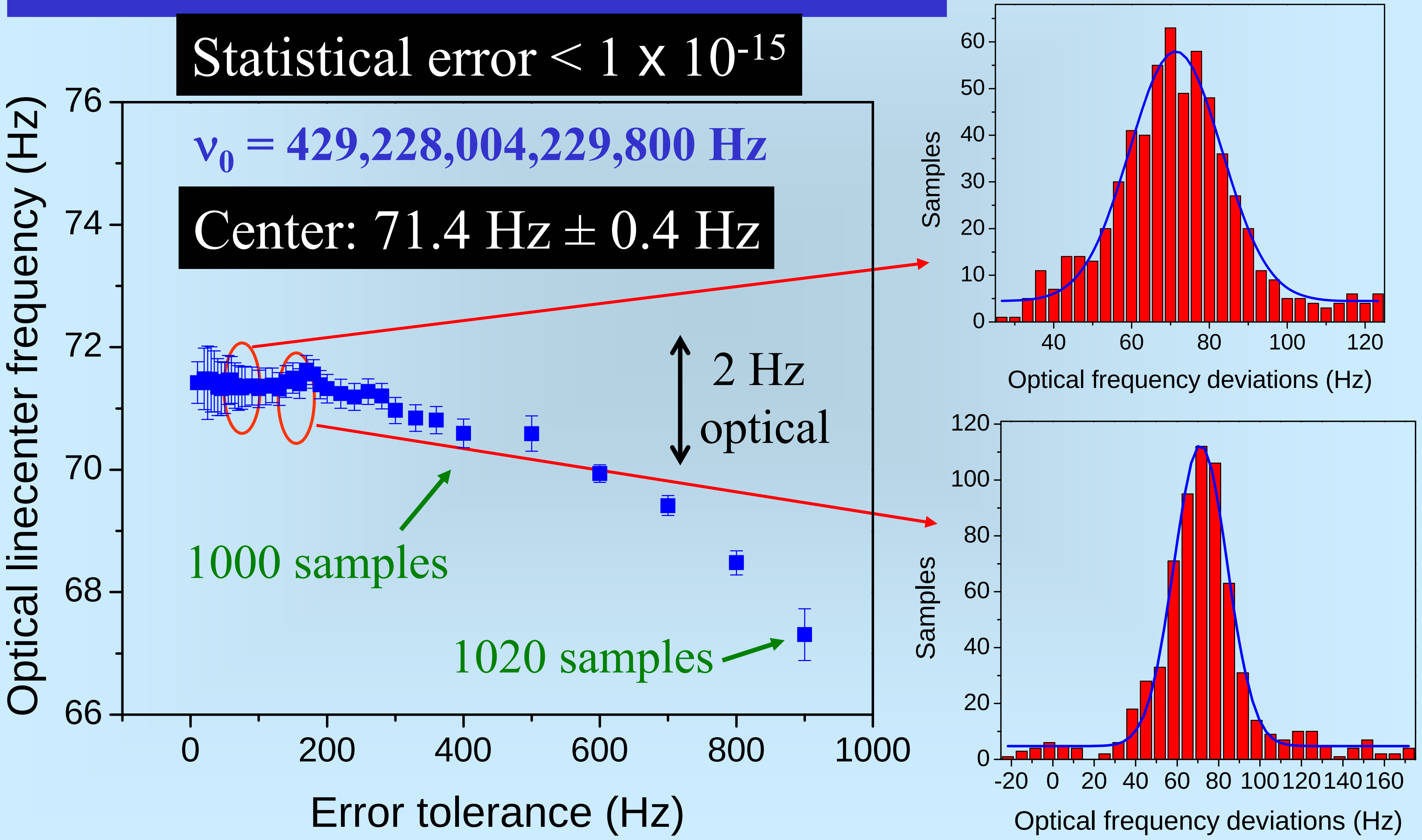
The Solution:
Match the AC Stark shift
between |e> and |g>

