Discovering X-ray Bright Neutron Stars for Current and Next-Generation Observatories

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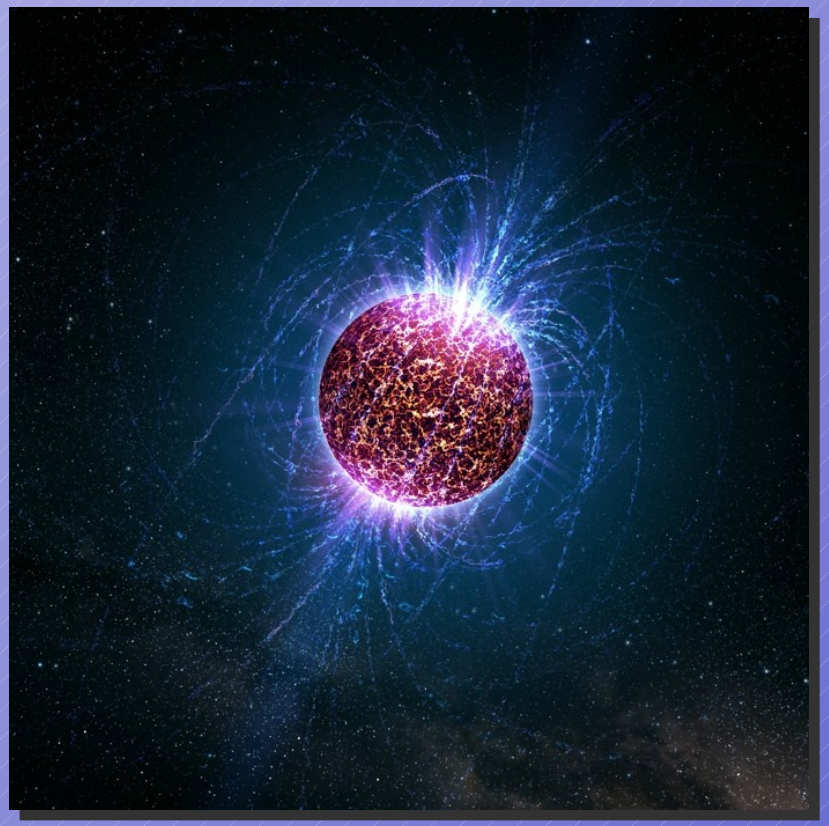
Isolated Neutron Stars

- "Isolated neutron stars"
  - Blackbody spectrum (dominant)
  - Peak in far-UV / soft X-ray
  - Cooling age < 1 Myr
  - Minimal X-ray variability
  - Not radio pulsars
  - No binary companions
  - No supernova remnant
- Optically faint – most extreme f_X/f_{opt} objects known
- Identified as ROSAT All-Sky Survey (Bright Source Catalog) X-ray

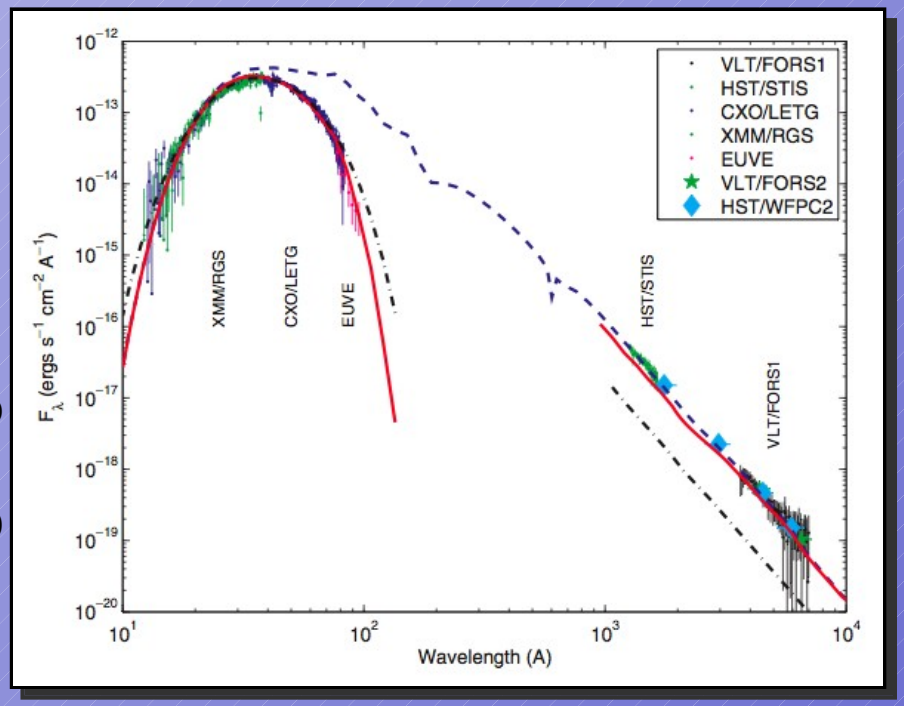


The Magnificent Seven

- Seven isolated neutron stars discovered over 1996–2001
- All BSC sources
  - Serendipity
  - Targeted survey work (RBS)
  - Positions refined with HRI
- Intriguing targets for detailed study
  - X-ray bright
  - Nearby (two with parallax)
  - Atmospheres amenable to modeling
- Ultimate goals:
  - Measure masses and radii
  - Constrain nuclear equation of state
  - Investigate possibility of persistent GW emission

