Title: Enhanced Sensitivity to Variation of me/mp in Molecular Spectra

Date: Jul 17, 2008 11:20 AM

URL: http://pirsa.org/08070026

Abstract: We propose new experiments with high sensitivity to a possible variation of the electron-to-proton mass ratio Âµ me/mp. We consider a nearly degenerate pair of molecular vibrational levels, each associated with a different electronic potential. With respect to a change in Âµ, the change in the splitting between such levels can be large both on an absolute scale and relative to the splitting. We demonstrate the existence of such pairs of states in Cs2, where the narrow spectral lines achievable with ultracold molecules make the system promising for future searches for small variations in Âµ.

Enhanced Sensitivity to Variation of m_e/m_p in Molecular Spectra

DeMille Group, Yale University

$$

NSF, DOE

Enhanced Sensitivity to Variation of m_e/m_p in Molecular Spectra

DeMille Group, Yale University

$$

NSF, DOE

Investigation of the optical transition in the ^{229}Th nucleus: Solid-state optical frequency standard and fundamental constant variation

UCLA

$$

Your name here

Enhanced Sensitivity to Variation of m_e/m_p in Molecular Spectra

DeMille Group, Yale University

$$

NSF, DOE

Investigation of the optical transition in the ^{229}Th nucleus: Solid-state optical frequency standard and fundamental constant variation

UCLA

$$

Your name here

OH Spectroscopy for Constraining the Evolution of the Fine Structure Constant

Ye Group, JILA

$$

NSF, Keck, DOE, NIST

Enhanced Sensitivity to Variation of m_e/m_p in Molecular Spectra

DeMille Group, Yale University

$$

NSF, DOE

- Why study me/mp?
- Why study me/mp with molecules?
  - Lever arm
- Apparatus
  - Ultra-cold Cs_2
- Results of search

Jeremy Sage
Sunil Sainis
Tom Bergemen
Svetlana Kotchigova
Eite Tiesinga

Why study time variation of electron-to-proton mass ratio μ?

$(\mu \equiv m_e/m_p)$

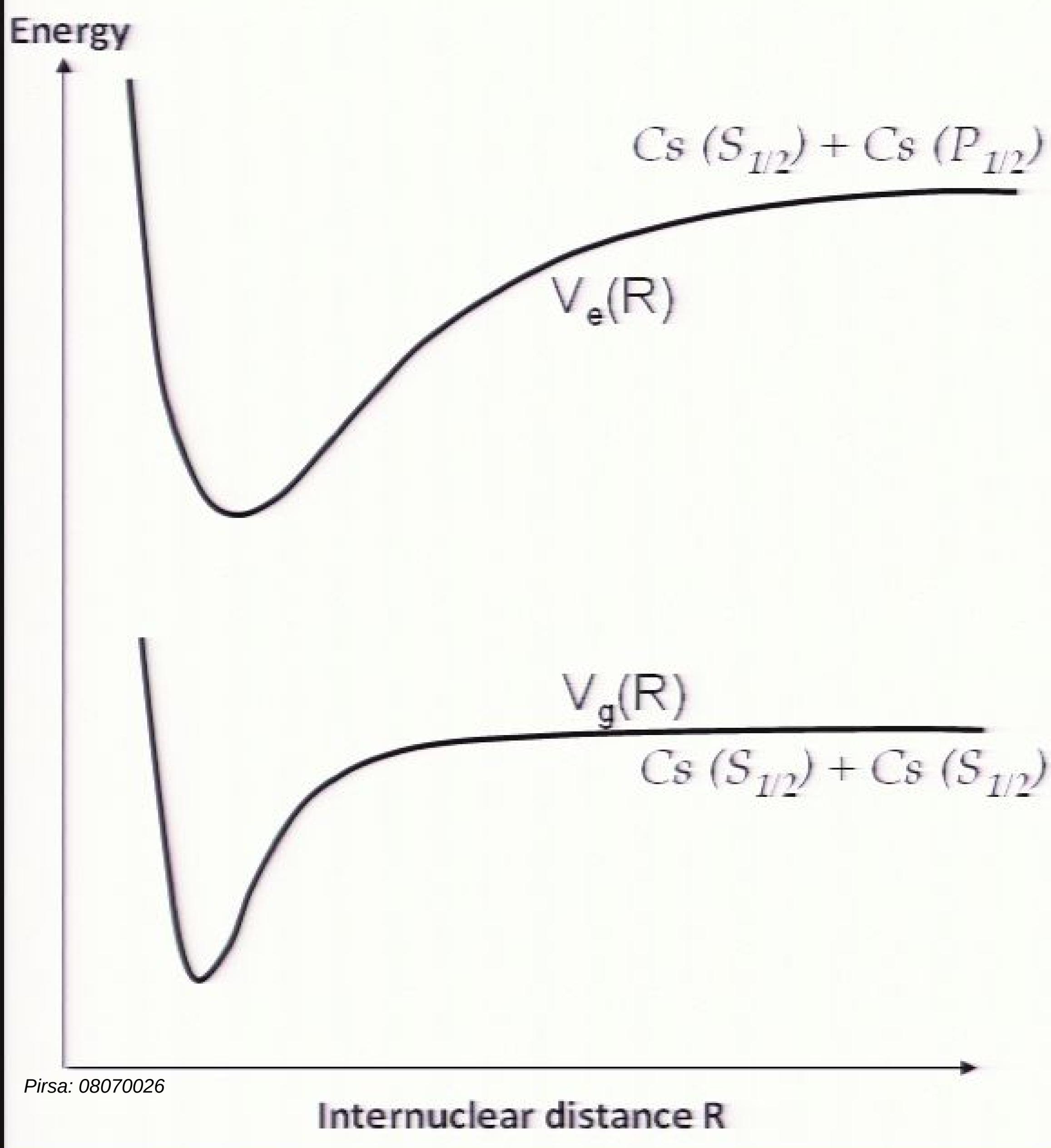
- Variation of "constants" motivated by
  - --naïve models of dark energy (*an experimental fact!*)
  - --ideas about extra dimensions (from string theory)
  - --connections to equivalence principle
  - --tentative observations in cosmological data

- Grand unified theories suggest $(\delta\mu/\mu) \sim 30(\delta\alpha/\alpha)$
  [variation of $\alpha \equiv$ fine structure constant strongly constrained]

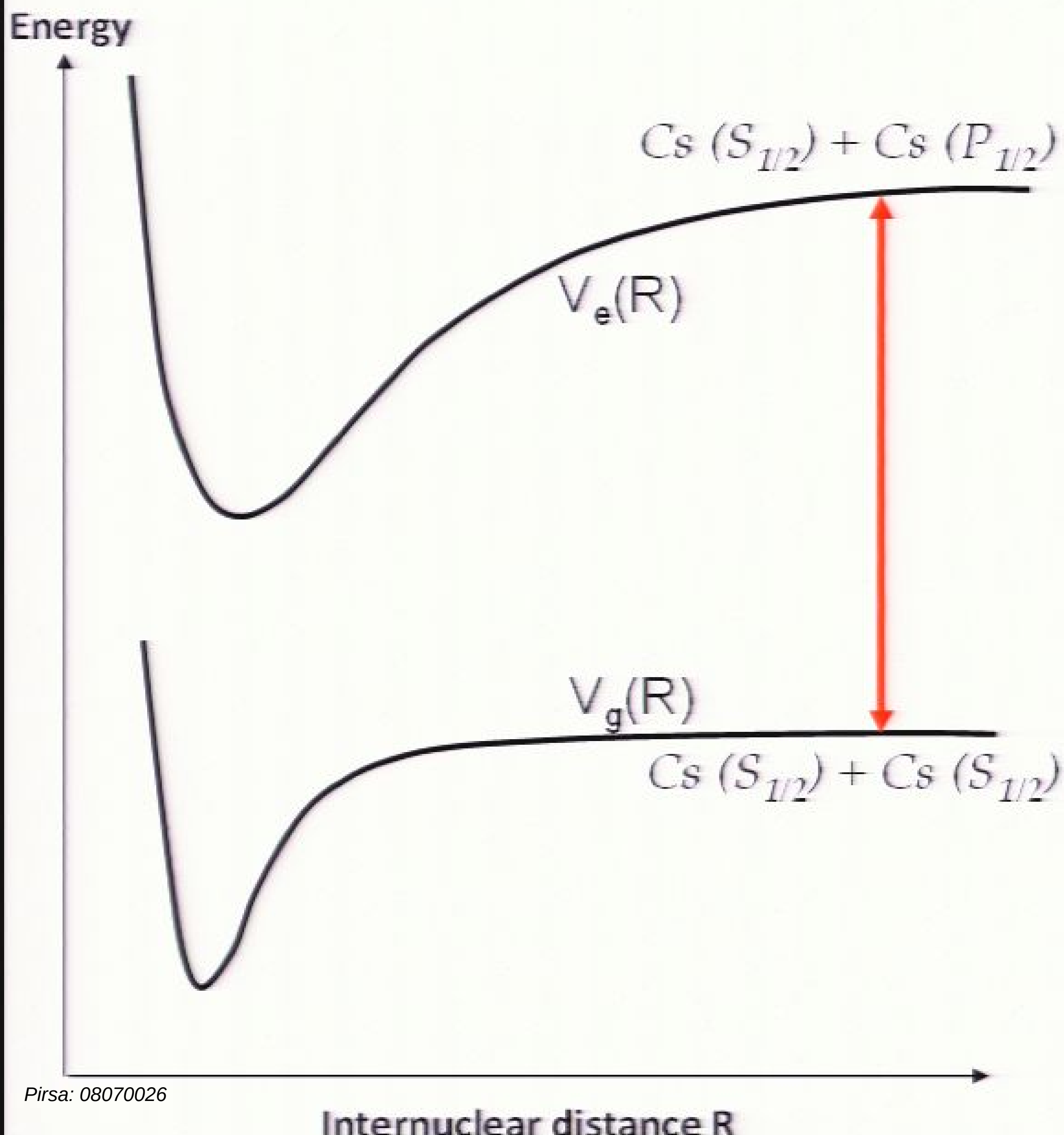
- Optical *atomic* clocks insensitive to $\delta\mu$

- Laboratory tests now comparable in sensitivity to cosmological limits

Molecular structure: What is a molecule?

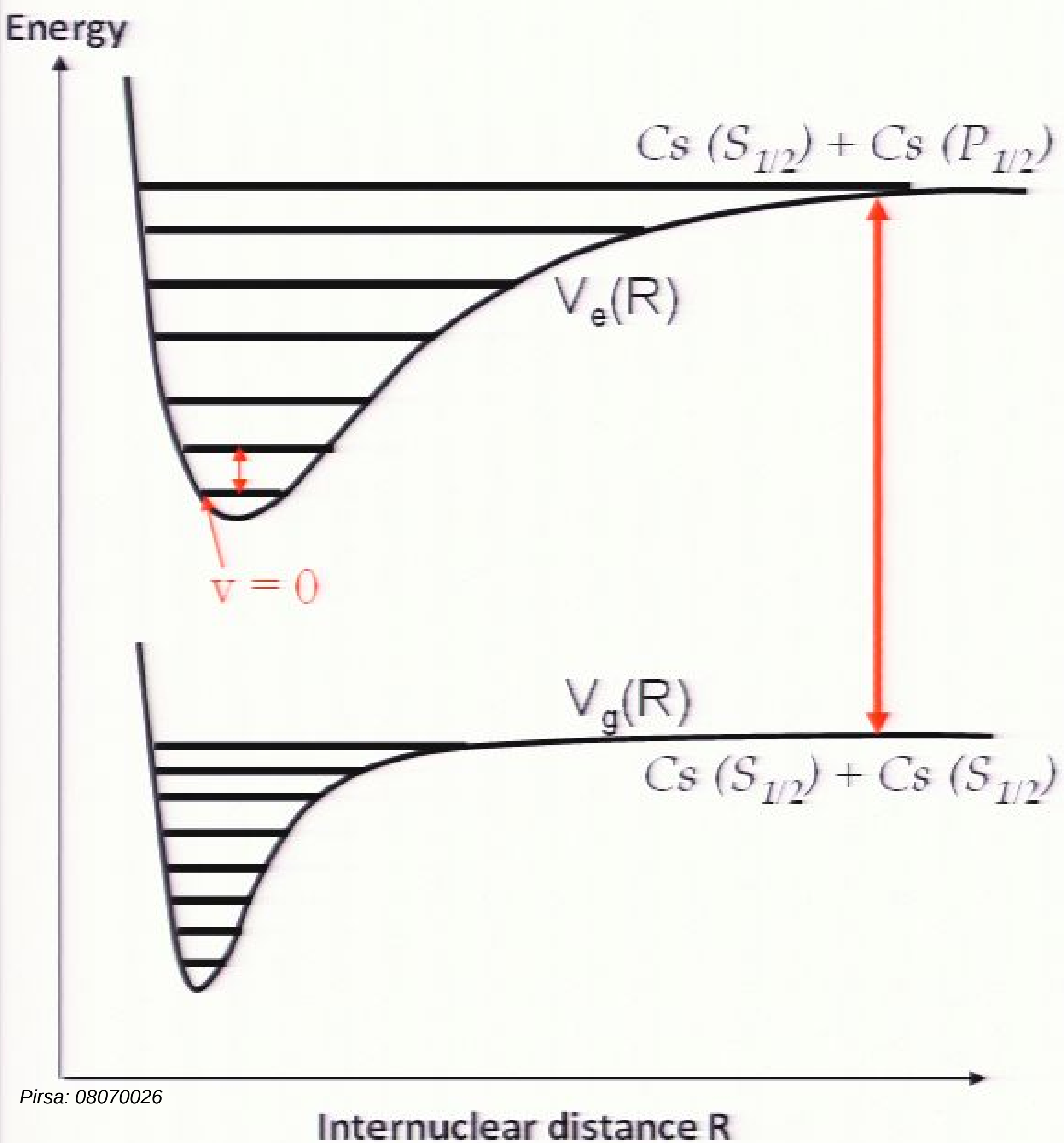


Molecular structure: What is a molecule?



- Electronic potentials
  ~ 300 THz (~ 1.5 eV)

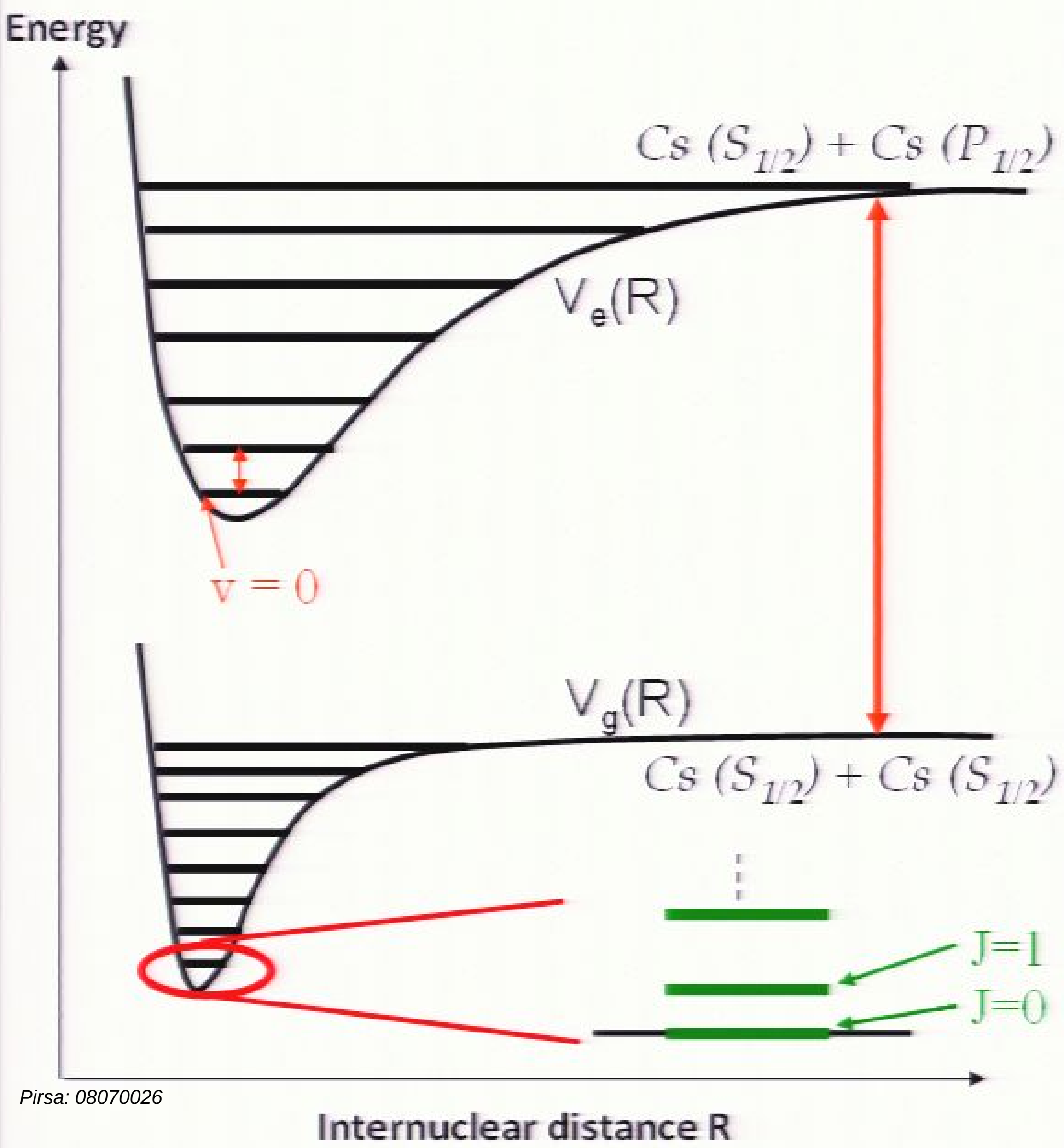
Molecular structure: What is a molecule?



- Electronic potentials
  ~ 300 THz (~ 1.5 eV)

- Vibrational levels
  ~ 0.1 - 1 THz

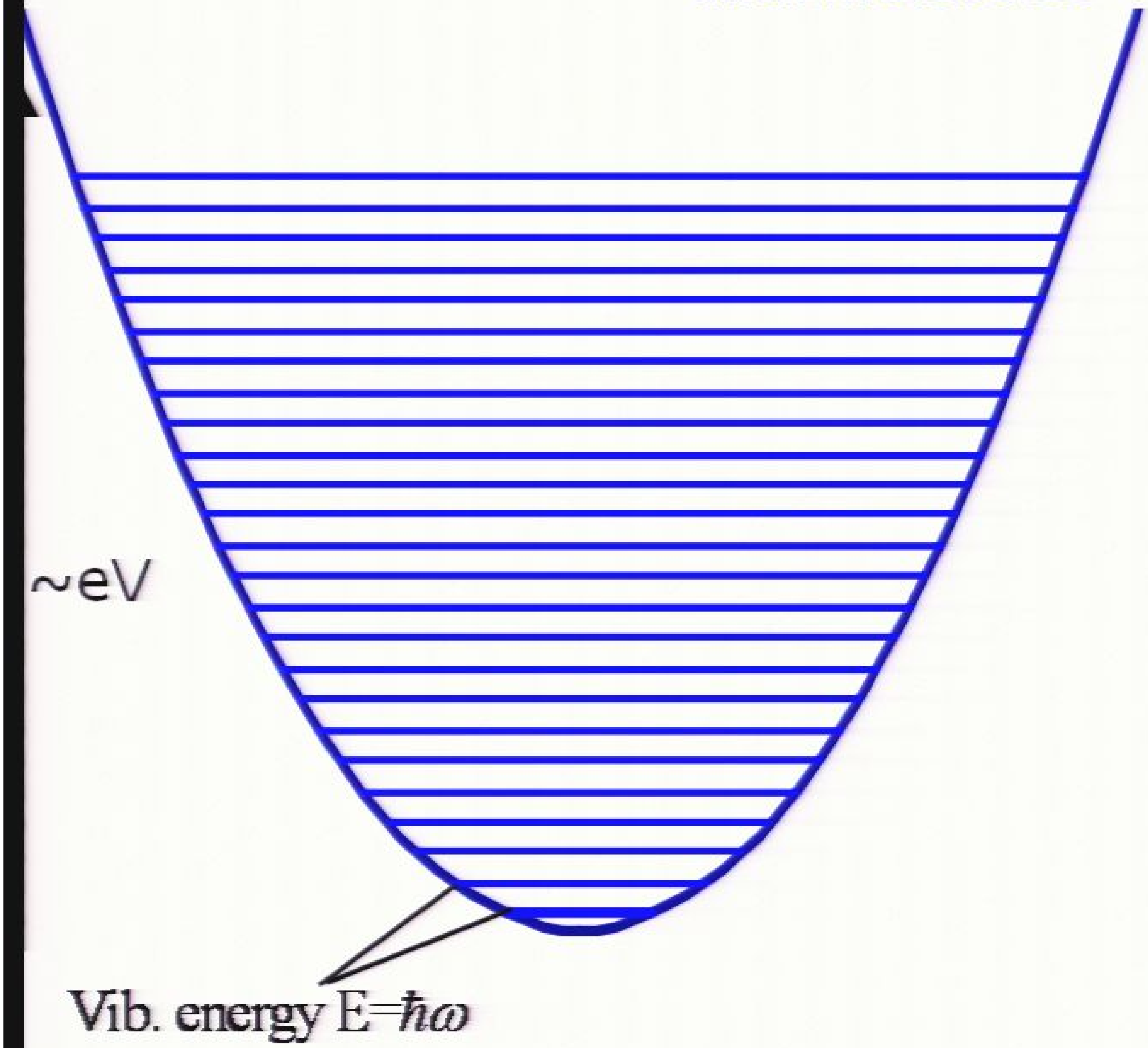
Molecular structure: What is a molecule?



- Electronic potentials
  ~ 300 THz (~ 1.5 eV)
- Vibrational levels
  ~ 0.1 - 1 THz
- Rotational levels
  ~ 0.1 - 1 GHz

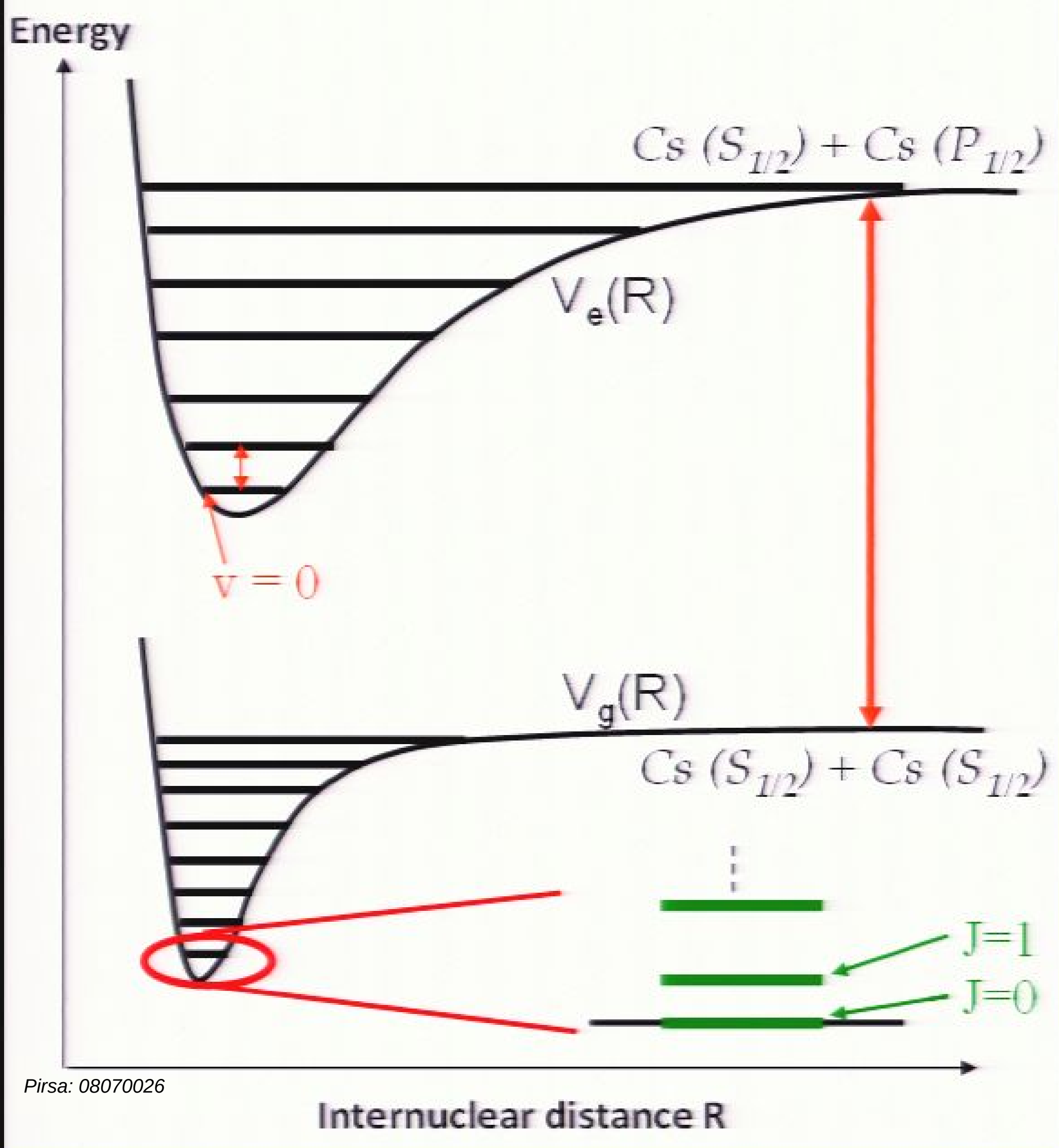
Harmonic Oscillator Model: **Enhanced** sensitivity to $d\mu/dt$ with molecules

$(\mu \equiv m_e/m_p$



$\propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

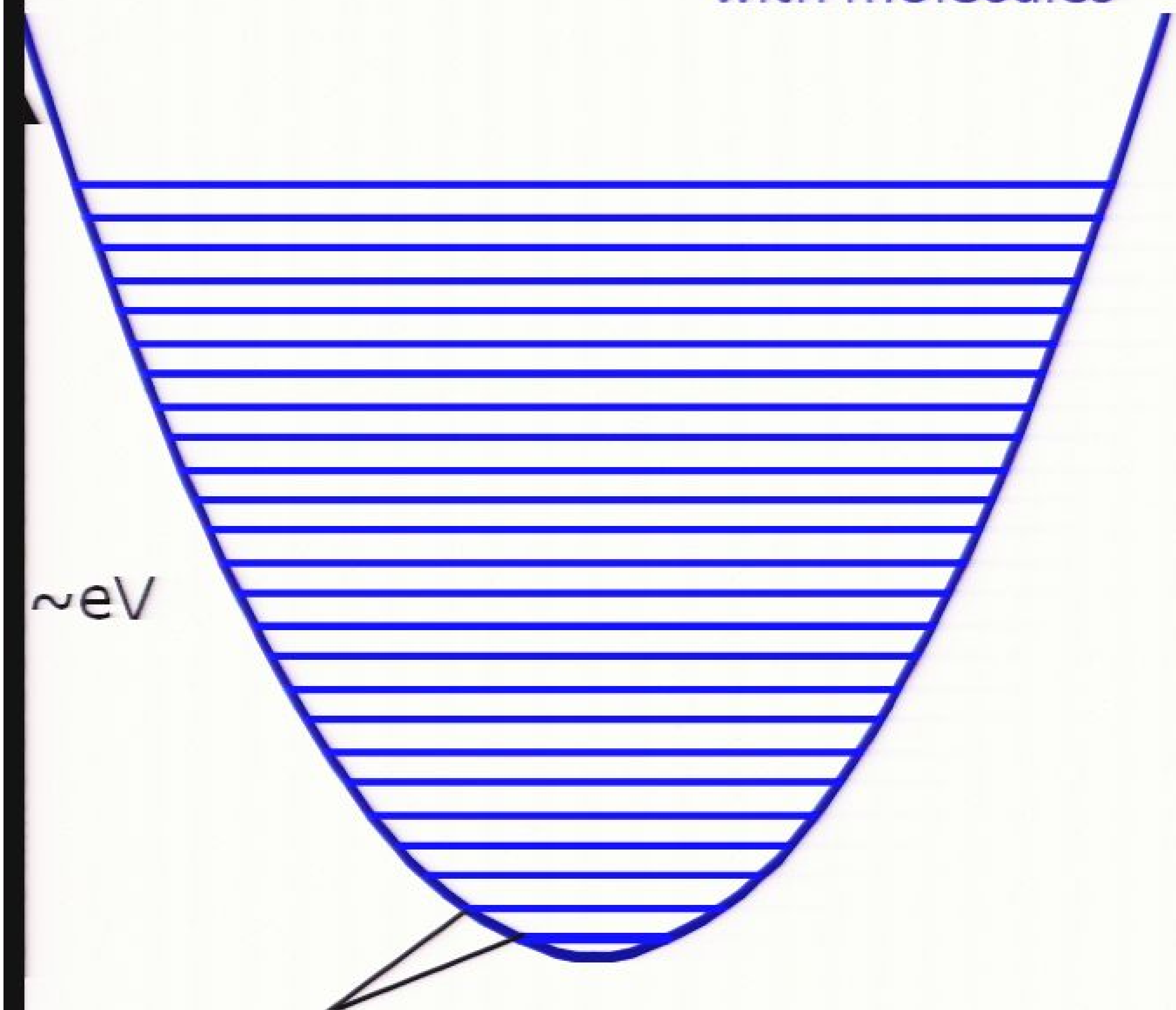
Molecular structure: What is a molecule?



- Electronic potentials
  ~ 300 THz (~ 1.5 eV)
- Vibrational levels
  ~ 0.1 - 1 THz
- Rotational levels
  ~ 0.1 - 1 GHz

Harmonic Oscillator Model: **Enhanced** sensitivity to *dμ/dt* with molecules

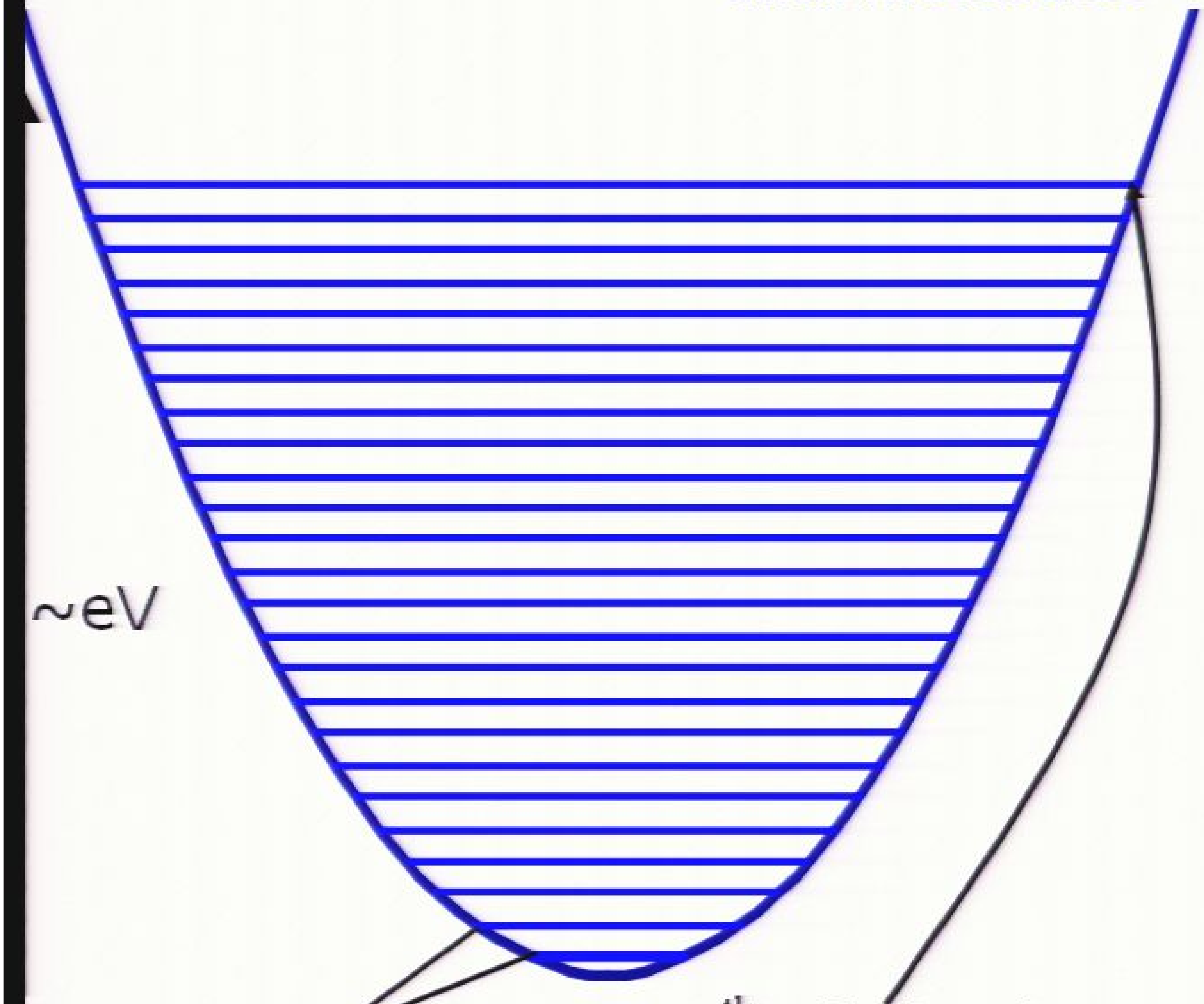
$(\mu \equiv m_e/m_p$



$\propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

Harmonic Oscillator Model: **Enhanced** sensitivity to $d\mu/dt$ with molecules

$(\mu \equiv m_e/m_p$

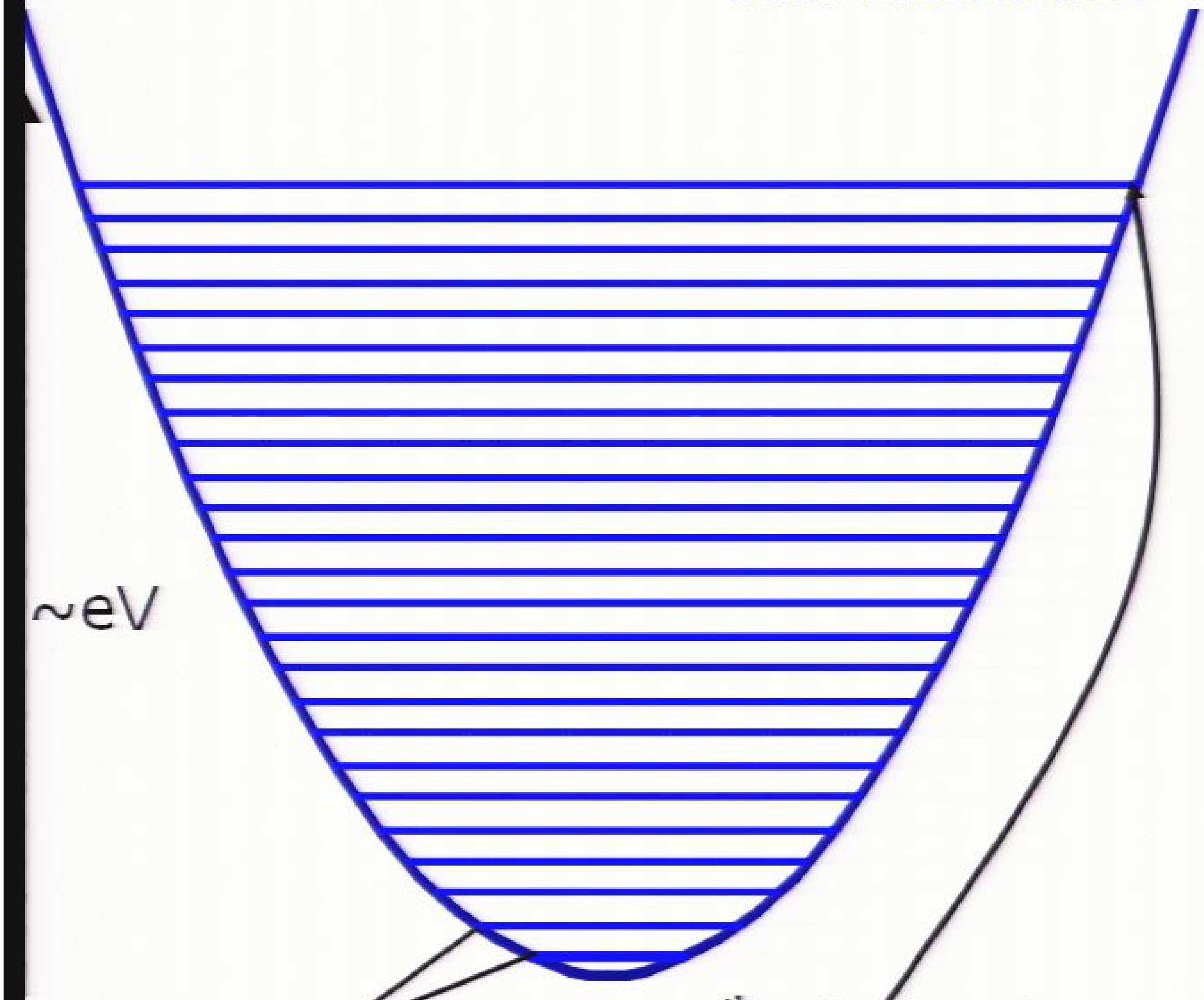


Vib. energy $E = \hbar\omega \propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