Kimble et al. ICOLS 99

Reproducibility

March – June 2006: 1020 measurements
3 different NIST Cs-calibrated masers

Statistical error < 1 x 10^{-15}

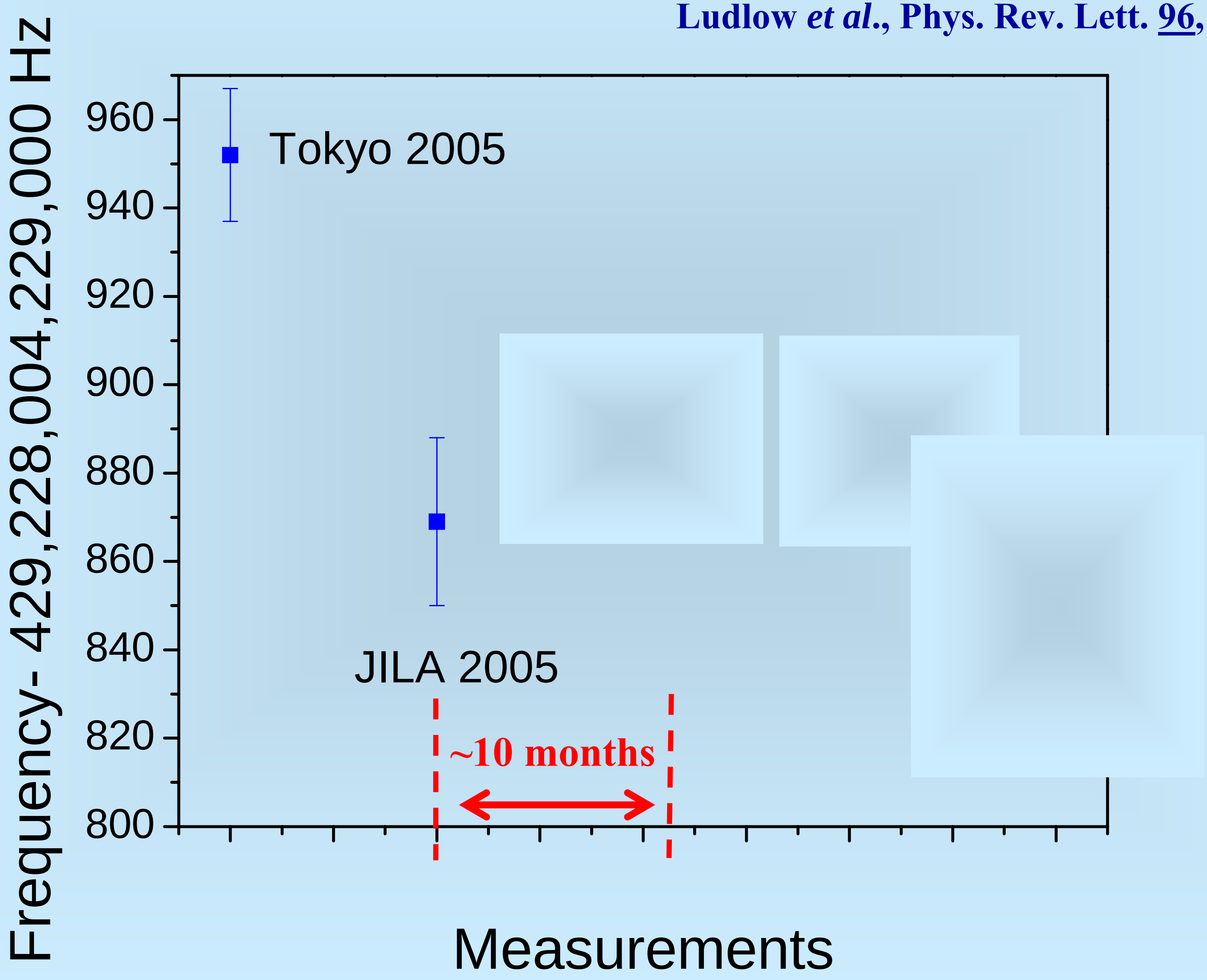


ν_0 = 429,228,004,229,800 Hz

Center: 71.4 Hz ± 0.4 Hz

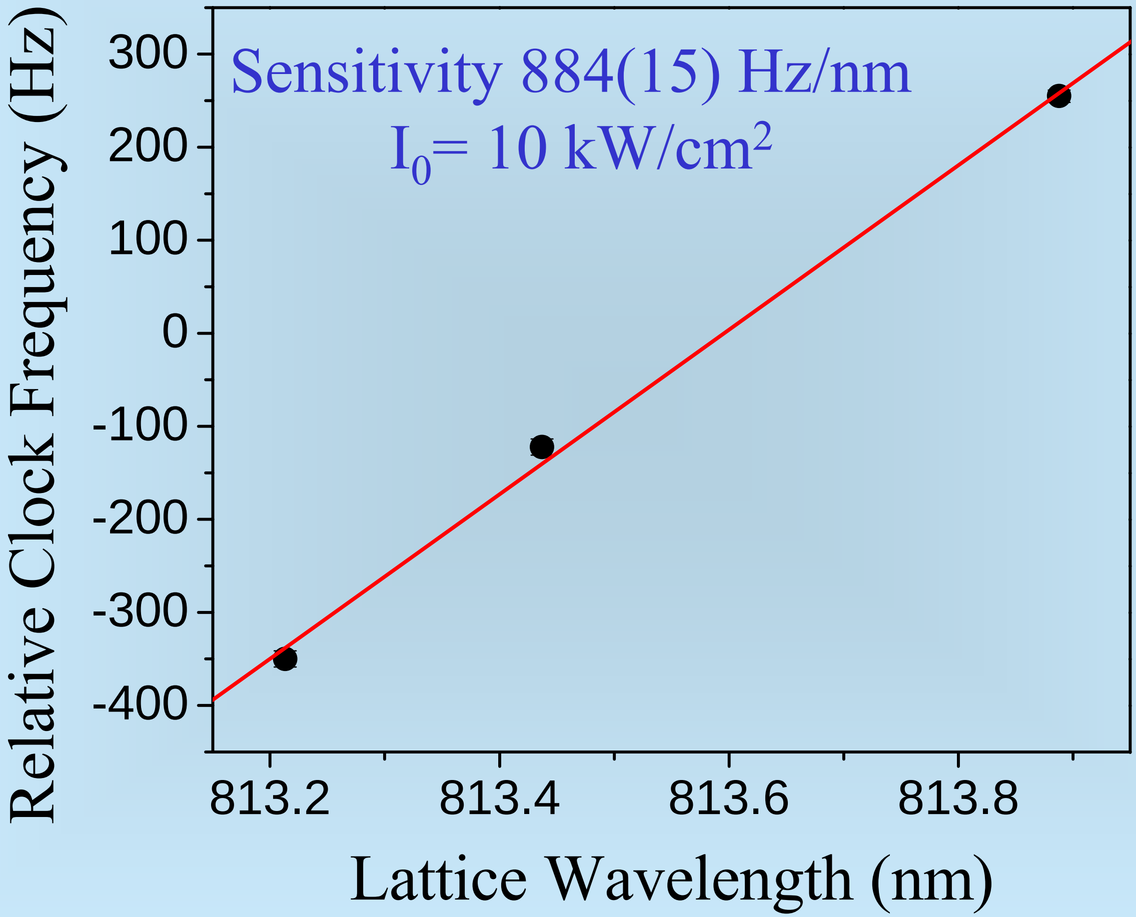
Global Sr Clock Comparison

Takamoto et al., Nature 435, 321 (2005).
Ludlow *et al.*, Phys. Rev. Lett. 96, 033003



How Magic is the wavelength?