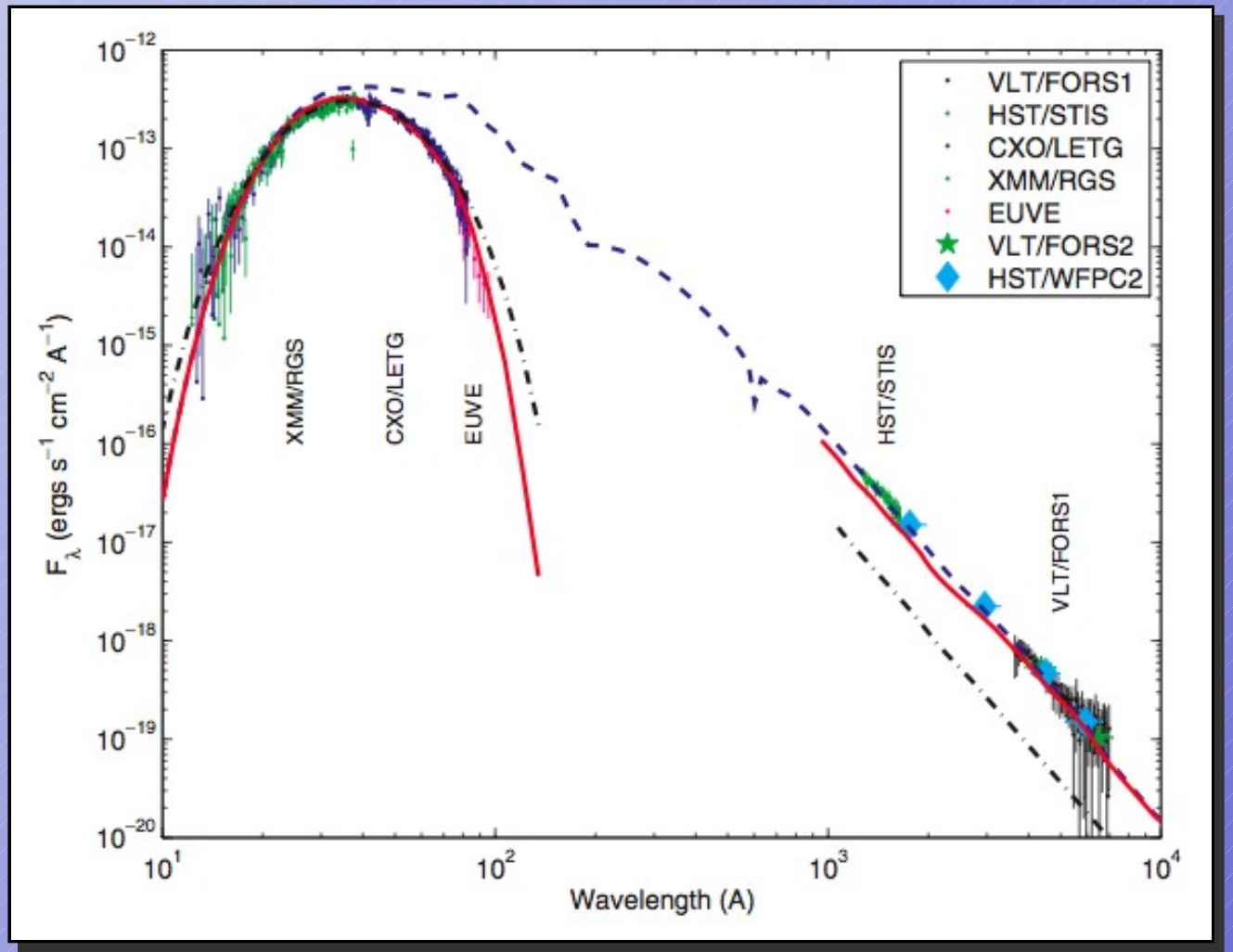
RXS J1856.5-3754

- Discovered by Fred Walter
- Bright X-ray source in front of the Corona Australis molecular cloud
- Must be close → Low luminosity
- Optical counterpart discovered with HST (*V*=25.6 mag)
- X-ray to optical flux ratio confirms neutron star nature
- Subsequent HST programs to measure parallax and proper motion
- Distance: ~160 pc
- Featureless spectrum, modeled as magnetic hydrogen atmosphere



Ho et al. 2006

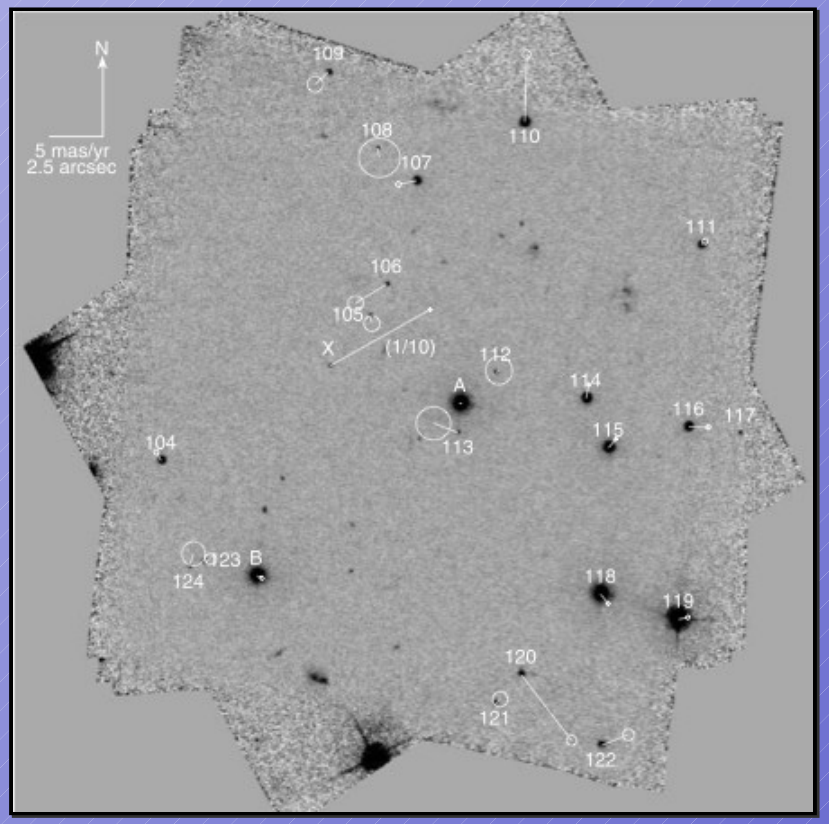
RXS J1856.5-3754



Ho et al. 2006

RXS J0720.4−3125

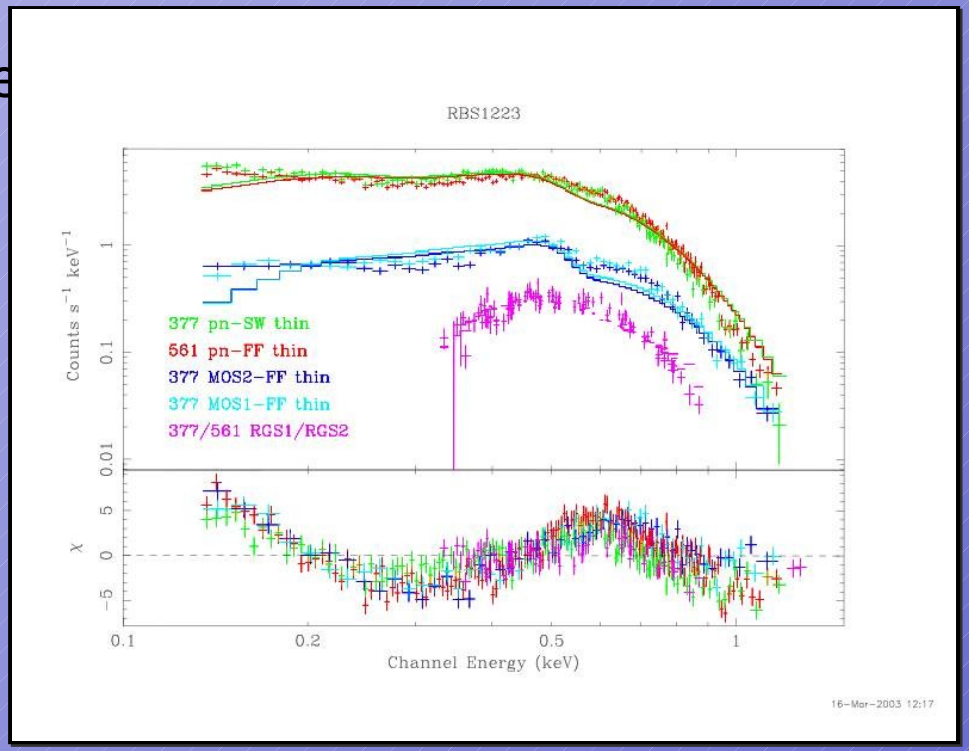
- Second INS with HST counterpart (*B*=26.6 mag)
- 8.39s X-ray pulsar
- Parallax and proper motion from HST observations (Kaplan & van Kerkwijk 2007)
- Distance: 360 (+170) (−90) pc



