Measuring the birth and growth of Black Holes:

Epoch of Reionization Energetic X-ray Survey

EREXS

Josh Grindlay
Harvard-Smithsonian Center for Astrophysics

and

N. Gehrels, S. Barthelmy, A. Kutyrev, H. Moseley (GSFC),
J. Bloom (UCB), P. Coppi (Yale),
B. Allen and J. Hong (CfA)

*(what we **should** have submitted to Astro2010 as a Probe mission that might EXIST)*

Talk Outline

- An all-sky, All-timescale approach to IXO science
- Key science questions and motivation for ***EREXS***
- Mission Requirements
- **Overview of proposed *EREXS* mission**
  - Science objectives
  - Instruments and Mission model
- Current development prototype: ***ProtoEXIST2/HXI***
- Summary and prospects

A *Wide-field*, *Wide-Timescale*, Approach to IXO/NWNH Science

- 4 of the 5 IXO Science Objectives center on BHs or NSs which are "rare" (vs. stars or normal galaxies) and require large samples over large redshift and temporal range: need ***wide field imaging-temporal surveys***

- **Growth of structure** requires WF-surveys and many sight-lines to sample and measure largest to smallest scales: ***GRBs are ideal probes at high-z***!

- **SMBH growth from spin (vs. mergers)** can be probed by ***deep full-sky Blazar surveys*** since Jet power ~ spin, and beamed jets require wide field surveys for significant sample sizes vs. redshift

- **SMBH masses** from temporal variability and PDS vs. luminosity, with *high cadence, high time resolution* WF suveys

- WF surveys with onboard NF followup capitolize on Time Domain Astrophysics (TDA), as recommended by NWNH, for optimum science

EREXS

Why start with the EoR (Epoch of Reionization) ?

- Because it traces back to the **very first stars**, which were massive (current best estimates ~30-100 $M_{\odot}$), and thus the **very first stellar BHs,** and thus *traced by GRBs*

- Because the ionization itself is now almost surely by these same massive stars, not the still rare AGN, and so GRBs at z >10 followed up by moderate resolution (R ~1000) spectroscopy can *trace the first growth of structure*

- Because it is clear that SMBHs must have formed by the end of the EoR (highest redshift SDSS QSO at z ~6.9; EOR not yet complete), so that **very first SMBHs and all subsequent growth begin in EoR**

- ***Thus to trace when and how SMBHs grow, it is necessary to begin with significant numbers of AGN at z > 7-8***

Beamed AGN (Blazars) are ideal since brightest and likely spin-powered

IXO science goals 2-4 begin with *Probes of Early Universe*

And will then also address fundamental NWNH science goals:

- **When** and how did the ***very* first ("Pop III") stars form** & evolve?
- Did they produce **>300 $M_\odot$ BHs or ~30 $M_\odot$ BHs** from Pop III binaries?
- How did subsequent generations of Pop II.5 stars then form & **evolve into first galaxies?**
- When did **reionization** of Universe (by hot stars) ***begin*** and **how did structure form** into galaxies ?
- ***When did the first ~10^8 $M_\odot$ Supermassive black holes form? Did they require >100 $M_\odot$ PopIII BH "seeds"?***
- **IXO Science Goal 5 (NS-EOS constraints):** ***short GRBs coincident with Advanced LIGO – Grav. Wave vs. GRB waveforms constrain EOS***

Requirements for the *desired* high-z GRB and BH survey mission

- GRB and BH survey sensisitivity ~10X greater than Swift/BAT at 15-150 keV and ∞ better at energies ~5-15 keV
- *IR (1-2.3μm) imaging and spectroscopy >10X more sens. than VLT or Keck!*
- Band width extending to both lower and higher energy than BAT
- Instantaneous FoV comparable to BAT, but *larger sky coverage and cadence*
- Rapid on-board image triggers on multi-timescales
- High energy resolution (~5-100keV) ≤3arcmin to avoid source confusion
- Optical (0.3-1μm) imaging and spectroscopy ~10X more sens. than UVOT

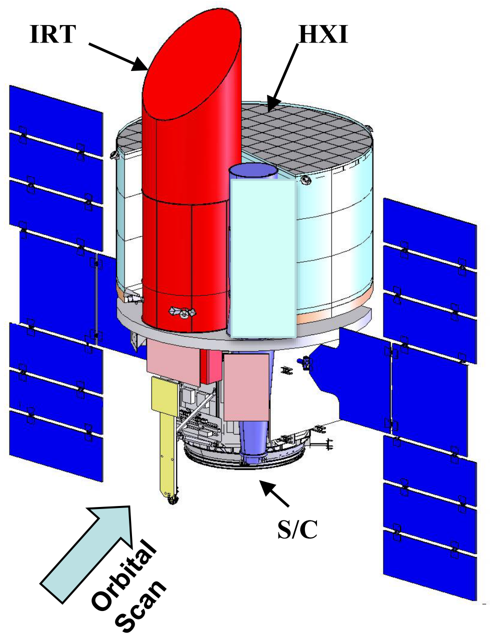
Such a mission requires more mass, power than Swift but (only) comparable to Fermi to enable both Discovery and Followup science to finally EXIST

What is *EREXS* ?

(Epoch of Re-ionization Energetic X-ray Survey)

- A <u>*Probe Class Mission*</u> to conduct the most sensitive *full-sky* survey for ***Black Holes*** on all scales (stellar to supermassive) to ***Probe the high-z Universe***
- A wide-field (80^o x 50^o) **hard X-ray (5-300 keV) imaging** (**3 arcmin resolution**, **<20" source positions**) telescope surveying/monitoring full sky *every 3h* with 10X higher sensitivity than any previous or planned full-sky HX imaging survey…
- *Plus* a 0.8m **optical -IR telescope** (***IRT)*** to obtain identifications, redshifts and diagnostics of black holes, transients & extreme objects for followup study by **Fermi, JWST, LSST, ALMA, SKA, ATHENA (?) and LISA(?)**
- Complements **NuSTAR, Astro-H, &** <u>**paticularly *eROSITA* for <10 keV survey**</u>
- Scaled down & *improved* from ***EXIST*** studied under ***Astrophysics Strategic Mission Concept (ASMC)*** *Study* program, in preparation for *Astro2010*
- ***EXIST* was recommended by the previous (2001) Decadal Survey & *EREXS* considerably improved in its science, implementation & unique capabilities**

A Hard X-ray, full-sky imaging mission with deep IR followup is required for the ultimate GRB & SMBH survey back to the EoR



HXI: CZT detector arrays + mask: 5-300 keV **1.8m^2 tiled CZT**, **coded mask** images 80^o x 50^o FoV, 3' resol. & <20" positions

IRT: 0.8m; cooled (-30C) (dichroic: 0.3-0.9μm (HyViSI) and 0.9–2.3 μm (NIRSPEC)

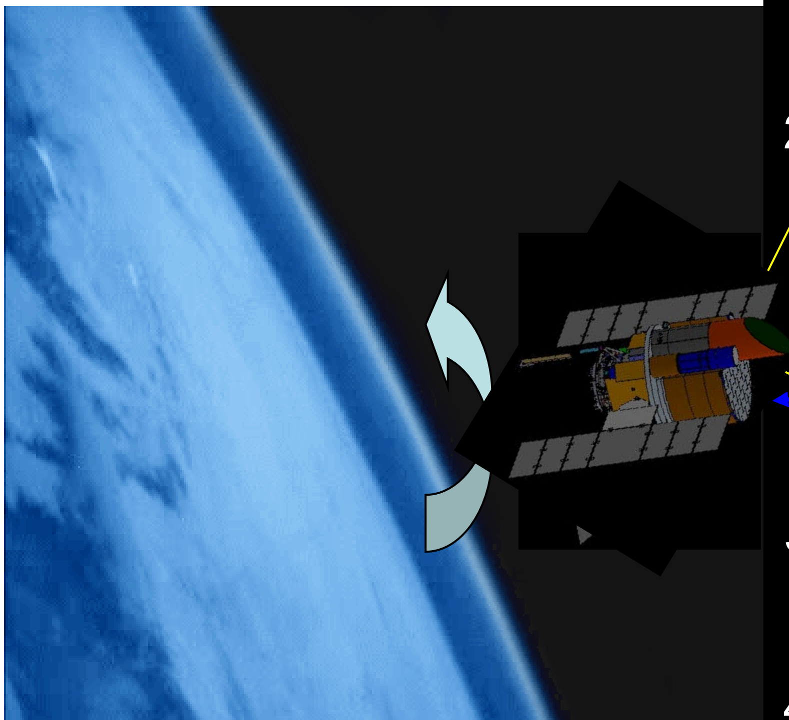
HXI at ~zenith ***scans*** at orbital rate & ***points*** **IRT**/**HXI** to GRBs within ~100s

Mass, power, cost <40% of *EXIST*

The *New EREXS* mission (600km LEO, i ≤15°):

- ***2y full sky survey:*** ±20deg *Zenith-pointed* **scanning**, 2sr FoV, *full-sky ea. 3h*.
- ***3y followup IDs:*** **IRT**/**HXI** **pointings** for IDs, ***redshifts***, spectra & timing

How does ***EREXS*** operate?



1. Zenith (+/-~30°) **scan** of 90° FoV of HXI at orbital rate to cover ~half-sky each orbit

2. Imaging in 80° FoV detects Gamma-ray burst (GRB) -- or variable AGN or transient

3. ***EREXS*** slews S/C onto GRB for IRT imaging ID and spectrum (optical + IR) for redshift

4. Pointing for 1-2 orbits to measure structure in distant Universe; HXI measures spectrum & variability of target *and* continues Survey

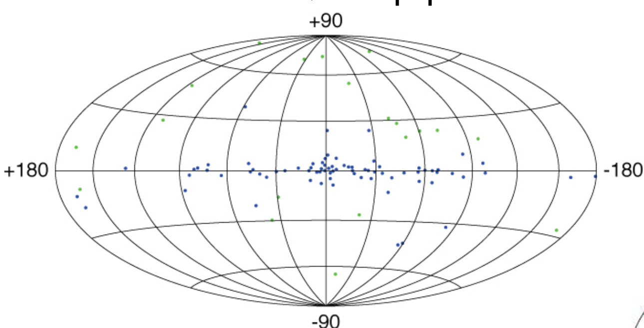
5. Resume scan (years 1 & 2) or new target

Deepest Hard X-ray *Full-Sky* Survey

- ***EREXS*/HXI: 5-300 keV <u>full sky mission</u> survey to Fx <u>~7 x 10^{-13} cgs, or 10X more sensitive than *Swift* or *INTEGRAL*,</u> gives ≥6 x 10^{4} sources, <20″ positions**

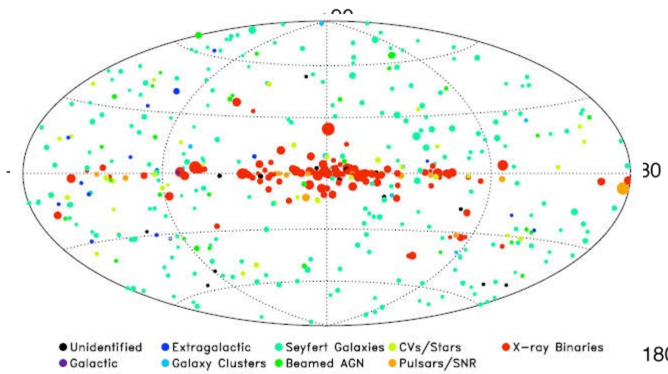
- ***EREXS*/*IRT*: 0.3-2.3μm imaging & spectra (AB ≤24, 19; R =30, 1000), <0.2" pos.**

