GAMMA RAY OPTICS

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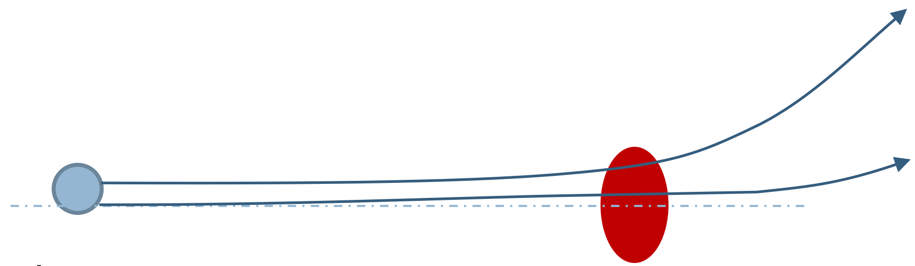
Acknowledgement

- ILL:
  - W. Urbam
  - M.J
- Ludwigs Maximilian University Munich
  - D. Habs
- MPQ Munich
  - M. Guenther

Outline

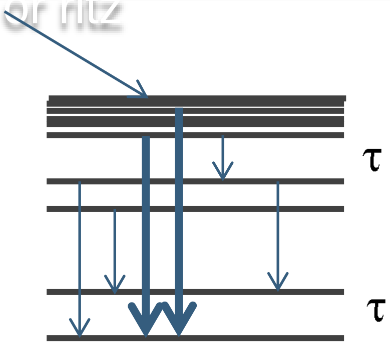
- Motivation
- Gamma Ray Optics
  - Diffractive
  - Refractive
- Measurements
  - Refractive index
  - Pair creation threshold
- Outlook
- Conclusion

Motivation: nuclear Photonics



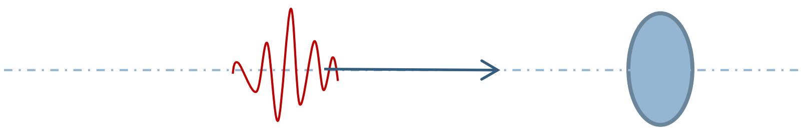
- measurement of many E_γ
- level scheme from coincidences

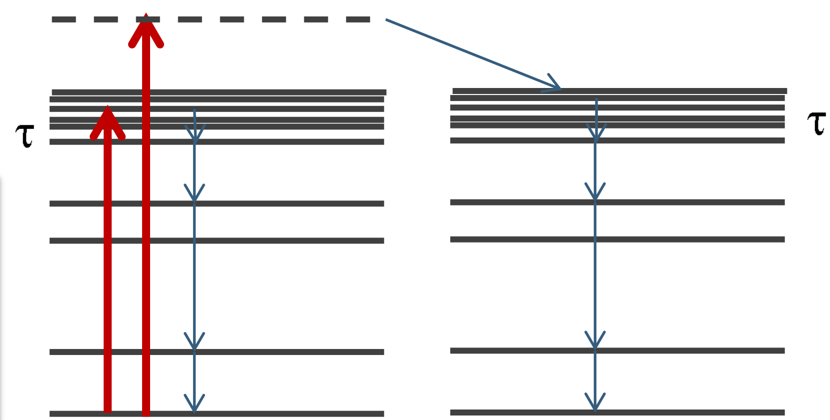
or ritz



Hadron (p, n, d, α,...) +
Energy produces excitated nucleus:

- Only partially selective
- Limited penetration power
- Complex excitations





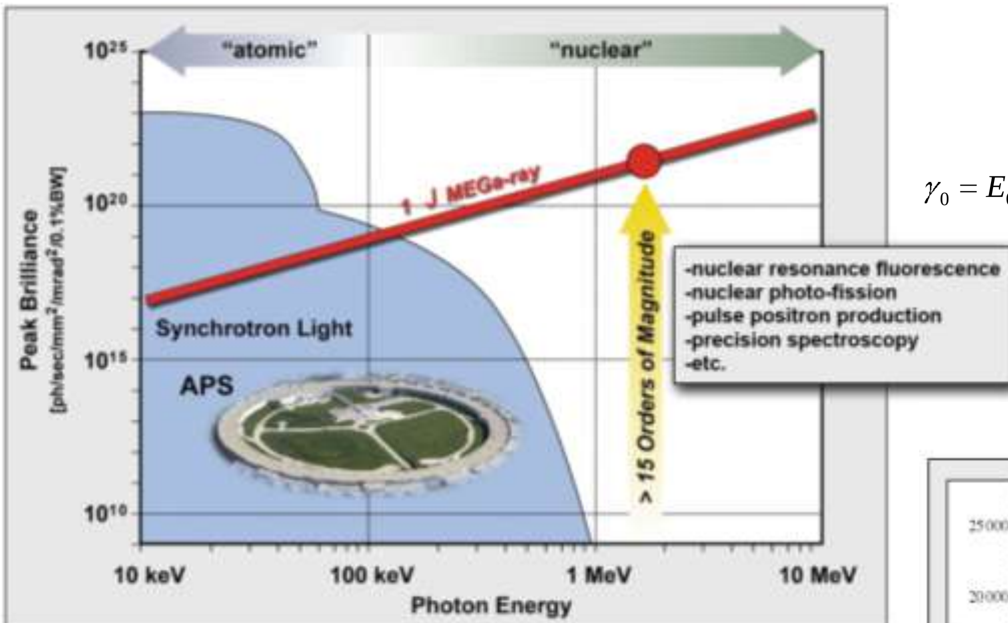
Photon hν

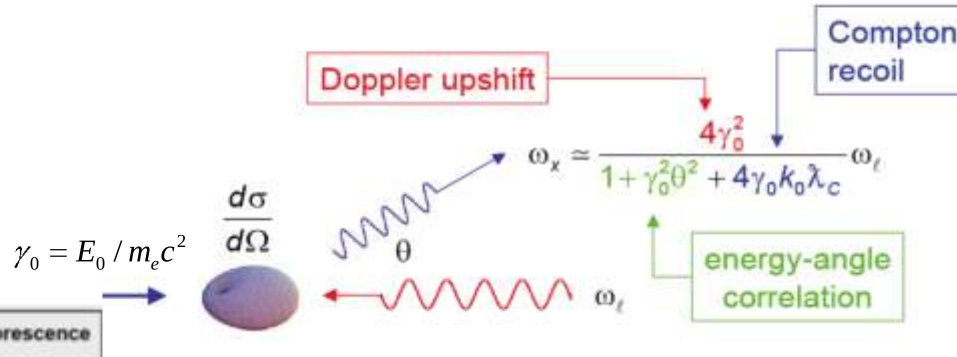
- Scanning photon energy and selective excitation from ground state
- Measurement of absorption or de-excitation

Requirement: brilliant tunable gamma ray source

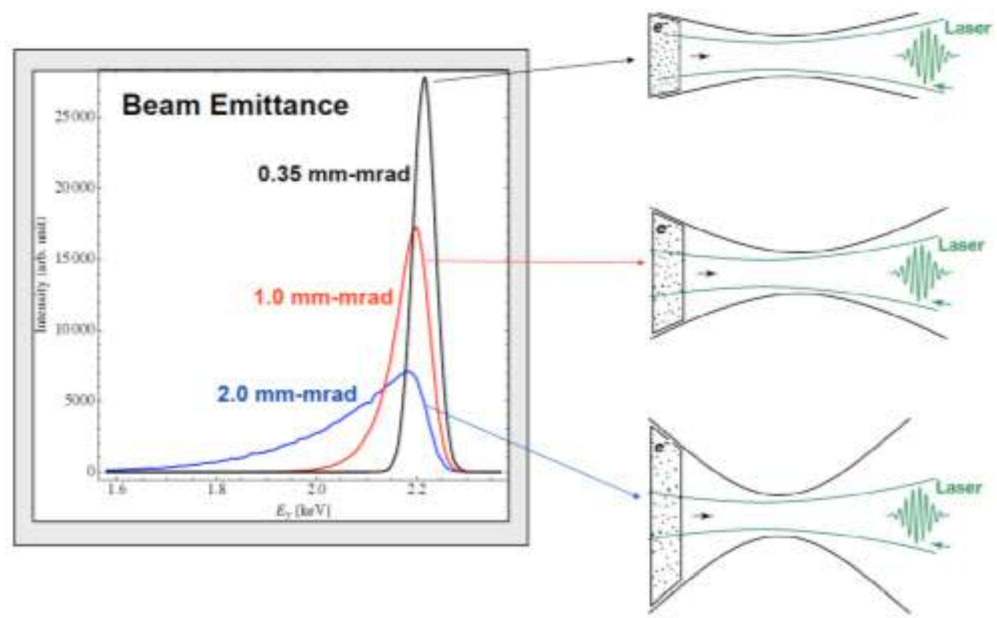
New brilliant sources based on Compton back scattering

Courtesy of C. Barty LLNL





yields ~$4\gamma_0^2$ Doppler upshift



http://www.eli-np.ro/

Motivation

All techniques base on γ-ray driven excitation of a nucleus:
(γ,γ'), (γ,n), (γ,p), (γ,f)...

The White Book of ELI Nuclear Physics
Bucharest-Magurele, Romania

5.2.8 Studies of enhanced decay of ^{26}Al in hot plasma environments

K.-M. Spohr[1,2], S.D. Pain[1,2], K.W.D. Ledingham[1,3,4], S. Brien[1,2], R. Chapman[1,2], M. Hassan[1,2] J. Melone[1,3], J.F. Smith[1,2]

5.4.10 Nuclear Resonance Fluorescence on Rare Isotopes and Isomers

N. Pietralla[1], D. Savran[1], K. Sonnabend[1]
[1] *Institut für Kernphysik, TU Darmstadt, Darmstadt (Germ...*

5.4.7 Study of pygmy and giant dipole resonances i... irect γ excitation

C. Borcea[1], M.N. Harakeh[2], A. Negret[1] and N.V...
[1] *Horia Hulubei National Institute for Ph... est - Magurele, 070125, Romania*

5.4.6 Nuclear Tra... n-Nucleon Coupling

D. Habs[1], M... N. Pietralla[2], D. Savran[2]
A. Kr...

...isotopes produced by γ Beams

...oster[2]

...udwig Maximilians University, Munich (Germany)
[2] *ILL Grenoble*

5.4.1 Measuring Narrow Doorway State... in the First Nuclear Minimu... (γ, f), (γ, α), (γ, p), (γ... Nuclear Potential...

...ctuating Quantities in Nuclear Physics of Highly Excited ... in Comparison to Random-Matrix-Theory and Quantum Chaos

...²⁰⁸Pb ... e evaluation

...verse Re...

5.4.11 M...

...G. Thirof[1], H.A. ...
...g Maximilians Universi...
...Max-Planck Institut für Kern...
[3] *Institut für Kernphysik, TU ...*

5.6... ing of medical isotopes via the (γ, n) r...

5.6.6 Extremely BRIlliant Neutron-Source produced via the (γ, n) Reaction without Moderation (BRIN)

D. Habs[1], M. Gross[1], P.G. Thirolf[1] and P. Böni[2]
[1] *Ludwig Maximilians University, Munich (Germany),*
[2] *Physik-Department E21, Technische Universität München, D-85747 Garching,(Germany)*

5.4.8 Gamma scattering on nuclei
The Pygmy Dipole Resonance (PDR) of deformed nuclei

D. Savran[1], N. Pietralla[1], K. Sonnabend[1],
R.A. Ionescu[2], D. Pantelica[2], C. Hațegan[2]
[1] *Institut für Kernphysik, TU Darmstadt, Darmstadt (Germany)*
[2] *IFIN-HH, Bucharest (Romania)*

... Radioscopy and Tomography

...a[1]
...lty of Physics, University of Bucharest, Romania

Spectrum delivered by Compton Backscattering source

Source: C. Barty, ELI-NP Meeting, August 2011

Monochromatization: $\Delta E/E \sim 10^{-3}$

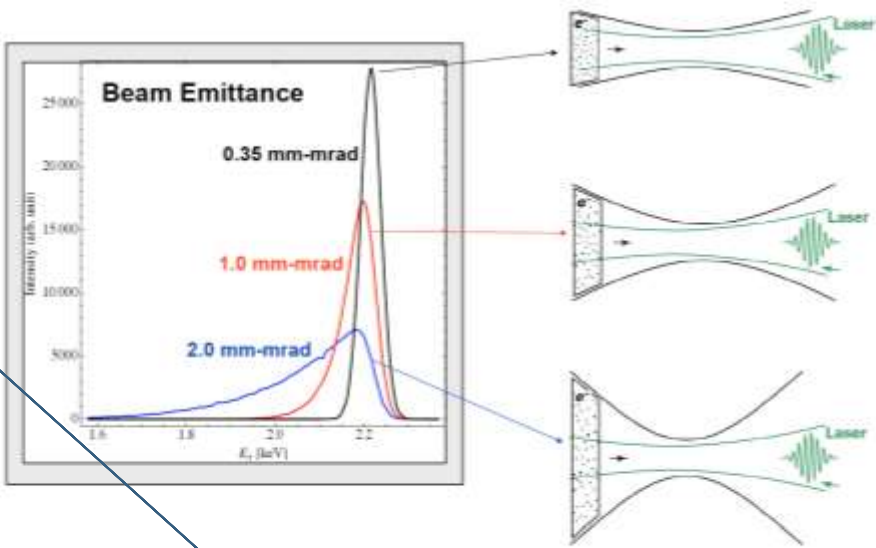


Table 9: The main specifications of the ELI-NP machine

Quantity	Value	Units
Peak gamma brilliance	$>1.5\times10^{21}$	Photons/sec/mm^2/mrad^2/(0.1% BW)
Effective Beam repetition	12,000	Hz (100 micro-bunches at 120 Hz rep rate)
Gammas per pulse	8×10^{8}	Photons at 100% BW
Spectral beam flux	10^{6}	Photons/sec/eV
Gamma pulse duration	2	Picoseconds
Gamma collimation	0.1	mrad at 0.1% BW
Gamma bandwidth	10^{-3}	ΔE/E
Gamma source size	10	Microns
Electron beam energy	600	MeV
Laser pulse energy	1.5	Joules
Gamma-ray energy	1–13 (with 532 nm laser interaction)	MeV

