
MAX School on Advanced Materials and Molecular Modelling
with QUANTUM ESPRESSO

QE-2021: Hands-on session - Day-5

(Density Functional Perturbation Theory – Part 1)

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Outline

1. Introduction
2. **Exercise 1a:** Phonons at Gamma in non-polar materials
3. **Exercise 1b:** Phonon dispersion in non-polar materials
4. **Exercise 2a:** Phonons at Gamma in polar materials
5. **Exercise 2b:** Phonon dispersion in polar materials
6. **Exercise 3:** Phonon dispersion of 2D materials (optional)

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Basic concepts

Let us consider a unit cell with N_{at} atoms.

$s = 1 \dots N_{at}$ index of an atom in the unit cell

$\alpha = x, y, z$ is the cartesian index

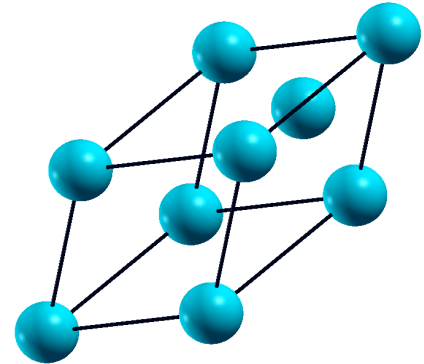
\mathbf{R} is the point in the Bravais-lattice,
identifying the position of a given unit cell

$N_{\mathbf{R}}$ is the number of unit cells in the crystal

$\mathbf{u}_{s\alpha}(\mathbf{R})$ is the α - component of the displacement of the s -th atom



$3 \times N_{at}$ variables



Interatomic Force Constants :

$$C_{s\alpha, s'\beta}(\mathbf{R}, \mathbf{R}') = C_{s\alpha, s'\beta}(\mathbf{R} - \mathbf{R}') = \frac{\partial^2 E_{tot}}{\partial \mathbf{u}_{s\alpha}(\mathbf{R}) \partial \mathbf{u}_{s'\beta}(\mathbf{R}')} \rightarrow N_{\mathbf{R}}^2$$

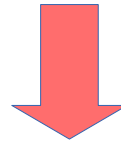
Basic concepts

Fourier transformation:

$$\tilde{\mathbf{u}}_{s\alpha}(\mathbf{q}) = \sum_{\mathbf{R}} \mathbf{u}_{s\alpha}(\mathbf{R}) e^{-i\mathbf{q}\cdot\mathbf{R}}$$

Essence of the Bloch theorem:

$$\frac{\partial^2 E_{tot}}{\partial \tilde{\mathbf{u}}_{s\alpha}^*(\mathbf{q}) \partial \tilde{\mathbf{u}}_{s'\beta}(\mathbf{q}')} = \delta_{\mathbf{q},\mathbf{q}'} \frac{\partial^2 E_{tot}}{\partial \tilde{\mathbf{u}}_{s\alpha}^*(\mathbf{q}) \partial \tilde{\mathbf{u}}_{s'\beta}(\mathbf{q})}$$



Important concept: We can perform calculations of Interatomic Force Constants for each \mathbf{q} independently!

Basic concepts

Important concept: Instead of $N_{\mathbf{R}}^2$ Interatomic Force Constants we need only $N_{\mathbf{R}}$!

Sampling theorem

The number of \mathbf{q} points is equal to the number of \mathbf{R} points at which Interatomic Force Constants are computed.

Basic concepts

Normal mode frequencies, ω , and eigenvectors, $\mathbf{u}_{s\alpha}$ are determined by the secular equation:

$$\sum_{s',\beta} \tilde{D}_{s\alpha,s'\beta}(\mathbf{q}) \tilde{\mathbf{u}}_{s'\beta}(\mathbf{q}) = \omega_{\mathbf{q}}^2 \tilde{\mathbf{u}}_{s\alpha}(\mathbf{q})$$

where

$$\tilde{D}_{s\alpha,s'\beta}(\mathbf{q}) = \frac{1}{\sqrt{M_s M_{s'}}} \sum_{\mathbf{R}, \mathbf{R}'} \boxed{\frac{\partial^2 E_{tot}}{\partial \mathbf{u}_{s\alpha}(\mathbf{R}) \partial \mathbf{u}_{s'\beta}(\mathbf{R}')}} e^{i\mathbf{q}(\mathbf{R}' - \mathbf{R})}$$

Interatomic Force Constants (IFC)

is the ***dynamical matrix***.

Diagonalization of the dynamical matrix gives phonon modes at \mathbf{q} .

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Exercise 1a: Phonons at Γ in non-polar materials

Go to the directory with the input files:

```
cd QE-2021/Day-5/example1a
```

In this directory you will find:

- `README.md` – File describing how to do the exercise
- `pw.Si.in` – Input file for the SCF ground-state calculation
- `ph.Si.in` – Input file for the phonon calculation at Γ
- `dynmat.Si.in` – Input file to impose the acoustic sum rule
- `reference` – Directory with the reference results

Exercise 1a: Phonons at Γ in non-polar materials

Step 1. Perform a Self-Consistent Field ground-state calculation for silicon *at the equilibrium structure* using the **pw.x** program.

pw.Si.in

Input file for the SCF calculation



pw.x < pw.Si.in > pw.Si.out



Input



Output

```
&control
  calculation='scf'
  restart_mode='from scratch',
  pseudo_dir='../pseudo'
  outdir='./out'
  prefix='Si',
/
&system
 ibrav = 2,
celldm(1) = 10.20,
nat = 2,
ntyp = 1,
ecutwfc = 16
/
&electrons
  diagonalization = 'davidson'
  mixing_mode = 'plain',
  conv_thr = 1.0d-8
  mixing_beta = 0.7
/
ATOMIC_SPECIES
Si 28.0855 Si.vbc.UPF
ATOMIC_POSITIONS
Si 0.00 0.00 0.00
Si 0.25 0.25 0.25
K_POINTS
10
0.1250000 0.1250000 0.1250000 1.00
0.1250000 0.1250000 0.3750000 3.00
0.1250000 0.1250000 0.6250000 3.00
0.1250000 0.1250000 0.8750000 3.00
0.1250000 0.3750000 0.3750000 3.00
0.1250000 0.3750000 0.6250000 6.00
0.1250000 0.3750000 0.8750000 6.00
0.1250000 0.6250000 0.6250000 3.00
0.3750000 0.3750000 0.3750000 1.00
0.3750000 0.3750000 0.6250000 3.00
```

Exercise 1a: Phonons at Γ in non-polar materials

Step 2. Perform a phonon calculation at Γ using the `ph.x` program.

`ph.Si.in`

Input file for the phonon calculation

```
Phonons at Gamma
&inputph
  prefix = 'Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  outdir = './out'
  fildyn = 'Si.dyn',
/
0.0 0.0 0.0
```

- ← The same prefix as in the SCF calculation
- ← Threshold for self-consistency
- ← Atomic mass
- ← Directory for temporary files
- ← File containing the dynamical matrix
- ← Coordinates of the \mathbf{q} point in units of 2π in Cartesian framework

`ph.x < ph.Si.in > ph.Si.out`

Exercise 1a: Phonons at Γ in non-polar materials

Step 2. Perform a phonon calculation at Γ using the **ph.x** program.

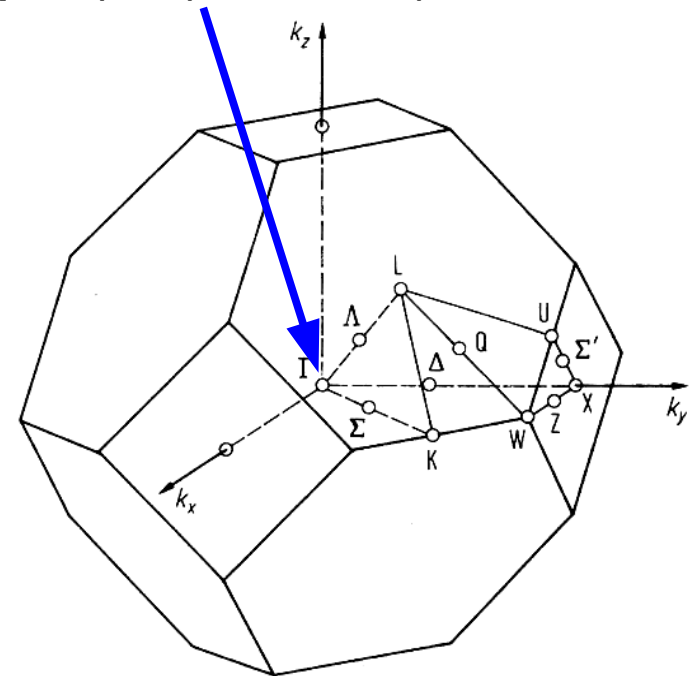
ph.Si.in

Input file for the phonon calculation

```
Phonons at Gamma
&inputph
  prefix = 'Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  outdir = './out'
  fildyn = 'Si.dyn',
/
0.0 0.0 0.0
```

