THE ASTRO-H IN-FLIGHT CALIBRATION PLAN

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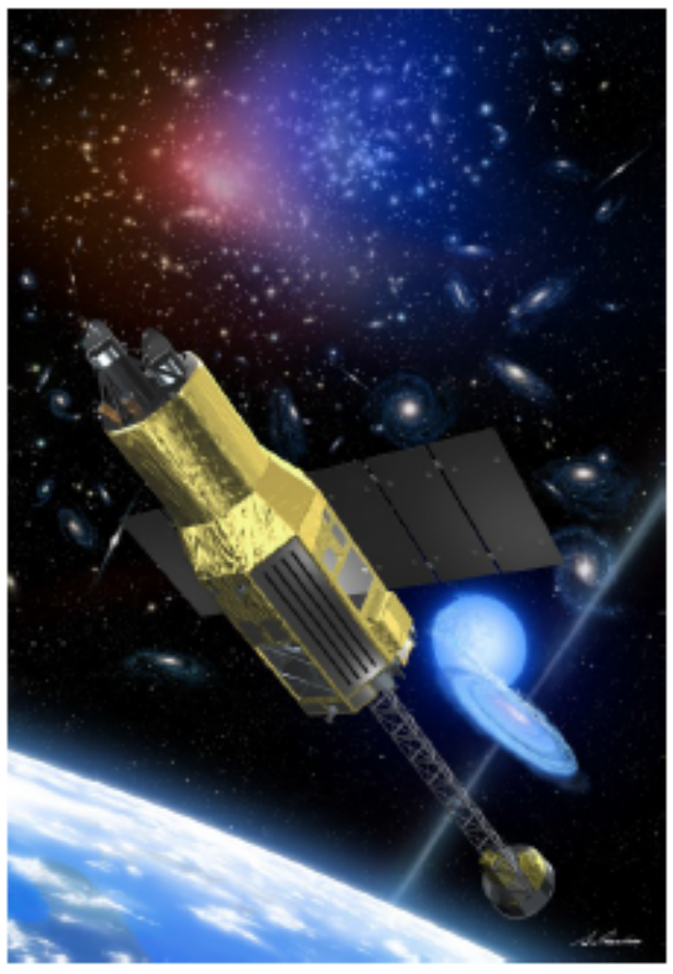
On Behalf of the Astro-H Team

Outline

- Current status of the ASTRO-H In-Flight Calibration Plan (IFCP)
  - Calibration requirements and priorities
  - Calibration observation time budget
  - Analysis and simulations supporting the selection of targets
  - Future consolidation of the IFCP
    - Synergies with the Performance Verification (PV) program
    - How can the ASTRO-H Science Working Team contribute?

Astro-H

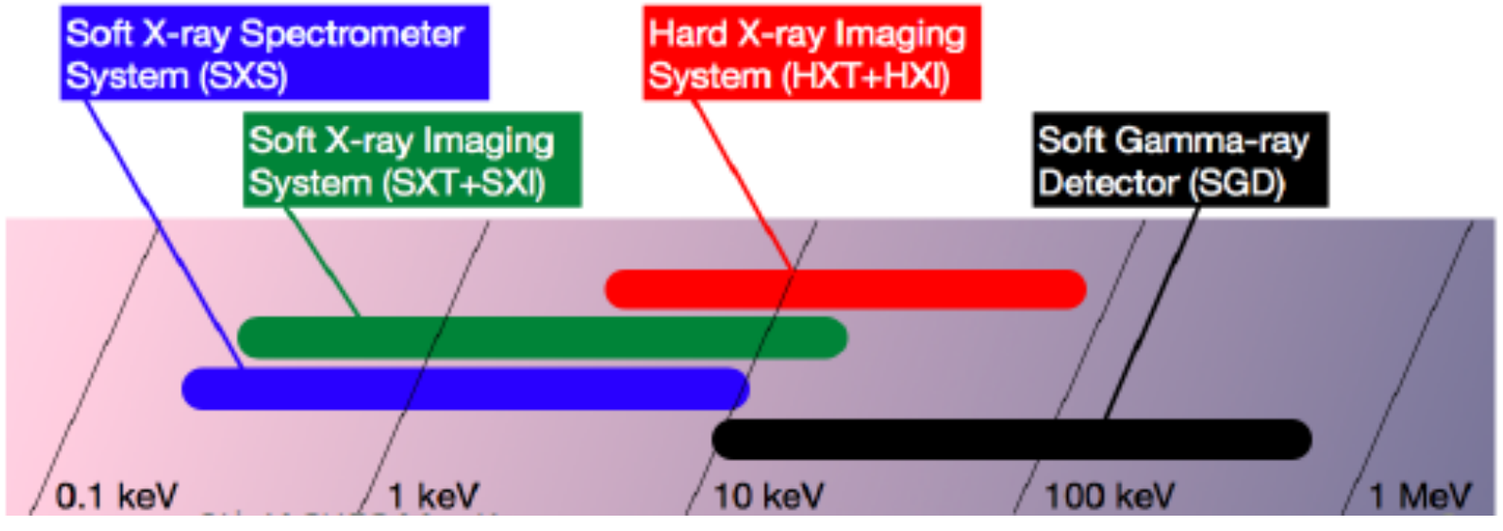


Scientific objectives :

- Revealing the large-scale structure and its evolution of the Universe
- Understanding the extreme conditions in the Universe
- Exploring the diverse phenomena of the non-thermal Universe
- Elucidating dark matter and dark energy

Key features :

- High resolution spectroscopy with X-Ray Microcalorimeter
- Hard X-ray focusing imaging
- High sensitive wide-band spectroscopy (0.3-600 keV)



T. Takahashi et al., "The Astro-H X-ray Satellite," Proc. SPIE, 9144, 25 (2014)

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Substantial Progress over Past Year

- At last IACHEC meeting:
  - Showed preliminary thoughts about potential targets and described target selection methodology
- Over Past Year:
  - Refined in-flight calibration requirements; still not final as we learn more about the instruments and the ground calibration results
  - Formed a Calibration Coordination Team to study, simulate calibration for all instruments (Matteo Guianazzi, Laura Brenneman, Brian Williams, Marc Audard, RP, with participation from IT reps and many others)
  - Produced several drafts of an In-Flight Calibration Plan

In-Flight Plan Development Methodology

- Planning being performed by calibration coordination team, with input from instrument teams and SWG
- Build a plan that assumes successful ground calibration, but allows for complete on orbit calibration
- Identify source for each calibration activity (multiple preferred to ensure visibility)
- Use "standard candles" when possible (IACHEC favorites like 3C 273, E0102, etc.)
- Try to find sources that satisfy multiple goals
- Determine needed exposure via simulation
- Perform perturbation exercise to determine what happens in the case of off-nominal performance
- Need plan that fits in available time:
  - Satellite/Instrument checkout (3 months). Primary aim is to bring observatory to operational readiness but we can select sensible targets. Maximum effective observing time is 3.5 Ms (45% observing efficiency)
  - Science Working Group (6 months, 90% SWG time and 10% observatory time). We assume that a significant part of the observatory time (say 7% of total 6 months) is inflight calibrations. This gives for the PV phase 0.5 Ms.
  - Next phases (assume 5% calibration time). 0.7 Ms/year
- Establish priority scheme to ensure most critical observations done during calibration time and to enable flexibility on orbit

Calibration requirements - I.

Summary from the SCT "Calibration Control Table": `http://www.astro.isas.jaxa.jp/next/astroh-sct/wiki/index.php?cal_control_table`

	SXS(+SXT)	SXI(+SXT)	HXI(+HXT)	SGD
Boresight stability	<2 arcmin	<2 arcmin	<1 arcmin	N/A
X-ray axis	2 arcmin	2 arcmin	1 arcmin	TBD
Astrometry/plate scale	$2x10^{-4}$	$2x10^{-4}$	$1x10^{-4}$	N/A
Energy scale uniformity (Knowledge of gain v. E)	1 eV; 0.2 eV goal	0.1%	3%; 0.5% goal	5%; 3% goal
Energy scale stability (Short term gain variability)	0.5 eV; 0.2 eV goal	0.2%; 0.1% goal (on axis)	5%, 3% goal	5%, 3% goal
Energy resolution	1.6 eV; 0.2 eV goal	5%; 3% goal	5% or 1 keV; 3% goal	5%; 3% goal
Energy redistribution	10%, 1% goal	10%, 1% goal	10%, 1% goal	10%, 1% goal
HPD; 90% PD on axis	10%; 5% goal (0.3-12 keV)	20% (0.3-12 keV)	20% (5-70 keV)	
Absolute effective area: broad band	10%; 5% goal	11%; 7% goal	10%; 5% goal	15%; 8% goal
Absolute effective area: broad band off-axis	N/A	15%; 10% goal	15%; 10% goal	
Relative effective area: broad band	5%; 2% goal	5%; 2% goal	5%; 2% goal	15%; 8% goal
Relative effective area:	N/A	10%; 5%	10%; 5%	

Calibration requirements still subject to revision by ITs

Calibration requirements - II.

