Color Centers as low threshold Radiation Detectors

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מכון ויצמן למדע
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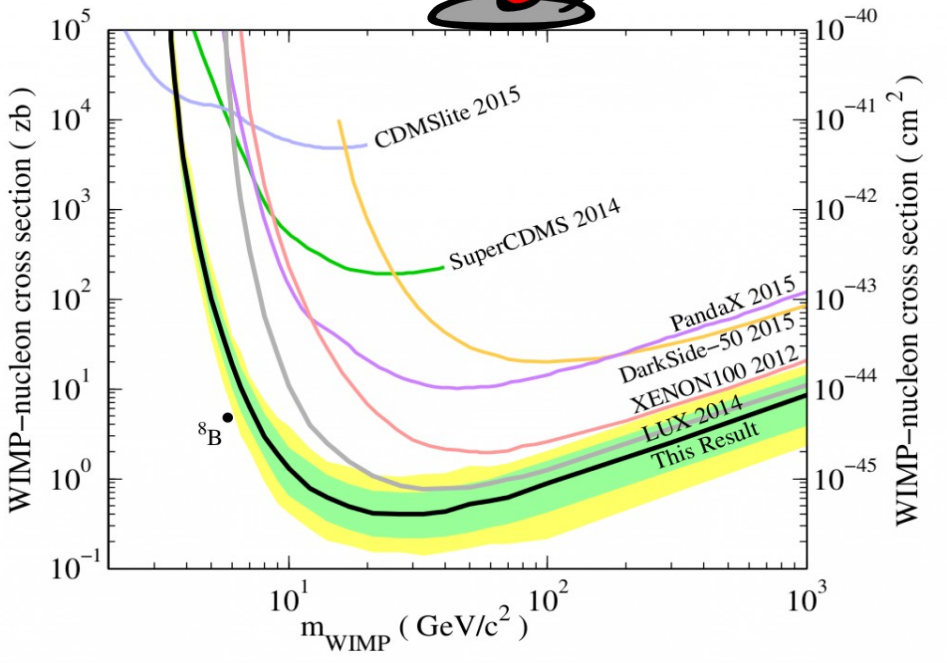
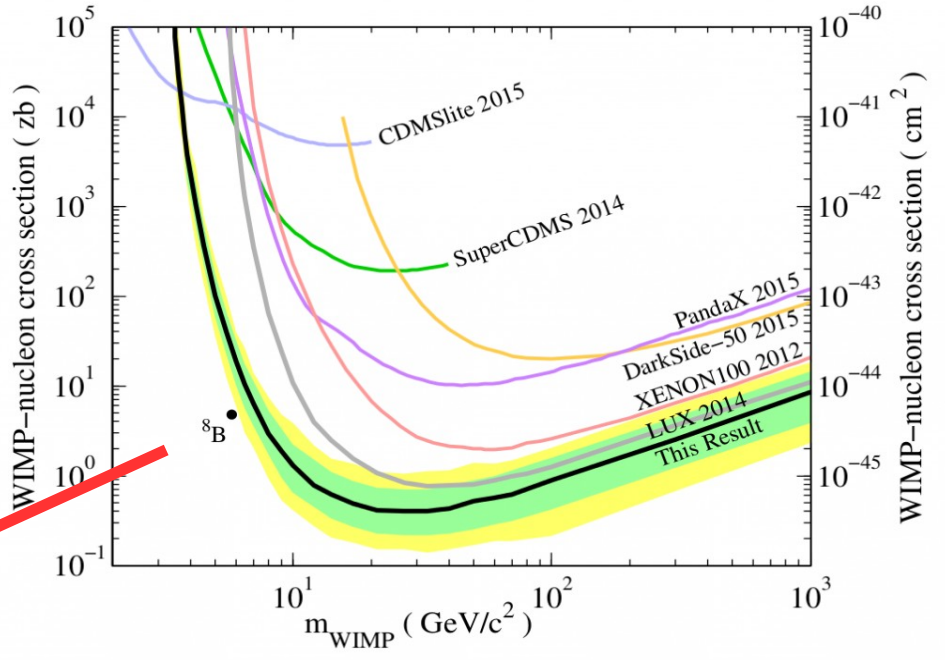
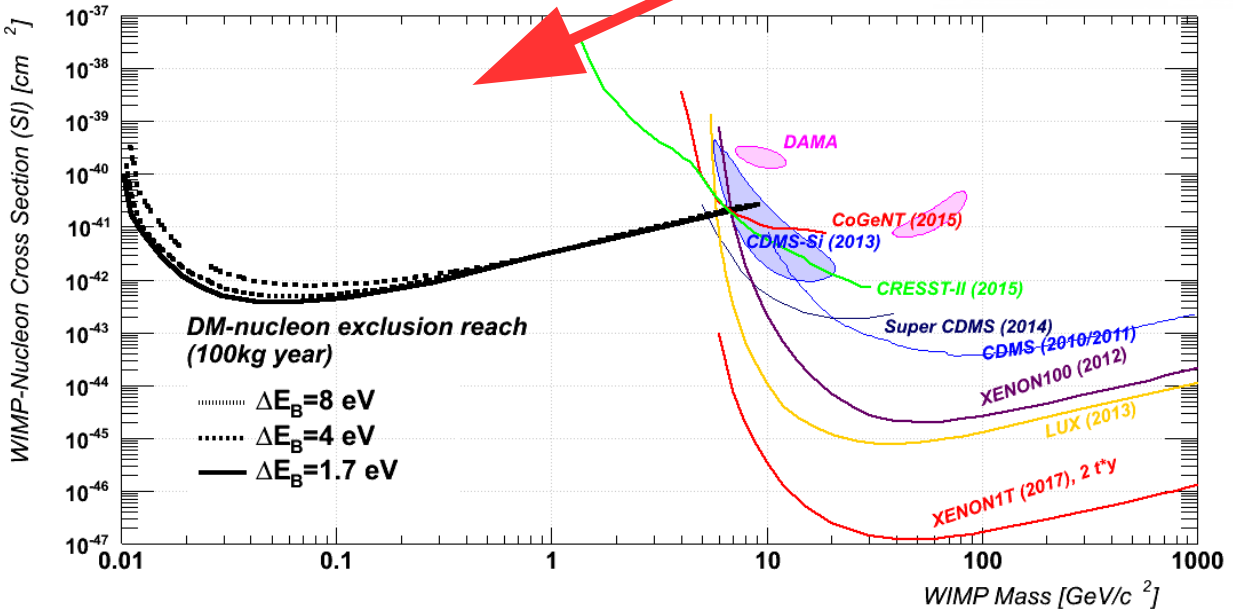
The goal:


