関西相対論・宇宙論合同セミナー

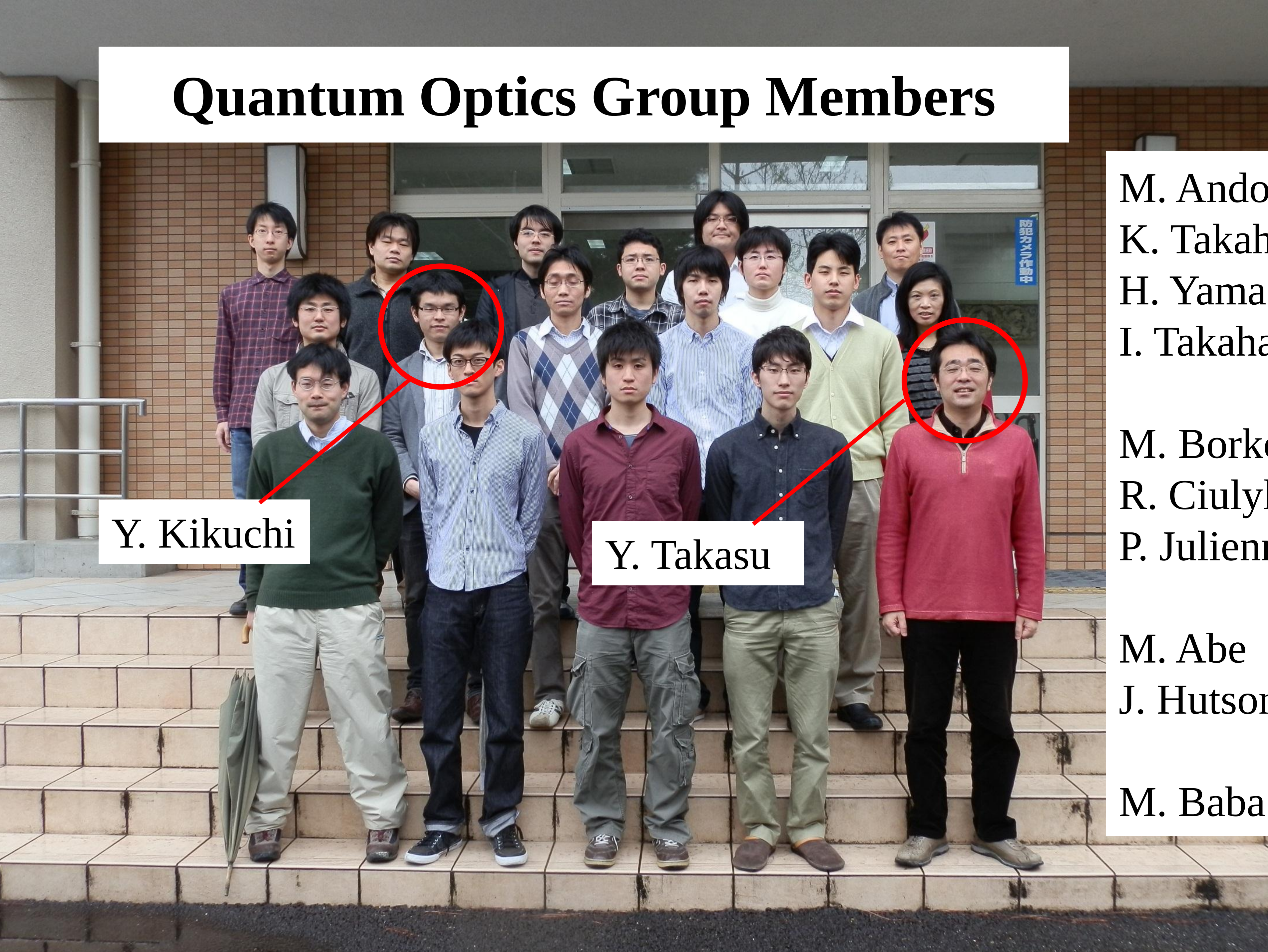
17 December 2012, Kyoto

“Studying Gravity with Quantum Optics
~ Test of Gravity at short range
using Bose-Einstein Condensates ~

Kyoto University, JST

Y. Takahashi

Quantum Optics Group Members



M. Ando
K. Takahashi
H. Yamada
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P. Julienne

M. Abe
J. Hutson

M. Baba

Outline

Introduction:

quantum optics researches for studying gravity

Proposed experiment:

test of gravity at short range using Bose-Einstein condensates:

current status and prospects

Outline

Introduction:

quantum optics researches for studying gravity

Proposed experiment:

test of gravity at short range using Bose-Einstein condensates:

current status and prospects

Gravity and Quantum Optics

Gravitational Effect

↓

Very Weak in Laboratory Scale

↓

Need of Precision Measurement
(sometimes, beyond quantum limit)

⇓

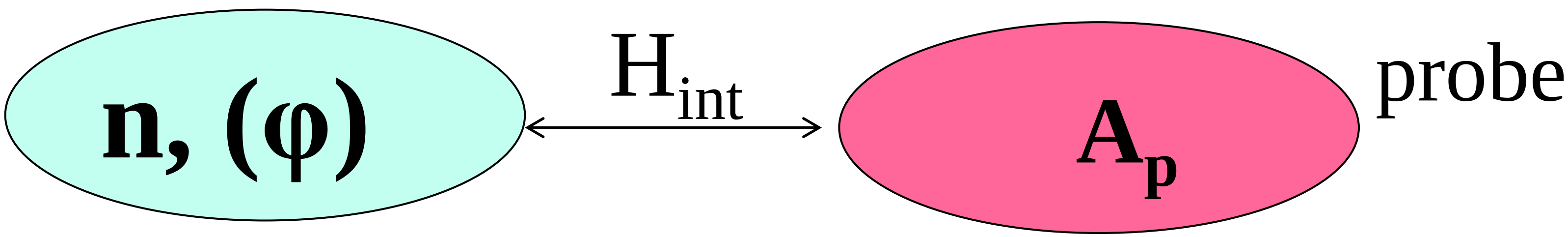
Quantum Optics Approach

Gravity and Quantum Optics

For gravitational wave detection:

Quantum Non-Demolition Measurement

(proposed by Braginsky)



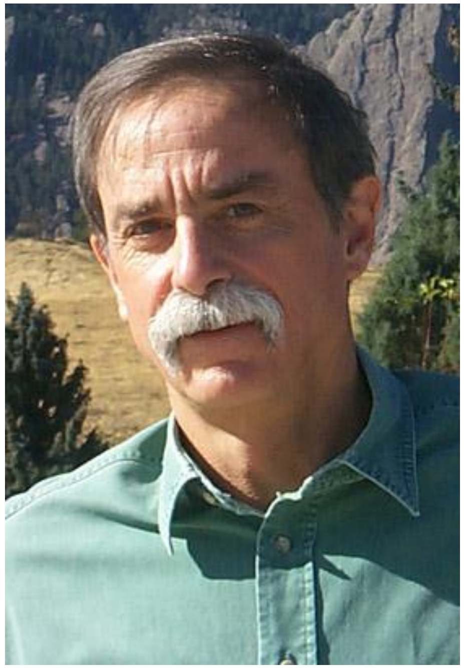
$[n, H_{int}]=0$ (Back-action evasion)

The Nobel Prizes in Physics 2012

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

“Development of Quantum Optics”