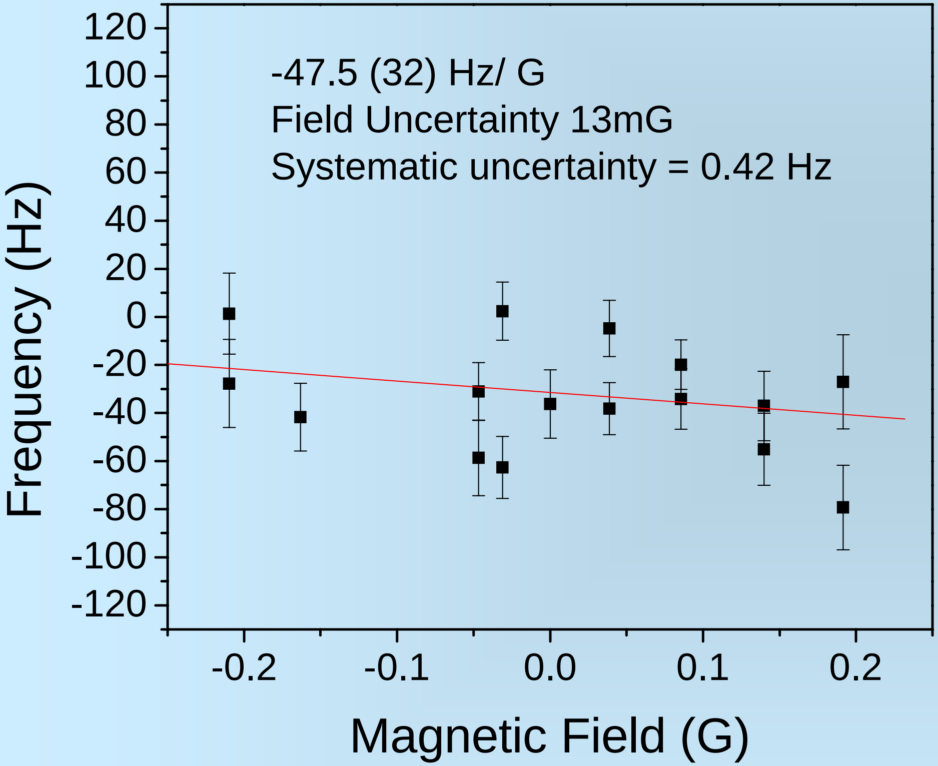
Ludlow *et al.*, Phys. Rev. Lett. 96, 033003
Brusch *et al.*, Phys. Rev. Lett. 96, 103003 (2006).



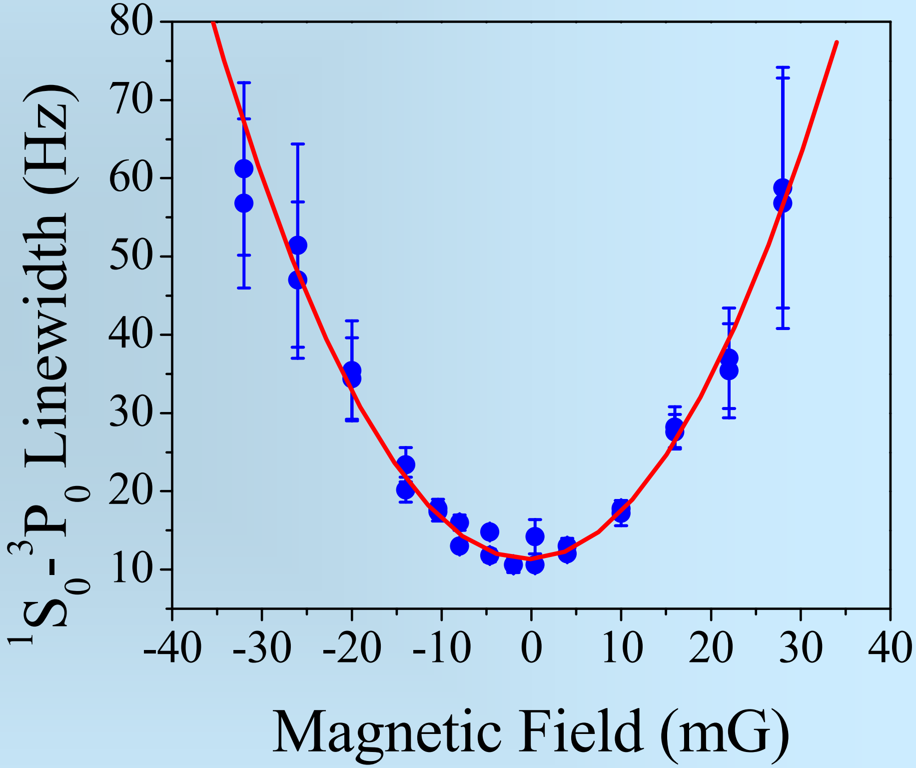
1 MHz error in lattice wavelength → 5×10^{-18} clock inaccuracy

