Nonlinear X-ray optics

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Outline

1. Nonlinear vs. linear optics
2. Laser radiation
3. X-ray two-photon absorption
4. Nonlinear X-ray Compton scattering
5. X-ray second harmonic generation
6. X-ray optical mixing
7. Parametric downconversion
8. Summary

Nonlinear vs. linear optics

Linear optics – study of interaction of electromagnetic radiation with linear media

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Linear media – their response is linear to the incident wave:

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$$\boldsymbol{P} = P_0 + \chi\, \varepsilon_0\, \boldsymbol{E}$$

the medium's polarization

the wave's electric field

electric constant (also: vacuum permittivity)

the medium's electric susceptibility

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Nonlinear vs. linear optics

Nonlinear optics – study of interaction of electromagnetic radiation with nonlinear media

Nonlinear media – their response is nonlinear to the incident wave:

$$\boldsymbol{P} = P_0 + \chi\, \varepsilon_0\, \boldsymbol{E}$$

- $\boldsymbol{P}$: the medium's polarization
- $\boldsymbol{E}$: the wave's electric field
- ε_0: electric constant (also: vacuum permittivity)
- χ: the medium's electric susceptibility

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$$\boldsymbol{P} = P_0 + \chi^{(1)}\,\varepsilon_0\,\boldsymbol{E} + \chi^{(2)}\,\varepsilon_0\,\boldsymbol{E}^2 + \chi^{(3)}\,\varepsilon_0\,\boldsymbol{E}^3 + \ldots \qquad \text{(the Taylor series)}$$

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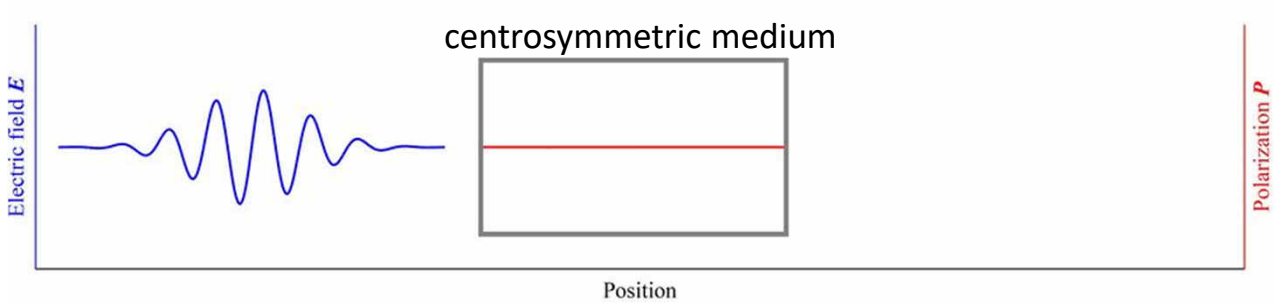

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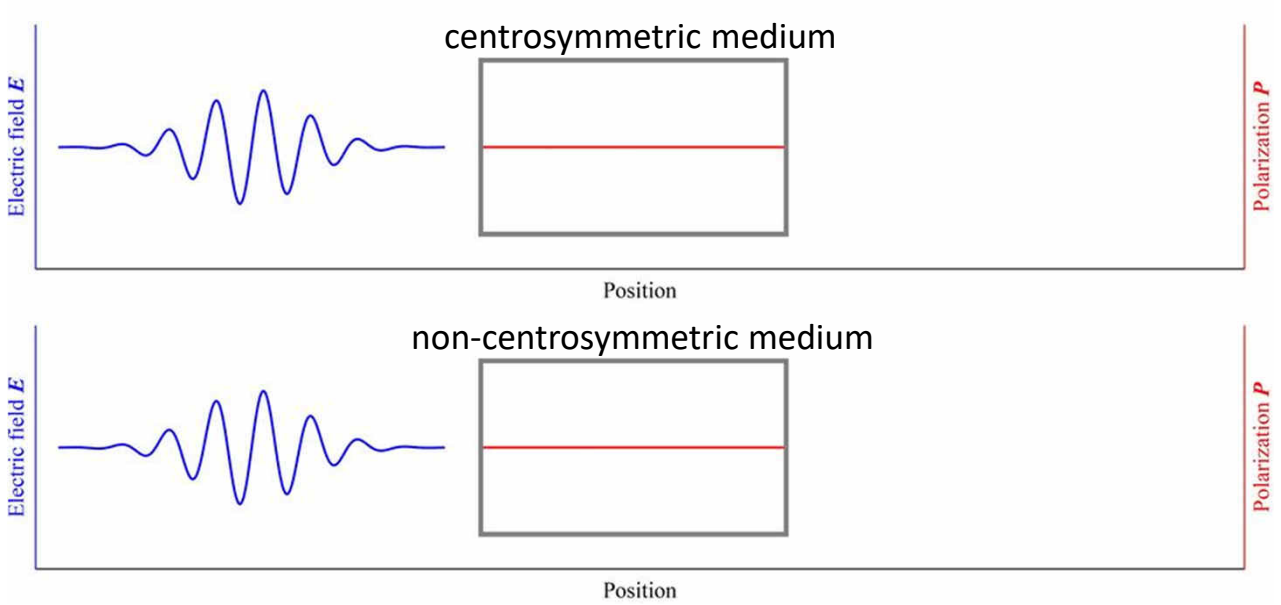

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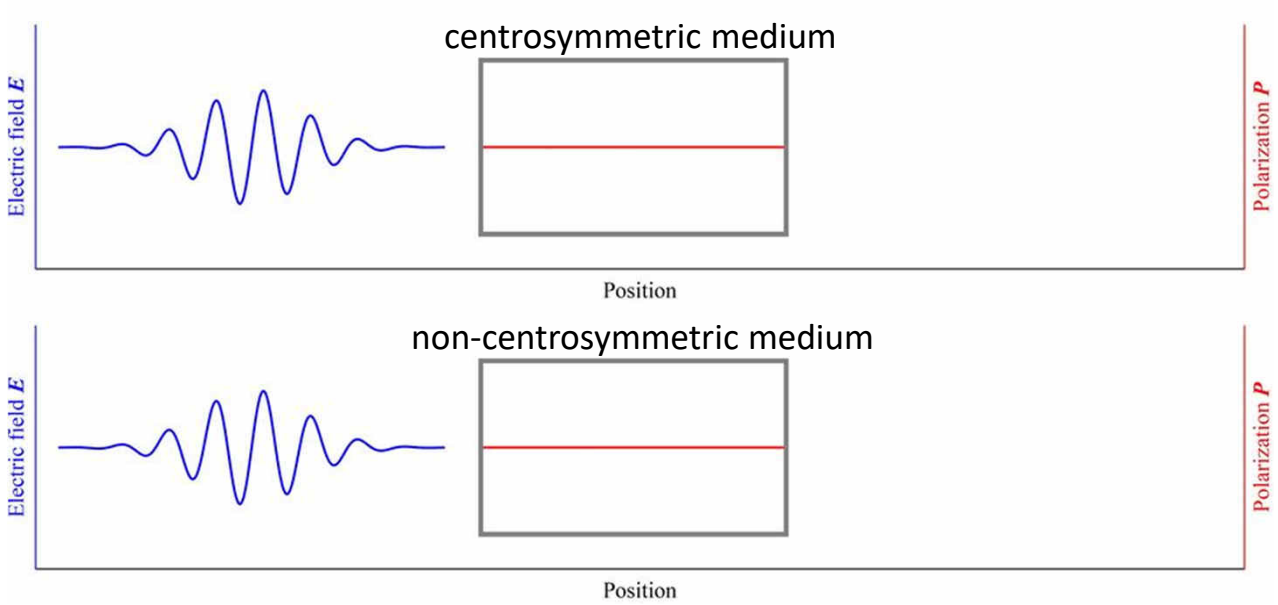
The wave equation taking into account the medium's nonlinear polarization delivers surprising solutions – mutliphoton interactions!



