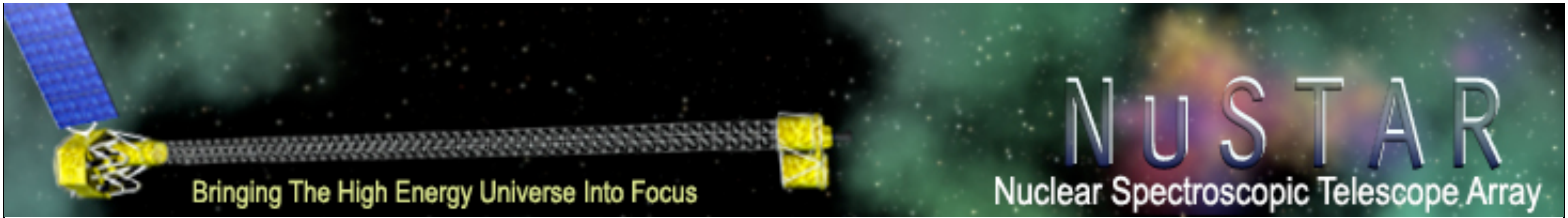
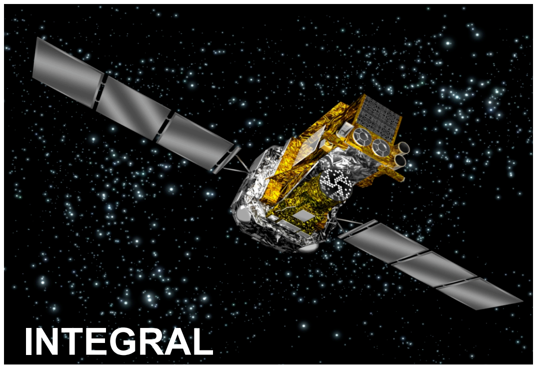
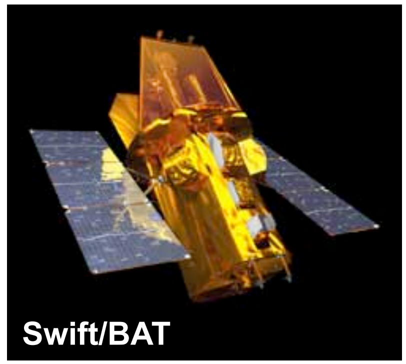


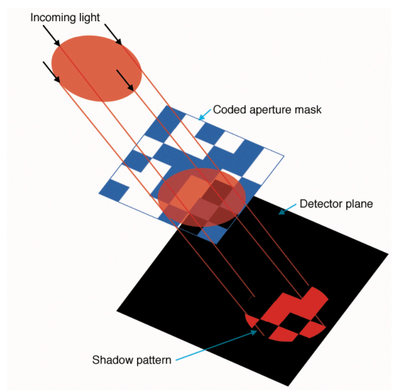
Galactic Science with NuSTAR

John A. Tomsick (UC Berkeley/SSL)
for the
NuSTAR Galactic Science Team

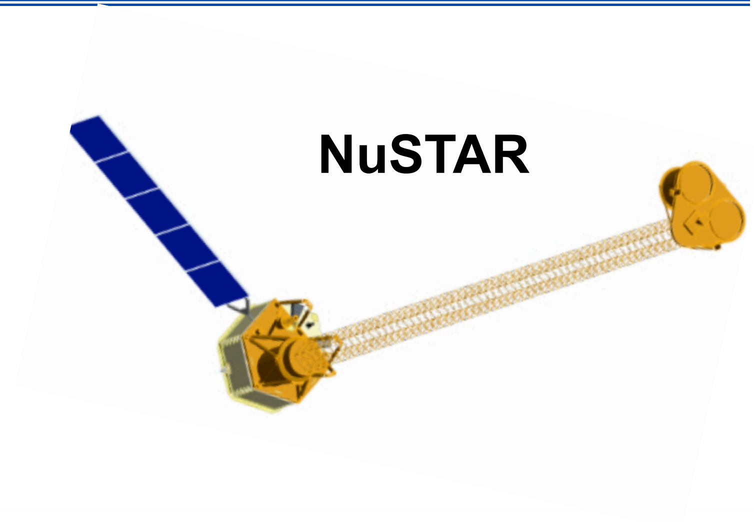
NuSTAR will be the first focusing hard X-ray satellite