This means we have 10^9 photons/s @ 1MeV

Spectral requirements nuclear point of view

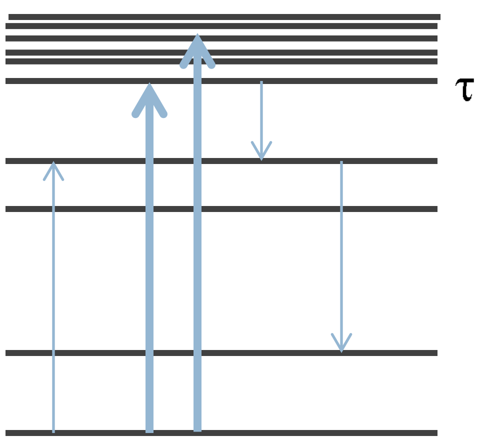
$$\Delta E_{\tau} = \frac{4.1\times 10^{-15}}{\tau} \leq 1 \quad \text{eV}$$

τ ~ 10^{-15} …10^{-6} s

Broadening due to thermal motion:

$$\Delta E_{Th} = E_{\gamma}\frac{v_{Th}}{c} = E_{\gamma}\sqrt{\frac{3k_B T}{mc^2}} \quad \rightarrow \quad \frac{\Delta E_{Th}}{E_{\gamma}} < 5\cdot 10^{-5}$$

In most cases dominating



Example:

τ > 10^{-15} s, E_{γ} = 1 MeV, T = 300 K

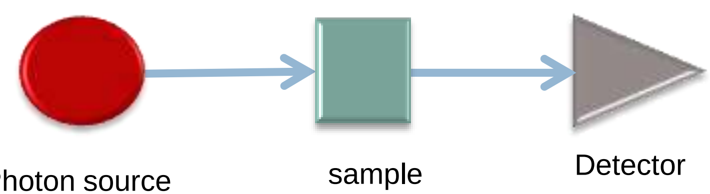
ΔE = 50 eV

What is really required from a nuclear point of view

<u>Example:</u>

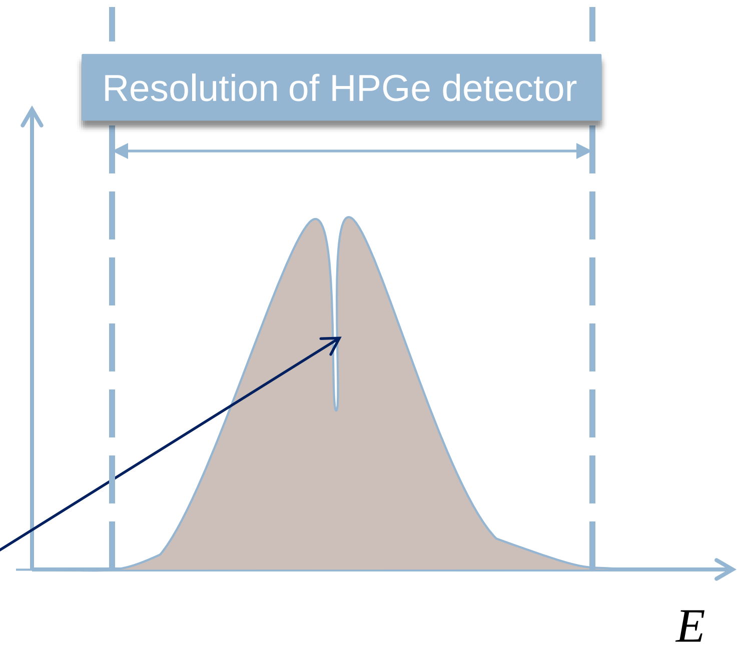
$\tau > 10^{-15}$ s, $E_\gamma = 1$ MeV, $T = 300$ K

$\Delta E = 50$ eV



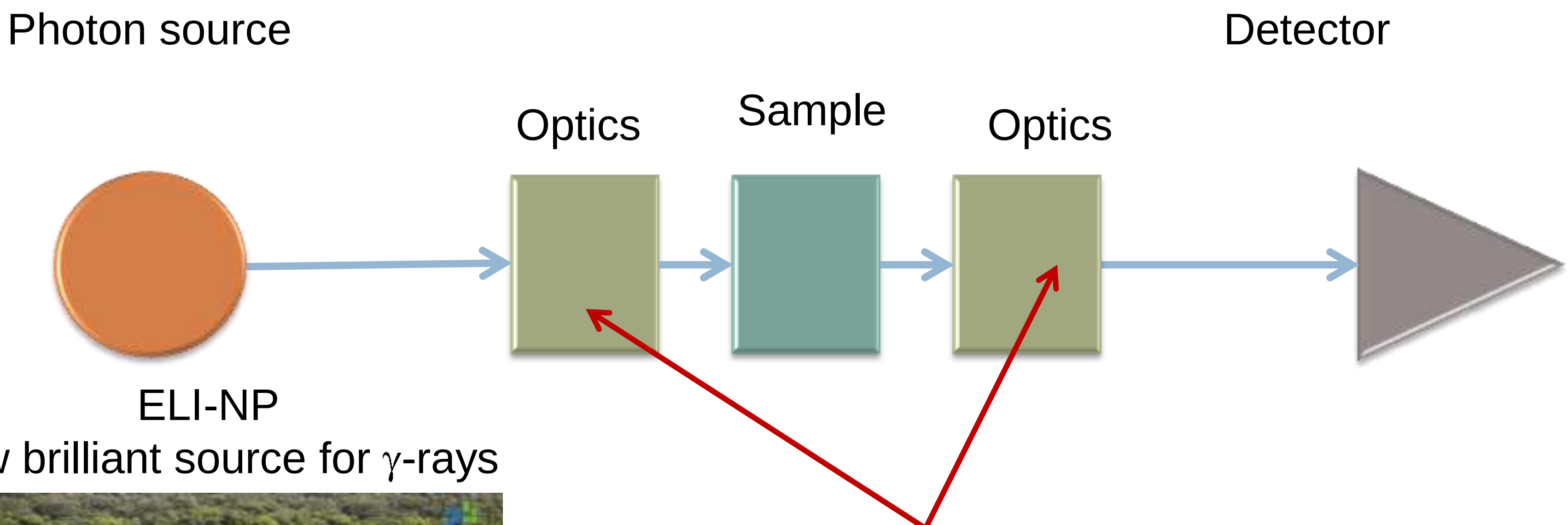
The dominating number of photons is not used:

@ 1MeV: we absorb max. 5% of photons



- Peak/Background bad
- Detector might be overloaded
  - (95% of 10^9 photons/s)

What is this talk about?



ELI-NP
new brilliant source for γ-rays

<u>Do we need to something here?</u>
<u>What can we do here?</u>

Monochromatization via Crystal Diffraction

$$I(\theta) \propto \frac{\sin^2\left(A\sqrt{1+y^2}\right)}{1+y^2}$$

$$y \propto \frac{\theta-\theta_B}{\lambda_\gamma}, A \propto \lambda_\gamma, E_\gamma = \frac{hc}{\lambda_\gamma}$$

