Scientific Potential and Possible Designs for Next-Generation Hard X-ray/Soft Gamma-ray Imaging Mission

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Feb. 5, 2015

Plan of talk:

- Motivation: *NuSTAR*.
- Technical Opportunities.
- Scientific Opportunities.

Washington University in St. Louis

NASA Request for Information X-ray Mission Architectural Concepts (2011, http://pcos.gsfc.nasa.gov/studies/x-ray-mission.php)

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Next Generation X-Ray optics:

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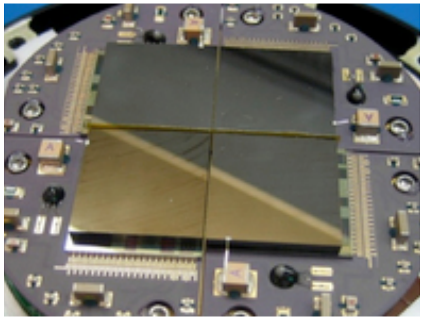
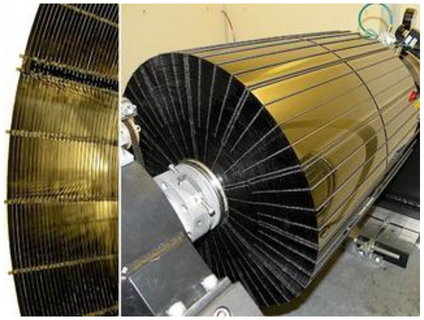
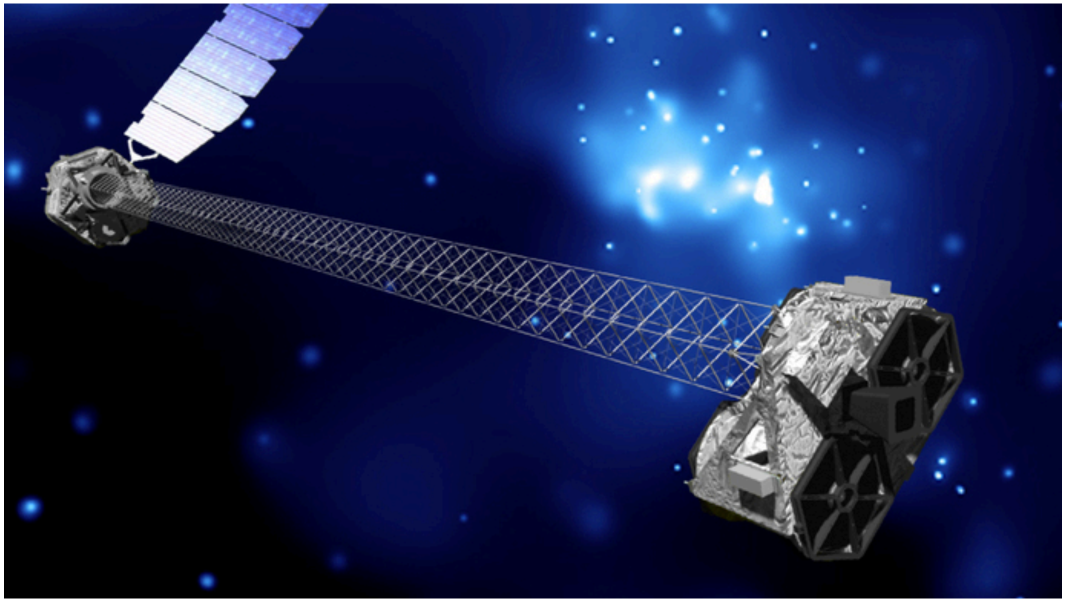
NuSTAR (Nuclear Spectroscopic Telescope Array)





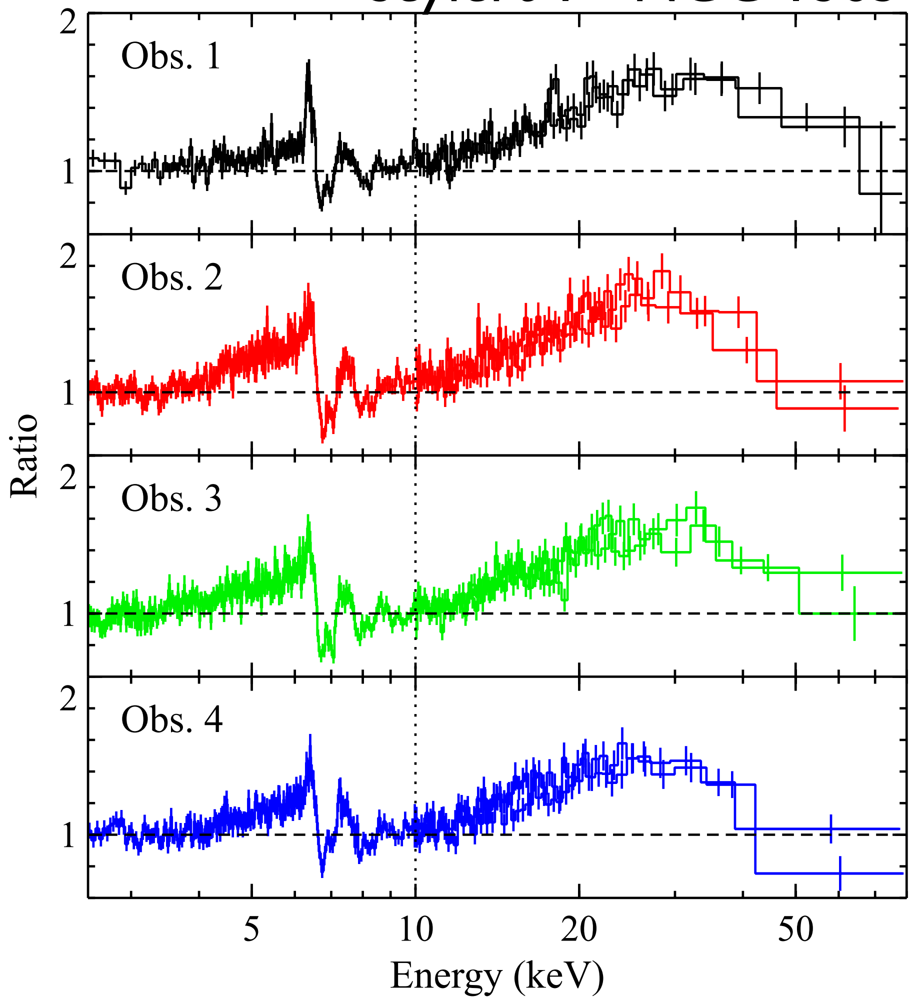


Harrison et al. 2013

Parameter	Value
Energy Range	3-78.4 keV
Sensitivity (6-10 keV)	2 x 10^{-15} (CGS)
Angular Res. HPD	58”
Field of View	10’ (10 keV)
Energy Res.	0.4 keV FWHM
Temporal Res.	2 μ sec-2msec