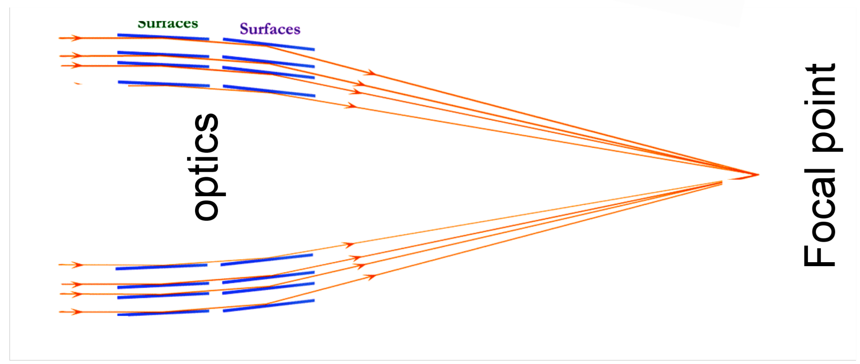






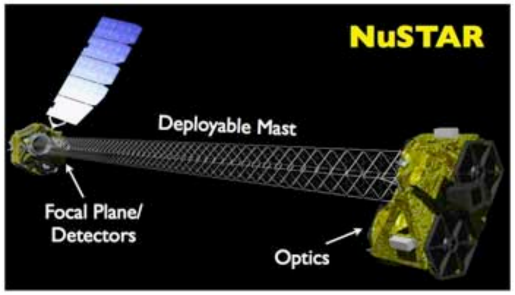
Coded Aperture Optics:
- large detector
- high background limiting sensitivity

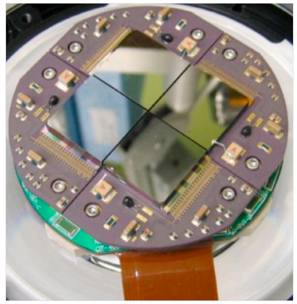




Focusing Optics:
- compact detector
- low background, high sensitivity

Information from the NuSTAR Factsheet

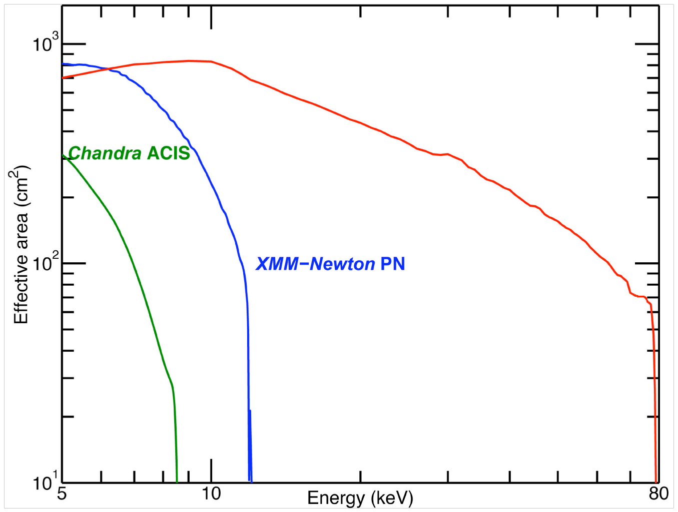




- PI: Fiona Harrison (Caltech)
- Project Scientist: Daniel Stern
- Hard X-ray Optics
  - glass slumping (GSFC)
  - multi-layer coatings (Denmark Technical University)
  - assembly and calibration (Columbia)
- Deployable Mast (10 m)
  - ATK (Alliant Techsystems Inc.)
- Detectors
  - CdZnTe with 0.6 mm pixels (Caltech)
- Significant contributions from ASI
  - Malindi: primary data downlink
  - Science software development
  - Extragalactic Science Team participation
  - A NuSTAR simulator

Energy Range:	~5-80 keV
Angular Resolution:	45 arcsec (HPD) 7.5 arcsec (FWHM)
Field of View:	12 x 12 arcmin
Spectral Resolution:	1.2 keV at 68 keV 600 eV at 6 keV
Timing Resolution:	0.1 msec (absolute) 2 microsecond (relative)
Sensitivity (3 σ, 1 Ms):	2 x 10^{-15} erg/cm^2/s (6-10 keV) 1 x 10^{-14} erg/cm^2/s (10-30 keV)
ToO Response:	<24 hr
Launch Date:	February 2012 on a Pegasus from Kajelein
Orbit:	6 degree inclination 550 km x 600 km
Mission Lifetime: **Orbit Lifetime:**	2 years baseline >7 years orbit lifetime

NuSTAR vs. Current Missions



Satellite (instrument)	Sensitivity
INTEGRAL (ISGRI)	~0.5 mCrab (20-100 keV) with >Ms exposures
Swift (BAT)	~0.8 mCrab (15-150 keV) with >Ms exposures
NuSTAR	~0.7 μCrab (10-30 keV) in 1 Ms