WIMP–nucleon cross section (zb)
WIMP–nucleon cross section (cm^2)
m_{WIMP} (GeV/c^2)
CDMSlite 2015
SuperCDMS 2014
PandaX 2015
DarkSide–50 2015
XENON100 2012
LUX 2014
This Result
^{8}B

The goal:

Open a ***new window:***

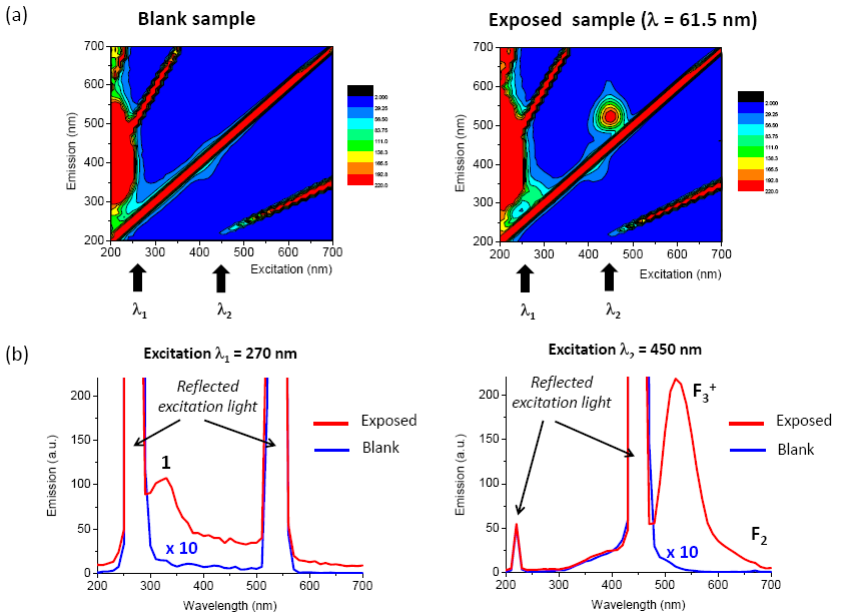


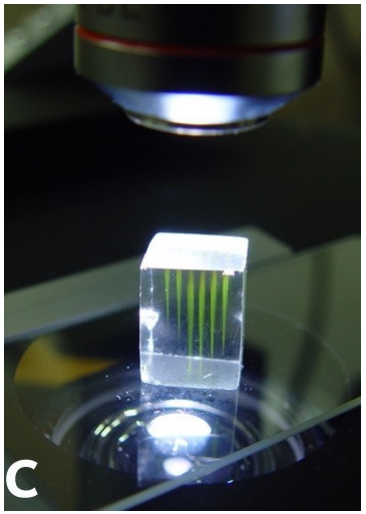


The Color of Fancy Sapphire

Color Centers

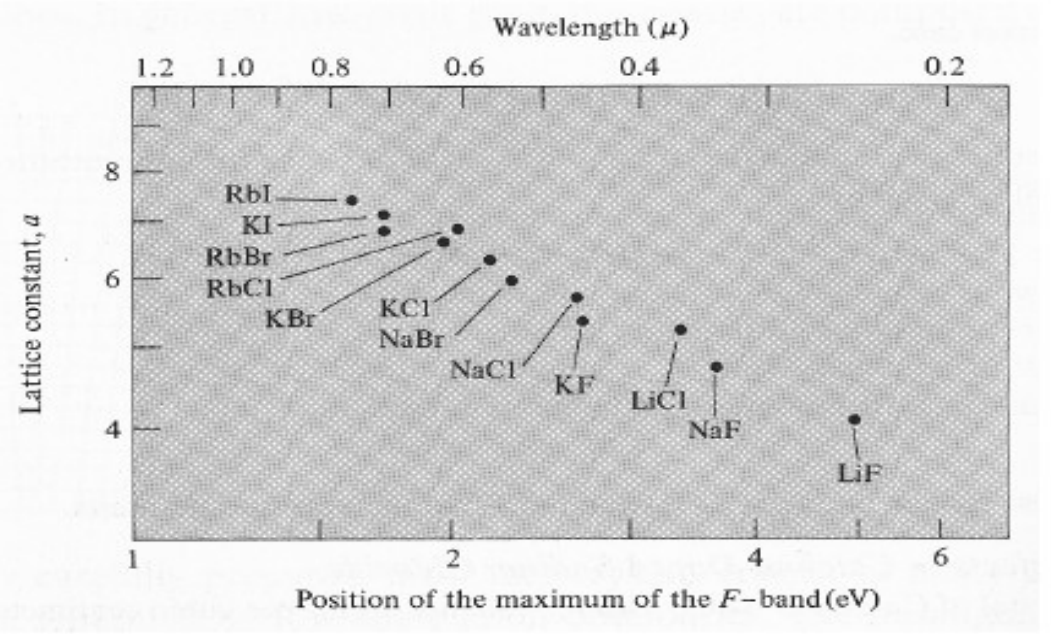
- It is known for many years that radiation damage gives color to transparent windows near e.g. nuclear power plants
- There are various mechanisms causing this effect, and the incident radiation can be gamma, neutron or charged particles

