BEST – Black Hole Evolution and Space Time

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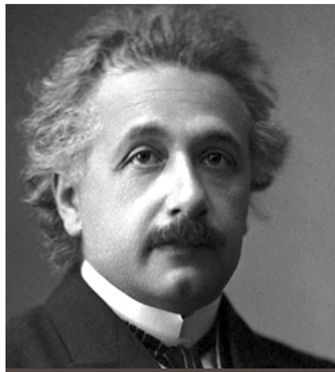
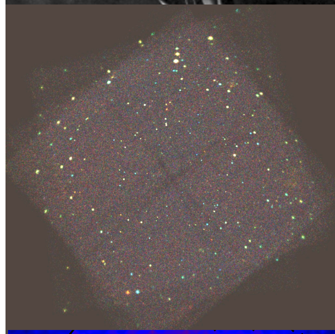
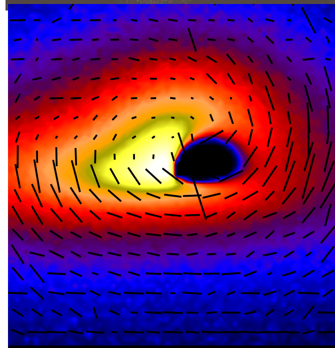
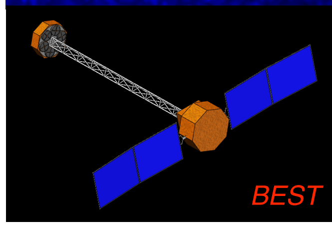




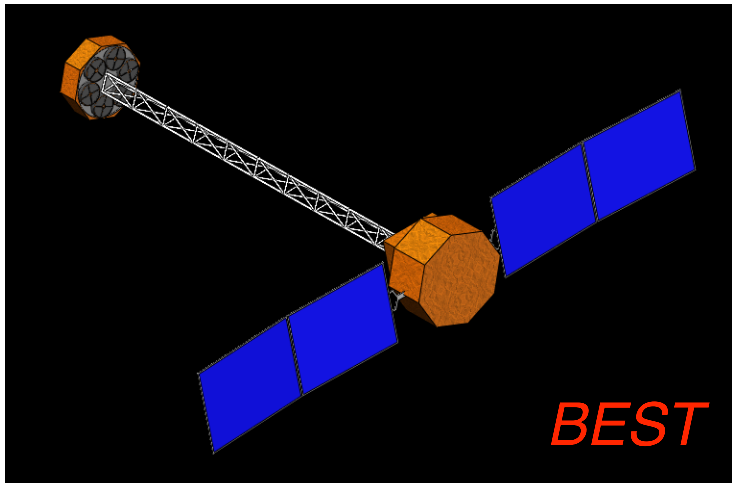


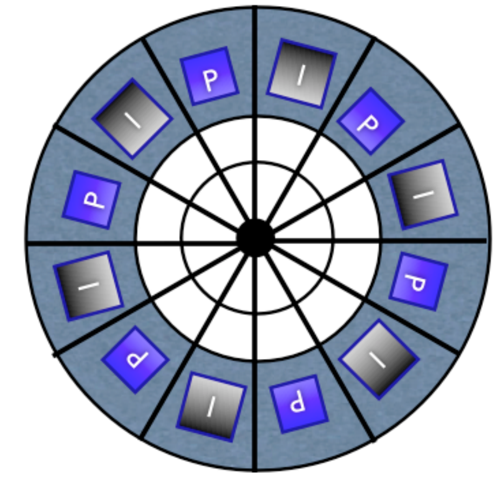


Plan of talk:

- Mission Design.
- *BEST* and the *IXO* Science Matrix.
- Summary and Discussion.

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

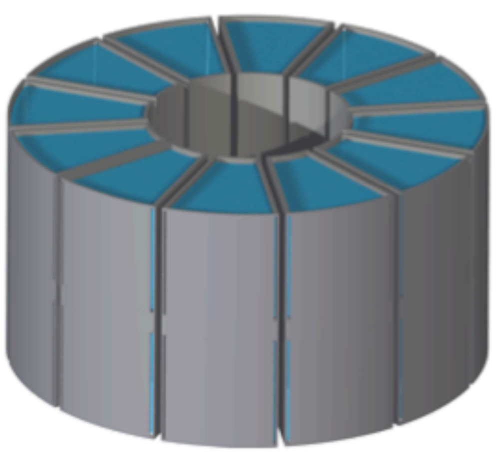




Dual Focal Plane Instrumentation:

- Hard X-ray Imager (5-70 keV).
- X-ray polarimeter (2-70 keV).

X-ray Mirrors:



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

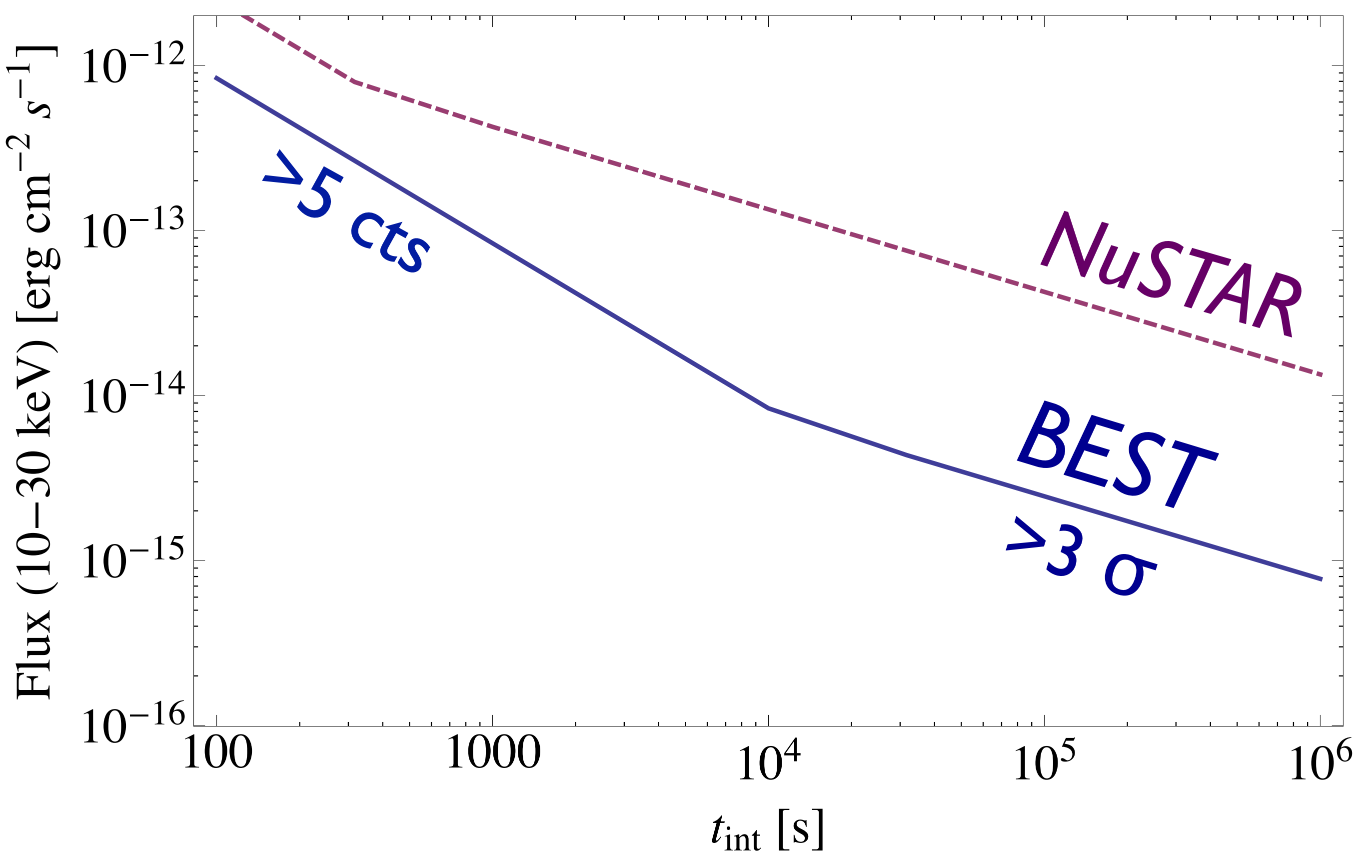
Performance:

- >10 times more sensitive than *NuSTAR*,
- 7.5 times mirror area than *GEMS*,
  7 times broader bandpass.

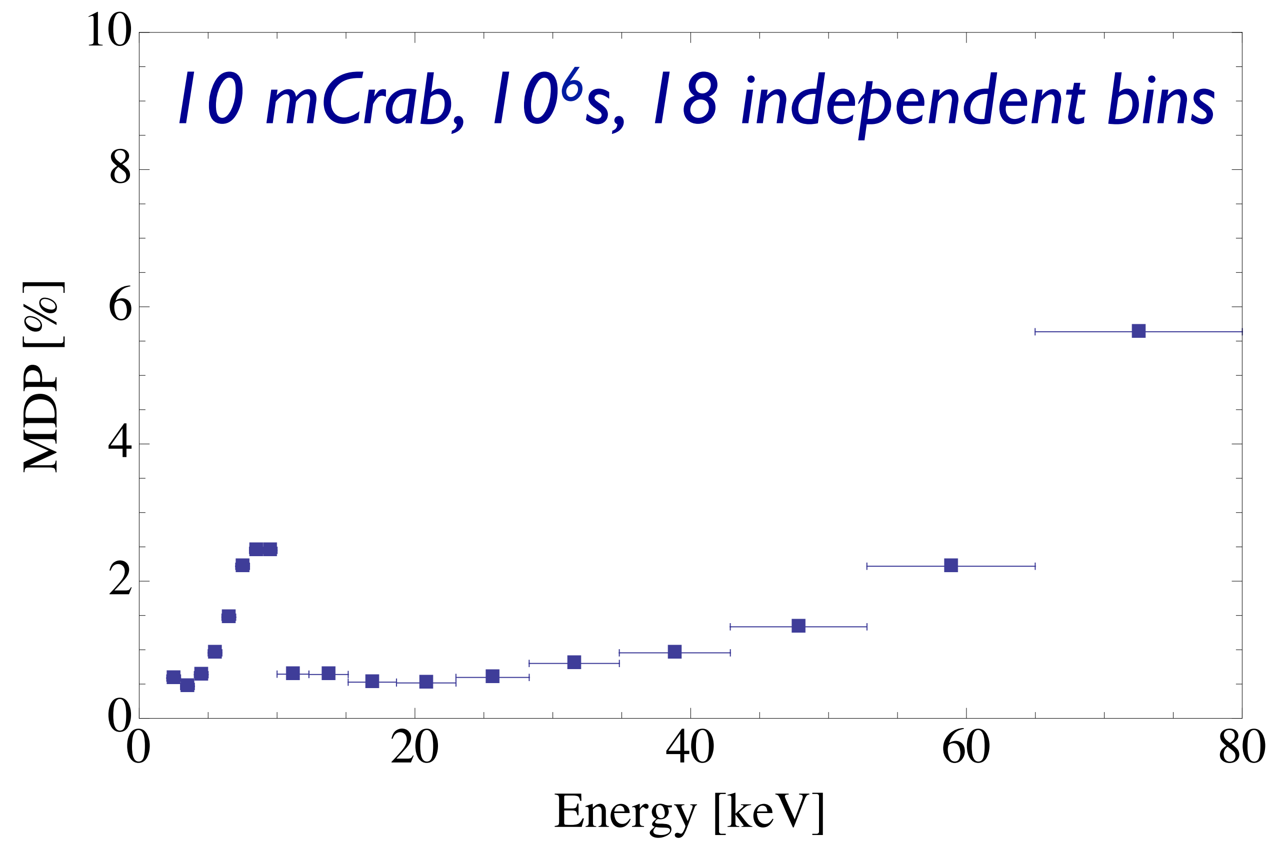
Mission Cost Estimate: $573M.

BEST Performance

Hard X-ray Imager:



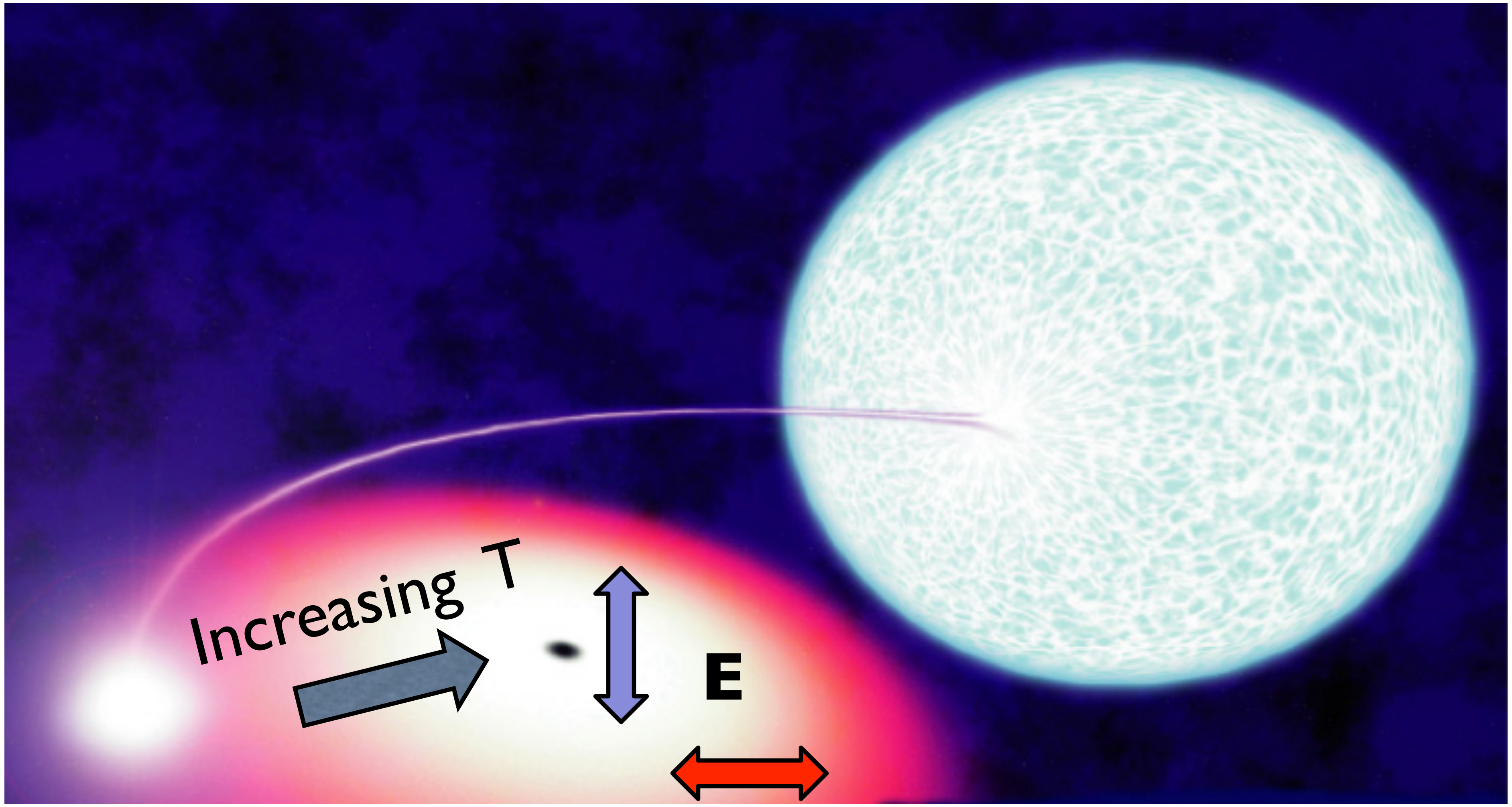
Broadband Polarimeter:



10^6 s: $F_{(10\text{-}30\ keV)}$= 8x10^{-16} erg cm^{-2} s^{-1}.