Understanding systematics: Magnetic sensitivities

Magnetic Shift: -47 (32 Hz)/G



Magnetic Broadening

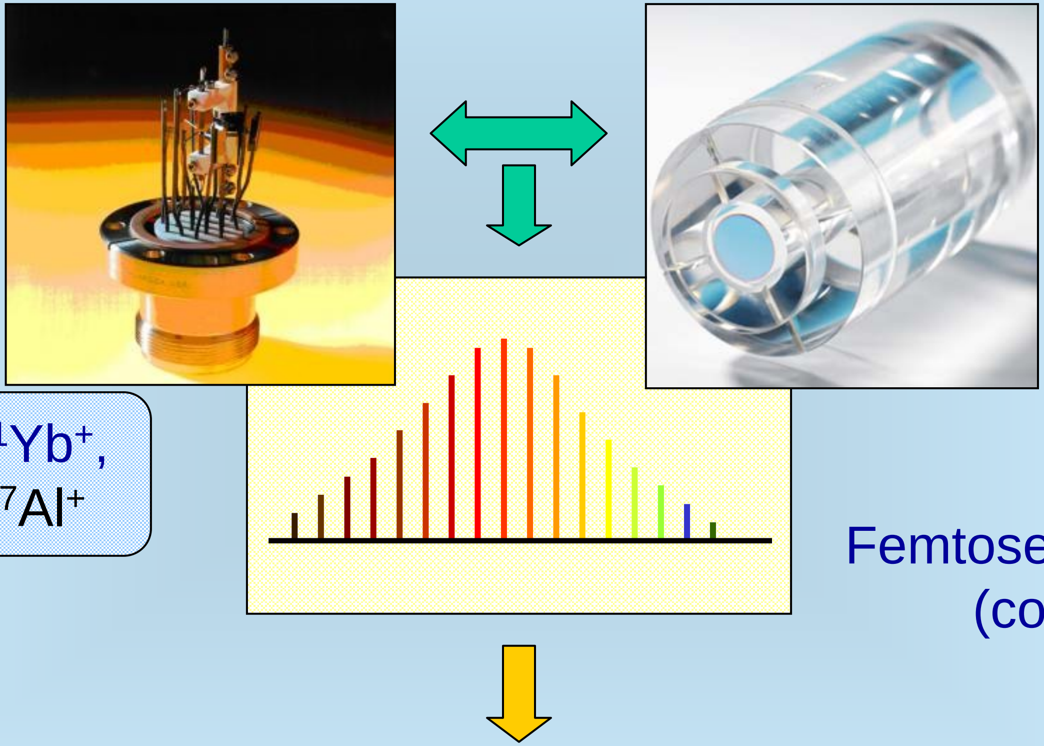


Total uncertainty ~0.5 Hz → 1 x 10^{-15}

Trapped ion optical frequency standards

Helen Margolis
Patrick Gill, *et al.*, NPL

NIST Hg+ systematic uncertainty
< atomic fountain clock
(Bergquist et al., 2006)



Single cold
trapped ion
(atomic reference)

Ultra-stable
probe laser
(local oscillator)

$^{199}\text{Hg}^+$, $^{88}\text{Sr}^+$, $^{171}\text{Yb}^+$,
$^{40}\text{Ca}^+$, $^{115}\text{In}^+$, $^{27}\text{Al}^+$

Femtosecond comb
(counter)

Optical clocks – future redefinition of the second?
Fundamental constants and tests of physics
Future satellite navigation and ranging?

Ion traps: Clean separation between the internal and external degrees of freedom

The point:
Long coherence time in quantum measurement

Precision Measurement/Standards:
NIST, NPL, PTB, NRC, JPL, …
Innsbruck, Harvard, MPQ, Dusseldorf, …

Quantum Information science:
NIST, Innsbruck, Michigan, Oxford, MIT, Ulm, …

Precision spectroscopy of H_2 and a possible variation of m_p/m_e over cosmological time

PRL 96, 151101 (2006).

Wim Ubachs

Laser Centre
vrije Universiteit amsterdam

Dimensionless constants of nature:

$1/\alpha = 137.035\,999\,11\,(46)$

$\mu = M_p/m_e = 1836.152\,672\,61\,(85)$

various g - factors

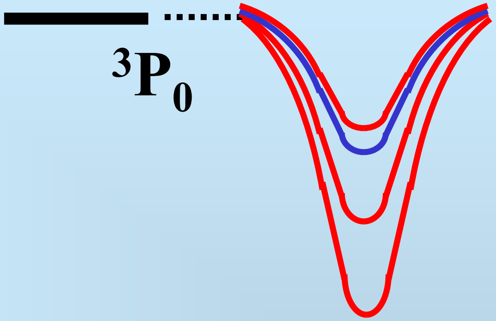
Fundamental constants ?

Just empirical or deeper theory ?