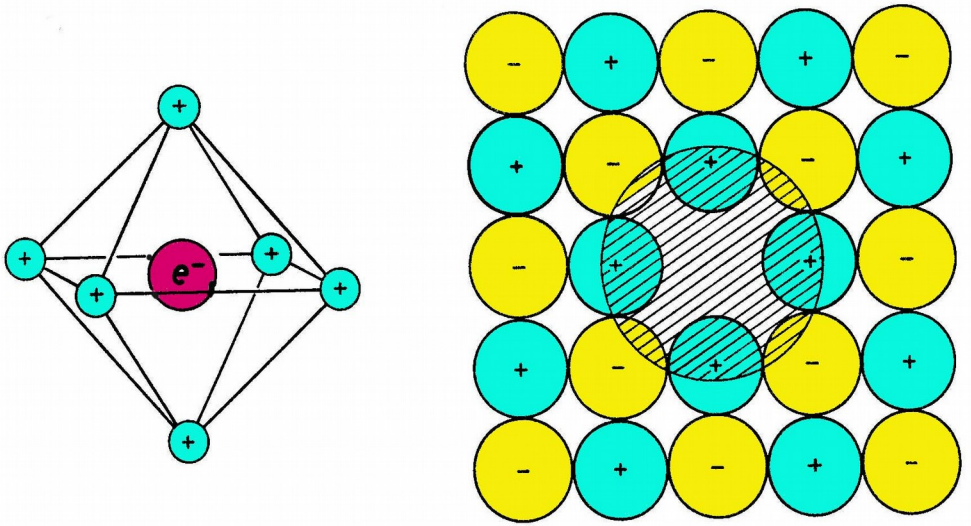




F-center in a nutshell

- The absorption dependency on the lattice constant is a power law (particle in a box)
- By this mechanism a transparent medium becomes colored
- Elastic collision may produce displacement (gamma, electron, neutron and ions)





Atomic structure of the F center

F-center in a nutshell

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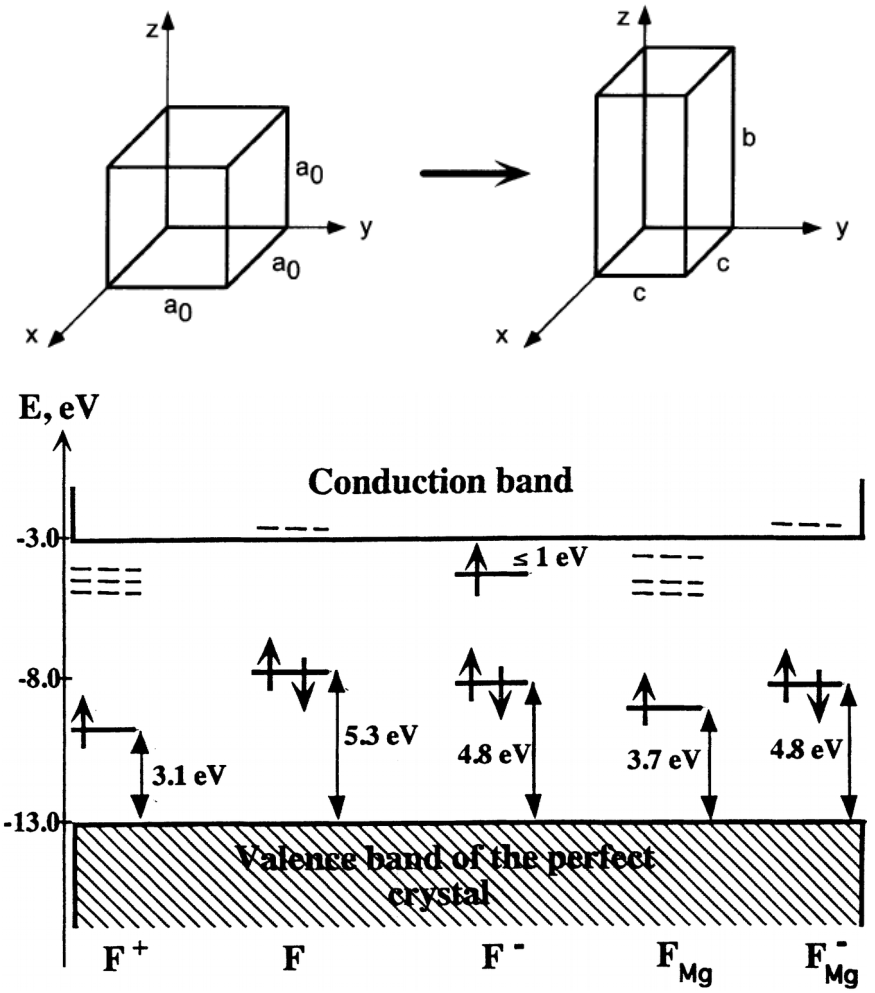
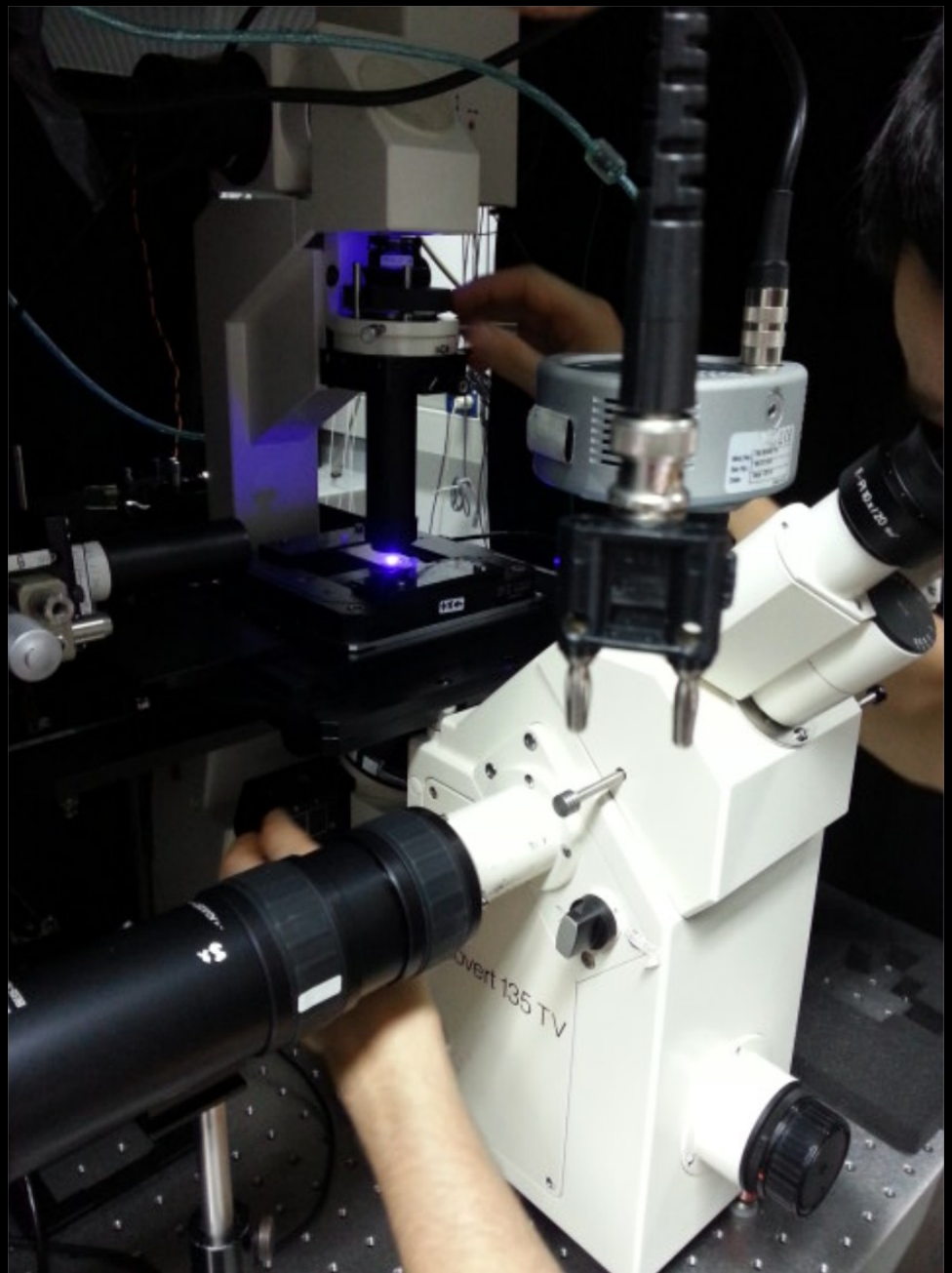