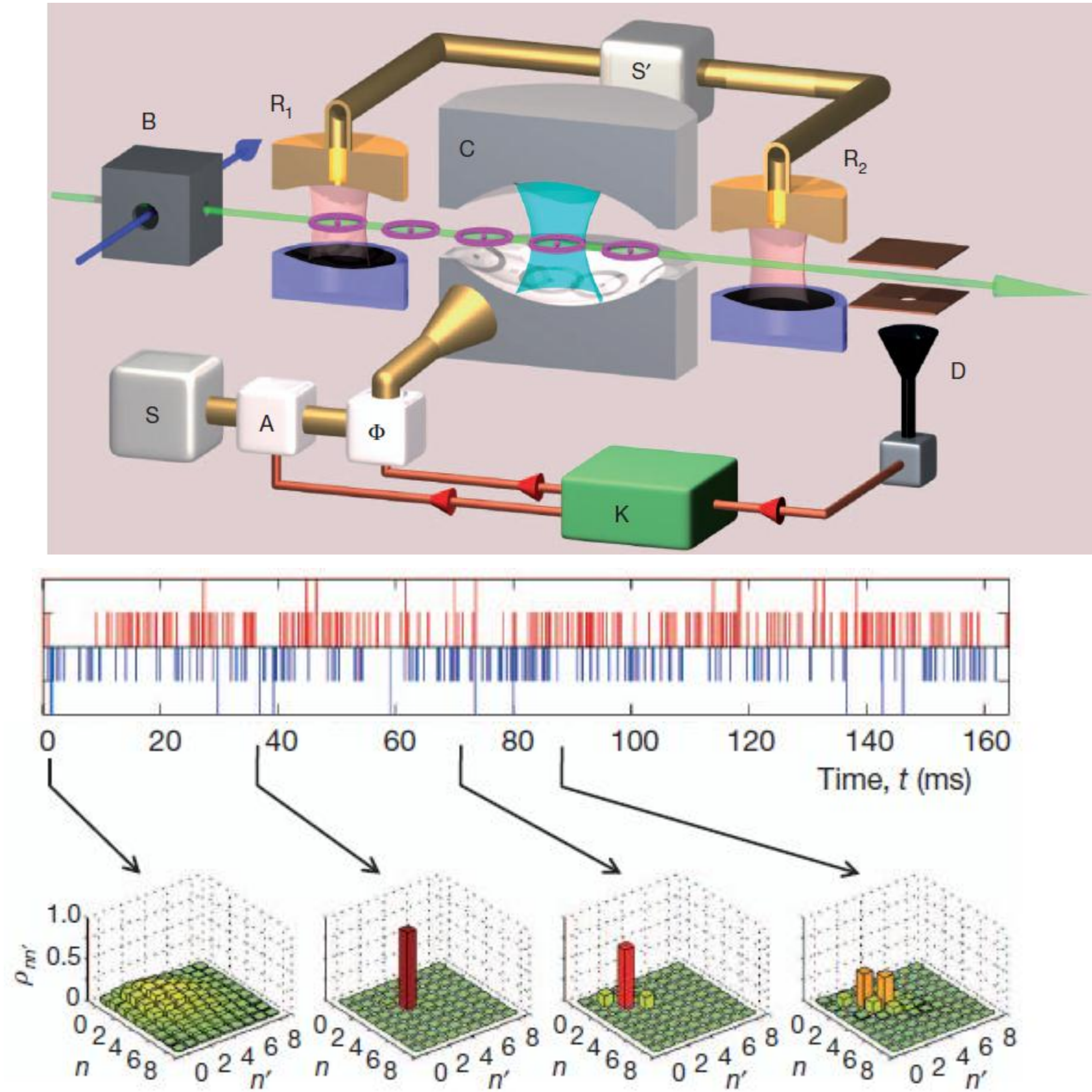
S. Haroche



D. Wineland

QND of photons and Quantum Feedback control

by S. Haroche



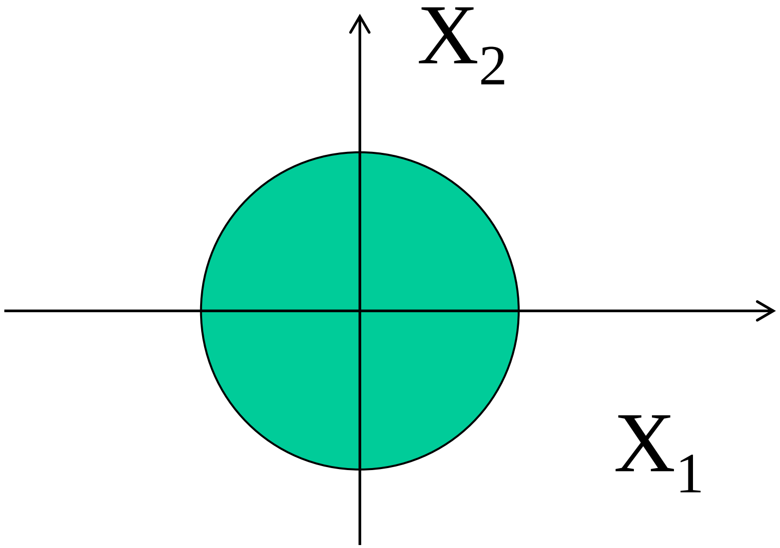
Gravity and Quantum Optics

For gravitational wave detection:

Squeezed States of Light

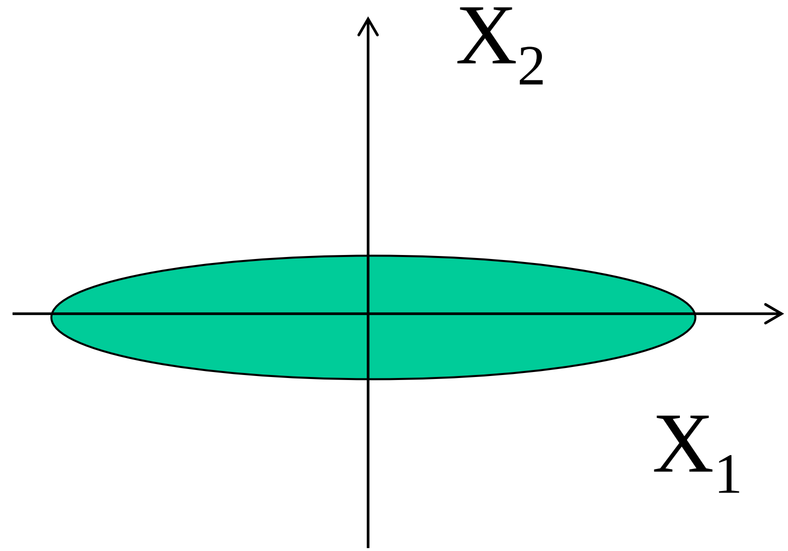
$$[X_1, X_2] = i/2$$

$$\Delta X_1 \Delta X_2 \geq 1/4$$



$$\Delta X_1 = \Delta X_2 = 1/2$$

Coherent states (laser)



$$\Delta X_1 > 1/2, \ \Delta X_2 < 1/2$$

Squeezed states

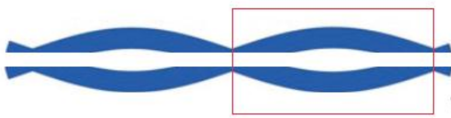
Gravity and Quantum Optics

For gravitational wave detection:

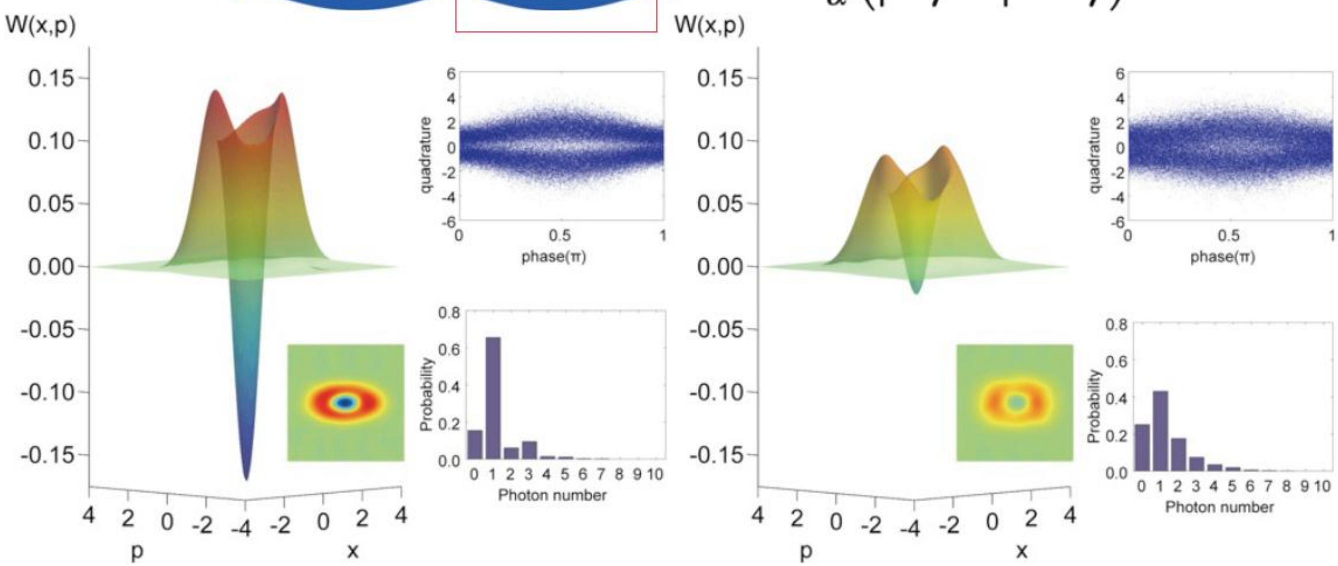
Squeezed States of Light

➡ Important resources for Quantum information processing

Teleportation of a Schrödinger cat state of light



$$N_\alpha \left(|\alpha\rangle - |-\alpha\rangle \right)$$



Input Output

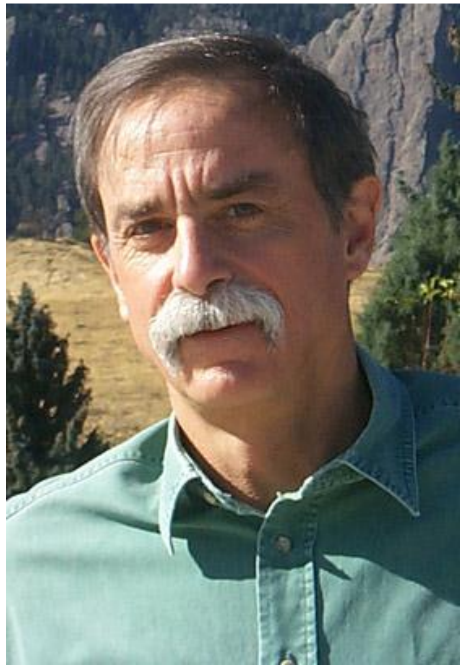
Furusawa G
(U. of Tokyo)

The Nobel Prizes in Physics 2012

"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

"Development of Quantum Optics"