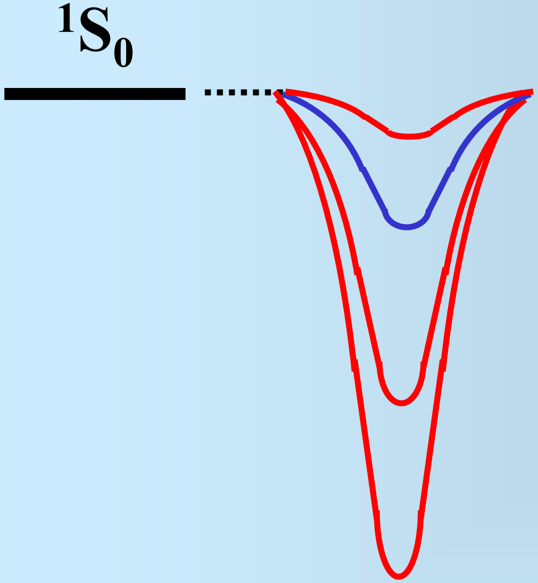
Molecular structure and possibility of lif

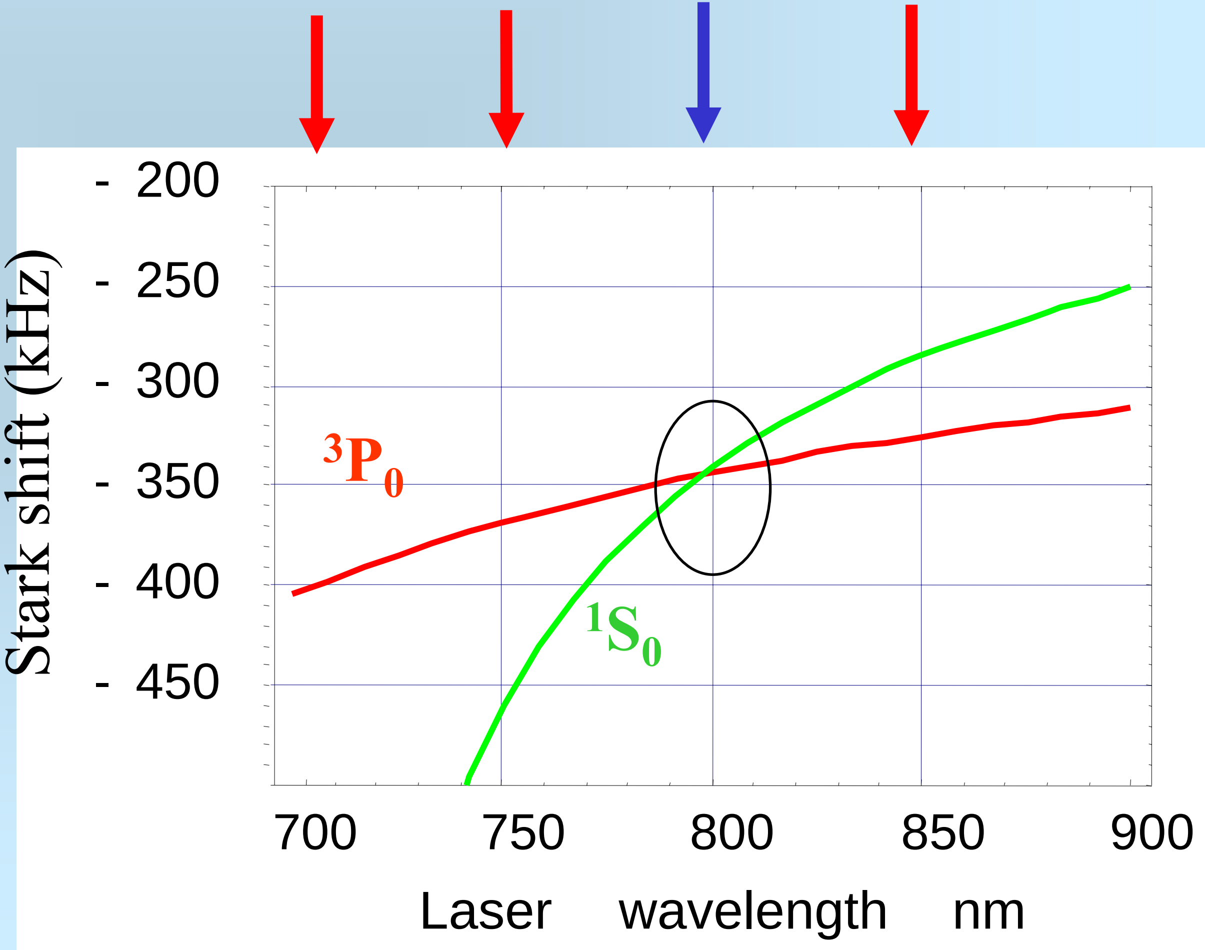
Constant or slightly varying ?