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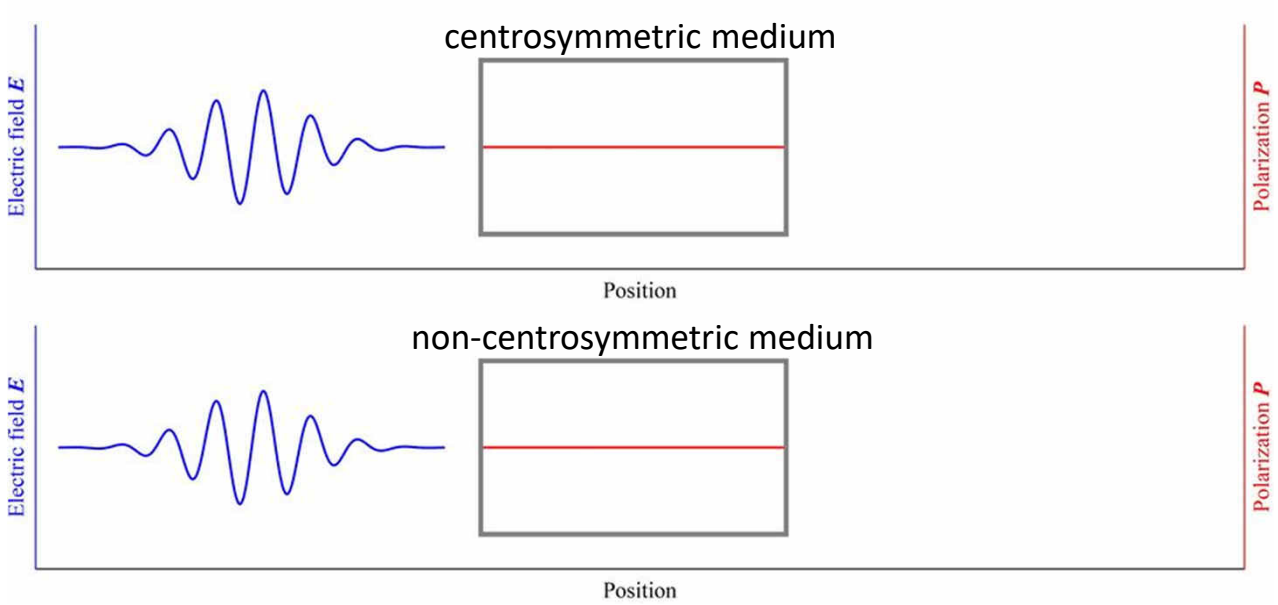
Since generally all materials are nonlinear, why haven't we observed those nonlinear processes before 1960s?



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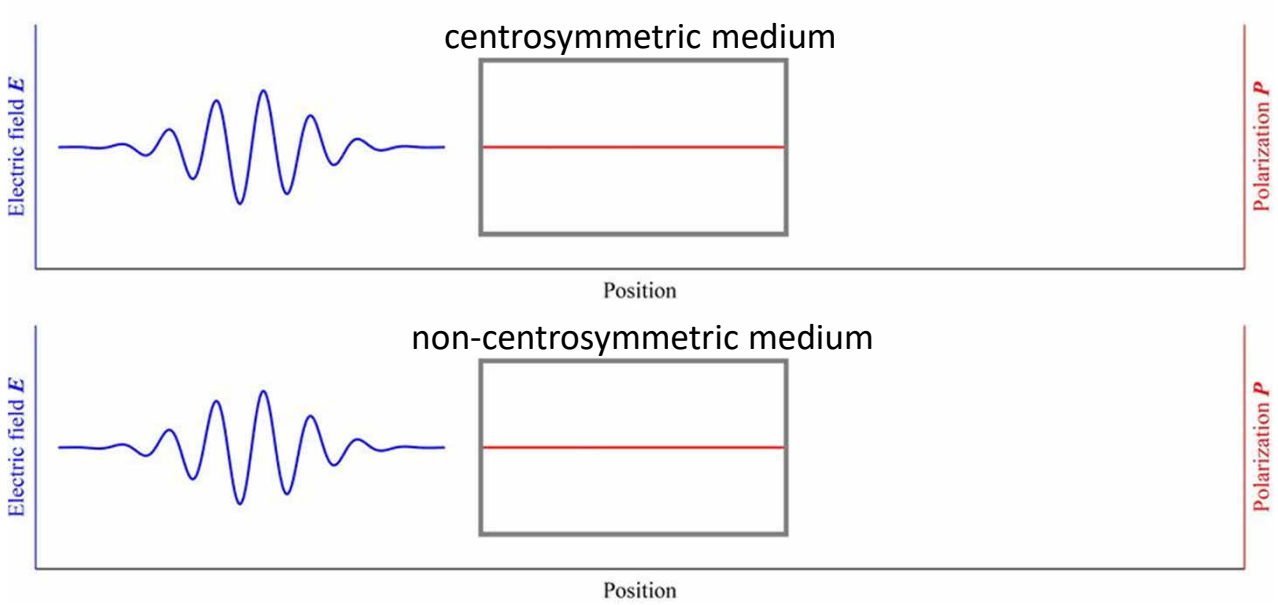
– photon flux



Laser radiation

Laser radiation

pginstruments.com

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$$\textbf{intensity} = \textbf{photon flux} \times \text{photon energy} = \frac{\text{number of photons} \times \text{photon energy}}{\text{time (i. e. pulse duration)} \times \text{area}}$$

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laser power = 2 W, wavelength = 445 nm, beam size = 2 mm × 5 mm

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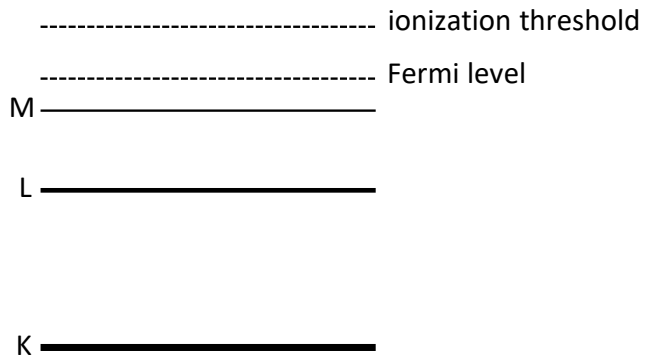
laser intensity = 2 W / (2 mm × 5 mm) = 20 W/cm^2

$\boldsymbol{P} = P_0 + \chi^{(1)}\,\varepsilon_0\,\boldsymbol{E} + \chi^{(2)}\,\varepsilon_0\,\boldsymbol{E}^2 + \chi^{(3)}\,\varepsilon_0\,\boldsymbol{E}^3 + \ldots$ - convergence at about 10^{11} W/cm^2

X-ray two-photon absorption (TPA)

X-ray multiphoton absorption



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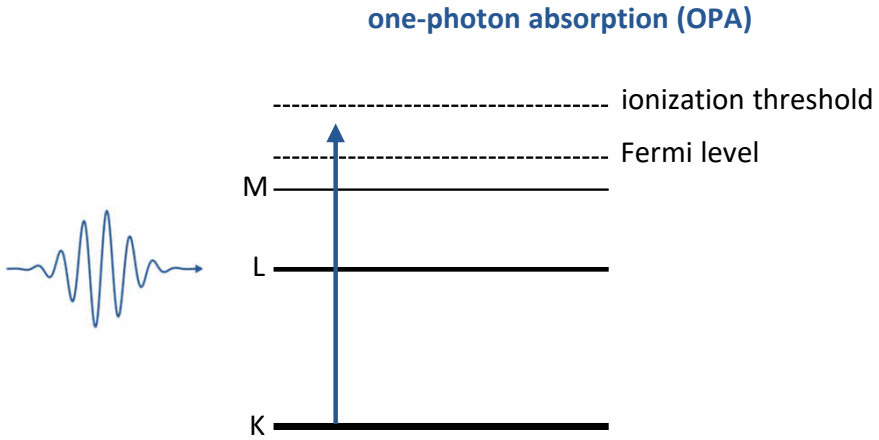

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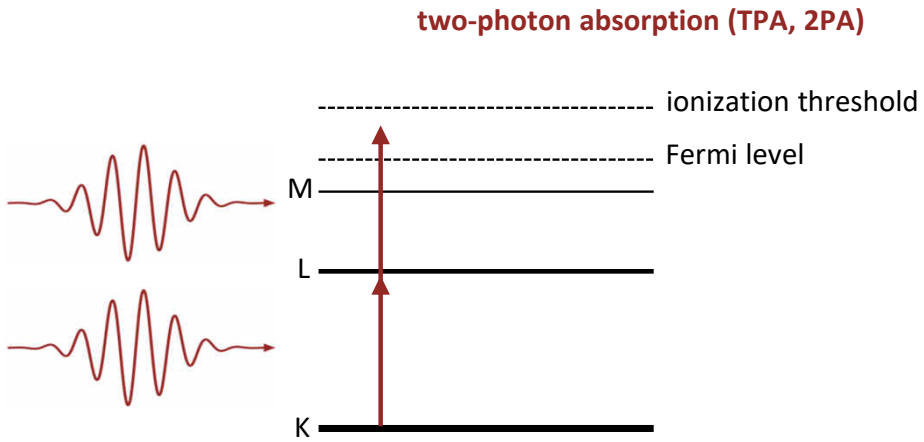

