Testing Spin-Statistics Connection by Highly Sensitive Spectroscopy of CO2

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Outline

- Introduction
- Apparatus
- Results & Discussion
- Future Works

Principle

The Well-know Spin-Statistics Theorem:

$$\begin{aligned} n\hbar &\longrightarrow \text{Boson} \\ (n+1/2)\hbar &\longrightarrow \text{Fermion} \end{aligned}$$

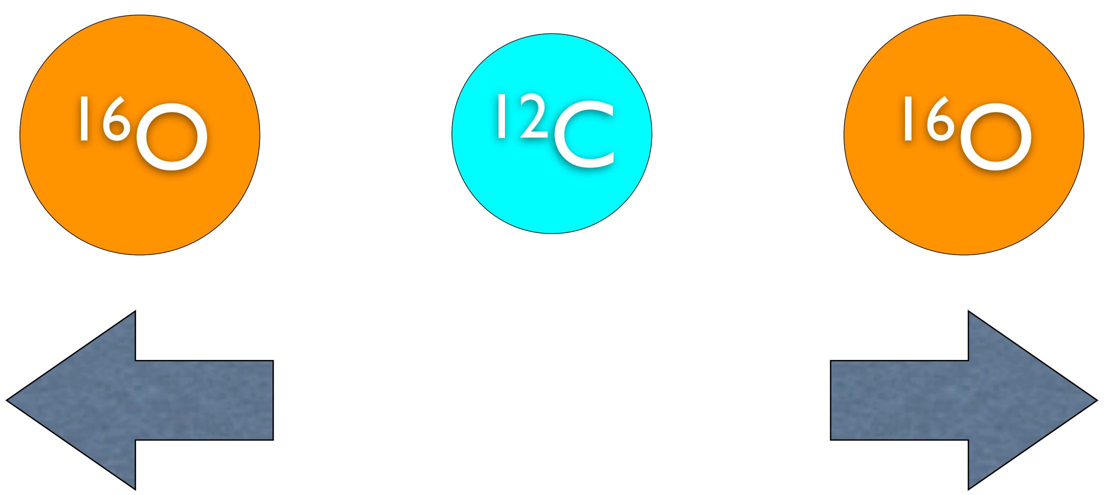
How about composite particles?

Ehrenfest & Oppenheimer (1931): Becoming invalid only when the interaction between clusters is large enough to disturb their internal motion