Summary from the SCT "Calibration Control Table": `http://www.astro.isas.jaxa.jp/next/astroh-sct/wiki/index.php?cal_control_table`

	SXS(+SXT)	SXI(+SXT)	HXI(+HXT)	SGD
Relative effective area: Fine structure	<2% around O, Si and Fe edges; goal <1%	15% around Si edge	N/A	N/A
Contamination	10%; 5% goal	10%; 5% goal	N/A	N/A
Pixel-pixel uniformity	QE 5%; gain 0.3 eV	3%	5%; 1% goal	N/A
Stray light	10% @ 4xFOV	10% @ 4xFOV	10% @ 4xFOV	N/A
Background reproducibility (flux)	10%	5%	5%; 3% goal	5% goal
Background reproducibility (image)	N/A	N/A	10%; 5% goal	N/A
Polarization (MDP)	N/A	N/A	N/A	10%
Dead time estimation	10%; 5% goal	TBD	10%; 5% goal	10%; 5% goal
Timing (absolute)	10 ms; 80 μs goal (design) 200 μs 30μs goal (science)	61.0352μs= 2^{-14} s goal (design) 200 μs 30μs goal (science)	60 μs goal (design) 200 μs 30μs goal (science)	60 μs goal (design) 200 μs 30μs goal (science)
Timing resolution (relative)	5 μs	61.0352 μs[1]	25.6 μs	25.6 μs
Instrument specific	Filters: BB effective area with filters 10%; 5% goal	Effective area, spectral performance of all modes	Cross instrument effective area 5%	Cross instrument effective area 10%

Calibration requirements still subject to revision by ITs

Boundary conditions

- Operations: visibility (most of the sources visible twice per year for about two months); spacecraft roll angle (±30°); launch date

- Instruments: instrument stabilisation time (unknown); pile-up (SXI_{FW}:~3.6 s^{-1}; SXS:~10 s^{-1}); SXS/PSP handling event rate (»10 s^{-1})

- Observing time: ~2.2Ms in the first 3 months; ~0.5Ms during PV; 5% (~0.7Ms/year) in the routine phase

- Early needs: hard source for quick check of boresight and response; SXS/SXI "first-light source" for contamination; pulsar for timing accuracy; Crab to be observed at different roll angle for SGD polarisation, together with a (supposedly) unpolarised source; SGD/CygX-1

Energy scale, LSF/RMF

(Sources listed in priority order. In brackets the exposure time in ks)

	SXS GVC	SXS GVO	SXI	HXI	SGD	SXT	HXT
Energy scale (on-axis)	HR 1099(50) AB Dor(50) CP, FW, MXS	Capella(30) HR 1099(50) AB Dor(50) CP, FW, [I]MXS	Perseus (140) *and* 1E0102-72 (?)	AM(1200/50000) Perseus (15) NXB Circinus (10)	TP, NXB	NA	NA
Energy scale (pixel-to-pixel, off-axis)	CP, FW, MXS	CP, FW, MXS	Perseus (320/640)	AM (1200/50000)	NA	NA	NA
Gain (short-term stability)	CP, MXS	CP	CS	TP	TP	NA	NA
LSF/RMF	FW(10) MXS(1) HR 1099(50) AB Dor(50)	FW(10) MXS(1) Capella(30) HR 1099(50) AB Dor(50)	see Energy scale (on-axis)	TP AM (1200/50000)	NA	NA	NA

AM=HXI ^{241}Am source, CP=Calibration Pixel, CS=Calibration Source, FW=Filter Wheel, MXS=Modulated X-ray Source, IMXS=Indirect MXS, TP=Test Pulse, NA=Not Applicable

Effective area and timing

(Sources listed in priority order. In brackets the exposure time in ks)

	SXS GVC	SXS GVO	SXI	HXI	SGD
Effective area on-axis	3C 273 (75) Centaurus A (75) PSR1509-58 (75)	3C 273 (75) Centaurus A (75) PKS2155-304 (75) PSR1509-58 (75)	3C 273 (75) 1ES0033+595 (75)	3C 273 (75) Centaurus A (75) PKS2155-304 (75) PSR1509-58 (75)	Crab (10) Cyg X-1 (40) Centaurus A (40)
Effective area off-axis	NA	NA	Abell1795 (180) Abell3571 (180)	G21.5-0.9 (240) Crab (60)	NA
Effective area (fine structure)	3C 273 *and* 4U0614+091(?)	3C 273 *and* 4U0614+091(?)	NA	NA	NA
Contamination (on-axis)	NA	1E0102-72 (60) RXJ1856-3754(120)	1E0102-72 (60) RXJ1856-3754(60)	NA	NA
Contamination (off-axis)	NA	NA	Vela SNR (60) Cygnus Loop (80)	NA	NA
Timing	B1509-58 (40)	B1509-58(40)	HMXRB and/or MCVs from PV (?)	B1509-58 (40) Crab (40)	Crab (40)

3C 273 is the target of a yearly IACHEC multi-observatory cross-calibration campaign; NA=Not Applicable

Astrometry, PSF, background, polarisation

(Sources listed in priority order. In brackets the exposure time in ks)

	SXS GVC	SXS GVO	SXI	HXI	SGD	SXT	HXT
Astrometry	NA	NA	NA	NA	NA	**Missing**	**Missing**
Boresight	**Missing**	**Missing**	**Missing**	**Missing**	**Missing**	NA	NA
Boresight stability	see SXS EA	see SXS EA	see SXI EA	see HXI EA	see SGD EA	NA	NA
Straylight	NA	NA	NA	NA	NA	**Missing**	**Missing**
Background	**Missing**	**Missing**	NE	DE	NE, DE	NA	NA
SWCX	NA	MBM12 (200)	MBM12 (200)	NA	NA	NA	NA
Pile-up/grade/ branching ratio	GB	GB	GB	GB	NA	NA	NA
Polarization	NA	NA	NA	NA	Crab (100) CygX-1 (100) CenA (100)	NA	NA
PSF	NA	NA	NA	NA	NA	**Missing**	**Missing**
PSF off-axis	NA	CygX-1 (280)	**Missing**	see SXS	NA	see SXS/SXI	**Missing**

DE=Dark Earth, EA=Effective area, GB=Ground-based, LMXRB=Low Mass X-ray Binary, NA=Not Applicable, NE=Night Earth

Instrument-dependent

(Sources listed in priority order. In brackets the exposure time in ks)

	SXS GVC	SXS GVO	SXI	HXI	SGD	SXT	HXT
Fillters	NA	1E0102-72 (25) RXJ1856-3754 (25)	NA	NA	NA	NA	NA
Instrument modes	NA	NA	**Missing**	NA	NA	NA	NA