First CC measurement



The goal:

Identifying a crystal which is sensitive to low-energy-neutrons

(and check the discrimination between Nuclear Recoils coming from neutrons, and Electronic Recoils originating from gammas)

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Two parallel ongoing efforts:

1) Irradiation of as many crystals as possible

2) Establishment a setup for F-centers measurement

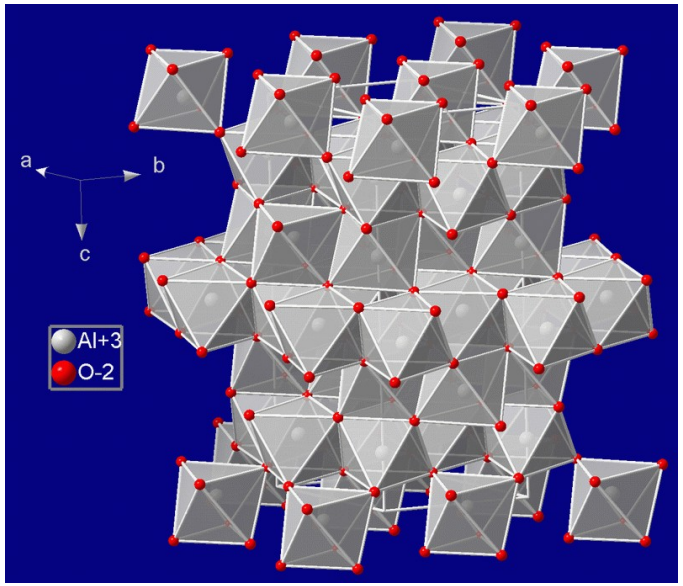
The Downs

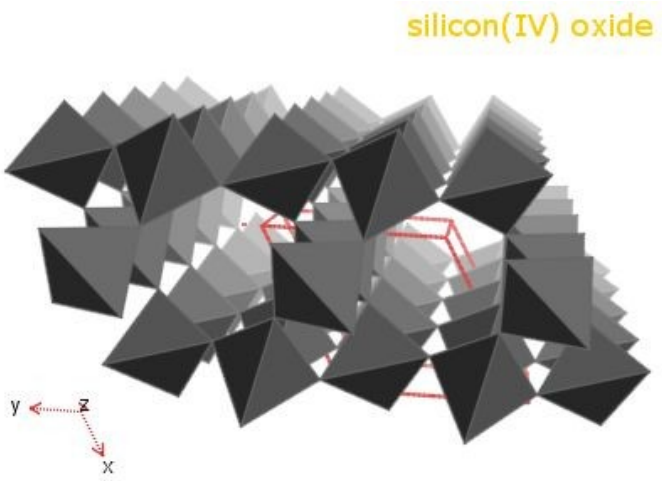
- Missing an order of magnitude of orders of magnitudes in background…
- Direct calculation impossible due to phase space
- However, only extremely difficult once established the signal
- Annealing, bleaching, counting, production, discrimination, accurate calibration sources, price ….

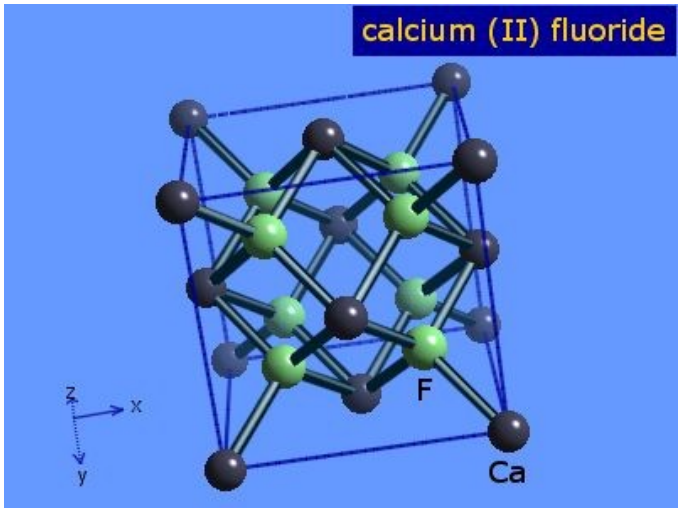
The Ups

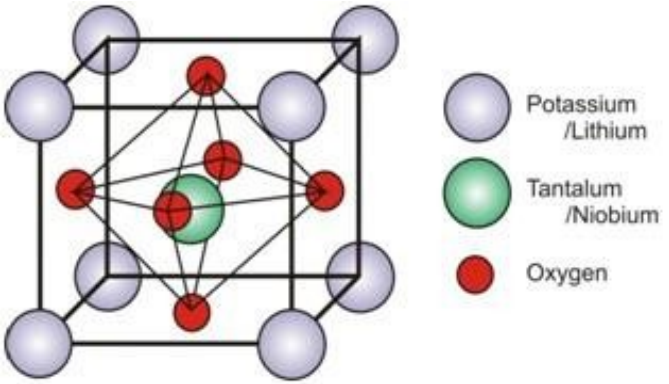
- Natural discrimination
- Likely directional
- Multiple targets, each with different signal
- Calibration is possible
- Many optional handles: B field, RF, polarization...
- And of course, the only one on that side of town (10 eV town)!