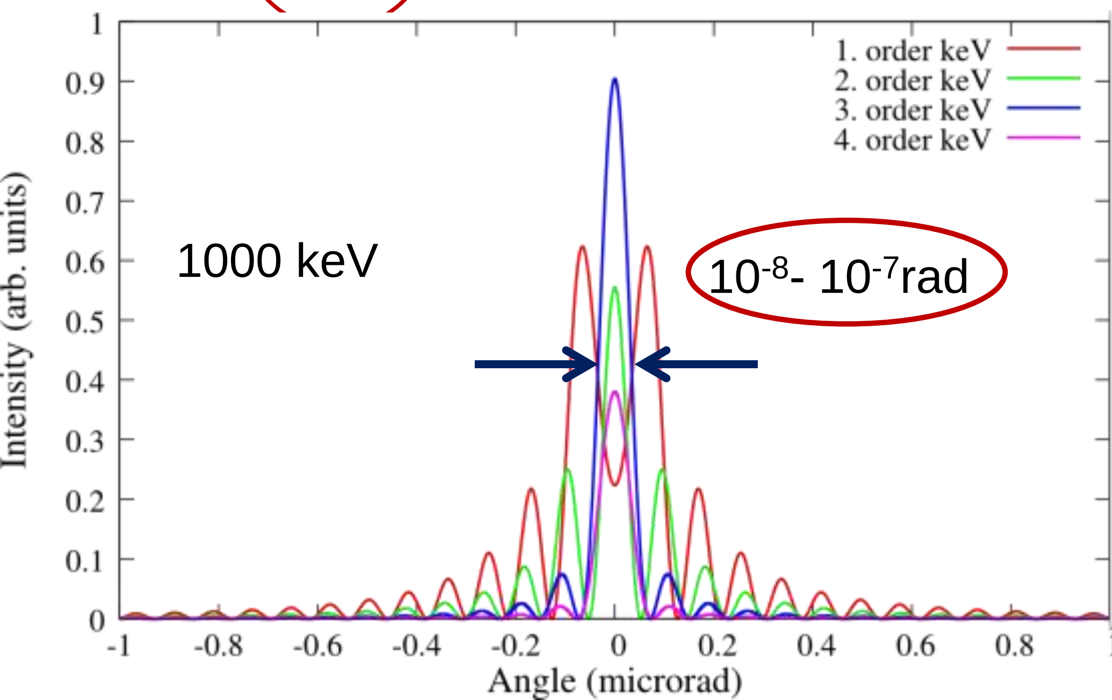
$$FWHM = 2\frac{hc}{E_\gamma}$$

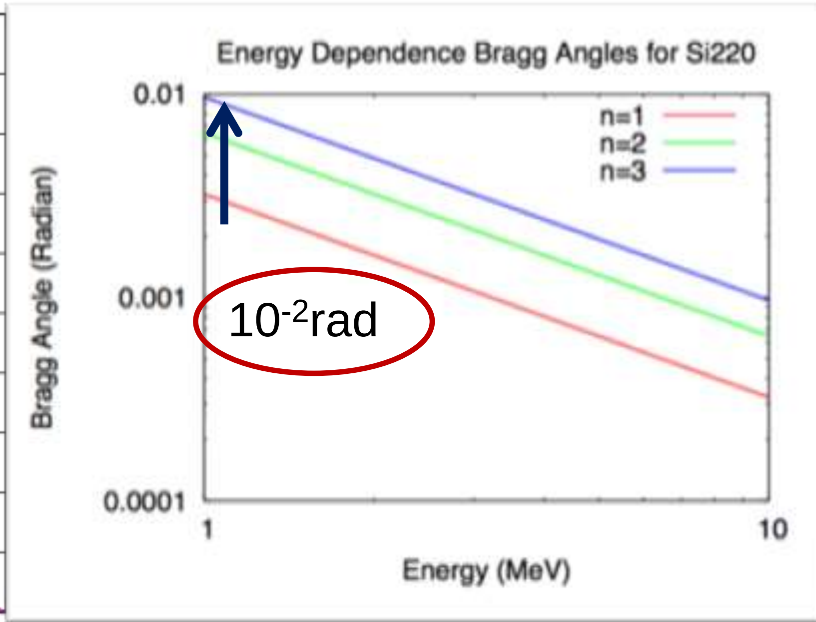
$$n\lambda_\gamma = 2d\sin\theta_B$$

$$\theta_B \cong n\frac{hc}{E_\gamma}$$

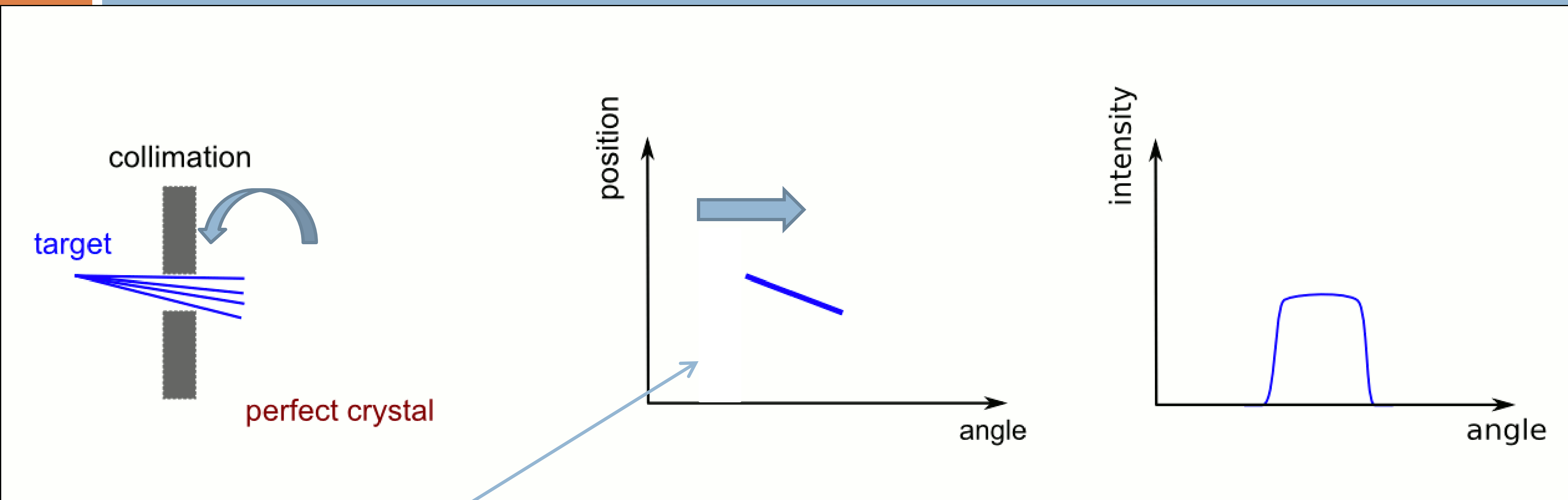
$$\boxed{\frac{\Delta E_\gamma}{E_\gamma} \cong \frac{\Delta\theta_B}{\theta_B} = const}$$

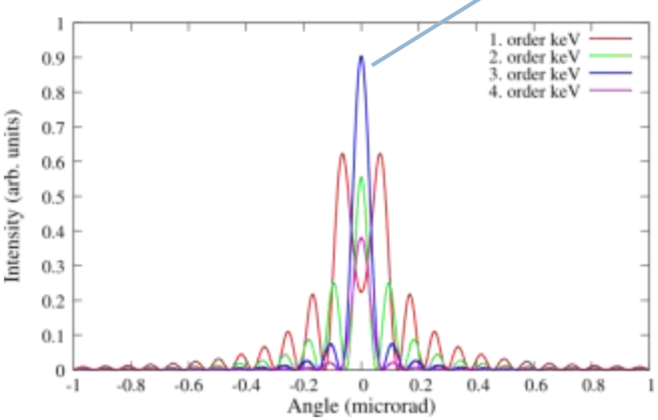
10^{-6}- 10^{-5} resolution constant over energy





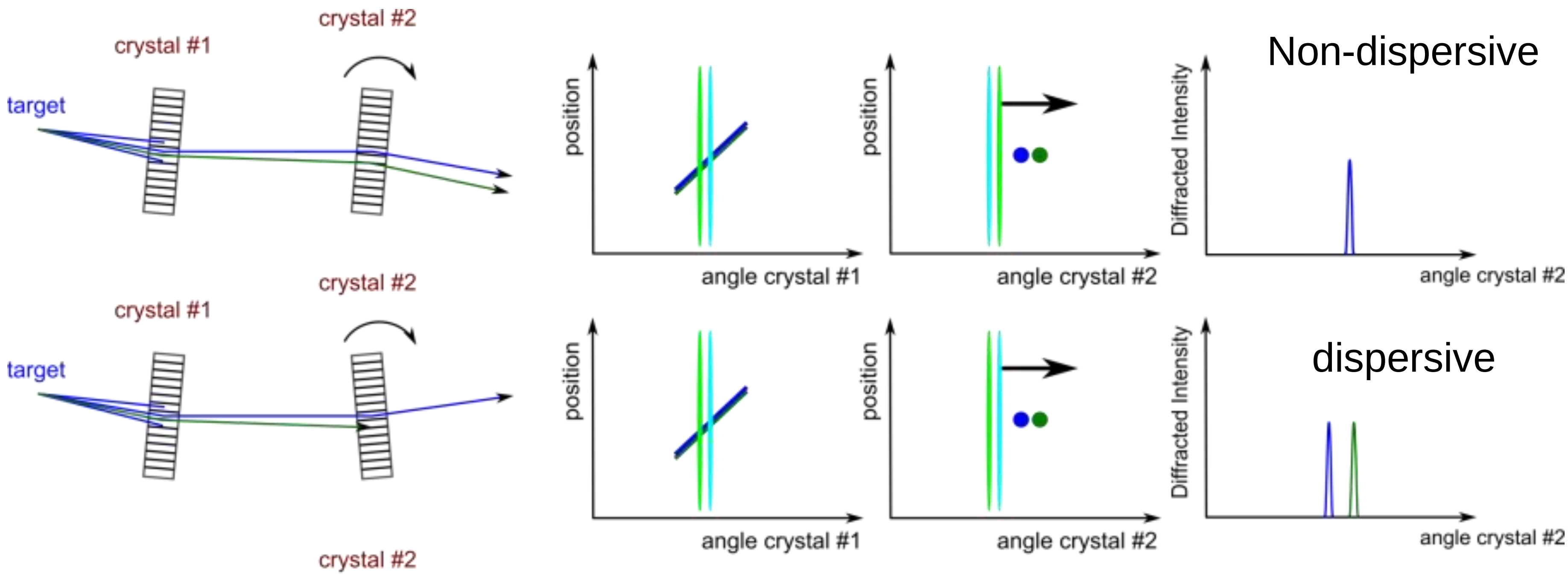
How to realize diffraction



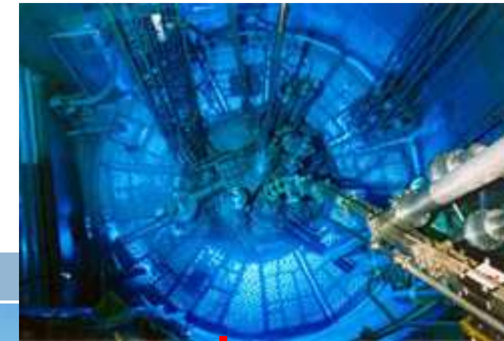


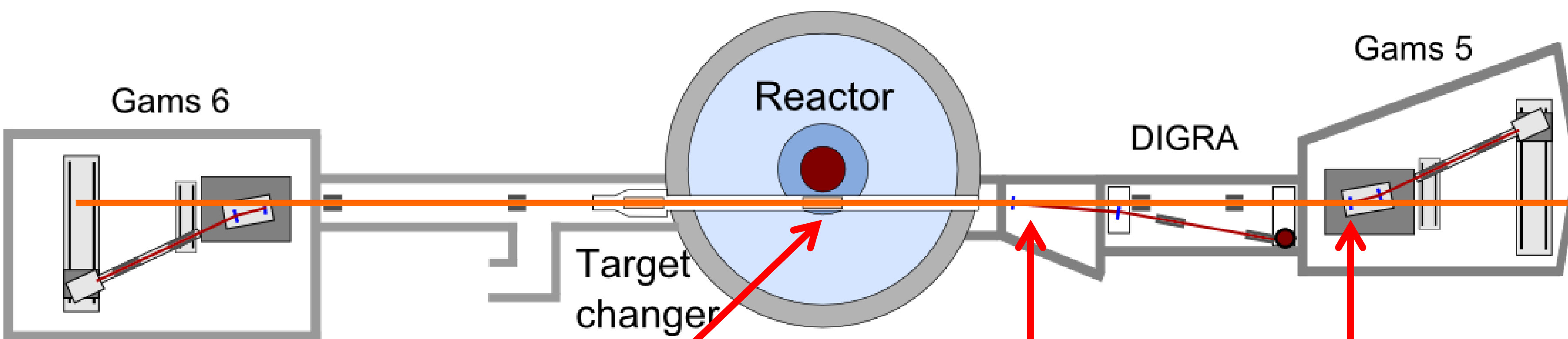
- Resolution is limited by divergence of incoming beam
- A beam with 10^{-8} rad divergence is needed

Double crystal geometry



PN3@ILL: General Layout





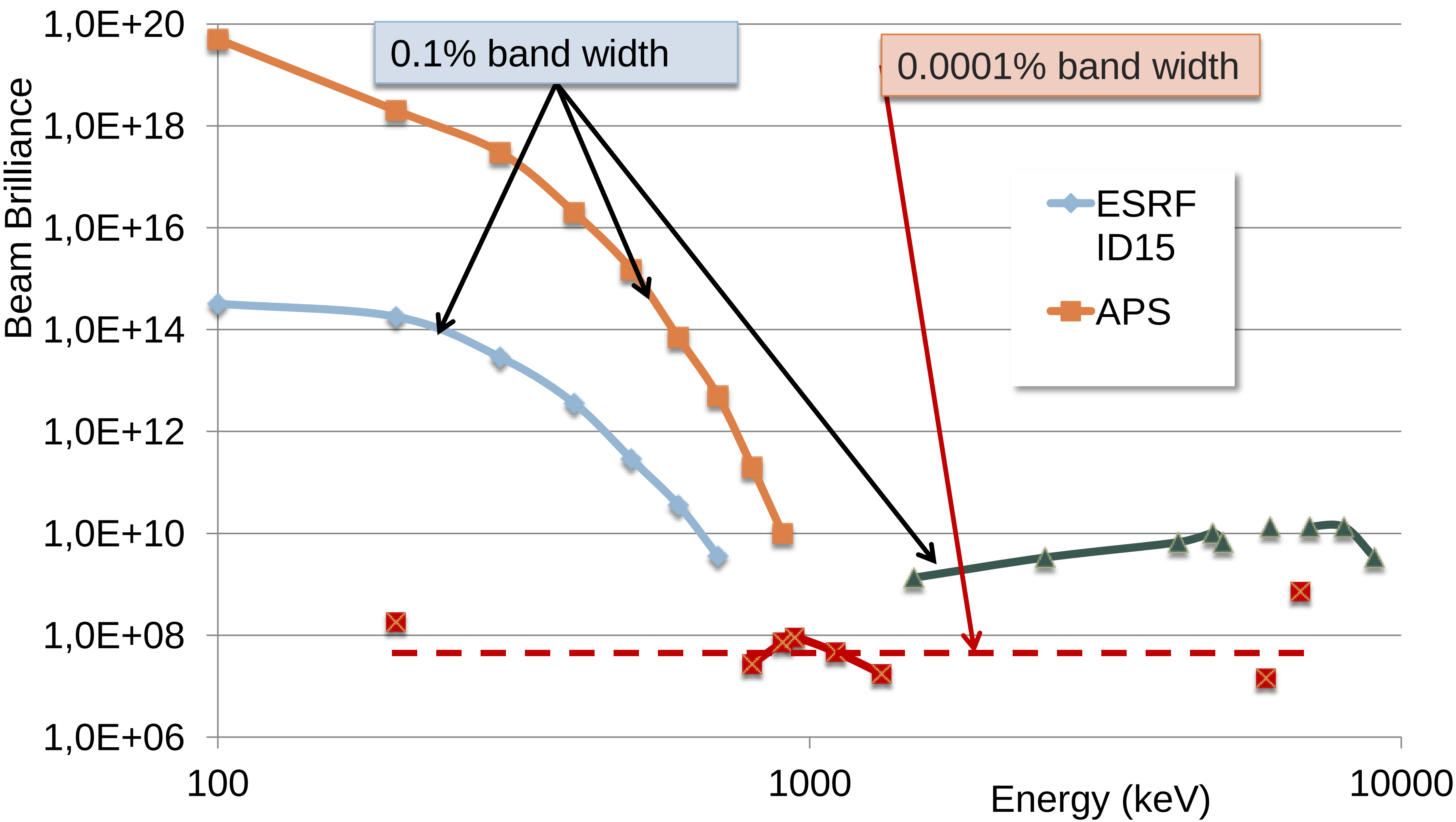
In-pile target position

- 5×10^{14} neutrons $cm^{-2}\ s^{-1}$
- Capture rate: $<10^{16}$
- Gamma emission rate $<10^{16}$