NuSTAR - Results

Seyfert I - NGC 1365

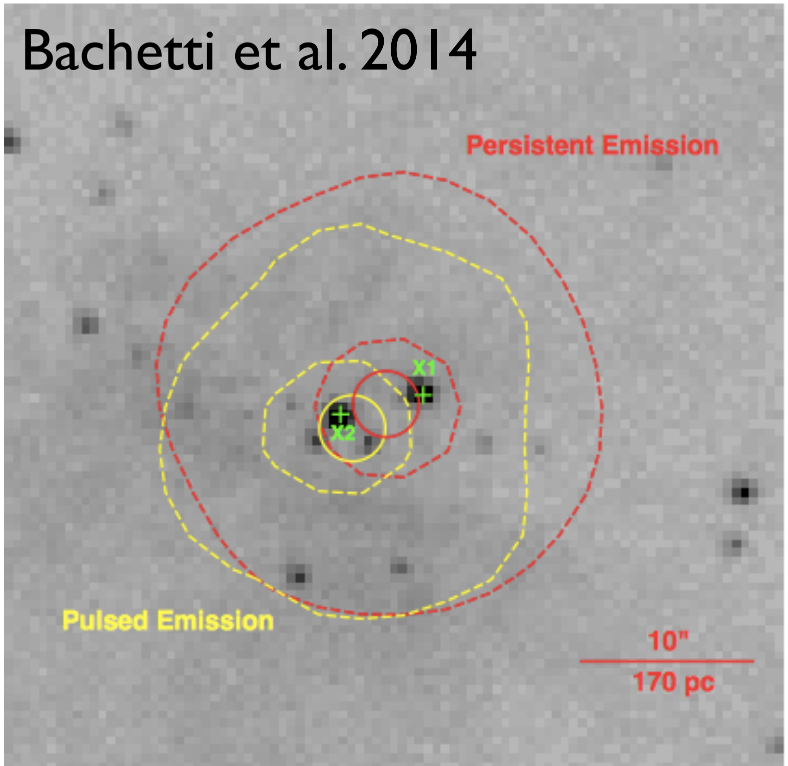


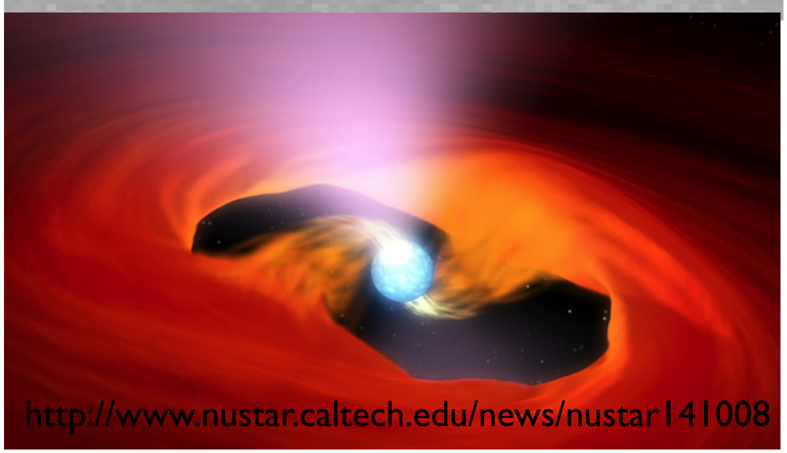
NuSTAR's ***broad energy bandpass*** allowed to disentangle variable absorption and reflection from the inner accretion disk.

$$a^* > 0.97$$

Walton et al. 2014

NuSTAR - Results





NuSTAR's ***Timing Resolution*** allowed to detect the 1.37 sec pulsed emission from M82 X-2.

Pulsed Flux:

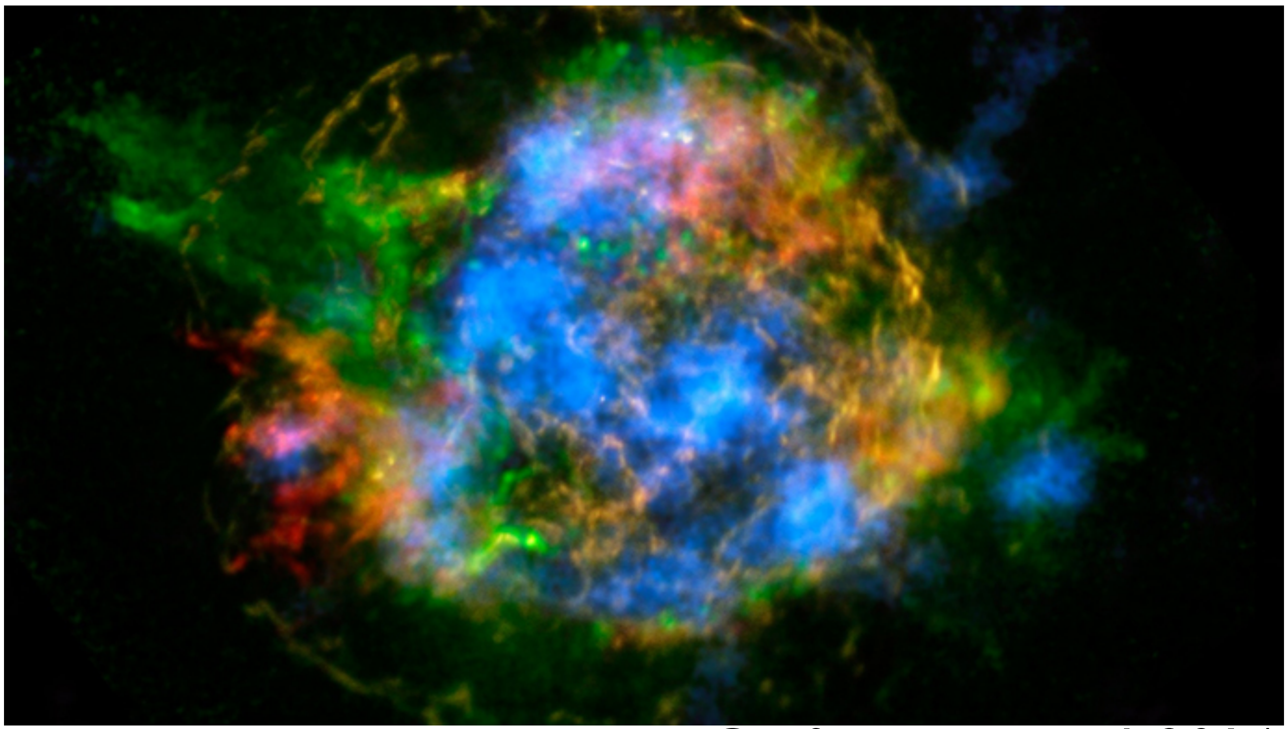
$L_X(3 – 30 \text{ keV}) =$

$4.9 \times 10^{39} \text{ erg s}^{-1}$

$\sim 100 \ L_{Edd}$

NuSTAR - Results

Cas-A: Ti-44 (blue), red-yellow-green Chandra (1.7 keV).



