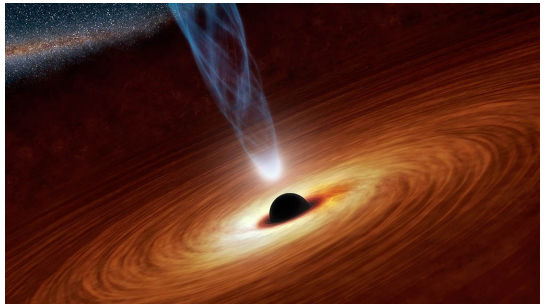
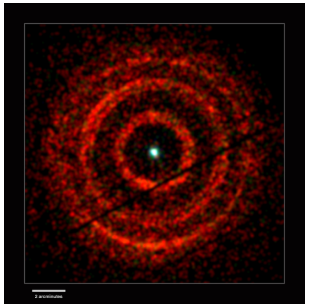
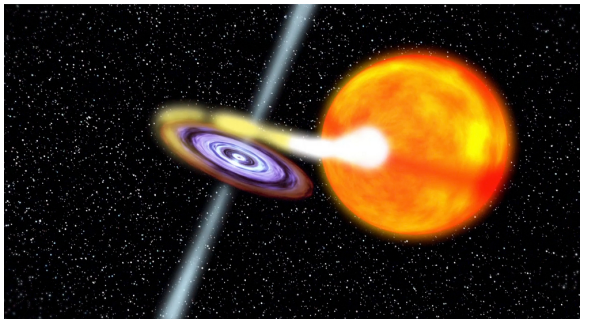




# *High-Energy Polarization Measurements:*

## *Past, Present, and Prospects for the Future*

John Tomsick

Space Sciences Laboratory/UC Berkeley

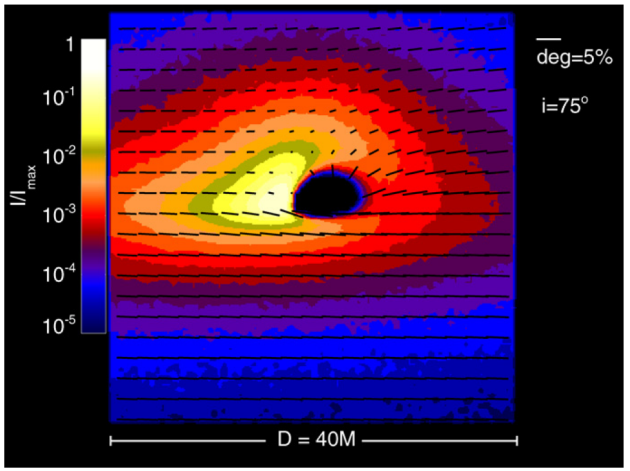
September 2018

# *Outline*

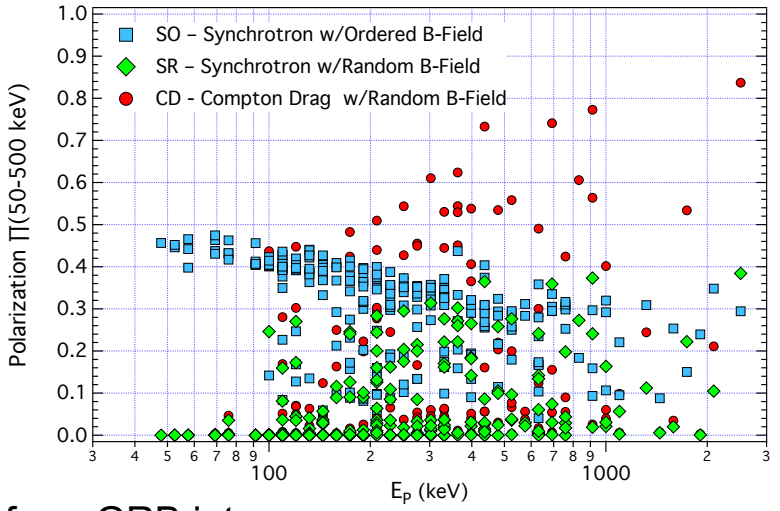
- Why measure polarization?
- >100 keV with the Compton technique
  - INTEGRAL (current satellite mission)
  - COSI (instrument flying as a balloon payload)
- ~20-200 keV
  - Polarized Gamma-ray Observer (PoGO+)
- <10 keV
  - OSO-8, SXRP
  - Imaging X-ray Polarimetry Explorer (IXPE)

# *Why measure polarization?*

- Constraining…
  - Emission mechanisms
  - Black hole spin
  - Phenomena in strong neutron star B fields
  - Jets from accreting compact objects
  - Gamma-ray bursts
  - Supernova remnants
  - And more…
- New discovery opportunities



