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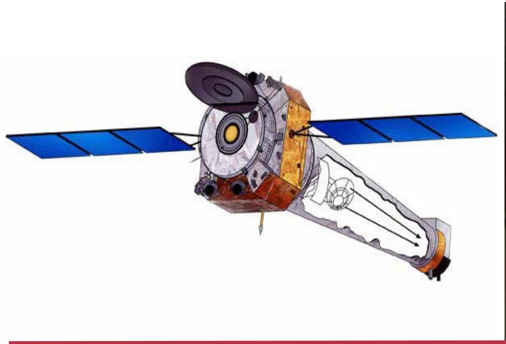
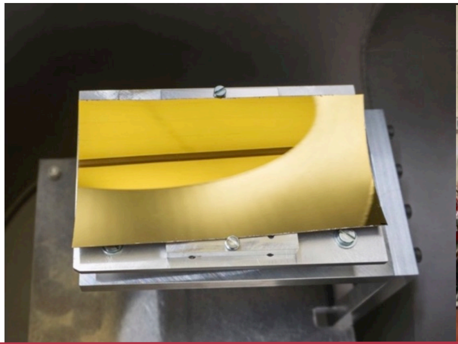
FACULTY OF SCIENCE
Institute for Astronomy und Astrophysics
High Energy Astrophysics


Grazing Angle Soft Proton Scattering Measurements for X-ray Optics

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Geant4 Space Users Workshop

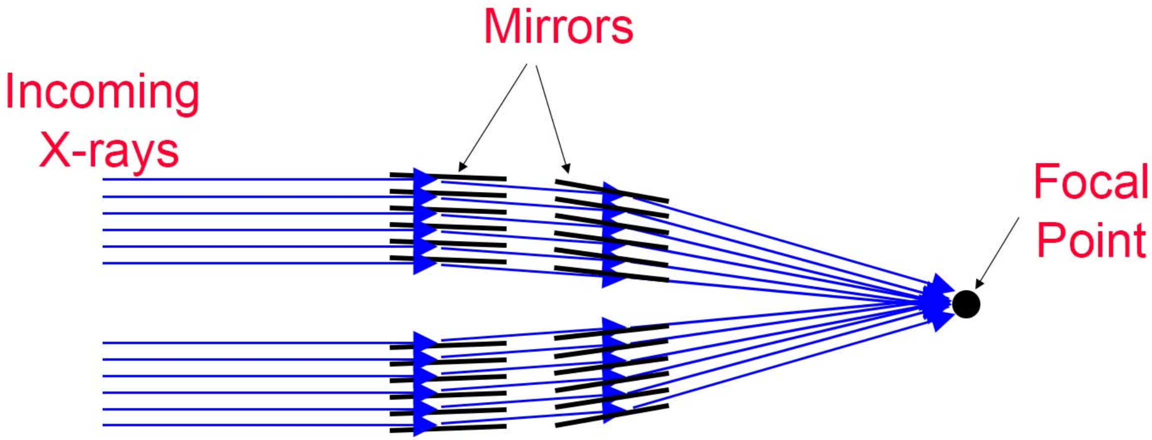
Guildford, April 11, 2017

Outline

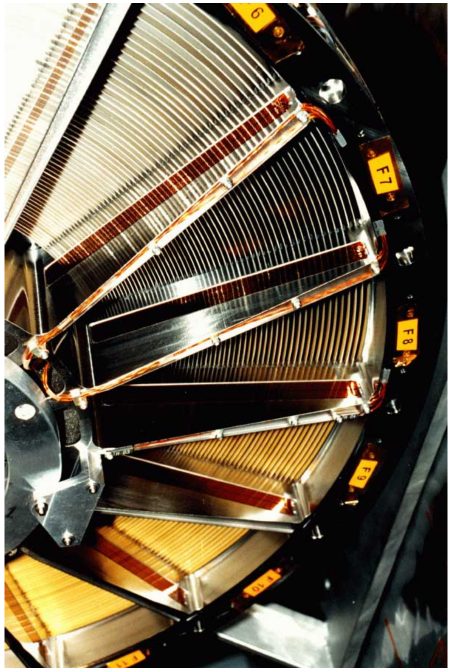
- Introduction and Motivation
- Experimental Setup
- Implementation of Experimental Results in Geant4
- Summary

Focusing X-Ray Optics

- Wolter Type I optics focus incoming X-rays via two reflections
- Reflections on combination of parabolic and hyperbolic mirrors
- Nested mirror shells enlarge effective area



Credit: NASA's Imagine the Universe



Credit: D. de Chambure, XMM Project (ESTEC)

But: (Soft) Protons are also focused – and the orbital focal plane soft proton flux exceeded expectations.