1 mCrab, 10^6 s, MDP:
0.7% (2-10 keV) & 1% (10-70 keV).

BEST – What Happens Close to a Black Hole?

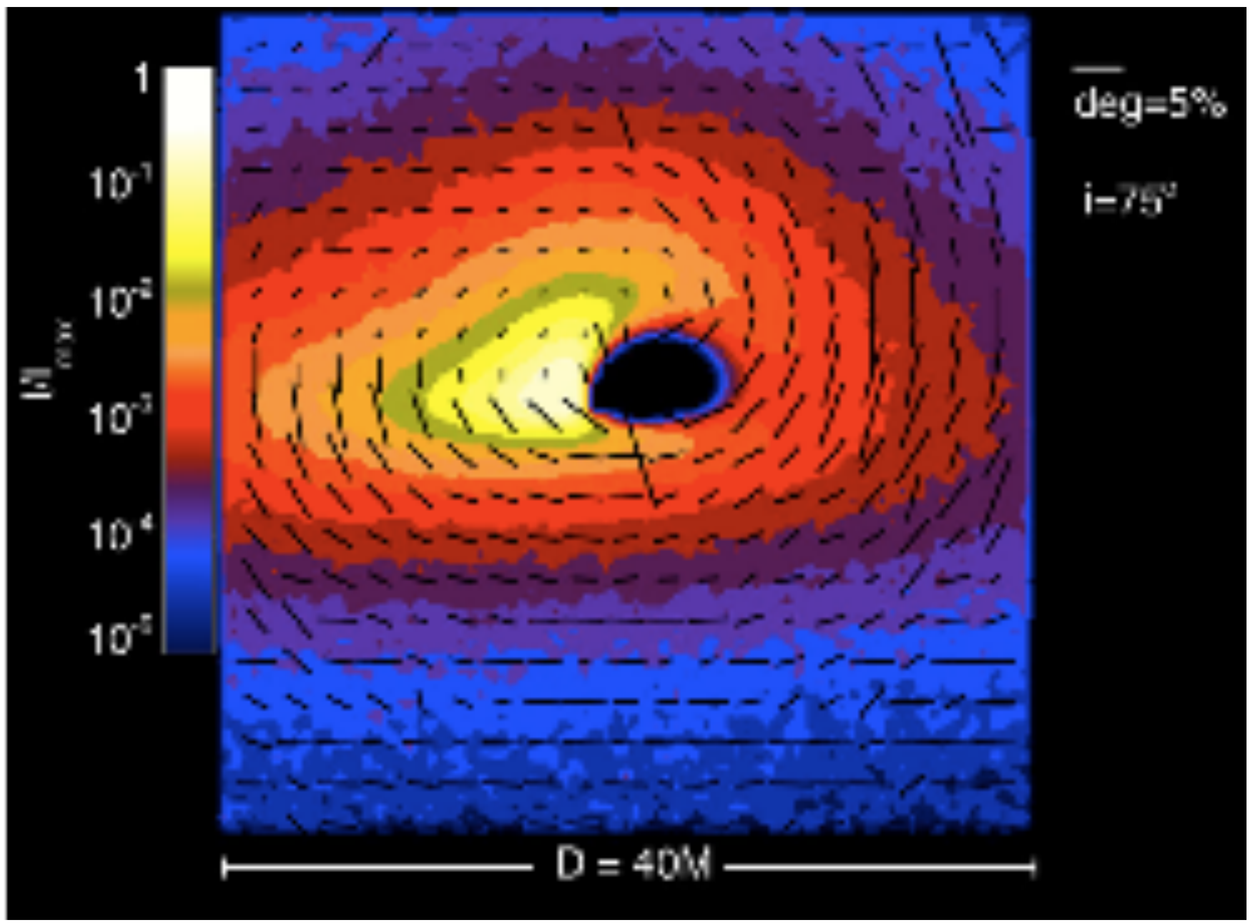


Curved trajectories close to black hole result in 90˚ polarization swing:

- 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.

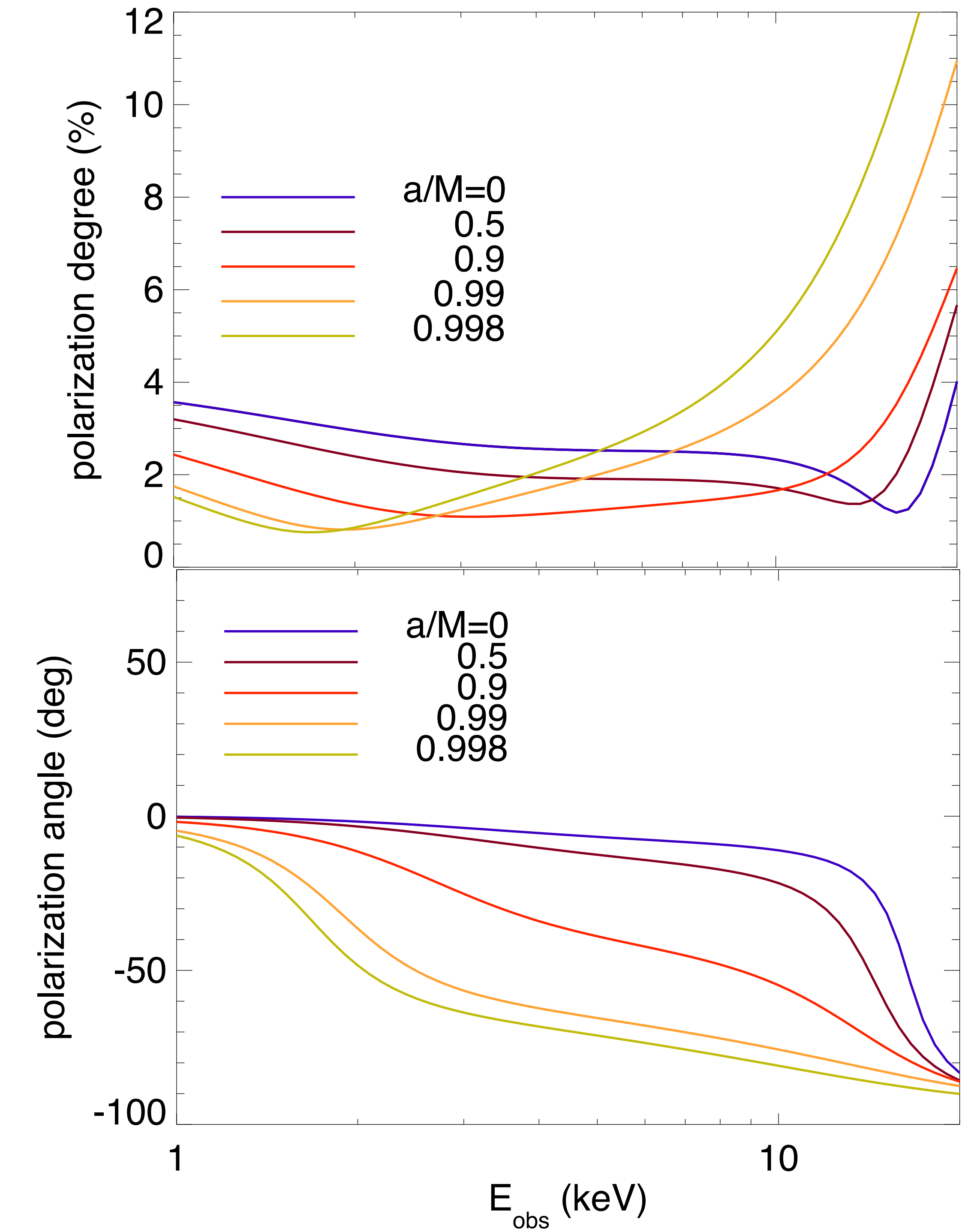
BEST – What Happens Close to a Black Hole?

Ray tracing of polarized emission including diffuse reflection:



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

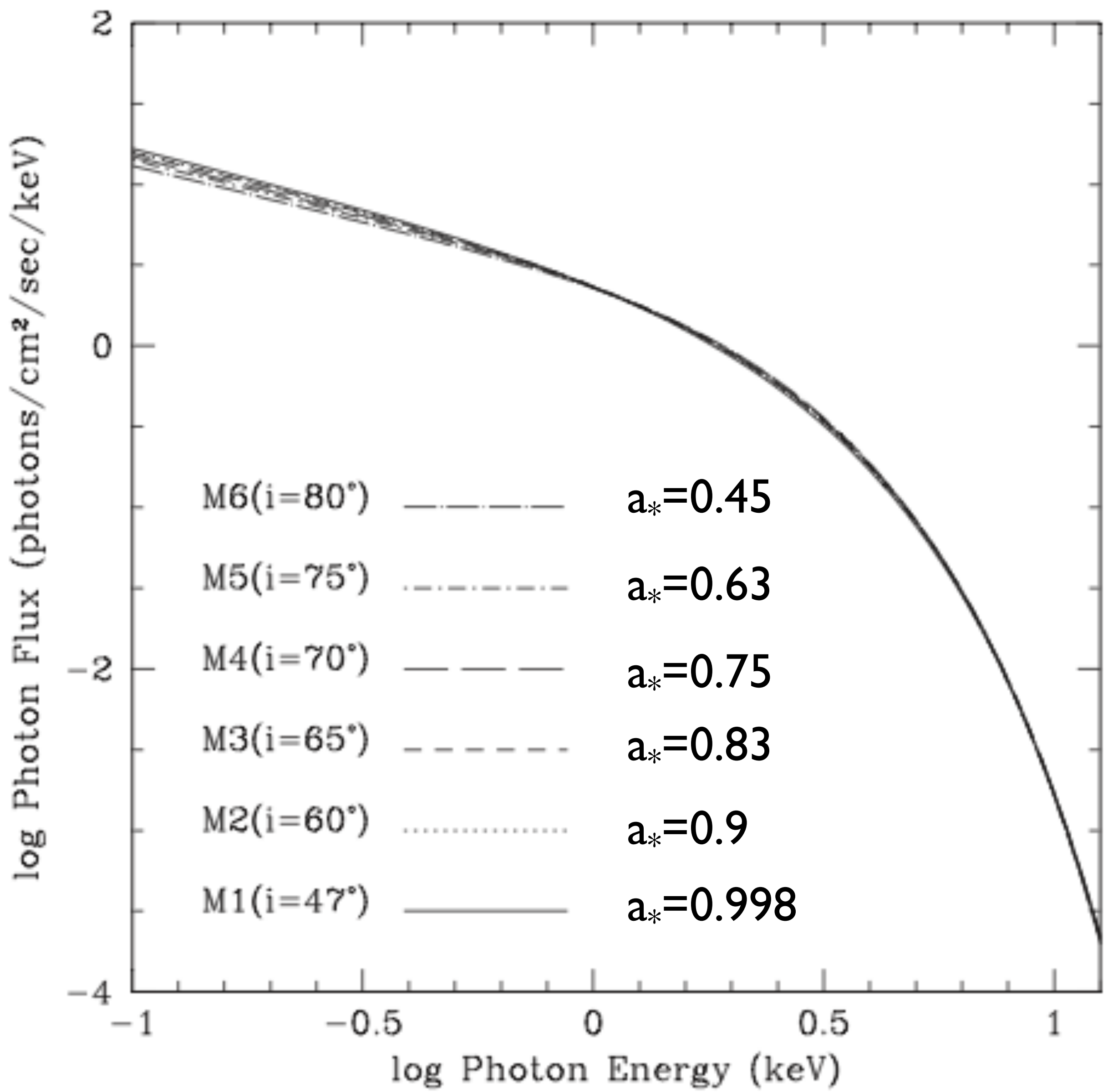
Schnittman & Krolik 2009, ApJ, 701, 1175



BEST: Measure black hole spins and test disk models!