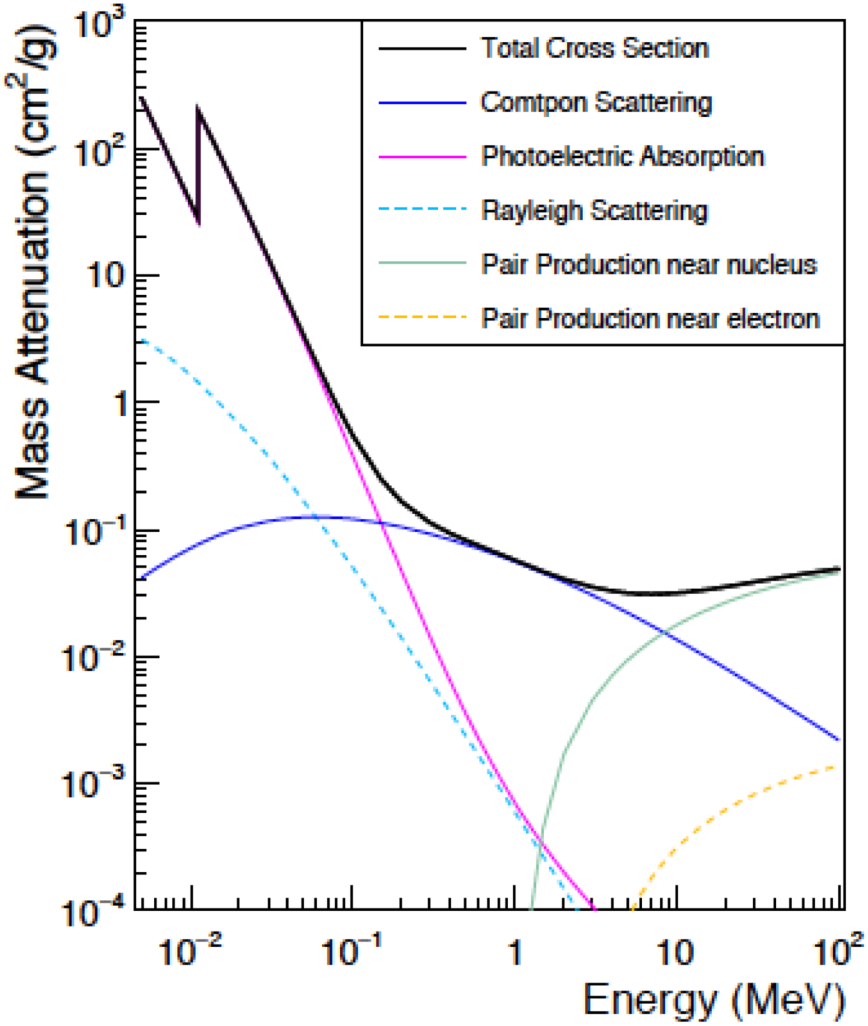

X-rays: Measuring BH spin (Schnittman & Krolik 2009)




Emission from GRB jets (Toma+09; McConnell+17)

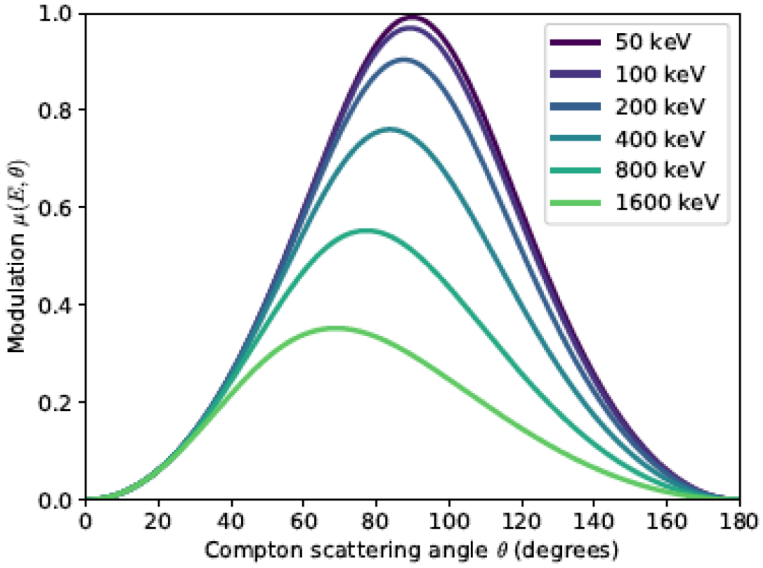
# *Photon interactions in detector materials*

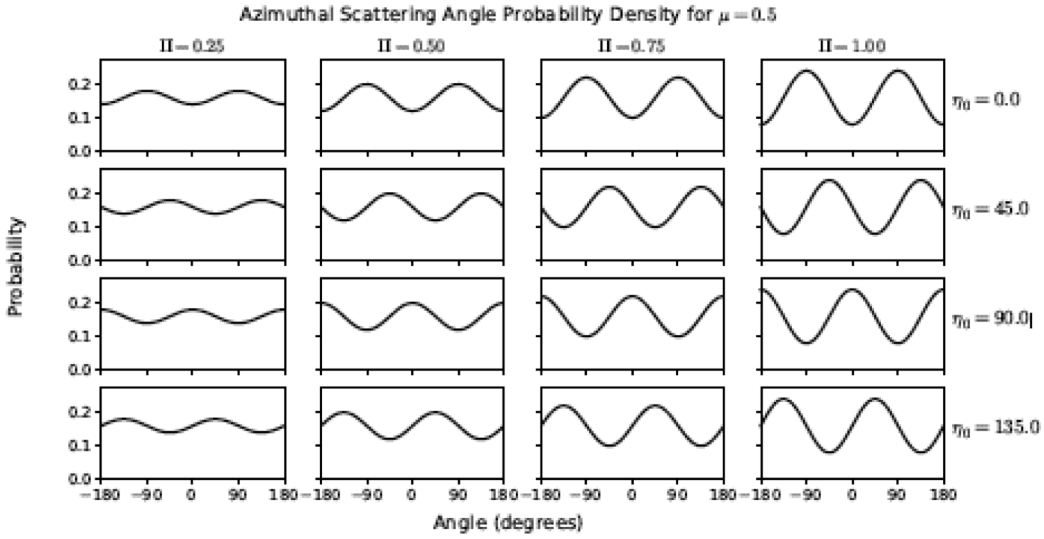
- Primary interactions are:
  - Photoelectric absorption
  - Compton scattering
  - Pair production
- Compton scattering is most likely in the 200 keV to several MeV range




