

1.

## Motivations

### Acoustic waves ( $\Omega, q$ ) in glasses

Linear dispersion  $\Omega = vq$

Energy mean free path  $l^{-1}$  (spatial attenuation  $\alpha$ ) or internal friction  $Q^{-1}$

$$l^{-1} = \alpha = \frac{2\Gamma}{v} \quad Q^{-1} = \frac{2\Gamma}{\Omega} = \frac{l^{-1}v}{\Omega}$$

In crystals mechanisms for  $Q^{-1}$  are phonon relaxations via anharmonic interactions (Akhiezer),  $\Gamma \propto \Omega^2$

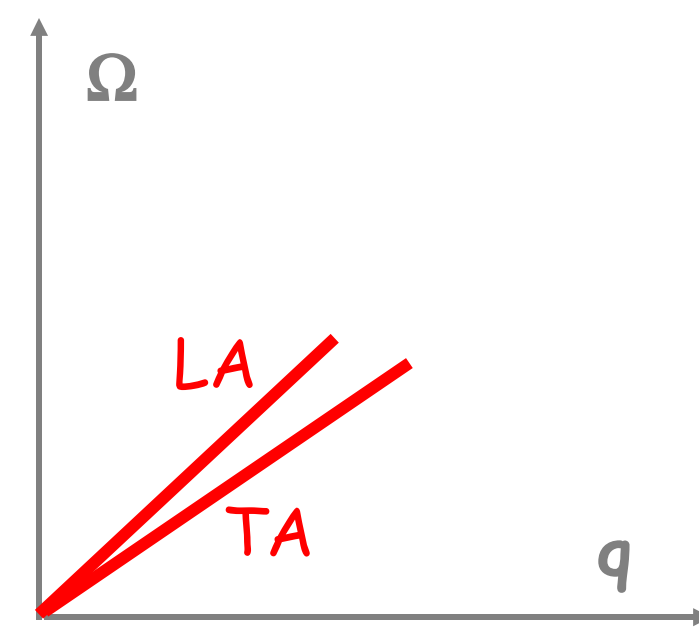
In glasses several mechanisms lead to sound attenuation and dispersion :

- coupling with two-level systems (TLS) dominant below 3K
- coupling with thermally activated relaxations (TAR) of structural « defects » : dominant at sonic and ultrasonic frequencies
- anharmonicity or « network viscosity »
- Rayleigh scattering of the sound waves by static density or elastic constant fluctuations
- coupling with modes in excess (Boson peak)  $\rightarrow$  end of acoustic branches (?)

### Damping of sound and velocity dispersion

Relative variation of sound velocity :  $\frac{\delta v}{v} = \frac{v(\Omega, T) - v_0}{v_0}, v_0 = v(\Omega, T \rightarrow 0)$

$Q^{-1}$  and  $2\delta v/v$  are Kramers-Krönig transforms of each other :  $-\frac{2\delta v(\Omega, T)}{v} = \frac{1}{\pi} P \int_{-\infty}^{+\infty} \frac{Q^{-1}(x, T)}{x - \Omega} dx$



2.

## High resolution Brillouin light spectroscopy

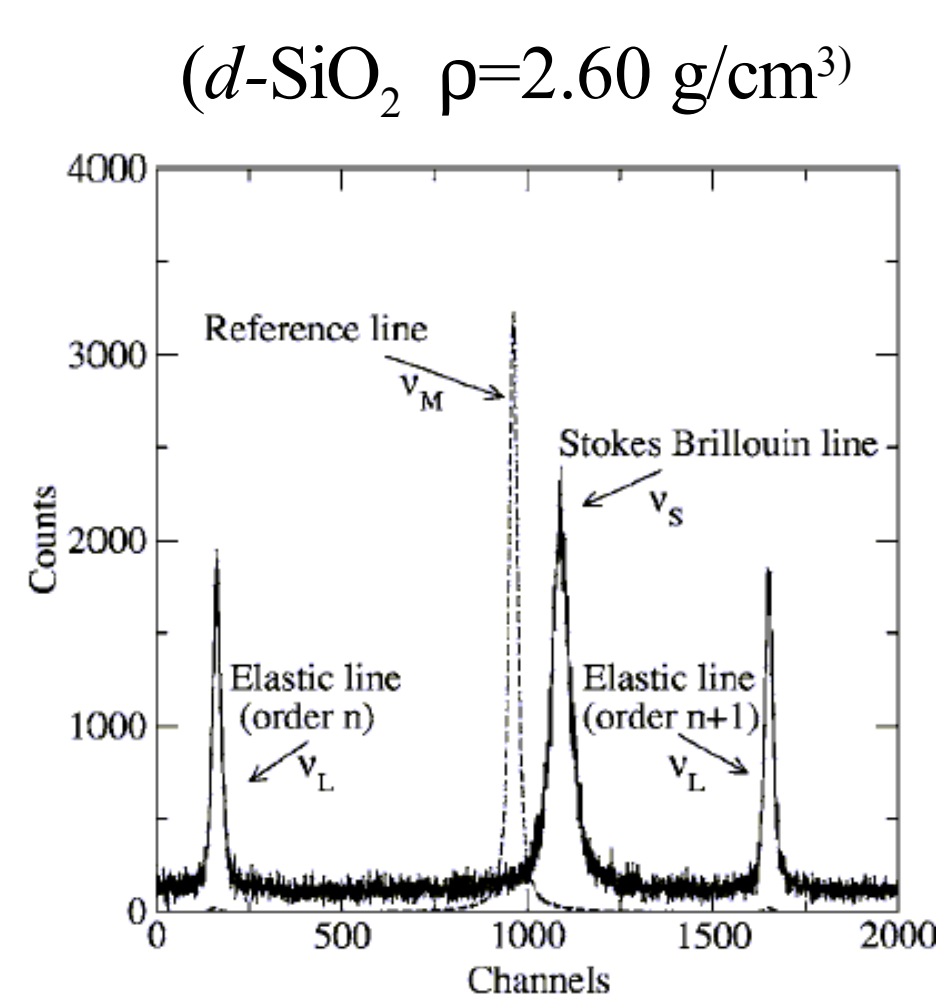
### Plane Fabry-Perot (PFP)