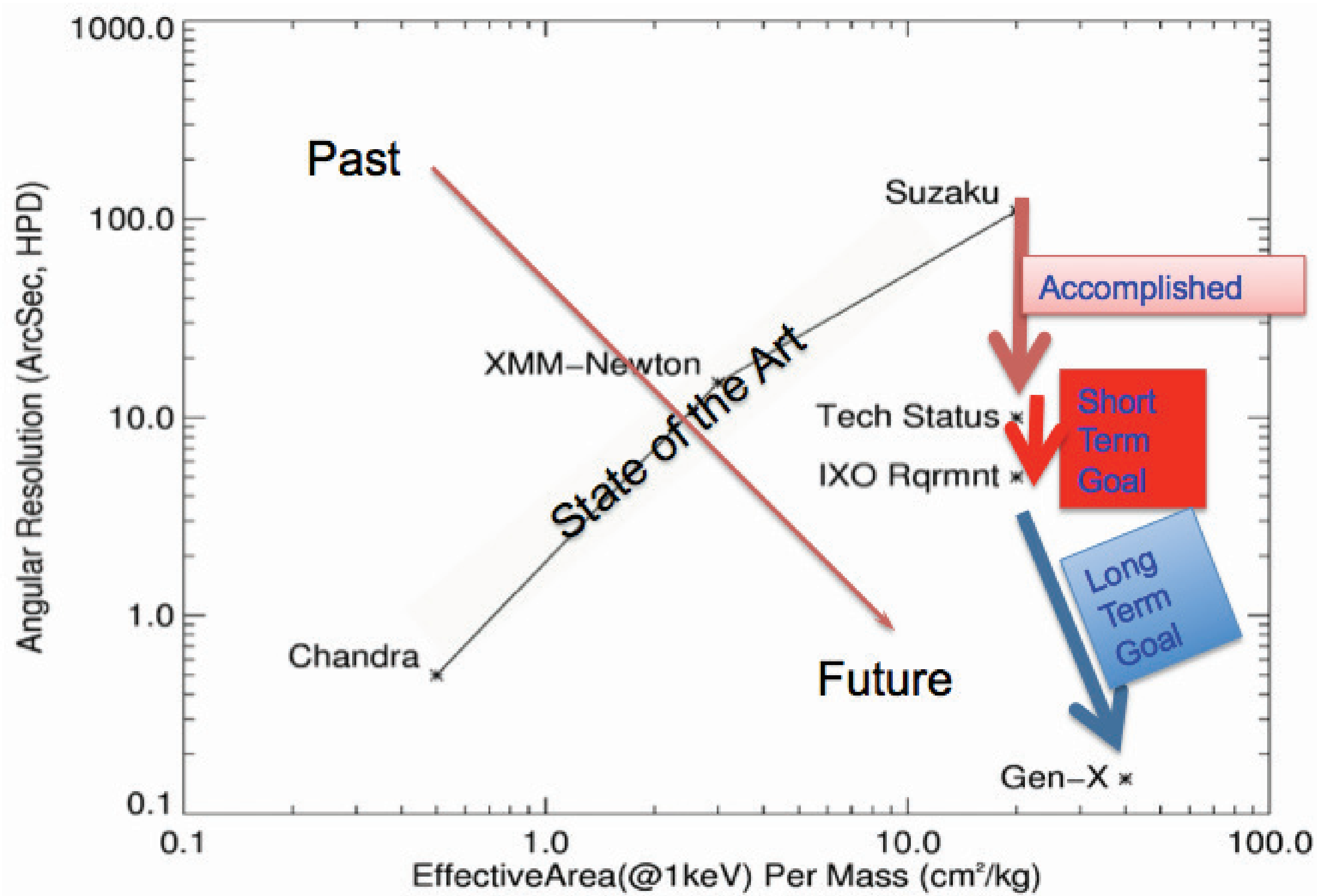
Grefenstette et al. 2014.

Broad energy range and imaging allows radioactive mapping.

Improvements on NuSTAR within reach of a medium-sized probe mission.

- 3-10 times larger collection area.
- ~10 times better angular resolution.
- Broader energy range: 3-80 keV →0.15-200 keV.
- Better energy resolution at low energies (400 eV → 150 eV).
- Add new capability of polarimetry.
- Better absolute timing (2msec → ~1μsec).

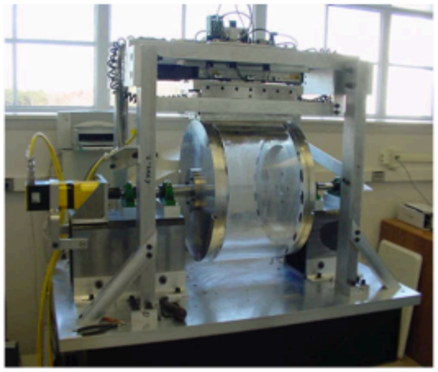
Technical Opportunities – X-ray Optics



Zhang et al. 2011

Technical Opportunities – X-ray Optics

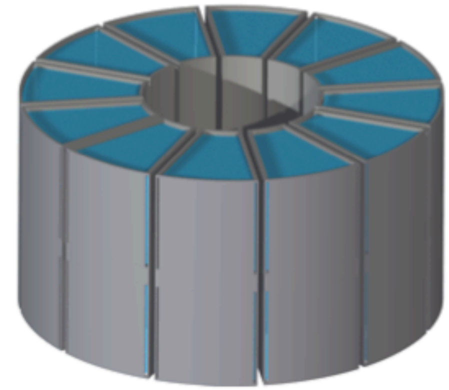
Mandrel Fabrication



Mirror Segment

Mirror Module

Mirror Assembly

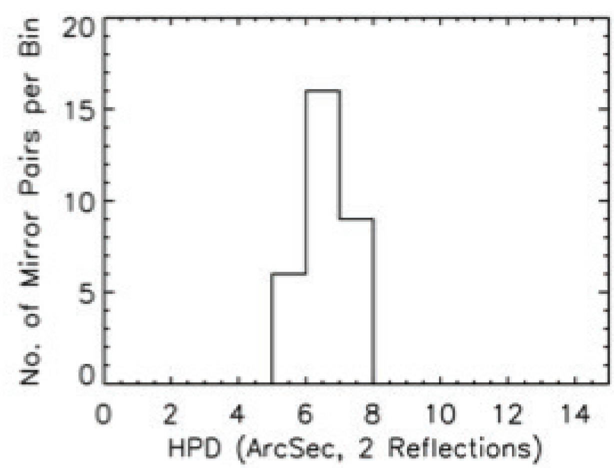


Mirror technology (Zhang et al.):

• *Precision slumping* of 0.4 mm thick borosilicate glass sheets.