We consider only the Γ point:

$$\mathbf{q} = 2\pi/a (0.0, 0.0, 0.0)$$



Brillouin Zone

Exercise 1a: Phonons at Γ in non-polar materials

Dynamical matrix file **Si.dyn** :

```
*****
freq ( 1) = 0.069949 [THz] = 2.333248 [cm-1]
( 0.006270 0.000000 0.104520 0.000000 -0.699311 0.000000 )
( 0.006270 0.000000 0.104520 0.000000 -0.699311 0.000000 )
freq ( 2) = 0.069949 [THz] = 2.333248 [cm-1]
( 0.644809 0.000000 0.286121 0.000000 0.048545 0.000000 )
( 0.644809 0.000000 0.286121 0.000000 0.048545 0.000000 )
freq ( 3) = 0.069949 [THz] = 2.333248 [cm-1]
( 0.290142 0.000000 -0.638130 0.000000 -0.092775 0.000000 )
( 0.290142 0.000000 -0.638130 0.000000 -0.092775 0.000000 )
freq ( 4) = 15.474501 [THz] = 516.173789 [cm-1]
( -0.534305 0.000000 -0.463023 0.000000 -0.011325 0.000000 )
( 0.534305 0.000000 0.463023 0.000000 0.011325 0.000000 )
freq ( 5) = 15.474501 [THz] = 516.173789 [cm-1]
( -0.202506 0.000000 0.217991 0.000000 0.641460 0.000000 )
( 0.202506 0.000000 -0.217991 0.000000 -0.641460 0.000000 )
freq ( 6) = 15.474501 [THz] = 516.173789 [cm-1]
( 0.416545 0.000000 -0.487944 0.000000 0.297322 0.000000 )
( -0.416545 0.000000 0.487944 0.000000 -0.297322 0.000000 )
*****
```

**Acoustic
modes**



**Optical
modes**



Exercise 1a: Phonons at Γ in non-polar materials

Acoustic sum rule at Γ

Because of the numerical inaccuracies the interatomic force constants do not strictly satisfy the acoustic sum rule (ASR).

ASR comes directly from the continuous translational invariance of the crystal. If we translate the whole solid by a uniform displacement, the forces acting on the atoms must be zero.

As a consequence:

For each α, β and i :

$$\sum_{\mathbf{L}, j} C_{\alpha i, \beta j}(\mathbf{R}_{\mathbf{L}}) = 0$$

As a consequence, the frequencies of the acoustic modes must be zero.

Exercise 1a: Phonons at Γ in non-polar materials

Acoustic sum rule at Γ

Because of the numerical inaccuracies the interatomic force constants do not strictly satisfy the acoustic sum rule (ASR) => acoustic frequencies are not exactly zero.

However, the ASR can be imposed using the `dynmat.x` program.

The input file is `dynmat.Si.in`:

```
&input  
  fildyn = 'Si.dyn',  
  asr = 'simple'  
/
```

← File containing the dynamical matrix
← A way to impose the acoustic sum rule

`dynmat.x < dynmat.Si.in > dynmat.Si.out`

Exercise 1a: Phonons at Γ in non-polar materials

The program `dynmat.x` produces the file `dynmat.out` which contains the new acoustic frequencies, which are *exactly* equal to zero.

```
diagonalizing the dynamical matrix ...

q =      0.0000      0.0000      0.0000
*****
freq ( 1) =      0.000000 [THz] =      0.000000 [cm-1]
( 0.000000  0.000000 -0.707107  0.000000  0.000000  0.000000 )
( 0.000000  0.000000 -0.707107  0.000000  0.000000  0.000000 )
freq ( 2) =      0.000000 [THz] =      0.000000 [cm-1]
( -0.707107  0.000000  0.000000  0.000000  0.000000  0.000000 )
( -0.707107  0.000000  0.000000  0.000000  0.000000  0.000000 )
freq ( 3) =      0.000000 [THz] =      0.000000 [cm-1]
( 0.000000  0.000000  0.000000  0.000000 -0.707107  0.000000 )
( 0.000000  0.000000  0.000000  0.000000 -0.707107  0.000000 )
freq ( 4) =     15.474329 [THz] =     516.168042 [cm-1]
( 0.000000  0.000000  0.707107  0.000000  0.000000  0.000000 )
( 0.000000  0.000000 -0.707107  0.000000  0.000000  0.000000 )
freq ( 5) =     15.474329 [THz] =     516.168042 [cm-1]
( 0.000000  0.000000  0.000000  0.000000 -0.707107  0.000000 )
( 0.000000  0.000000  0.000000  0.000000  0.707107  0.000000 )
freq ( 6) =     15.474329 [THz] =     516.168042 [cm-1]
( -0.707107  0.000000  0.000000  0.000000  0.000000  0.000000 )
( 0.707107  0.000000  0.000000  0.000000  0.000000  0.000000 )
*****
```


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6. **Exercise 3:** Phonon dispersion of 2D materials (optional)

Exercise 1b: Phonon dispersion in non-polar materials

Go to the directory with the input files:

```
cd QE-2021/Day-5/example1b
```

In this directory you will find:

- `README.md` – File describing how to do the exercise
- `pw.Si.in` – Input file for the SCF ground-state calculation
- `ph.Si.in` – Input file for the phonon calculation on a uniform \mathbf{q} -grid
- `q2r.Si.in` – Input file for calculation of Interatomic Force Constants
- `matdyn.Si.in` – Input file for Fourier Interpolation for various \mathbf{q} points
- `plotband.Si.in` – Input file for plotting a phonon dispersion
- `reference` – Directory with the reference results

Exercise 1b: Phonon dispersion in non-polar materials

Step 1. Perform a SCF calculation for silicon *at the equilibrium structure* using the `pw.x` program.

`pw.x < pw.Si.in > pw.Si.out`

Step 2. Perform a phonon calculation on a uniform grid of \mathbf{q} points using the `ph.x` program.

```
Phonons on a uniform q-grid
&inputph
  prefix='Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  ldisp = .true.,
  nq1 = 4,
  nq2 = 4,
  nq3 = 4,
  outdir='./out'
  fildyn='Si.dyn',
/
```

← Option for the calculation on a grid

← Uniform grid of \mathbf{q} points

$$\mathbf{q}_{ijk} = \frac{i-1}{nq1} \mathbf{G}_1 + \frac{j-1}{nq2} \mathbf{G}_2 + \frac{k-1}{nq3} \mathbf{G}_3$$

`ph.x < ph.Si.in > ph.Si.out`

Exercise 1b: Phonon dispersion in non-polar materials

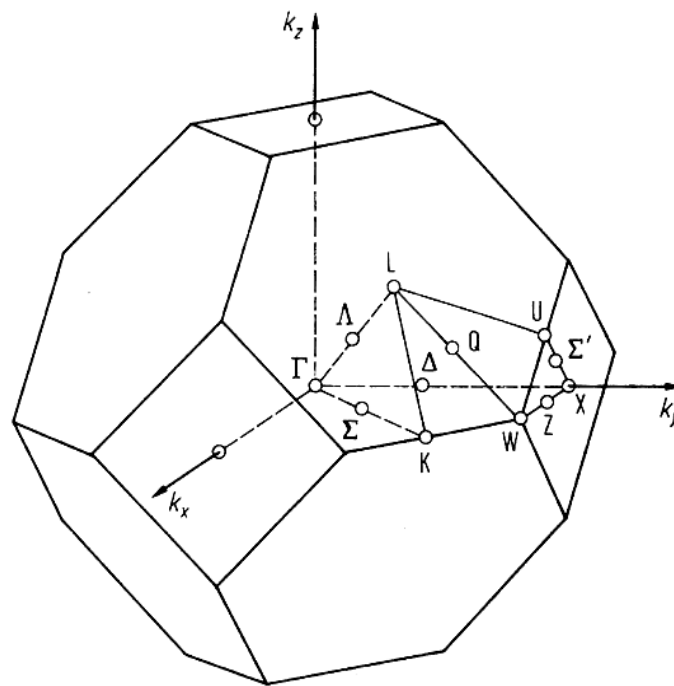
Step 1. Perform a SCF calculation for silicon *at the equilibrium structure* using the `pw.x` program.

