EXIST Concept for BHFP:
Hard X-ray Black Hole Surveys in Space and Time

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NRC Beyond Einstein Program Assessment Committee

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Black Holes as Fundamental Objects

(*Background for Black Hole Finder Probe Science*)

- Black holes, long conjectured and now confirmed with masses ranging from ~4 – 4 billion solar masses, are essential for understanding the physics of the Universe as well as the extremes of space-time near their horizons

- BHs power the most energetic phenomena (quasars, gamma-ray bursts…) yet may be essential for formation of galaxies and ultimately life

- Accretion onto BHs is a significant (but still uncertain) fraction of the Luminosity of the Universe, but BH growth from stellar to intermediate (?) to supermassive still highly uncertain

- Black Hole Finder Probe (*EXIST*) will survey BHs on all size and luminosity scales to give first Global View of BH numbers, total energy output, and detailed phenomena

Context for BHFP to *EXIST*

- *Black holes are best revealed by their accretion of matter, which often obscures them except at "hard" X-rays (>10 keV)*

- Hard X-ray (HX) band is still poorly explored, but the promise of rich source counts and physics has been revealed by pathfinder coded aperture imaging missions ***INTEGRAL*** and ***Swift***

- BHs are inherently time-variable; and some classes (luminous obscured quasars) are rare: need *All-Sky, All-time Surveys with >10-20X previous sensitivity (for sample) and <10" positions*

- *EXIST (Energetic X-ray Imaging Survey Telescope)*, *recommended by AANM Decadal Survey*, provides science and mission best matched to BHFP and highly complementary to future missions:
  - BH survey for detailed spectroscopy with ***Con-X***
  - Tidal disruption of stars onto massive BHs: trigger for ***LISA***
  - Essential HX spectra to measure IR background with ***GLAST***
  - Trigger deep mid-IR spectroscopy of z >7-10 GRBs with ***JWST***

EXIST Science objectives

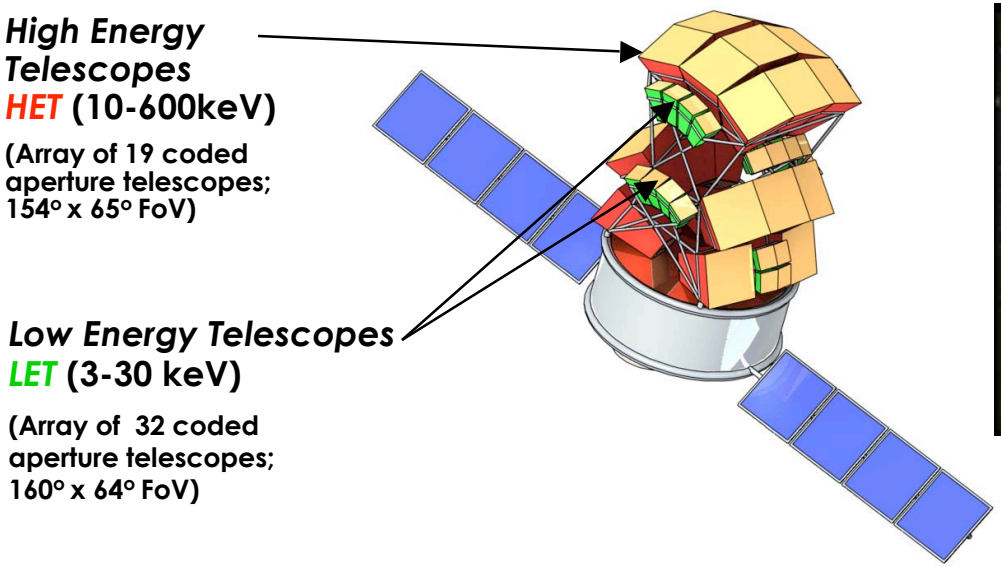
(from the earliest stellar BHs to supermassive BHs in Galaxies)

- Obscured SMBHs and origin of the Cosmic X-ray Bkgd
- Dormant SMBHs (tidal disruption of stars & ***LISA*** triggers)
- SMBH masses & spins from timing & spectra
- Blazar spectra from ***EXIST*** vs. ***GLAST***: Cosmic IR Bkgd
- GRBs from $z \geq 7$-10: birth of 1st BHs & probes of universe
- Nature/number of BHs (vs. NSs, WDs) in Galaxy

Overview of *BHFP-EXIST* Science and Design

Hard X-ray (~3-600 keV) all-sky imaging *each orbit* to measure:

- GRBs out to z ~20 and *first stellar Black Holes* ***(~5-20X Swift sensitivity)***
- Obscured AGN and accretion (BHs) vs. nuclear (stars) luminosity of universe
- Stellar Black Holes in Galaxy & IMBHs in Local Group & BHs



EXIST measures Cen-A <u>every orbit</u>:
characteristic time variability (QPOs) constrain BH mass and spin

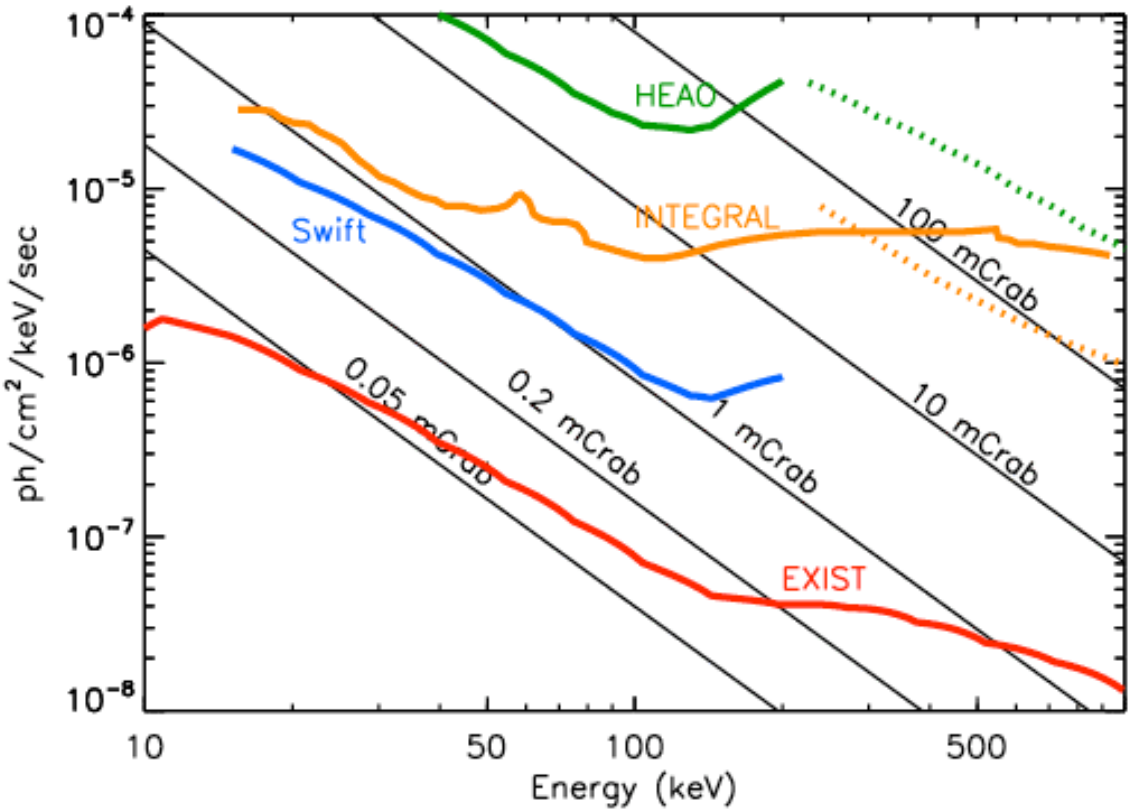
Mission Design parameters:

- Extend ROSAT sens. (~5 x 10^{-13}cgs) to 3-150 keV with 0.9-5' resolution & ~10" positions
- Two wide-field coded aperture telescopes: 10-600 keV (*6m^2 CZT*) & 3-30 keV (*1.3m^2 Si*)

http://EXIST.gsfc.nasa.gov

EXIST Survey Sensitivities vs. previous missions

(5σ survey threshold, 1year survey, full-sky)



5σ in 1 yr (calendar) sensitivities over band $E_{low} \rightarrow 2E_{low}$ with 20% duty cycle:

- **0.05mCrab = 5 x 10^{-13} cgs, (~20X *Swift/BAT*) for LET 3-30 keV & HET 10-100 keV**
- **~0.5mCrab = 5 x 10^{-12} cgs (~20-100X *INTEGRAL)* for HET 100-600 keV**
- ***unique* ~20-40% duty cycle coverage on any source, *full-sky ea. 95min***

Hard X-ray Sky

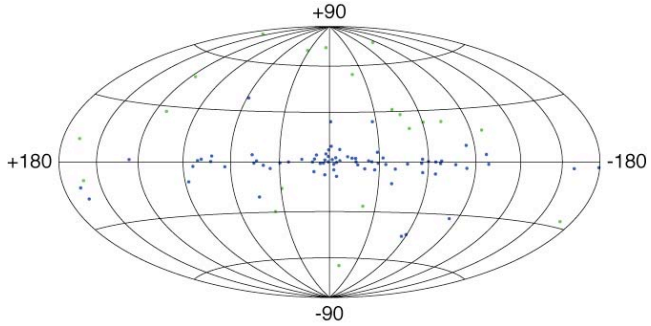
- **Hard X-ray (10-600 keV) sky not yet surveyed to ROSAT sensitivity. *EXIST* would be ~20X more sensitive than *Swift* or *INTEGRAL* and cover full sky**

- ***EXIST* will detect ≥3 x 10^4 sources, ≤10″ positions, 3-600 keV spectra**

- ***EXIST* would provide unique temporal survey: *full sky imaging each orbit***