2000 Hard X-ray Sky
HEAO-1, BeppoSAX



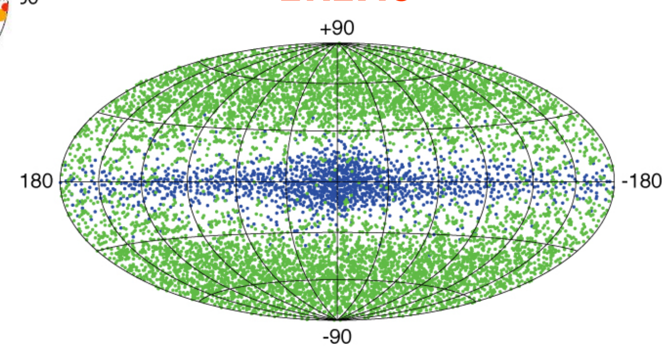
~100 sources

2011 Hard X-ray Sky
Swift (& INTEGRAL)



~900 sources

2018(?) Hard X-ray Sky
EREXS



~60,000 sources

Primary Science Goals for *EREXS*

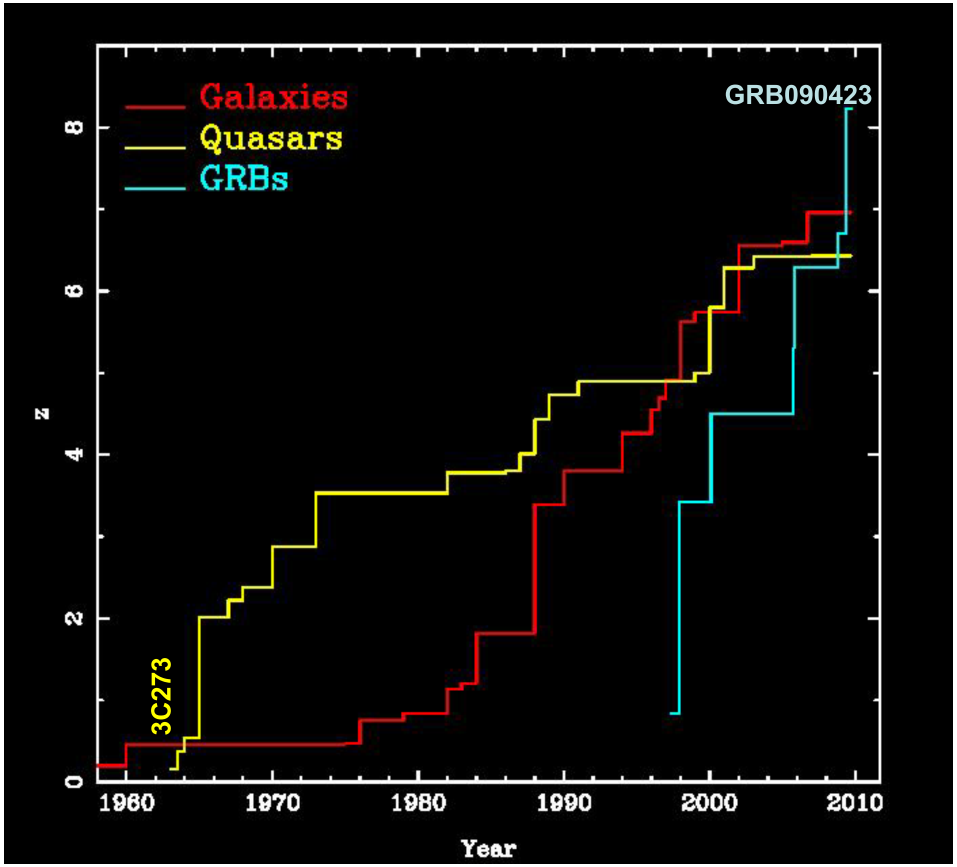
(to survey and study Black Holes on all scales: stellar to supermassive)

- **G1: Measure** cosmic gamma-ray bursts as in-situ probes of the ***Epoch of Reionization at redshifts z >7-12*** from prompt GRB redshifts and spectra

- **G2: Measure supermassive BHs in galaxies**, including *obscured* or *dormant*, to constrain SMBH demographics, growth and evolution, and ***to constrain the accretion luminosity of the universe & SMBH evolution***

- **G3: Measure the stellar and intermediate mass BH populations in the Galaxy and Local Group** by a generalized survey for Transients for which prompt IDs and X-ray/HX/IR spectra distinguish SNe, SGRs & Blazars and complement ***Fermi, JWST, LSST, Astro-H, LOFAR/ALMA/GMT-TMT-ELT*** with prompt alerts for unique objects

GRBs *must* preceed QSOs: highest-z stellar Probes

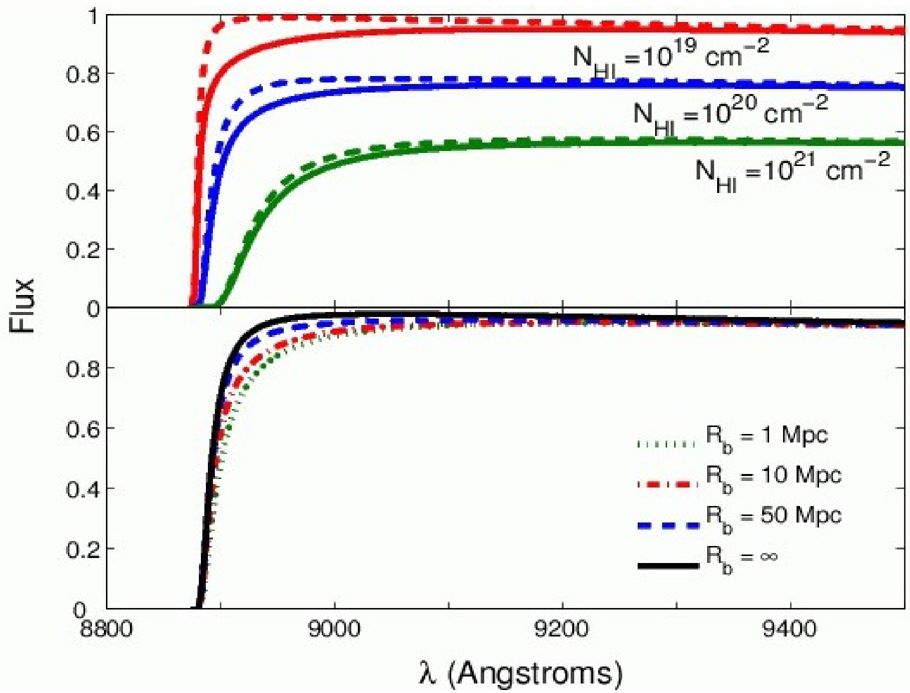


GRBs clearly outpace AGN for most effective probes of Early Universe at z >7-8!

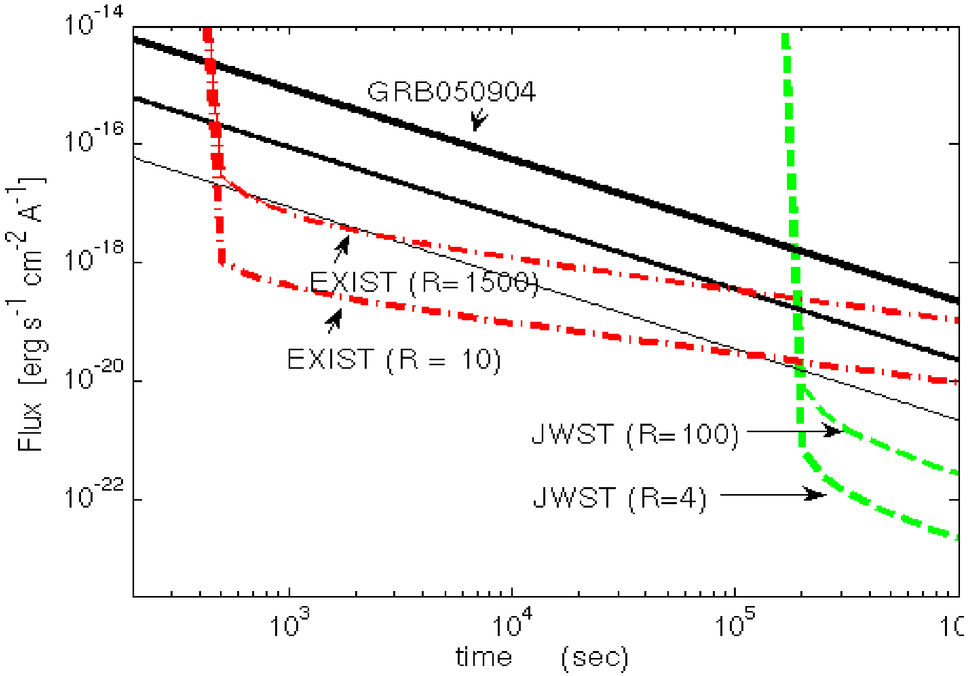
- *Swift* GRBs at z = 6.3, 6.7 and record spectroscopic z =8.3 for GRB090423! *GRBs **are detectable** out to at least z ~8-10 and early Pop II & possibly even PopIII?*
- Broader energy band, higher sensitivity & FoV needed for large sample at z ≥ 8-12
- IR from space needed for z ≥7 since Ly-dropout then in NIR & spectra less sensitive from ground (OH lines bkgd)
- GRBs provide "back-light" for IR spectroscopy of host ISM & IGM gas. *Measure galactic structure (vs. z) back to epoch of re-ionization (EOR)*

EXIST IRT spectra (R = 30) in 300-1000s: AB(H) ~22-23

2 VIS + 2 IR bands enable ***GRB redshifts*** out to z ~20(!)



Sensitivity of Ly-break *shape* to local IGM & EOR (McQuinn et al 2008) **but need gal. IGM ≤10^{21}cm^{-2}**



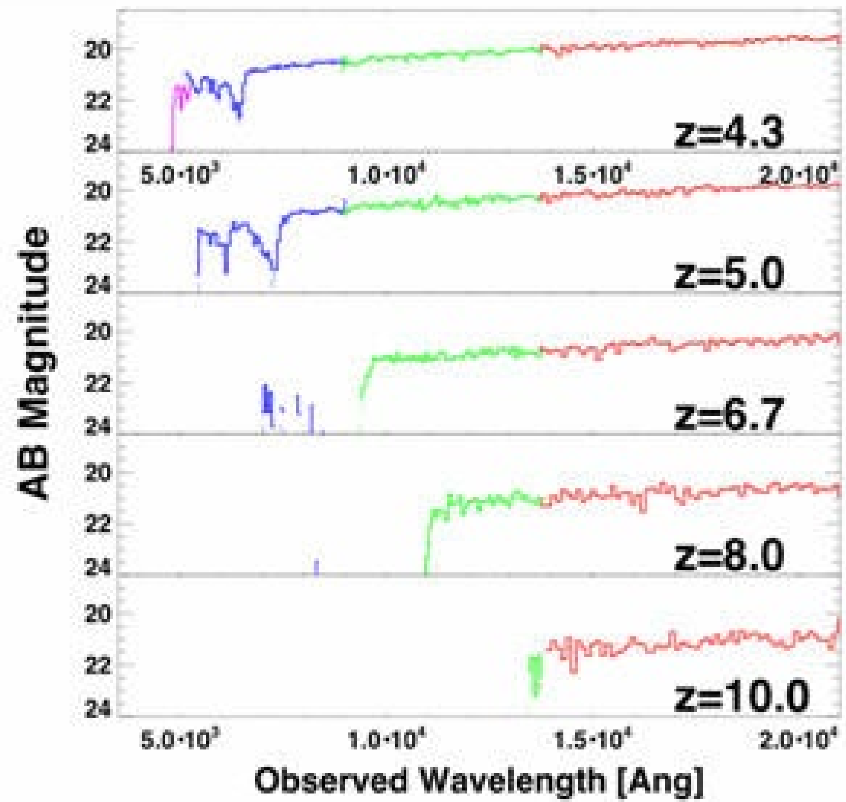
IRT vs. JWST for GRBs 1X, 0.1X and 0.01X flux of GRB050904.

- **IRT spectra (R ~1000) for AB(H) ~18-20 in 3000sec exp. *simultaneously* for optical (0.3-0.9μm) and IR (0.9-2.1 μm): Ly profiles for EOR studies of high-z IGM**

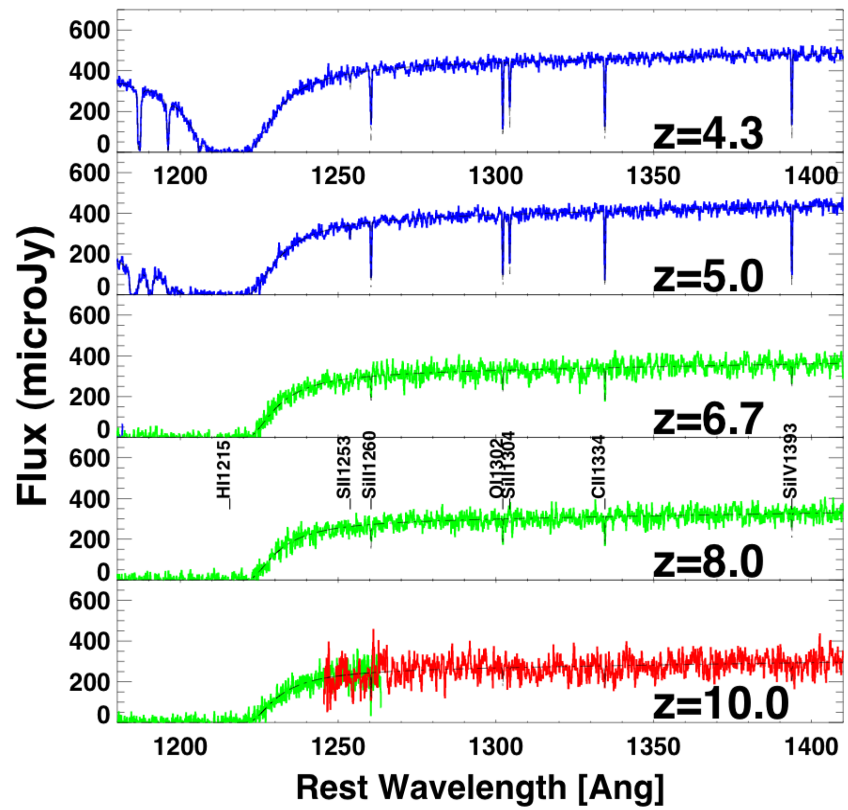
- **Simulations: > 450 GRBs/yr *of EXIST GRBs would have z measured* ; and ~30/yr at z >8. Over 5y mission, expect N(z>8) ~ 100 EOR sight-lines to be measured.**

Simulated Ly-breaks for ***EREXS IRT*** vs. z (*R = 1000, T = 2000sec*)
for a GRB 3mag brighter than the anomalously faint GRB080913 (z = 6.7)

R = 30 Grism, imaging or slit, for AB(H) > 20



R = 3000 long slit (4”), for AB(H) <20



Assumed model (which *IRT* tests!):

AB(H) = 15.5 at T =200s, then GRB lightcurve decays: F ~ T^{-1} ν^{-1} Log(NH) = 20 in GRB host

Metallicity vs. z: z < 6, [Fe/H] = -2; 6 < z < 7, [Fe/H] = -3; Z > 7, [Fe/H] = -4

Simultaneous spectra obtained in 4 IRT bands: **0.3 – 0.9µm, 0.52 – 0.9µm, 0.9 – 1.38µm, 1.38 – 2.1µm**

EOR & Fe/H can be measured vs. z!

