Exploring Black Hole Jets with X-ray Polarimetric Observations

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Outline

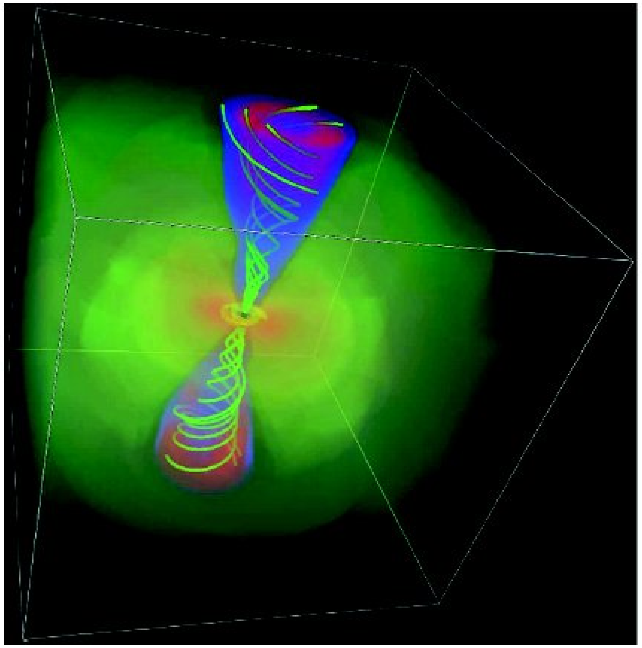
- X-ray polarimetry: history
- X-ray polarimetry: what the future holds?
- Blazars in polarized light
- Black hole systems in polarized light

X-ray polarimetry: motivation

– **jets** → excellent target for X-ray polarimetry

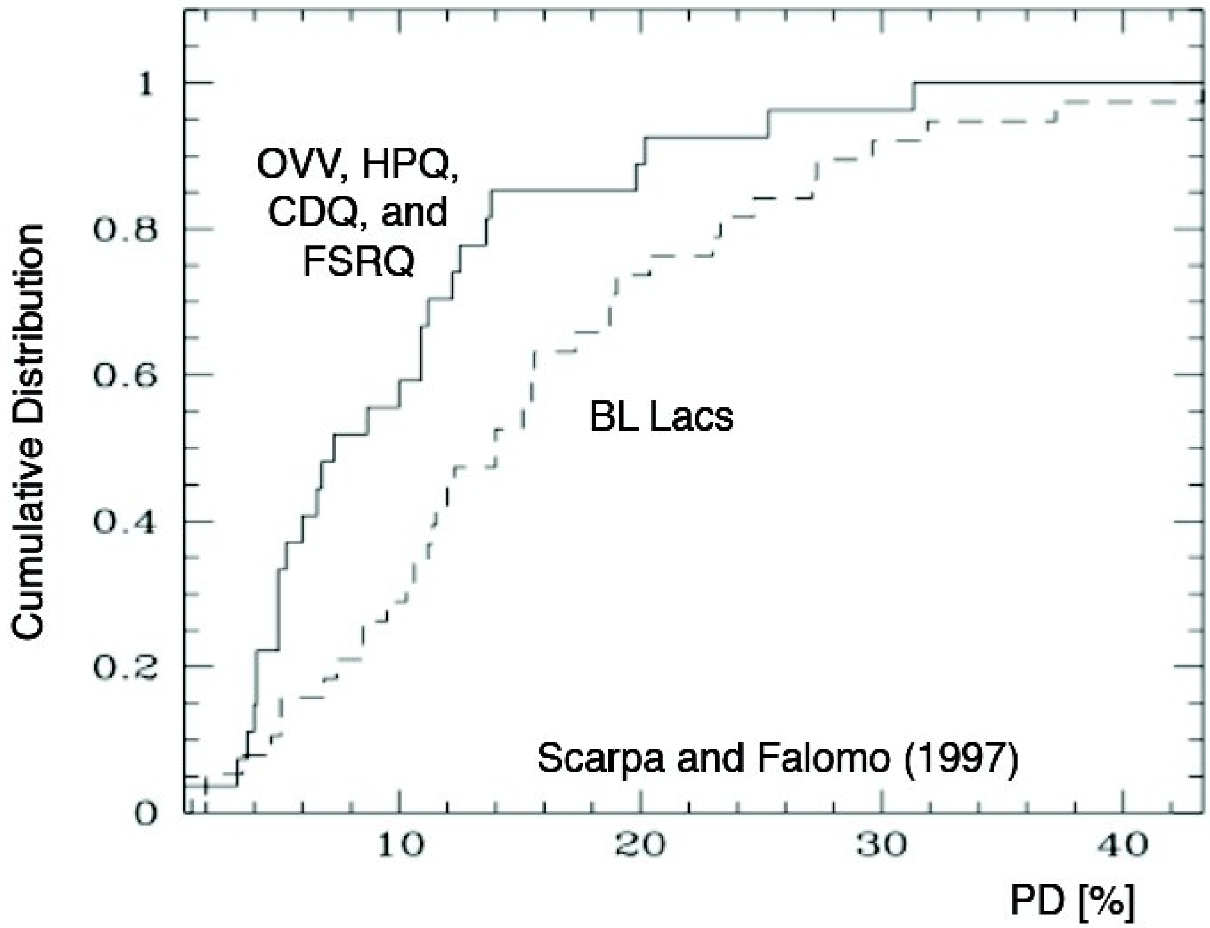
– high polarized fraction expected from:

- AGN jets (B-field structure, jet launching mechanism)
- GRBs (B-field structure in ejecta; how energy is transferred: Poynting flux vs kinetic energy)



McKinney & Blandford 2009

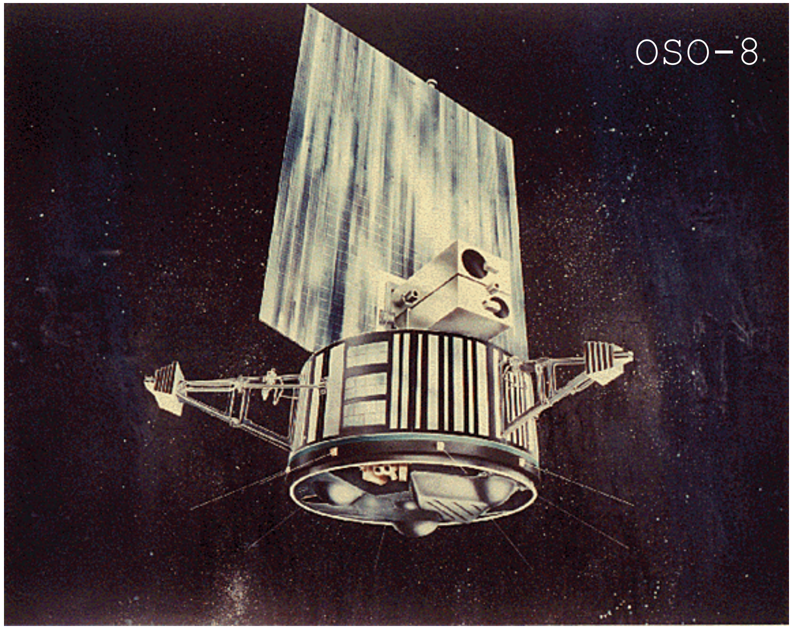
X-ray polarimetry: motivation



- high polarization of jets detected in the optical
- X-ray polarization expected to be higher

X-ray polarimetry: history

- still unexplored window to the Universe



– **OSO-8** → measured polarization from Crab nebula (~20%, ~30^{o} relative to jet) at 2.6/5.2 keV (Weisskopf et al. 1978a) and yielded upper limits on polarization signal from Cyg X-1 (Weisskopf et al. 1977), Sco X-1 (Weisskopf et al. 1978b)

– **INTEGRAL** → determined polarization of Crab nebula (~46%, aligned with spin axis of NS) in 0.1-1 MeV (Dean et al. 2008) and of Cyg X-1 (<20% in 0.2-0.4MeV, ~67% in 0.4-2MeV; Laurent et al. 2011)

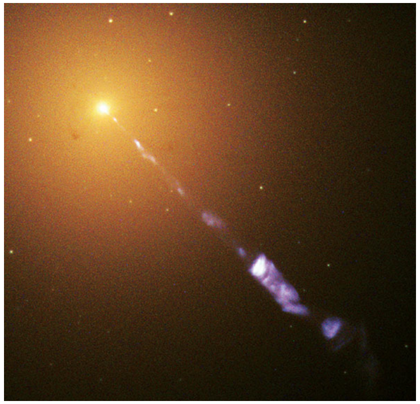
– tentative detection of polarization from GRBs with **BATSE** (>35%, >50%; Willis et al. 2005), **INTEGRAL** (as high as ~96%; McGlynn et al. 2007, Kalemci 2007) and **GAP** instrument onboard IKAROS (>6%, >30%; Yonetoku et al. 2011, 2012)

Science with **PolSTAR**

(Polarization Spectroscopic Telescope Array)

Energies: few keV – 70 keV

- ***2.5-70 keV X-ray polarimetry with 1% polarization fraction sensitivity for mCrab sources.***
- Scrutinize:
  - Black Holes (stellar mass and supermassive black holes).
  - Blazar Jets.
  - Magnetars and Neutron Stars.
- *PolSTAR* will give geometric information of ~10 km large regions!