Forbidden internal states of molecules

Regarding $00^{0}0 \Rightarrow 00^{0}1$ rovibrational transitions of CO_2

The allowed transitions are R(2J) $R \Rightarrow J_{upper} - J_{lower} = +1$



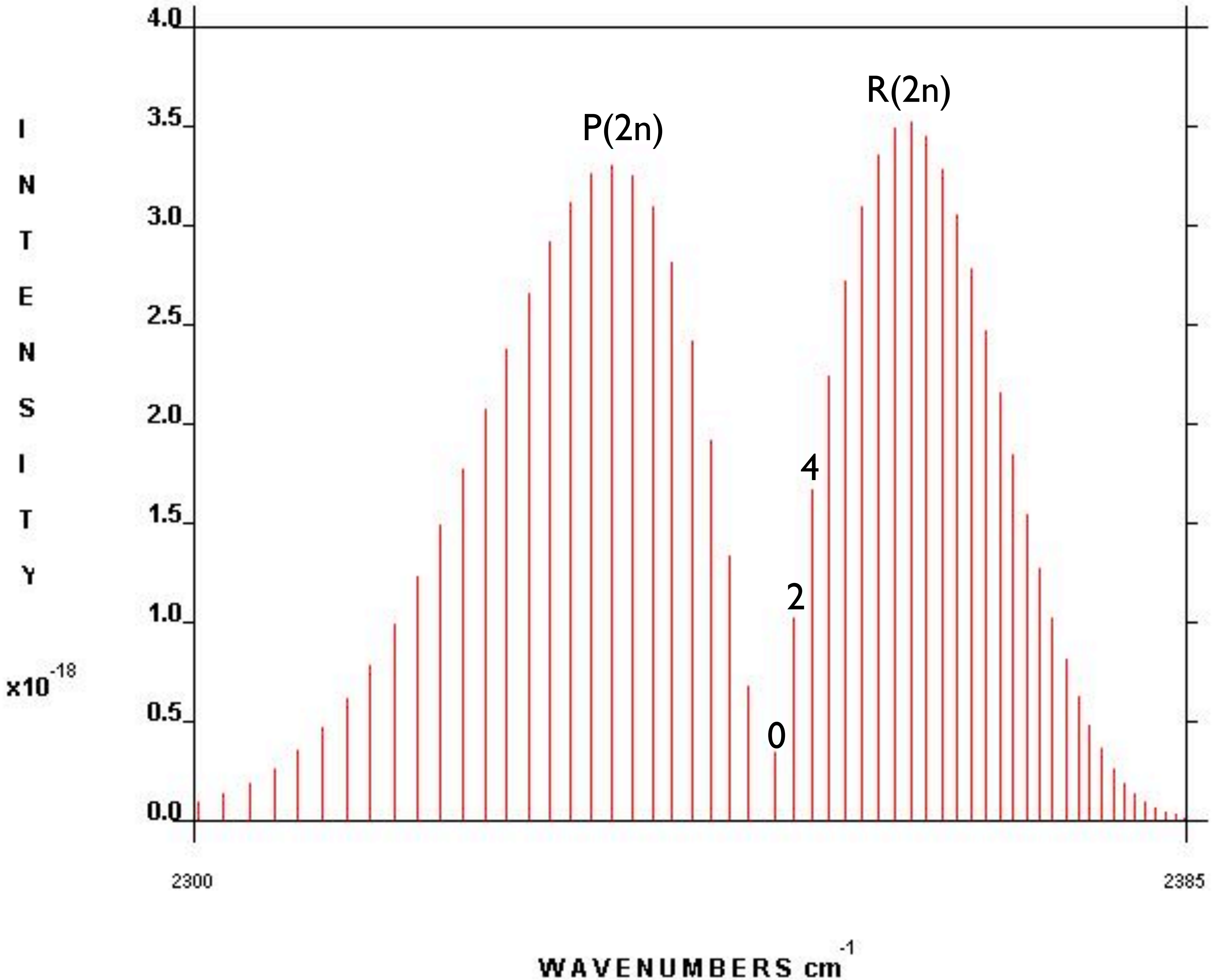
^{16}O nucleus ⇒ boson

^{16}O wavefuntion ⇒ symmetric

$00^{0}0$ is symmetric
⇒allowed Js are even

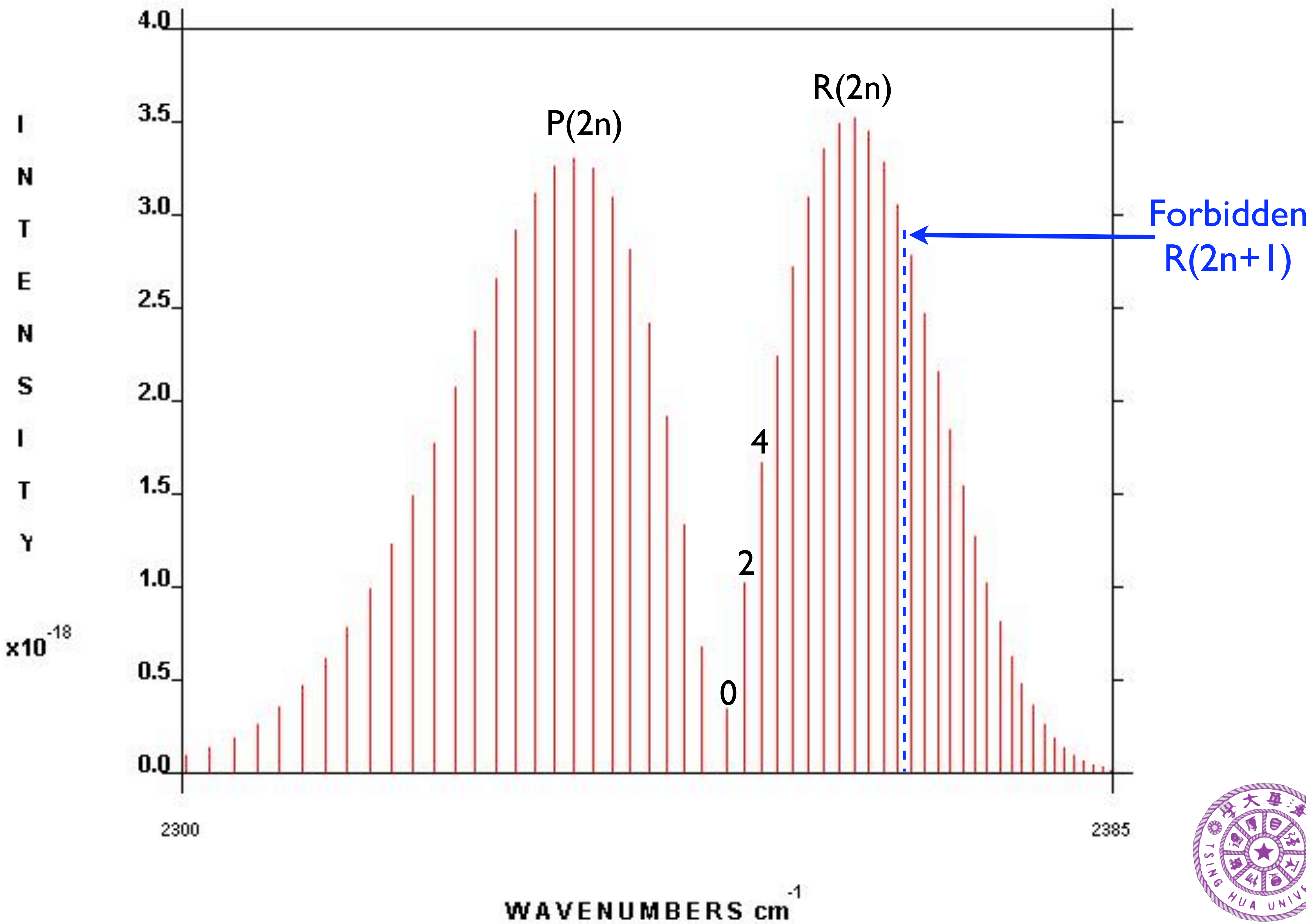
$00^{0}1$ is anti-symmetric
⇒allowed Js are odd

The 4.3 μm spectrum of CO_2



Forbidden R(2n+1)

The 4.3 μm spectrum of CO_2



Experimental Scheme

Searching for the very weak J=(2n+1) transitions

A neighboring marker line serves as both frequency and line intensity indicators

2 μm $00^{0}0$-$12^{0}1$ R(25), G. Modugno, et al. (1998)

4.3 μm $00^{0}0$-$00^{0}1$ R(25), D. Mazzotti, et al. (2001)

Why CO_2

- A well-known molecule
- Very strong absorption around 4.3 μm
- Rich absorption lines
- High precision molecular constants available
  ⇒ good predictions of the forbidden line