`pw.x < pw.Si.in > pw.Si.out`

Step 2. Perform a phonon calculation.

```
Phonons on a uniform q-grid
&inputph
  prefix='Si',
  tr2_ph = 1.0d-14,
  amass(1) = 28.0855,
  ldisp = .true.,
  nq1 = 4,
  nq2 = 4,
  nq3 = 4,
  outdir='./out'
  fildyn='Si.dyn',
/
```

We sample the Brillouin zone with a uniform grid of $4 \times 4 \times 4$ \mathbf{q} points.



Exercise 1b: Phonon dispersion in non-polar materials

- $4 \times 4 \times 4 = 64$ q-points \Rightarrow Use of symmetry \Rightarrow 8 non-equivalent **q** points

The file **Si.dyn0** contains a list of the non-equivalent **q** points (8, in this case).

	4	4	4	(q-grid)
	8	(number of non-equivalent q-points)		
q1 =	0.0000000000000000E+00	0.0000000000000000E+00	0.0000000000000000E+00	
q2 =	-0.2500000000000000E+00	0.2500000000000000E+00	-0.2500000000000000E+00	
q3 =	0.5000000000000000E+00	-0.5000000000000000E+00	0.5000000000000000E+00	
q4 =	0.0000000000000000E+00	0.5000000000000000E+00	0.0000000000000000E+00	
q5 =	0.7500000000000000E+00	-0.2500000000000000E+00	0.7500000000000000E+00	
q6 =	0.5000000000000000E+00	0.0000000000000000E+00	0.5000000000000000E+00	
q7 =	0.0000000000000000E+00	-0.1000000000000000E+01	0.0000000000000000E+00	
q8 =	-0.5000000000000000E+00	-0.1000000000000000E+01	0.0000000000000000E+00	

- The phonon program **ph.x** generates files for every non-equivalent **q** point **Si.dyn1**, **Si.dyn2**, ..., **Si.dyn8**, which contain information about dynamical matrices, phonon frequencies and atomic displacements.

Exercise 1b: Phonon dispersion in non-polar materials

Step 3. Calculation of the **Interatomic Force Constants (IFC)** using the **q2r.x** program.

Fourier transforms of IFC's :

$$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}_{ijk}) = \frac{\partial^2 E_{tot}}{\partial \tilde{\mathbf{u}}_{s\alpha}^*(\mathbf{q}_{ijk}) \partial \tilde{\mathbf{u}}_{s'\beta}(\mathbf{q}_{ijk})}$$

α, β are Cartesian components, and \mathbf{s}, \mathbf{s}' are atomic indices.

$$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}_{ijk}) \xrightarrow{C_{s\alpha,s'\beta}(\mathbf{R}_{lmn}) = \frac{1}{N_{\mathbf{q}}} \sum_{i,j,k} \tilde{C}_{s\alpha,s'\beta}(\mathbf{q}_{ijk}) e^{i\mathbf{q}_{ijk} \cdot \mathbf{R}_{lmn}}} C_{s\alpha,s'\beta}(\mathbf{R}_{lmn})$$

Fourier transforms of IFC's on a grid
of \mathbf{q} points $nq1 \times nq2 \times nq3$
in reciprocal space

IFC's in a supercell $nq1 \times nq2 \times nq3$
in real space

Exercise 1b: Phonon dispersion in non-polar materials

Input file `q2r.Si.in` :

```
&input  
  fildyn='Si.dyn',  
  zasr='simple',  
  flfrc='Si444.fc'  
/
```

- ← Dynamical matrices from the phonon calculation
- ← A way to impose the acoustic sum rule
- ← Output file of the interatomic force constants

The denser the grid of \mathbf{q} points, the larger the vectors \mathbf{R} for which the Interatomic Force Constants are calculated!

To perform the calculation:

`q2r.x < q2r.Si.in > q2r.Si.out`

Exercise 1b: Phonon dispersion in non-polar materials

Step 4. Calculate phonons at generic \mathbf{q}' points using IFC by means of the code `matdyn.x`

$$C_{s\alpha,s'\beta}(\mathbf{R}_{lmn}) \xrightarrow{\text{Fourier interpolation}} \tilde{C}_{s\alpha,s'\beta}(\mathbf{q}')$$

$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}') = \sum_{l,m,n} C_{s\alpha,s'\beta}(\mathbf{R}_{lmn}) e^{-i\mathbf{q}' \cdot \mathbf{R}_{lmn}}$

IFC's on a grid in real space Fourier transforms of IFC's at generic \mathbf{q}' points in reciprocal space

Input file `Si.matdyn.in` :

<pre>&input</pre>		
<pre> asr='simple',</pre>	←	Acoustic sum rule
<pre> amass(1)=28.0855,</pre>	←	Atomic mass
<pre> flfrc='Si444.fc',</pre>	←	File with IFC's
<pre> flfrq='Si.freq'</pre>	←	Output file with the frequencies
<pre>/</pre>		
<pre>396</pre>	←	Number of \mathbf{q} points
<pre> 0.000000 0.000000 0.000000 0.000000</pre>		
<pre> 0.012658 0.000000 0.000000 0.012658</pre>	←	Coordinates of \mathbf{q} points
<pre> </pre>		

`matdyn.x < matdyn.Si.in > matdyn.Si.out`

Exercise 1b: Phonon dispersion in non-polar materials

Step 5. Plot the phonon dispersion using the `plotband.x` program and `gnuplot`.

Input file `plotband.Si.in` :

<code>Si.freq</code>	←	Input file with the frequencies at various q
<code>0 600</code>	←	Range of frequencies for a visualization
<code>freq.plot</code>	←	Output file with frequencies which will be
<code>freq.ps</code>	←	Plot of the dispersion (we will produce and
<code>0.0</code>	←	Fermi level (needed only for band structur
<code>100.0 0.0</code>	←	Freq. step and reference freq. on the plot fi

`plotband.x < plotband.Si.in > plotband.Si.out`

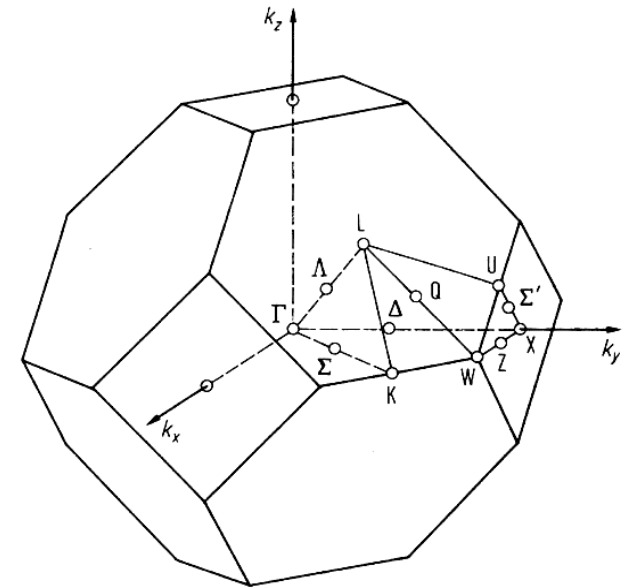
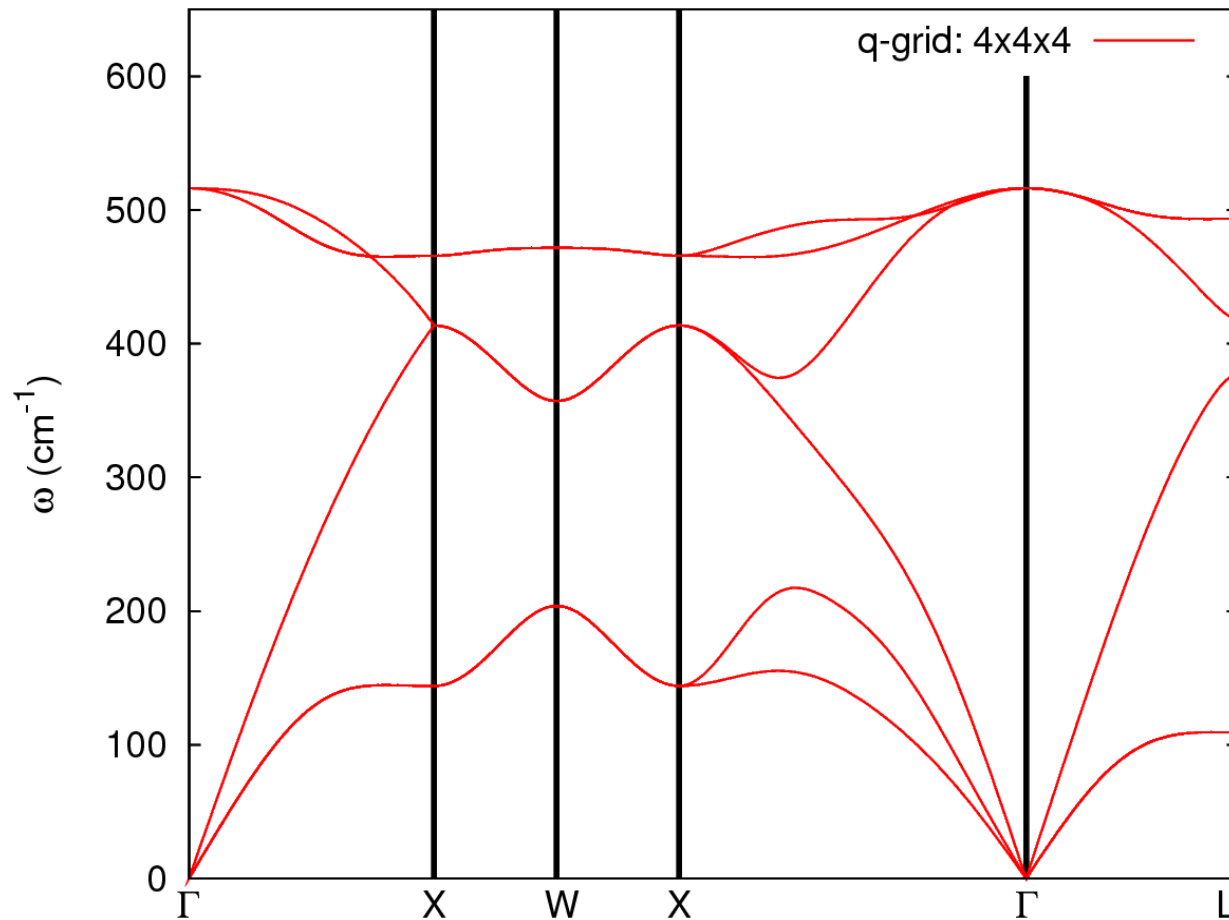
Use `gnuplot` and the file `plot_dispersion.gp` in order to plot the phonon dispersion of silicon (`experimental_data.dat`).