- Free Spectral Range (FSR) ~ 100 GHz
- 4 passes  $\Rightarrow$  high contrast  $C \sim 10^{10}$
- stabilized with a reference signal generated by electro-optic modulation of the laser light ( $v_0 \pm v_M$ )
- $v_M$  fixed to  $v_B$

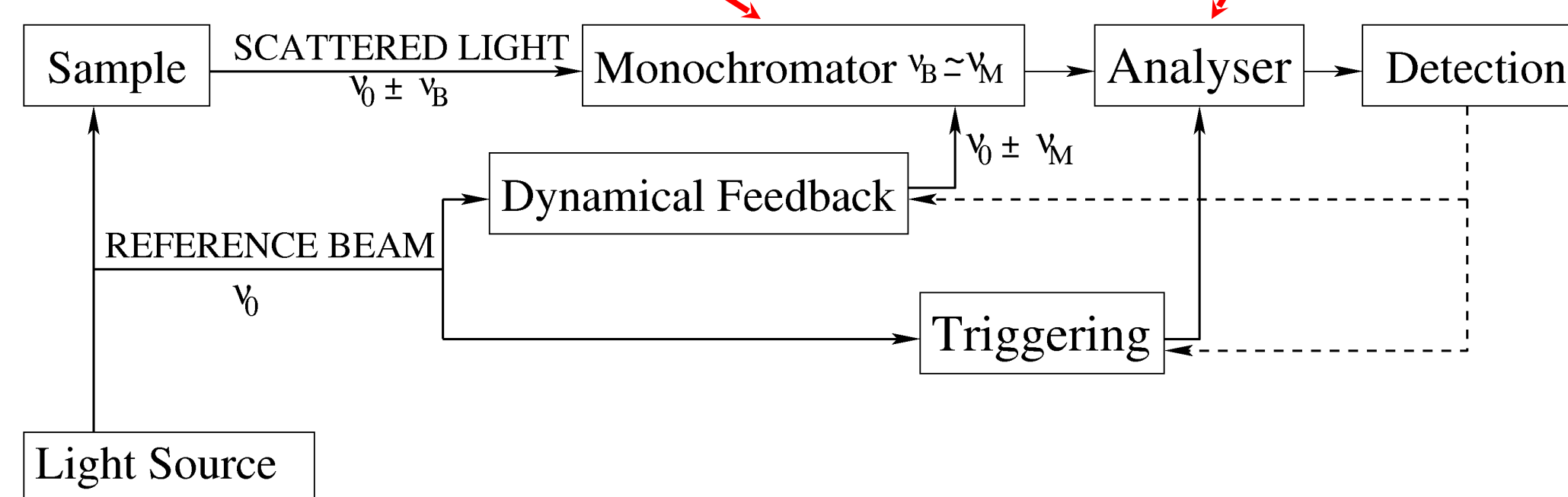
### Spherical Fabry-Perot (SFP)

- FSR ~ 1.5 GHz
- instrumental Half-Width ~ 15 MHz
- calibration with the reference signal  $v_0$
- $\Rightarrow$  high accuracy on  $v_B$

### Typical spectrum in densified silica



High resolution and accuracy  
 $v_B = 42.320 \pm 0.003$  GHz  
 $\Gamma = 25 \pm 3$  MHz