  positions

Q mutator

$$\rho_2 = (1 - \frac{1}{2}\beta^2)\rho_s + \frac{1}{2}\beta^2\rho_a$$

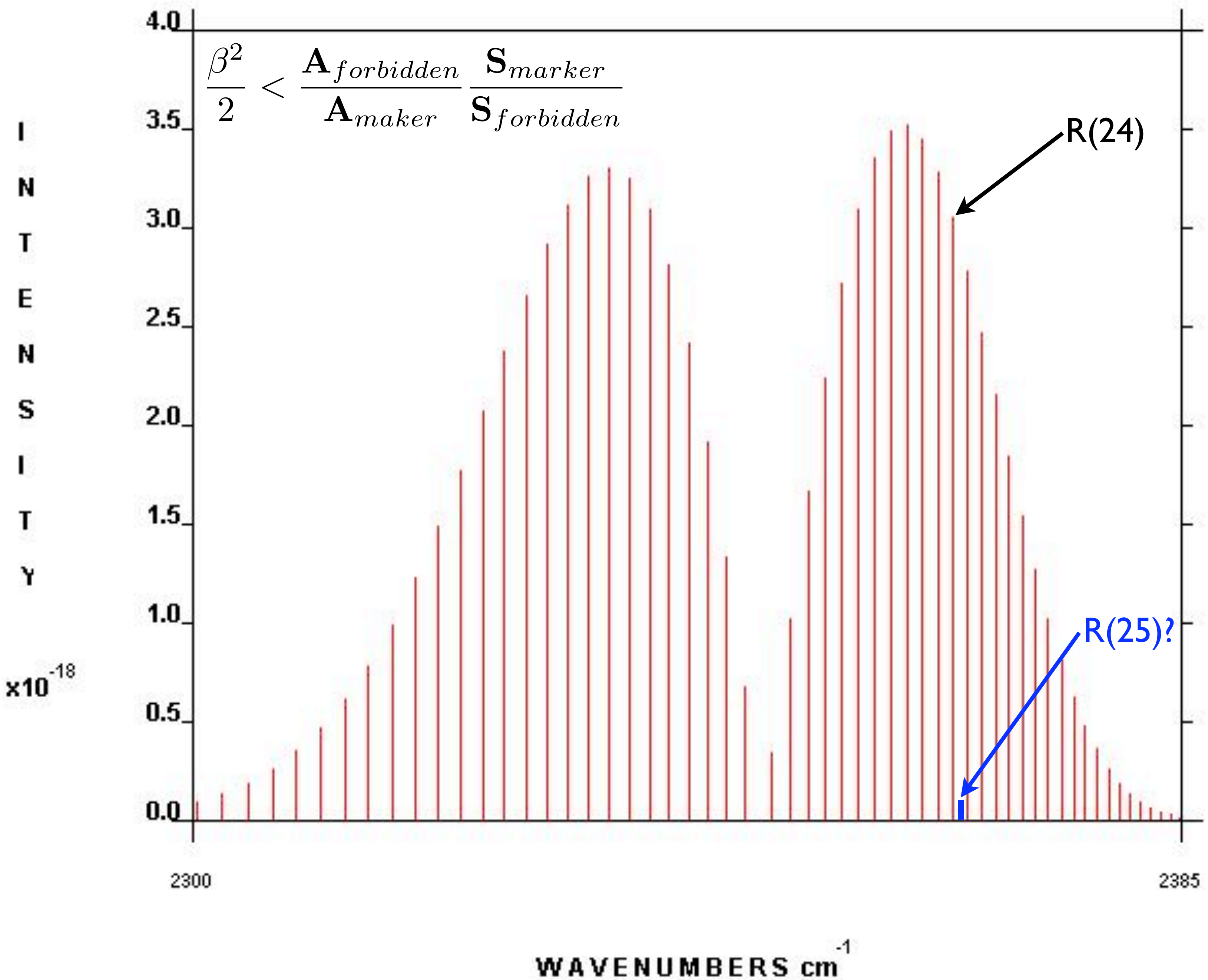
$$\frac{\beta^2}{2} < \frac{\mathbf{A}_{forbidden}}{\mathbf{A}_{maker}} \frac{\mathbf{S}_{marker}}{\mathbf{S}_{forbidden}}$$

A: Measured strength, S: Theoretical Strength

$$S(J,T) \quad \propto \quad (J+1)\exp\left(-\frac{h\nu_0 + E_r(J)}{k_B T}\right)$$

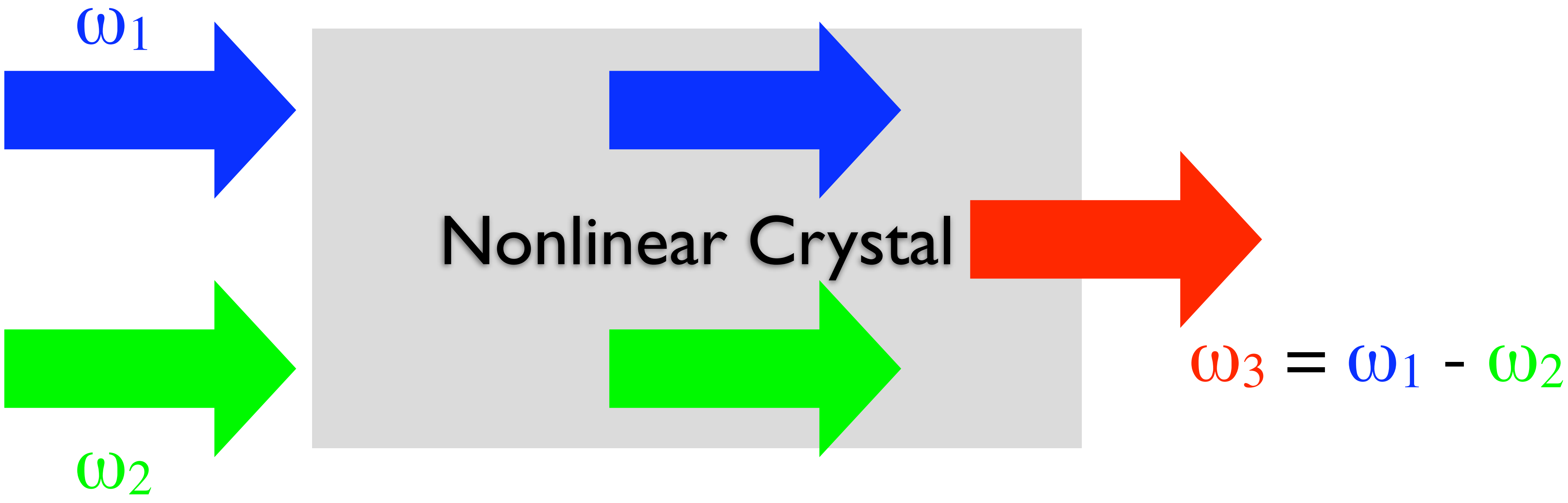
$$S(25,T) \quad \approx \quad S(24,T)\frac{26}{25}\exp\left(-\frac{E_r(25) - E_r(24)}{k_B T}\right)$$