• Fabrication, alignment, bonding of segments: 5-10″ HPD at 4.5 keV.

• R&D: Multi-layer coatings that maintain ang. resolution (stress cancellation: atomic layer deposition or multi-layers).

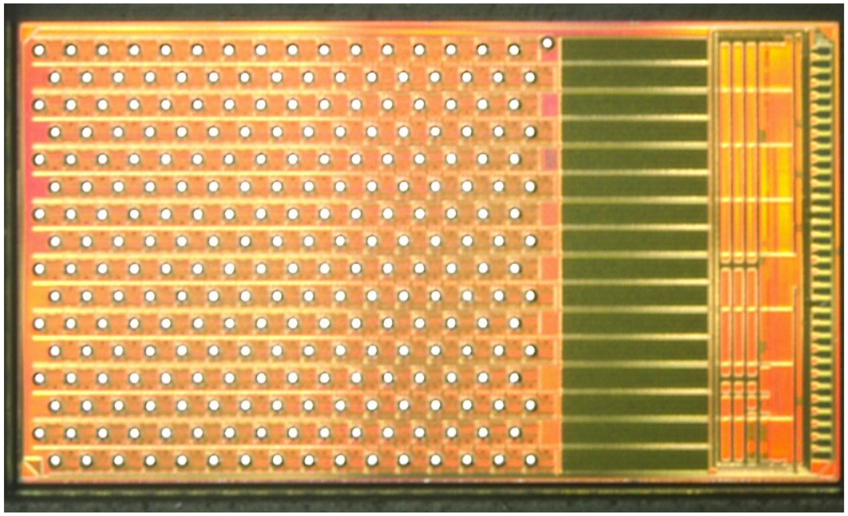


Zhang et al. 2011

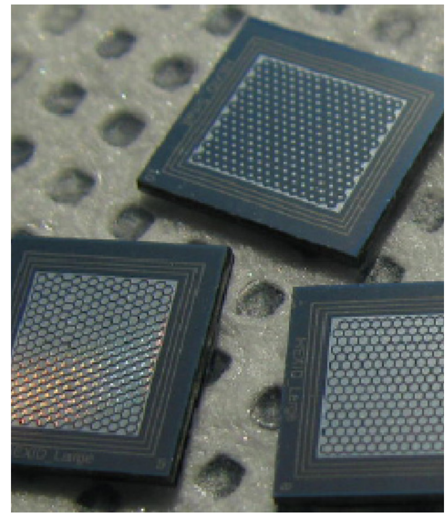
• HEX-P: NiV/S coating can extend the energy range to 200 keV (Christensen et al. 2014)

Technical Opportunities - Detectors

Brookhaven ASIC (130 nm CMOS)



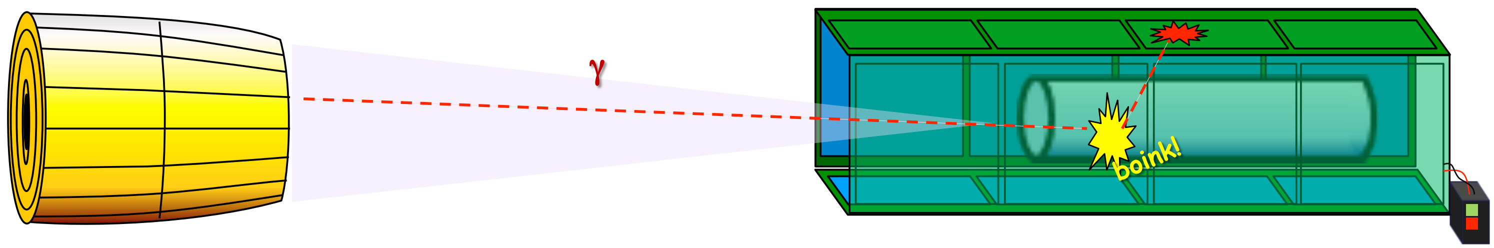
Pixel-Detectors



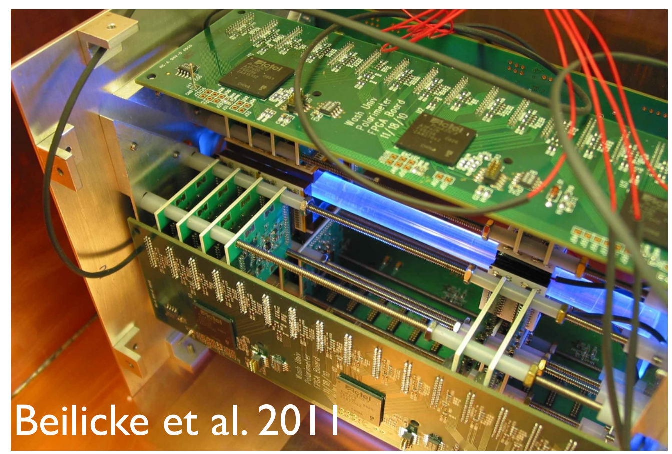
• Development of 1mm and 2mm thick CdTe and CZT detectors with pixels at a pitch of 200-250 µm pixels and readout ASIC (Beilicke, Zajczyk, de Geronimo, S. Li, HK).

• HEX-P: Si/CdTe sandwhich: 150 eV FWHM @ 6 keV.

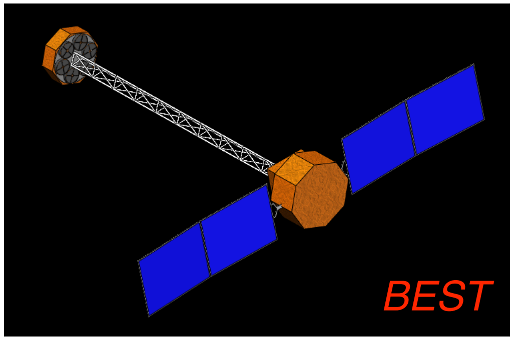
Technical Opportunities – Polarization Detector



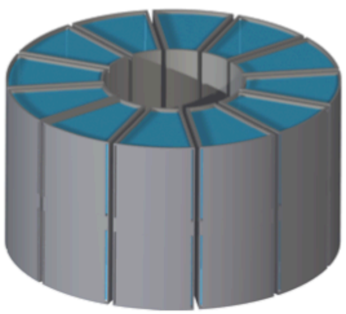
Satellite (LiH-scatterer): 2.5-70 keV; Balloon (plastic scatterer): 20-70 keV.



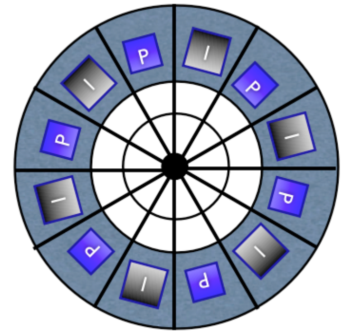
BEST (Black Hole Evolution and Space Time) in a Nutshell



X-ray Mirrors:



- 10-12m focal length.
- Broadband: 2-70 keV.
- Area: 3000 cm^2 at 6 keV.
- Ang. Res.: <10″ HPD.