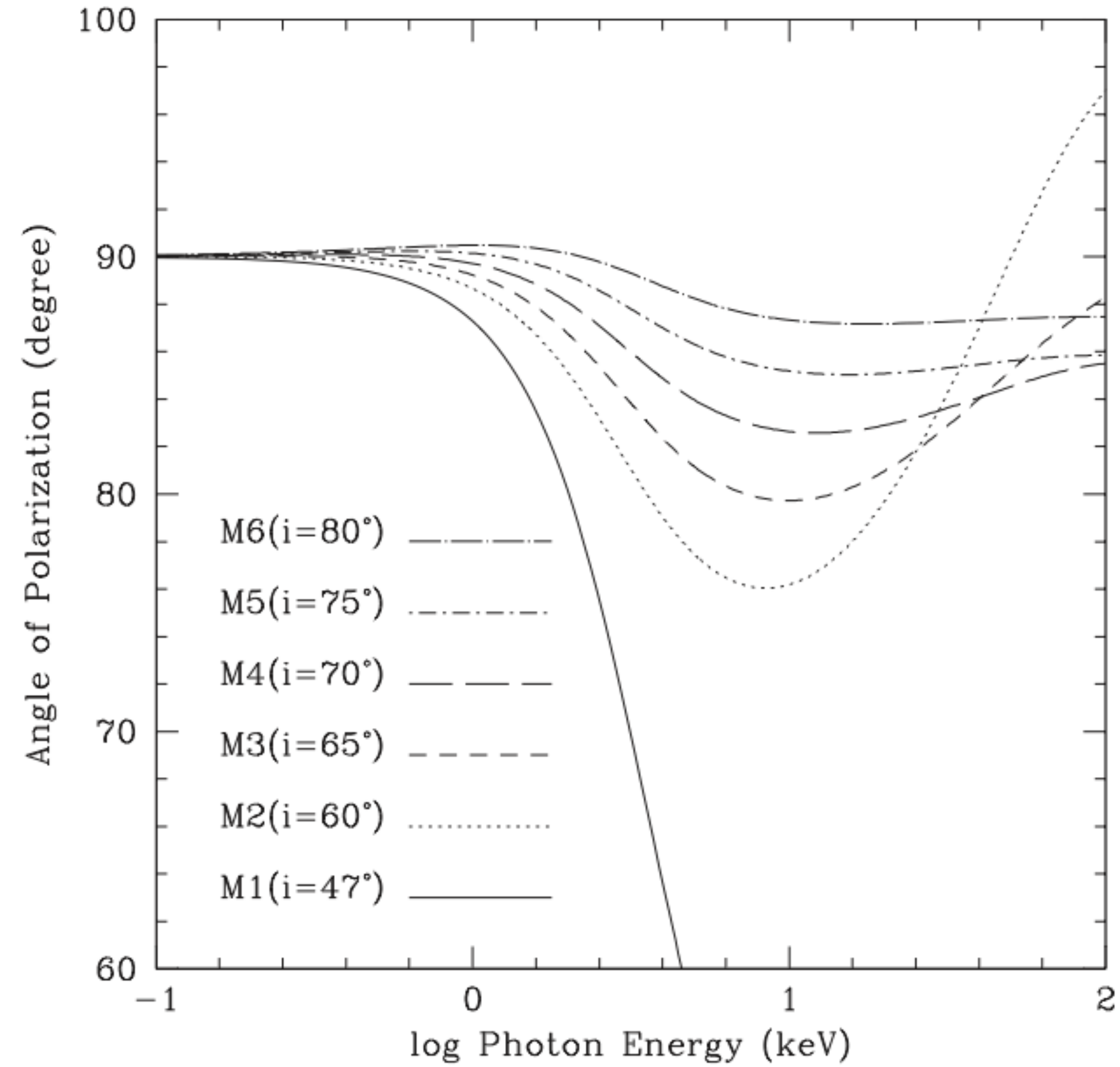
The Role of X-Ray Polarimetry

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



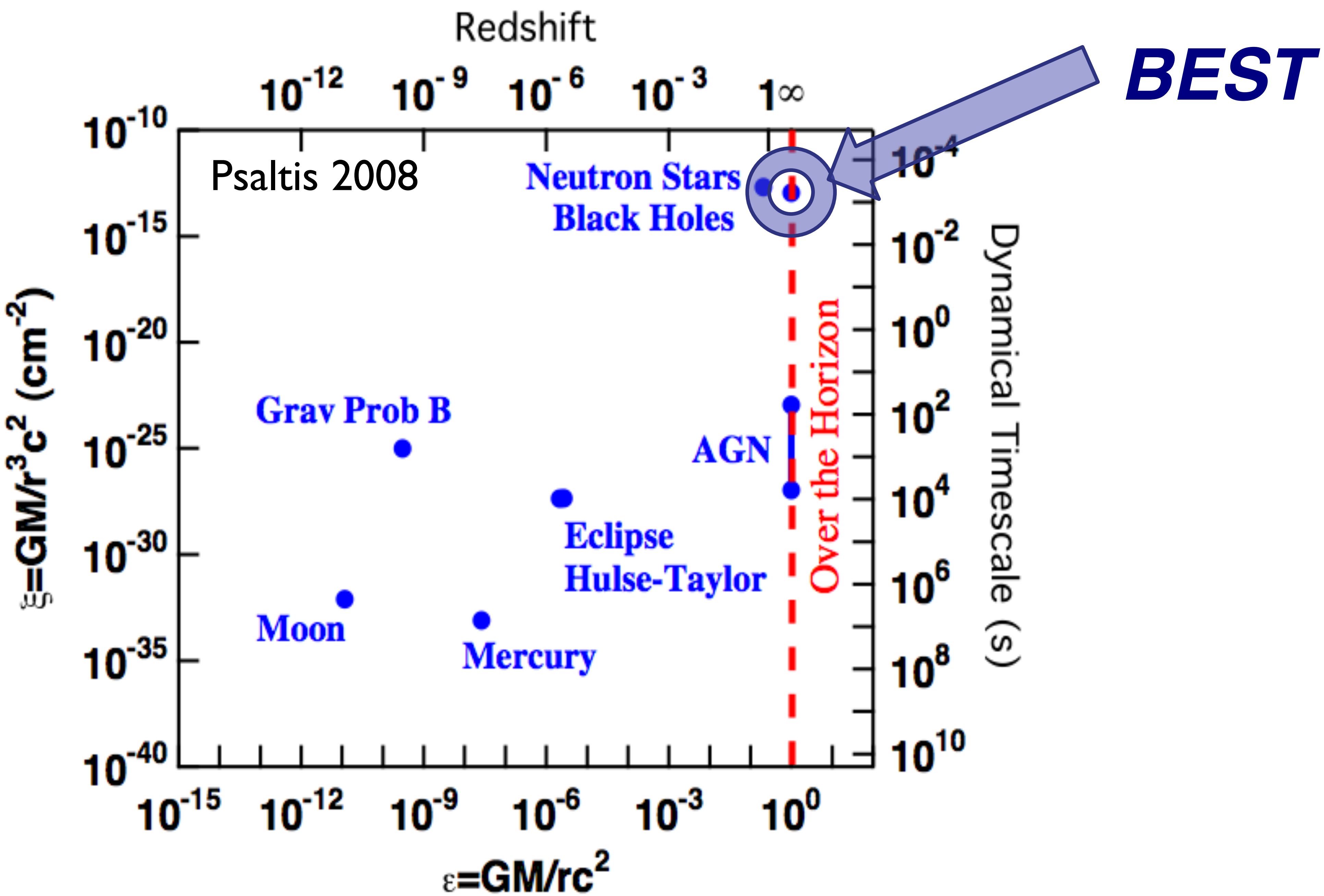
M=10 $M_\odot$; D=10 kpc, spect. hard. factor 1.6, disk truncated at ISCO with zero torque.

Li, Narayan & McClintock et al. 2009



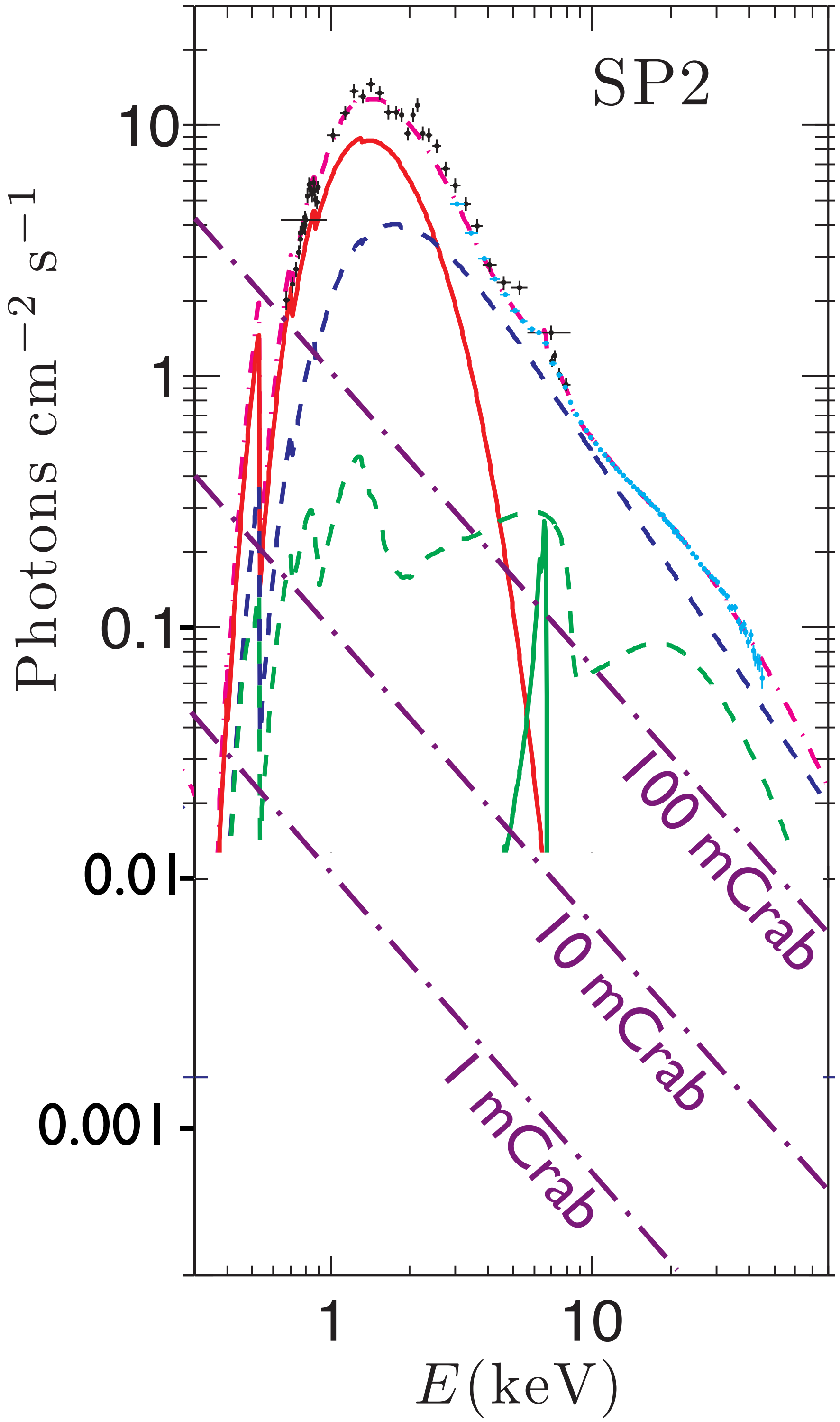
X-ray polarization can break model degeneracies!

BEST – What Happens Close to a Black Hole?

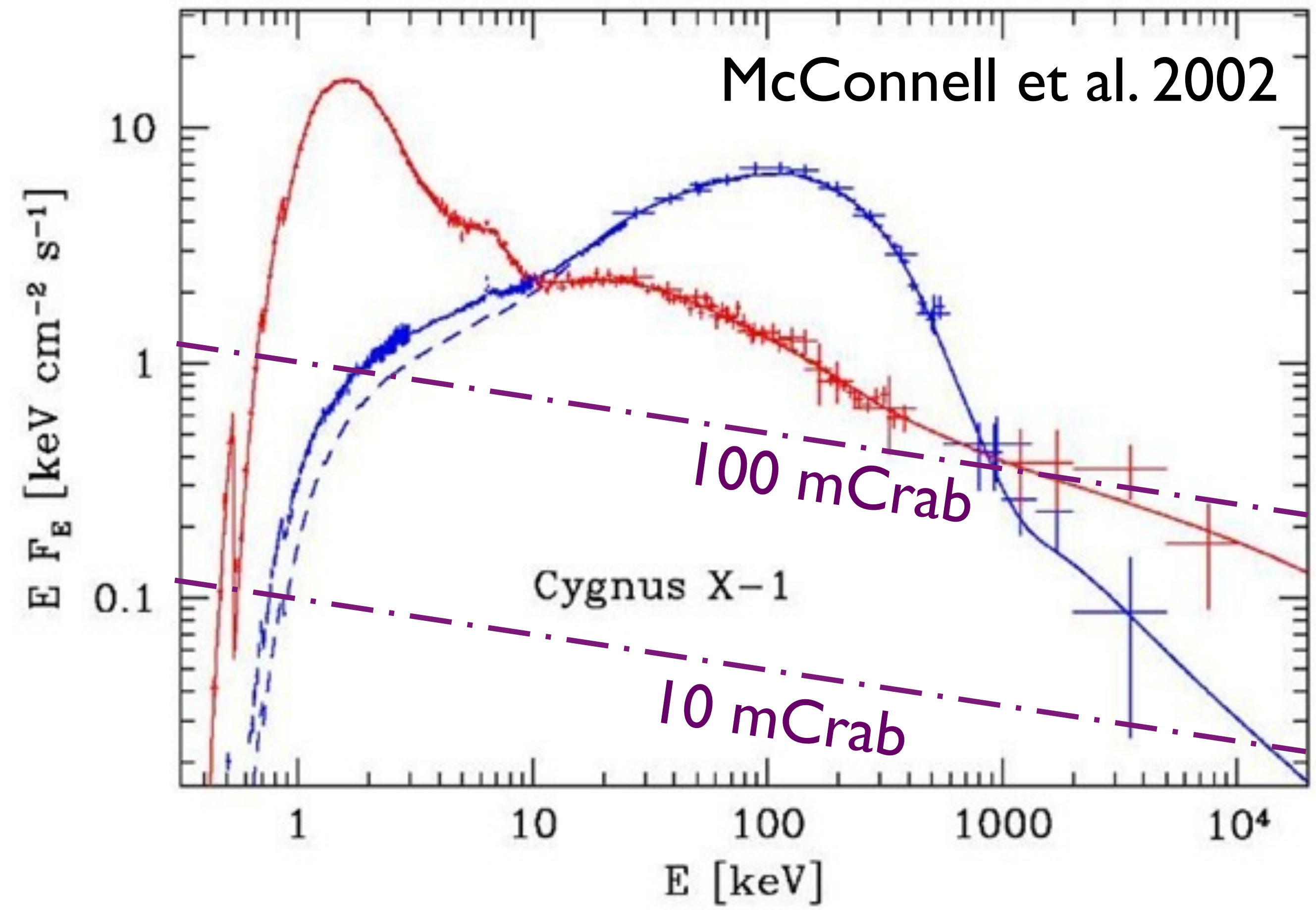


Use alternative metric for quantitative test of Kerr-Metric, No-Hair Theorem, and General Relativity (e.g. Johannsen & Psaltis 2011)!