***EREXS*/IRT can measure z for All Swift GRBs and high res. spectra for ~3/4 of all Swift sample for spectra extrapolated to J, H, K and redshifted to z ~12!**

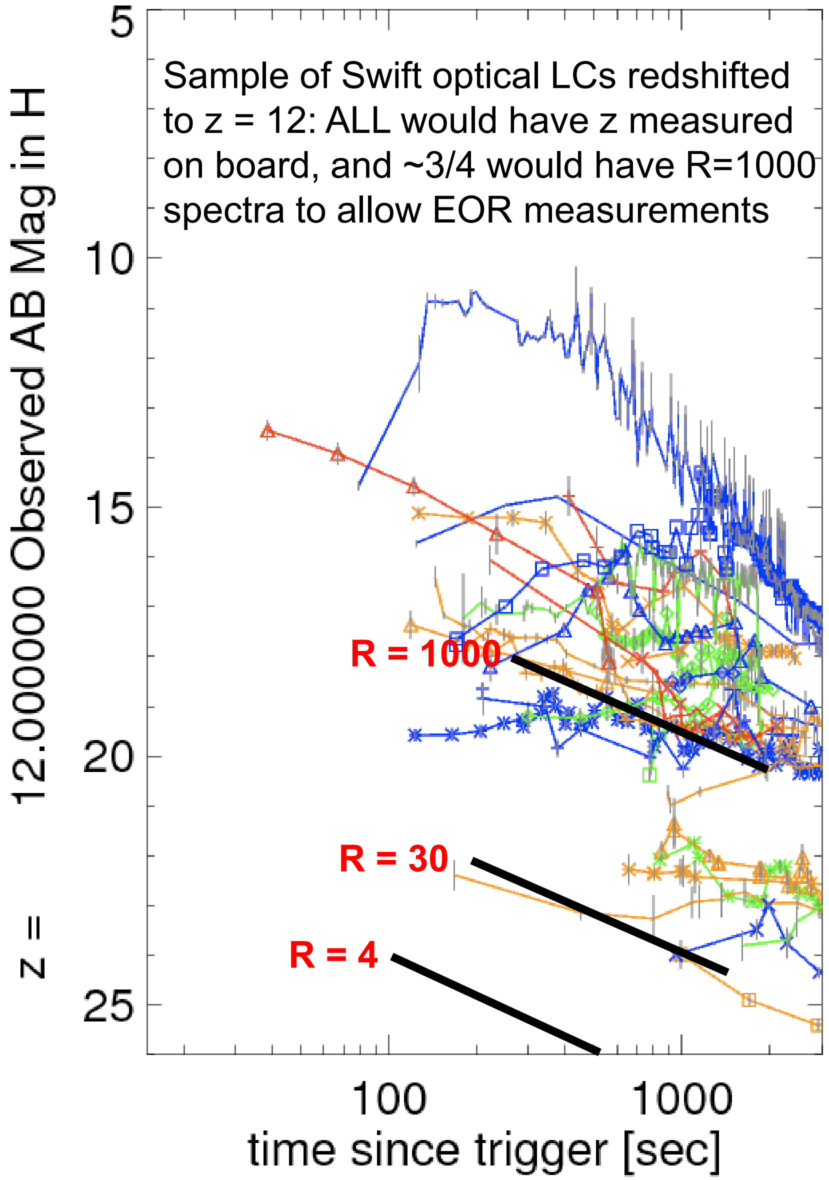
Swift GRB AGs with spectra in/extrap. to H band and redshifted to z = 12.

IRT sensitivities for prompt imaging in 4 bands (0.3 – 2.2μm):

4-band **Imaging** (R = 4) :
AB ~24 (10σ) in 100s
photo-z's

R =30 **Spectra** :
AB ~22 (10σ) in 200s
accurate-z's

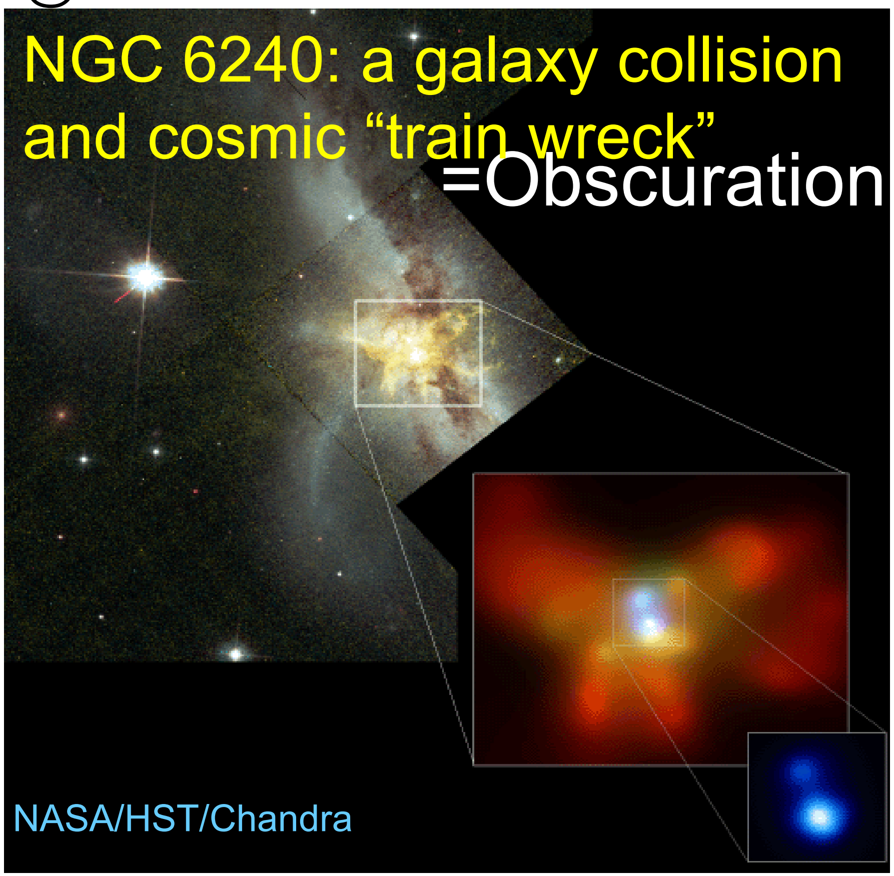
R=1000 **Spectra** :
AB ~19 (10σ) in 2000s
EOR & Fe/H measures!!

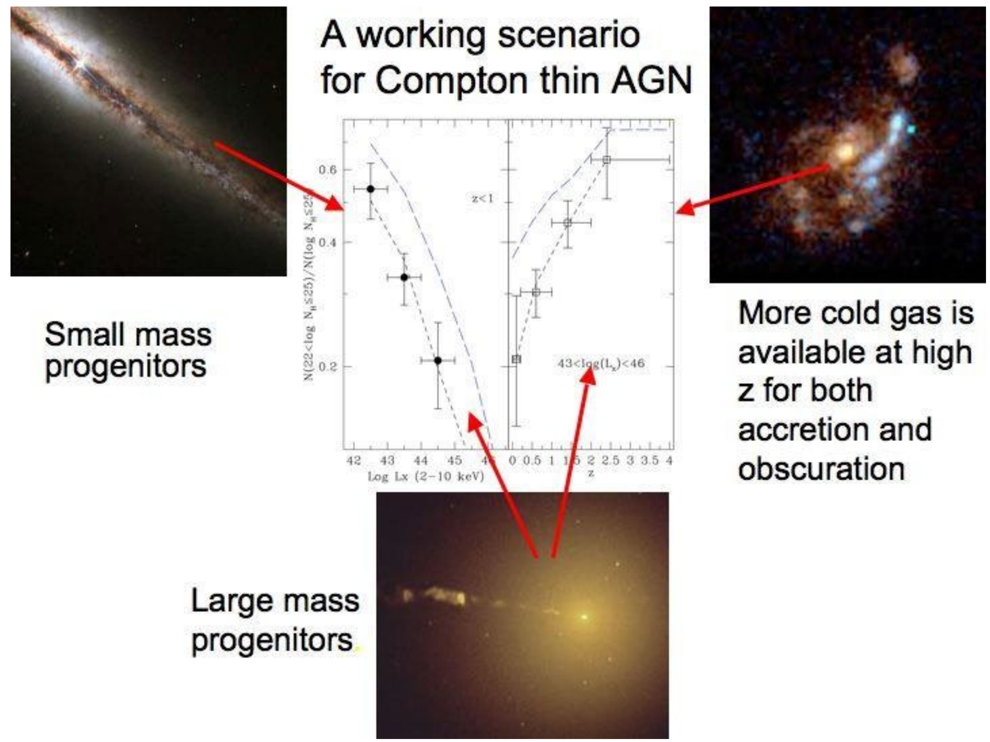


G2: Obscured or Dormant AGN (all types) & Blazars vs. z?

• ***EXIST*** discovers: 1) ***obscured AGN*** over a broad range of Lx and absorption column NH *to constrain NH vs. z and growth of SMBHs*, and 2) ***Dormant SMBHs*** (like SgrA*) *revealed by HX flares from Tidal Disruption of field stars → **LISA triggers***

• ***EXIST*** best suited to discover rare ***Type 2 QSOs*** at z ≤3 and study Type 2s vs. SFGs @z~1

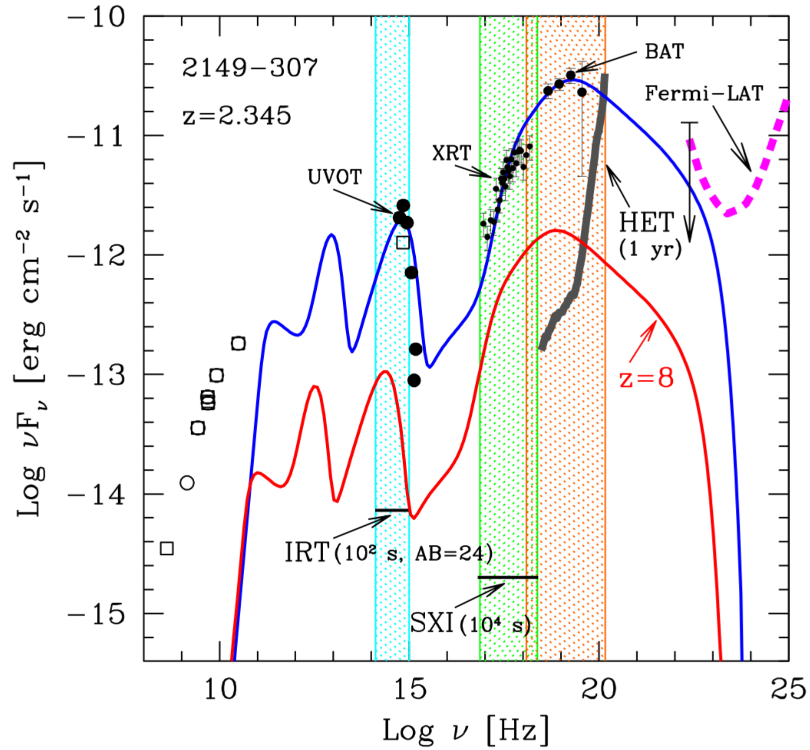




EXIST **survey will explore the evidence (e.g. La Franca et al 2005 and Treister & Urry (2006) that obscured AGN are *increasing as* $(1+z)^{0.4}$**

EREXS could extend Blazar surveys to z ≥8 !