The criterion for forbidden line

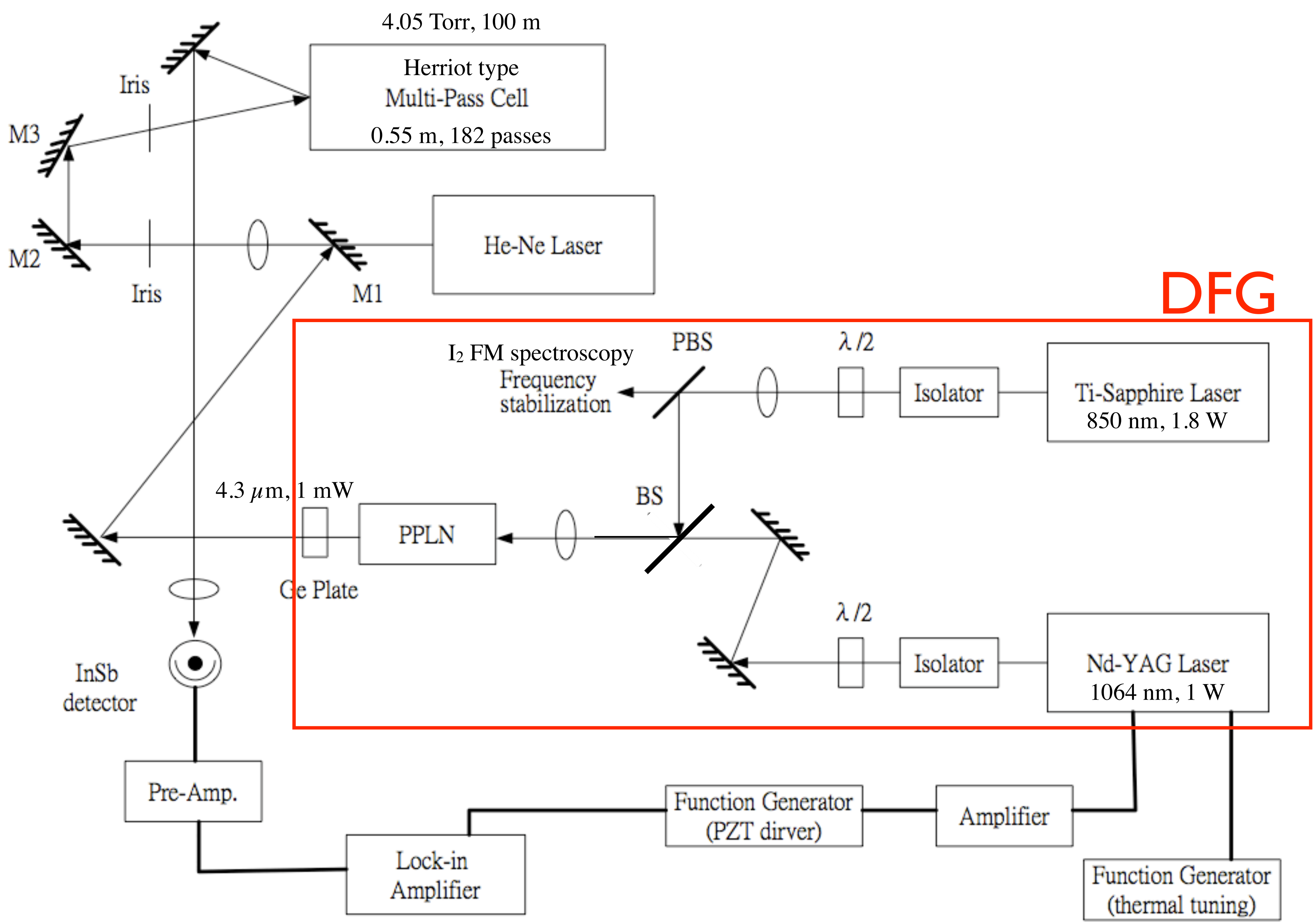


- Close to band peak
- No close-spaced strong line around it
- A well-separated weak line within frequency scanning range