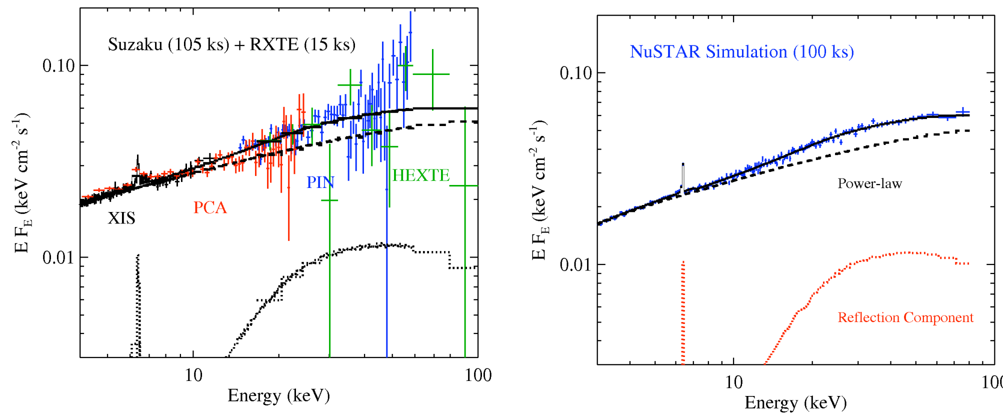
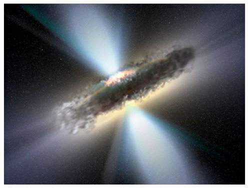
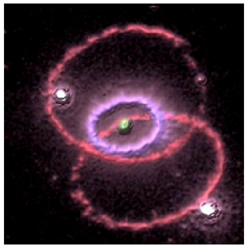


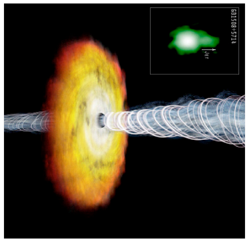
Figure and table: RXTE and Suzaku rates are those measured for the accreting BH GX 339-4 in the hard state at 5.3x10^{-11} erg/cm^2/s (2-10 keV) and L/L_{Edd} = 0.14%.

Satellite	Source rate	Background rate
RXTE (PCA)	17 c/s (5-50 keV, 3 PCUs)	56 c/s (5-50 keV, 3 PCUs)
Suzaku (HXD/PIN)	0.21 c/s (15-60 keV)	0.35 c/s (15-60 keV)
NuSTAR	2.6 c/s (5-80 keV)	0.008 c/s (5-80 keV)

NuSTAR Baseline Science Plan (first 2 years)







- *The observing plan for the 2 year baseline mission is being designed by the Science Team to address the following questions:*

Question #1: How are black holes distributed through the cosmos, and how do they affect the formation of galaxies?

Question #2: How are stellar remnants distributed within the Galaxy and near the Galactic center?

Question #3: How do stars explode and forge the elements that compose the Earth?

Question #4: What powers the most extreme active galactic nuclei?

- *In the first 2 years, ToO suggestions from the community will be considered.*
- *At the discretion of the PI, the extended mission will emphasize a competitive GO program*

Creating the Plan for Galactic Observations

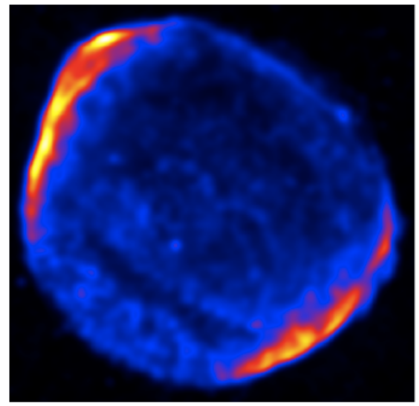
- 2008: ~20 internal proposals for Galactic science
- Science team meetings in 2009 (Caltech) and 2010 (Montreal)
- October 2010: Main science topics grouped into 7 white papers
  - SNRs & PWNe (~6 Ms)
  - Galactic plane surveys (~7 Ms)
  - Magnetars (~2 Ms)
  - Rotation-powered pulsars (~0.4 Ms)
  - X-ray binaries (~1.3 Ms)
  - Gamma-ray binaries (~0.4 Ms)
  - Protostars & planet formation (TBD)
- Currently: NuSTAR project "TAC" performing a scientific and technical evaluation of the white papers to plan ~17 Ms of Galactic observing time in the first 2 years of the mission