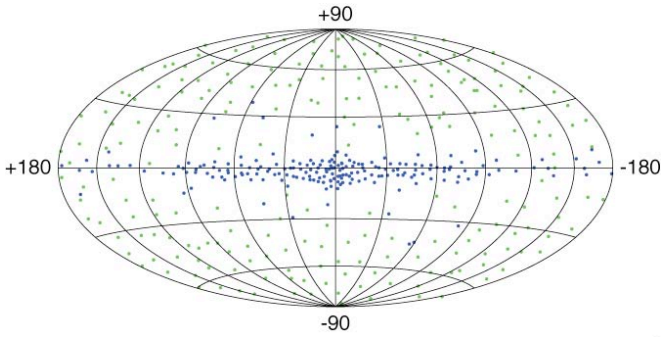
Previous Hard X-ray Sky

HEAO-1, BeppoSAX



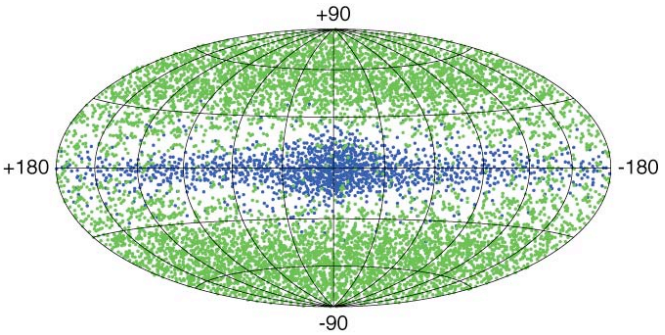
≤2010 Hard X-ray Sky

Swift & INTEGRAL



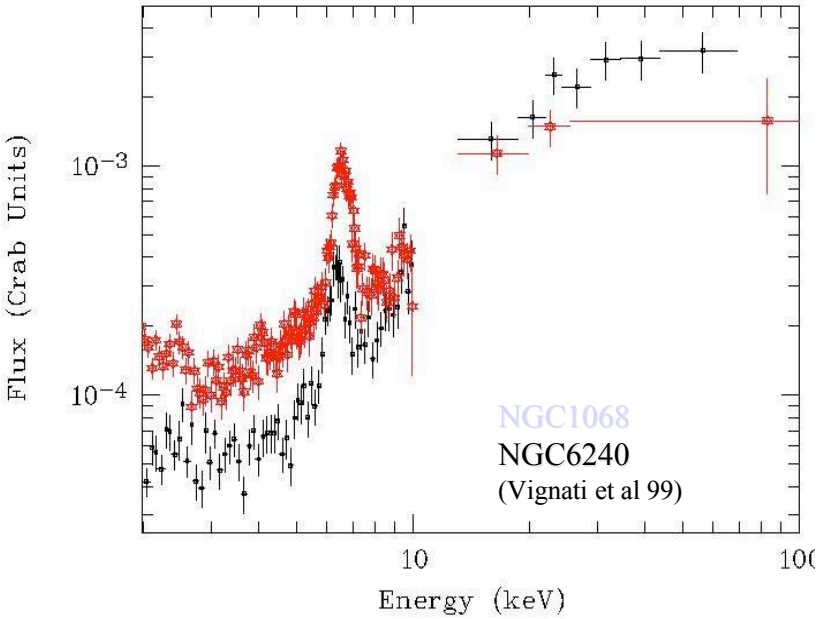
2015(?) Hard X-ray Sky

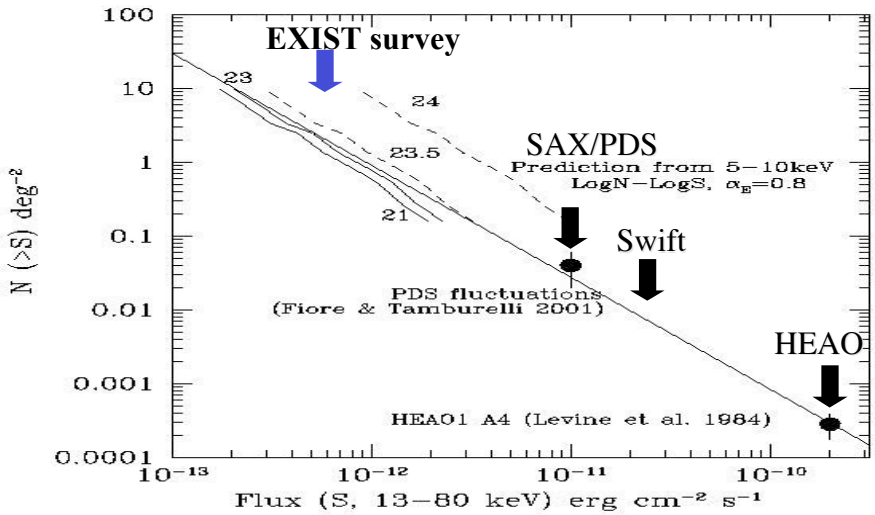
EXIST



Obscured AGN and origin of the Cosmic X-ray Background

(the cumulative glow of BHs in active galactic nuclei measured by ***EXIST***)





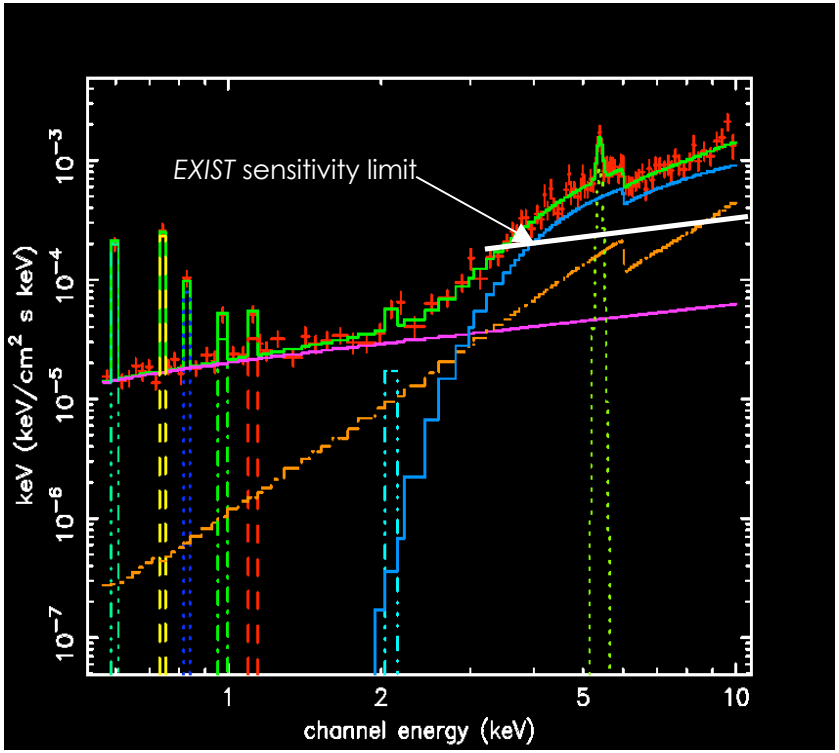
Chandra & **XMM** surveys find >40% unresolved CXB from obscured AGN but at peak of CXB, E ~20-30 keV, only ~10% of CXB is resolved!

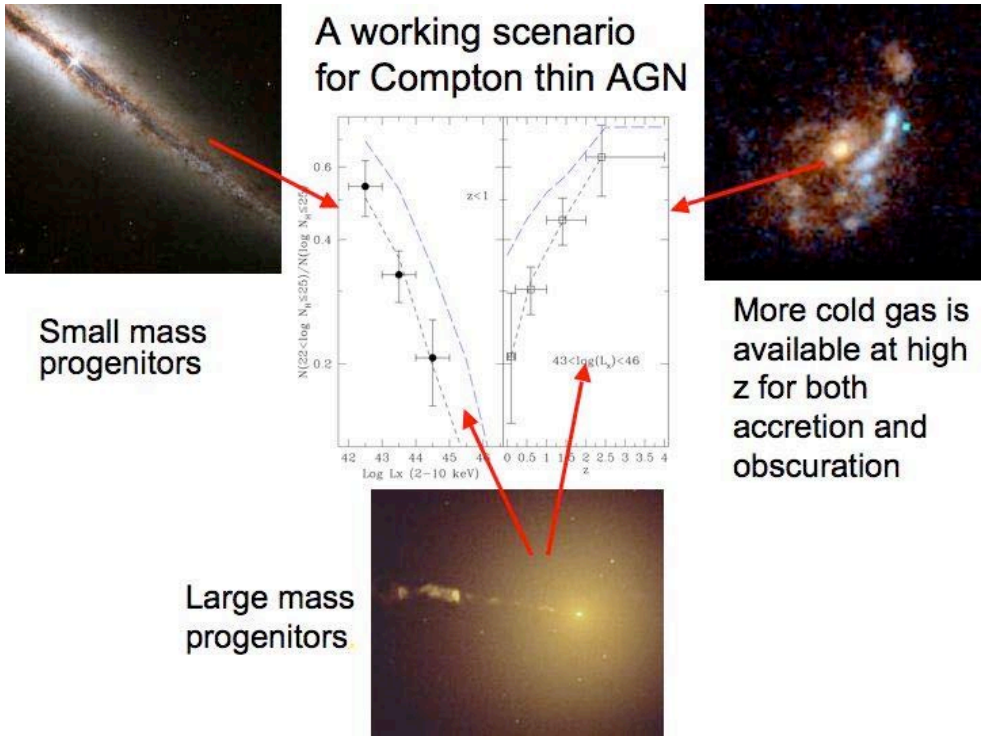
➡ ***EXIST*** will find >1-10 obscured AGN/square degree and obtain first *all-sky* measure of Seyfert 2 ⇨ QSO 2 luminosity function and constrain obscuration vs. z for supermassive BHs.

All-sky survey needed for rare objects (e.g. Type 2 QSOs) and NH vs. z and Lx

Obscured Seyferts, Radio Galaxies & QSOs vs. z?

EXIST can detect and discover obscured AGN over a broad range of Lx and absorption column NH to further constrain NH vs. z growth of BHs



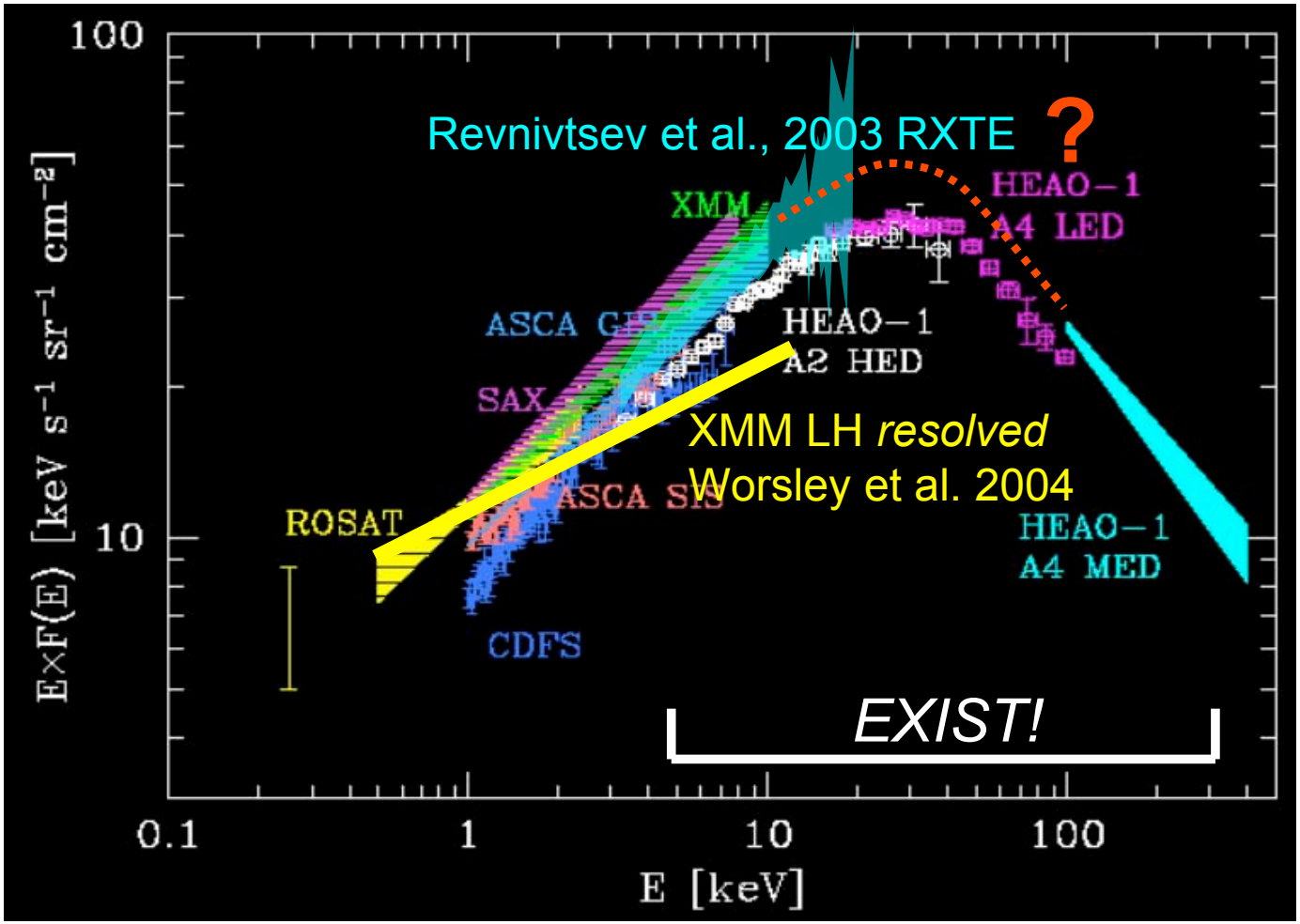


e.g., Narrow-line radio galaxy (NLRG) and Type 2 QSO, 3C234 barely detected with Einstein Obs., with XMM spectrum shown from Piconcelli et al. 2006, would be found with the *EXIST* survey.