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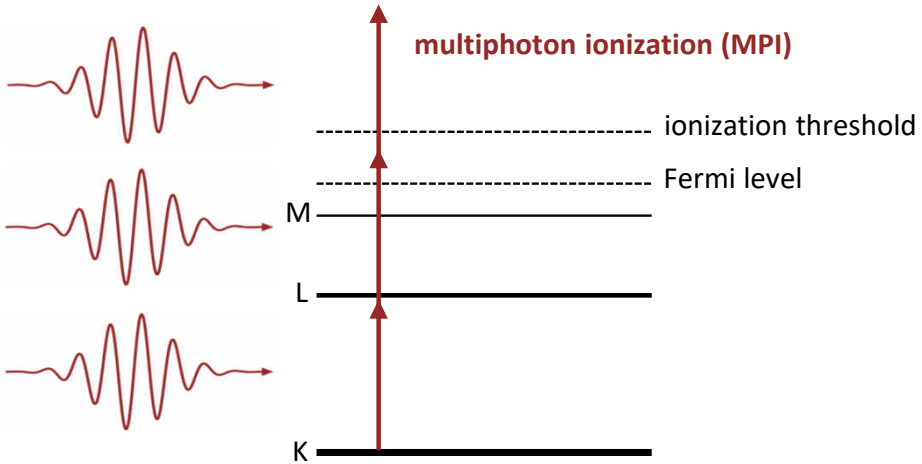
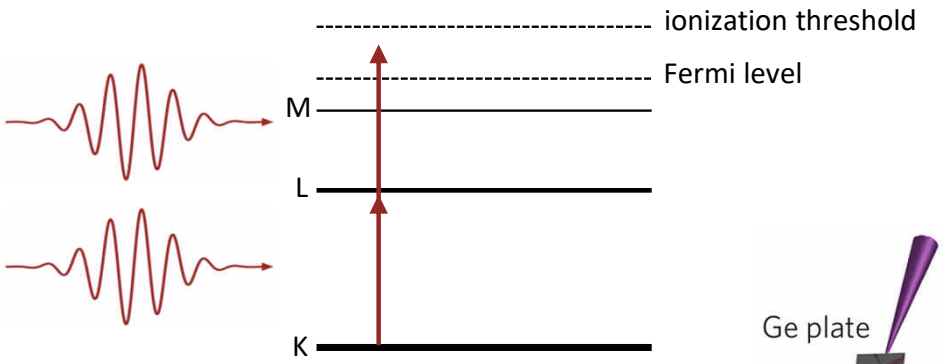
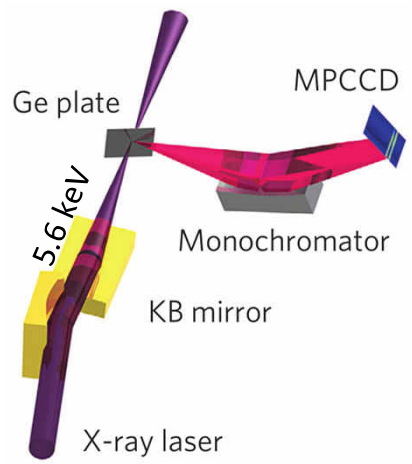


X-ray two-photon absorption (TPA)

X-ray multiphoton absorption

two-photon absorption (TPA, 2PA)





K. Tamasaku *et al.*, *Nature Photon* **8**, 313 (2014)

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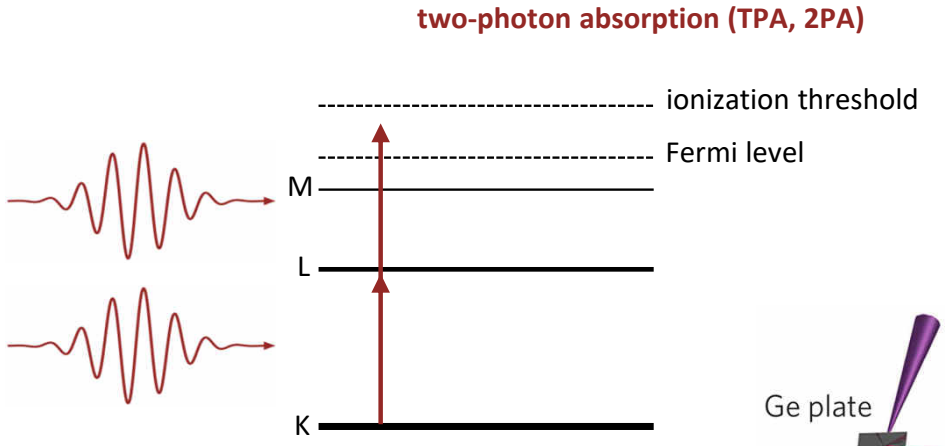

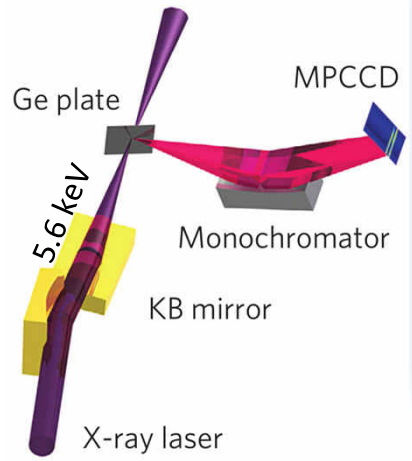

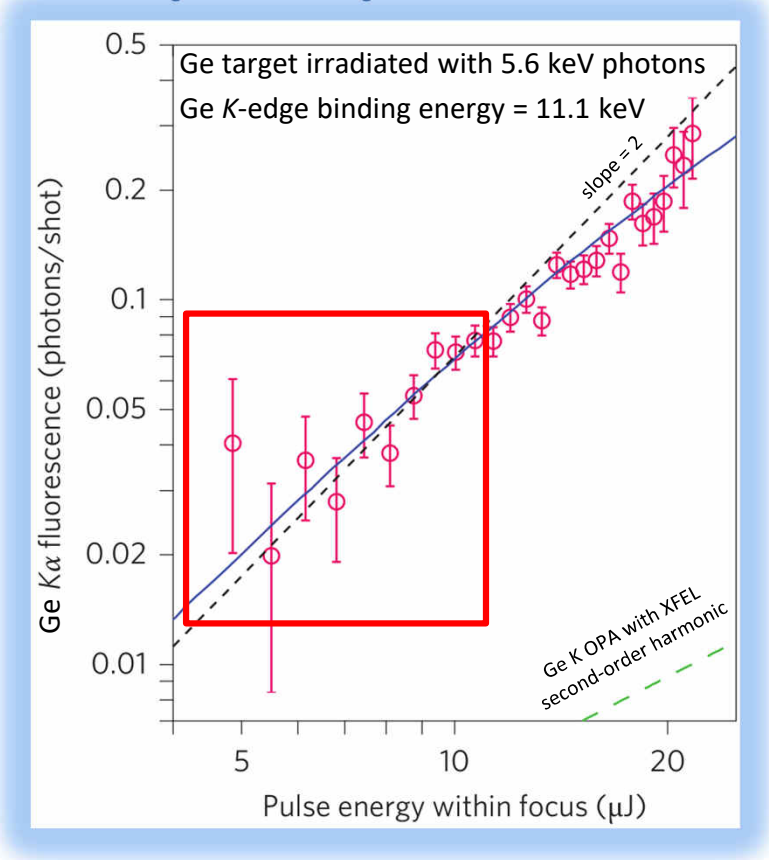

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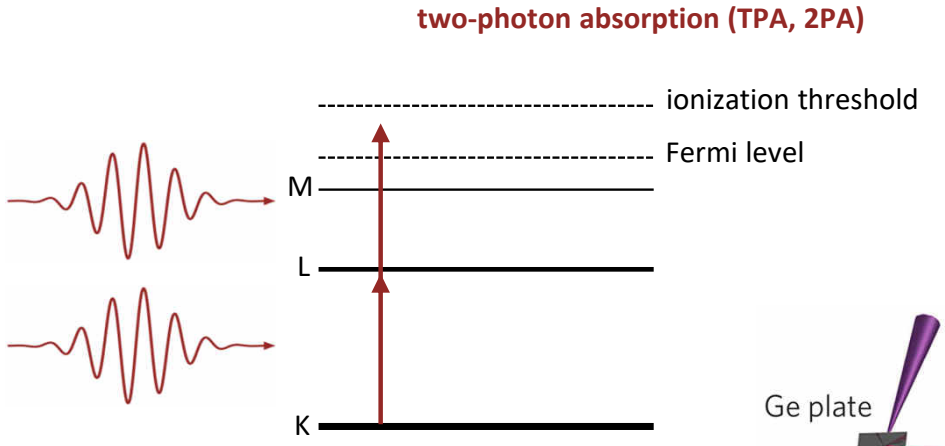