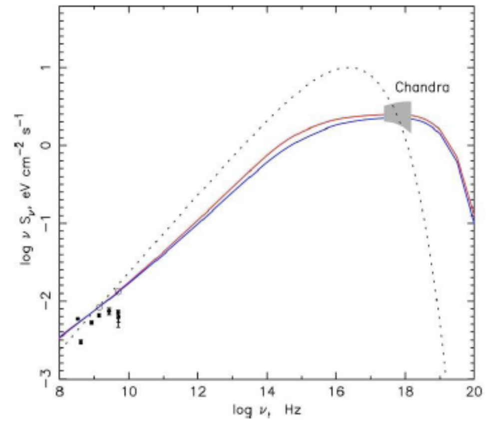
Supernova Remnants

- Constraining the synchrotron spectrum
  - relevant for understanding particle acceleration and the origin of cosmic rays
  - 4 targets (e.g., Cas A, Kepler, Tycho) where 20 ks NuSTAR exposures are sufficient

- 68 keV ^{44}Ti emission line
  - Predictions for the amount of ^{44}Ti depend on the type of SN (Ia or core collapse) and whether the explosion is symmetric or not.
  - Targets:
    - G1.9+0.3: 400 ks
    - Cas A: 700 ks (mapping intensity in 49 regions)
    - SN 1987A: 3 Ms

36x36 arcmin

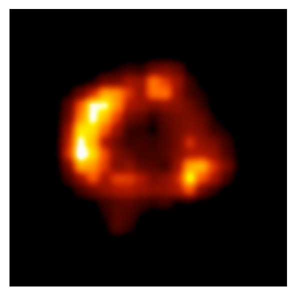




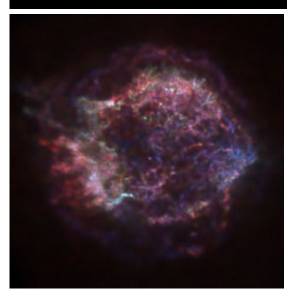
Chandra images of SN 1006 (above) and SN 1987A and Cas A (below)

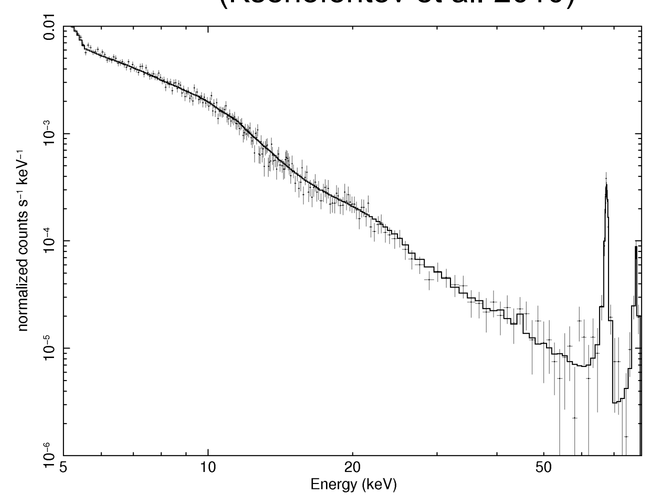
G1.9+0.3 spectral predictions for different particle acc. eff. (Ksenofontov et al. 2010)