EXIST survey will explore the recent evidence (La Franca et al 2005 and Treister & Urry, astroph/0610525) that obscured AGN are *increasing as* $(1+z)^{0.4}$

EXIST measures Cosmic X-ray Background from *all* BHs

(***EXIST*** detector backgrounds *dominated* by CXB from faint AGN)



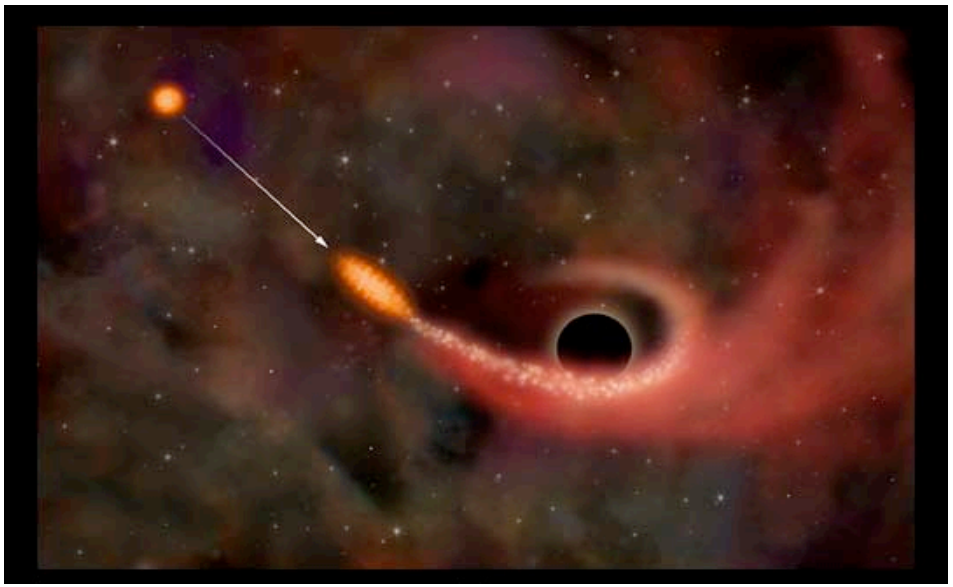
EXIST optimally matched in Energy band to measure still uncertain CXB spectrum, isotropy, and spatial fluctuations with HET (5arcmin) vs. LET (1arcmin). High CXB count rate and HET vs. LET collimator FoVs and continuous scanning allow low-systematics measurements.

Dormant SMBHs revealed by Tidal disruption of stars

(and predicting gravitational waves from "invisible" supermassive BHs)

***Tidal disruption of stars spiraling into Dormant SMBHs* with mass ~10^7 Mo:**

if 1% of L_{acc} in HX band, ~10^{-5} events/year/Mpc^3 allow ***EXIST*** *to see ~10-30 flares/yr out to ~200Mpc* (Grindlay 2004).
HX spectral comp. "confirmed" with PL spectral decay of RX1242 measured with Chandra/XMM!



Artists conception of tidal disruption of star in RXJ1242-1119 detected with ROSAT (1991) and confirmed with Chandra (Komossa et al 2004).

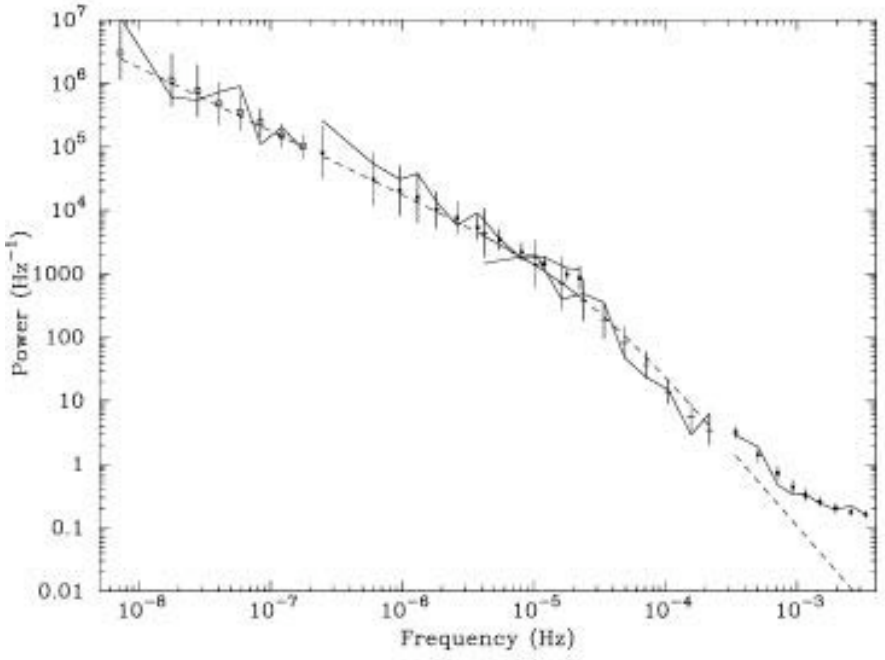
Sub-giants with WD cores are gravitational wave LISA triggers.

Possible soft (~5keV) prompt (~1d) burst detectable out to ~100 Mpc directly with EXIST (LET); ***LISA trigger***

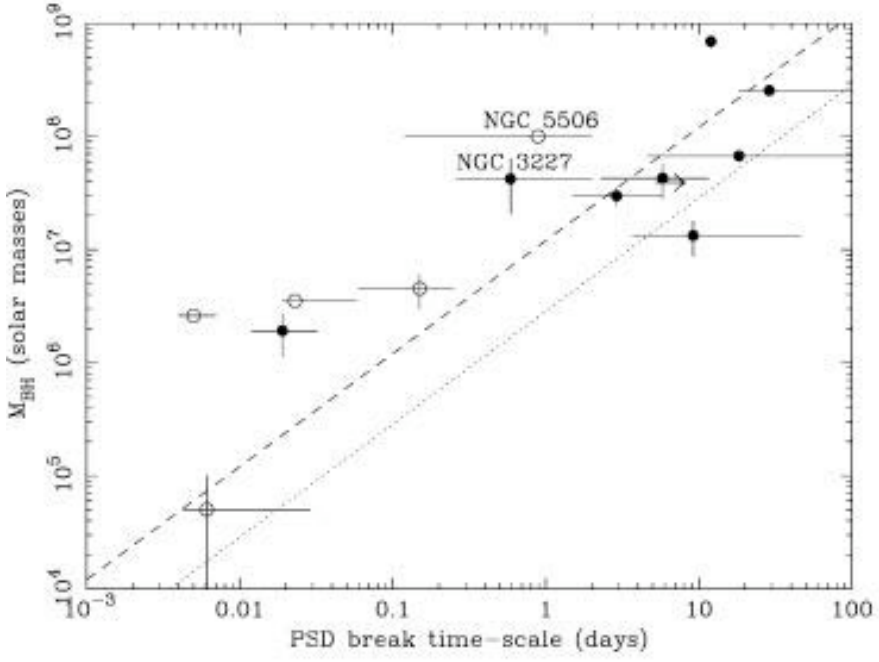
Measure $10^{6\text{-}8}M_{\odot}$ SMBH content/evolution of nearby galaxies
(to understand BH-Galaxy Bulge mass relation & BH-galaxy evolution)

AGN variability constrains SMBH masses

(Variability frequencies correlate with BH mass – Uttley & McHardy 2005)



Power spectral density (PSD) for NGC 3227 derived from RXTE (PCA) data.



PSD break vs. BH mass measured from optical reverberation mapping (filled circles).

- Pointed X-ray telescopes get very limited samples; <10 thus far!

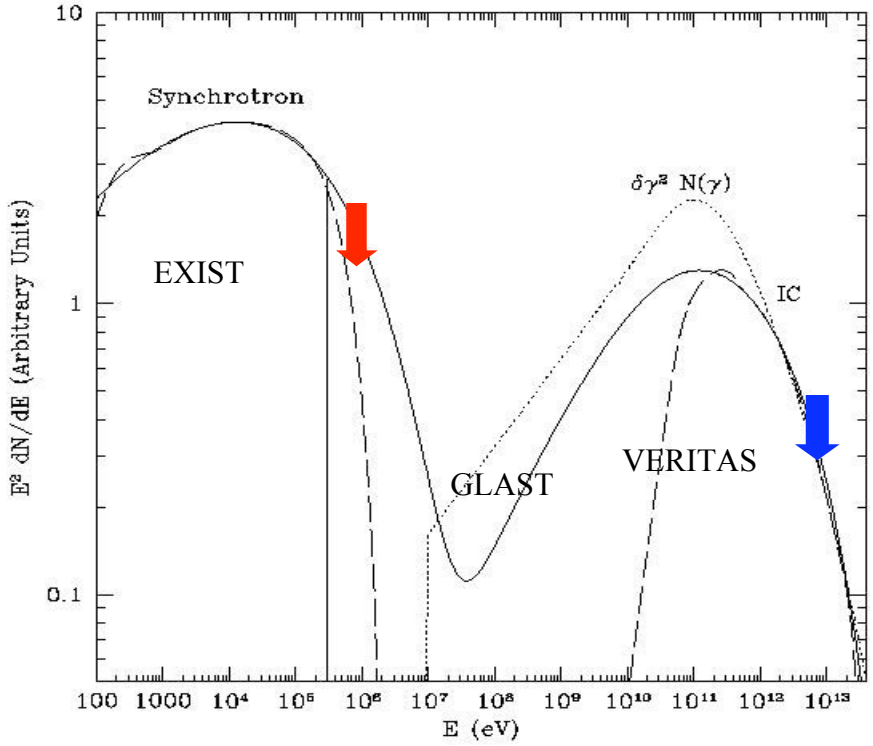
- *EXIST* will go factor of 10-30X deeper than RXTE and measure variability spectrum for ≥10^3 AGN to give BH masses vs. z and NH

Blazar Spectral variability

Extragalactic Background Light (EBL): Stellar vs. Accretion Luminosity of Universe