Kaplan & van Kerkwijk 2007

RXS J1308+2127

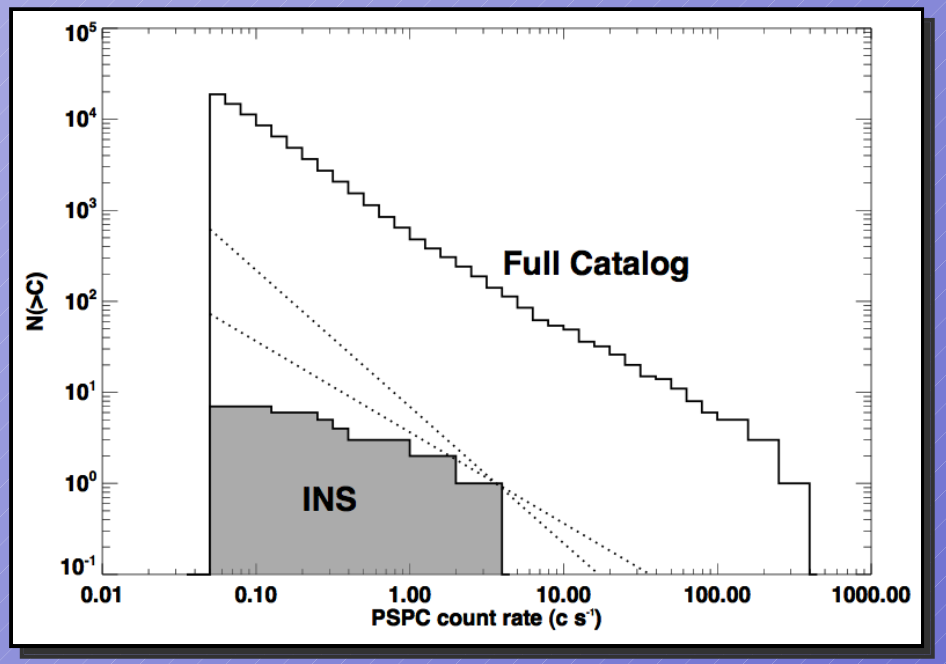
- RBS1223
- Broad absorption feature in X-ray spectrum
- Similar features at 0.5 – 1.0 keV seen in most INS sources
- Possibly magnetic (proton cyclotron)
- Possibly atmospheric
- Higher “harmonics” complicating the interpretation



Haberl et al. 2003

Mining the ROSAT BSC

- Seven original INSs drawn from the brightest part of the catalog
- XID developed by Rutledge +00
  - Probability of association for every BSC source
  - Probability of non-association with any off-band object (i.e. INS)
  - Successfully “catches” known INSs
- *Chandra* follow-up program yields no new objects (Rutledge+03)
- Precision of X-ray positions the key limiting factor

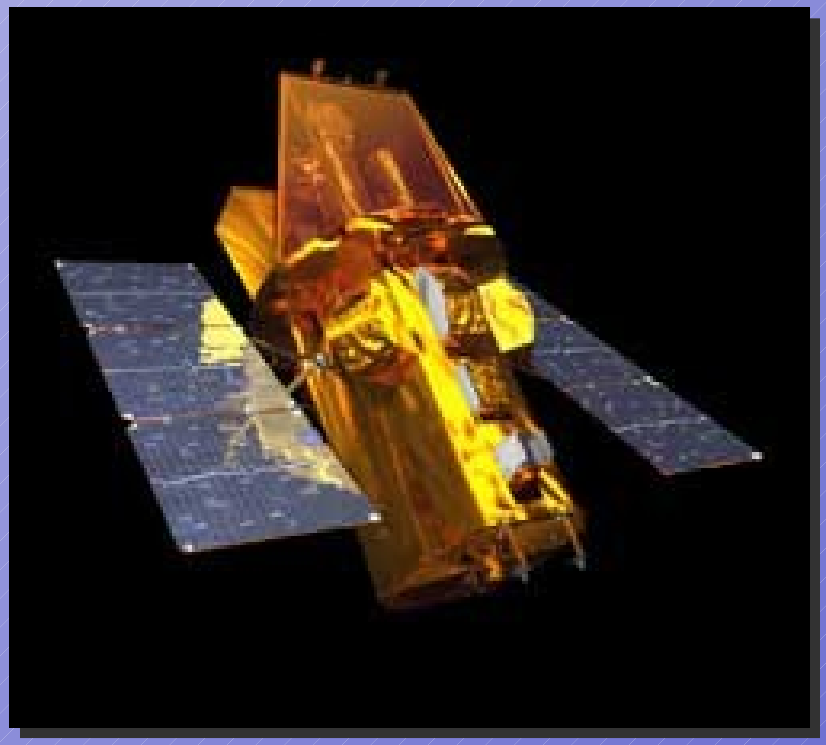


A Swift Survey

Collaborators: Bob Rutledge (McGill), Andrew Shevchuk (PSU ‘09), Ryan Letcavage (PSU ‘09)

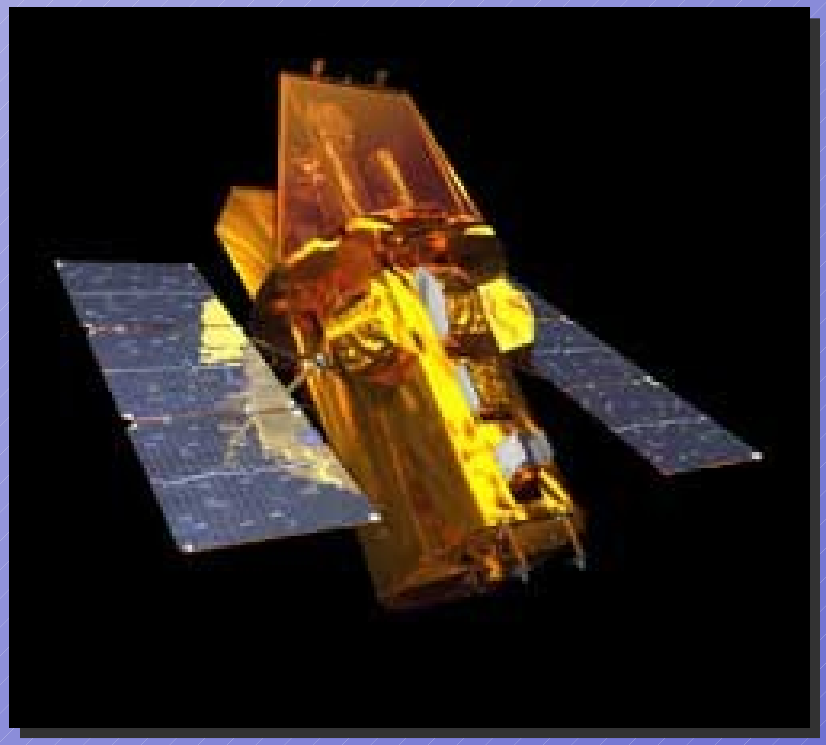
A Swift INS Survey

- *Swift* is an excellent platform for many-target surveys (Fox 04)
- Rapid slewing give high duty cycle for short observations (c.f. Chandra, XMM)
- Multiple targets per orbit
- X-ray telescope
  - Better PSF than ROSAT PSPC
  - Similar sensitivity
  - Detect BSC sources in < 1 ksec
- UV/Optical telescope provides simultaneous UV coverage