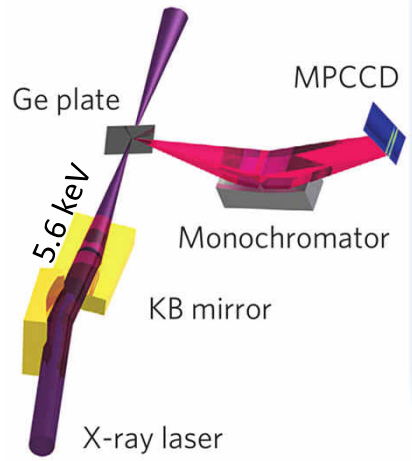

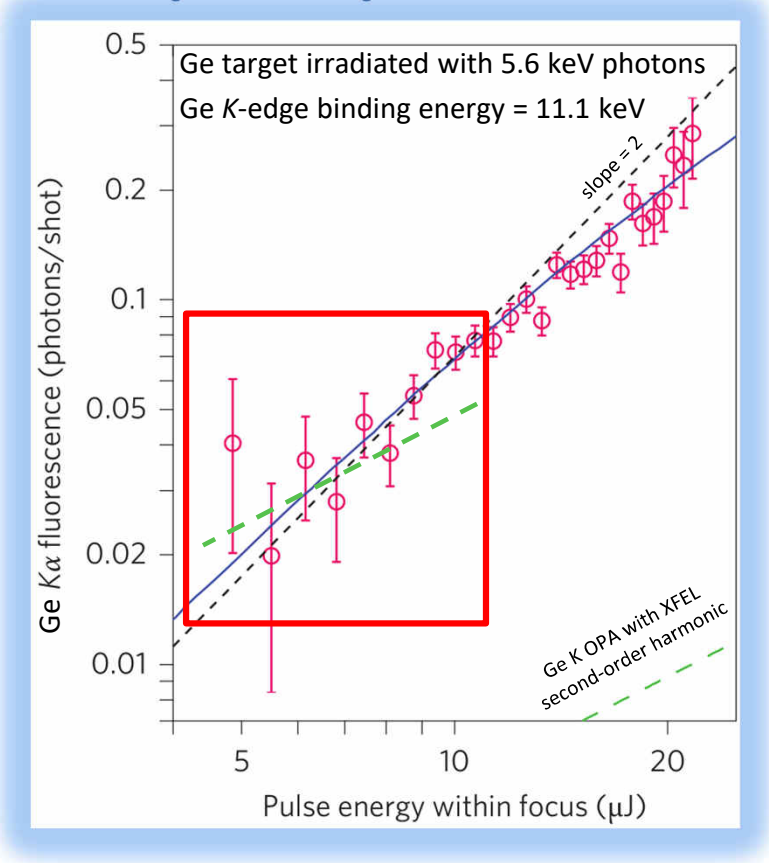

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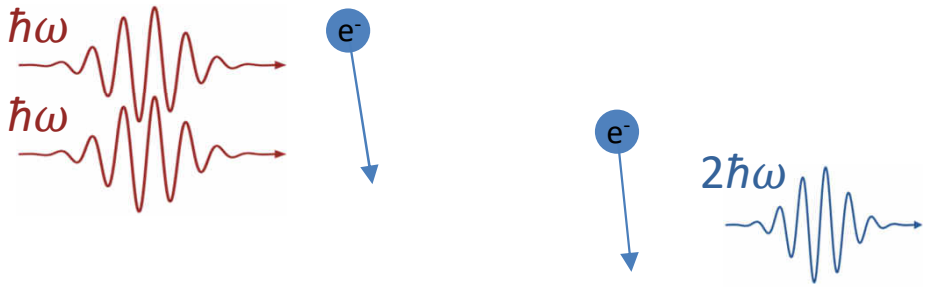
Nonlinear X-ray Compton scattering



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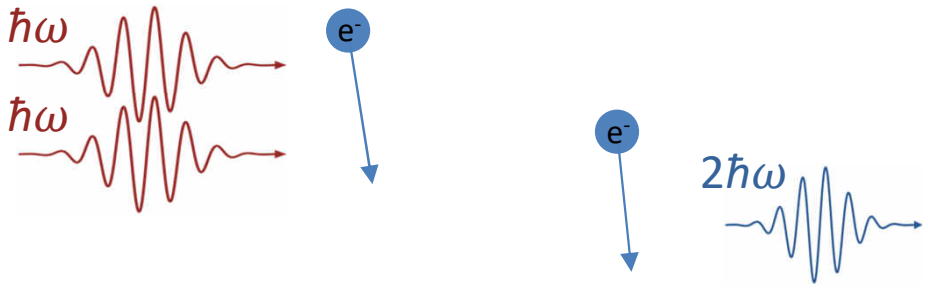

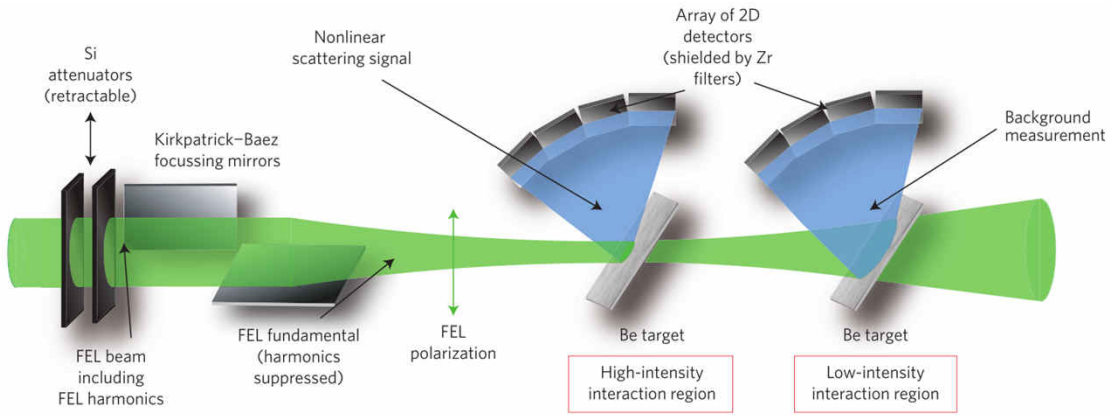

M. Fuchs *et al.*, *Nature Phys* **11,** 964 (2015)

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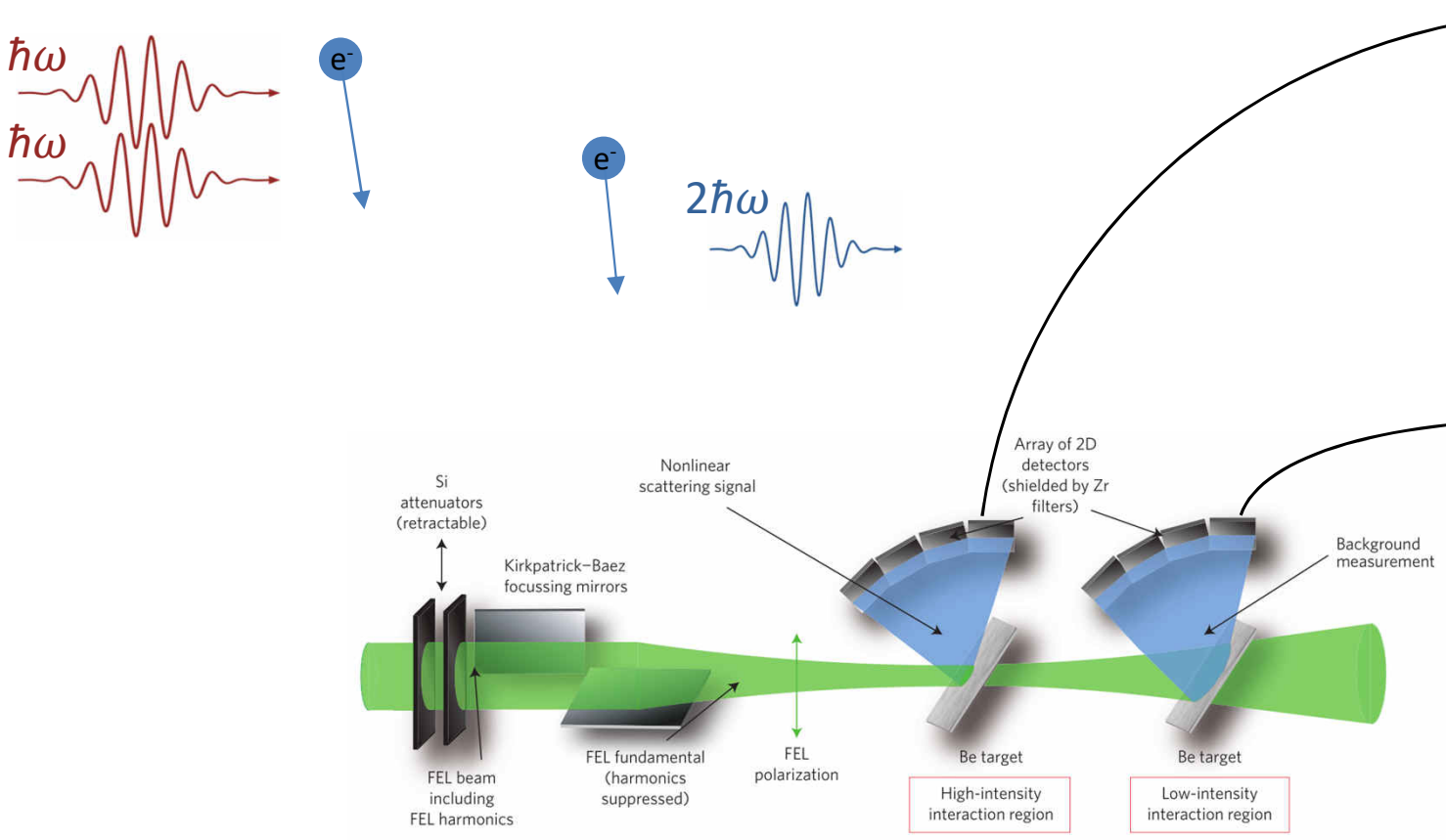