Soft Protons Effects on X-ray Detectors

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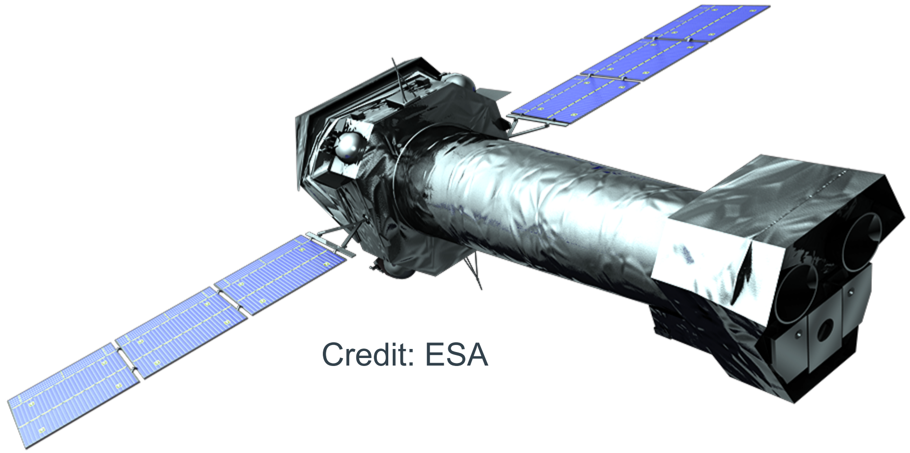
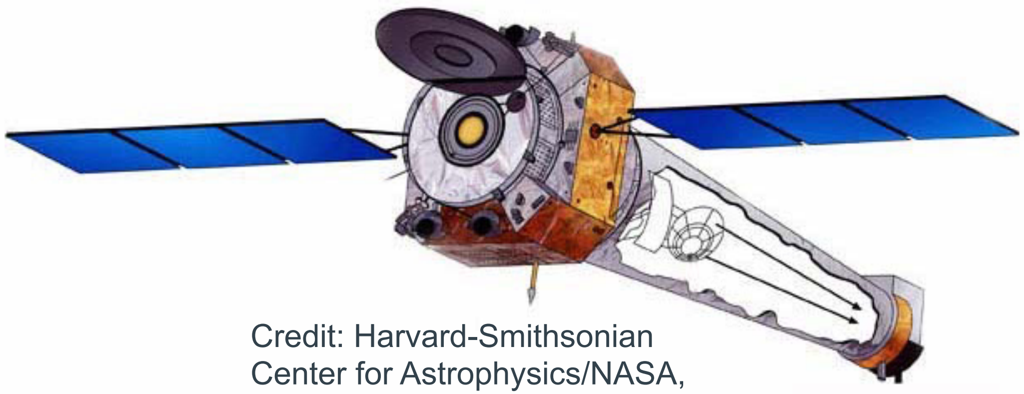
- Soft proton energy range:

  ~10 keV–10 MeV

- Two types of proton radiation effects concerning astronomical observations:
  - Contributions to background of observations (e.g. *XMM-Newton* EPIC background)
  - Degradation of the detector performance (e.g. front illuminated CCDs of *Chandra* ACIS instrument)



Credit: ESA



Credit: Harvard-Smithsonian Center for Astrophysics/NASA, modified

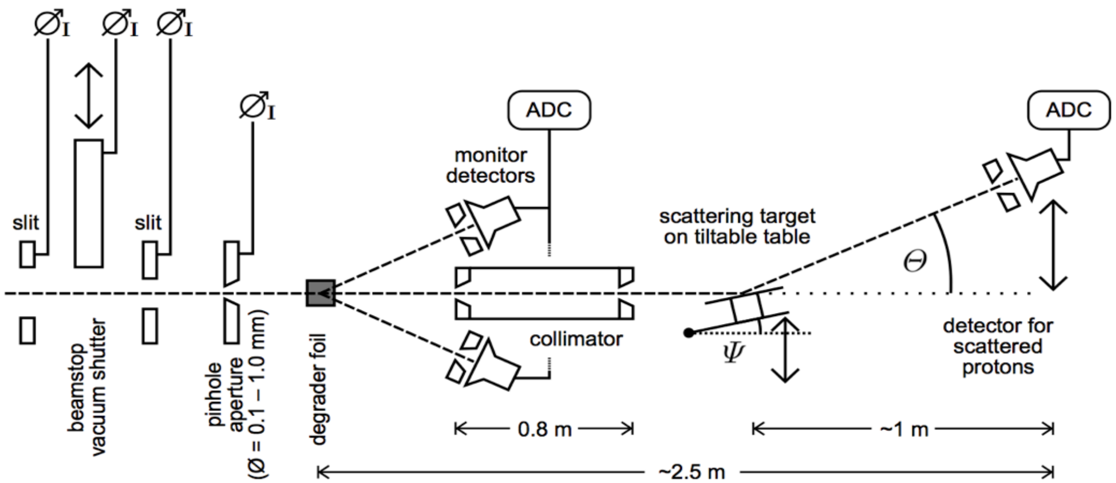
Soft protons have a stronger impact on X-ray instrumentation than energetic protons – experimental data is needed to verify simulation results.

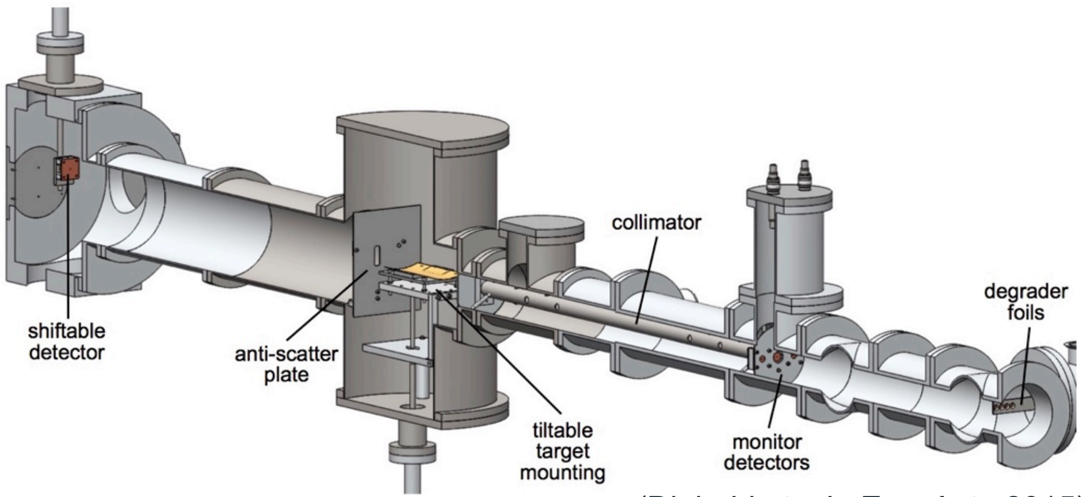
Accelerator Facility in Tübingen

- 3 MV single-ended Van de Graaff accelerator:
  - Beam energy range: 400 keV–2.5 MeV
  - Beam current: 200 nA–40 μA
  - 6 beam lines
  - Several light ion types besides protons (e.g. helium)