NA=Not Applicable

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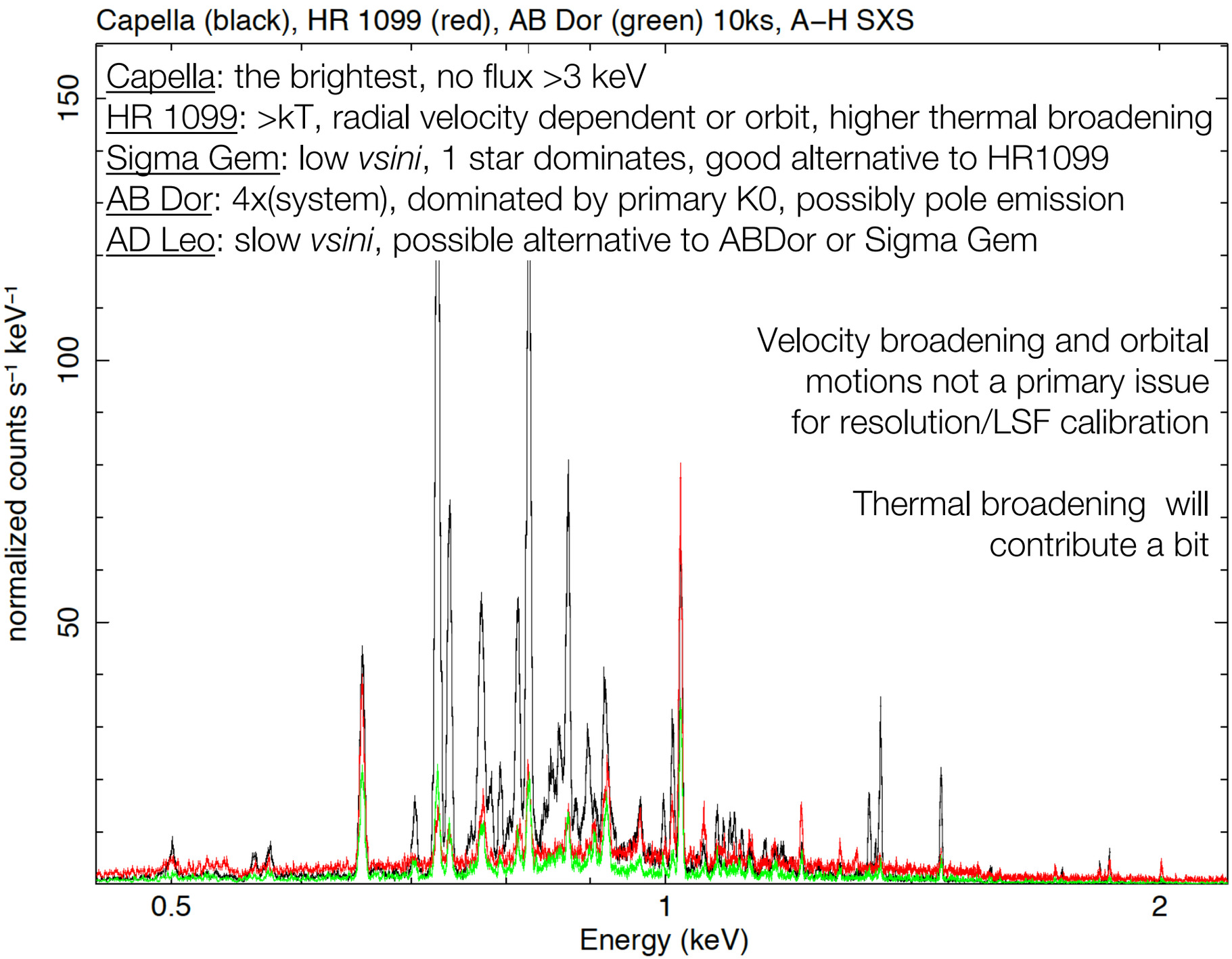
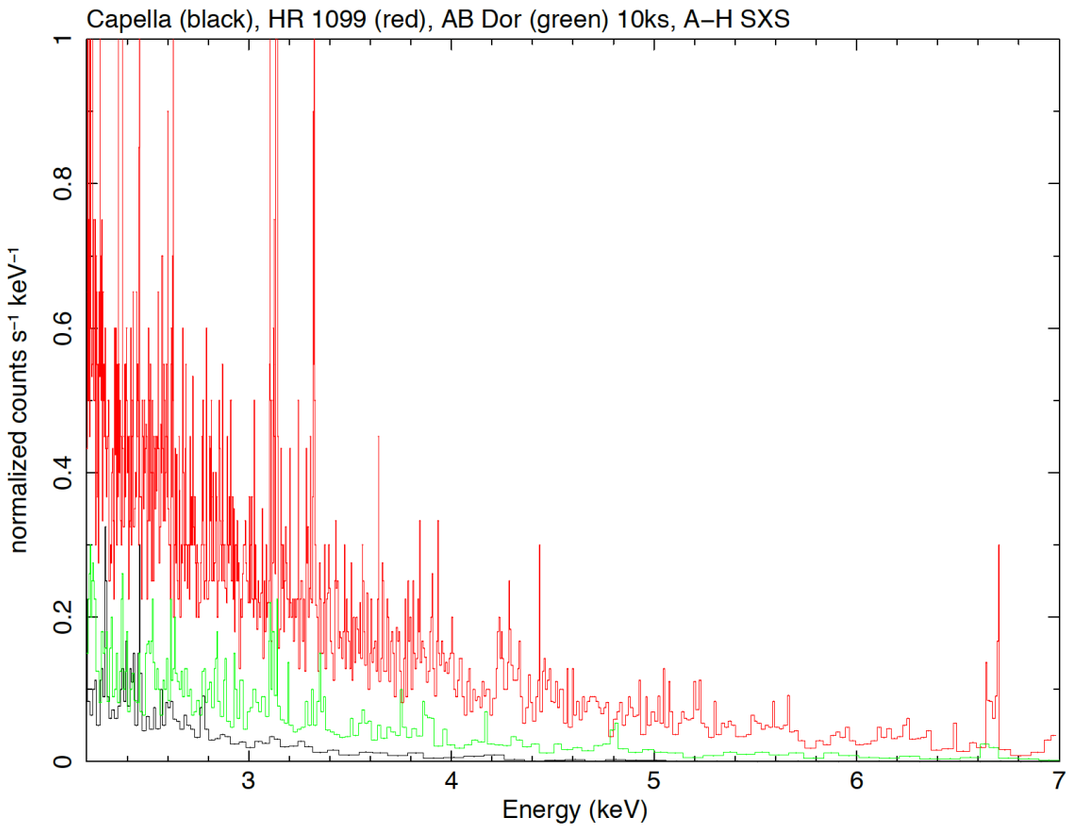
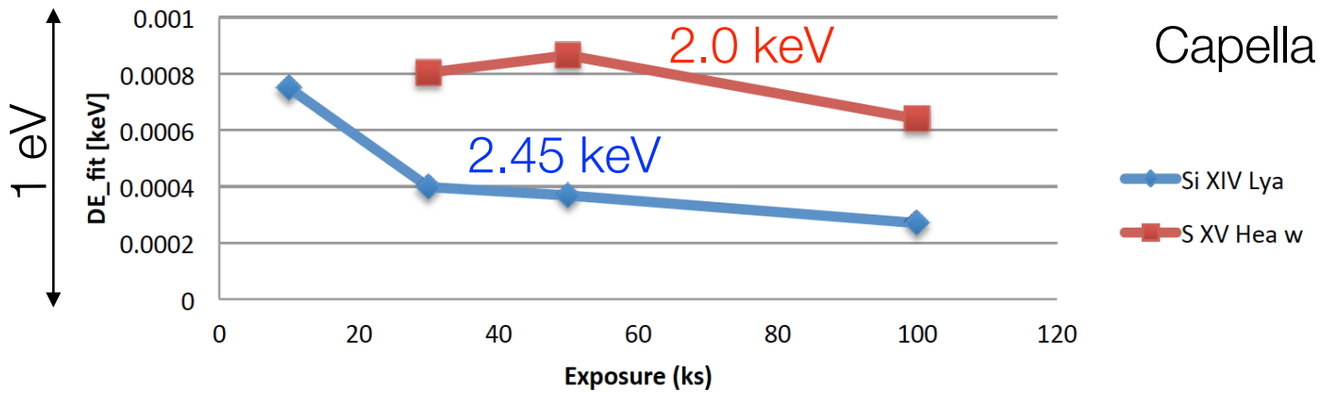
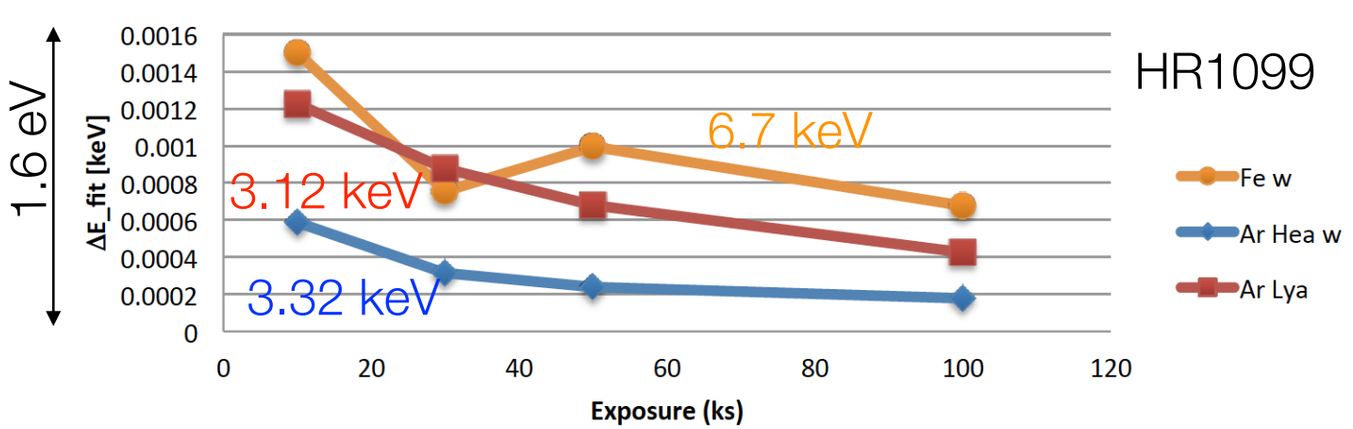
SXS resolution/LSF: celestial sources