3x3 arcsec



8.9x8.9 arcmin



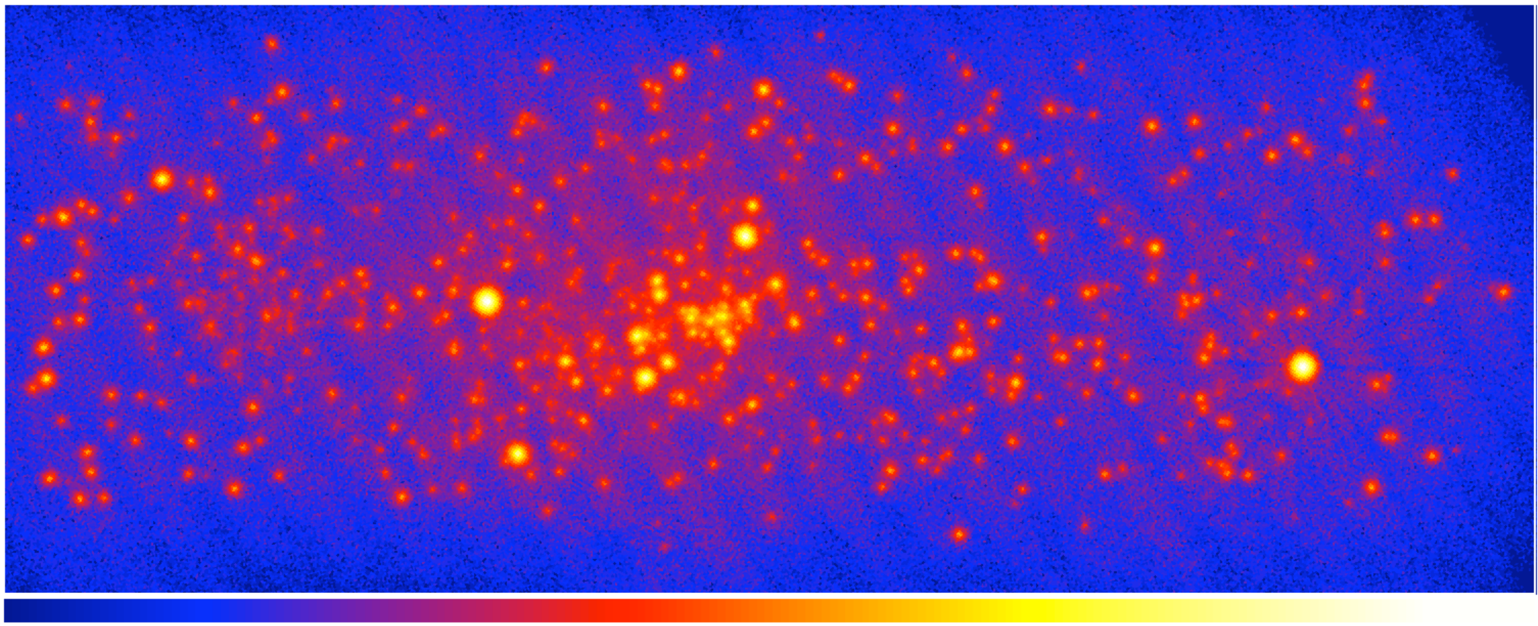


NuSTAR simulation for 3 Ms on SN 1987A (line flux = 2×10^{-6} ph/cm^2/s)

Galactic Surveys

- Finding the extreme members of the compact object populations that produce strong non-thermal emission
  - what fraction of CVs are magnetic CVs?
  - single massive stars vs. High Mass X-ray Binaries
  - HMXBs with black hole accretors
  - new magnetars, X-ray binaries, etc.
- Diffuse hard X-ray emission
  - Do reflection nebulae (e.g., Sgr A, B, C) have a hard X-ray reflection component?
  - Galactic ridge emission

Galactic Center NuSTAR Simulations

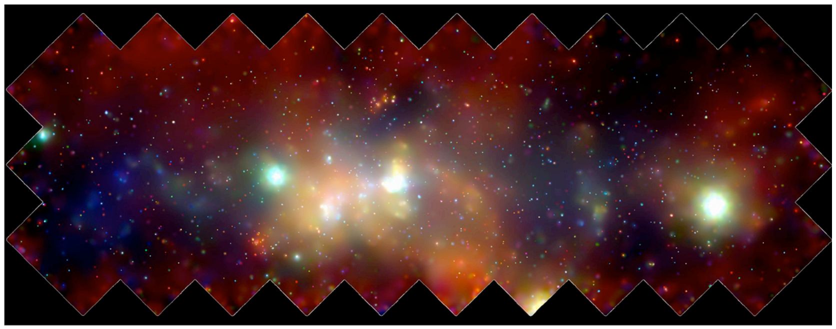


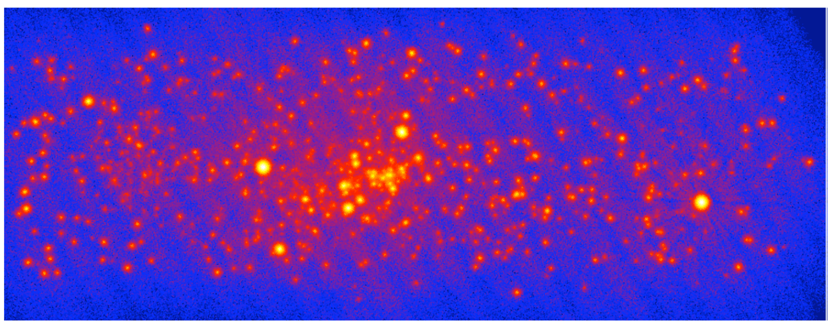
NuSIM ray-tracing simulator (Madsen & Zoglauer)