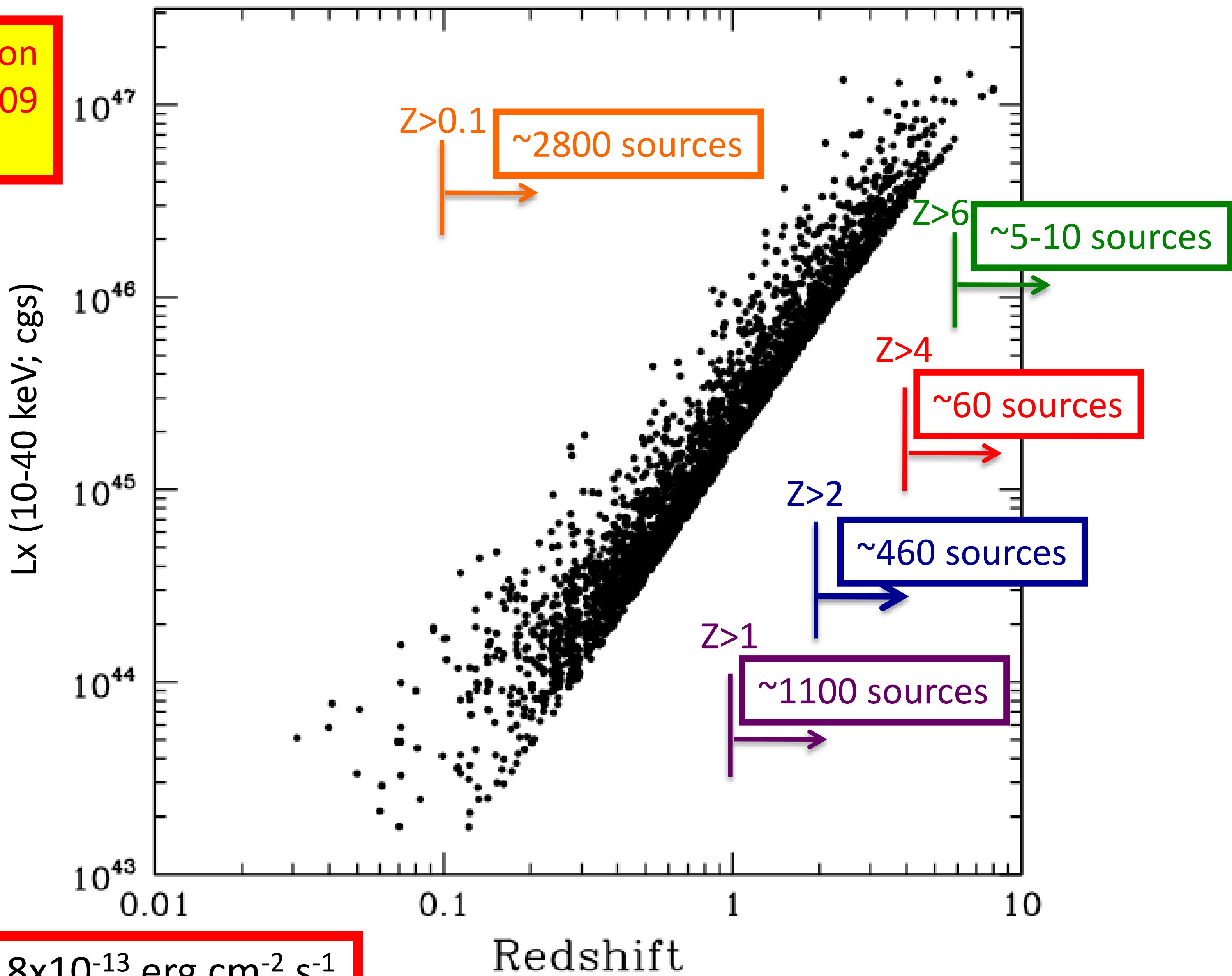
- Blazars are the AGN analog of GRBs: persistent, extreme-beamed and exceptionally luminous and variable
- Understanding their formation and evolution requires deep full sky samples with sensitivi to rapid variability
- ***EREXS*** could detect the Blazar 2129-307 (detected by Swift/BAT, XRT, UVOT) out to ~8. Blazars might best probe SMBH growth (Ghisellini et al 2010)
- Blazar jets imply high spin SMBHs form first?
- Sensitivity for detection and variability study with ***EREXS***/HXI exceeds Fermi/LAT



IRT and *eROSITA/***SXI** sensitivities allow short observations during **HXI** survey or pointings. ***IRT*** measures redshifts directly for Blazar survey

EREXS expected for blazars (all sky, 1y survey)

Best fit XLF + Evolution from Ajello et al., 2009 (Swift/BAT sample)



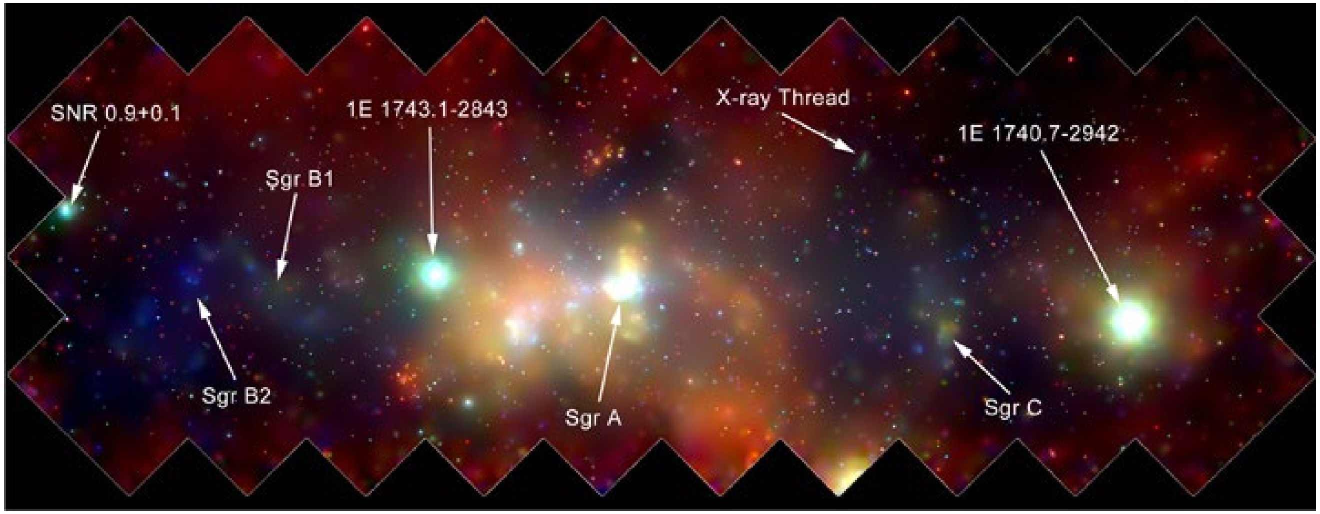
F_{lim} (10-40 keV) = 8×10^{-13} erg cm^{-2} s^{-1}

G3: *EXIST measures* stellar BHs & IMBHs as *Transients* in Galaxy, Local Group

- ***EREXS*** detects ***all*** bright stellar BHs in transients (Lx(>10 keV) ~10^{36-38} erg/s) throughout Galaxy, LMC/SMC and M31. ***Reveal population of obscured HX sources. QPO monitoring of bright BH-LMXBs; ULX's in Local Group***

- ***Isolated* stellar BHs in Galaxy and IMBHs** in Local Group accreting via Bondi-Hoyle (with ~10^{-4} efficiency) from GMCs nearly Compton thick

- **Faint BH transients in *Central Galactic Bulge*?**: BHs in nuclear cusp (Alexander & Livio 2004) detected (~10d) as VFXTs if Lx(>10 keV) ~$10^{34.5}$ erg/s BH vs. NS or WD binaries around *SgrA** distinguished by Type I bursts & novae



Chandra view of central Bulge (~ 2° x 1°)

EREXS scanning demonstrated with BAT Slew Survey (***BATSS***)

- Swift conducts ~4 slews per orbit (to/from targets and Earth limb avoidance) at ~45arcmin/sec, moving BAT FoV by ~2-3 diameters. Aspect file gives S/C pointing direction each 0.2sec (~9' ~BAT resolution/2 for Nyquist sampling of scan image)

- By turning "event mode" data on during a slew, and sending it down on next TM pass, BAT imaging tools can be run on each 0.2sec data segment to make 500 images in given band for a 100sec slew and then co-add for sky image (not trivial…). *BATSS provides the only high-time res. imaging from Swift/BAT; all other data (except GRBs) comes down as **5min** integrations!*

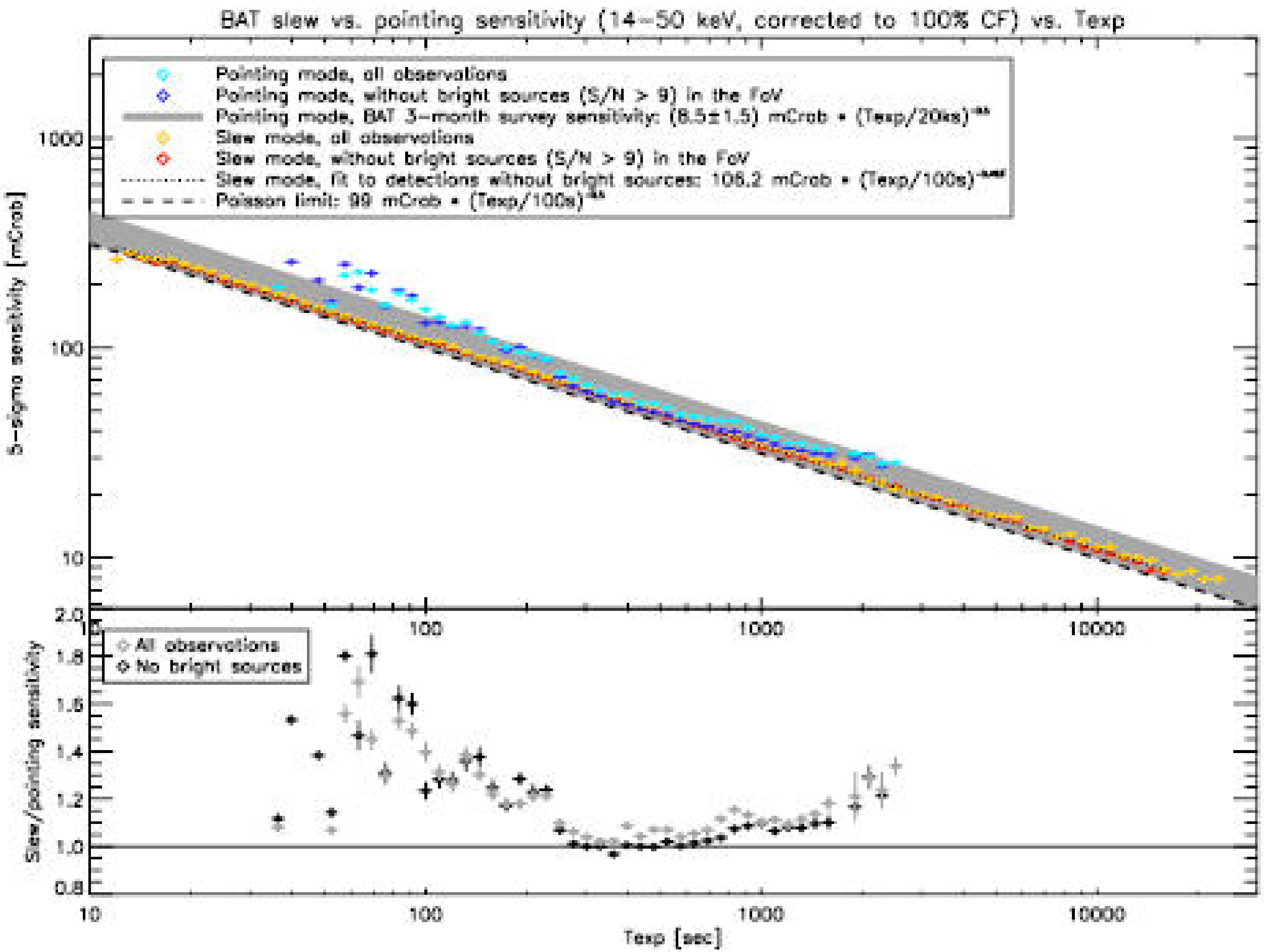
- BATSS images formed in 2 bands (S= 15-50keV and H= 50-150keV) and BAT detect run on each separately as well as on co-added broad band image (B = 15-150keV)

- **~90% sky coverage/day optimizes GRBs and search for PopIII GRBs(?), possibly ~0.5d duration (!) events (Meszaros and Rees 2010)**

- **Re-processing of all BATSS catalogs (single slews, orbits, day, week, month, year slew sums) coming *SOON* on CfA website**

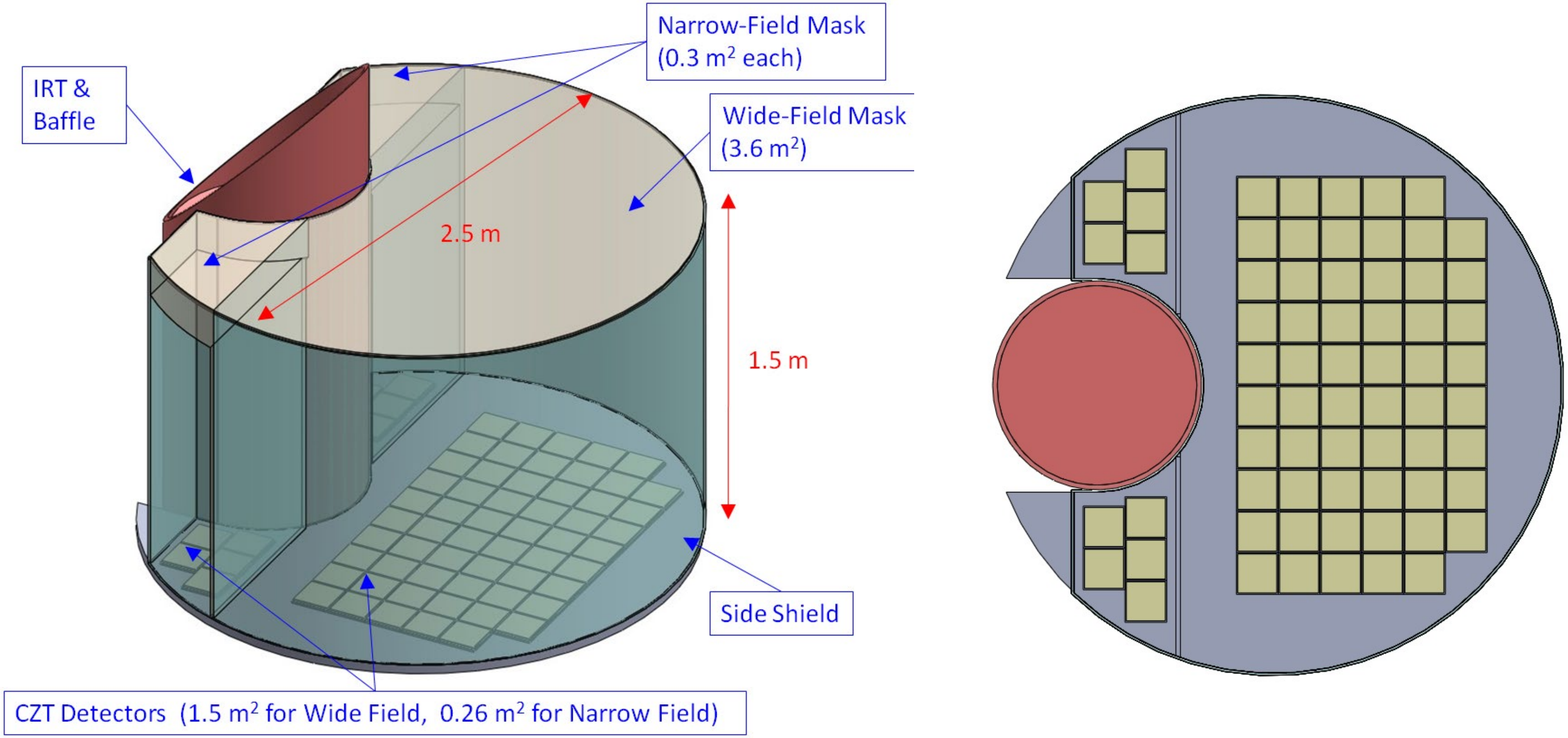
See Copete et al (2012a,b) for description of BATSS processing; Copete et al (2012c,d) for GRB results and new transients, and Grindlay et al (2012) for Blazars

