X-ray Polarisation in Astrophysics
-a window about to open?
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ASTRO-H & MONACO for X-ray Polarimetry

precise measurement and calculation

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and the A-H/SGD team and the A-H/Science team

Polarization: New Window

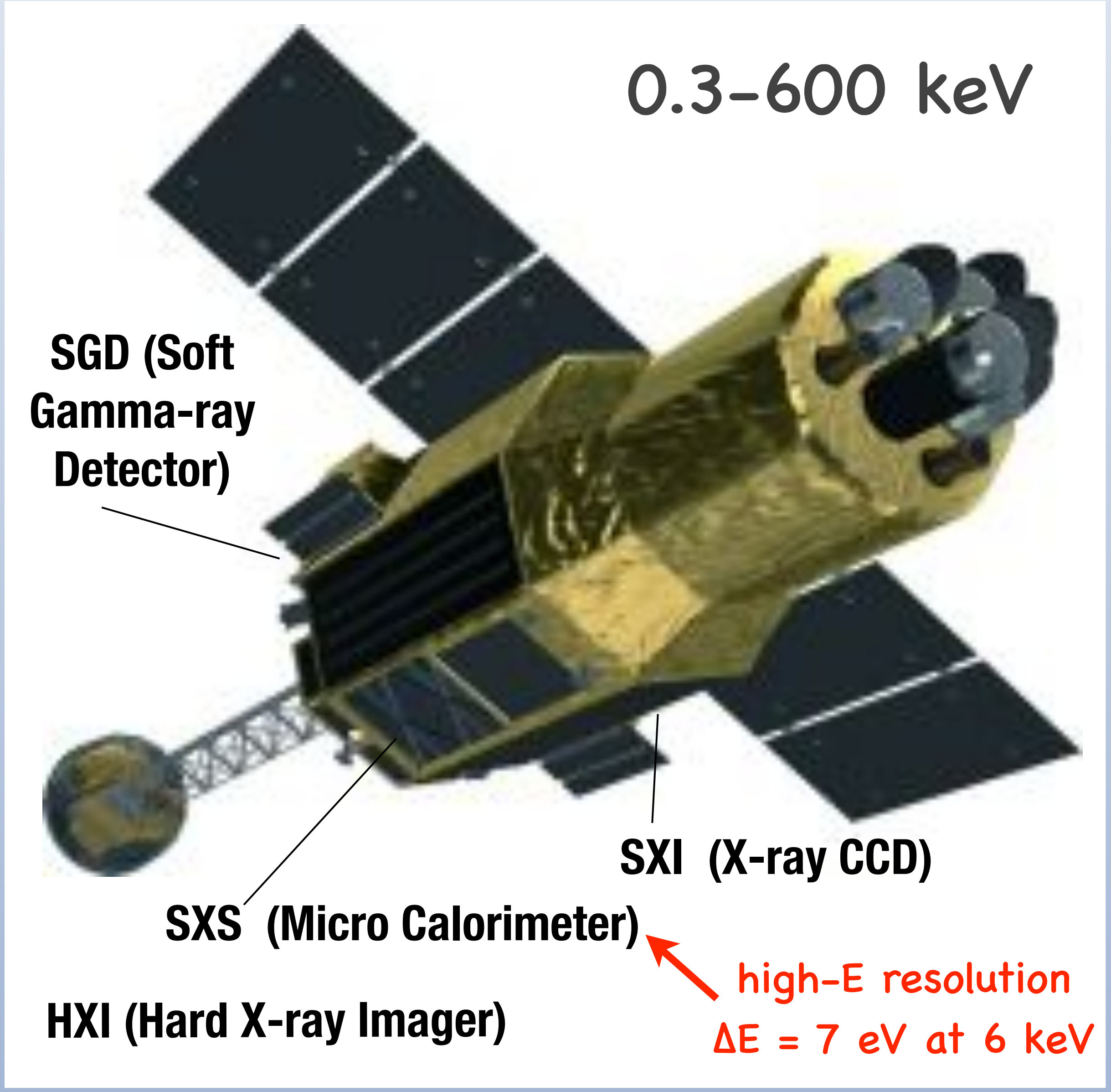
- In addition to spectroscopy, imaging, and timing information, polarization will be the fourth probe of X-ray and gamma-ray observations.
- Polarization provides us with information on radiation mechanisms, orientation and uniformity of magnetic field, and structure of emitting objects.
- INTEGRAL has reported polarized emissions from relativistic outflows: the Crab nebula and Cygnus X-1 (jet?)
- We need to more precise measurements of X-ray & gamma-ray polarization.

ASTRO-H

ASTRO-H is an international X-ray observatory, which is the 6th Japanese X-ray satellite scheduled for launch in 2015 (FY of Japan) from Tanegashima Space Center, Kagoshima, Japan.

Takahashi+10

Takahashi+12

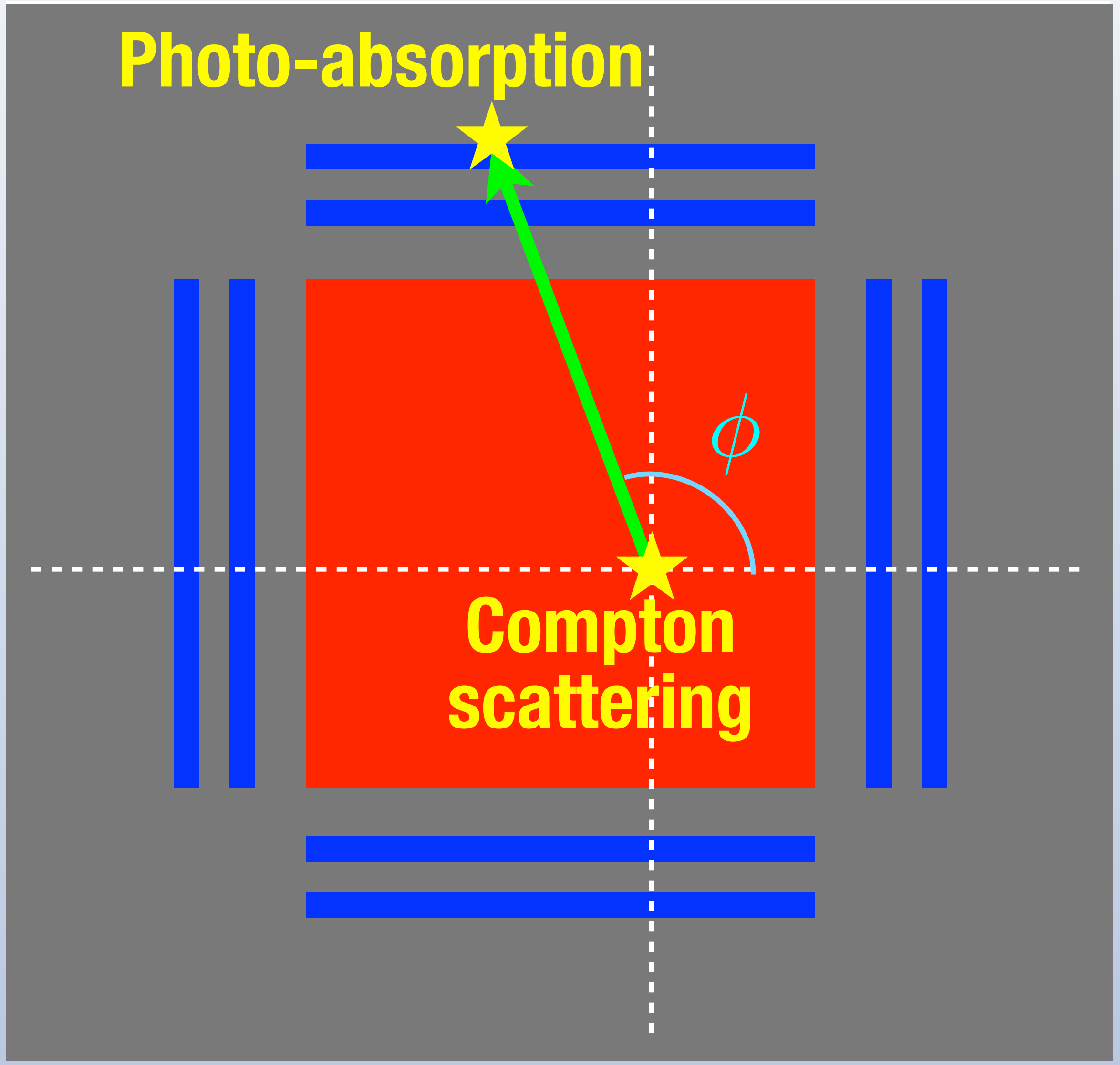


Soft Gamma-ray Detector (SGD)

- a narrow field-of-view Compton telescope
- 50 keV up to 600 keV
- 10 times better sensitivity than Suzaku-HXD

$$\cos\theta = 1 - \frac{m_{\mathrm{e}}c^2}{E_2} + \frac{m_{\mathrm{e}}c^2}{E_1 + E_2}$$

Tajima+10, Watanabe+12

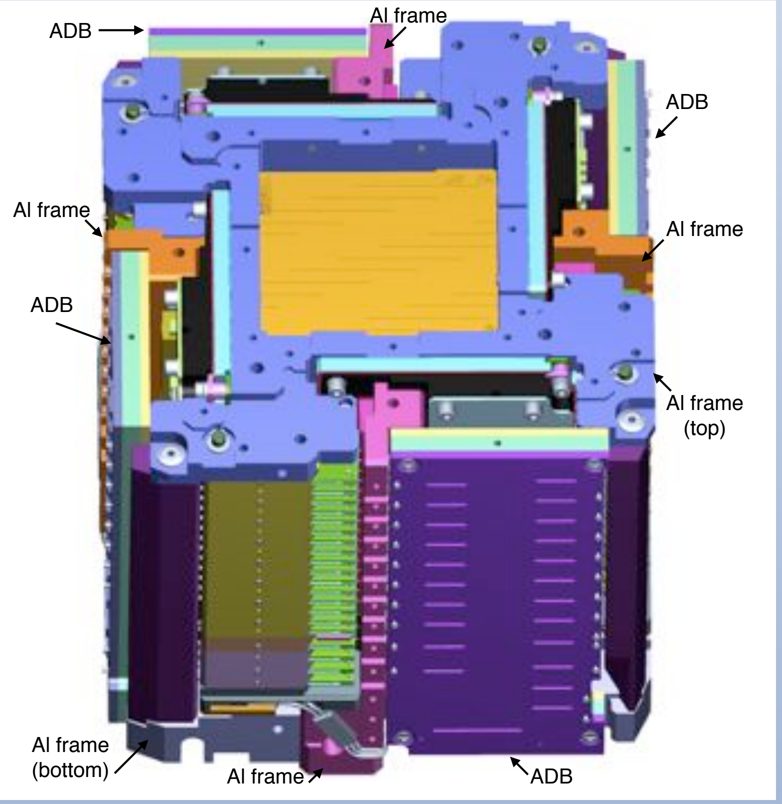


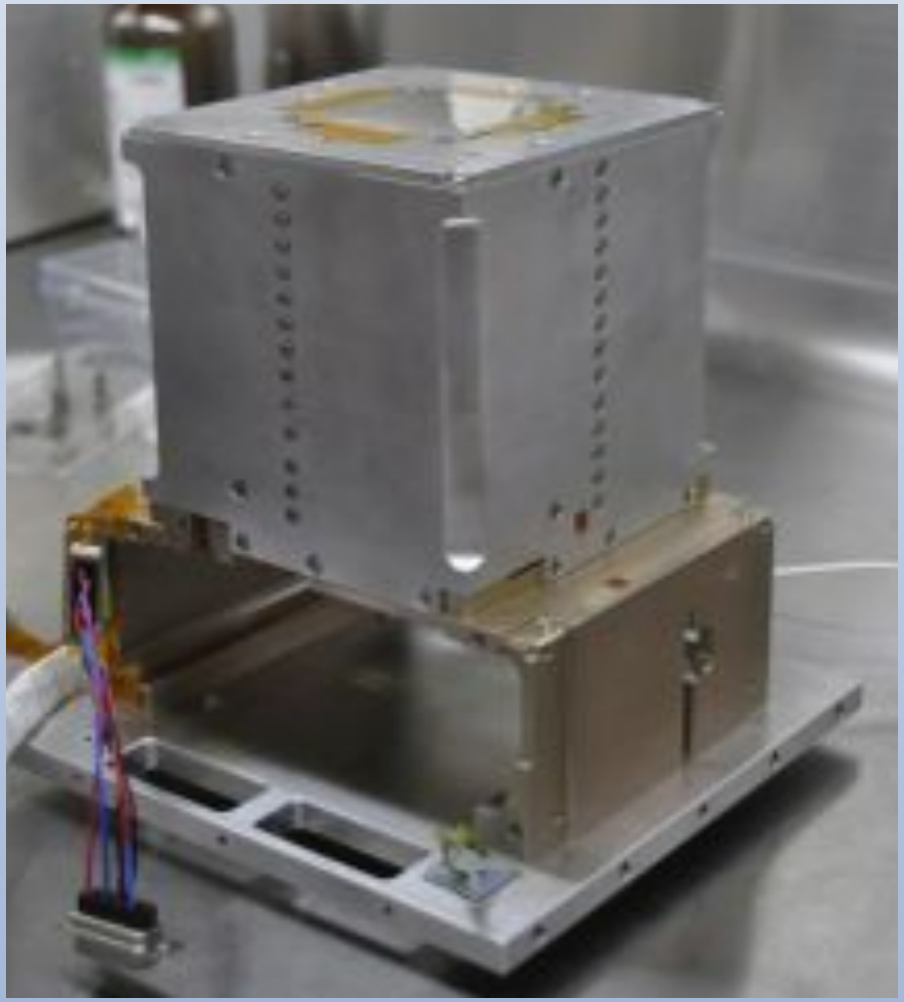
The SGD is also designed for a high-precision polarimeter using the azimuth distribution of Compton scattering.

