

A Closer Look at THz Attenuation Mechanisms and Propagation

Two types of attenuation, both more common than in lower RF bands:

(1) Absorption

- Conversion of electromagnetic radiation into heat

(a) Conduction current (Joule) heating: $P_{\text{diss}} = \overline{\mathbf{J} \cdot \mathbf{E}}$

(e.g., losses in undepleted semiconductors)

(overbar denotes time average)

(b) Polarization current heating $P_{\text{diss}} = \overline{(\mathbf{dP}/dt) \cdot \mathbf{E}}$

(e.g., polar liquids, such as water in a microwave oven)

(2) Scattering

(a) Non-resonant internal scattering from inhomogeneous dielectrics

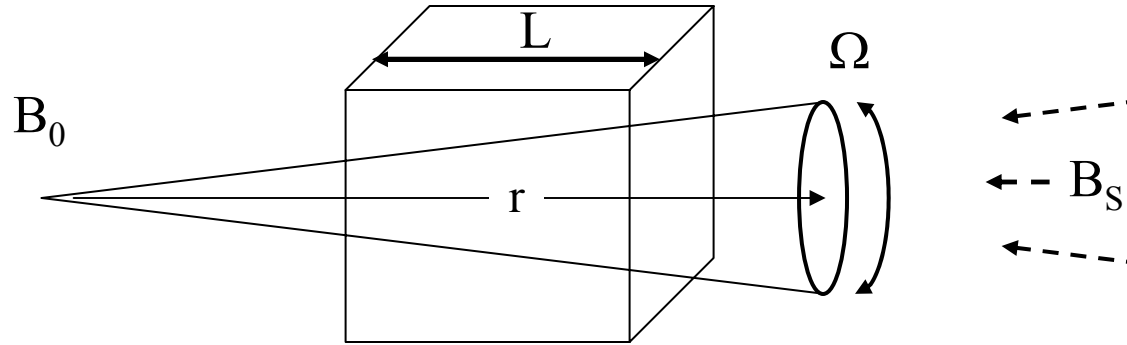
(e.g., composite materials such as RT-Duroid)

(b) Resonant scattering from particles of dimension $\sim \lambda$ (e.g., raindrops)

(c) Mixture of specular scattering from smooth surfaces and

diffuse scattering from rough surfaces (in infrared, more surfaces tend to be diffuse; in RF bands more surfaces tend to be specular)

Radiative Transfer



$$\frac{dB}{dr} + \alpha B = \frac{\rho J}{4\pi}$$

1D Radiative Transport Equation

$\alpha \rightarrow$ attenuation constant ; $\rho \rightarrow$ density ; $J \rightarrow$ emission coefficient

$$B(r) = B_s \exp(-\tau) + (\rho J / 4\pi \alpha) [1 - \exp(-\tau)] \quad \tau = \int_0^L \alpha(r) dr$$

Homogeneous Solution

Particular Solution

“Optical Depth”

Special Cases: (1) $j = 0 \Rightarrow B = B_s \exp(-\tau)$ Beer-Lambert Law

(2) $B = \text{uniform} \Rightarrow dB = 0 \Rightarrow B = (\rho J / 4\pi \alpha)$ Kirchhoff's Law

Good Introductory Reference: J.D. Kraus, “Radio Astronomy” (McGraw-Hill, New York, 1966).

Beer-Lambert Law

Describes attenuation effects for many THz point sensors (active and passive), and for remote active systems. Especially useful when intervening material is a linear, isotropic, and homogeneous (LIH) dielectric, or an array of independent scatterers:

$$T \equiv \frac{I_t}{I_i} = \exp(-\alpha_A \cdot z) \quad T \rightarrow \text{transmission, } \alpha_A \rightarrow \text{attenuation coefficient}$$

$I_i \rightarrow \text{incident intensity, } I_t \rightarrow \text{transmitted intensity}$

For absorption, $\alpha_A = \alpha_{\text{ABS}}$, the absorption coefficient
(a characteristic of the material, and generally a function of frequency)

For scattering $\alpha_A = \rho \sigma_s$, ρ being the density and σ_s the scattering cross section

Atmospheric Attenuation Simulation

Simulation Tool:

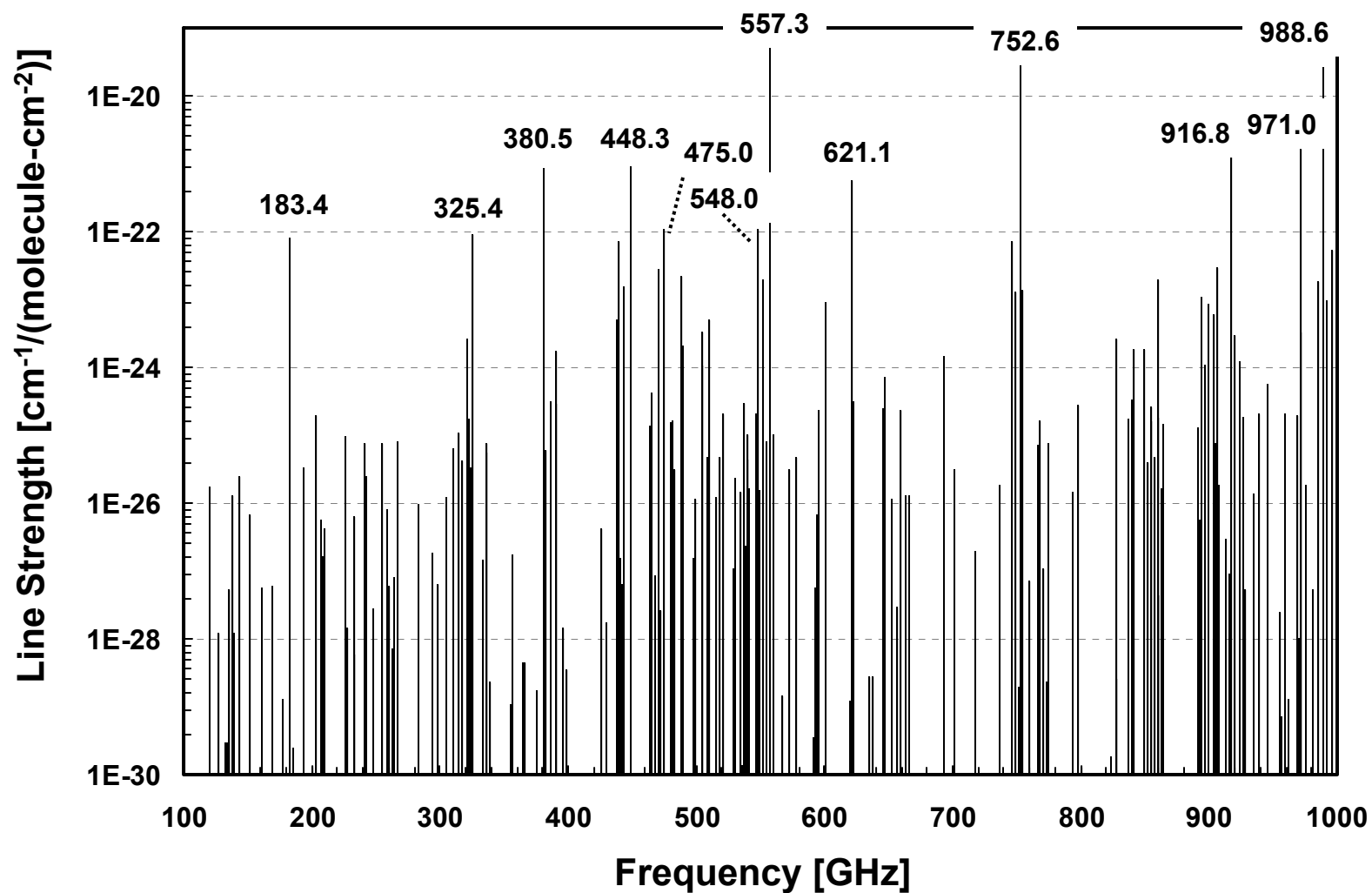
- **Windows[®]-based atmospheric propagation tool called PcLnWin (Ontar, Corp.)**
- **FASCODE radiative transfer engine developed by U.S. Air Force Geophysics Lab in 1970s.**
- **HITRAN96 database (> 1 million molecular lines) developed by molecular chemists and maintained by U.S. Air Force (Hanscom AFB)**

Atmospheric Conditions

- **Seven “standard” molecules: H₂O, CO₂, O₃, N₂O, CO, CH₄, O₂**
- **1976 U.S. standard atmospheric model @ sea level**
 - **Temperature = 288 K, Pressure = 1 atm, Humidity = 46%**

Between 300 GHz and 2.0 THz, water vapor dominates the attenuation by way of molecular dipole transitions

Stick Diagram of Atmospheric Molecular Lines



Why is Water Vapor Absorption So Strong and So Complicated ?