You will get a postscript file `phonon_dispersion.eps` which you can visualize.

Exercise 1b: Phonon dispersion in non-polar materials

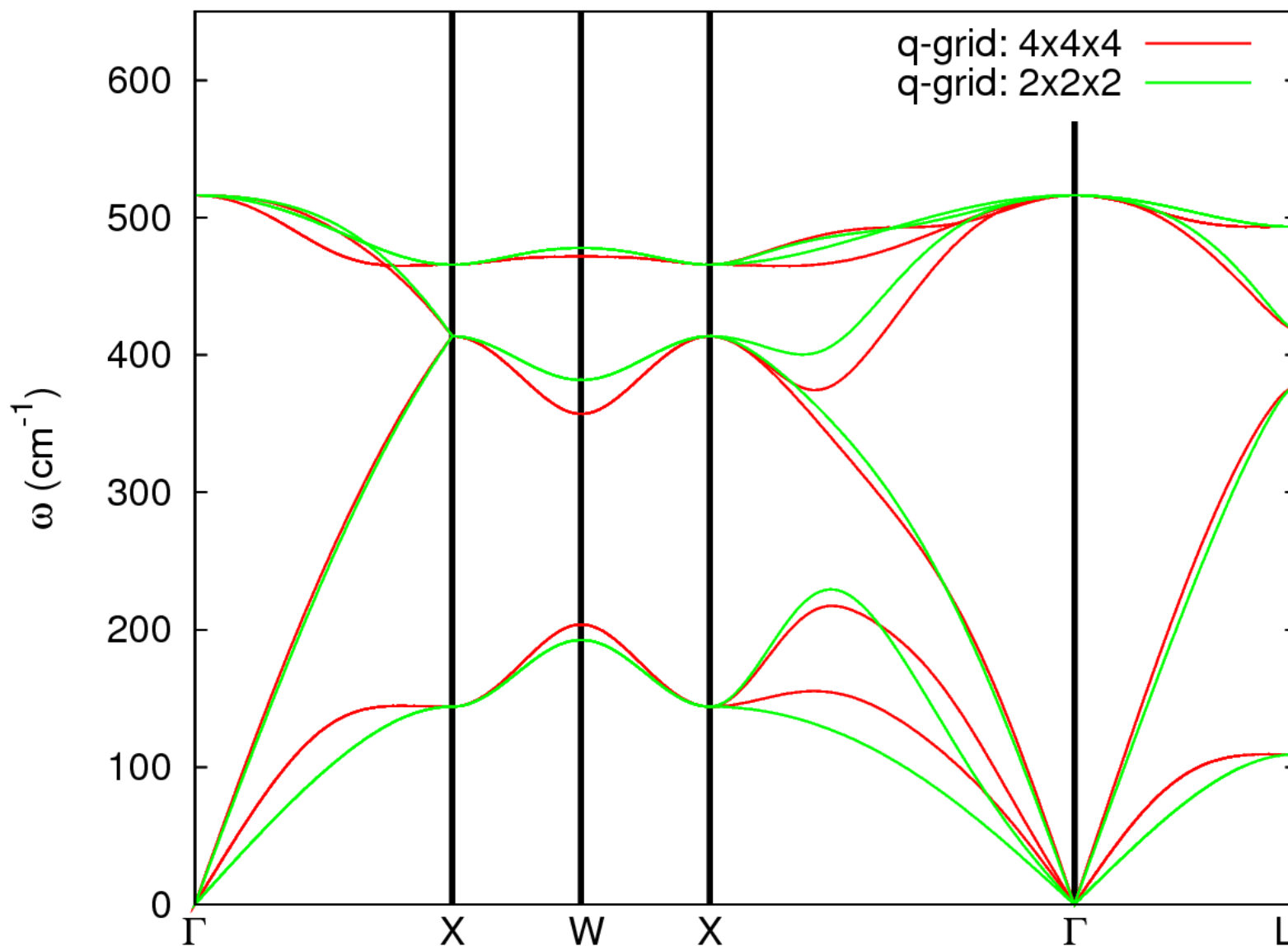
Phonon dispersion of silicon along some high-symmetry directions in the Brillouin zone

(file `phonon_dispersion.eps`):



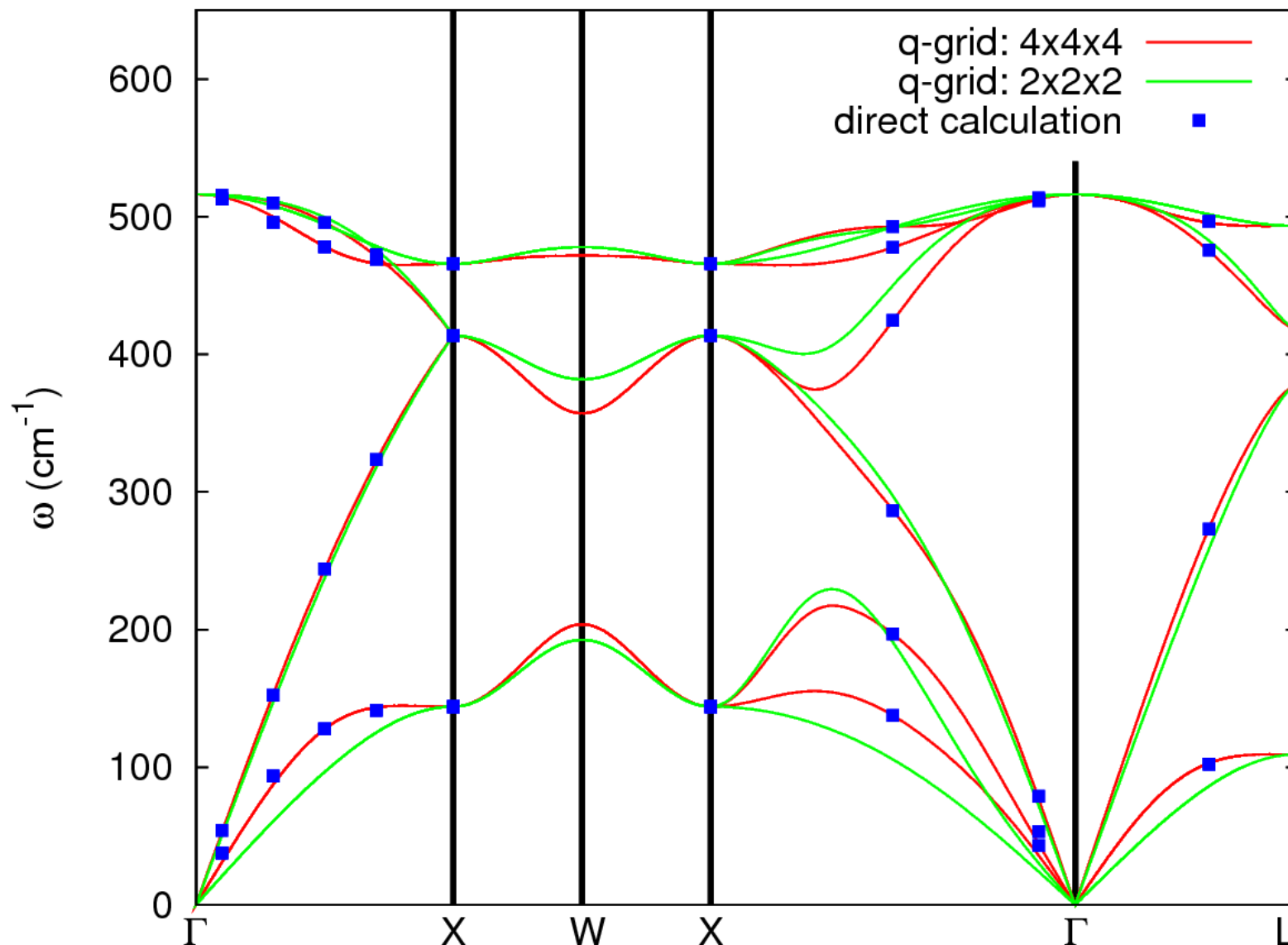
Exercise 1b: Phonon dispersion in non-polar materials