Cross-sections for germanium

# *Compton technique*



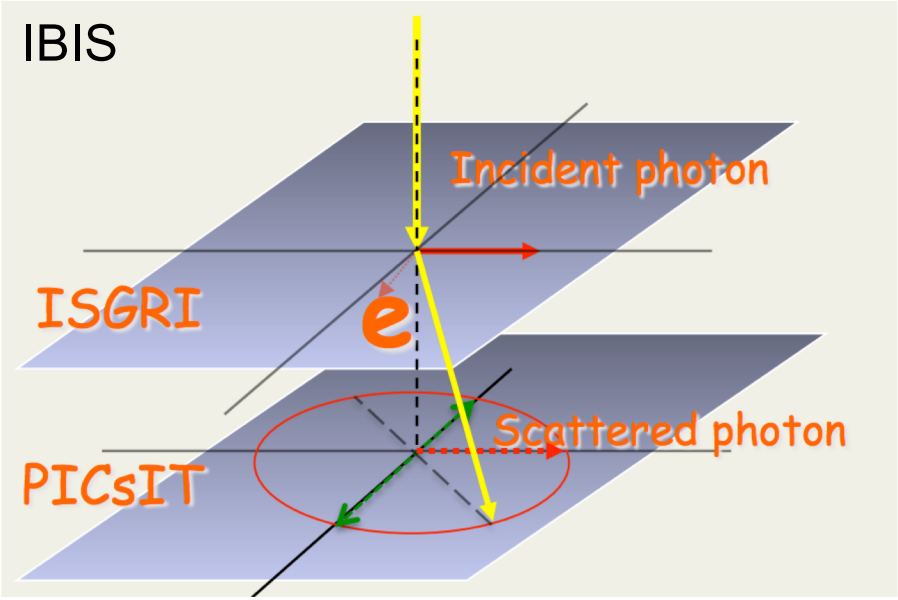




- Polarized sources give the strongest modulation for energies below 400 keV and scattering angles of 90 degrees

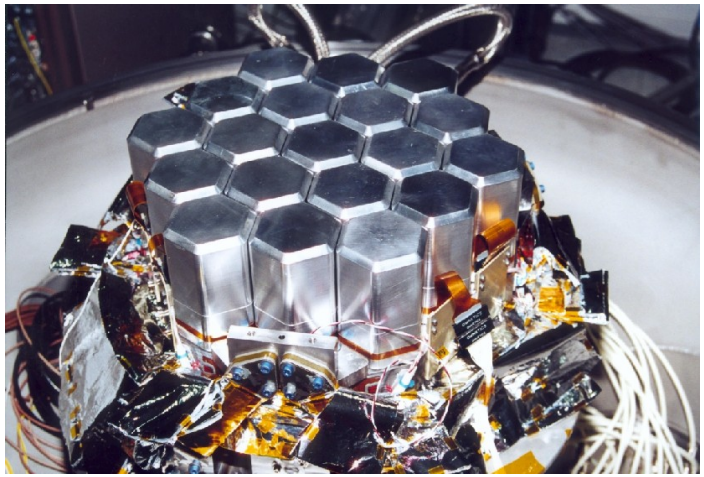
# *INTEGRAL*

- Launched in 2002
- Two instruments with Compton polarization capabilities
  - IBIS
  - SPI