Matching the polarizabilities

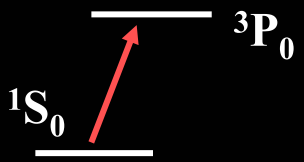


Sr, Yb, Ca, Hg, …





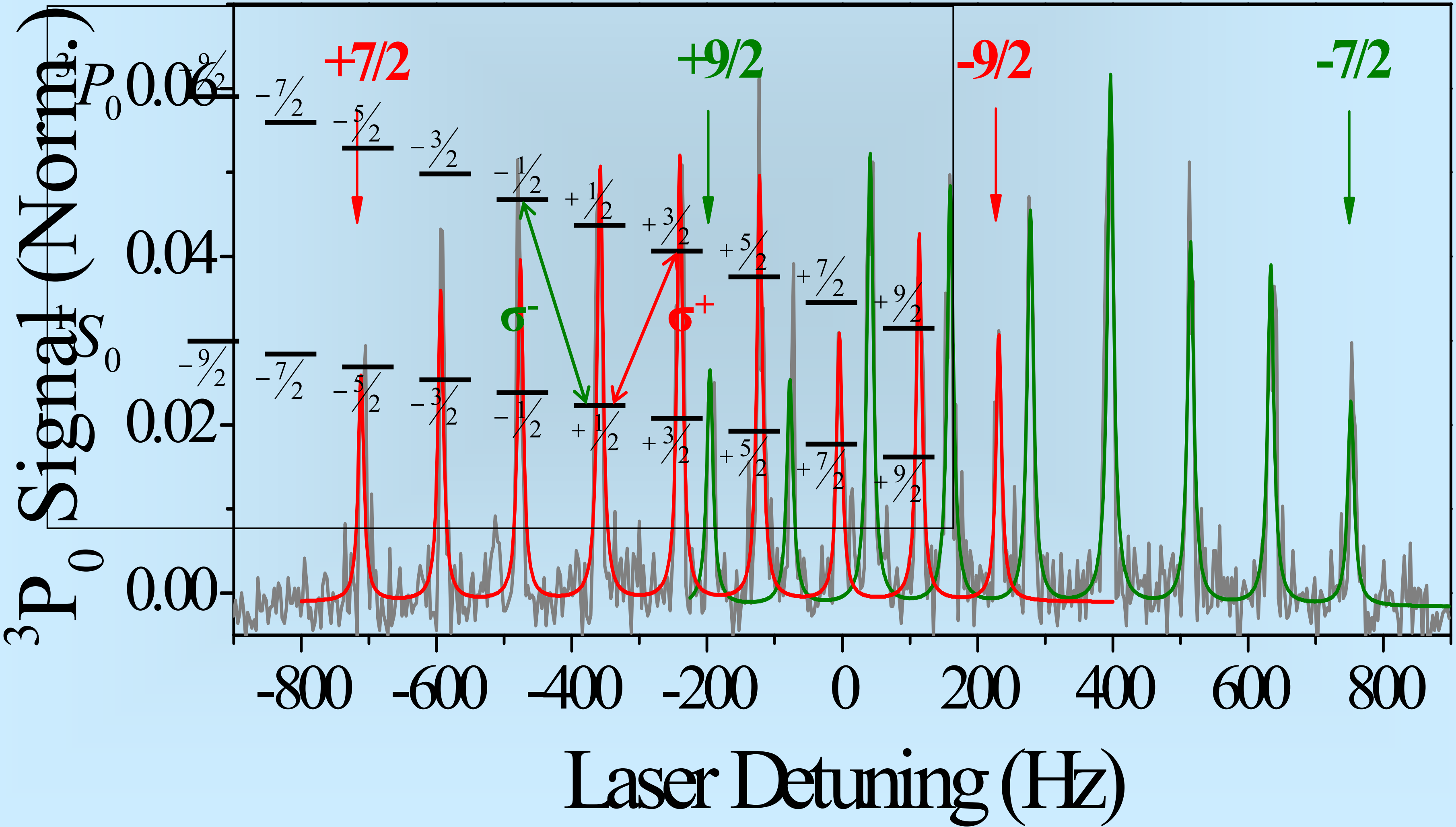
Optical Measurement of Nuclear *g*-factor



No net electronic angular momentum

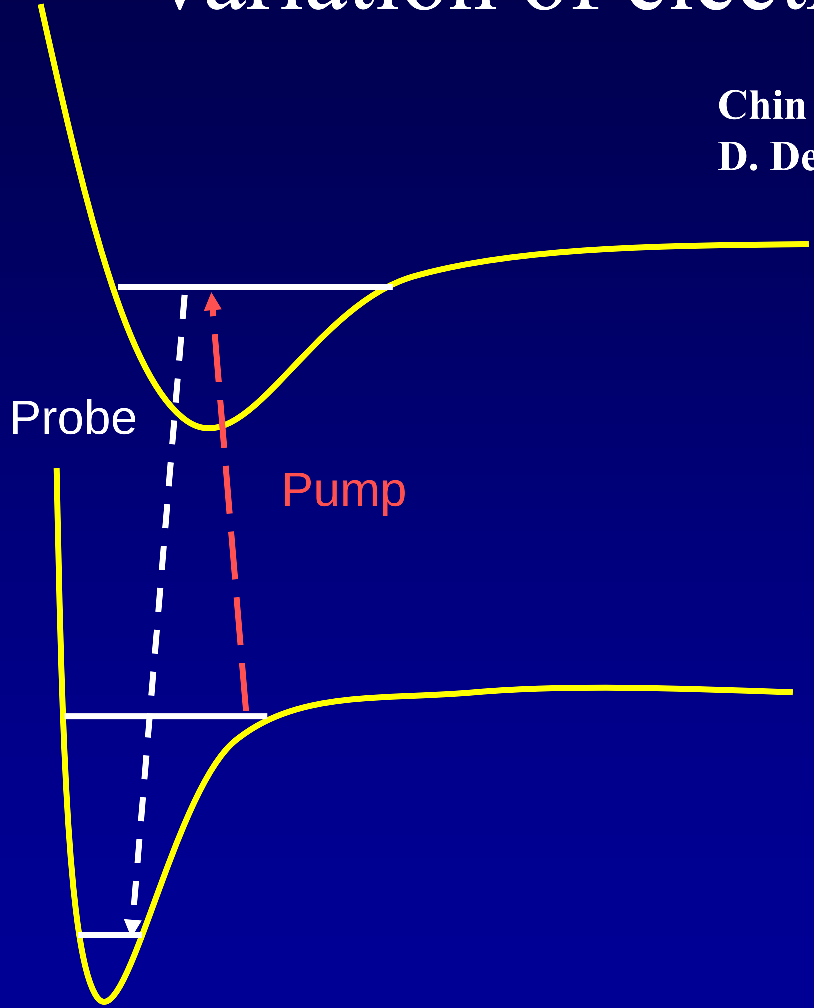
Δg = -108.5(4) Hz/(G m_F)