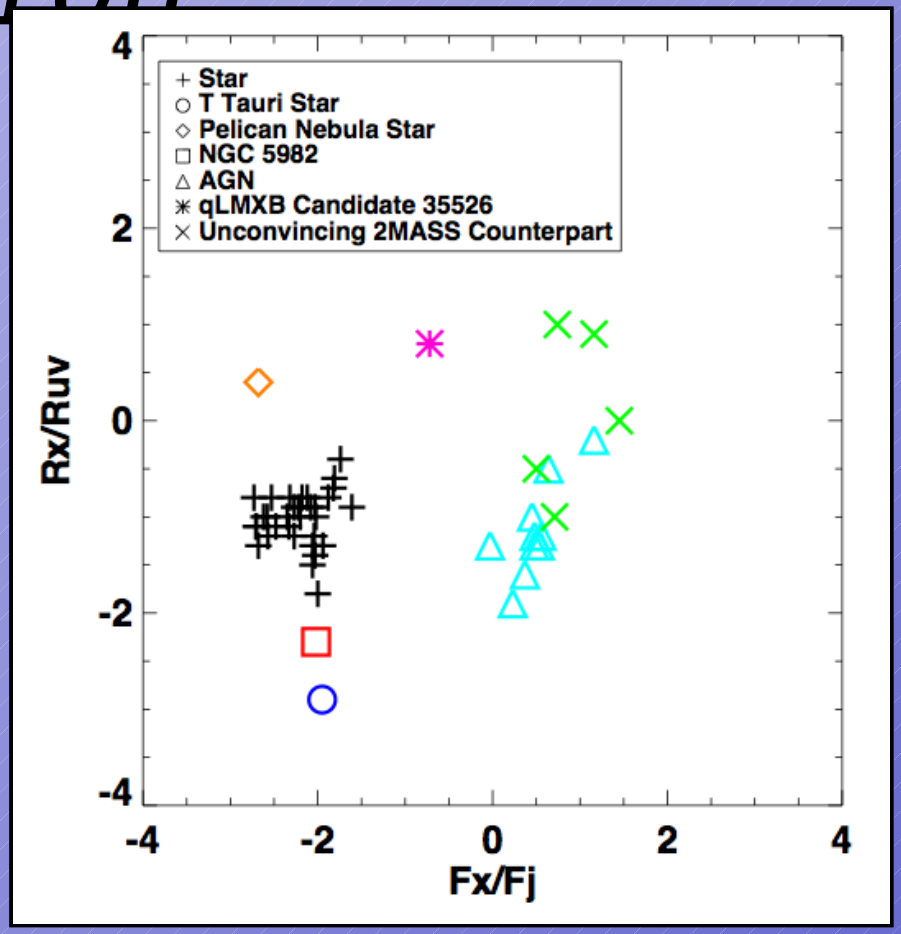
A Swift INS Survey

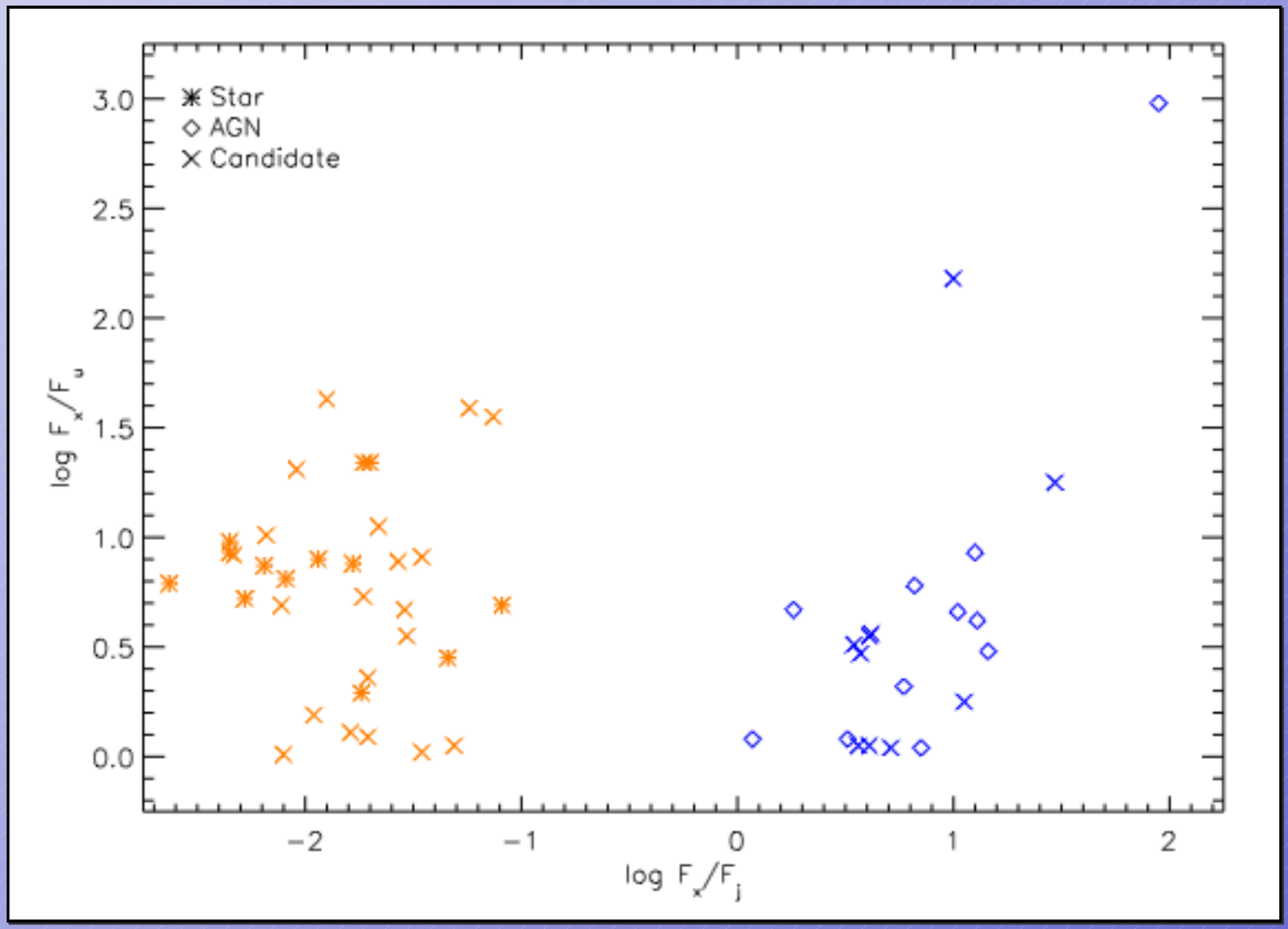
- 254 targets selected by XID against USNO and 2MASS
- Screened against previous X-ray follow-up
- Submitted in three “fill-in target” rounds for 1-ks exposure each
- 232 observed to-date, approx. two per week average



Swift Source Identification

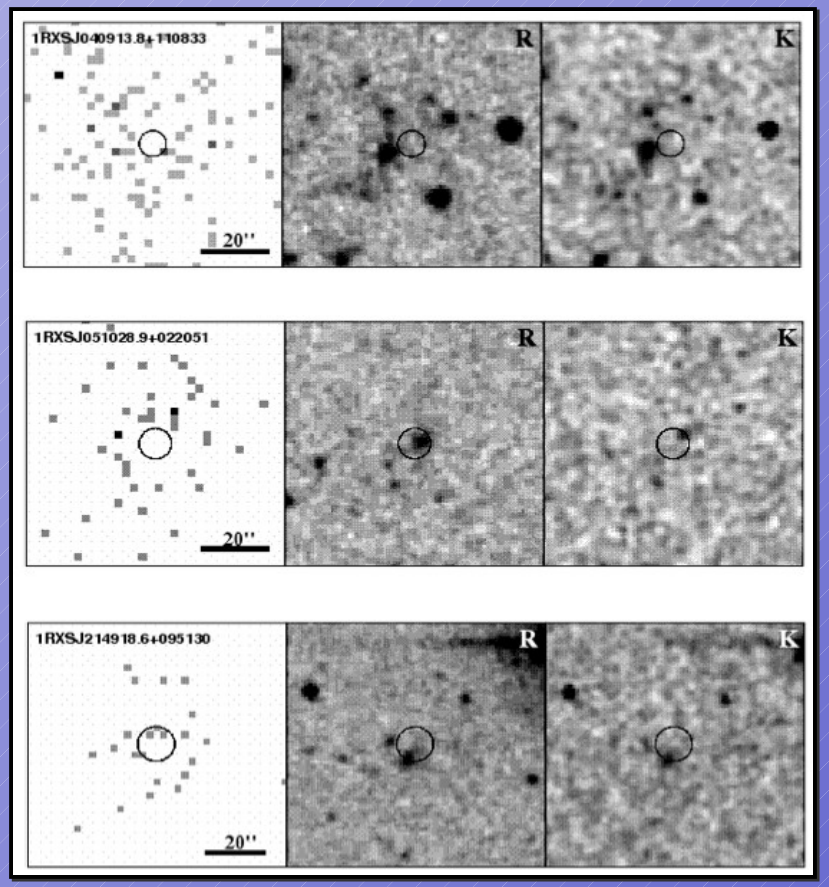
- Sources often receive >1 ks exposure
- XRT data useful as predicted
  - Recover >90% of BSC objects
  - 5” radius at 90%-confidence after UVOT correction (typical)
  - Occasional resolved sources
  - Spectral fitting for ~50% (>25 cts)
- UVOT data valuable
  - Most BSC counterparts obvious
  - Distinguish stars from AGN by color (incl. 2MASS)
  - Resolve AGN host
  - Distinguish star vs. AGN by