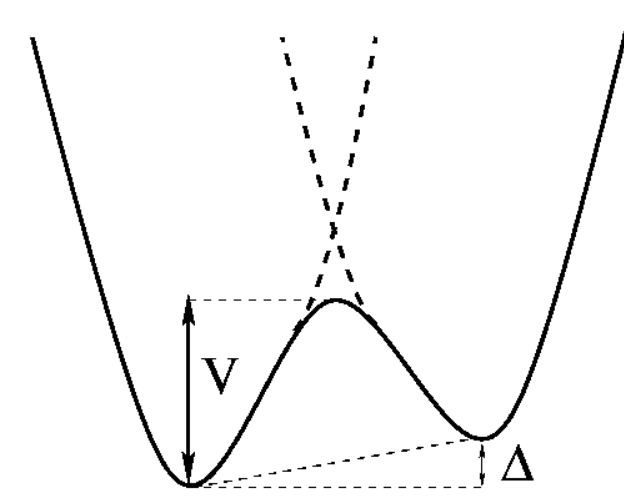


[H. Sussner, R. Vacher, Appl. Opt. 18 3815 (1979) • R. Vacher, H. Sussner, M. Schickfus, Rev. Sci. Instrum. 51 288 (1980)  
R. Violla, Opt. Instrum., Coll. de la société française d'optique, ed. Bouchareine (1996) • E. Rat et al, PRB, 72 214204 (2005)]

3.

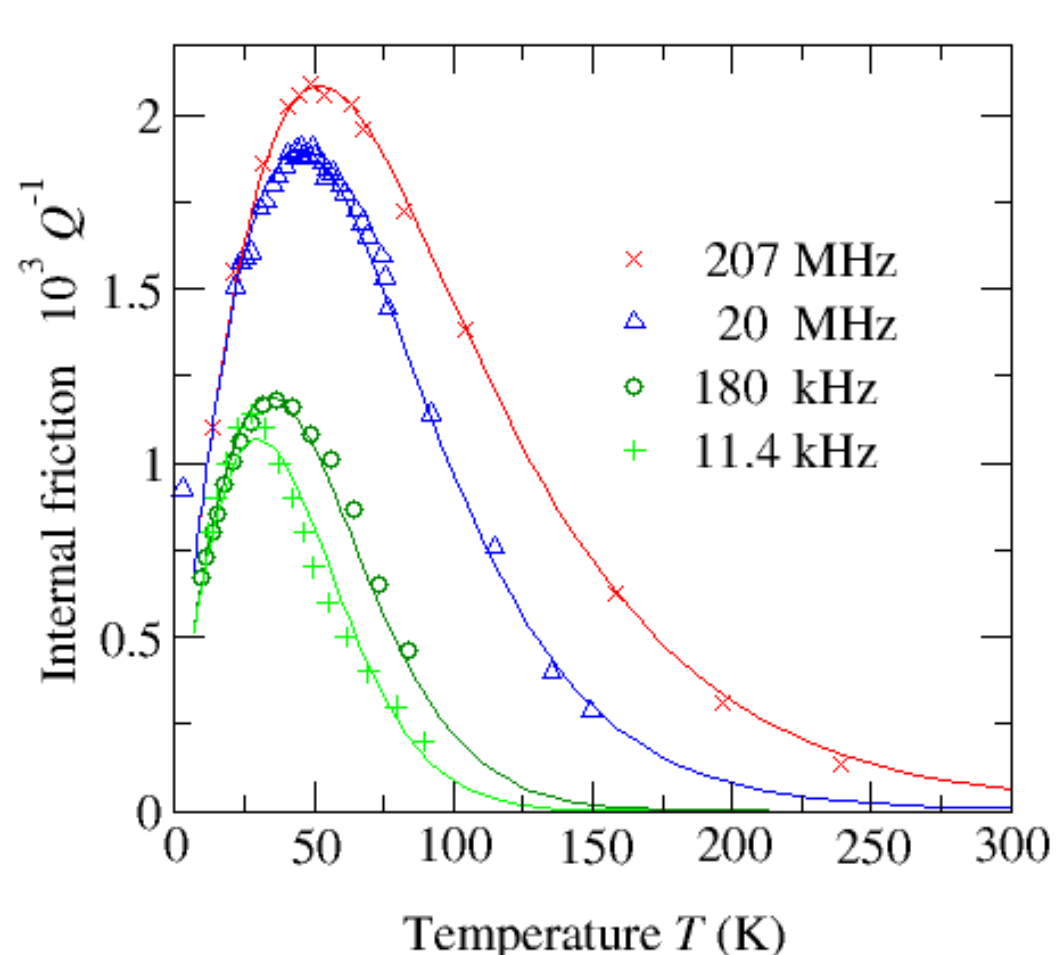
## Sonic and ultrasonic data

Thermally activated relaxations (TAR) : atoms or groups of atoms move in a double-well potential  $\rightarrow$  when the temperature is sufficient, the atoms jump above the barrier  $V$  with thermic activation



[W.A.Phillips, J.Low.Temp.Phys. 7 351 (1972) • P.W.Anderson, B.I.Halperin and C.M.Varma, Philos.mag 25 (1972)]