Other missions in this energy band:
PRAXYS (NASA), **IXPE** (NASA) and **XIPE** (ESA)

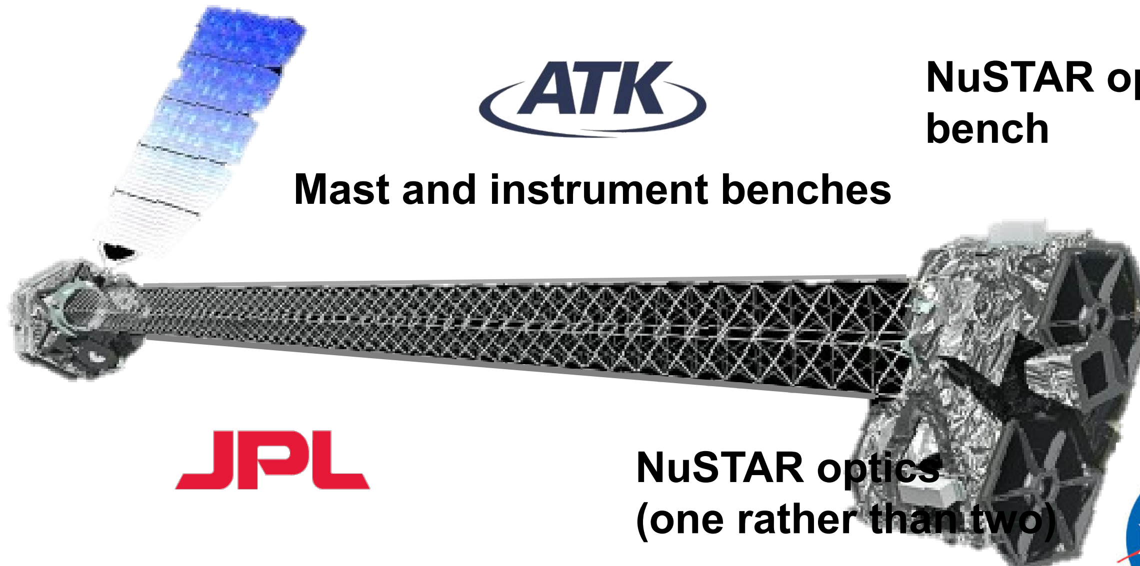
Future experiments: **PolSTAR**

From NuSTAR to PolSTAR

Orbital
LEOSTAR-II

ATK
Mast and instrument benches

NuSTAR optics bench

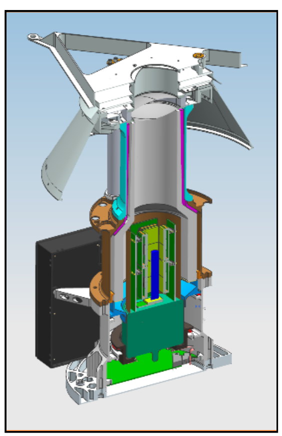


JPL

NuSTAR optics (one rather than two)

DTU

NASA



Focal plane

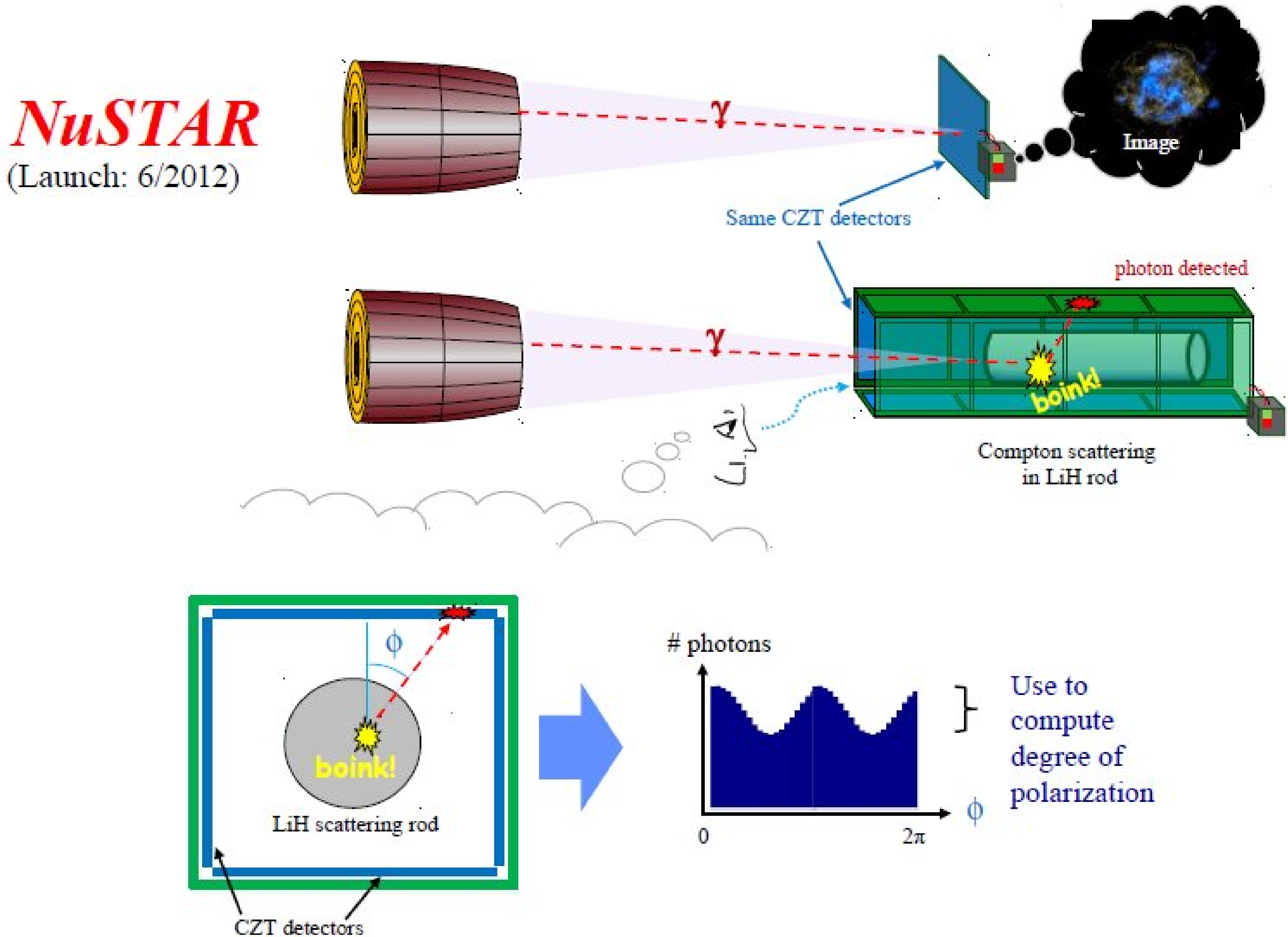
Build-to-print: CZT detectors

New: scatterer

Lawrence Livermore National Laboratory

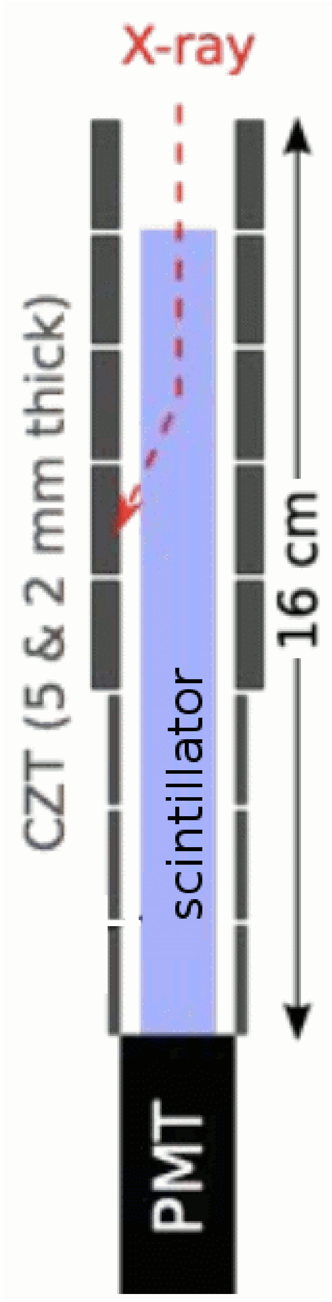
PolSTAR **will use** ***NuSTAR*** **technology plus a passive scattering slab to do completely new science.**