Soft Gamma-ray Detector (SGD)

Production and function/performance check are on going toward the final integration check of the spacecraft.

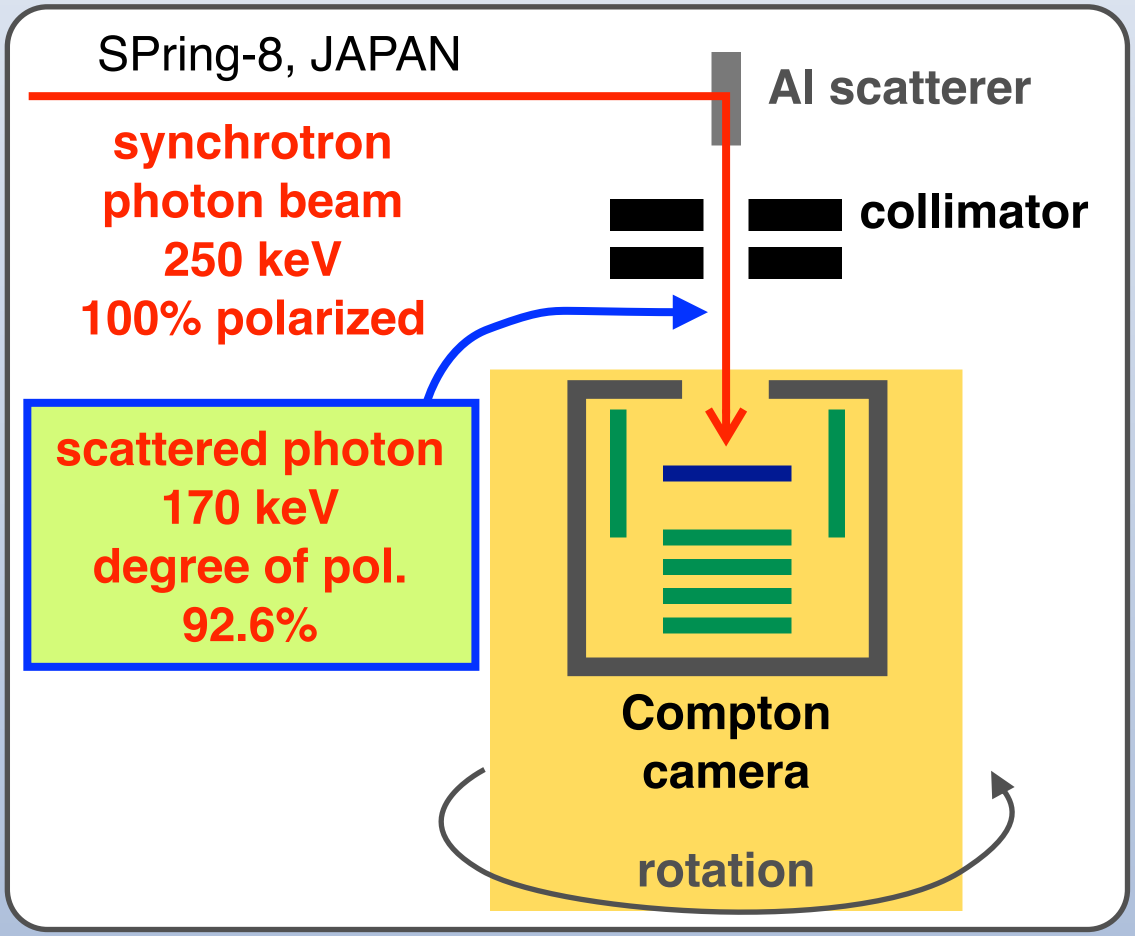
Watanabe+12

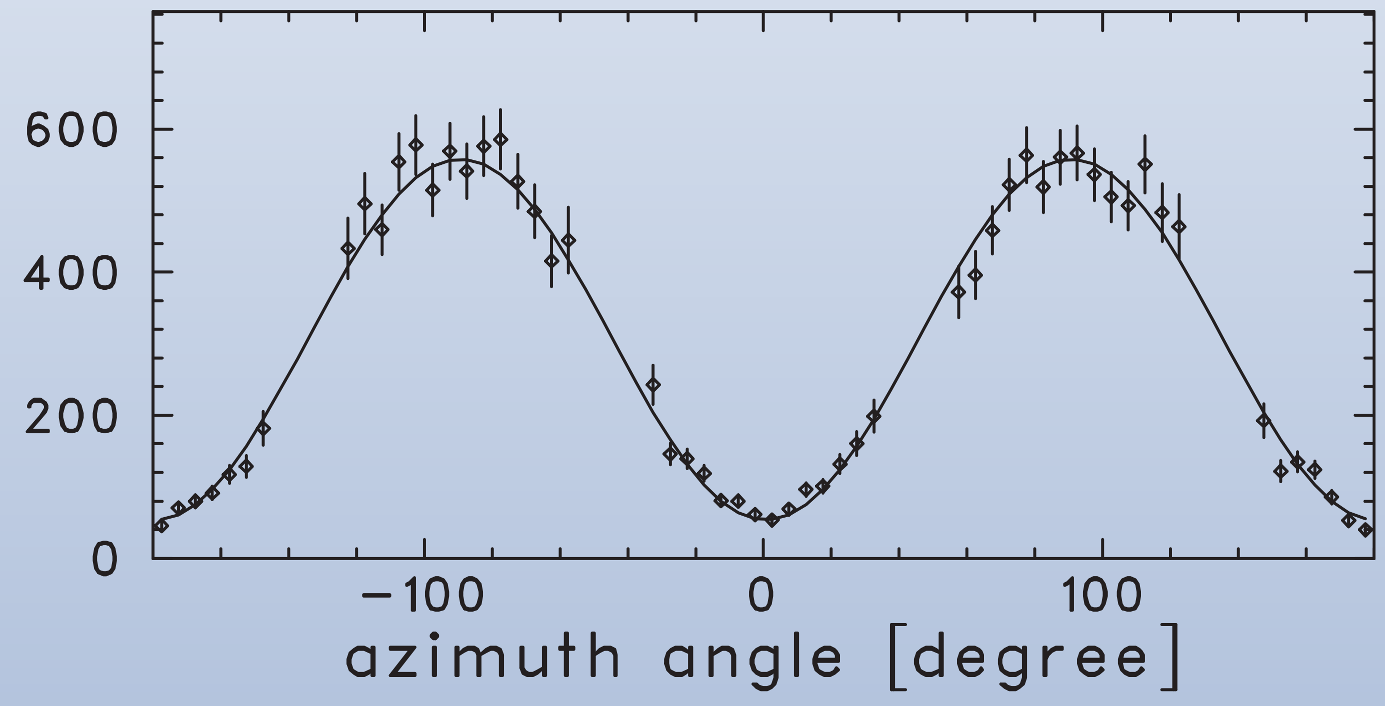




Experimental Verification

We performed an experimental test using an early prototype of the SGD at a synchrotron photon factory SPring-8 (Hyogo, Japan), and demonstrated high-precision polarimetry for 170 keV gamma rays.





Takeda+10

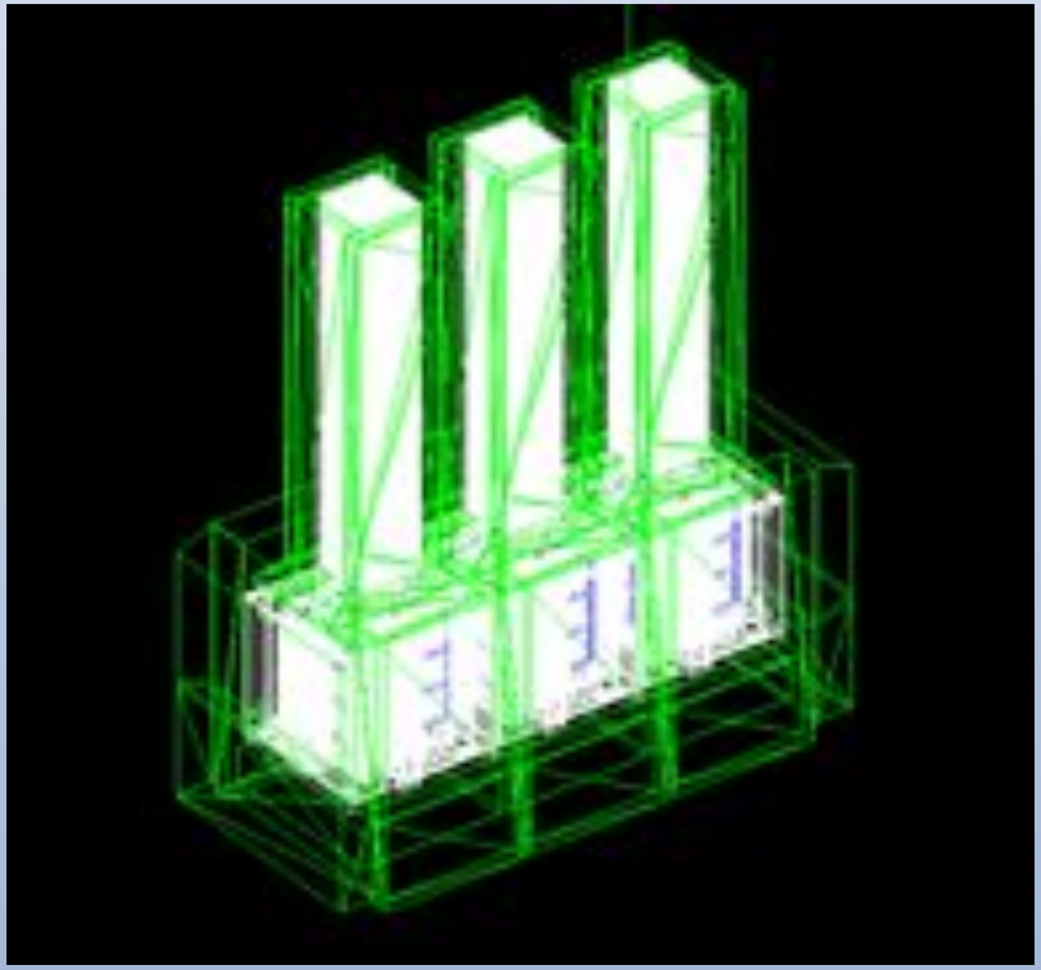
Polarization fraction = 0.91 ± 0.01(stat.)

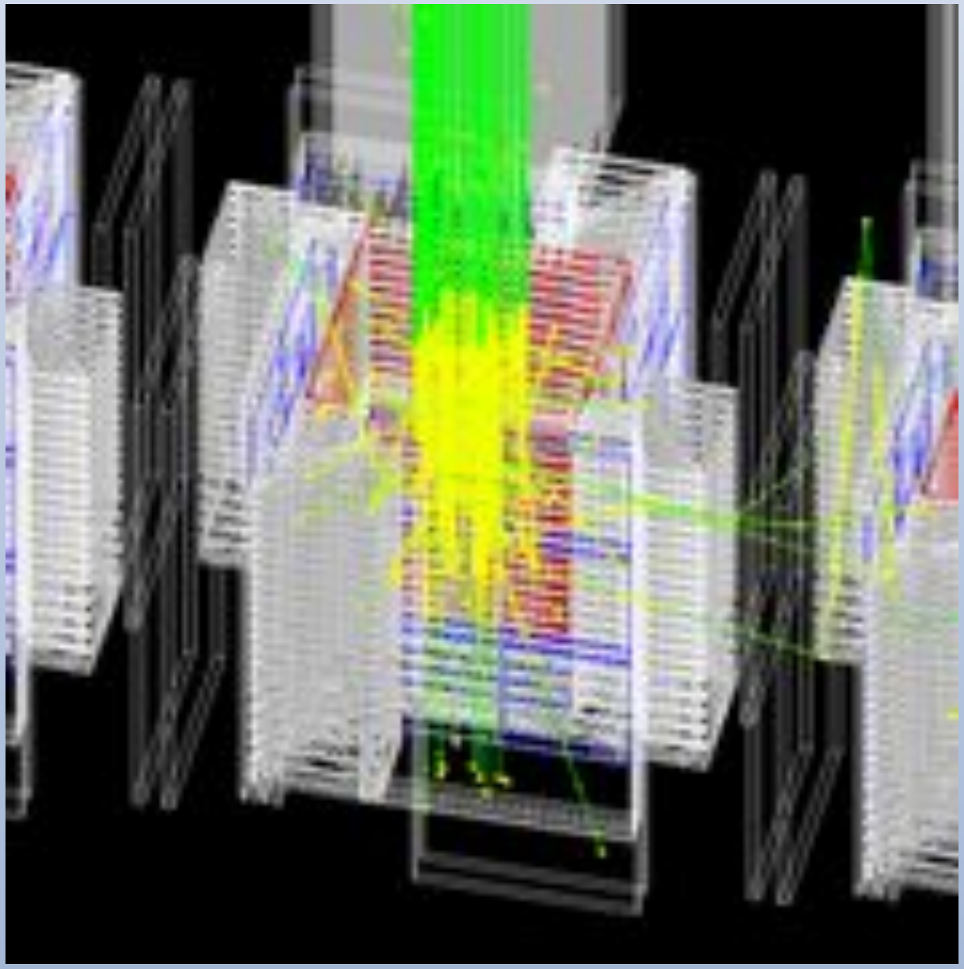
Polarization angle = 0.2° ± 0.4°(stat.)