IBIS

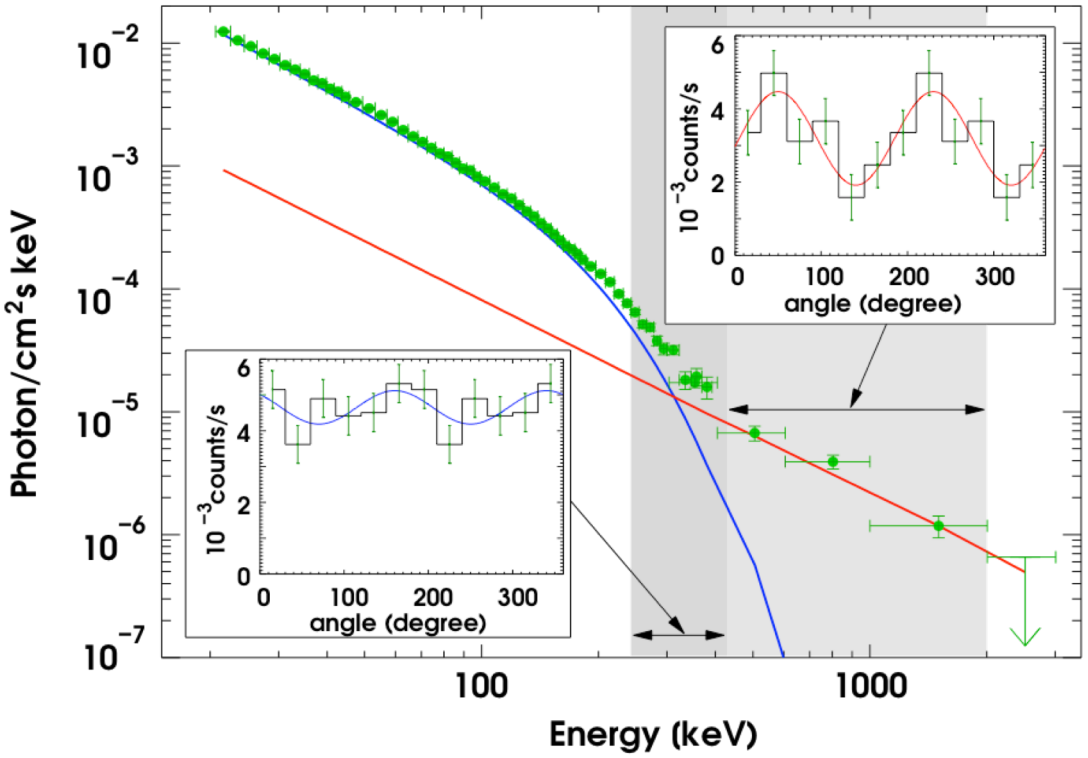



SPI

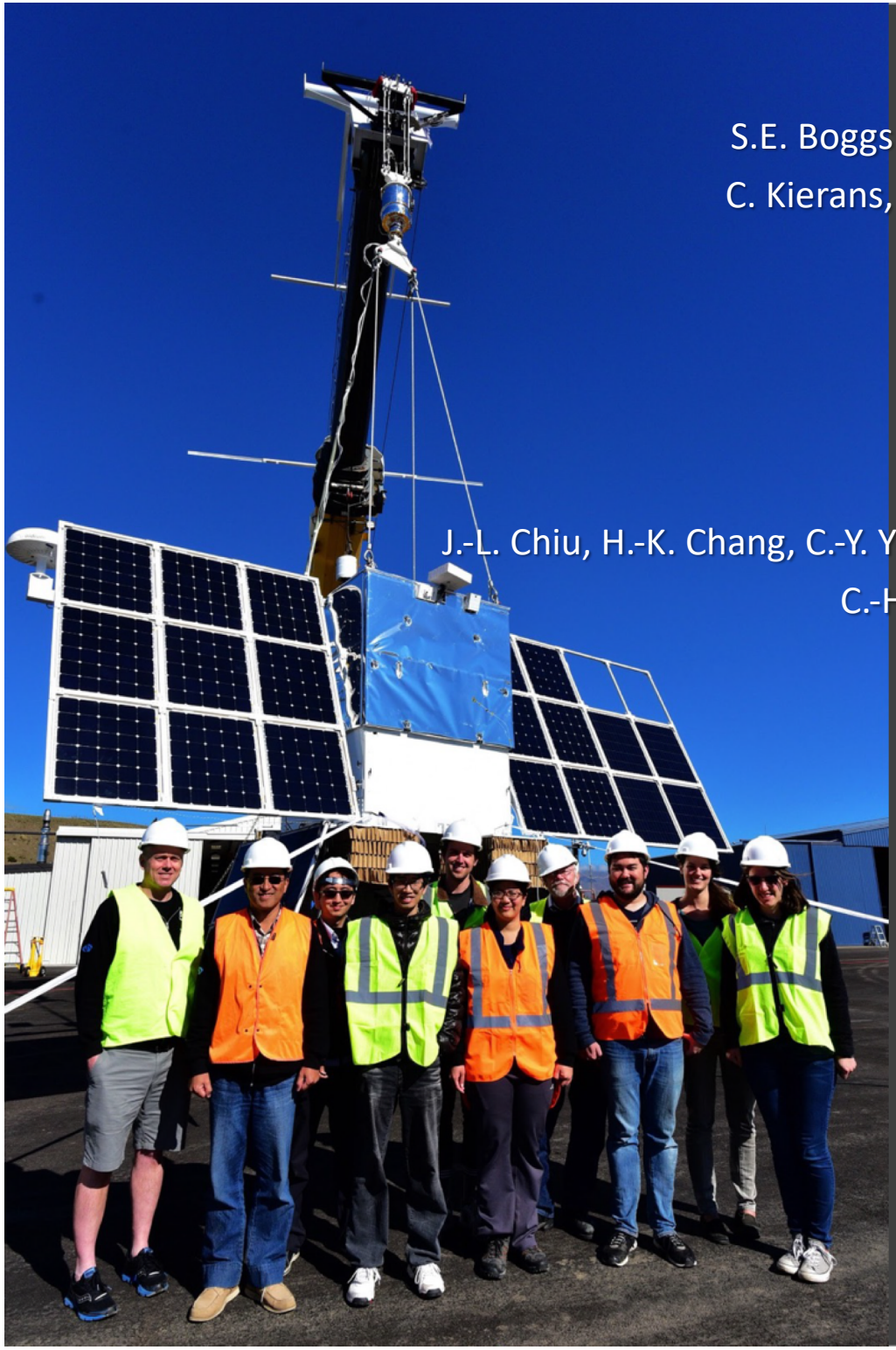


# *Hard X-ray/soft gamma-ray polarization measurements for spectral decomposition*

- Polarization measurements by *INTEGRAL*
  - IBIS (Laurent et al. 2011)
    - <20% (0.25-0.4 MeV)
    - 67±30% (0.4-2 MeV)
  - SPI (Jourdain et al. 2012)
    - <20% (0.13-0.23 MeV)
    - >75% (0.37-0.85 MeV)
- 2 spectral components
  - Unpolarized component due to Comptonization by hot thermal electrons
  - Polarized non-thermal component, possibly from the jet




Cyg X-1 spectrum and modulation curves (from ESA press release)



# The COSI/COSI-X Collaboration:


S.E. Boggs (PI), A. Lowell, J. Roberts *(UCSD and UC Berkeley/SSL)*

C. Kierans, C. Sleator, J.A. Tomsick, A. Zoglauer *(UC Berkeley/SSL)*

C. Tindall, M. Amman *(LBNL)*

*T. Brandt , A. Smale (GSFC)*

P. Jean, P. von Ballmoos *(IRAP, France)*

*E. Wulf, E. Grove, B. Phlips (NRL)*

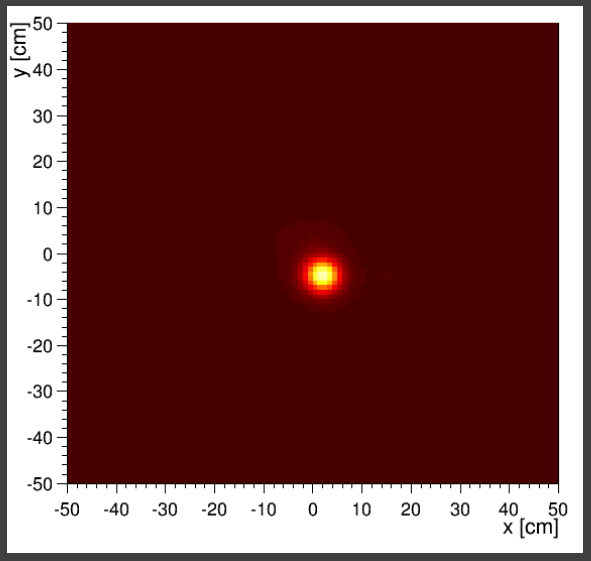
*Dieter Hartmann (Clemson University)*

J.-L. Chiu, H.-K. Chang, C.-Y. Yang, C.-H. Tseng, C.-Y. Chu, Y.-C. Chang *(NTHU, Taiwan)*