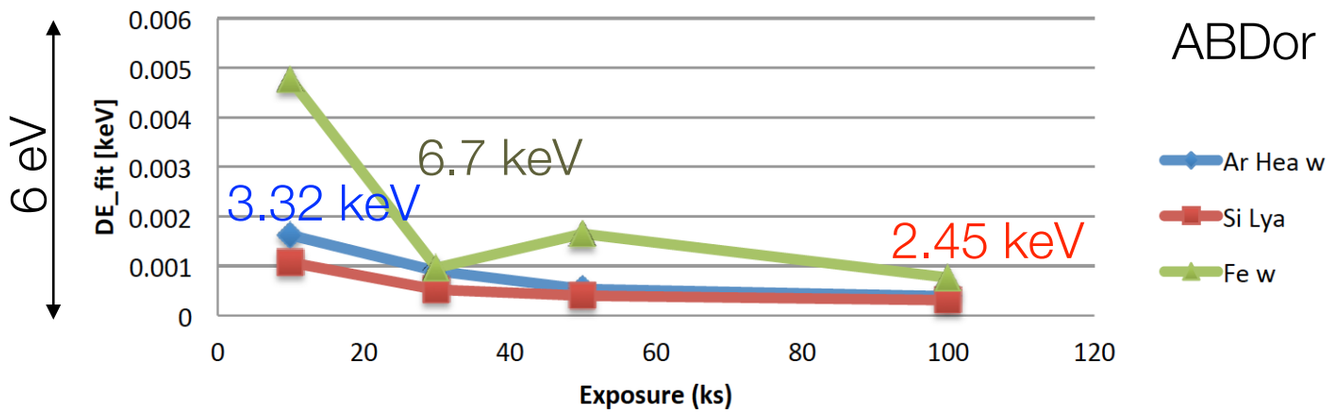


SXS energy scale



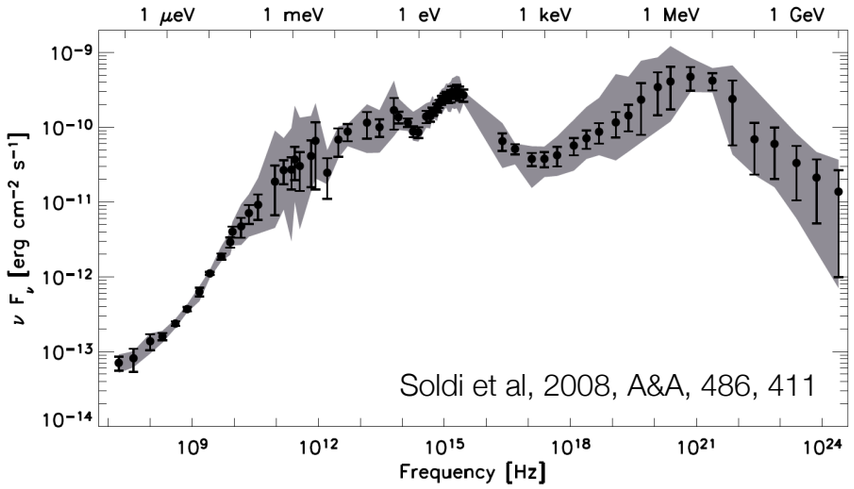




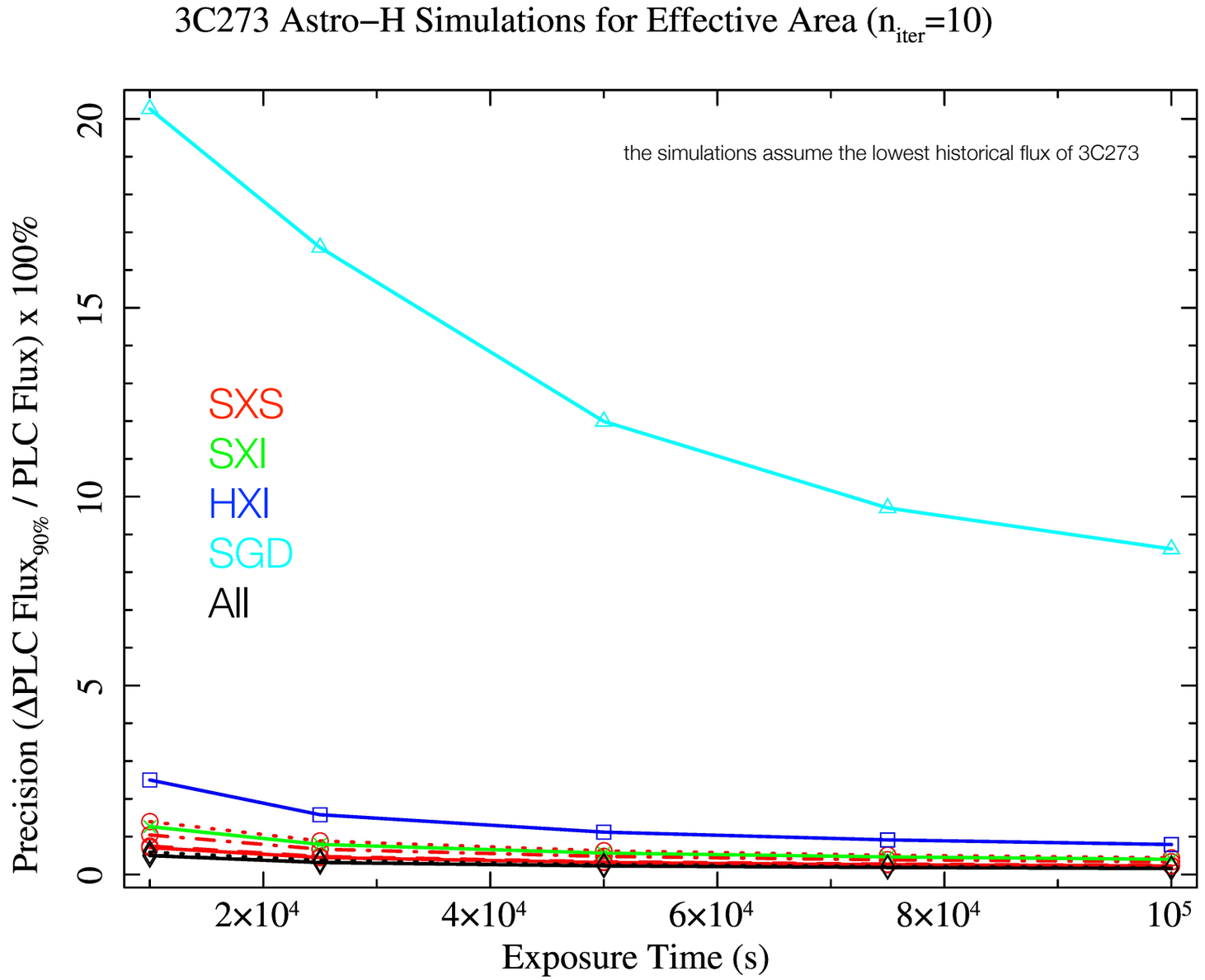


- Requirement: 1 eV (goal: 0.2 eV)
- **30 ks** on **Capella** (no GVC)
- **50 ks** on **HR1099** (GVC)
- *Similar exposure times* for *ABDor* or *Sigma Gem*
- Satisfy resolution requirements as well
- Variable sources! Stay on the safe T_{exp} side

Broad-band effective area

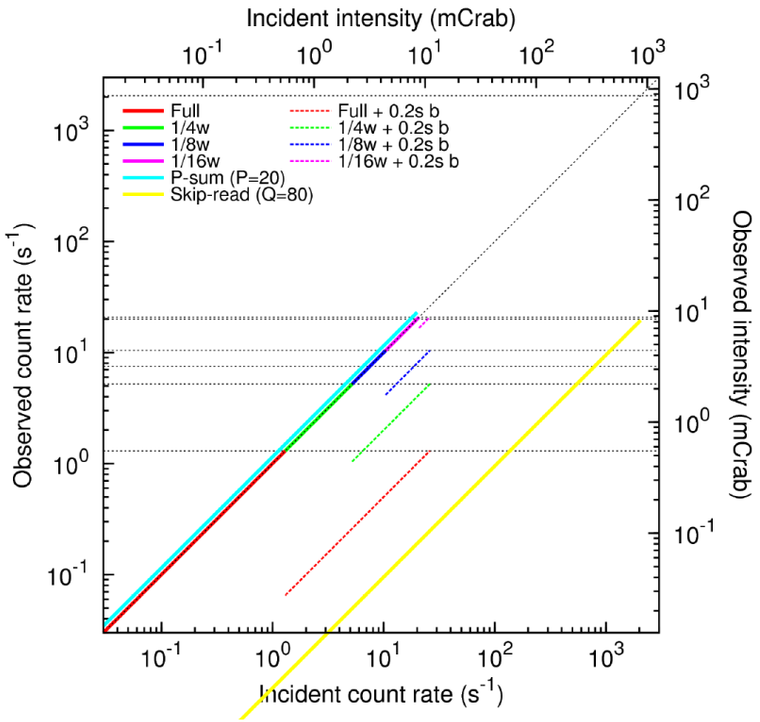


- Requirement relative effective area: 5% (goal: 2%)
- Achieved in **75 ks** with **3C273**
- 3C273 is the target of a yearly cross-calibration campaign with *Chandra*, NuSTAR, Suzaku, Swift, XMM-Newton
- [formerly PKS2155-305; see Ishida et al., 2011, PASJ, 63. 657]
- Alternatives: *Centaurus A* (obscured), *PKS2155-304* (soft), *PSR1509-58* (slightly extended)

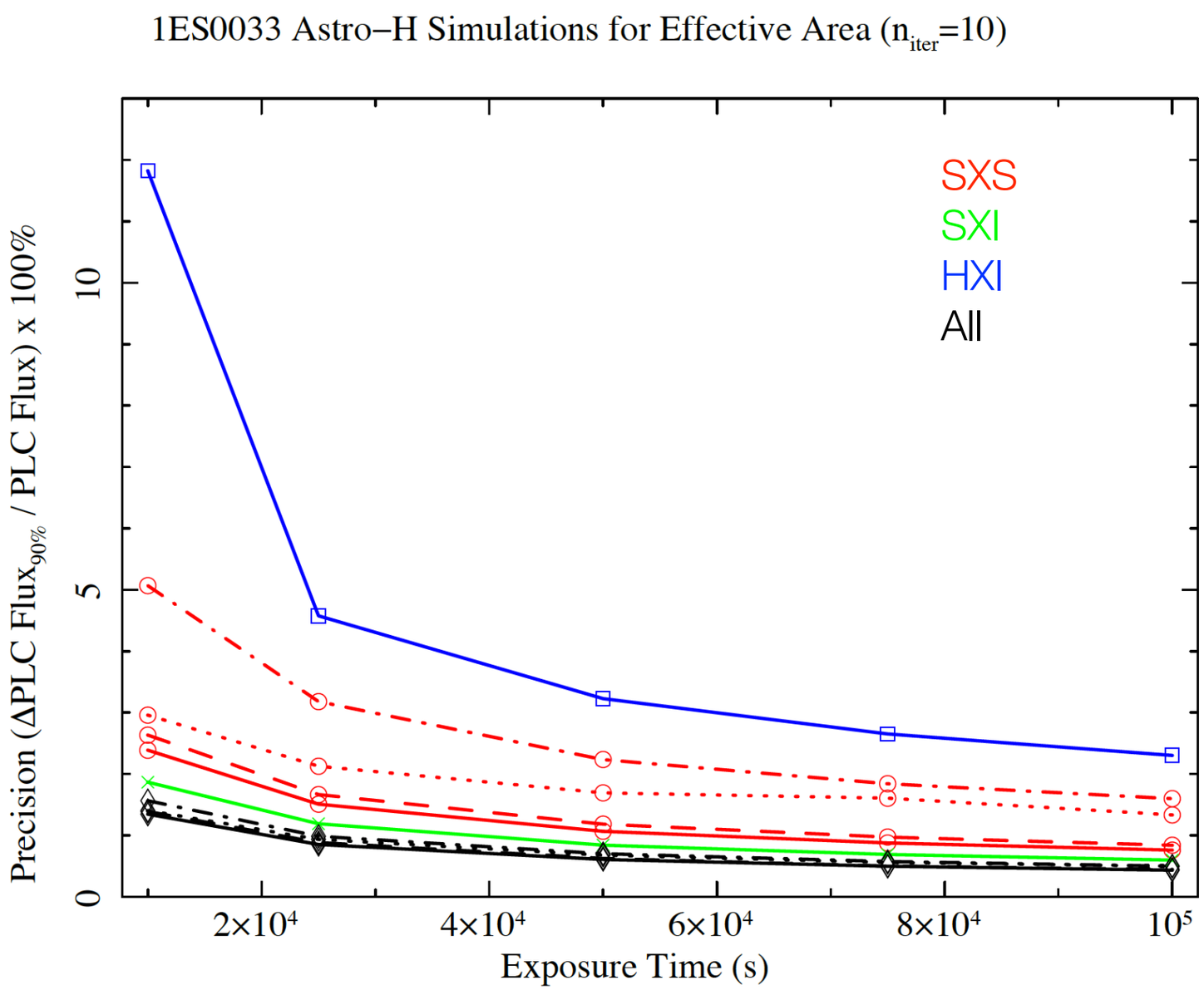


SXI effective area

(from a presentation by M.Tsujimoto at the 4th ASTRO-H Science Meeting)