Monte Carlo Simulations

It is essential to understand the detector response to the polarized emission and effects of background. We have developed a full Monte Carlo simulation (Geant4) to generate the response, to study data analysis procedure and systematic uncertainties, and to make observation plans.

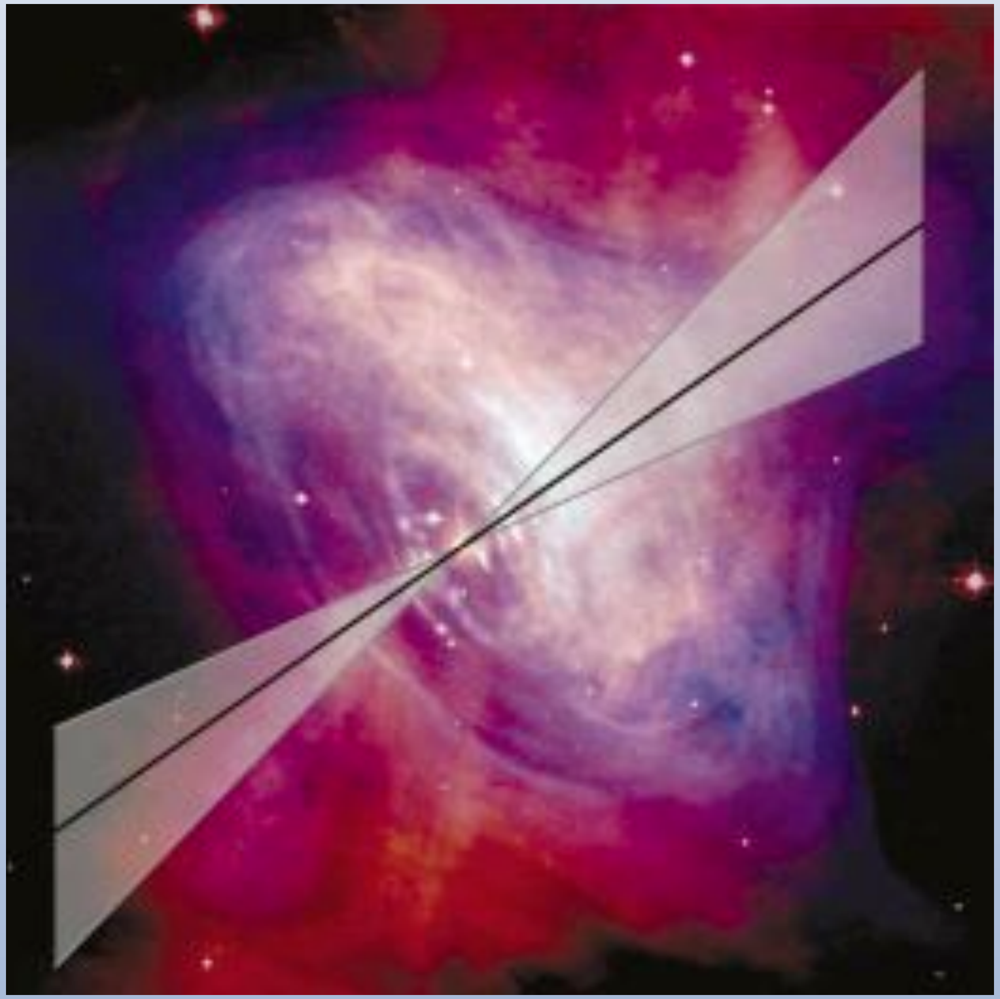
Odaka+10





Crab Pulsar & Nebula

- The Crab nebula is the most feasible target of the SGD polarimetry.
- Spin-phase resolved polarimetry will distinguish emissions from the nebula component and the pulsar component.

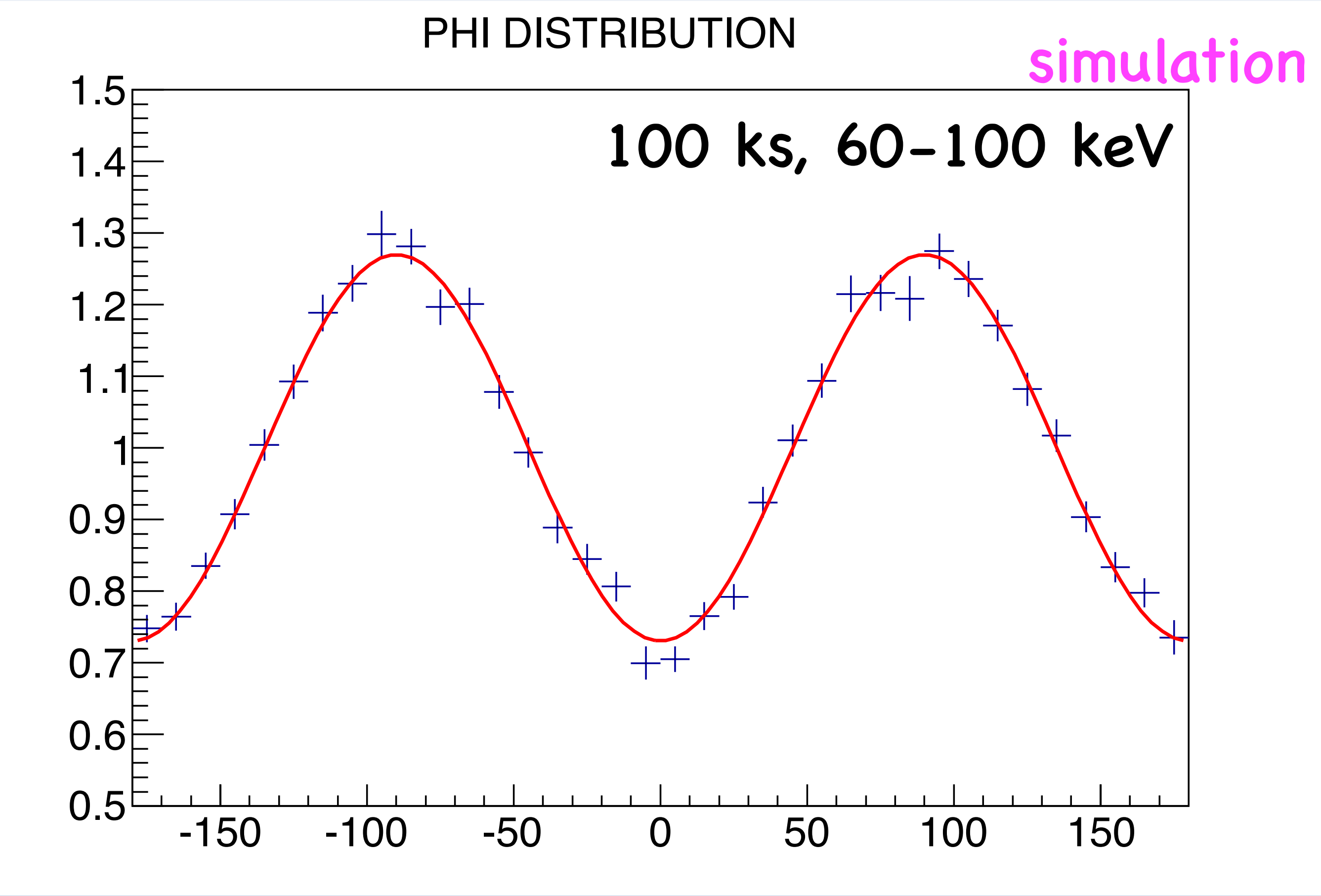


INTEGRAL reported linearly polarized emission aligned to the pulsar spin axis.

- 0.1-1 MeV
- Polarization angle = 123°±11°
- Polarization fraction = 46±10%

Dean+08

Crab Pulsar & Nebula



Assumption for simulation

Polarization fraction = 50%

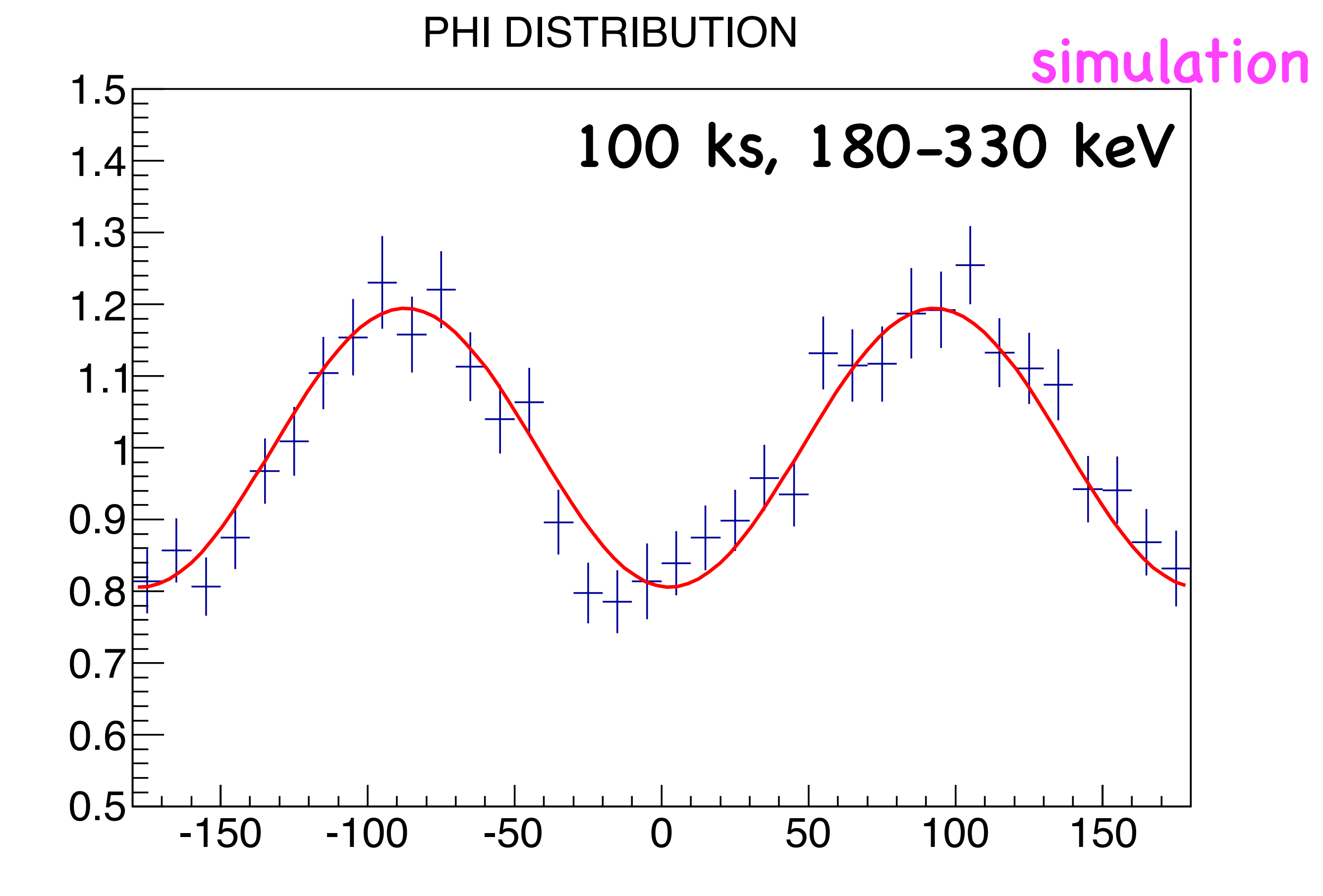
Polarization angle = 0°

Fit values of the simulation data

Polarization fraction = 48 ± 1% (stat.)

Polarization angle = 0.1° ± 0.5° (stat.)