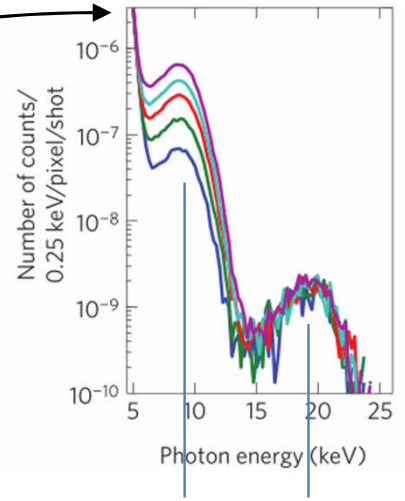

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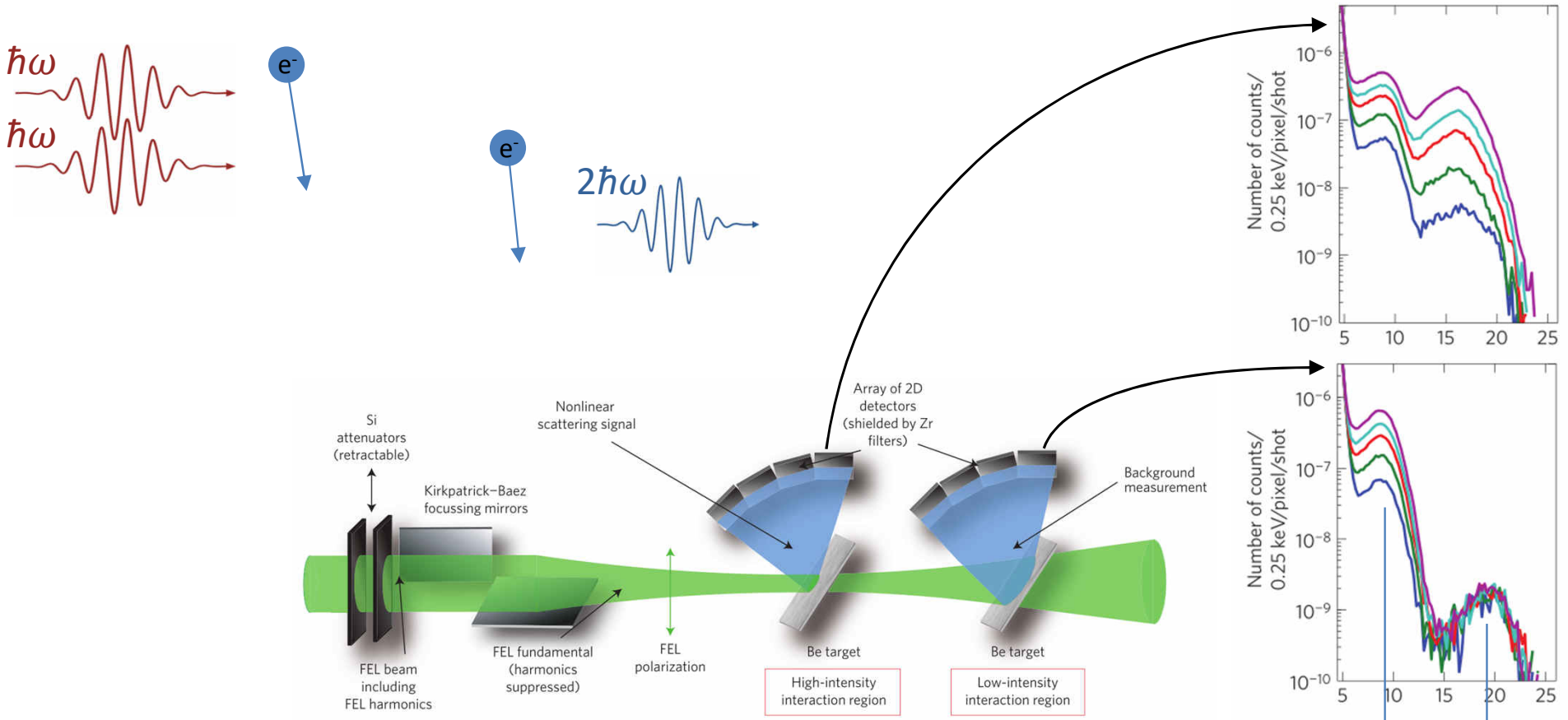

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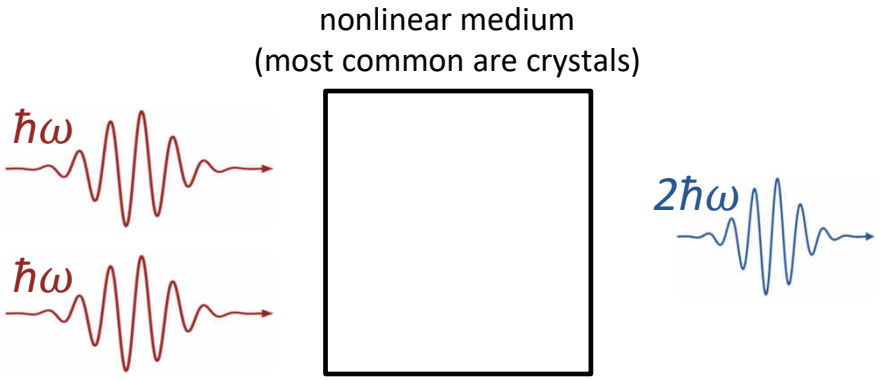
X-ray second harmonic generation (SHG)



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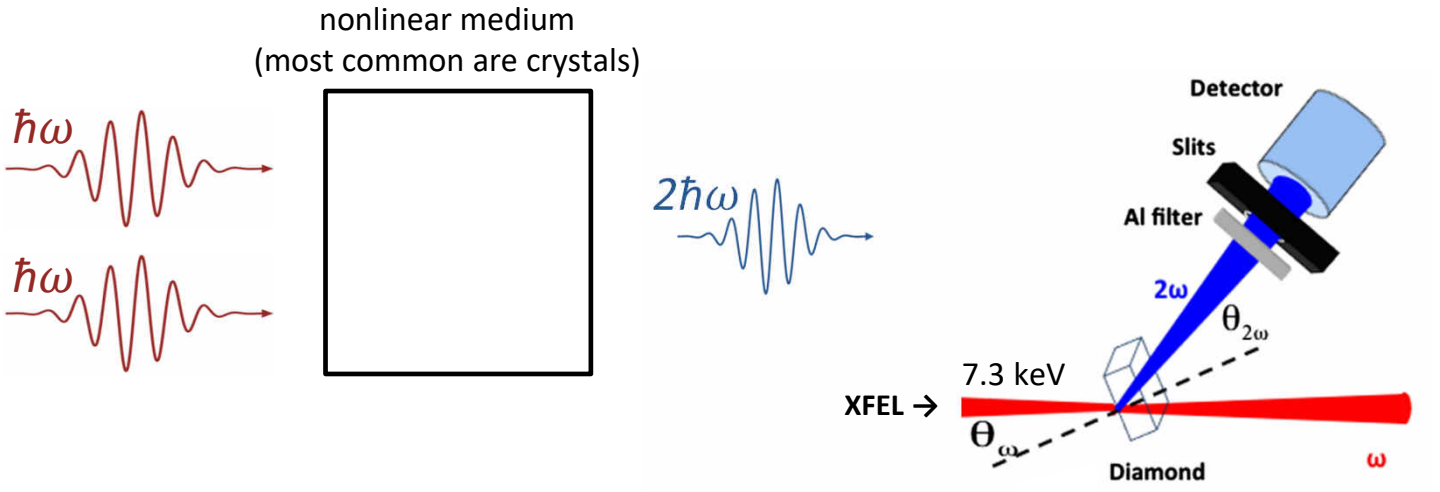

S. Shwartz *et al.*, *Phys. Rev. Lett.* **112**, 163901 (2014)

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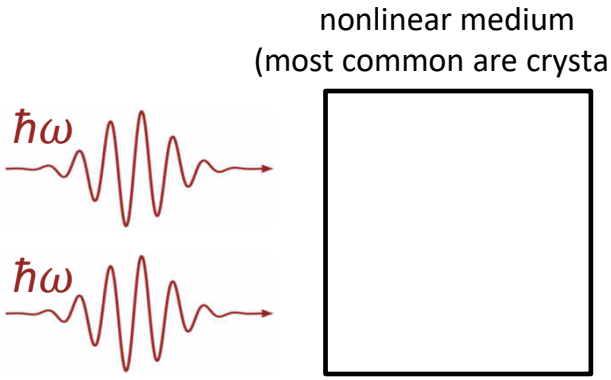