BEST – Powerful Tests of Disk Models Owing to Broad Energy Coverage



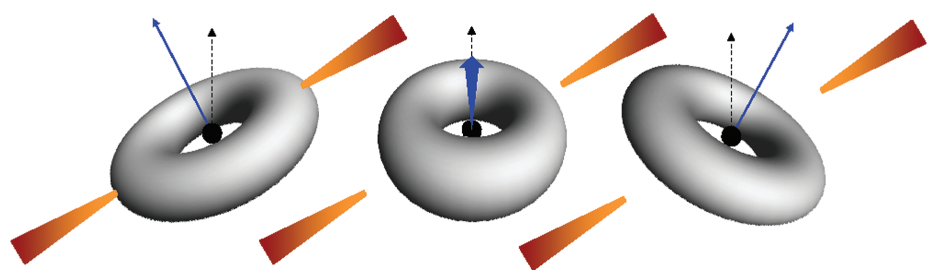
Gou et al. 2011



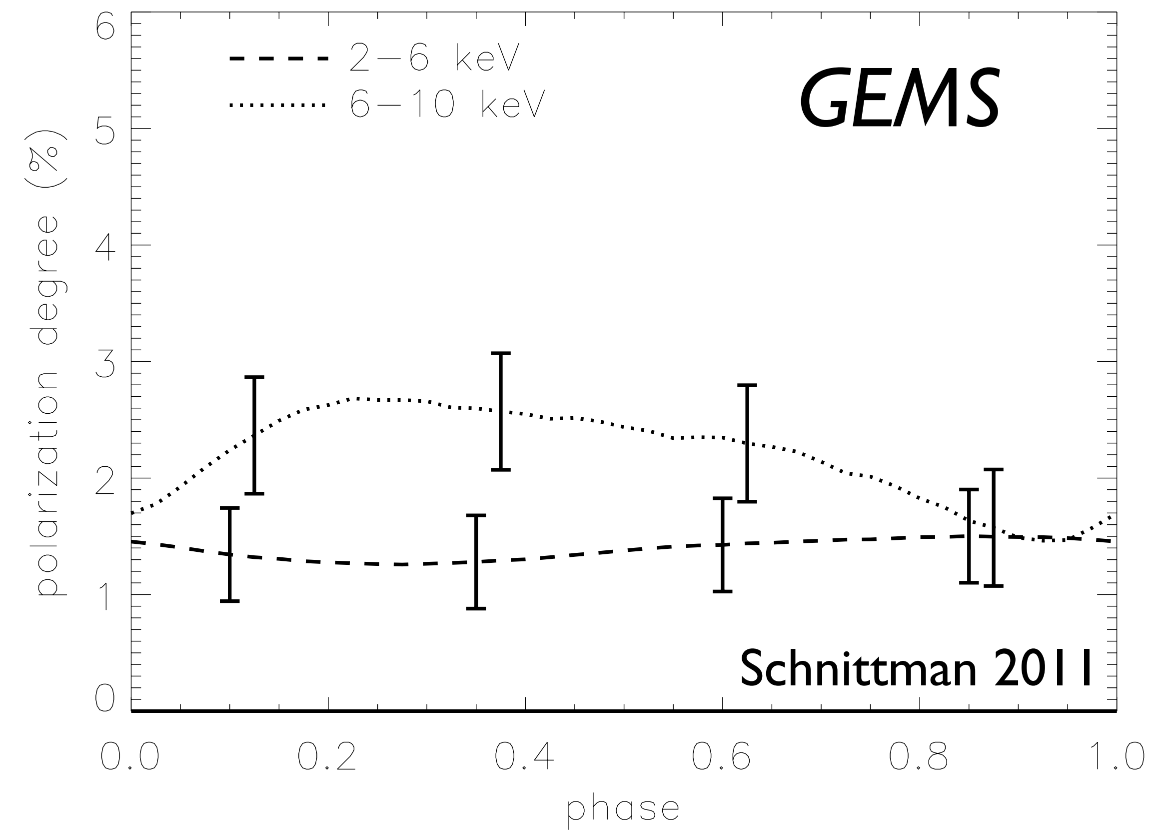
- *BEST:* precision measurements of polarization characteristics from 2-70 keV.
- Hard X-rays ➙ refine <10 keV results.
- Powerful tests of disk+corona+jet models.

BEST – Time & Phase Resolved Polarimetry

Identify Origin of QPOs and make them useable as tool:

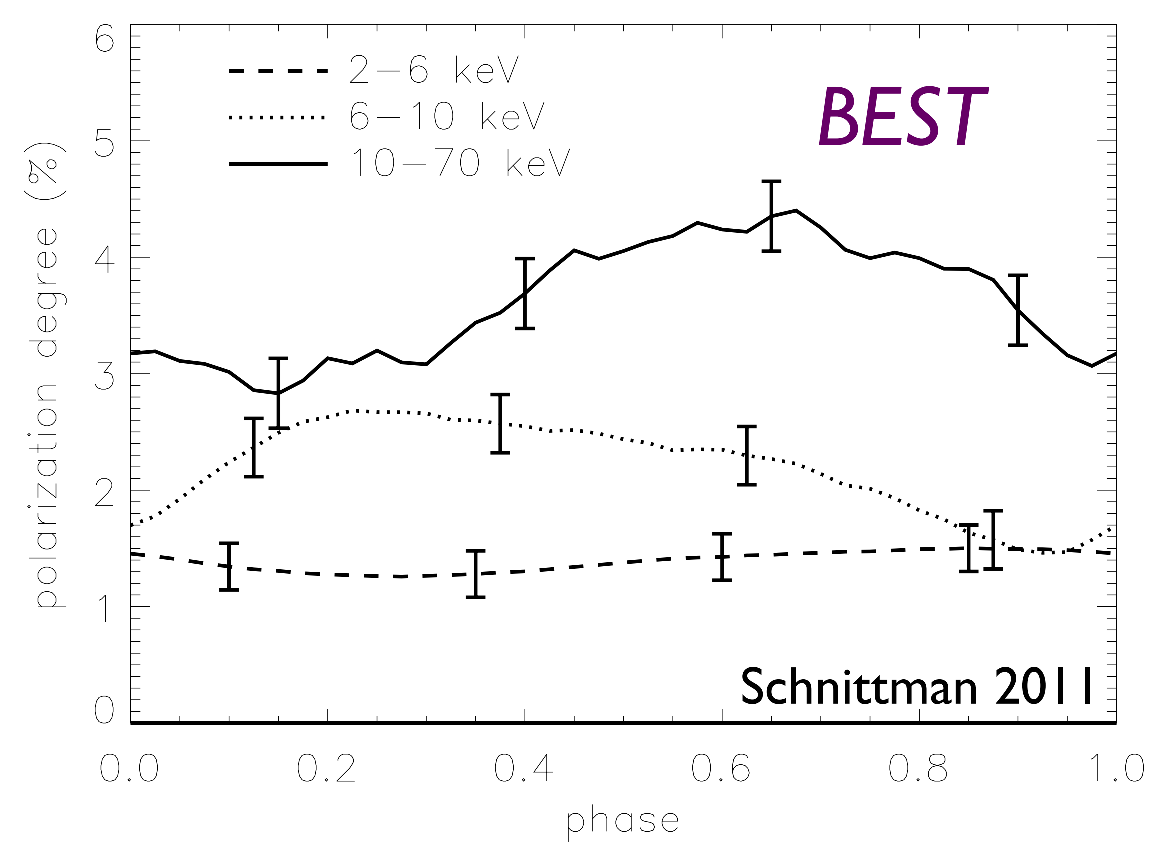


Ingram, Done, & Fragile 2009



Simulation:

- 1 Crab, 10^4 s, 10 $M_\odot$, a/M=0.9, i=70°.
- Disk: 1 keV, Corona: 50 keV.
- Precessing torus:
  R=6-10 M, α=25°, f_{QPO}=10 Hz.



BEST will enable time and phase resolved polarimetry!

BEST – How and When Did Supermassive Black Holes Grow?

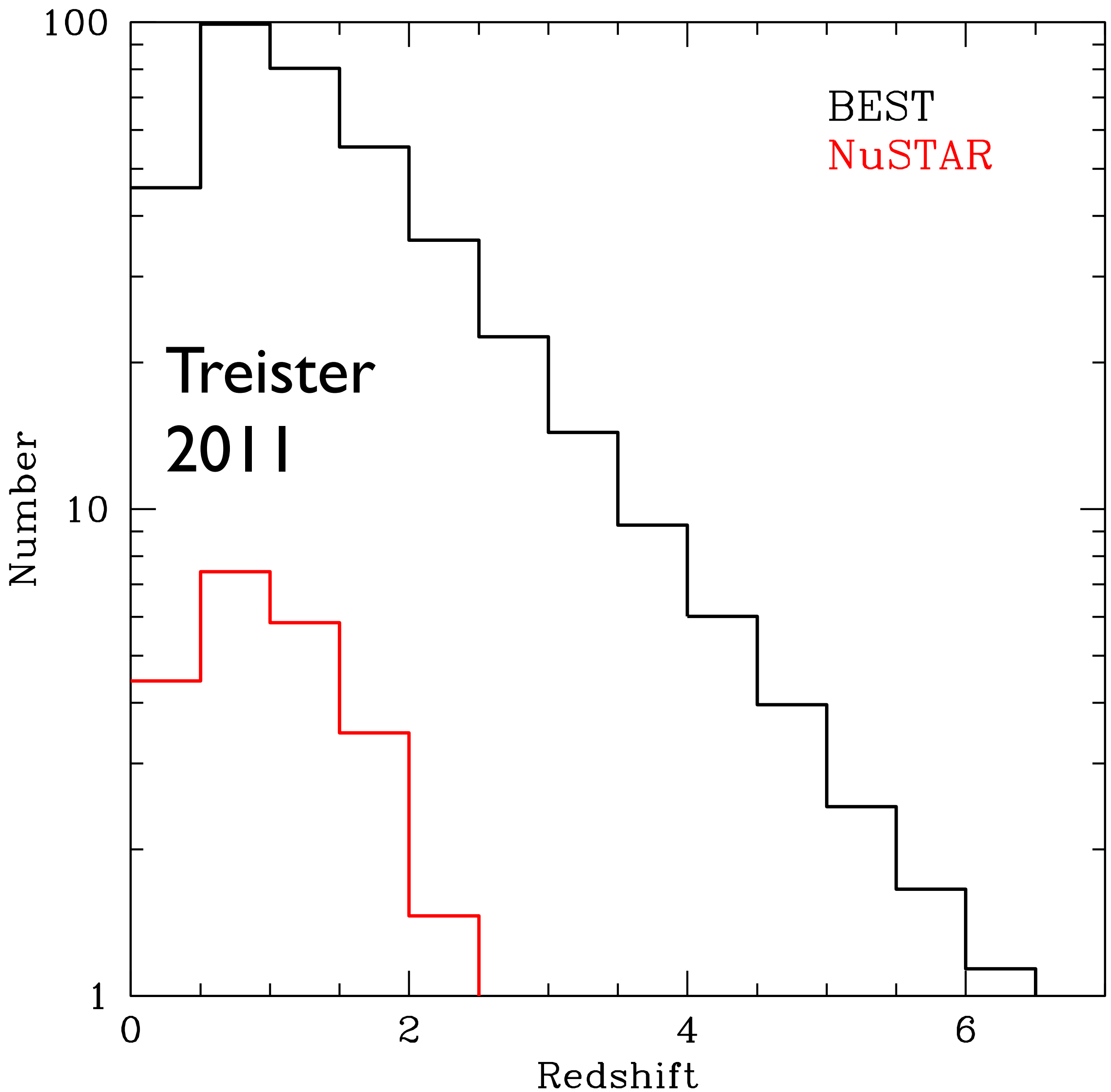
Rationale:

- Current 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* will improve on this situation, but only to z~1 (Ballantyne et al. 2011).
- Bulk of black hole growth is most likely at z~2 (Treister et al. 2010), and will be missed by *NuSTAR*.

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.

Number of z>6 AGNs can distinguish between different SMBH seeds (Treister 2011)!

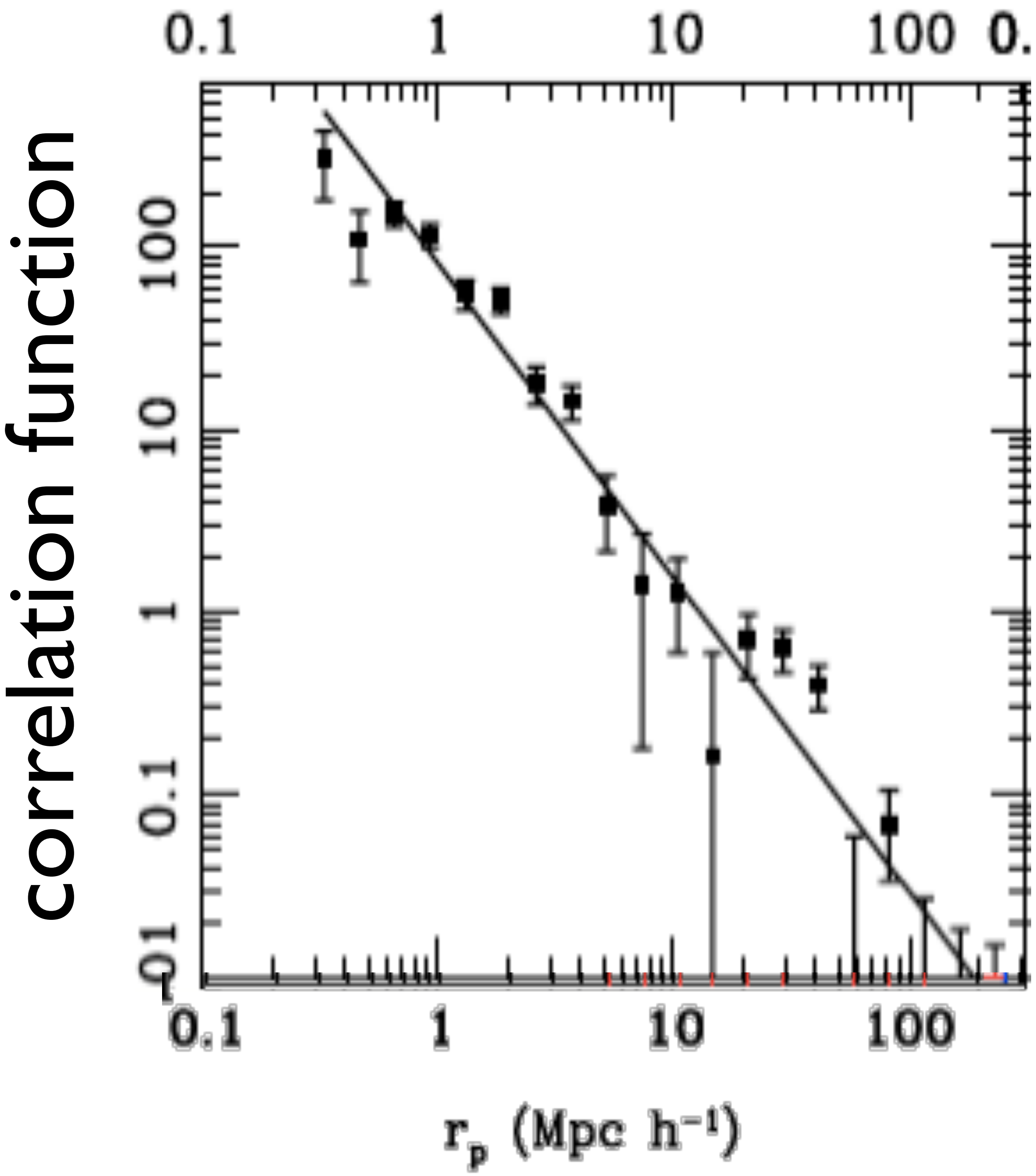
BEST – How and When Did Supermassive Black Holes Grow?