Crab Pulsar & Nebula



Assumption for simulation

Polarization fraction = 50%

Polarization angle = 0°

Fit values of the simulation data

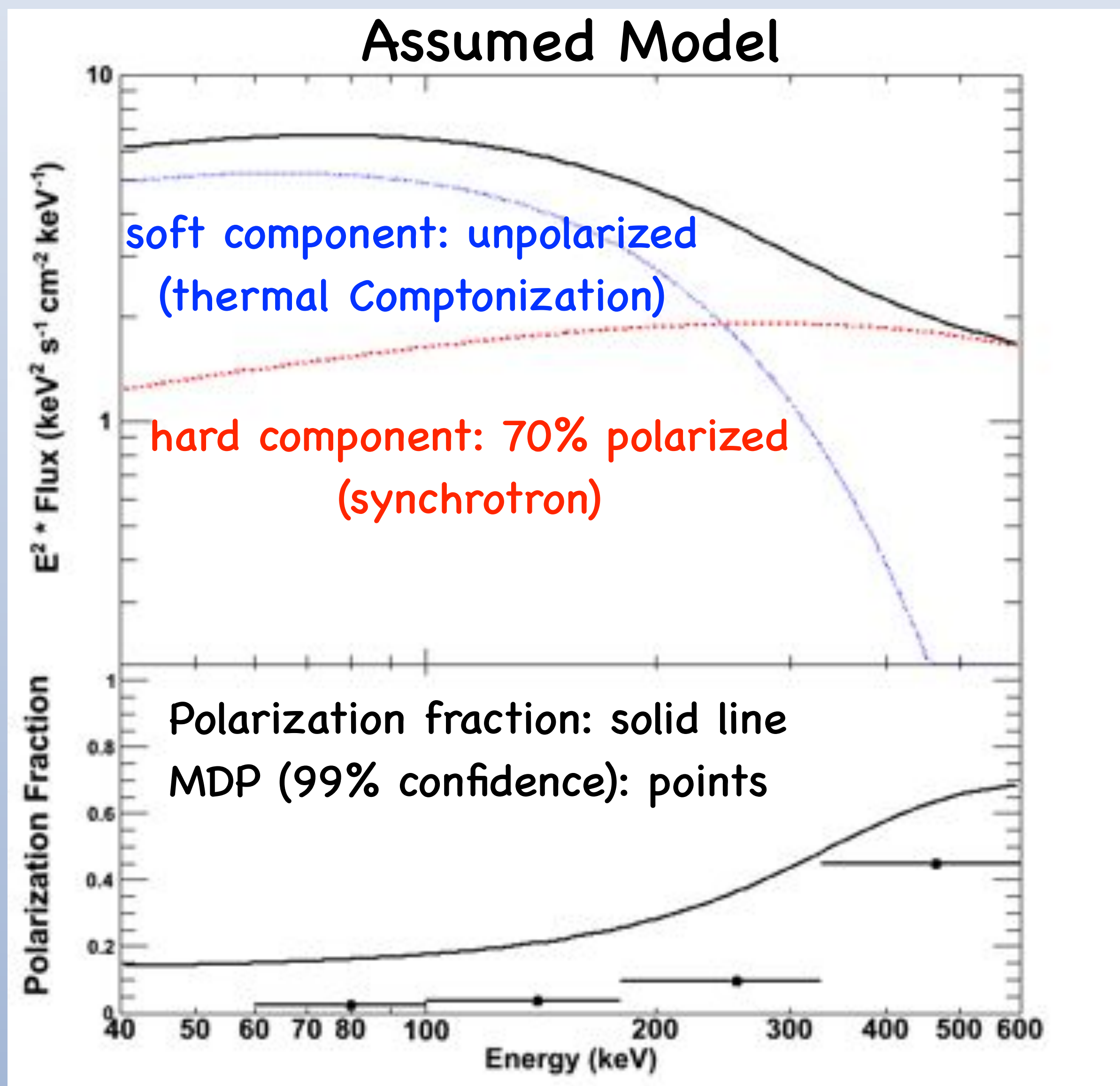
Polarization fraction = 48 ± 3% (stat.)

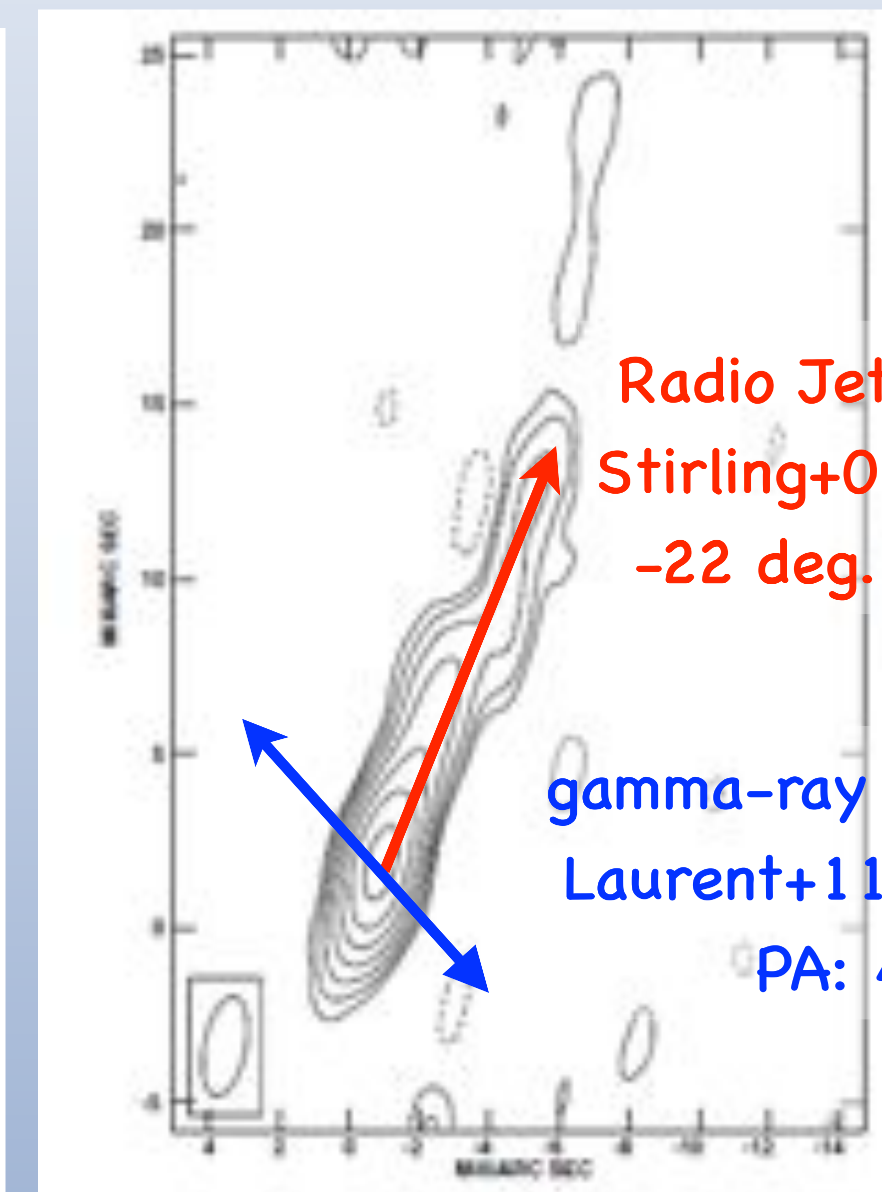
Polarization angle = 2.7° ± 1.6° (stat.)

The SGD will be able to measure polarization of Crab in an energy range between 50 keV and 500 keV with high precision!

Microquasar: Cygnus X-1

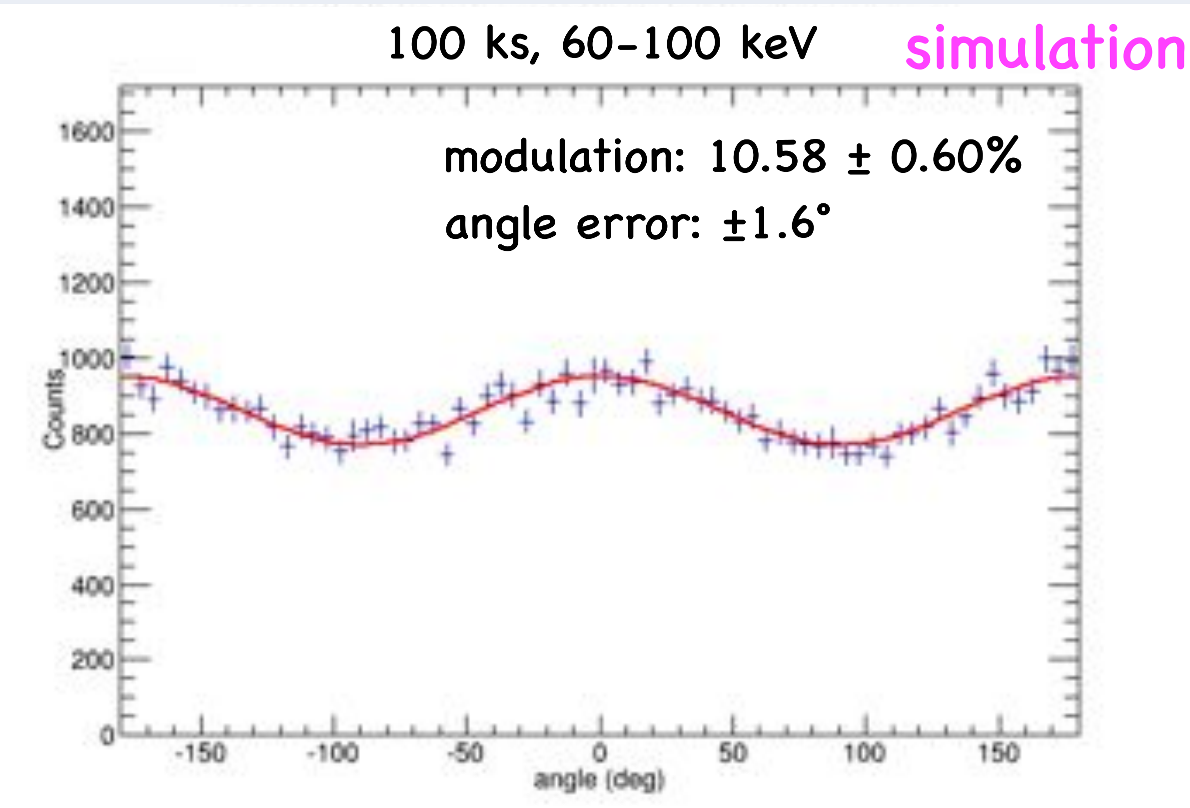
- The brightest galactic black hole with a radio jet.
- INTEGRAL reported polarization associated with nonthermal jet (?) emission.