BATSS has demonstrated enhanced ***scanning*** coded aperture imaging sensitivity vs. Pointings: **average over pixel-pixel systematics**



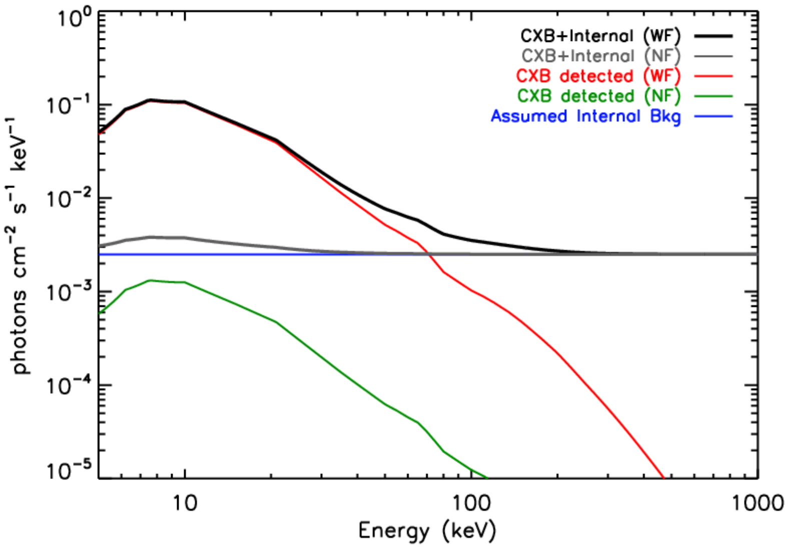
Factor of ~1.2-1.6 enhanced sens. For T_{exp} <200sec; factor ~1.3 for T_{exp} >2ksec

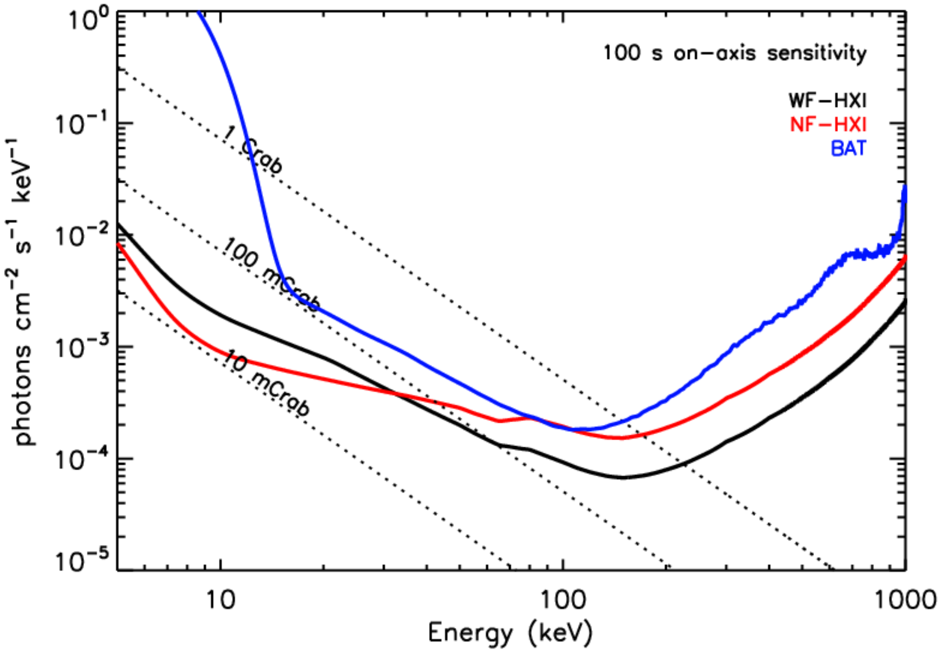
EREXS scanning survey and pointing instruments



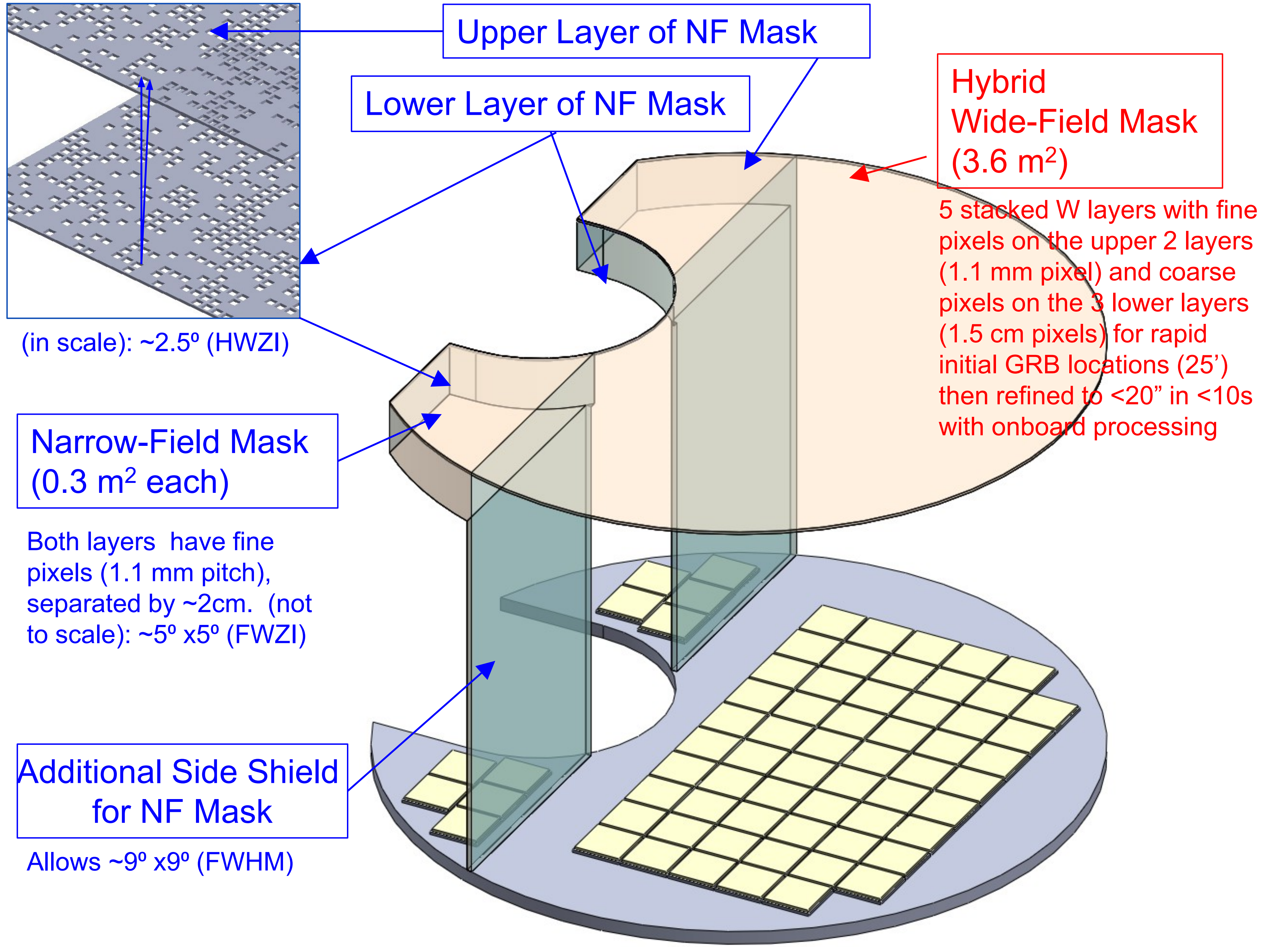
HXI: Identical imaging CZT modules (5-300 keV) divided into Wide-field (80° x 50°) for Scanning survey and Narrow-field (low bkgd.) modules for sensitive followup-pointing.
IRT: 0.8m passively cooled (-30C) imaging & spectroscopy over 0.3 – 2.3μm

Relative background and sensitivities, WF vs. NF-HXI



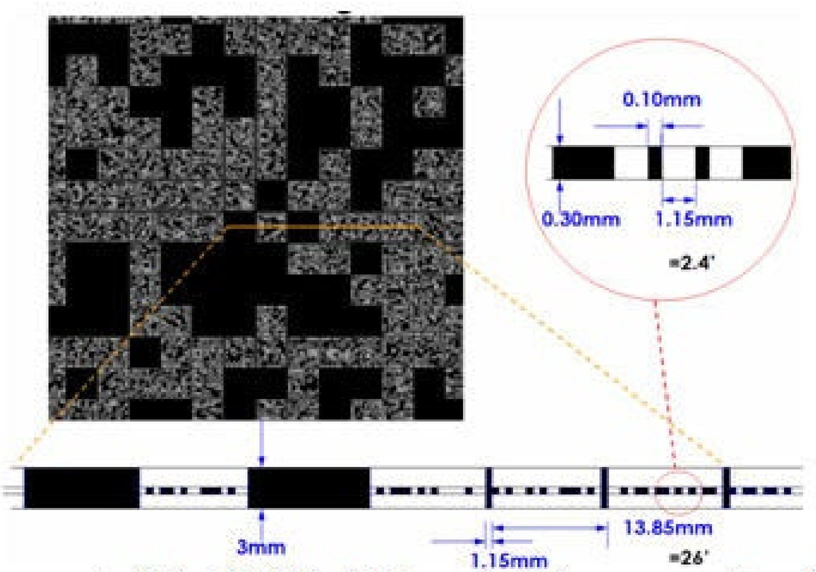


CXB Background (left) in NF-HXI with 5^o x 5^o FoV defined by 2-layer mask is ~30X Lower than WF-HXI, giving sensitivity (right) ~2-3X better at ~6-30 keV for pointing and timing studies during the pointed mission phase.



Upper Layer of NF Mask
Lower Layer of NF Mask
Hybrid Wide-Field Mask (3.6 m²)
5 stacked W layers with fine pixels on the upper 2 layers (1.1 mm pixel) and coarse pixels on the 3 lower layers (1.5 cm pixels) for rapid initial GRB locations (25’) then refined to <20” in <10s with onboard processing
(in scale): ~2.5º (HWZI)
Narrow-Field Mask (0.3 m² each)
Both layers have fine pixels (1.1 mm pitch), separated by ~2cm. (not to scale): ~5º x5º (FWZI)
Additional Side Shield for NF Mask
Allows ~9º x9º (FWHM)

HXI *Hybrid* coded mask design for WF imaging



Hybrid (2-scale) mask for HXI would be 3 x 0.3mm thick for coarse mask, not 3mm, and 2 x 0.3mm thick for fine mask above, for total mask thickness of 1.5mm which allows >90% attenuation of opaque elements at 200 keV.