N^{th} vib. level $\Rightarrow N\times$ enhancement in $dE/d\mu$

Harmonic Oscillator Model: **Enhanced** sensitivity to $d\mu/dt$ with molecules

$(\mu \equiv m_e/m_p$



Vib. energy $E = \hbar\omega$

$\propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

N^{th} vib. level

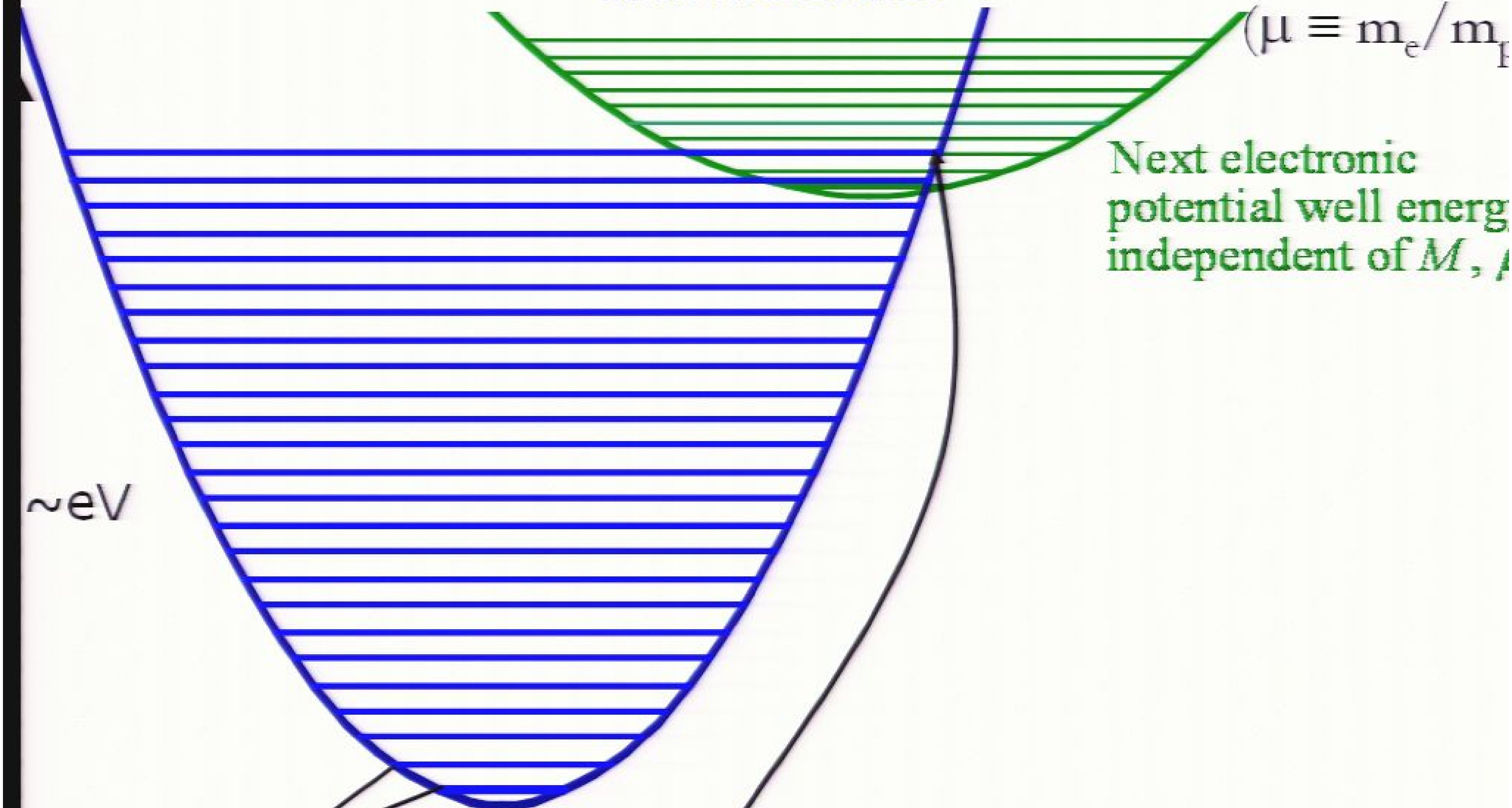
$\Rightarrow N \times$ enhancement

in $dE/d\mu$

$(E = N\hbar\omega)$

$$\frac{\delta E}{E} = \frac{N}{2}\frac{\delta\mu}{\mu}$$

Harmonic Oscillator Model: **Enhanced** sensitivity to $d\mu/dt$ with molecules



Vib. energy $E = \hbar\omega$

$\propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

N^{th} vib. level

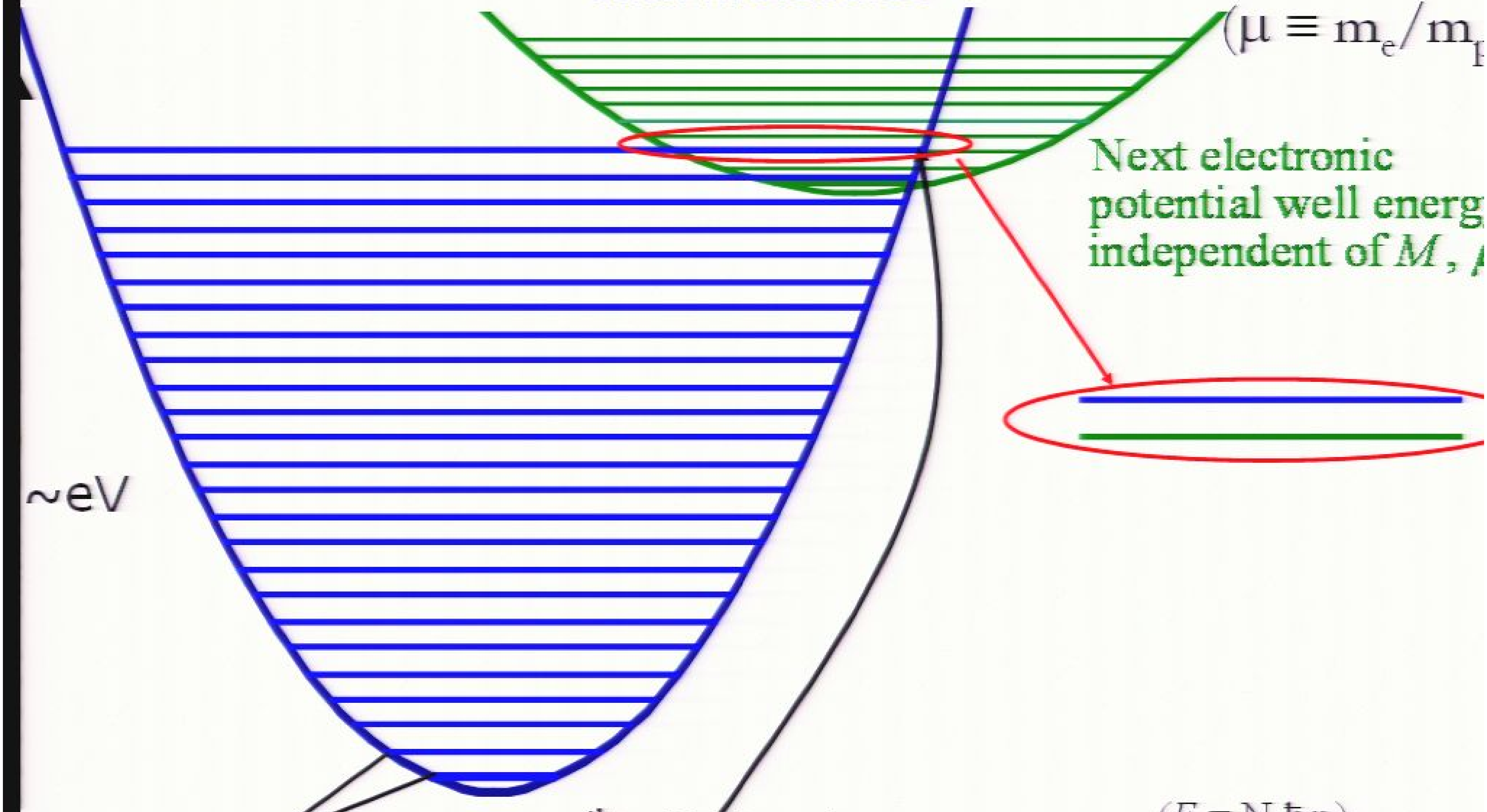
$\Rightarrow N \times$ enhancement

in $dE/d\mu$

$(E = N\hbar\omega)$

$\frac{\delta E}{E} = \frac{N}{2}\frac{\delta\mu}{\mu}$

Harmonic Oscillator Model: **Enhanced** sensitivity to $d\mu/dt$ with molecules



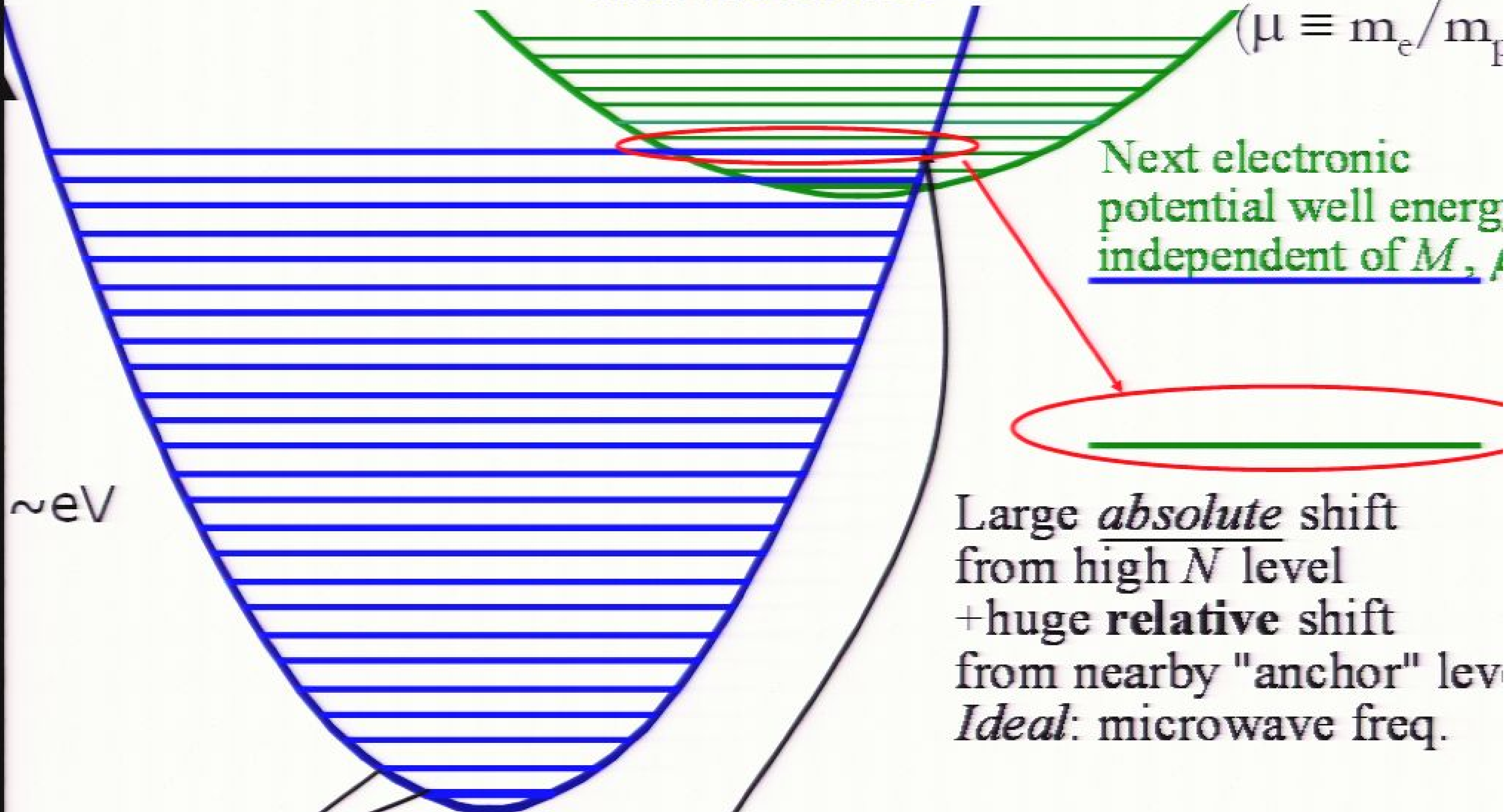
Vib. energy $E = \hbar\omega \propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

N^{th} vib. level $\Rightarrow N \times$ enhancement in $dE/d\mu$

$(E = N\hbar\omega)$

$$\frac{\delta E}{E} = \frac{N}{2}\frac{\delta\mu}{\mu}$$

Harmonic Oscillator Model: **Enhanced** sensitivity to *dμ/dt* with molecules



Large ***absolute*** shift
from high N level
+huge **relative** shift
from nearby "anchor" lev
Ideal: microwave freq.

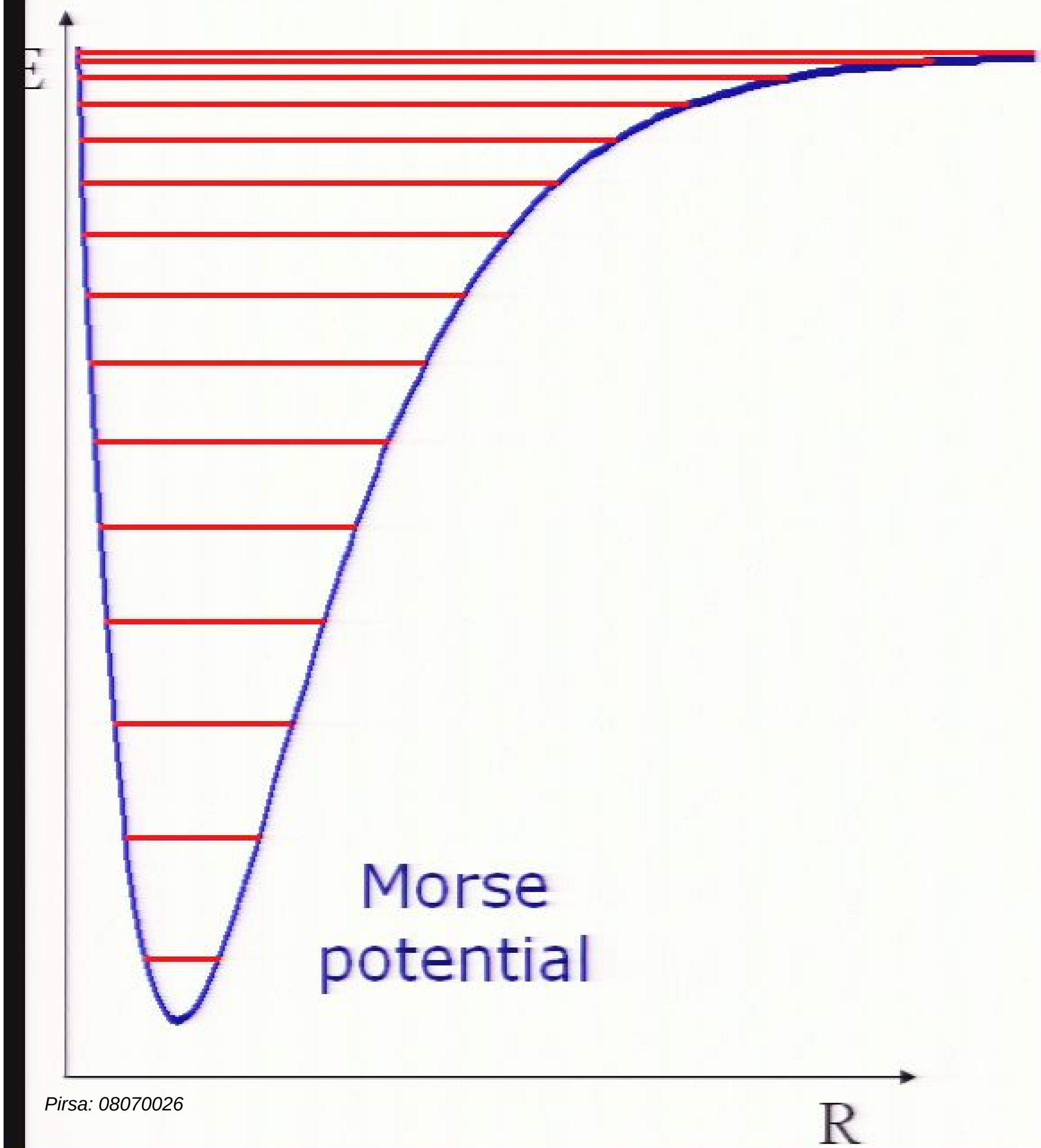
Vib. energy $E = \hbar\omega$
$\propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

N^{th} vib. level
$\Rightarrow N \times$ enhancement
in $dE/d\mu$

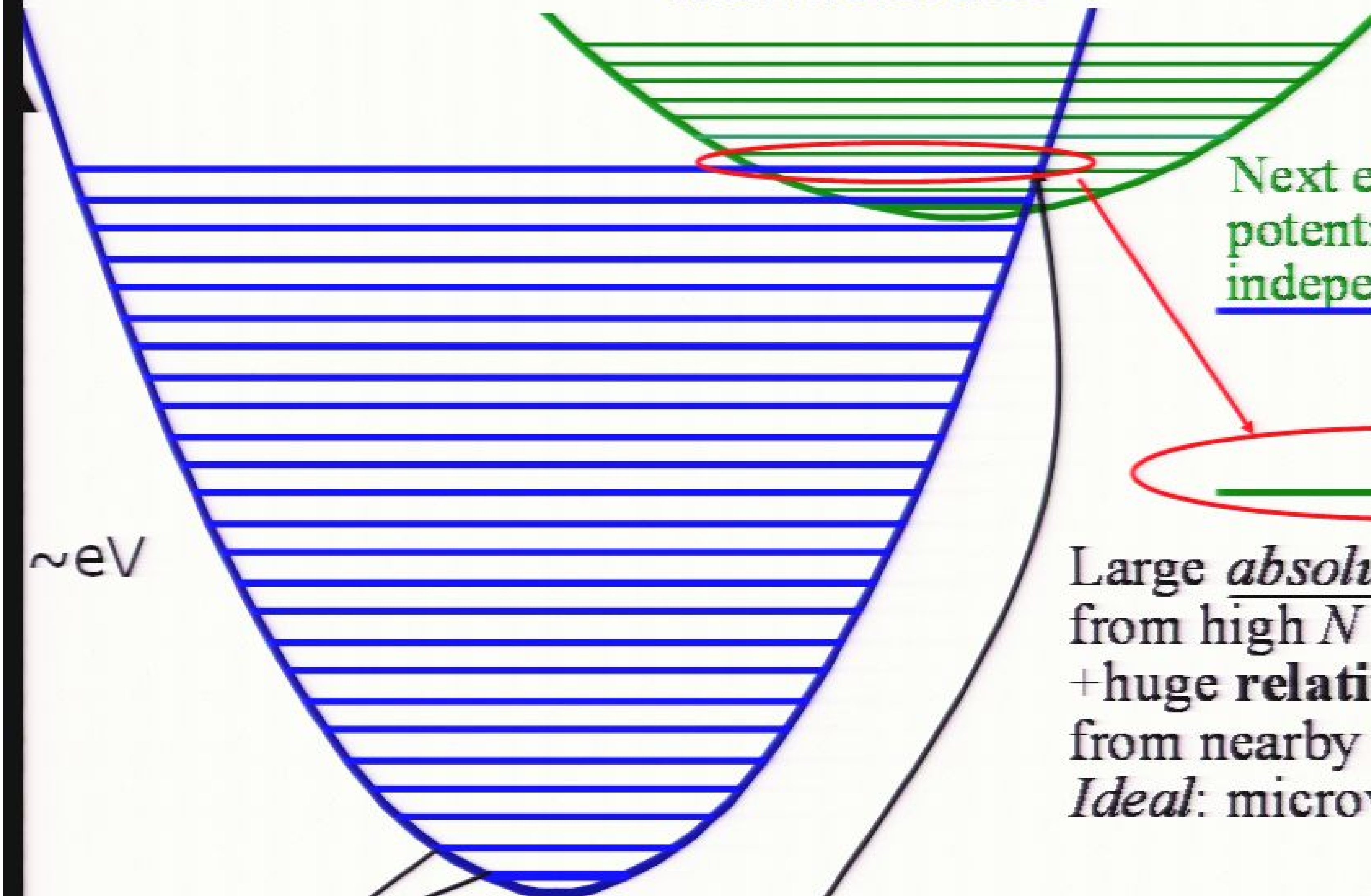
$(E = N\hbar\omega)$

$$\frac{\delta E}{E} = \frac{N}{2}\frac{\delta\mu}{\mu}$$

Realistic Model: Sensitivity to dμ/dt vs. binding energy



Harmonic Oscillator Model: **Enhanced** sensitivity to $d\mu/dt$ with molecules



$(\mu \equiv m_e/m_p$

Next electronic potential well energ independent of M, μ

Large ***absolute*** shift from high N level +huge **relative** shift from nearby "anchor" lev *Ideal*: microwave freq.

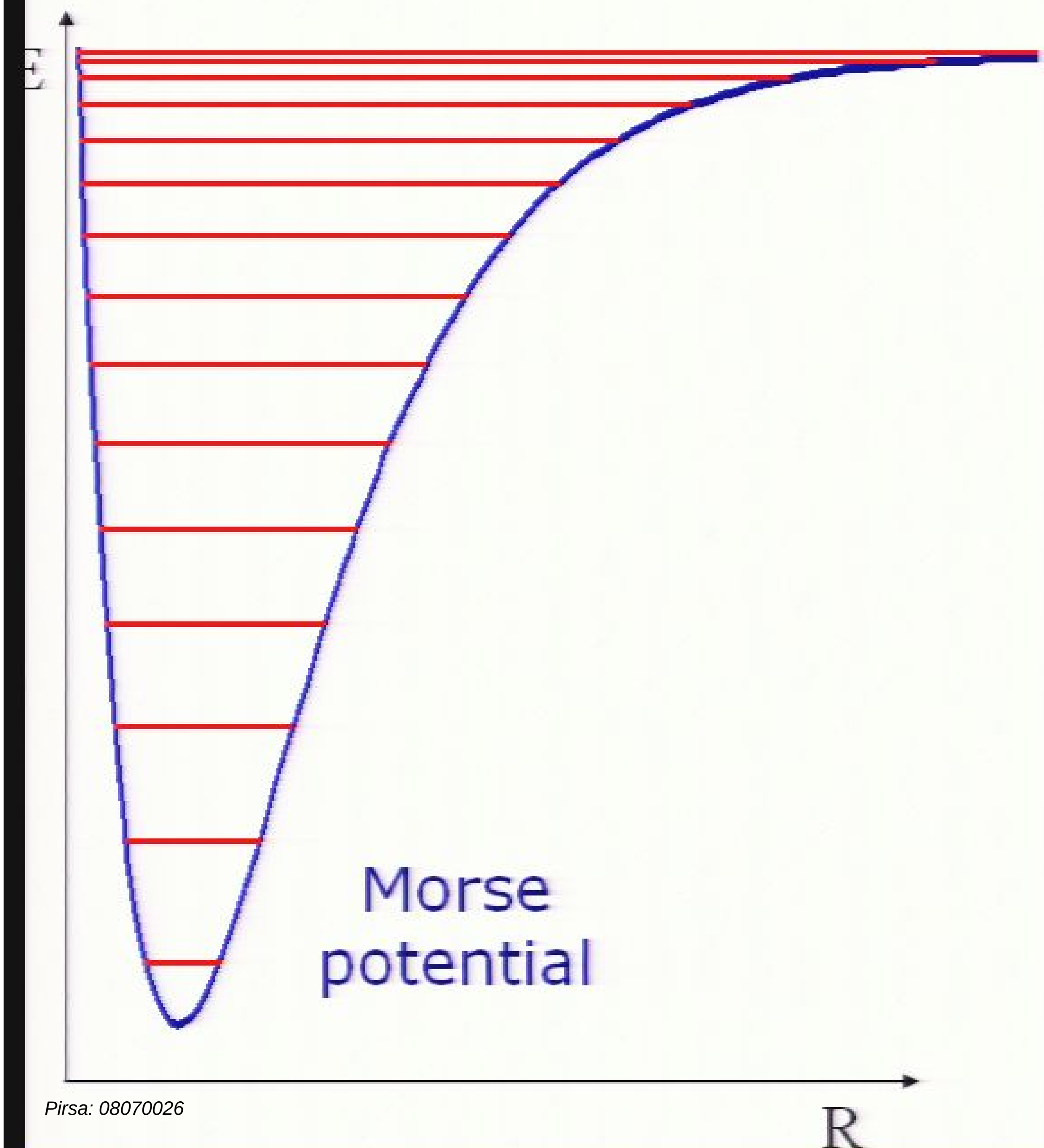
Vib. energy $E=\hbar\omega \propto \sqrt{k/M} \sim Ry\sqrt{\mu}$

N^{th} vib. level $\Rightarrow N\times$ enhancement in $dE/d\mu$

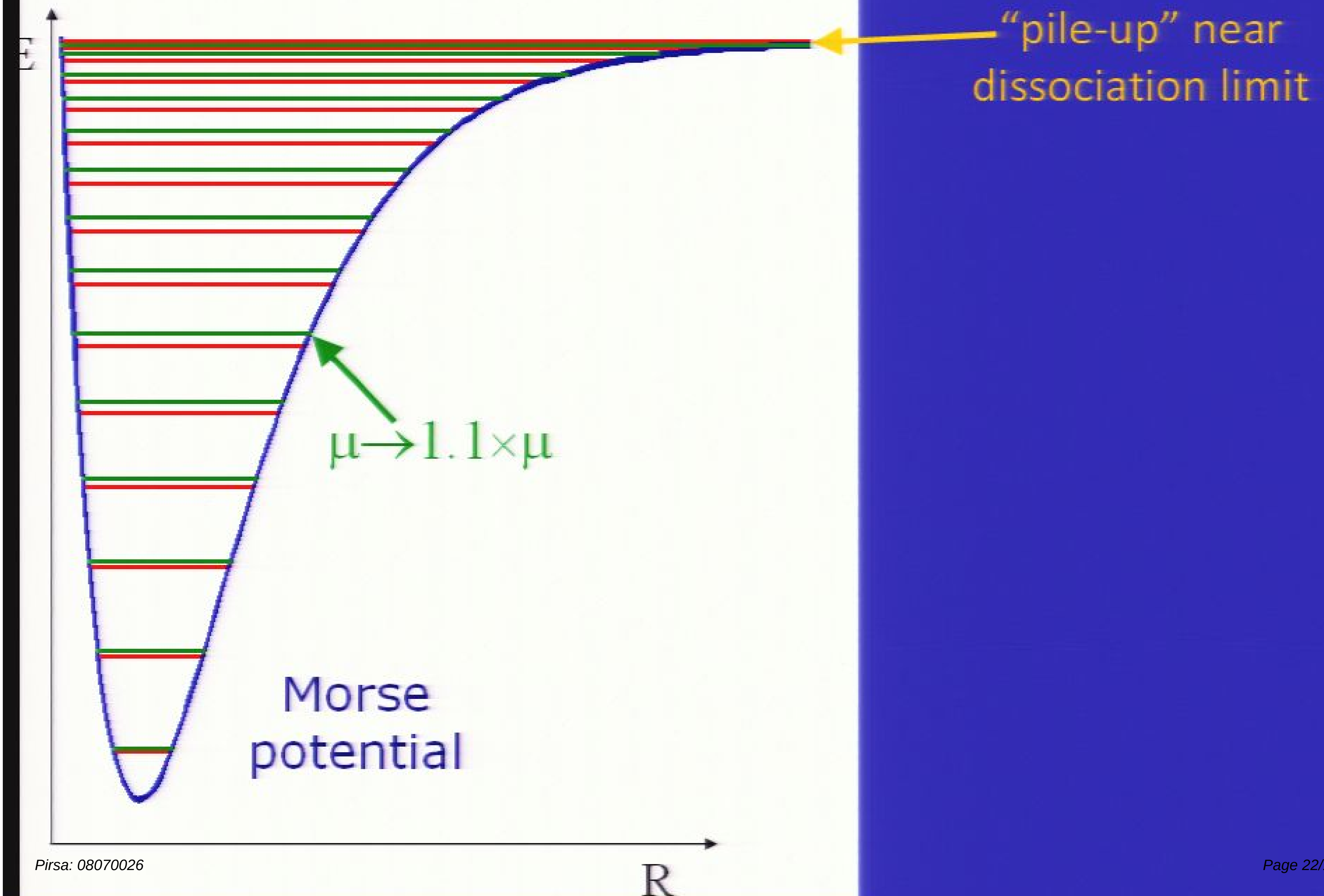
$(E = N\hbar\omega)$

$$\frac{\delta E}{E} = \frac{N}{2}\frac{\delta\mu}{\mu}$$

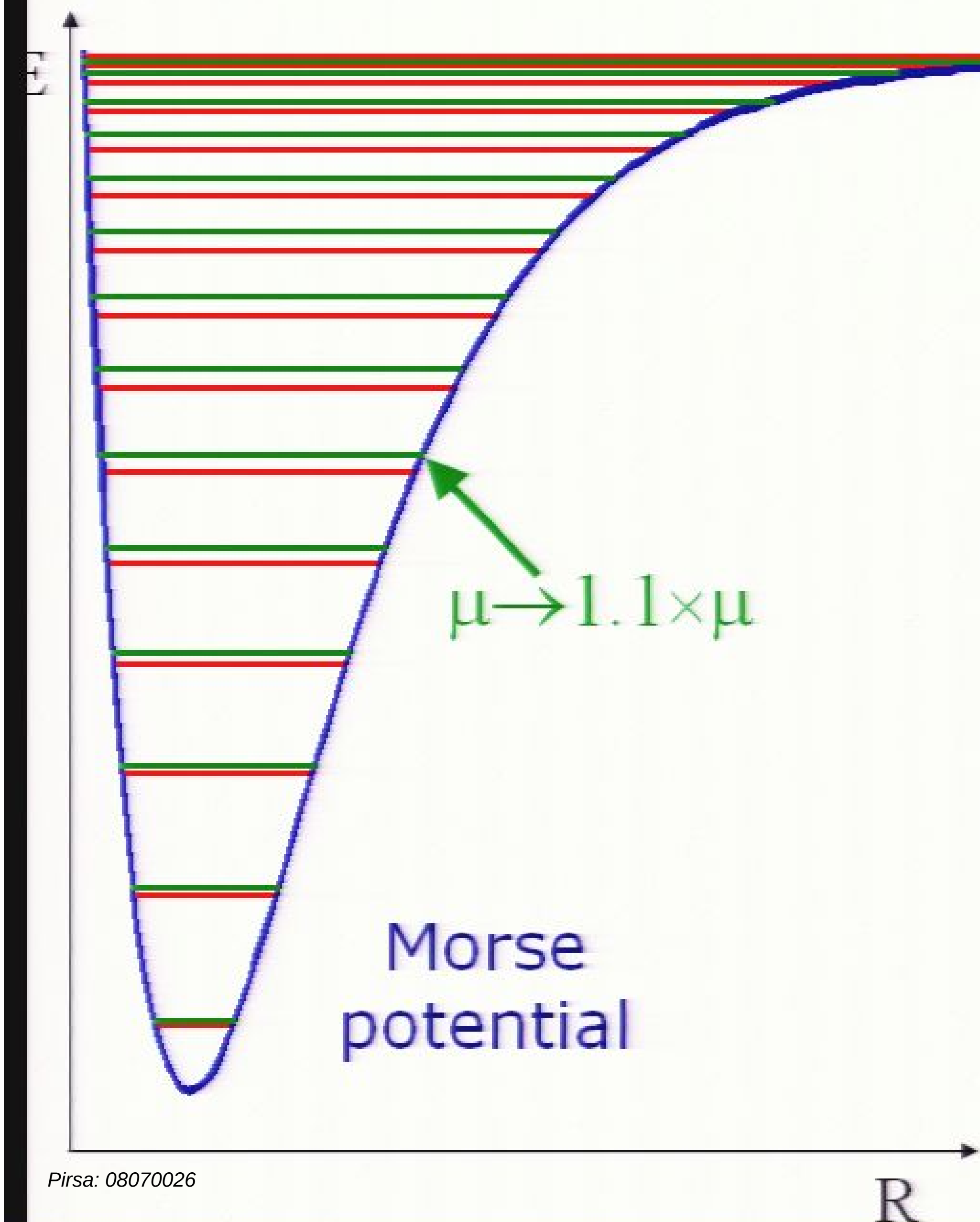
Realistic Model: Sensitivity to $d\mu/dt$ vs. binding energy



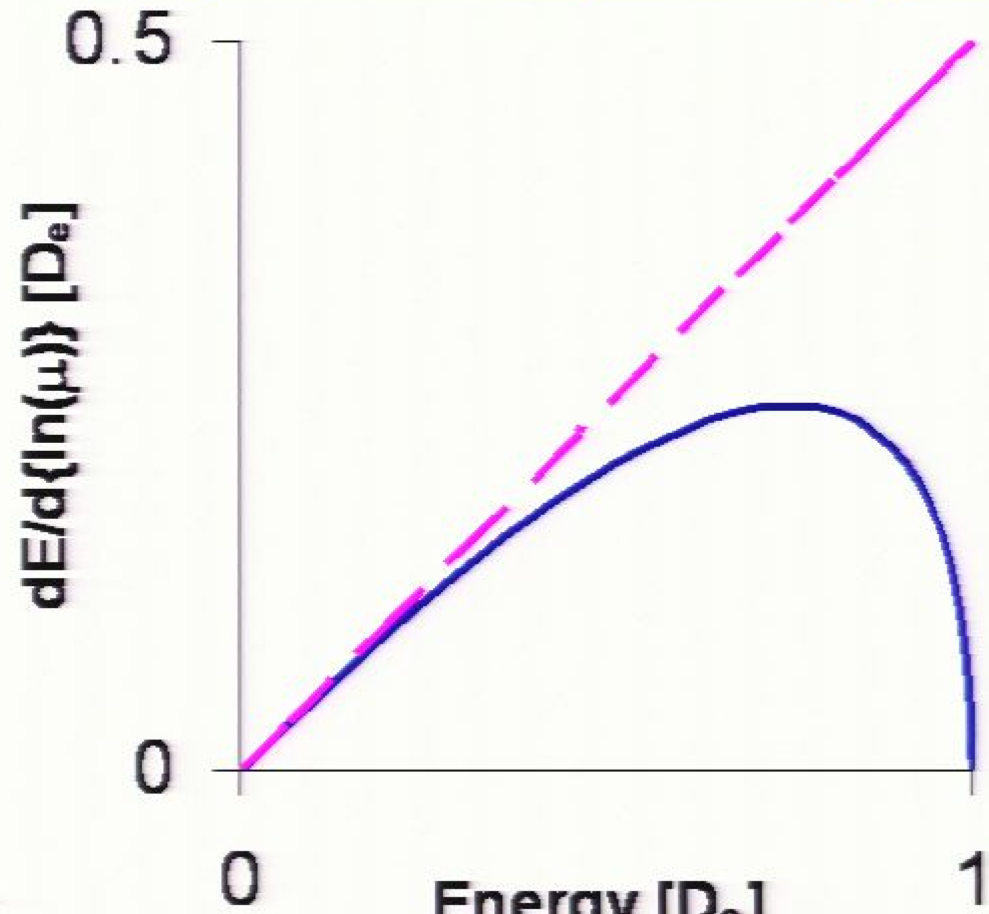
Realistic Model: Sensitivity to dμ/dt vs. binding energy



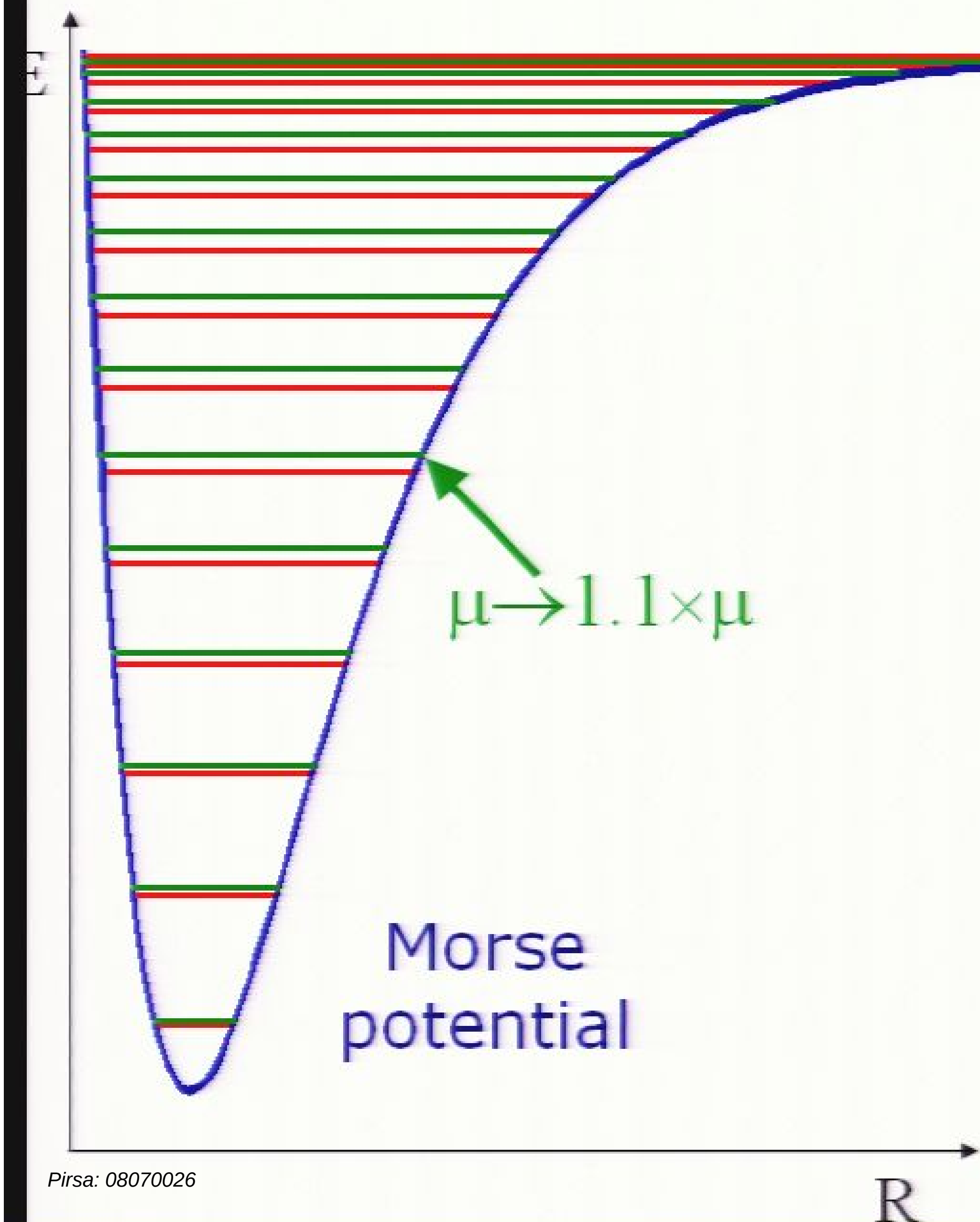
Realistic Model: Sensitivity to dμ/dt vs. binding energy