EBL: Hard x-ray (synchrotron) spectral breaks (~5-200keV) for *Blazars* at known redshift allow SSC gamma-ray (~10 GeV - 10 TeV) spectral breaks measured by *GLAST & HESS/VERITAS* to constrain poorly known diffuse IR background from total stellar light of universe *absorbing gammas to* e^+-e^-

Time-variability: spectral breaks *required* from *simultaneous* HX measurements. Wide-field HX imaging needed for simultaneous X,Gamma-ray observations of Blazars



SSC model for Mkn 501 (Coppi & Aharonian 1999)

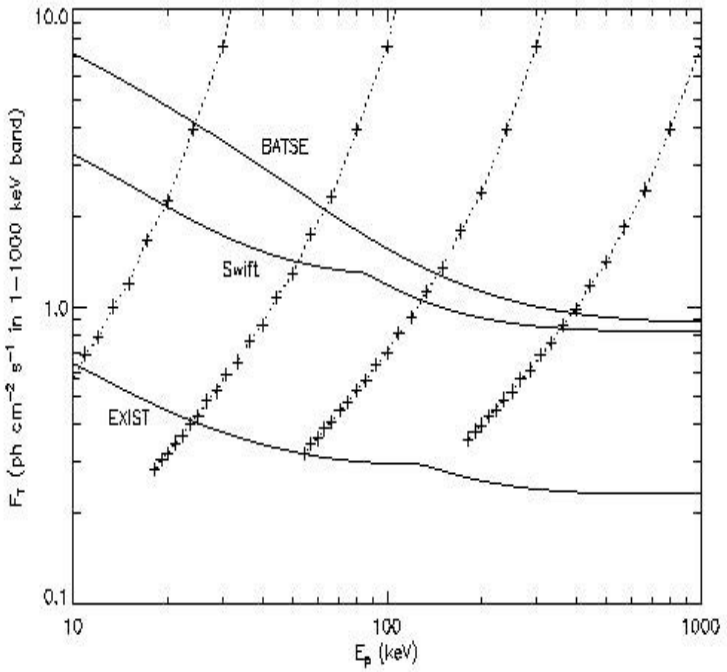
EXIST will provide the *continuous HX spectral-monitoring* to study Blazars and non-thermal AGN to constrain diffuse IR (~10-100μ) background from obscured AGN and thus ***nuclear vs. accretion luminosity of the universe***

Complements GRB science: star formation vs. redshift from L_{GRBs} vs. z

EXIST measures *Gamma-ray Bursts* at z~0.1-15

(*Birth of stellar-mass Black Holes*, including the very First?)

- ***"Long"-GRBs*** are from SNIb,c & likely due to stellar BH formation
- Likely that first stars were ~100M_o and collapse to BHs ➡ GRBs
- ***"Short"-GRBs*** from merging NSs in globulars (Grindlay et al 2006): are Short GRBs enhanced at z of globular cluster formation?



Horizontal curves: flux at detection threshold vs. E_{peak} Vertical curves: observed flux and E_{peak} for same GRB at z=1 (top +) to 10 (bottom +) (Band 2004).

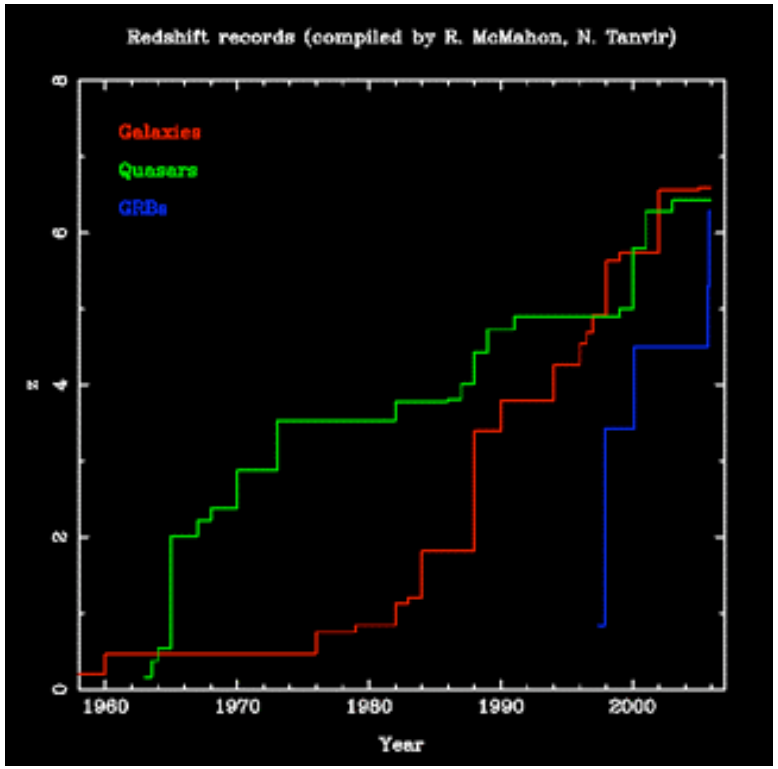
***EXIST* could detect GRBs to z~10-15 from PopIII BHs at re-ioniz. epoch suggested by WMAP.**

Photometric z from Lum-E_{peak} ➡ need response to E>300keV, *And* from Lum-Variability (Firmani Relation) ➡ need large area det.

X-ray flashes and high z GRBs ➡ need response to E~3 keV

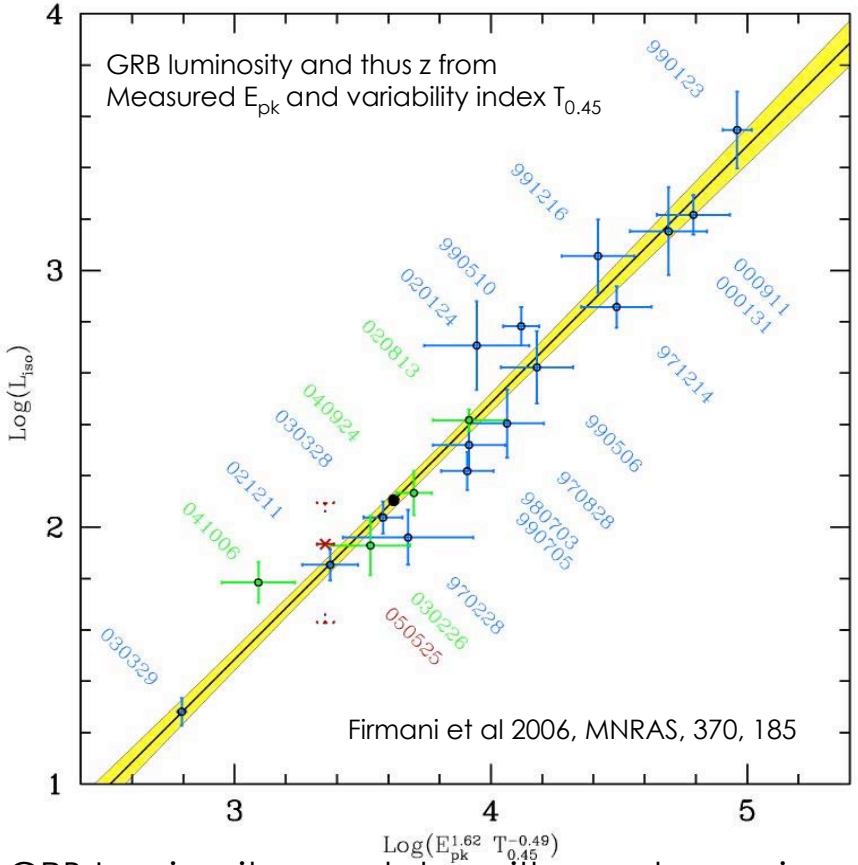
~5sr instantaneous GRB coverage & increased sensivity: ~700GRBs/y ➡ capture *rare* (high z?) events

Most distant stars & galaxies probed by GRBs



Record redshift vs. time: GRBs nearly max!

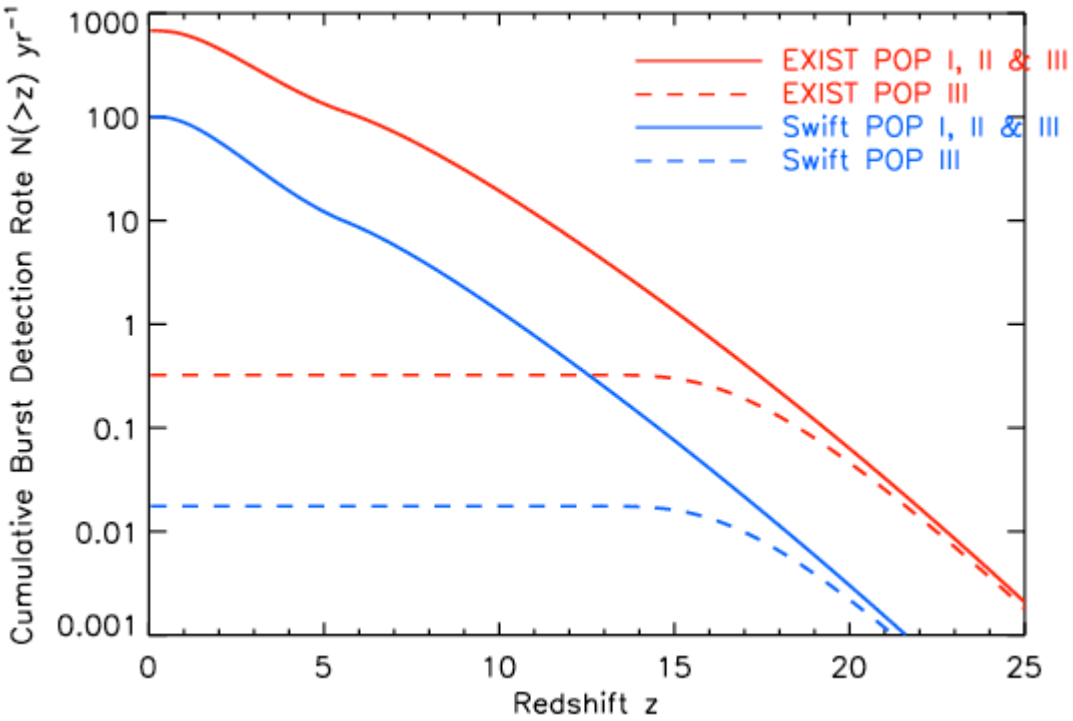
- *Swift* GRB at z = 6.3 & Spitzer galaxies at z ~8 show *GRBs must be detectable out to at least z ~8-10*
- Broader energy band, higher sensitivity & FoV needed for large sample at z ≥ 8-10
- IR from space (***JWST***) needed for z ≥10!