- For all polar molecules in the vapor state, THz transitions can occur between angular momentum eigenstates of the entire molecule if the energy difference between eigenstates = $h\nu$, and if the change in angular momentum along the axis of photon propagation = $h/2\pi$
- For symmetric rotors (e.g., carbonyl monoxide CO, hydrogen chloride HCl, etc.), two of the moments (along two orthogonal axes) are identical and the third is trivially small, so that

$$\begin{array}{c} \leftarrow R \rightarrow \\ \oplus \text{---} \ominus \end{array} \quad I = \mu R^2 \quad \text{Ignoring spin, } U_x = \frac{L_x^2}{2I_x} \quad L^2 = \hbar^2 l(l+1)$$

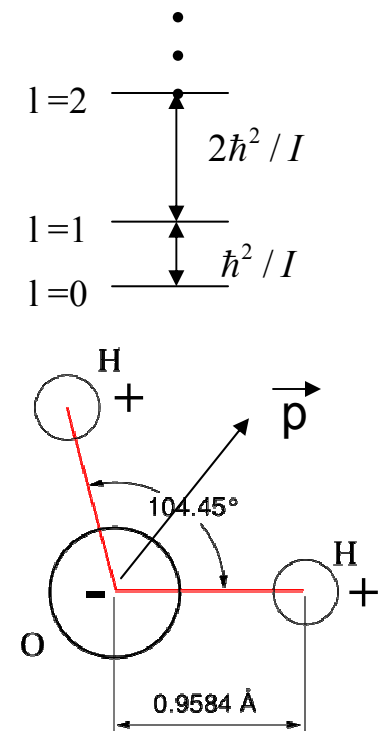
$I_x \rightarrow$ moment of inertia for rotation about a given axis, x
 $L \rightarrow$ orbital angular momentum eigenvalue

- Photon absorption or emission can occur of $\Delta l = 1$, for which

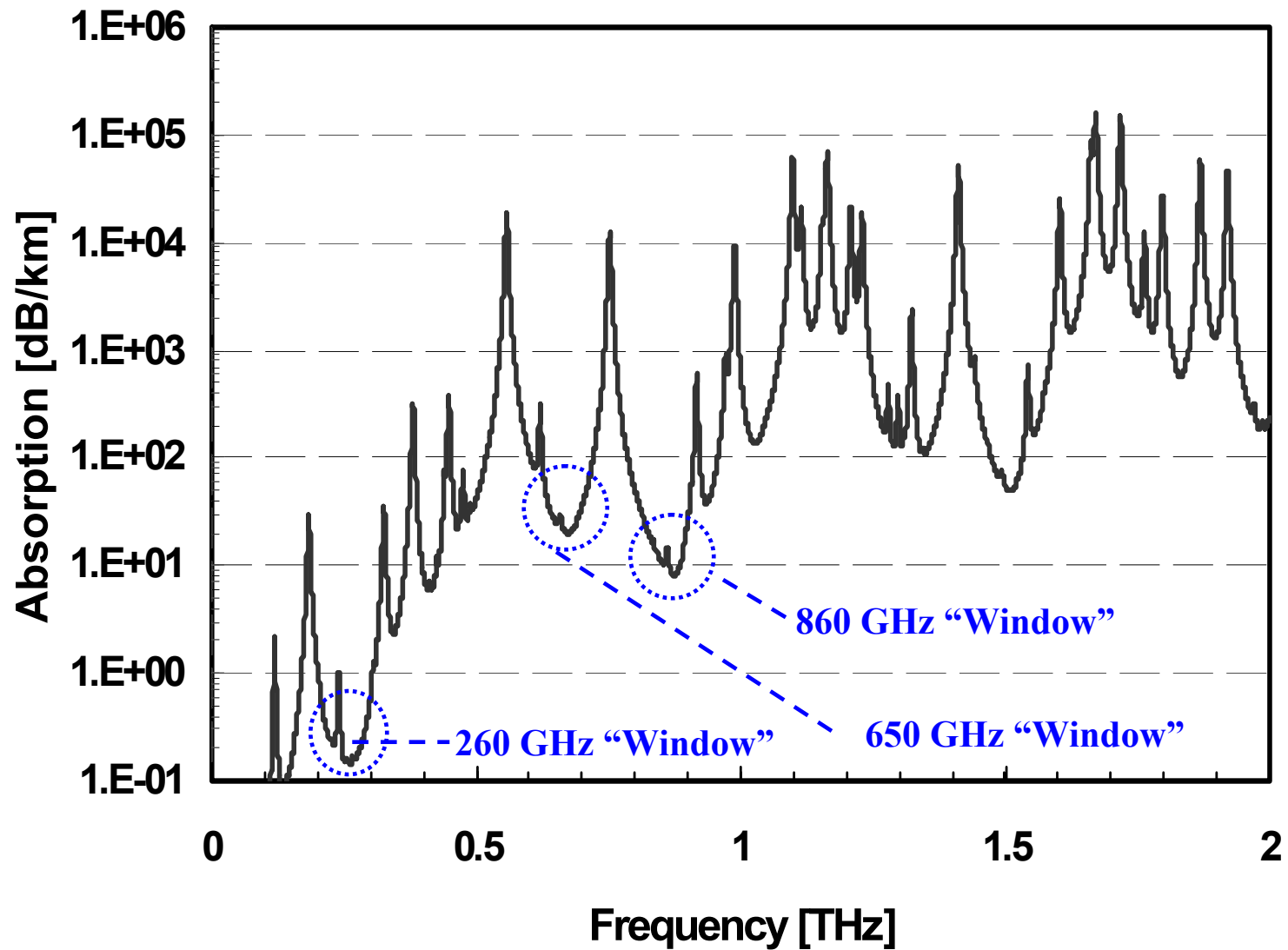
$$\Delta U = \frac{\hbar^2}{2I_x} [(l+1)(l+2) - l(l+1)] = \frac{\hbar^2}{I} (l+1) = \hbar\omega$$

This creates a “ladder” of photon frequencies as shown to the right

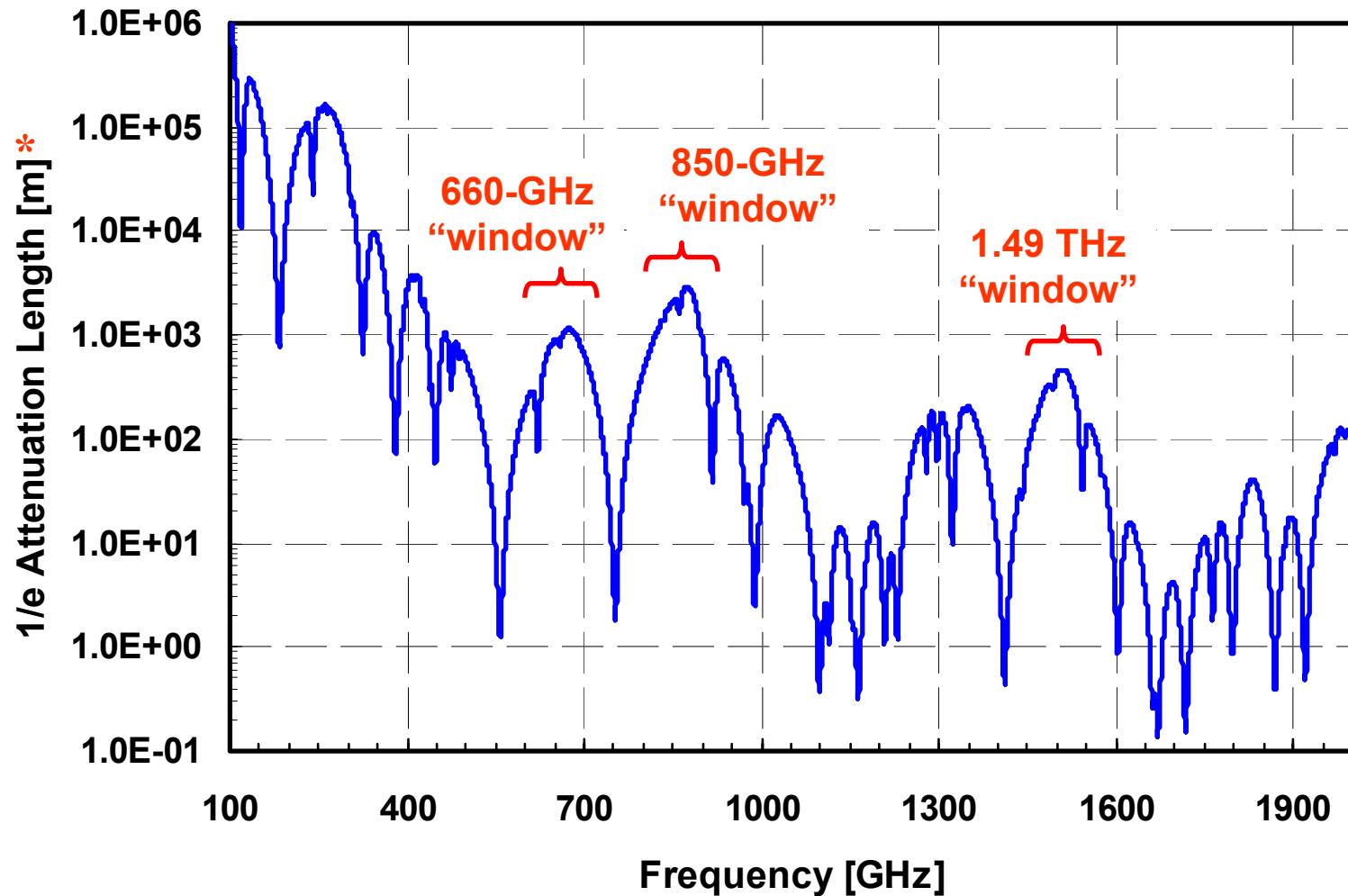
- Although highly polar, water is asymmetric rotor meaning that no two moments of inertia are equal. This follows from its non-colinear alignment between the three atoms
- Any of these purely rotational transitions will be easily observed if $\omega\tau \gg 1$ where τ is the momentum relaxation time (or dephasing time)
- Generally, $\tau > 100$ ps or more under STP conditions, so THz transitions are obvious



Atmospheric Simulation, Propagation “Windows”



Equivalent Attenuation Length



* Since Lambert-Beer law of transmission, $T = \exp(-\alpha z)$ applies the 1/e attenuation length is a “natural” metric

Notes #3, ECE594I, Fall 2008, E.R. Brown

Ten Strongest Water Vapor Lines in THz Region

(the big “whoppers”)

Freq [THz]	Peak Attenuation [dB/m]
0.558	18.4
0.758	12.7
0.989	9.4
1.098	61.6
1.164	71.6
1.412	52.9
1.671	163.6
1.718	150.0
1.869	59.9
1.920	46.3