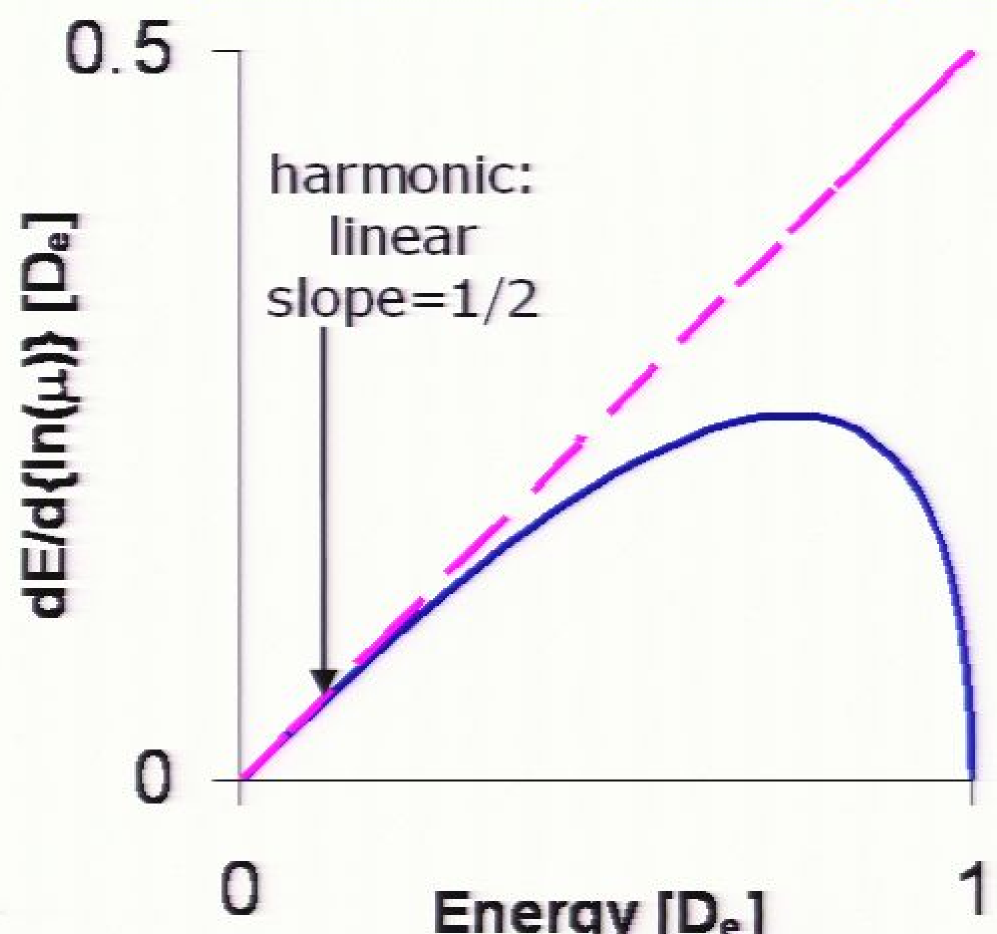
Sensitivity vs. energy



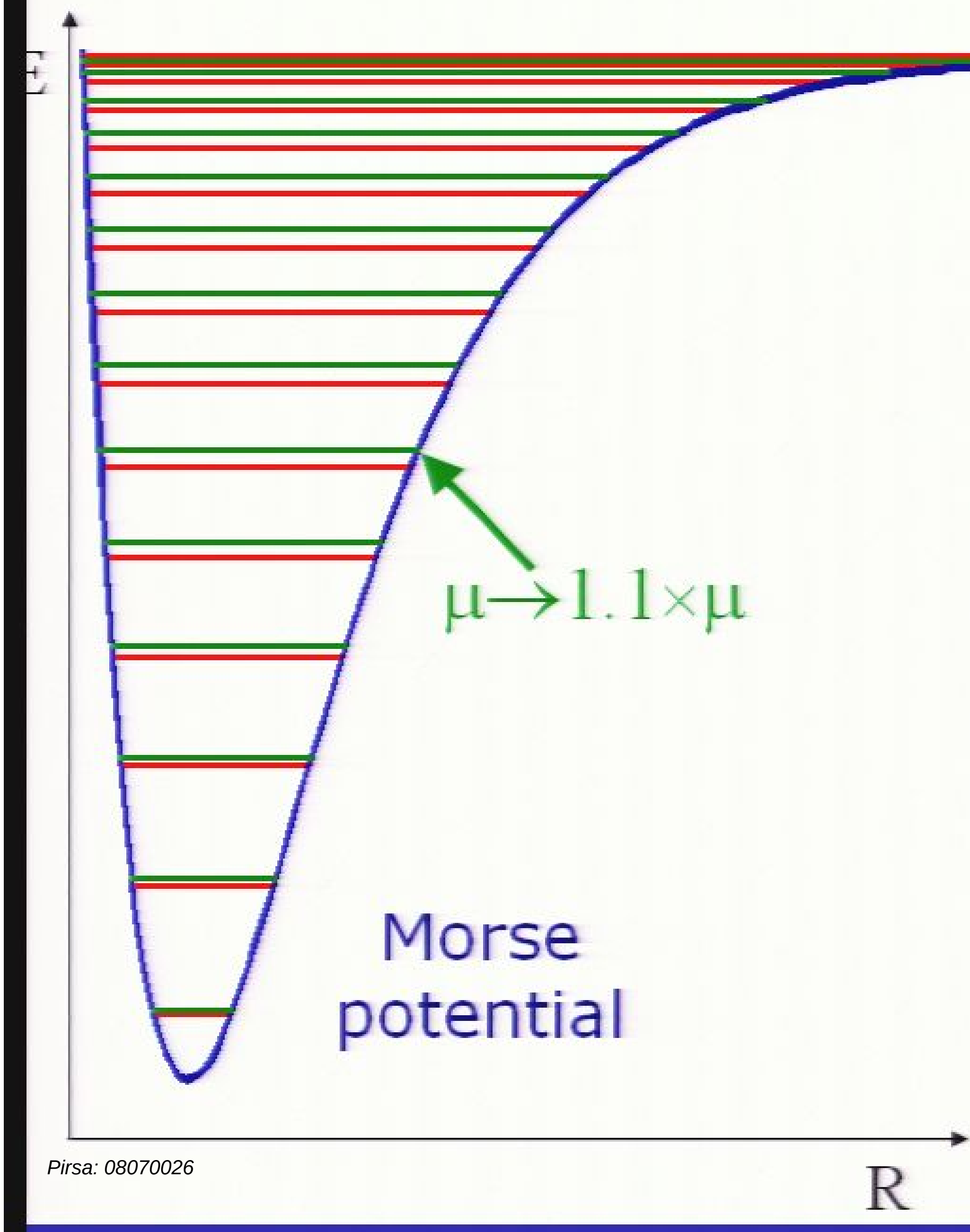
Realistic Model: Sensitivity to dμ/dt vs. binding energy



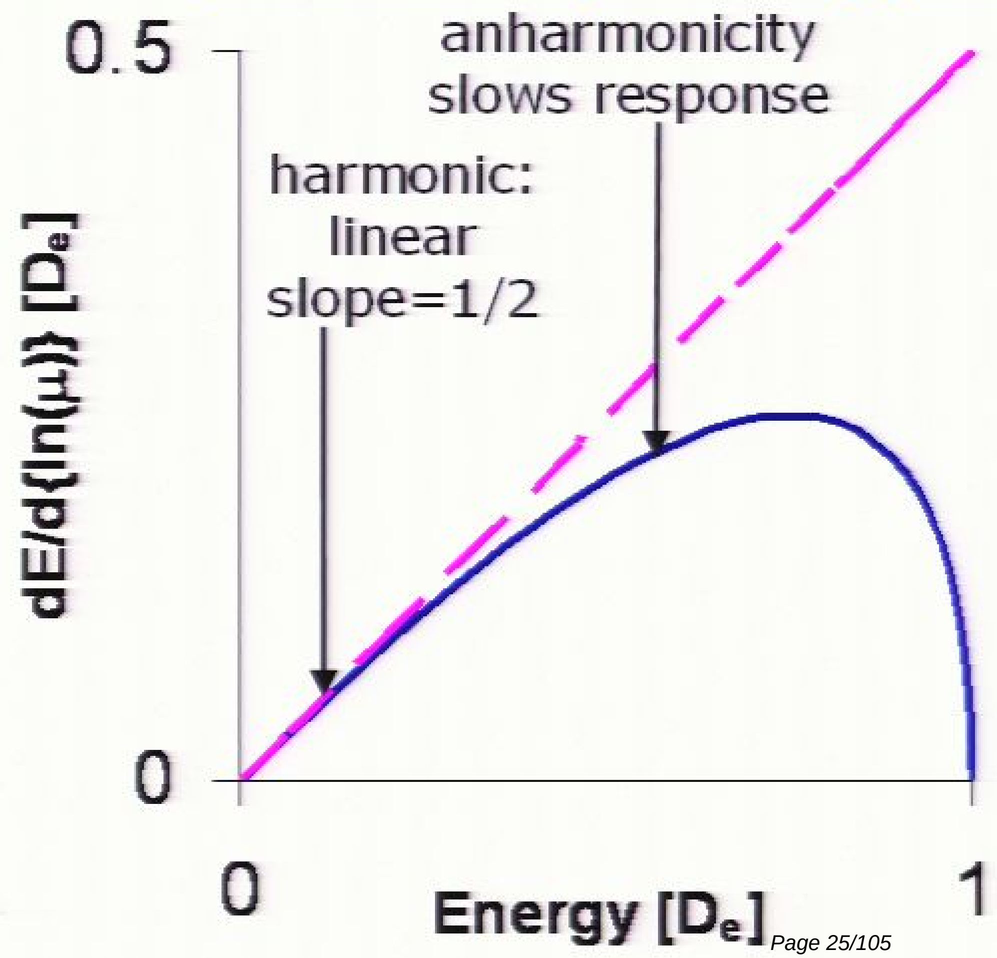
Sensitivity vs. energy



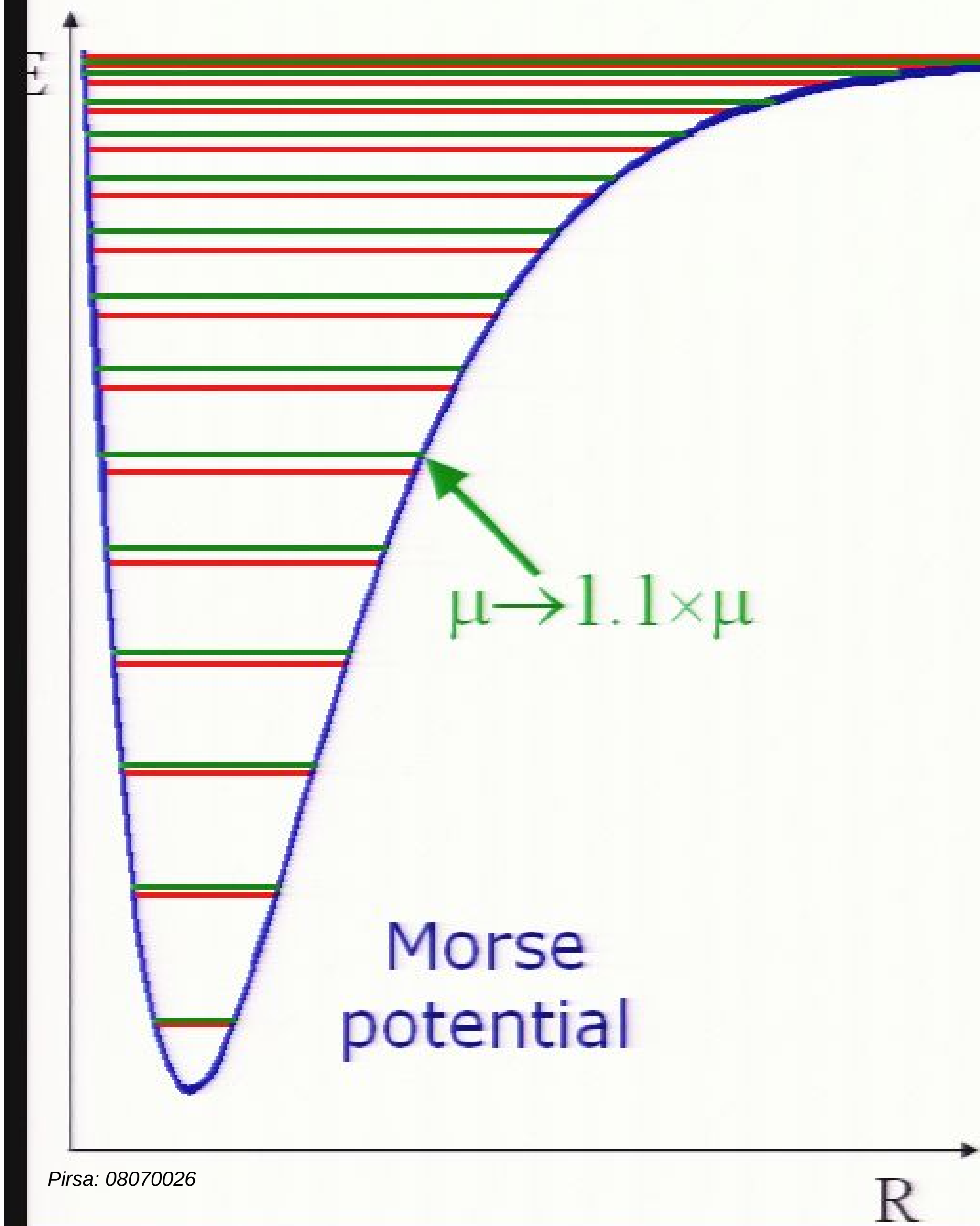
Realistic Model: Sensitivity to dμ/dt vs. binding energy

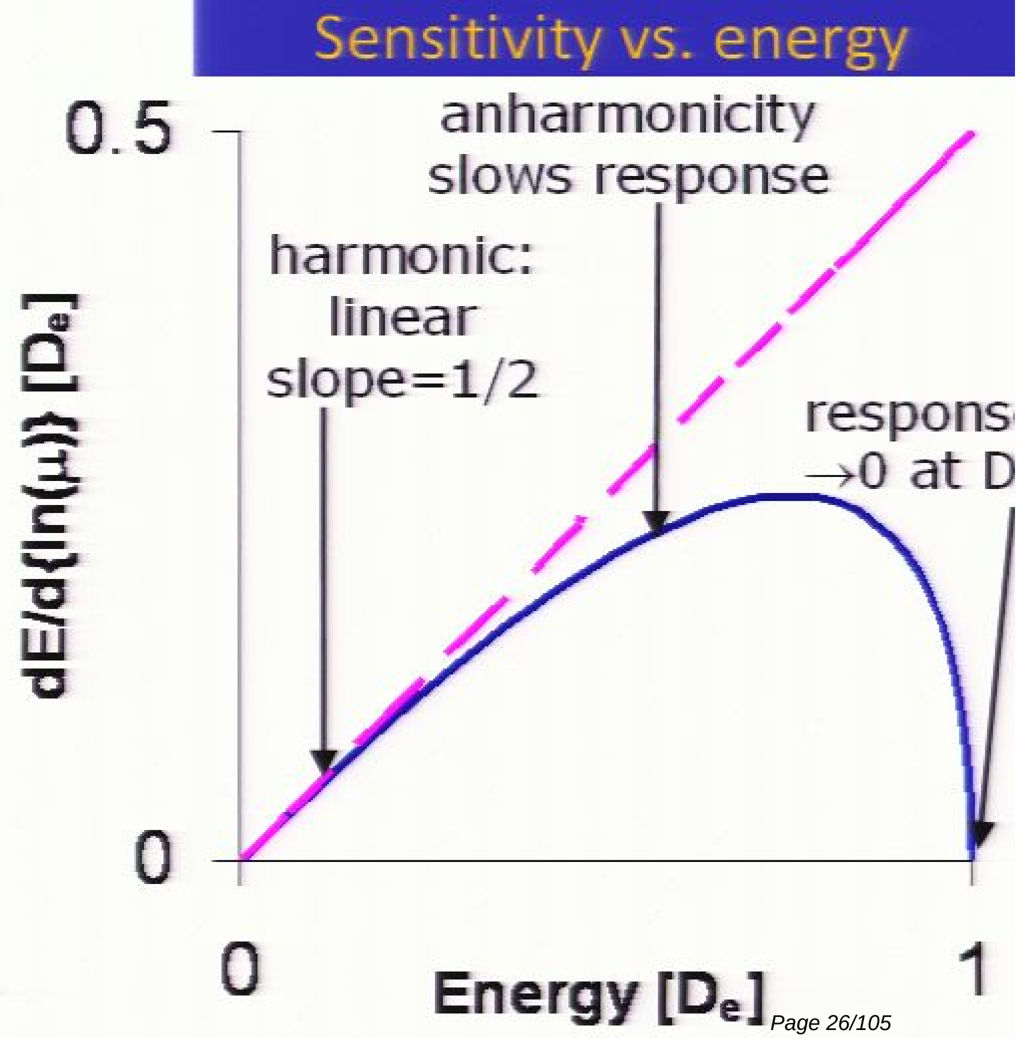


Sensitivity vs. energy

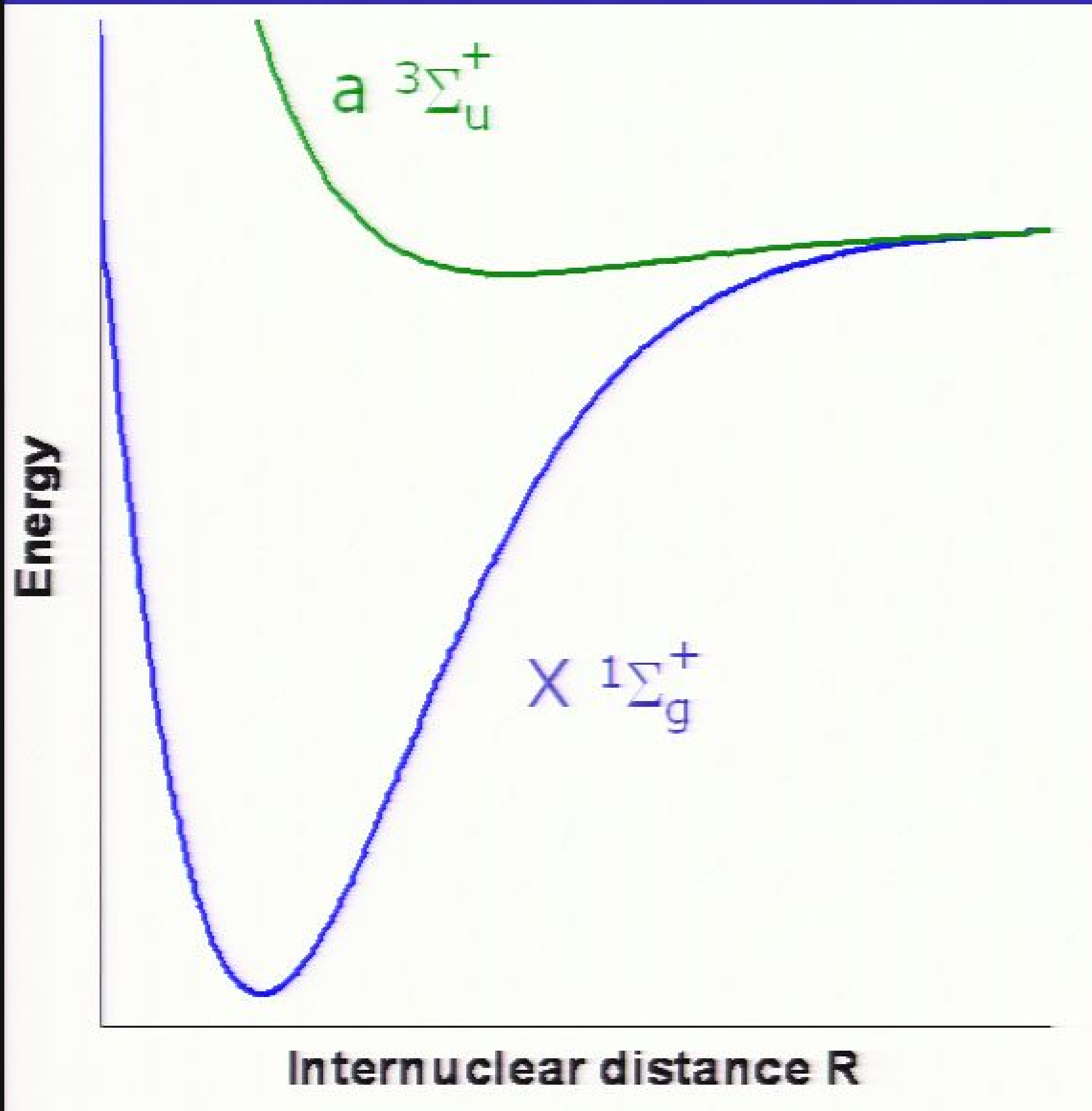


Realistic Model: Sensitivity to dμ/dt vs. binding energy



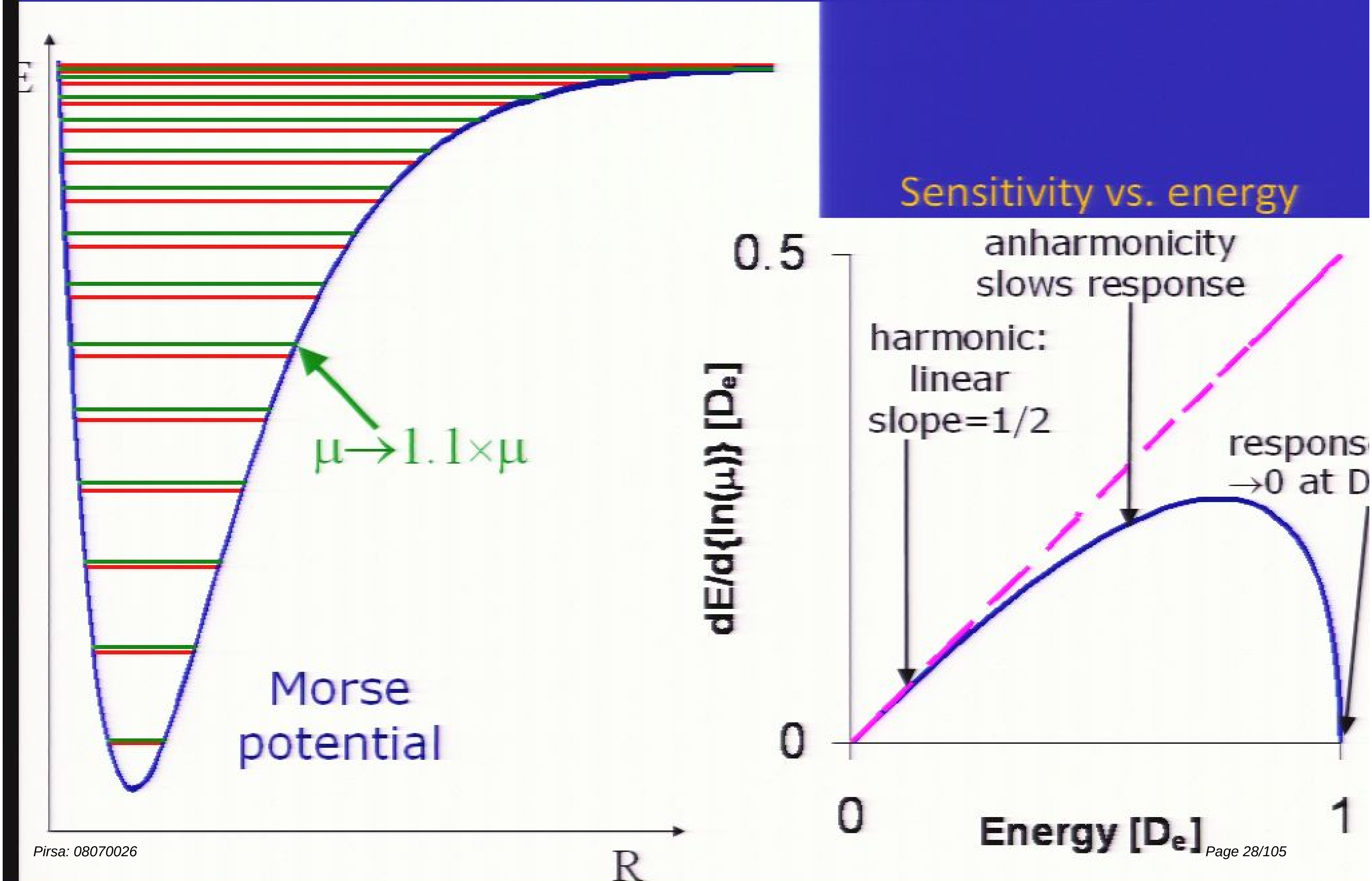


$d\mu/dt$ with ultracold Cs_2

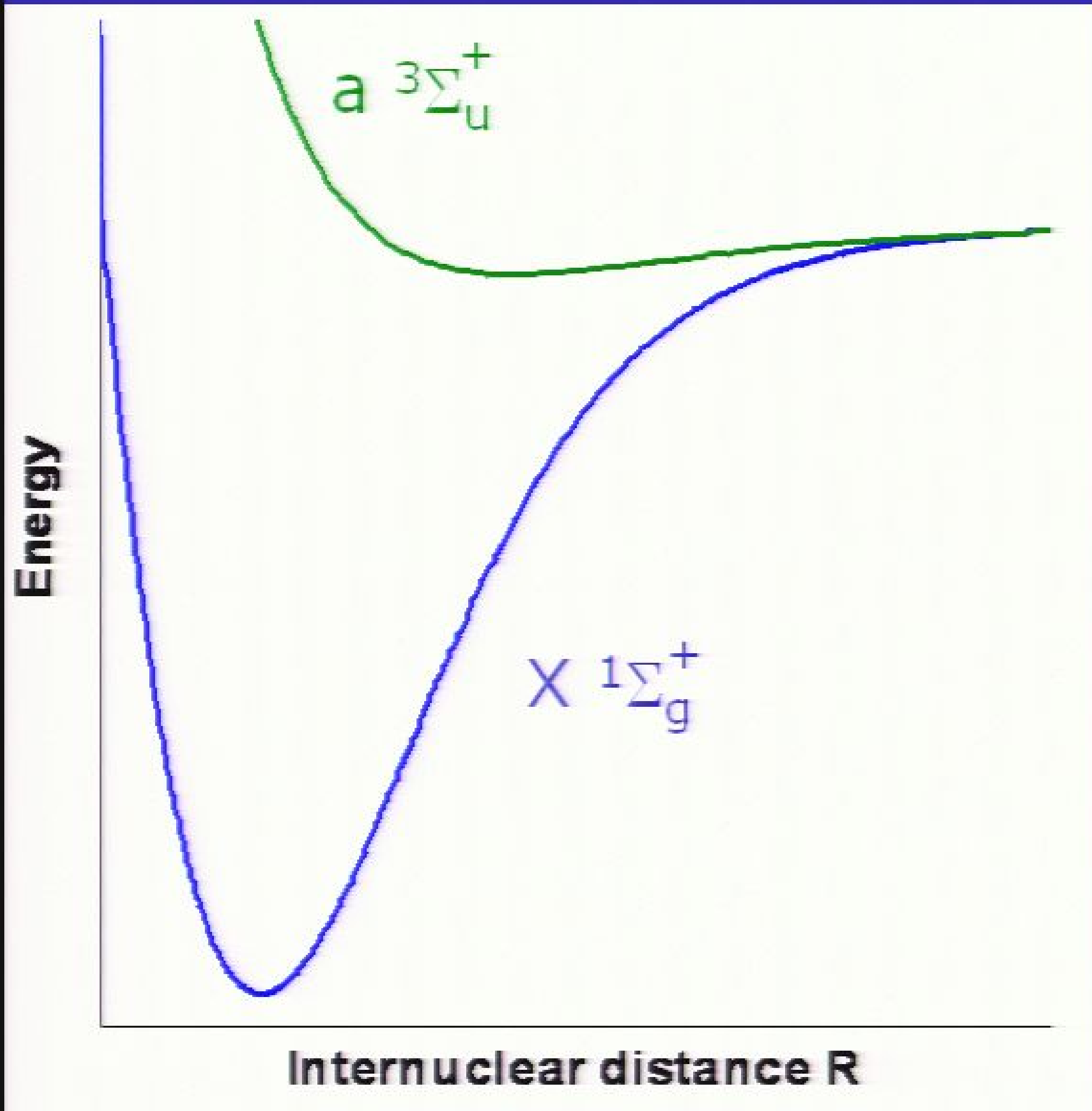


- Ultracold $Cs_2 \Rightarrow$ narrow lines (~1 Hz?)
- Efficient Cs_2 formation (via photoassociation or Feshbach + stim. Raman) into deeply-bound a $^3\Sigma_u$ leve possible [favorable FC factors]
- High level densities $\Rightarrow$ singlet-triplet overlaps common (?)

Realistic Model: Sensitivity to dμ/dt vs. binding energy

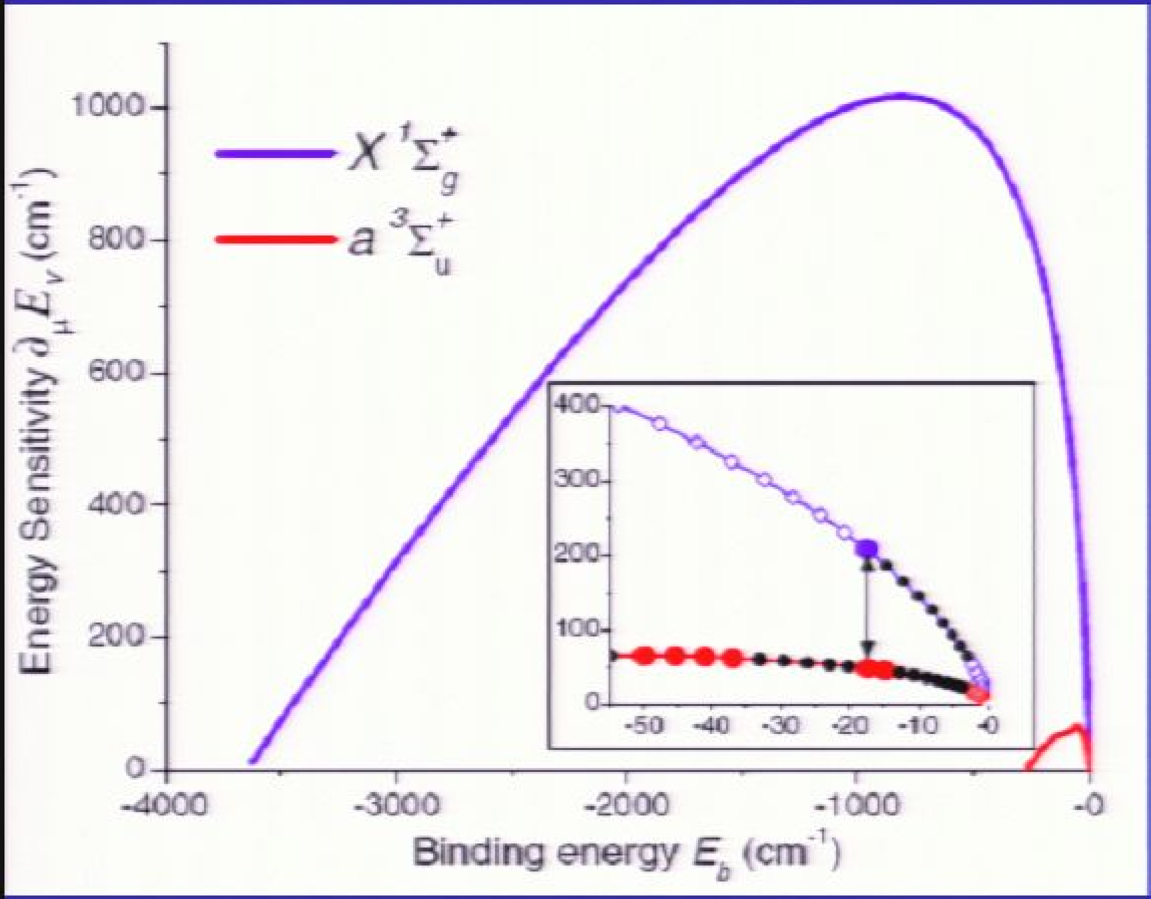


$d\mu/dt$ with ultracold Cs_2



- Ultracold Cs_2 $\Rightarrow$ narrow lines (~1 Hz?)
- Efficient Cs_2 formation (via photoassociation or Feshbach + stim. Raman) into deeply-bound a $^3\Sigma_u$ leve possible [favorable FC factors]
- High level densities $\Rightarrow$ singlet-triplet overlaps common (?)

$d\mu/dt$ with ultracold Cs_2

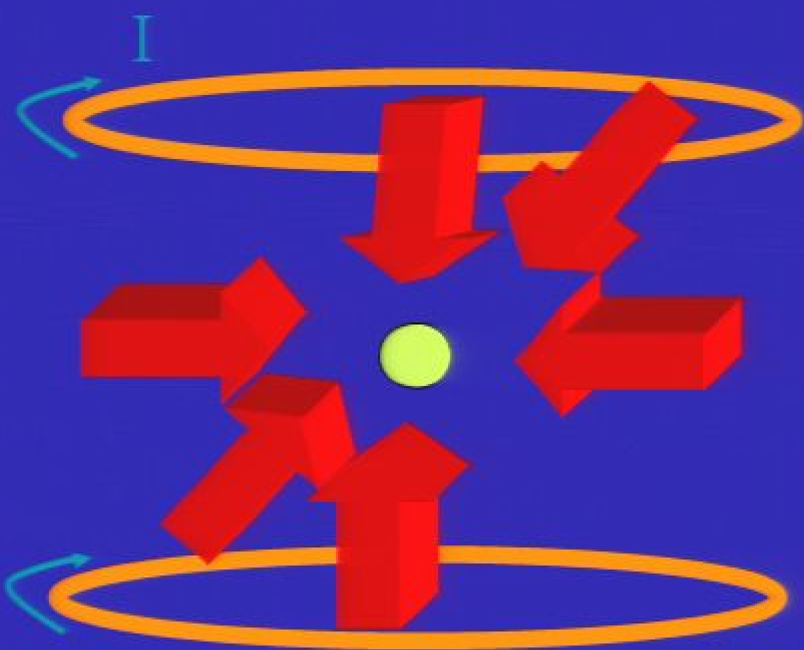


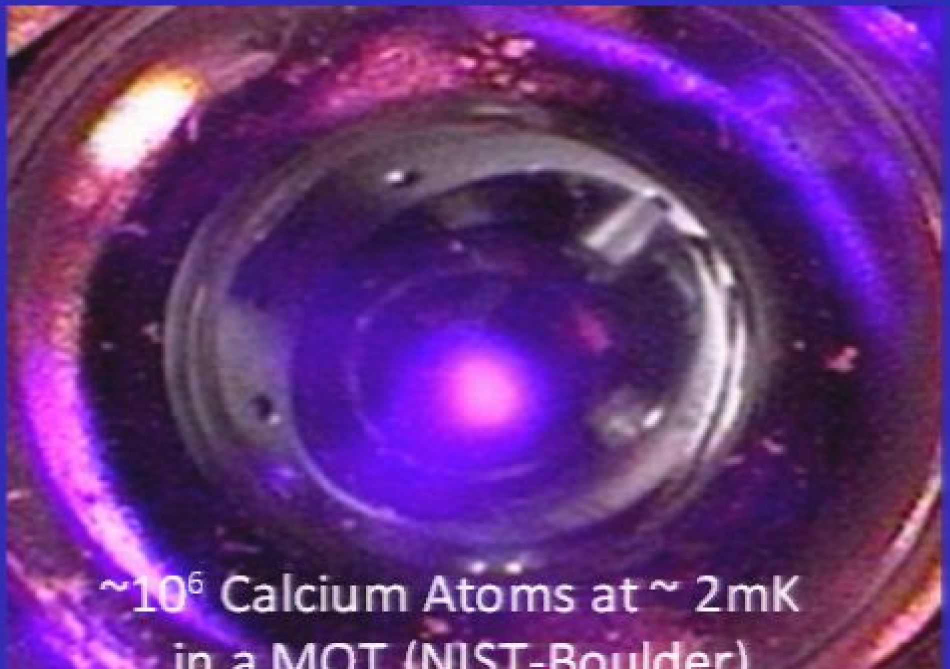
- Ultracold Cs_2 $\Rightarrow$ narrow lines (~1 Hz?)
- Efficient Cs_2 formation (via photoassociation or Feshbach + stim. Raman) into deeply-bound a $^3\Sigma_u$ leve possible [favorable FC factors]
- High level densities $\Rightarrow$ singlet-triplet overlaps common (?)