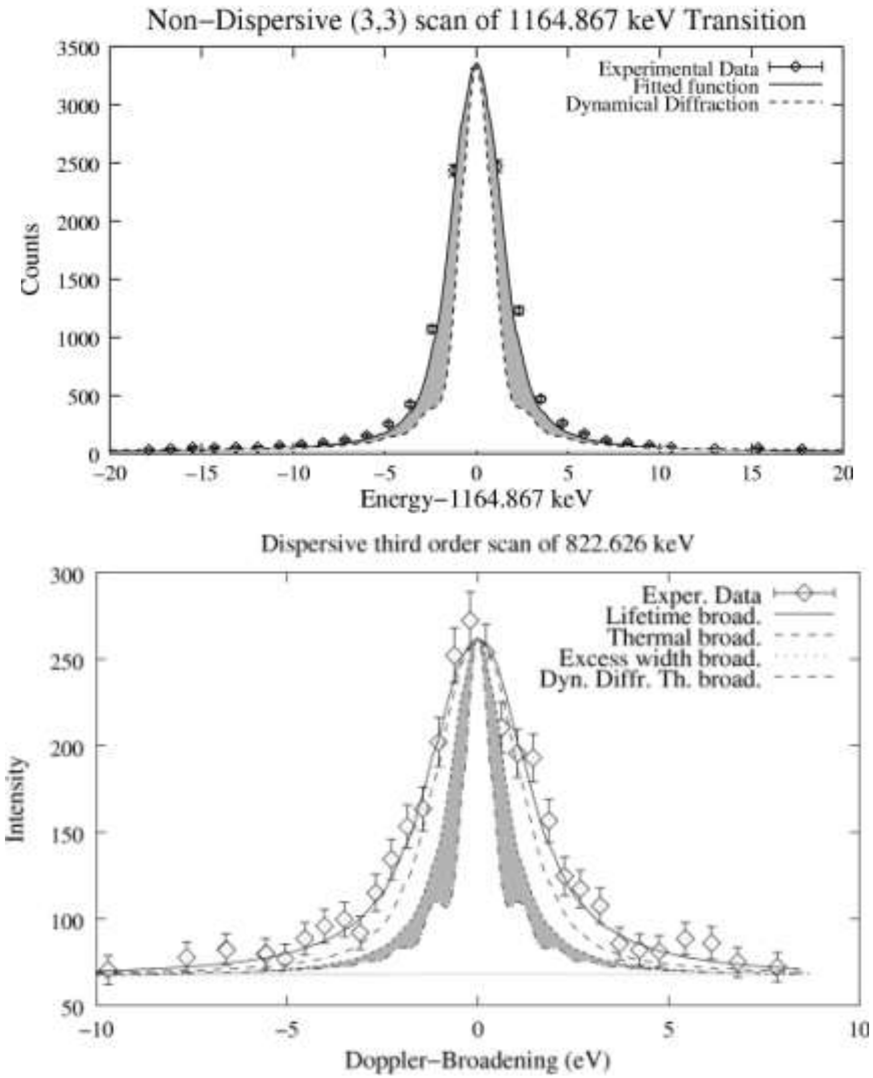
Solid angle: 10^{-6}

Solid angle: 10^{-7}

ILL as photon source

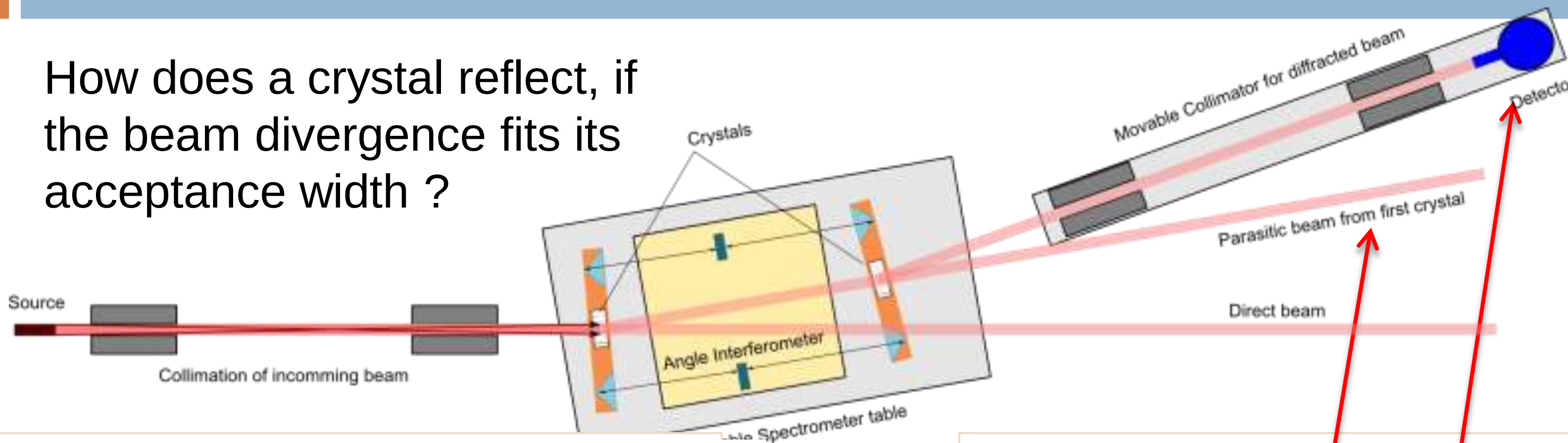


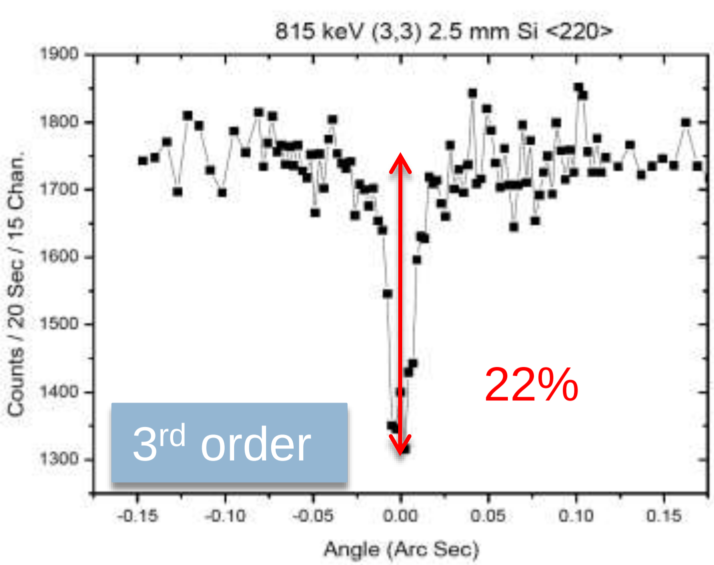
GAMS5 operating in dispersive and nondispersive geometry

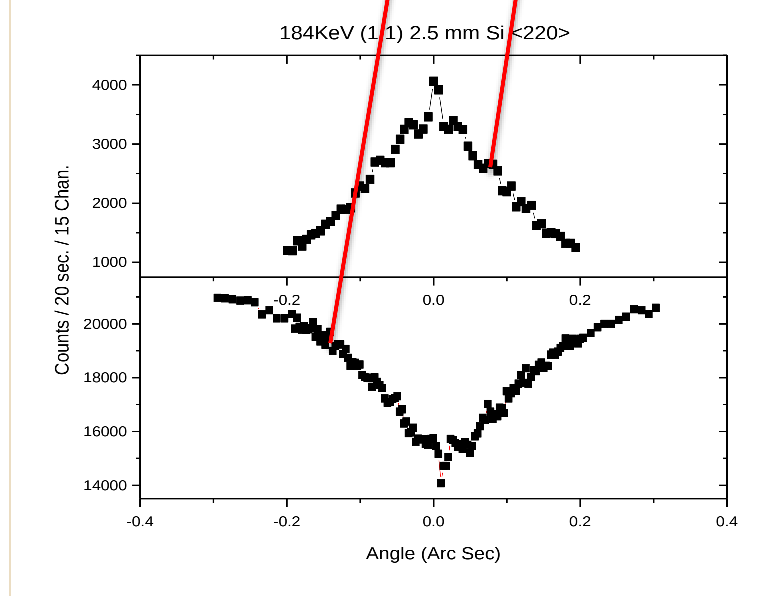


Diffraction efficiency of a perfect crystal

How does a crystal reflect, if the beam divergence fits its acceptance width ?







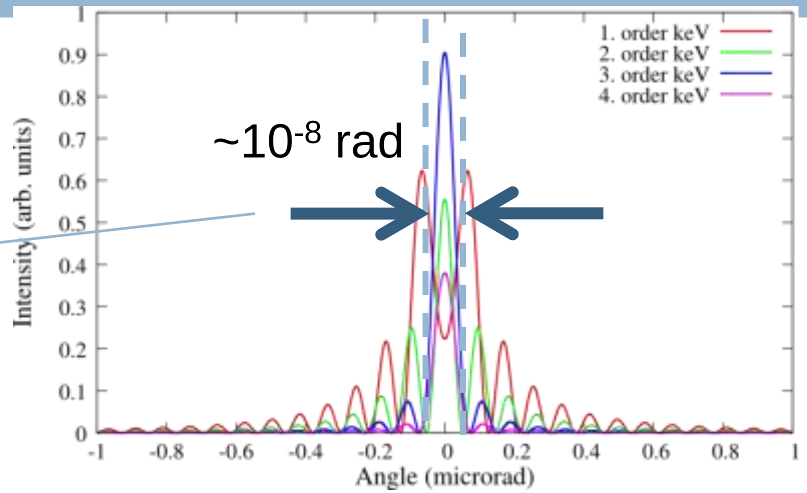
How much do we really diffract?

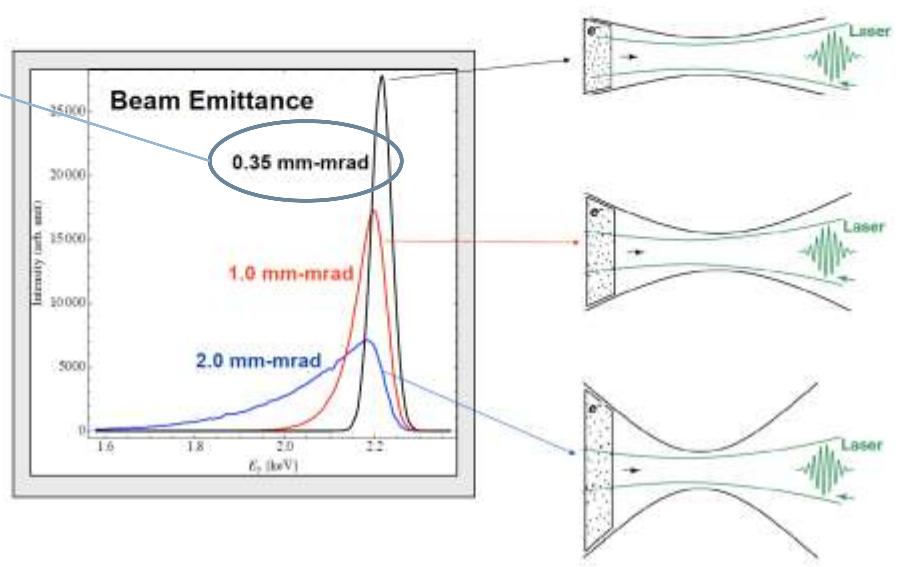
$10^9\ s^{-1}$ for 1keV

$5\ \ 10^7\ s^{-1}$ for 50 eV

$$I_0 \times \underbrace{\frac{\Delta\theta_{Diff}}{\Delta\varphi_{Div}}}_{10^{-4}} \times \underbrace{R^2}_{10^{-2}}$$

$\boxed{50\ s^{-1}}$





Max. count rate for HpGe detectors
Could be $10^4\ s^{-1}$

→ We need to improve throughput
by 2 orders of magnitude

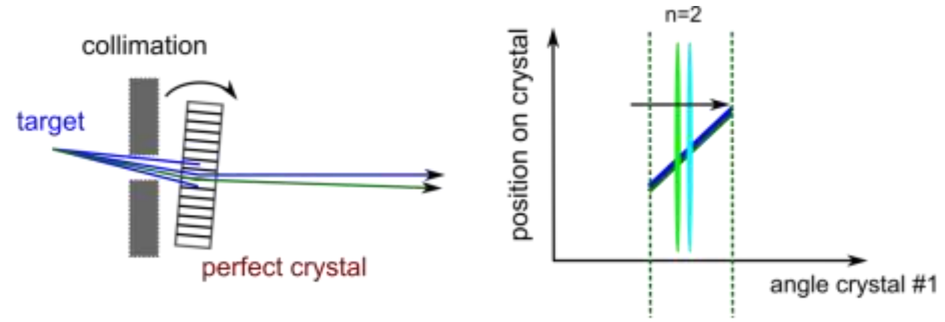
Approach 1: Correcting completely the divergence by refractive optics

$$\underbrace{I_0 \times \frac{\Delta\theta_{Diff}}{\Delta\varphi_{Div}}}_{10^{-4}} \times \underbrace{R^2}_{10^{-2}}$$

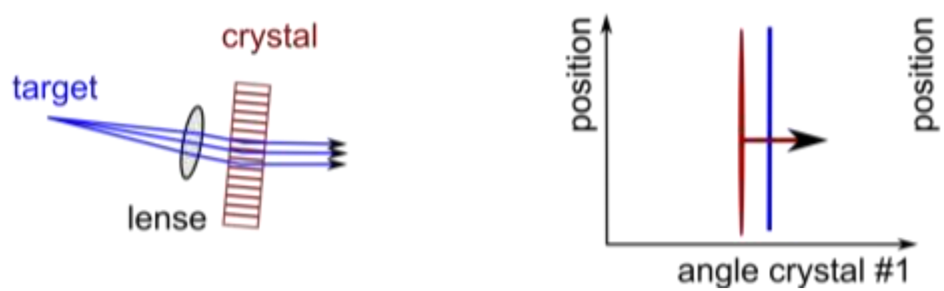
Could be pushed to by 1000

Could be pushed to by 10

Normal single crystals scheme:



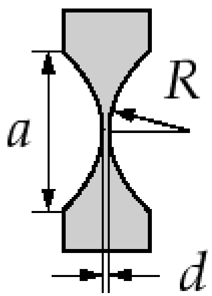
Lens - single crystals scheme:



Requires lens system for g-rays: **REFRACTION @ γ-ray Energies?**

Refractive Index

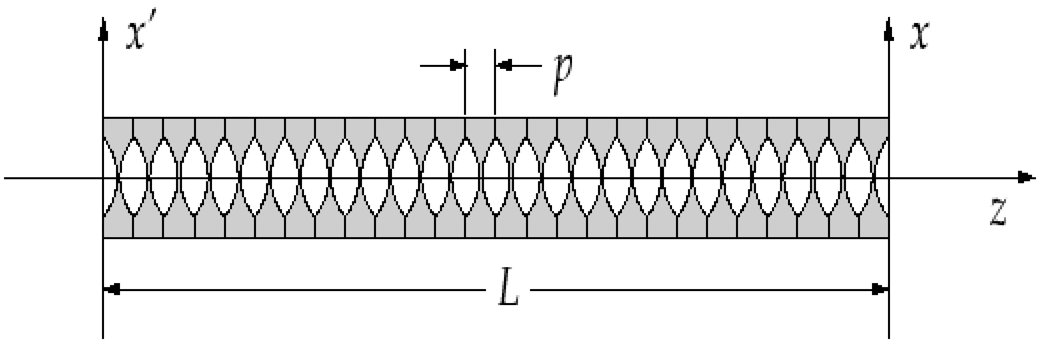
$$n(E) = 1 + \underbrace{\delta(E)}_{\text{If } \neq 0 \text{ then one can build refractive opitcs}} + i\beta(E)$$



$$f = \frac{n}{2\delta}$$

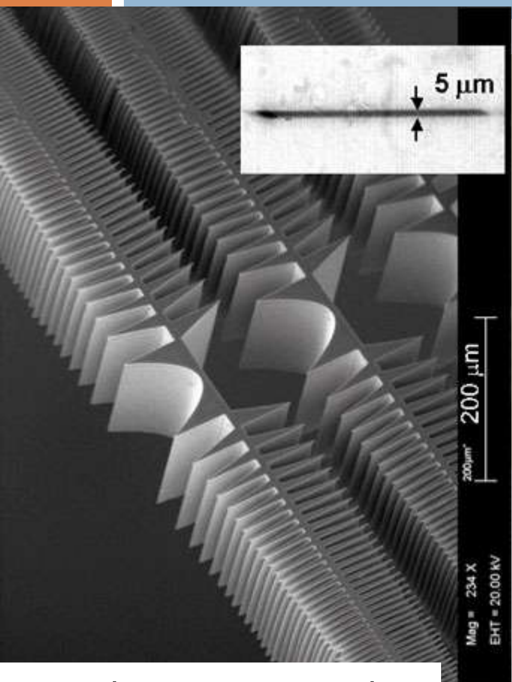
A. Snigirev et al., Nature Vol 384, 1996

For X-rays $\delta = -10^{-5} .. -10^{-6}$



$$f = \frac{n}{2\delta N}$$

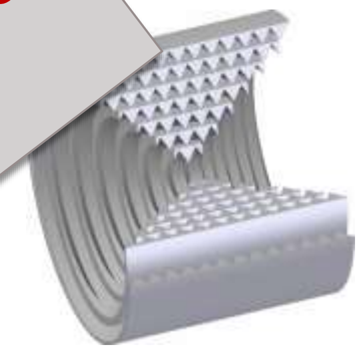
For X-rays refractive optics is known



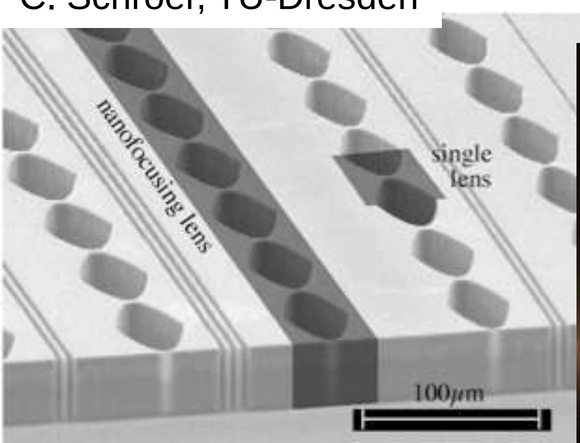
M. Wegener, Karlsruhe Institute of Technology

And for Gamma Rays?
$\delta \sim 1/E^2$

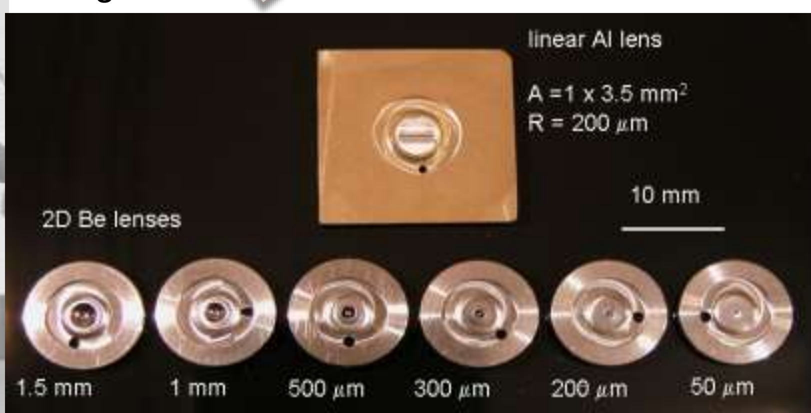
ray-optics.com



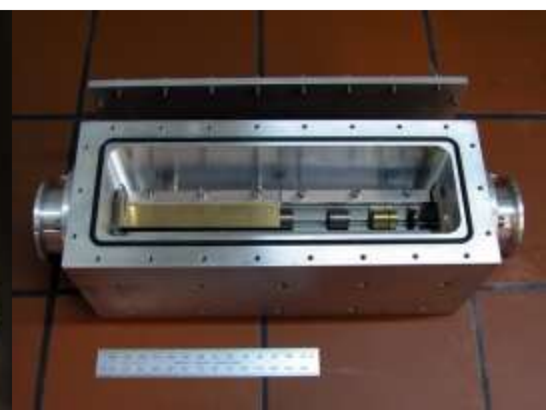
C. Schroer, TU-Dresden



Snigerev, ES F, Grenoble

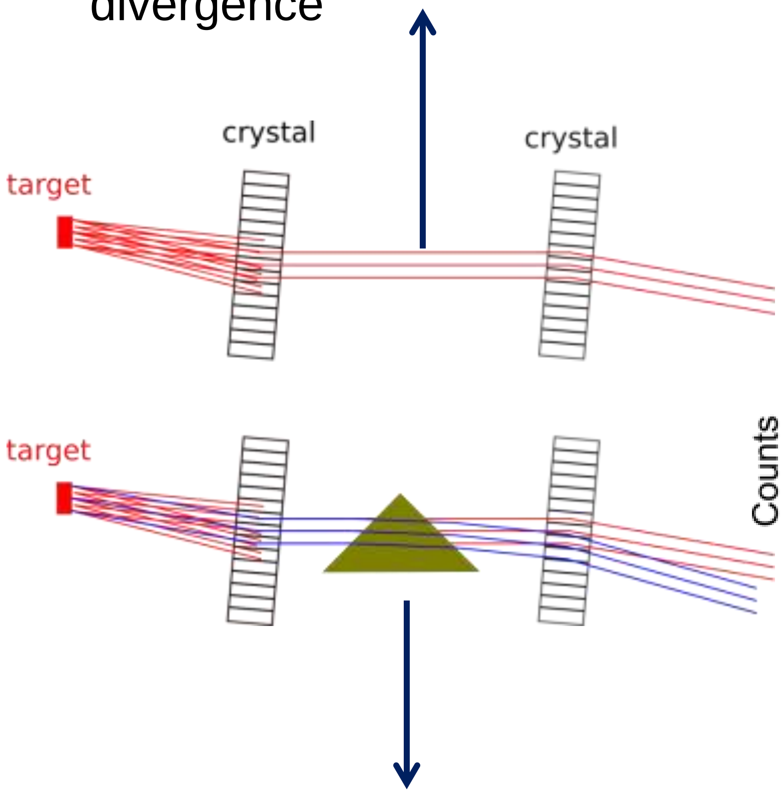


B. Lengeler, RWTA Aachen

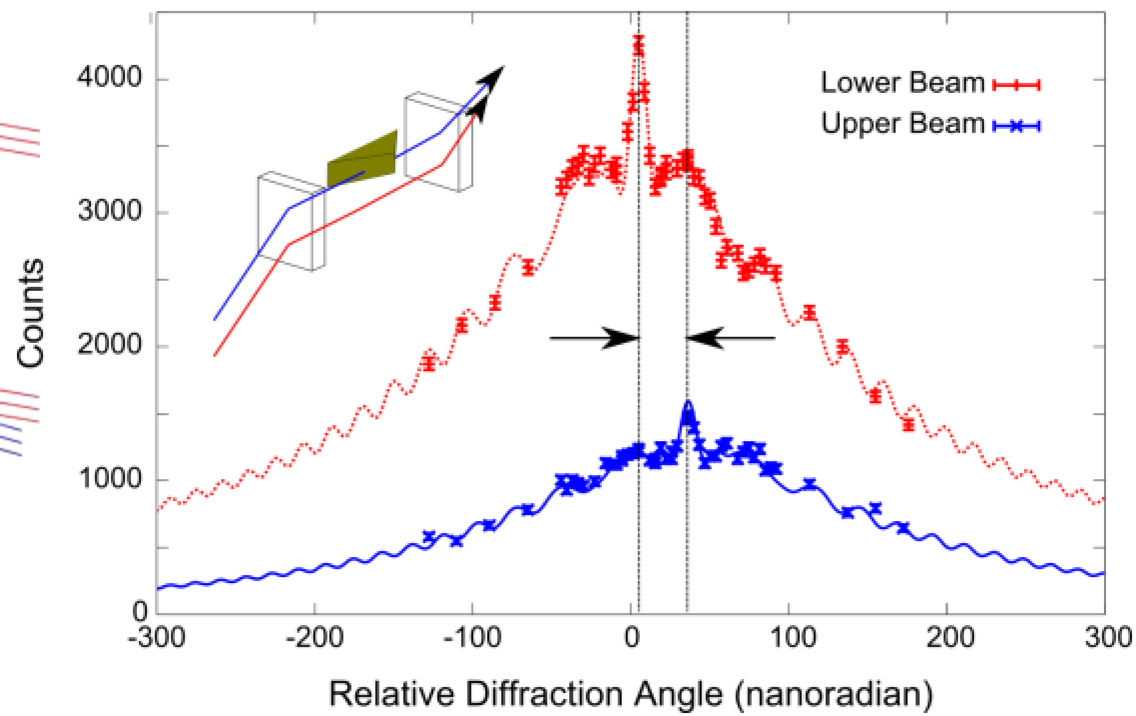


Measuring the refractive Index

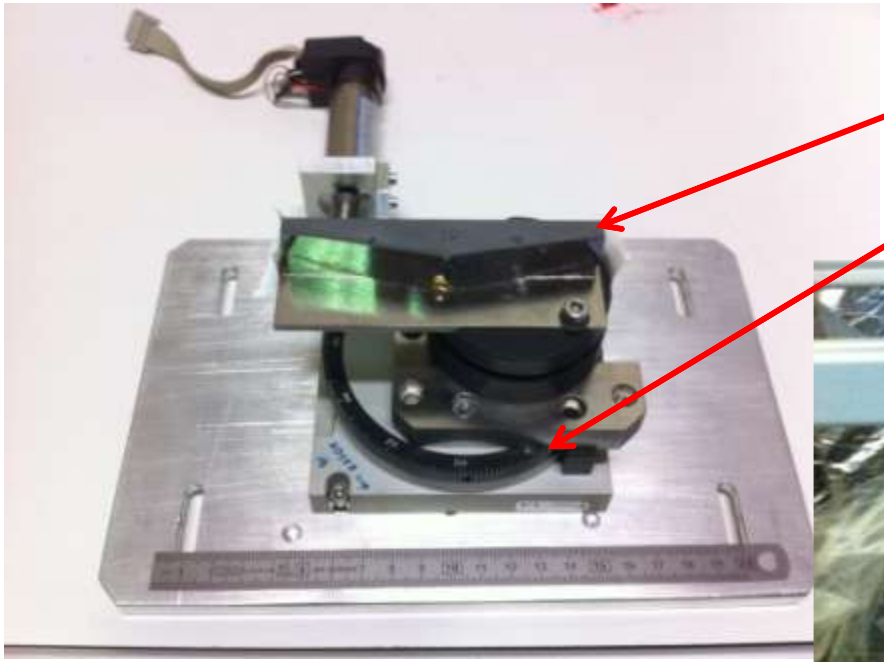
We use crystal as collimator to generate beam with < μrad divergence