Absorption Models for Liquids and Solids

(1) Drude model of conductors :

$$\epsilon = \epsilon_{back} - j \frac{\sigma}{\omega} \quad \sigma = \frac{\sigma_0}{1 - j\omega\tau} \quad \left\{ \begin{array}{l} \tau \rightarrow \text{momentum relaxation time} \\ \sim 10 \text{ fs in common metals @300 K} \\ > 100 \text{ fs in semiconductors @300 K} \end{array} \right.$$

(2) Debye model of polar liquids (single component):

Single Debye

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_0 - \epsilon_{\infty}}{1 + j(\nu / \nu_1)}$$

Double Debye

$$\epsilon = \epsilon_{\infty} + \frac{\epsilon_0 - \epsilon_1}{1 + j(\nu / \nu_1)} + \frac{\epsilon_1 - \epsilon_{\infty}}{1 + j(\nu / \nu_2)}$$

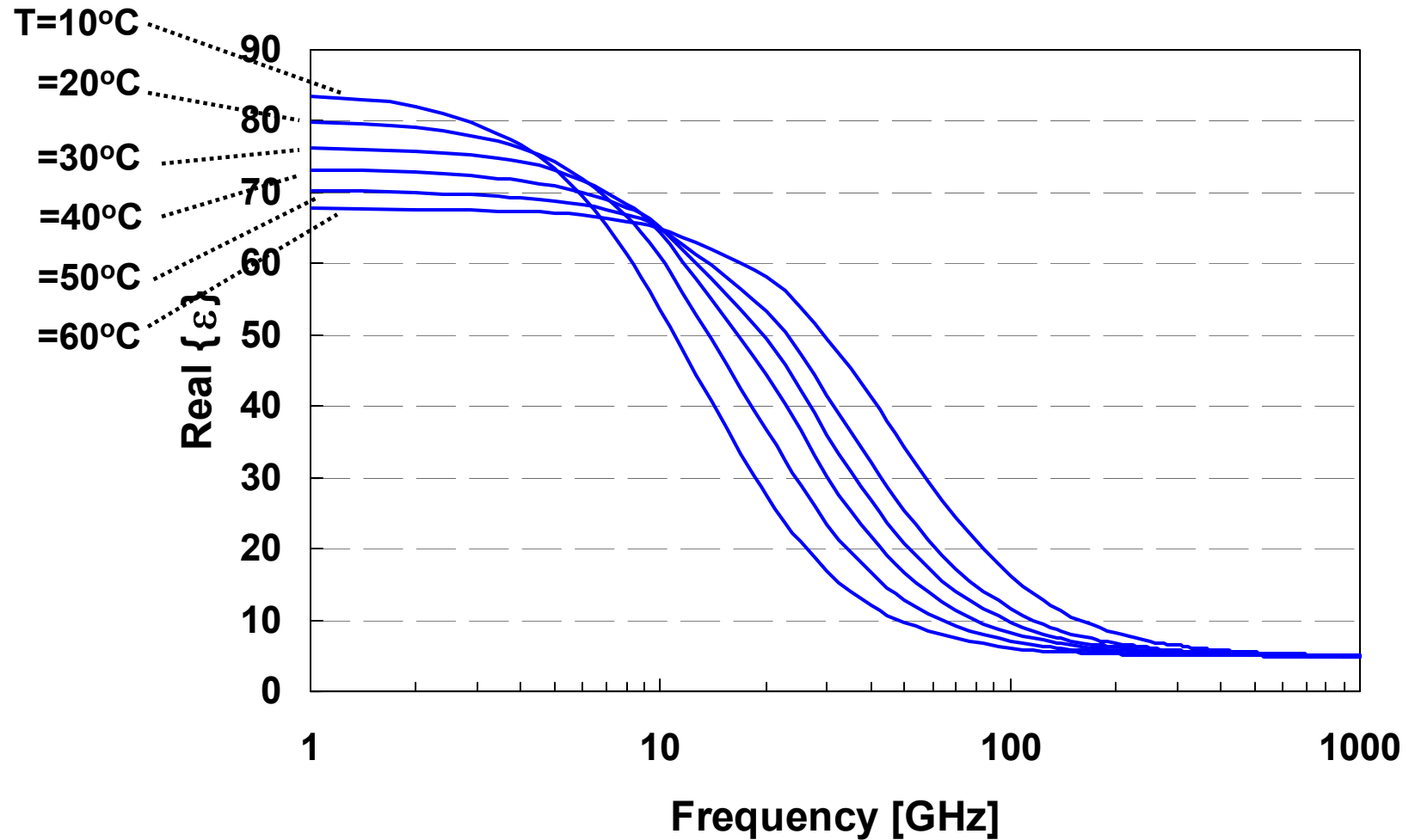
e.g., for pure water at 300 K, single Debye relaxation frequency $\nu_1 = 17.5$ GHz, and the dielectric constants ϵ_0 and ϵ_{∞} are 79.7 and 5.26, respectively

(3) Independent of absorption model, Maxwell's eqns predict:

$$\alpha = 2\omega \left\{ \frac{\mu\epsilon'}{2} \left[\sqrt{1 + (\epsilon''/\epsilon')^2} - 1 \right] \right\}^{1/2} \quad \text{where} \quad \epsilon \equiv \epsilon' + j\epsilon''$$

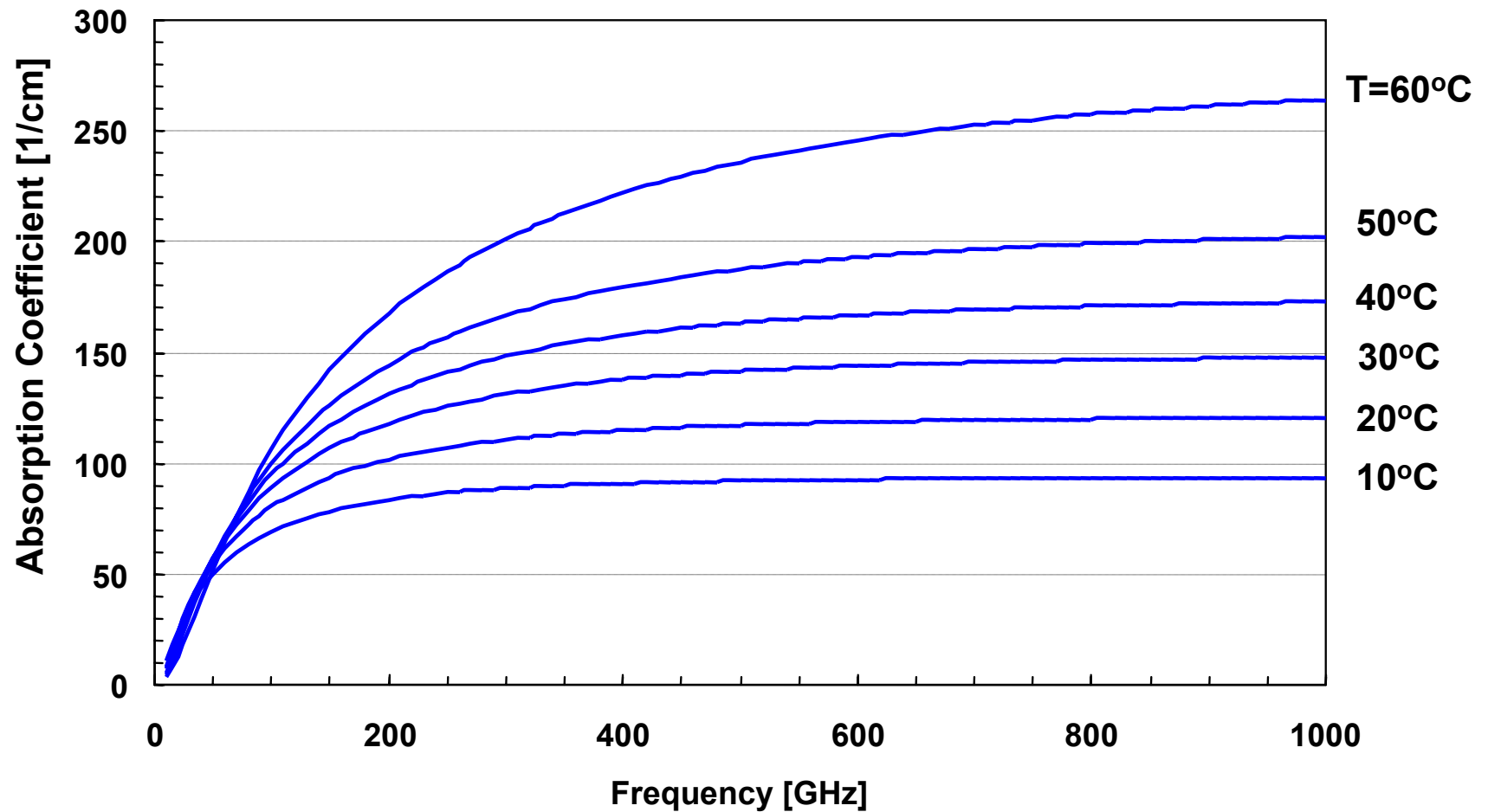
Single-Debye Model for Liquid Water

($\epsilon_0 = 78.2$, $\epsilon_\infty = 4.9$, $\tau = 8.1$ ps, all at 25°C)