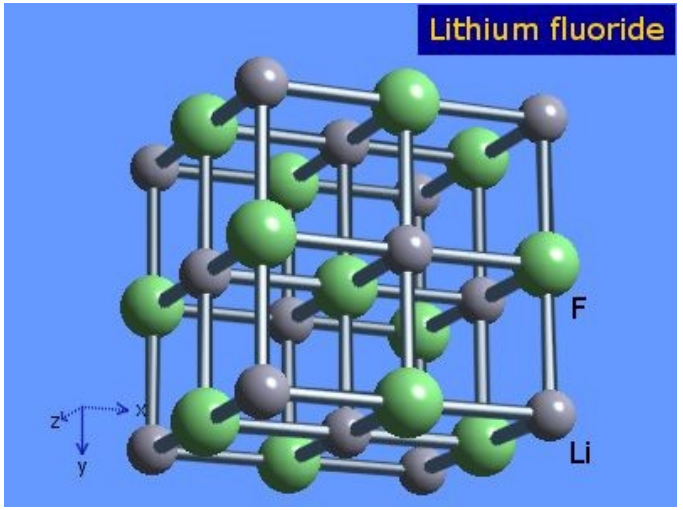
Many optional targets, but little is known

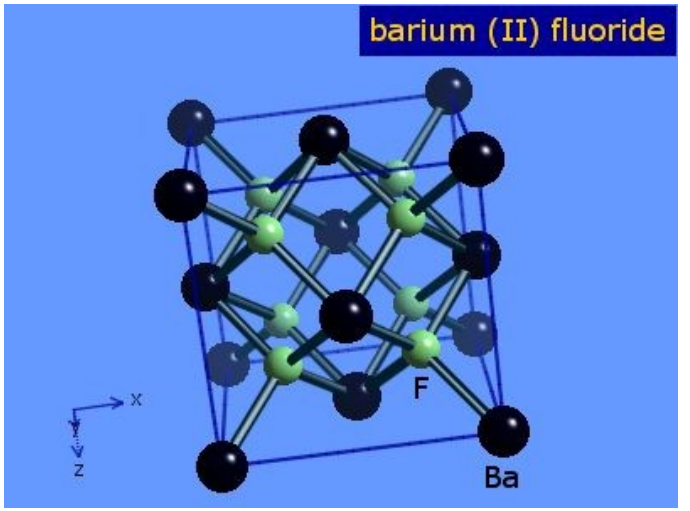




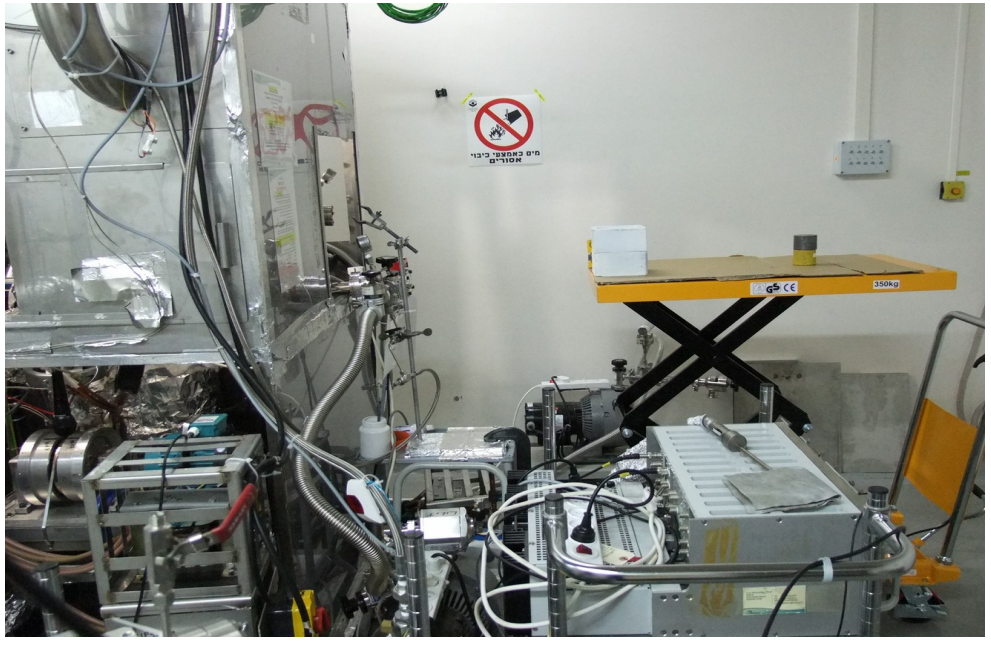


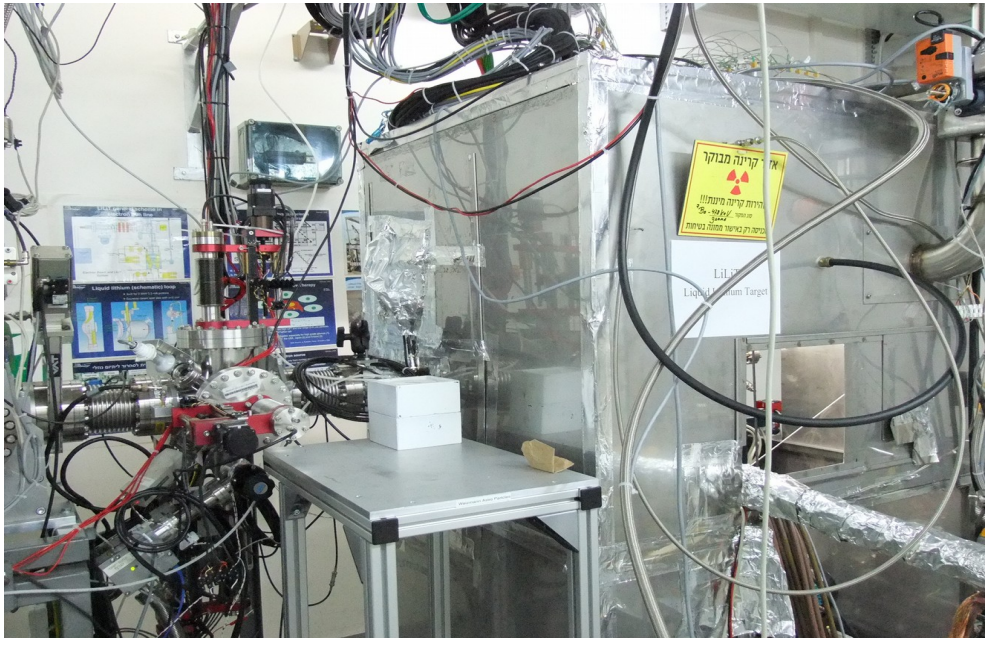






Crystal Irradiation in SARAF – 30 keV neutrons



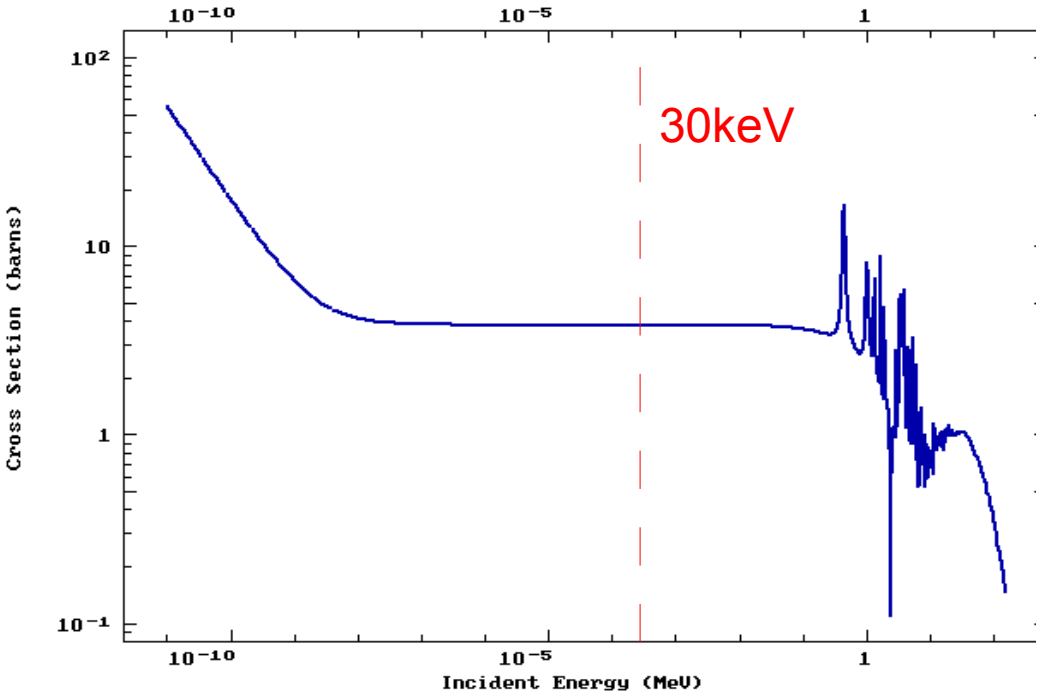


Number of defects
first order calculation

For a 1mmX1mmX1mm **Sapphire** crystal:

Number of interactions per neutron is approximately

$$\lambda = \sigma n_0 l$$



Using the oxygen elastic cross-section we get:

$$\lambda_o = 2.6\text{x}10^{-3}$$

$$\left(2\text{x}10^{-42} cm2 \times 1.3\text{x}10^{22}/cm3 \times 0.1\text{cm} = 2.6\text{x}10^{-3}\right)$$

Number of defects