S. Haroche

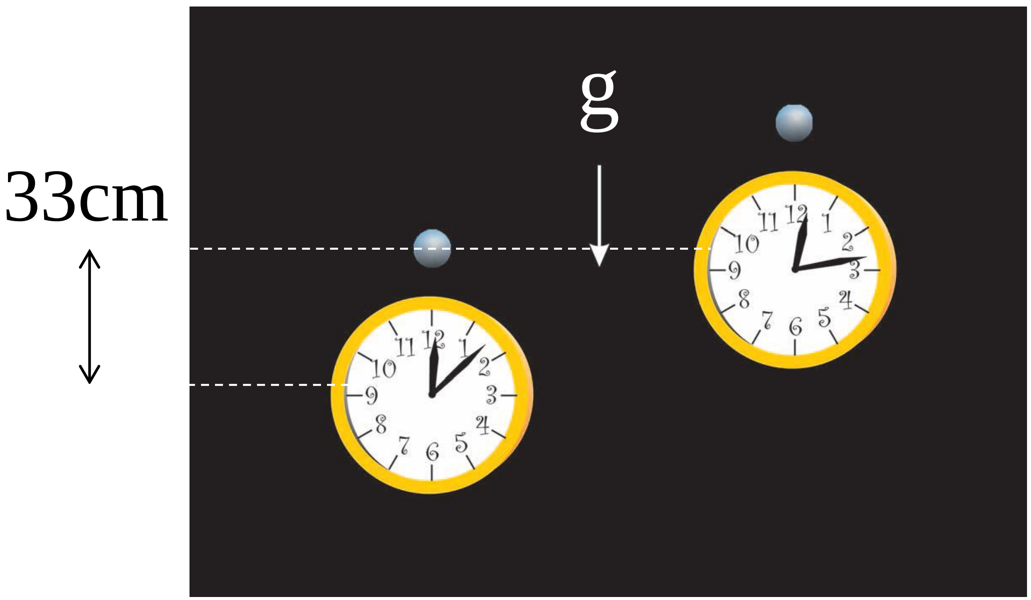


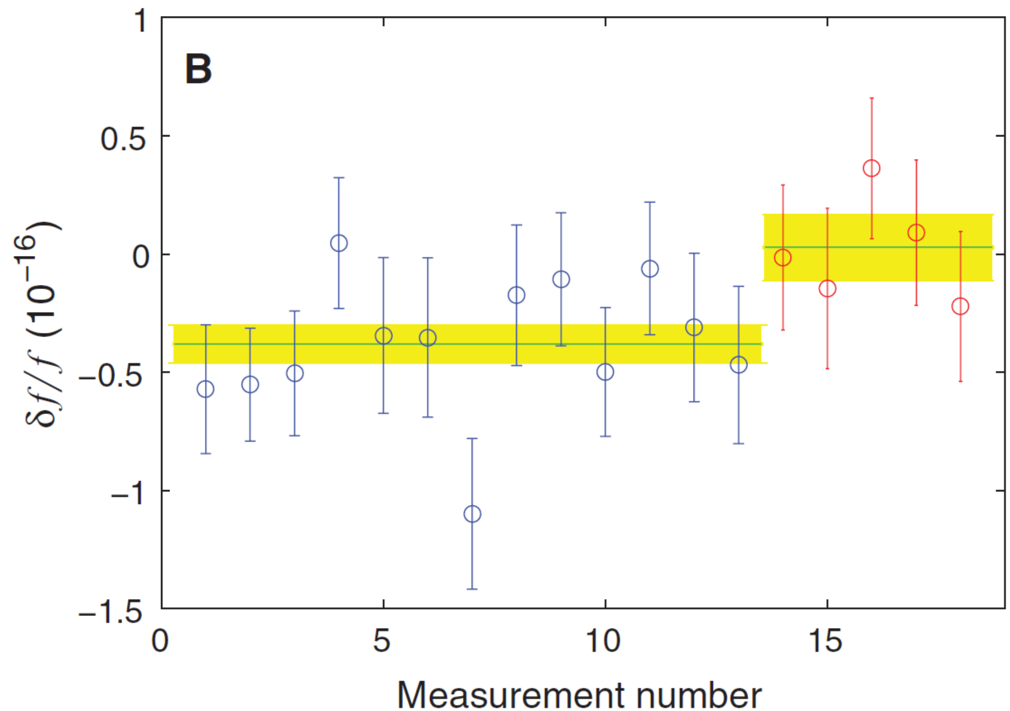
D. Wineland

Optical clocks and relativity

D. Wineland Group, [Science 329,1630 (2010)]

$$\Delta f/f : \sim 10^{-17}!$$





$\longrightarrow$ $f(Hg^{+})/f(Al^{+}) : 10^{-17}$

$$\dot{\alpha}/\alpha = (-1.6 \pm 2.3)\times 10^{-17}\ /\ yr$$

Precise measurement of g using atoms

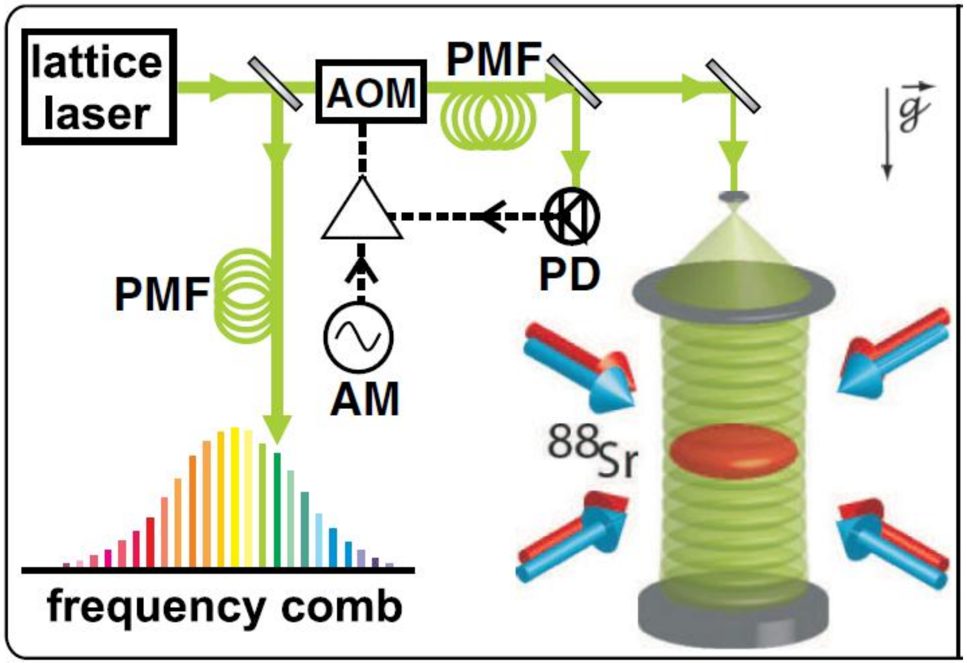
[PRL 106, 038501(2011)]

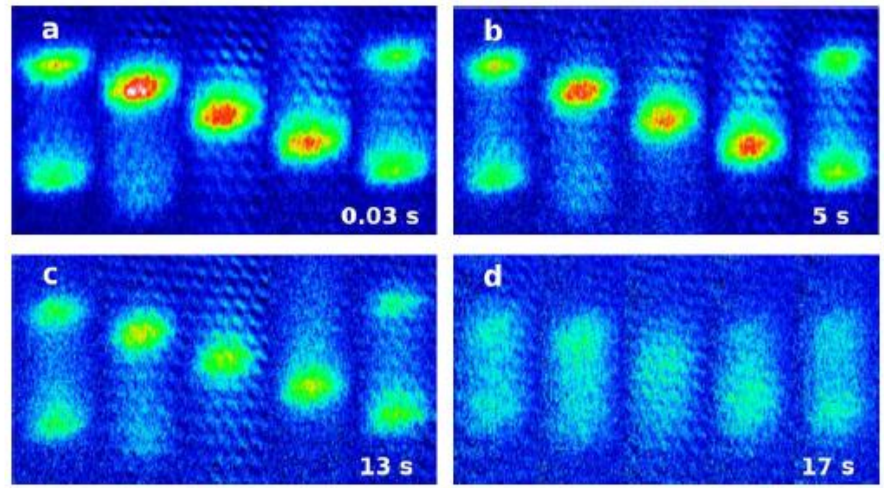
^{88}Sr atoms: N~ 10^6, T~ 0.6μK, almost non-interacting

"Bloch oscillation"

1st BZ: $2\hbar k_L = F\tau_B$, $F = m_{Sr} g$

$$\nu_B = m_{Sr} g \lambda_L / 2h$$





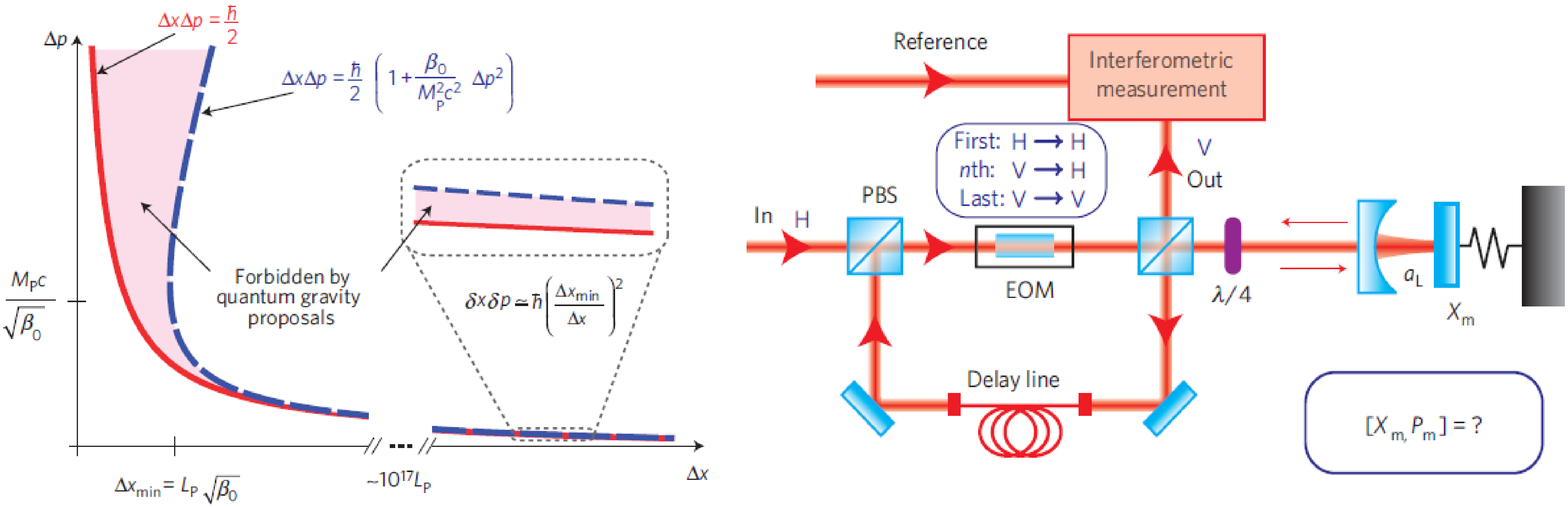
$$\Rightarrow \quad g_{\text{atom}} = 9.804\,923\,2(14)\ \text{m/s}^2$$

⇒ no change up to 15 μm near surface

nature physics
ARTICLES
PUBLISHED ONLINE: 18 MARCH 2012 | DOI: 10.1038/NPHYS2262

Probing Planck-scale physics with quantum optics

Igor Pikovski[1,2]*, Michael R. Vanner[1,2], Markus Aspelmeyer[1,2], M. S. Kim[3]* and Časlav Brukner[2,4]