Soft Proton Scattering Setup

- **Two pairs of slits** align the proton beam with the setup
- **Pinhole aperture** reduces incoming beam current and, therefore, the rates on detectors
- **Degrader foil** widens beam to measure incident proton flux via monitor detectors
- **Collimator** focuses part of the beam on target
- **Target** is mounted on a tiltable table to be able to change the incidence angle Ψ
- Scattering angle θ is defined by the position of the detector at the end of the beam line





(Diebold et. al., Exp. Ast., 2015)

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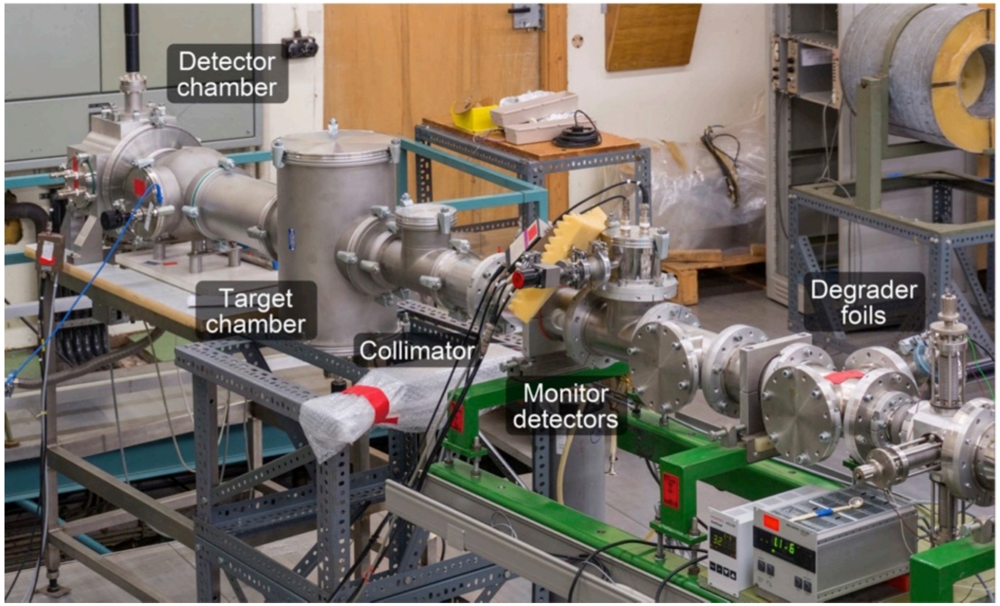
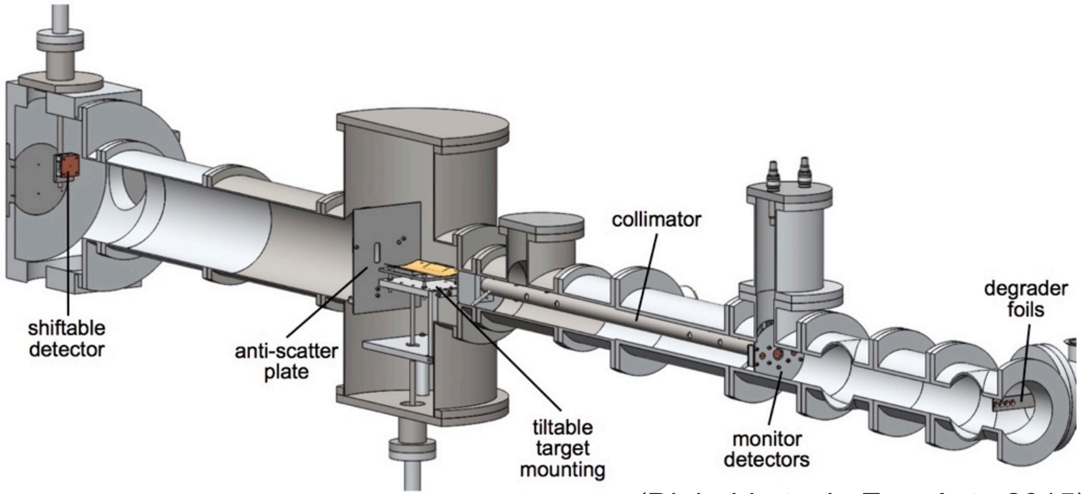
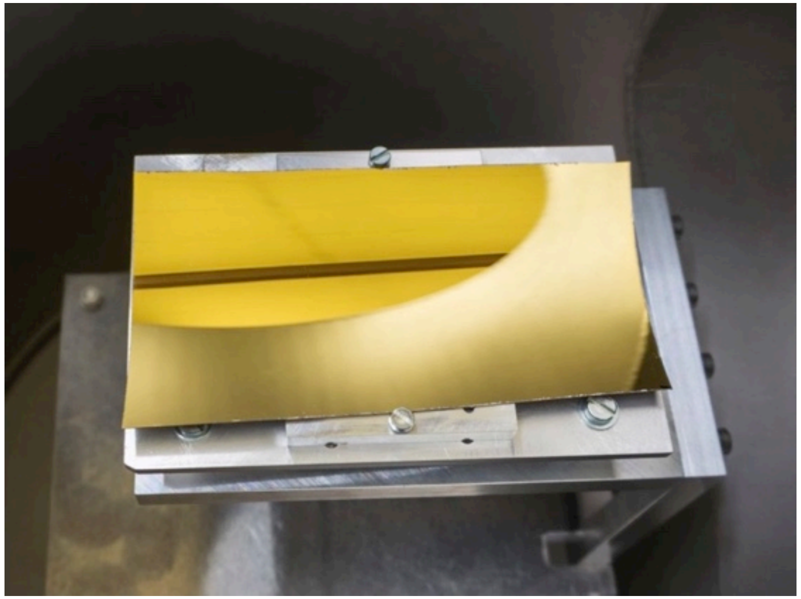




(Diebold et. al., Exp. Ast., 2015)