first order calculation

For a 1mmX1mmX1mm **Sapphire** crystal:

If the rate of LILiT is: $R_n = 10^{11}\, n/s$

The flux of a crystal placed 112cm from LiLiT for 10 hours

$$f_n = 2.25^{10}\, n/cm^2/10\, hr$$

Therefore the expected defects concentration for the first run is:

$$n_v = f_n \lambda_O / l = 5.85\, x\, 10^8 / cm^3$$

Is it measurable?

The estimated concentration:

$$n_v = 5.85\, x\, 10^8 / cm3$$

The estimated optical depth:

$$\tau = \sigma_{cc} n_v l = O\left(10^{-10} - 10^{-8}\right)$$

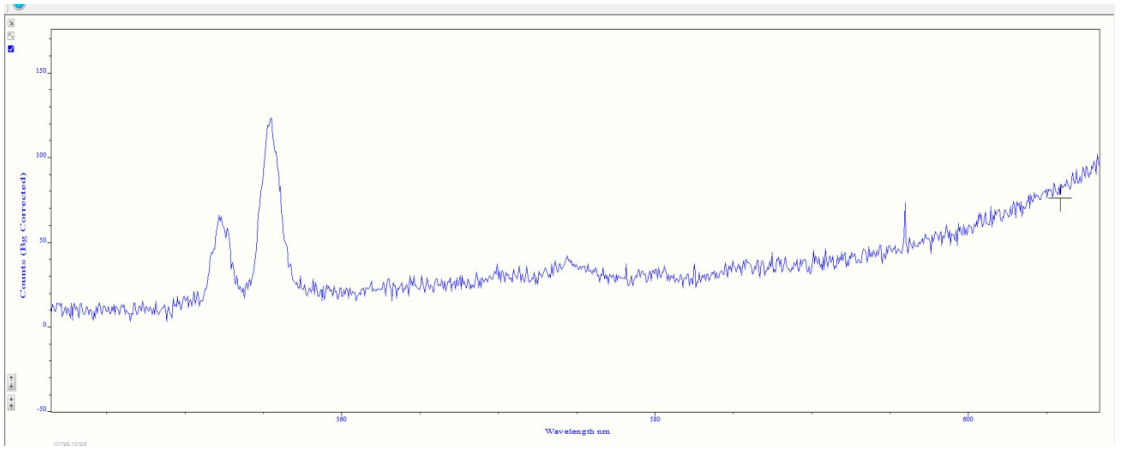
$$\left(\sigma_{cc} = O\left(10^{-17} - 10^{-16}\right) cm2\right)$$

It can not be measured by means of absorption!

However, the fluorescence is within reach.