Outline

Introduction:

quantum optics researches for studying gravity

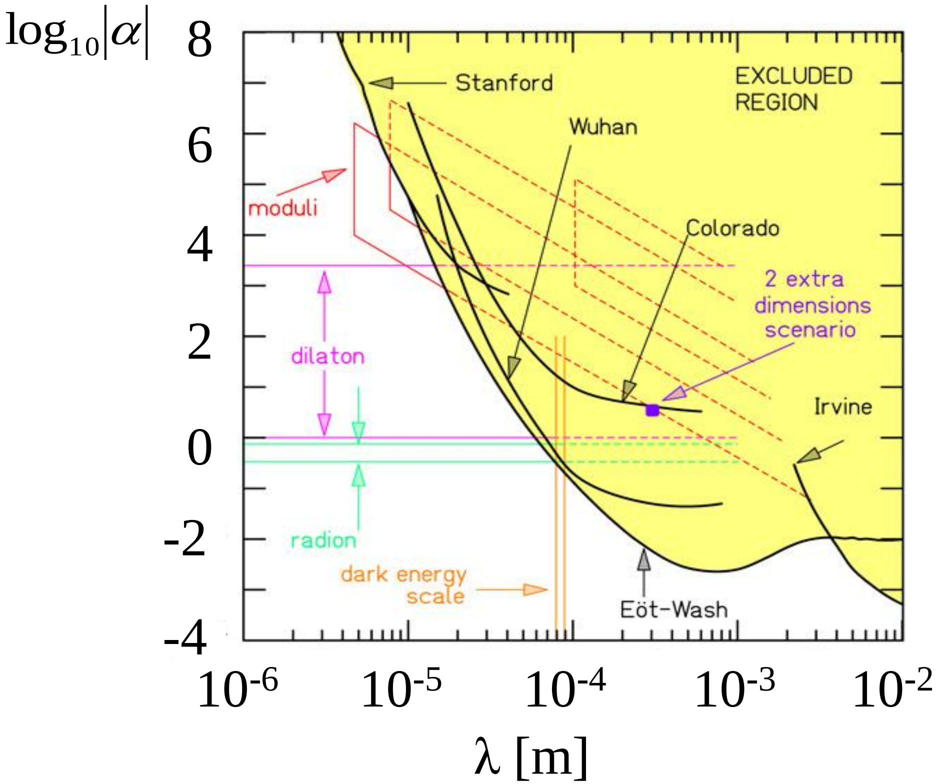
Proposed experiment:

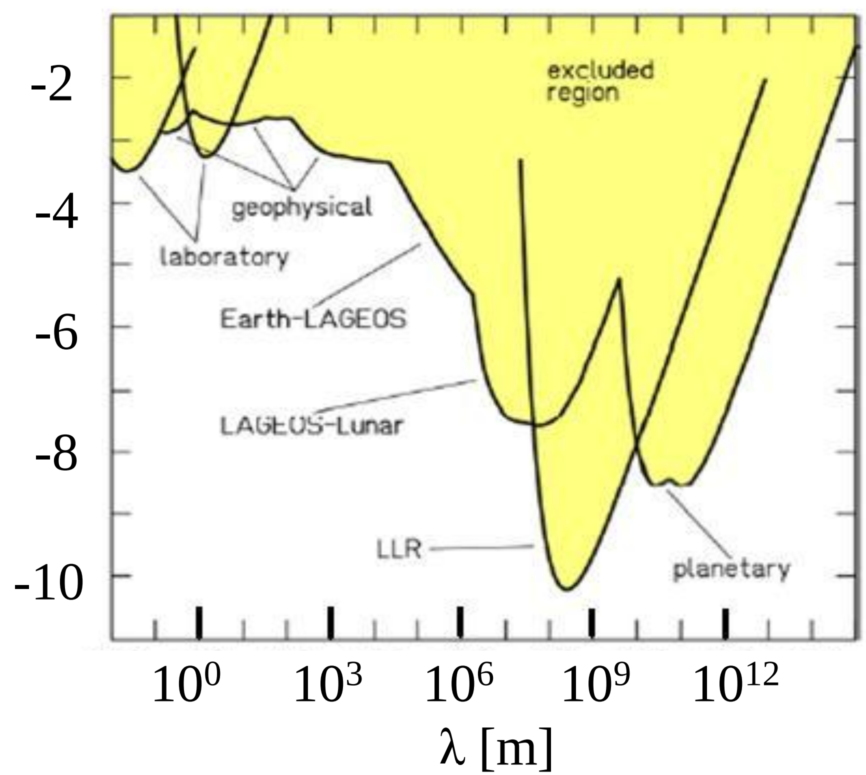
test of gravity at short range using Bose-Einstein condensates:

current status and prospects

Test of the Gravitational r^{-2} Law at Short Range

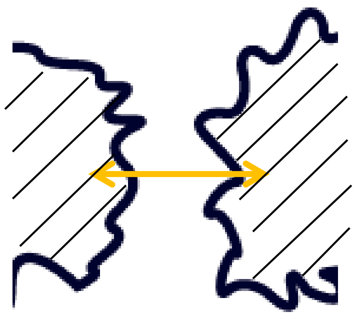
$$V(r) = -\frac{GM_1M_2}{r} \quad \Rightarrow \quad V(r) = -\frac{GM_1M_2}{r}\left(1+\underline{\alpha\, e^{-r/\lambda}}\right)$$





Prog.Part.Nucl.Phys., **62**, 102(2009)

Gravity at Short Range



“neutron scattering data”

[*PRD*, **77**, 034020 (2008)]

$|\alpha| \sim 10^{22}$ @1 nm

“New Boson”

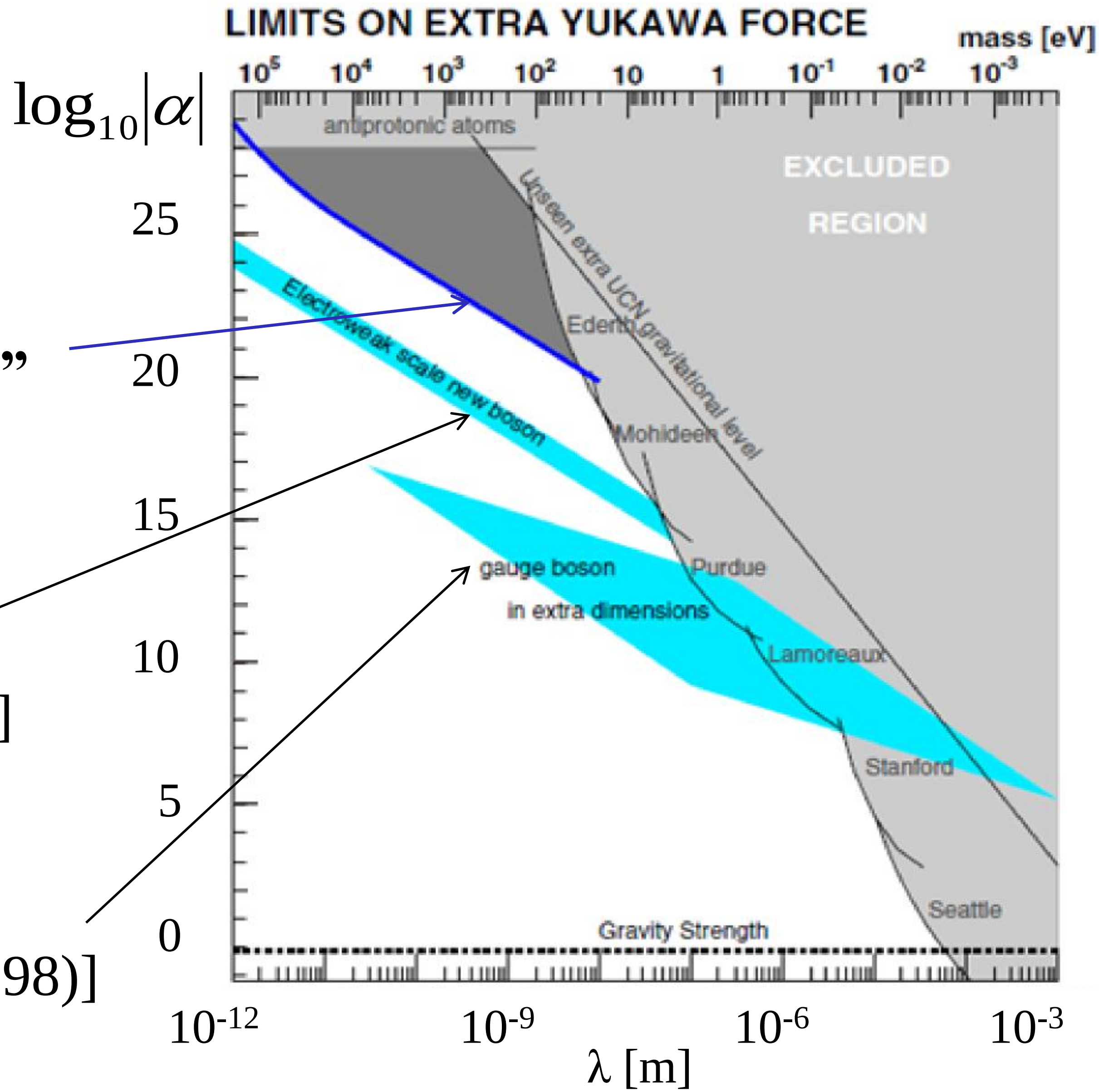
[*PRD*, **75**, 115017 (2007)]

$|\alpha| \sim 10^{18}$ @1 nm

“Extra-Dimension”

[*Phys. Lett. B*, **429**, 263(1998)]

$|\alpha| \sim 10^{15}$ @1 nm



PHYSICAL REVIEW D **77,** 034020 (2008)

Neutron scattering and extra-short-range interactions

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(Received 14 November 2007; published 25 February 2008)

The available data on neutron scattering were reviewed to constrain a hypothetical new short-range interaction. We show that these constraints are several orders of magnitude better than those usually cited in the range between 1 pm and 5 nm. This distance range occupies an intermediate space between collider searches for strongly coupled heavy bosons and searches for new weak macroscopic forces. We emphasize the reliability of the neutron constraints insofar as they provide several independent strategies. We have identified a promising way to improve them.