Focal Plane Instrumentation:

- Hard X-ray Imager (2.5-70 keV).
- X-ray polarimeter (2.5-70 keV).

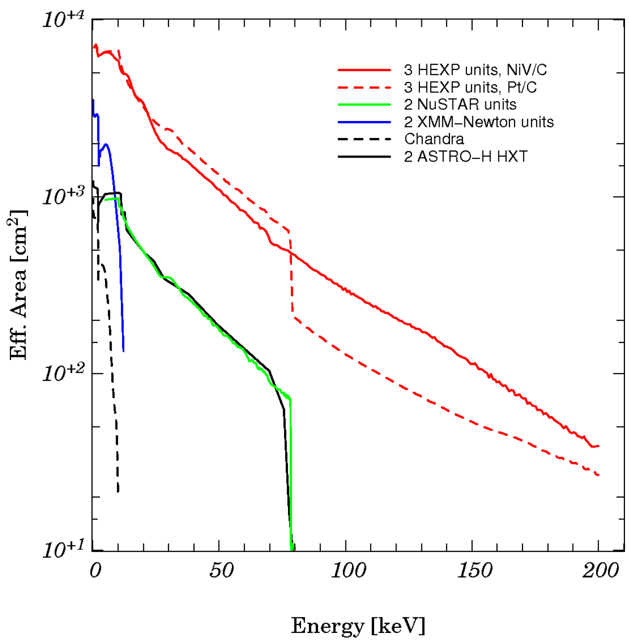
Performance:

- >10 times more sensitive than *NuSTAR*,
- <1% Minimum Detectable Polarization (99% Confidence Level) for 1 mCrab Sources.

Mission Cost Estimate: ~$600M.

arXiv:1205.3691

High Energy X-Ray Probe HEX-P (Harrison et al.)



Parameter	*IXO* (HXI+WFI)	*HEX-P*	*ATHENA* (XMS)	*NuSTAR*
bandpass	0.1 - 40 keV	0.15 - 200 keV	0.1 - 10 keV	5 - 80 keV
angular resolution [HPD]	5″ (3 - 7 keV) 30″ (7 - 40 keV)	10″ - 15″	10″	50″
spectral resolution [FWHM]	150 eV @ 6 keV 1.5 keV @ 60 keV	150 eV @ 6 keV .5 keV @ 60 keV	3 eV @ 6 keV	600 eV @ 6 keV 1.2 keV @ 60 keV
timing resolution	1.3 msec	0.1 msec	—	—
field of view [FWZI]	18′ × 18′ (0.1 - 15 keV)	13′ × 13′ (0.1 - 100 keV)	2.4′ × 2.4′	13′ × 13′

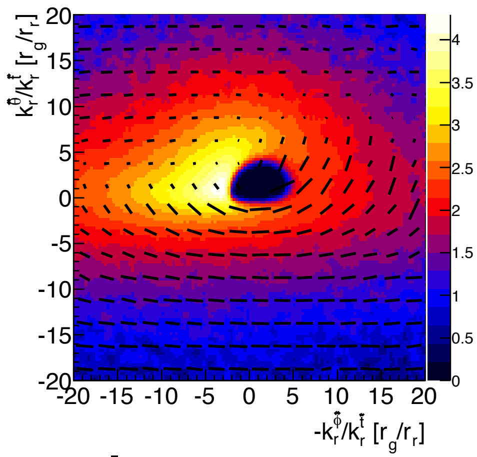
3 20m focal length mirrors, each: 390 shells (NiV/C,W/Si).

Si active pixel sensors & CdTe sandwhich detectors

Mission Cost Estimate: ~$500M.

Coverage from Soft X-Rays (<1 keV) to Soft Gamma-Rays (~200 keV)

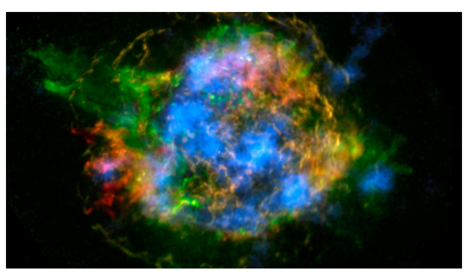
Thermal emission from the most extreme objects in the Universe



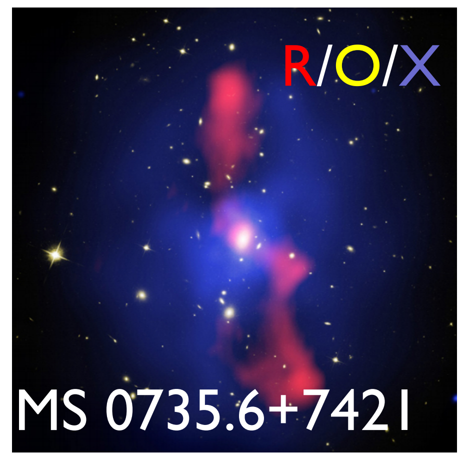
Innermost
BH accretion disks

Magnetars

Nuclear
gamma-rays
^{44}Ti ^{56}Ni ^{57}Co



Non-thermal emisson from the most violent processes n the Universe



NASA/CXC/Univ.Waterloo/B.McNamara; Optical: NASA/ESA/STScI/Univ.Waterloo/B.McNamara; Radio: NRAO/Ohio Univ./L.Birzan et al.

Weakness: narrow field of view.

BEST – How and When Did Supermassive Black Holes Grow?

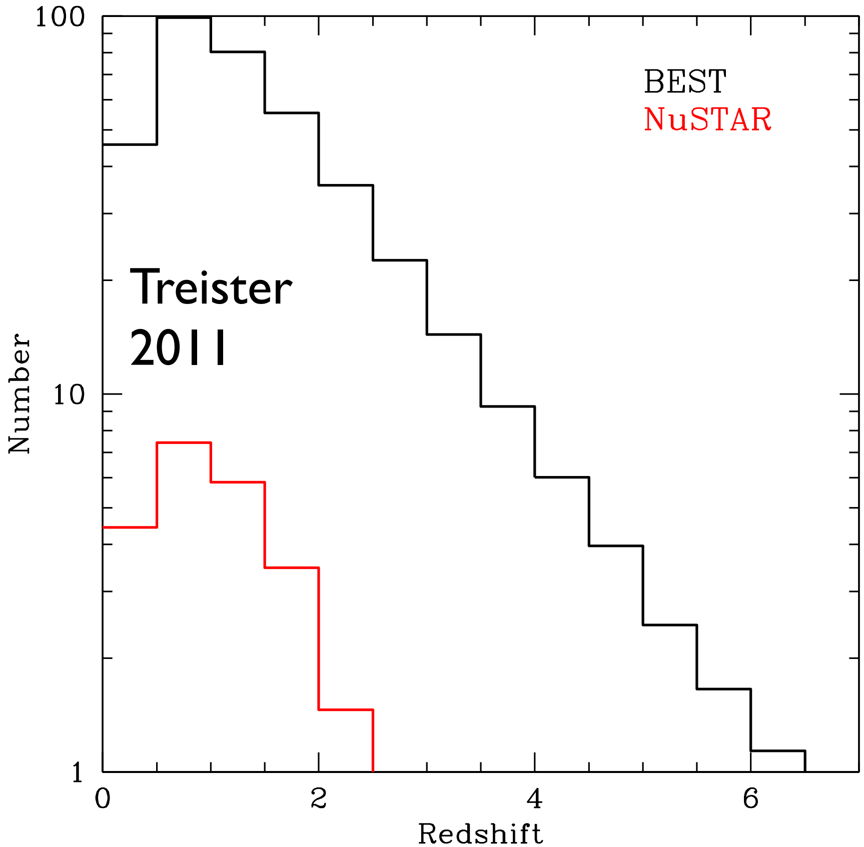
Rationale:

- Most surveys of black growth severely biased.
- Heavily obscured AGN are not included in optical, UV and E<10 keV X-ray surveys
- XMM-Newton/Chandra data at E<10 keV strongly affected by obscuration. Compton-thick AGN nearly missing in these surveys. Even the deepest Chandra surveys miss as much as 50% of the AGN activity (Treister et al. 2004, 2010).
- IR surveys are based on a secondary indicator depending on emitted spectrum and geometry, and properties of the host galaxy (Ballantyne et al. 2011).

Current and upcoming missions:

- Swift/*BAT* and *INTEGRAL* only sensitive to AGN in the local Universe, $z<0.1$.
- *NuSTAR* improves this situation, to z~1.
- Bulk of black hole growth is most likely at z~2 (Treister et al. 2010).

BEST – How and When Did Supermassive Black Holes Grow?



Based on AGN E<10 keV luminosity function (Ueda et al. 2003) • Compton-thick AGN matched to z=0 Swift/BAT and INTEGRAL (Treister et al. 2009) • Match spectrum and intensity of extragalactic X-ray background (Treister et al. 2009) • Numbers at z>2 uncertain. Probably lower limit.

BEST in 10^6s:

- ~380 AGN detections in F.o.V.,
- >40% obscured AGN,
- >10 AGN at z>4,
- >1 AGN at z>6.

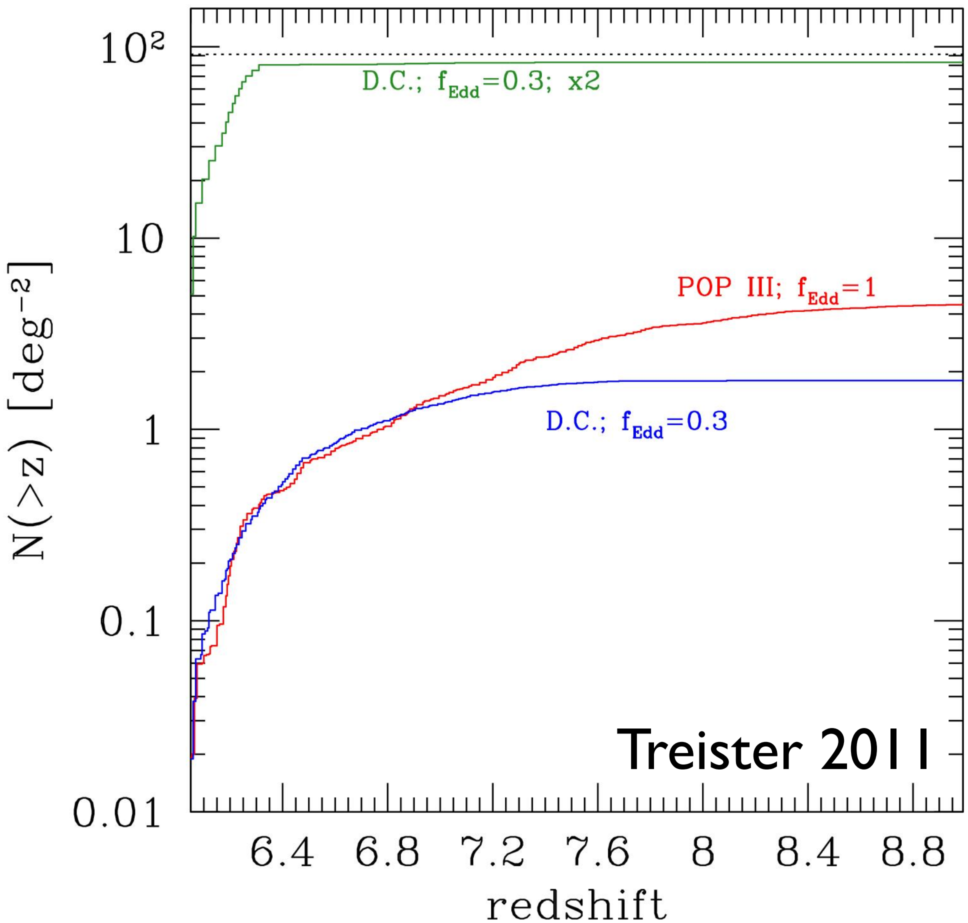
A 10^6 s pointing would resolve 93% of the background between 10 and 30 keV.

BEST – How and When Did Supermassive Black Holes Grow?

Potential *BEST* AGN Survey (1.5 years with 50% efficiency):

- Wedding-cake scheme with the following surveys:
  - Deep 0.1°^{2} GOODS-like (two 4×10^6s-pointings, $F_{10\text{-}30\ \mathrm{keV}} \geq 4\times10^{-16}$ cgs),
  - Medium-depth 1°^{2} COSMOS-like (fifty 20ks-pointings, $F_{10\text{-}30\ \mathrm{keV}} \geq 1.7\times10^{-15}$ cgs),
  - Shallow BOOTES-like 10°^{2} survey (500 10ks-pointings, $F_{10\text{-}30\ \mathrm{keV}} \geq 8\times10^{-15}$ cgs).
- Motivation:
  - High-z AGN from deep survey,
  - Many sources for luminosity function from medium-depth survey,
  - Luminous sources from the shallow survey.