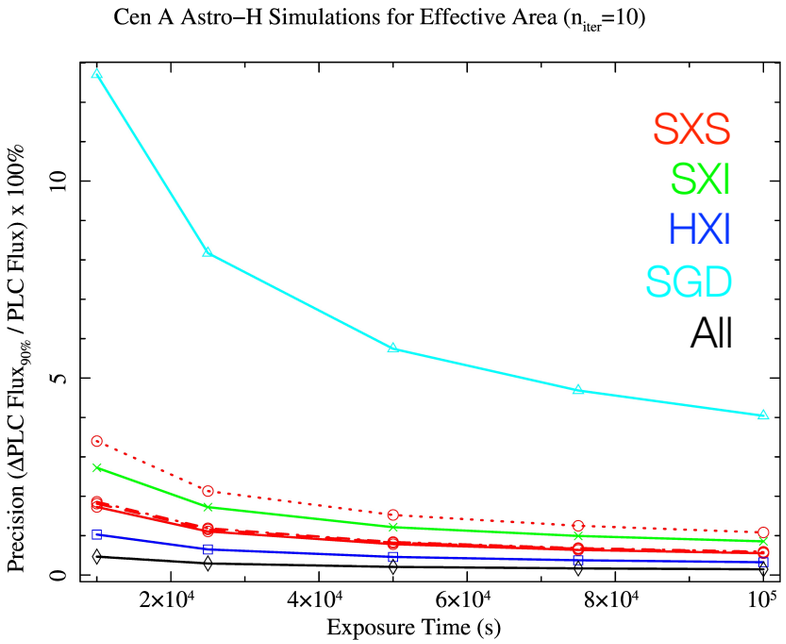


- ~1.3 mCrab (~3.6 counts/sec) in SXI Full Window ⇒ pile-up
- Alternative blazars for effective area calibration: 3XMM sample, flux <0.5 mCrab (de la Calle, in prep.)
- **75 ks** on **1ES0033+595** satisfy the calibration requirements

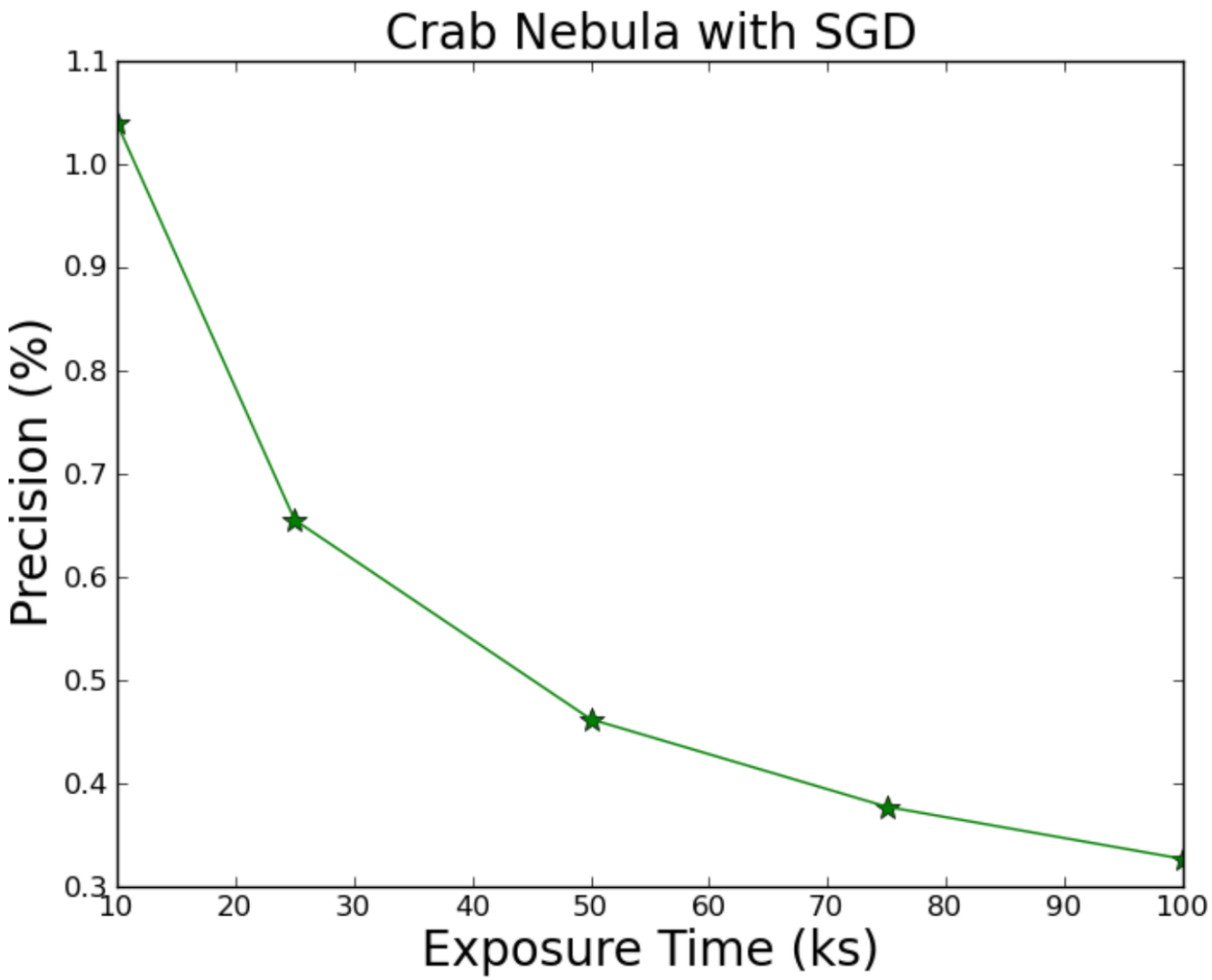


- Alternatives: *1ES1028+511*, *2E0414+557*
- Multi-observatory coverage advisable (relatively poorly known sources)

SGD effective area

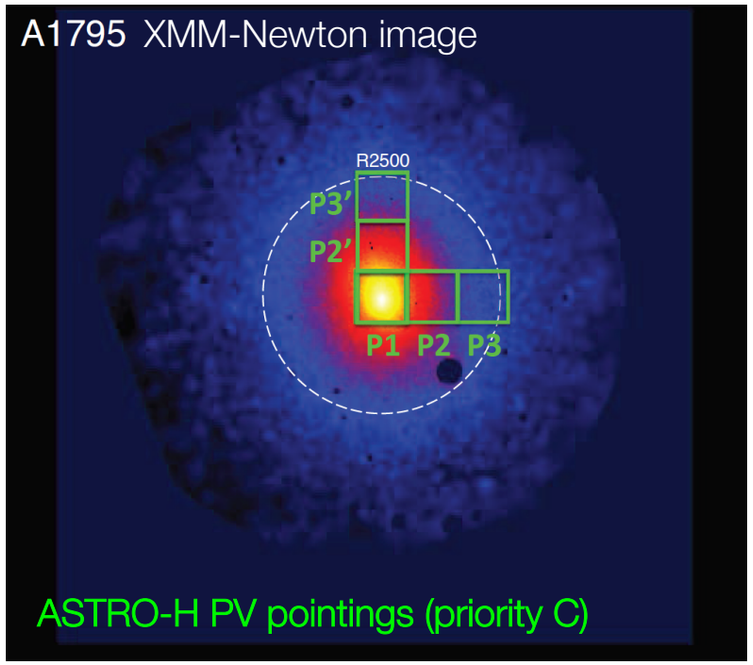


- SGD effective area calibration requires brighter sources
- **Crab Nebula** (**10 ks** suffice)
- Alternatives: *CygX-1* (*40 ks*), *Centaurus A* (*40 ks*)
- The same sources are good targets for polarisation calibration