The Magneto-optic trap (Nobel 1998)

Workhorse of atomic physics:

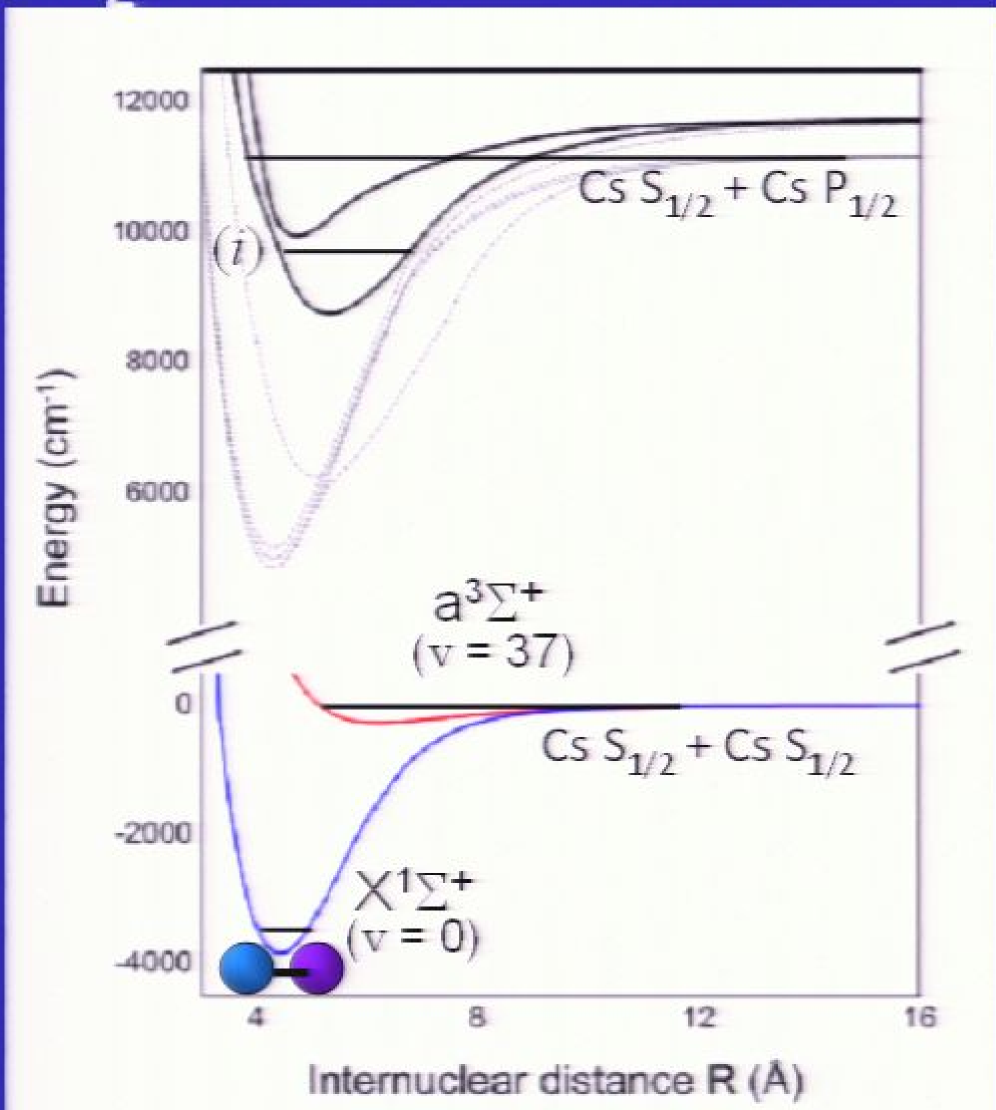
- Scattering of laser photons cools AND traps atoms
- Captures millions of atoms "in free space"
- Density as high as 10^{12} cm^{-3}
- "Ultracold" temperature T < 1 mK routine
- Precursor to further cooling for Bose-Einstein condensation, etc. (Nobel 2002)





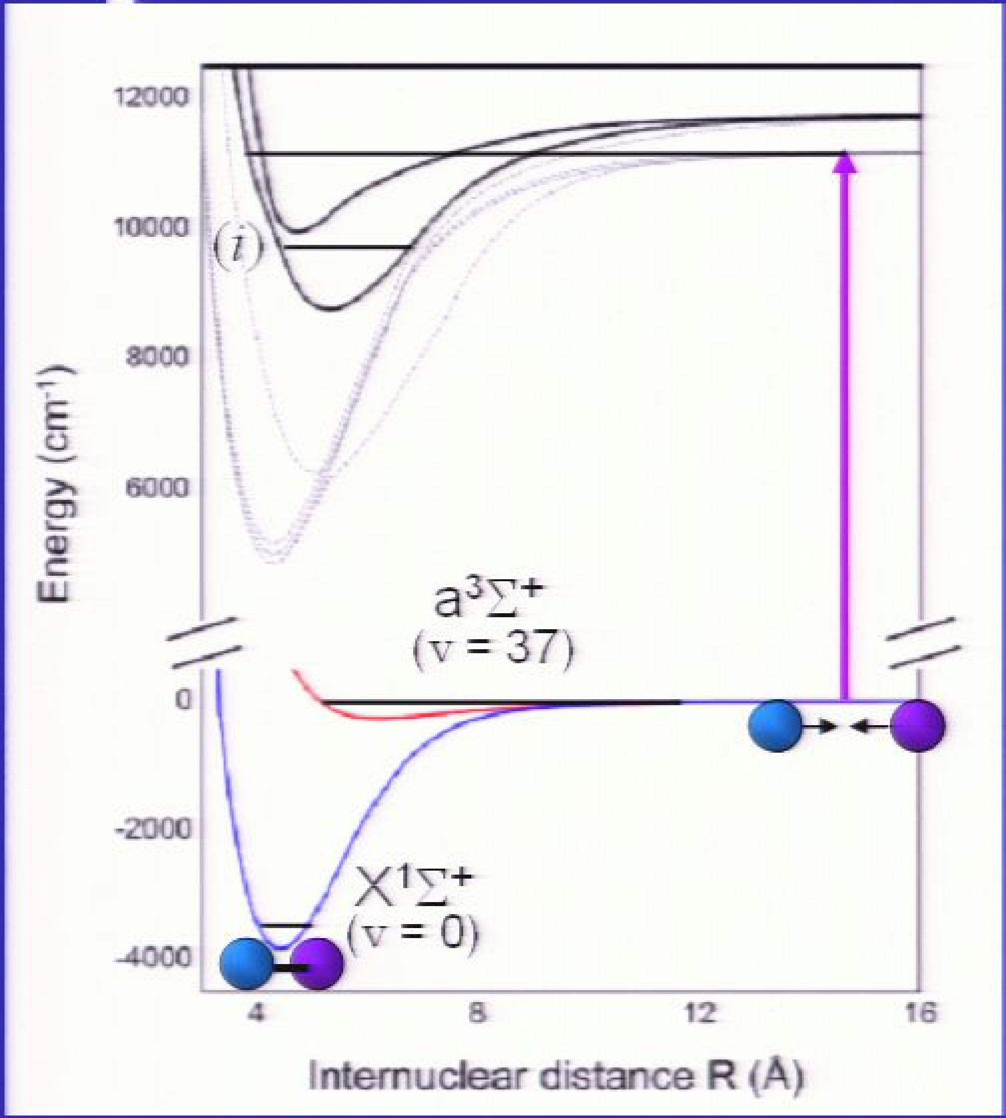
Optical production method

Cs_2



Optical production method

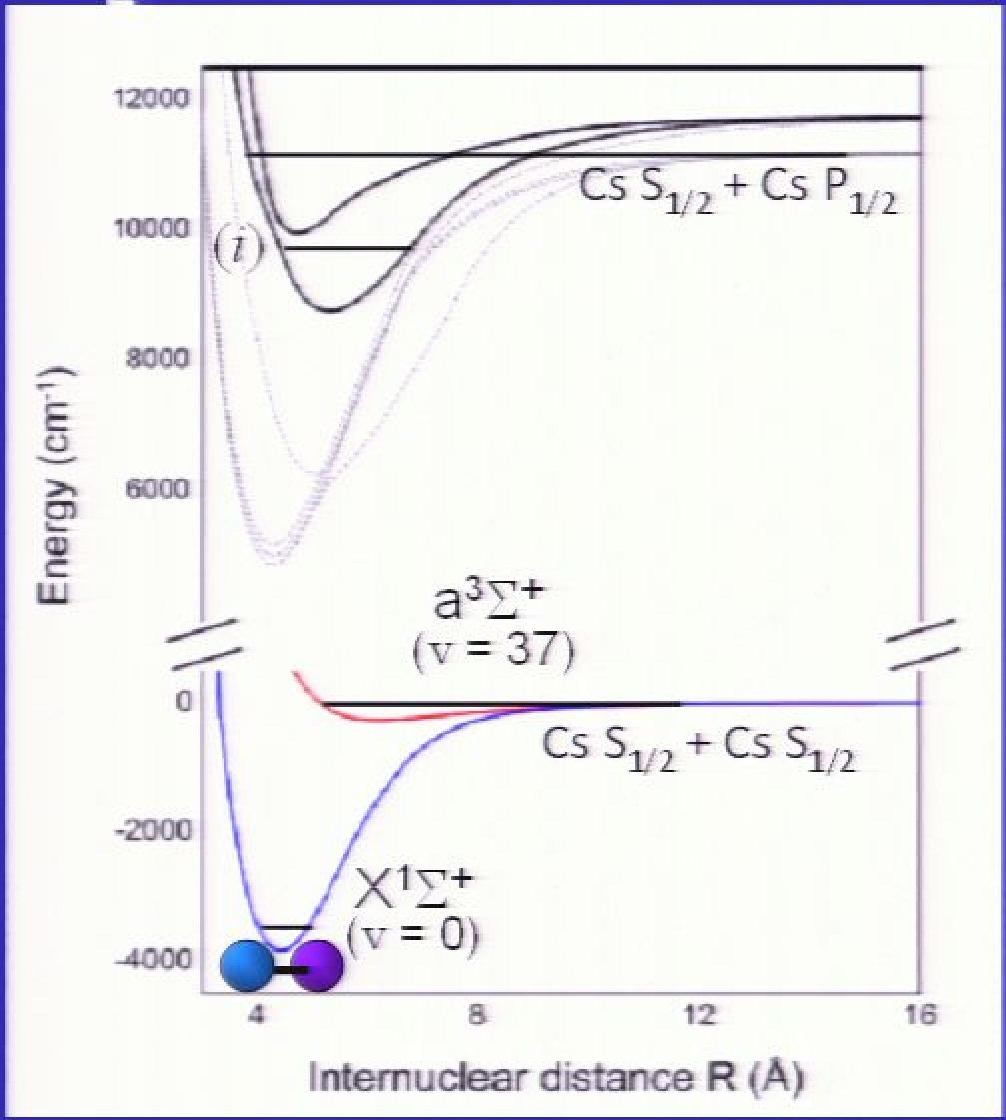
Cs_2



- Photoassociation
  - ultracold free atoms to excited bound state

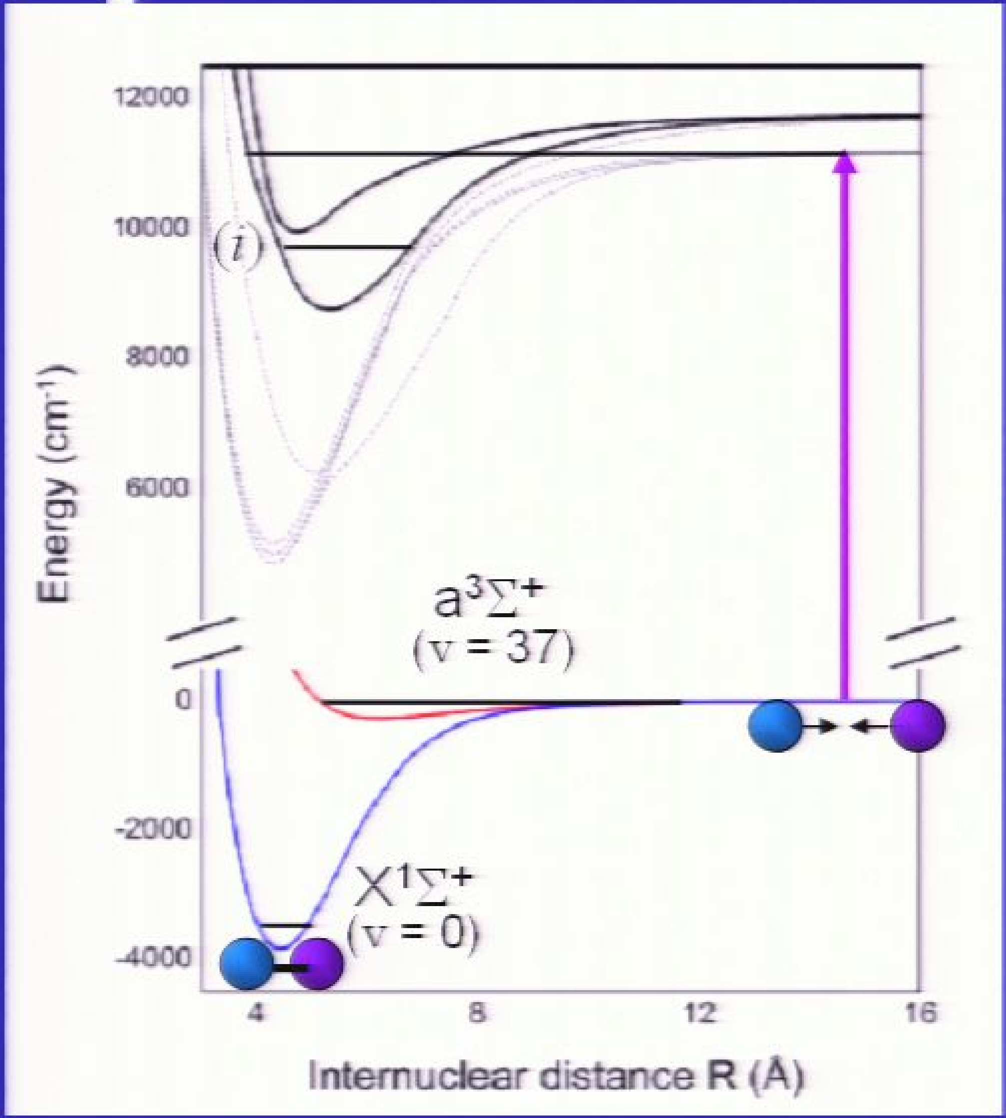
Optical production method

Cs_2



Optical production method

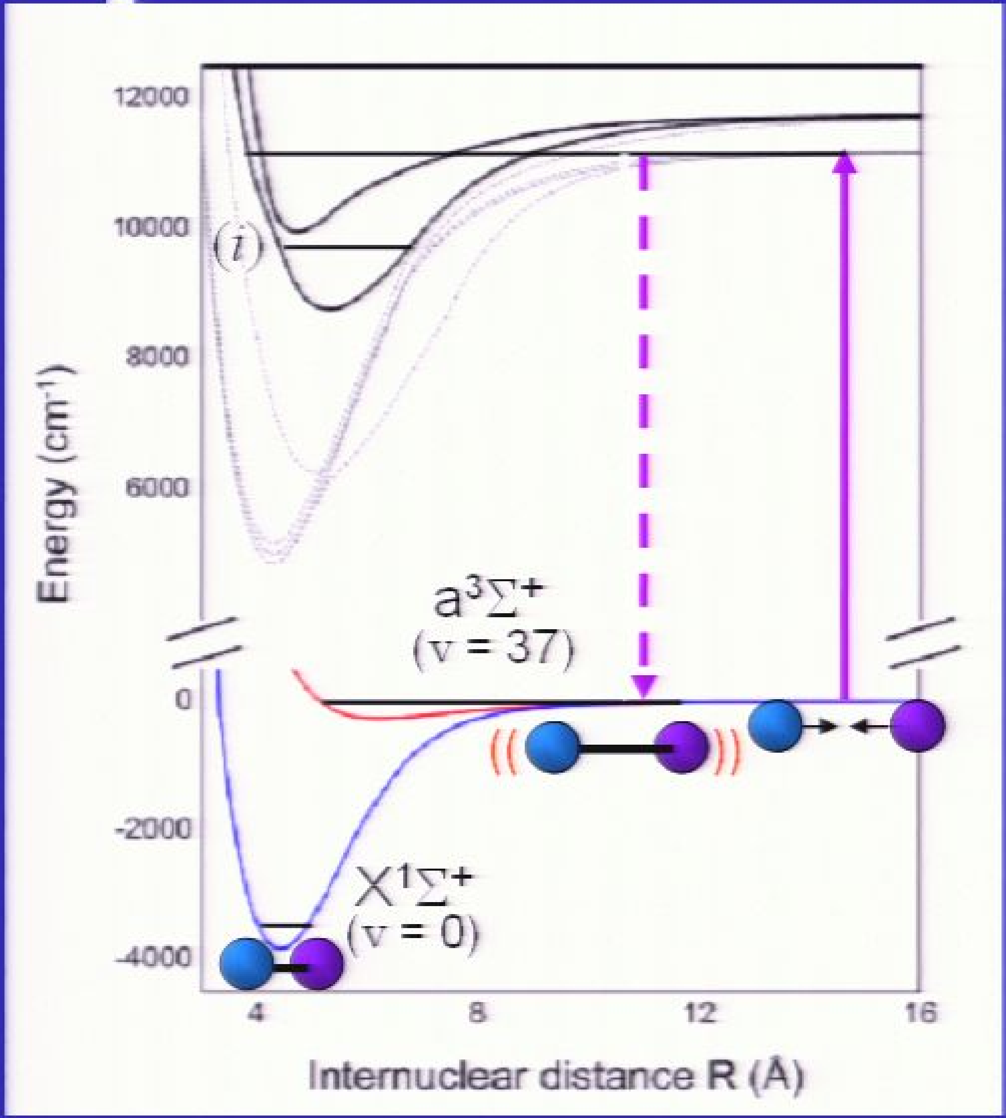
Cs_2



- Photoassociation
  - ultracold free atoms to excited bound state

Optical production method

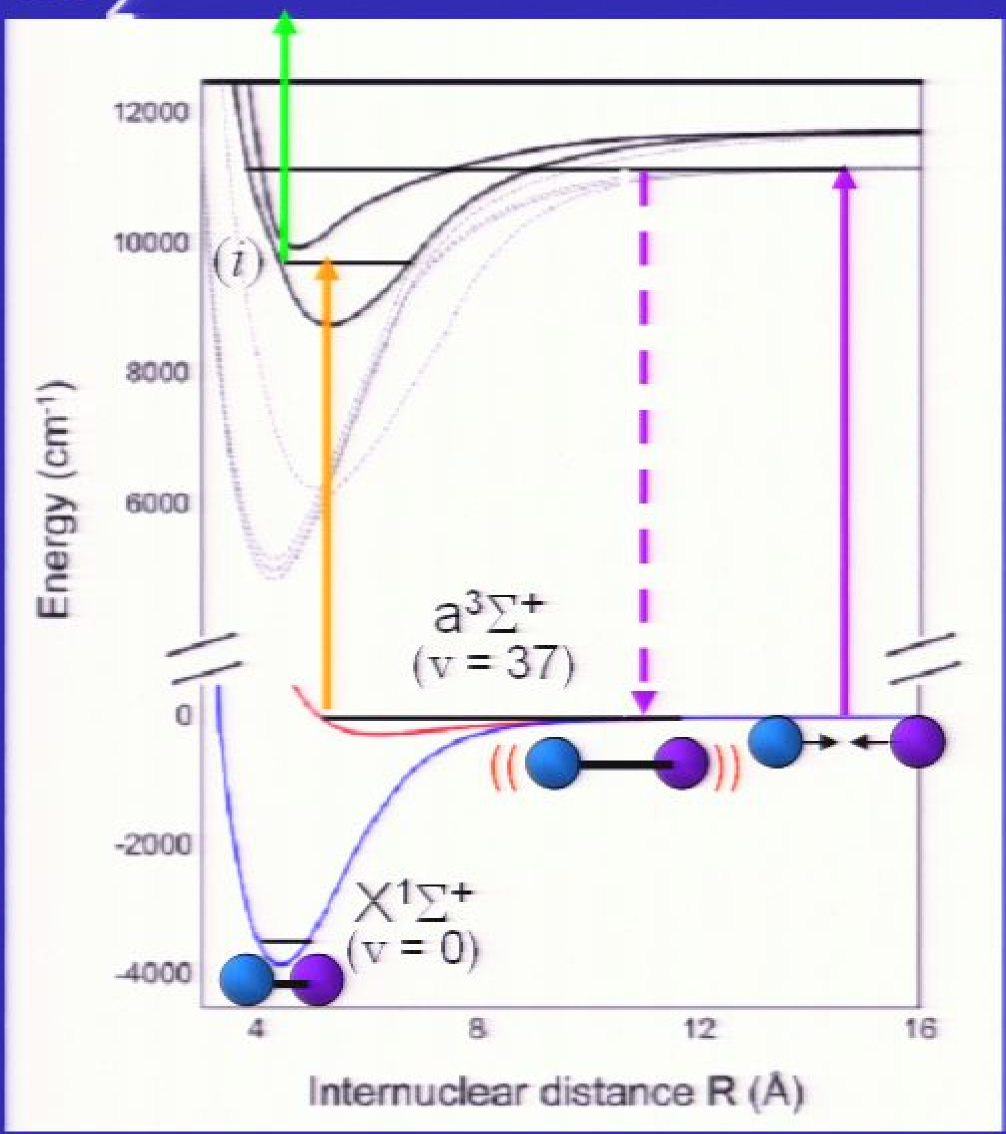
Cs_2



- Photoassociation
  - ultracold free atoms to excited bound state
- Spontaneous decay
  - to vibrationally excited ground state

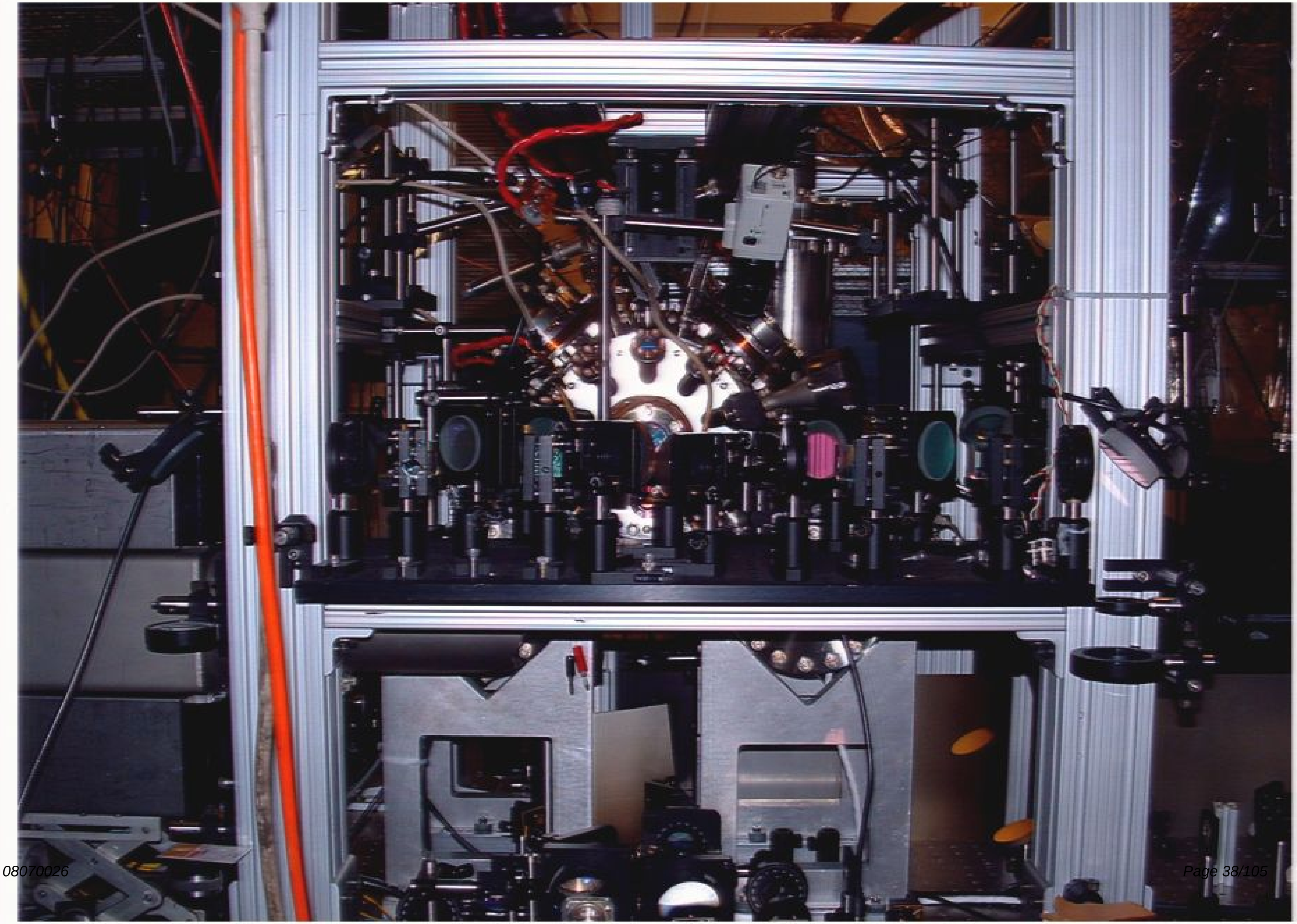
Optical production method

Cs$_2$

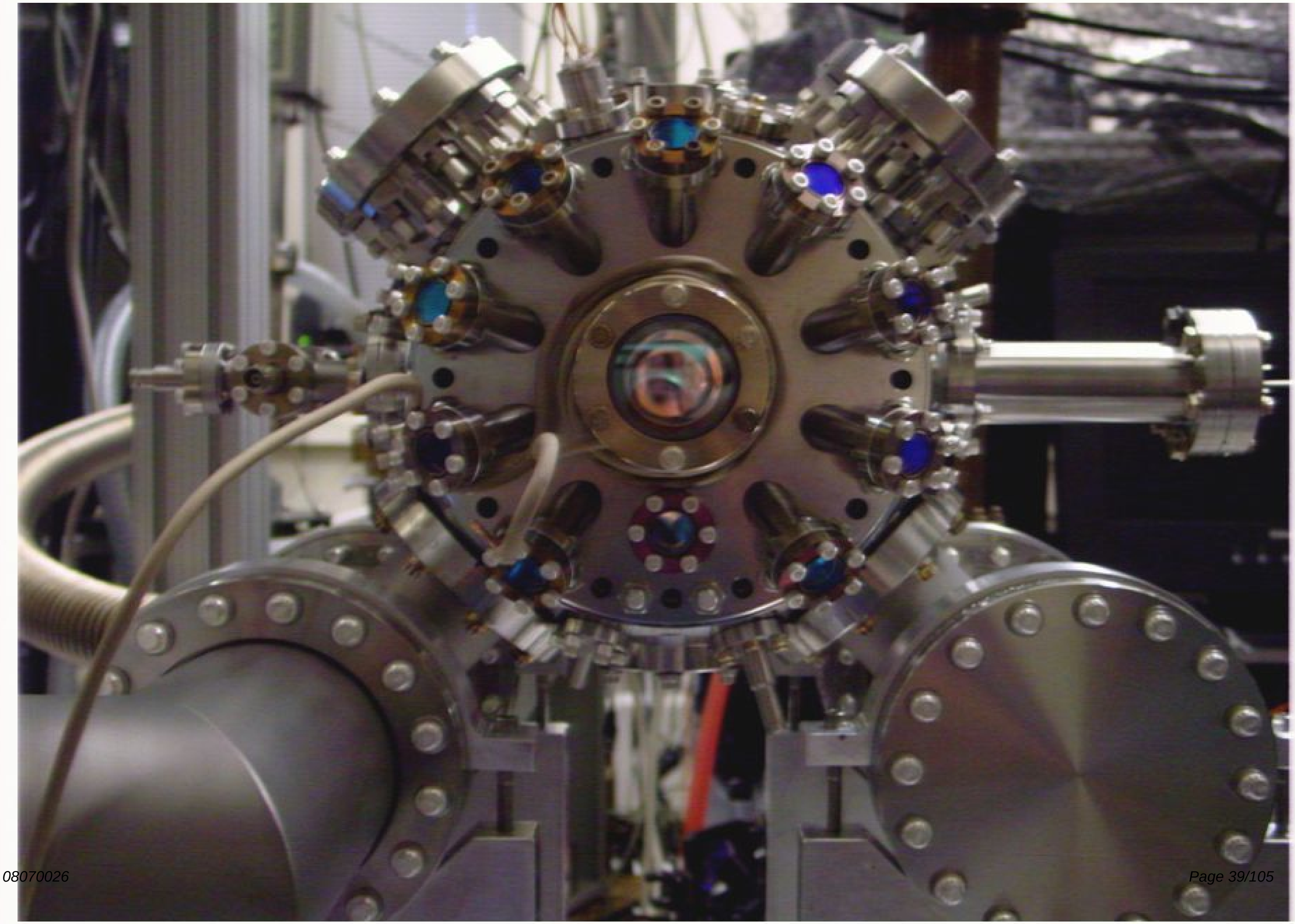


- Photoassociation
  - ultracold free atoms to excited bound state
- Spontaneous decay
  - to vibrationally excited ground state
- REMPI
  - to intermediate state
  - then to ion state
  - detect ions