How to determine whether the quality of the Fourier interpolation is satisfactory? → Compare with the direct calculation (no interpolation)!



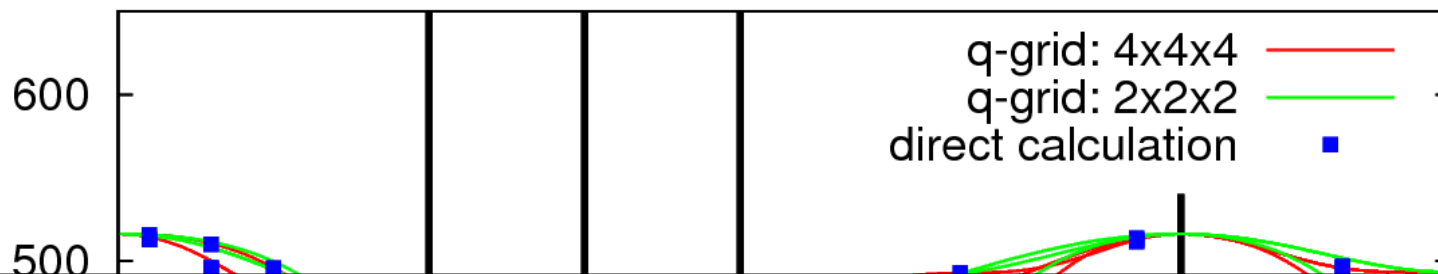
Exercise 1b: Phonon dispersion in non-polar materials

Comparison of the phonon dispersion computed using the Fourier interpolation with the direct calculation at several \mathbf{q} points. The \mathbf{q} -grid 4x4x4 is satisfactory for the Fourier interpolation for silicon!



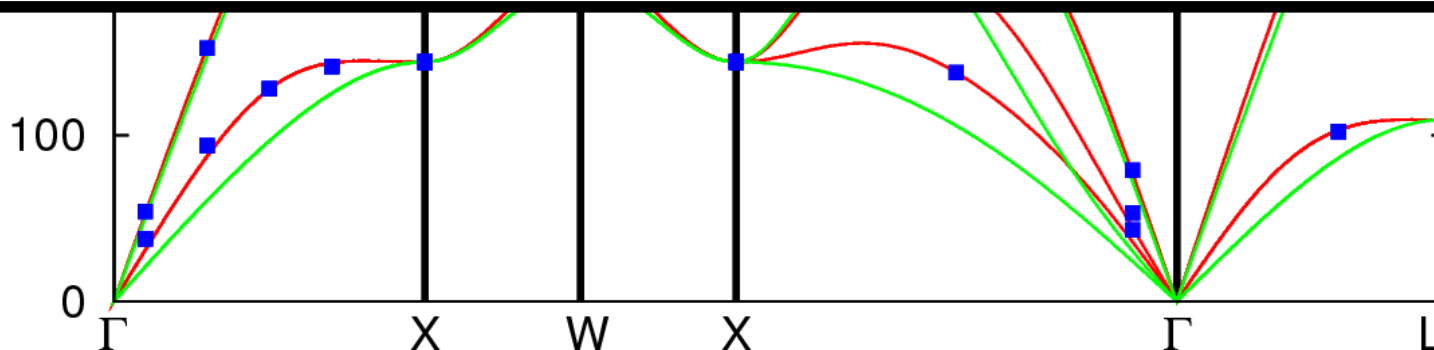
Exercise 1b: Phonon dispersion in non-polar materials

Comparison of the phonon dispersion computed using the Fourier interpolation with the direct calculation at several \mathbf{q} points. The \mathbf{q} -grid 4x4x4 is very satisfactory for the Fourier interpolation for silicon!



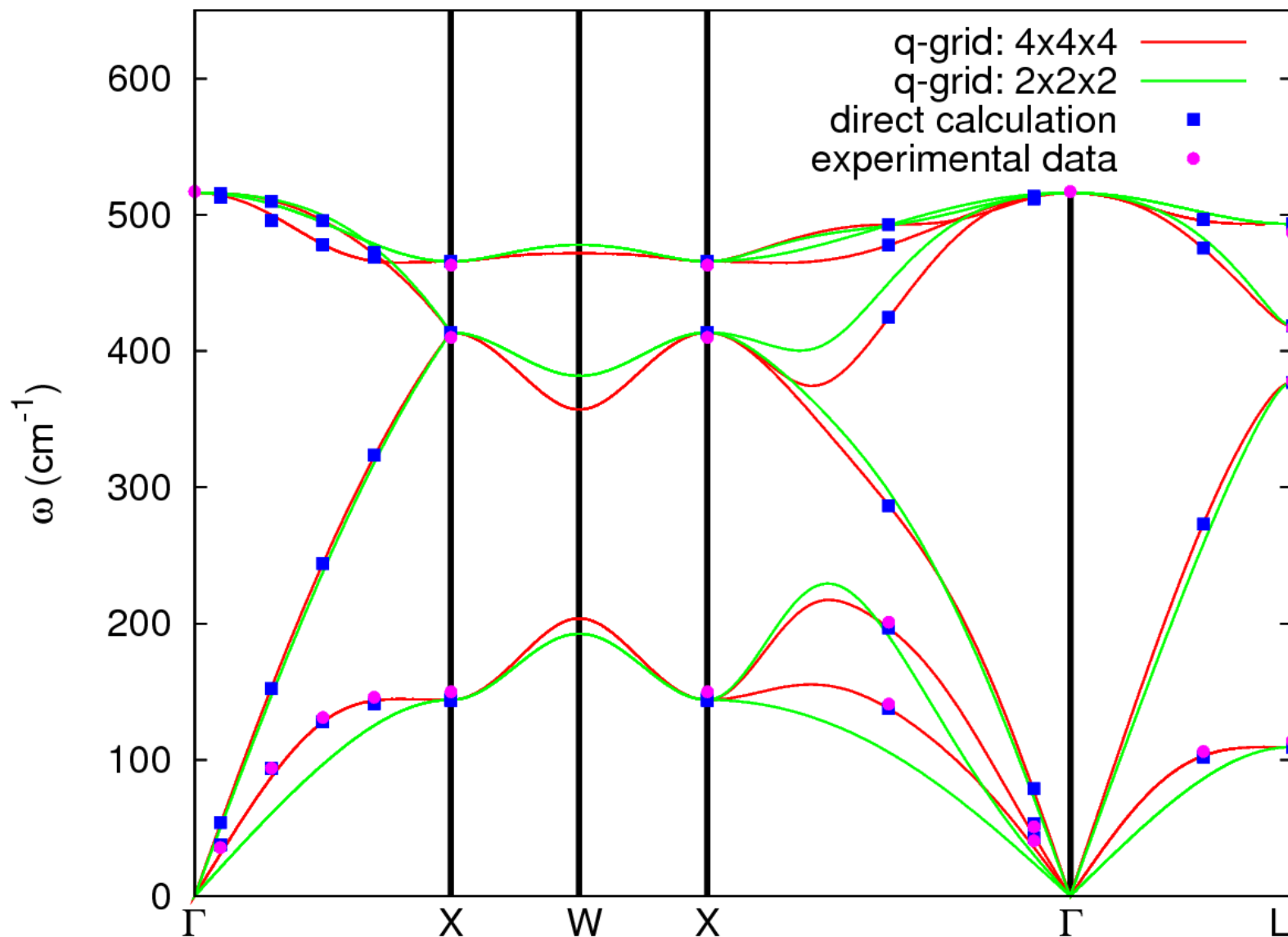
Perform a direct phonon calculation (no interpolation) at several \mathbf{q}' points and make a comparison with the phonon frequencies obtained from the interpolation.