### Ultrasonic data for $\nu$ -SiO<sub>2</sub>



### Random defects distribution

$$P(\Delta, V) = f(\Delta)g(V) \quad \begin{cases} g(V) \propto V^{-1} \exp\left(-\frac{V^2}{2V_0^2}\right) \\ f(\Delta) \propto \exp\left(-\frac{\Delta^2}{\Delta_c^2}\right) \\ \tau = \tau_0 \exp\left(\frac{V}{T}\right) \sec\left(\frac{\Delta}{2T}\right) \end{cases}$$

### Parameters of the TAR model

- $V_0 = 659 \pm 19$  K (high value of  $V_0$ )
- $\log_{10} \tau_0 = -12.2 \pm 0.18$
- $V_0/\Delta_c = 8.2 \pm 0.6$  (small cutoff value  $\Delta_c$ )
- $\xi = 1/4$
- $C = 1.4 \cdot 10^{-3}$  (constant value over 4 decades)

[R.Vacher, E.Courtens and M.Foret, PRB 72 214205 (2005)]

× R.Vacher et al JNCS 45 397 (1981)

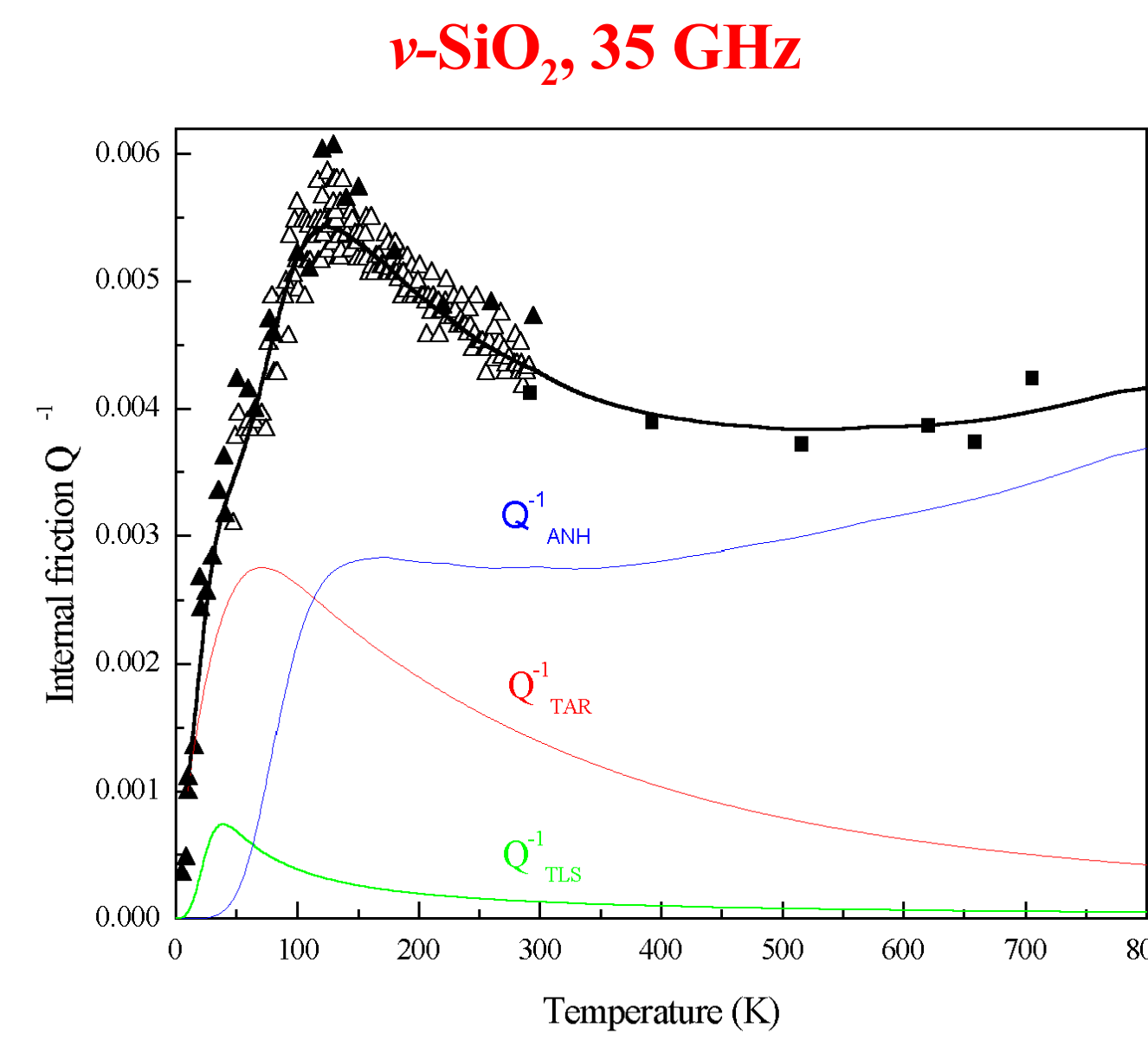
$\Delta$  Q.L.Anderson et al J.Am.Ceram.Soc. 38 125 (1955)

O R.Keil et al JNCS 164 1183 (1993)

+ D.Tielbürger et al PRB 45 2750 (1992)c

4.