DFG: Difference Frequency Generation

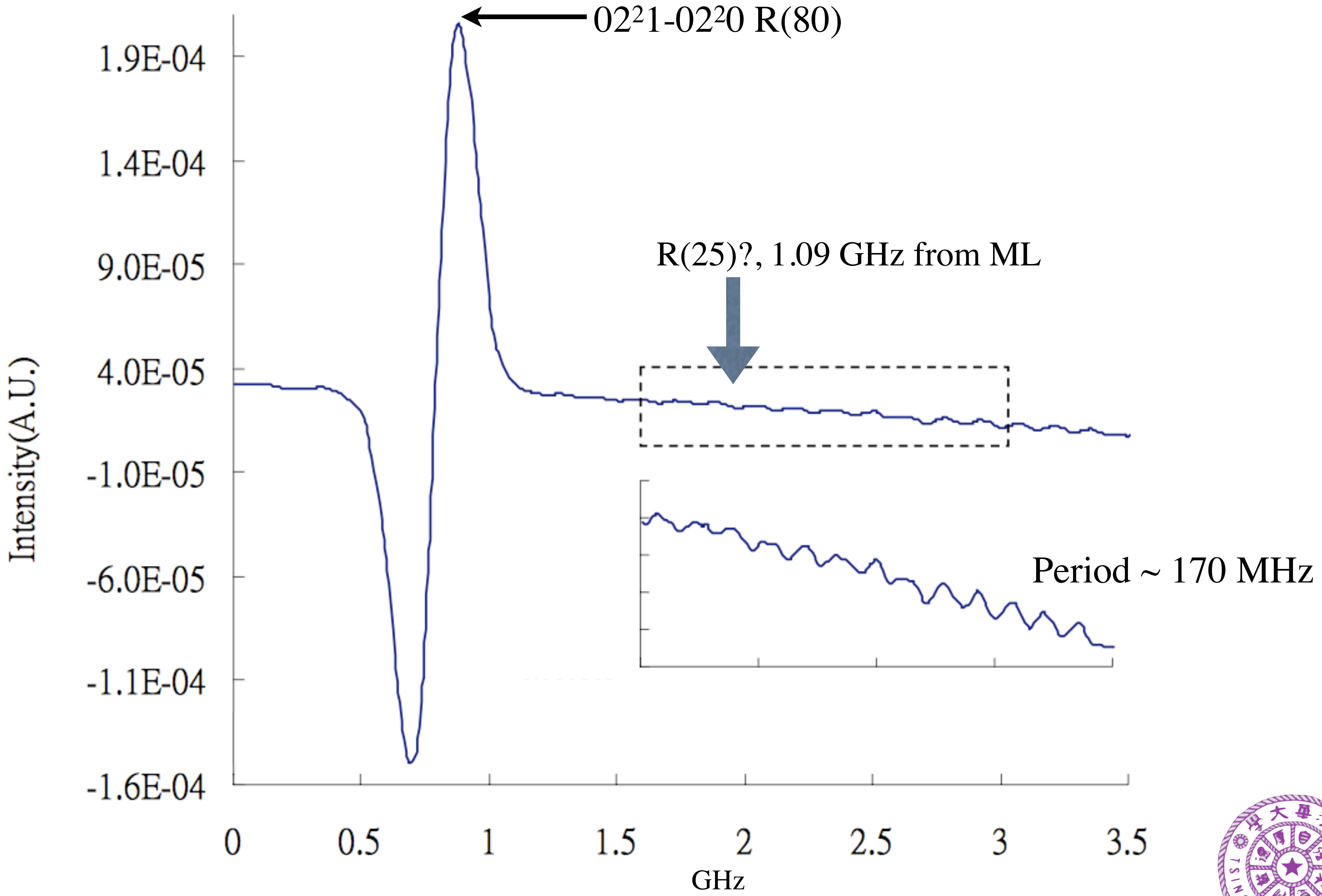


Apparatus



4.05 Torr, 100 m
Herriot type
Multi-Pass Cell
0.55 m, 182 passes
Iris
M3
M2
Iris
M1
He-Ne Laser
DFG
I₂ FM spectroscopy
Frequency
stabilization
PBS
λ /2
Isolator
Ti-Sapphire Laser
850 nm, 1.8 W
4.3 μm, 1 mW
PPLN
BS
Ge Plate
λ /2
Isolator
Nd-YAG Laser
1064 nm, 1 W
InSb
detector
Pre-Amp.
Lock-in
Amplifier
Function Generator
(PZT dirver)
Amplifier
Function Generator
(thermal tuning)

Spectrum

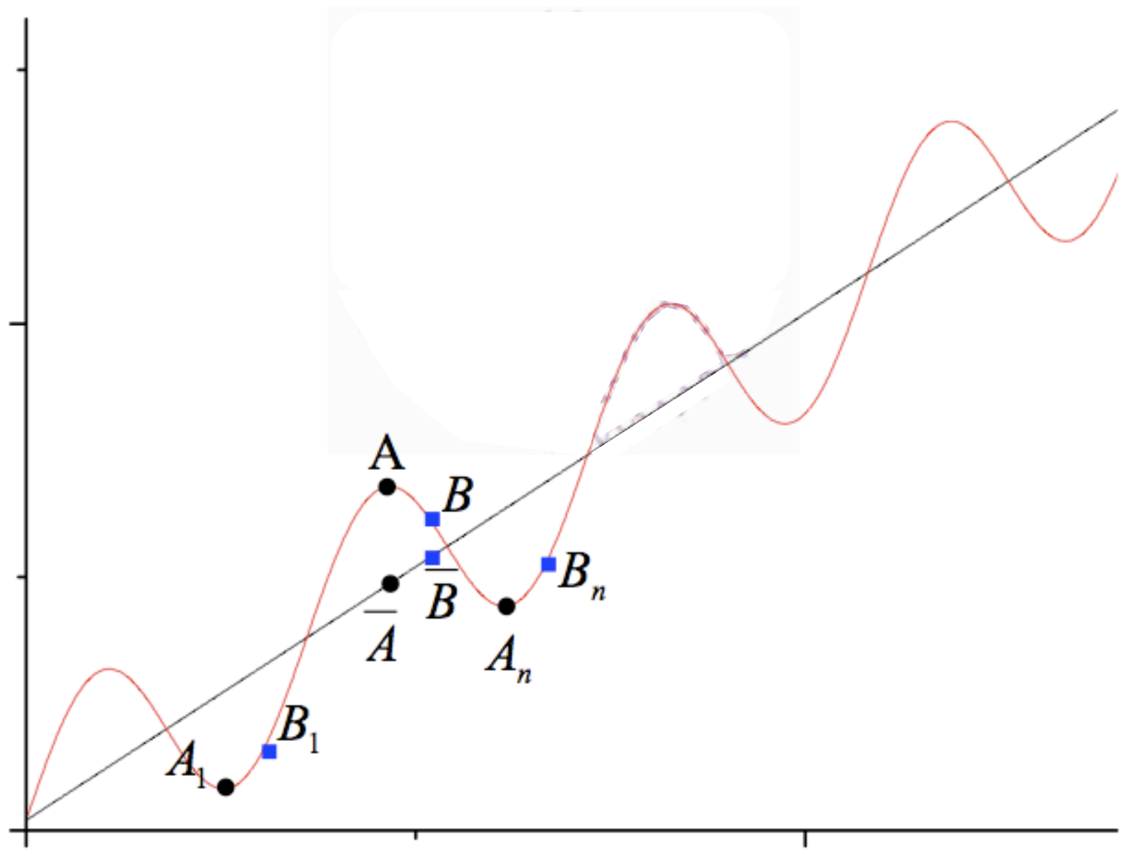


02²1-02²0 R(80)
R(25)?, 1.09 GHz from ML
Period ~ 170 MHz
Intensity(A.U.)
1.9E-04
1.4E-04
9.0E-05
4.0E-05
-1.0E-05
-6.0E-05
-1.1E-04
-1.6E-04
0
0.5
1
1.5
2
2.5
3
3.5
GHz