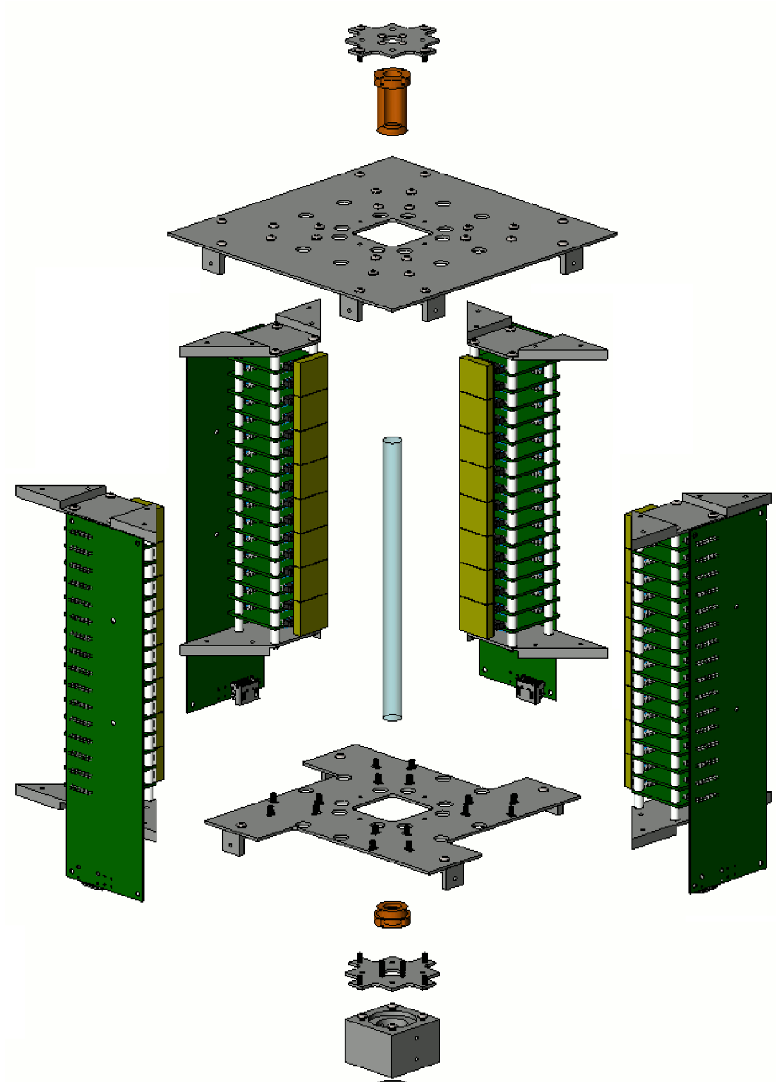
From NuSTAR to PolSTAR

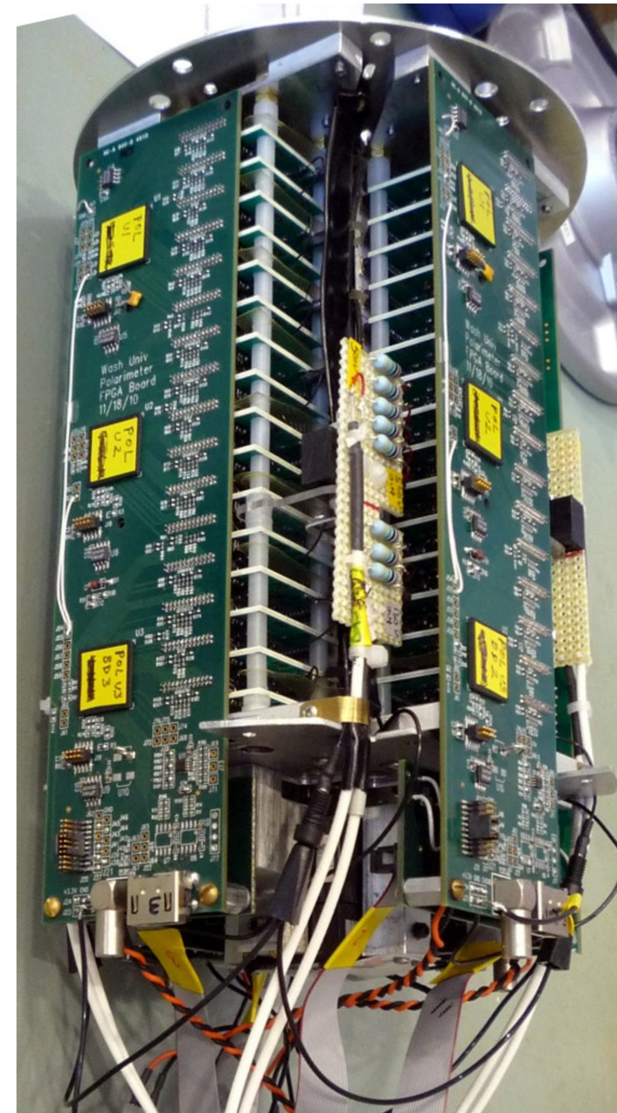


X-Calibur: pathfinder for PolSTAR

Energies: 25 – 60 keV

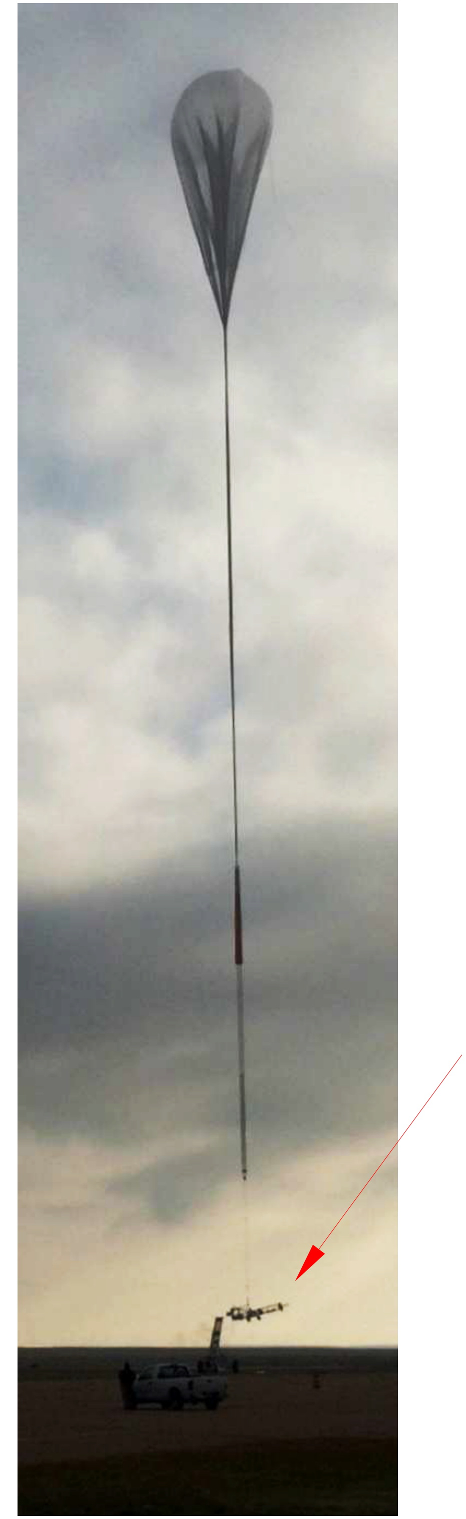






- balloon-borne experiment
- placed in the focus of Wolter-type mirror (8m focal length)

X-Calibur: pathfinder for PolSTAR

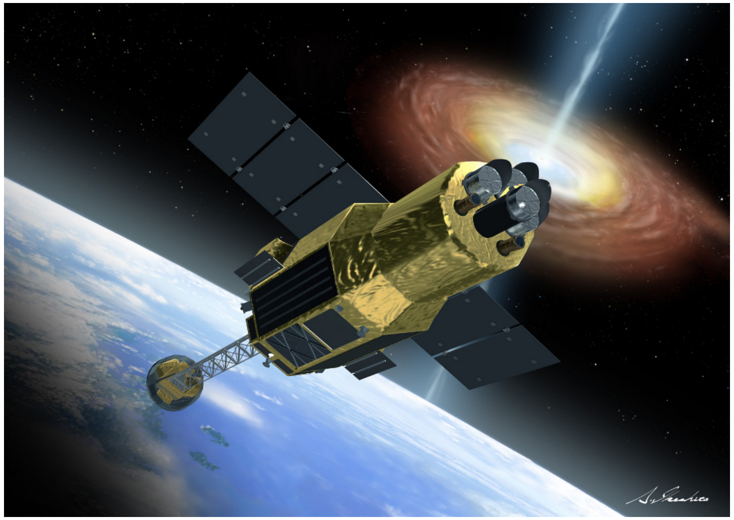


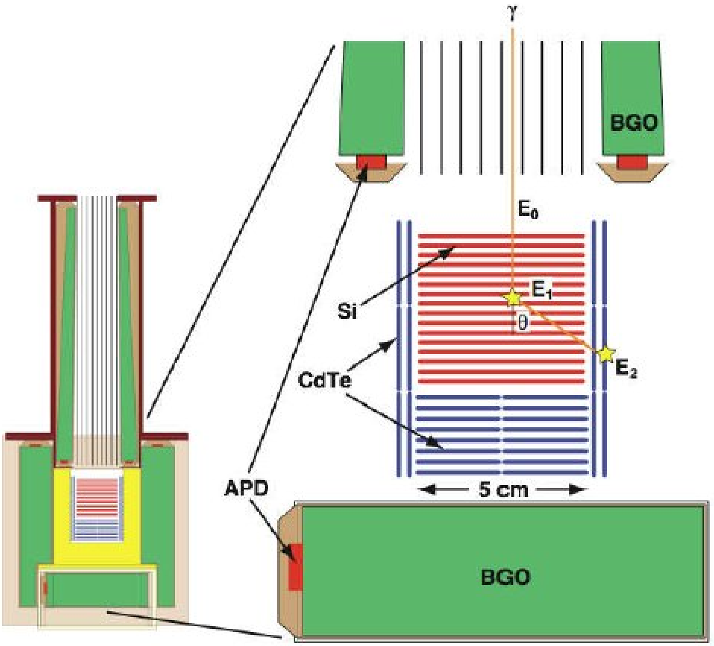
- already flown with InFOCuS in Sept. 2014
- will be flown with WASP (Wallops Arc-Second Pointer)
- short-duration flight planned for autumn 2016
- long-duration flight planned for winter 2017

Future experiments: **Astro-H**

Energies: hard X-ray band

- ***SGD (Soft Gamma-Ray Detector) → not only spectroscopy but also polarimetry***
- ***50-200 keV X-ray polarimetry with polarization sensitivity for sources of few tens of mCrab.***
- Science objectives:
  - Crab Pulsar and Nebula
  - Microquasars
  - Blazars
  - Jet-disk coupling in AGNs





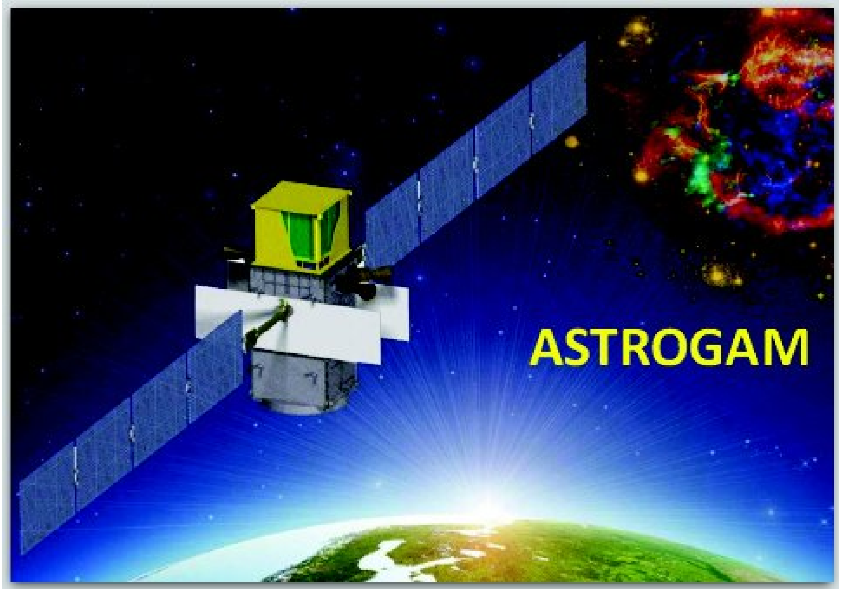
Coppi et al. 2014

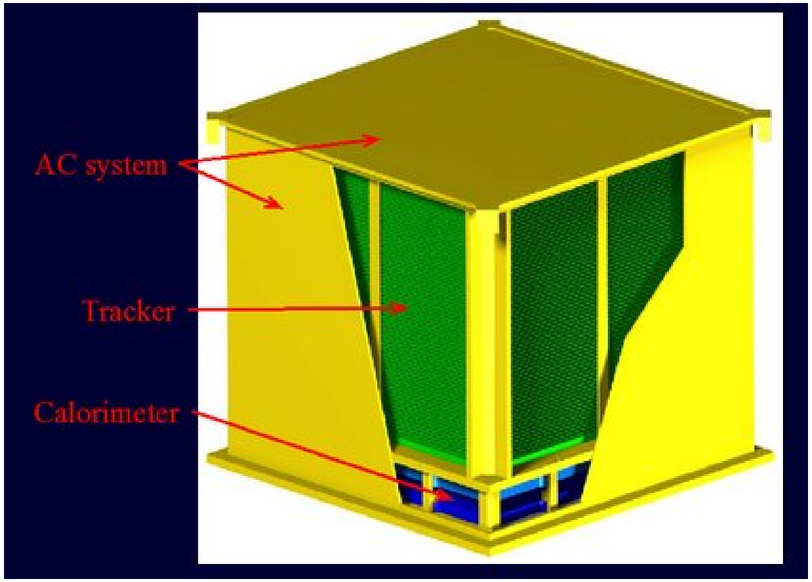
Other missions in this energy band:
Astrosat (100 – 300 keV) → for details see poster of Tanmoy Chattopadhyay