Scattering Target and Detectors

- eROSITA mirror shell:
  - Nickel substrate with 50 nm gold coating
  - 12 cm length, 6 cm width



- Silicon surface barrier detectors:
  - Used as monitor detectors and to detect scattered protons
  - Energy resolution between 10–20 keV
  - Typical count rates up to $2\times10^{5}\ \mathrm{s}^{-1}$ can be achieved
  - Low energy threshold 80–100 keV

Credit: Canberra Industries, Inc., modified

Measurements

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- Scattering efficiency:

$$\eta(\Psi,\Theta) = \frac{N_{\mathrm{det}}(\Psi,\Theta)}{N_{\mathrm{inc}}} \cdot \frac{1}{\Omega(\Theta)}$$

- Incidence angle Ψ
- Scattering angle Θ
- Number of detected protons N_{det}
- Number of incident protons N_{inc}
- Solid angle of detector Ω

- Most probable energy loss:

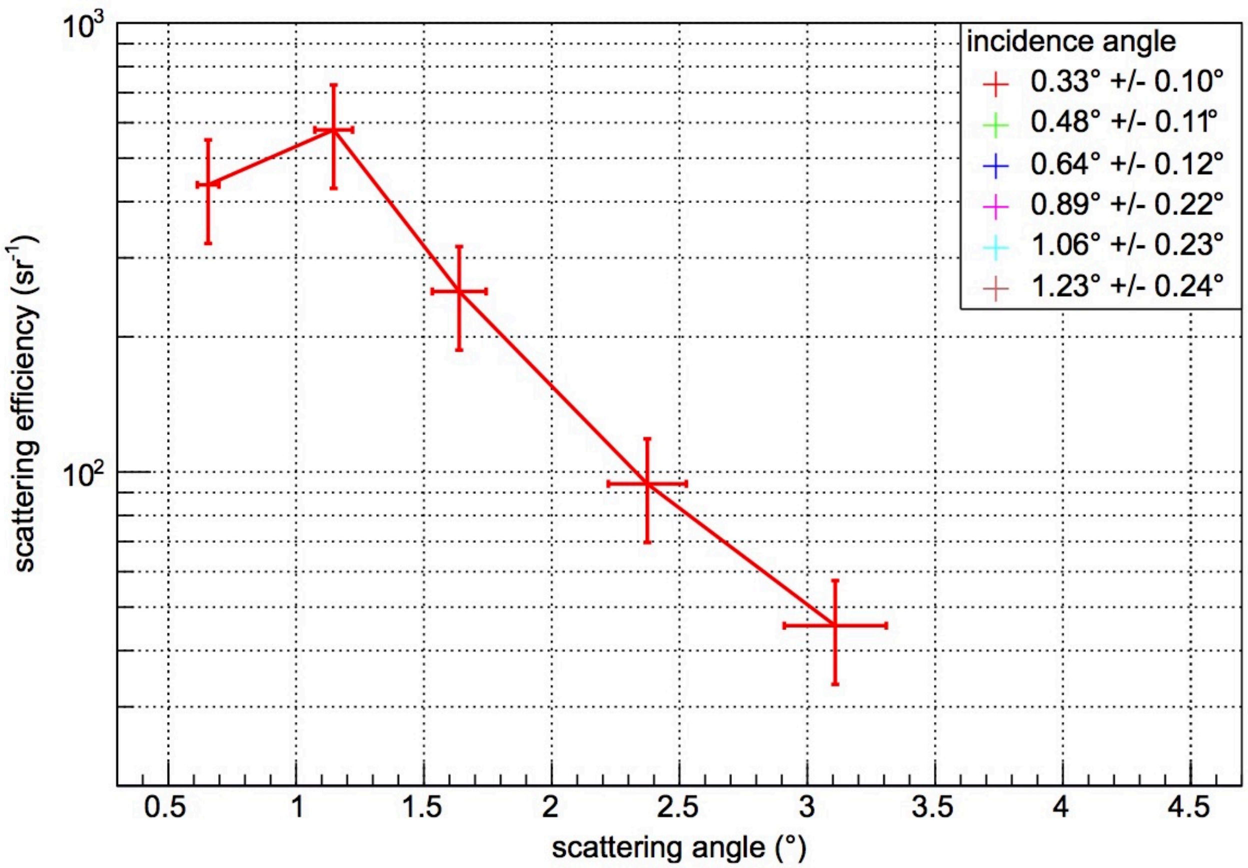
$$\Delta E(\Psi,\Theta) = \mu_{\mathrm{Gauss,inc}} - \mu_{\mathrm{Gauss,det}}(\Psi,\Theta)$$

- Parameters selected for efficiency and energy loss measurements:

Proton energies (keV)	Incidence angle Ψ (deg)	Scattering angle Θ (deg)
250, 500, 1000	0.3 – 1.2	0.5 – 4.1