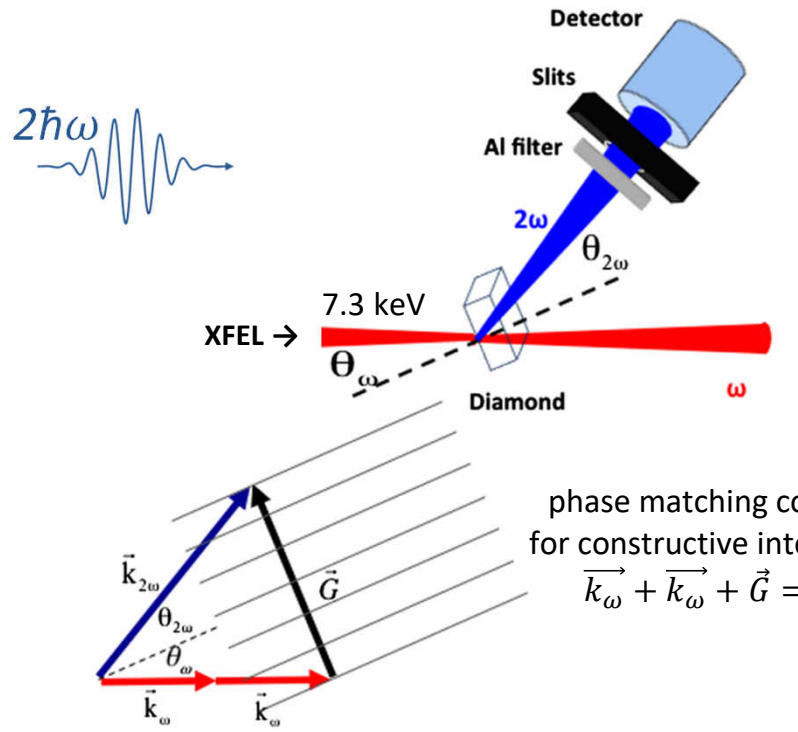

phase matching condition
for constructive inteference:

$$\overrightarrow{k_\omega} + \overrightarrow{k_\omega} + \vec{G} = \overrightarrow{k_{2\omega}}$$

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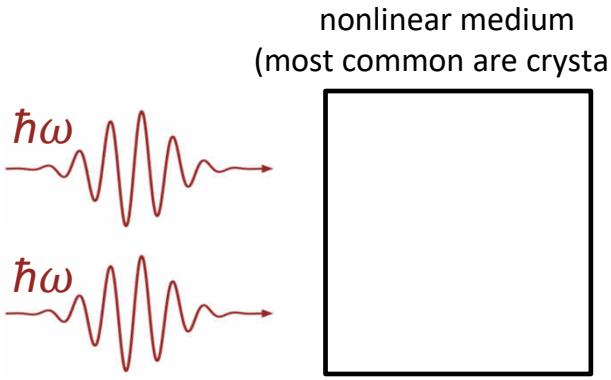

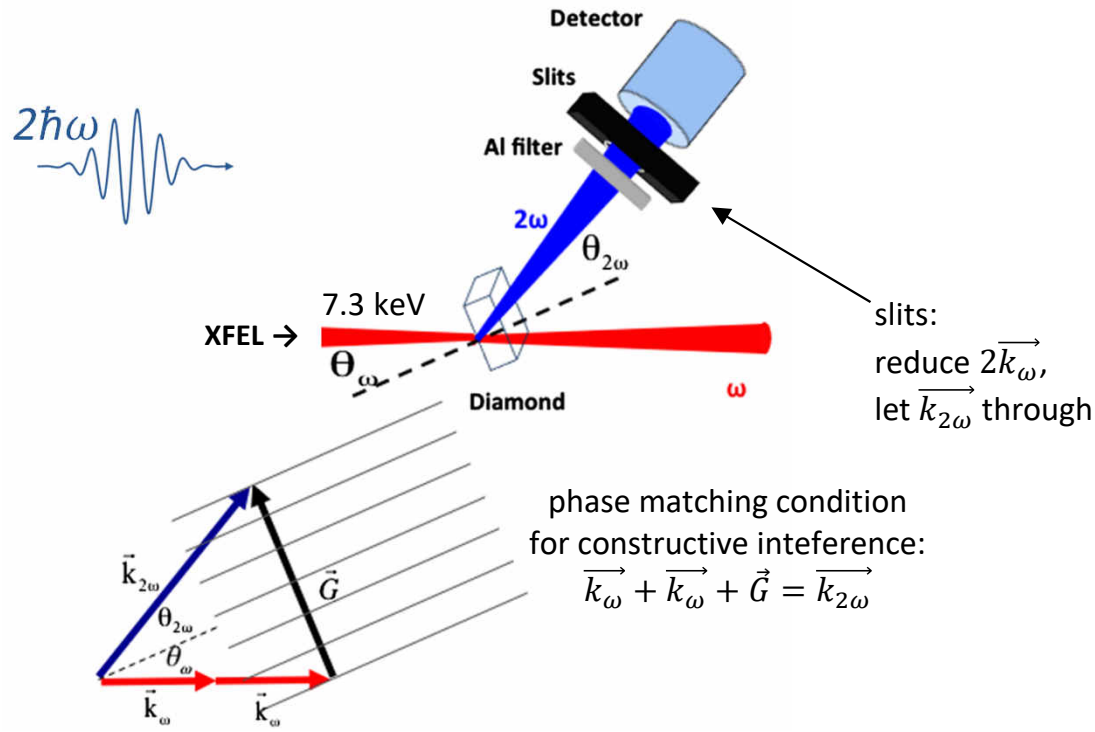

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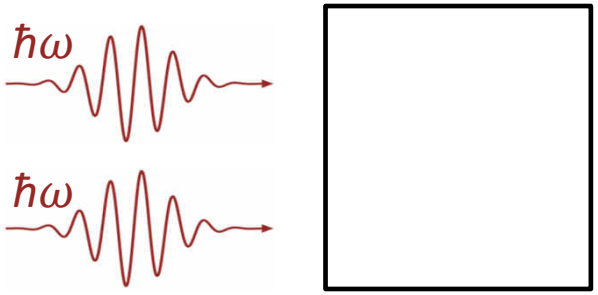

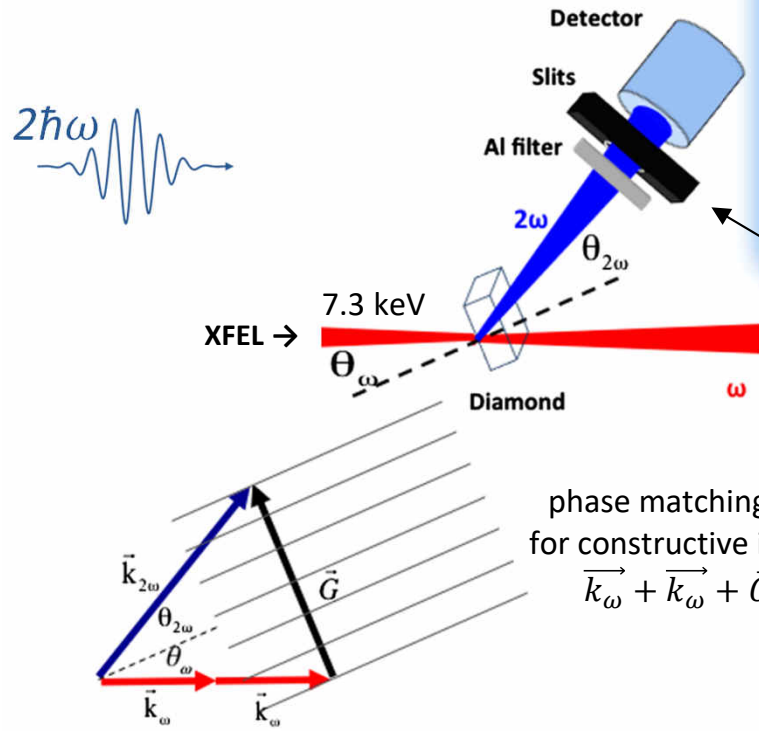

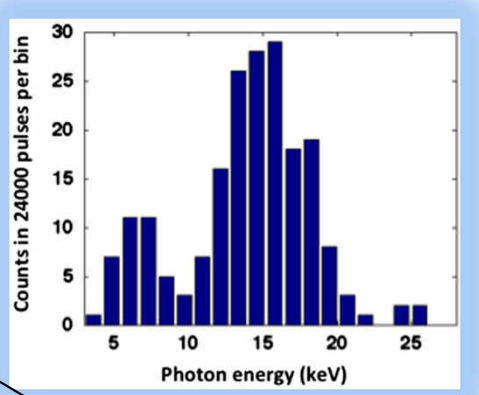

slits:
reduce $2\overrightarrow{k_\omega}$,
let $\overrightarrow{k_{2\omega}}$ through

phase matching condition
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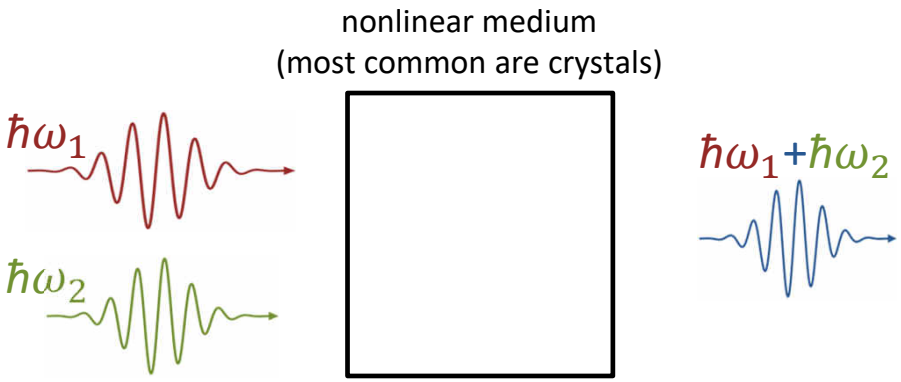
S. Shwartz *et al.*, *Phys. Rev. Lett.* **112**, 163901 (2014)