Deviation is detected by second crystal as analyzer

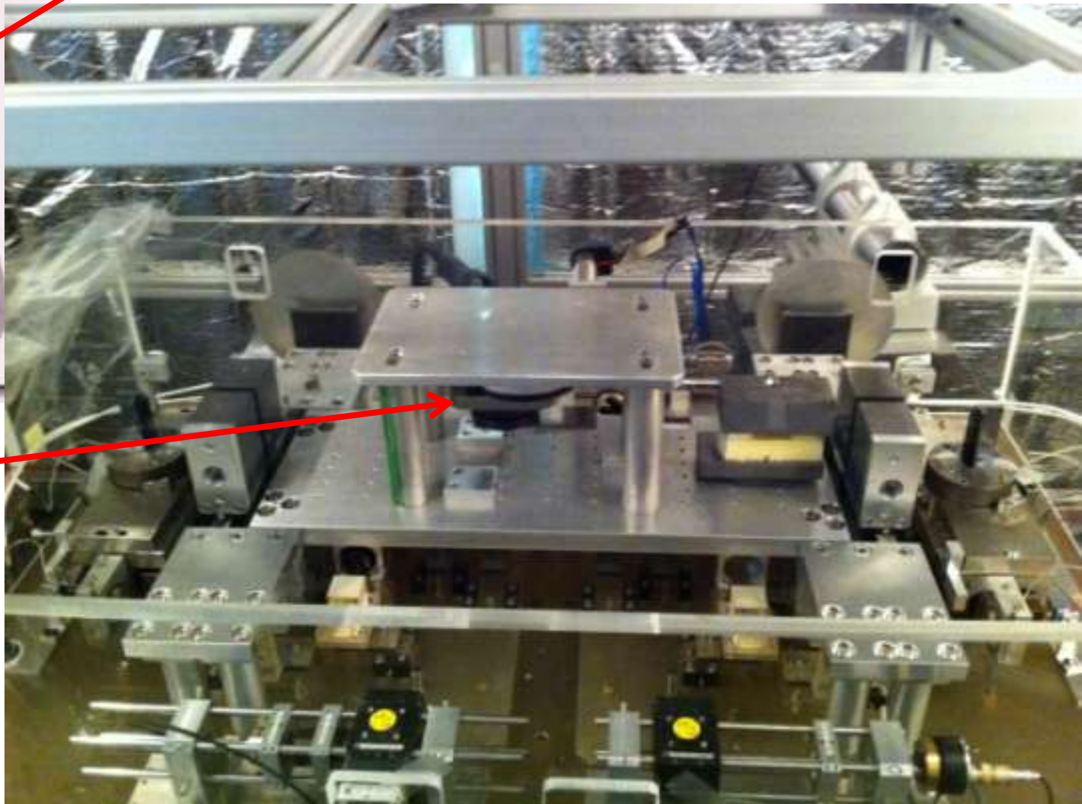


Measuring the refractive Index for γ-Rays



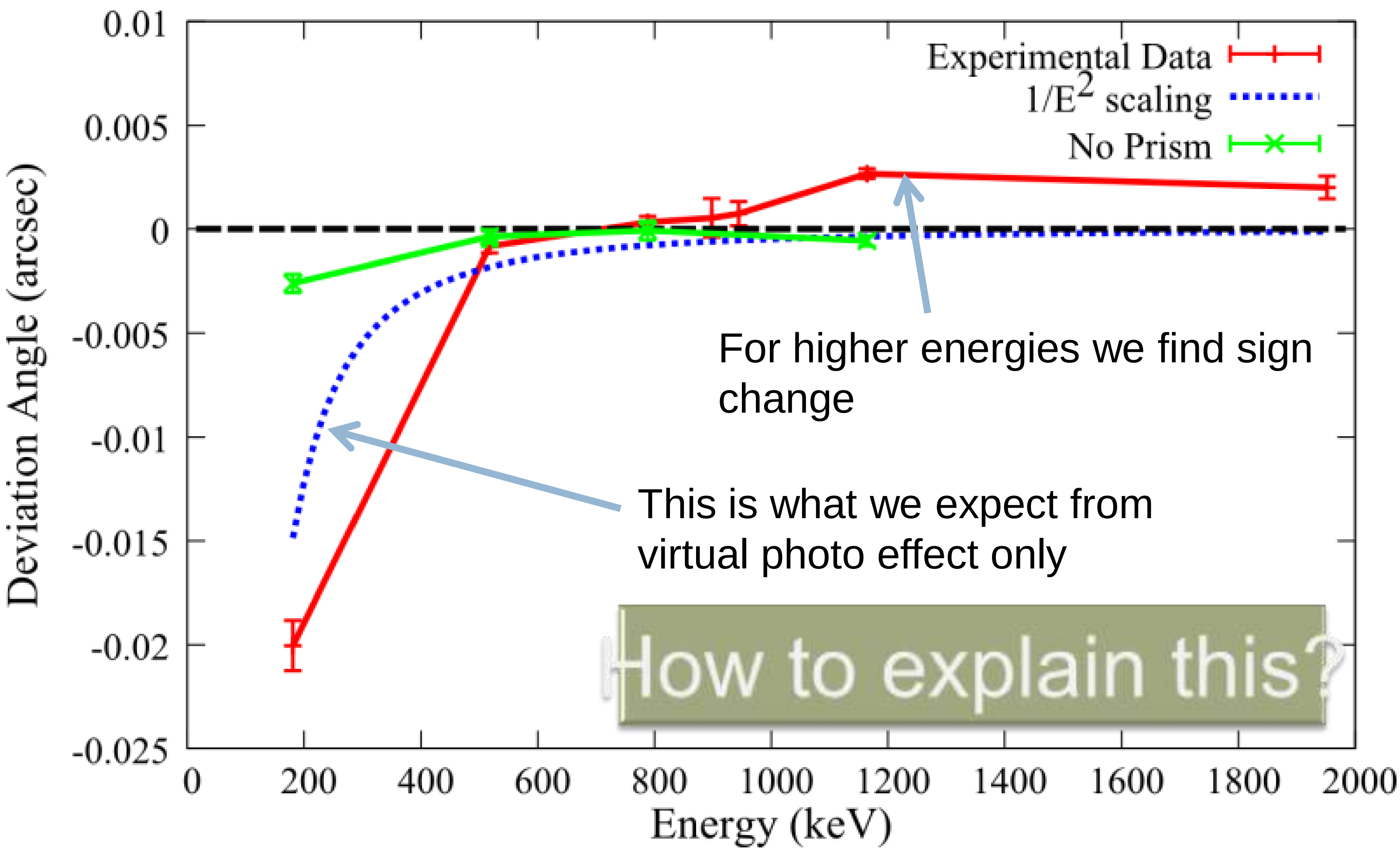
Si prism, 160 degree, faces optically polished

Alignment stages



Prism installed between the two crystals

Results


Experimental Data
1/E2 scaling
No Prism
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
Deviation Angle (arcsec)
0
200
400
600
800
1000
1200
1400
1600
1800
2000
Energy (keV)
For higher energies we find sign change
This is what we expect from virtual photo effect only
How to explain this?

Possible Explanation (D. Habs)

Refractive index is related to forward scattering amplitude

$$n(E_\gamma) = 1 + \delta(E_\gamma) + i\beta(E_\gamma)$$

$$\delta(E_\gamma) = \frac{\lambda_\gamma^2 N_C A_{rf}}{2\pi}$$

Kramers-Kronig dispersion relation:

$$A_f = A_{rf} + iA_{if}$$

$$A_{rf}(E_\gamma) = \frac{E_\gamma^2}{\pi(4\pi^2\hbar c)^2} \lim_{\varepsilon\to 0+} \int_0^\infty \frac{A_{if}(E)}{E\left(E^2 - (E_\gamma + i\varepsilon)^2\right)} dE$$

$$A_{rf}(E_g) = \frac{E_g^2}{2p^2\hbar c} \lim_{e\to 0+} \int_0^{\square} \frac{s_{abs}(E)dE}{E^2 - (E_g + ie)^2}$$

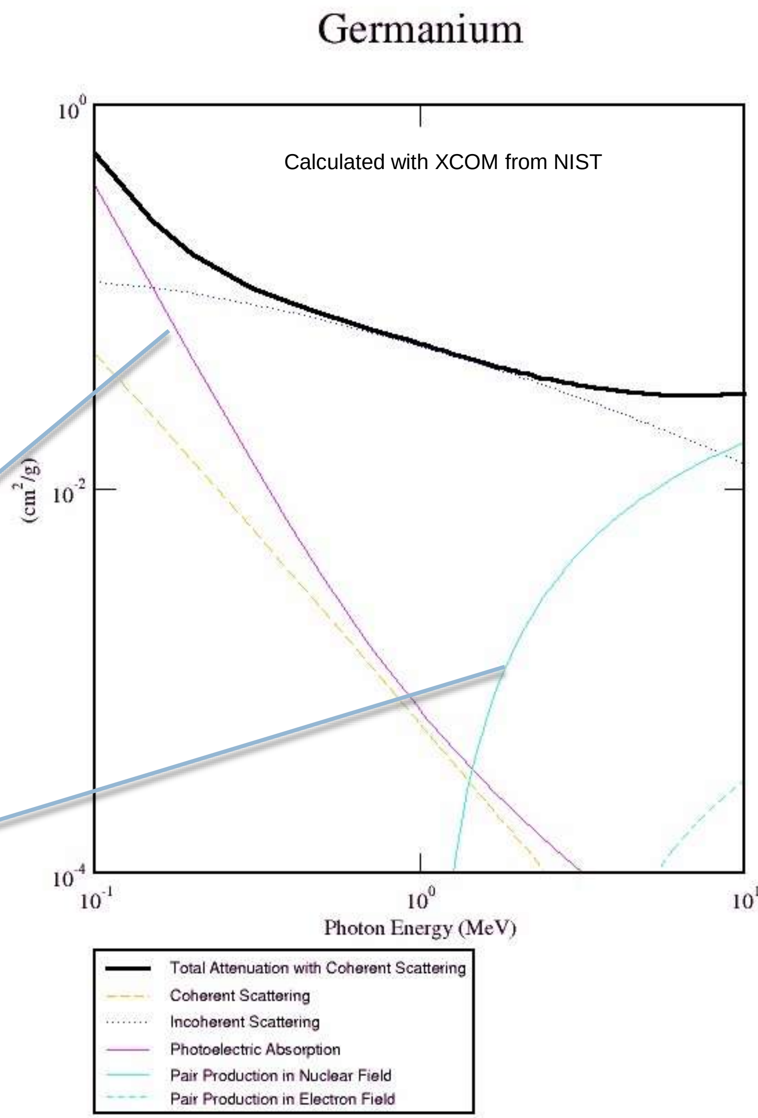
If we want to explain positive index of refraction we need to look for processes, which increase strongly with energy

Possible explanation (D. Habs)

$$\delta(E_\gamma) = \frac{\hbar^2 c^2}{2\pi E_\gamma^2} N_C \cdot A_{rf}(E_\gamma)$$

$$A_{rf}(E_\gamma) = \frac{E_\gamma^2}{2\pi^2 \hbar c} \lim_{\varepsilon \to 0+} \int_0^{\infty} \frac{\sigma_{abs}(E)\,dE}{E^2 - (E_\gamma + i\varepsilon)^2}$$

There is a correlation between absorption and refraction

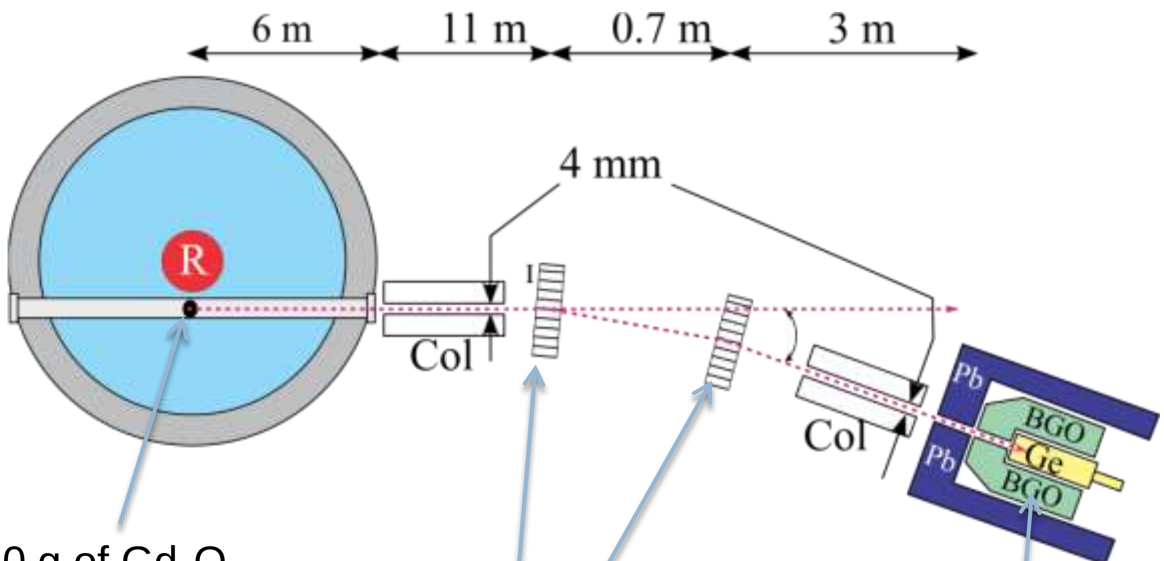


Absorption cross section:

- Up to 500 keV Photo effect is dominating
- Pair creation sets in from 1022 keV

- Rising with E_γ would produce positive A_{rf}
- Exact knowledge of σ_{Pair} needed

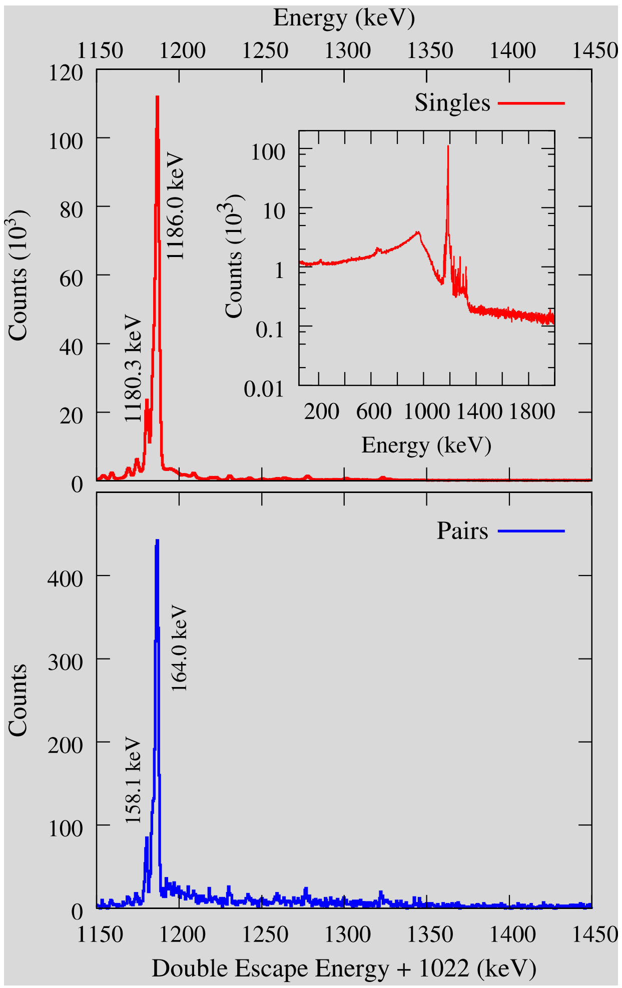
New Measurement @ ILL



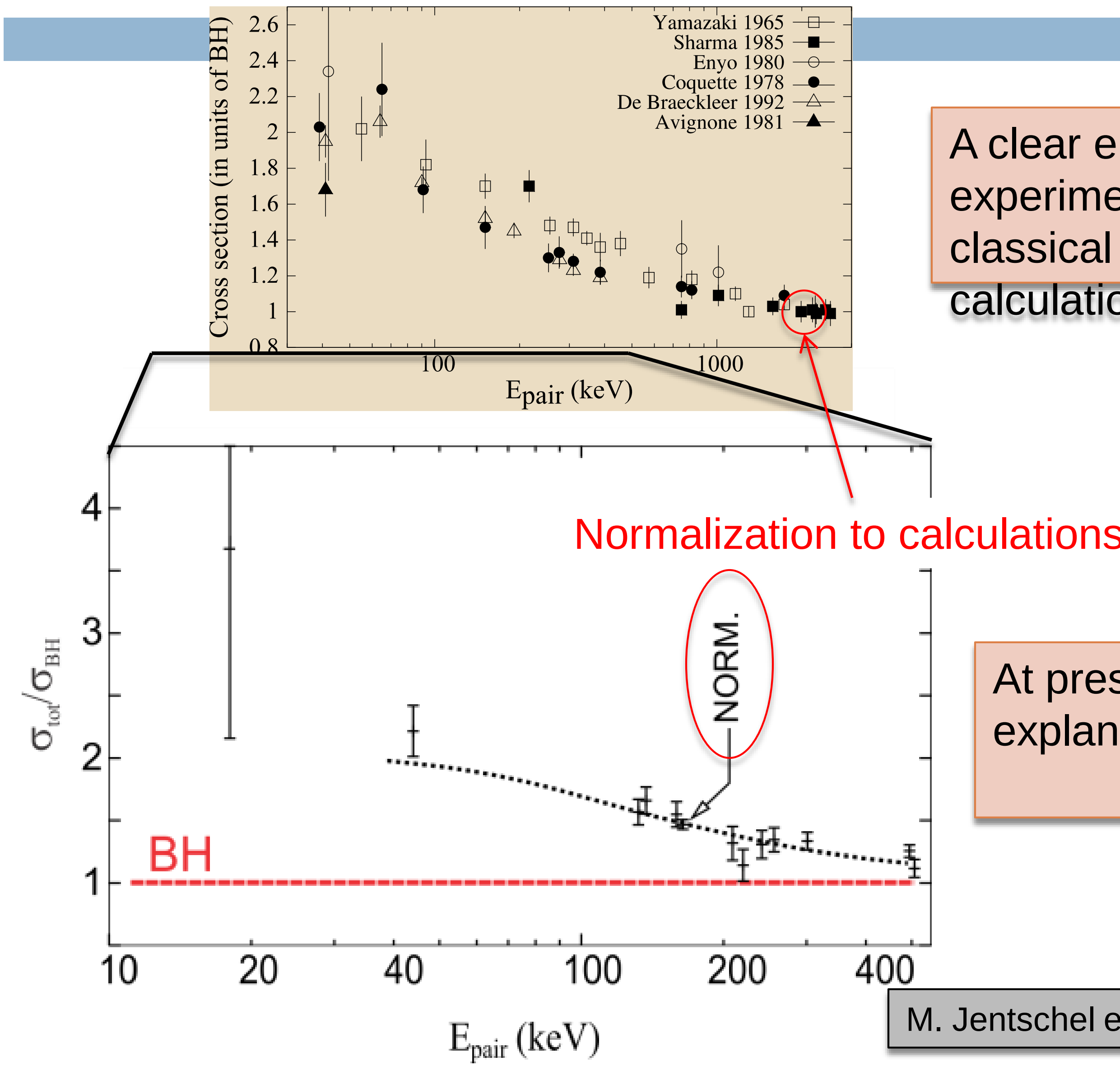
10 g of Gd_2O_3
10^{16} captures per second

Two copper crystals as
tunable monochromator

8 fold segmented
BGO as pair spectrometer



Measurement of the Pair creation cross section



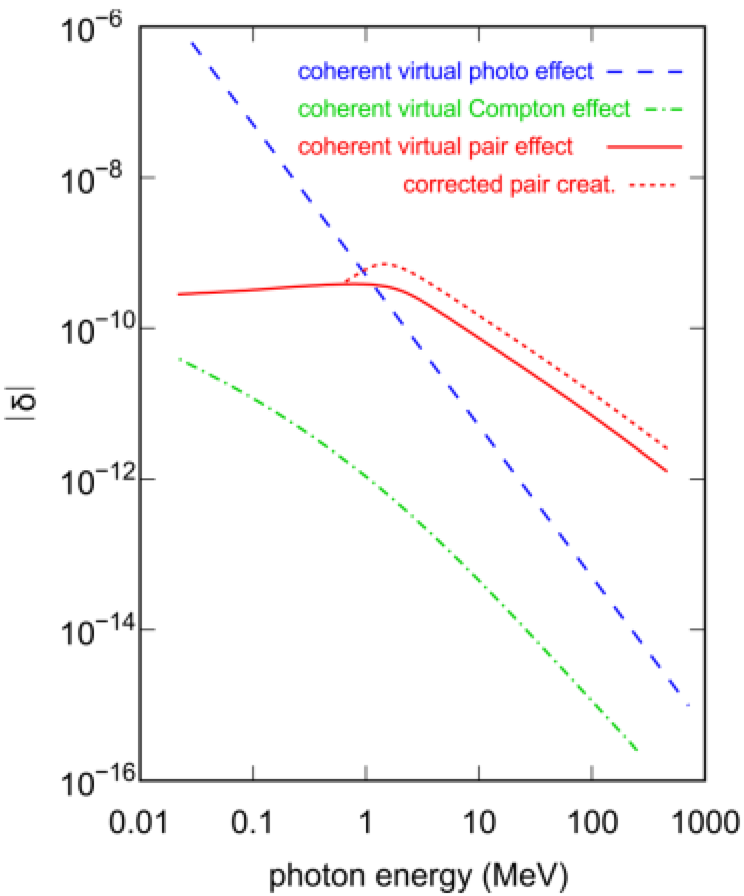
A clear enhancement of all experimental data with respect to classical Bethe-Heitler calculation

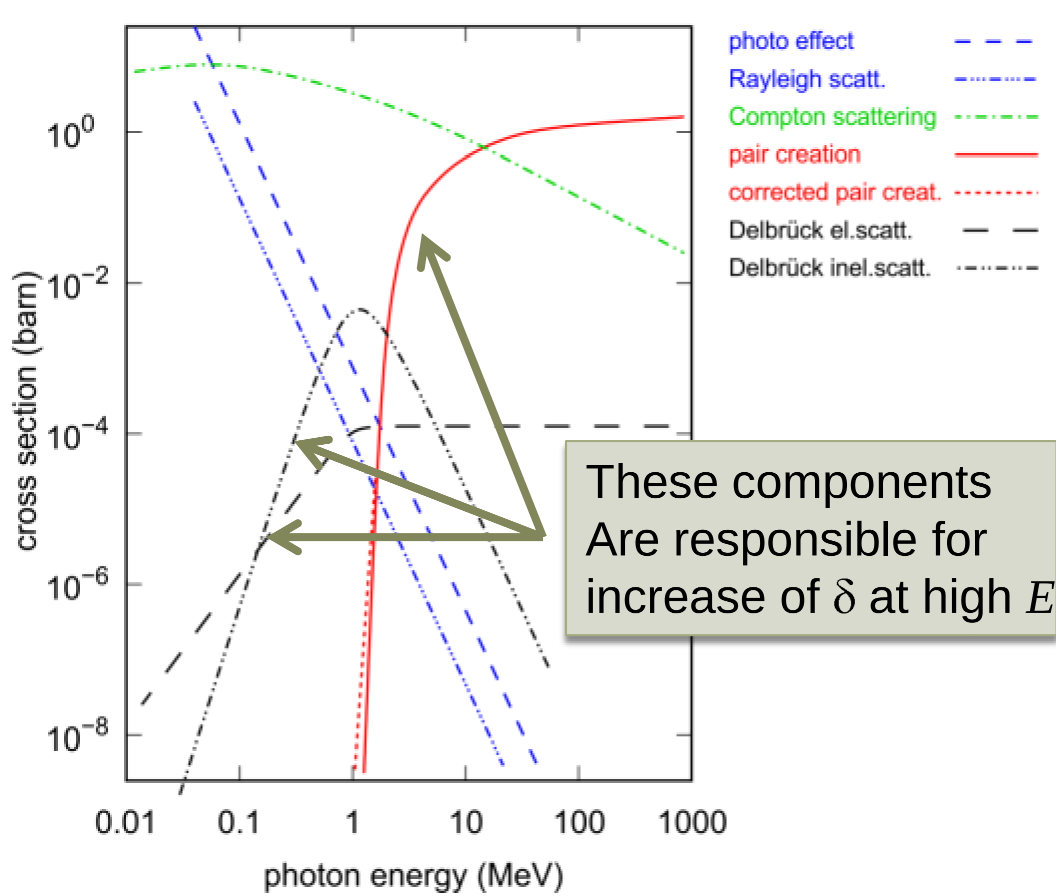
At present no theoretical explanation available