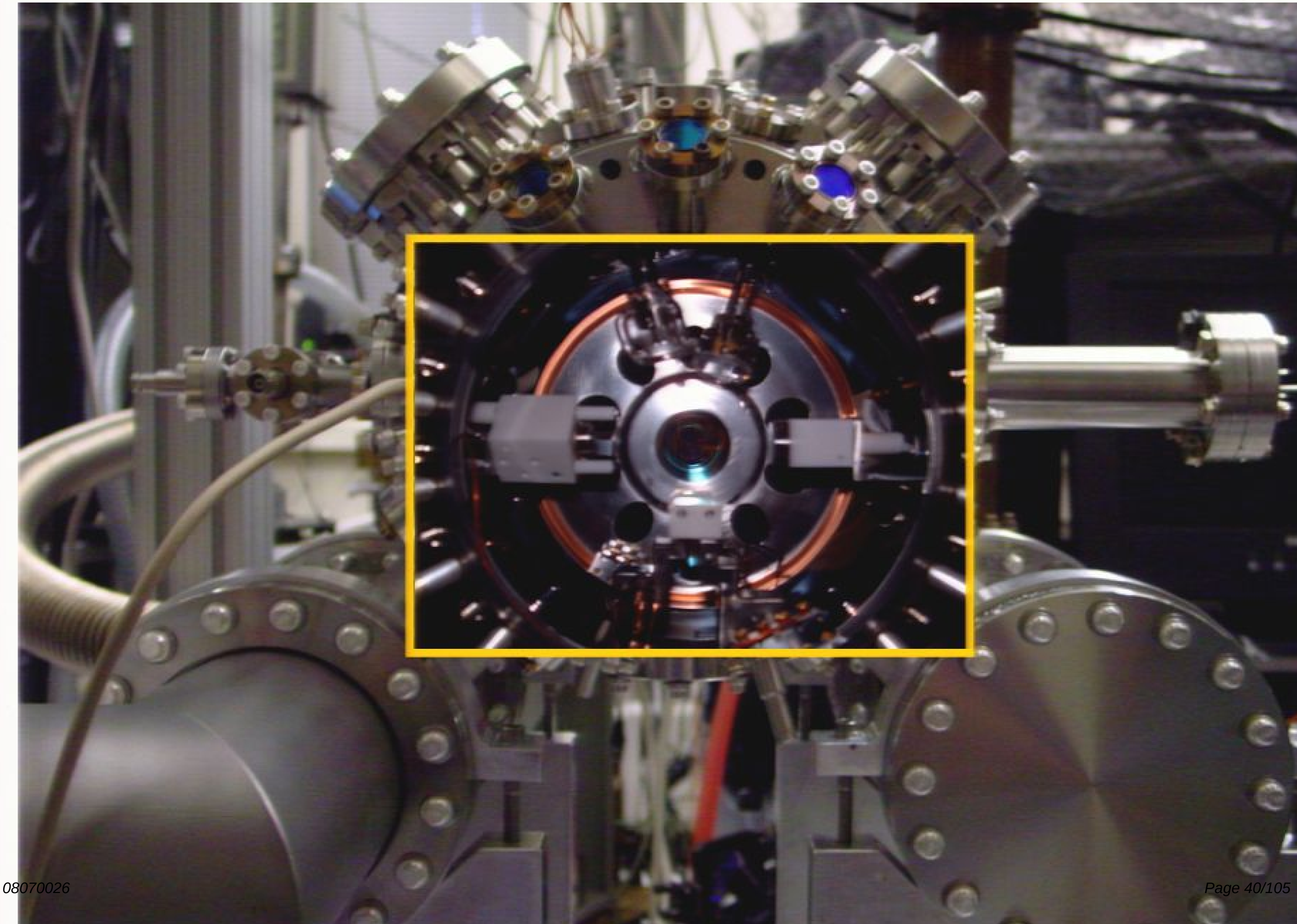
Trapping Experiment



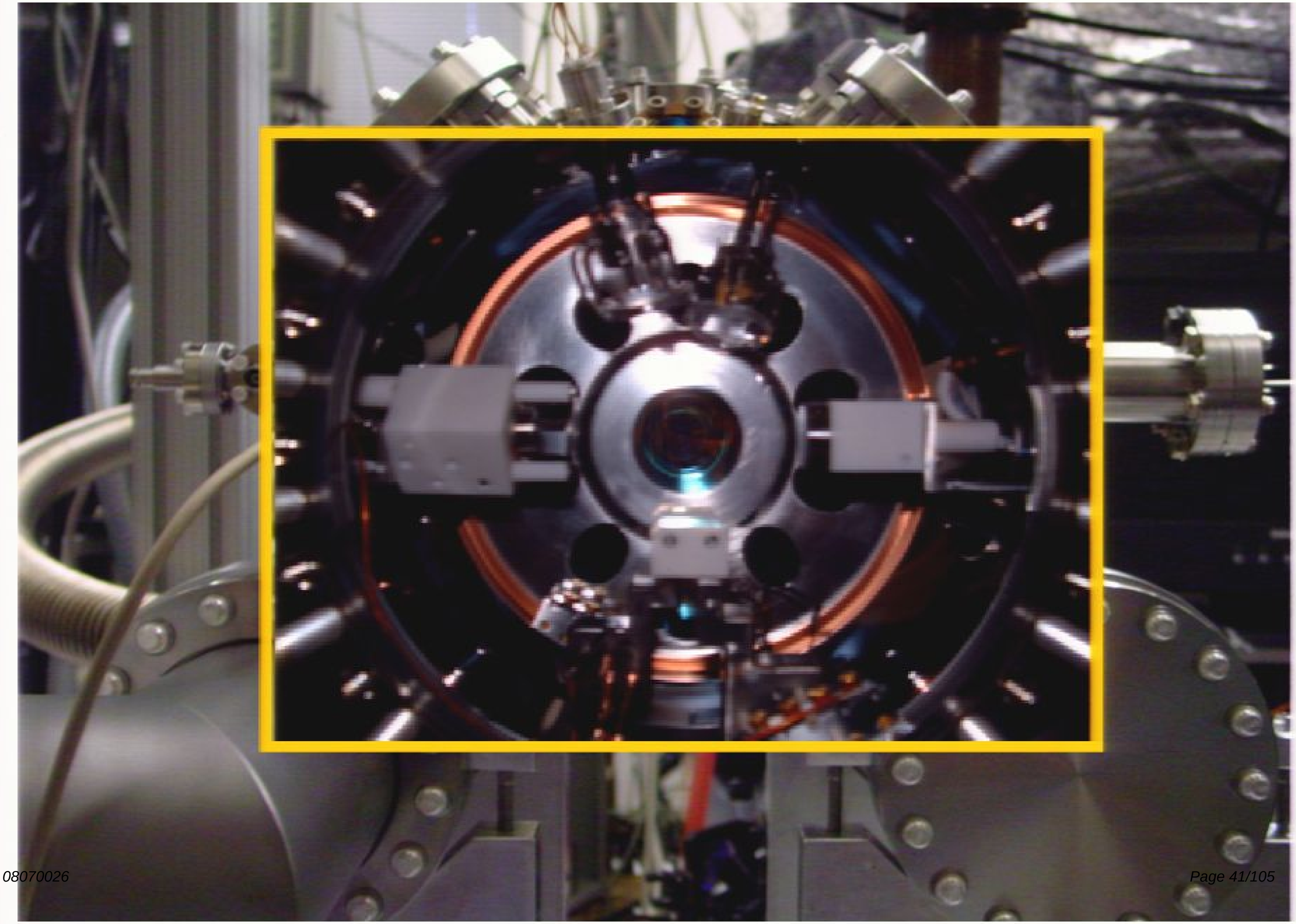
Trapping Experiment



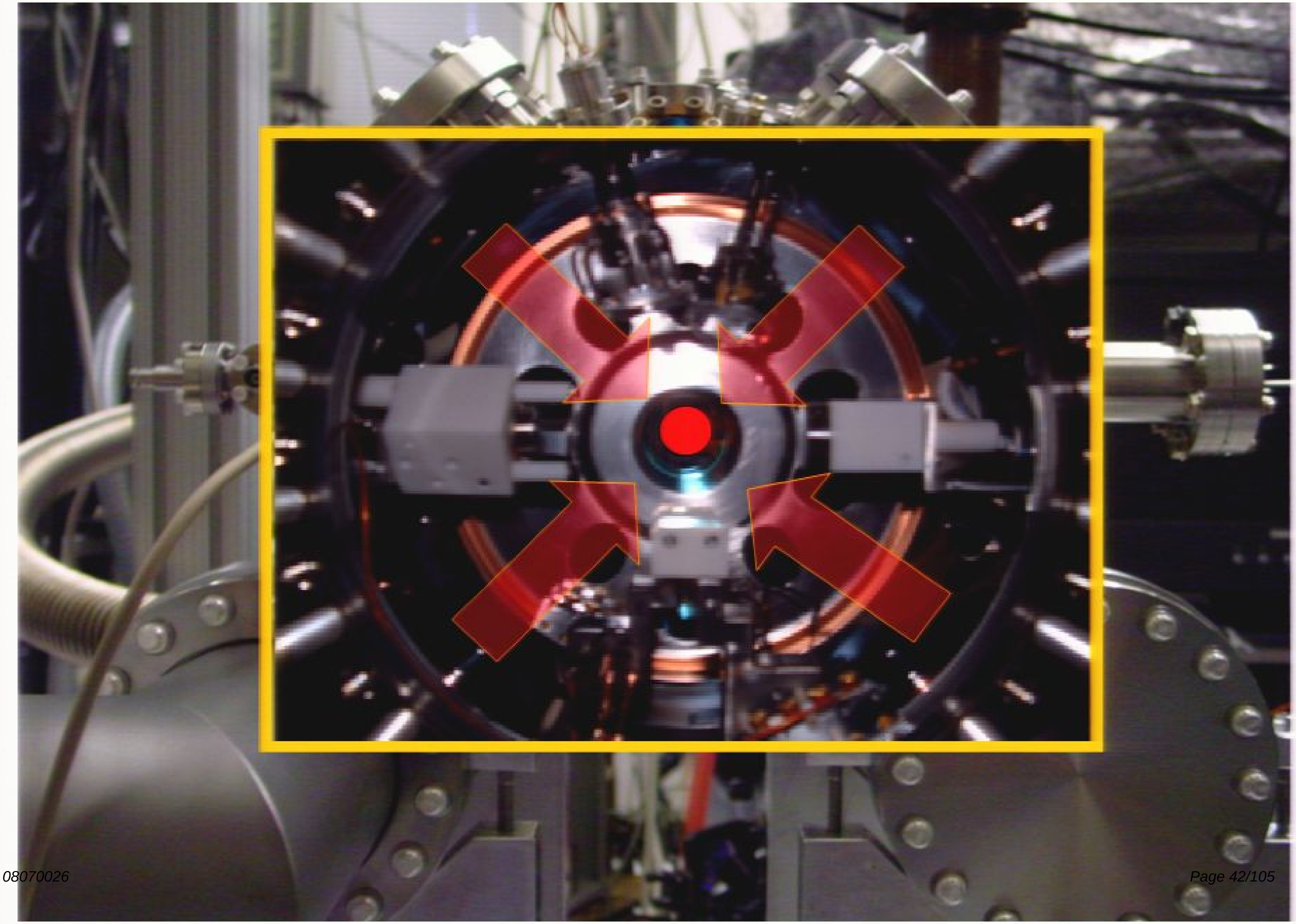
Trapping Experiment



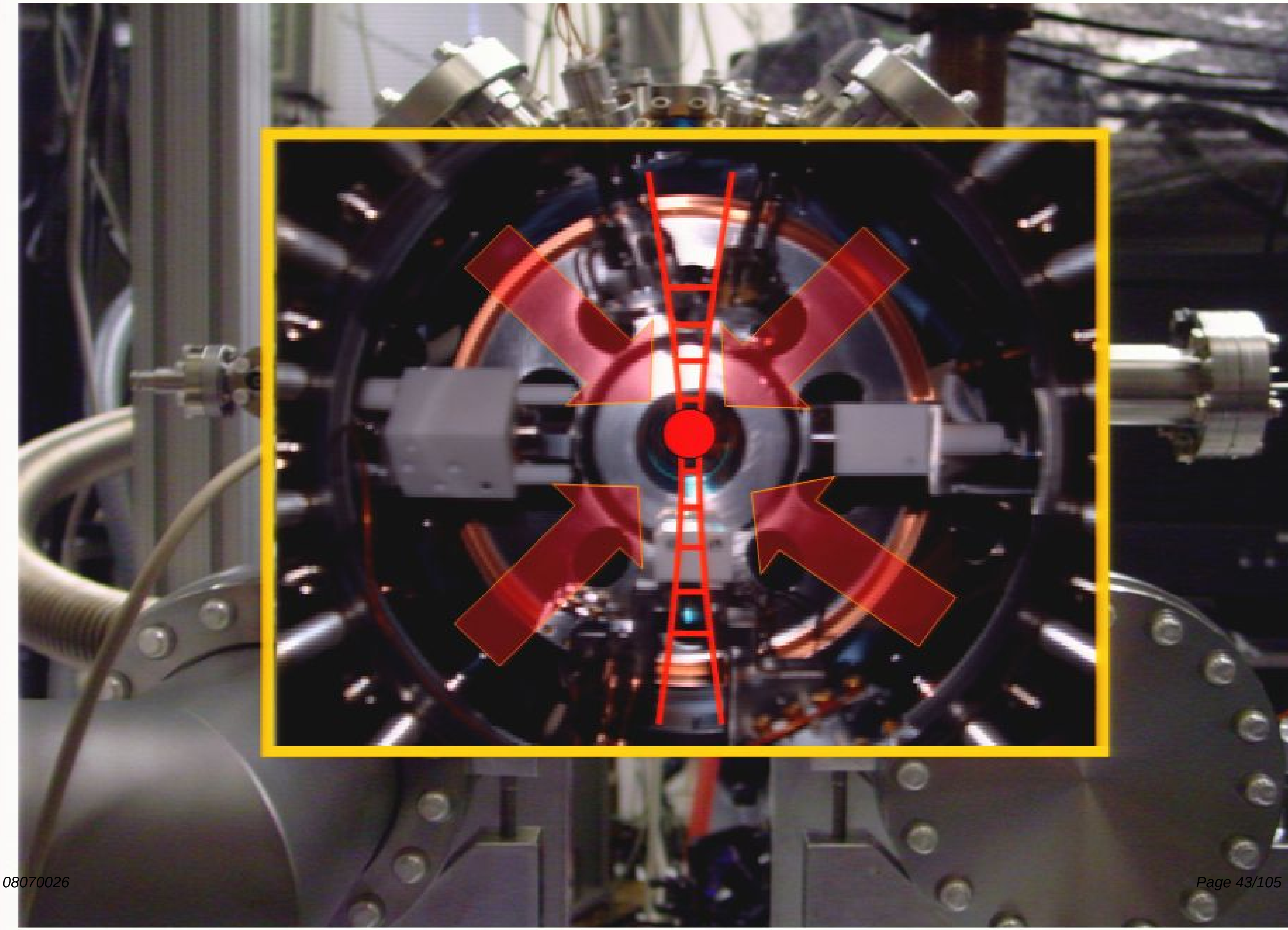
Trapping Experiment



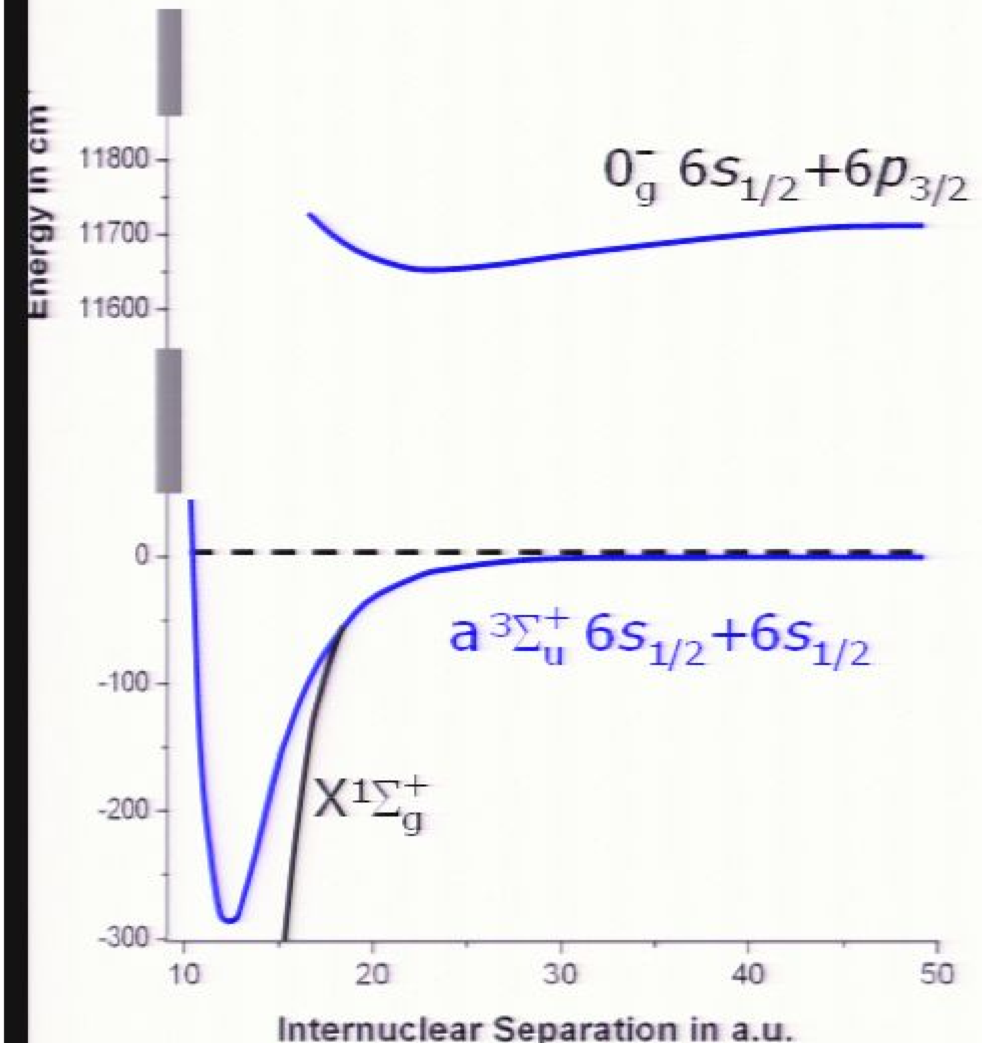
Trapping Experiment



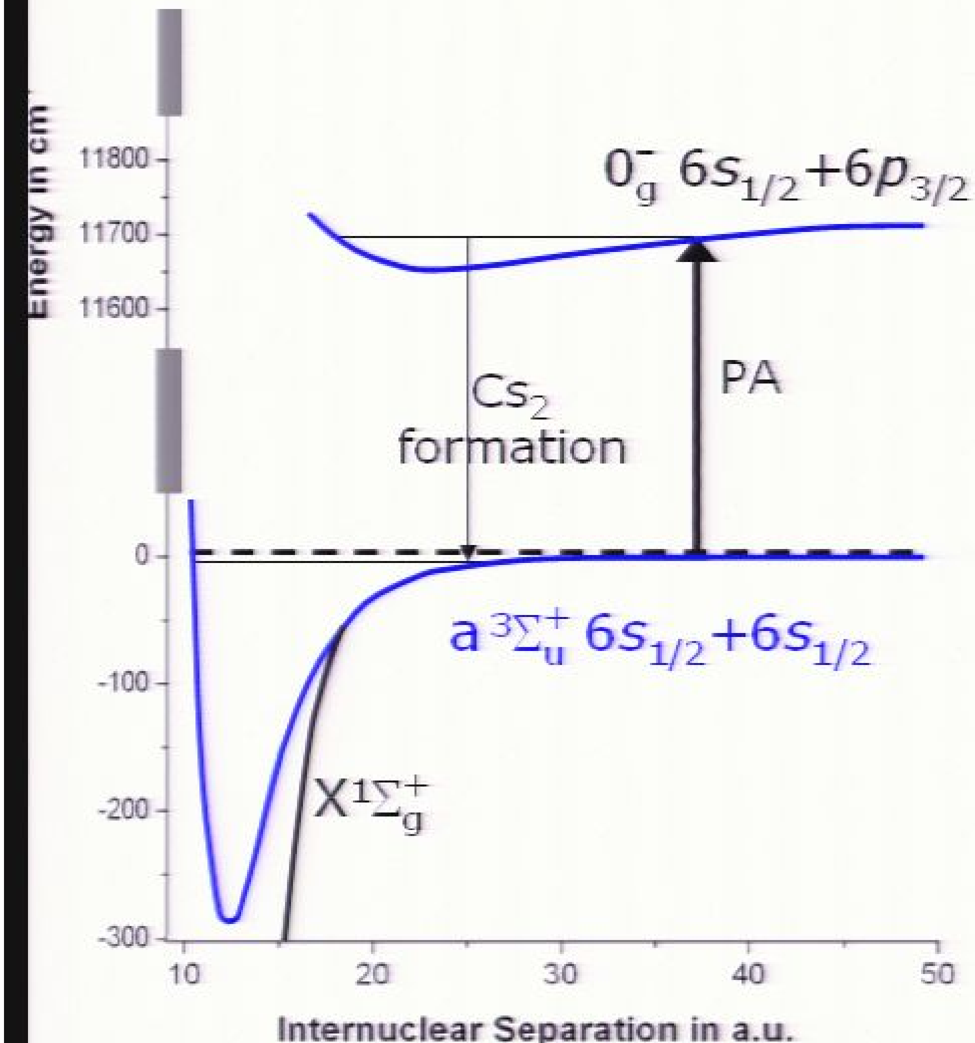
Trapping Experiment



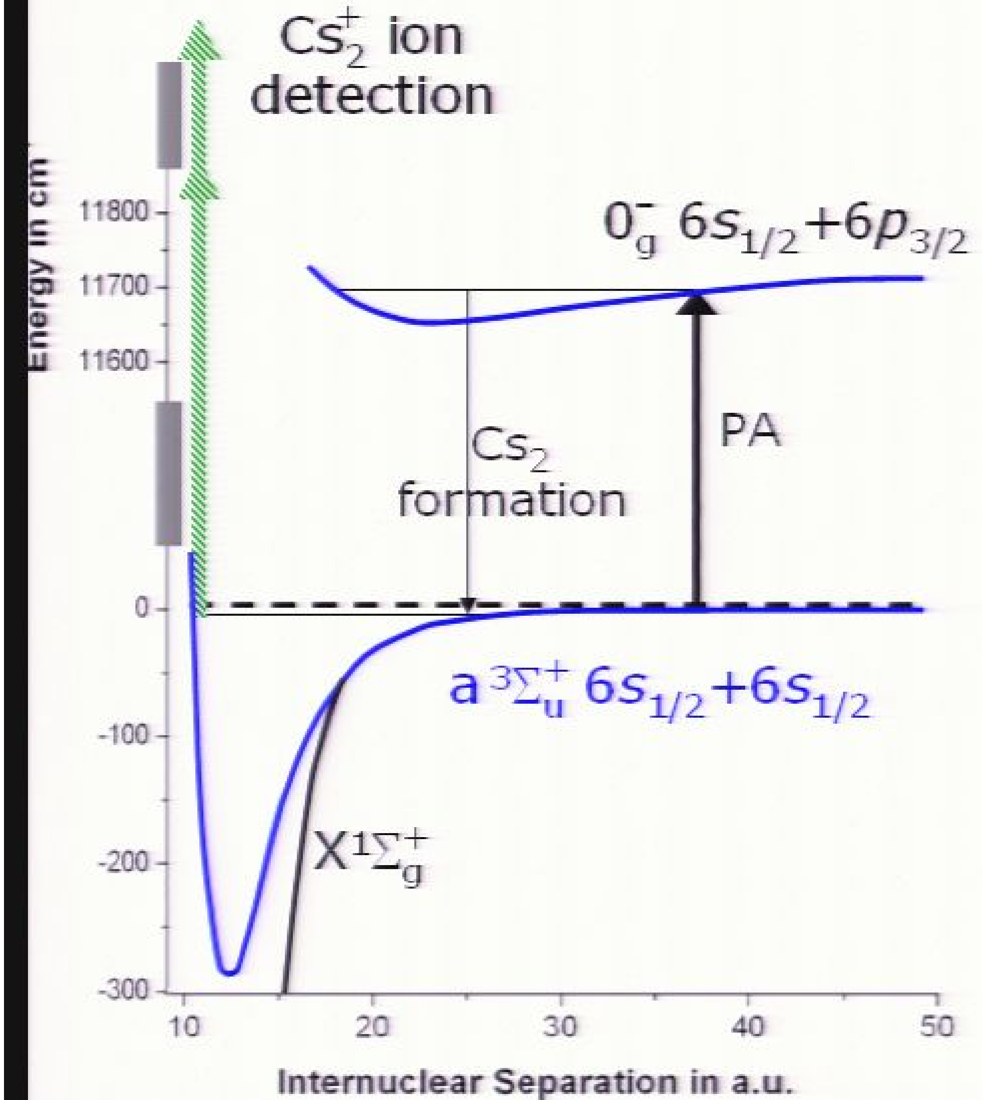
Two-color PA spectroscopy of Cs_2



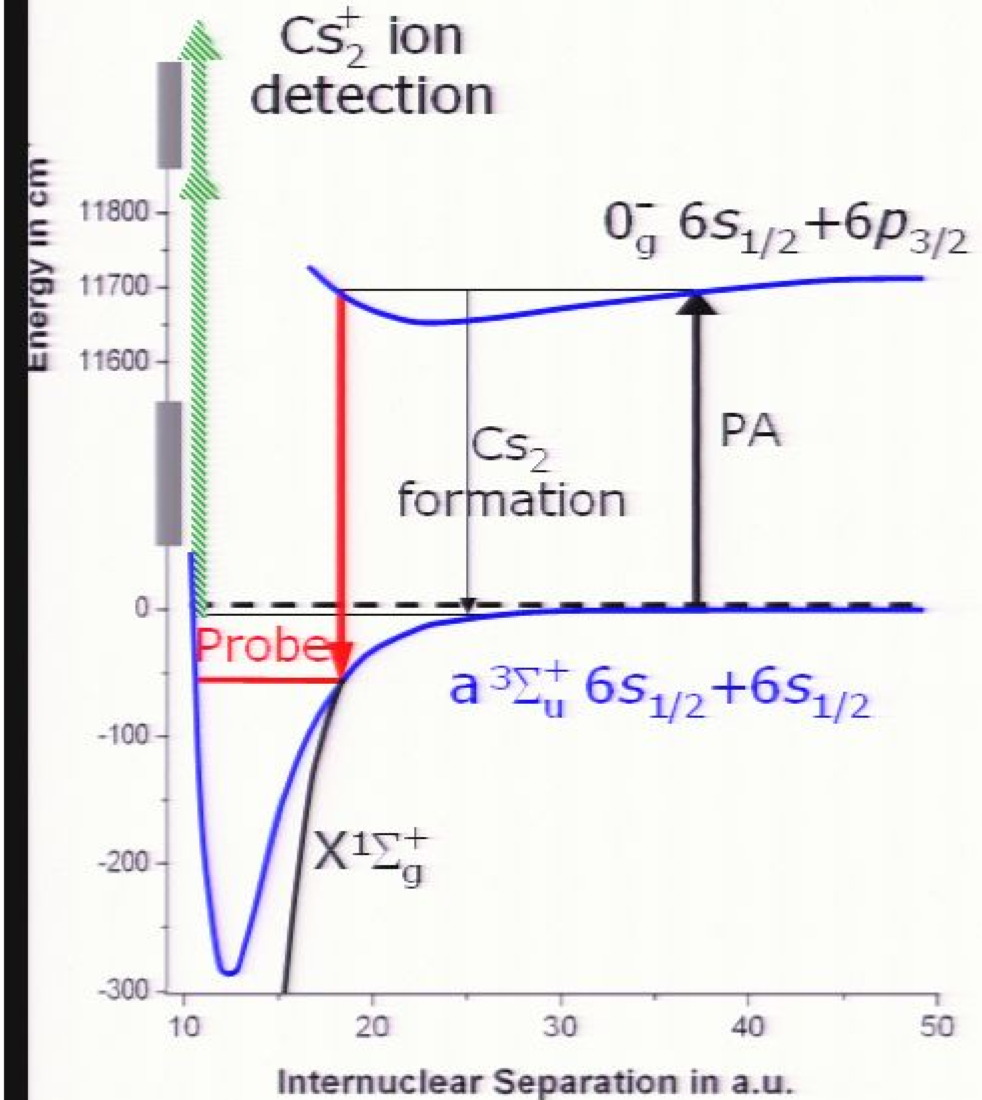
Two-color PA spectroscopy of Cs_2



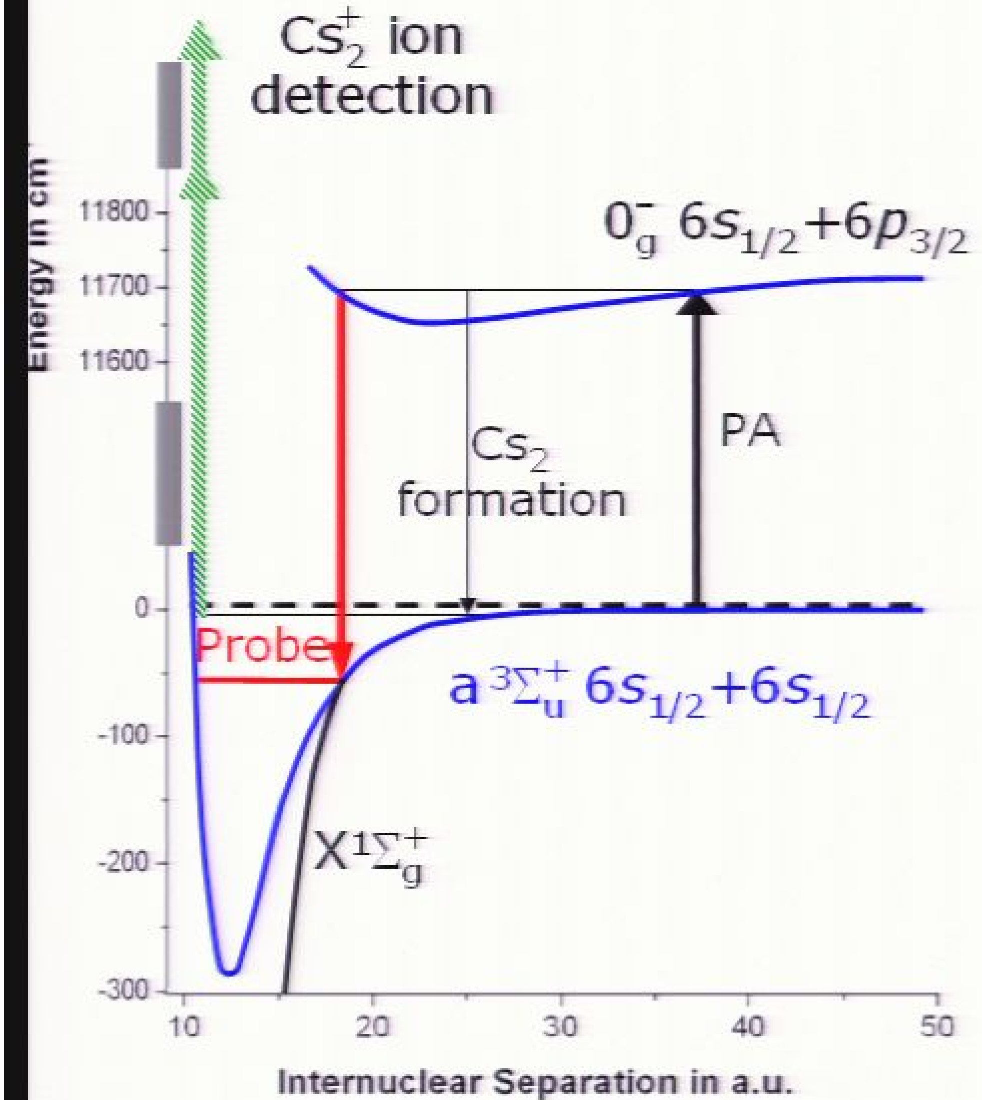
Two-color PA spectroscopy of Cs_2

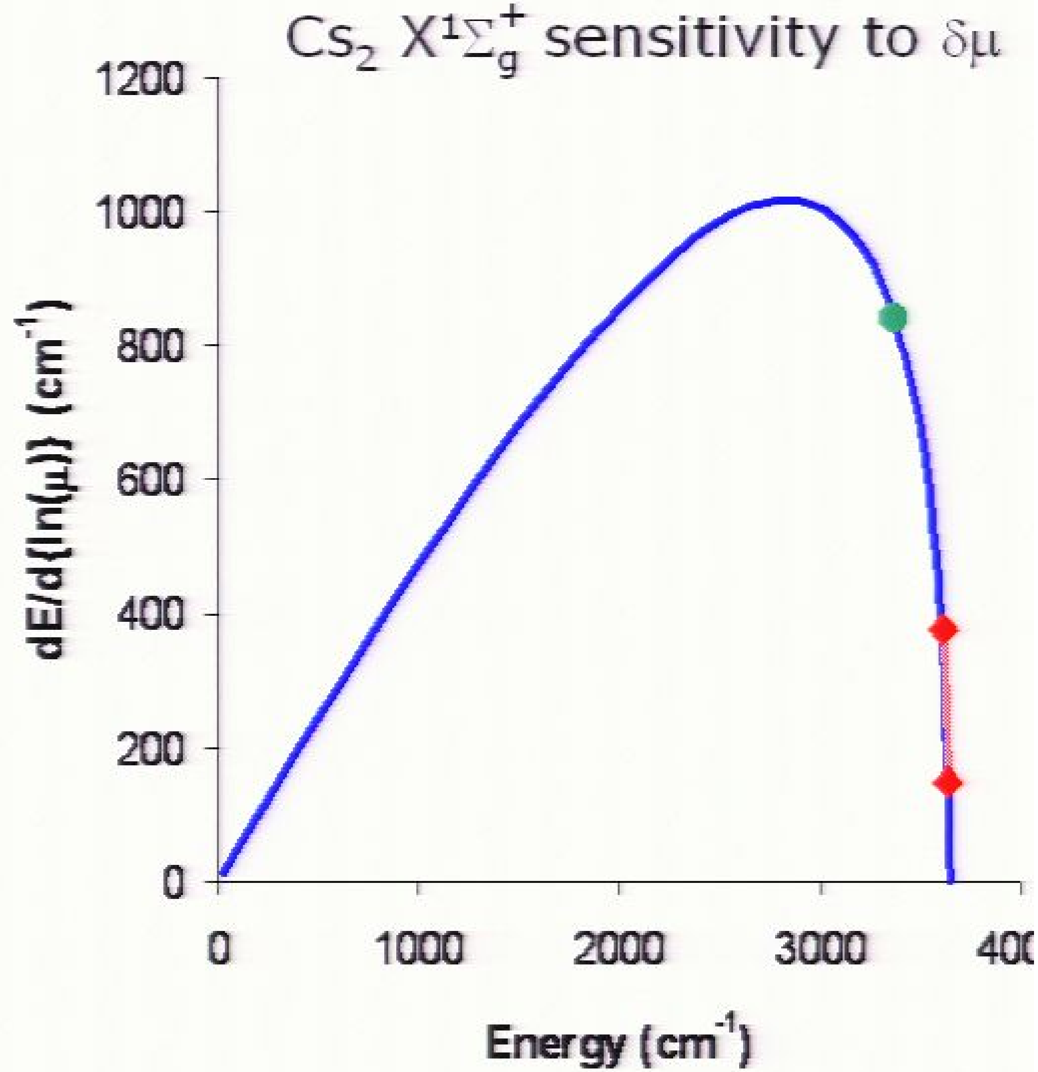


Two-color PA spectroscopy of Cs_2

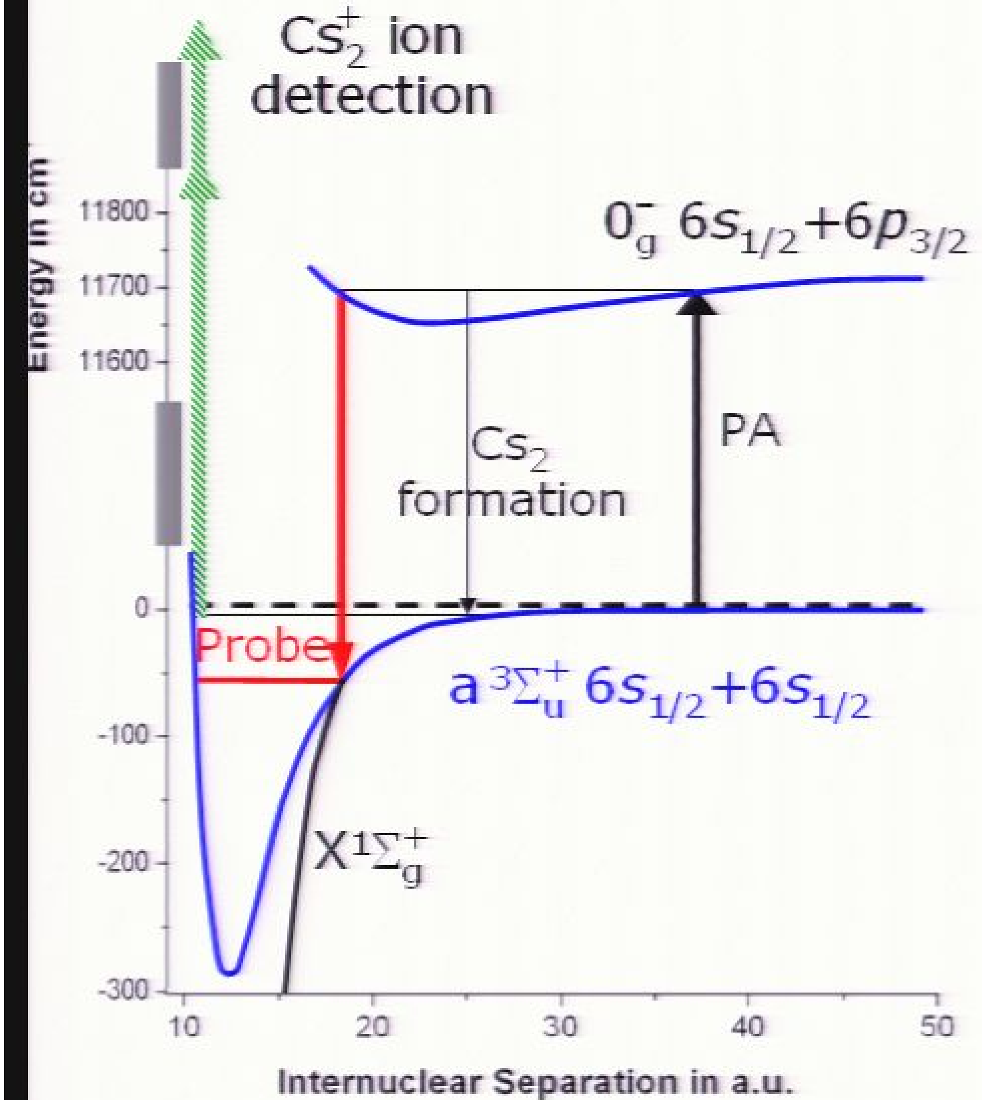


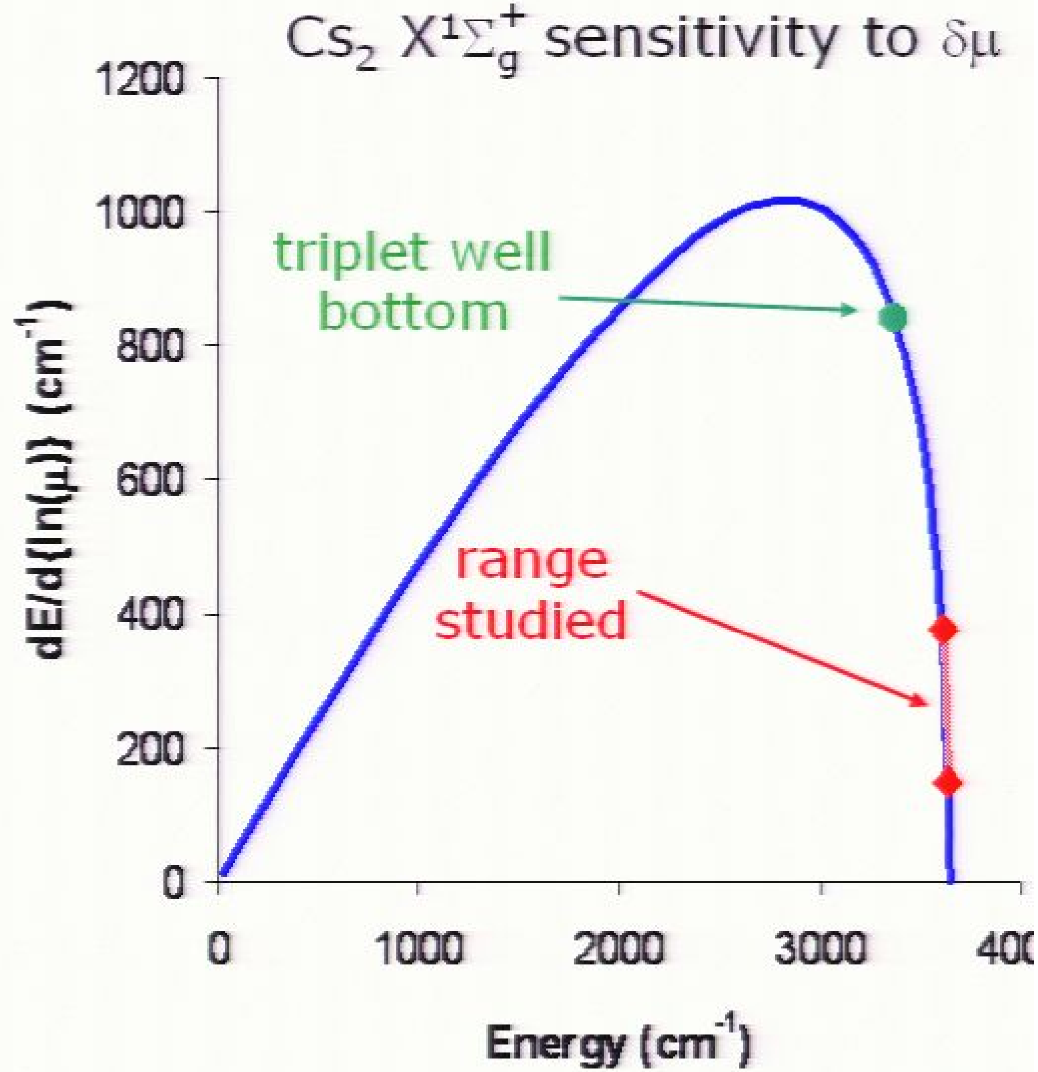
Two-color PA spectroscopy of Cs_2



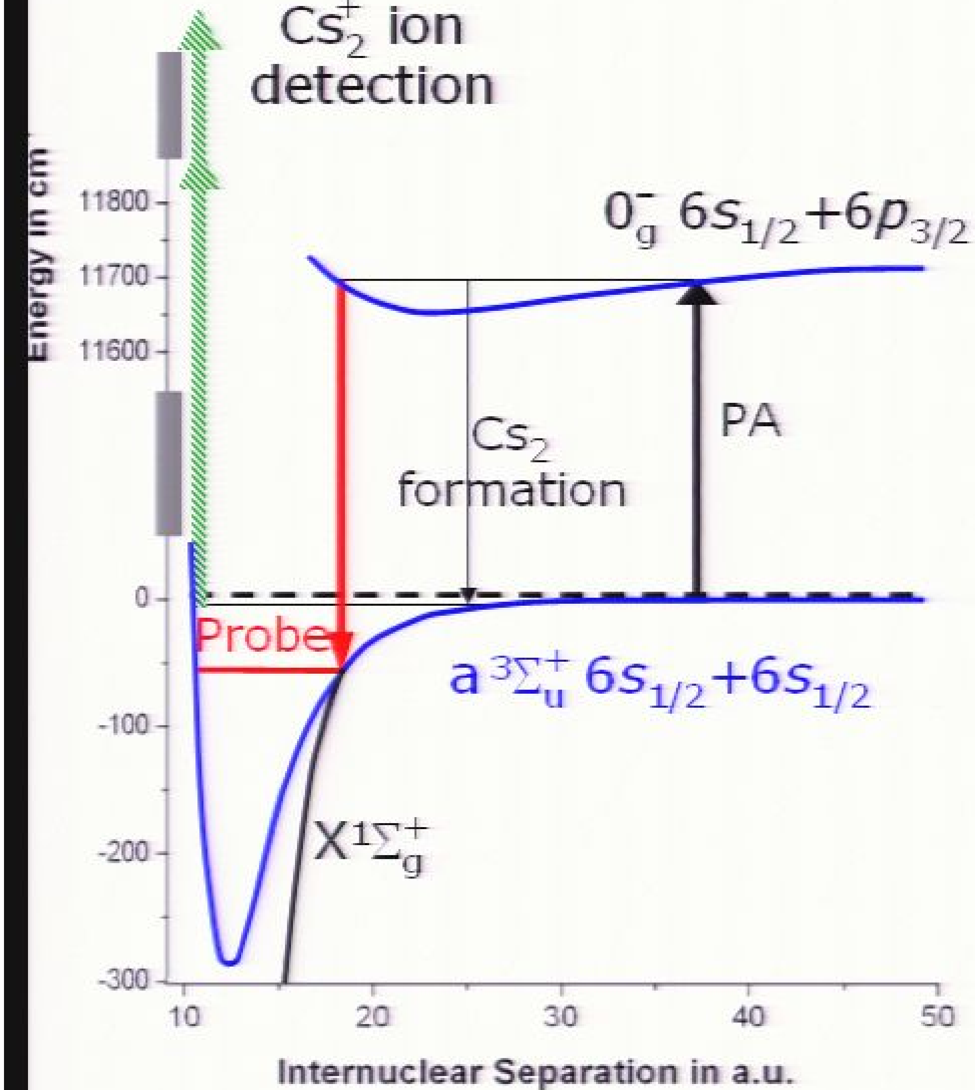


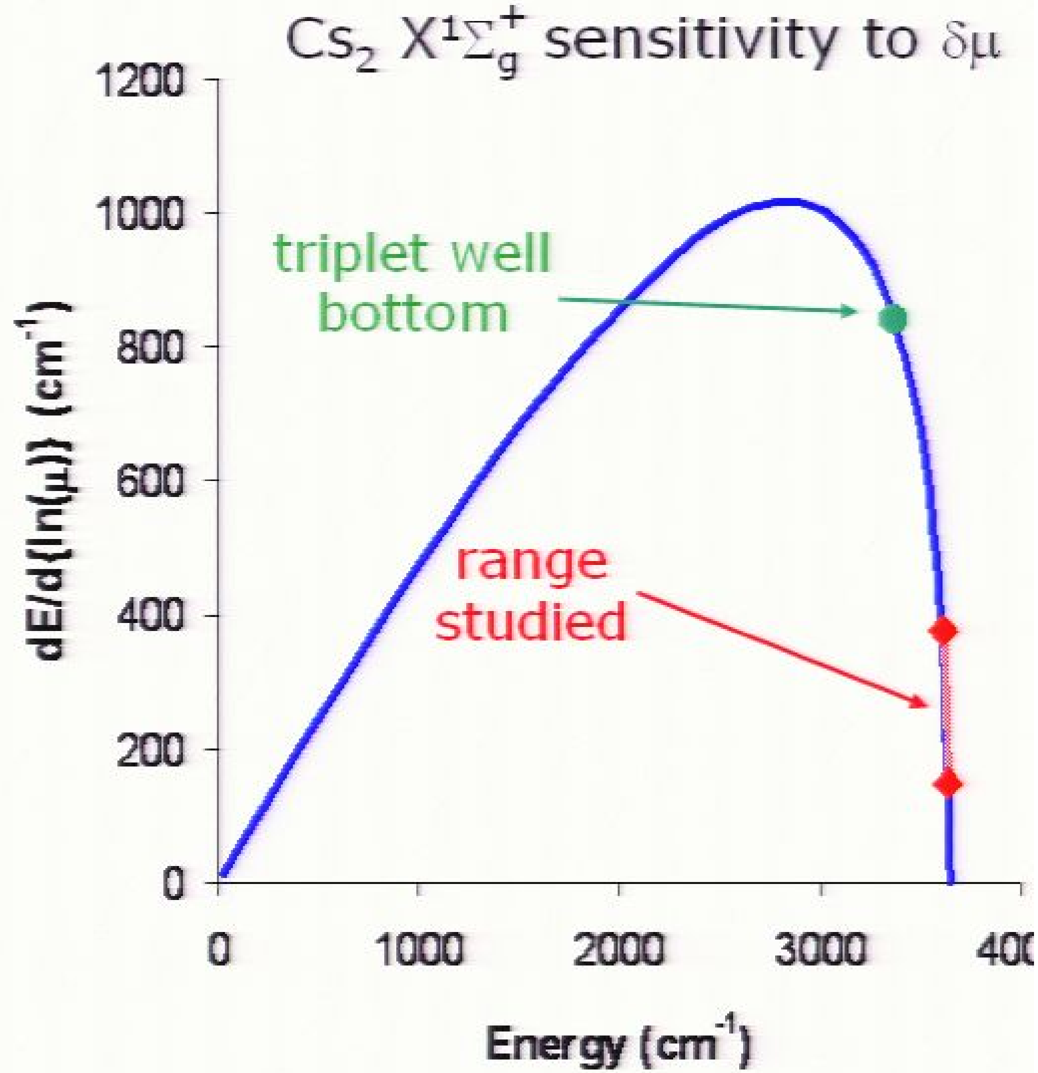
Two-color PA spectroscopy of Cs_2





Two-color PA spectroscopy of Cs_2

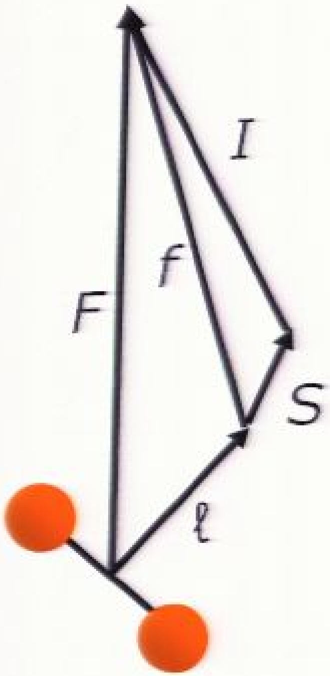


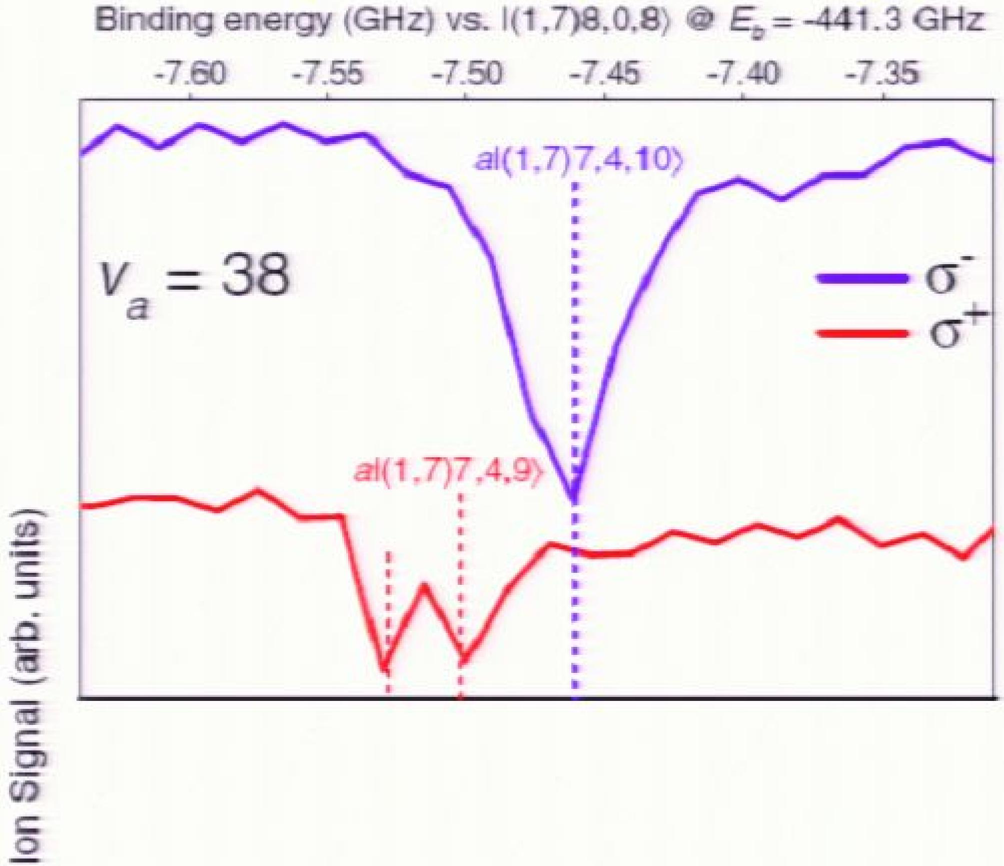


"Typical" abs. sensitivity $\delta\Delta$ ~ 0.01 Hz for $\delta\mu/\mu$ = 10^{-15}

$\Rightarrow$100-1000$\times$ improvement over current limits feasible?