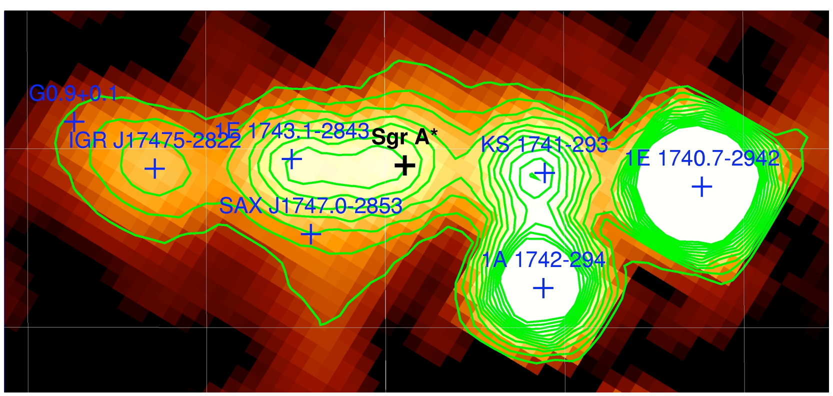
5-80 keV image

- 1 Ms over 2 deg x 0.8 deg (about 12 ks/pix)
- Input (Muno et al. 2004, 2006 Chandra catalogs):
  - ~1500 Chandra sources after hardness cuts
  - Extrapolate 0.5-8 keV power-law into NuSTAR band (probably an overestimate)
  - Note that diffuse emission from Sgr cloud complexes is not included (but this is also interesting)
- Results:
  - ~1000 sources above the 5-σ detection threshold (0.076 c/s, 6 microcrab, 2.8×10^{-13} erg/cm^2/s, 2.1×10^{33} erg/s at 8 kpc
  - 250 sources in the field with >2,400 counts (before PSF correction) collected during the survey

Comparison to other GC Images



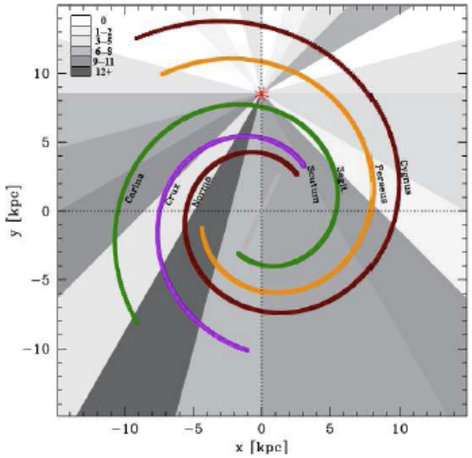


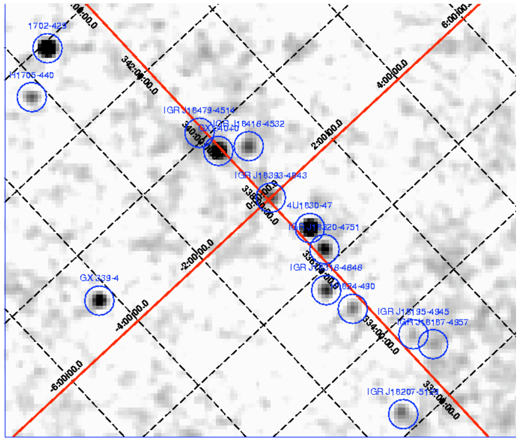


- Chandra
  - 0.5-8 keV
  - Wang et al. (2002); Muno et al. (2004, 2006, 2009)
- NuSTAR simulation
  - 5-80 keV
  - Detection limit ~2x10^{33} erg/s at 8 kpc
- INTEGRAL
  - 20-60 keV
  - Belanger et al. (2005)

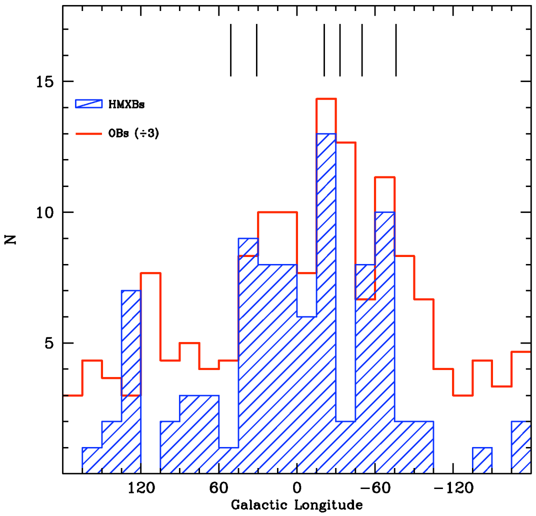
Spiral Arm Survey: Norma Region

- INTEGRAL: Found the highest numbers of HMXBs in the Norma region
- Also, where the numbers of OB associations is maximum
- This is a good place to study young and intermediate age populations to compare them to what we find in the GC region
  - NuSTAR will provide tight constraints on the low end of the HMXB luminosity function.
- This region is also the subject of a Chandra large program that will take place in June 2011





HMXBs detected by INTEGRAL and spiral arms



HMXBs and OB associations peak in this region (updated from Bodaghee et al. 2007)

X-ray Binaries

- Targets in WP include:
  - Detailed measurements of bright HMXBs
  - First high-quality spectral and timing studies of faint HMXBs
  - Type I X-ray bursters
  - First hard X-ray measurements of NS and BH transients in quiescence (e.g., Cen X-4 and V404 Cyg, respectively)
  - Studies of the reflection component in BH transients in the hard state (e.g., GX 339-4)

High Mass X-ray Binaries

- Cyclotron line studies use NuSTAR's sensitivity and energy resolution
- Significant advances in physical spectral models (Schonherr et al. 2007)
- INTEGRAL has discovered ~50 new HMXBs
  - NuSTAR will be much more sensitive for measuring cyclotron lines and continuum cutoffs, which are NS signatures.