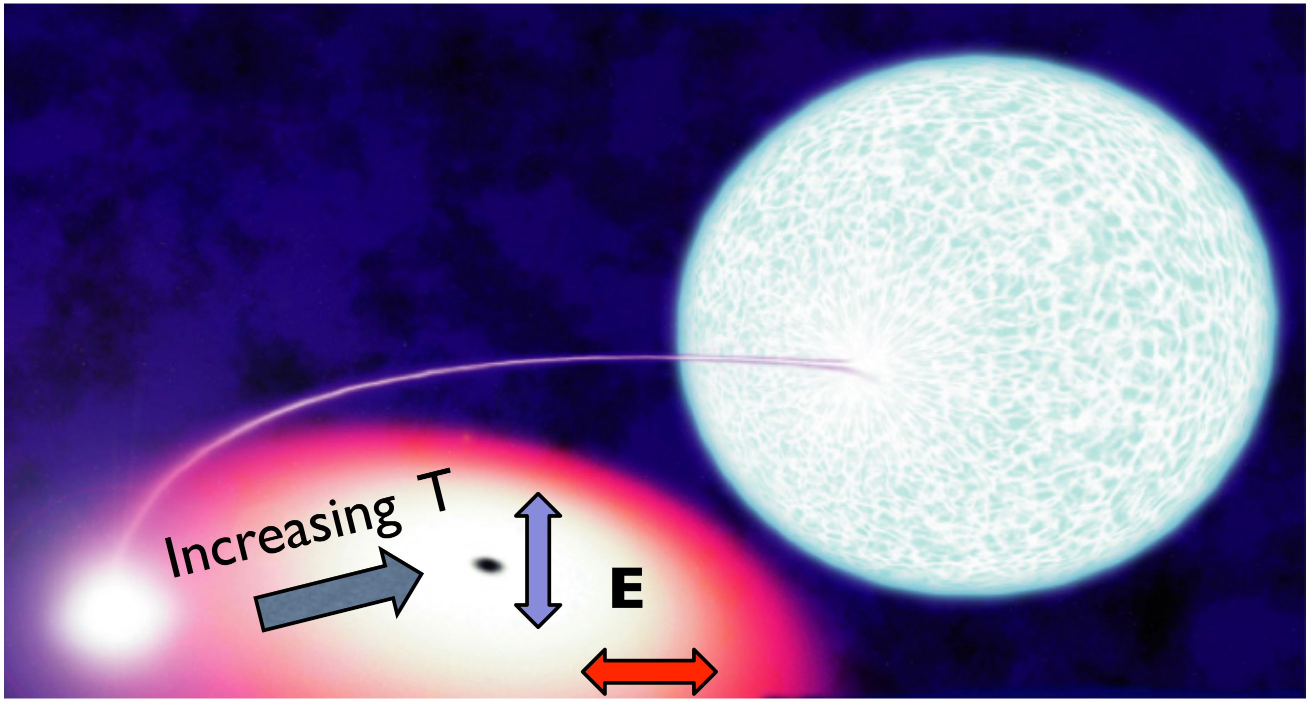
BEST – How and When Did Supermassive Black Holes Grow?



A few AGN can separate models of the formation of the first super-massive black holes (from Pop III stars or direct collapse of H clouds).

Detecting 10-20 AGNs at z>6 → formation of first supermassive black holes.

BEST – What Happens Close to a Black Hole?

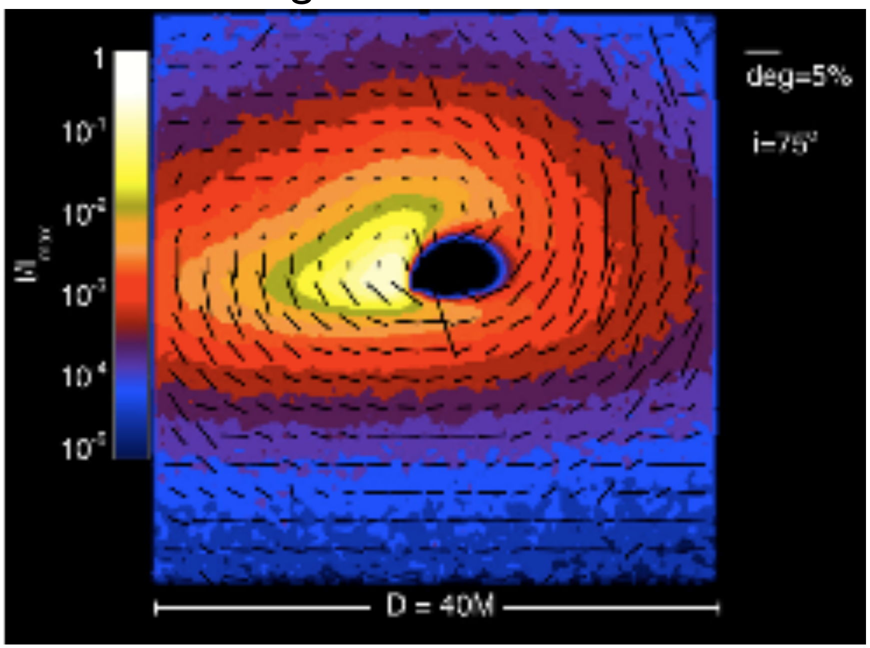


Curved trajectories close to black hole result in 90˚ polarization swing:

- Precision tests of accretion disk models.
- Measurements of black hole parameters including spin.
- Detailed probe of corona geometry.
- Test General Ralativity in strong gravity regime.

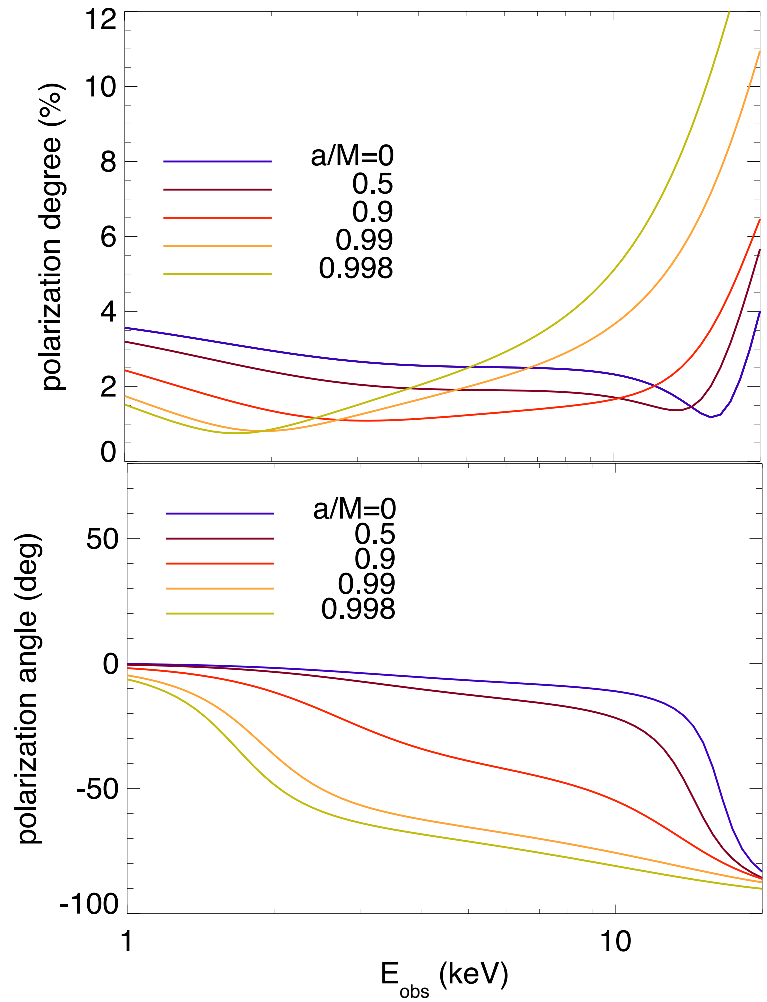
BEST – What Happens Close to a Black Hole?