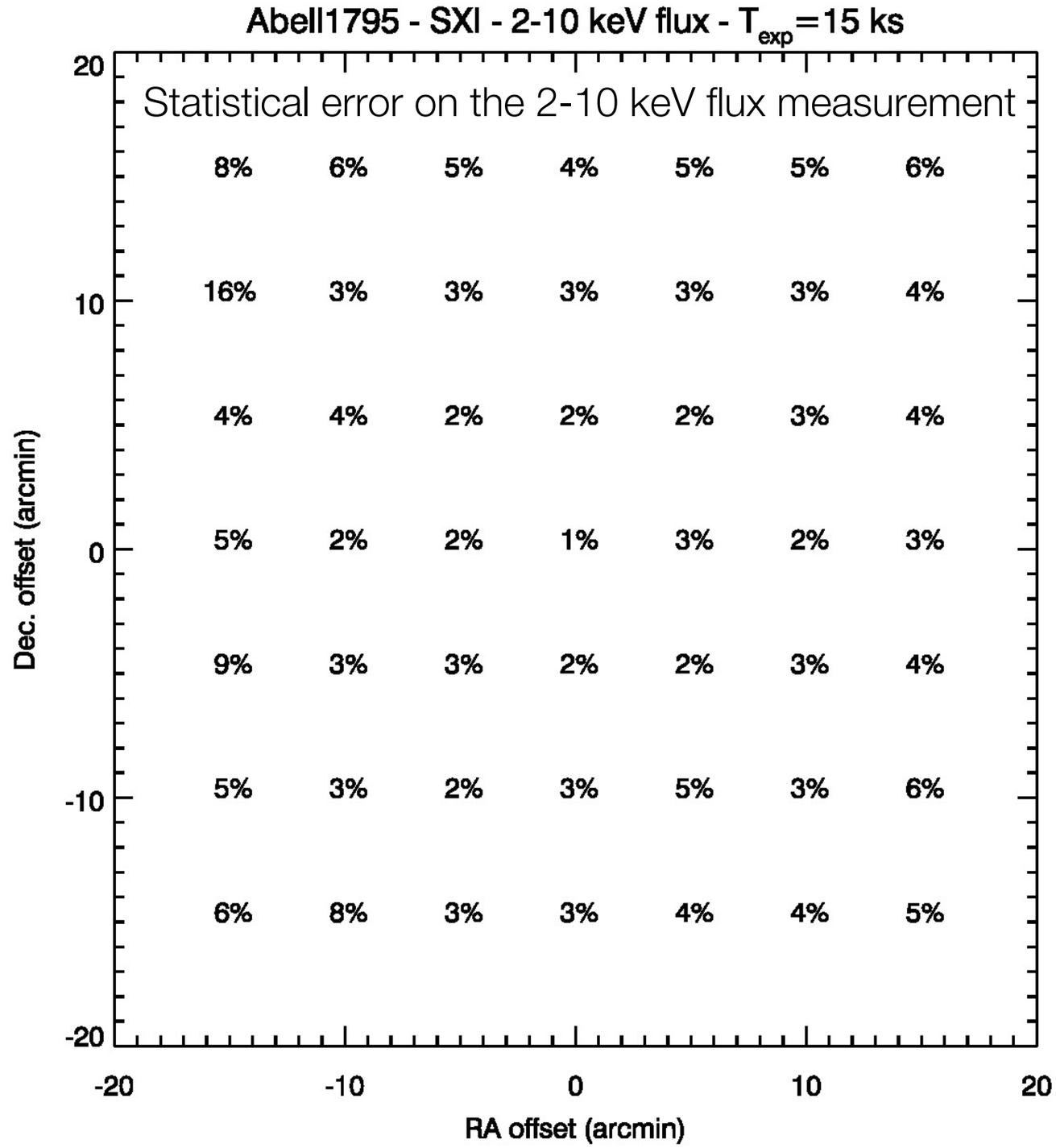


SXI off-axis effective area

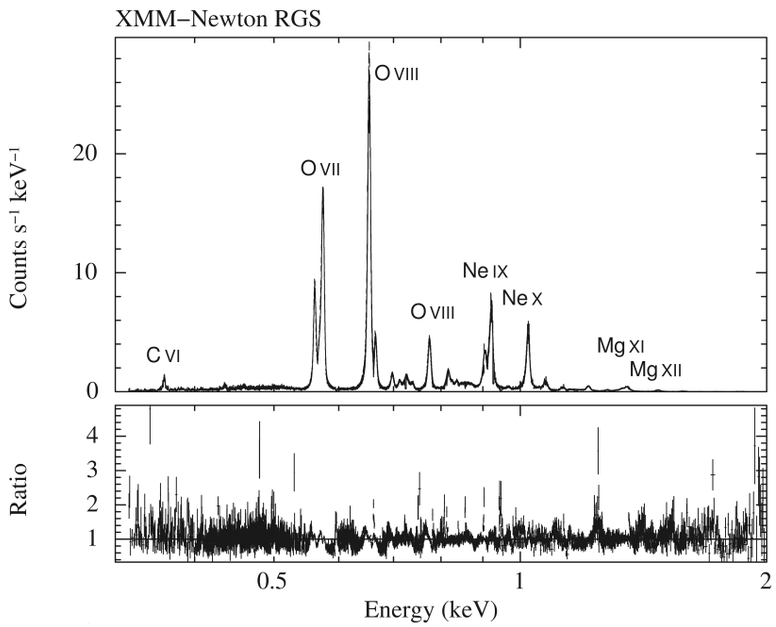
(from the ASTRO-H PV proposal by M.Bautz)



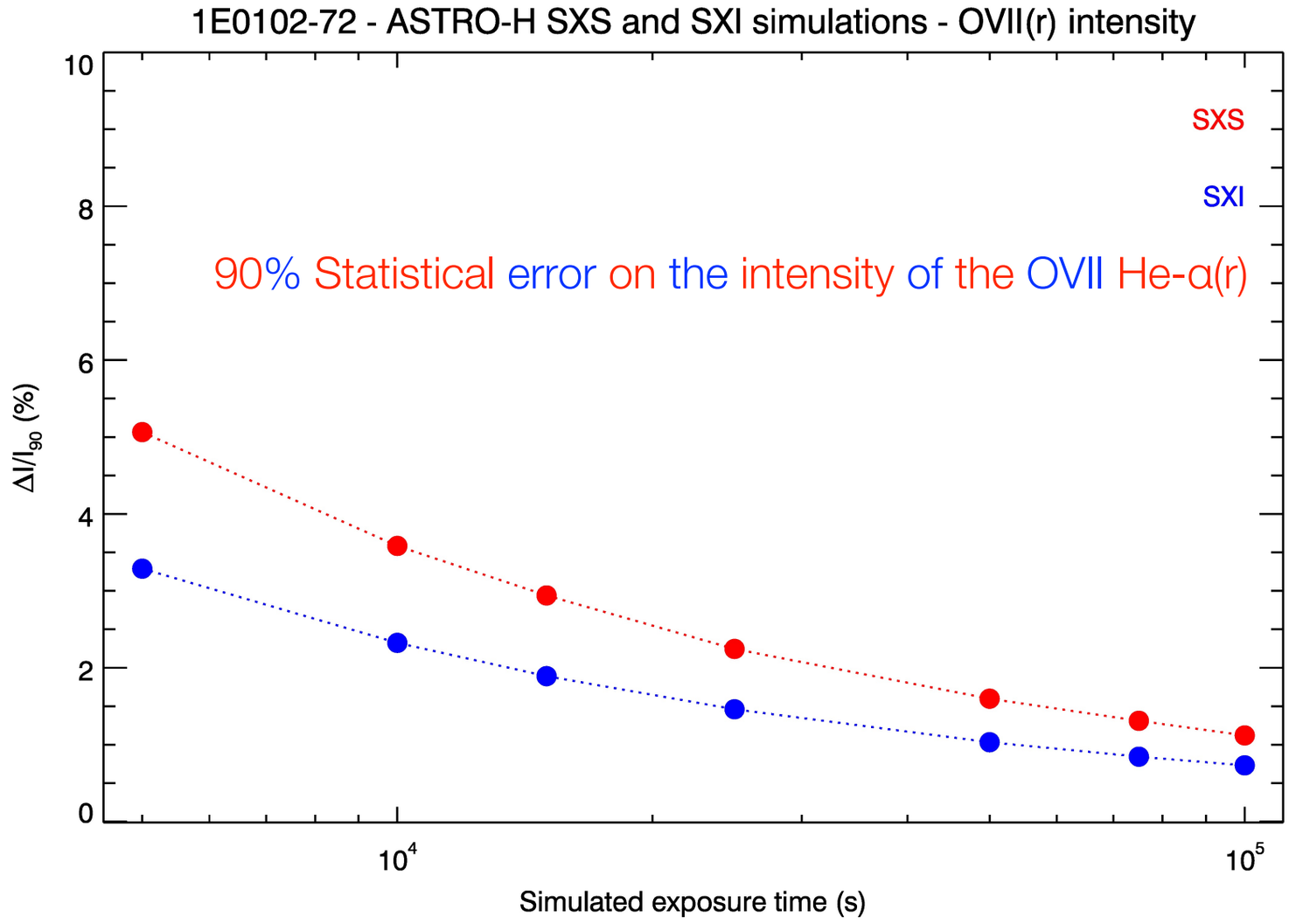
- Requirement: 10% (goal: 5%)
- Proposed raster of a relaxed cluster
- Strategy: 3 pointings per CCD. @ 5', 10', 15' off-axis
- **Abell1795** (*15 ks* p.p., total **180 ks**)
  - Hot (kT~5.3 keV), relaxed cluster (99% of the flux within 2'), cool core
  - Reference source for ACIS contamination monitoring
- Alternatives: *Abell3751*, *Abell2029* (similar T_{exp})



Contamination



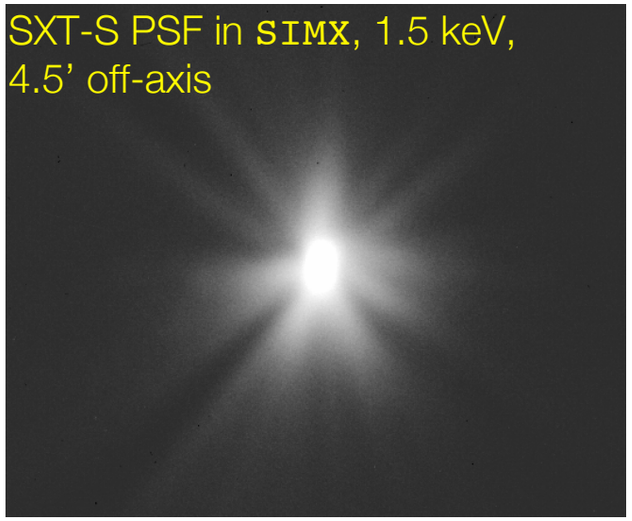
- Requires constant target, extensively visible in early 2016, strong soft X-ray flux/features
- Primary: **1E0102-72**:
  - compact (~40") SNR
  - Always visible
  - Reference calibration source for ACIS, XIS, EPIC
- Stronger features than gal.clusters
- Alternative: *RXJ1856-3754* (~2xT_{exp})



Strategy:

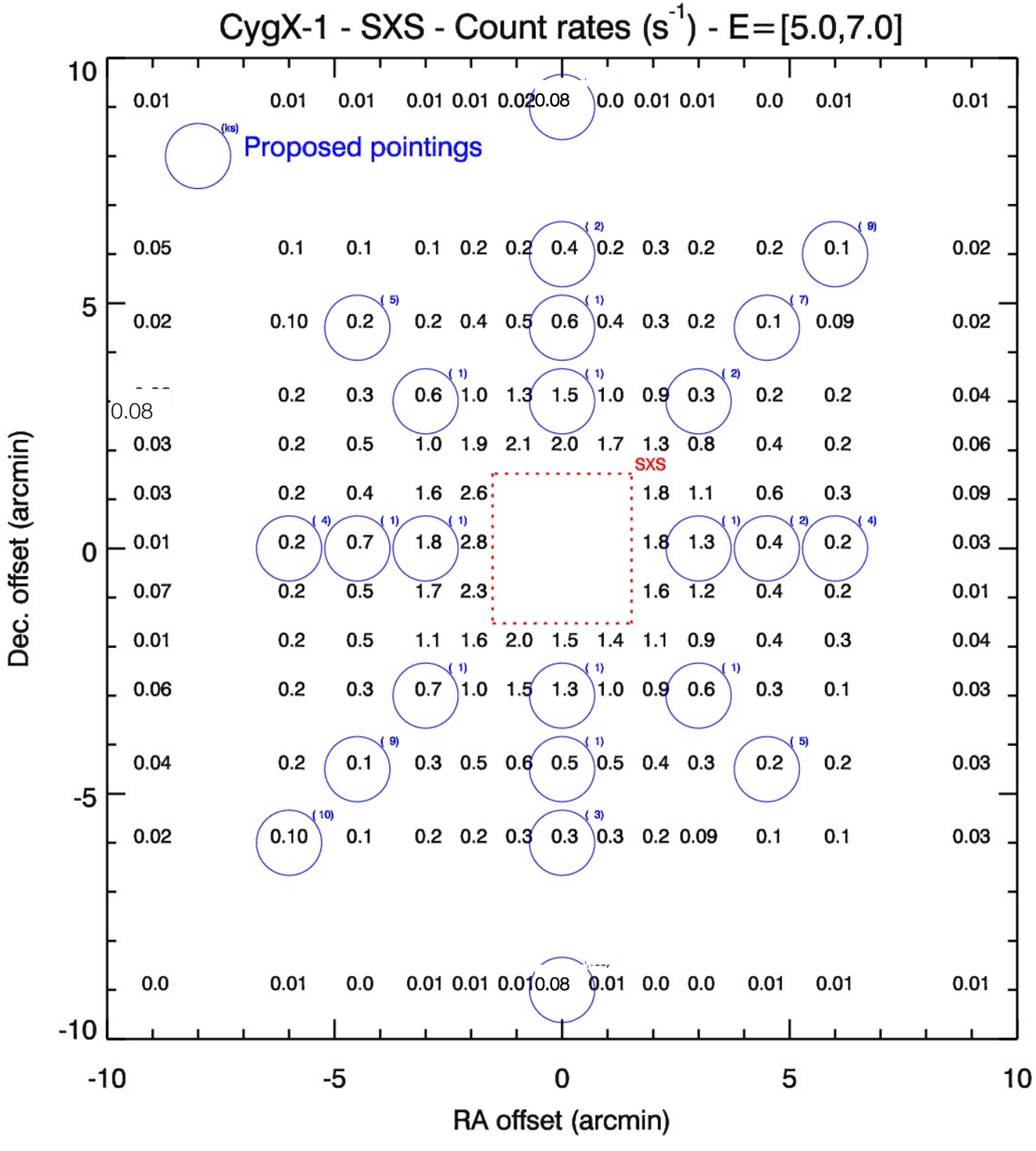
- **15 ks monthly** observations the first *3 months*
- **15 ks quartely** observation during the *following year*
- **15 ks yearly** observation in the *routine phase*
- Compositon: 50 ks observation of *RXJ1856-3754/Abell1795*
- Off-axis: *Vela SNR* (60 ks) or *Cygnus Loop* (80 ks)

SXT-S PSF wings



- Accuracy of the calibration of the SXT-S PSF wings crucial for extended sources SXS science
- Extensive ground calibration. Still, a few points at large offsets only
- Solution: in-flight raster at various off-axis and position angles
- AGN too weak. Binary needed (variable!)
- Primary: **CygX-1** (**120 ks**) (+ overheads!) + **Suzaku/Swift** monitoring
- Alternative: *ScoX-1* (*30 ks*) (+ overheads!) + *MAXI* monitoring - if PSP can deal with it
- To be complemented with 4x(1' or 2') off-axis observations of, e.g., *3C273* (*~10 ks*) for optical-axis calibration

Choice of the energy band driven by galaxy cluster science



Polarisation

(Courtesy T.Kallmann, GSFC)

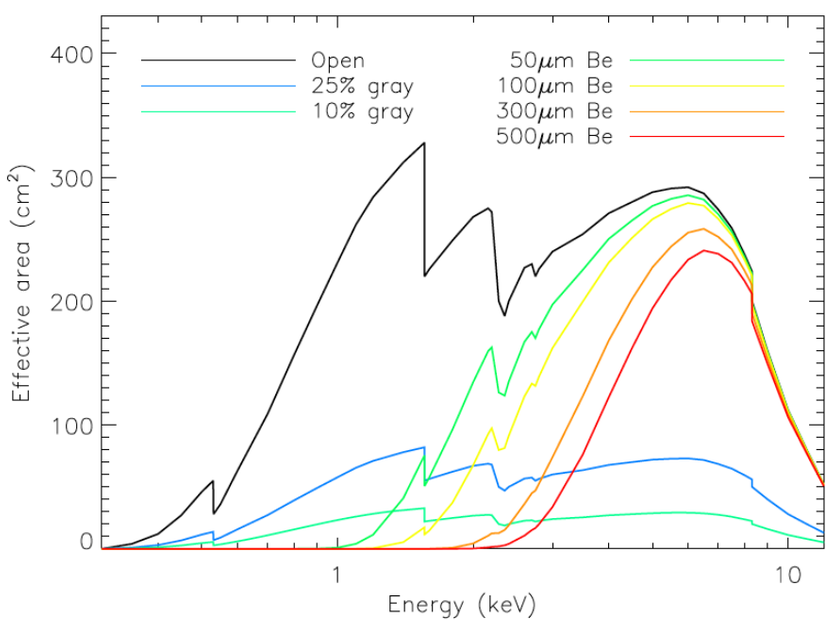
Not many sources have *a priori* sufficient polarised counts (or lack thereof!)

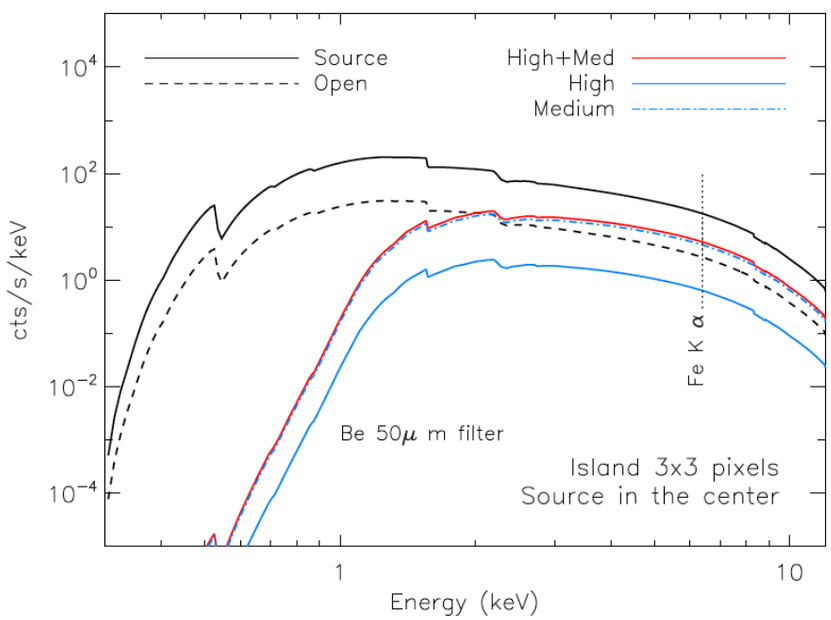
- Crab: 100 ks, as soon as possible (*science-driven*)
- CygX-1: 100 ks, as soon as possible (*science-driven*)
- Others candidates for MDP (fluxes from the 40-100 keV fluxes in the INTEGRAL catalogue)
  - ✳ VelaX-1 (54 mCrab) → variable
  - ✳ GX339-4 (43 mCrab) → ~1year duty-cycle outbursts, undetected in soft state
  - ✳ Centaurus A (40 mCrab) → secular variability by a factor 4
  - ✳ NGC4151 (20 mCrab) → Seyfert 1, variable by a factor a few, at least
  - ✳ ScoX-1 (17 mCrab), 3C273 (12 mCrab), SNR (CasA, RXJ1713.7-3946; ~4 mCrab) …

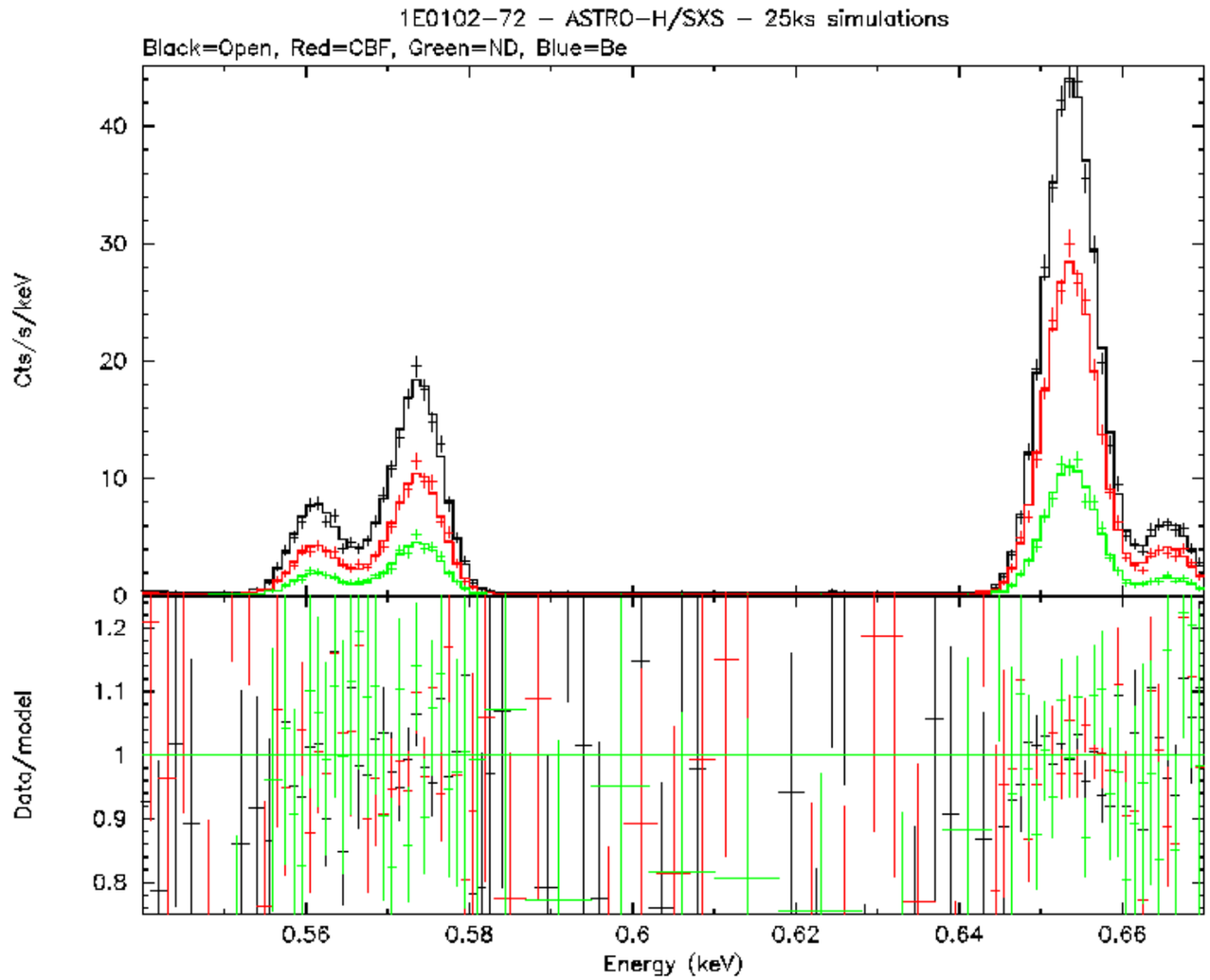
Uncertainty on the astrophysics: emission probably due to thermal Comptonisation in XRBs and AGN, could be polarised at the 5-10% level