Summary

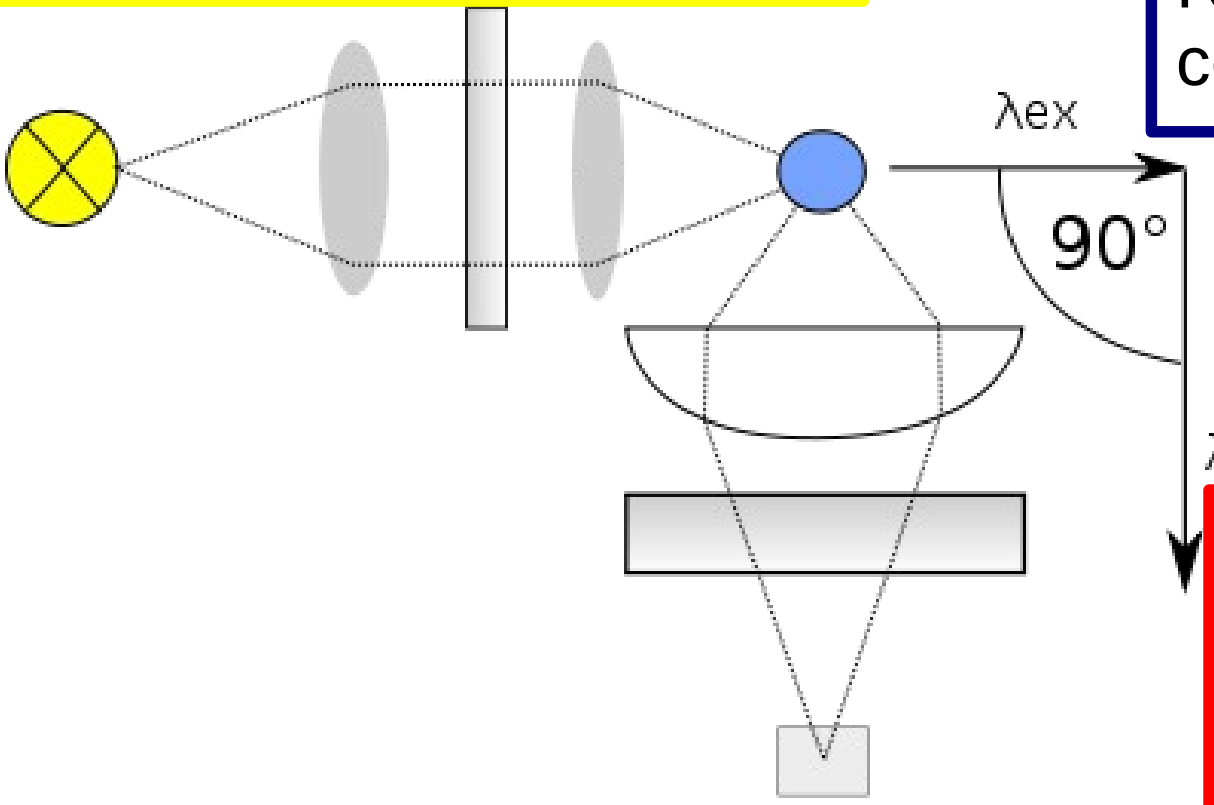
- Color Centers are a promising avenue for low energy NR detection
- The current experimental and theoretical knowledge is insufficient, much work is needed on both
- Irradiation of multiple samples ongoing/done
- Optical system with the required sensitivity is being developed, expected to give results this year
- After identifying the “promising avenues”, the real work begins!



Fluorescence measurement

Monochromatic light source:
LED, laser, Xenon lamp + monochromator, filters, etc.

Optics:
Refractive/reflective, light collection efficiency, etc.



Spectrometer:
Single/double gratings, filters,
PMT vs CCD, etc.

Raman Scattering of crystals

- In Sapphire 2 modes are active in Raman scattering –

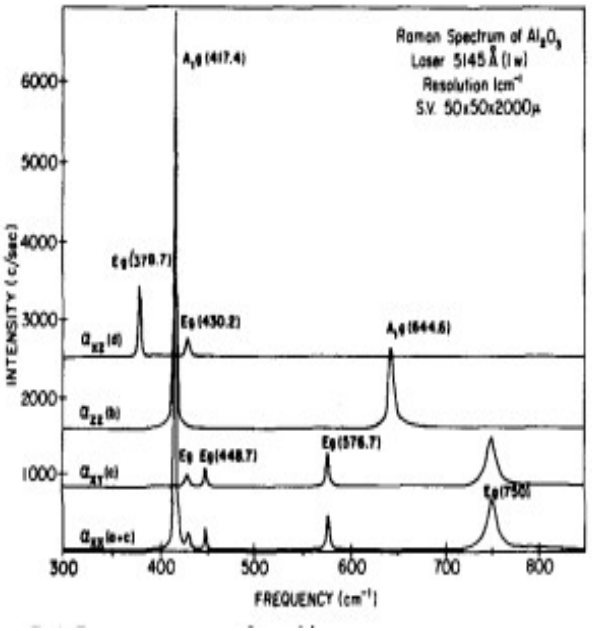
$$A_{1g} = \begin{pmatrix} \alpha_{xx} & & \\ & \alpha_{xx} & \\ & & \alpha_{zz} \end{pmatrix} \; ; \; E_g = \begin{pmatrix} -\alpha_{xy} & \alpha_{xy} & \alpha_{xz} \\ \alpha_{xy} & -\alpha_{xy} & -\alpha_{xz} \\ \alpha_{xz} & -\alpha_{xz} & \end{pmatrix}$$

- The intensity of the scattering is:

$$I_{ij}(\lambda) \propto \left| \langle e_i(\theta,\phi)| R(\lambda) |e_j(\theta,\phi)\rangle \right|^2$$