## Brillouin light scattering data



### Anharmonic processes :

interaction of the acoustic wave with the thermal phonons. The return to the equilibrium is characterized by  $\tau_{th}$  (mean thermal lifetime).

$$\Omega \tau_{th} \ll 1 : \begin{cases} Q_{anh}^{-1} = A\Omega \tau_{th} \\ \delta v/v = -A/2 \end{cases}$$

Otherwise :  $Q_{anh}^{-1} = A\Omega \tau_{th} / (1 + \Omega^2 \tau_{th}^2)$

[H.J.Maris in Physical Acoustics Vol. VIII (1971)]

▲ R.Vacher J.Pelous PRB 14 823 (1976)

■ J.Pelous R.Vacher, Sol.Stat.Com. 18 657 (1976)

△ D.Tielbürger et al, PRB 45 2750 (1992)

Mathiessen rule :  $Q^{-1} = Q_{TAR}^{-1} + Q_{anh}^{-1} + (Q_{TLS}^{-1})$

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## Broadening due to finite size effects

[R.Vacher, S.Ayrinhac et al (2006)]

Restricted scattering volumes  $\Rightarrow$  additional broadening resulting from the spread in  $Q$

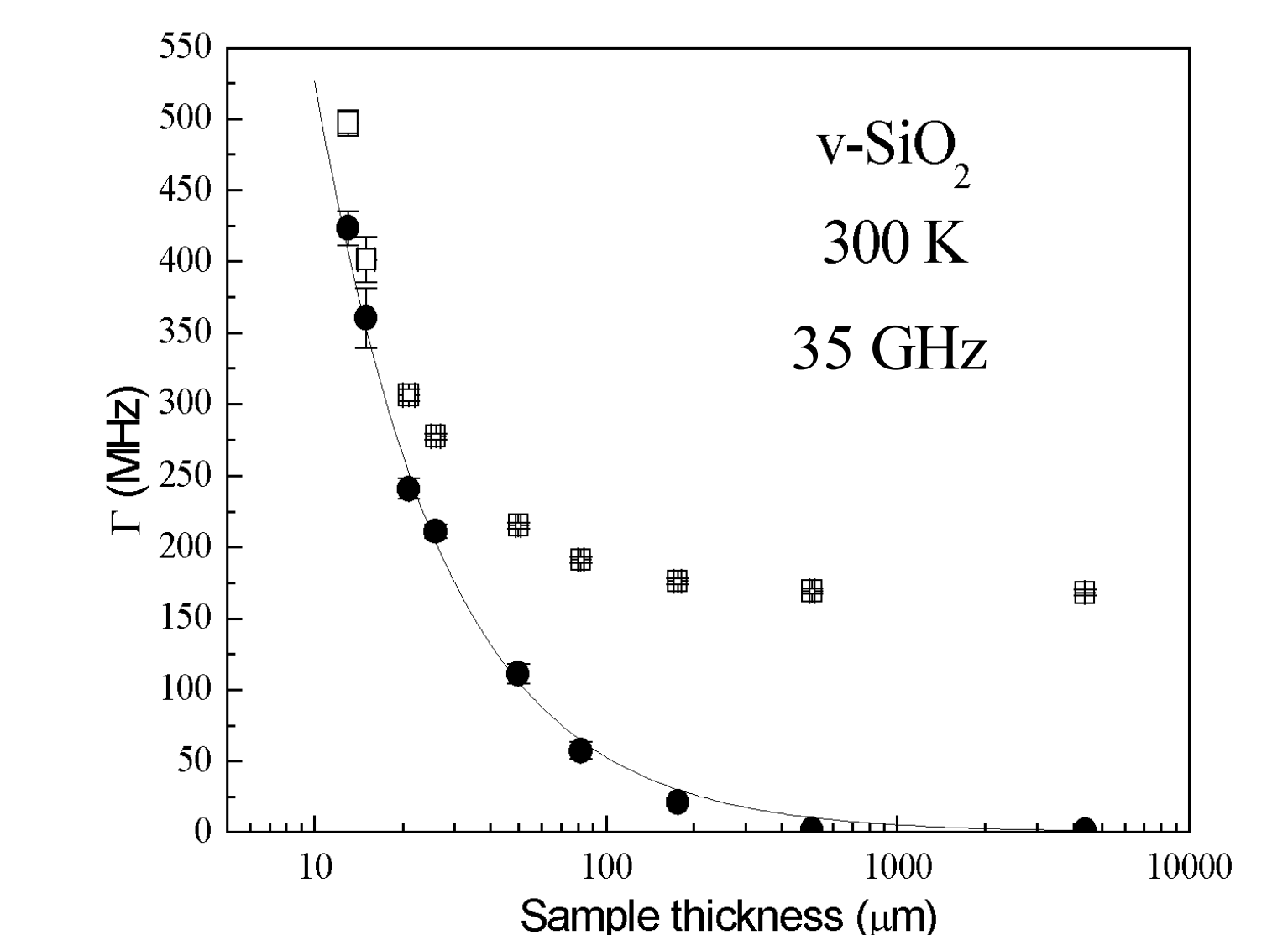
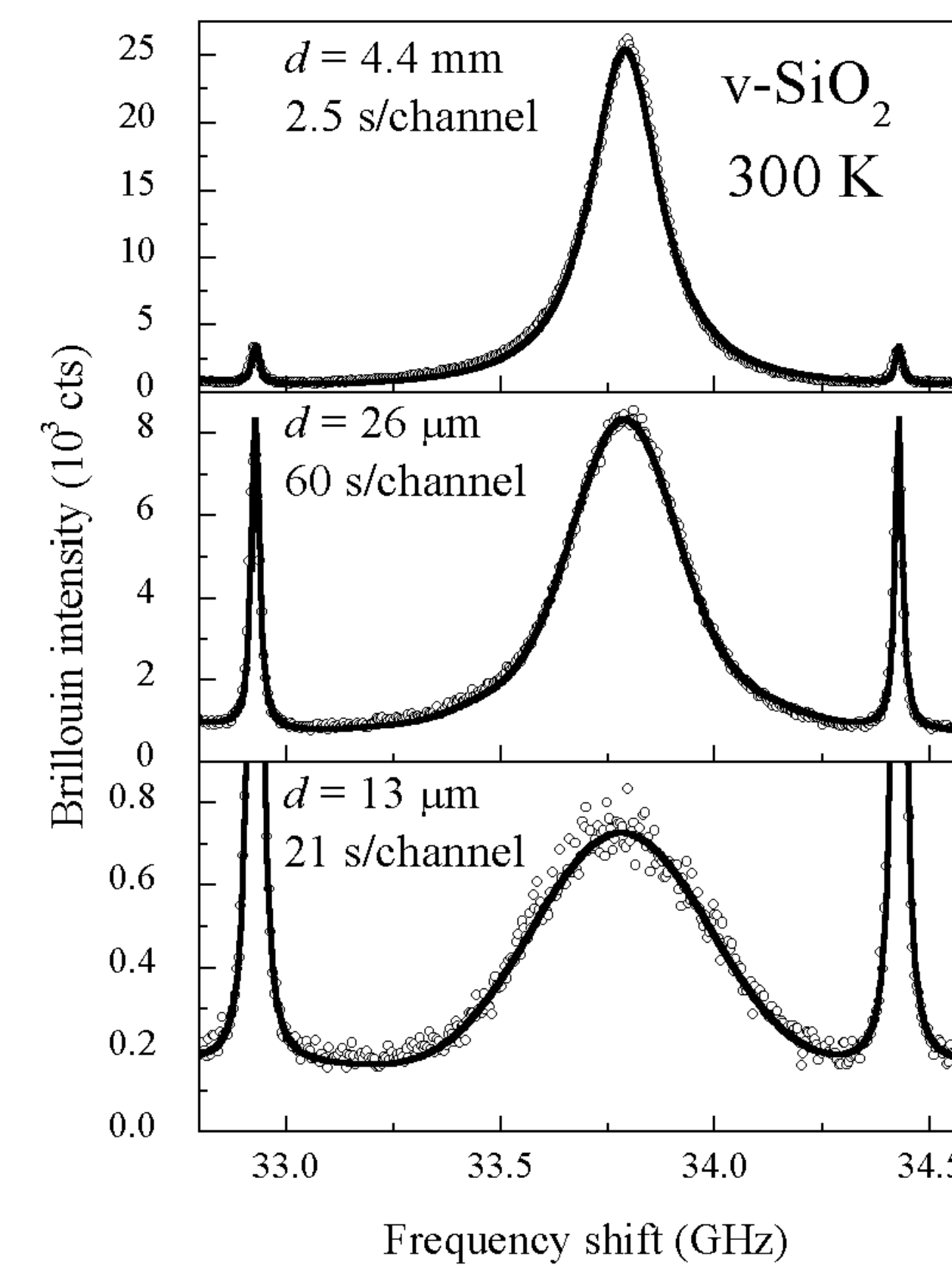
### Brillouin scattering in thin samples

Broadening is characterized by :

Brillouin Stokes spectra in backscattering geometry ( $\lambda_0 = 514.5$  nm)

$$f(\omega) \sim \frac{\sin^2[(\omega - \Omega)d/2\nu]}{[(\omega - \Omega)d/2\nu]^2}$$

[A.Dervish and R.Loudon, J.Phys.C: Solid State Phys. 9 L669 (1976)  
J.R.Sandercock, PRL 29 1735 (1972)]



• thickness dependence of the width of the function  $f(\omega)$  derived from fits of the measured spectra to a DHO convoluted with both the instrumental function and  $f(\omega)$ .

— calculated width of  $f(\omega)$  using the known values of thickness.

□ apparent width resulting from fits of measured spectra to a DHO convoluted with instrumental function.