Observation of singlet-triplet degeneracy in Cs_2

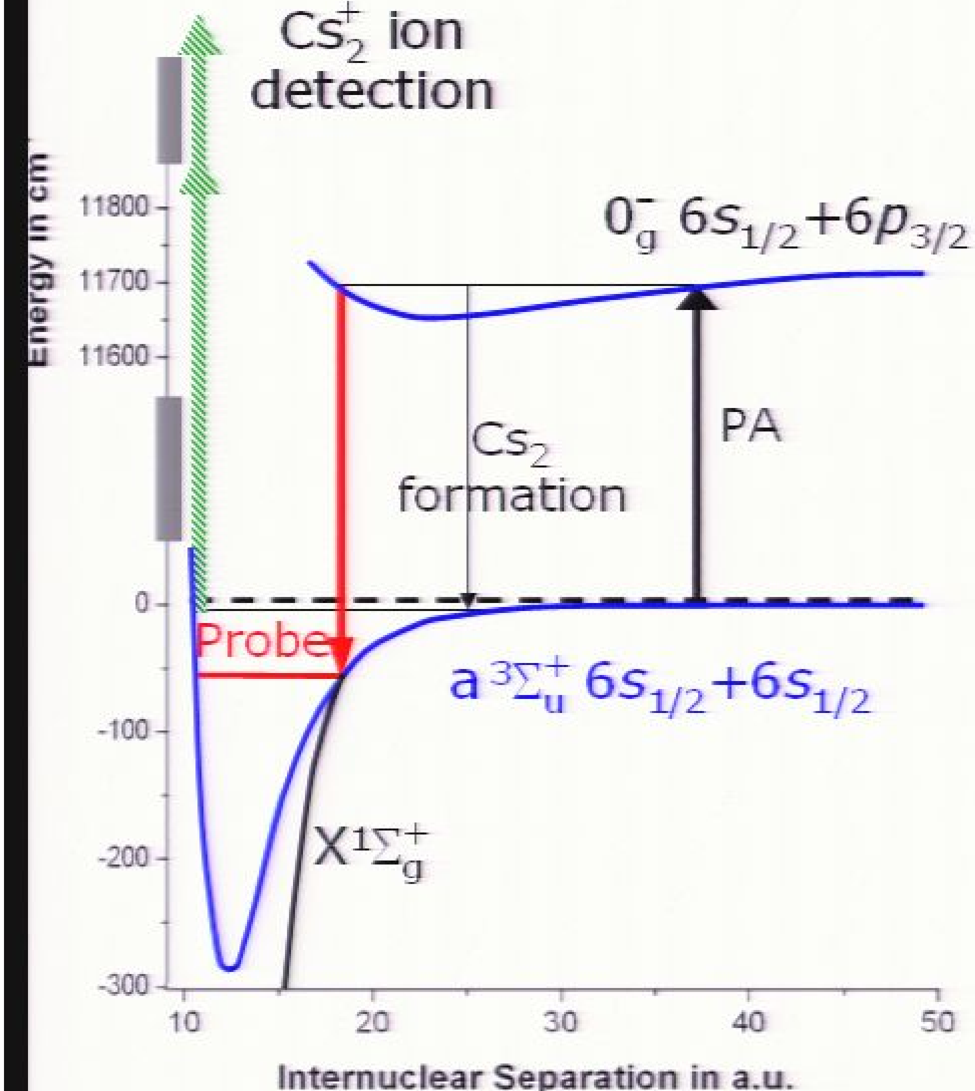


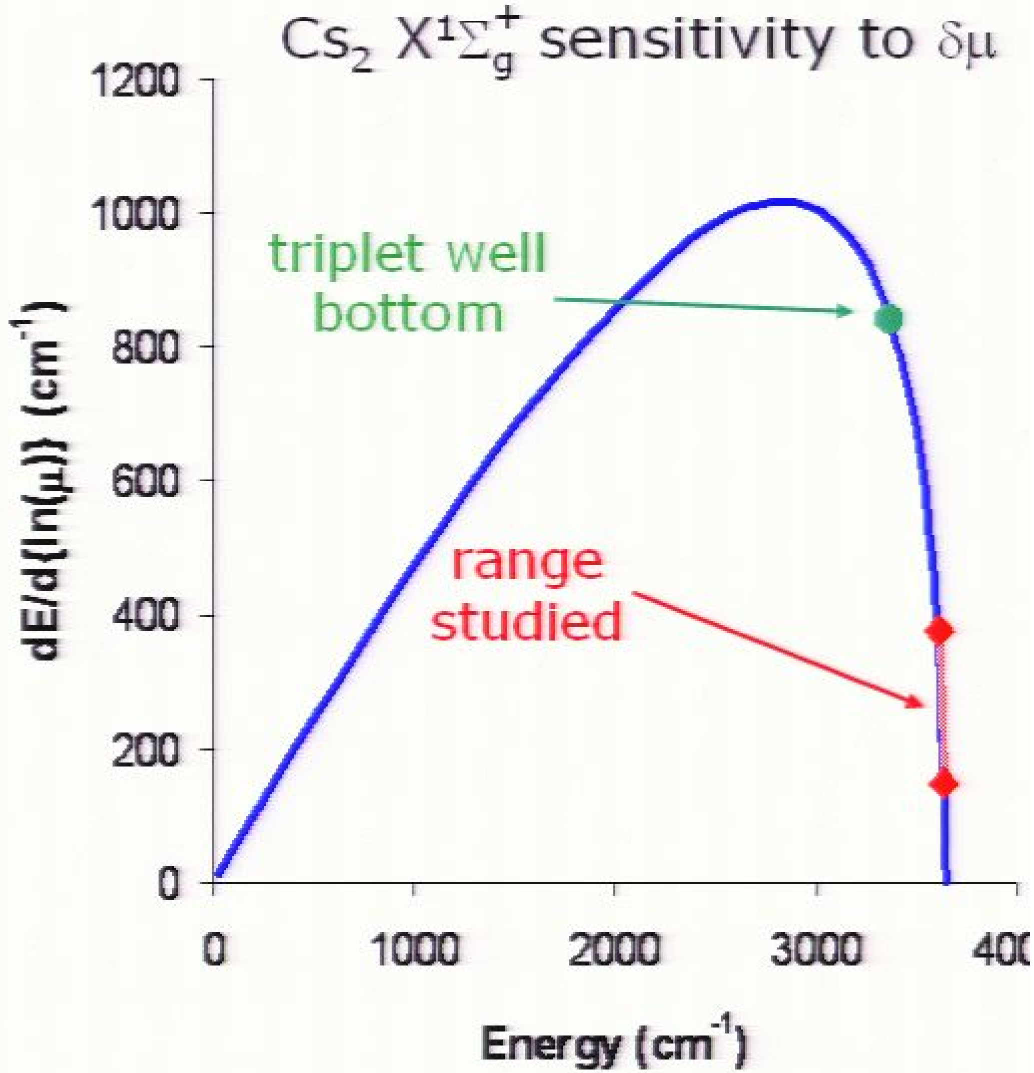


GHz bindin

Theory:
E. Tiesenga
T. Bergema

Two-color PA spectroscopy of Cs_2

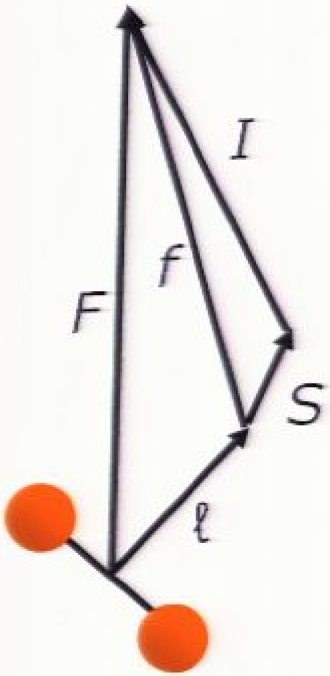


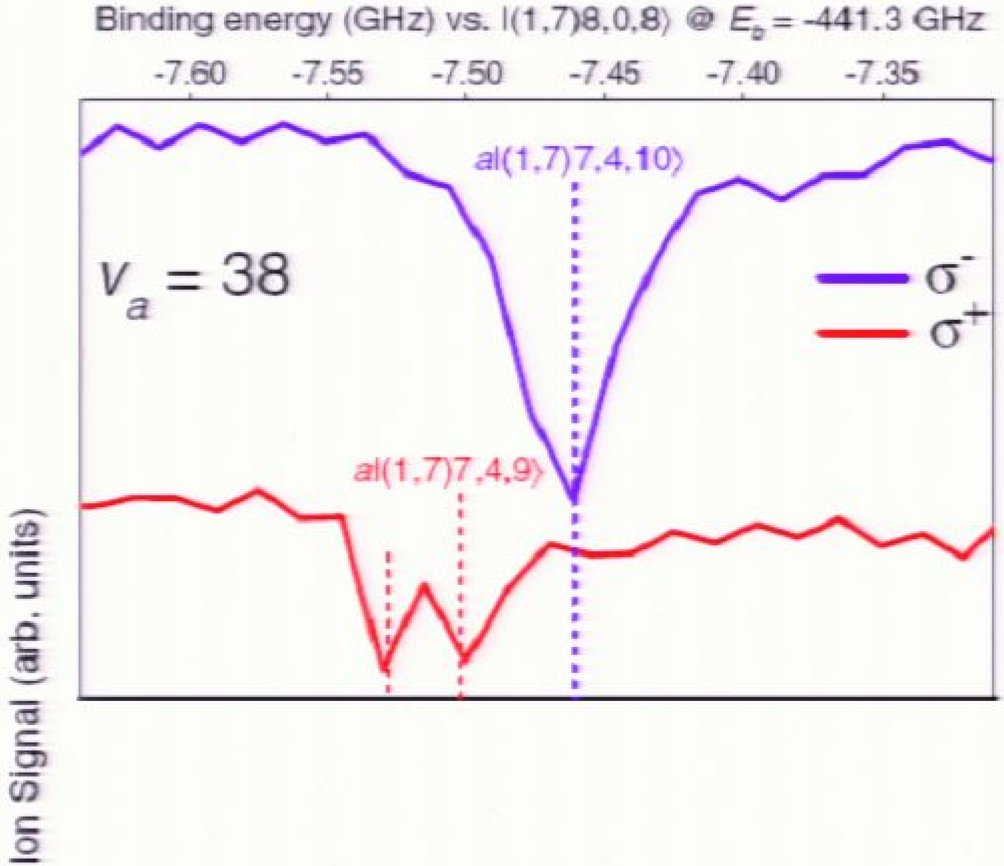


"Typical" abs. sensitivity $\delta\Delta \sim 0.01$ Hz for $\delta\mu/\mu = 10^{-15}$

$\Rightarrow$100-1000$\times$ improvement over current limits feasible?

Observation of singlet-triplet degeneracy in Cs_2

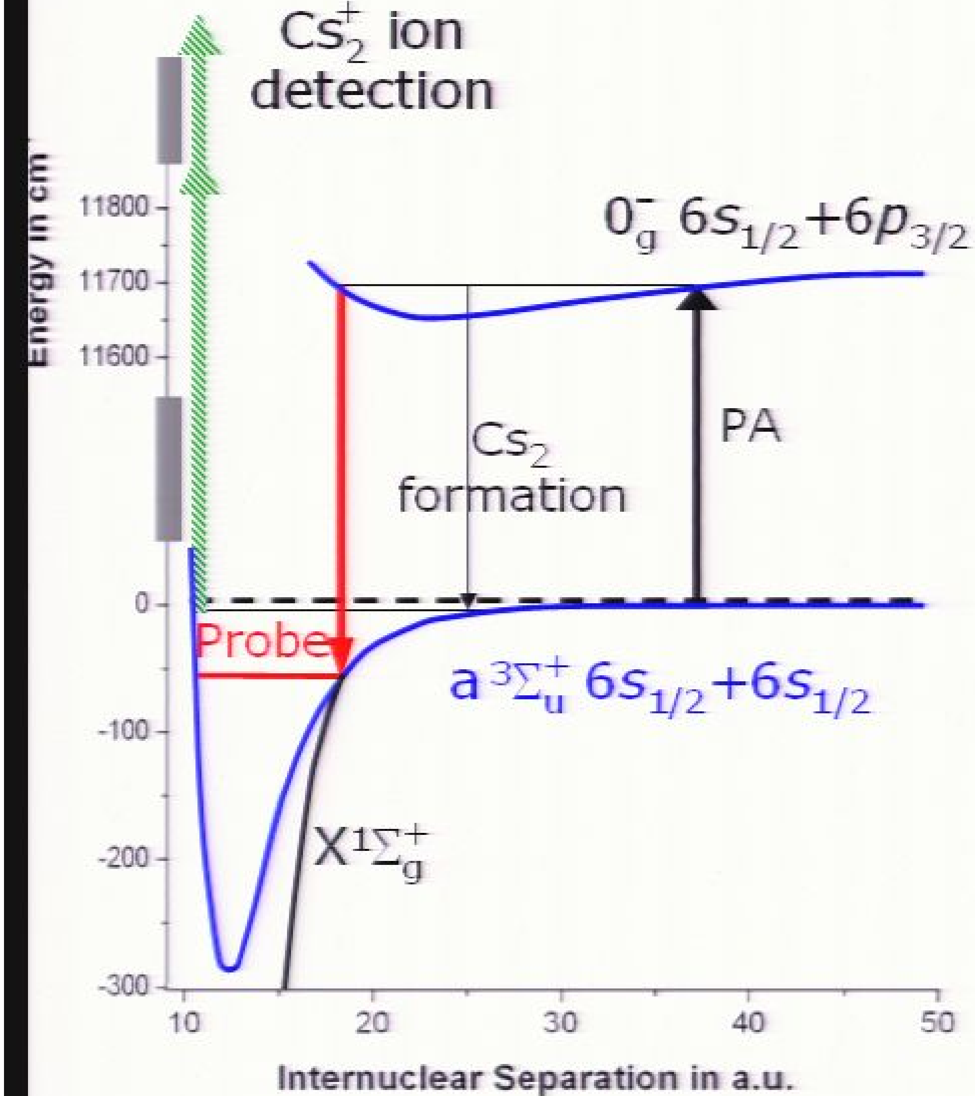


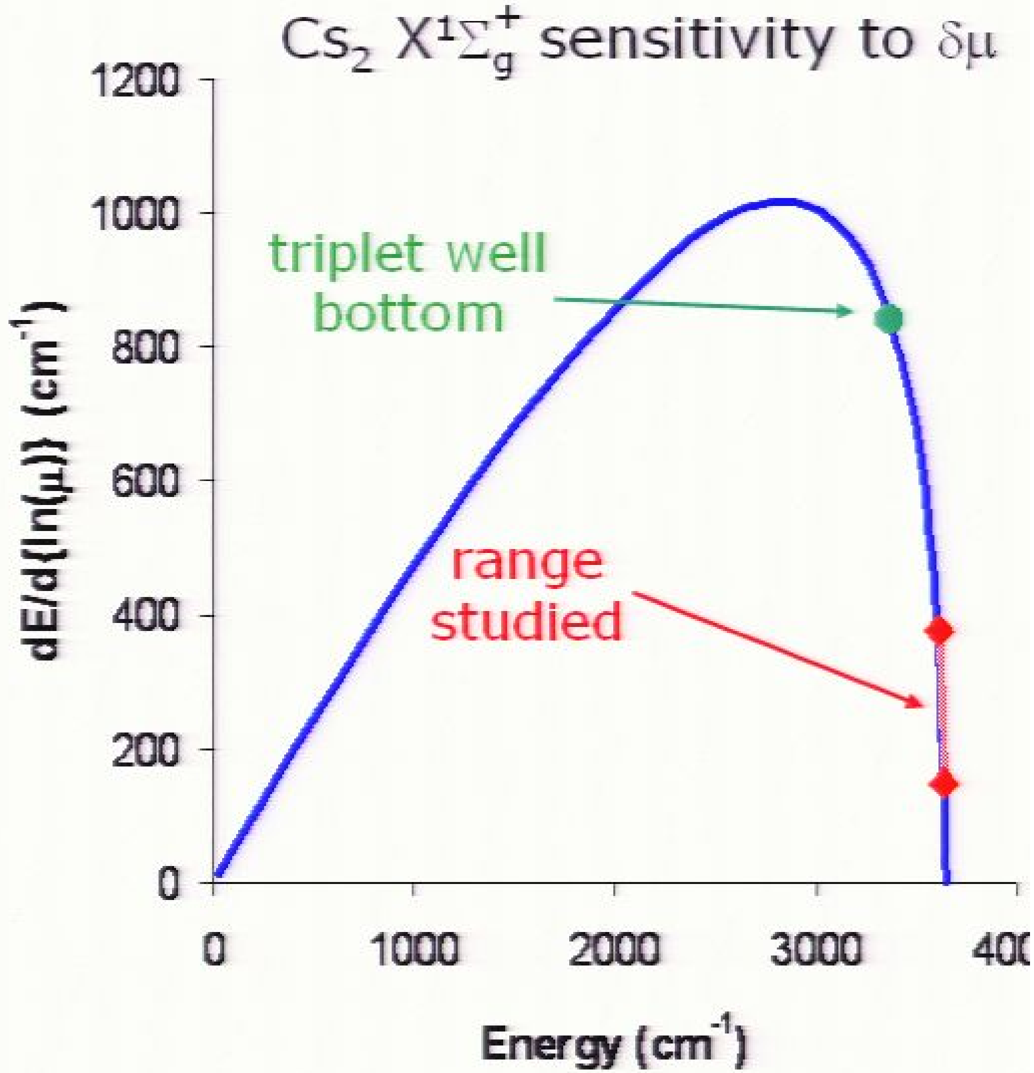


GHz bindin

Theory:
E. Tiesenga
T. Bergema

Two-color PA spectroscopy of Cs_2

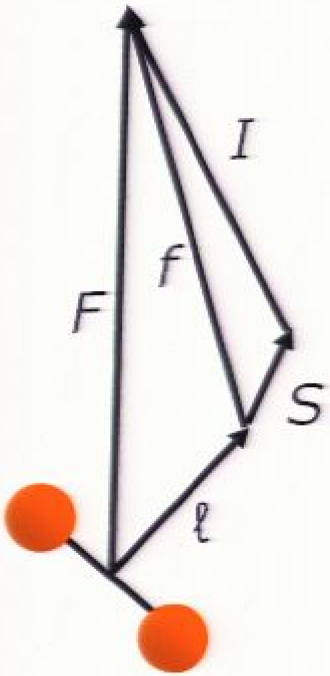


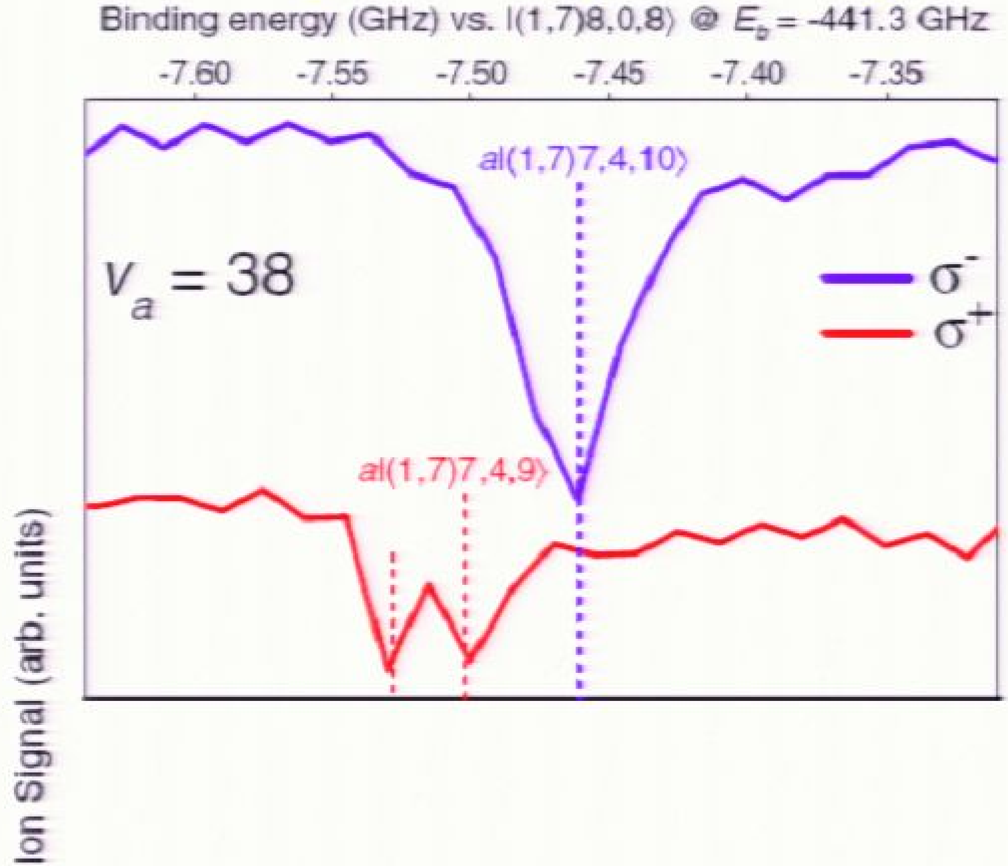


"Typical" abs. sensitivity $\delta\Delta \sim 0.01$ Hz for $\delta\mu/\mu = 10^{-15}$

$\Rightarrow$100-1000$\times$ improvement over current limits feasible?

Observation of singlet-triplet degeneracy in Cs_2



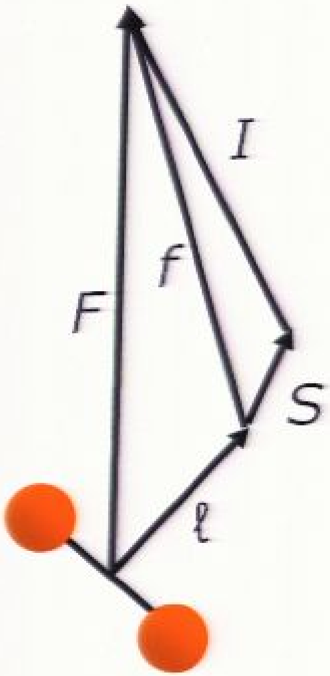


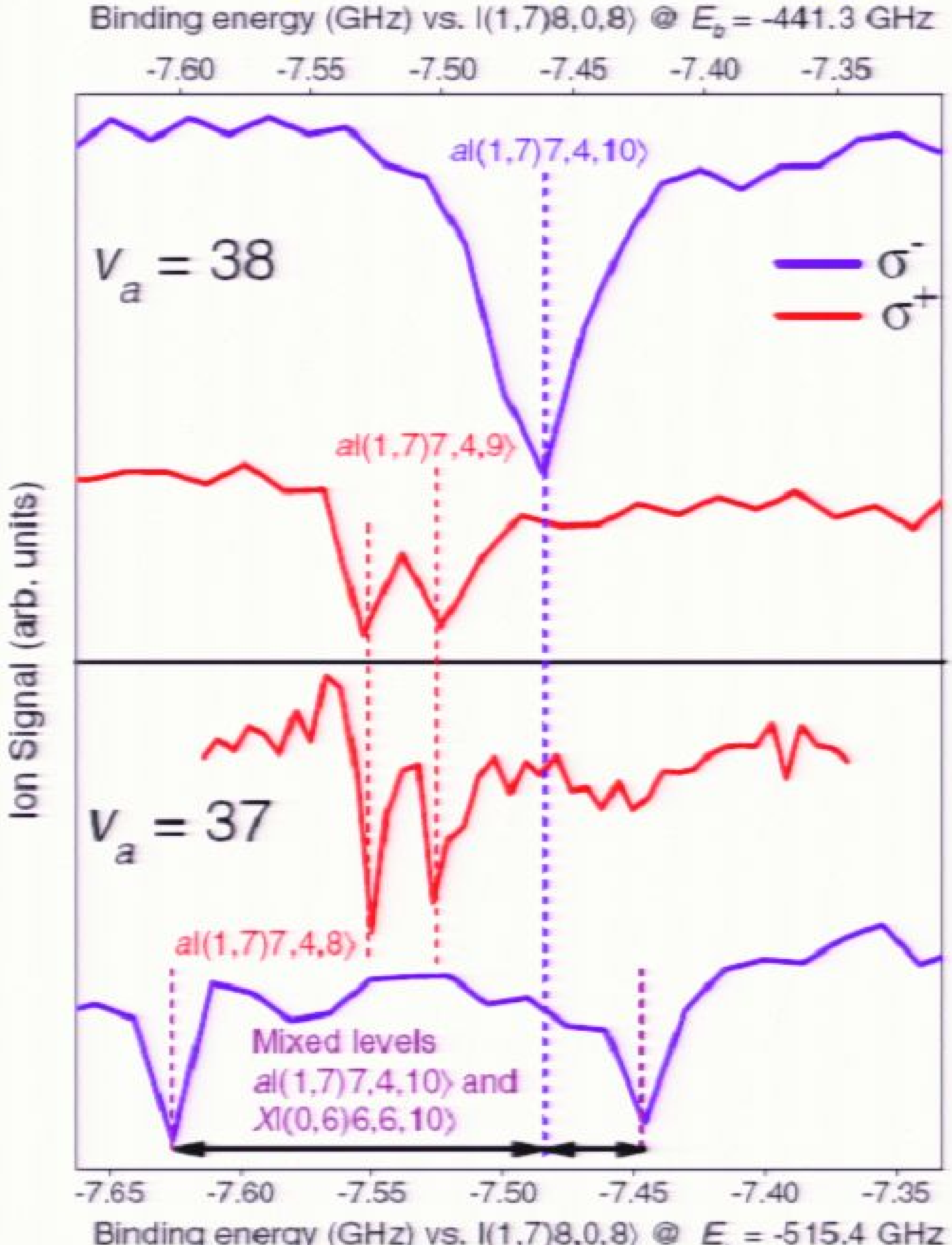
C
C

GHz bindin

Theory:
E. Tiesenga
T. Bergema

Observation of singlet-triplet degeneracy in Cs_2





C

C

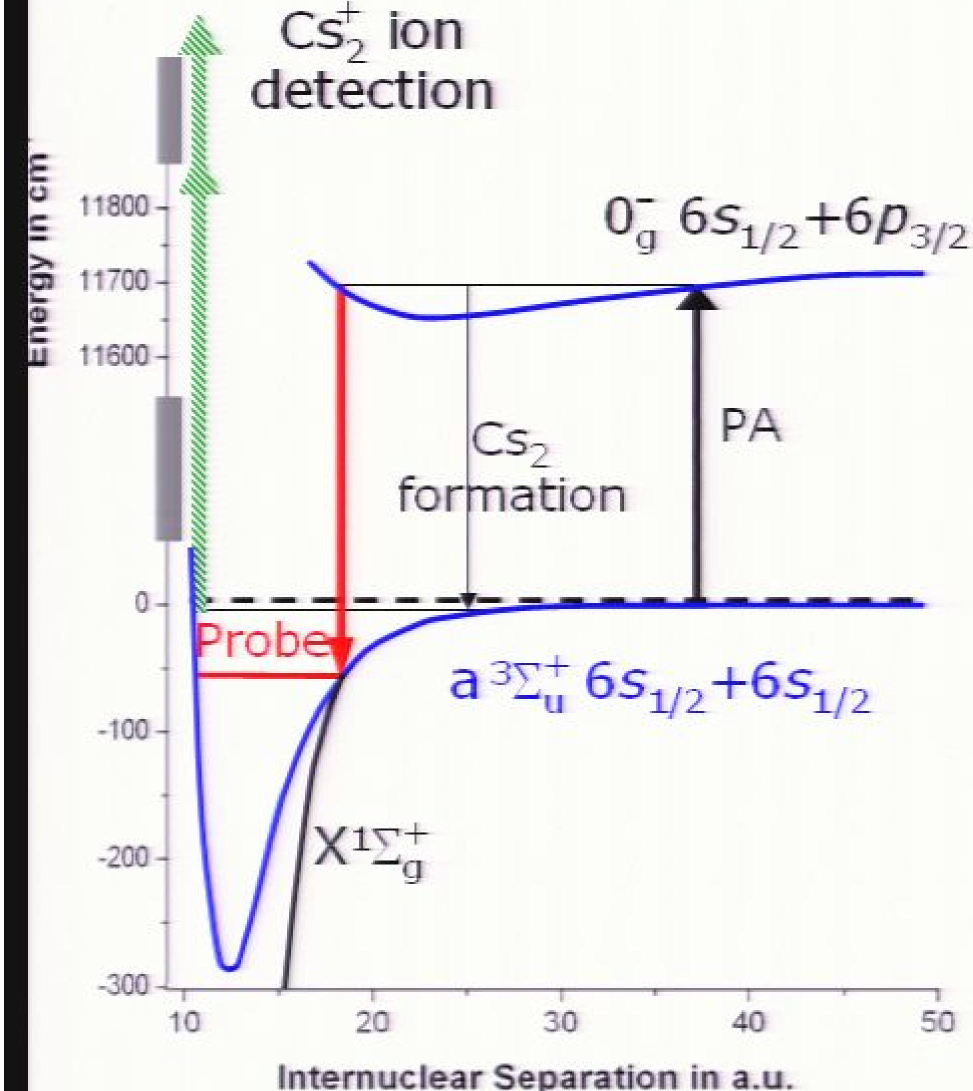
GHz bindin

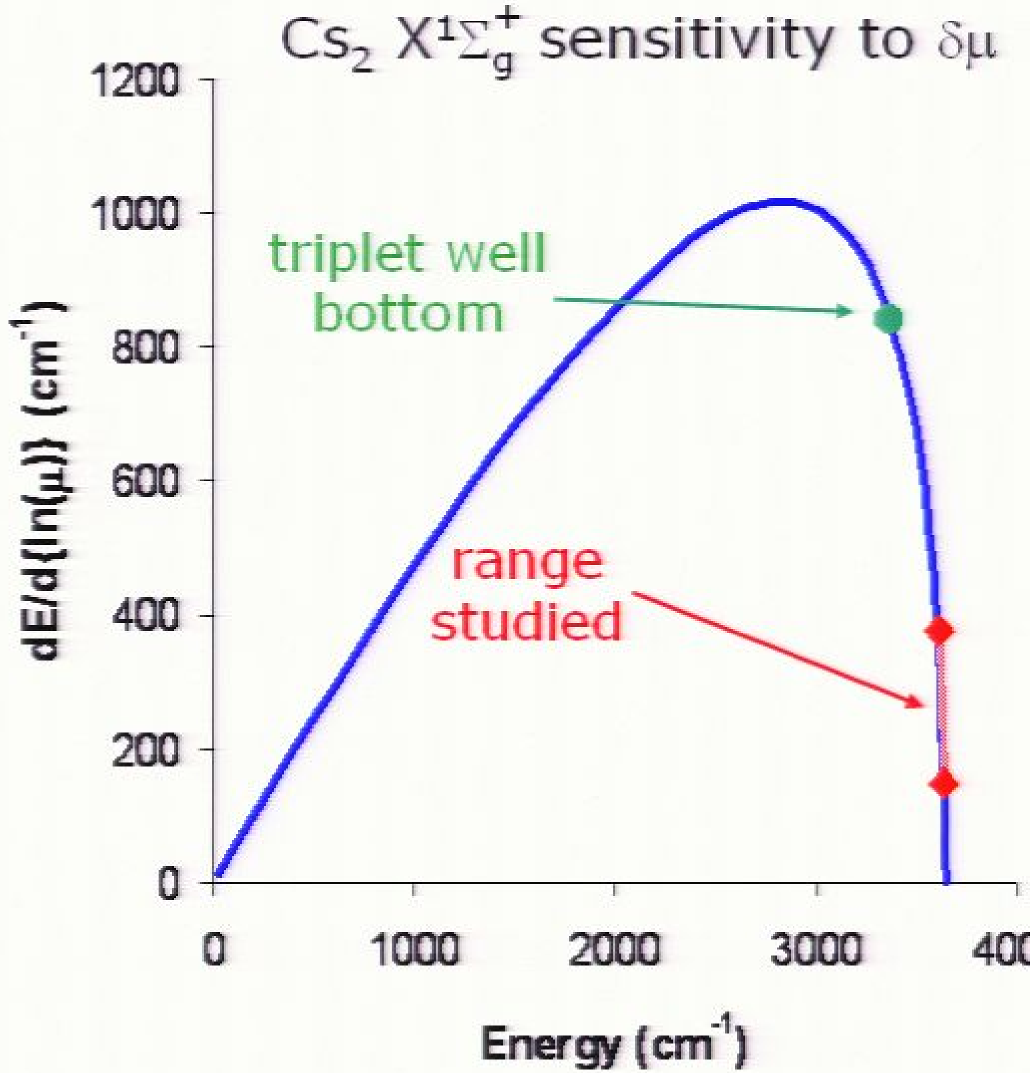
Theory:

E. Tiesenga

T. Bergema

Two-color PA spectroscopy of Cs_2

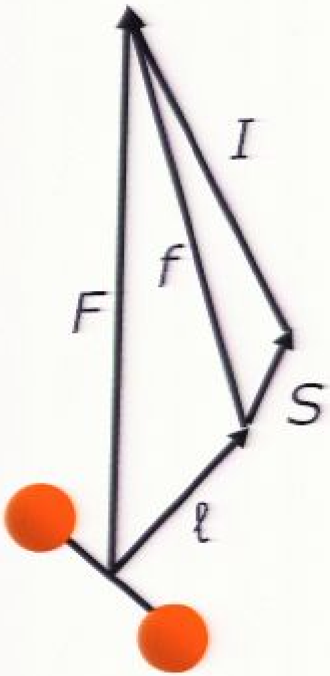


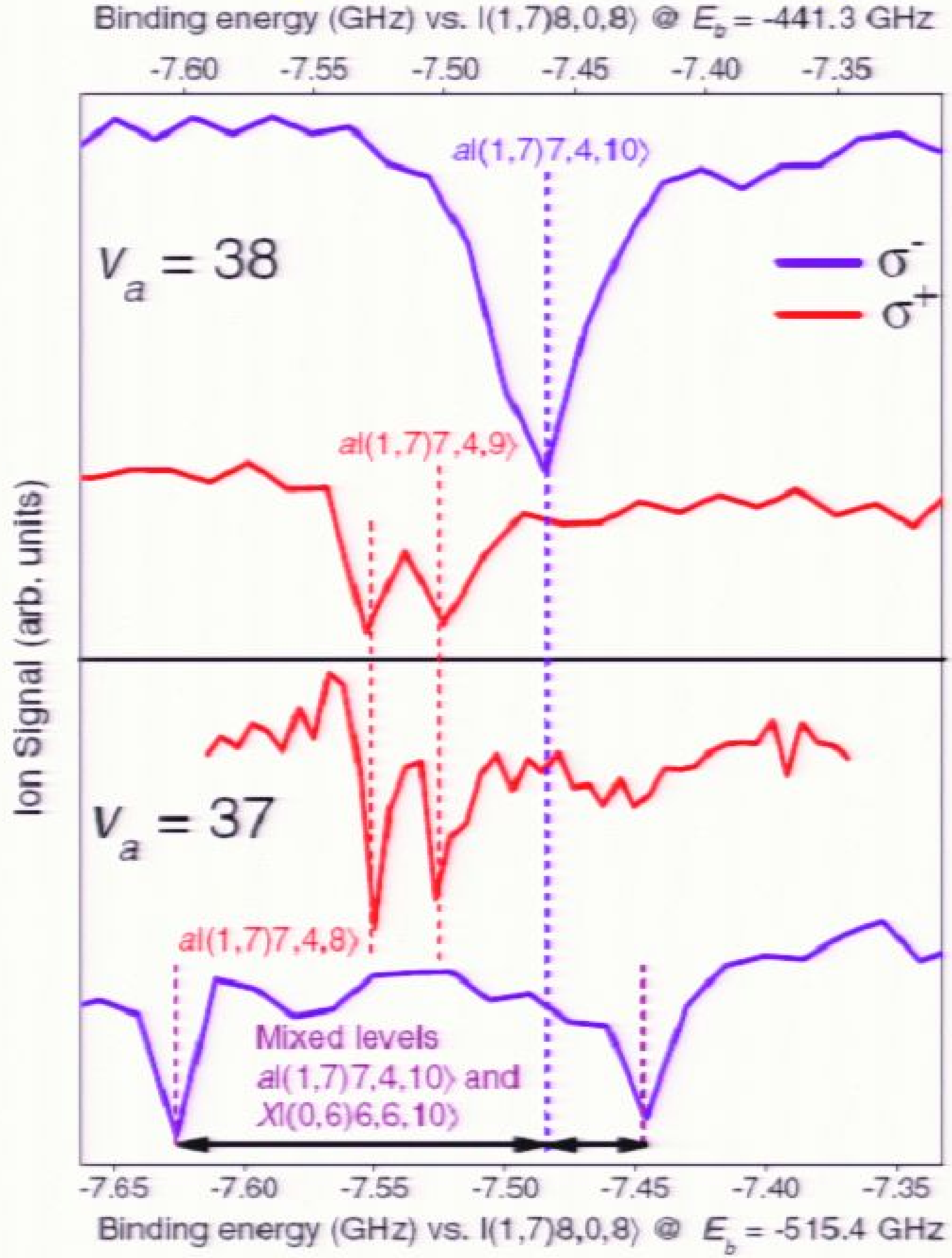


"Typical" abs. sensitivity $\delta\Delta \sim 0.01$ Hz for $\delta\mu/\mu = 10^{-15}$

$\Rightarrow$100-1000× improvement over current limits feasible?