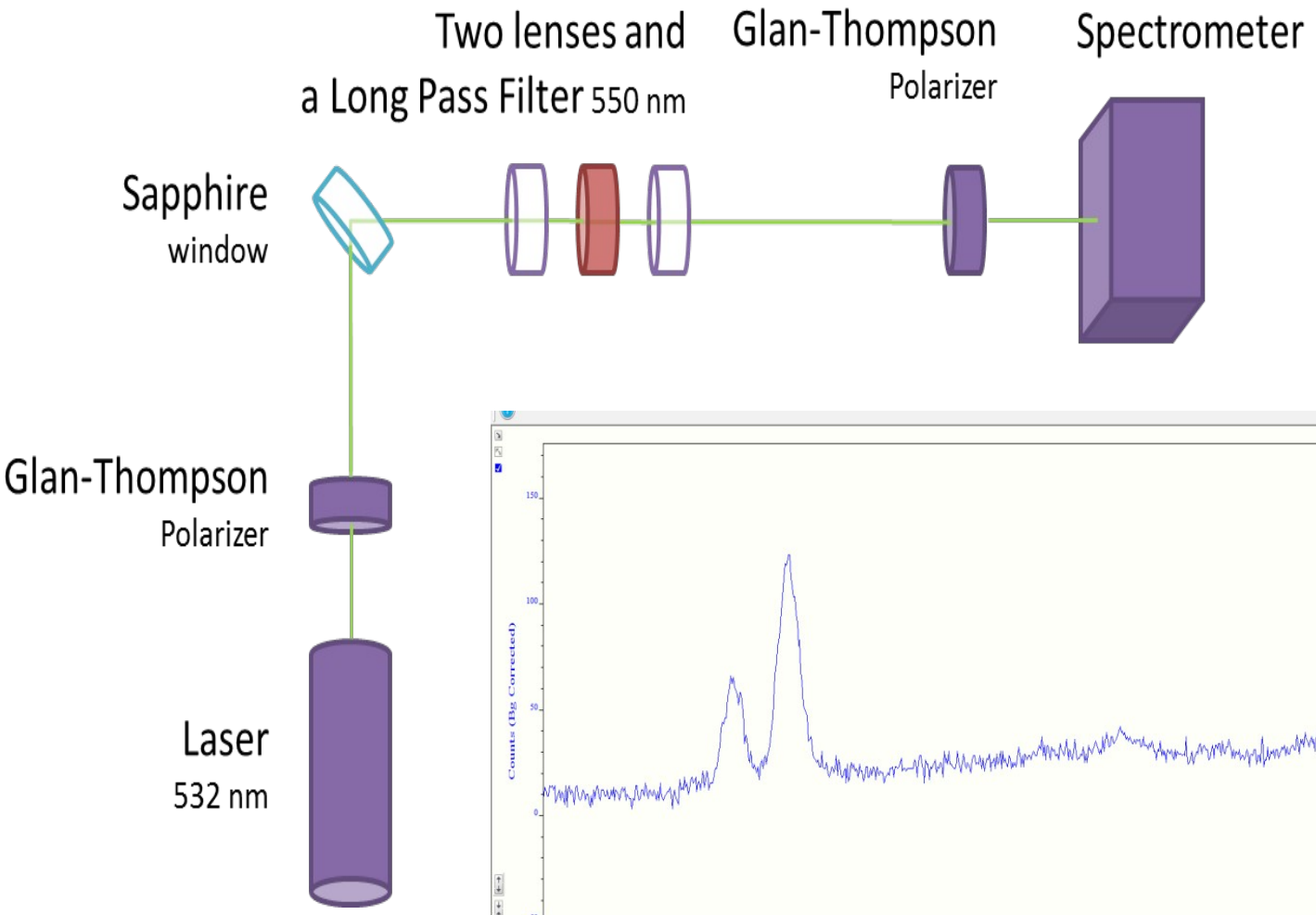
- The cross section is:

$$\left.\frac{d\sigma}{d\Omega}\right|_{\Delta q = 417.4\, cm^{-1}} = 1.59 \cdot 10^{-30}\, cm^2/\text{sr unit cell}$$



Watson Jr, G. H., W. B. Daniels, and C. S. Wang "Measurements of Raman intensities and pressure dependence of phonon frequencies in sapphire" *Journal of Applied Physics* 52.2 (1981)

Experimental Setup



Orientation of the crystal

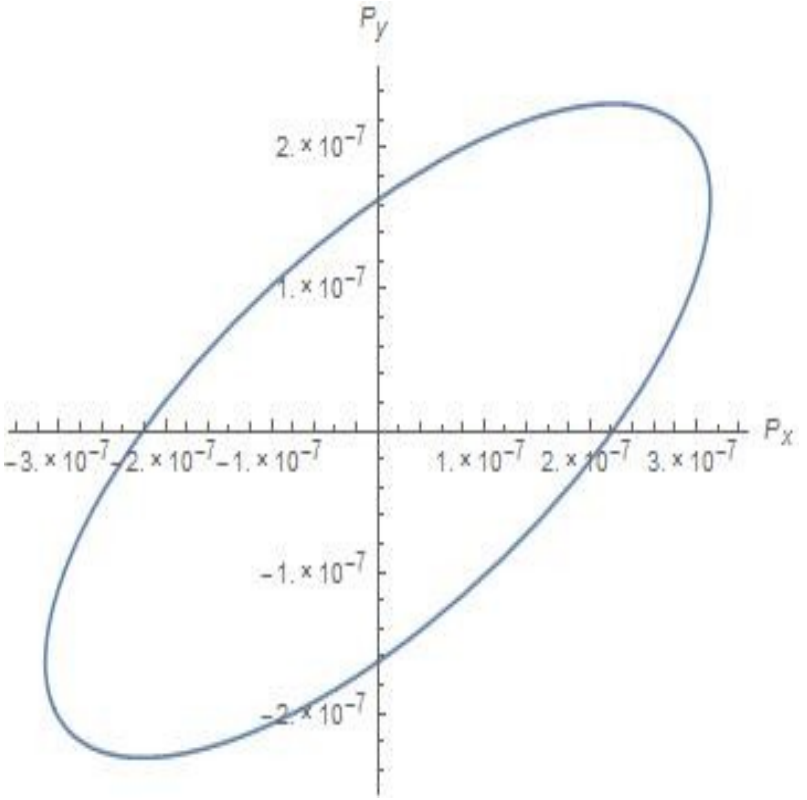
- Using the Raman tensors, we found the orientation of the lattice –

$$I_{ij}(\lambda) \propto \left|\langle e_i(\theta,\phi)| R(\lambda) |e_j(\theta,\phi)\rangle\right|^2$$

$$\begin{cases} \theta = 1.57 - 0.32\,i = 90° + \text{Attenuation term} \\ \phi = 29.3° \end{cases}$$

where θ, φ are the spherical angles

- The polarization obtained is the expected one -



Polarization of the scattered wave