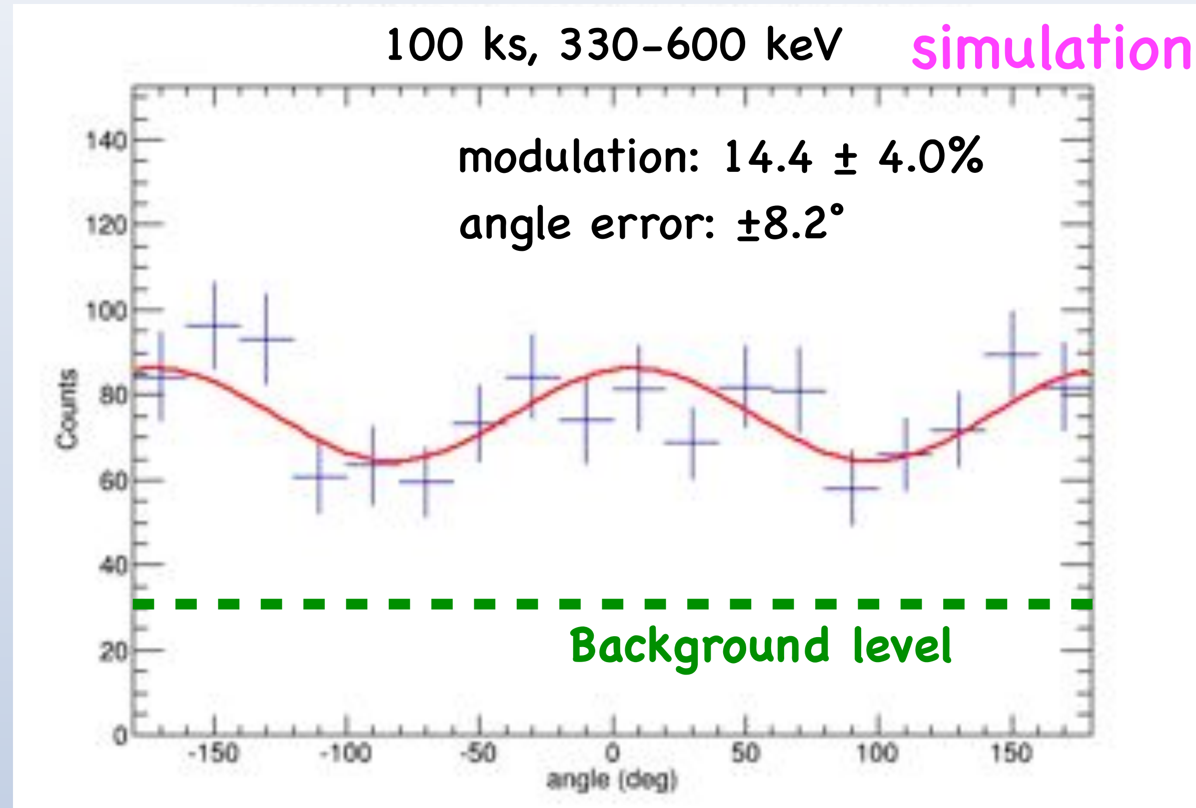




Microquasar: Cygnus X-1

Mizuno





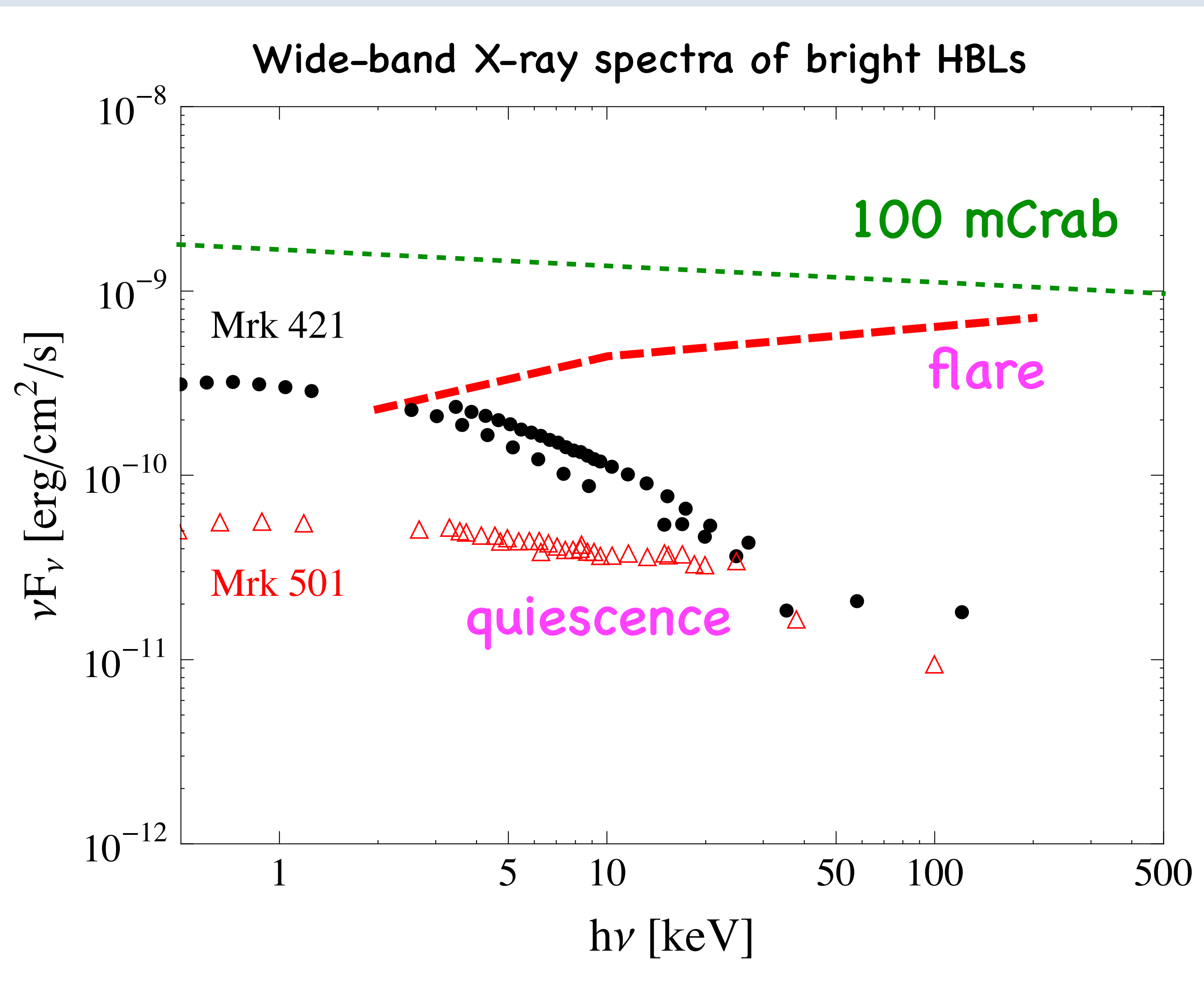
higher energies => to confirm the INTEGRAL results about the jet radiation

lower energies => precise measurement of coronal emission & disk reflection

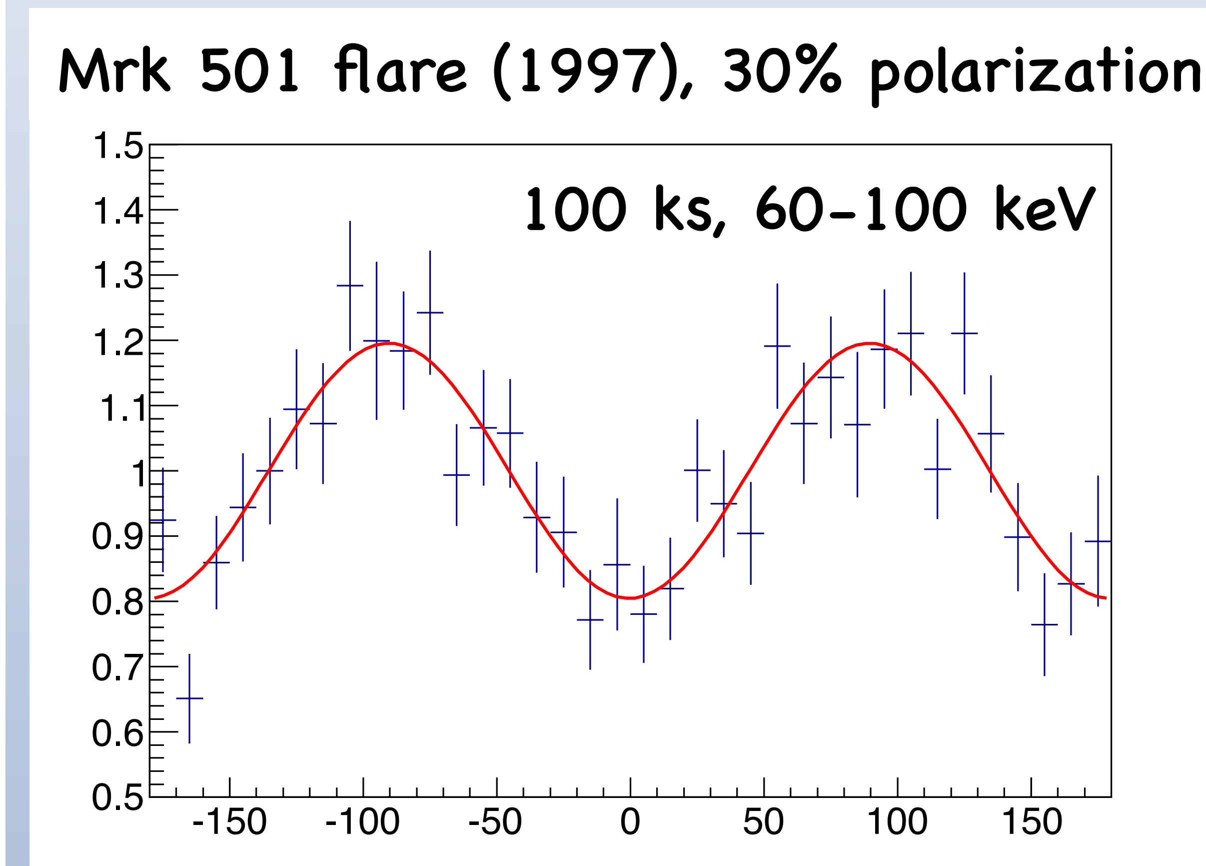
AGN gets: Blazars

Odaka & Stawarz

- Polarimetry of blazar flares will provide us with information on magnetic field uniformity, structure & variability of the jets.



simulation



Polarization fraction = 35.1 ± 3.7% (stat.)

Polarization angle = -0.4° ± 2.9° (stat.)

Astrophysical Modeling

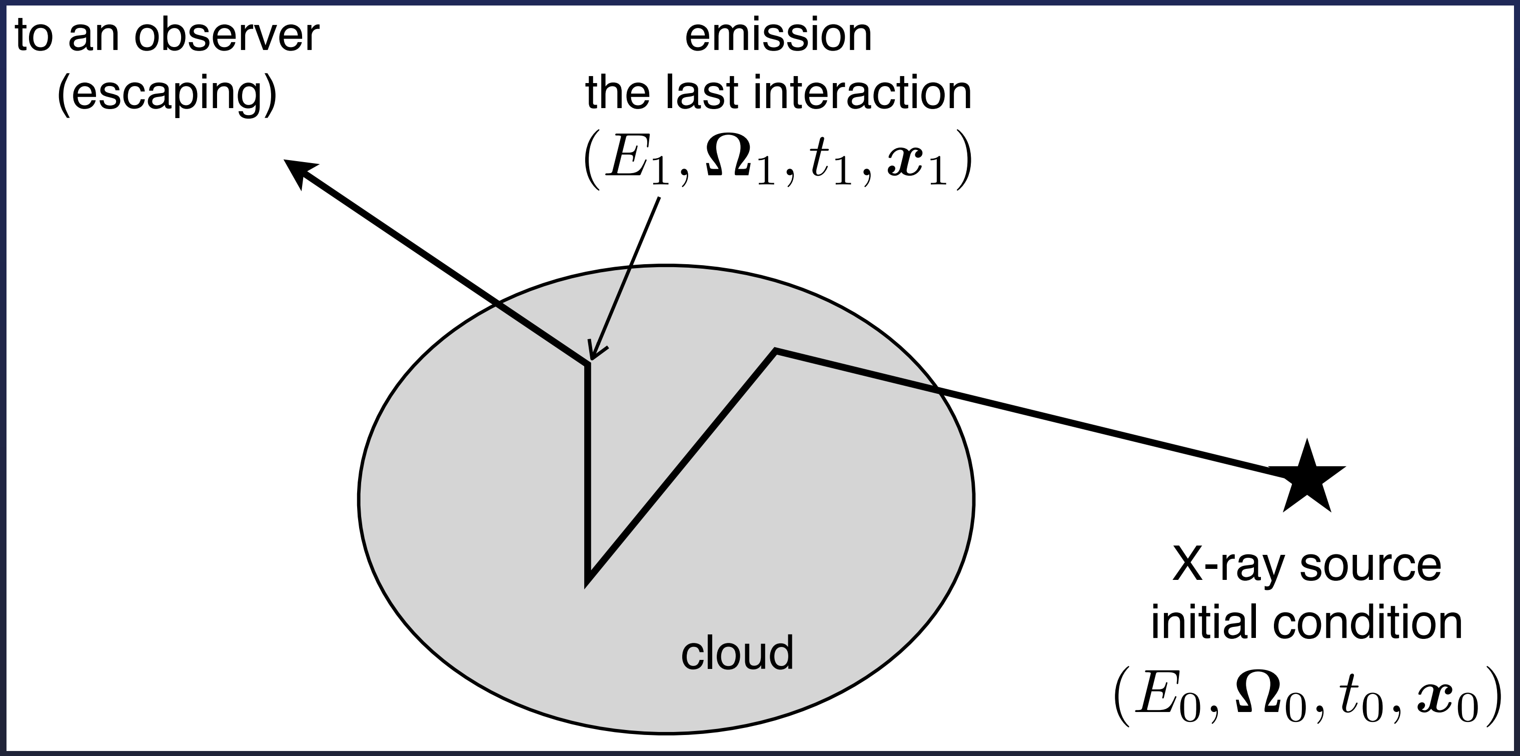
In addition to polarization measurements, astrophysical modeling of X-ray polarization is also difficult. It is necessary to calculate polarized radiation accurately.

Synchrotron radiation is relatively straightforward if the electron energy and magnetic field distributions are determined. (but this is not easy…)

Scattering (or reflection) is very complicated since the emission is a result of multiple scatterings in complicated geometry. →Monte Carlo approach

Monte Carlo Simulation

The simulation tracks photons by calculating their propagation and interactions based on Monte Carlo method.



Process of one event

1) generate a photon, record initial conditions
2) calculate the next interaction point
3) invoke the interaction, reprocess photons
4) repeat 2-3
5) record the last interaction information if a photon escapes from the system.

A MC simulation generates a list of events which have information on a response of the system to the photon irradiation.