Use **exercise1a** as an example. Some \mathbf{q}' points along the Gamma-X high symmetry line are listed in the file `reference/q_points_direct_calc.txt`



Exercise 1b: Phonon dispersion in non-polar materials

The agreement of *ab initio* calculation of the phonon dispersion using the Fourier interpolation on a \mathbf{q} -grid $4 \times 4 \times 4$ is excellent with the experimental data!



Exercise 1b: Phonon dispersion in non-polar materials

The Fourier interpolation works well if the Interatomic Force Constants (IFC's) are known on a sufficiently large supercell, i.e. on a large enough grid of \mathbf{q} points in the phonon calculation.

There are cases when the IFC's are long range and the Fourier interpolation does not work properly:

- When there are **Kohn anomalies** in metals. In this case the dynamical matrices are not a smooth function of \mathbf{q} and the IFC's are long range.
- In **polar insulators** where the atomic displacements generate long range electrostatic interactions and the dynamical matrix is not analytical for $\mathbf{q} \rightarrow 0$. However, this case can be dealt with by calculating the Born effective charges and the dielectric tensor of the material.

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Exercise 2a: Phonons at Γ in polar materials

Polar materials in the $\mathbf{q} = \mathbf{0}$ limit: a macroscopic electric field appears as a consequence of the long-range character of the Coulomb interaction (incompatible with Periodic Boundary Conditions).

A **non-analytic term** must be added to Interatomic Force Constants at $\mathbf{q} = \mathbf{0}$:

$$\tilde{C}_{s\alpha,s'\beta}(\mathbf{q}) = \tilde{C}_{s\alpha,s'\beta}^{\text{analytic}}(\mathbf{q}) + \frac{4\pi}{\Omega} \frac{(\mathbf{q} \cdot \mathbf{Z}_s^*)_{\alpha} (\mathbf{q} \cdot \mathbf{Z}_{s'}^*)_{\beta}}{\mathbf{q} \cdot \epsilon_{\infty} \cdot \mathbf{q}}$$

Effective charges \mathbf{Z}_s^* are related to polarization \mathbf{P} induced by a lattice distortion:

$$Z_{s,\alpha\beta}^* = \Omega \frac{\partial P_{\alpha}}{\partial u_{s\beta}}$$

Dielectric tensor $\epsilon_{\infty}^{\alpha\beta}$ is related to polarization \mathbf{P} induced by an electric field \mathbf{E} :

$$\epsilon_{\infty}^{\alpha\beta} = \delta_{\alpha\beta} + 4\pi \left. \frac{\partial P_{\alpha}}{\partial E_{\beta}} \right|_{u_s(q=0)=0}$$

All of the above can be calculated from (mixed) second order derivatives of the total energy.

Exercise 2a: Phonons at Γ in polar materials

Go to the directory with the input files:

```
cd QE-2021/Day-5/example2a
```

Step 1. Perform a Self-Consistent Field ground-state calculation for a polar semiconductor AlAs.

Step 2. Perform a phonon calculation at Gamma for AlAs.

```
Phonons at Gamma
&inputph
  prefix='AlAs',
  tr2_ph = 1.0d-14,
  amass(1) = 26.98,
  amass(2) = 74.92,
  outdir='./out'
  fildyn='AlAs.dyn',
  epsil = .true.
/
0.0  0.0  0.0
```

← If .true. will calculate and store the dielectric tensor and effective charges

Exercise 2a: Phonons at Γ in polar materials

In the file `ph.AlAs.out` you will find an information about the dielectric tensor and effective charges:

Dielectric constant in cartesian axis

```
(      13.743494475      -0.000000000      0.000000000 )
(      -0.000000000      13.743494475      0.000000000 )
(       0.000000000       0.000000000     13.743494475 )
```

Effective charges (d Force / dE) in cartesian axis

```
      atom      1      Al
Ex (       1.88274       0.00000       0.00000 )
Ey (       0.00000       1.88274      -0.00000 )
Ez (       0.00000      -0.00000       1.88274 )
      atom      2      As
Ex (      -3.23377      -0.00000       0.00000 )
Ey (      -0.00000      -3.23377       0.00000 )
Ez (      -0.00000       0.00000      -3.23377 )
```

Diagonalizing the dynamical matrix

```
q = (      0.000000000      0.000000000      0.000000000 )
```

```
freq (   1) =      0.147836 [THz] =      4.931268 [cm-1]
freq (   2) =      0.147836 [THz] =      4.931268 [cm-1]
freq (   3) =      0.147836 [THz] =      4.931268 [cm-1]
freq (   4) =     11.258207 [THz] =    375.533365 [cm-1]
freq (   5) =     11.258207 [THz] =    375.533365 [cm-1]
freq (   6) =     11.258207 [THz] =    375.533365 [cm-1]
```

No LO-TO splitting

Exercise 2a: Phonons at Γ in polar materials

Step 3. Impose Acoustic Sum Rule and add the non-analytic LO-TO splitting using the `dynmat.x` program.

Input file `dynmat.AlAs.in` :

```
&input
  fildyn = 'AlAs.dyn',
  asr='simple',
  amass(1)=26.98,
  amass(2)=74.92
  q(1) = 1.0,
  q(2) = 0.0,
  q(3) = 0.0
/
```



Direction for the LO-TO splitting

Output file `dynmat.out` :

```
*****
      freq (    1) =      -0.000000 [THz] =
(   0.538473   0.000000   -0.458309   0.000000
(   0.538473   0.000000   -0.458309   0.000000
      freq (    2) =      -0.000000 [THz] =
(   0.000000   0.000000   0.000000   0.000000
(   0.000000   0.000000   0.000000   0.000000
      freq (    3) =       0.000000 [THz] =
(  -0.458309   0.000000   -0.538473   0.000000
(  -0.458309   0.000000   -0.538473   0.000000
      freq (    4) =      11.257454 [THz] =
(   0.000000   0.000000   0.940852   0.000000
(  -0.000000   0.000000  -0.338817   0.000000
      freq (    5) =      11.257454 [THz] =
(   0.000000   0.000000   0.000000   0.000000
(   0.000000   0.000000   0.000000   0.000000
      freq (    6) =      12.307908 [THz] =
(   0.940852   0.000000  -0.000000   0.000000
(  -0.338817   0.000000   0.000000   0.000000
*****
```

LO-TO splitting

`dynmat.x < dynmat.AlAs.in > dynmat.AlAs.out`

Outline

1. Introduction
2. **Exercise 1a:** Phonons at Gamma in non-polar materials
3. **Exercise 1b:** Phonon dispersion in non-polar materials
4. **Exercise 2a:** Phonons at Gamma in polar materials
5. **Exercise 2b:** Phonon dispersion in polar materials
6. **Exercise 3:** Phonon dispersion of 2D materials (optional)

Exercise 2b: Phonon dispersion in polar materials

Go to the directory with the input files:

```
cd QE-2021/Day-5/example2b
```

- Calculate phonon dispersion in AIs following the same steps as in **exercise 1b**.
- Where necessary insert the missing information in the input files.

Exercise 2b: Phonon dispersion in polar materials

Step 1. Perform a SCF ground-state calculation for AIs using `pw.x`

Step 2. Perform a phonon calculation on a 4x4x4 \mathbf{q} -grid using `ph.x`
(dielectric tensor and effective charges will be calculated)

Step 3. Perform Fourier Transformations (FT) of $\tilde{C}_{s\alpha,s'\beta}(\mathbf{q})$ in order to obtain Interatomic Force Constants in real space $C_{s\alpha,s'\beta}(\mathbf{R})$ using `q2r.x`.