Star
AGN
Candidate
3.0
2.5
2.0
1.5
1.0
0.5
0.0
log F_x/F_u
−2
−1
0
1
2
log F_x/F_j

XRT Extended Sources

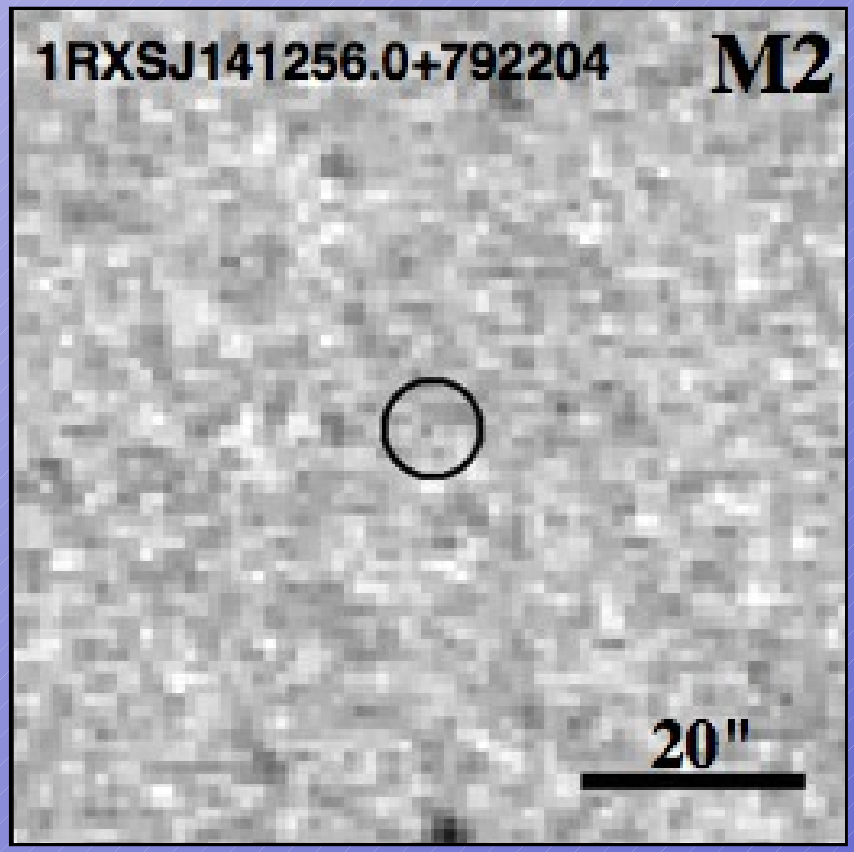
- The BSC has been extensively mined for clusters & SNRs, yet –
- Three new associations between Abell clusters and BSC sources
- Seven entirely new clusters



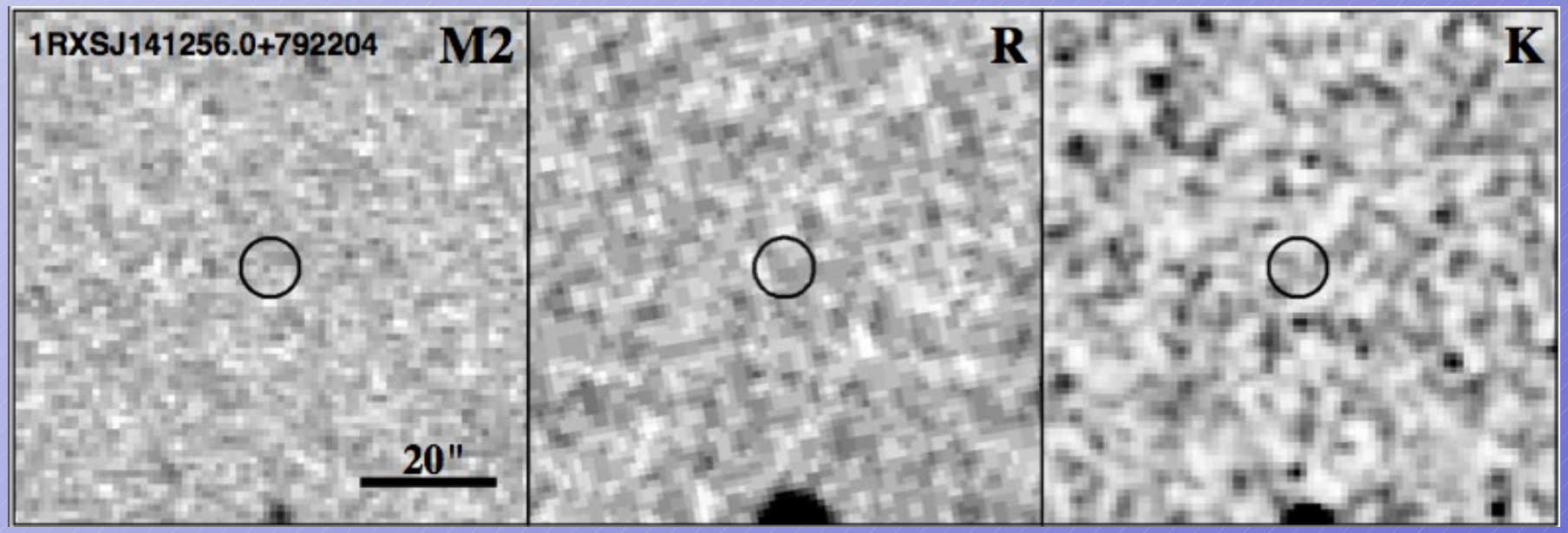

The Outlaw Calvera

Swift Observations

- Observed with *Swift* on 25 Aug 2006
- Bright X-ray source
- No UVOT source
- Also nothing in archival surveys (DSS, 2MASS)