C.-H. Lin (AS, Taiwan), Y.-H. Chang , Y. Chou *(NCU, Taiwan)*



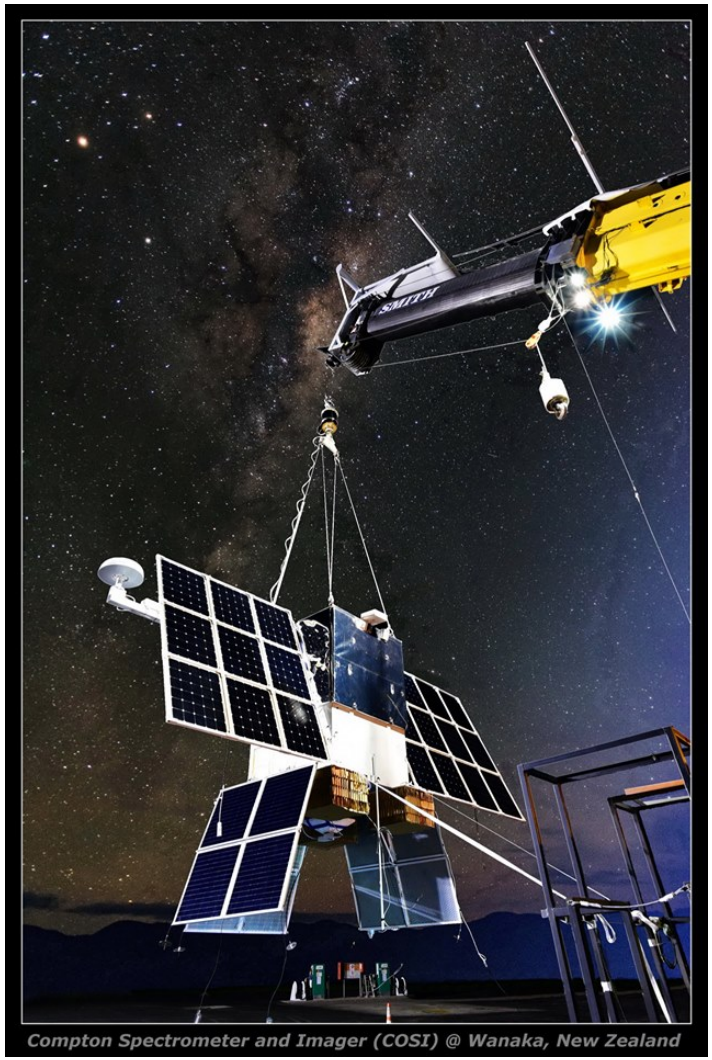
*COSI US is supported through grants by NASA*


Calibration image of a 662 keV $^{137}$Cs source ~56 cm above the instrument.

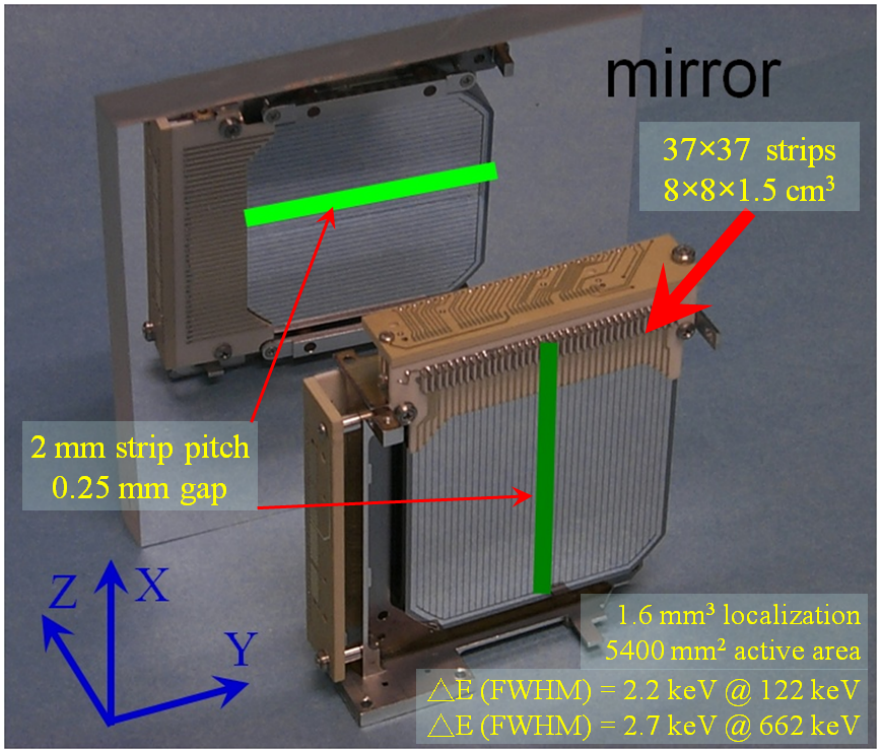
# *COSI*

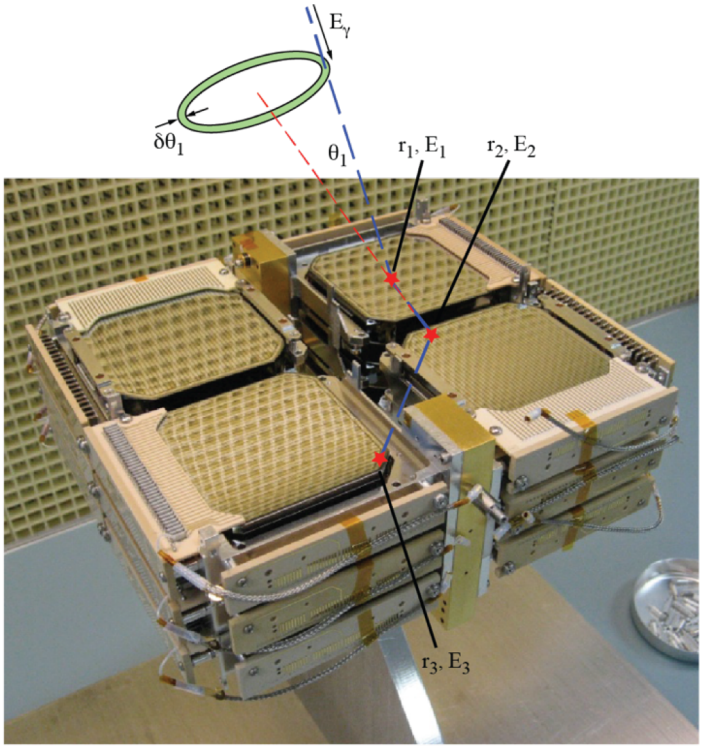
- Wide field of view (25% of the sky at one time)
- 0.2-5 MeV
- Science goals:
  - Positrons (511 keV annihilation line)
  - Nucleosynthesis
  - Polarization
  - Multi-messenger (GRBs)
- 46 day balloon flight from New Zealand in 2016