X-ray optical mixing

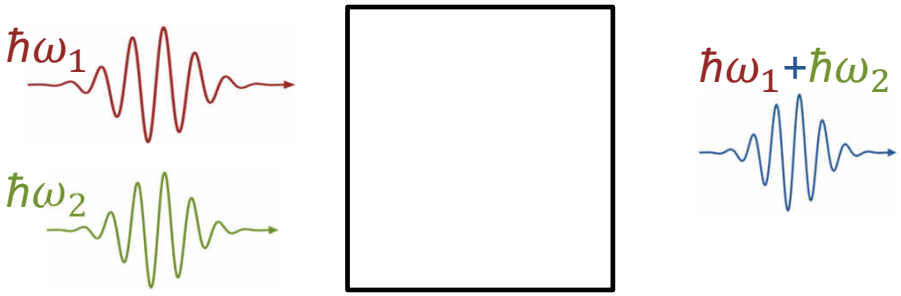
Sum-frequency generation (SFG)

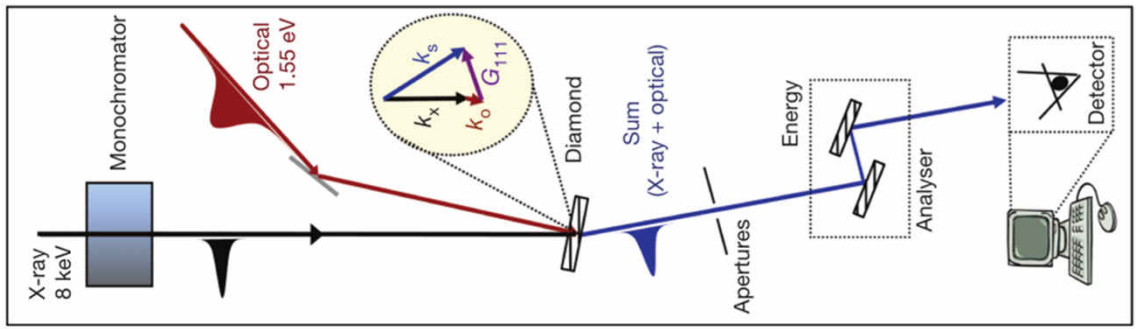


X-ray optical mixing

Sum-frequency generation (SFG)

nonlinear medium
(most common are crystals)





T. Glover *et al.*, *Nature* **488**, 604 (2012)

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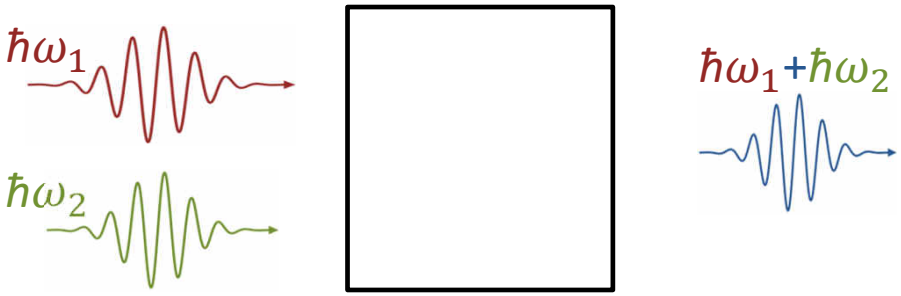

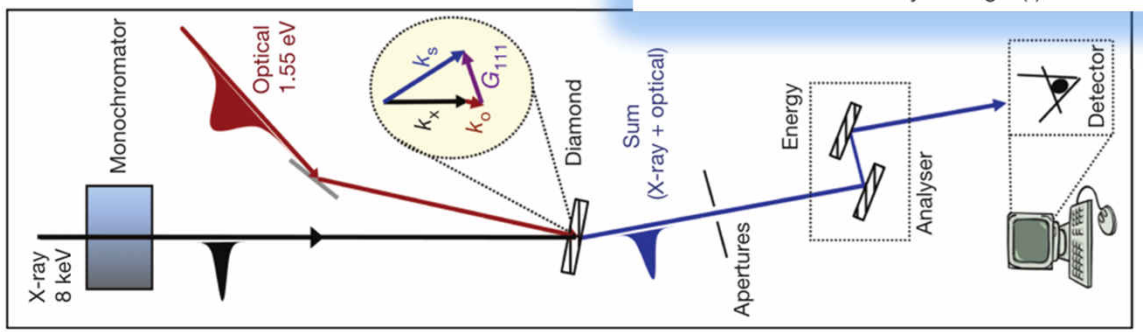

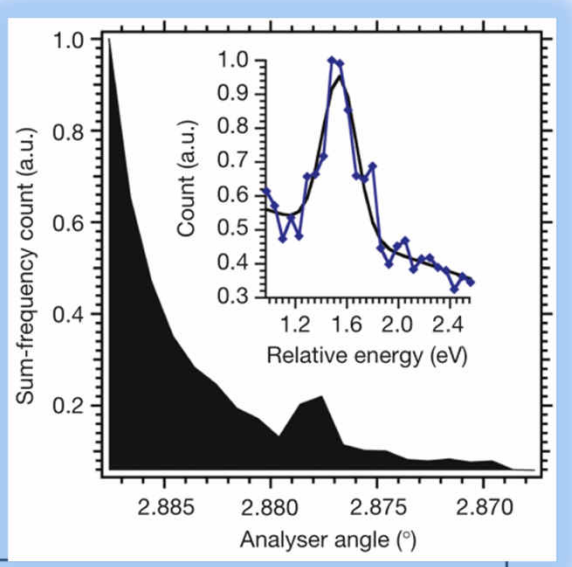

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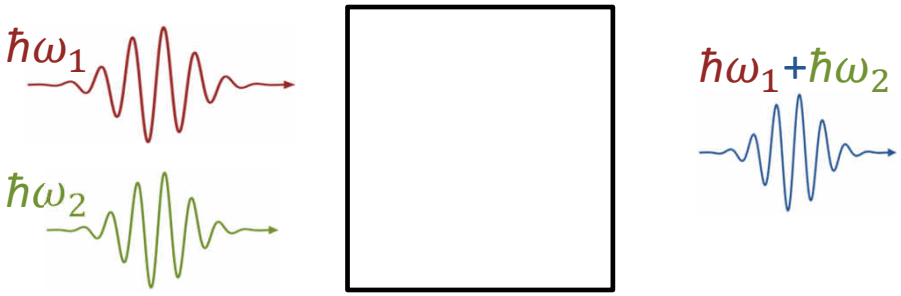
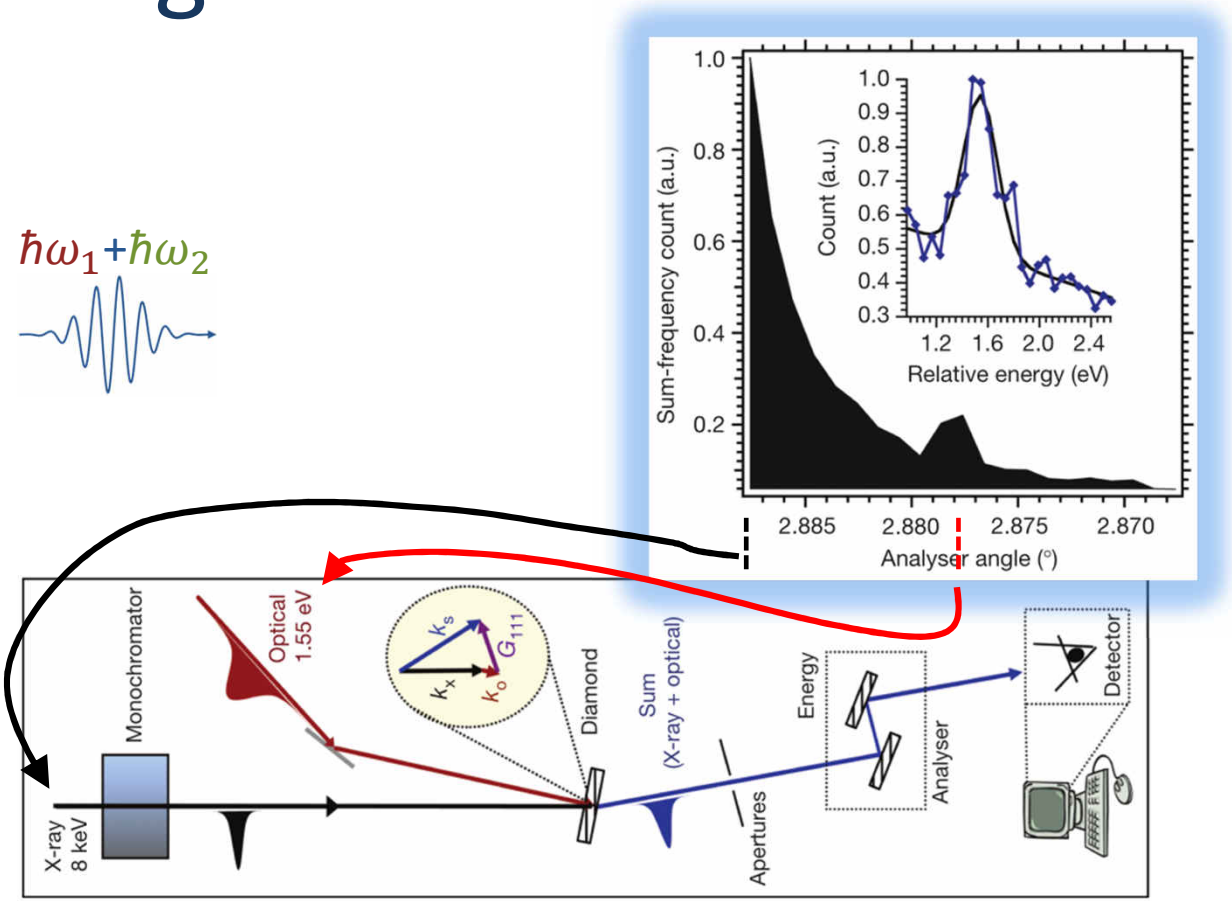
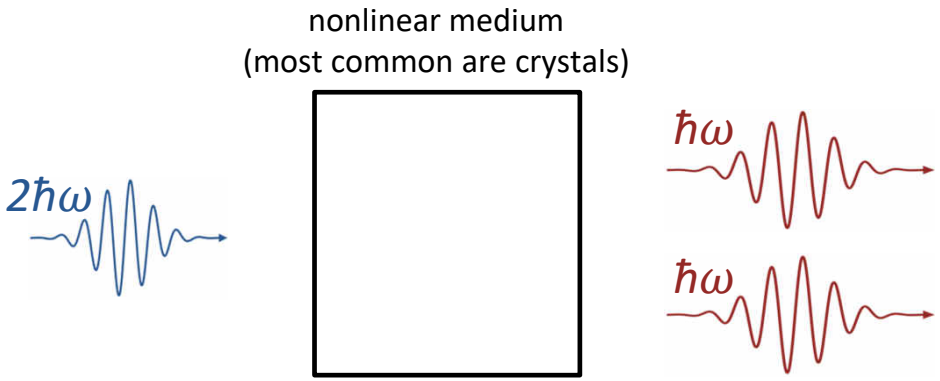