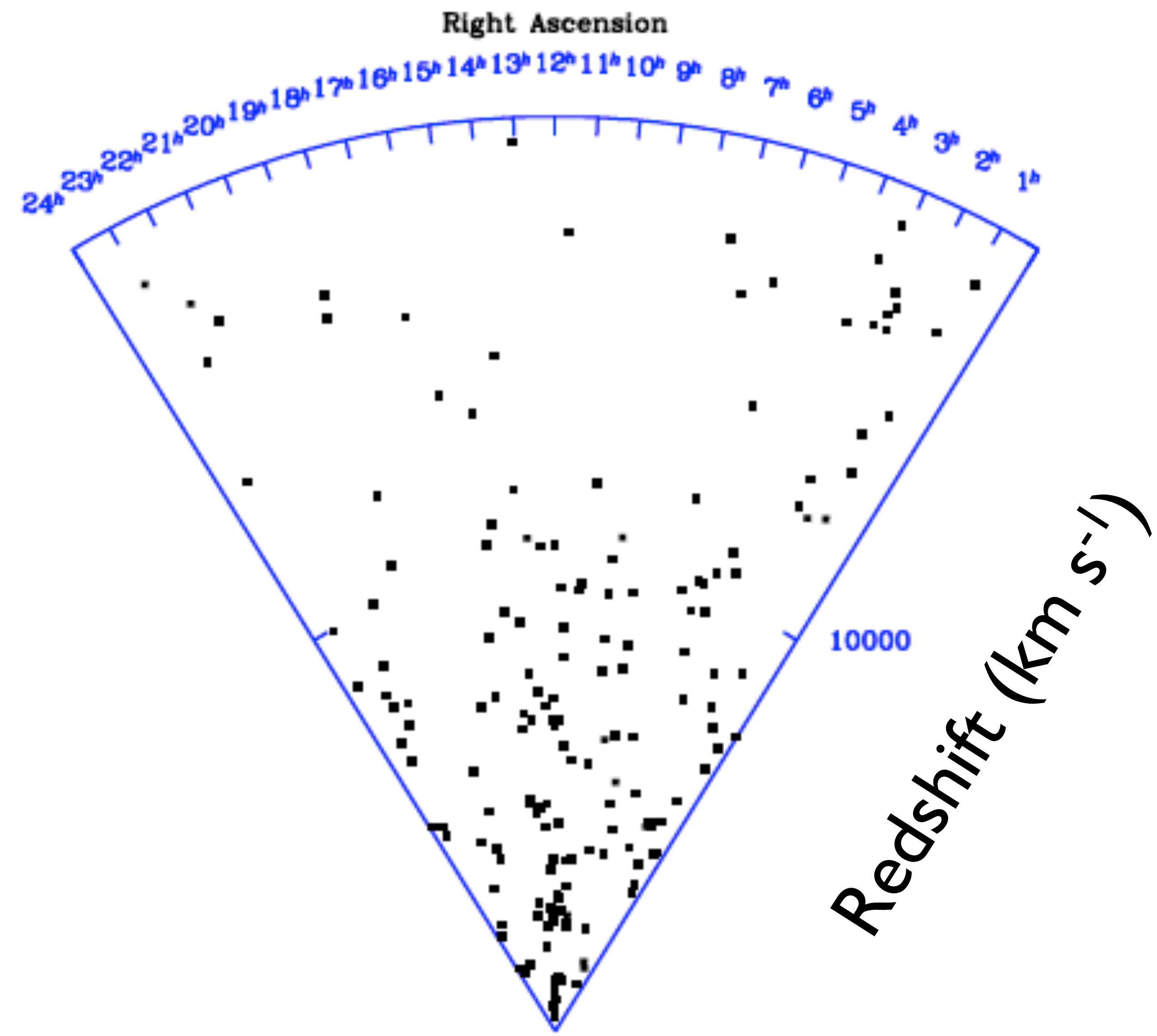
Potential *BEST* AGN Survey (1.5 years with 50% efficiency):

- 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 Does Large Scale Structure Evolve?

Cappelluti et al.: Cosmic Structure based on 199 Swift *BAT* Sources

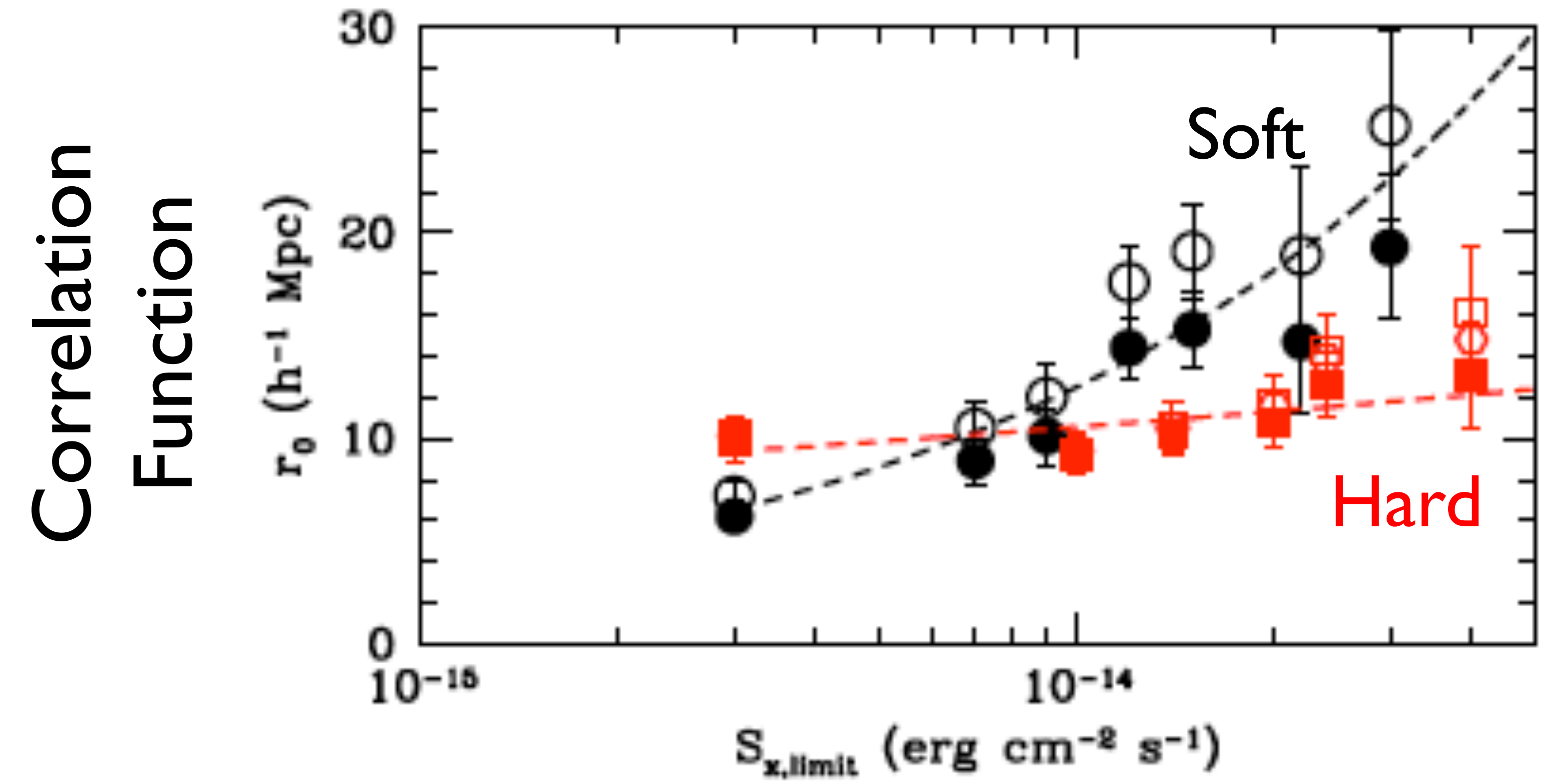




Local Distribution of hard X-ray selected AGN.

***BEST* – How Does Large Scale Structure Evolve?**

Elyiv et al 2011: Hard X-ray selected AGN have ~8 x more massive hosts!



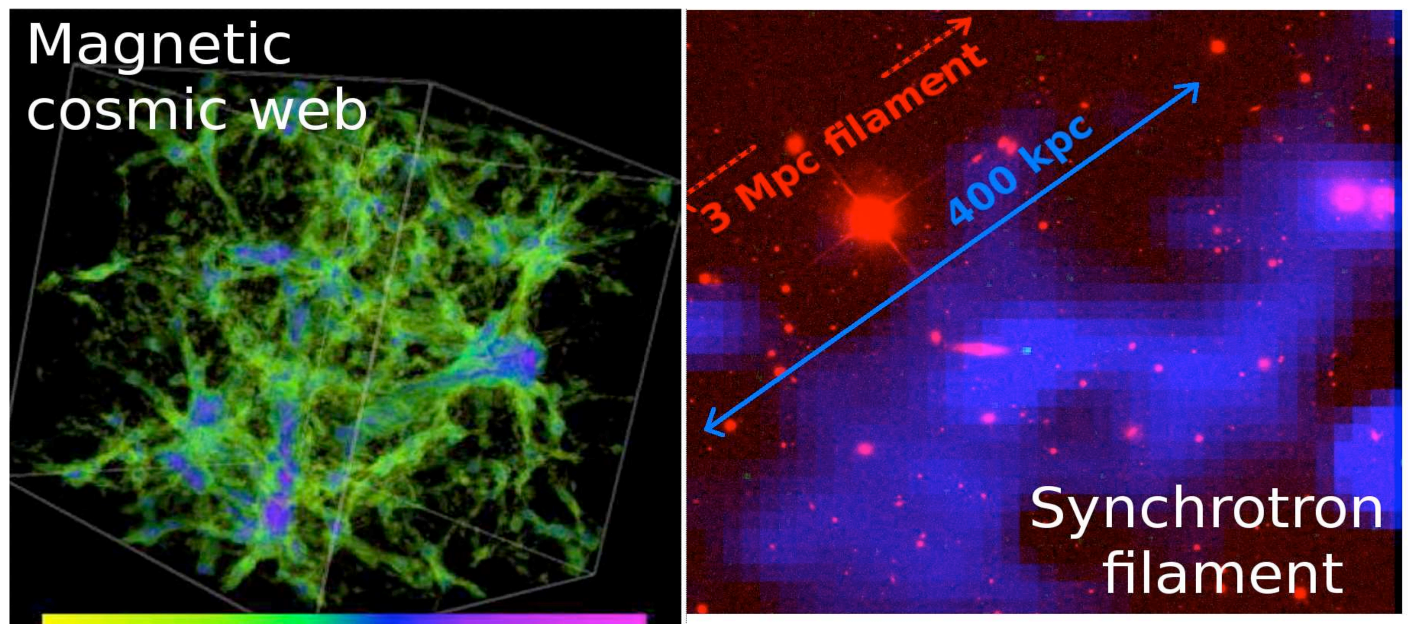
Conclusions:

• Hard X-ray observations will scrutinize cosmic structure and its cosmic evolution for different (larger) dark matter halo masses than other observations.

• Penetrating nature of hard X-rays will remove a major source of uncertainty that plagues surveys at other wavelengths.

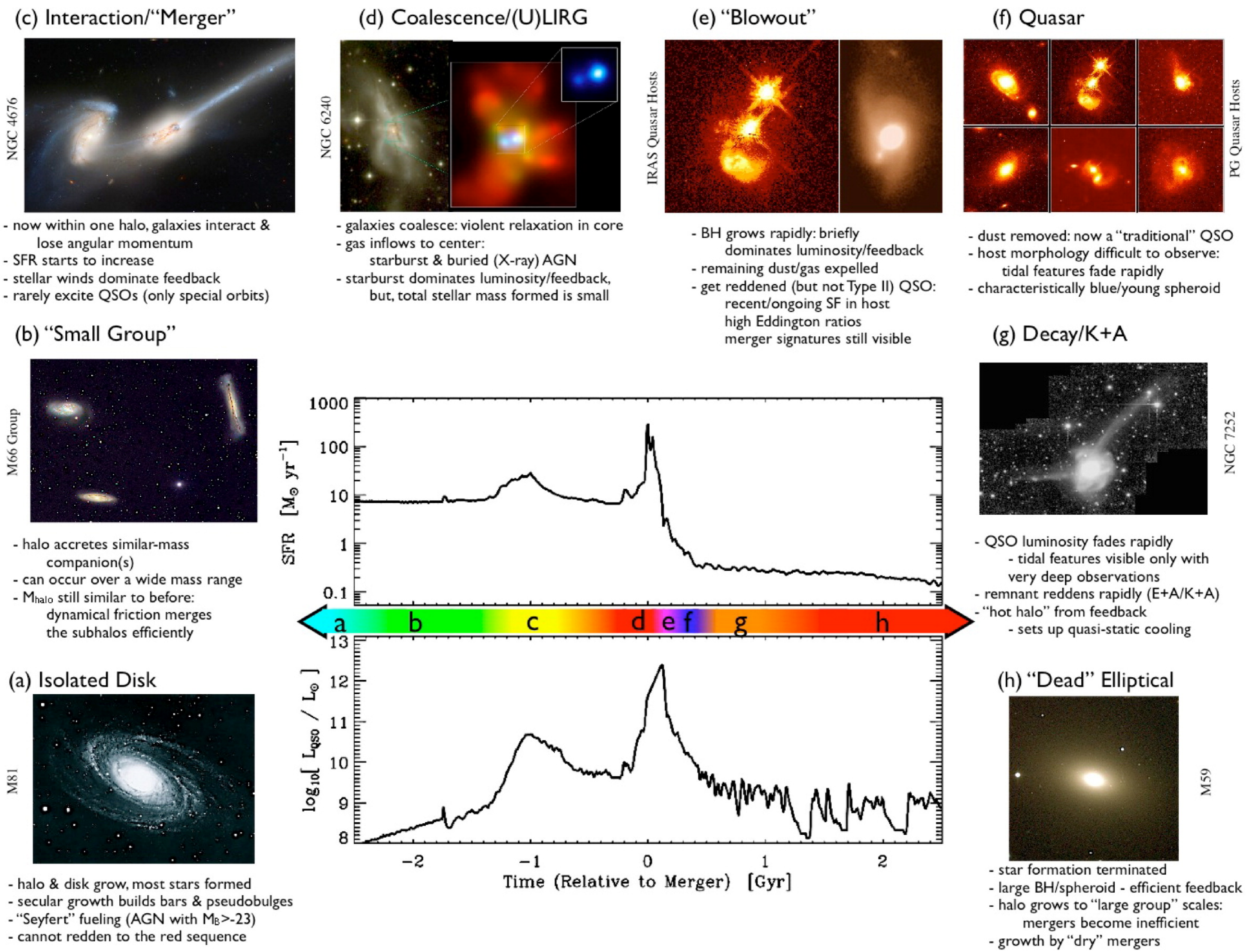
BEST – How Does Large Scale Structure Evolve?