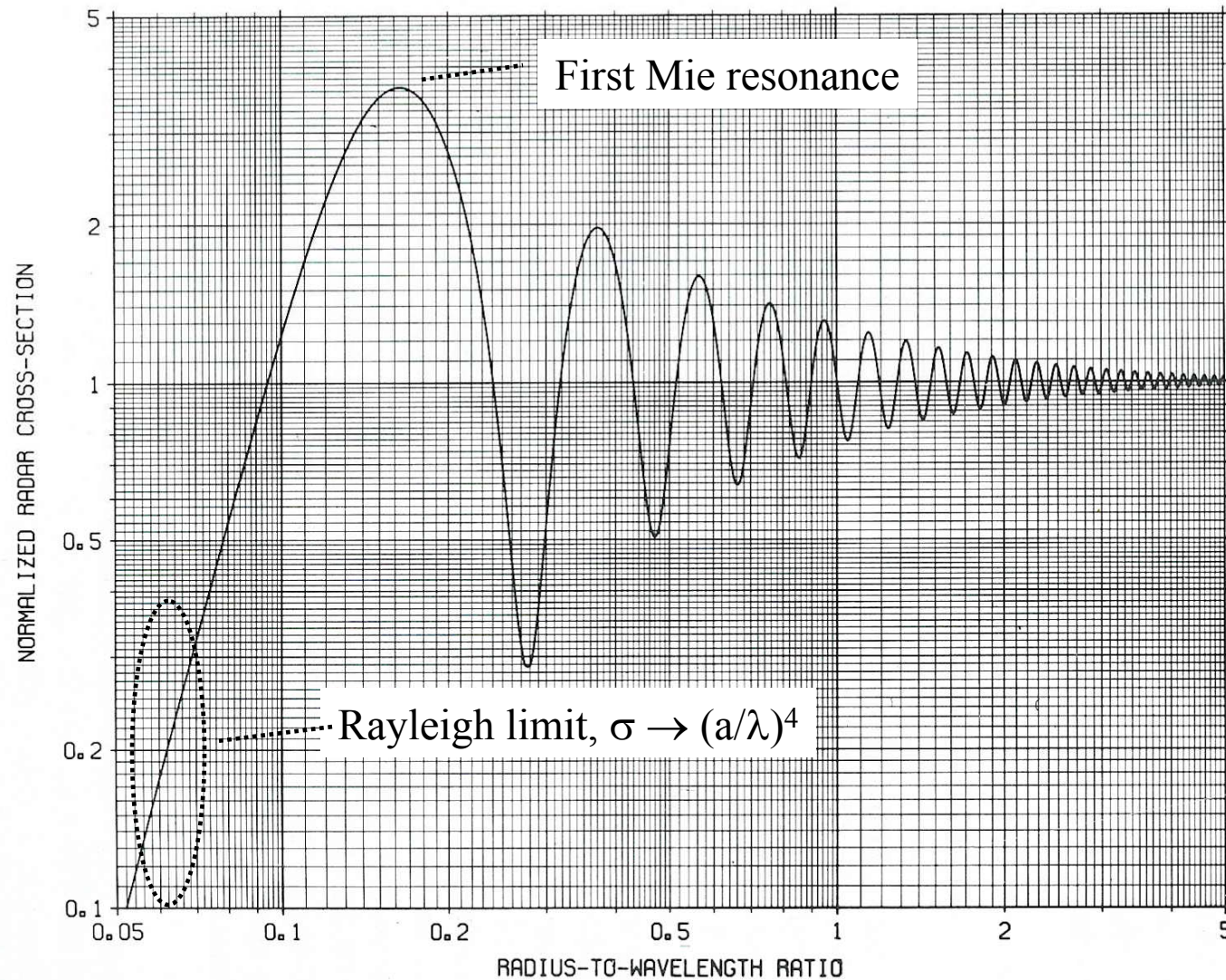


Single-Debye Model for Liquid Water (cont)

($\epsilon_0 = 78.2$, $\epsilon_\infty = 4.9$, $\tau = 8.1$ ps, all at 25°C)



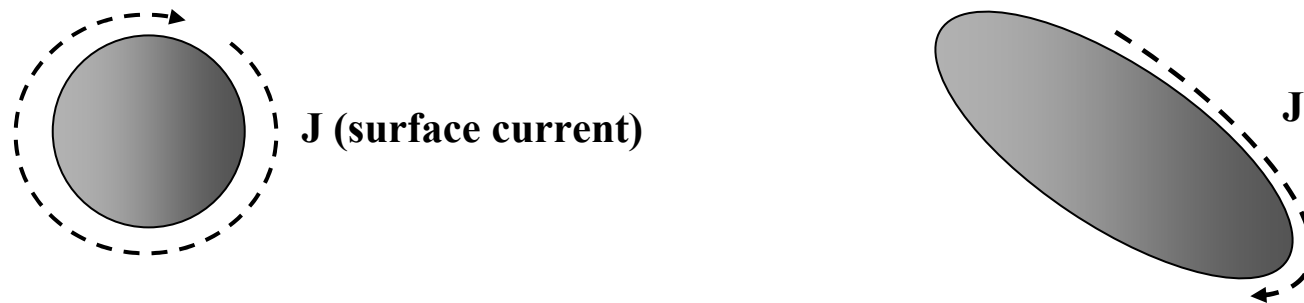
Scattering from a Conducting Sphere



[L.V. Blake, "Radar Range Performance Analysis," (Artech House, Norwood, MA, 1986), Fig. 3-1].

Resonant Scattering

The maximum is $\sigma \approx 3.65 \pi a^2$ at $a = 0.163 \lambda$. This is called resonant (Mie) scattering and is caused by constructive interference of surface currents flowing around the sphere. Same effect occurs in ellipsoids and arbitrary-shaped solids... just not as strong as in spheres



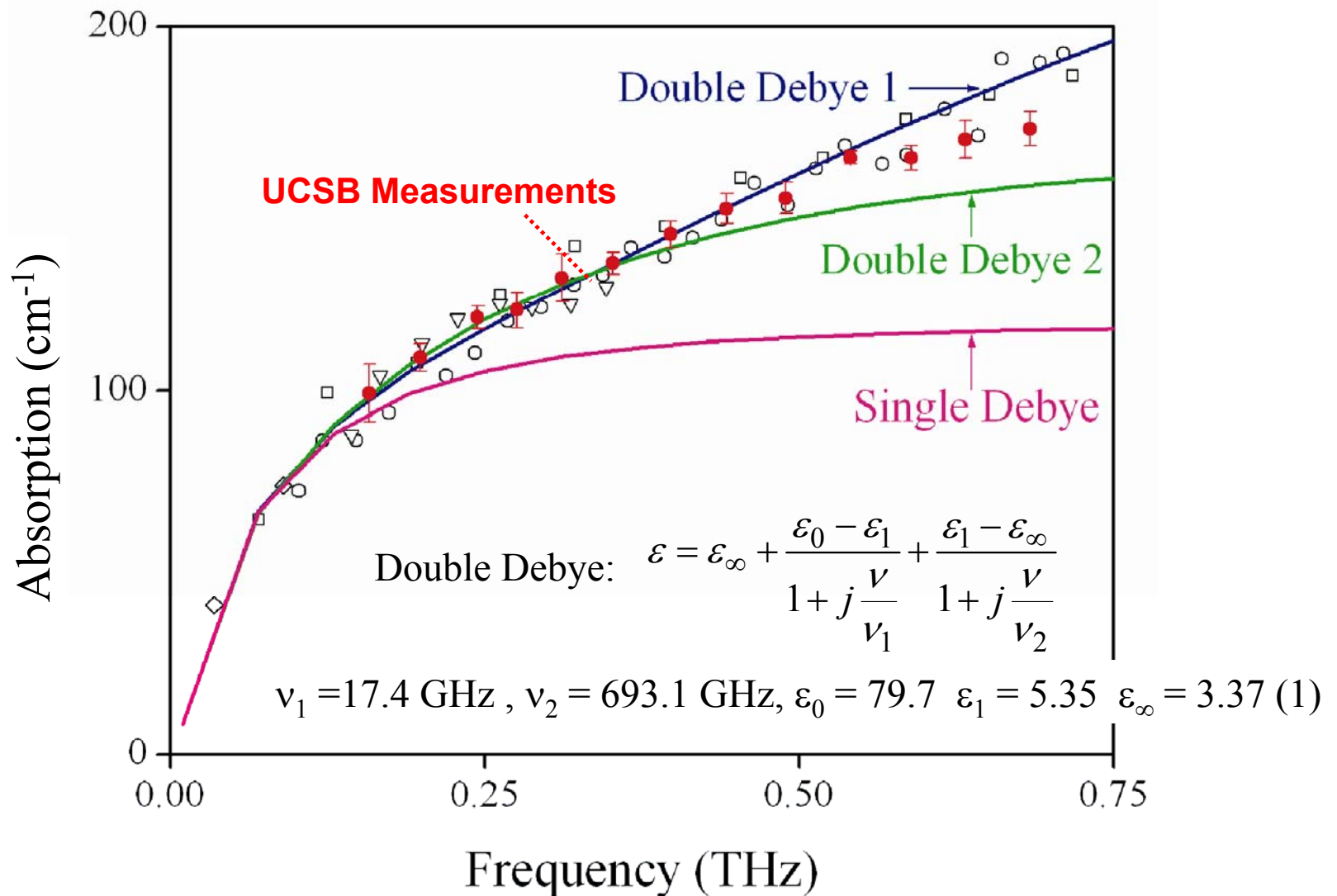
Intuitive estimate of surface resonance assuming surface current velocity of c :

$$2\pi = \omega t = \omega(2\pi a/c) \Rightarrow a = \lambda/2\pi = 0.159 \lambda$$

Example: at 1.0 THz ($\lambda = 333 \mu\text{m}$), resonant Mie scattering occurs for a particle diameter of $106 \mu\text{m}$