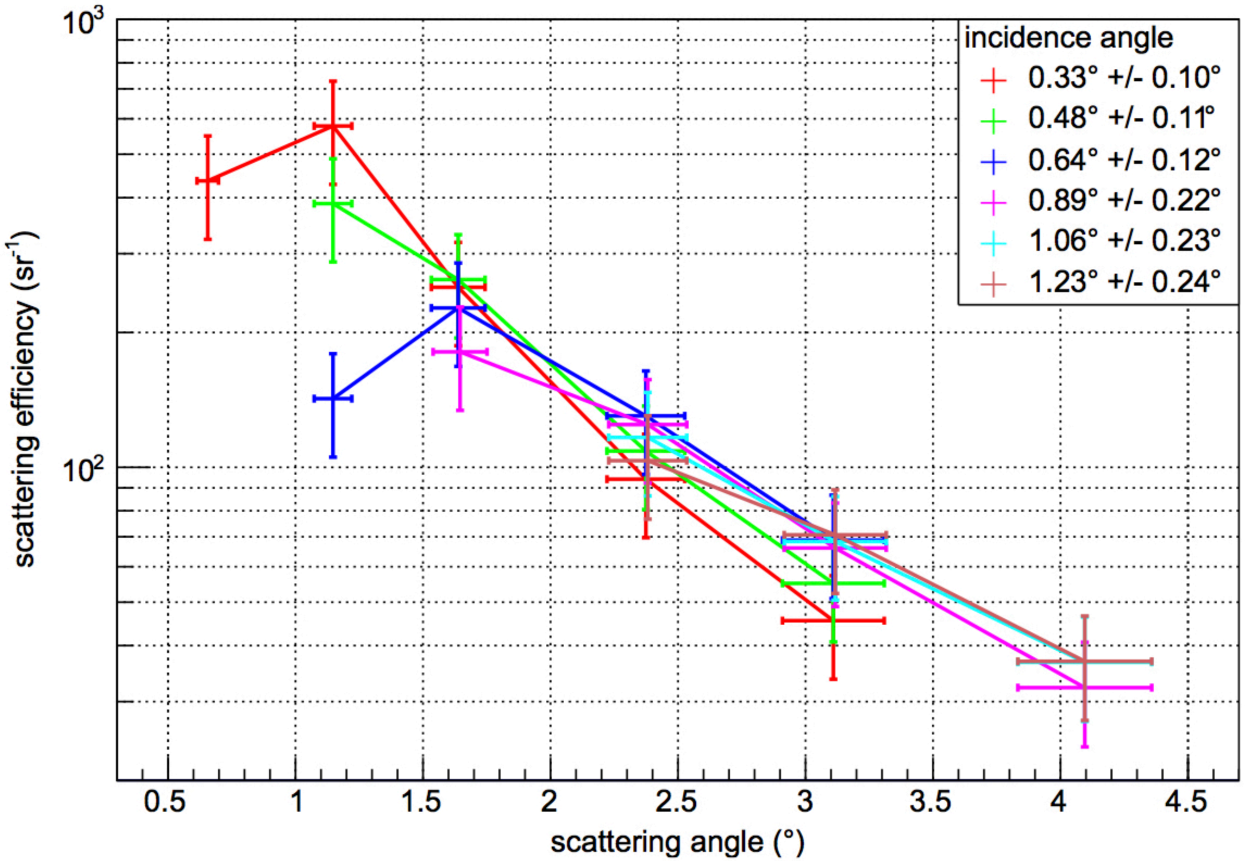
Experimental Setup

Scattering Efficiency for 500 keV Protons (1)



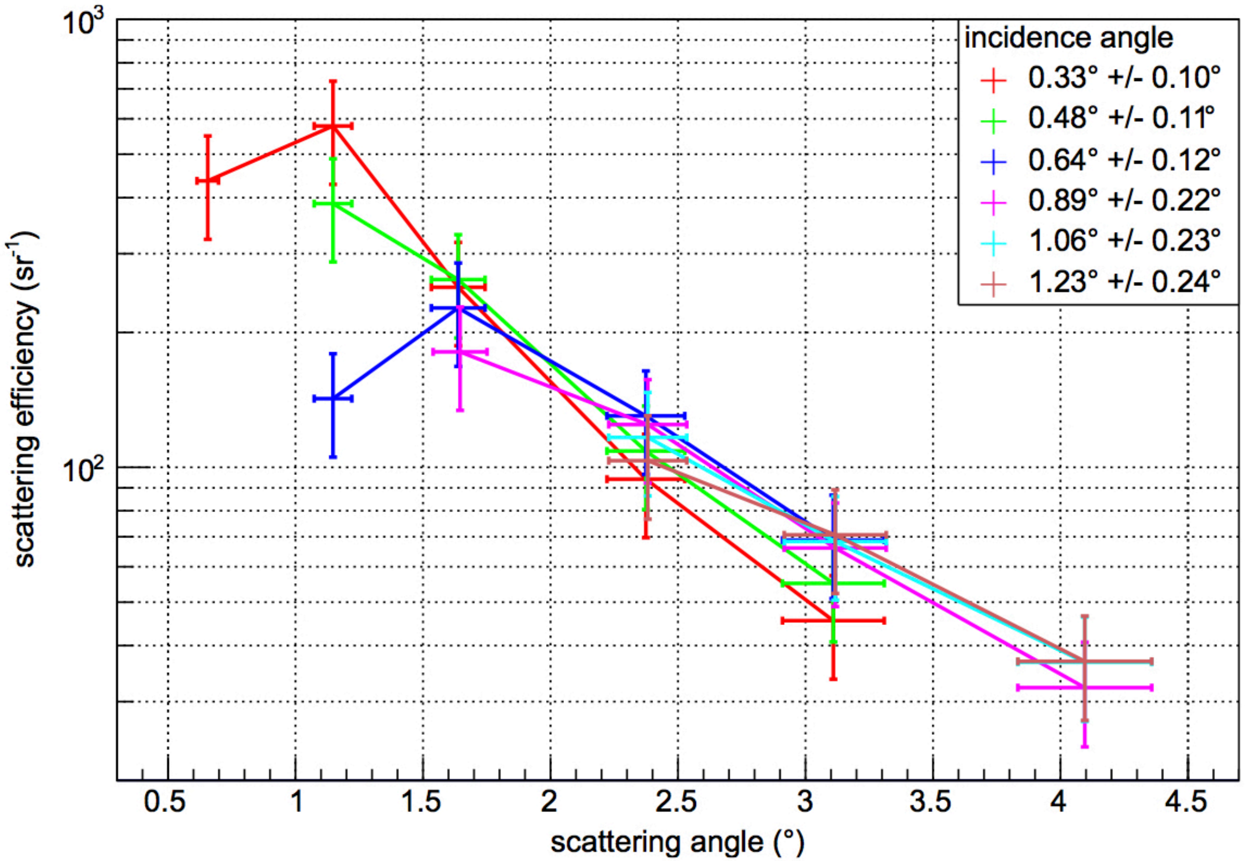
(Diebold et al., Exp. Ast., 2015)