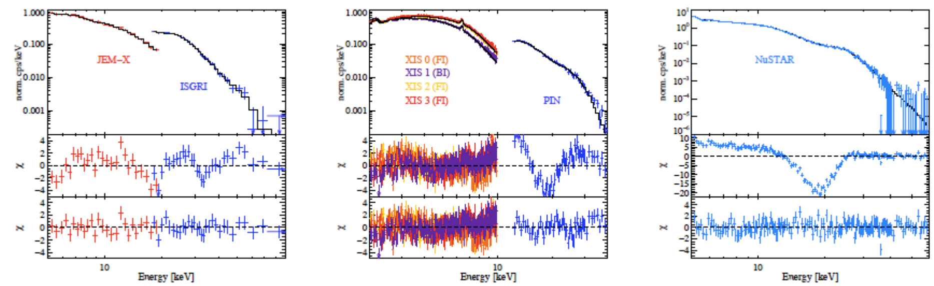
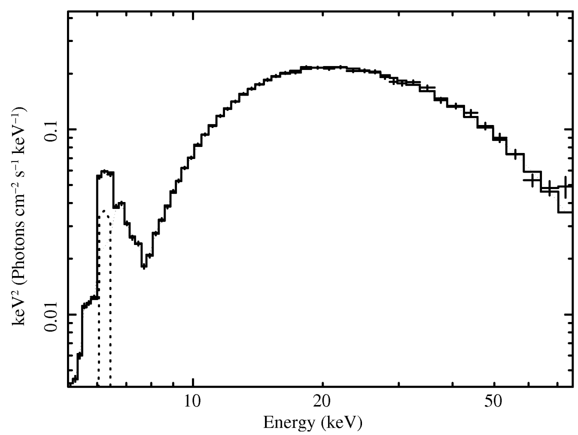


Figure 1: *INTEGRAL* observation of 4U 1907+09, 1200 ks.

Figure 2: *Suzaku* observation of 4U 1907+09, 60 ks.

Figure 3: *NuSTAR* simulation of 4U 1907+09, 10 ks.

Spectra of the 20 millicrab HMXB 4U 1907+09 (Figure from K. Pottschmidt). Other potential targets include: Her X-1, Vela X-1, Cen X-3, and others.

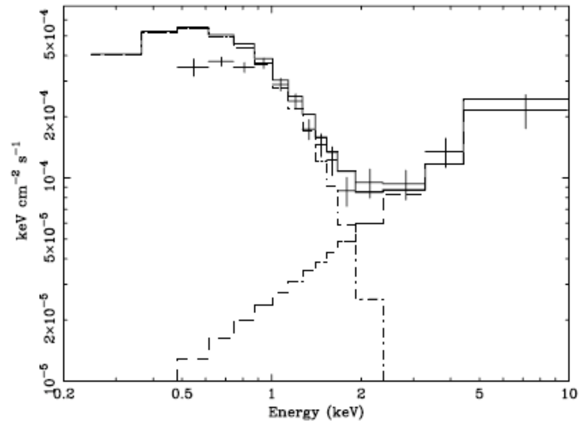


NuSTAR simulation for IGR J16318-4848. This flux for this system is typically near 10 millicrab, and here it is simulated with a cutoff at 20 keV.

LMXBs: NSs in Quiescence and Type I X-ray Bursts

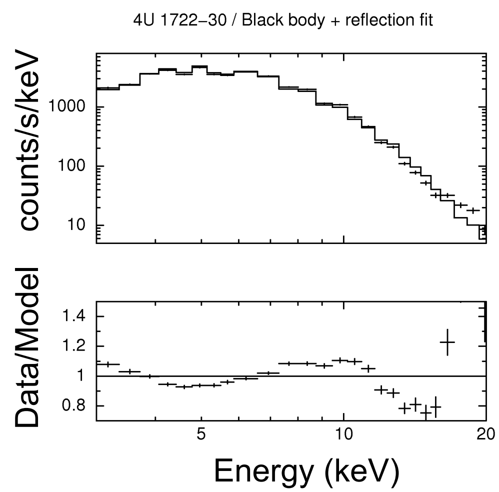
NuSTAR

- NSs in quiescence
  - A hard component with Γ~1 is very commonly seen >3 keV
  - NuSTAR will detect it at >10 keV for the first time to help determine its origin (e.g., accretion disk corona or rotation-powered pulsar)



Quiescent Chandra spectrum of the NS LMXB Cen X-4 (Rutledge et al. 2001)