Future experiments: soft-gamma ray telescopes

Energies: gamma-ray band

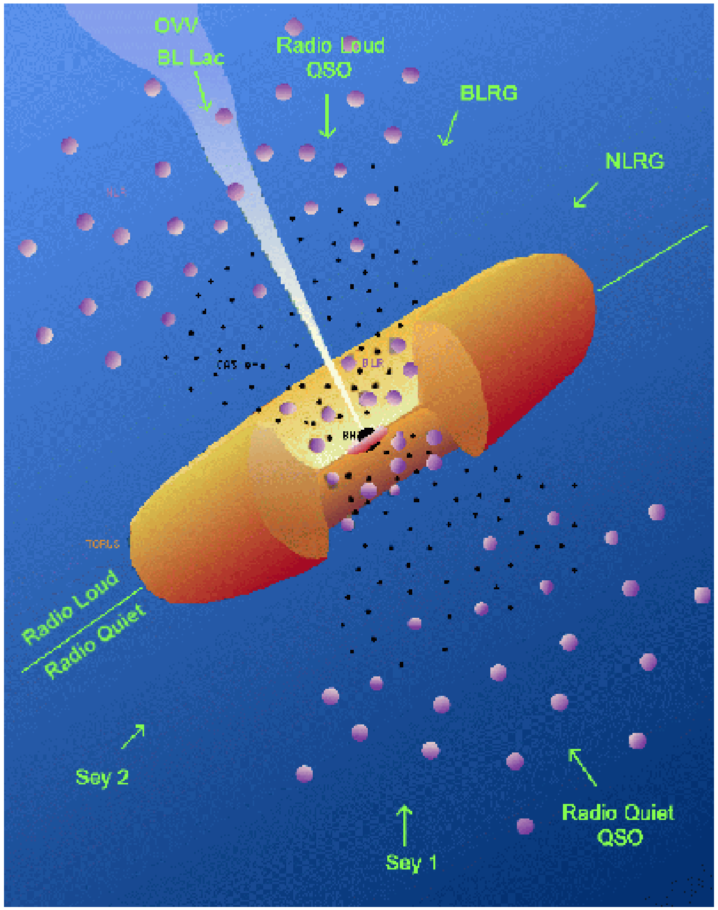
- ***future MeV telescopes like ASTROGAM (proposed to ESA as M4 mission)***
- ***soft gamma-ray band: few to hundred MeV***
- ***polarization sensitivity for Crab-like source (MDP~1%)***
- Science objectives:
  - Jets
  - GRBs and AGNs
  - Galactic black hole systems



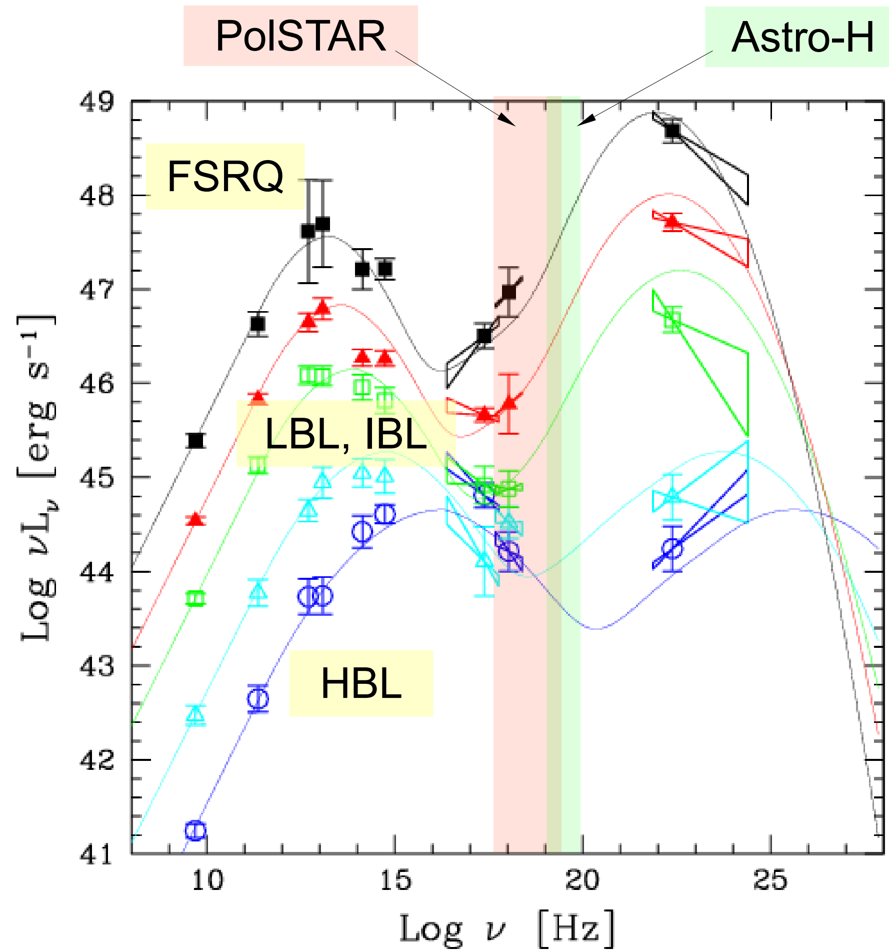


http://astrogam.iaps.inaf.it

Blazars



Urry & Padovani 1995



Fossati et al. 1998

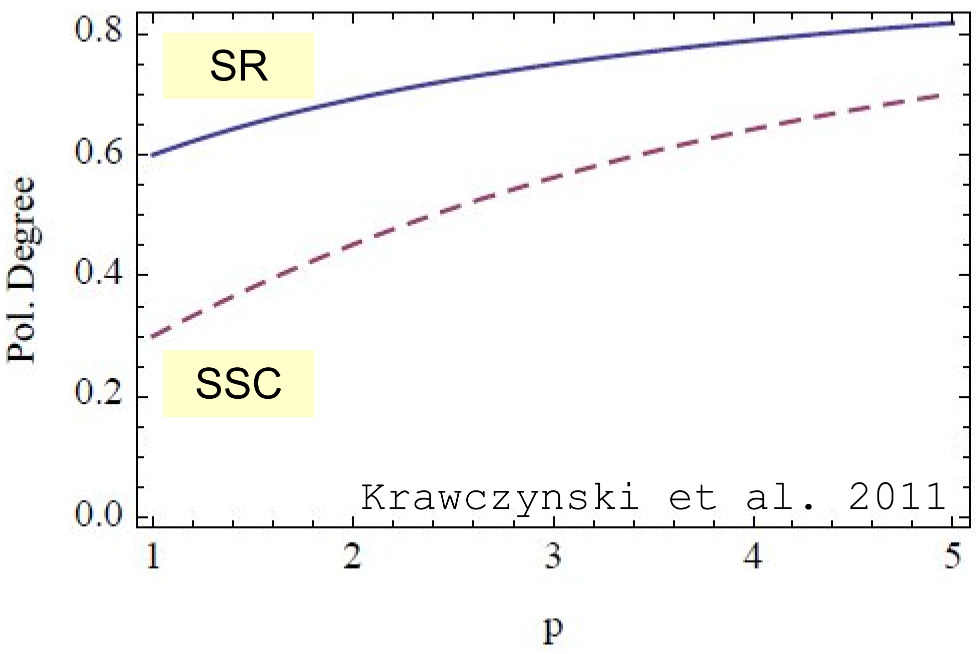
- different flavours of blazars: FSRQs and LBLs, IBLs, HBLs
- different emission mechanisms dominate at X-ray energies, so different polarization signatures expected

Emission processes in blazars

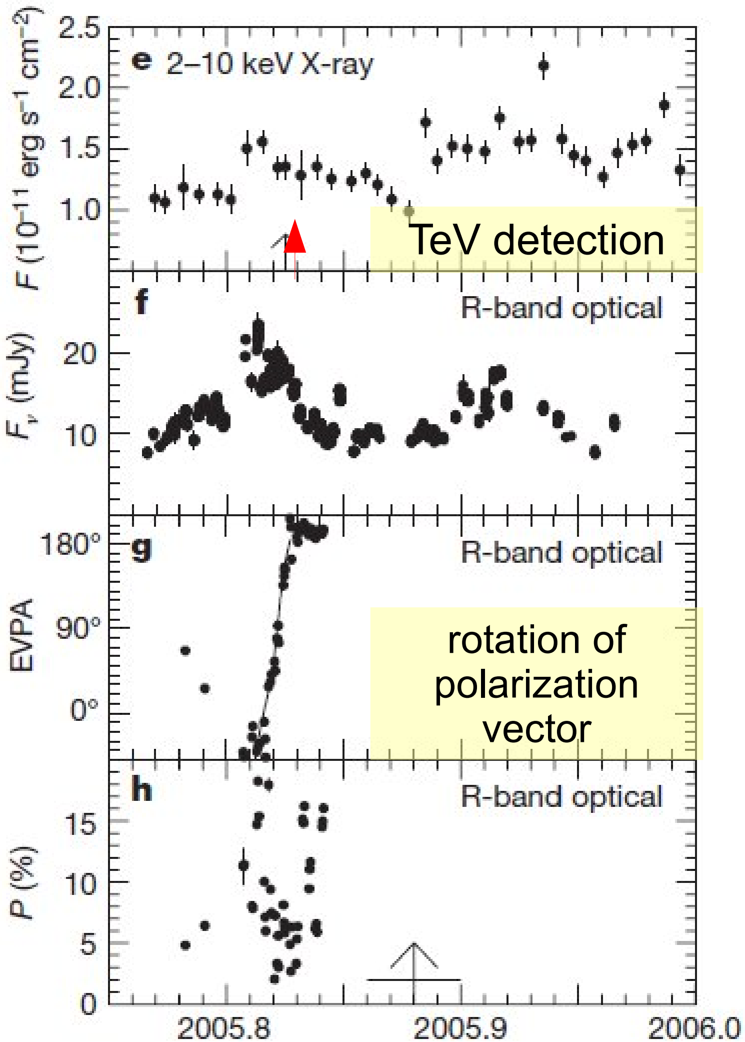
- synchrotron (SR) emission intrinsically highly polarized
- SR polarized fraction depends on the spectral index
- SSC: Inverse Compton scattering (ICS) reduces polarization by factor ~2
- external Compton: <<10% polarization
- hadronic models predict higher polarized fractions (50 – 70%) than leptonic models (~30%)