Scattering Efficiency for 500 keV Protons (2)



(Diebold et al., Exp. Ast., 2015)

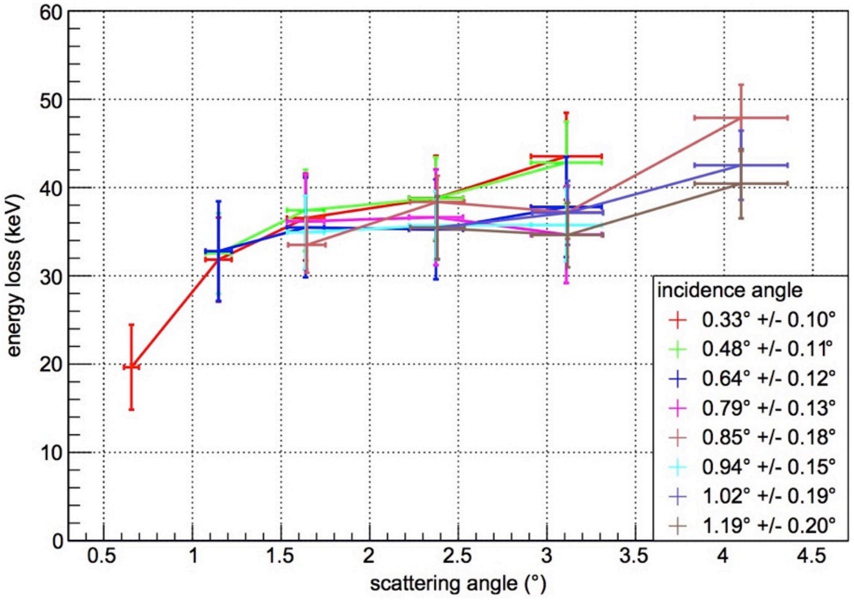
Scattering Efficiency for 500 keV Protons (3)



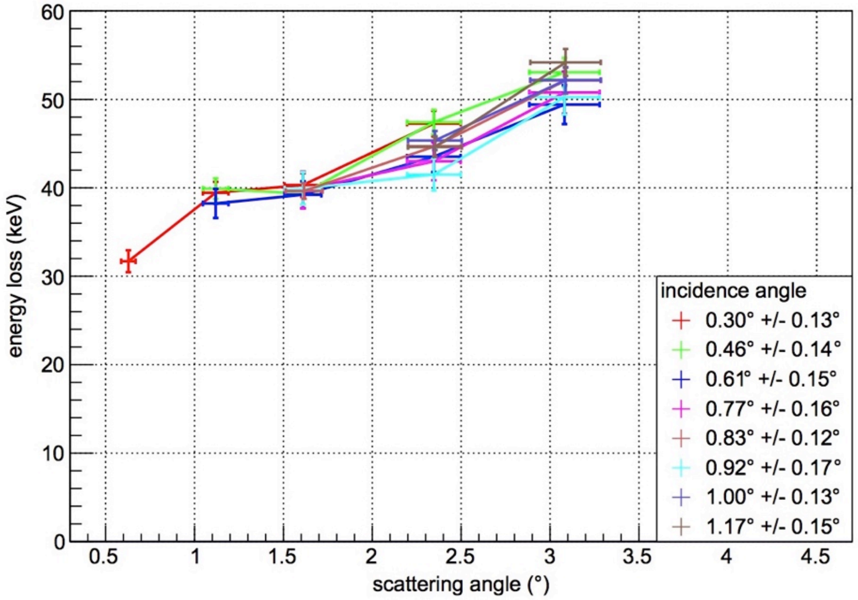
Measured scattering efficiencies have shown no significant dependency on incidence energy.

(Diebold et al., Exp. Ast., 2015)

Energy Loss Analysis



a) Energy loss for 500 keV Protons



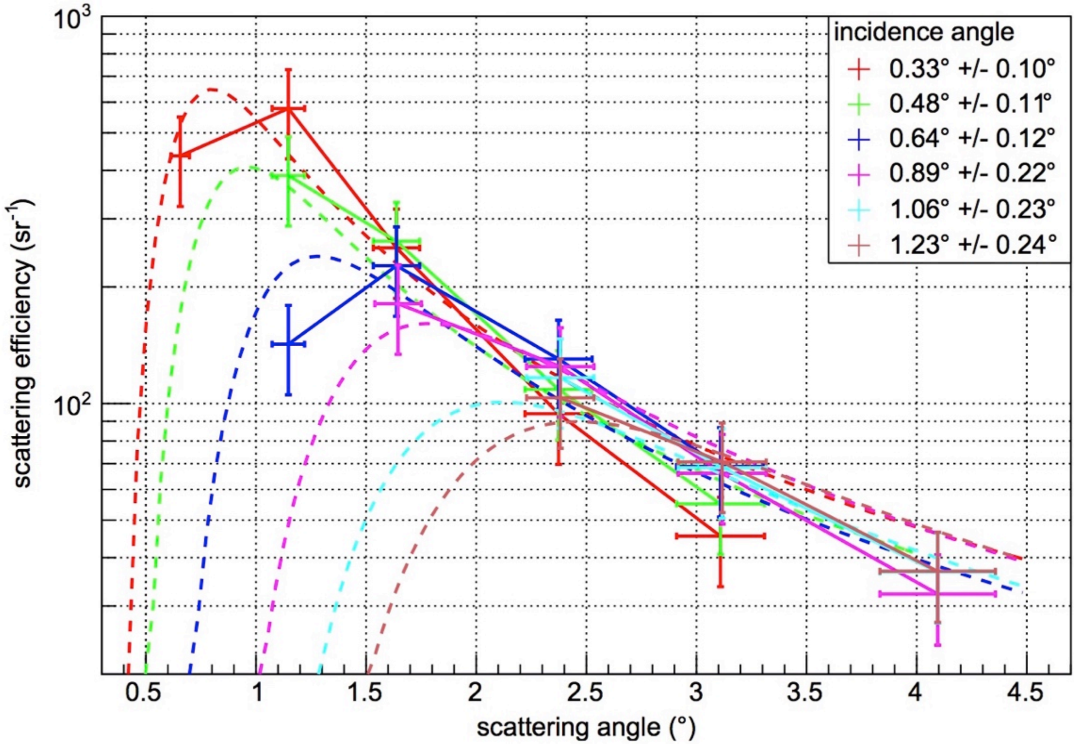
b) Energy loss for 1000 keV Protons

Most probable energy loss depends on the incidence energy, increases to larger scattering angles and is almost independent of the incidence angle.