Observation of singlet-triplet degeneracy in Cs_2





C
C

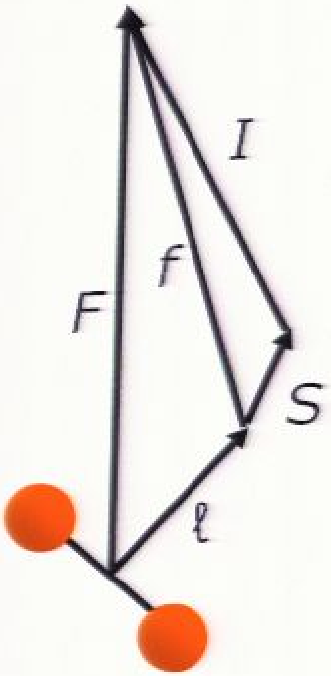
GHz bindin

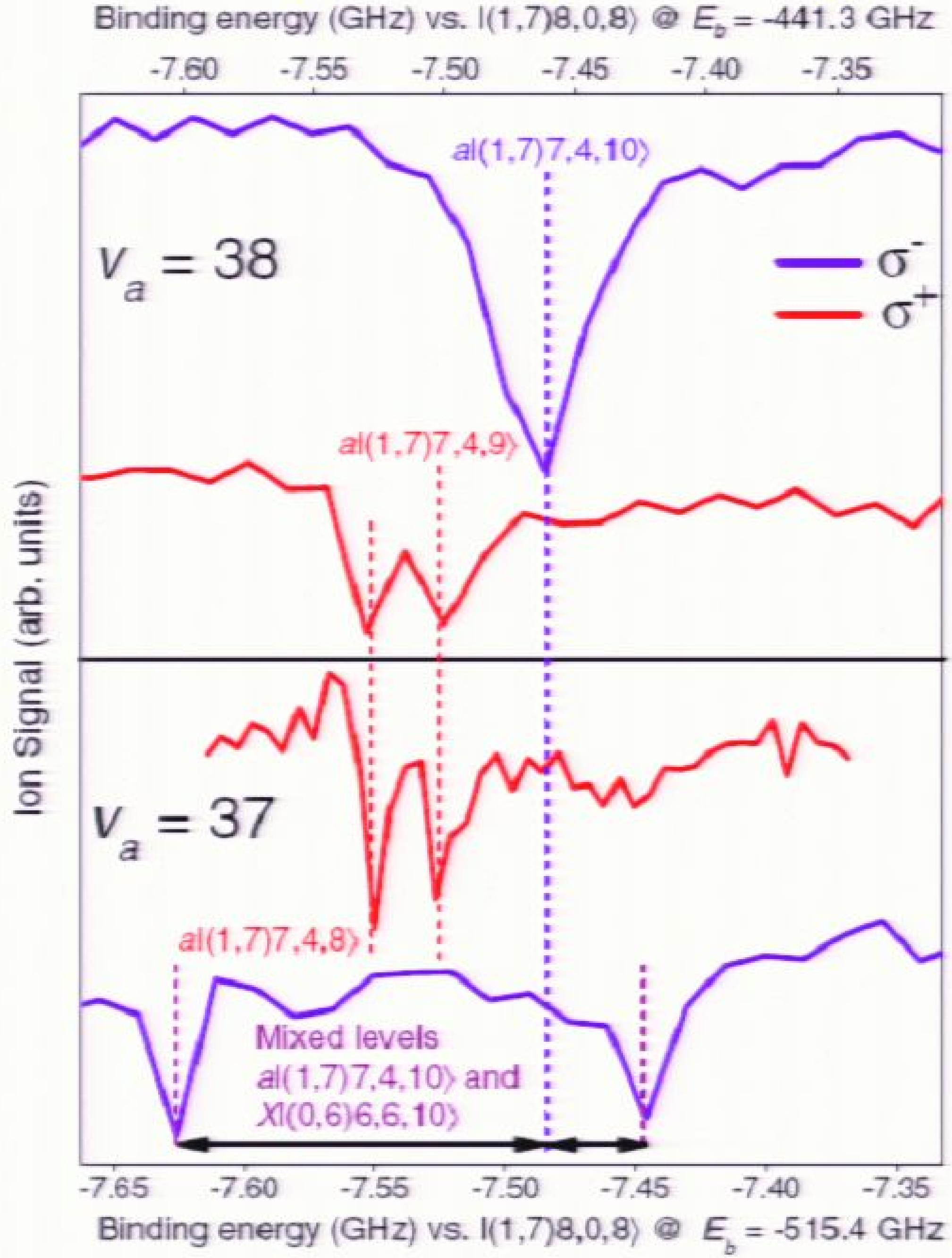
Theory:
E. Tiesenga
T. Bergema

Summary and outlook

- Experimentally identified near degeneracy between hyperfine levels of $(v = 138)X^1\Sigma^+_g$ and $(v = 37)a^3\Sigma^+_u$

Observation of singlet-triplet degeneracy in Cs_2





C

C

GHz bindin

Theory:

E. Tiesenga

T. Bergema

Summary and outlook

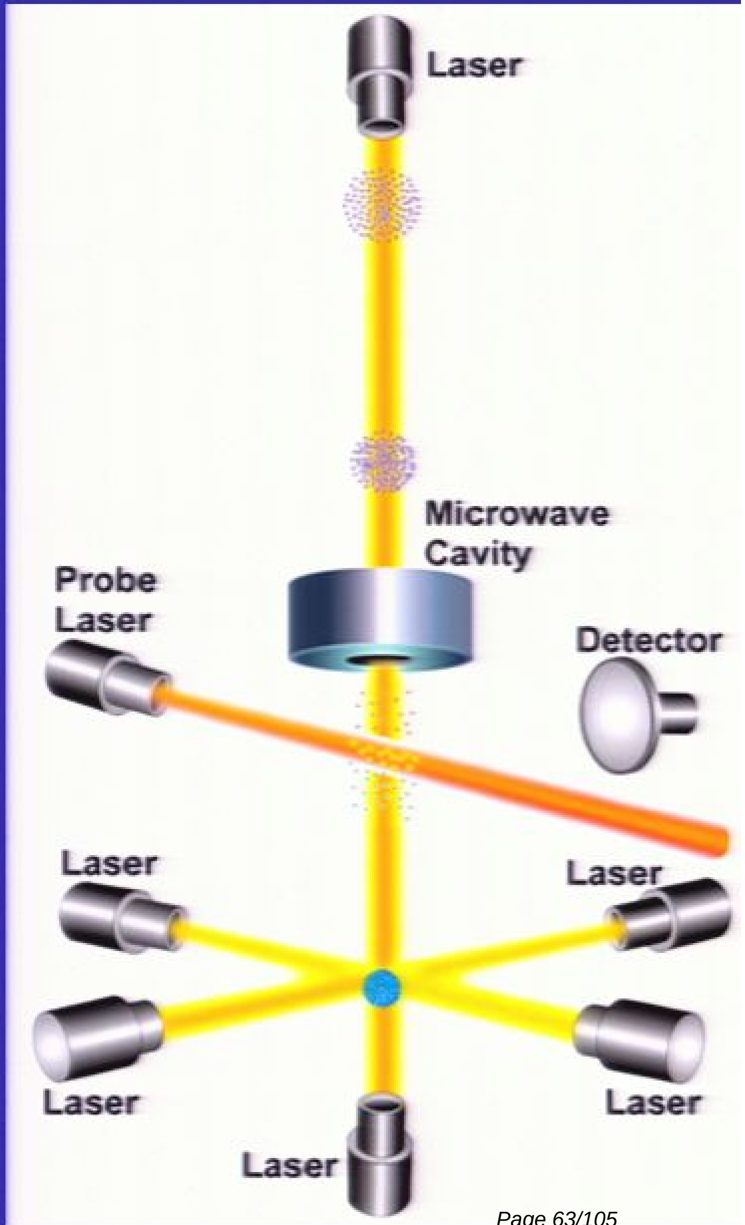
- Experimentally identified near degeneracy between hyperfine levels of $(v = 138)X^1\Sigma^+_g$ and $(v = 37)a^3\Sigma^+_u$

Summary and outlook

- Experimentally identified near degeneracy between hyperfine levels of $(v = 138)X^1\Sigma^+_g$ and $(v = 37)a^3\Sigma^+_u$
- From model predicted two other viable transitions (one at 9.8 GHz)

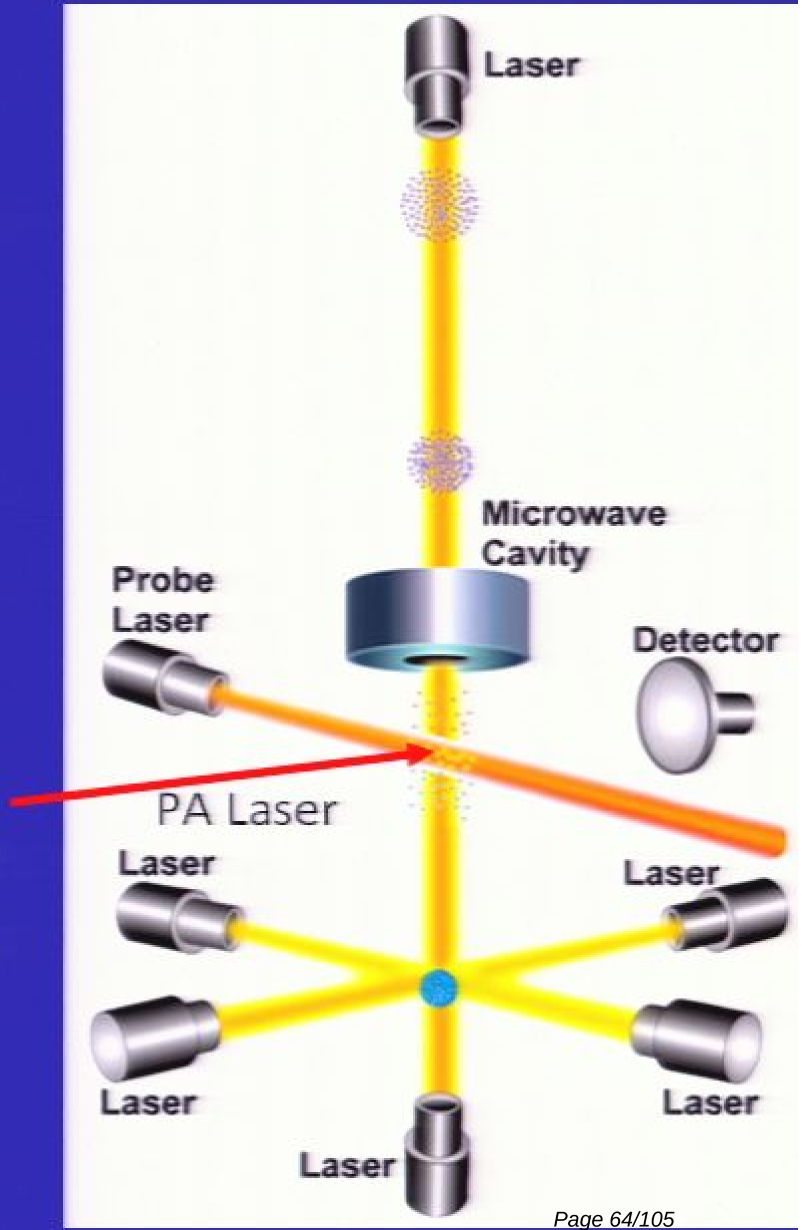
Summary and outlook

- Experimentally identified near degeneracy between hyperfine levels of $(v = 138)X^1\Sigma^+_g$ and $(v = 37)a^3\Sigma^+_u$
- From model predicted two other viable transitions (one at 9.8 GHz)



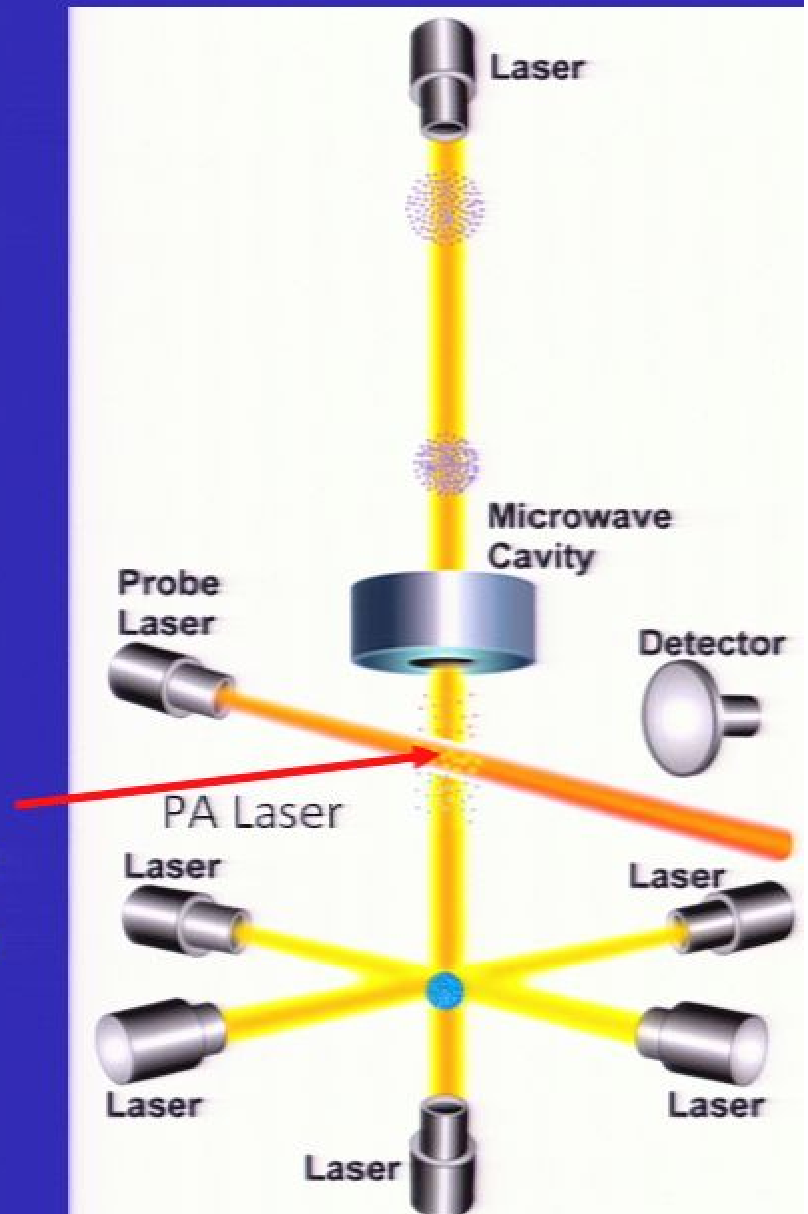
Summary and outlook

- Experimentally identified near degeneracy between hyperfine levels of $(v = 138)X^1\Sigma^+_g$ and $(v = 37)a^3\Sigma^+_u$
- From model predicted two other viable transitions (one at 9.8 GHz)
- With fountain apparatus could achieve $\delta(\Delta\mu/\mu) < 10^{-17}$ in 1 day of integration



Summary and outlook

- Experimentally identified near degeneracy between hyperfine levels of $(v = 138)X^1\Sigma^+_g$ and $(v = 37)a^3\Sigma^+_u$
- From model predicted two other viable transitions (one at 9.8 GHz)
- With fountain apparatus could achieve $\delta(\Delta\mu/\mu) < 10^{-17}$ in 1 day of integration



^{229}Th nucleus: Solid-state optical frequency standard and fundamental constant variation

UCLA

- Introduction (motivation)
  - Solid-state optical frequency standard
  - Dependence on constants
  - Outlook

- Experimental Progress
  - Crystal characterization

Collaborators:
Dave DeMille
Craig Taatjes
Steve Lamoreaux
Amar Vutha

Introduction

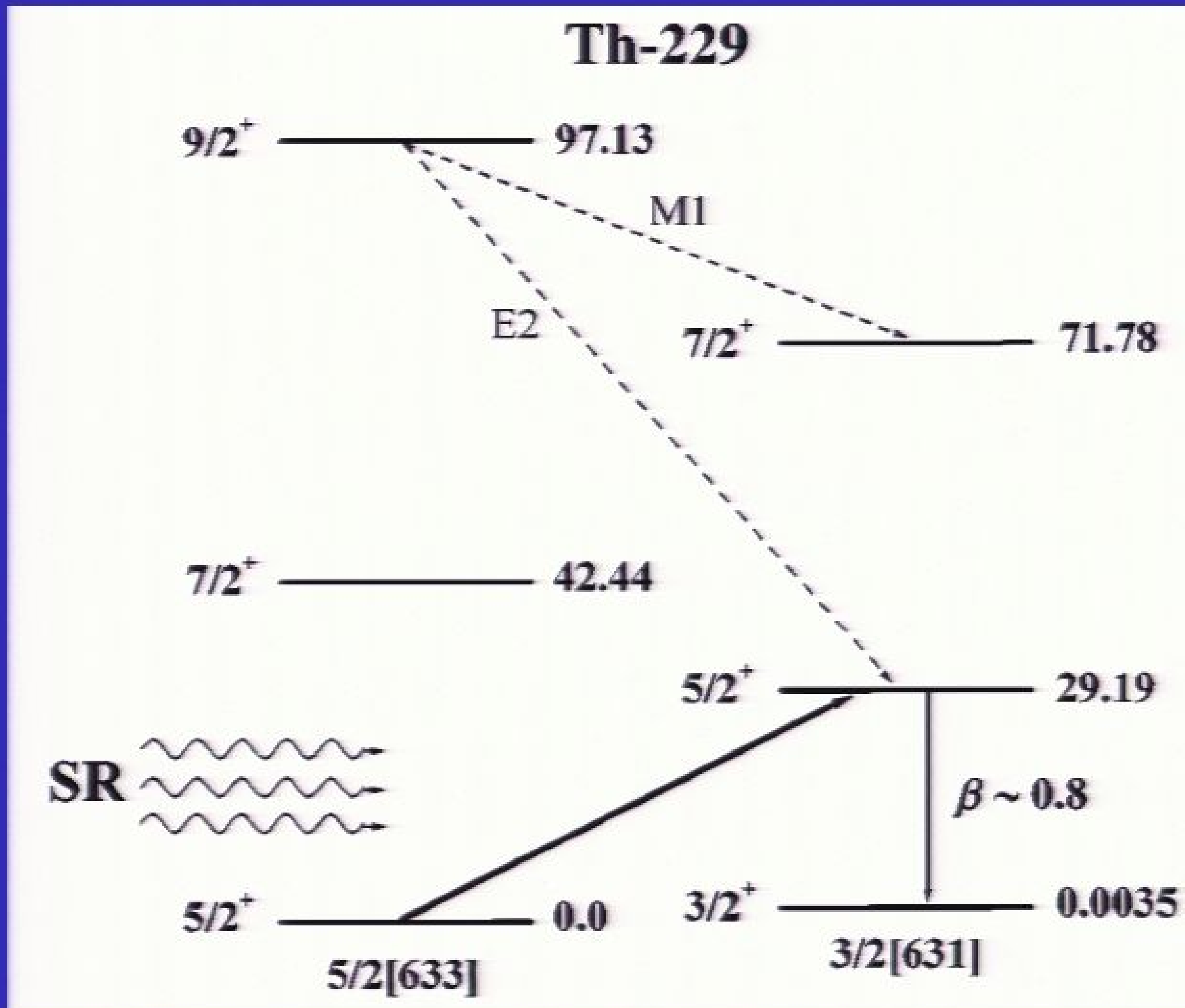


Figure taken from PRC **61** 064308

Introduction

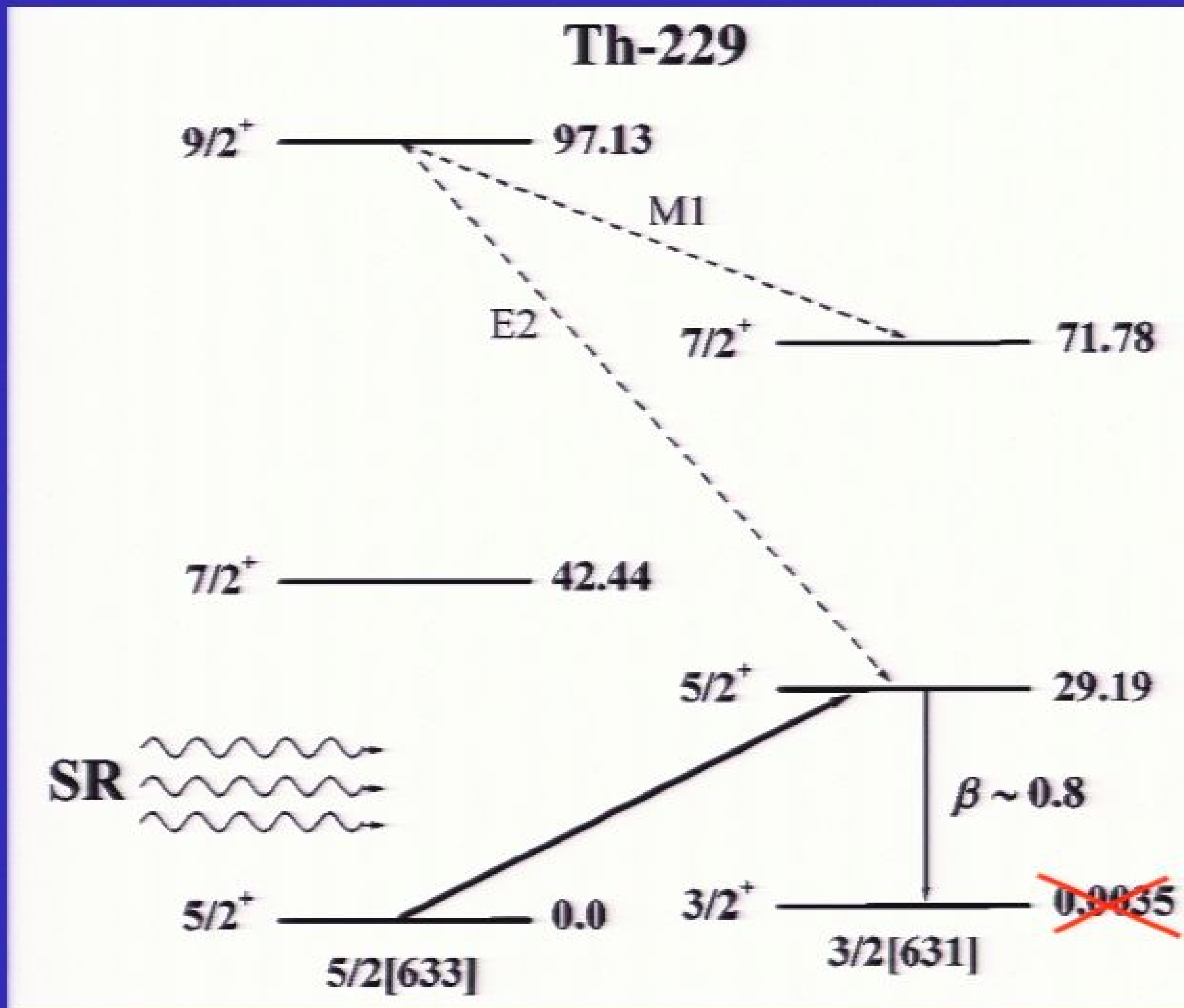


Figure taken from PRC **61** 064308

$\lambda = \{ \begin{matrix} 7.6 \text{ eV} \\ 165 \text{ nm} \end{matrix}$

$\Gamma = 10\ \mu\text{Hz}$

$Q \sim 10^{20}$

Introduction

Laser "Mössbauer" Spectroscopy

Introduction

Laser "Mössbauer" Spectroscopy

↓

Nuclei relatively insensitive to environment

Introduction

Laser “Mössbauer” Spectroscopy

↓

Nuclei relatively insensitive to environment

↓

Dope ^{229}Th into VUV transparent crystal

Introduction

Laser "Mössbauer" Spectroscopy

↓

Nuclei relatively insensitive to environment

↓

Dope ^{229}Th into VUV transparent crystal

- Lamb-Dicke regime (no Doppler or recoil)
- Mössbauer spectroscopy has told us what to expect
- High-density

Introduction

Laser "Mössbauer" Spectroscopy

↓

Nuclei relatively insensitive to environment

↓

Dope ^{229}Th into VUV transparent crystal

- Lamb-Dicke regime (no Doppler or recoil)
- Mössbauer spectroscopy has told us what to expect
- High-density

Solid-state optical frequency standard?

Introduction

Laser "Mössbauer" Spectroscopy

↓

Nuclei relatively insensitive to environment

↓

Dope ^{229}Th into VUV transparent crystal

- Lamb-Dicke regime (no Doppler or recoil)
- Mössbauer spectroscopy has told us what to expect
- High-density

Solid-state optical frequency standard?

NIST – F1

Introduction

Solid-state optical frequency standard

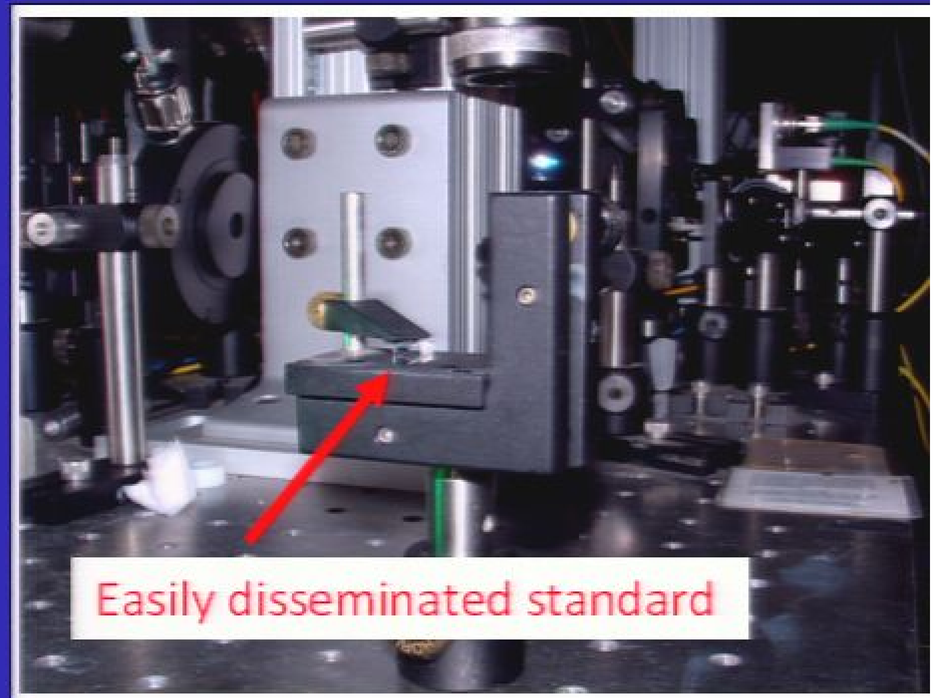
Laser "Mössbauer" Spectroscopy

↓

Nuclei relatively insensitive to environment

↓

Dope ^{229}Th into VUV transparent crystal



- Lamb-Dicke regime (no Doppler or recoil)
- Mössbauer spectroscopy has told us what to expect
- High-density

Solid-state optical frequency standard?

Sensitivity to constants

$\delta\omega/\omega \approx 2(10^5)\ (\ 0.02\ \delta\alpha/\alpha + 0.4\ \delta m_q/m_q - 5\ \delta m_s/m_s)$

X. He and Z. Ren, J. Phys. G: Nucl. Part. Phys. 34 1611 (2007).

NB: $\delta\omega/\omega$ not so important → $\delta\omega$, Γ, or $\delta\omega/\Gamma$

Introduction

Laser "Mössbauer" Spectroscopy

↓

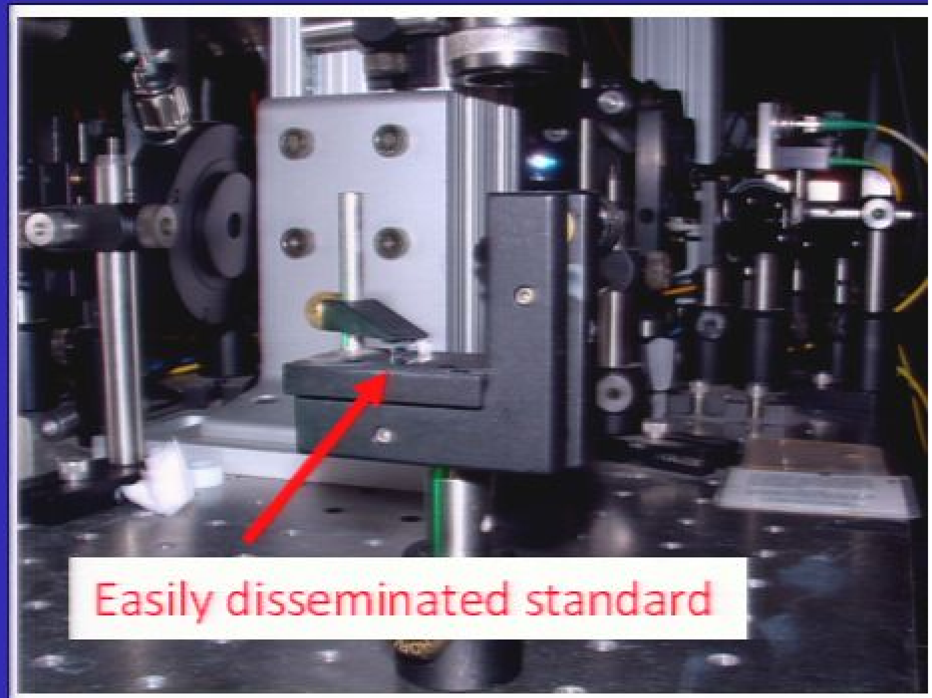
Nuclei relatively insensitive to environment

↓

Dope ^{229}Th into VUV transparent crystal

- Lamb-Dicke regime (no Doppler or recoil)
- Mössbauer spectroscopy has told us what to expect
- High-density

Solid-state optical frequency standard



Solid-state optical frequency standard?

Sensitivity to constants

$\delta\omega/\omega \approx 2(10^5)\ (\ 0.02\ \delta\alpha/\alpha + 0.4\ \delta m_q/m_q - 5\ \delta m_s/m_s)$

X. He and Z. Ren, J. Phys. G: Nucl. Part. Phys. 34 1611 (2007).

NB: $\delta\omega/\omega$ not so important → $\delta\omega$, Γ, or $\delta\omega/\Gamma$

Sensitivity to constants

$\delta\omega/\omega \approx 2(10^5)\,(0.02\,\delta\alpha/\alpha + 0.4\,\delta m_q/m_q - 5\,\delta m_s/m_s)$

X. He and Z. Ren, J. Phys. G: Nucl. Part. Phys. 34 1611 (2007).

NB: $\delta\omega/\omega$ not so important → $\delta\omega$, Γ, or $\delta\omega/\Gamma$

$\delta\omega \approx 1.4\text{ MeV}\,(0.02\,\delta\alpha/\alpha + 0.4\,\delta m_q/m_q - 5\,\delta m_s/m_s)$

Sensitivity to constants

$\delta\omega/\omega \approx 2(10^5)\,(\,0.02\,\delta\alpha/\alpha + 0.4\,\delta m_q/m_q - 5\,\delta m_s/m_s)$

X. He and Z. Ren, J. Phys. G: Nucl. Part. Phys. 34 1611 (2007).

NB: $\delta\omega/\omega$ not so important → $\delta\omega$, Γ, or $\delta\omega/\Gamma$

$\delta\omega \approx 1.4\text{ MeV}\,(\,0.02\,\delta\alpha/\alpha + 0.4\,\delta m_q/m_q - 5\,\delta m_s/m_s)$

i.e., $\delta\alpha/\alpha = 10^{-17}$ → $\delta\omega = 3$ kHz!

$\delta\omega/\Gamma \sim 10^6$

Outlook

Oscillator	Primary Cs Standard	Hg+ Ion Clock	Sr Lattice Clock	^{229}Th Nuclear Clock
Group	NIST	NIST	JILA	UCLA
Transition frequency	9.2 GHz	1064 THz	430 THz	1800 THz
Transition natural linewidth	~0	1.6 Hz	10 mHz	~10 μHz
Actual linewidth (source of broadening)	1 Hz (time of flight)	1.6 Hz	300 mHz (laser)	3 Hz (magnetic)
Q	10^{10}	10^{15}	10^{15}	10^{15}
Number of Oscillators (N)	10^{8}	1	4000	10^{18}
$F = QN^{1/2}/ (Q_{Cs}N_{Cs}{}^{1/2})$	1	40	630	10^{10}
Clock fractional statistical uncertainty	$4X10^{-16}$	$2X10^{-17}$	$1X10^{-18}$*	$\geq 10^{-25}$ (predicted)
Intrinsic sensitivity to alpha: $\delta\omega = K\ \delta\alpha/\alpha$; K [Hz]	$3X10^{10}$ Hz	$3X10^{15}$ Hz	$3X10^{12}$ Hz	$7X10^{18}$ Hz
α sensitivity statistical figure of merit = $(\delta\alpha/\alpha\ Q\ N^{1/2})/ (\delta\alpha/\alpha\ Q\ N^{1/2})$	1	$4X10^{6}$	$6X10^{4}$	10^{18}
$d\alpha/dt$ sensitivity in 1 year	----	$2.3X10^{-17}\ yr^{-1}$	$3X10^{-16}\ yr^{-1}$	$4X10^{-19}\ yr^{-1}$ (predicted)
Reference:	28	8	7	

Table II. Comparison of the ^{229}Th Nuclear Clock to the primary Cs standard as well as the next generation optical standards.

*based on the quantum projection noise limit ~ $7X10^{-16}/\sqrt{\tau}$ Currently the Sr clock is at a fractional uncertainty of $1X10^{-17}$.

Outlook

Oscillator	Primary Cs Standard	Hg+ Ion Clock	Sr Lattice Clock	^{229}Th Nuclear Clock
Group	NIST	NIST	JILA	UCLA
Transition frequency	9.2 GHz	1064 THz	430 THz	1800 THz
Transition natural linewidth	~0	1.6 Hz	10 mHz	~10 μHz
Actual linewidth (source of broadening)	1 Hz (time of flight)	1.6 Hz	300 mHz (laser)	3 Hz (magnetic)
Q	10^{10}	10^{15}	10^{15}	10^{15}
Number of Oscillators (N)	10^{8}	1	4000	10^{18}
$F = QN^{1/2}/(Q_{Cs}N_{Cs}^{1/2})$	1	40	630	10^{10}
Clock fractional statistical uncertainty	$4X10^{-16}$	$2X10^{-17}$	$1X10^{-18*}$	$\geq 10^{-25}$ (predicted)
Intrinsic sensitivity to alpha: $\delta\omega = K\ \delta\alpha/\alpha$; K [Hz]	$3X10^{10}$ Hz	$3X10^{15}$ Hz	$3X10^{12}$ Hz	$7X10^{18}$ Hz
α sensitivity statistical figure of merit = $(\delta\alpha/\alpha\ Q\ N^{1/2})/(\delta\alpha/\alpha\ Q\ N^{1/2})$	1	$4X10^{6}$	$6X10^{4}$	10^{18}
$d\alpha/dt$ sensitivity in 1 year	----	$2.3X10^{-17}$ yr^{-1}	$3X10^{-16}$ yr^{-1}	$4X10^{-19}$ yr^{-1} (predicted)
Reference:	28	8	7	

Table II. Comparison of the ^{229}Th Nuclear Clock to the primary Cs standard as well as the next generation optical standards.

*based on the quantum projection noise limit ~ $7X10^{-16}/\sqrt{\tau}$ Currently the Sr clock is at a fractional uncertainty of $1X10^{-17}$.

Experimental Progress

- One viable crystal (so far):

Expect: $^{232}Th_{0.001}:Na_{0.4}Y_{0.6}F_{2.2}$

Th	Na	Y	F
.001	.396	.592	2.2

*Measured with e-beam microprobe

- Characterizing Crystals
  - NMR → Expected linewidt
  - VUV transmission (ALS)

Outlook

Oscillator	Primary Cs Standard	Hg+ Ion Clock	Sr Lattice Clock	^{229}Th Nuclear Clock
Group	NIST	NIST	JILA	UCLA
Transition frequency	9.2 GHz	1064 THz	430 THz	1800 THz
Transition natural linewidth	~0	1.6 Hz	10 mHz	~10 μHz
Actual linewidth (source of broadening)	1 Hz (time of flight)	1.6 Hz	300 mHz (laser)	3 Hz (magnetic)
Q	10^{10}	10^{15}	10^{15}	10^{15}
Number of Oscillators (N)	10^{8}	1	4000	10^{18}
$F = QN^{1/2}/(Q_{Cs}N_{Cs}^{1/2})$	1	40	630	10^{10}
Clock fractional statistical uncertainty	4×10^{-16}	2×10^{-17}	1×10^{-18}*	$\geq10^{-25}$ (predicted)
Intrinsic sensitivity to alpha: $\delta\omega = K\,\delta\alpha/\alpha$; K [Hz]	3×10^{10} Hz	3×10^{15} Hz	3×10^{12} Hz	7×10^{18} Hz
α sensitivity statistical figure of merit = $(\delta\alpha/\alpha\, Q\, N^{1/2})/(\delta\alpha/\alpha\, Q\, N^{1/2})$	1	4×10^{6}	6×10^{4}	10^{18}
$d\alpha/dt$ sensitivity in 1 year	----	2.3×10^{-17} yr^{-1}	3×10^{-16} yr^{-1}	4×10^{-19} yr^{-1} (predicted)
Reference:	28	8	7	

Table II. Comparison of the ^{229}Th Nuclear Clock to the primary Cs standard as well as the next generation optical standards.

*based on the quantum projection noise limit ~ $7\times10^{-16}/\sqrt{\tau}$ Currently the Sr clock is at a fractional uncertainty of 1×10^{-17}.

Experimental Progress

- One viable crystal (so far):

Expect: $^{232}Th_{0.001}:Na_{0.4}Y_{0.6}F_{2.2}$

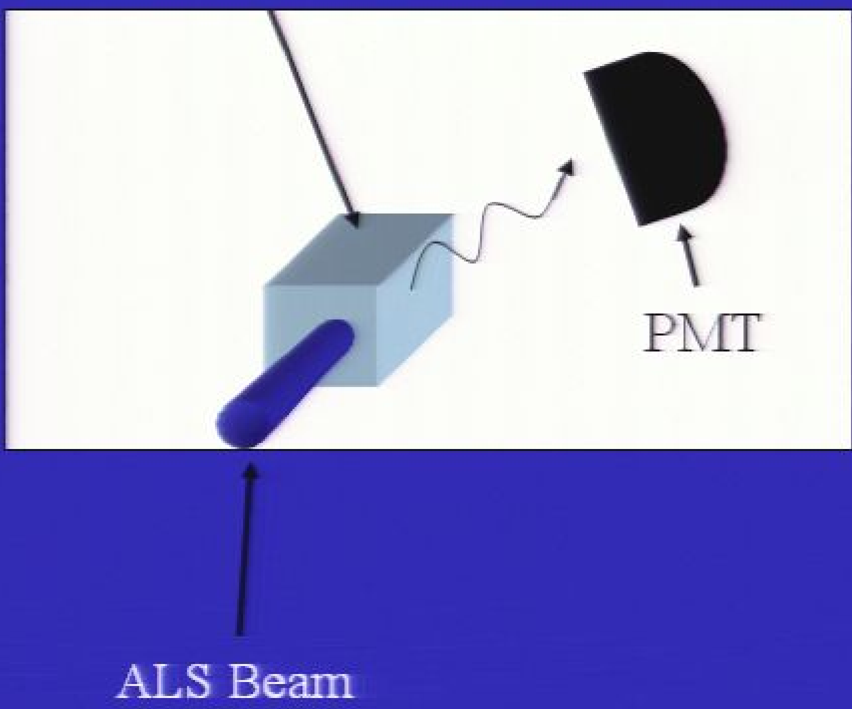
Th	Na	Y	F
.001	.396	.592	2.2

*Measured with e-beam microprobe

- Characterizing Crystals
  - NMR → Expected linewidt
  - VUV transmission (ALS)

Finding the transition

VUV transmissive material doped with Th-229



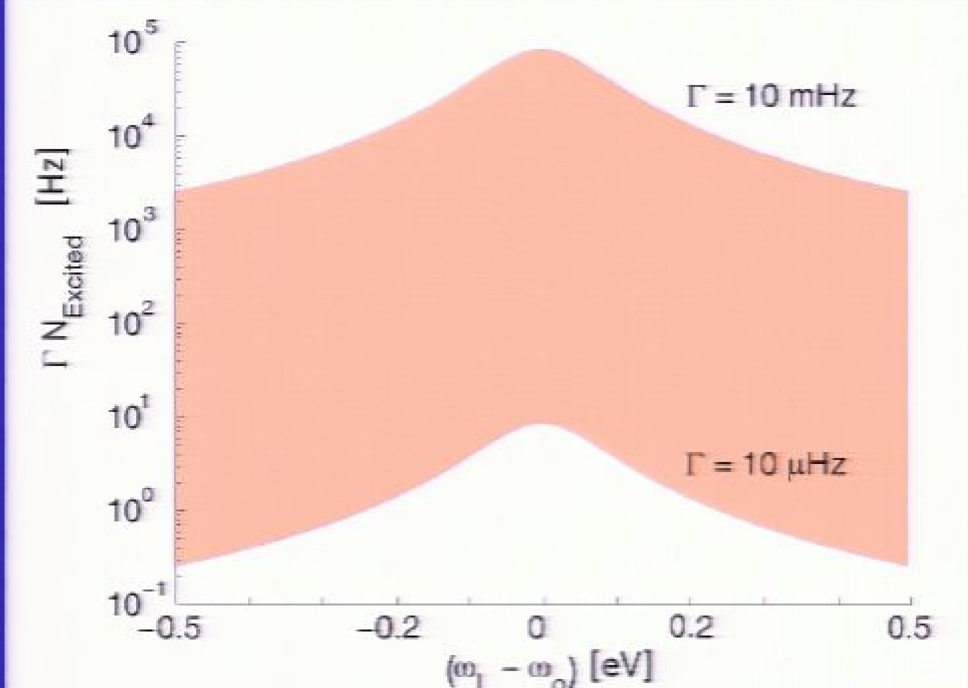


Fig. 2. The shaded region indicates the possible ²²⁹Th fluorescence rate after 1 second of illumination with the ALS.