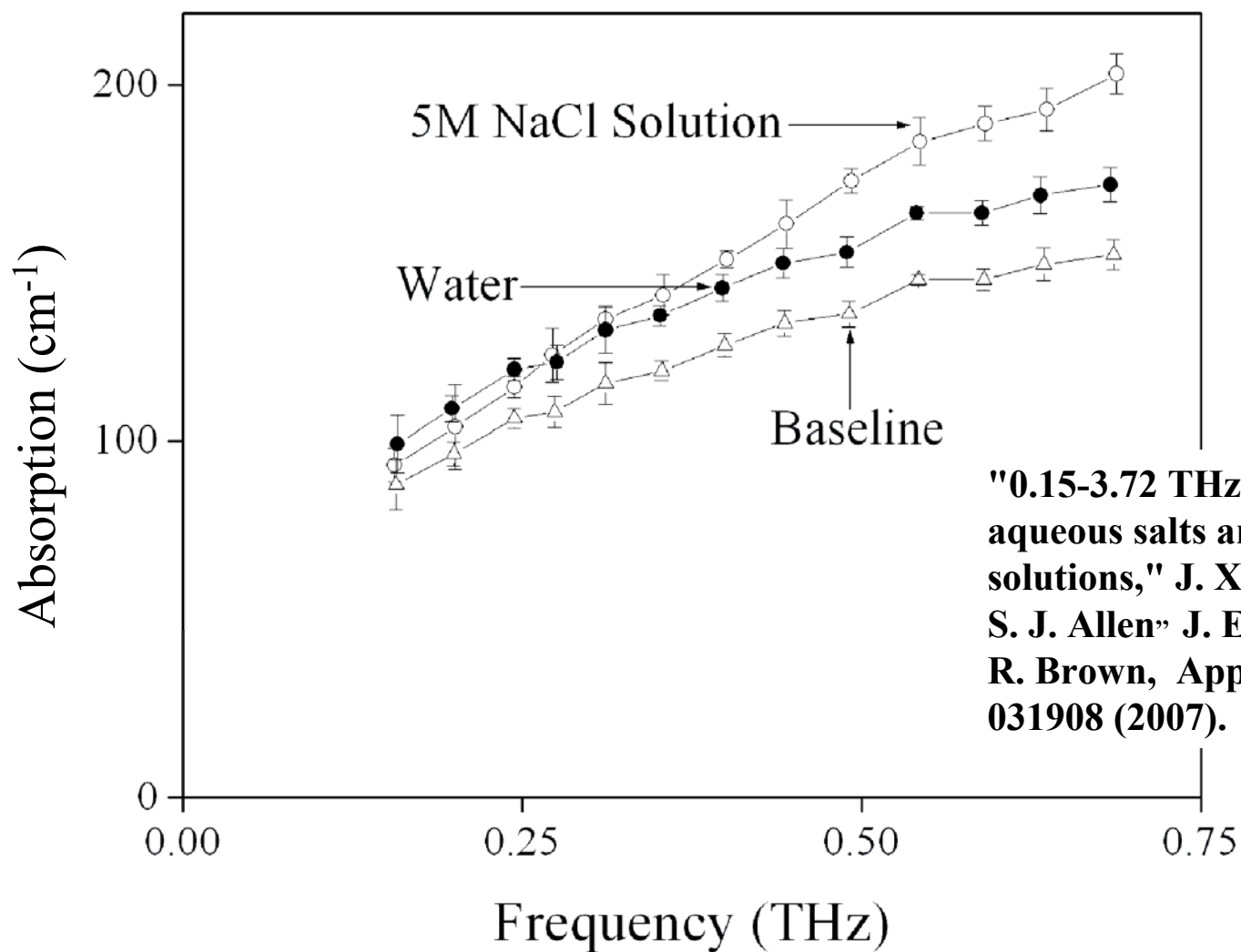
- Many materials (e.g., powders such as sugar; composites such as RT-Duroid) have inhomogeneity on the 100 micron scale $\Rightarrow$ strong THz scattering

Pure Liquid Water at THz Frequencies



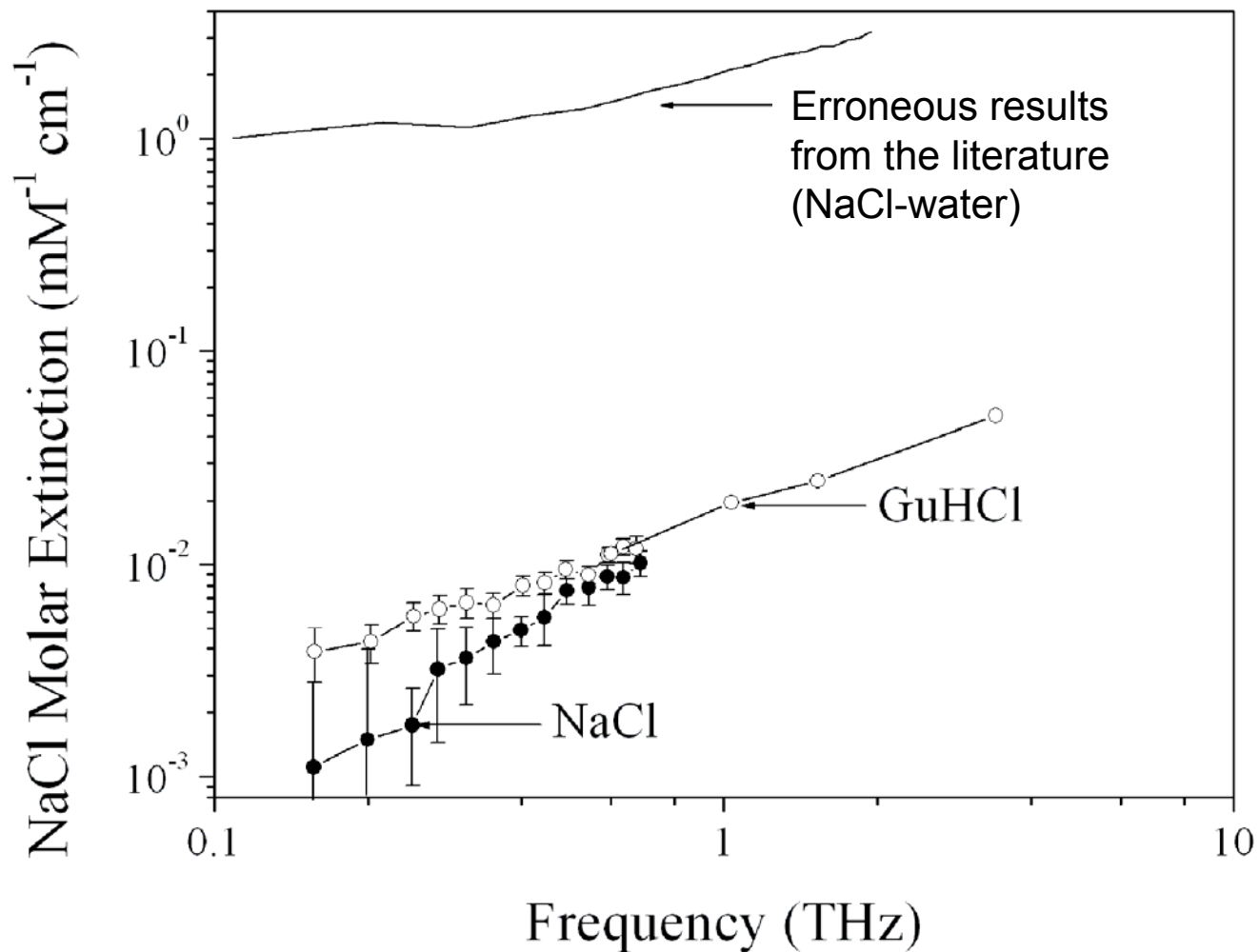
(1) H. J. Liebe, G. A. Hufford, and T. Manabe, Int. J. Infr. Millim. Waves, 12, 659 (1991).

Salt Water



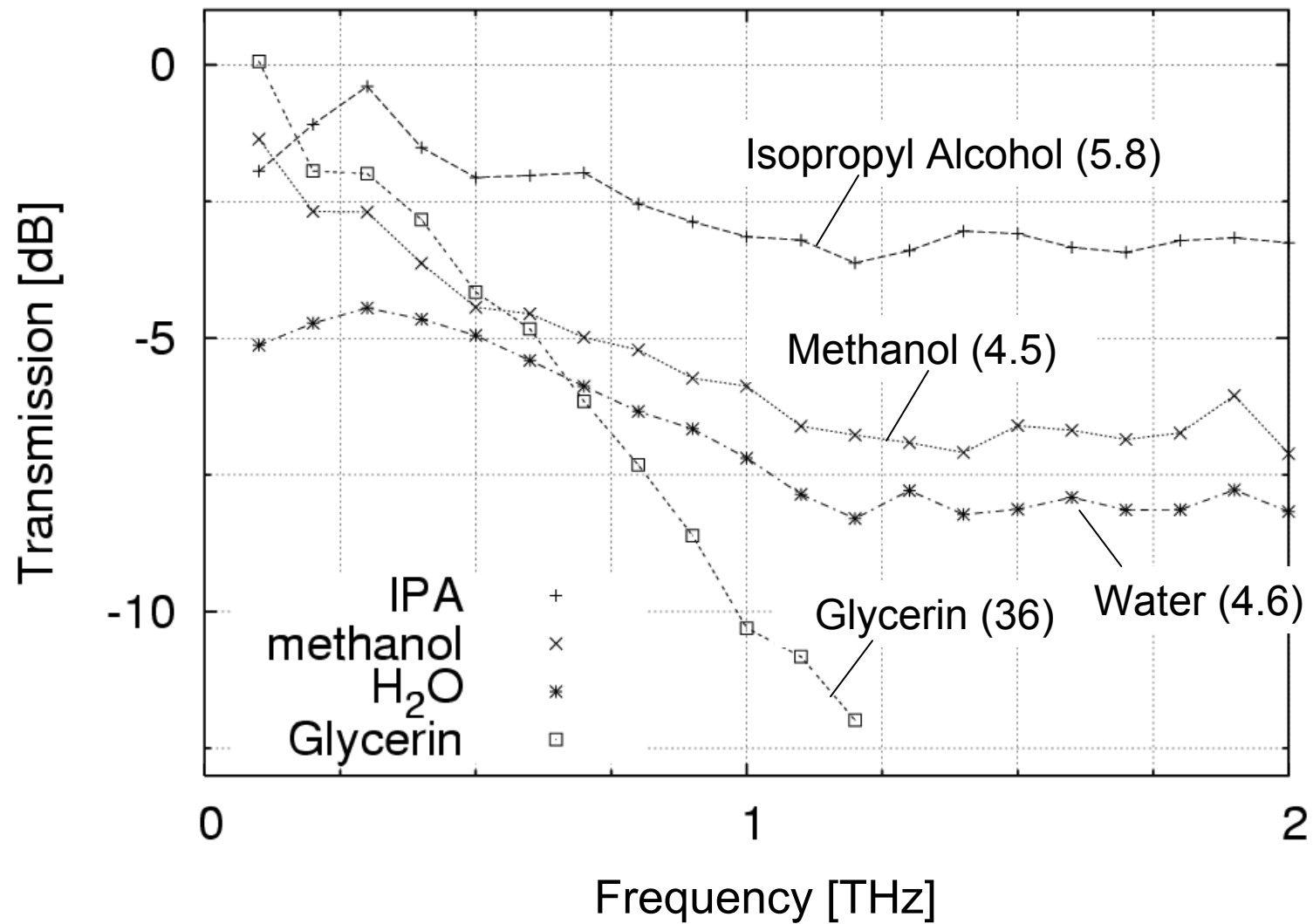
"0.15-3.72 THz absorption of aqueous salts and saline solutions," J. Xu, K. W. Plaxco, S. J. Allen" J. E. Bjarnason, E. R. Brown, Appl. Phys. Lett, 90, 031908 (2007).