$$P_S = \frac{p+1}{p+7/3}$$

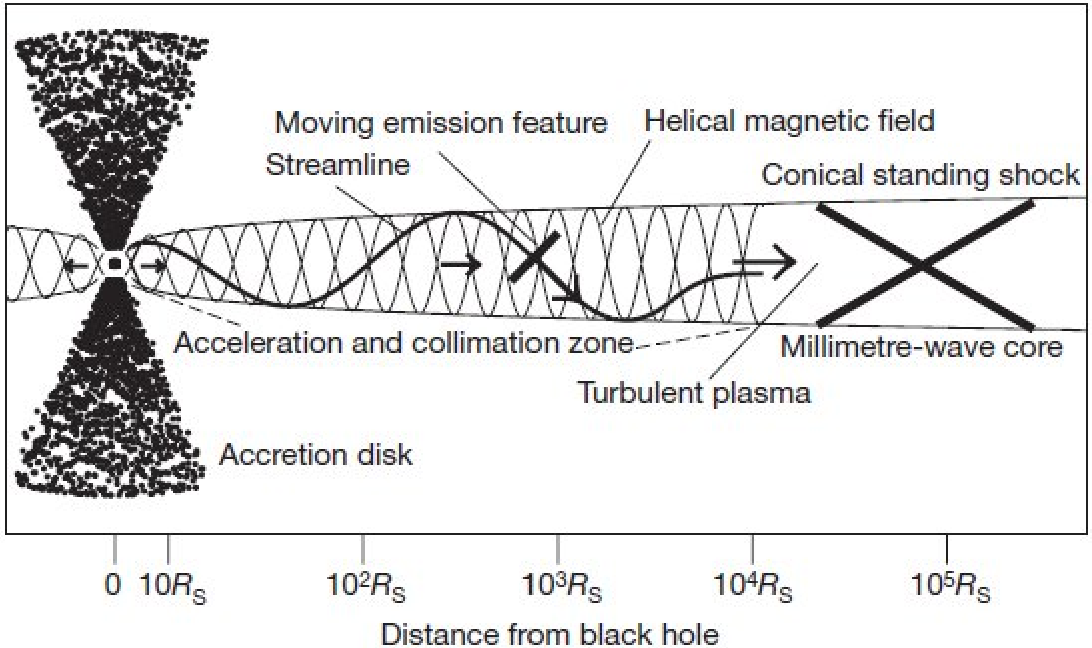
$$P_{SSC} = P_S \frac{(p+1)(p+3)}{p^2+4p+11} \sin^2\zeta$$



Probing the magnetic field structure in the jet

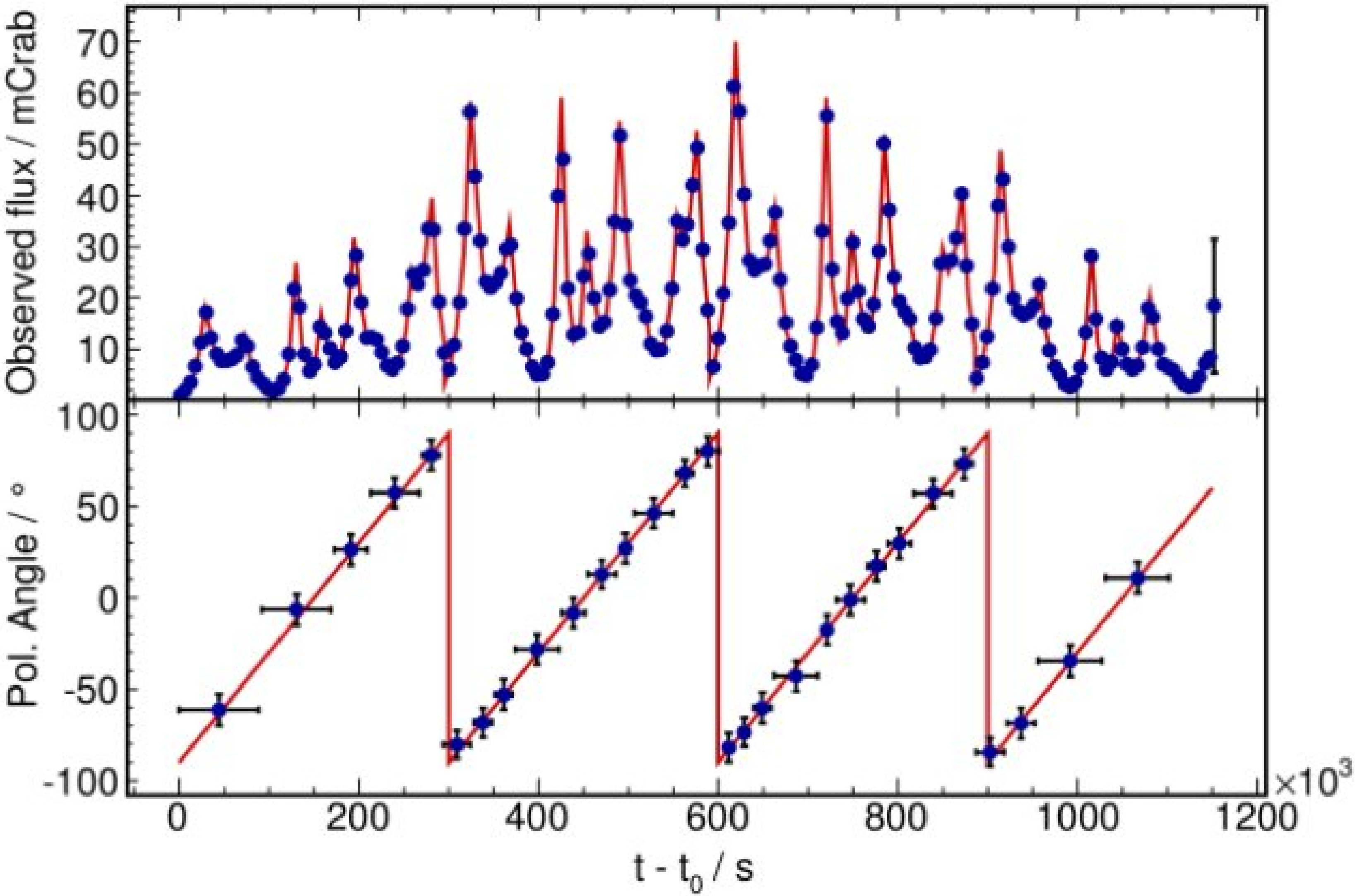


Marscher et al. 2008



- polarization angle swings correlated with flaring activity occuring in the optical and gamma-rays
- X-ray polarimetry should reveal cleaner picture of the underlying magnetic field structure → high-energy electrons lose their energy on shorter timescales, so X-ray emitting regions are more compact
- polarization angle swings should be more frequent at X-ray energies

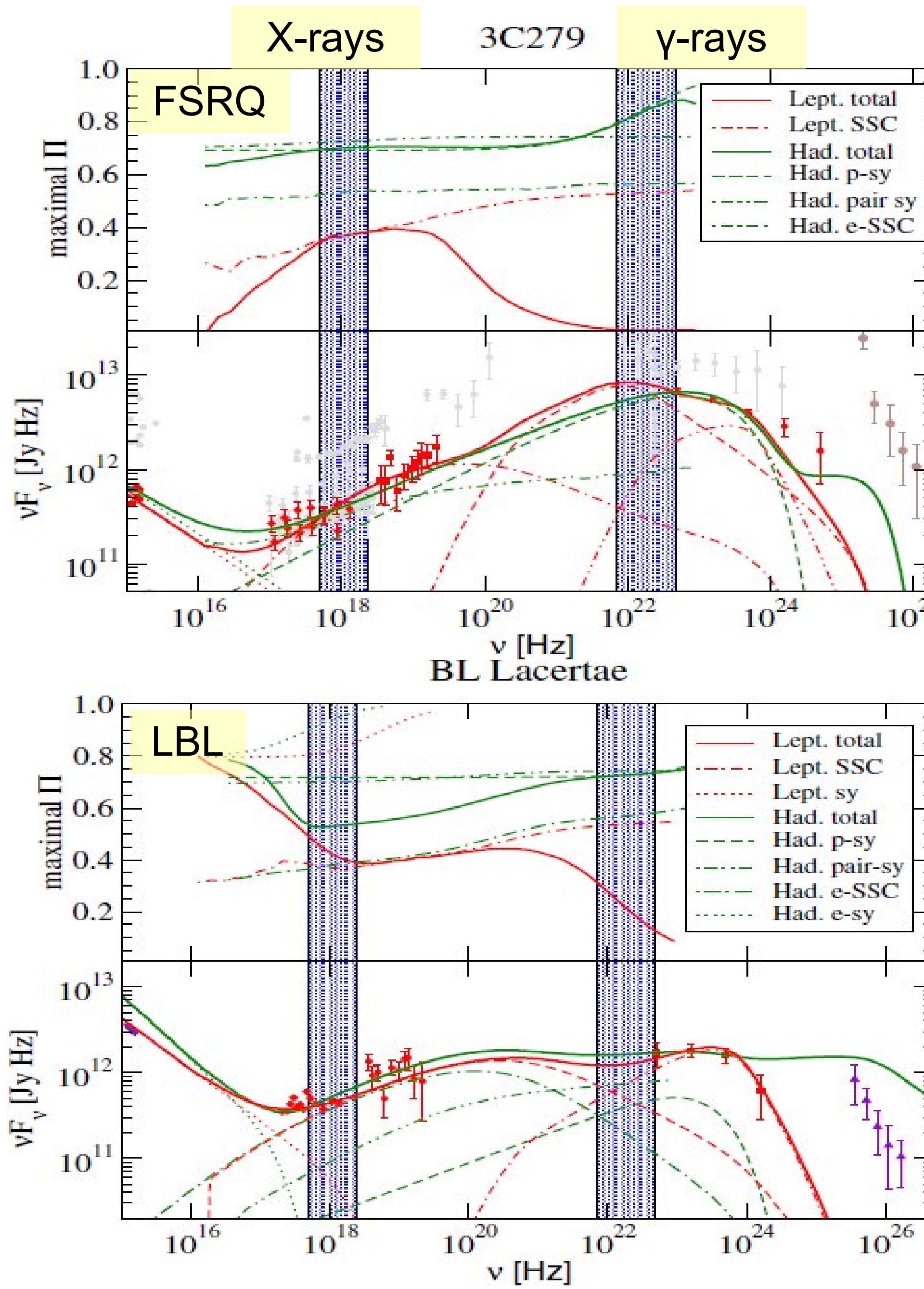
Probing the magnetic field structure in the jet