(Diebold et al., Exp. Ast., 2015)

G4GrazingAngleScattering Class

- Two models implemented: Analytical scattering descriptions by Firsov (1967) and Remizovich et al. (1980)
- Recent experimental results included as third "model" – the Tübingen measurements
- Inherits from G4VDiscreteProcess: Trajectories will only be modified after current step

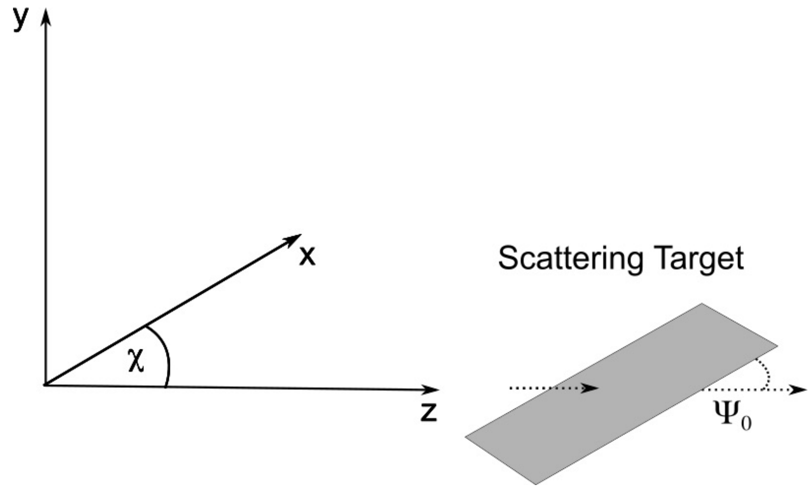


- Measured scattering efficiencies for 500 keV Protons with analytical Firsov functions (dashed lines)

(Diebold et al., Exp. Ast., 2015)

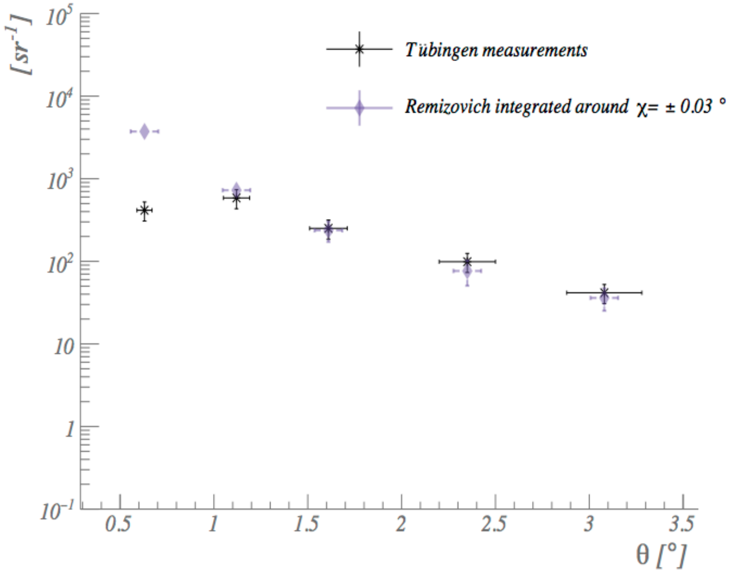
Usage

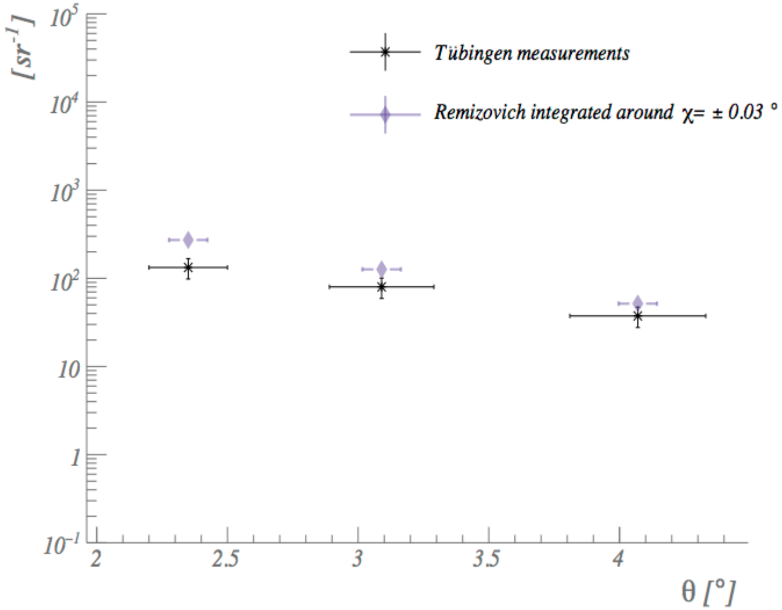
- Add process to user physics list in simulation
- Set suitable parameters:



Scattering model	Firsov, Remizovich or Tübingen measurements
Maximum incidence angle Ψ_0	Process will only scatter particles whose incidence angle is within this value
Mean angle χ	Scattering in xz-Plane (for Firsov and Tübingen model), provided via a simple gaussian, ignored in case of Remizovich model
Standard deviation for χ	Corresponding to mean angle χ

Status (1)