Disagreement about Salt Water



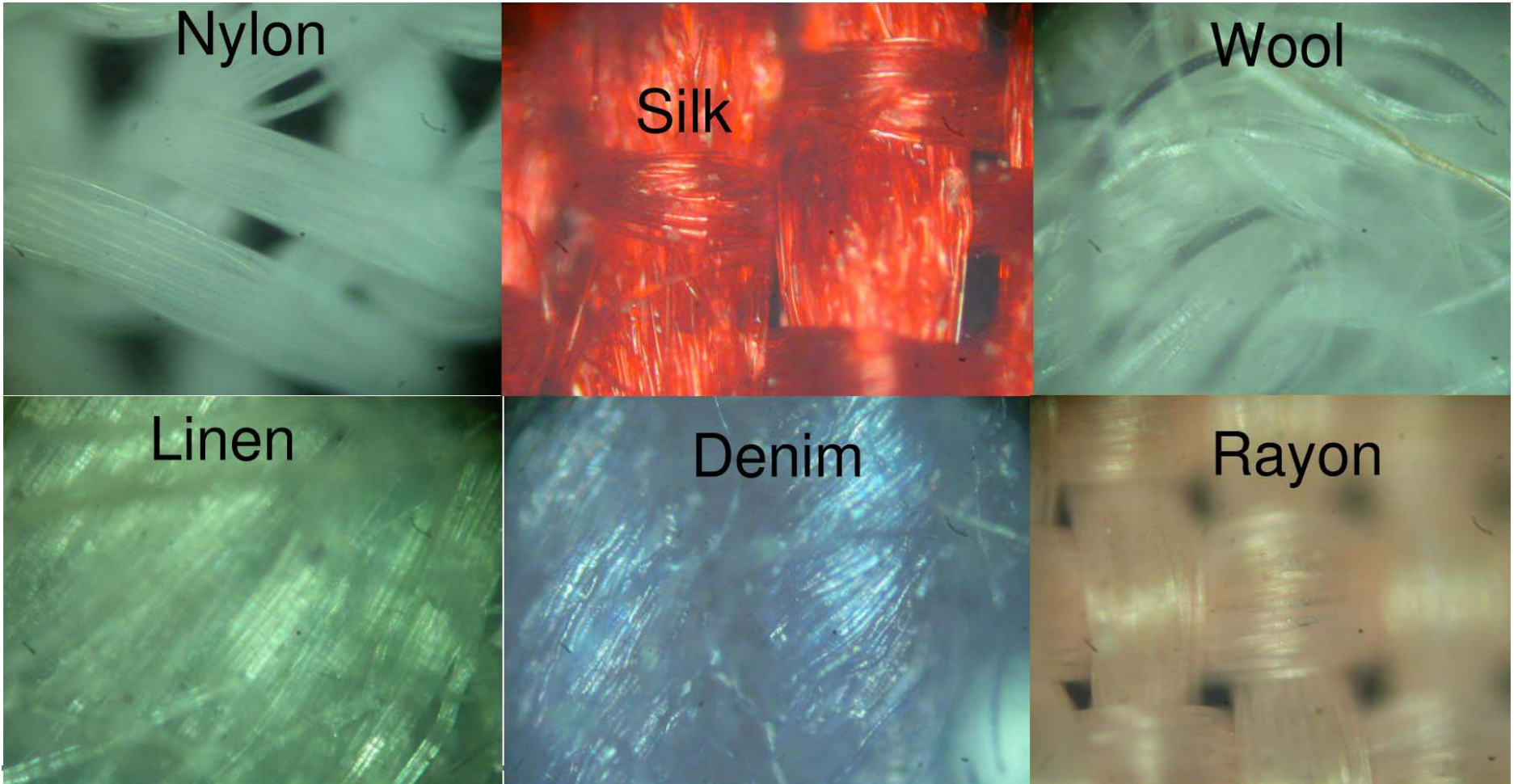
"0.15-3.72 THz absorption of aqueous salts and saline solutions," J. Xu, K. W. Plaxco, S. J. Allen, J. E. Bjarnason, E. R. Brown, *Appl. Phys. Lett.*, 90, 031908 (2007).

Other Liquids of Varying Polarity



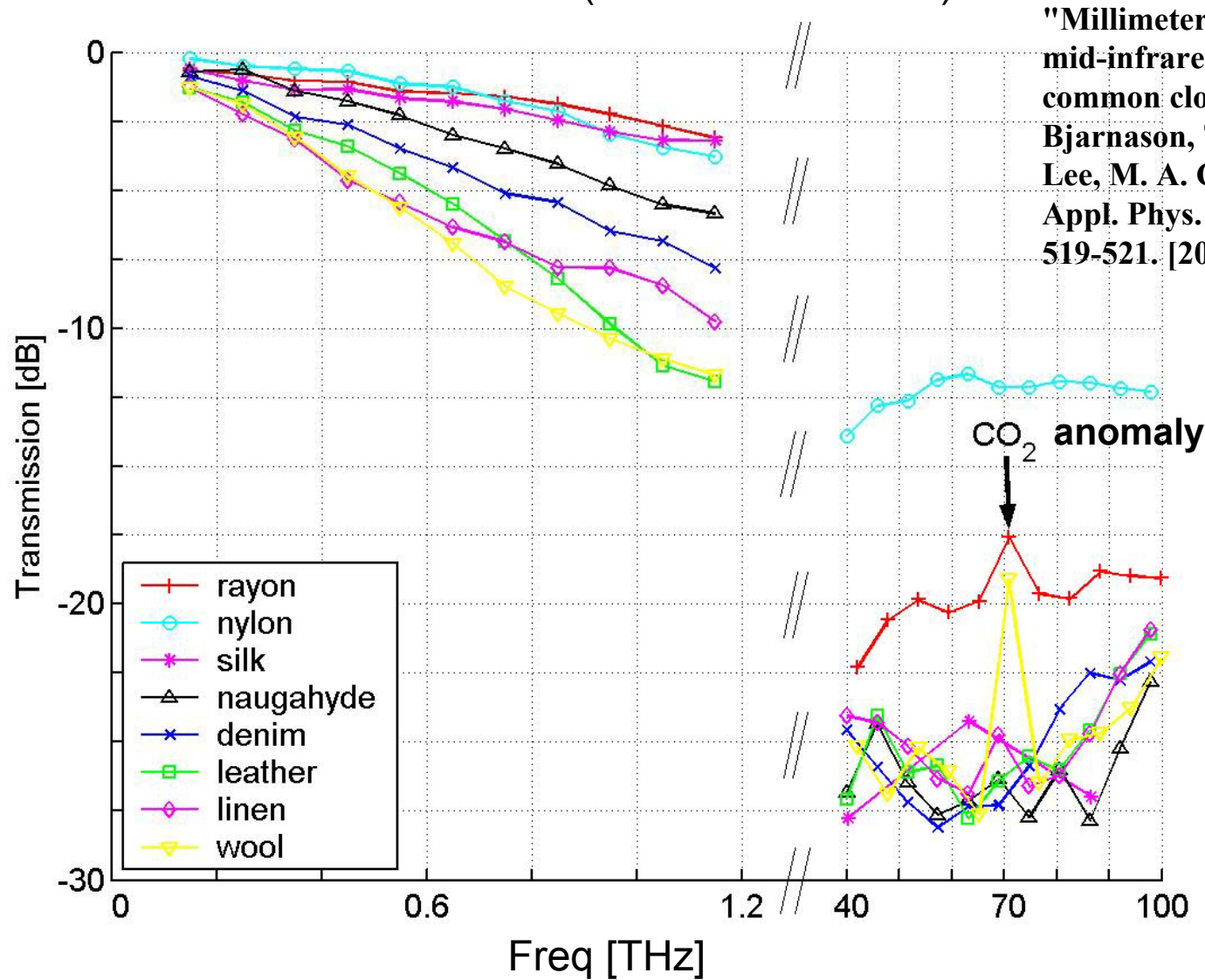
Common Cloathing Samples

300 μm



Transmission through Common Clothing

(The "Linen Closet")