(Hybrid masks proposed by Skinner & Grindlay 1993)

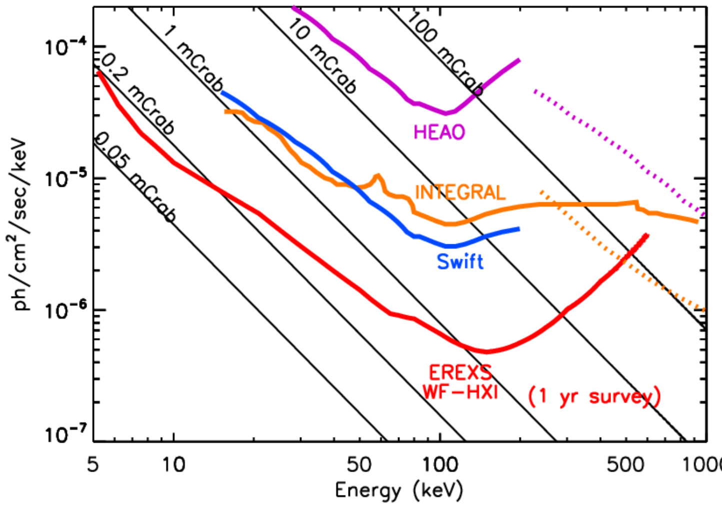
Additional *new GRB science from* HXI:

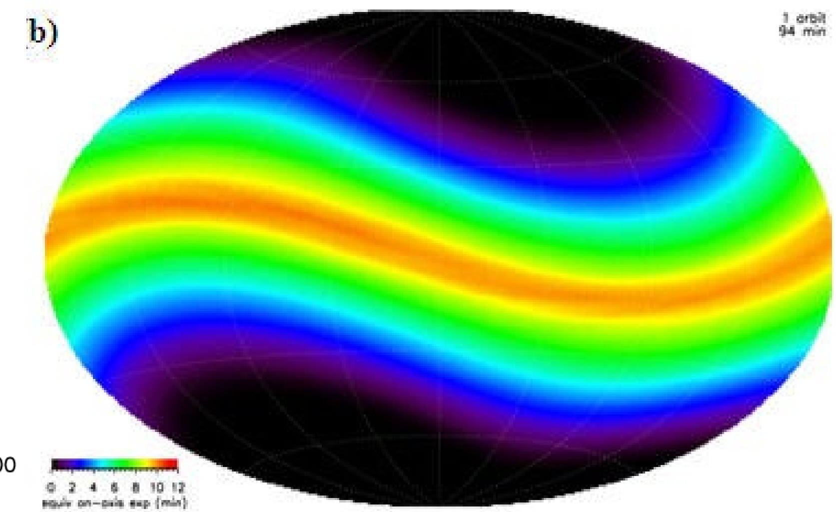
- Image triggers and ***fast FFTs from 2-scale mask*****: well-defined triggers**

- Polarization in GRBs: ≤10% for Fluence ≥10^{-6} erg/cm^2 : **test for *EM jets?!***

EREXS sensitivity and sky survey coverage

(5σ survey threshold, 1year of mission ops., **full-sky**; 15° orbit incl.)





EREXS-HXI survey sensitivity and sky coverage over 1 orbit. S/C "nods" N then S ***on alternating orbits OR alternating Summer/Winter for IRT always >30° from Sun!***

5σ in *2 yr sky survey* flux sens. over band ΔE=E , with image psf 3' & pos. <20"

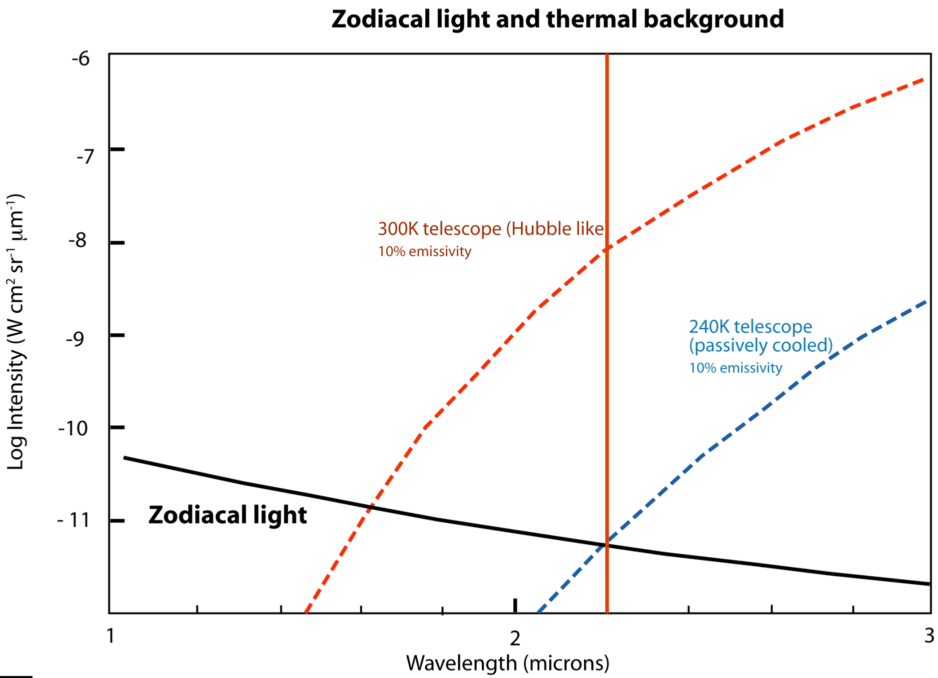
- **0.07mCrab = 7 x 10^{-13} cgs, (*>10X below Swift/BAT*) for HXI (5-100 keV)**
- **~0.5mCrab = 1 x 10^{-11} cgs (*~20X below INTEGRAL/IBIS*) for HXI (100-300 keV)**
- ***~600 GRBs/yr (~6X Swift/BAT rate) and ~30,000 AGN: IRT redshifts for most!***
- ***unique* ~10% duty cycle coverage on any source, ~90% *full-sky every 3 hours!***

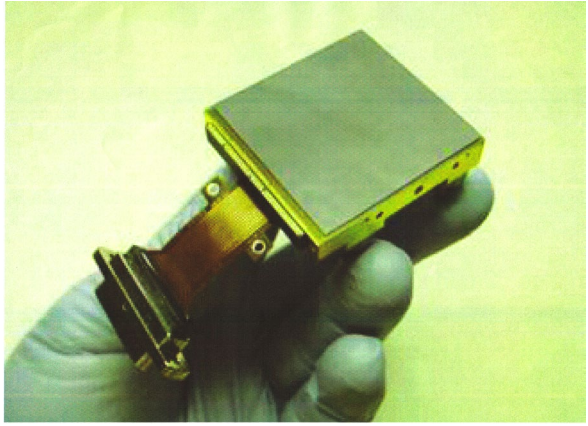
***EREXS* IRT:** *<u>0.8m cold telescope</u> for* 0.3-2.3μm imaging & spectra

- IRT mirrors (primary and secondary) **<u>passively cooled to -30C</u>** <u>(radiator)</u> give zodiacal light limited backgrounds: *<u>IRT is</u>* ***<u>~10X faster than Keck</u>*** *<u>at 2μm and has sens. limits only 2mag brighter than JWST!</u>*

  ***EREXS*-IRT imaging: AB(JHK) = 23 in 100s**
  = 28 in 1Ms

- IRT based on space-qualified 1.1m telescope (ITT-*GeoEye*) and H2RG IR arrays with readout ASIC (developed for JWST-NIRSPEC/NIRCAM)

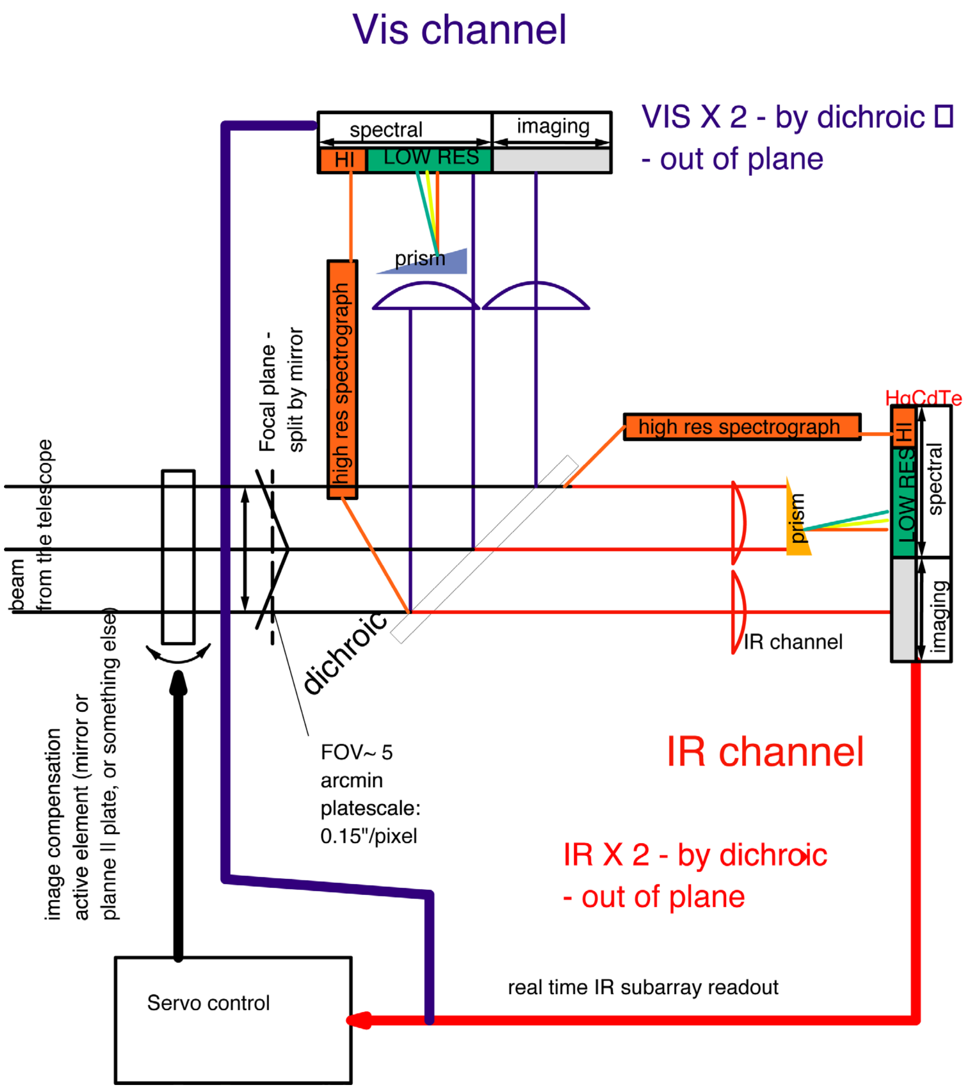




IR: HgCdTe +H2RG detectors (2K x 2K)
Vis: CMOS+H2RG (2K x 2K); pix size 0.15”

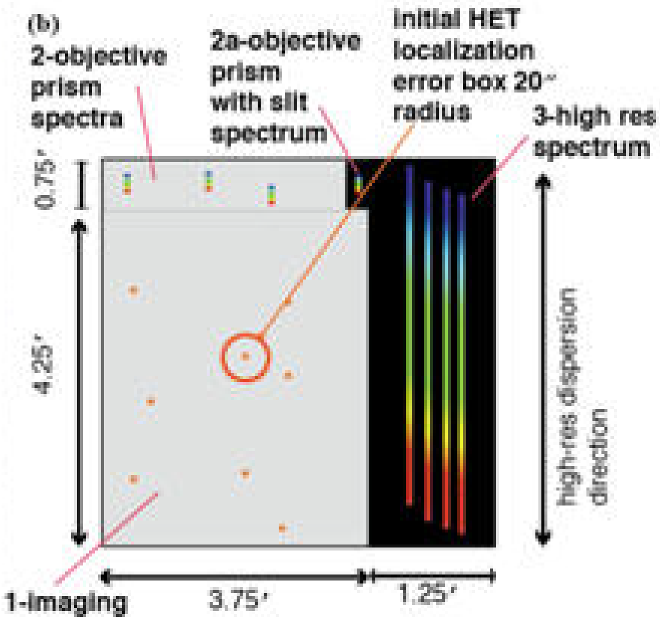
IRT telescope and instrument **layout**

(H. Moseley & A. Kutyrev,GSFC)



Imaging/Spectroscopy Focal Plane:

Simultaneous 4-band imaging & spectra



EXIST-IRT Parameters

Telescope	1.1m aperture Cassegrain		
Ang. Res.	≤0.3" PSF (0.15"/pixel pl. scale)		
Spectral Bands (4)	0.3 – 0.52, 0.52 – 0.9µm (HyViSi) 0.9 – 1.38, 1.38 – 2.2µm (H2RG)		
Mode	Field of view	Spec. Res.	AB @ S/N≥10σ (int. time sec)
Imaging (4 bands)	3.75'x4.25' (16arcmin^2)	~3	Vis: 24 (100 sec) IR: 24 (200 sec)
Low Res. Obj. Prism	3.75'x0.75' (1.8arcmin^2)	~30	Vis: 22 (200 sec) IR: 22 (700sec)
Low Res. Single Slit	20" long slit	~30	Vis: 22 (150 sec) IR: 22 (300sec)
High Res. Single Slit	4" long slit	3000	Vis: 19 (1500sec) IR: 19 (3000 sec)

At same S/N, fainter AB ~ $T_{exp}^{1/2}$ (ZL bkgd.)