DOI: 10.1103/PhysRevD.77.034020 PACS numbers: 28.20.Cz, 12.38.Qk

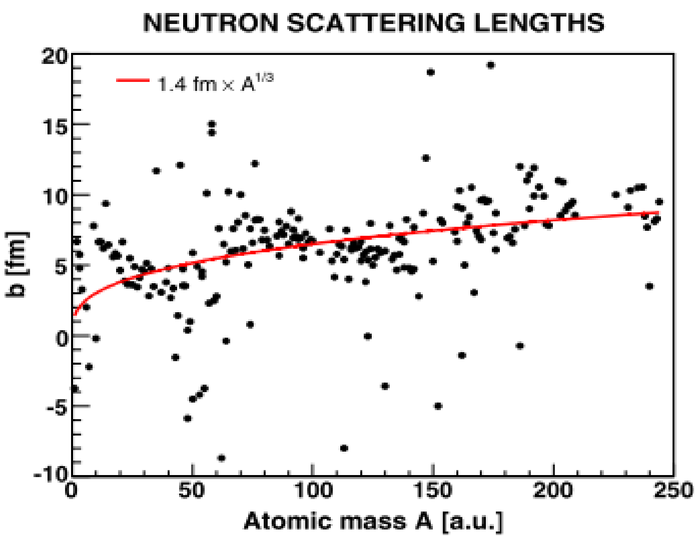


FIG. 1 (color online). Measured scattering lengths as a function of nucleus atomic number.

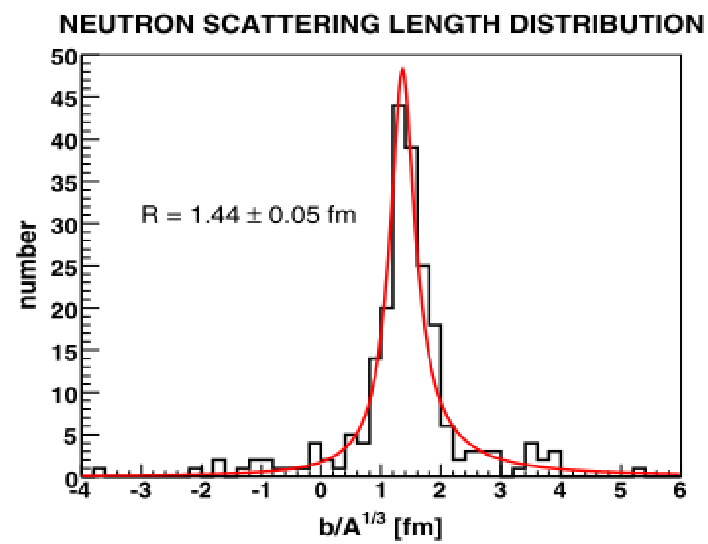
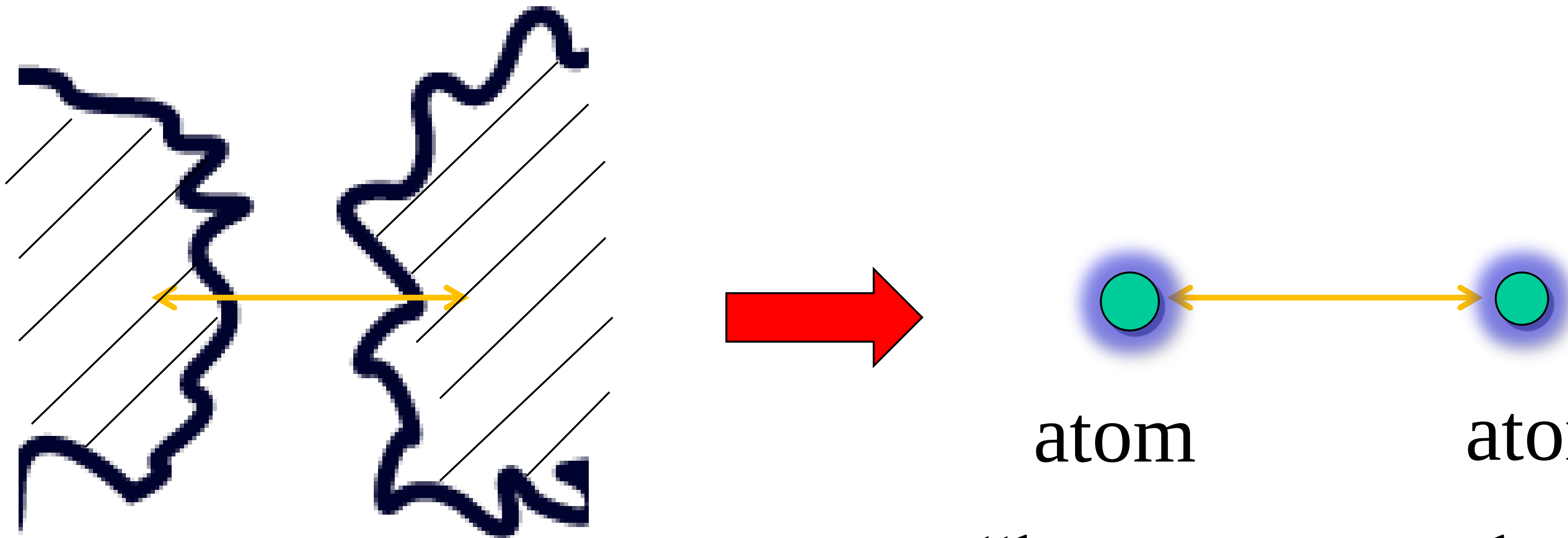


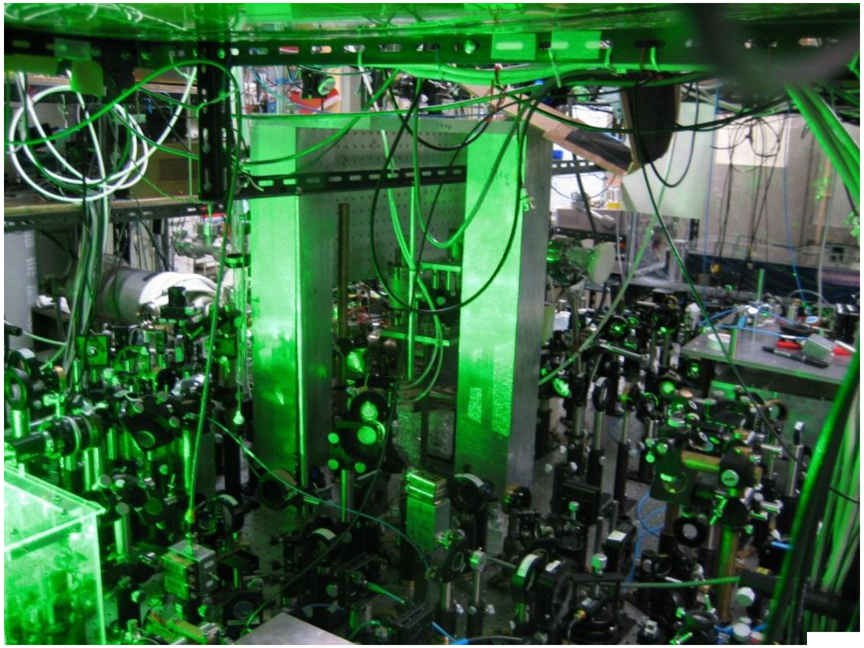
FIG. 2 (color online). This histogram shows the distribution of measured scattering lengths normalized to the radius of the nuclei. The curve corresponds to the random potential model.

Our Approach : Photo-association

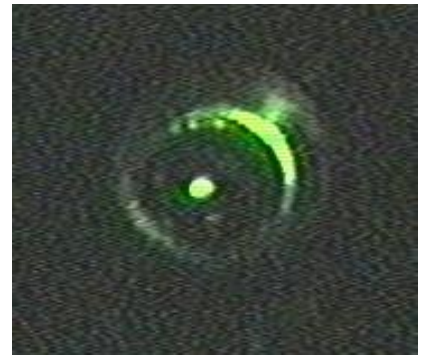


“long-range molecule”

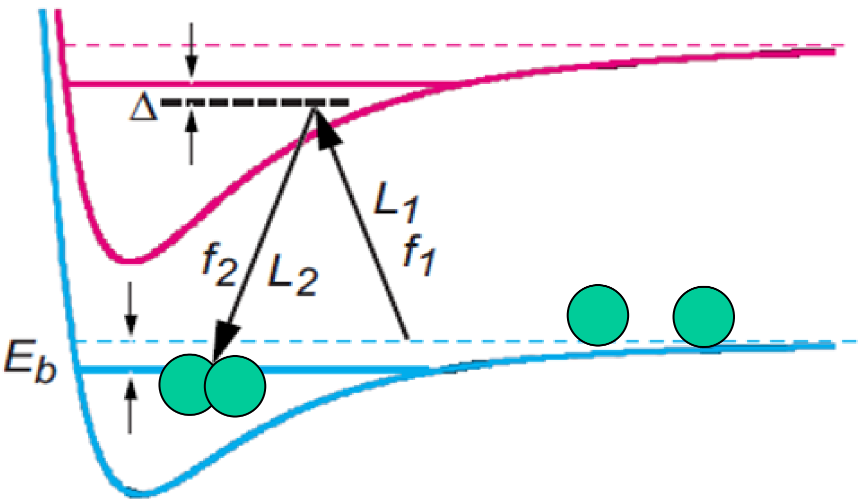
Our Approach : Photo-association



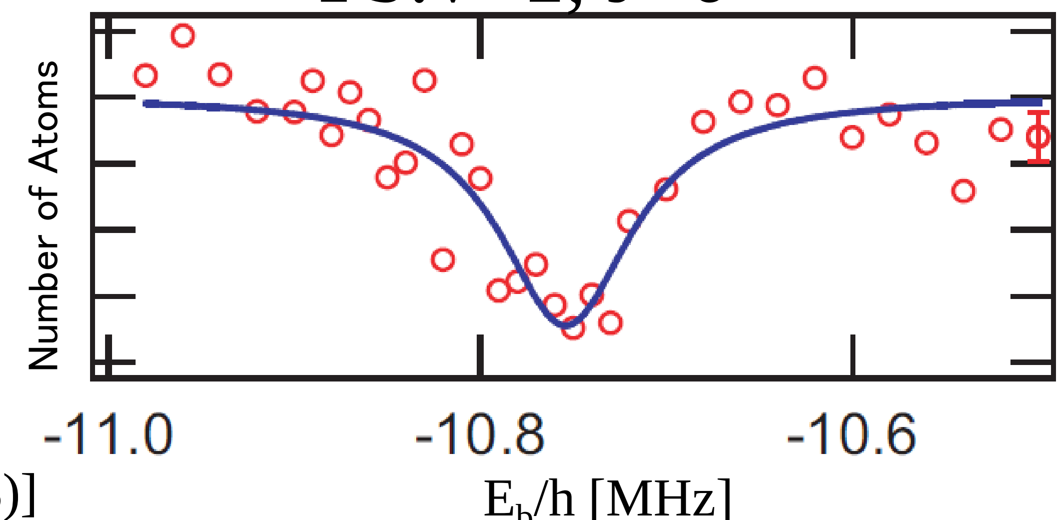
"Magneto-optical Trap"