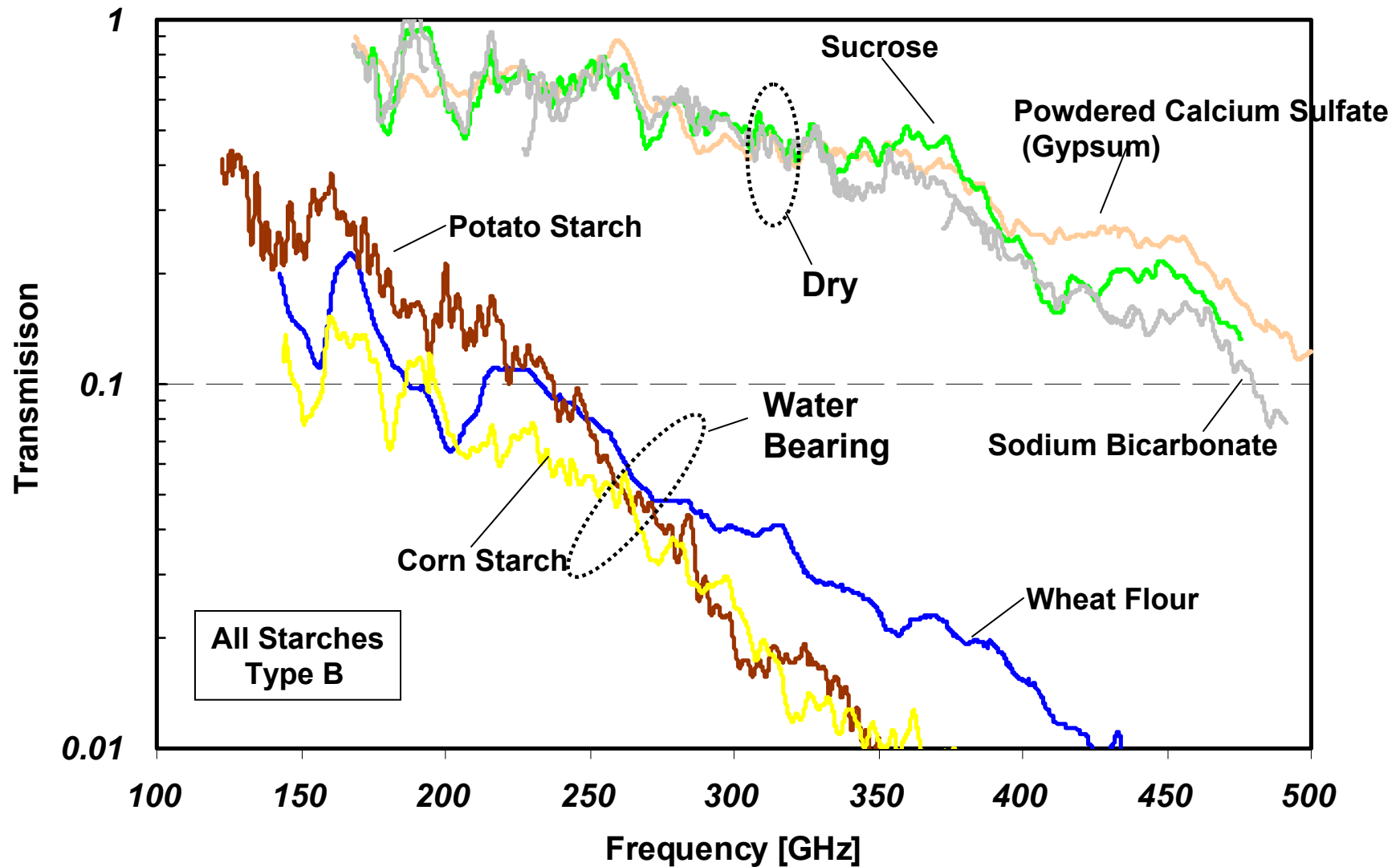


"Millimeter-wave, terahertz, and mid-infrared transmission through common clothing", J. E.

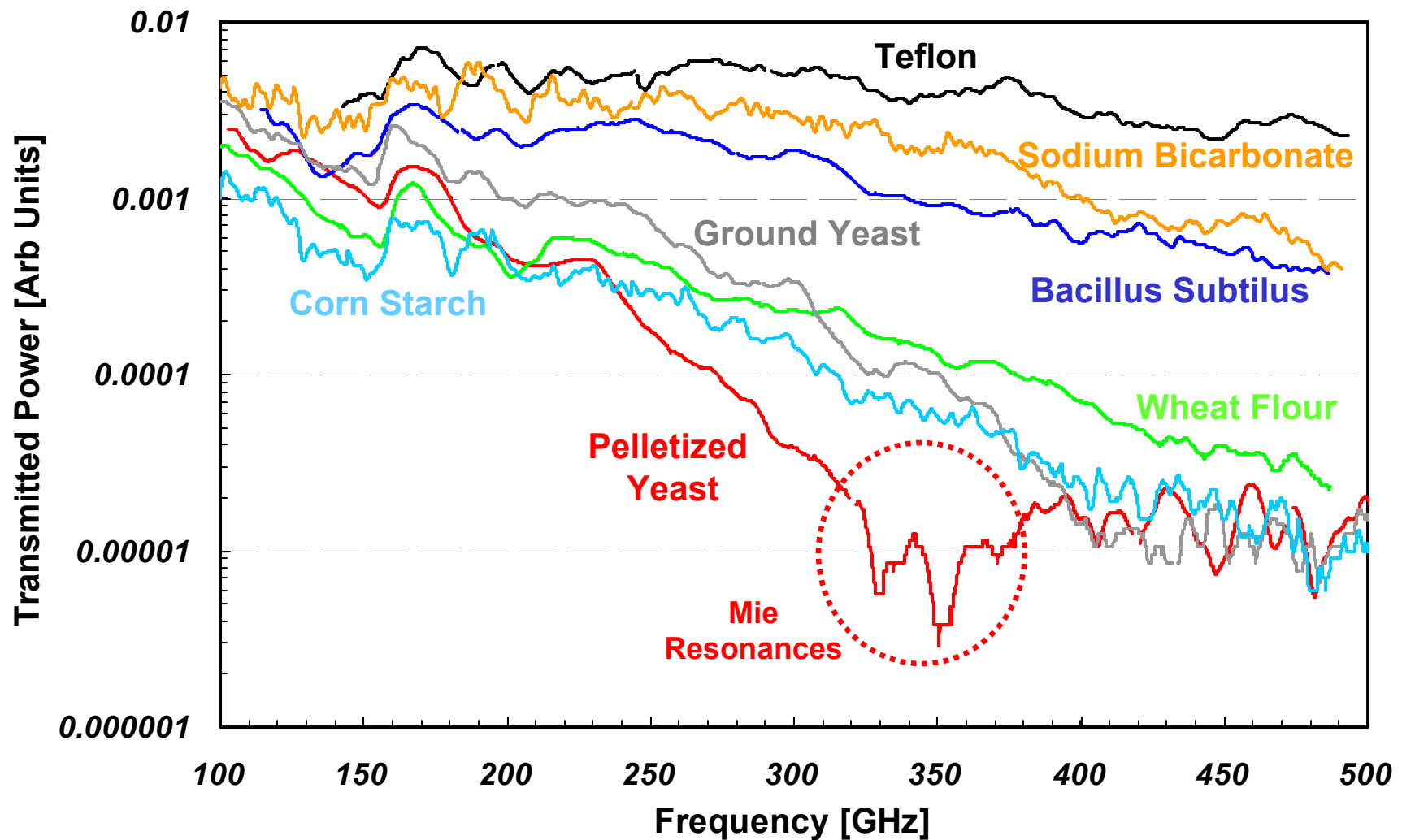
Bjarnason, T. L. J. Chan, A. W. M. Lee, M. A. Celis, and E. R. Brown, Appl. Phys. Lett. vol. 85 (no. 4), pp. 519-521. [2004]

THz Transmission through Organic and Biomaterials

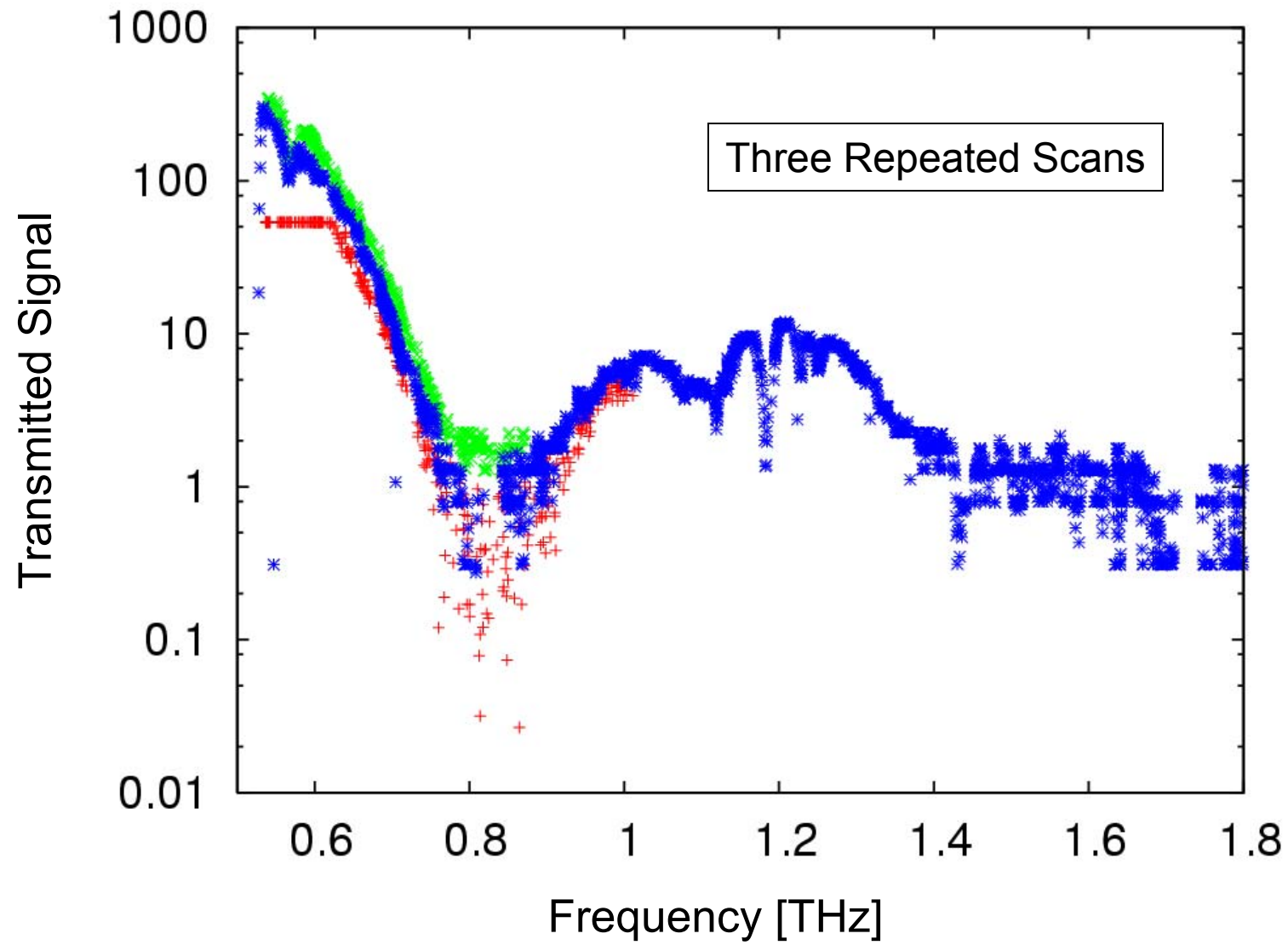
(The “Kitchen Cupboard”)