M. Jentschel et al, Phys. Rev. C. 84(5) 2011

The complete picture

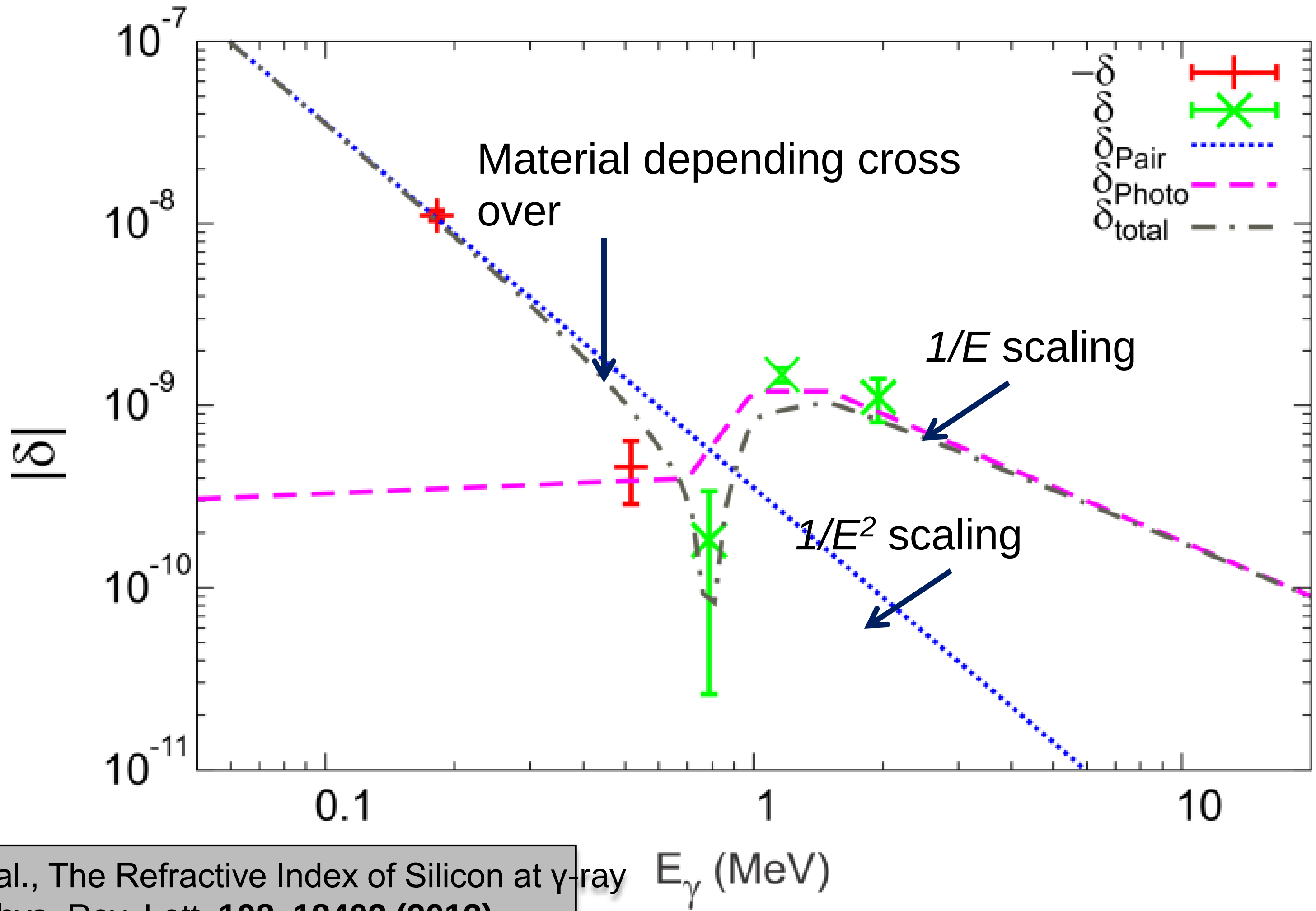
More processes to be considered: elastic and inelastic Delbrück scattering
(Calculations by D. Habs and M. Günther from LMU/MPQ Munich)





These components Are responsible for increase of δ at high E_γ

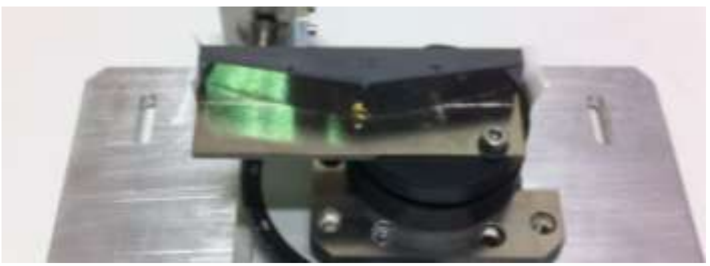
Results (comparison with expectation)

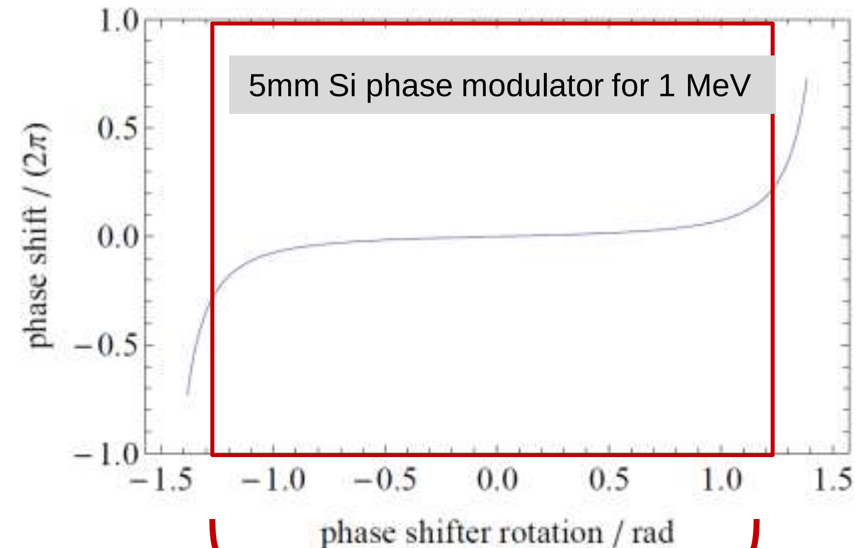


D. Habs et al., The Refractive Index of Silicon at γ-ray energies, Phys. Rev. Lett. **108, 18402 (2012).**

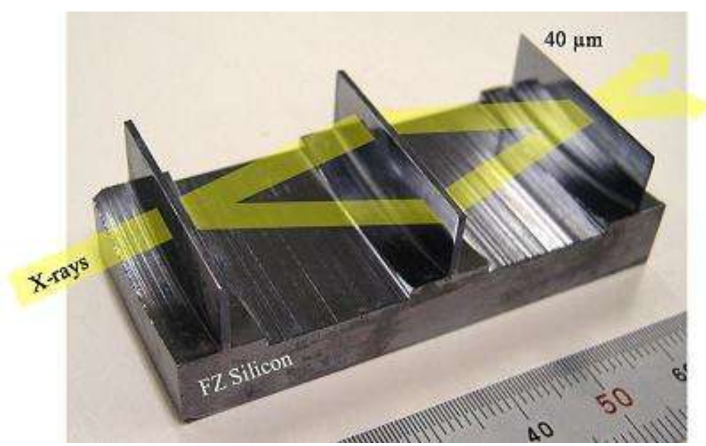
Next measurements: very near future

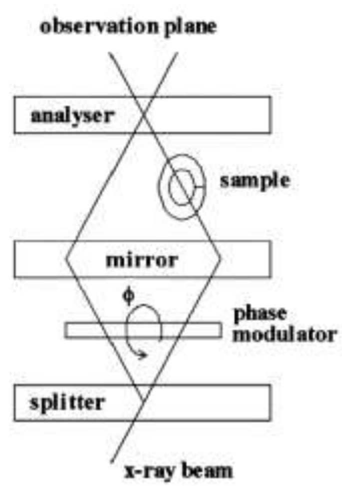
- Physics: measurement of Z-dependence
- precision Prism would be needed
- thick material → homogeinity?





Interferometric measurement



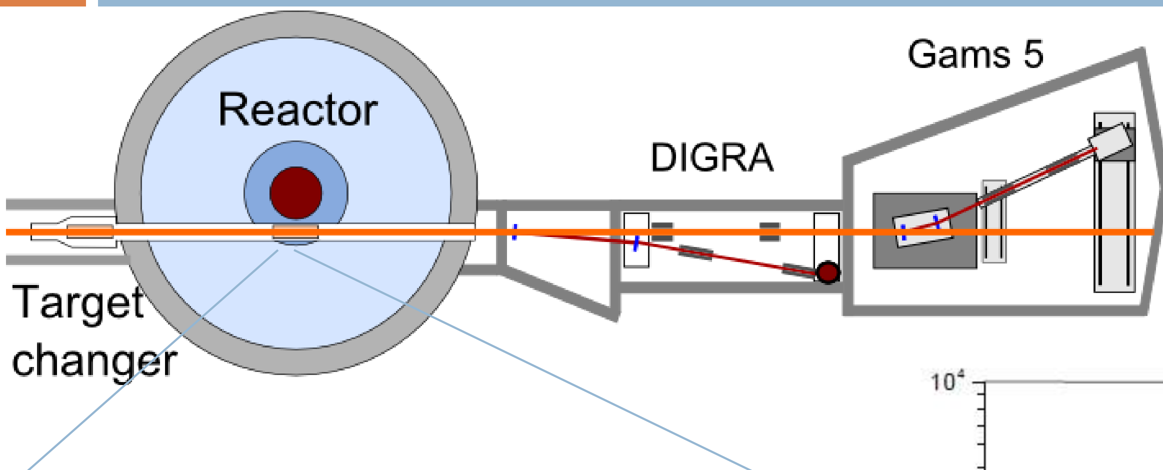


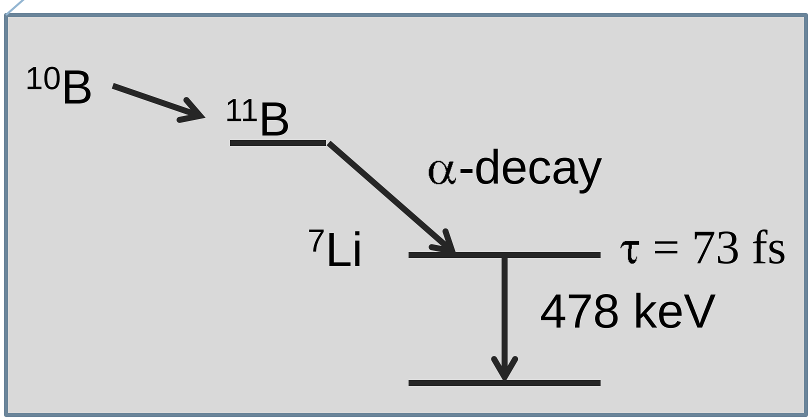
Possible working range:

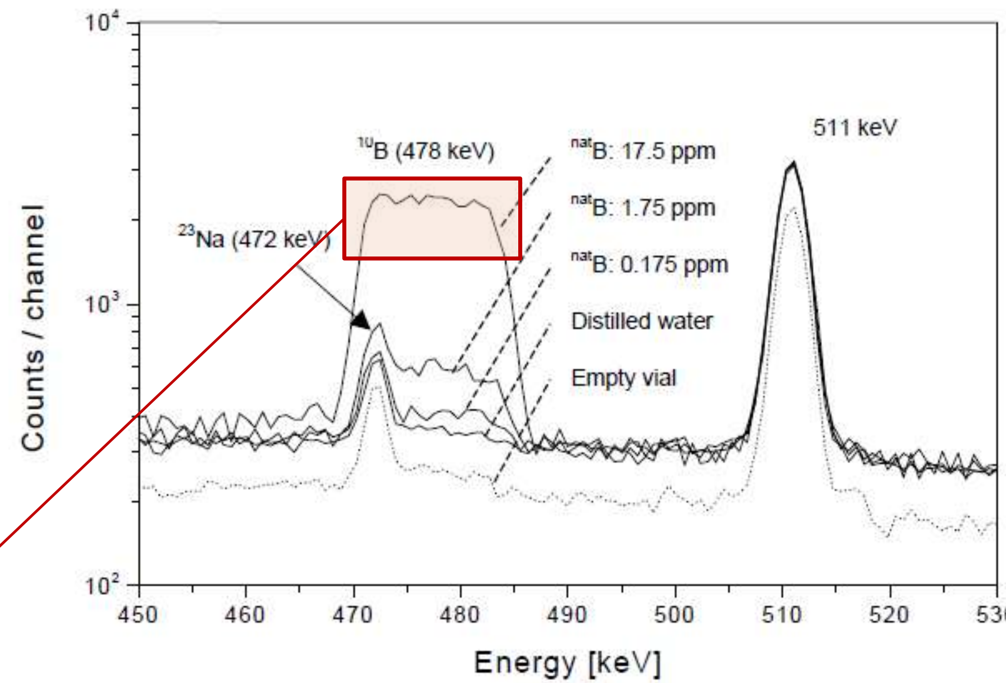
Calculation for Si:

- ~ 0.8 period phase shift
- enough to detect sign
- for higher Z materials stronger effect expected

First test of techniques and applications: still this year







We can work on nuclear resonance fluorescence of ^{7}Li and test all techniques right now

From PhD Tesis S. Baechler, Uni Fribourg

Conclusion

- Crystals can be used as optical elements for γ-rays
  - Beam splitter
  - Collimator
  - Monochromator
  - (lens)
- Refractive Optics for gamma rays is possible
  - Refractive index ≠ 0 for γ-rays
  - Investigations of more materials planned
- Combining Refracting and Diffracting Optics – very promising
- ILL is perfect test bench to develop technologies