cold atomic gas at *1 μK !*



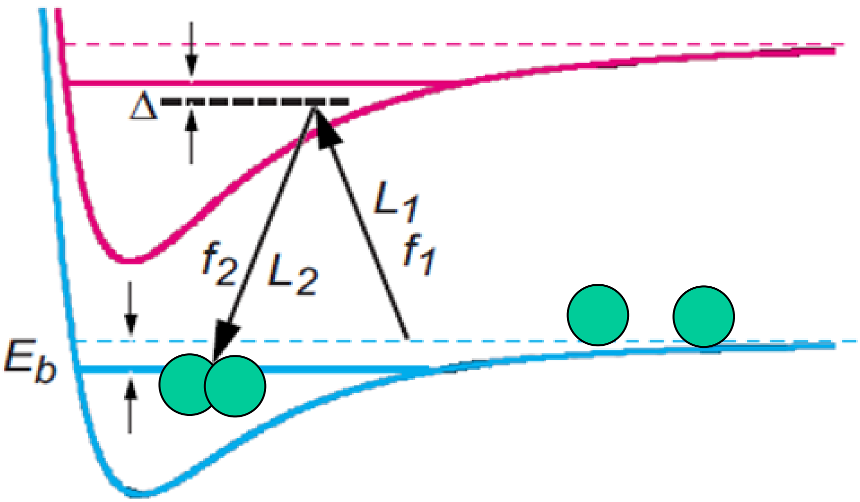
^{174}Yb:v=1, J=0 :~100kHz

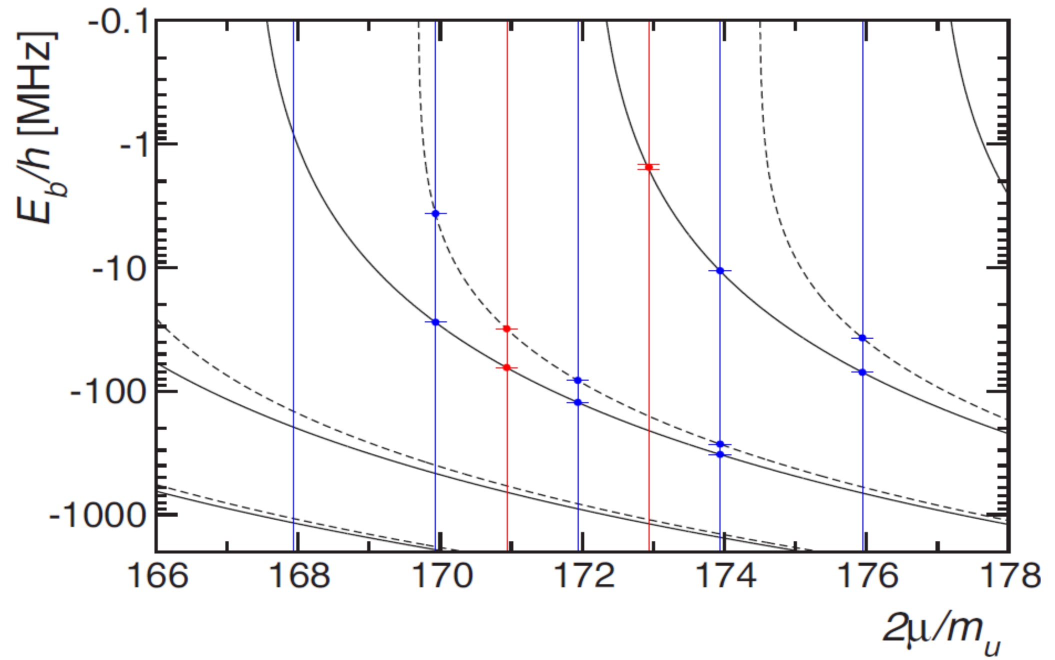


[M. Kitagawa, et al., PRA **77**, 012719(2008)]

Our Approach : Photo-association

[M. Kitagawa, et al., PRA **77**, 012719(2008)]





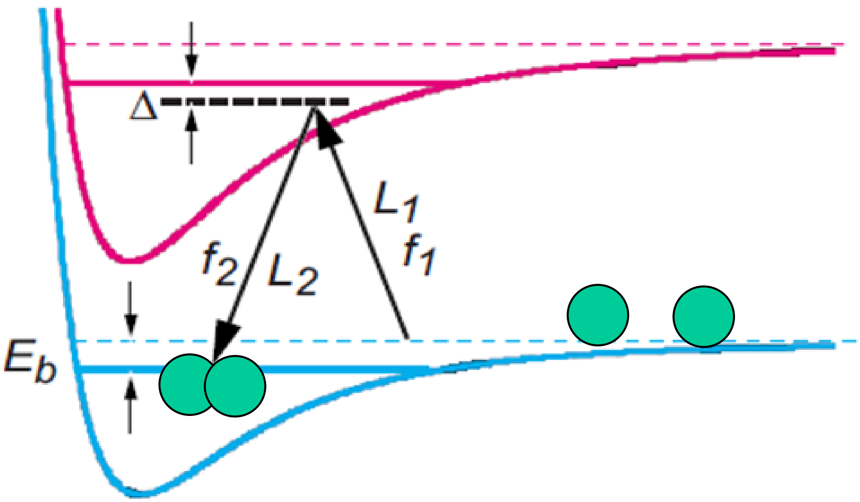
Lenard-Jones-type Potential

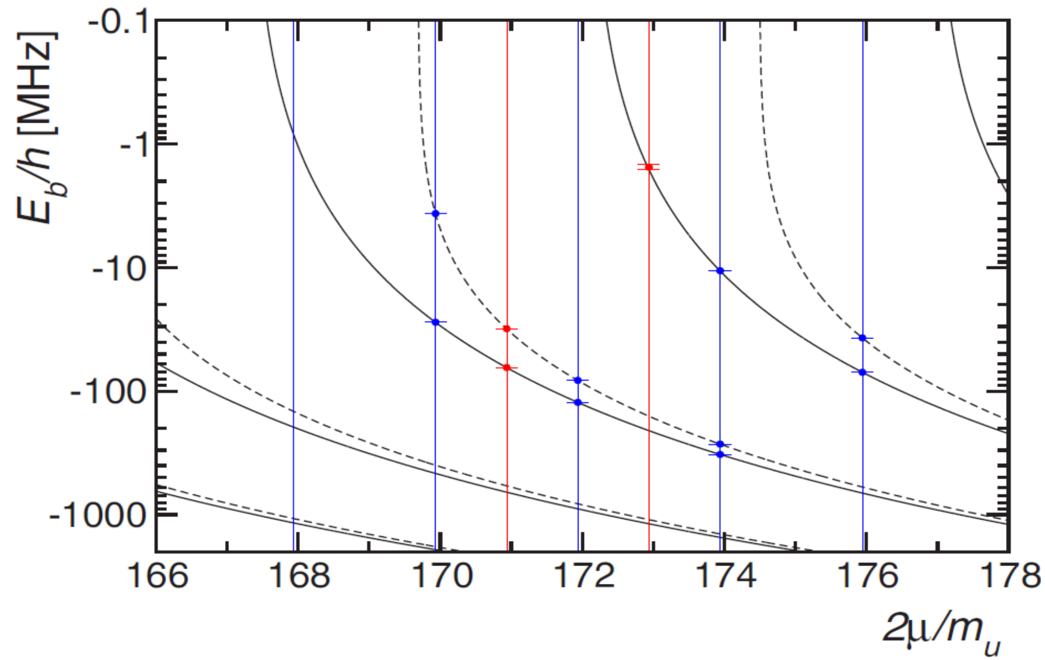
$$\Rightarrow V(r) = \frac{C_{12}}{r^{12}} - \frac{C_6}{r^6} - \frac{C_8}{r^8}$$

C_6=1931.7 $E_h a_0^6$, C_8=1.93×10^6 $E_h a_0^8$, C_{12}=1.03041 $E_h a_0^{12}$

Our Approach : Photo-association

[M. Kitagawa, et al., PRA **77**, 012719(2008)]





Lenard-Jones-type Potential

$$\Rightarrow V(r)=\frac{C_{12}}{r^{12}}-\frac{C_6}{r^6}-\frac{C_8}{r^8}-\frac{GM_1M_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

Δf=1kHz

$|\alpha| <\sim 10^{20}$

@1 nm

C_6=1931.7 $E_h\, a_0^6$, C_8=1.93 × 10^6 $E_h a_0^8$, C_{12}=1.3041 $E_h a_0^{12}$

Many Advantages of Ytterbium

Nice Atomic Species for this experiment !