T. Glover *et al.*, *Nature* **488**, 604 (2012)

Parametric downconversion (PDC)



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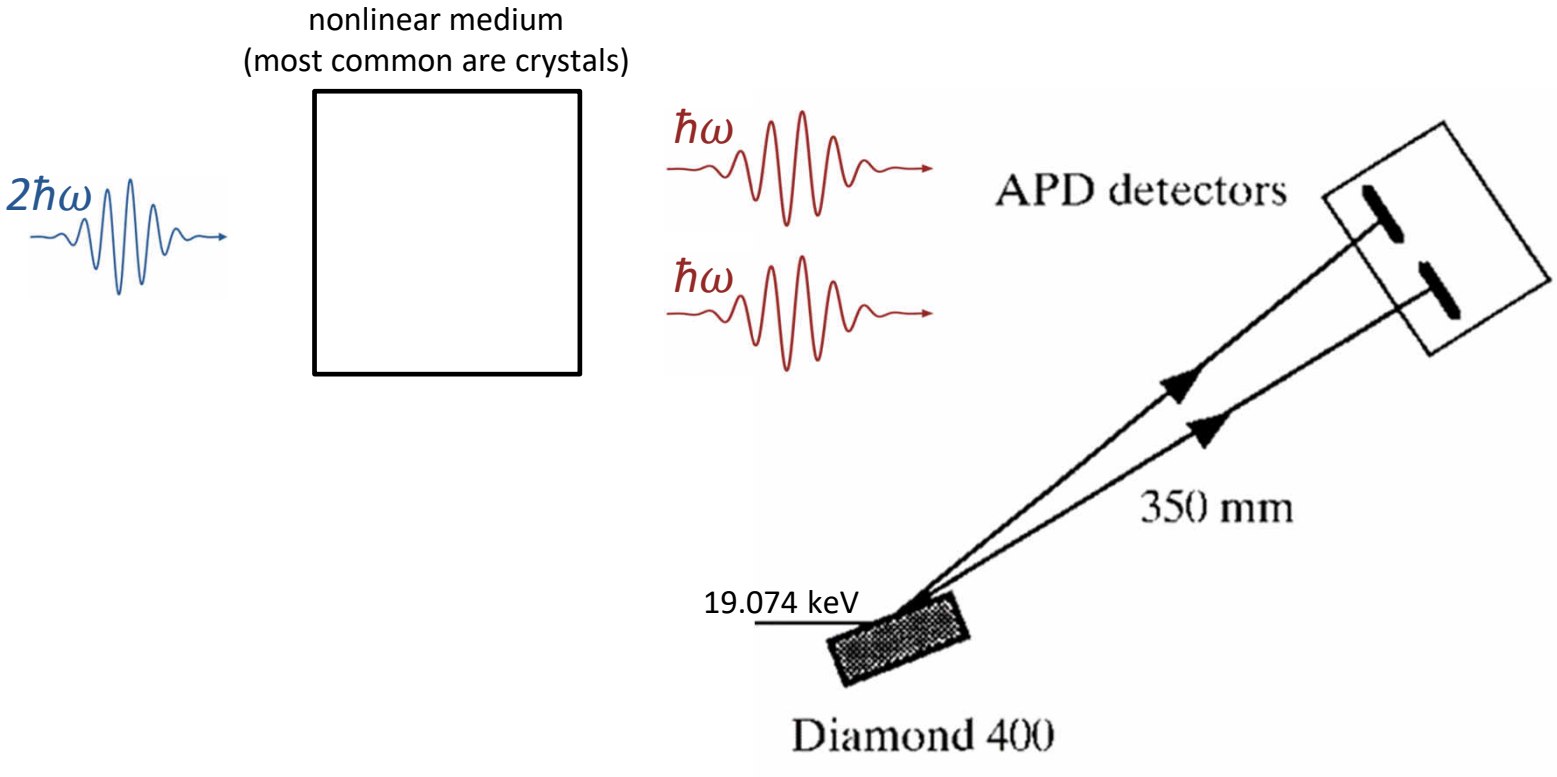

Y. Yoda *et al.*, *J. Synchrotron Rad.* **5**, 980 (1998)

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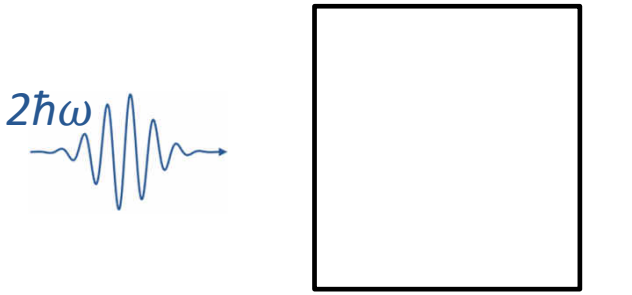
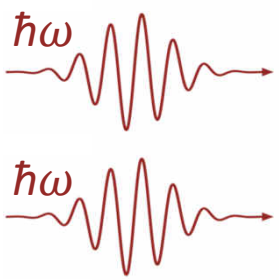
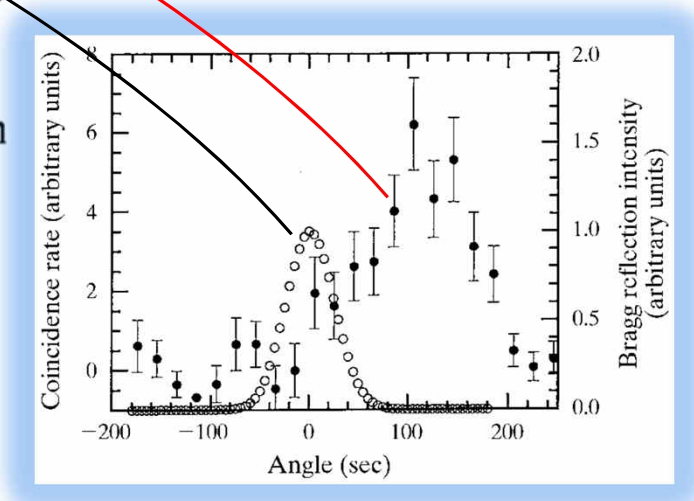
nonlinear medium
(most common are crystals)





Y. Yoda *et al.*, *J. Synchrotron Rad.* **5**, 980 (1998)



Summary

1. X-ray two-photon absorption
2. Nonlinear X-ray Compton scattering
3. X-ray second harmonic generation
4. X-ray optical mixing
5. Parametric downconversion