The MONACO Framework

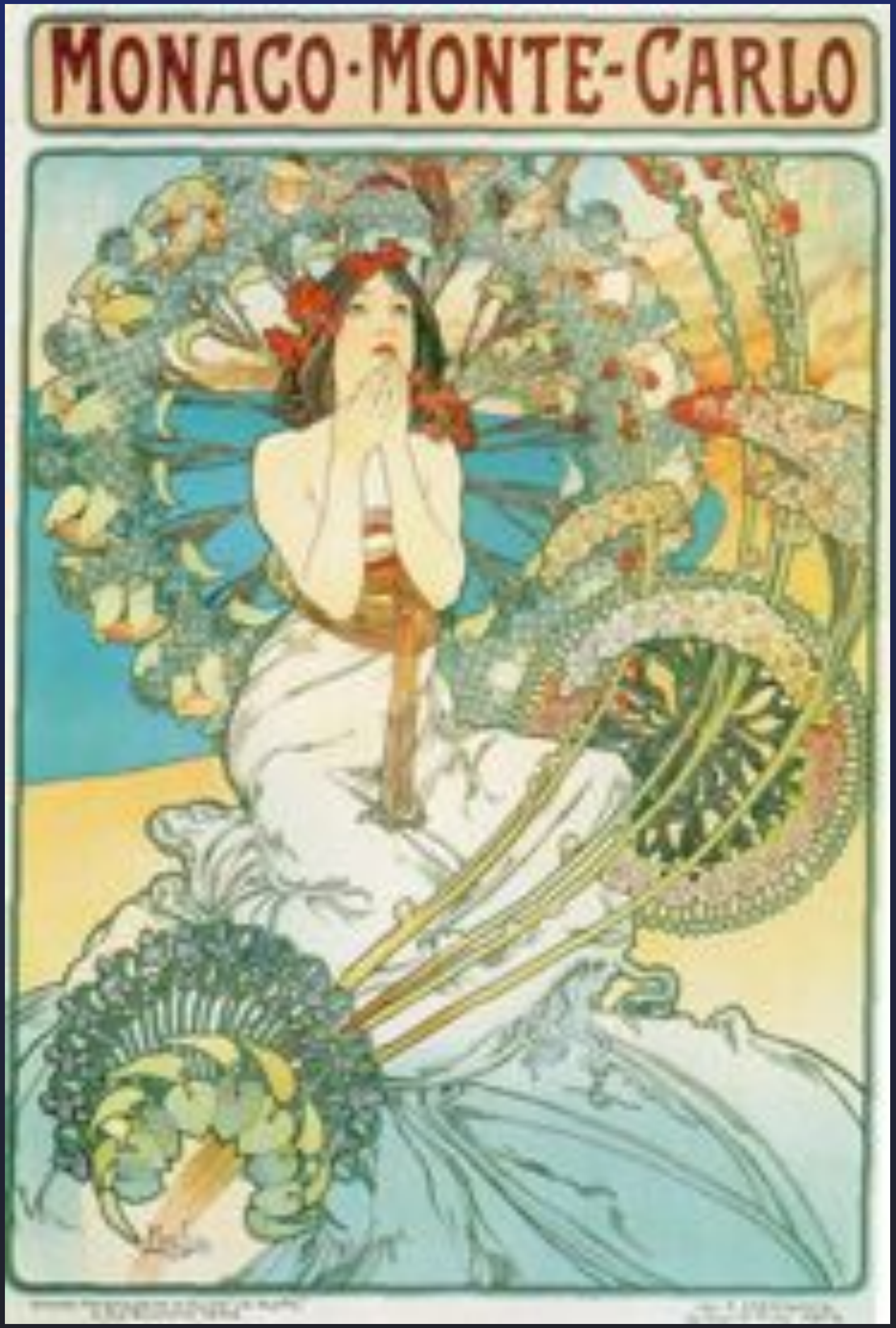
We have developed a new multi-purpose calculation framework of X-ray radiation based on Monte Carlo Simulations for observational study.

Odaka et al. 2011

MONACO:

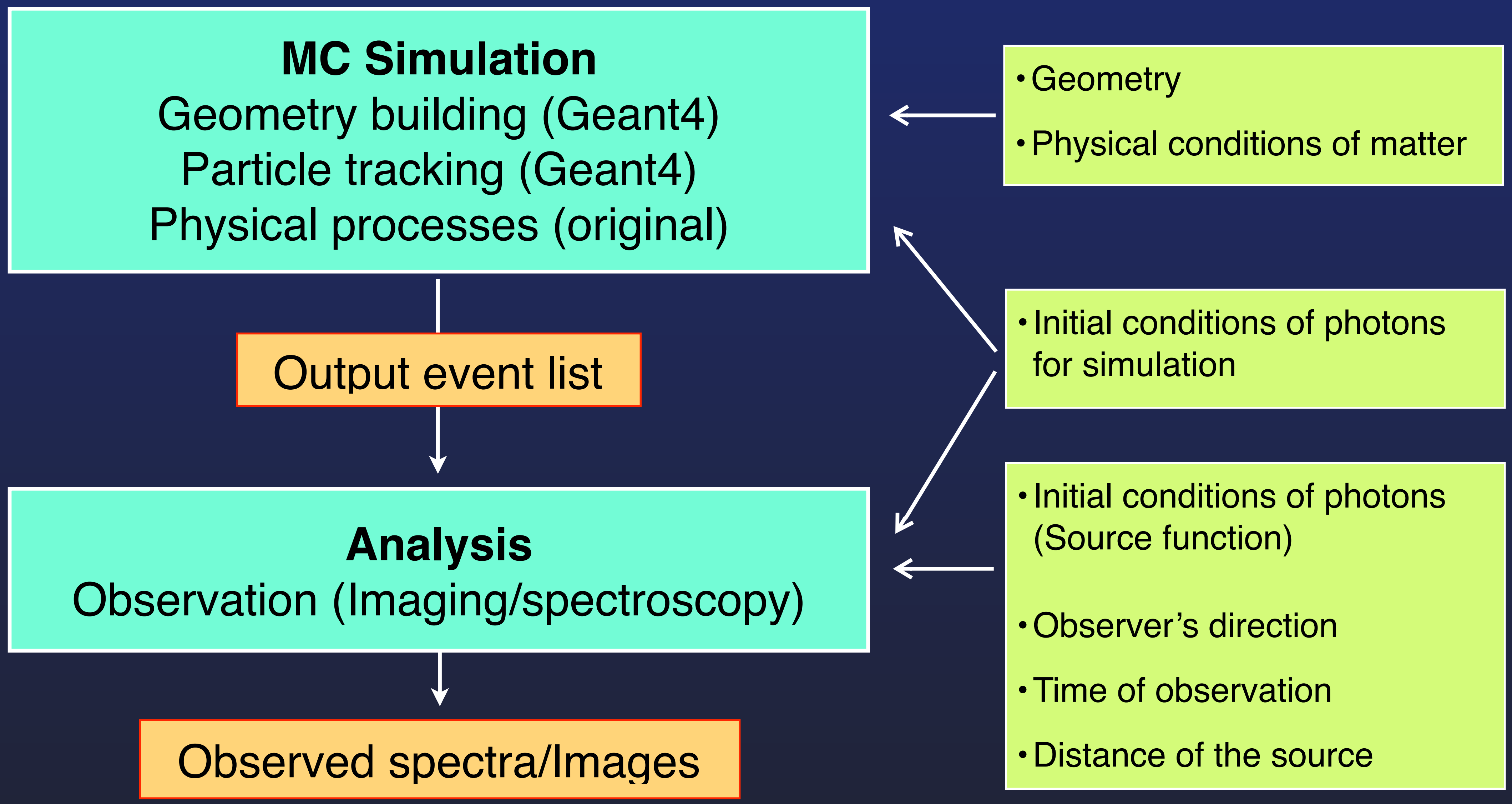
Monte Carlo simulation for

Astrophysics and **Co**smology



Alphonse Mucha (1897)

The MONACO Framework



- Building geometry and tracking particles: Geant4 toolkit library
  ←Sophisticated treatment of complicated geometry (e.g. radiation detector simulation)
- Physical processes: original implementation.
  ←Existing codes have been inadequate to treat binding effects of atoms and gas motion (Doppler effect of thermal/bulk/micro-turbulent motions).
  We also extend the Geant4 geometry builder for astrophysical objects.

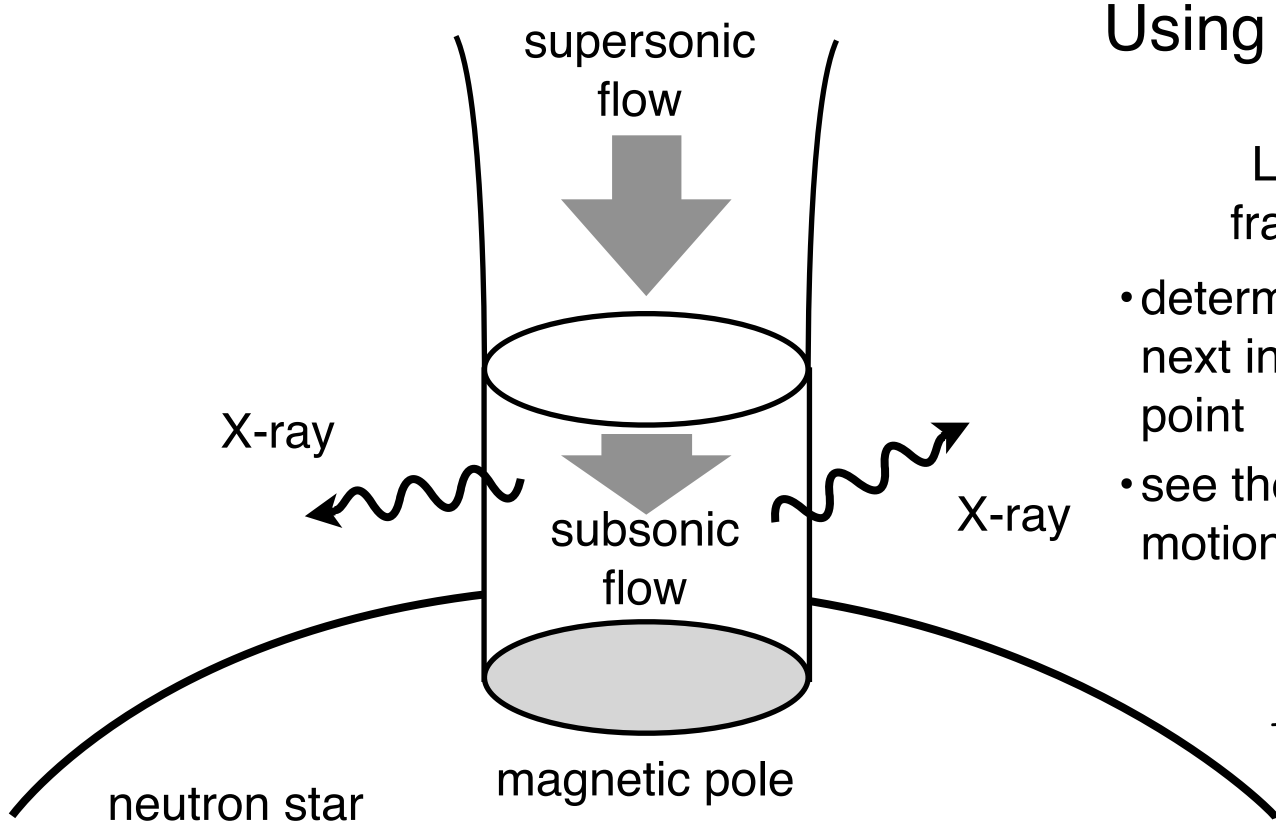
Physical Processes

MONACO has extensible structure. You can add new physical processes. We have implemented:

State of matter	Processes	Applications
Hot plasma	(Inverse) Compton scattering	Accretion flows Hot coronae around compact objects
Photoionized plasma	Photoionization Photoexciation	Stellar winds in X-ray binaries AGN outflows
Neutral matter	Photoabsorption Scattering by bound electrons	X-ray reflection nebulae (molecular clouds) AGN tori

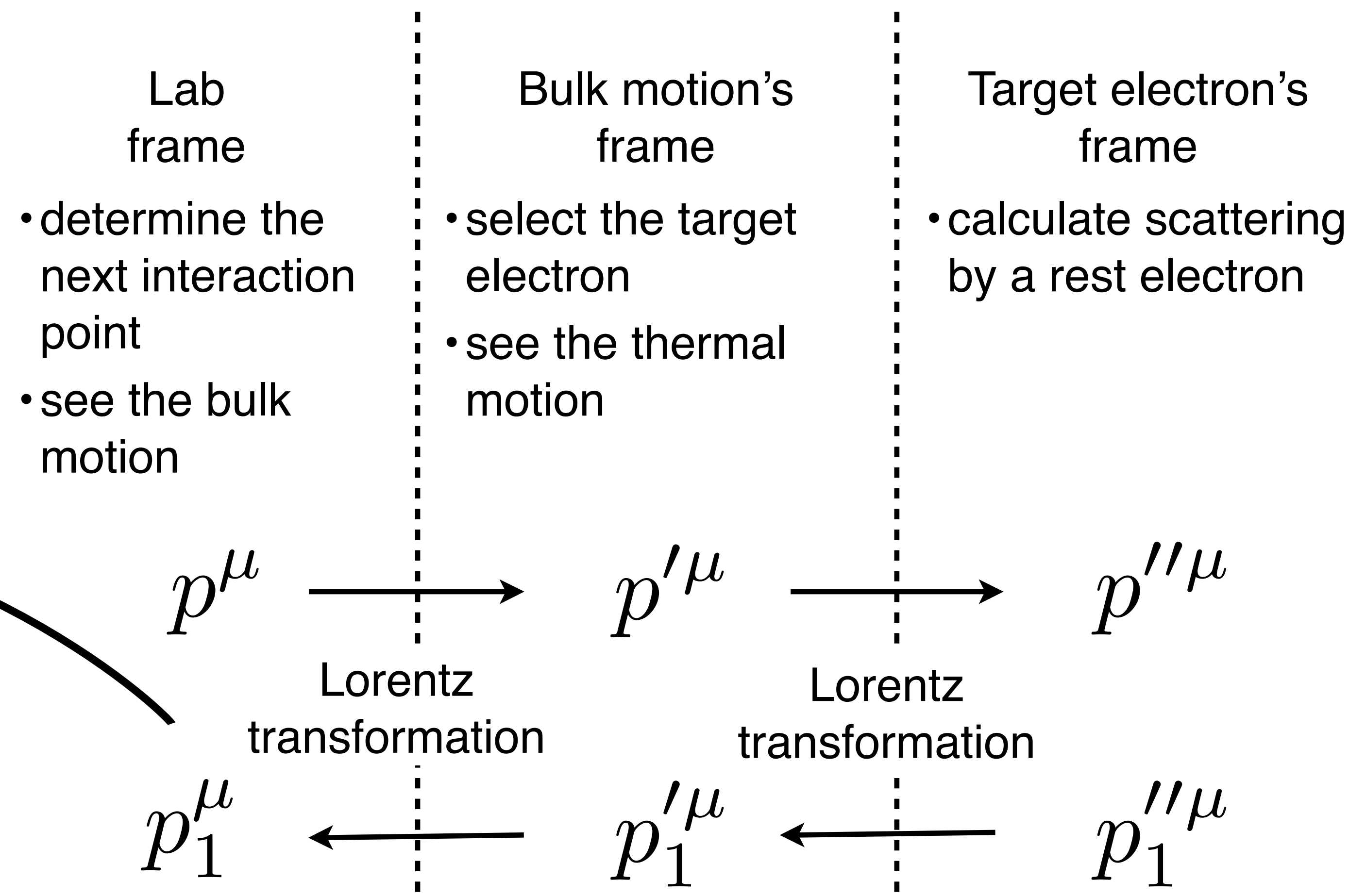
Comptonization in Accretion Flow

Optically thick	Analytical/numerical methods are effective.
Not optically thick Complicated geometry High energy band	The process is essentially discrete. →Monte Carlo approach is suitable.