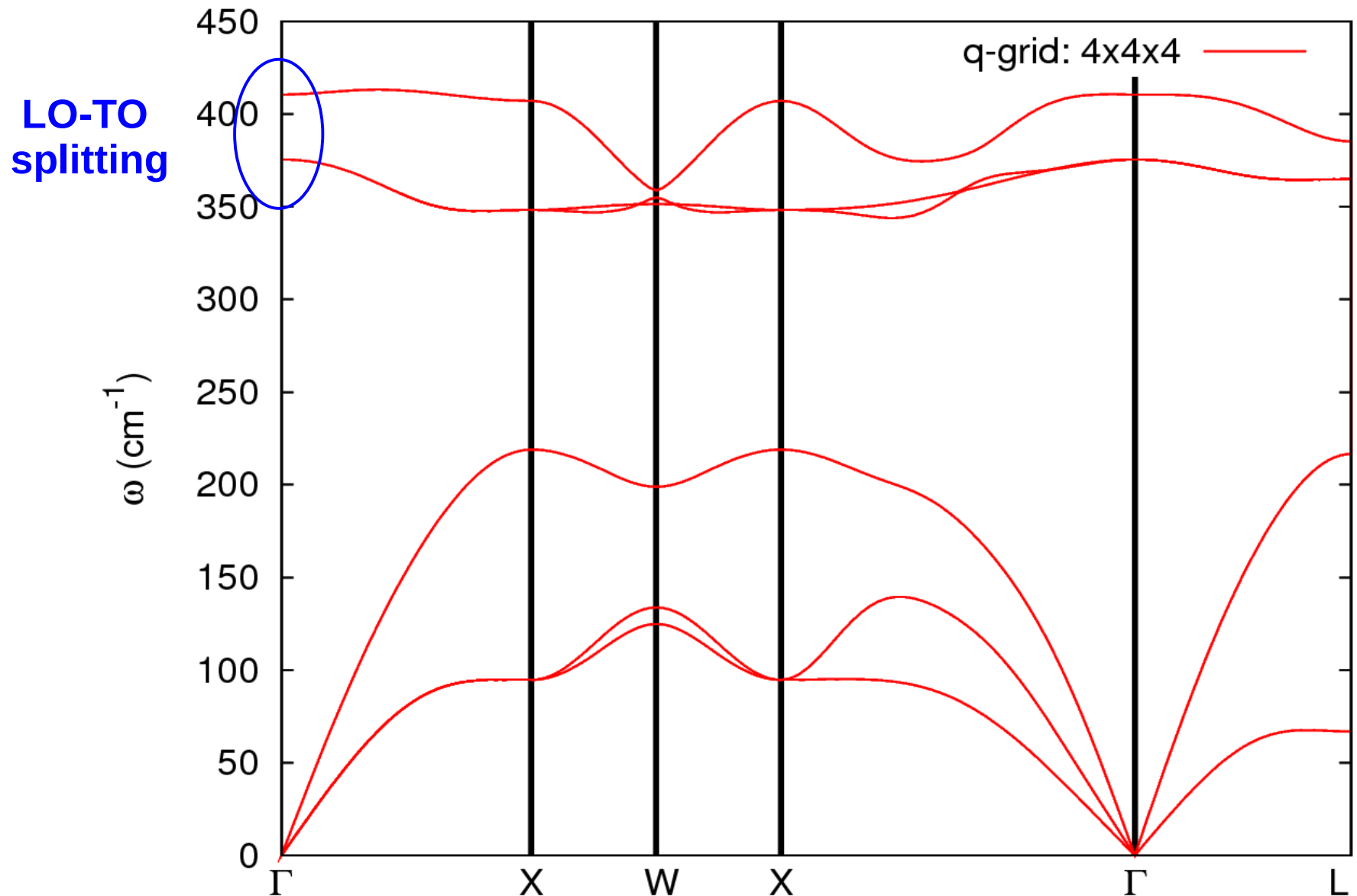
A term having the same behaviour for $\mathbf{q} \rightarrow \mathbf{0}$ as the non-analytic term is subtracted from $\tilde{C}_{s\alpha,s'\beta}(\mathbf{q})$ before the FT and re-added to $C_{s\alpha,s'\beta}(\mathbf{R})$, so that no problem related to non-analytic behaviour and related long-rangeness arises in the FT.

Step 4. Calculate phonons at generic \mathbf{q}' points using Interatomic Force Constants (including the non-analytic term) using the code `matdyn.x`

Step 5. Plot the phonon dispersion of AIs using `plotband.x` and `gnuplot`.

Exercise 2b: Phonon dispersion in polar materials

The phonon dispersion of AlAs:



Outline

1. Introduction
2. **Exercise 1a:** Phonons at Gamma in non-polar materials
3. **Exercise 1b:** Phonon dispersion in non-polar materials
4. **Exercise 2a:** Phonons at Gamma in polar materials
5. **Exercise 2b:** Phonon dispersion in polar materials
6. **Exercise 3:** Phonon dispersion in 2D materials (optional)

Exercise 3: Phonon dispersion in 2D materials

Go to the directory with the input files:

```
cd QE-2021/Day-5/example3
```

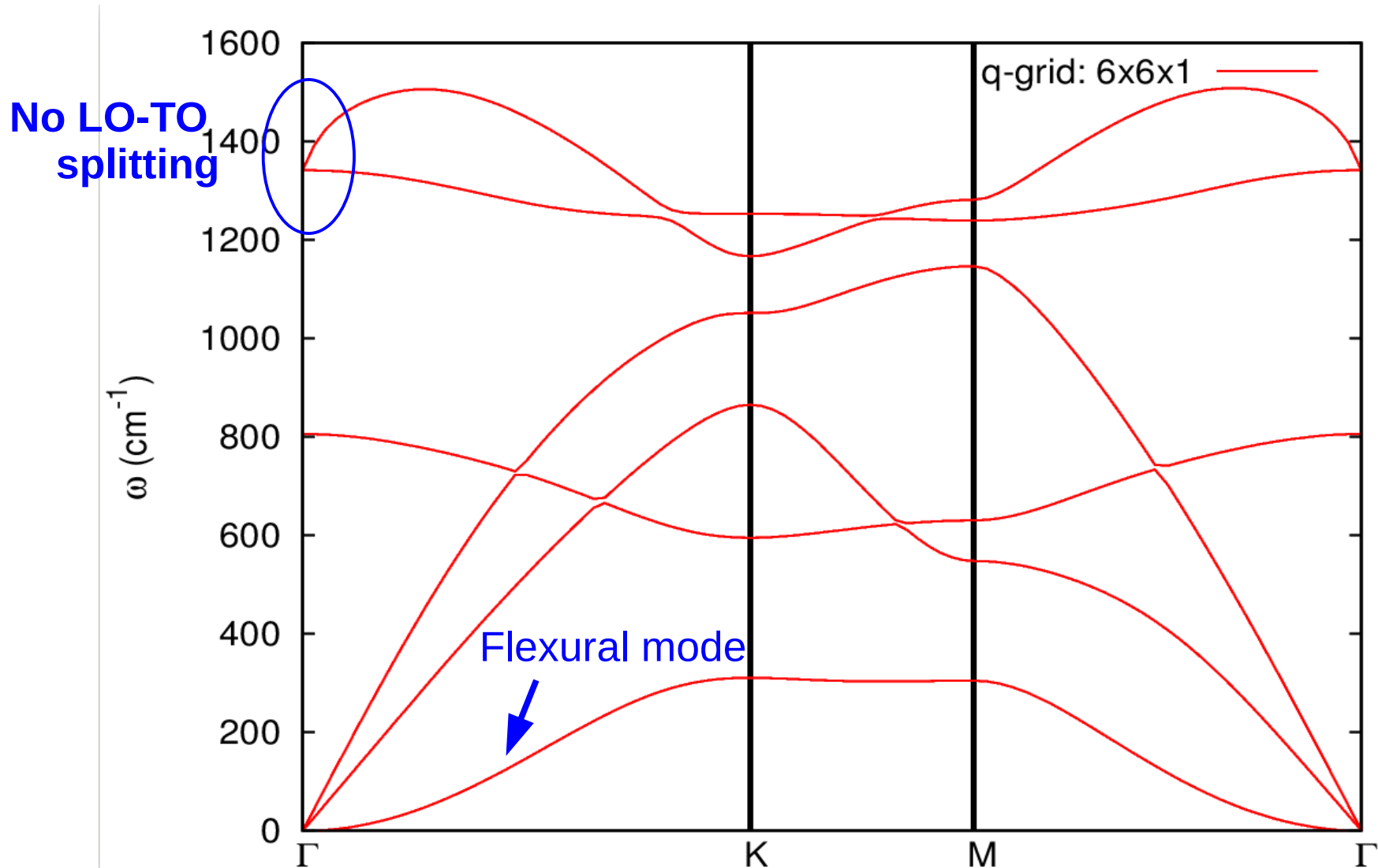
- Calculate phonon dispersion in 2D hexagonal BN following the same steps as in **exercise 1b** and **exercise 2b**.
- Notice that the options `assume_isolated='2D'` in `pw.bn.in` and `loto_2d=.true.` in `q2r.bn.in` and `matdyn.bn.in` have been set to properly deal with 2D materials.