Fringe Reduction: Smooth

Smooth, Box Averaging, Moving Averaging

$$F(x_i) = \sum_{j=i-n/2}^{i+n/2} f(x_j)$$



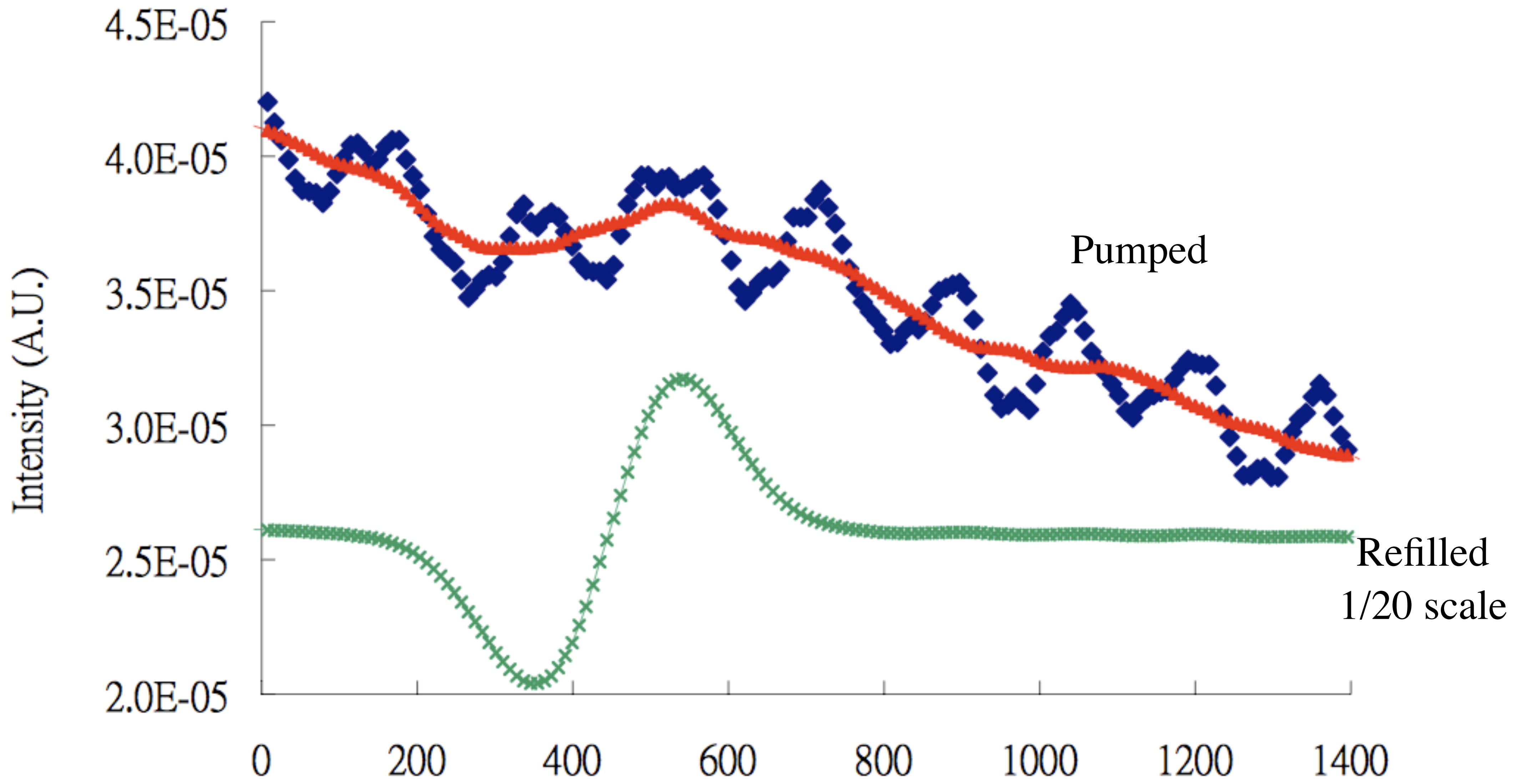
Advantages of smooth algorithm:

- Suppression of periodic pattern
- Noise cancellation

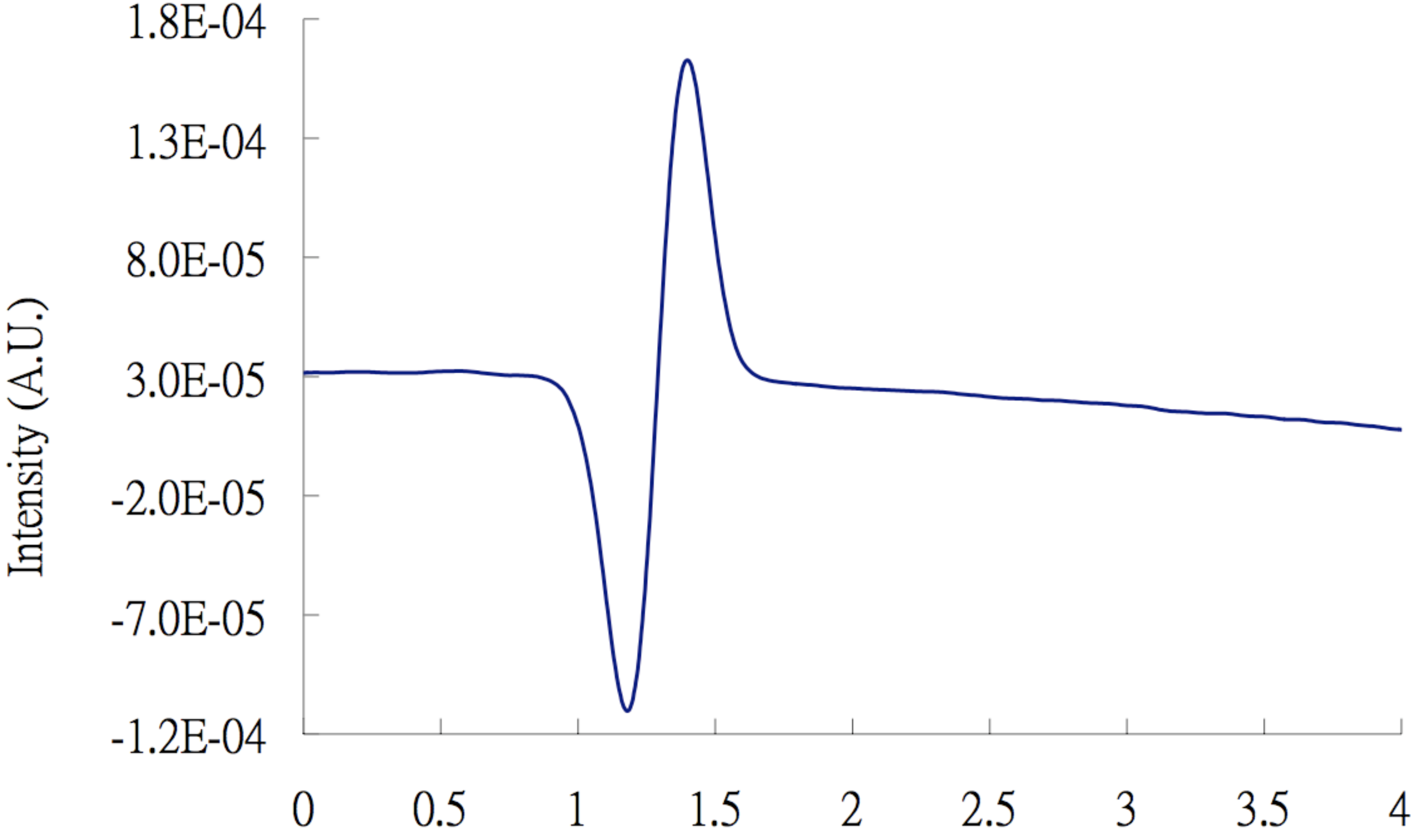
The smoothed derivative Gaussian profile

$$
\begin{aligned}
S(x) &= (ax+b) + A\frac{x-x_c}{W^2}\exp\left(-\frac{(x-x_c)^2}{2W^2}\right) \\
S(\bar{x}) &= \int_{x-L/2}^{x+L/2} S(x')dx' \\
&= (ax+b) - \frac{2A}{L}\exp\left(-\frac{(x-x_c)^2 + L^2/4}{2W^2}\right) \times \sinh\frac{L(x-x_c)}{2W^2}
\end{aligned}
$$