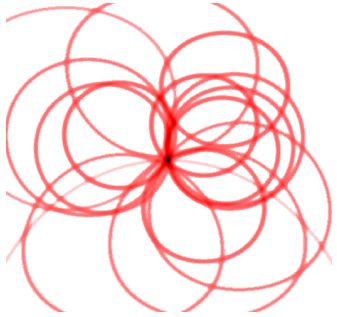
Compton Spectrometer and Imager (COSI) @ Wanaka, New Zealand

# COSI instrument



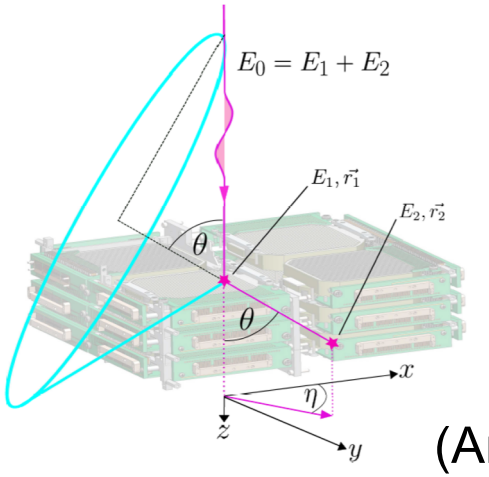




- Germanium strip detectors with 3D positioning
- 2x2x3 detector configuration
- Compact Compton telescope

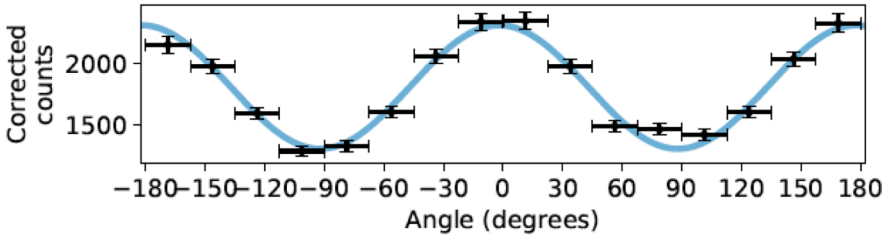


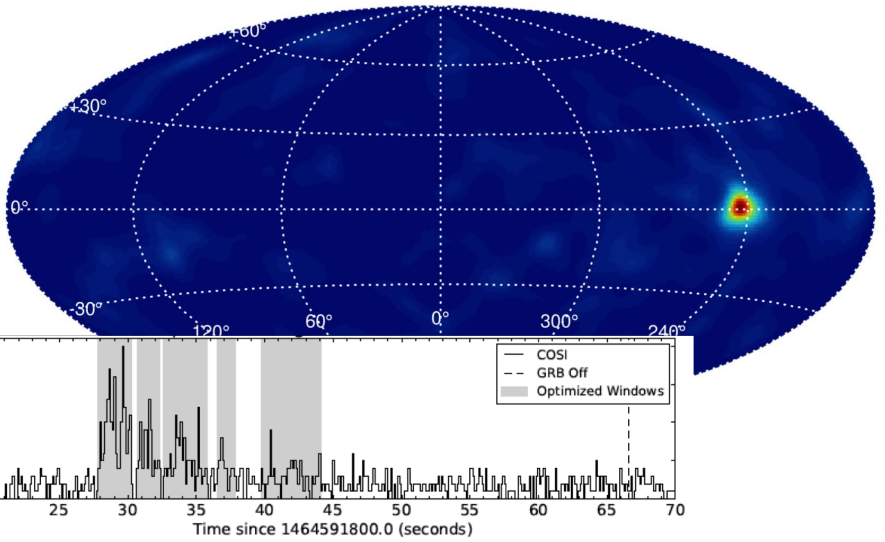
"Event circles" from a point source of gamma-rays

# COSI polarization capabilities and GRB result

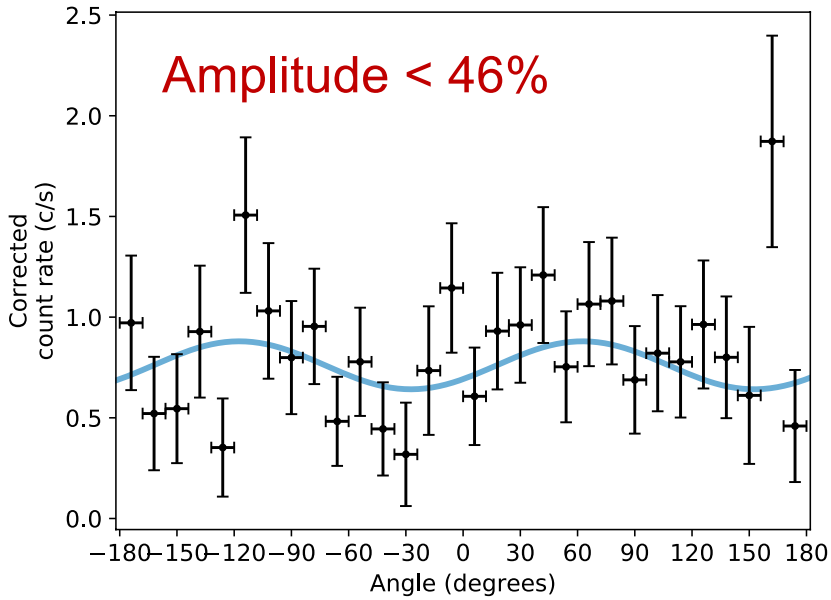



(Angle = η)