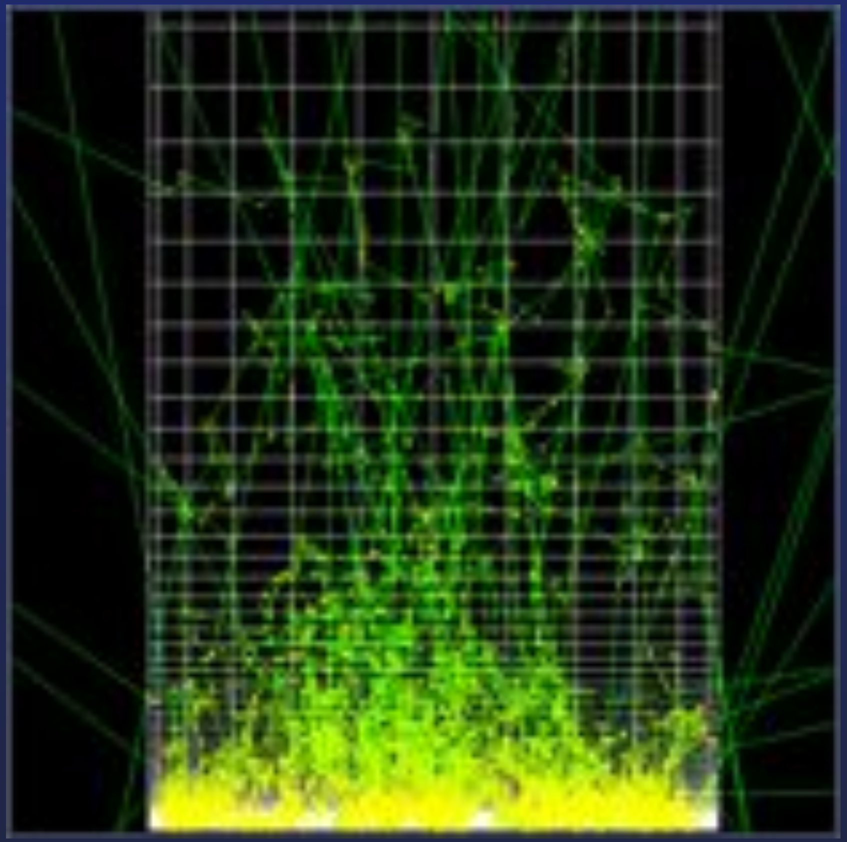
Thermal & bulk Comptonization
Becker & Wolff (2007)

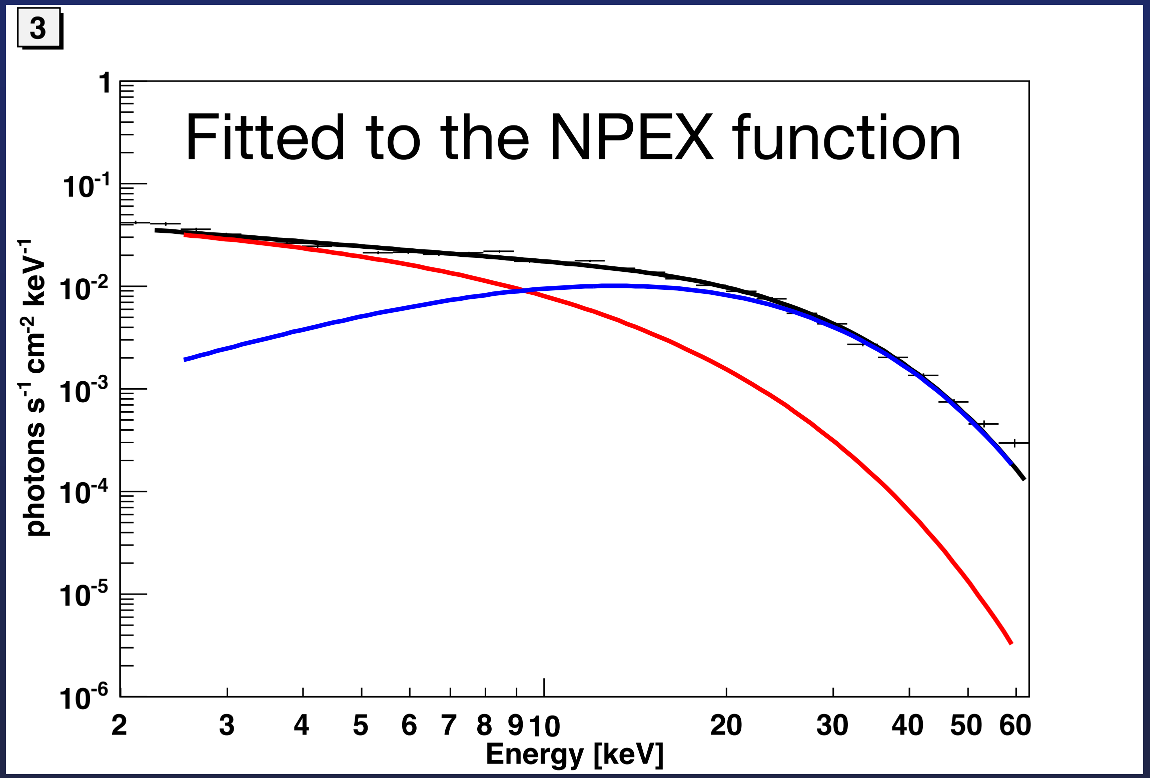
Using Lorentz transformation (Odaka et al. 2014)



Magnetic field effects can be included.

Comptonization in Accretion Flow





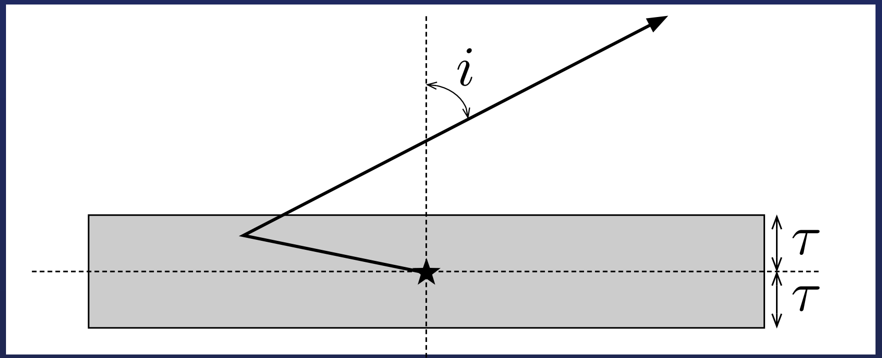
Odaka et al. 2014

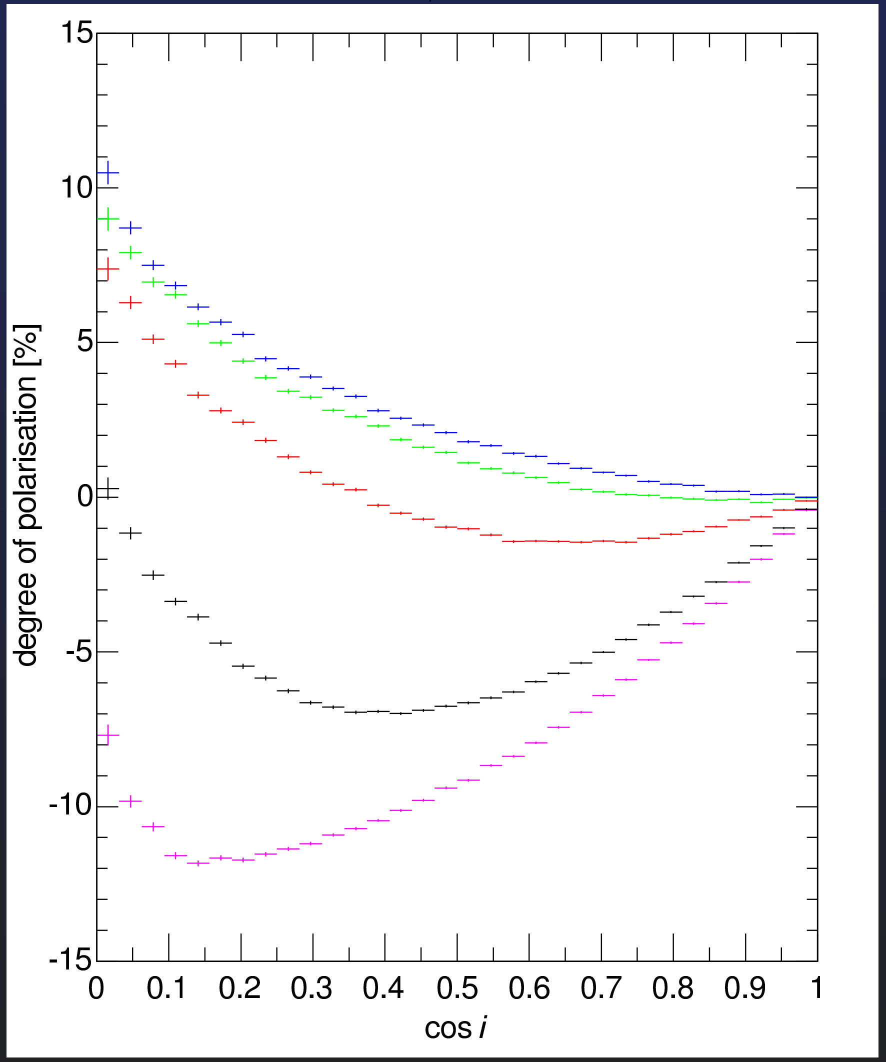
- ✓ Assuming Vela X-1's column
- ✓ Temperature: 6 keV
- ✓ Seed photons: thermal bremsstrahlung
- ✓ Column radius: 200 m
- ✓ Magnetic field effect included approximately
- ✓ Successfully generated a power law with a quasi-exponential cutoff.

Polarization by Comptonization

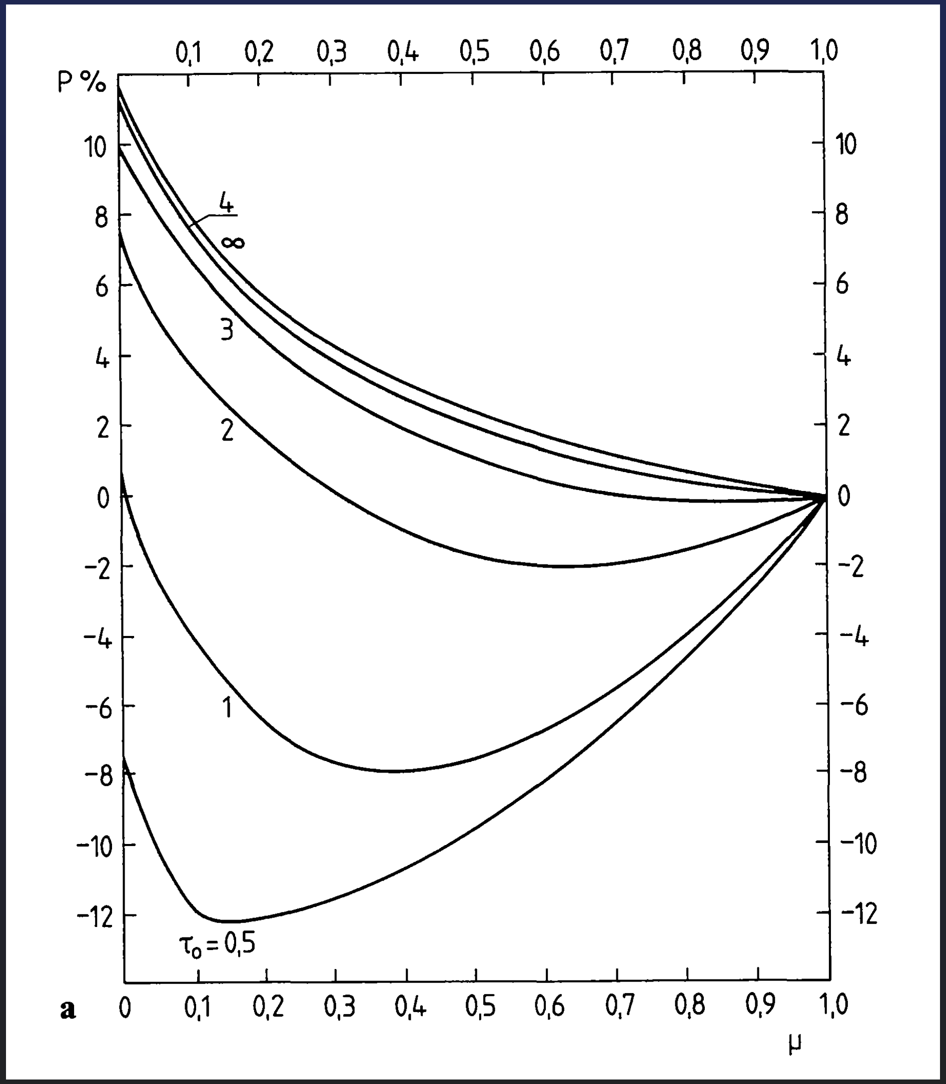
We use the same framework for a plane-parallel slab geometry.