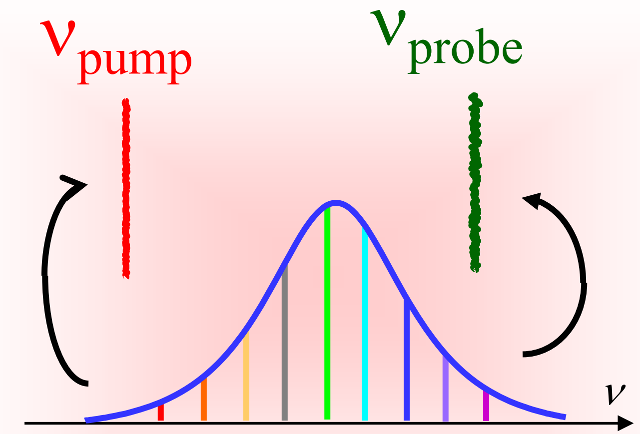
$^3P_0$ lifetime 140(40) s



Ultracold Sr_2 molecules to test time-variation of electron-proton mass ratio

Chin and Flambaum, Phys. Rev. Lett. 96, 230801 (2006).
D. DeMille, private communications (2005).



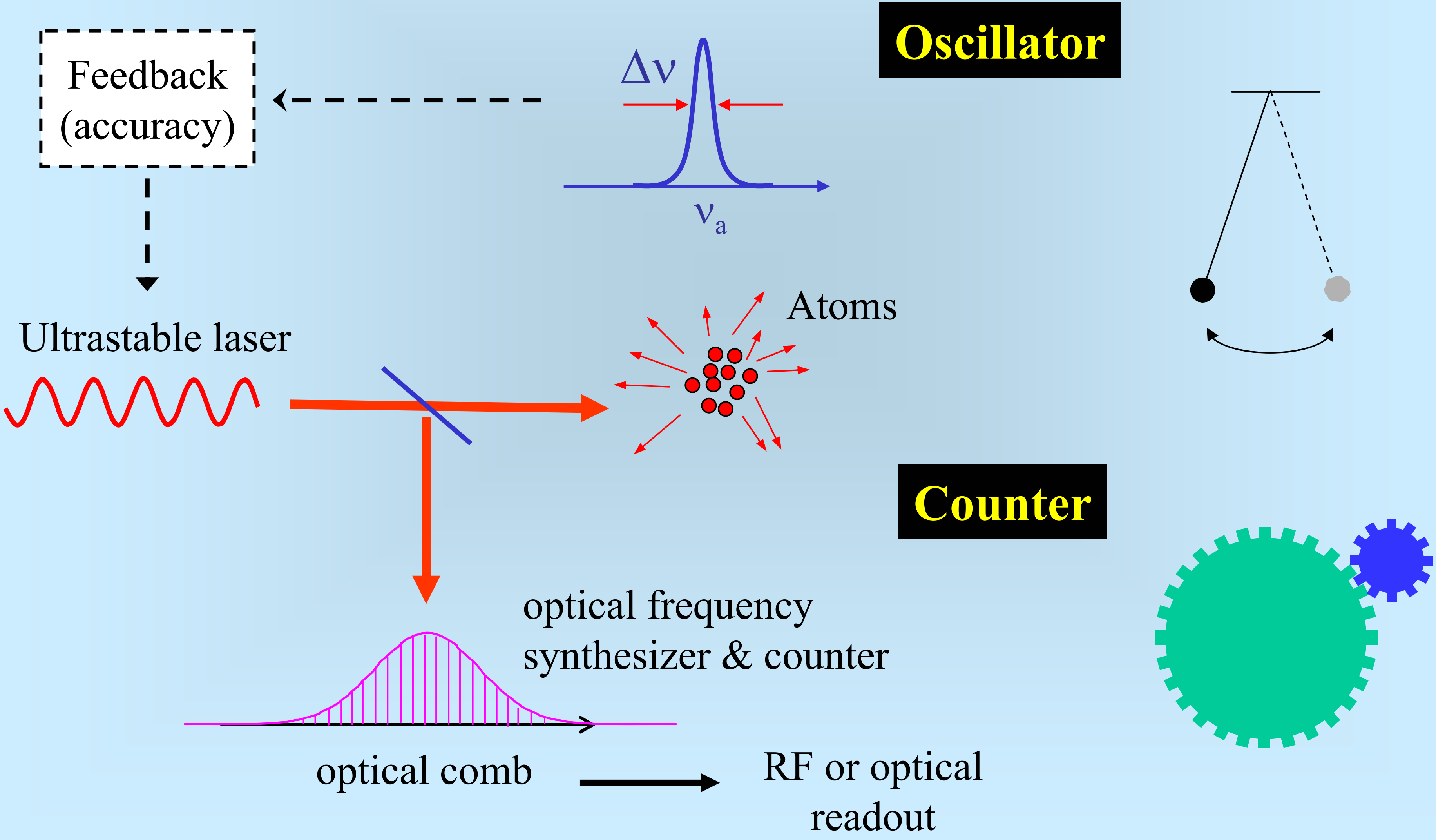


$$\delta(\nu_{pump} - \nu_{probe}) < 0.5\ \text{Hz}$$

Magic wavelength trap for molecules?
Theory: P. Julienne and A. Derevianko

New era for optical atomic clocks

NIST, JILA, PTB, NPL, SYRTE, …



Feedback
(accuracy)