Hard X-ray observations can map emission from non-thermal particles accelerated in large scale structure shocks in the local Universe.



Proper characterization of large scale structure at z=0 contributes to our understanding of large scale structure at all cosmic epochs.

BEST – Connection AGN – Large Scale Structure Formation

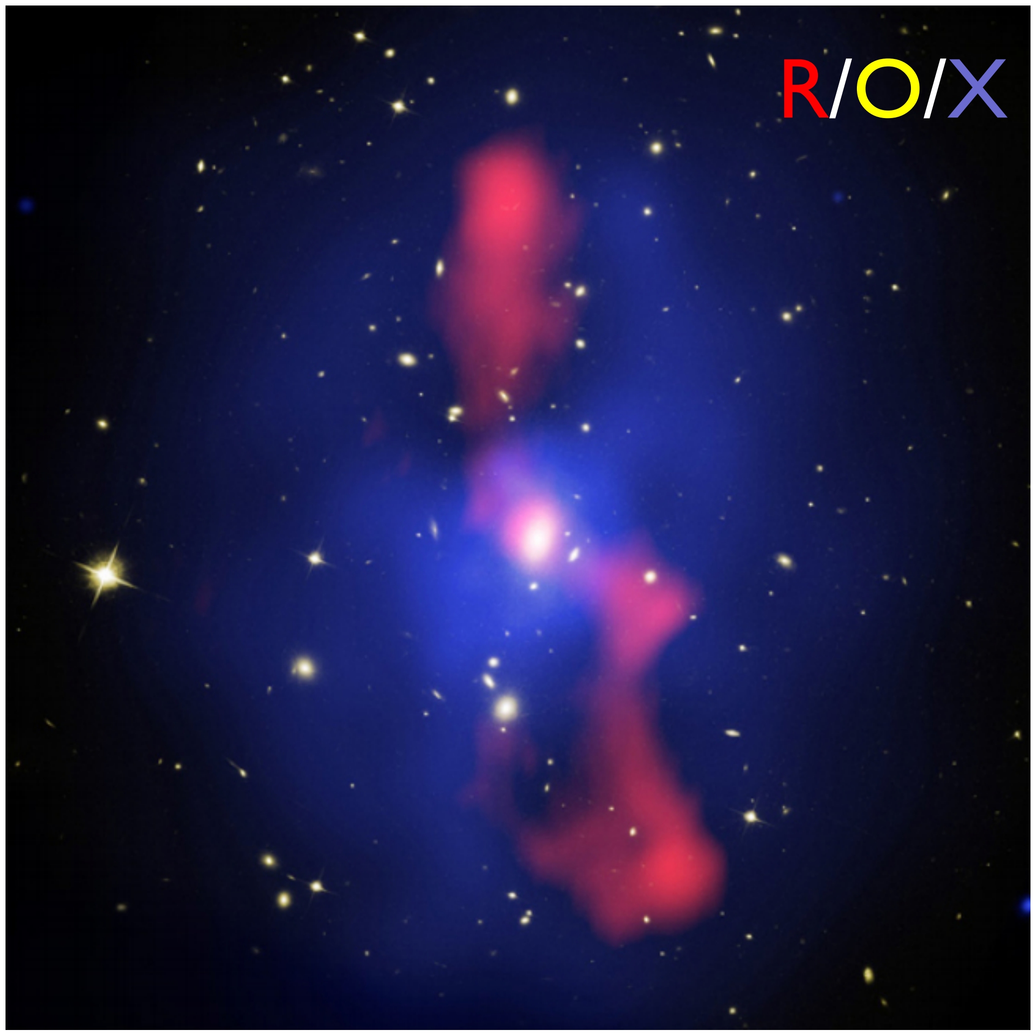


Hopkins et al.

BEST will detect obscured AGNs in galaxy merger.

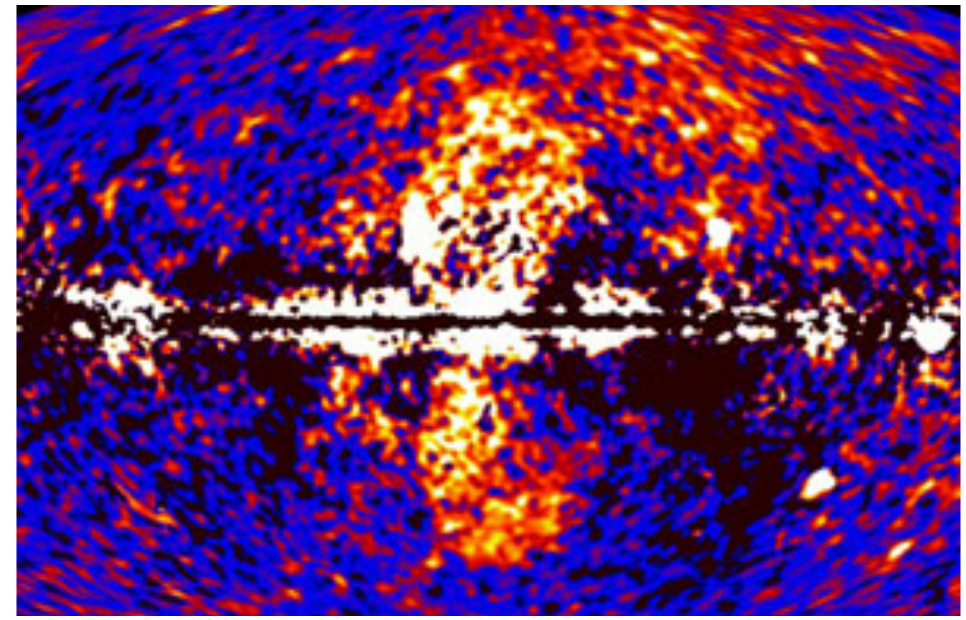
BEST – AGN Feedback

MS 0735.6+7421

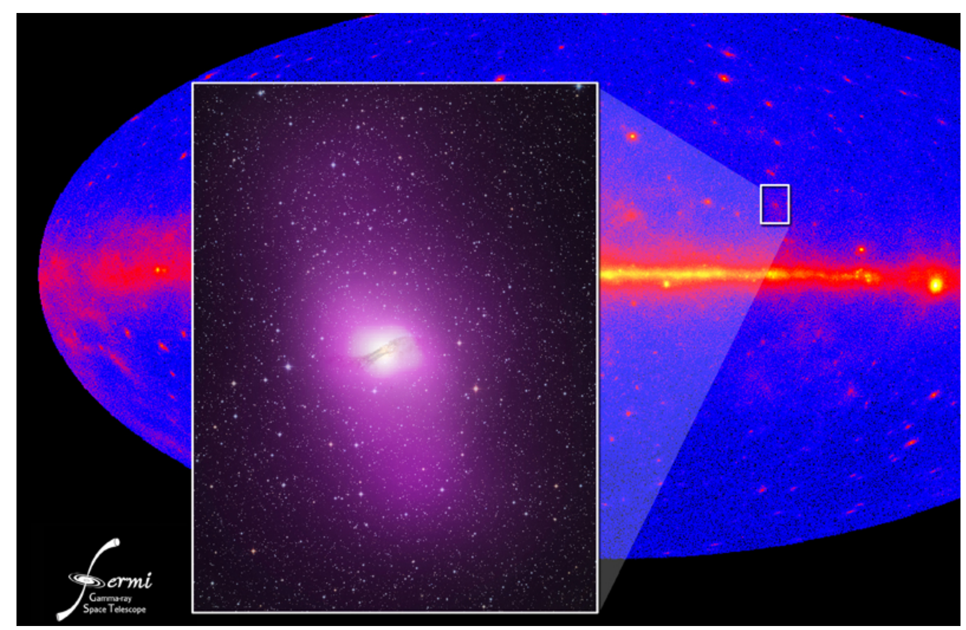


NASA/CXC/Univ.Waterloo/B.McNamara; Optical: NASA/ESA/STScI/ Univ.Waterloo/B.McNamara; Radio: NRAO/Ohio Univ./L.Birzan et al.

Fermi: non-thermal particles!



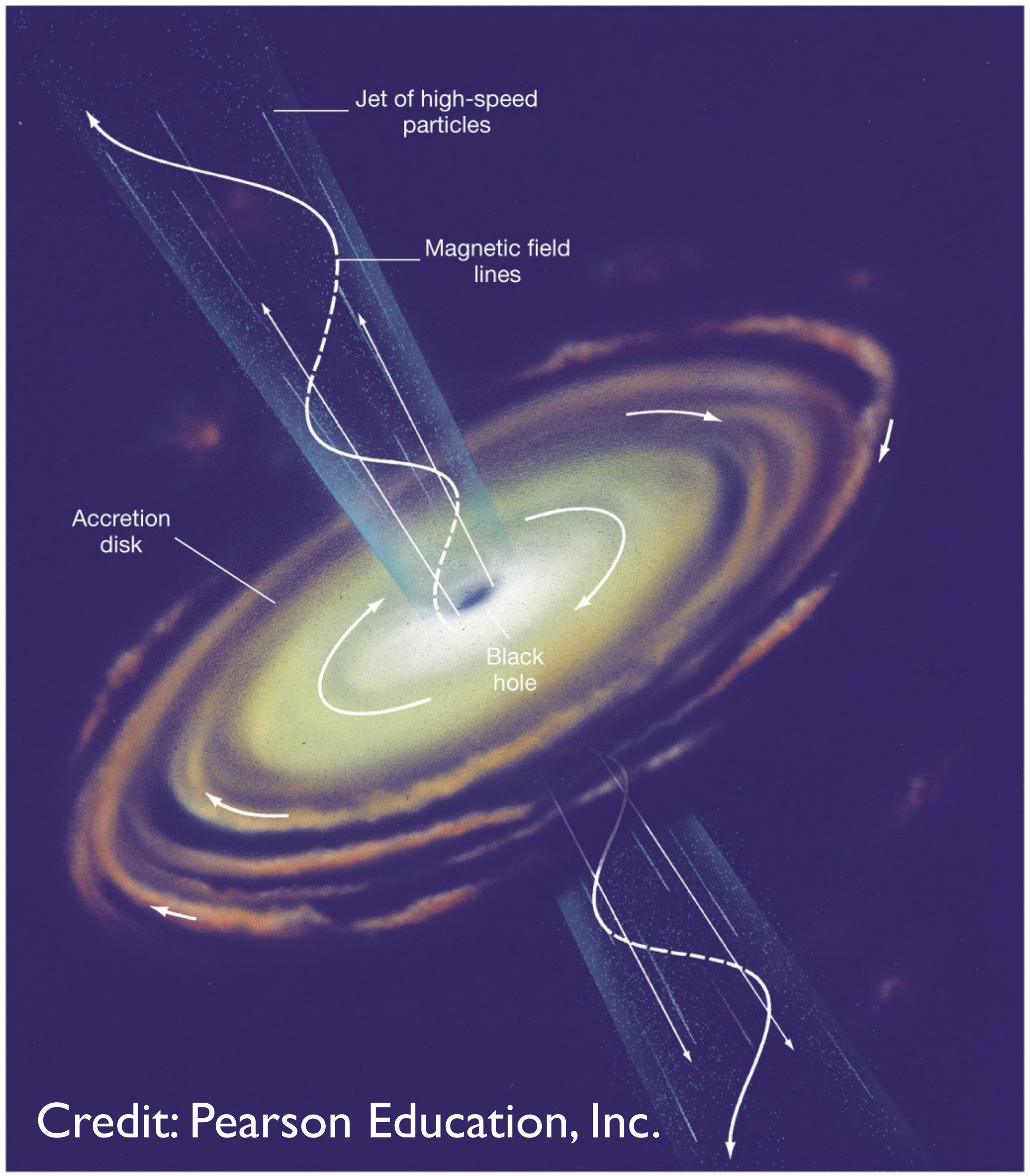
Milky Way



Cen-A

BEST: Map *non-thermal particles* ➙ AGN feedback!