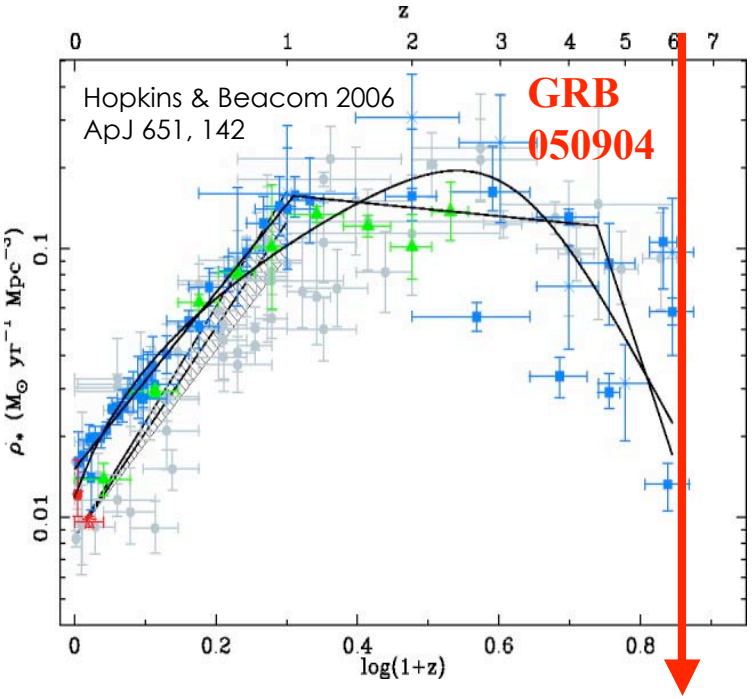


GRB Luminosity correlates with spectrum: gives z !

- *EXIST* measures E_{pk} and $T_{0.45}$ and Firmani reln. gives "photo-z" with uncertainties typically Δ(log(1+z)) ~0.1.
- *EXIST* measures E_{pk} up to 3 MeV using active shields
- GRBs provide "back-light" for IR spectroscopy of IGM, gas, & galactic structure back to re-ionization

Predicted *EXIST* GRB rate opens universe to z ≥ 10





EXIST GRBs vs. z will probe the star formation rate (SFR) vs. z at highest redshifts, and constrain/measure Pop III.

Predicted GRB rates vs. z based on Bromm and Loeb (2005). *EXIST* will detect many GRBs at z >7 and may detect Pop III GRBs for which models are uncertain.

GRBs allow cosmology at highest redshifts (non-CMB), and *EXIST* will open this window.

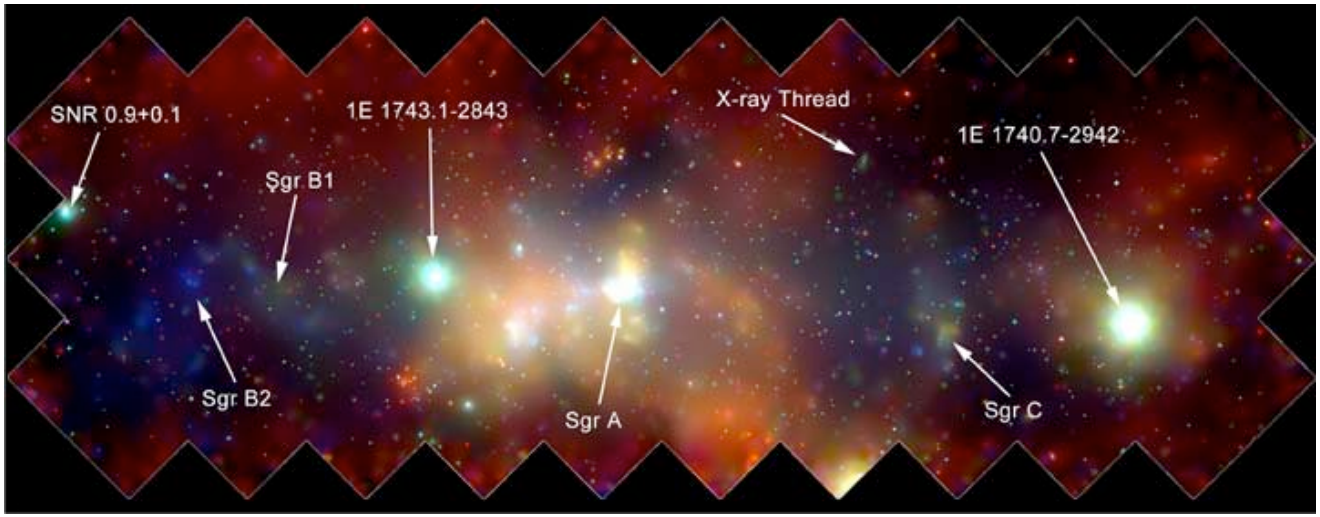
***EXIST will* probe:**

EXIST measures stellar BHs & IMBHs in Local Group

- ***EXIST* detects all bright stellar BHs in transients** (Lx(>10 keV) ~$10^{37\text{-}38}$ erg/s) throughout Galaxy, LMC/SMC and M31. ***Reveal population of obscured HX sources found with INTEGRAL/Swift: discrete sources at >10 keV***

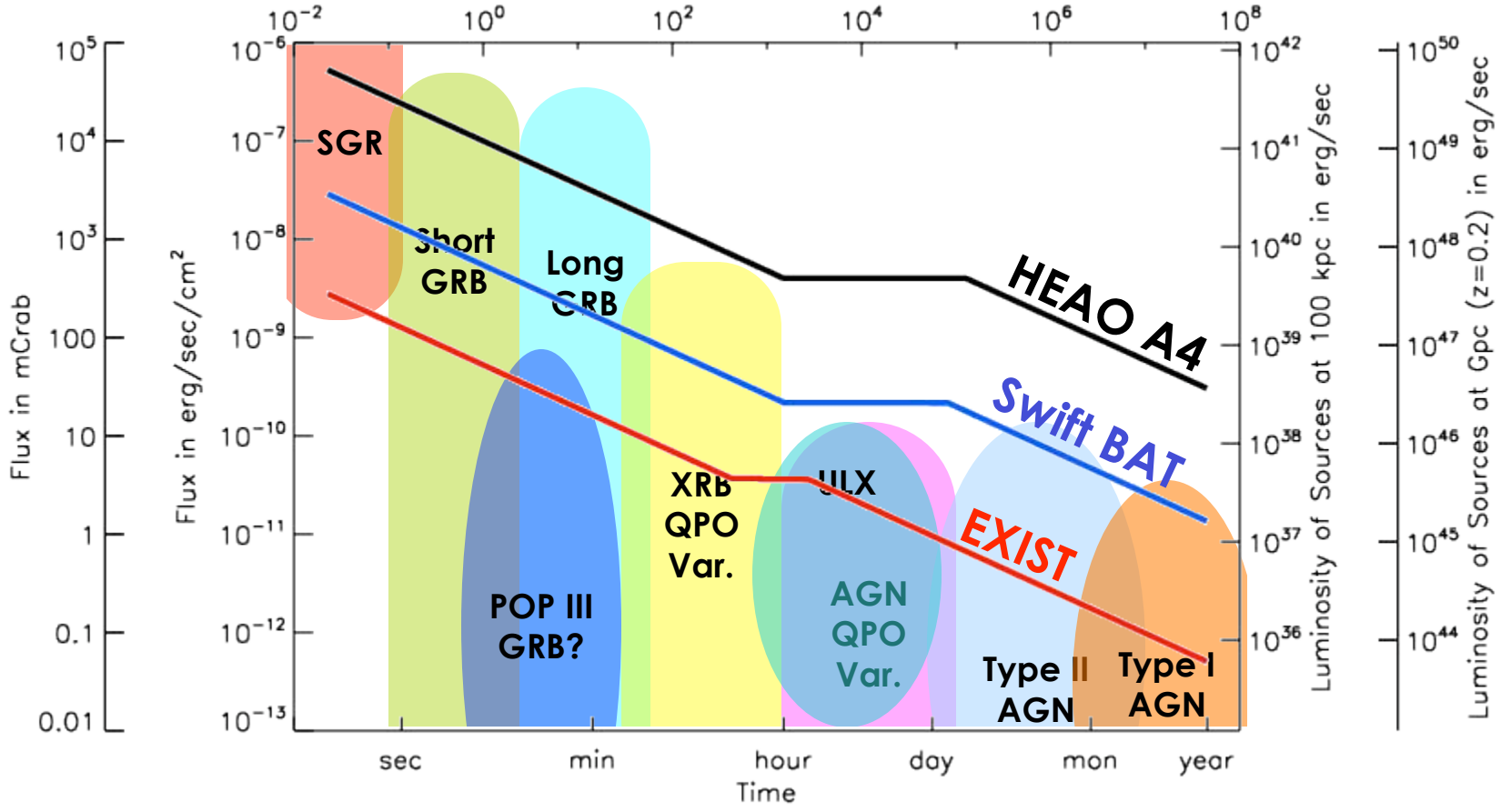
- ***Isolated* stellar BHs in Galaxy and IMBHs** in Local Group accreting via Bondi-Hoyle (with ~10^{-4} efficiency) from GMCs nearly Compton thick

- **Faint BH transients in *Central Galactic Bulge*?**: BHs in nuclear cusp (cf. Alexander & Livio 04) detected if Lx(>10 keV) ~10^{35} erg/s CI Cam type outbursts (~1-2d?) of Bulge BH vs. WD binaries around *SgrA**



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

Expected *EXIST* Sensitivity for Variability

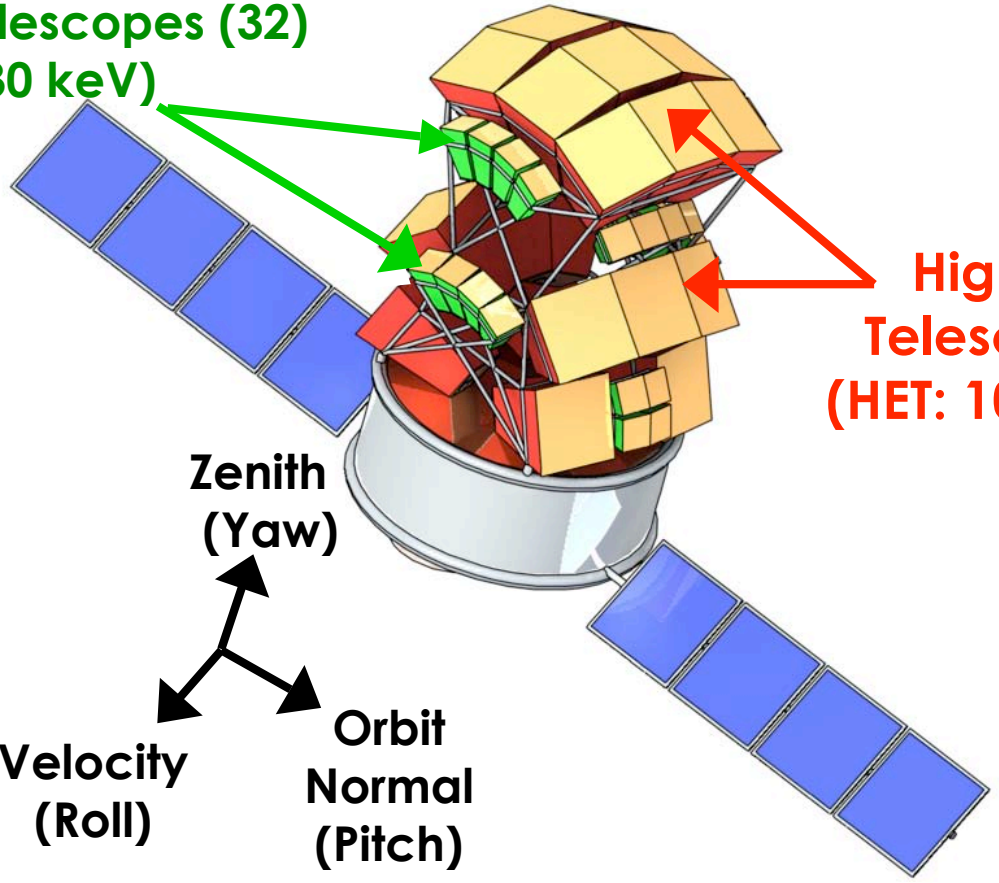


EXIST sensitivity on each timescale allows key measurements across BH types

EXIST: current Baseline Mission Design Concept

(General Dynamics mission concept)