- Simulated *PolSTAR* observations of Mrk 421
- Assumption: P_{SR}~6%.

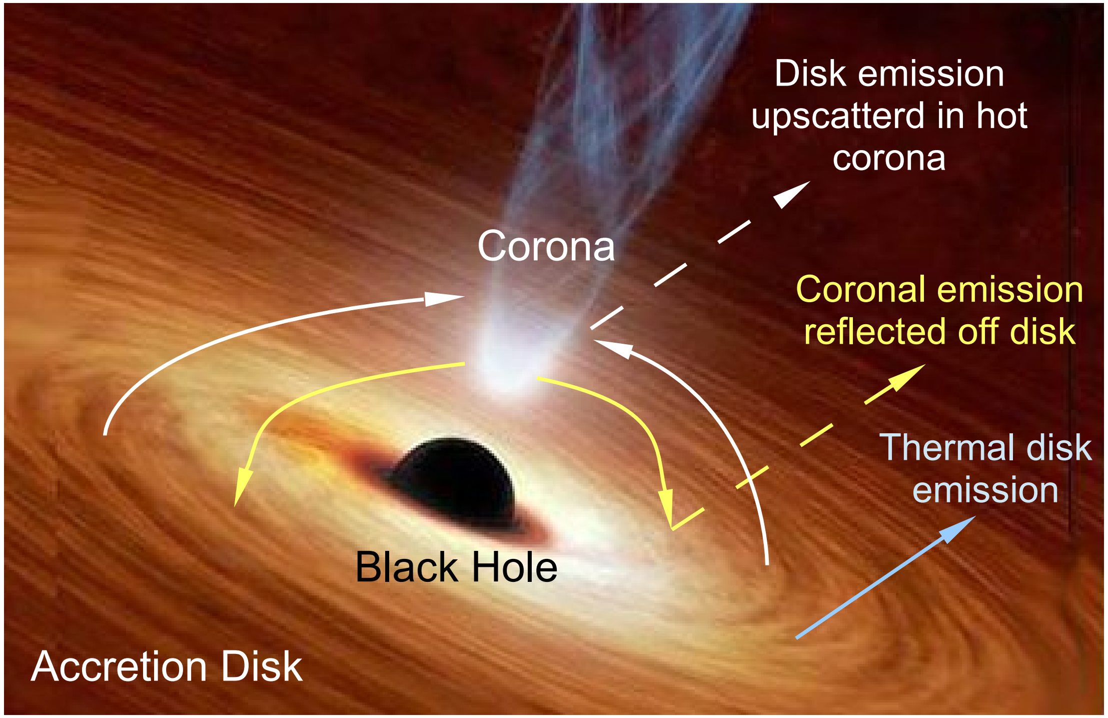
Identifying blazar emission mechanisms

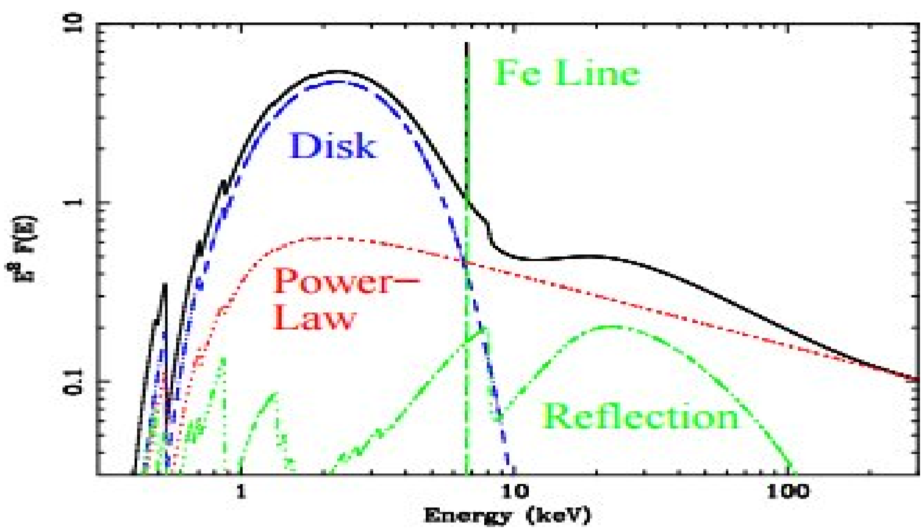
- leptonic or hadronic emission?
- hadronic models predict systematically higher polarization fractions (up to 70-75% for FSRQs and up to 50-55% for LBLs) than leptonic models (up to 30%)
- if very high polarization fraction levels detected → hadronic models favoured
- ICS reduces polarization fraction of target photons, but still resulting polarization of SSC high
- EC virtually unpolarized
- origin of inverse Compton emission → SSC or EC?



Zhang & Böttcher 2013

Accretion flows around black holes





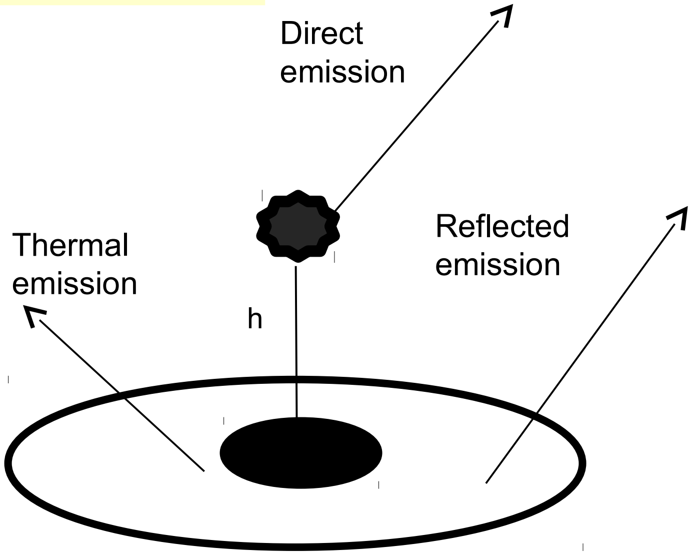
Miller 2007

Stellar-mass BH X-ray spectrum

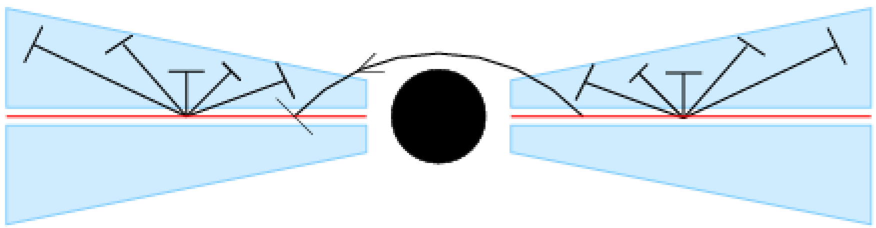
- complex emission spectrum of accreting BH
- different emission components carry different polarization signatures
- direct disk – polarized to ~few %
- corona emission – unpolarized
- scattering and reflection introduce polarization – electric field vector perpendicular to the scattering plane
- strong gravitational field around BH influences the polarization angle