### Brillouin scattering in strongly absorbing medium for the exciting radiations

Additional contribution to the width in case of light absorption [J.R. Sandercock, PRL 28 237 (1972)]

$$\frac{\Delta\Omega}{\Omega} = \frac{2n_2}{n_1} = \frac{\alpha_0 \lambda_0}{2\pi n_1} \quad \alpha_0 \text{ absorption coefficient}$$

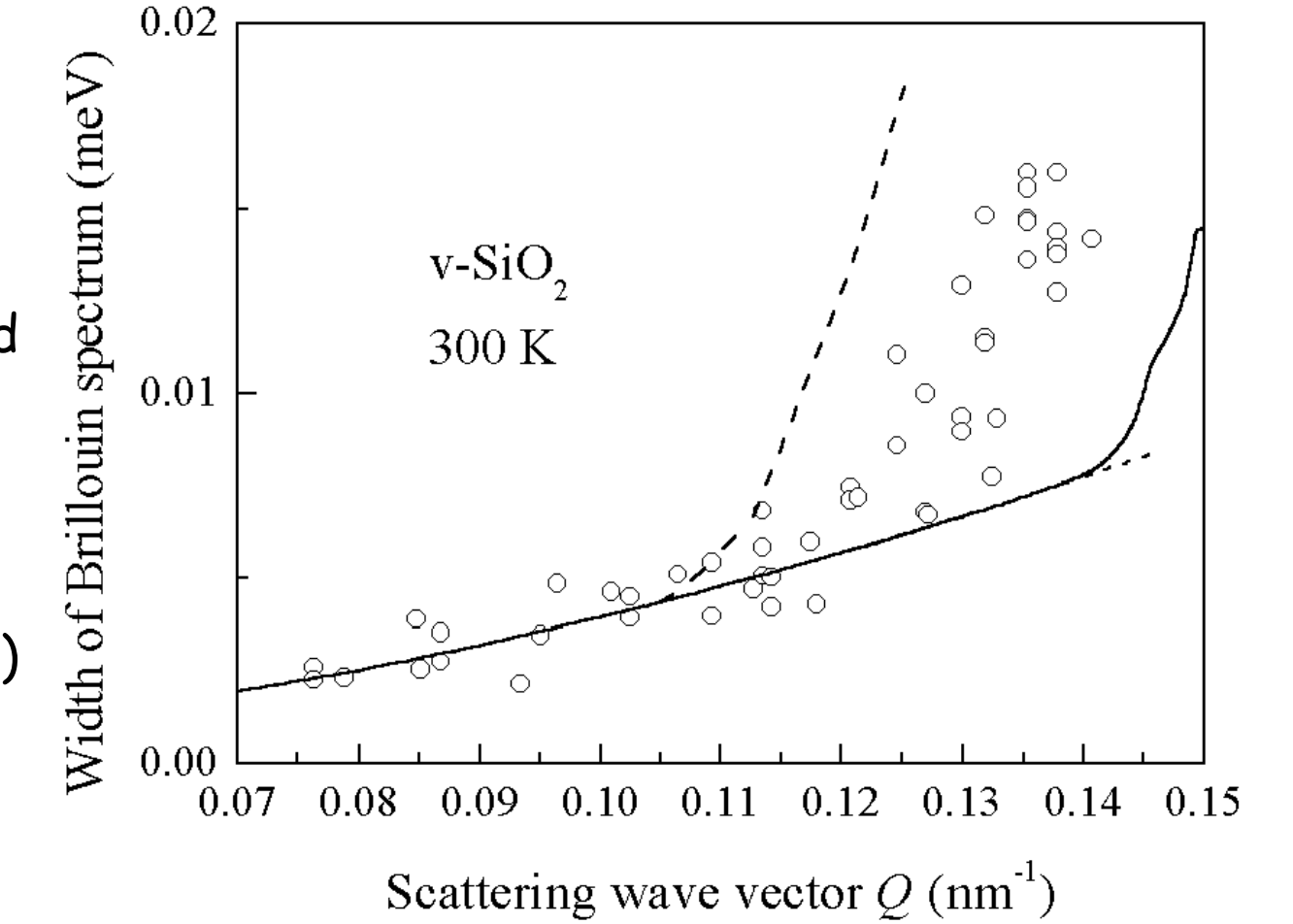
○ experimental data from C.Masciovecchio, G.Ruocco et al presented at 5th IDRMC (Lille-2005)

calculated width ( $\Delta\Omega + \Gamma_{anh}$ ) using  $\Gamma_{anh} = A\Omega^2$  and  $(n_1, n_2)$  data from :

— A.Appleton et al in The physics of SiO2 and its interfaces (1978)

--- G.L.Tan et al, PRB 12 205117 (2005)