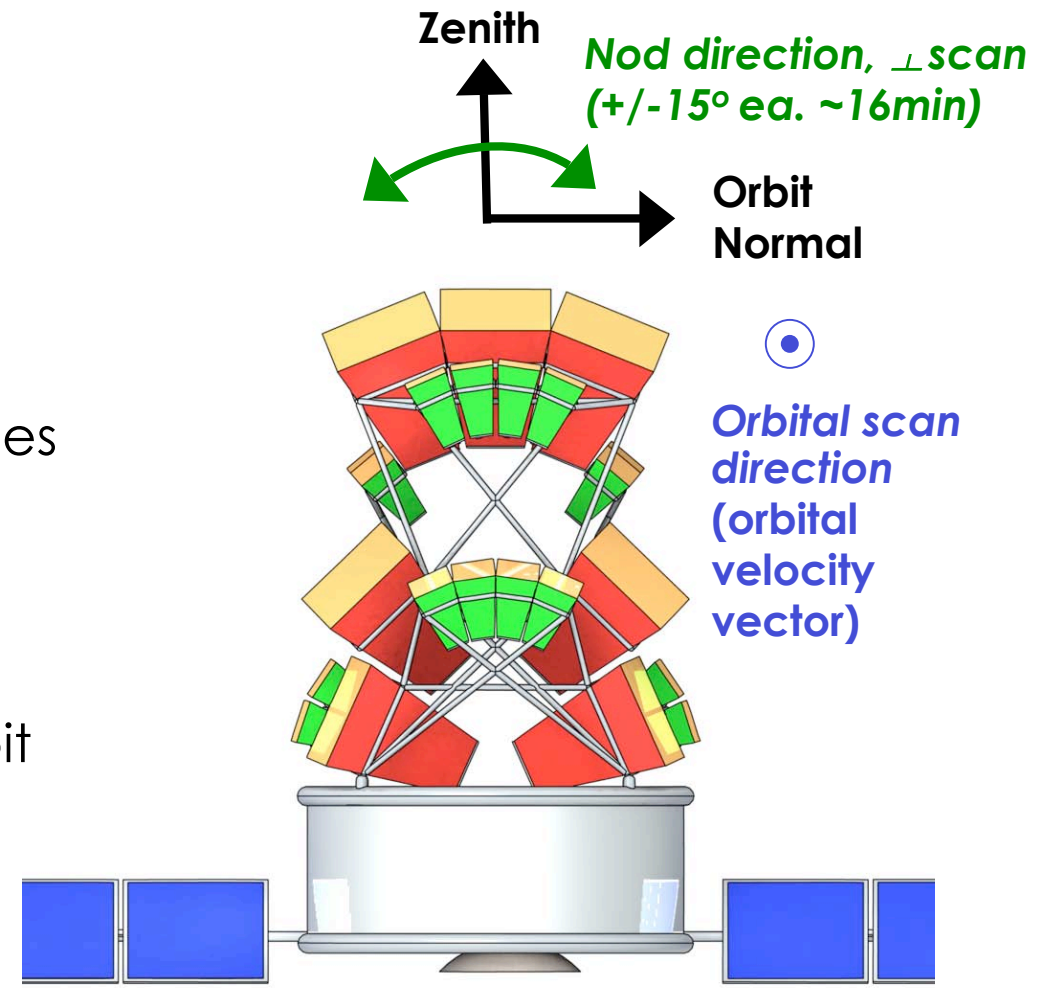
In Delta IV or Atlas V
(5m Fairing)



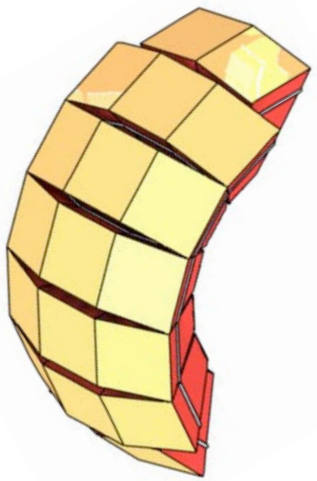
- Survey the hard X-ray sky 10-50x deeper than previous HX missions, with <10″ source positions (for >5σ survey threshold)
- Cover the 3 - 600 keV band with two telescope systems:
  HET: 10 - 600 keV (6 m^2 CZT pix) and LET: 3 - 30 keV (1.3 m^2 Si pix)

EXIST Mission Design Parameters

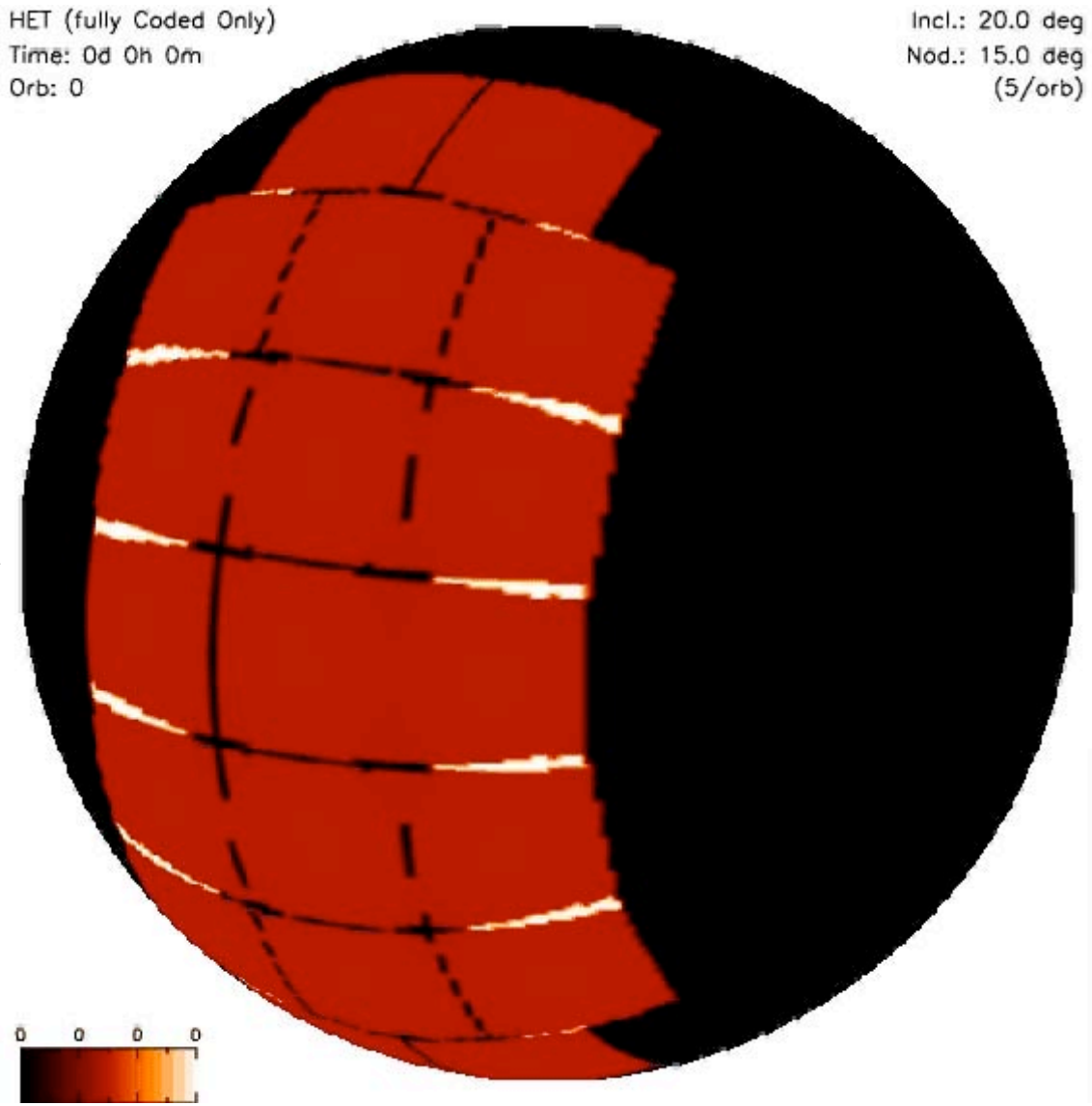
- Zenith pointer - scanning & nodding for ~full-sky coverage each orbit (95min)
- 19 coded aperture HE telescopes (6m^2 total area CZT pixel det.)
- 32 coded aperture LE telescopes (1.3m^2 total area Si pixel det.)
- Mass, power, telemetry: 9500kg, 3kW, 3Mbps
- Delta IVH launch to 500 km orbit (i ~5°) *or* Atlas V-551 launch (i ~20°) – *study bkgd. trades*
- Mission lifetime: 5 years
- Cost: $650M (incl. 20% conting. IMDC costing FY05 $)



EXIST scan/nod sweeps out full sky each orbit



HET telescopes field of view (LET very similar) defines sky view in **movie**



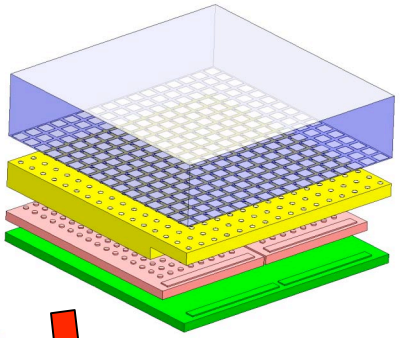
- **Scan the *full* sky every 95min orbit**
- **20 deg orbit Incl., +/-15 deg Nodding at 5 times/orbit**
- **Movie: orbits 0 .. 3; jumps to 15th orbit**

EXIST mission operations

- *Very simple operations*: nominal continuous scan
- Can do pre-planned pointings for longer continuous observations (but gain factor ≤2 vs. scan ea. orbit)
- GRB positions (~2/d) processed on board and QL link (TDRSS?) to ground within 10sec; all data (photon times, positions, energies) dumped each 1-2 orbits
- 5y mission life desired to accumulate large samples of survey objects and rare events

Detector packaging: Cd-Zn-Te crystals to Telescope

(building a very large area CZT detector/telescope)



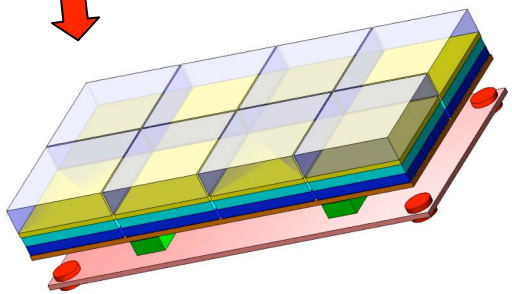
Detector Crystal Unit (DCU)

Cd-Zn-Te (CZT) Crystal (2x2 cm^2)

(*with Interposer Board?*)