Getting a handle on corona properties

lamp post

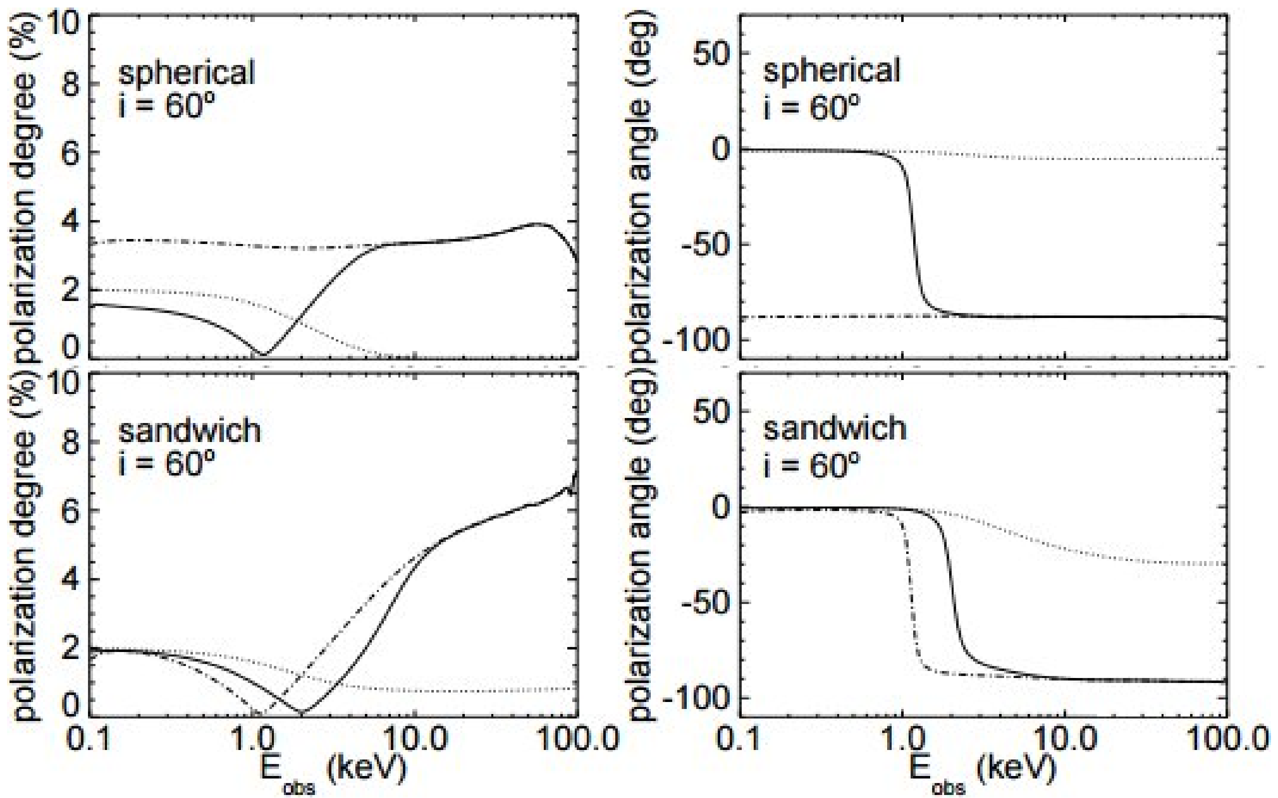


wedge-type



- X-ray polarization → distinguishing between different corona models, e.g. wedge-type, clumpy or spherical (see Schnitmann & Krolik 2010)
- inferr properties of corona (geometry, temperature, optical depth, and clumpiness)

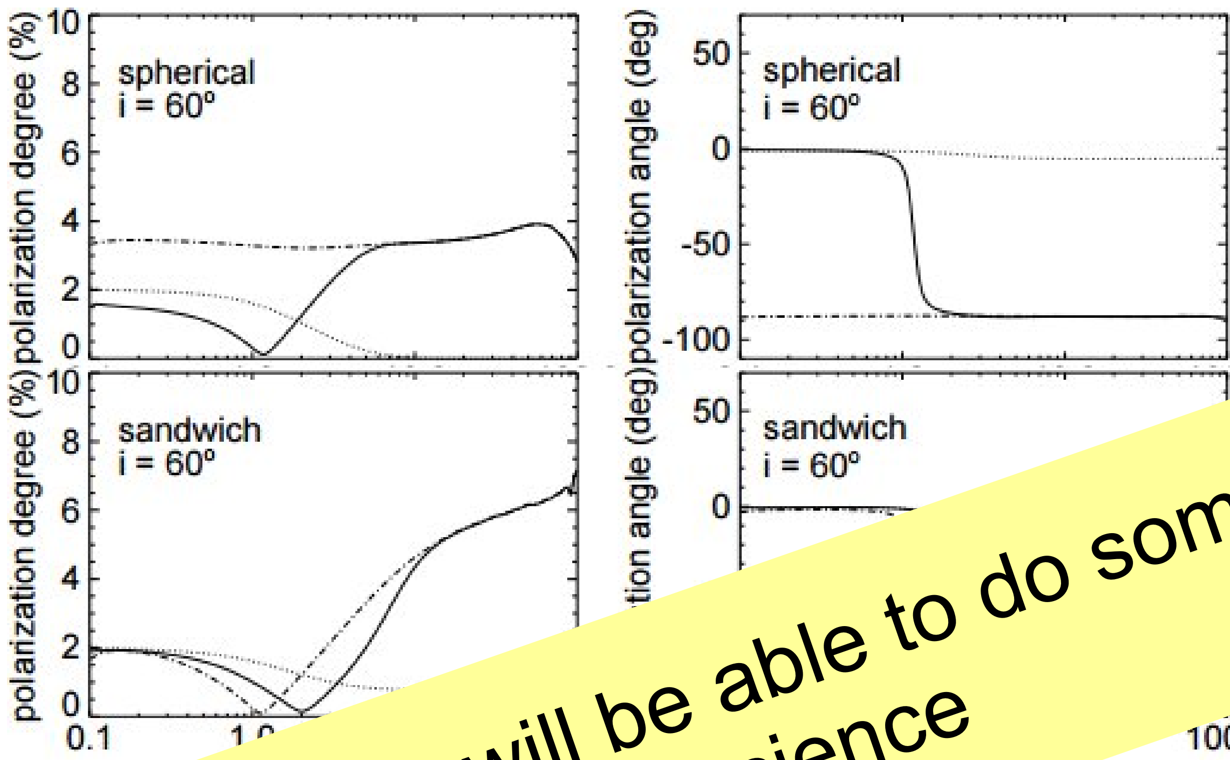
Getting a handle on corona properties



Schnittman & Krolik 2010

- energy-dependent polarization fraction → higher polarization expected at higher photon energies
- polarization angle swing by 90° → from horizontal at lower energies to vertical at higher energies

Getting a handle on corona properties



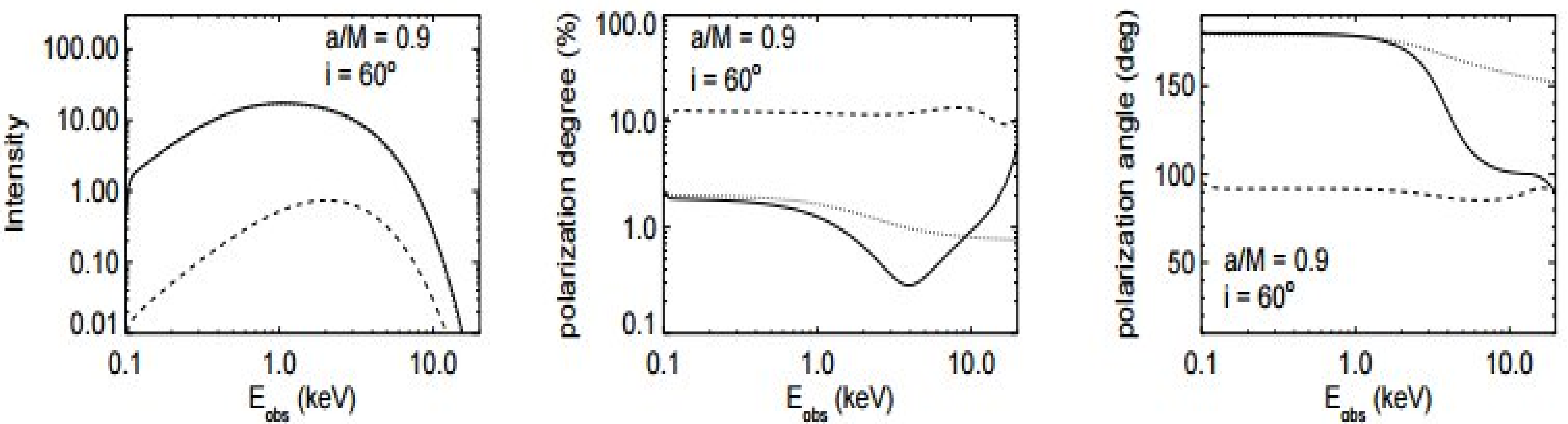
Schnittm … 2010

X-Calibur will be able to do some of the science

- energy- … fraction → higher polarization expected … oton energies
- polarizatio… angle swing by 90° → from horizontal at lower energies to vertical at higher energies

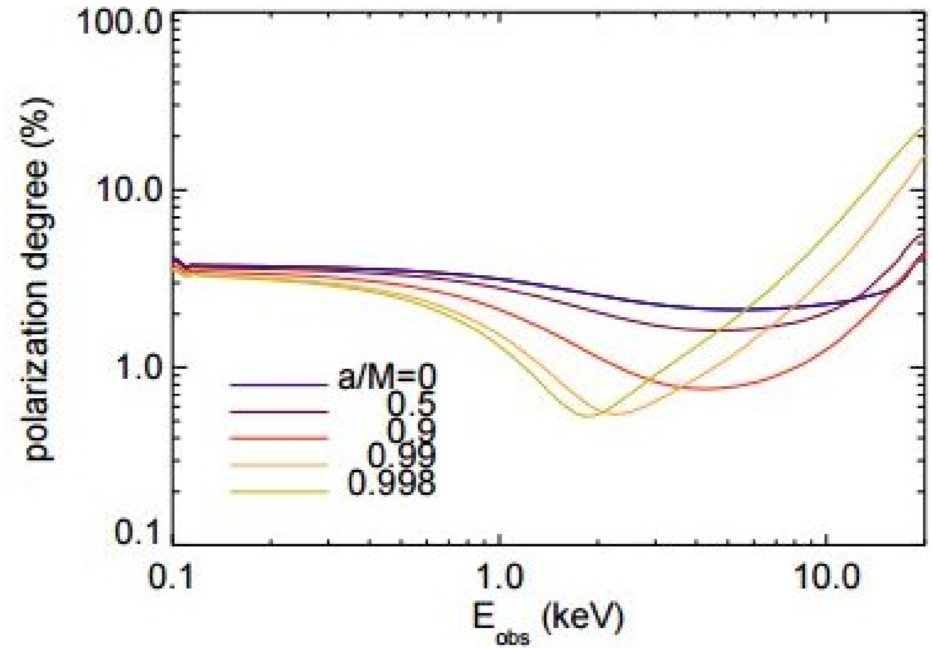
Getting a handle on accretion disk properties