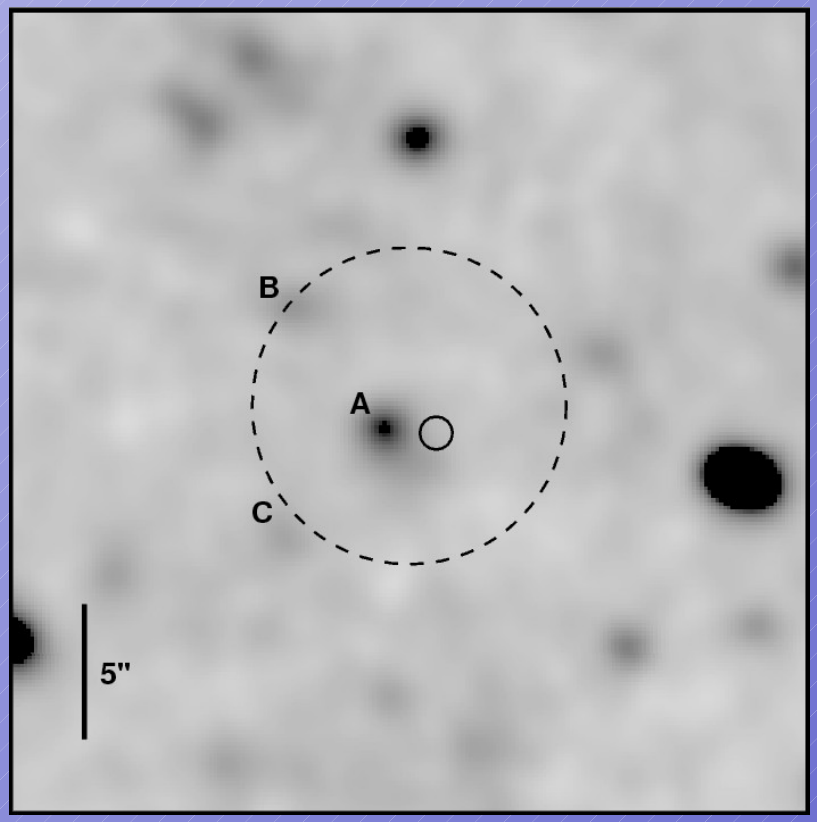


Swift Observations



Confirmation

- Gemini *g*-band imaging of Swift localization (dashed circle)
  - Three possible counterparts
- *Chandra* HRC pointing (solid circle)
- Confirms absence of optical counterpart to *g* > 26.3 mag



Rutledge, Fox & Shevchuk 2008

Properties

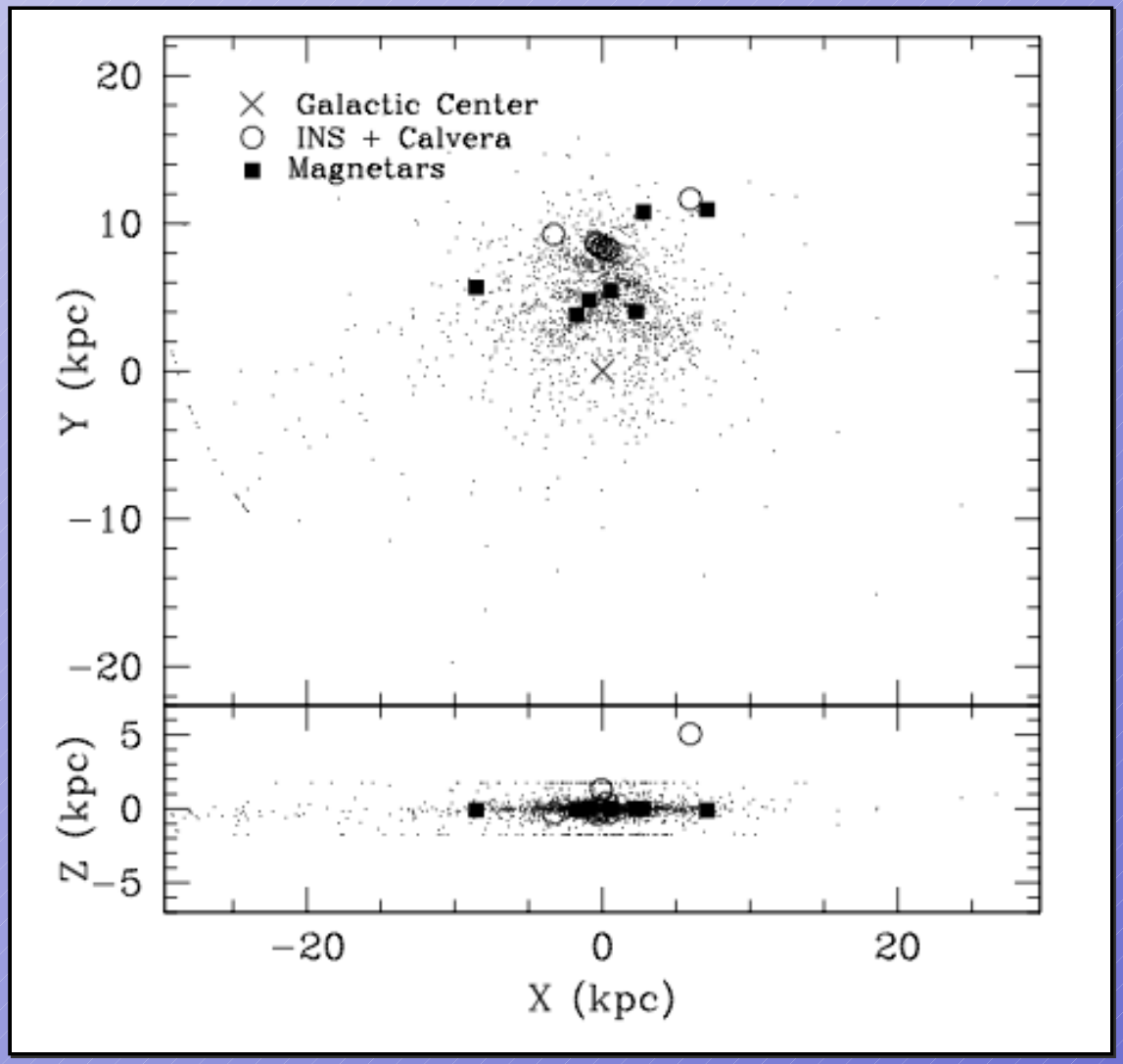
- *kT* = 215 eV
  - Hottest temp for any INS
- Flux normalization:
  7.2 R_{km} / D_{10kpc}
- High Galactic latitude, b=+37 deg
- INSs are <1 Myr old
- "A conundrum…"

Table 1. Characteristics of Calvera

Characteristic	Value
Right Ascension (J2000)	$14^h12^m55^s.885$
Declination (J2000)	$+79°22'04''.10$
Uncertainty radius (90%)	$0.57''$
UVOT Limit	$f_{UVM2} < 1.3 \times 10^{-17}$ erg cm^{-2} s^{-1}
Gemini Limit (3σ)	$g > 26.3$ mag
Blackbody Energy Spectrum	
kT_{eff}	215±25 eV
Normalization	$7.2^{+2.4}_{-1.8}$ (R_{km}/D_{10kpc})
Corrected X-ray Flux	1.2×10^{-12} (erg cm^{-2}s^{-1}; 0.1–2.4 keV)
N_H (fixed)	3×10^{20} cm^{-2}
C-statistic	23.97
Power Law Energy Spectrum	
Photon Slope α	2.8±0.3
Corrected X-ray Flux	2.5×10^{-13} (erg cm^{-2}s^{-1}; 2-10 keV)
N_H (fixed)	3×10^{20} cm^{-2}
C-statistic	30.03