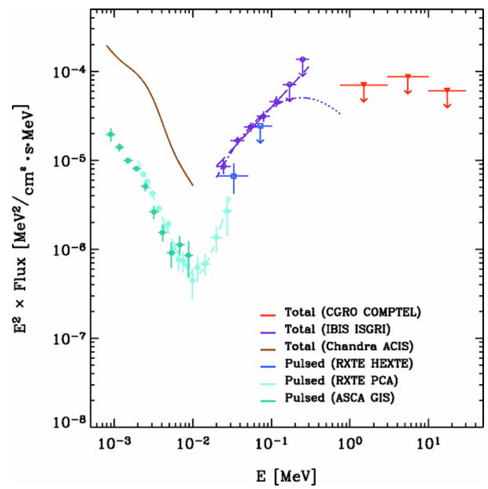
- Type I X-ray bursts
  - in ‘t Zand & Weinberg (2010) found evidence for absorption edges in the 9-13 keV range from two bursters
  - May be from ^{58}Fe, ^{59}Co, ^{60}Zn, ^{62}Zn (exposed ashes of nuclear burning)
  - Detection feasible with NuSTAR and this would provide a new probe of bursts and NSs



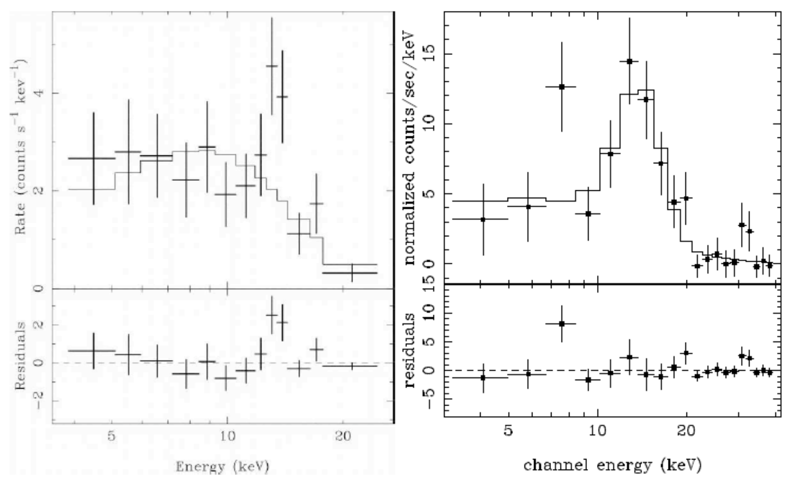
RXTE/PCA spectrum from a 7s interval during a type I X-ray burst from 4U 1722-30 (in ‘t Zand & Weinberg 2010)

Magnetars: Hard X-ray Component and Emission Lines

- Pulsed hard X-ray emission with Γ ~ 0 to -1 is seen from several magnetars.
  - NuSTAR covers both spectral components, and will test the Beloborodov & Thompson (2007) model prediction that they should be correlated.
- Emission features near 13 keV following bursts
  - NuSTAR may confirm that they are real, and its better spectral resolution may allow us to determine their origin.



SED of the AXP 4U 0142+61 (Kuiper et al. 2006). The hard X-ray component is pulsed.



Two spectra measured with RXTE/PCA following bursts from the AXP 1E 1048.1-5937 (Gavriil et al. 2002, 2006)

Additional Surveys and Science being Considered

- Young Massive Clusters: e.g., Westerlund 1 has had an estimated ~100 SNe in the recent past (Clark et al. 2008), but where are the compact objects now? Also, consider Carina, Cygnus, etc.
- Small Magellanic Cloud: A ~1x1 deg region rich in HMXBs could be done to a level of 6×10^{34} erg/s in 1.6 Ms. For example, this would tell us about HMXB evolution in another metallicity environment.
- Sgr A*: X-ray flares detected by Chandra and XMM-Newton. Constraining their hard X-ray spectrum may become a dedicated NuSTAR program
- Ultra-luminous X-ray Sources (ULXs): Continue comparisons to Galactic BHs in terms of spectral cutoffs, reflection components, and Quasi-Periodic Oscillations (QPOs)
- Rotation-powered pulsars: Including hard X-ray measurements of recently discovered Fermi pulsars
- Gamma-ray binaries: LS I+61 303, LS 5039, PSR B1259-63, PSR J1023+0023
- Pulsar Wind Nebulae

Summary and Conclusions

- For Galactic science, the primary advances that NuSTAR will provide are:
  - ~3 orders of magnitude in hard X-ray sensitivity for studies of Galactic source populations
  - imaging of extended objects like SNRs and reflection nebulae
  - CZT energy resolution for ^{44}Ti lines from SNRs, cyclotron lines, confirming and measuring details of the 9-13 keV features from bursters and magnetars
- Looking forward to launch in early 2012!