+ 2 x 128 channel ASIC

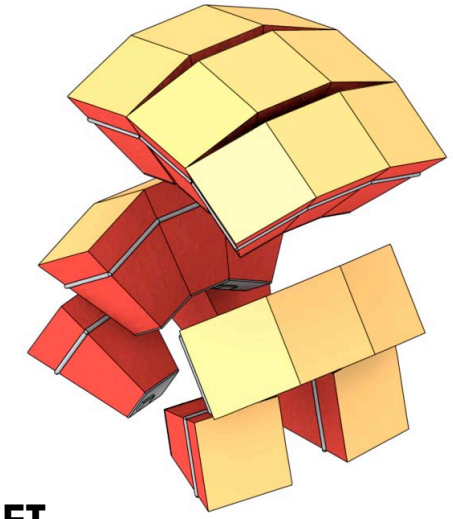
(*with micro-via tech?*)



Detector Crystal Array (DCA)

2x4 DCUs (4x8 cm^2)

+ FPGA Board



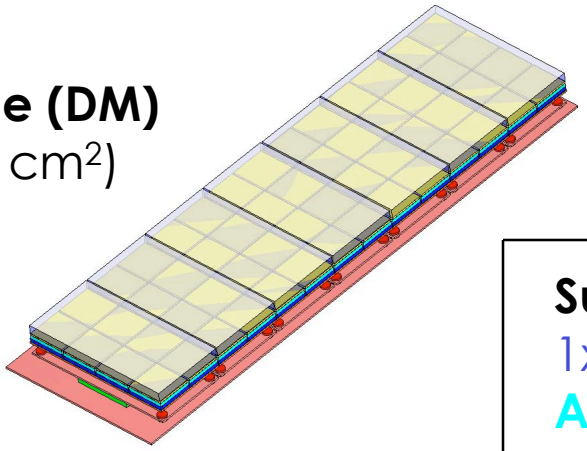
HET

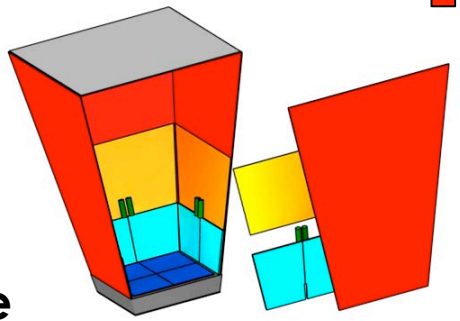
19 Sub-Tels (6 m^2)

Detector Module (DM)

1x7 DCAs (8x56 cm^2)

+ FPGA Board



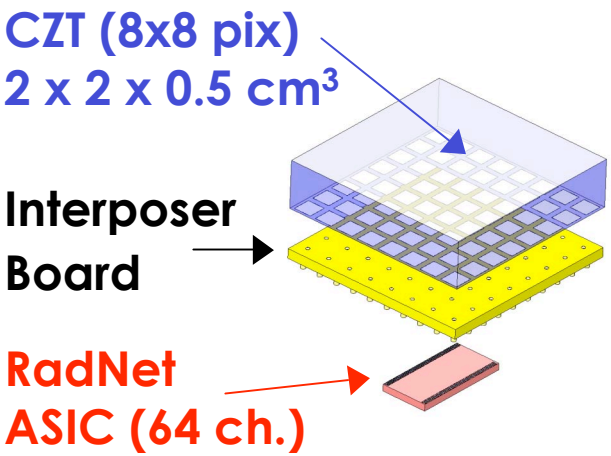


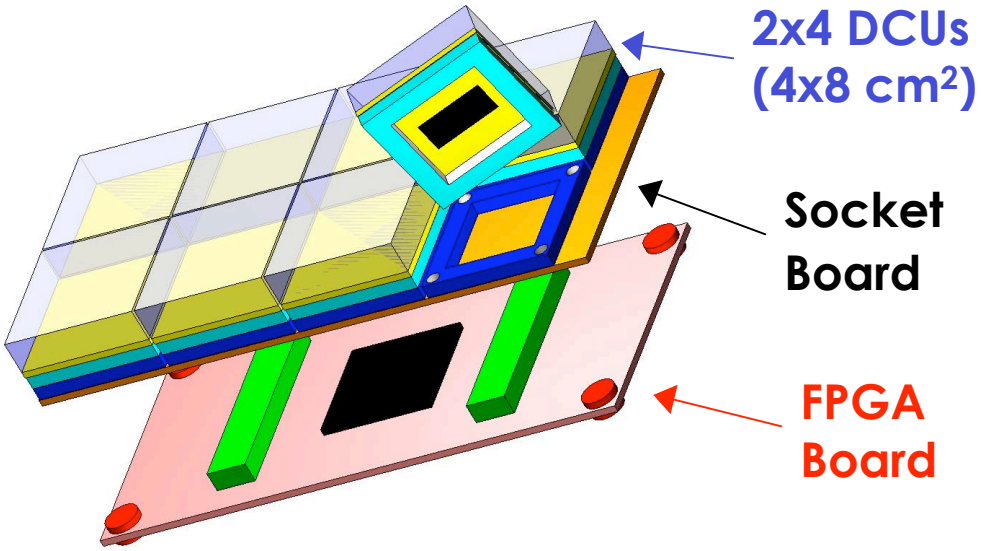
Sub-Tel Module

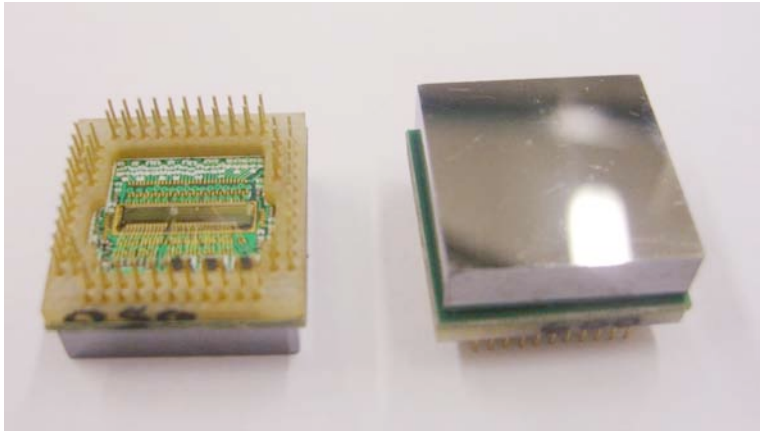
1x7 DMs (56x56 cm^2)

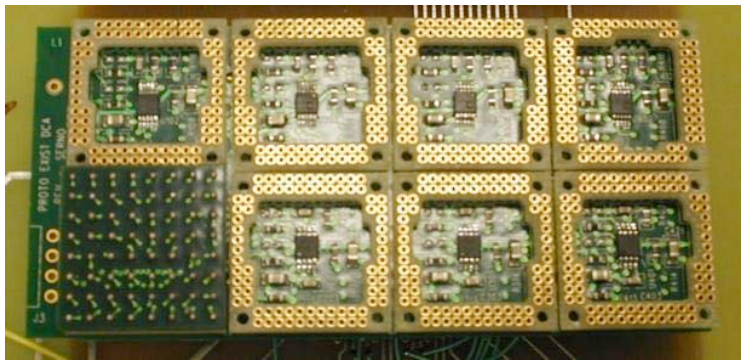
Active & Passive shields

CZT Imager for EXIST: detectors for *ProtoEXIST1*







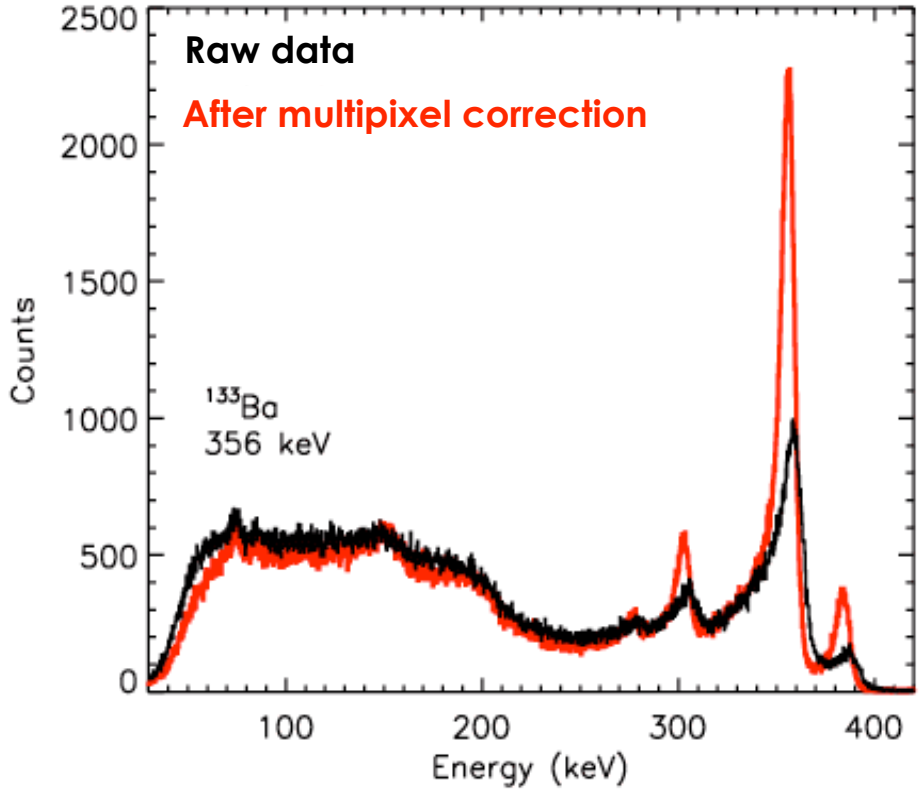


Detector Crystal Unit (DCU: 4 cm²)

Detector Crystal Array (DCA: 32 cm²)

ProtoEXIST imaging detectors exist for *EXIST!*

(multipixel imaging with CZT & *depth-sensing*-corrected spectra)