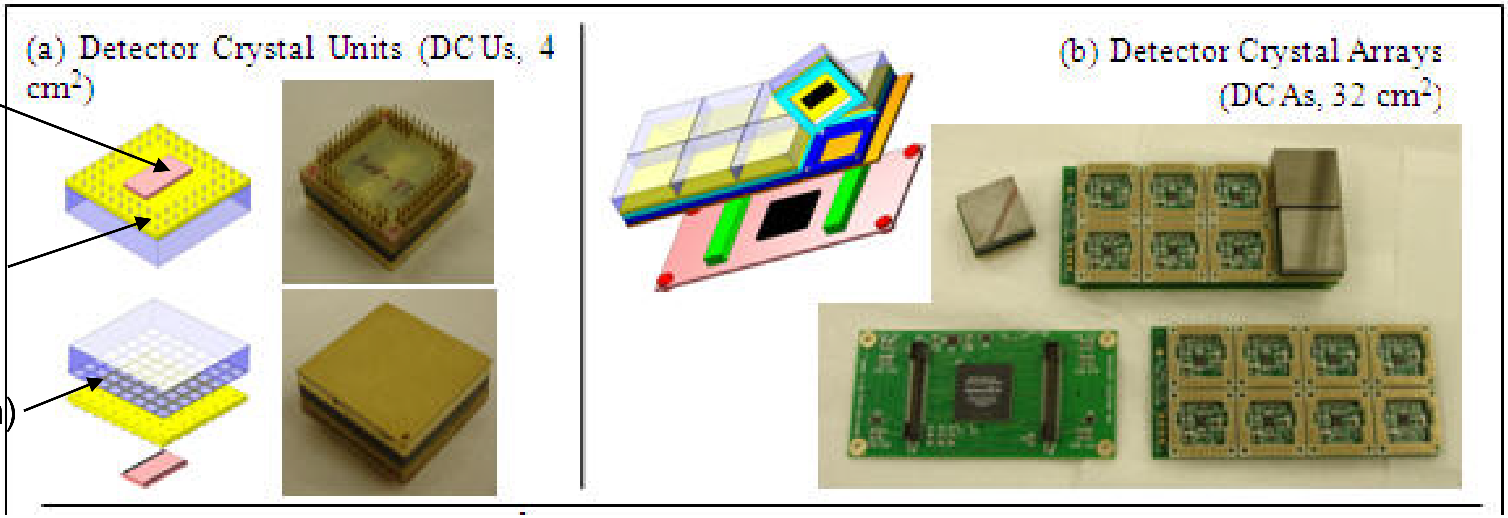
***EXIST-IRT* competitive with JWST! Unique for surveys!**

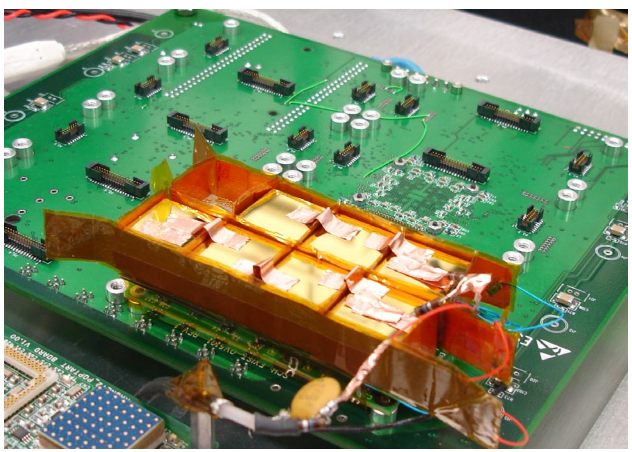
HXI Detector develoment: building a large area CZT detector/telescope prototype *ProtoEXIST1, successfully tested on first balloon flight*

RadNet ASIC: 1D, 64 pixels

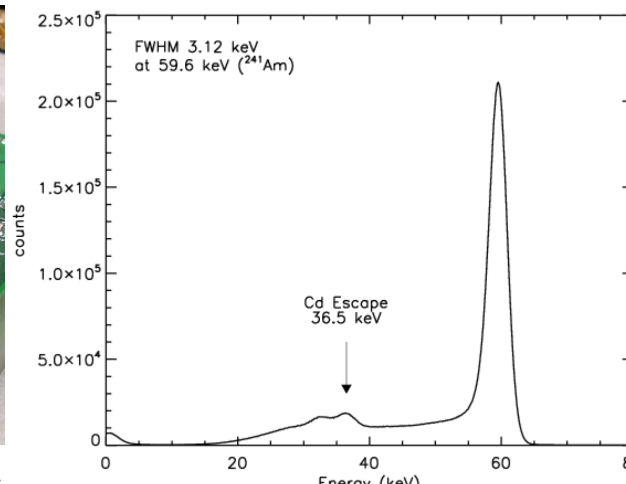
2D→1D Interposer Board (IPB)

2D 8 x 8 pix CZT (2x2cm)

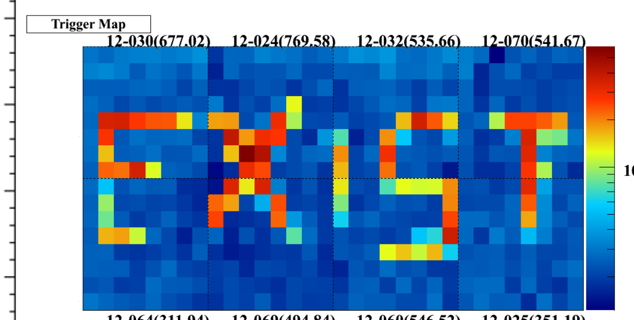




Test flight DCA board (1 of 8). DCUs Isolated by mylar-coated thin Cu shields

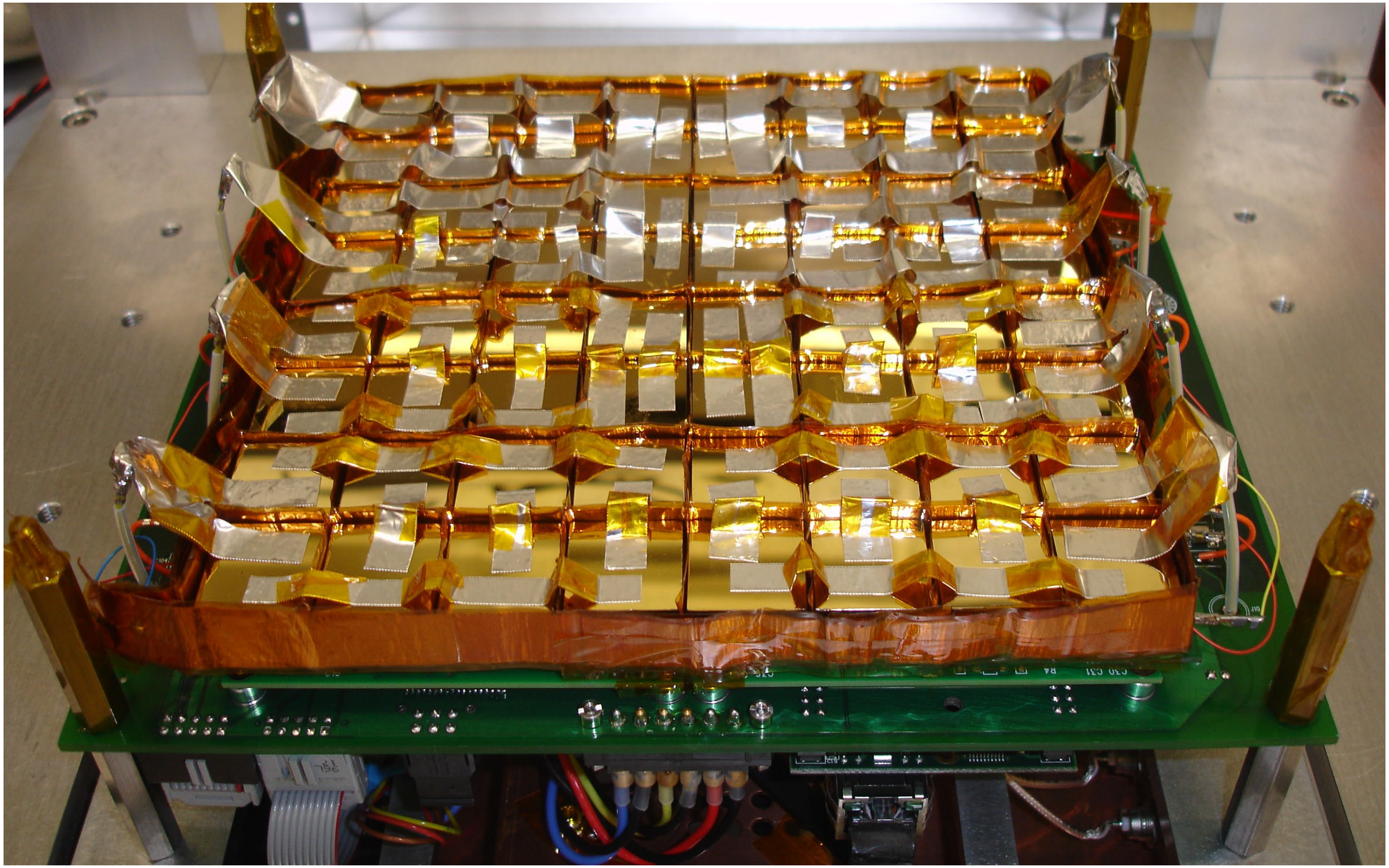


Summed array pixels: 3keV Energy resolution (FWHM)



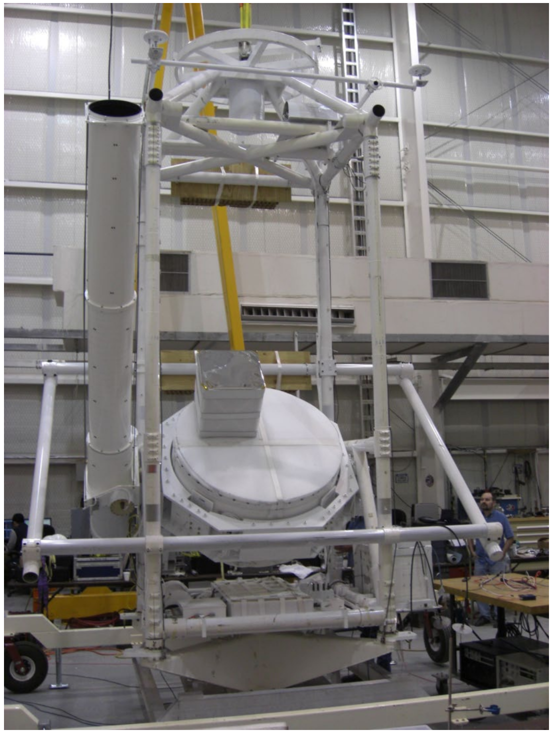
60keV spectrum & DCA image (2.5mm pixels) through Pb mask

Fully integrated first ***ProtoEXIST1*** detector array



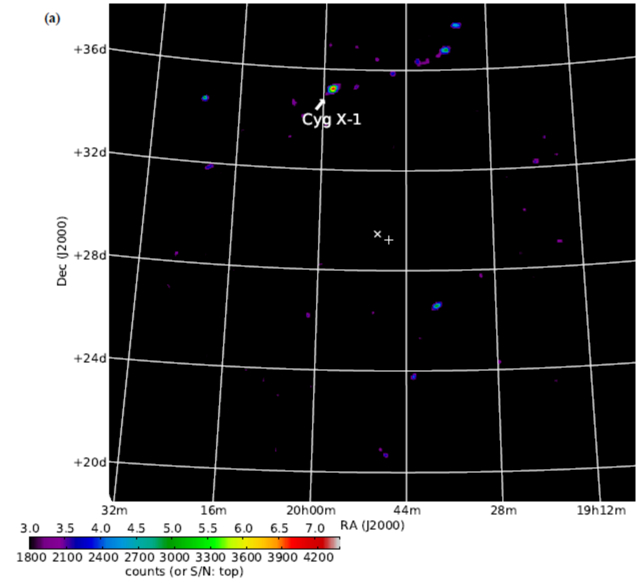
8 x 8 array of close-tiled (0.4mm gaps) CZT crystals (20 x 20 x 5mm), each with 8 x 8 pixels (2.5mm) for 256cm^2 imaging through coded mask

ProtoEXIST1 in Gondola, 2009 flight & First CygX-1 image

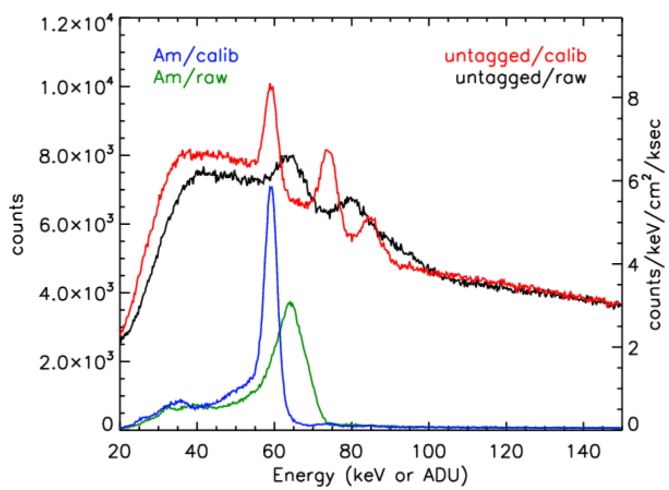


ProtoEXIST1 payload for first Ft. Sumner flight, Oct. 2009

Fully-inflated 40mcuft balloon for Oct. 9, 2009, first flight (success!)