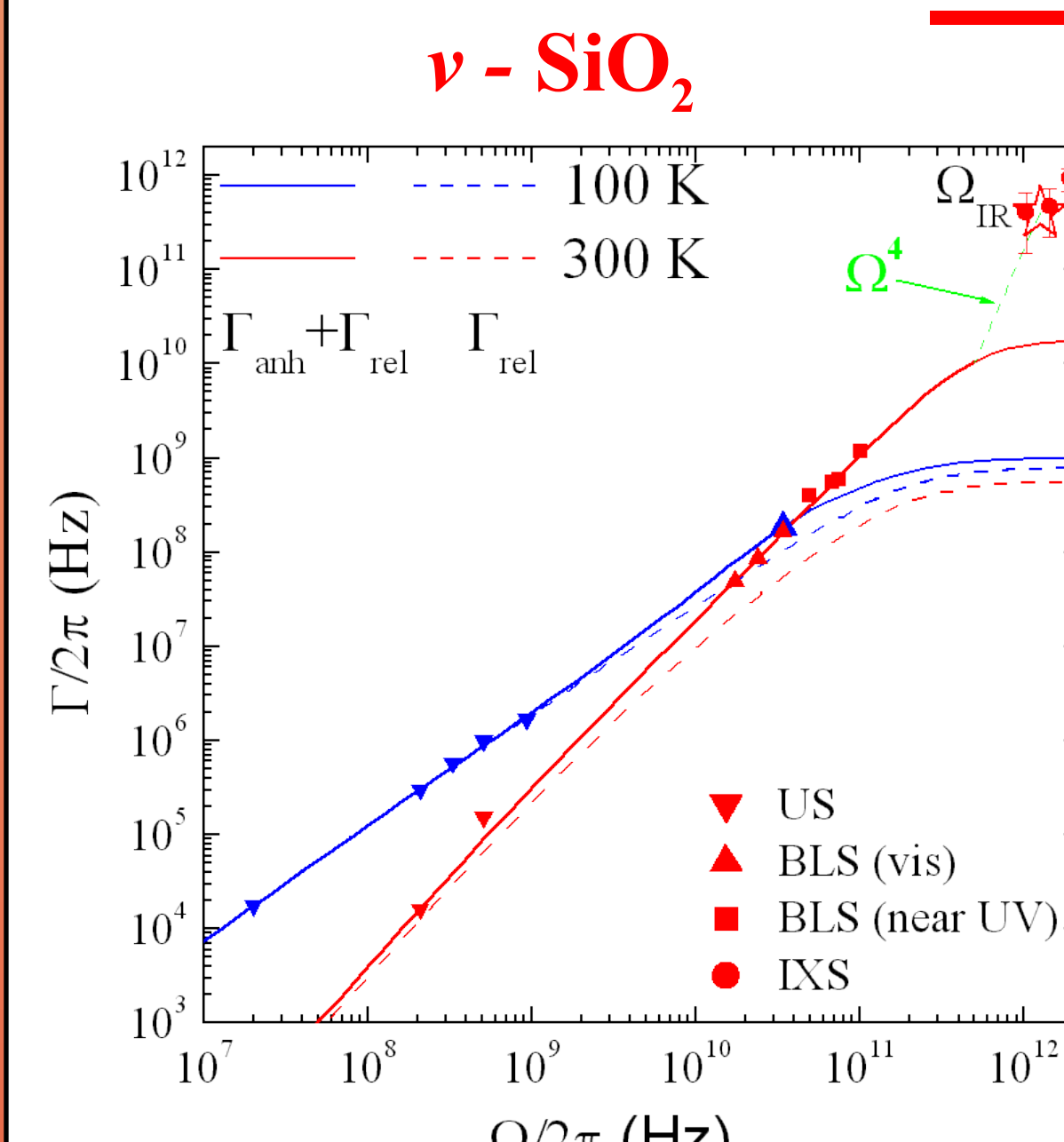
### Brillouin width near the UV absorption edge of $\nu$ -SiO<sub>2</sub>



$\Rightarrow$  The apparent rapid increase in the sound damping near 0.12 nm<sup>-1</sup> might simply result from light absorption.

6.

## Overall frequency dependence of damping



[E. Courtens, B. Rufflé, R. Vacher, Journal of Neutron Research (2006)]

$\Rightarrow$  Ioffe-Regel crossover ( $\Omega_{IR}$ ) at resonance with the boson peak modes

$\rightarrow$  end of acoustic branches

• R.Vacher et al JNCS 45 397 (1981)

O.L.Anderson et al J.Am.Ceram.Soc. 38 125 (1955)

R.Keil et al JNCS 164 1183 (1993)

D.Tielbürger et al PRB 45 2750 (1992)c

• C.Masciovecchio et al PRL 92 247401 (2004)

P.Benassi et al PRB 71 172201 (2005)

• C.Masciovecchio et al, PRL 76 3356 (1996)

To summarize, there exist several sound damping mechanisms glasses whose strength generally depends on the material and on T. Several crossovers may be present in  $\Gamma(\Omega)$  and a single law  $\Gamma \propto \Omega^2$  is generally not meaningful. The analysis of sound damping requires high quality measurements over a broad range of  $\Omega$ .