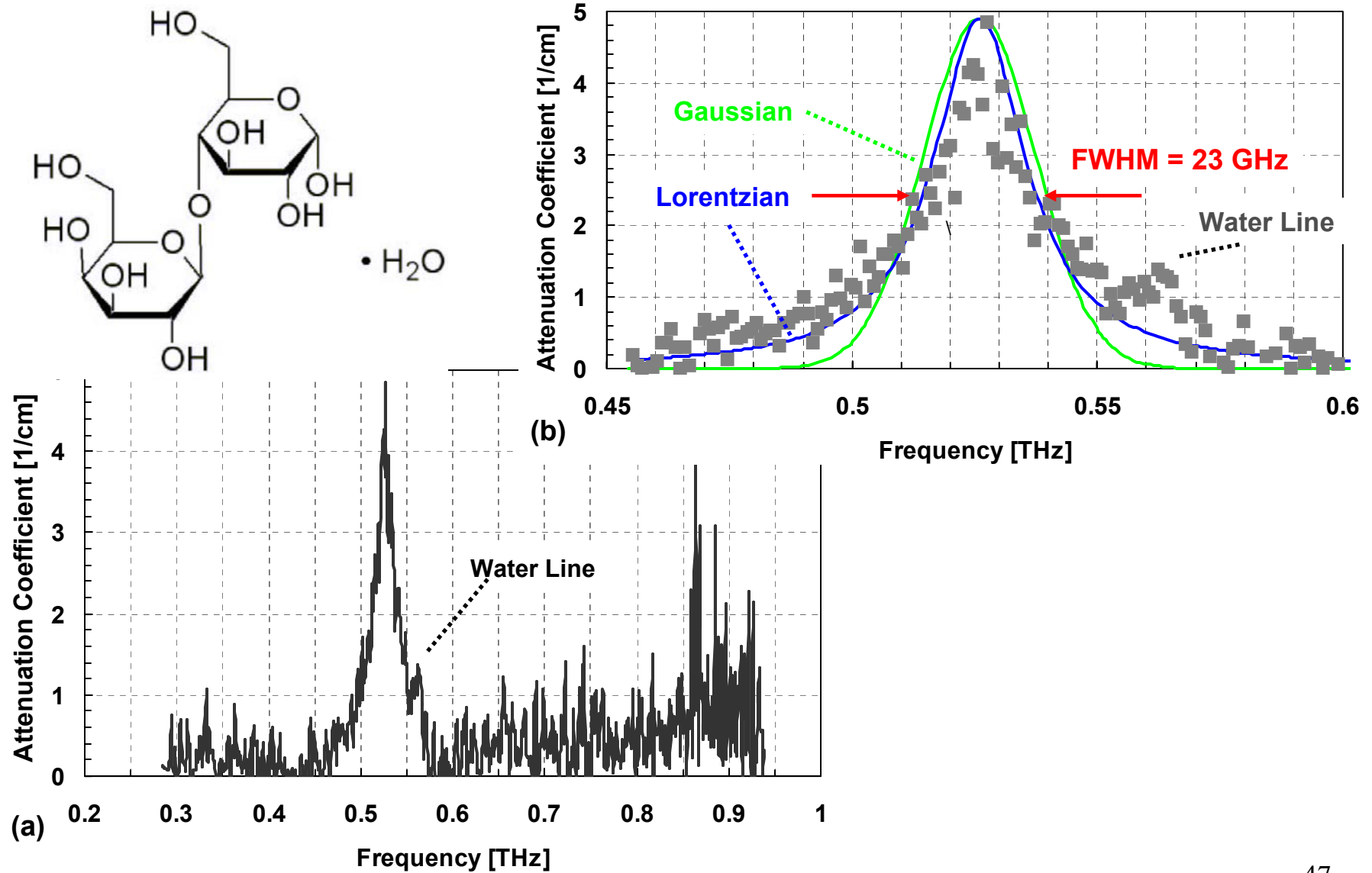
THz Transmission through Organic and Biomaterials (cont)



C4 Explosive (~90% RDX)

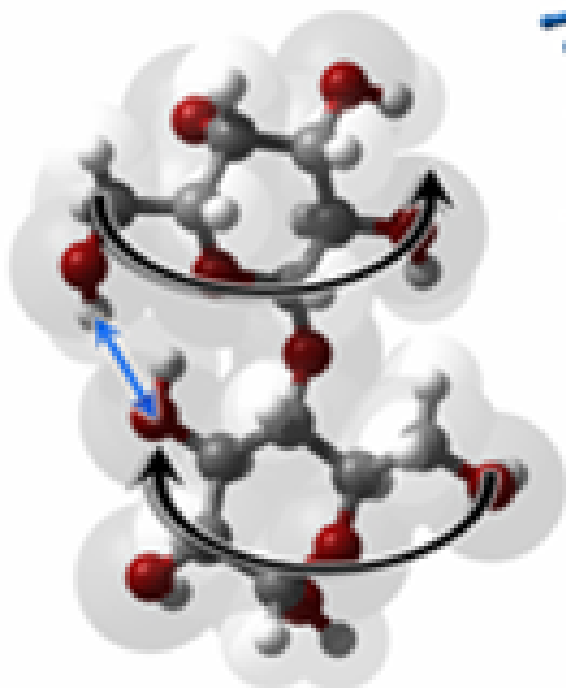


Notes #3, ECE594I, Fall 2008, E.R. Brown
Narrow Macromolecular Resonances
(Lactose Monohydrate)

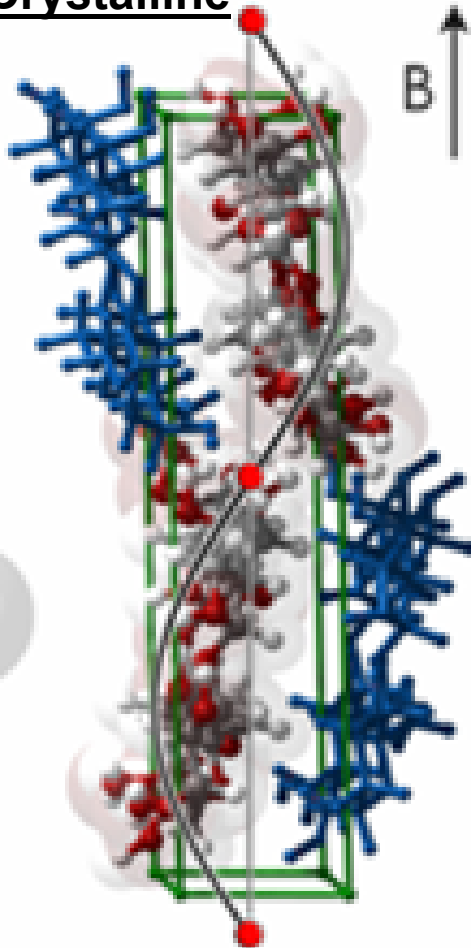


THz Vibrational Resonance of Lactose Monohydrate

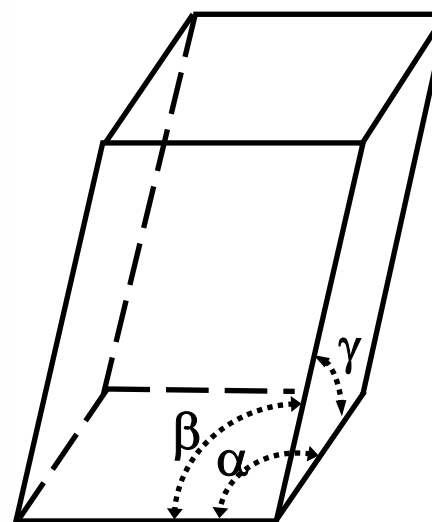
Isolated



Crystalline



“Assignment of the Lowest-Lying THz Absorption Signatures in Biotin and Lactose Monohydrate by Solid-State Density Functional Theory,” D.G. Allis, A.M. Fedor, T.M. Korter, J.E. Bjarnason, and E.R. Brown, accepted to Chem. Phys Lett, Feb. 2007.



Monoclinic
Primitive
Unit Cell

Low-lying Sub-THz resonances can be explained only by combination of intramolecular “twisting” (hindered rotation) plus intermolecular coupling