20 x 20deg image, 20' resol., from short exp. on CygX-1 on first flight of *ProtoEXIST1*



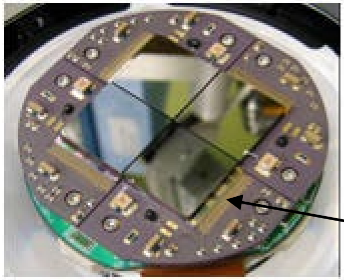
Spectra (raw vs. calib.) of background and Tagged ^{241}Am calib. Source in flight

Now developing *ProtoEXIST2/HXI*, with 32 x 32 pixel Nu ASIC

- ***EEREXS*** requires 3' imaging resolution to avoid source confusion; need 0.6mm pixel size on CZT for 1.2mm pixels on mask at f = 1.5m

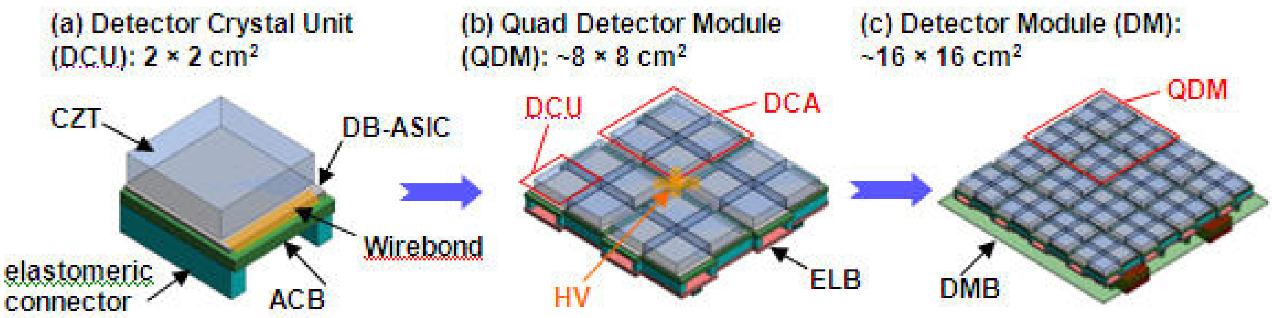
- Use Direct Bond (DB) ASIC developed by Rick Cook (Caltech) for readout of CZT on *NuSTAR* focusing HX telescope for 2013 NASA SMEX:

2 close-tiled DB ASICs ea. with 32 x 32 input pads



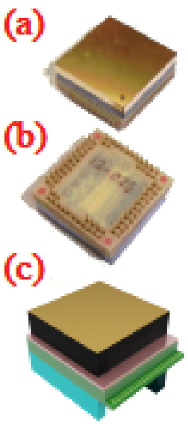
NuSTAR focal plane: 2 x 2 CZTs (ea. 2 x 2 x 0.2cm), a 2K x 2K pixel imager. Note ~5mm wirebond pad extension

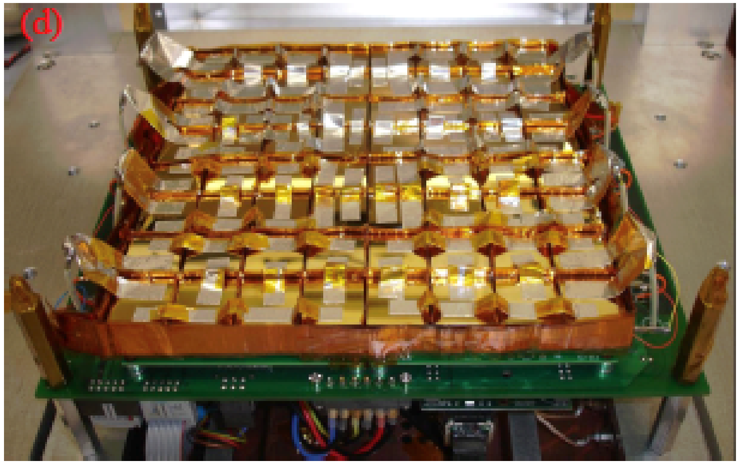
- HXI extends 2 x 2 CZT tiling to close-tiled hierarchical array packaging:



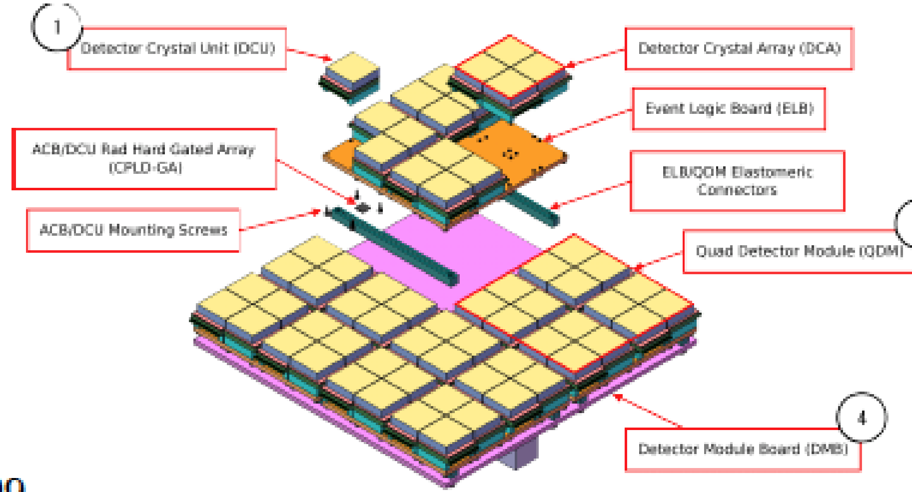
DCA has 0.6mm gaps (1 pix), but QDM has 5.4mm gaps (9 pix); **pixel Pitch preserved**

P2 High Res imaging HXI detectors with 4X finer resol.

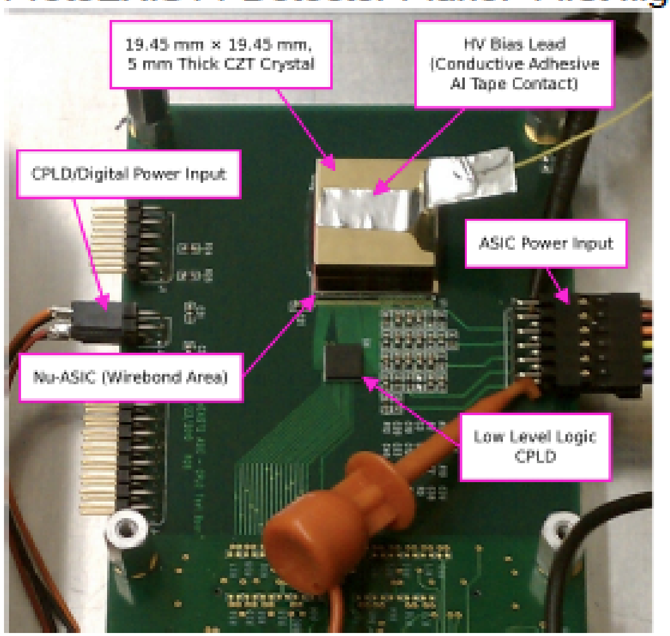




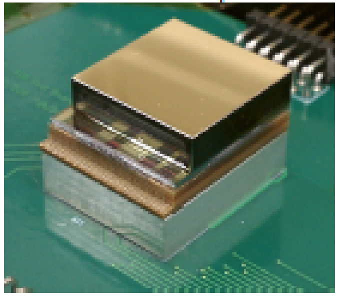
ProtoEXIST1 Detector Plane. First flight October 9, 2009.



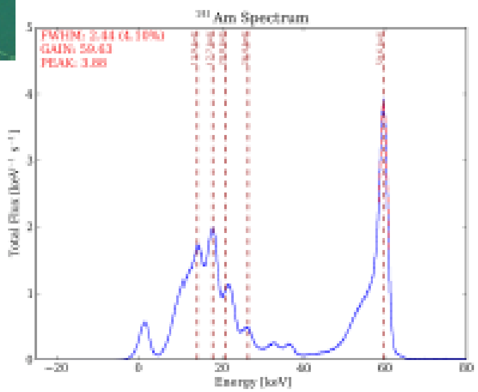
The ProtoEXIST2 Detector Plane Architecture: 64 DCUs arranged in an 8×8 array.

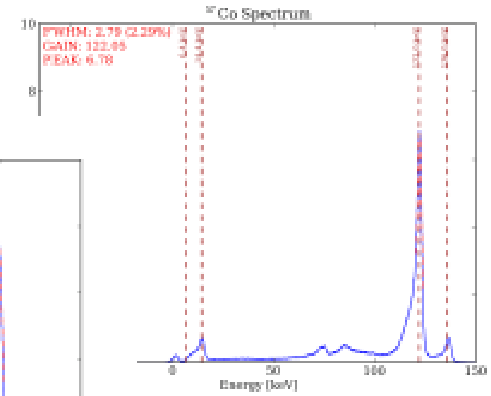


ProtoEXIST2 Test Detector D1 utilizing the NuSTAR ASIC



D4- The First P2 Detector Crystal Unit (DCU). A single DCU contains a 32×32 pixilated anode (1024 pixels total).





2keV FWHM on initial P2 testboard, full DCU, minimal calibrations

Composite Spectra Collected from D4.

Balloon flight test of P2/HXI imager in Sept. 2012!

EREXS mission summary

Mission parameters:

Parameters	Values
Orbit	600 km, 15° inclination, 5yr mission
Mode	Zenith orbital scan (2yr); inertial pointing (3yr)
High Energy Telescope (**HXI**): Coded aperture, WF & NF imaging 1.8m² CZT: 58 WF modules (scanning) 10 NF modules (pointing)	5–300 keV, 80°×50° FoV (WF), 7° x 7° (NF), ≤20″ positions (90% CL) 0.08–0.4 mCrab in1yr survey; ~1mCrab in1d (5-100 keV, 5σ) 10mCrab in 100s pointing; 1mCrab in 10^4 s ptg. (5-100 keV, 5σ)
Optical/IR telescope (**IRT**): 0.8m aperture R-C	0.3–2.2 µm, 4′x4′ FoV, 0.15″ resolution AB~23 mag in 100 s; AB ~21, 19 for R = 30, 1000 spectra in 1000 s
Spacecraft (S/C)	Pointing: 2″ stability; Aspect: 2″ (90% conf.)
Mass	2150 kg (incl. 30% contingency and 156 kg propellant)
Power	1180 W (incl. all instruments and S/C with 30% contingency)
Telemetry	30 GB/day; realtime (TDRSS) GRB downlinks
Launcher	Delta II 7920 with 2.9m fairing
Cost range (GSFC Price H vs. Astro2010, scaled for mass & power from *EXIST*)	$400M (GSFC Price H) vs. $900M (Astro2010 for 2.5X larger HXI, 1.1m IRT, larger S/C, AtlasV launch and 5y mission ops.)

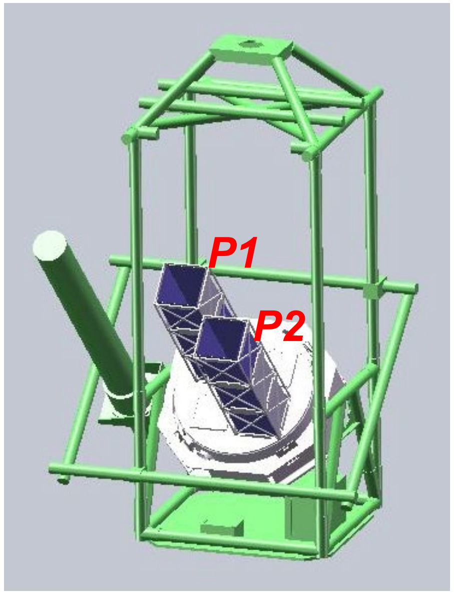
EREXS TRL levels and costing

- HXI relies on NuSTAR ASIC but new high-density 0.6mm pixel array packaging and readout, derived from 2.5mm P1 prototype

- ***P2***/HXI telescope & ***P1*** to fly Sept. 2012

- Balloon flight demo brings **HXI to TRL6**

- *EREXS* cost **~$400M** from GSFC/MDL:
  - Price H 70%CK cost scaled for mass from *EXIST*
  - Astro2010 costing (unrealistic) scaled: ~$900M



- Scaling from ***EXIST*** is conservative since now have Delta II launch and simpler ground ops and analysis (no SXI)

- ***EREXS*** cost and TRL consistent with a ~2018 mission: **Finder for JWST**!

EREXS Imaging/Spectra: **Summary & Prospects**

- *Highest z stellar universe only measured via GRBs*: >10X Swift sensitivity and 5X resolution and ***IRT*** essential for rapid **IDs & redshifts.** Locate ~2500 GRBs and opt-IR (0.3-2.2μm) **R=1000 spectra** for ≥500 GRBs to constrain structure to Pop III (!)
- Obscured, dormant & *First (?) SMBHs* as luminous Blazars best studied with ***HXI*** imager and ***IRT***: *complete BH census/evolution & accretion luminosity of universe*
- *Tidal Disruption Flares (TDFs) from Blazars (like Swift J16444)* measured out to z ~1 and non-beamed TDFs constrain SMBH mass by IRT lightcurve decay timescales
- *Short GRBs imaged in coincidence with Advanced LIGO (>2016):* precision Hubble constant ***constrains NS-EOS*** *from GW vs. EM waveforms*
- Broad band (~5 – 300 keV), large area & FoV and IRT are unique for ***EREXS***: image half-sky each orbit. ALL sources observed with ≥10% continuous coverage. ***Continuously measure*** *stellar BH states, bright QPOs and reflection spectra for bright AGN to constrain reflection* **spectra and 6.4 keV line emission** and thus **SMBH spin**
- **A wide-field, high time resolution imaging survey can achieve complementary and breakthrough science for at least 4 of the 5 IXO science objectives. Galaxy cluster AGN surveys constrain feedback and cluster structure (magnetic fields) is constrained by inverse Compton of radio electrons off the CMB for HX detected non-AGN clusters**