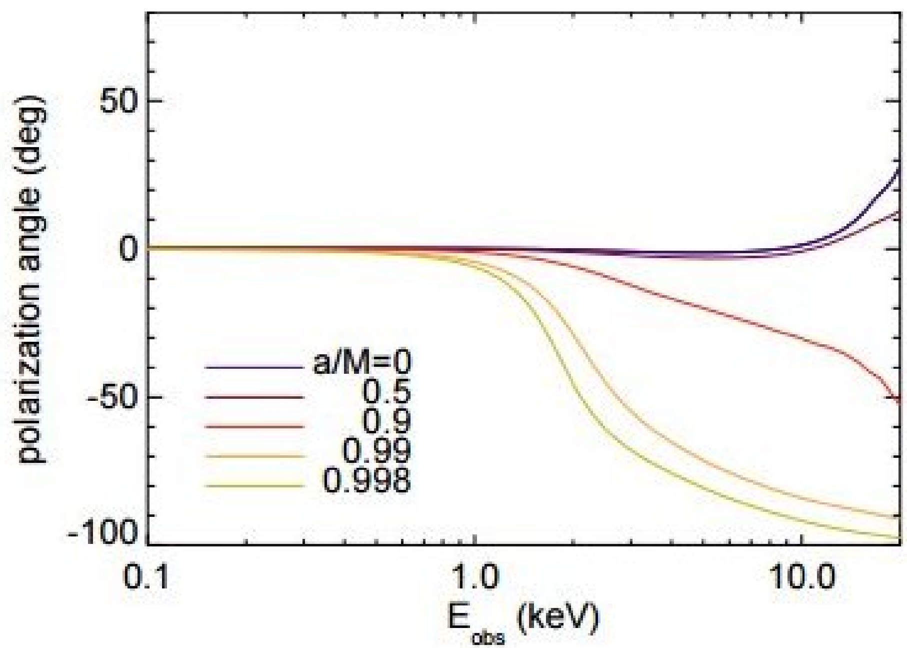
- at low energies emission weakly polarized and polarization parallel to emission surface
- at high energies much higher polarization oriented parallel to disk rotation axis (as projected onto the sky)
- polarization signature strongly depends on the behaviour of gas near and inside of ISCO



Schnittman & Krolik 2009

BH spin and inclination of inner accretion disk can be determined through X-ray polarimetry





Schnittman & Krolik 2009

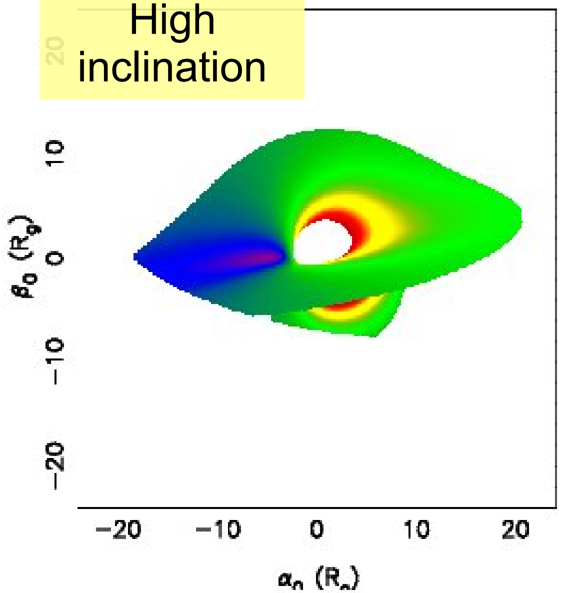
Inclination i=75°, BH mass of 10M_{sun}, luminosity L/L_{Edd}=0.1
and Novikov-Thorne radial emission profile

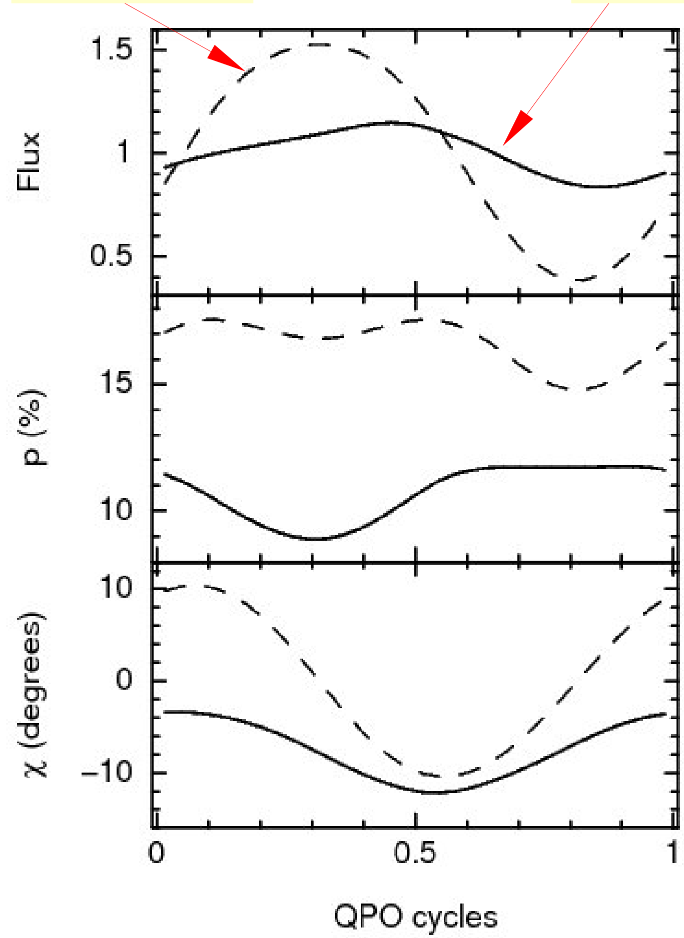
Test the Quasi-Periodic Oscillations hypothesis

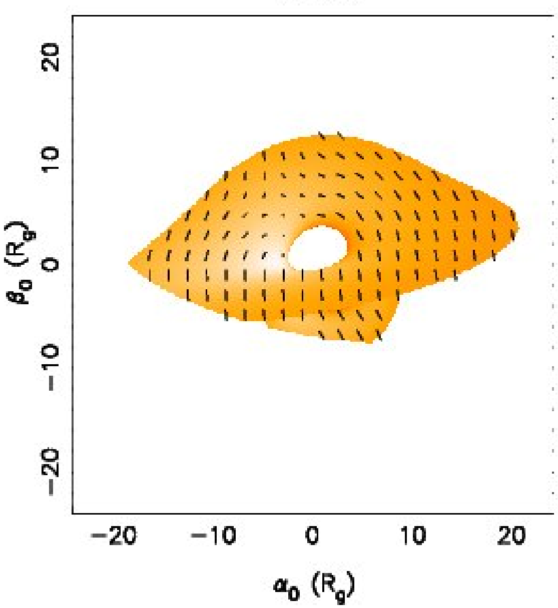
High inclination

Newtonian approx.

Relativistic model





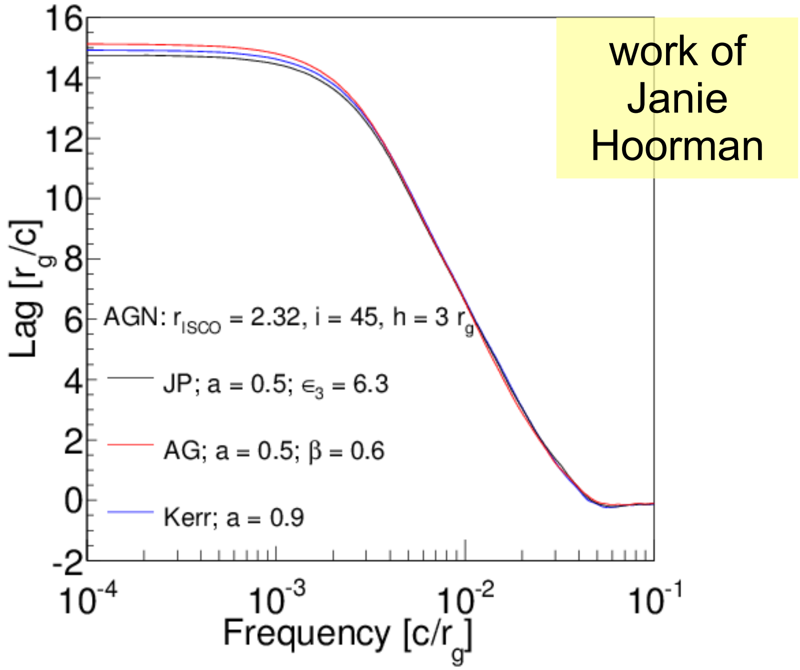


- QPOs result from Lense-Thirring precession of the corona in the stellar-mass BH binary systems
- precession results in quasi-periodinc changes of polarization fraction and angle in the Comptonized emission (10-20 keV)

→ Test GR in strong field regime

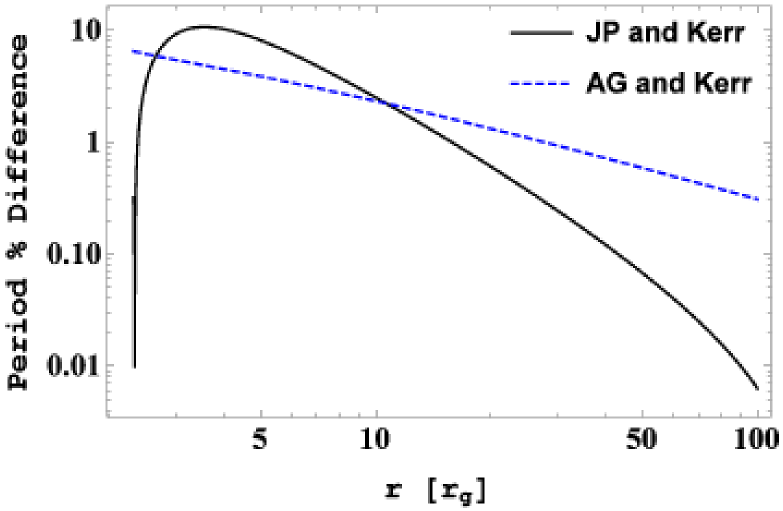
Details: stay tuned for **Ingram et al.(in prep.)**

Other GR tests: distinguishing between different BH metrics



Combined spectral, timing, and polarimetric observations can break the degeneracy:

- orbital period at the ISCO differ by up to ~10%.
- lag at low frequency differs by ~ a percent.



Details: stay tuned for **Hoorman & Krawczynski (in prep.)**

Summary

- X-ray polarimetry – still an unexplored window to the universe.
- X-ray polarimetry can be used to probe the magnetic field in the blazar jets and to distinguish between emission mechanism in these systems.
- Through spectropolarimetry one can get a handle on corona properties and also acrretion flows around black holes.
- X-ray polarimetry will provide tests of QPO hypothesis of black hole binaries as being due to Lense-Thirring precession of the corona.
- X-ray polarimetry can be used to test GR in the strong field regime.

Thank you for your attention!