BEST – AGN Feedback

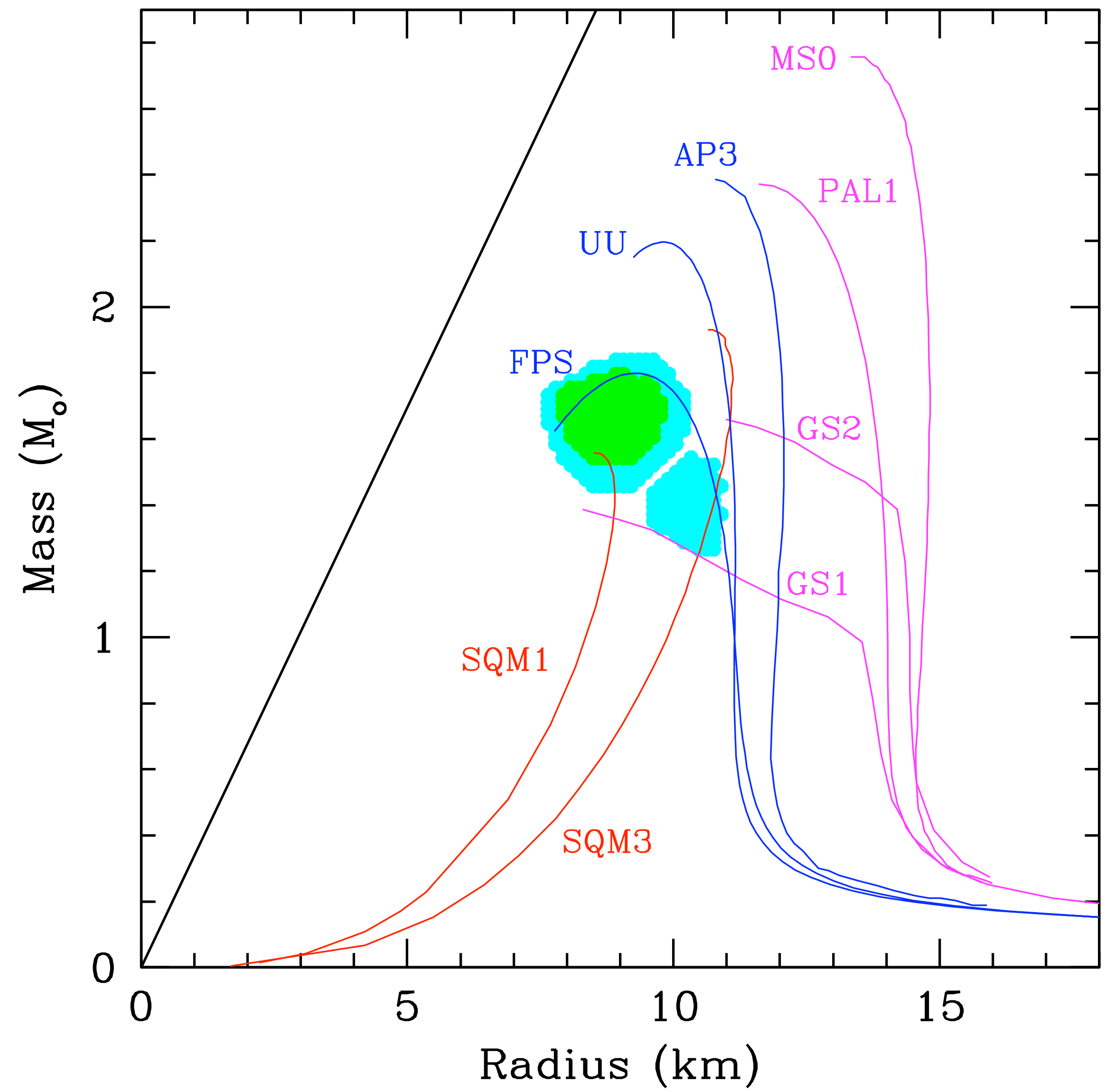


- *BEST polarimetry:*
  B-field structure of AGN jets.
- Structure and composition of jets is important for understanding of *accretion* process and *feedback*.

BEST – How Does Matter Behave at Very High Density?

- Burst spectra in LMXBs:
  T & R of emission region;
- Photospheric radius expansion (PRE) is limited by L_{Edd} at surface touchdown;
- Given an opacity, L_{Edd} gives emission radius (flux & Stefan-Boltzmann law);
- Corrected for GR, L_{edd} gives M/R ratio for LMXB (e.g. Özel et al. 2009), thereby constraining EOS;
- **Works also for magnetars (Watts et al. 2010)**.

Özel, Güver & Psaltis (2009)

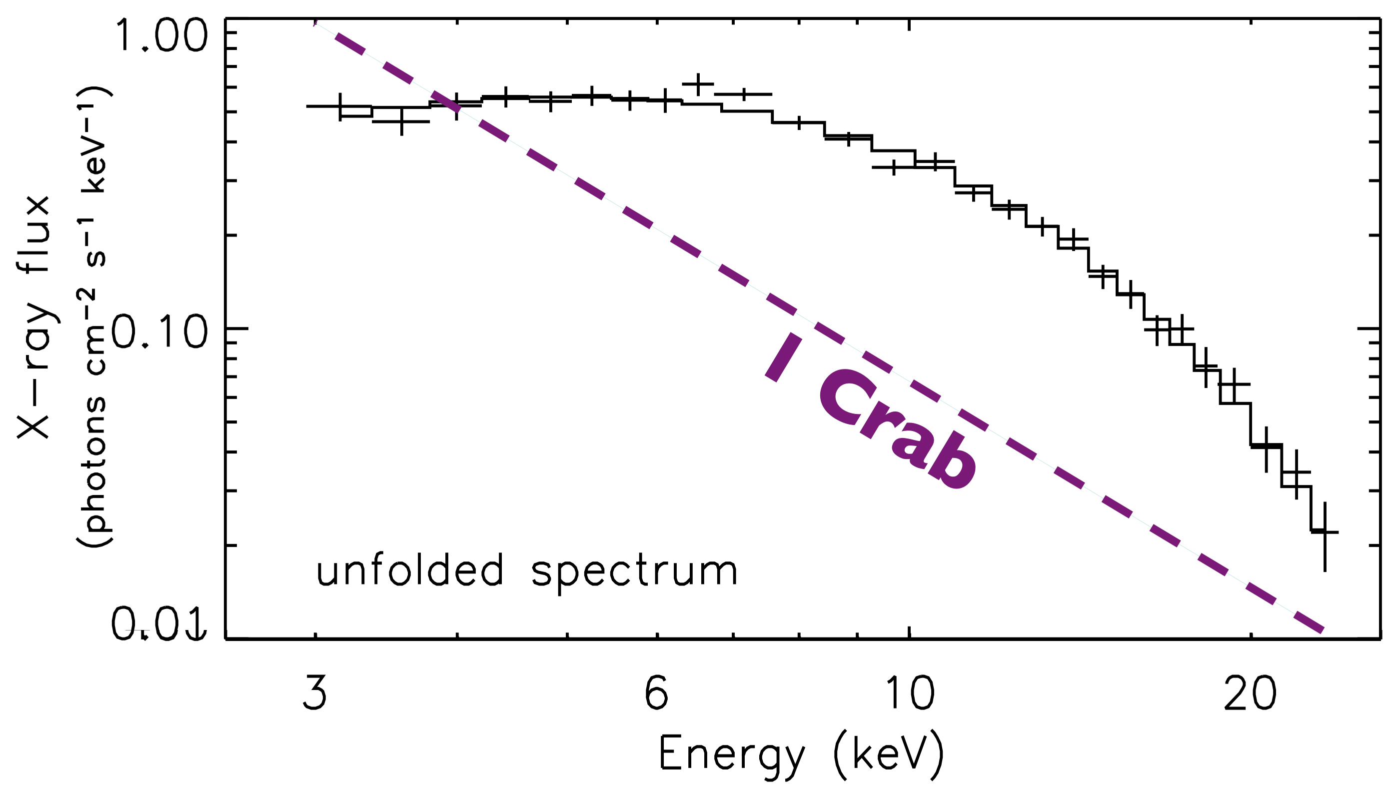


Mass-radius diagram for EXO 1745-248 and select NS equations of state.

BEST – How Does Matter Behave at Very High Density?

- *BEST* polarimetry: size of PRE region, viewing angle with respect to **B**;
- Opacity and L_{Edd} depend strongly on polarization in PRE volume;
- BEST will refine mean field geometry and L_{Edd} measurement to give M/R ratios for both LMXBs and magnetars;
- Strong **B**-fields: polarization particularly interesting below and above electron cyclotron energy!
- Constraining magnetar EOS would be a first.

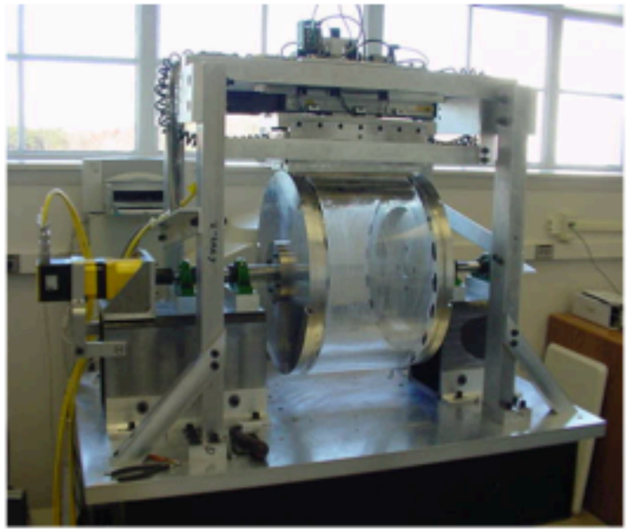
RXTE spectrum for 4U 1728-34 on 1999 June 30:



BEST MDP for 5 s burst @ 5 Crab: 3% (2-10 keV) and 5% (10-20 keV)

Mission Details - Mirrors

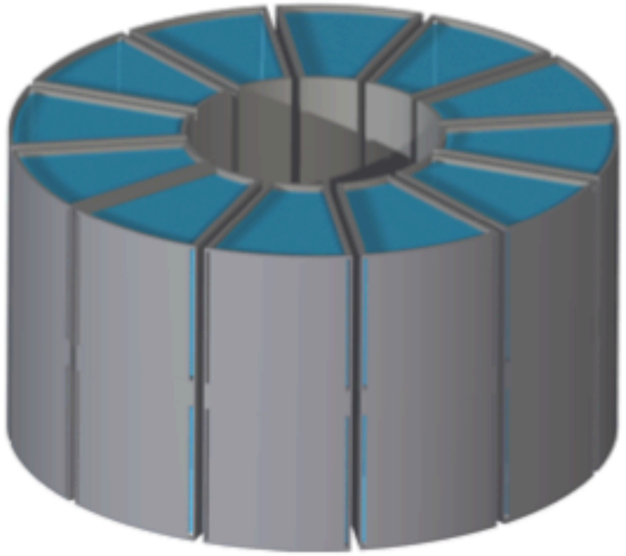
Mandrel Fabrication



Mirror Segment

Mirror Module

Mirror Assembly



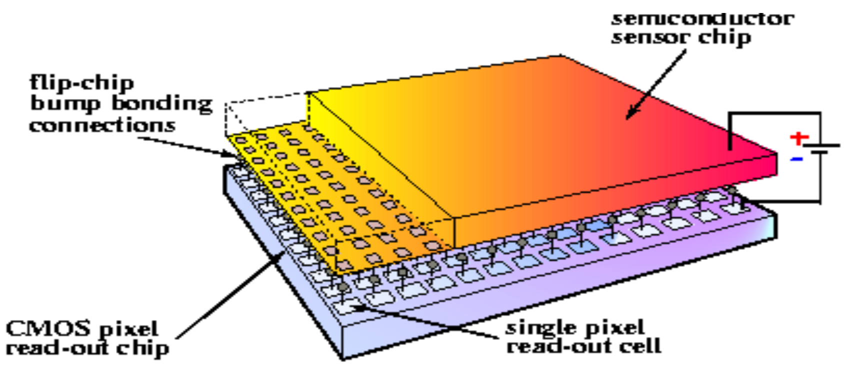
Mirror technology (F=10m):

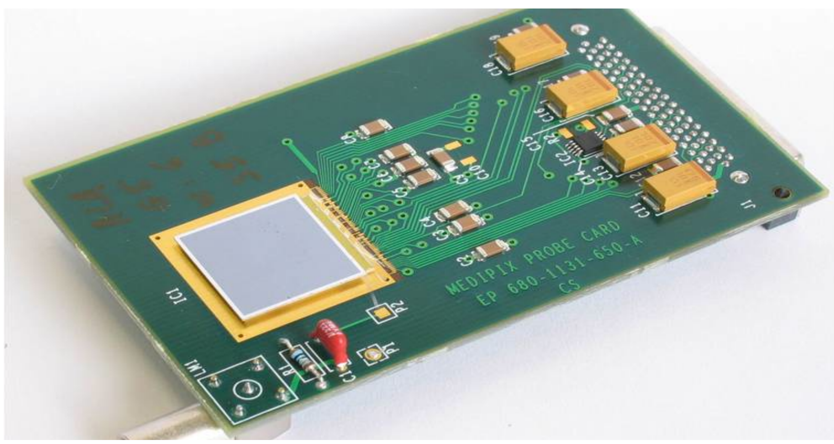
- High-quality mandrels and 0.4 mm thick glass mirror substrates.
- Fabrication, alignment, bonding of segments: <10″ HPD at 4.5 keV.
- R&D: Multi-layer coatings that maintain ang. resolution

(stress cancellation: atomic layer deposition or multi-layers).

Mission Details – Imaging Detectors

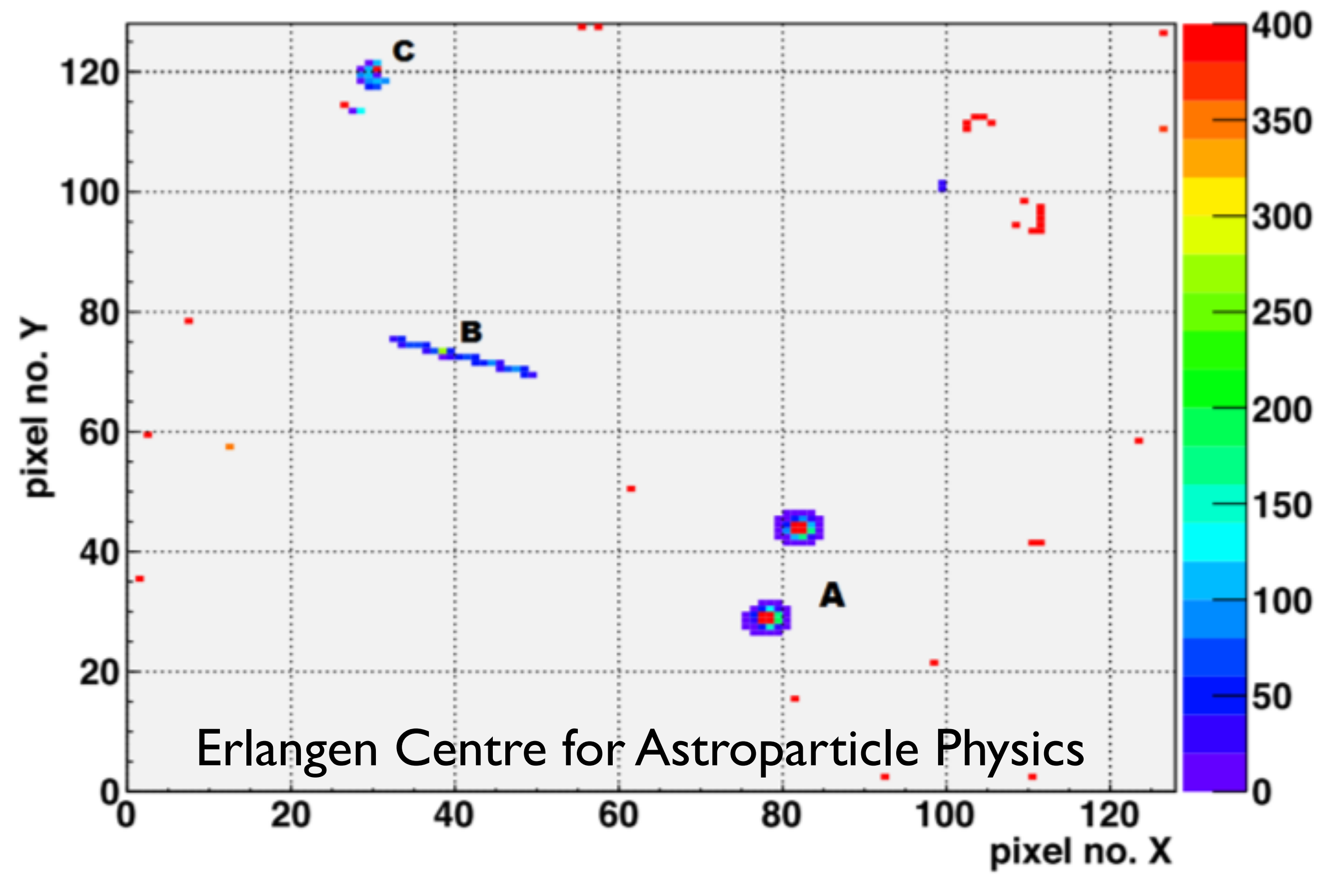
2mm CZT (5-70 keV): 240μm(120μm) pixel pitch; 3.5x3.5cm^2 (5.8x5.8cm^2).