Ray tracing of polarized emission including diffuse reflection:



Mass: 10 $M_\odot$, a_*=0.99

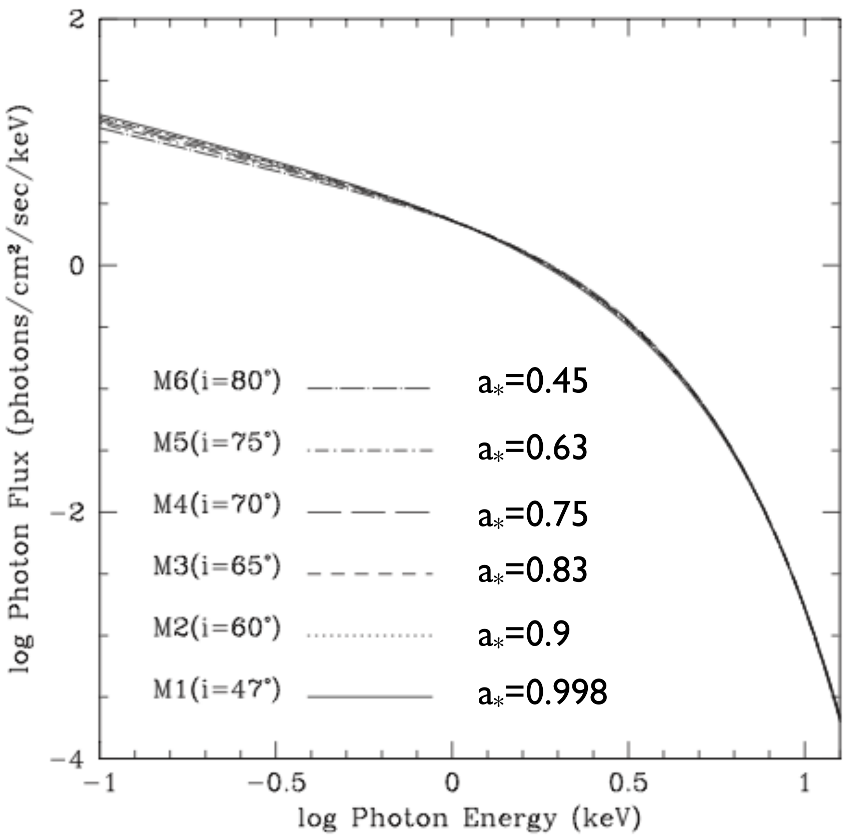
Schnittman & Krolik 2009, ApJ, 701, 1175



BEST: Measure black hole spins and test disk models!

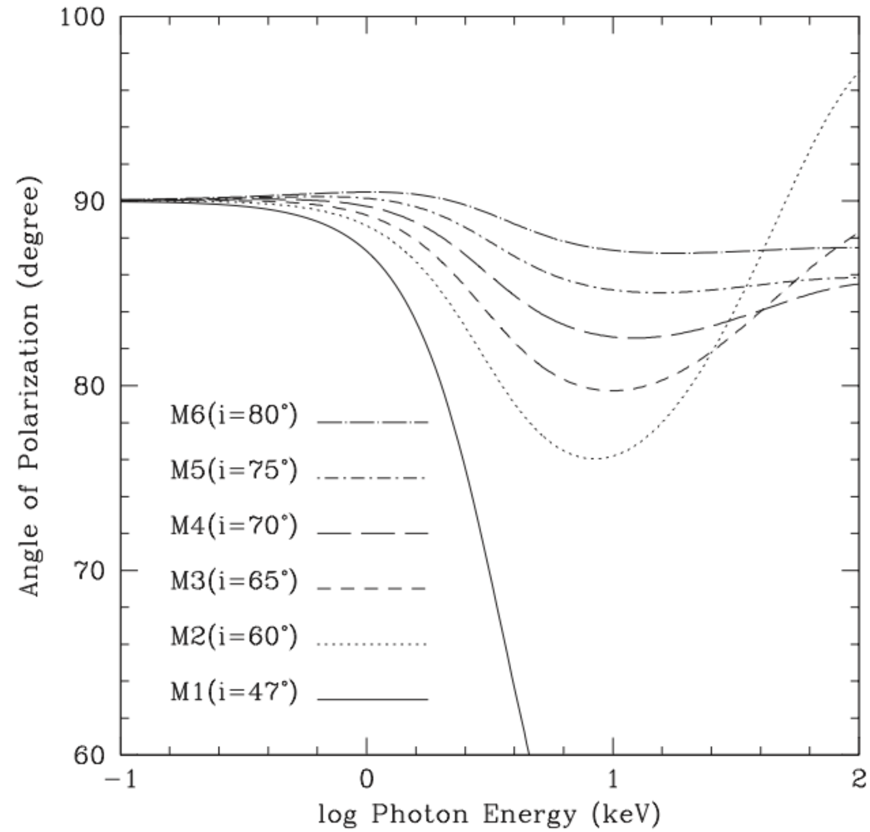
The Role of X-Ray Polarimetry

X-ray energy spectra for 6 different a_*, *I*, *M-dot* combinations:



M=10 $M_\odot$; D=10 kpc, spect. hard. factor 1.6, disk truncated at ISCO with zero torque.

Li, Narayan & McClintock et al. 2009



X-ray polarization can break model degeneracies!

Additional Science Drivers

Stellar mass black holes:
- Origin of QPOs (time resolved spectroscopy, polarimetry).

Neutron stars:
- Particle acceleration (polarimetry).
- Masses and radii (time-resolved spectroscopy of Type 1 X-ray bursts, accretion disk emission).
- New Physics of Magnetars.

Supermassive black holes:
- Cosmic history of black hole formation, growth, and accretion.
- Measure ~100 black holes spins (Fe K-α energy spectra).
- Constrain structure of inner accretion flow (reverberation mapping, polarimetry).
- Structure/content of AGN jets (imaging of kpc-jets, polarimetry of blazar jets)

Gamma Ray Bursts Afterglows:
- Jet structure (polarimetry).

Starburst Galaxies: Compact objects, hot gas.

Large Scale Structure: Search for hard X-ray emission from non-thermal particles in cluster haloes, relics, and large scale structure formation shocks.

Fundamental Physics:
- GR (spectroscopy, timing and polarimetry).
- QED (magnetar and neutron star polarimetry).
- Lorentz and CPT Invariance (polarimetry).