Rutledge, Fox & Shevchuk 2008

Implications



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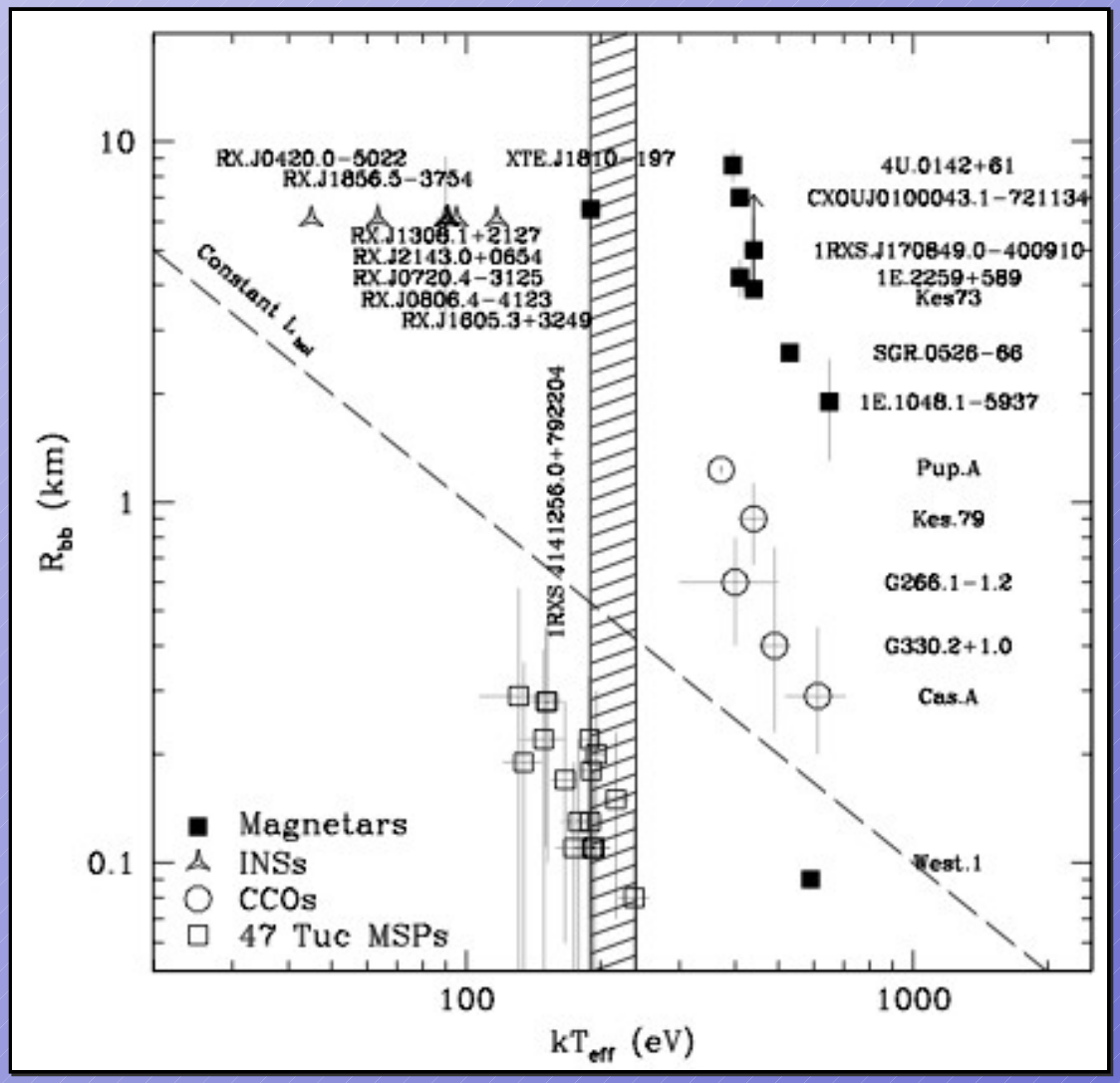
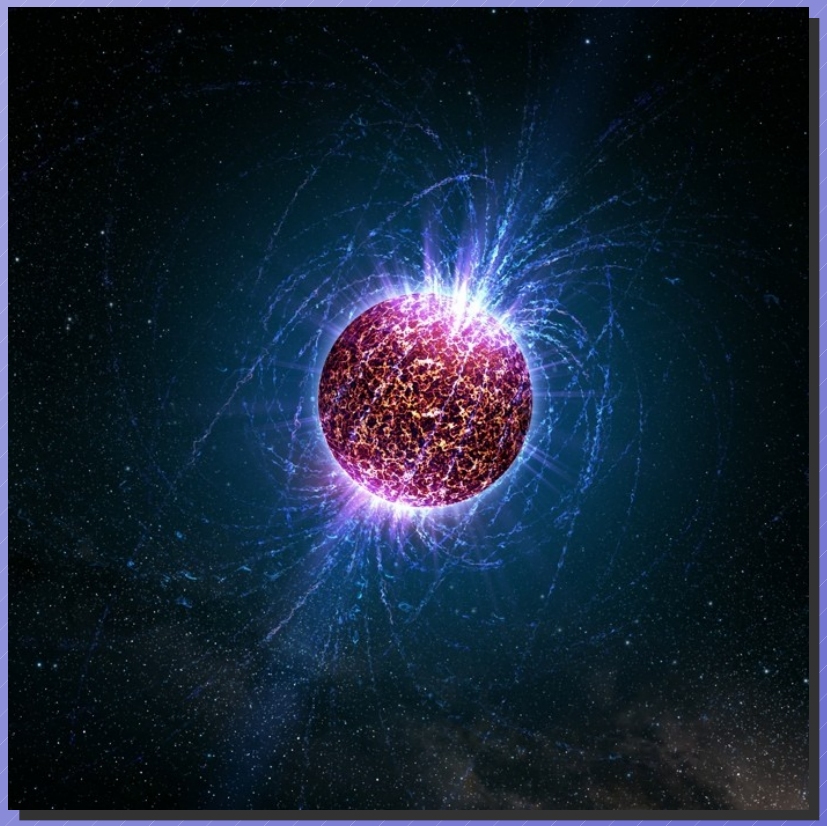