Exercise 3: Phonon dispersion in 2D materials

- Step 1.** Perform a SCF ground-state calculation for 2D h-BN using `pw.x`
- Step 2.** Perform a phonon calculation on a 6x6x1 \mathbf{q} -grid using `ph.x`
- Step 3.** Perform Fourier Transformations (FT) of $\tilde{C}_{s\alpha,s'\beta}(\mathbf{q})$ in order to obtain Interatomic Force Constants in real space $C_{s\alpha,s'\beta}(\mathbf{R})$ using `q2r.x`.
- Step 4.** Calculate phonons at generic \mathbf{q}' points using Interatomic Force Constants using the code `matdyn.x`
- Step 5.** Plot the phonon dispersion of 2D h-BN using `plotband.x` and `gnuplot`.

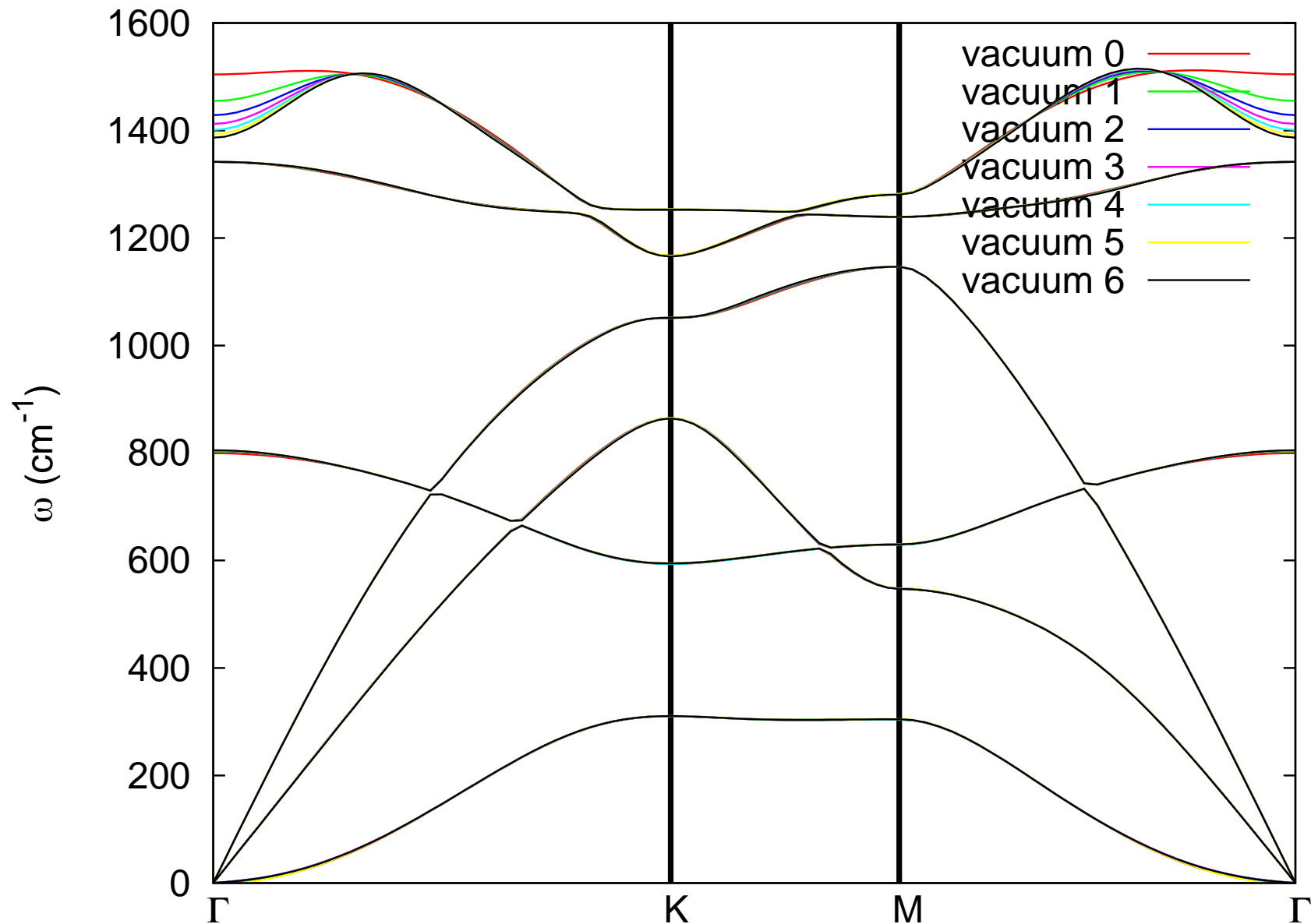
Exercise 3: Phonon dispersion in 2D materials

The phonon dispersion of 2D hexagonal BN:



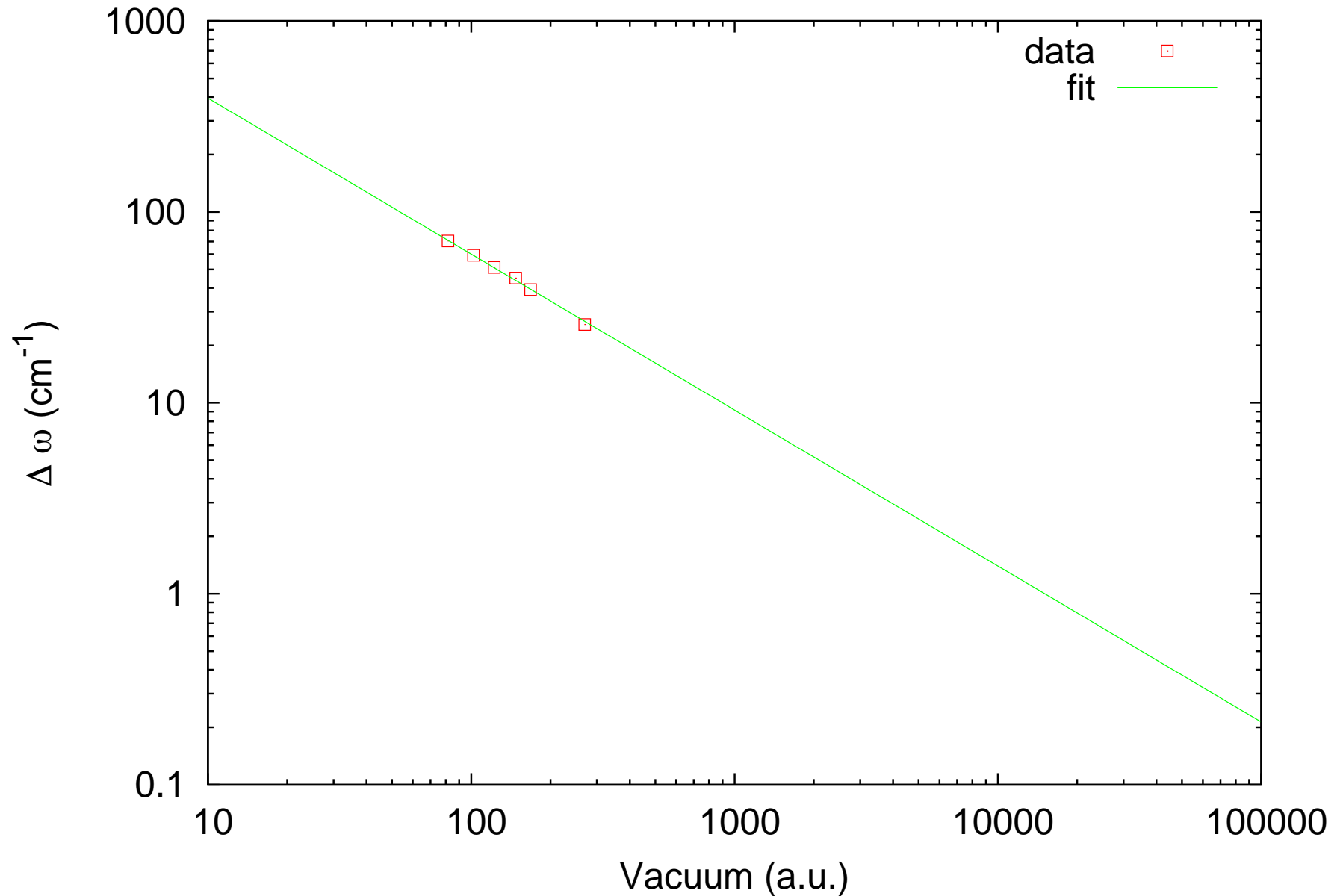
Exercise 3: Phonon dispersion in 2D materials

Effect of vacuum



Exercise 3: Phonon dispersion in 2D materials

Effect of vacuum



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"That's all Folks!"