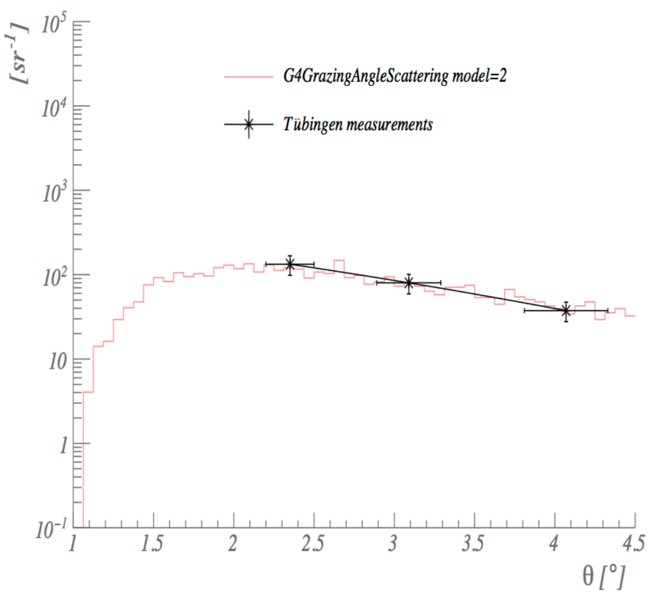


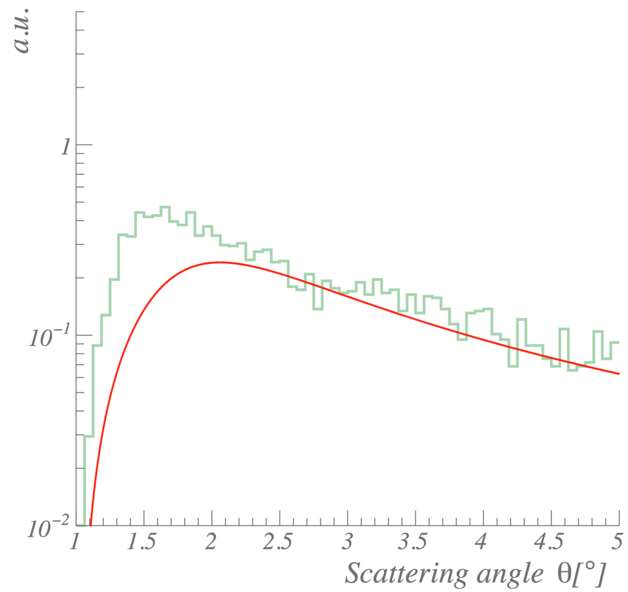
- Experimental results (dark blue) compared to Remizovich description around $\chi = \pm\, 0.03°$ (light violett) for E = 1000 keV, $\Psi_0 = 0.33°$

- Same as on the left, but with E = 1000 keV, $\Psi_0 = 1.03°$

(Guzman et al. 2017, submitted)

Status (2)





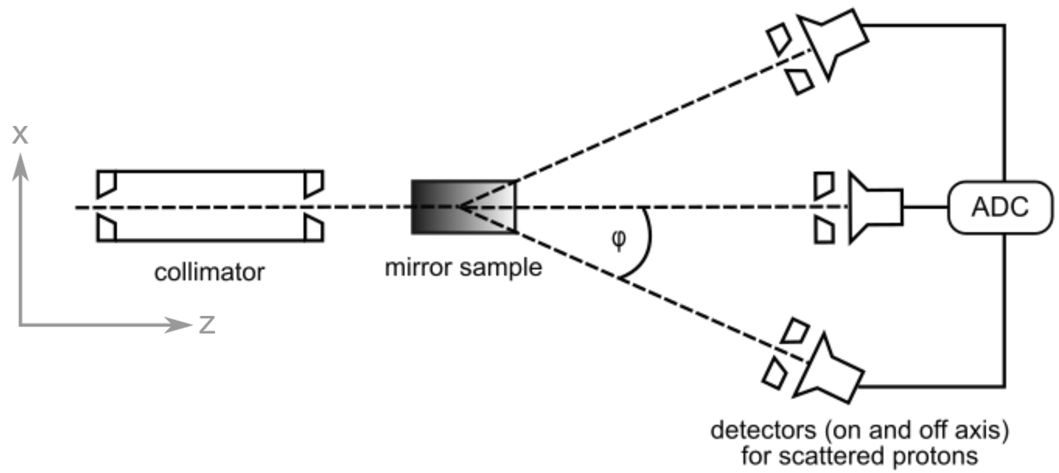
- Scattering efficiency for Tübingen model simulated with G4GrazingAngleScattering (red) and experimental results (black) for E_0 = 1000 keV, Ψ_0 = 1.03° around $\chi = \pm$ 0.03°

- Tübingen model simulated with G4GrazingAngleScattering (green) and Remizovich Function (red) for E_0 = 977keV, Ψ_0 = 1.03°

(Guzman et al. 2017, submitted)

Ongoing Work

- Experimental setup:
  - Two off axis detectors added to gather scattering data in azimuthal directions
  - Running scattering tests with different mirror samples, e.g. plane surface with aluminium coating, silicon pore optics (similar to the ones from *ATHENA*)



Ongoing Work

- Simulation:
  - Refining processes with new measurement results: distribution information in azimuthal direction, measurements with different mirror samples
  - Goal: Simulate soft proton scattering effects (e.g. flux in focal plane and on detectors as well as surroundings) for whole observatory mirror geometry

Summary

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- Scattering efficiencies and most probable energy loss for eROSITA mirror prototypes (gold coated nickel) for grazing incidence angles have been studied at the accelerator facility of the University of Tübingen.
- Measured scattering efficiencies are significantly higher than previously estimated efficiencies.
- Most probable energy loss depends on the incidence energy, increases to larger scattering angles and is almost independent of the incidence angle. Measured energy loss is significantly higher than previously estimated.
- Results have been implemented in a G4GrazingAngleScattering class together with analytical descriptions of Remizovich and Firsov to enable the usage of recent experimental data in simulations.

Thank you!