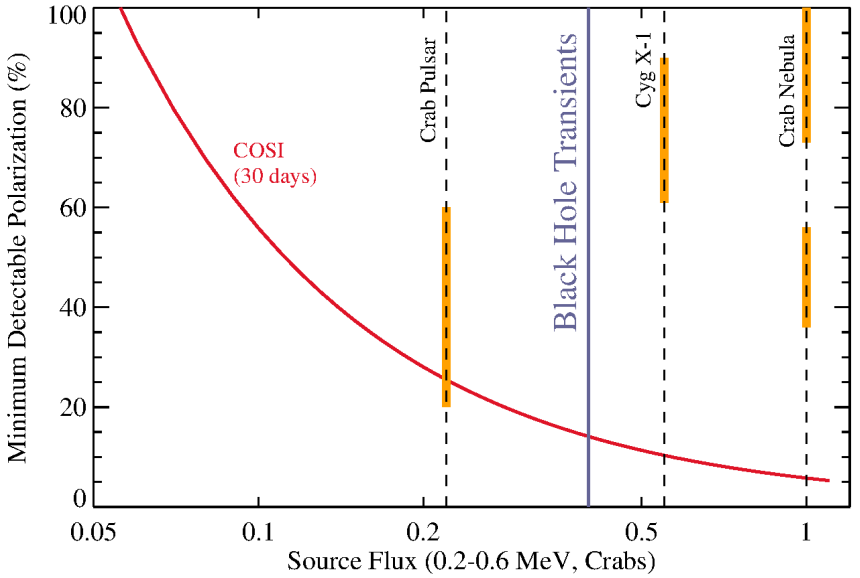




- Calibration with a partially polarized source (Lowell, PhD thesis)
- Polarization constraints for GRB 160530A (Lowell+17ab) →



# *Polarization capabilities for accreting BHs*

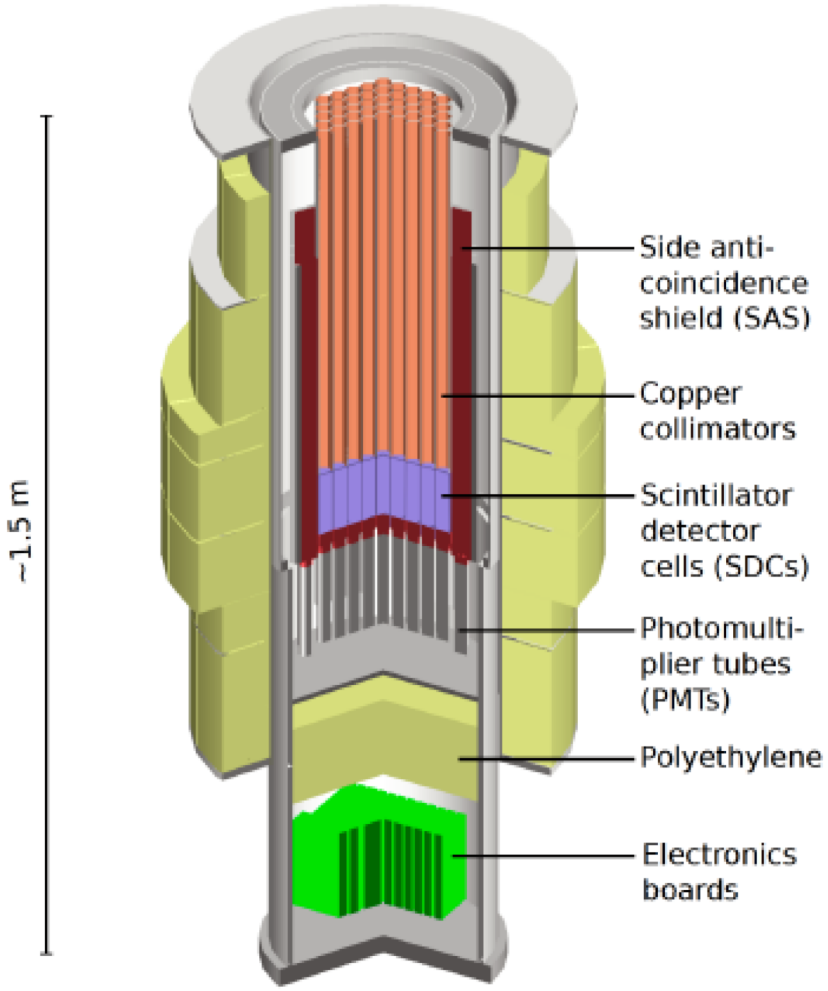
- *COSI* provides good polarization constraints for sources brighter than ~0.2 Crab
- Planning for an upgraded version of the instrument (*COSI-X*)




Red curve = polarization fraction detectable at the 99% confidence level in 30 days of coverage by *COSI*

# *PoGO+ (20-200 keV)*

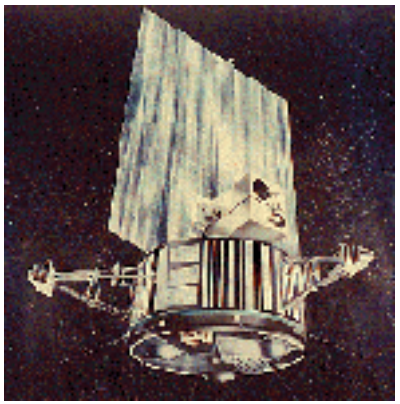
- Has flown on balloon flights and detected polarization of the Crab nebula
- Upper limit of <8.6% on Cyg X-1 polarization in the 19-181 keV band




Chauvin+17,18

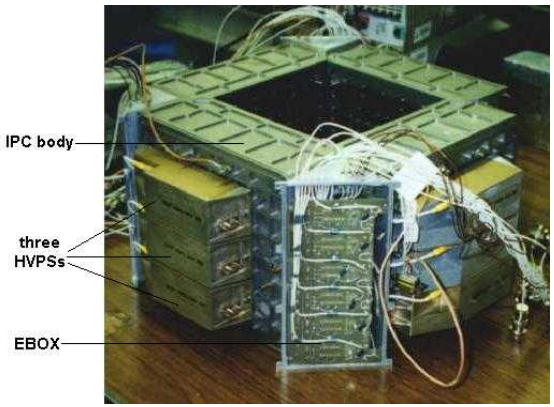
# *<10 keV polarimetry*

- Orbiting Solar Observatory (OSO-8)
- Stellar X-ray Polarimeter (SXRP)
- Imaging X-ray Polarimetry Explorer (IXPE)