- Heavy (N~174)
- Single Molecular Potential :No Hyperfine Structure

  Contrary to Alkali Dimers

  Insensitivity to magnetic field
- Many Isotopes:

  ^{168}Yb, ^{170}Yb, ^{171}Yb, ^{172}Yb, ^{173}Yb, ^{174}Yb, ^{176}Yb

  Check the mass dependence
- Ultracold Quantum Gases :

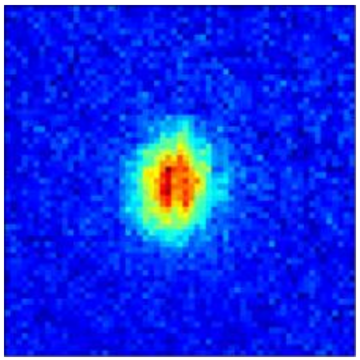
  Free from thermal shift and broadening

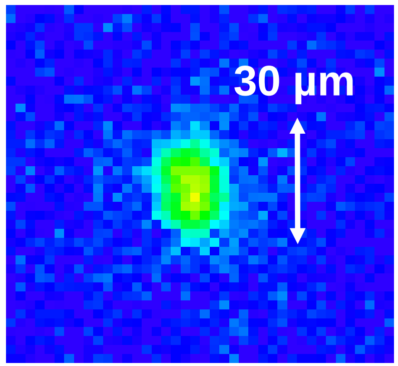
Quantum Degenerate Gases of Yb

[Y. Takasu *et al.*, PRL **91**, 040404 (2003)]   [T. Fukuhara *et al.*, PRA **76**, 051604(R)(2007)]
[S. Sugawa *et al.*, PRA **84**, 011610(R)(2011)]

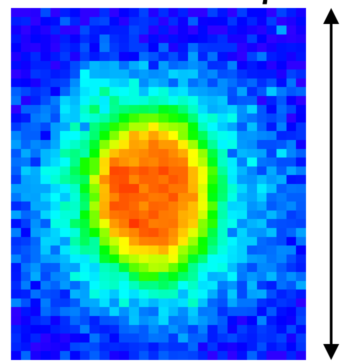
^{168}Yb(0.13%) ^{170}Yb ^{174}Yb ^{176}Yb

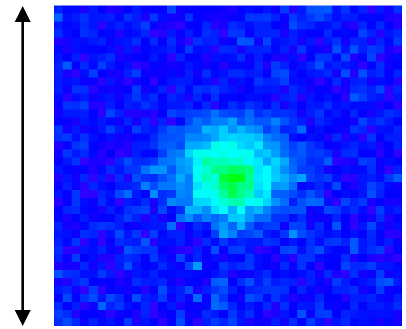
160μm   120 μm   TOF: 8 ms





TOF: 10ms

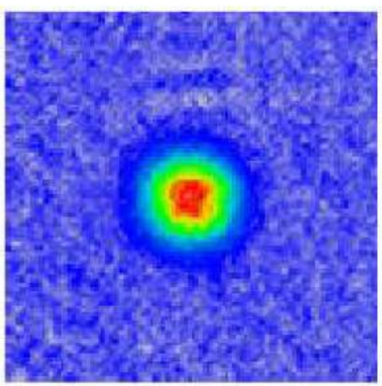


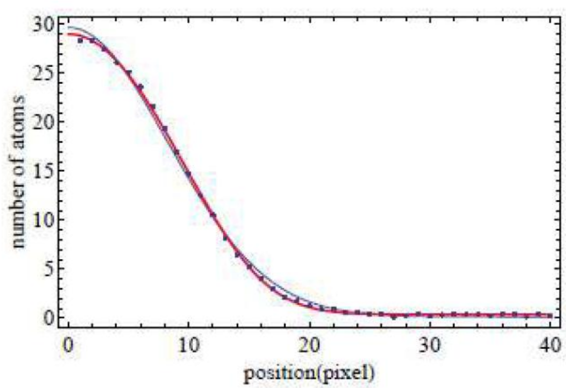


Fermion

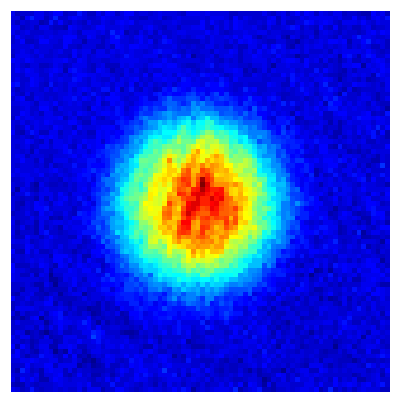
[T. Fukuhara *et al.*, PRL. **98**, 030401 (2007)] [S. Taie *et al* ., PRL**105**, 190401(2010)]

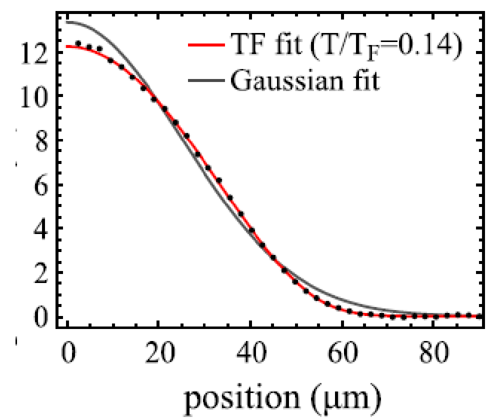
^{171}Yb(I=1/2)   **T/T_F =0.3**





^{173}Yb(I=5/2)   **T/T_F =0.14**

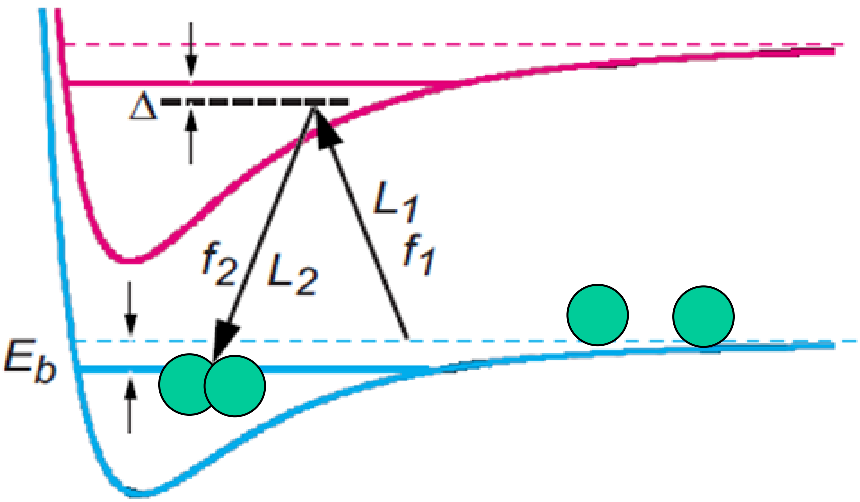


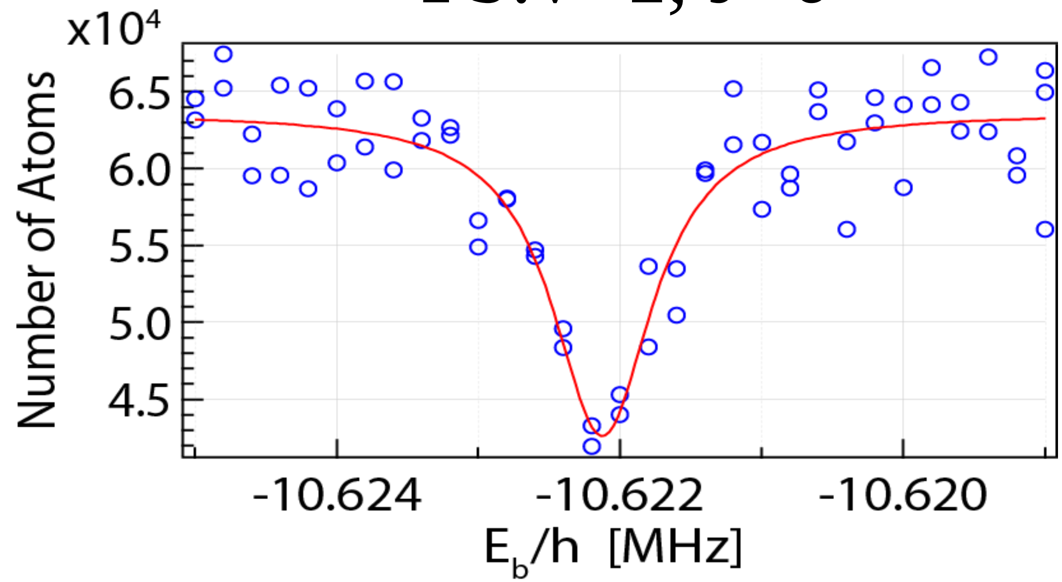


Our Approach : Photo-association

BEC :~1kHz !

^{174}Yb:v=1, J=0





Lenard-Jones-type Potential

$$\Rightarrow V(r) = \frac{C_{12}}{r^{12}} - \frac{C_6}{r^6} - \frac{C_8}{r^8} - \frac{GM_1M_2}{r}\left(1+\alpha e^{-r/\lambda}\right)$$

Δf=1kHz

$|\alpha| <\sim 10^{20}$

@1 nm

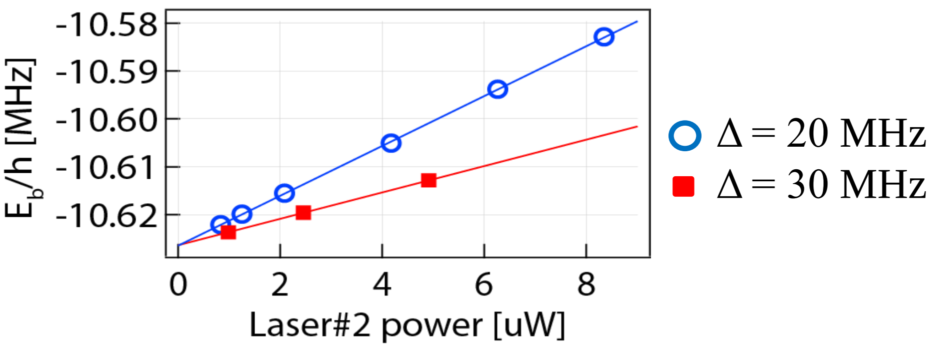
C_6=1931.7 $E_h\, a_0^6$, C_8=1.93×10^6 $E_h a_0^8$, C_{12}=1.3041 $E_h a_0^{12}$