Odaka, Done et al. in preparation



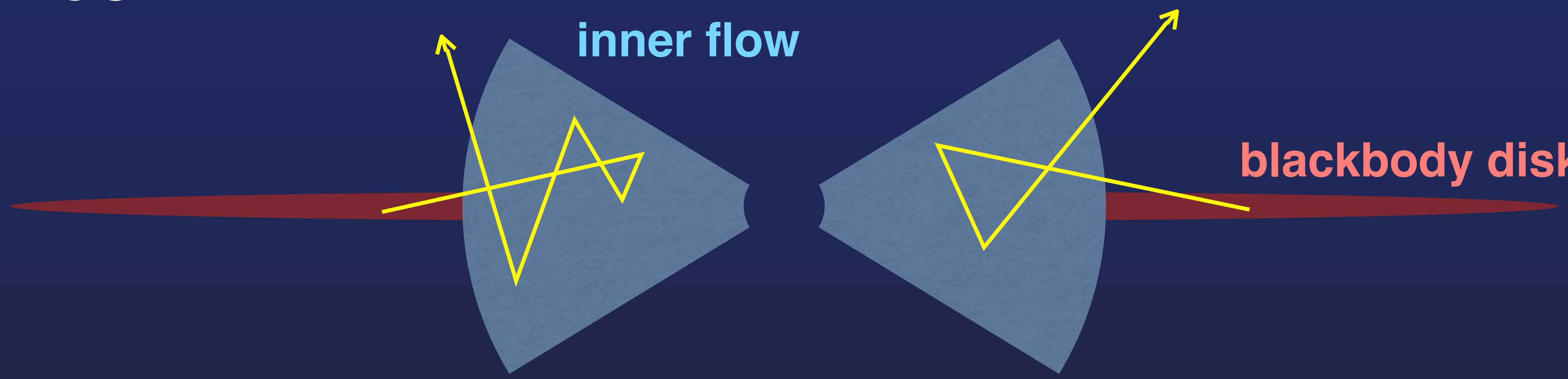


Sunyaev & Titarchuk (1985)

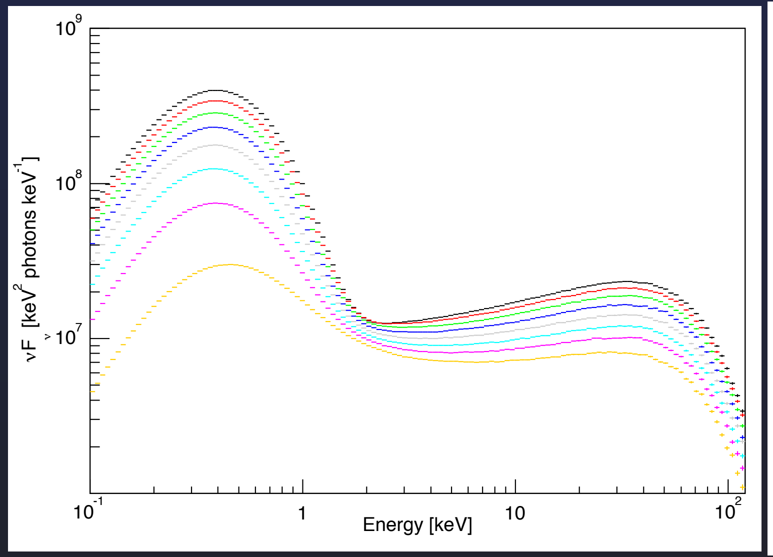


Accretion Flow into Black Holes

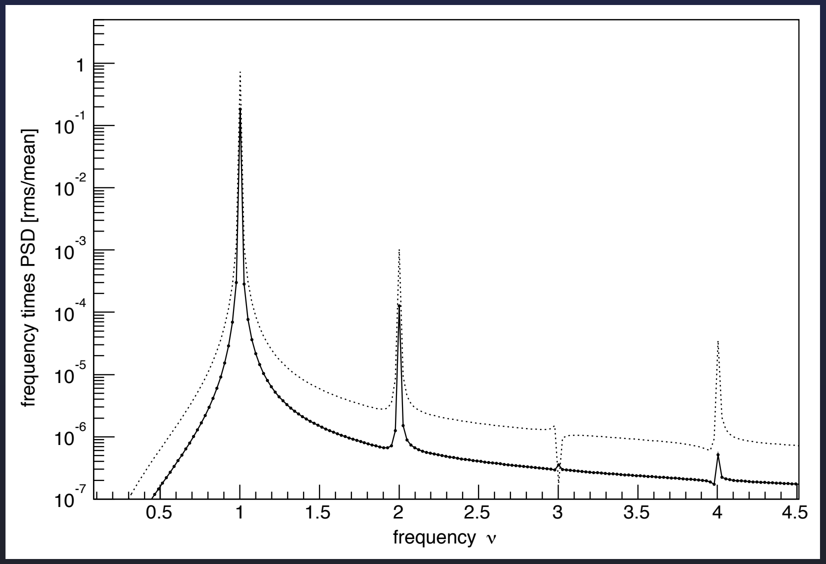
We build a truncated disk + a geometrically thick inner flow model with MONACO.



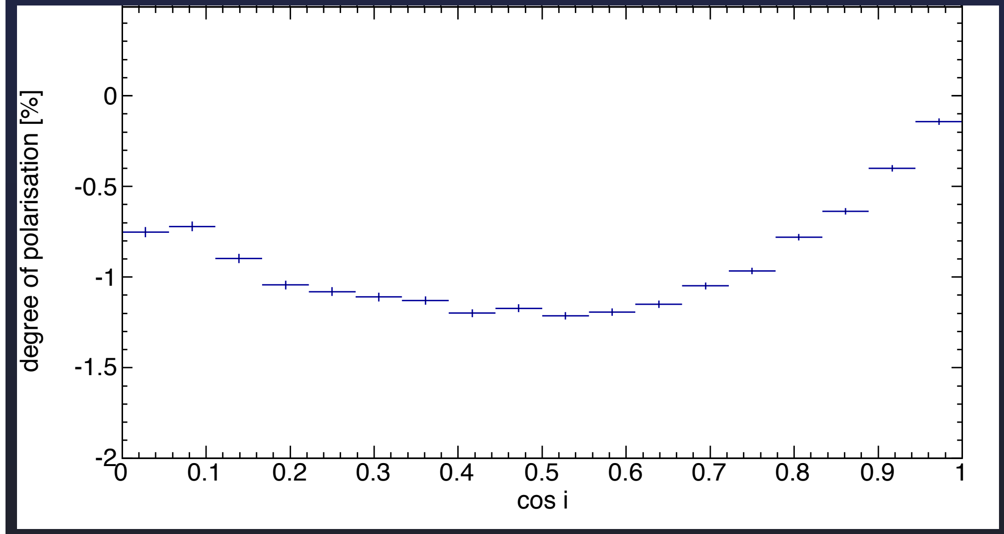
spectra



QPO (timing)



polarization



Odaka, Done et al. in preparation

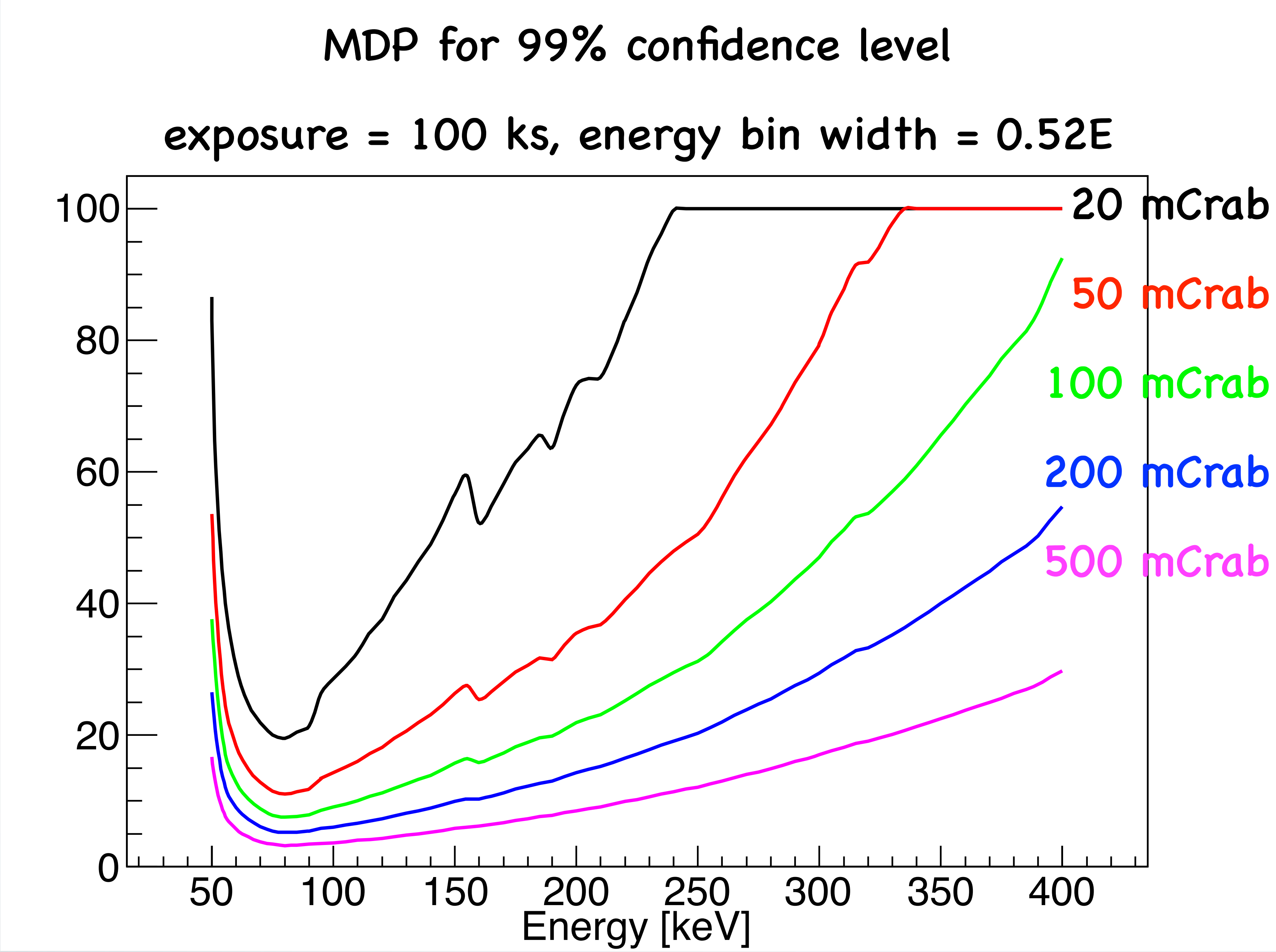
Summary

- The SGD onboard ASTRO-H (launch in 2015) is a high-precision Compton spectro-polarimeter with a low background level.
  - 1 Crab sources: up to 600 keV
    Crab, Cyg X-1
  - 100 mCrab sources: 60-180 keV
    GRS 1915+105, Cyg X-3, Mrk 421, Mrk 501, Cen A, etc.
- Statistics (a long observation) is important, and systematic errors should be controlled.
- MONACO provides us with an accurate way to calculate reprocessed X-rays (scattering/reflection), which can be polarized, in a complicated geometry.

Polarization Sensitivity

- Minimum detectable polarization (MDP) is a useful figure of merit.

NOTE: systematic errors due to non x-ray background are not considered here.



<u>Crab spectrum</u>

$N(E) = 11.6\ (E/1\mathrm{keV})^{-2.1}$

$[\mathrm{ph\ cm^{-2}\ s^{-1}\ keV^{-1}}]$

flux: 1.6×10^{-8} erg $\mathrm{cm^{-1}\ s^{-1}}$

(in 15-50 keV)