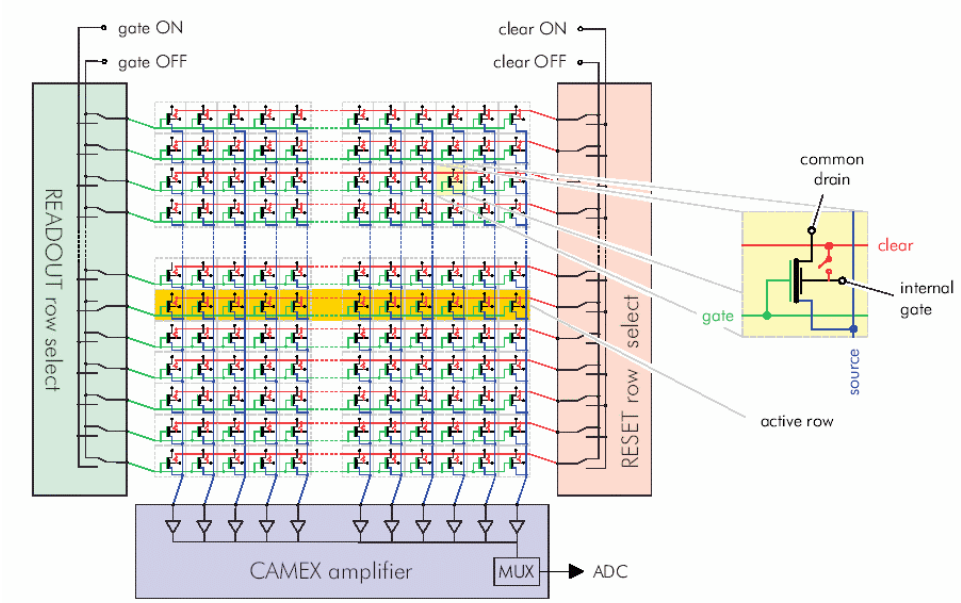


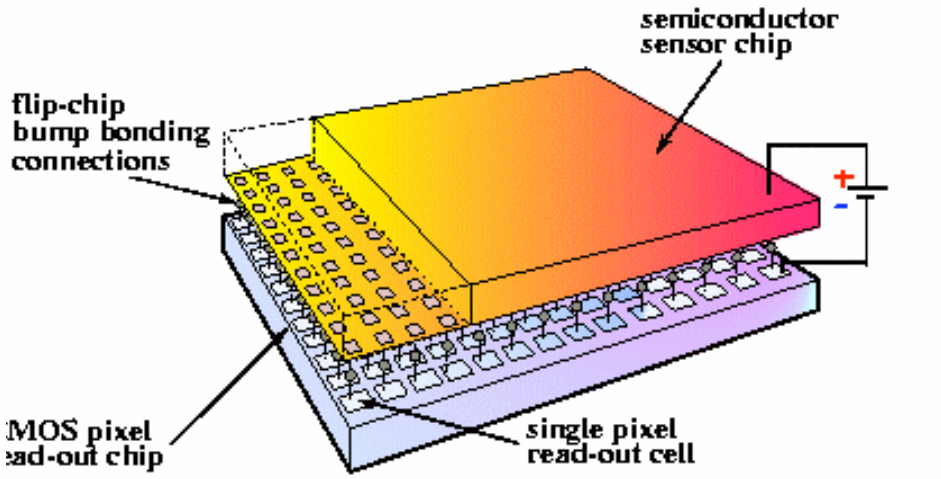
Multipixel correction reduces FWHM by 40% and improves photopeak efficiency by 60%. We achieve 2% FWHM at 356 keV (~1% at 662 keV). Resolution improves by additional ~30% with improved flight boards. Depth-sensing req. for large FoV imaging. *EXIST* will have spectacular energy resolution (~1-3% across full band).

See Hong et al 2006, astro-ph/0608711

Two options for LET imager

(R&A needed for further development by 2009)





DEPFET detectors

- Developed by MPE for XEUS and possible for EXIST with commerical development. Allows Intl. Collab.
- Excellent energy resolution (200 eV) and modest cooling (-30deg C)
- Low power (300W) for full array

Vs. Hybrid pixel detectors

- Similar to candidate LSST camera, but charge/pixel gives ~200eV resolution
- Low power and allows thicker (1mm) Si for better response to 30 keV
- Packaging and tiling for large arrays require further development

Ensuring *EXIST* imaging sensitivity

(to enable imaging for Signal/Background from ~10^{-4} to 1)

- Wide dynamic range (≥$10^{3\text{-}4}$) needed to achieve high sensitivity imposes challenges for coded-aperture imaging

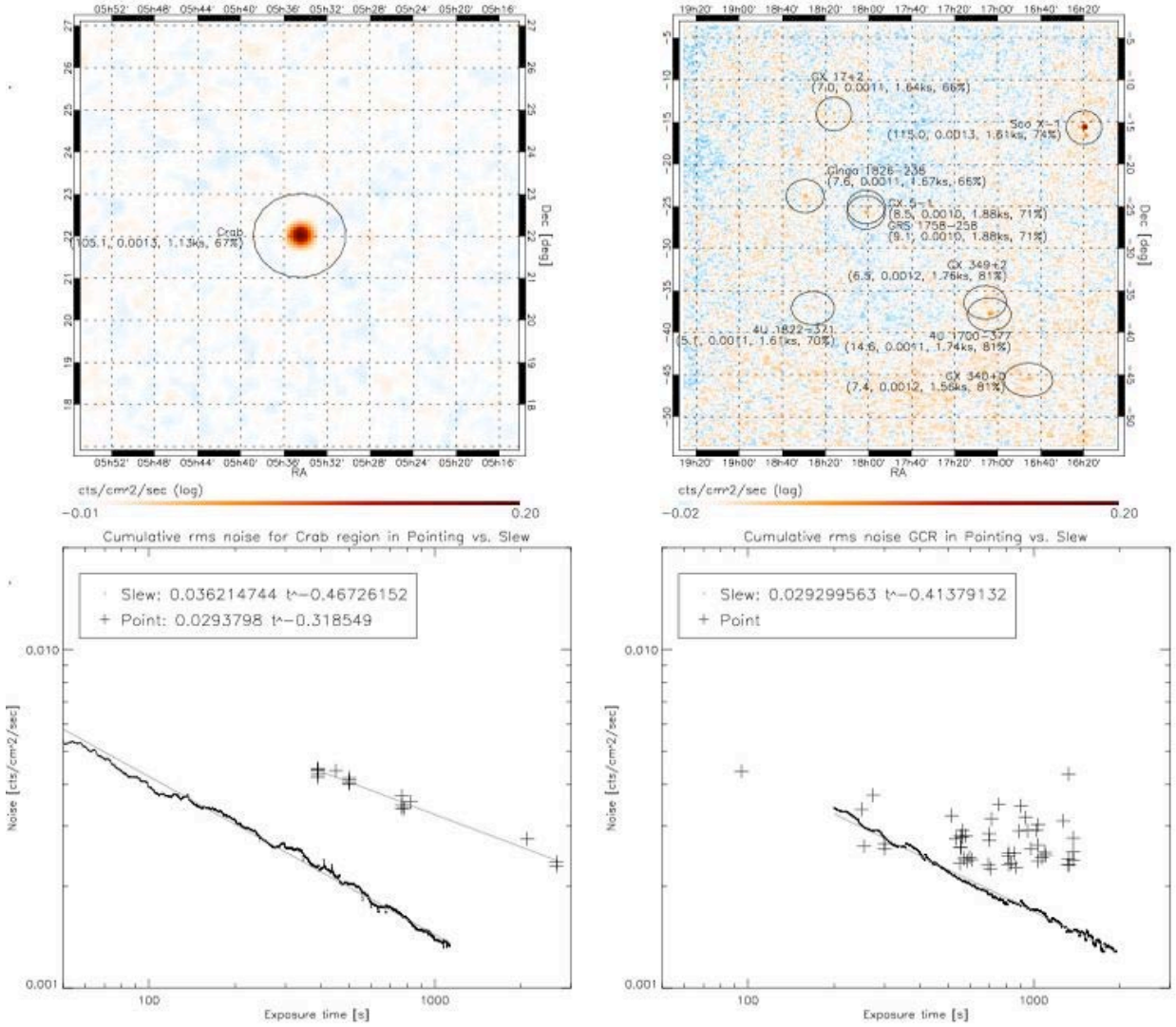
- The main factor for limiting the performance in coded-aperture telescopes is noise caused by unknown systematics in the system (pixel efficiency & background variations, etc.)

- ***EXIST's*** **scanning/nodding motion designed for surveying the sky is also a key to reduce the unknown systematics**

- We demonstrate imaging performance of *EXIST* by a series of progressively realistic simulations. *Swift/BAT* slew imaging tests are in progress; and demonstration of *EXIST* detectors and imaging planned with ***ProtoEXIST*** balloon experiments

Swift/BAT slew imaging provides on-orbit test

(and new *BAT* slew survey (***BATSS)*** science…)



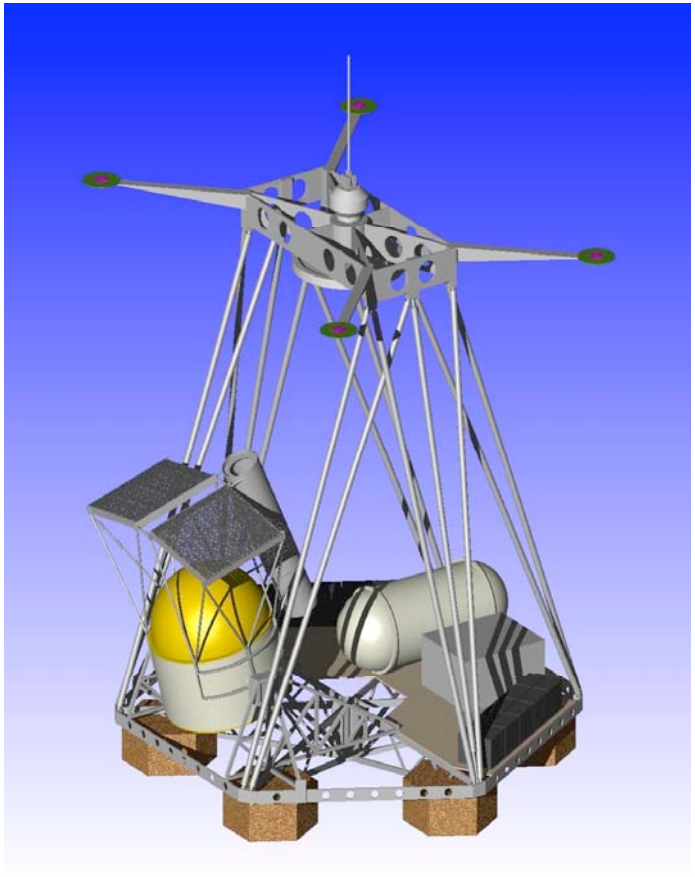
Stacked slews (60sec ea.) vs. pointing on Crab vs. Gal. Ctr. region

Noise reduced vs. equiv. time pointing due to averaging effects of scan

Prototyping *EXIST*: ***ProtoEXIST***

Balloon borne Hard X-ray Survey Telescope

(Harvard, GSFC, Caltech, Stanford collaboration)



- **Pathfinder & technology development for *EXIST* HET (CZT imager)**

- **Building a large area CZT detector with fine resolution, covering 10 – 600 keV**

ProtoEXIST1 **~ 1000 cm^2 (2.5 mm pixels)**
ProtoEXIST2 **~ > 256-1000 cm^2 (1.25 mm pixels)**

EXIST (HET) **~ 6 m^2 (1.25 mm pixels)**

- **Prototype for LET needed: package Si pixel *DepFET* (MPE collab.) or CMOS pixel Sensor (LSST imager option)**

Summary and Prospects

- *INTEGRAL* and *Swift* imaging have glimpsed the *rich HX sky* (obscured binaries, AGN, high z GRBs…!)
- Broad band (3 – 600 keV), large area & FoV are unique for *EXIST*: image all-sky each orbit. ALL sources observed with ≥20% continuous coverage; *EXIST opens temporal universe in the extreme; complements LSST*
- Highest z universe uniquely measured via GRBs: >7X *Swift* rate; trigger *JWST*
- Both obscured and dormant SMBHs best studied with HX imager: complete BH census/evolution & accretion luminosity of universe
- HX Blazar surveys combined with GeV-TeV (*GLAST-VERITAS*): measure EBL and thermal (stellar) luminosity of universe ; complements *WISE*
- *ProtoEXIST1* balloon flight in 2008, *ProtoEXIST2* in 2009 to establish readiness
- *EXIST* Technology & costs relatively well-understood; TRL-7 for HET but TRL-5 for LET (need R&A by 2009). Candidate for 2009 BHFP start!
- ***EXIST*** under study for BHFP ***– can*** launch in ~2013-2015 window if 2009 start
  - See *EXIST* website (***http://EXIST.gsfc.nasa.gov*****)** for Study & **Team**