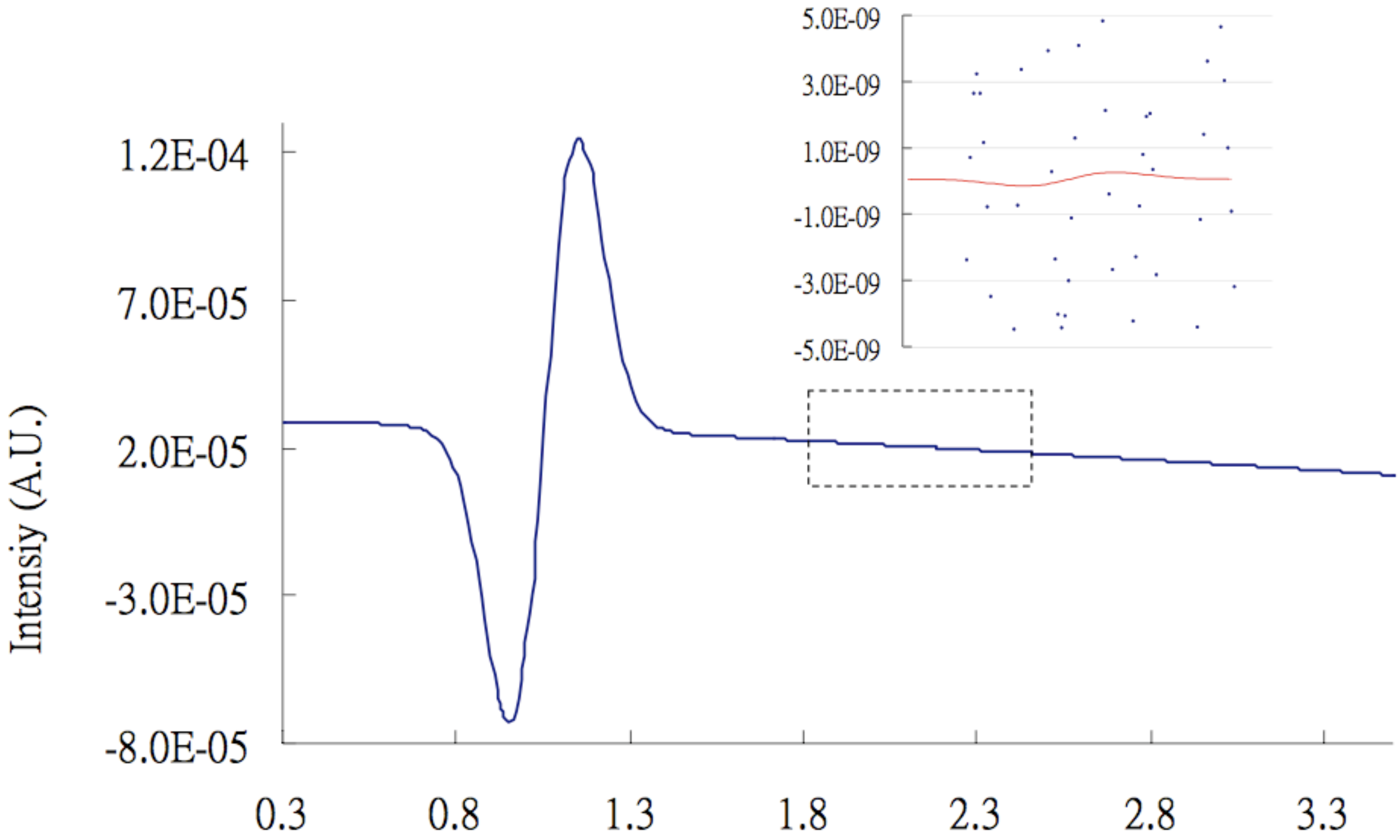
Effectiveness of smooth algorithm



Data Processing: Smoothing



Data Processing: Averaging 688 sets



Result

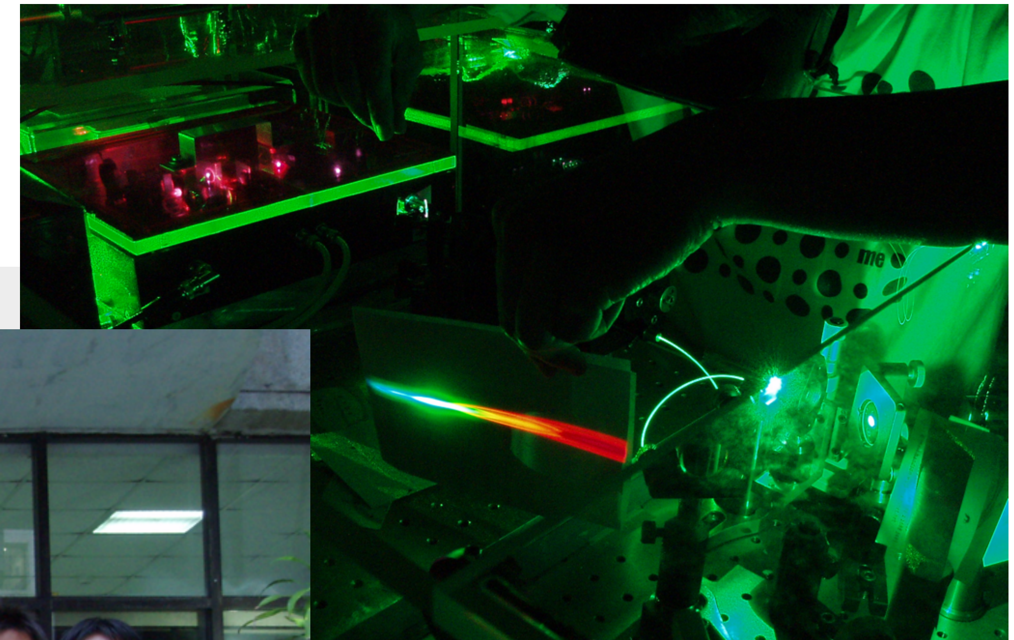
Estimating by RMS and Fitting, respectively

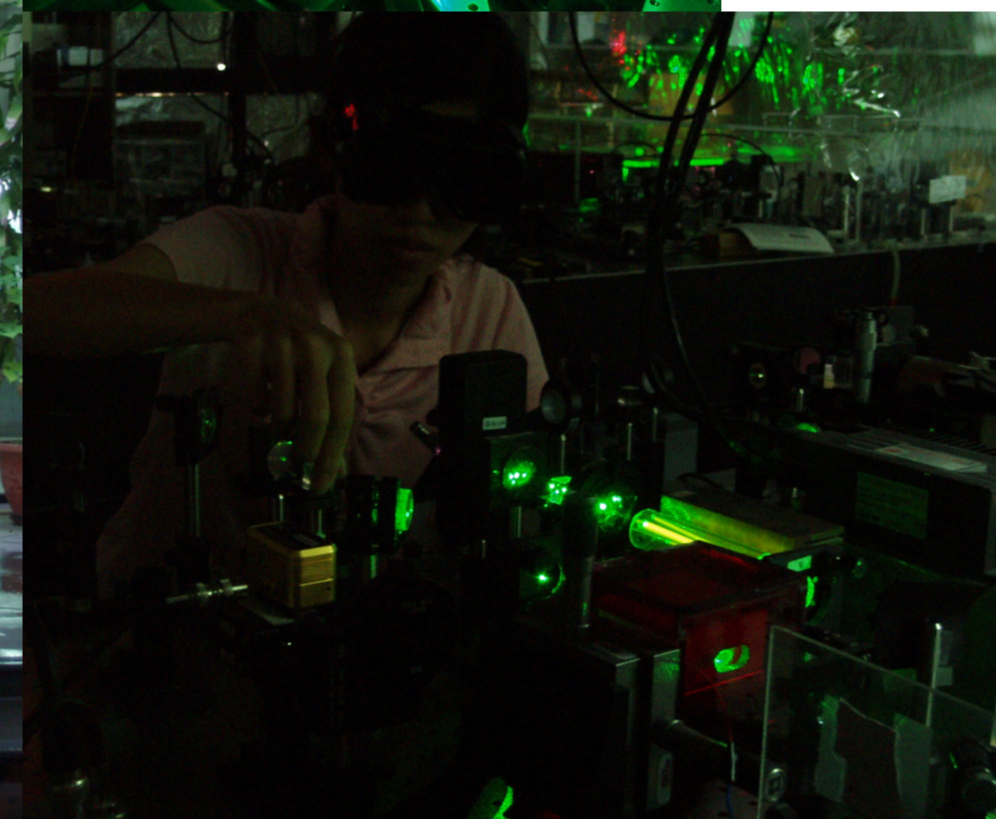
$$\frac{\beta^2}{2} < \frac{2.609 \times 10^{-9}}{0.974 \times 10^{-4}} \frac{2.29 \times 10^{-25}}{2.89 \times 10^{-18}} = 1.68 \times 10^{-12}$$

$$\frac{\beta^2}{2} < \frac{2.697 \times 10^{-8}}{2.250 \times 10^{-3}} \frac{2.29 \times 10^{-25}}{2.89 \times 10^{-18}} = 9.5 \times 10^{-14}$$

Future Works

- Suppressing the atmospheric absorption: only 20% optical power available for experiments.
- Locking DFG to optical frequency comb
  - Longer integration time
  - Smaller scanning steps
  - Smaller scanning range



Thank your for your attention!