SXS filters

(de Vries et al., 2012, SPIE, 8443, 53)







- Strategy: **3x25 ks** observations of **1E0102-72**
- Alternative: *RXJ1856-3754* (same T_{exp})

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Time budget (in ks)

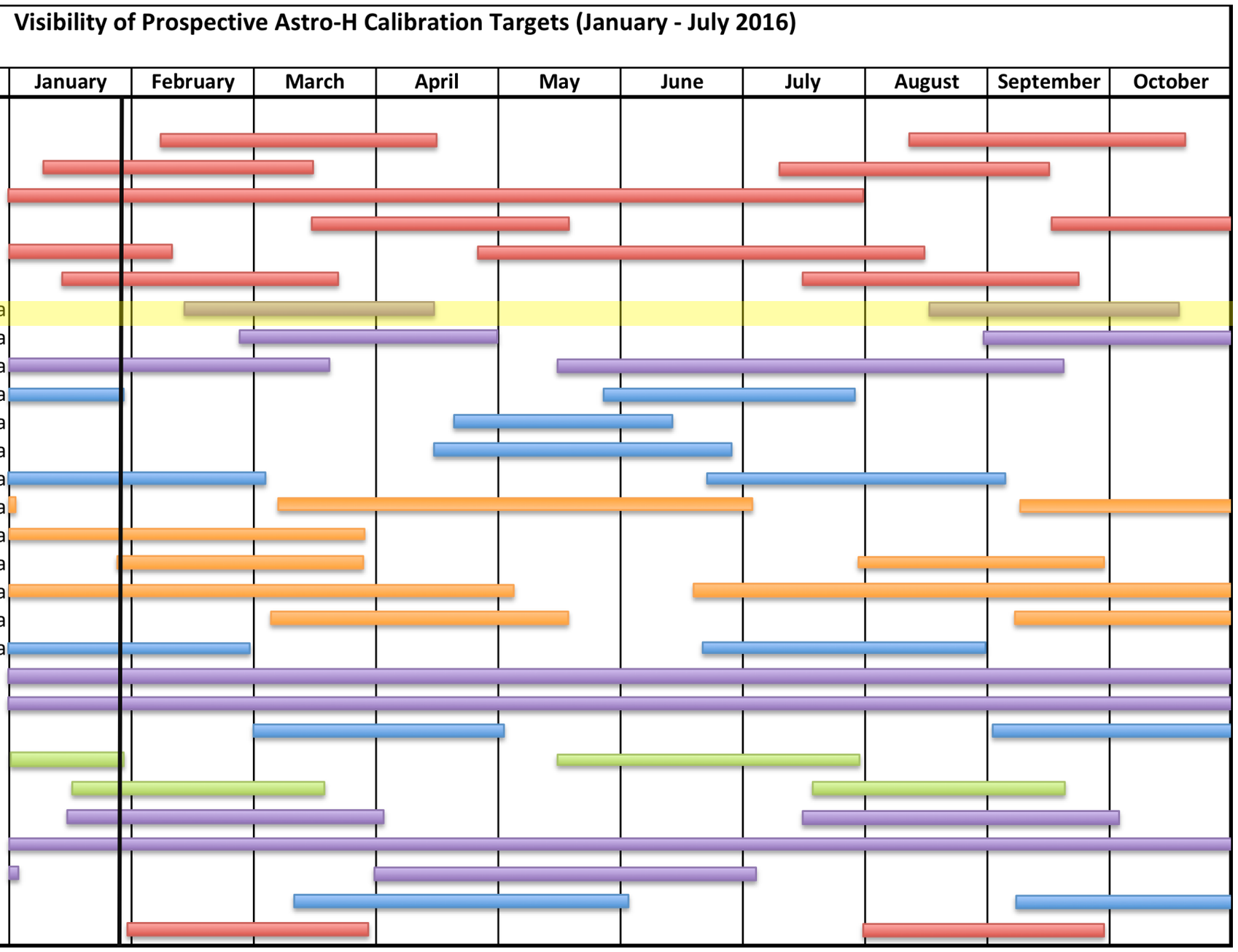
As soon as possible - on-axis calibration - off-axis calibration

Item	T_{exp} (needed)	Σ T_{exp}	T_{exp} (optional)	GVC?
Boresight	?		?	**Y**
Energy scale+ RMF/ LSF (SXI boresight CCD)	50(SXS)+140(SXI)	**190**	0	**N**
SXT-S off-axis PSF	120	**310**	0	**Y**
Contamination	60	**370**	110	**N**
Broad band effective area	75(SXS/HXI)+75(SXI)	**520**	0	**N**
Fine structure	?		0	**N**
Timing	80	**600**	0	**Y**
Astrometry	?		0	**N**
Boresight	?		0	**Y**
Background	200	**800**	0	**N**
PSF	?		0	**N**
SXS filters	75	**875**	0	**N**
SXI modes	?		0	**N**
Polarisation	300	**1175**	0	**Y**
SXI energy scale off-axis	320	**1495**	0	**N**
Effective area off-axis	420	**1915**	0	**N**

Actual calibration plan depends on source visibility

Visibility of Prospective Astro-H Calibration Targets (January - July 2016)

Source name	Type	Purpose
Capella	Star	SXS spectral resolution
HR 1099	Star	SXS spectral resolution
AB Dor	Star	SXS spectral resolution
Procyon	Star	SXS spectral resolution
AR Lac	Star	SXS spectral resolution
Algol	Star	SXS spectral resolution
Crab	PSR/PWN	Broad band effective area
G21.5-0.9	PSR/PWN	Broad band effective area
Cas A	SNR	Broad band effective area
3C 273	AGN	Broad band effective area
PKS 2155-304	AGN	Broad band effective area
Markarian 421	AGN	Broad band effective area
Cen A	AGN	Broad band effective area
Cyg X-1	XRB	Broad band effective area
GX 301-2	XRB	Broad band effective area
Sco X-1	XRB	Broad band effective area
Her X-1	XRB	Broad band effective area
GRS 1915+105	XRB	Broad band effective area
MCG-6-30-15	AGN	Broad band effective area
1E0102.2-7219	SNR	Contamination
N132D	SNR	Contamination
RX J1856.6-3754	NS	Contamination
Coma	Cluster	SXI flat field
Perseus	Cluster	SXI flat field
PSR 1509-58	PSR/PWN	Timing
Vela	SNR	SXI flat field
Cygnus Loop	SNR	SXI flat field
PSR 1937+21	PSR	Timing
Rho Oph	Star Cluster	Astrometry



Synergies with PV

Source	Main goal	T_{exp} (Cal.)	Cal. priority	T_{exp} (PV)	PV priority
NGC4151	Polarisation	100	Back-up	100	N.D.
Circinus	SXI energy scale, RMF	100	Back-up	100	A
CygX-1	Polarisation	100	Primary	100	A
3C273	Effective area	75	Primary	100	N.D.
Cen A	Effective area	75	Back-up	100	N.D.
Perseus (centre)	SXI energy scale, RMF	15	Primary	100	A
Perseus (off-axis)	SXI energy scale, RMF	540	Primary	830	ABC
Abell2029	SXI energy scale, RMF	2xPerseus	Back-up	10+590	B
HMXRB/MCV	Timing	?	?	?	?

Cross-calibration requirements

Source	Scope	Required	Obervatories
3C 273	Eff. Area	Y	All
Centaurus A	Eff. Area	N	NuSTAR, Suzaku
Cyg X-1	Eff. Area	Y	NuSTAR, Suzaku
1E S0033+595	Eff.Area	N	Any (<10 keV)
Cyg X-1	SXT-S PSF	Y	Suzaku, Swift
*Sco X-1**	*SXT-S PSF*	*Y*	*MAXI*

*currently back-up for Cyg X-1

Summary

- Hard work ongoing to achieve an agreed and Project-endorsed IFCP by July
- Horizontal collaboration between ASTRO-H scientists in different teams
- Choice of sources based on: a) Project calibration requirements; b) SWG scientists' requirements and experience; c) Instrument Teams' analysis of ground-based calibration; d) prior experience of past and operational missions; e) extensive `SIMX` simulations (Thanks Randall and his Team!)
- Current budget: **~1.2 Ms** on-axis, **~0.7 Ms** off-axis, **~40%** calibration items unknown (overheads and Routine Calibration Plan not included)
- **IFCP v.0.50 draft**, under revision. Inputs from the IACHEC **crucial,** and **welcome**!