$\Delta\nu$

ν_a

Oscillator

Ultrastable laser

Atoms

Counter

optical frequency
synthesizer & counter

optical comb

RF or optical
readout

Possible systematics in space

Electro-Magnetic field in space

Different velocities for different lines

Solutions:

OH sum rule

Main lines versus satellite lines

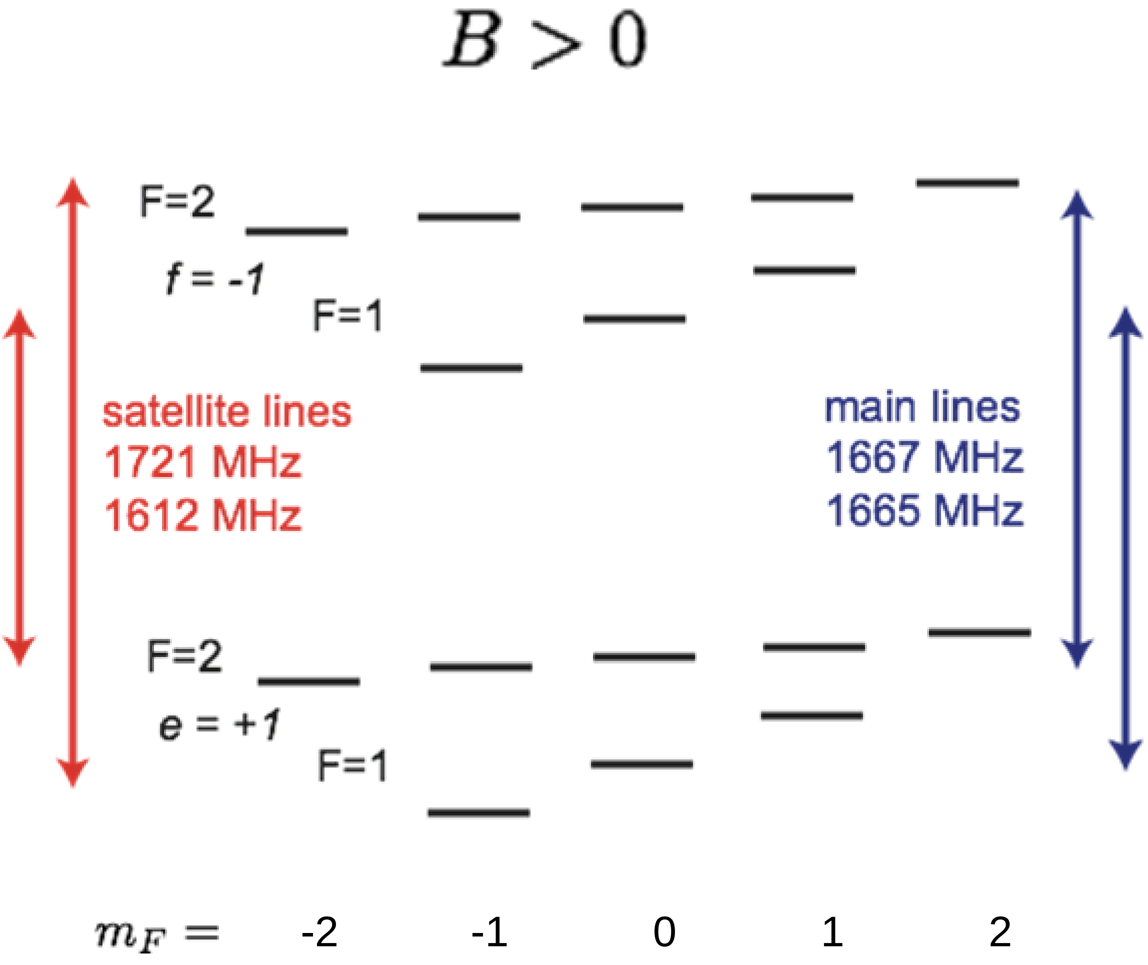
Emission and conjugate absorption

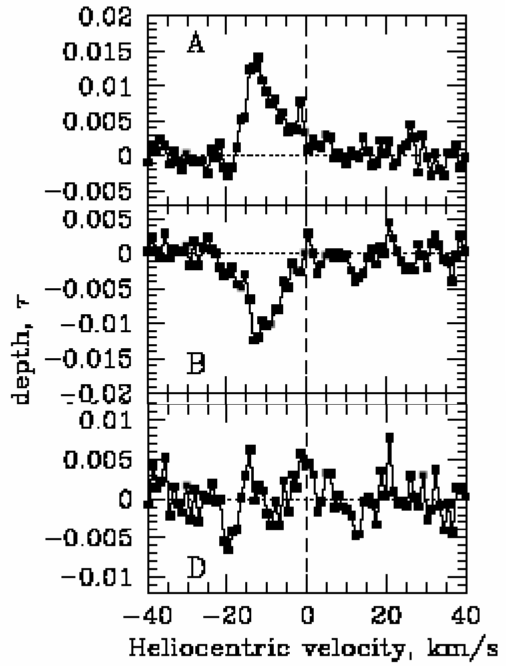
The OH $^2\Pi_{3/2}$ ground state in a B-Field

SUM (2 satellites)
= SUM (2 main lines)

Satellites calibrate B

Observed satellites conjugate





Kanekar *et al*., Phys. Rev. Lett. 93, 051302 (2004).