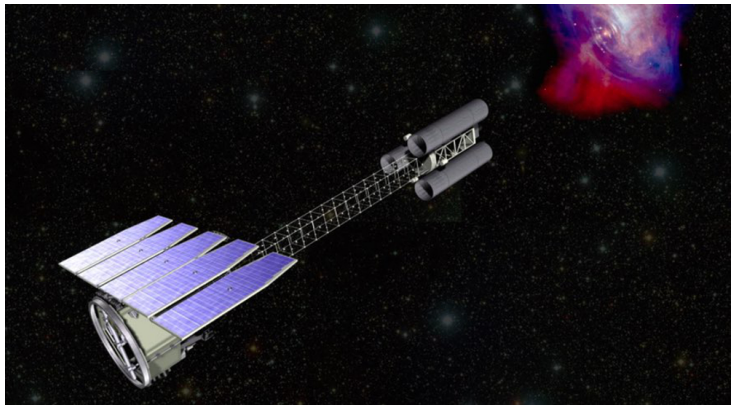


OSO-8 from the 1970s

- Measured polarization of the Crab Nebula to be 19%



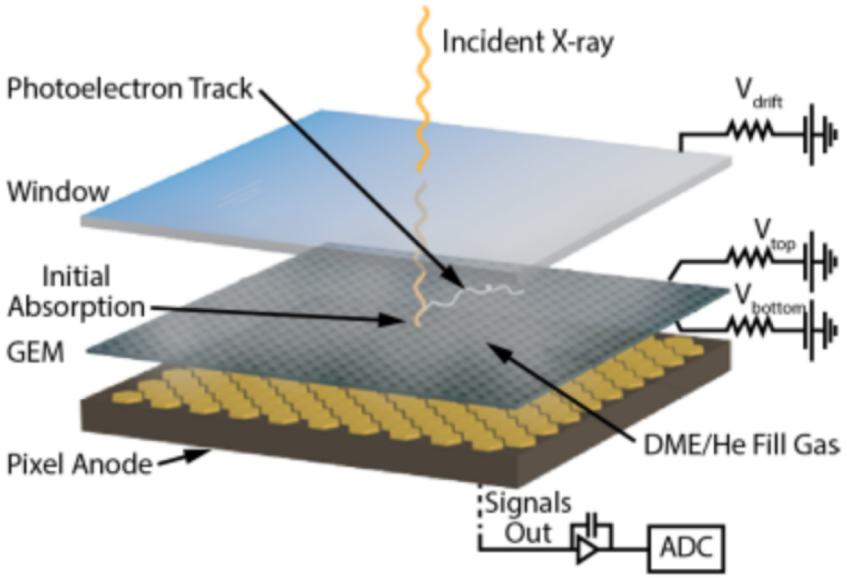

SXRP from the 1990s but did not fly



IXPE planned for launch in 2021

# *Imaging X-ray Polarimetry Explorer (IXPE)*

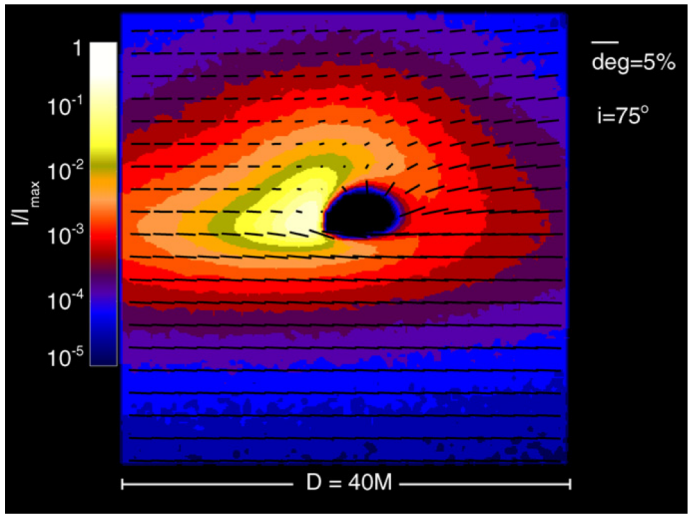
- Approved mission planned for launch in 2021
- 2-8 keV bandpass
- Polarization of each photon measured by tracking the direction of the photoelectron



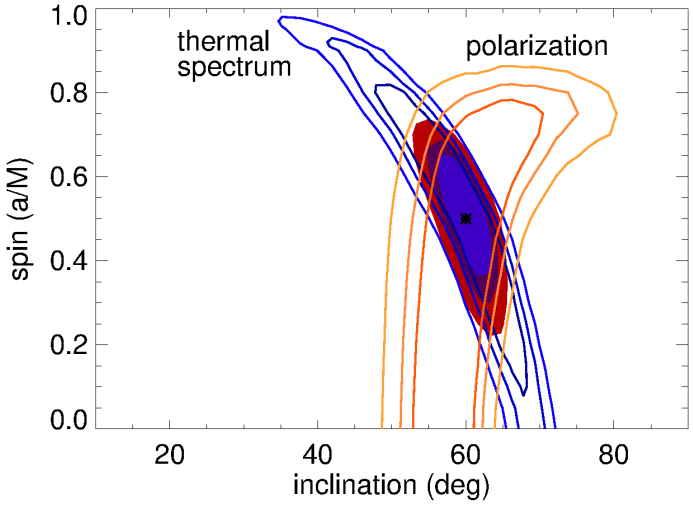

Gas Pixel Detector with a Gas Electron Multiplier (GEM) Weisskopf+17

# *IXPE for BH spin*

- There are distinctive polarization patterns that depend on the BH spin
- Especially good for measuring the inner disk inclination




Schnittman+09+16



# *Summary of Polarization Science*

- >100 keV
  - Can we use polarization to separate the high-energy components?
  - Is there a component from the jet?
- 10-100 keV
  - Measuring the reflection component to determine the geometry of the source
- <10 keV
  - Measuring the thermal component to constrain the spin of the black hole