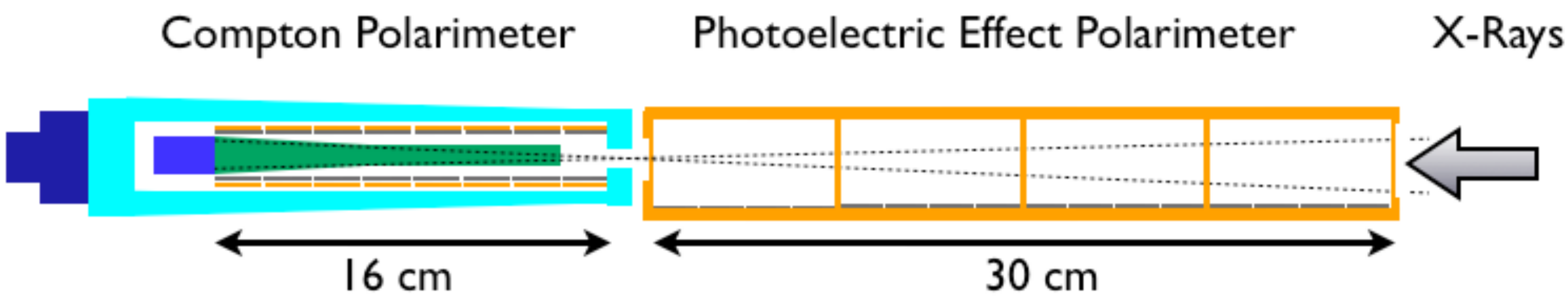


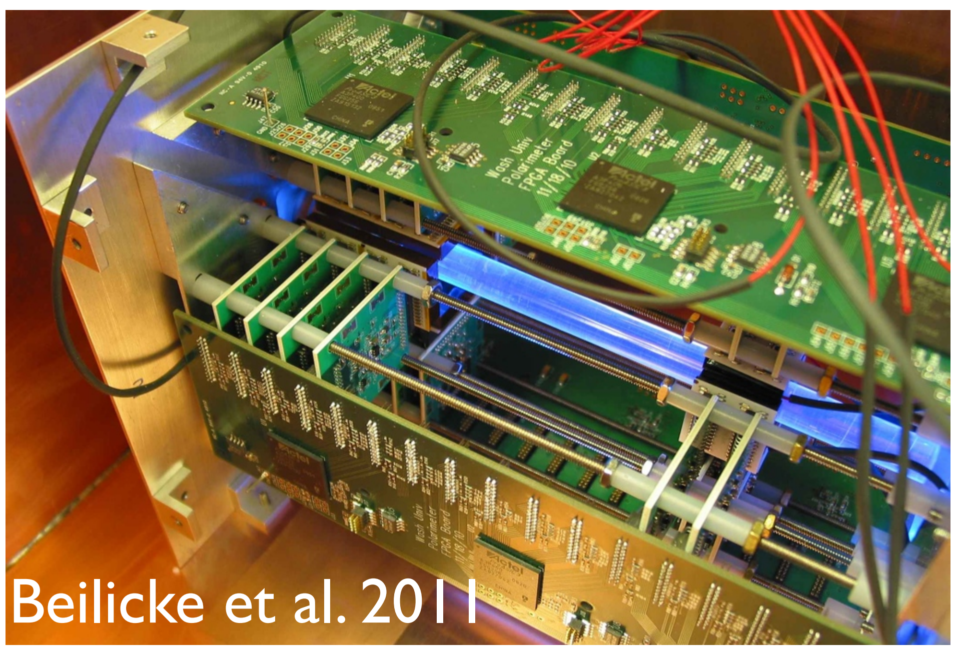
TimePix ASIC: 256×256 pixels, 55 μm pitch, area 1.4×1.4 cm^2 (Esposito et al. 2011).

Muon and alphas recorded with 1mm thick CdTe detector with 110 μm pixels, <5 keV energy threshold (Filipenko, Michel et al.):

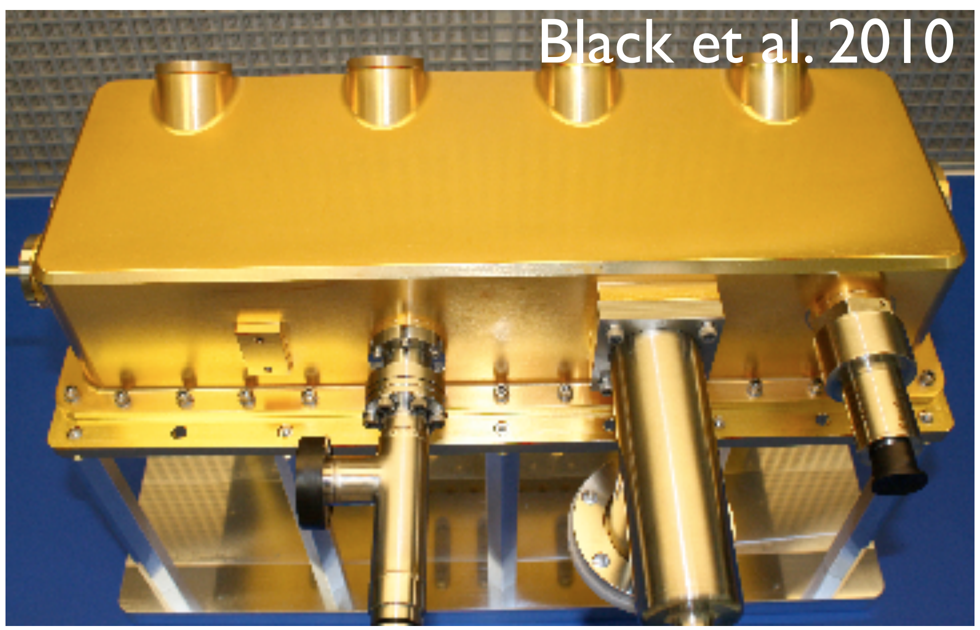


Mission Details – Broadband Polarimeter





Balloon flight of Compton polarimeter (X-Calibur) in 2014.



GEMS launch in 2014.

Mission Details – Technical Readiness Levels & Complexity

Component	TRL	Years to TRL 6
Optical Bench	5	1
Mirrors	2-4	3
Imaging Detectors	5	2
Photo-Effect Polarimeter	6	-
Compton Polarimeter	4	3 (2014)

Detector	Channels
Imaging Detector	6 x 292 (584)
Broadband Polarimeter	6 x 4614

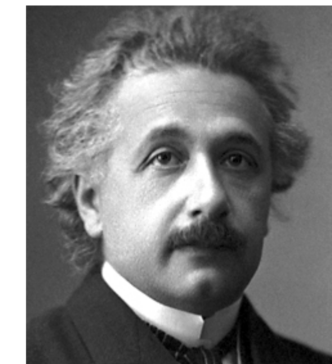
Mission Details – Costing

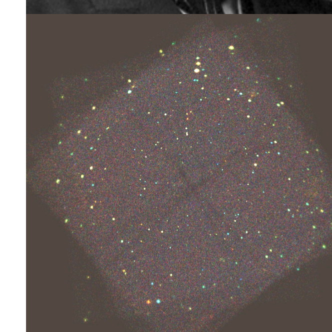
Mission	Cost (then)	Year (then)	Cost (FY12)	Delta Cost	Adjust Cost	Mass [kg]	Delta Mass	Adjust Mass	Comments
Swift	140	2004	167	335	562	1200	25	1225	Existing
Lobster	200	2010	206	368	634	398	520	988	Proposal
NuSTAR	110	2009	117	365	542	360	602	1022	L-4 mo
GEMS	125	2011	125	370	555	313	552	925	In Phase B
BEST	n/a	n/a	n/a	n/a	**573**	n/a	n/a	**1040**	**Average**

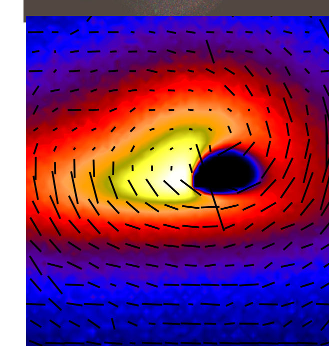
- Costs from *Swift*, *Lobster*, *NuSTAR*, *GEMS* scaled to 2012.
- Adjustment for additional/non-existing *BEST* subsystems.
- Adjustment according to redundancy architecture.
- Added cost for a Taurus launcher ($70M).
- Based on existing missions, nearly-existing missions, and high-fidelity proposal study ➔ calculations include 30% reserve.

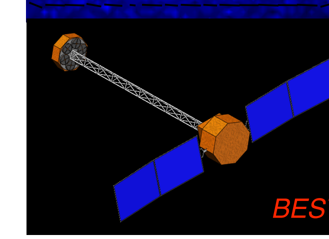
Summary - Black Hole Evolution and Space Time

IXO Question	*BEST* Observation	*BEST* Potential
What Happens Close to A Black Hole?	**Precision Tests of Accretion Disk Models and Underlying Spacetime.**	✓✓✓
When and How Did Supermassive Black Holes Grow?	**Completely resolving hard X-ray background yields complete history of the black hole evolution.**	✓✓✓
How Does Large Scale Structure Evolve?	**Use AGNs as Tracers of Large Scale Structure.**	✓✓
What Is the Connection between Black Hole Formation and Large Scale Structure Formation?	**AGN-galaxy cross correlation; reveal AGNs in galaxy merger; map non-thermal particles.**	✓✓✓
How Does Matter Behave at Very High Density?	**X-ray Polarimetry of Neutron Stars and Magnetars.**	✓✓✓









Other Science Drivers: • Probe history of massive black hole at galactic center • Constrain energy release in magnetars • Vacuum birefringence • Particle Acceleration by Pulsars and Supernova Remnants

Backup Slides

Scaled by Similar Mission Costs (DETAILS):

Mission	Cost (then)	Year(then)	Cost (now)	Delta(s)	AdjCost	Mass	DeltaMass	AdjMass	Reasons
Swift	140	2004	167.2	80		1200	cant		Mirrors: 15+10+10M$, 50+25+4*10=115M$; net is -35+115=80M$
				55			cant		Detectors: Pol_loE: 45+25M$, 45+20+4*15=125M%; net is -70+125=55M$
				75			cant		Detectors: Imager_MidE: 20M$+15+4*10=75M$
				75			cant		Detectors: Polar_HiE: 20+15+4*10=75M$
				20			cant		Bus: -10, +20M$ for redundant subsystems, plus 10M$ for beefer mech structure
				30			cant		Mission Ops: -2*10, +5*10=30 M$
				BEST=	**502.2**		**BEST=**	**1225**	
Lobster	200	2010	206.0	113		398	270		Mirrors: 8+2+2M$, 50+25+4*10=115M$; net is -12+115=113M$. M: +6*45=270kg.
				55			-34		Detectors: Pol_loE: 45+25M$, 45+20+4*15=125M%; net is -70+125=55M$. M: -184 + 6*25= -34
				85			60		Detectors: Imager_MidE: 20M$+15+4*10=75M$, plus 10M$ for FSW. M: 6*10=60
				85			204		Detectors: Polar_HiE: 20+15+4*10=75M$, plus 10M$ for FSW. M: 6*34=204
				20			90		Bus: -10, +20M$ for redundant subsystems, plus 10M$ for beefer mech structure. M: +40kg beefier. +50 PwrSys
				10			0		Mission Ops: -2*10, +3*10=10 M$. M: 0
				BEST=	**574.0**		**BEST=**	**988.0**	
NuSTAR	110	2009	116.7	80		360	238		Mirrors: 15+10+10M$, 50+25+4*10=115M$; net is -35+115=80M$. M: -2*16, +6*45, = 238kg.
				65			150		Detectors: Pol_loE: 45+15M$, 45+20+4*15=125M%; net is -60+125=65M$. M: +6*(15+10)=150
				85			-40		Detectors: Imager_MidE: 20M$+15+4*10=75M$, plus 10M$ for FSW. M: -2*20kg.
				85			204		Detectors: Polar_HiE: 20+15+4*10=75M$, plus 10M$ for FSW. M: +6*34=204
				40			110		Bus: 20M$ for redundant subsystems, plus 20M$ for beefer mech structure. M: +60kg beefier. + 50 PwrSys
				10			0		Mission Ops: -2*10, +3*10=10 M$. M: 0.
				BEST=	**481.7**		**BEST=**	**1022.0**	
GEMS	125	2011	125.0	95		313	238		Mirrors: 10+5+5M$, 50+25+4*10=115M$; net is -20+115=95M$. M: -2*16 +6*45 = 238
				65			0		Detectors: Pol_loE=40+15M$, 40+20+4*15=125M%; net is -55+120=65M$ M: 0deltas.
				85			60		Detectors: Imager_MidE=20M$+15+4*10=75M$, plus 10M$ for FSW. M: +60
				85			204		Detectors: Polar_HiE=20+15+4*10=75M$, plus 10M$ for FSW. M: +6*34=204
				20			110		Bus: 20M$ for redundant subsystems, plus 10M$ for beefer mech structure. M: +60kg beefier. + 50 PwrSys
				20			0		Mission Ops: -1*10, +3*10=20 M$. M: 0.
				BEST=	**495.0**		**BEST=**	**925.0**	