Evaluation of Systematic Shifts

Light Shift due to Photoassociation Laser

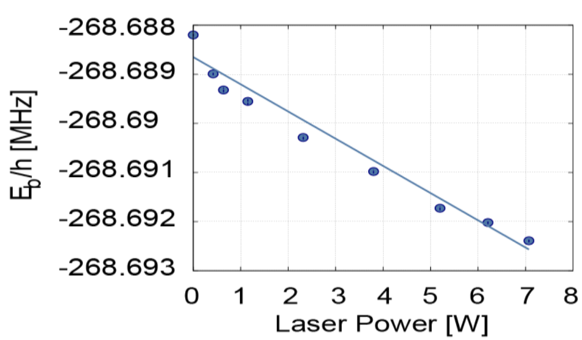
$$\delta_{LS} = \beta\left(\frac{I_1}{\Delta + f_1 - f_2} + \frac{I_2}{\Delta}\right)$$

$$= \alpha_1(\Delta) I_1 + \alpha_2(\Delta) I_2$$



Light Shift due to Optical Trapping Laser

Atoms and Molecules have slightly different polarizabilities

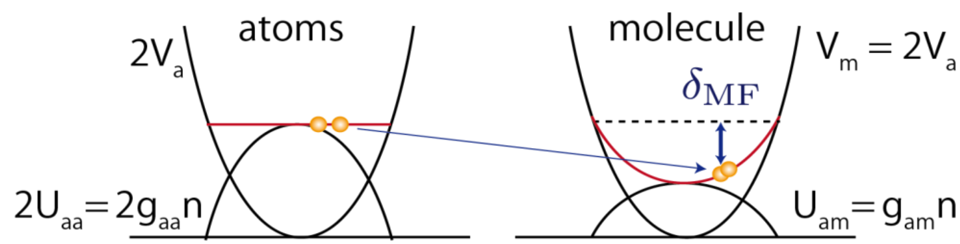


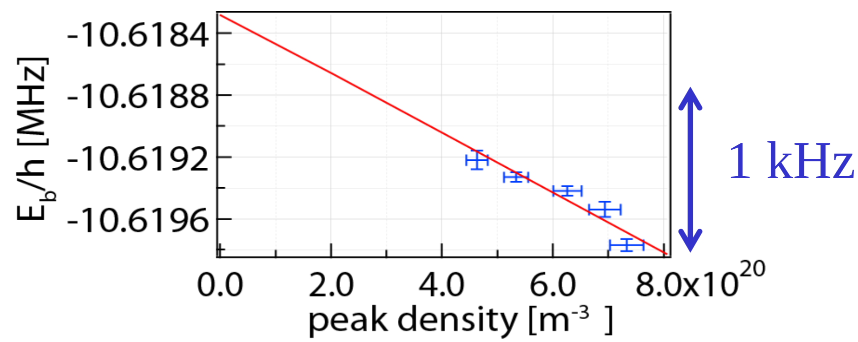
Collision Shift due to Atom-Dimer Collision

$$\delta_{\mathrm{MF}} = 2\pi\hbar^2\left(\frac{2a_{\mathrm{aa}}}{\mu_{\mathrm{aa}}} - \frac{a_{\mathrm{am}}}{\mu_{\mathrm{am}}}\right) n_{\mathrm{atom}}(r)$$

a_{am} : scattering length between atom and molecule

$$\{V(r) + g|\psi(r)|^2\}\psi(r) = \mu\psi(r)$$





Experimental Results

Level	Binding energy[MHz]
^{168}Yb(v=2, J=0)	-195.18141(46)
^{168}Yb(v=1, J=2)	-145.53196(48)
^{170}Yb(v=1, J=0)	-27.70024(44)
^{170}Yb(v=2, J=0)	-463.72552(80)
^{170}Yb(v=3, J=0)	-1922.01467(504)
^{170}Yb(v=1, J=2)	-3.66831(32)
^{170}Yb(v=2, J=2)	-398.05626(46)
^{170}Yb(v=3, J=2)	-1817.14074(80)
^{174}Yb(v=1, J=0)	-10.62513(53)
^{174}Yb(v=2, J=0)	-325.66378(98)
^{174}Yb(v=3, J=0)	-1527.88543(34)
^{174}Yb(v=1, J=2)	-268.63656(56)
^{174}Yb(v=2, J=2)	-1432.82493(64)

13 binding energies with about **500Hz** accuracy

$\Delta f/f$ $=2.6\times10^{-7}$

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v=1	v=2	v=3
-27.70024(44)	-463.72552(80)	-1922.01467(505)
-27.72151	-463.78895	-1920.86562
-27.22112	-463.77931	-1924.93591

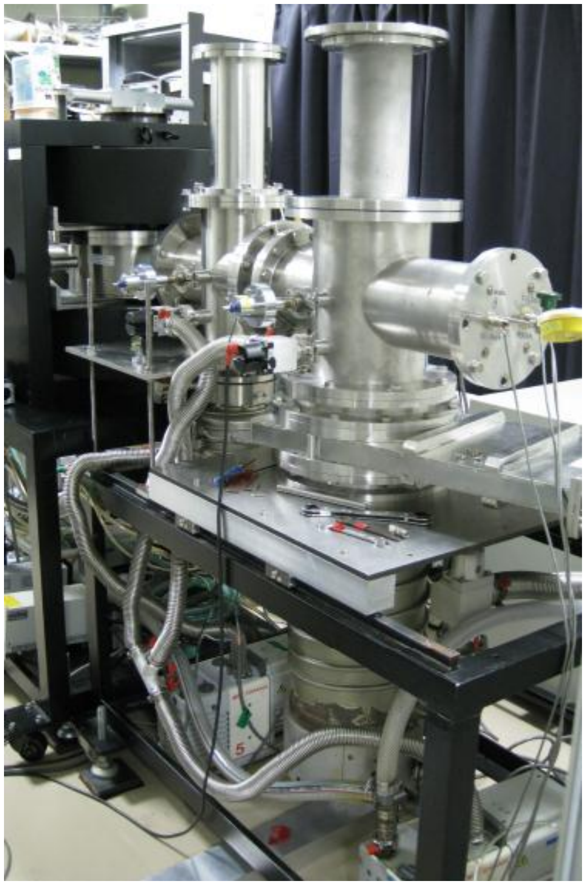
no good Fit with
Lenard Jones Potential

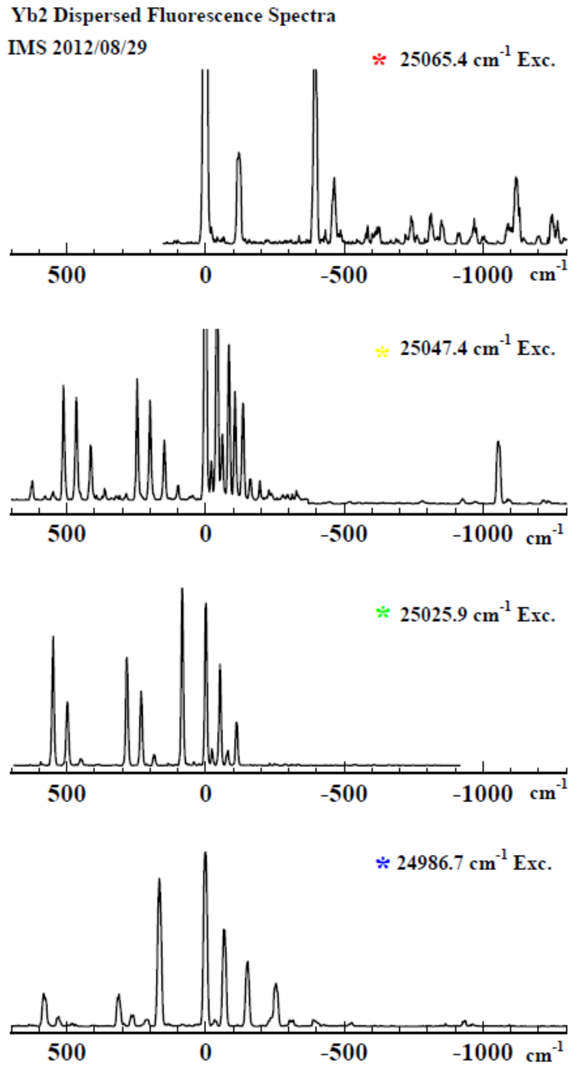
v=1	v=2	v=3
-10.62513(53)	-325.66378(98)	-1527.88543(34)
-10.66637	-325.94879	-1527.87270
-10.20006	-324.59570	-1527.93747

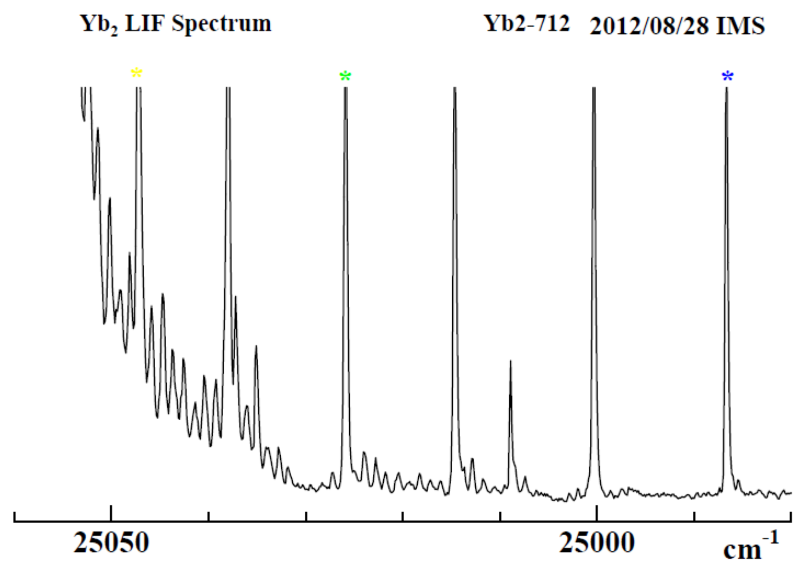
no good Fit with
Lenard Jones Potential

Conventional Molecular Spectroscopy

by M. Baba







Plan to do

- Determination of all molecular vibrational binding energies (N=70) with sub-kHz accuracy

↑ Conventional Spectroscopy using molecular beam: Collaboration with Prof. Baba

↑ Resonant Ionization Spectroscopy using cold Photo-associated molecule: New construction

- Determination of molecular potential energies with quantum chemical calculation

↑ BO Correction, Nuclear Finite-size effect: Collaboration with Prof. Hutson, Dr. Abe

↑ Potential Fitting: Collaboration with Dr. P. Julienne Dr. R. Ciulylo, M. Borkowski

Thank you very much for attention

16 August　　Mount Daimonji at Kyoto