Outlook

- 10^6 precision improvement over *next-generation* optical clocks

Outlook

- 10^6 precision improvement over *next-generation* optical clocks
- $\geq 10^3$ sensitivity increase over *next-generation* optical clocks to variation of fundamental constants

Outlook

- 10^6 precision improvement over *next-generation* optical clocks
- $\geq 10^3$ sensitivity increase over *next-generation* optical clocks to variation of fundamental constants
- Characterization under way

OH Spectroscopy for Constraining the Evolution of the Fine Structure Constant

Ye Group, JILA

$$
NSF, Keck,
DOE, NIST

- Idea
  - J. Darling, PRL **91**, 011301 (2003).
  - J. N. Chengalur and N. Kanekar, PRL. **91**, 241302 (2003).
- Measurement
  - Multiple transitions from same gas cloud
  - Previous measurement resolution ~ 100 Hz - 200 Hz

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

- Status

Ye lab folks:
J.R. Bochinski
H.J. Lewandows
Brian C. Sawyer
Benjamin Lev
Jun Ye

Outlook

- 10^6 precision improvement over *next-generation* optical clocks
- $\geq 10^3$ sensitivity increase over *next-generation* optical clocks to variation of fundamental constants
- Characterization under way

OH Spectroscopy for Constraining the Evolution of the Fine Structure Constant

Ye Group, JILA

$$
NSF, Keck,
DOE, NIST

- Idea
  - J. Darling, PRL **91**, 011301 (2003).
  - J. N. Chengalur and N. Kanekar, PRL. **91**, 241302 (2003).
- Measurement
  - Multiple transitions from same gas cloud
  - Previous measurement resolution ~ 100 Hz - 200 Hz

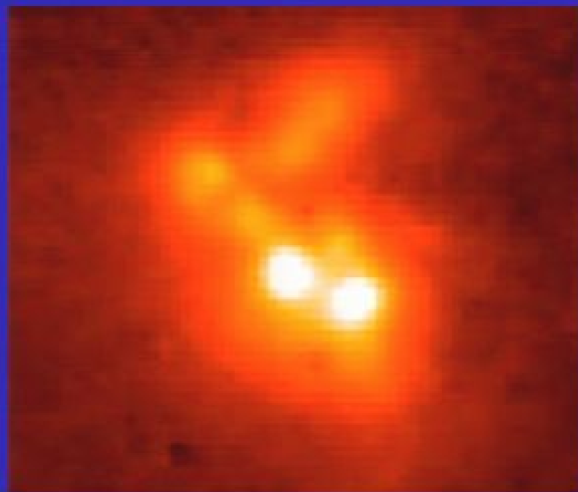
J.J. ter Meulen & Dymanus, Astrophys. J. 172, L21(1972).

- Status

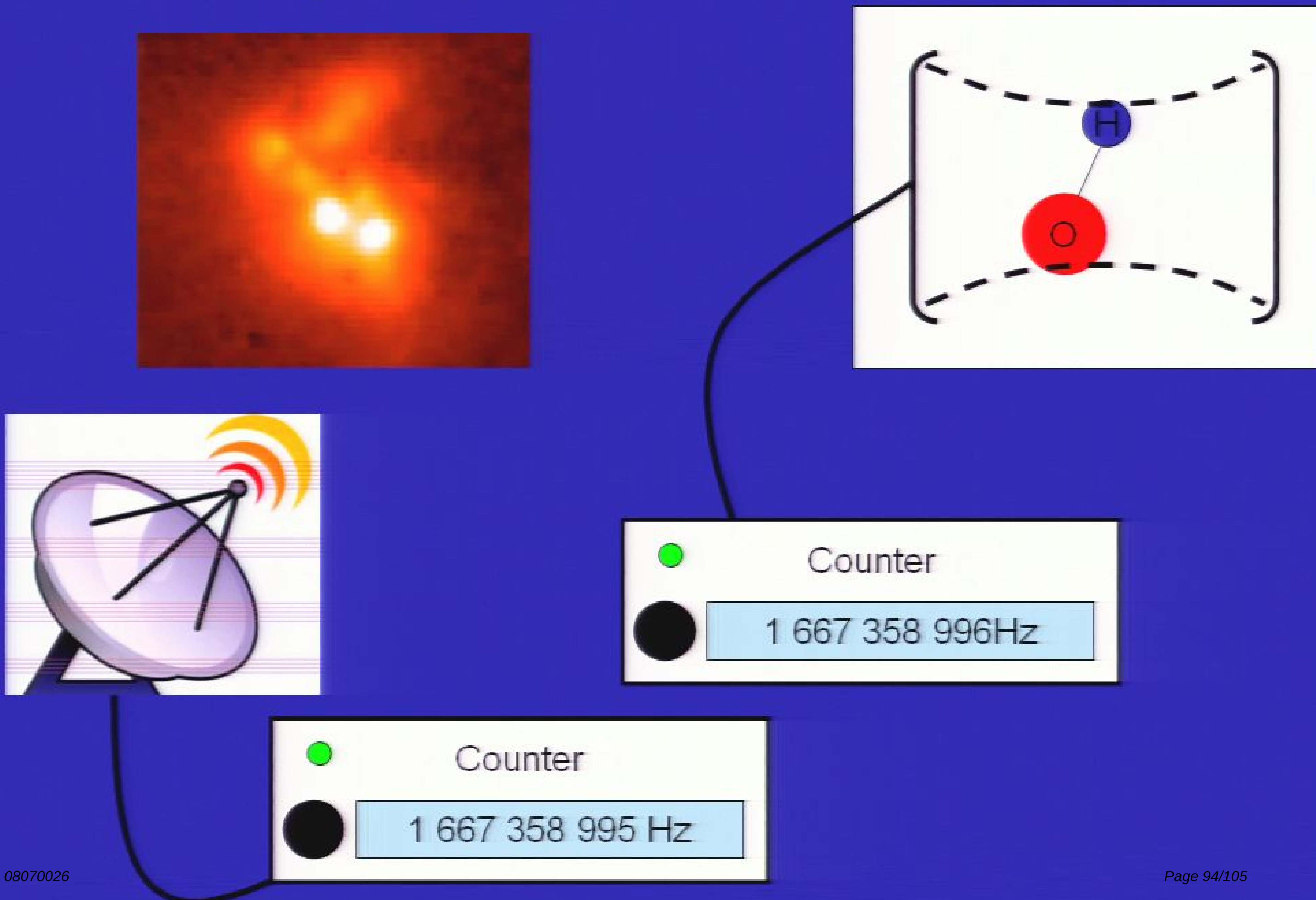
Ye lab folks:

J.R. Bochinski
H.J. Lewandows
Brian C. Sawyer
Benjamin Lev
Jun Ye

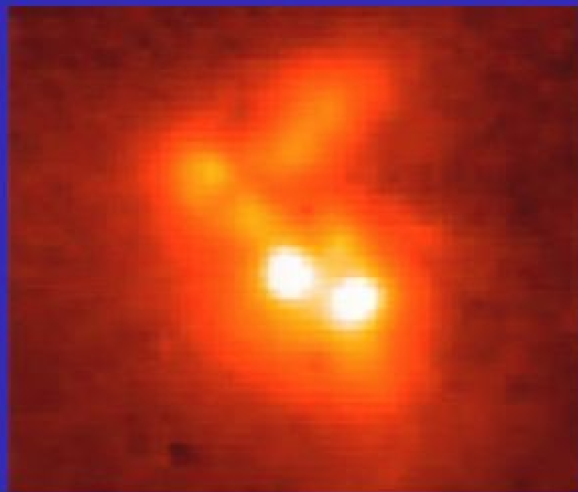
OH megamasers

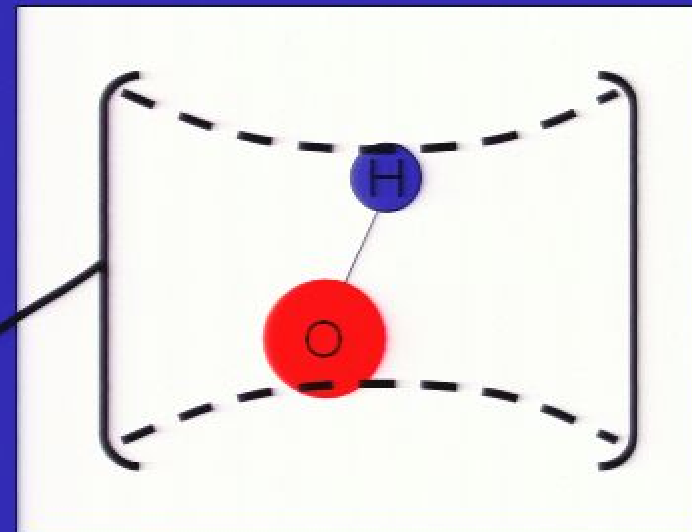


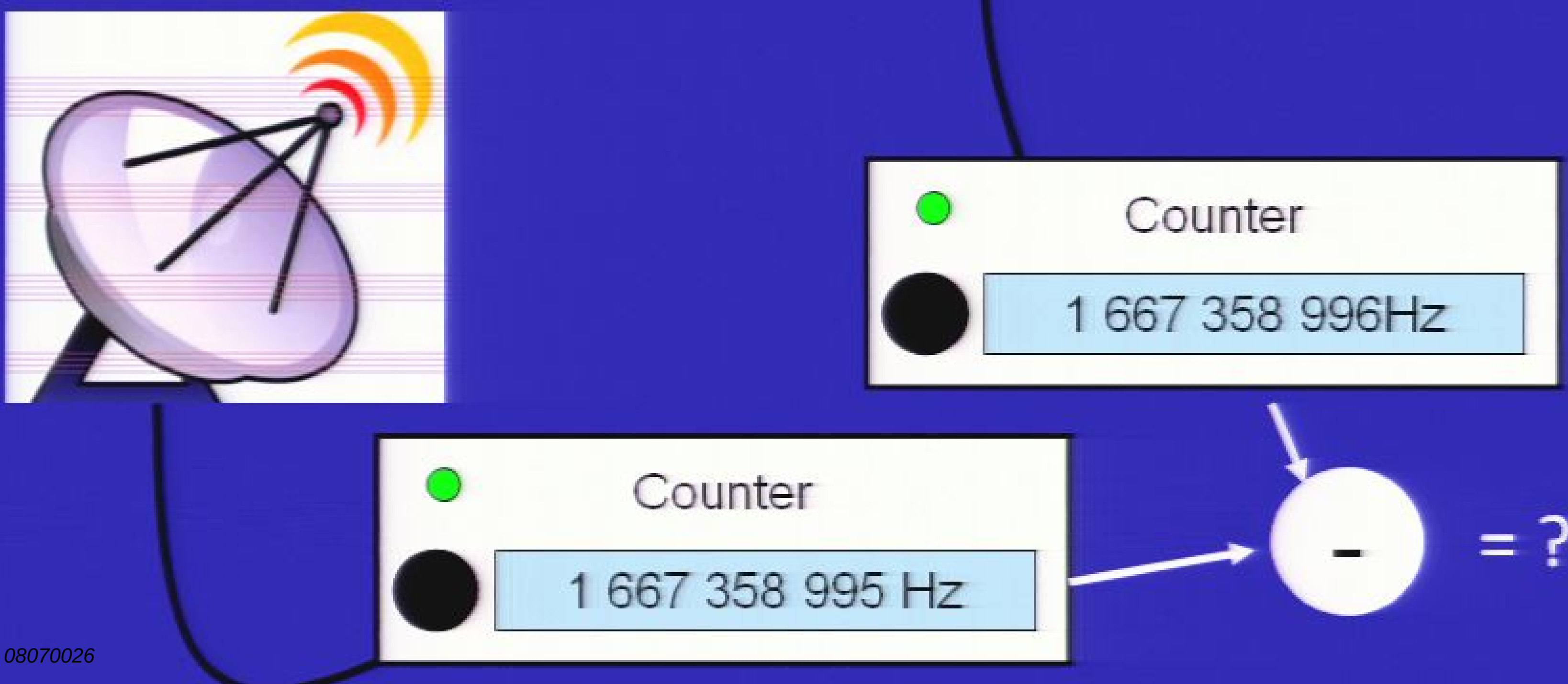
OH megamasers



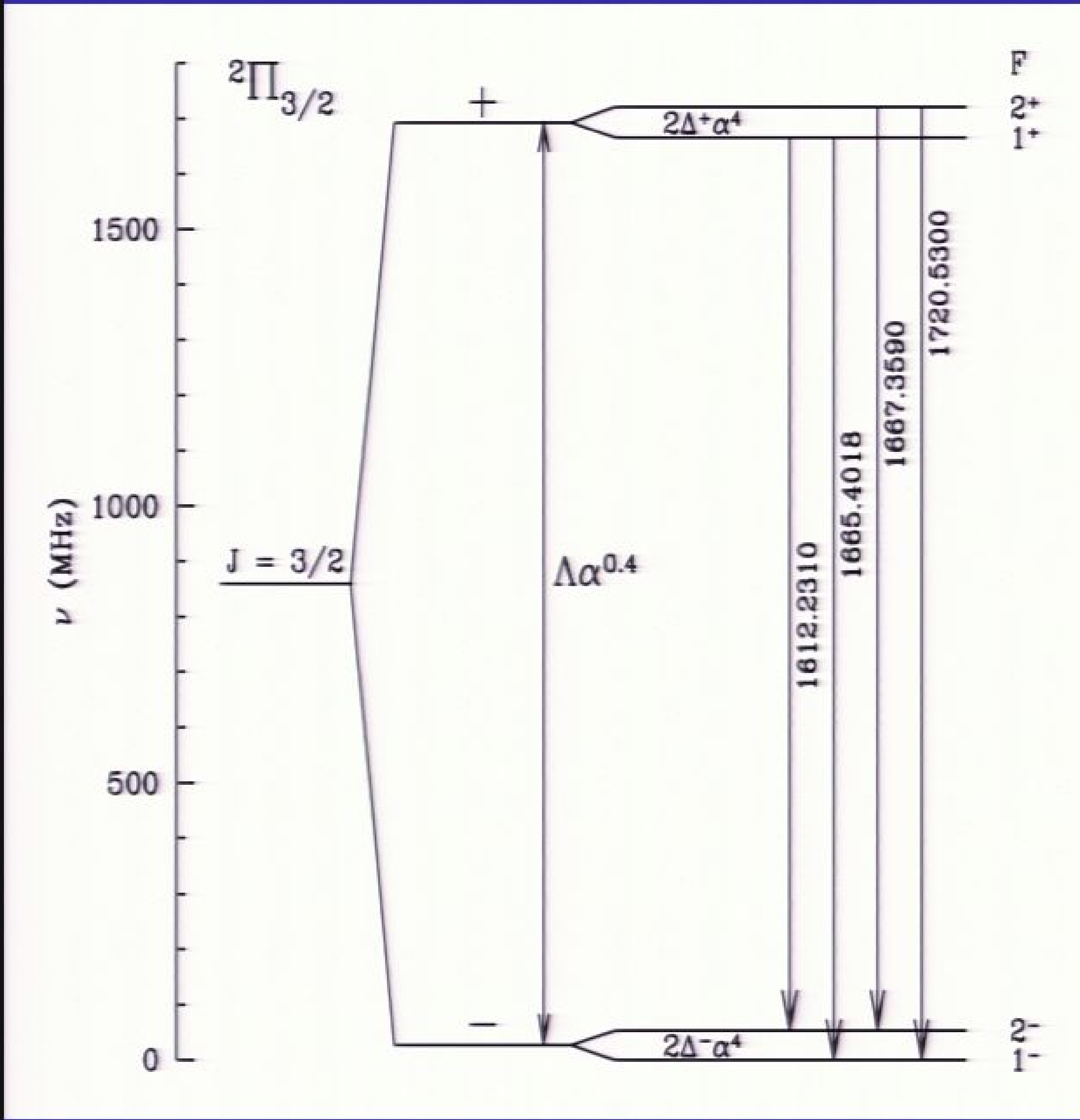
OH megamasers







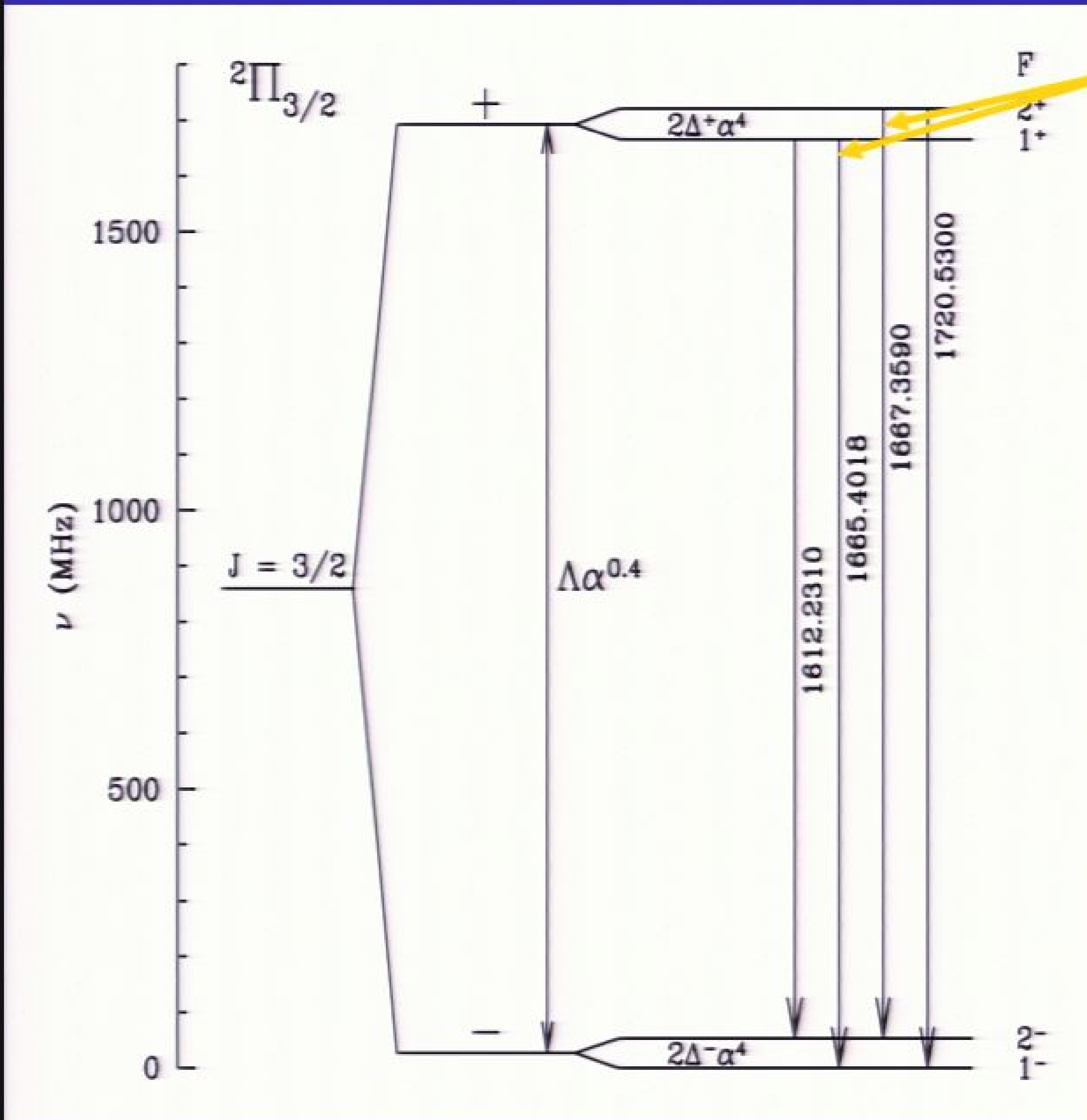
OH Ground State



J. Darling, PRL **91**, 011301 (2003).

J. N. Chengalur and N. Kanekar, PRL **91**, 241302 (2003)

OH Ground State



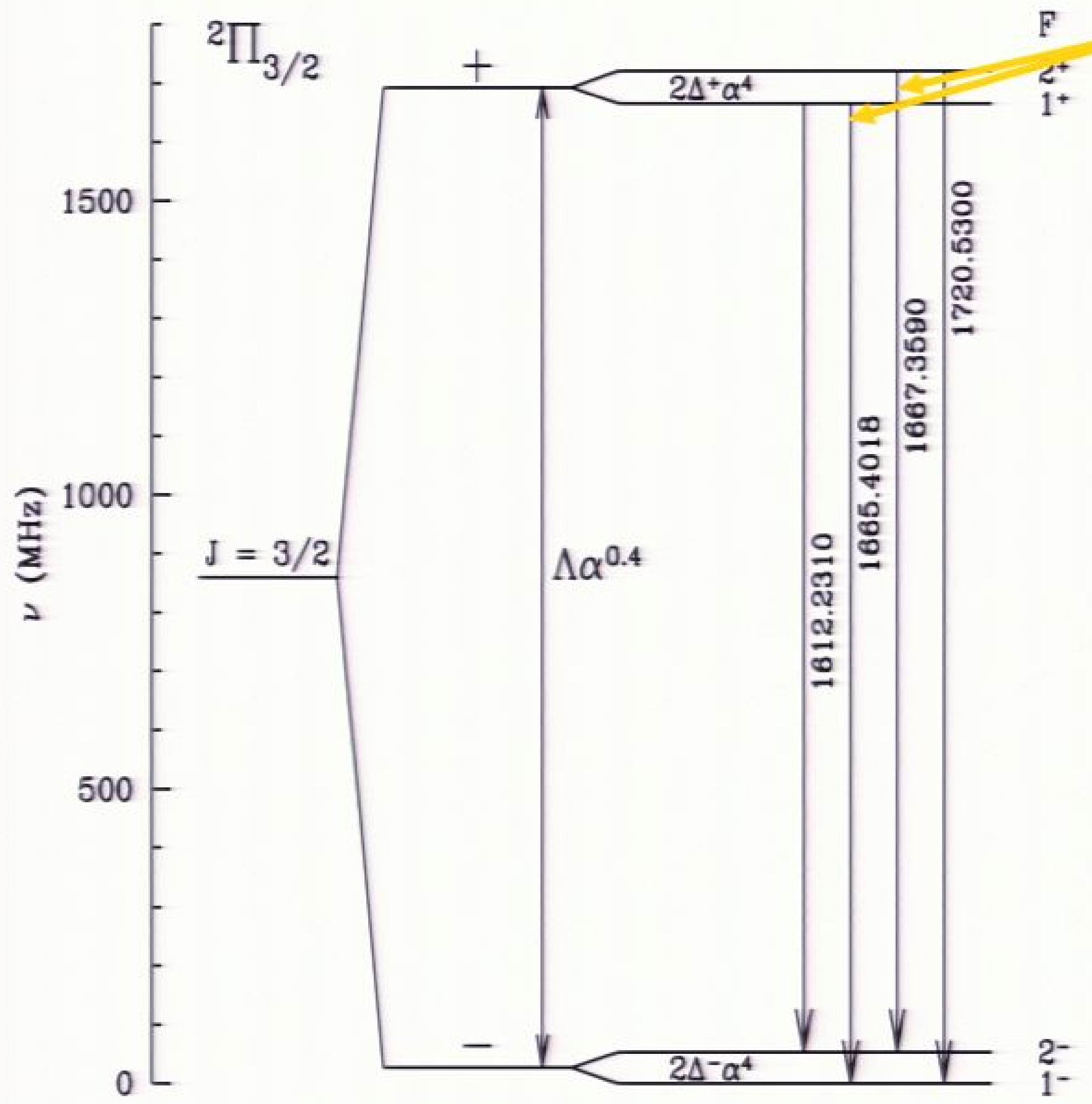
Main line gives poor sensitivity

$\Delta^+ \approx \Delta^-$ → Hyperfine (α^4) cancels

Satellite lines don't suffer from this

J. Darling, PRL **91**, 011301 (2003).
J. N. Chengalur and N. Kanekar, PRL **91**, 241302 (2003)

OH Ground State



Main line gives poor sensitivity

$\Delta^+ \approx \Delta^-$ → Hyperfine (α^4) cancels

Satellite lines don't suffer from this

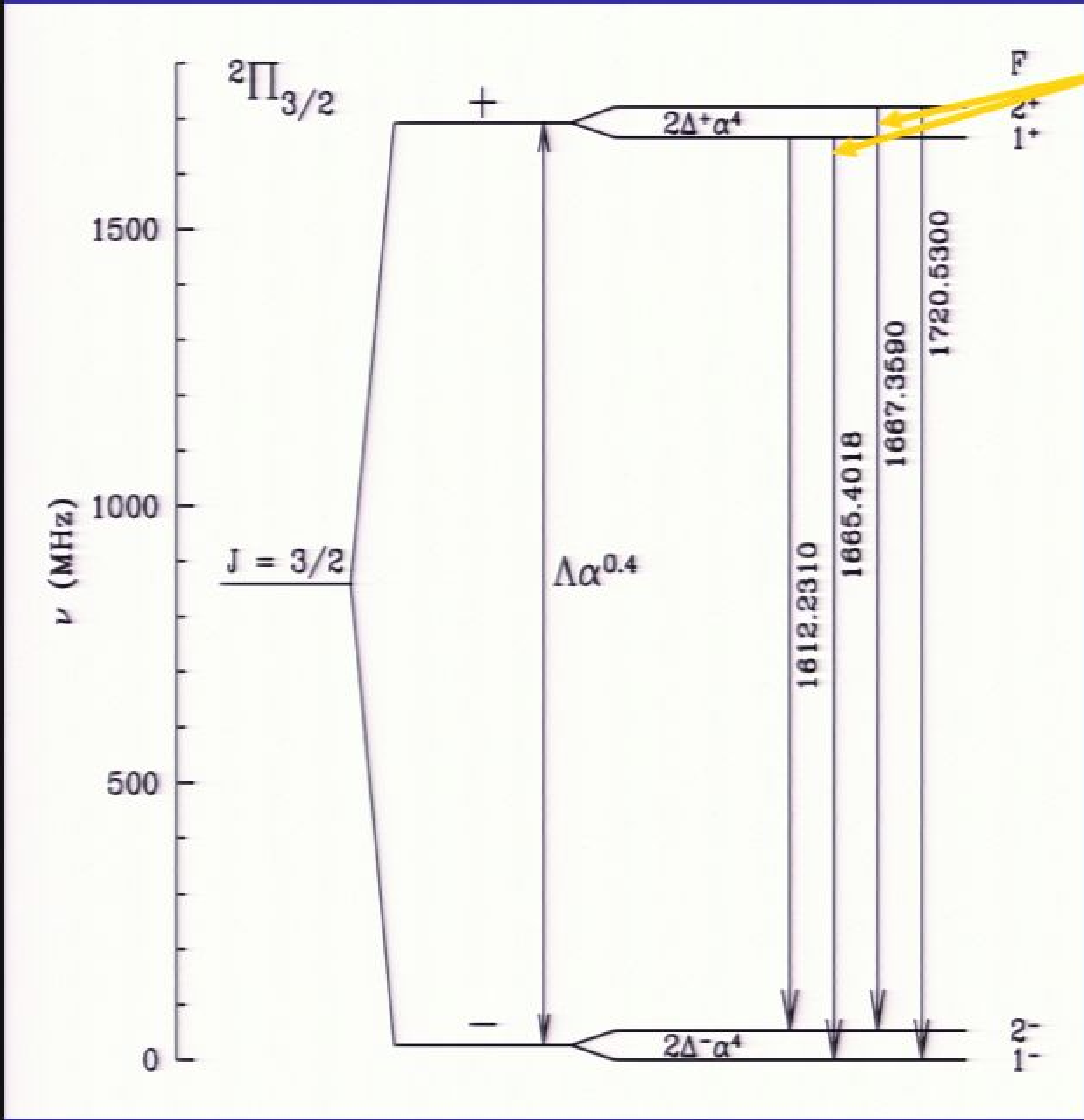
OH "advantage":

- No relative Doppler Shift
- Closure relation
- α^4 dependence

J. Darling, PRL **91**, 011301 (2003).

J. N. Chengalur and N. Kanekar, PRL **91**, 241302 (2003)

OH Ground State



Main line gives poor sensitivity

$\Delta^+ \approx \Delta^-$ → Hyperfine (α^4) cancels

Satellite lines don't suffer from this

OH "advantage":

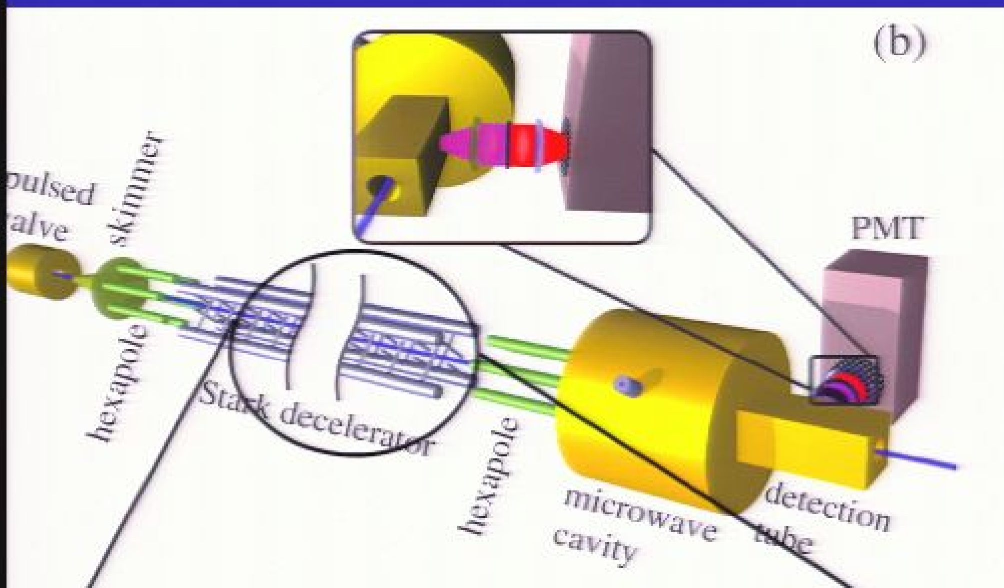
- No relative Doppler Shift
- Closure relation
- α^4 dependence

OH "problem":

- Lab measurements

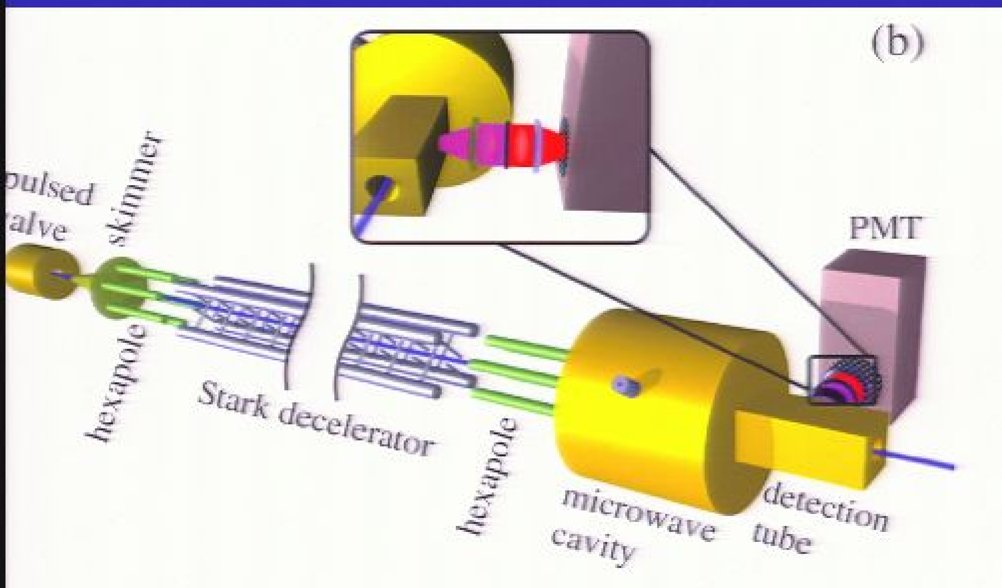
J. Darling, PRL **91**, 011301 (2003).
J. N. Chengalur and N. Kanekar, PRL **91**, 241302 (2003)

Constraining the Evolution of α

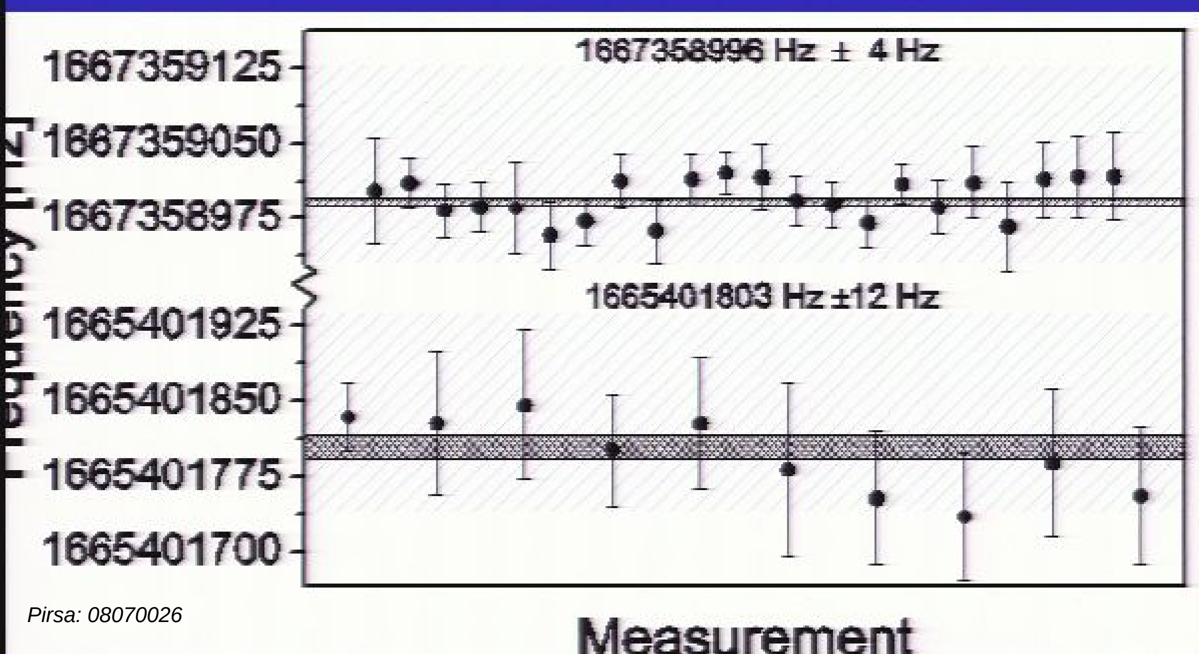


- Stark Deceleration of OH molecule
- High-resolution spectroscopy experiment on cold molecules
  - Measured OH λ-doublet transitions (10-25X improvement over previous measurement)

Constraining the Evolution of α



- Stark Deceleration of OH molecule
- High-resolution spectroscopy experiment on cold molecules
  - Measured OH λ-doublet transitions (10-25X improvement over previous measurement)



With astrophysical measurements OH "mega-masers" can constrain possible variation of α:

$\Delta\alpha/\alpha \leq 30$ ppb over ~10^{10} yea

PRL **96,** 143004 (2006)

PRA **74**, 061402 (2006)

Status

- Current limits: $\Delta\alpha/\alpha < 6.7 \times 10^{-6}$, $\Delta\mu/\mu < 1.4 \times 10^{-5}$ } Over 6.5 Gyr

Kanekar et al., PRL **95**, 261301 (2005)

Status

- Current limits: $\Delta\alpha/\alpha < 6.7 \text{ X } 10^{-6}$ and $\Delta\mu/\mu < 1.4 \text{ X } 10^{-5}$ } Over 6.5 Gyr

Kanekar et al., PRL **95**, 261301 (2005)

New data taken in 2005 -2006 with aim of getting below 100 Hz

- Still waiting on astrophysical result...
  - Over 100 hours of data taken on GBT, but analysis is bogged down by some terrestrial noise
  - New data set from Arecibo being analyzed (N. Kanekar)

Status

- Current limits: $\Delta\alpha/\alpha < 6.7 \times 10^{-6}$, $\Delta\mu/\mu < 1.4 \times 10^{-5}$ } Over 6.5 Gyr

Kanekar et al., PRL **95**, 261301 (2005)

New data taken in 2005 -2006 with aim of getting below 100 Hz

- Still waiting on astrophysical result...
  - Over 100 hours of data taken on GBT, but analysis is bogged down by some terrestrial noise
  - New data set from Arecibo being analyzed (N. Kanekar)
- (The claim is that) the future is bright
  - Because the frequency is in the cooled L-band no resolution limits yet
  - New telescopes coming on-line in the next 10 years can approach our resolution with only a few hours of data collection

Status

- Current limits: $\Delta\alpha/\alpha < 6.7 \times 10^{-6}$, $\Delta\mu/\mu < 1.4 \times 10^{-5}$ } Over 6.5 Gyr

Kanekar et al., PRL **95**, 261301 (2005)

New data taken in 2005 -2006 with aim of getting below 100 Hz

- Still waiting on astrophysical result...
  - Over 100 hours of data taken on GBT, but analysis is bogged down by some terrestrial noise
  - New data set from Arecibo being analyzed (N. Kanekar)
- (The claim is that) the future is bright
  - Because the frequency is in the cooled L-band no resolution limits yet
  - New telescopes coming on-line in the next 10 years can approach our resolution with only a few hours of data collection
- Need more searches