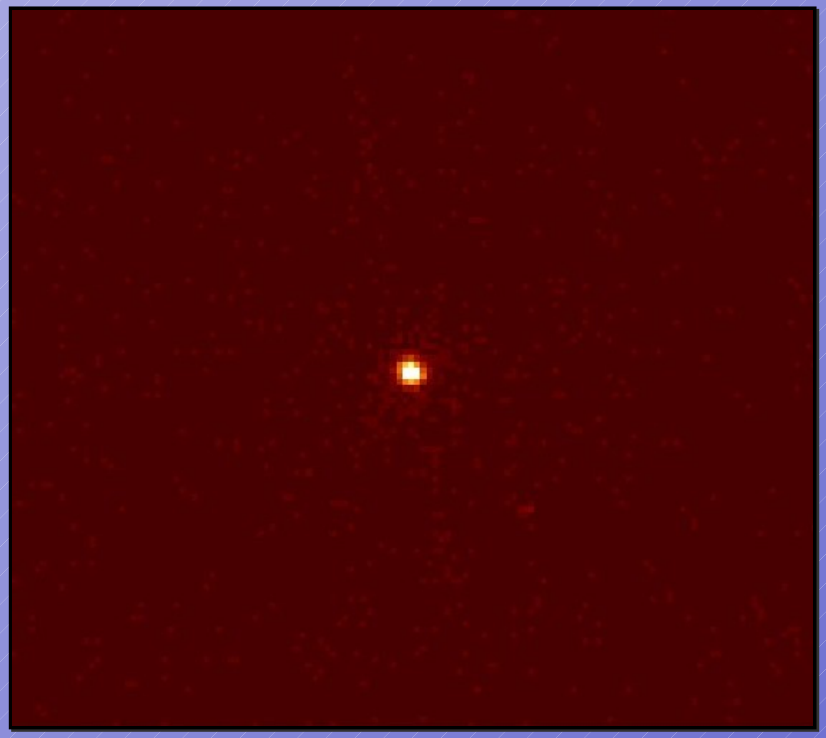
Calvera

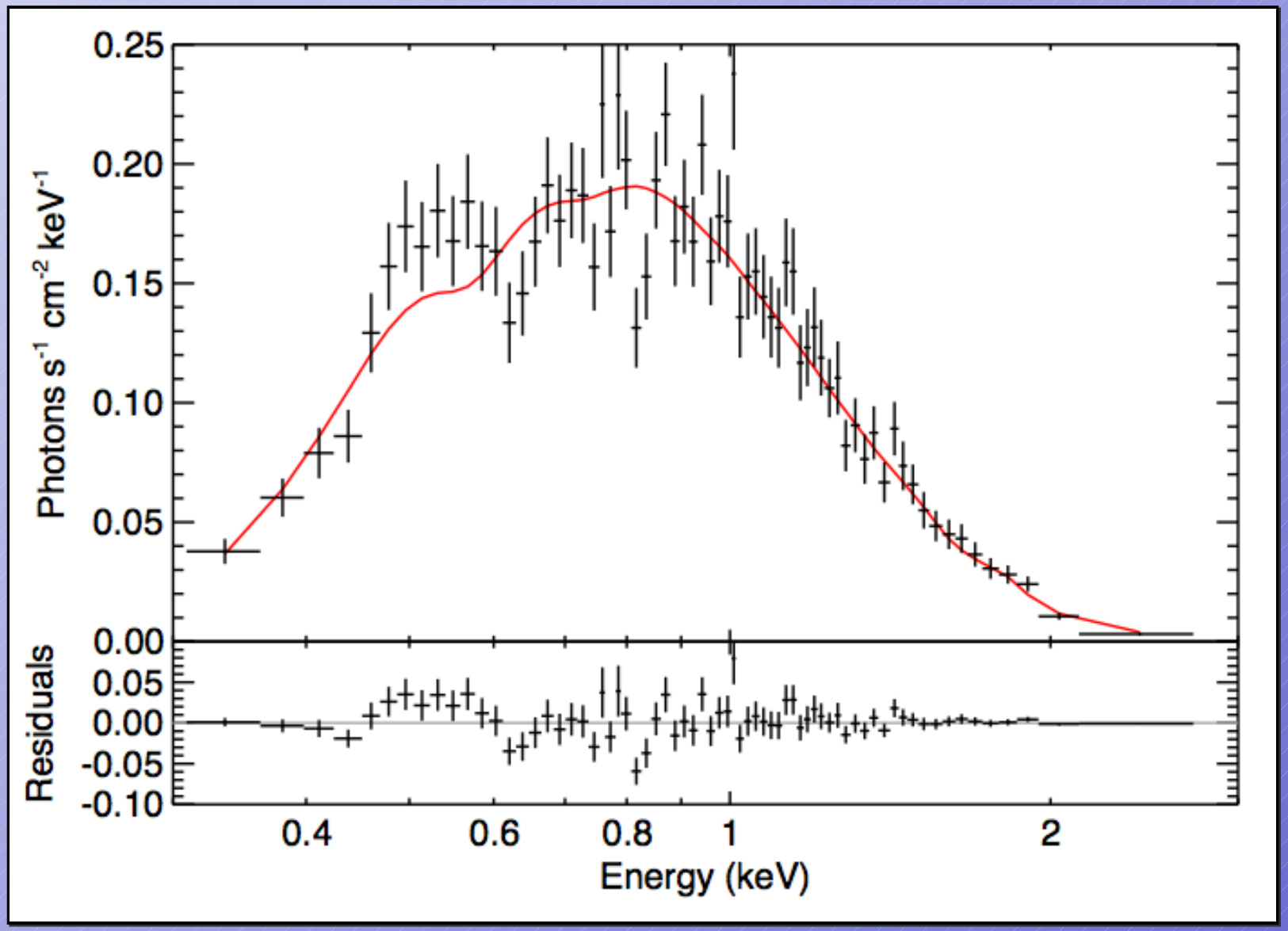
- A new, X-ray bright neutron star
- The hottest INS known
- As an INS: High in the Galactic halo and too hot for its age
- As an X-ray bright MSP: Possibly closer than RXS J1856
- Possibly the closest neutron star to Earth – good for LIGO
- Not detected as radio pulsar (Hessels+07, A&A, 476, 331)
  - S_{400} < 4 mJy
  - S_{1400} < 0.3 mJy



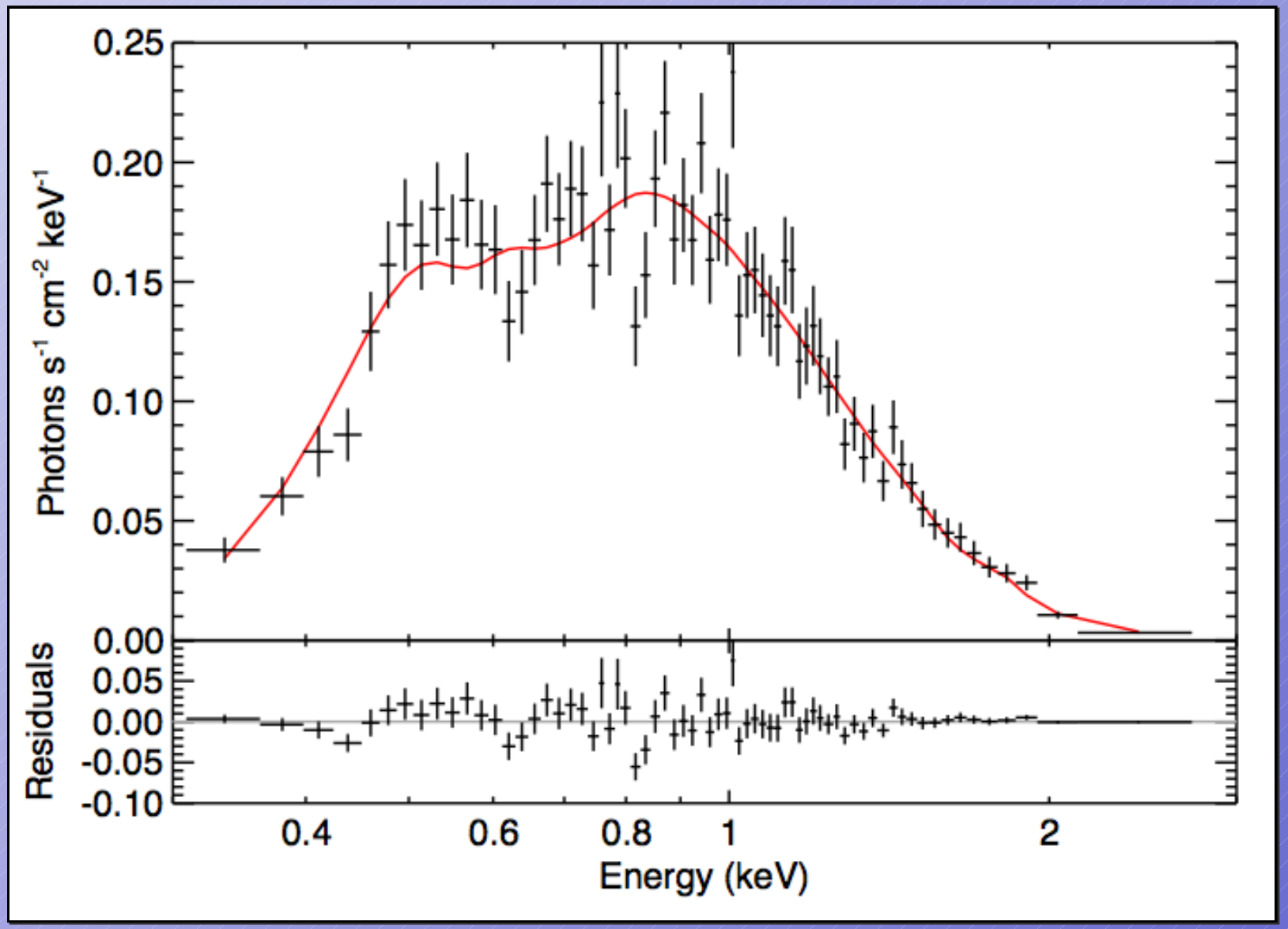
Chandra & Calvera

- Confirmed as hottest INS known (ApJ in press, arxiv: 0907.4352)
- Hydrogen atmosphere preferred to blackbody model
- Atmosphere normalization:
  $R^{\infty} / d = 4.1$ km kpc^{-1}
- No power-law component needed
- X-ray flux detected down to E=0.1 keV
- Possible spectral feature at low energies





Shevchuk, Fox & Rutledge 2009



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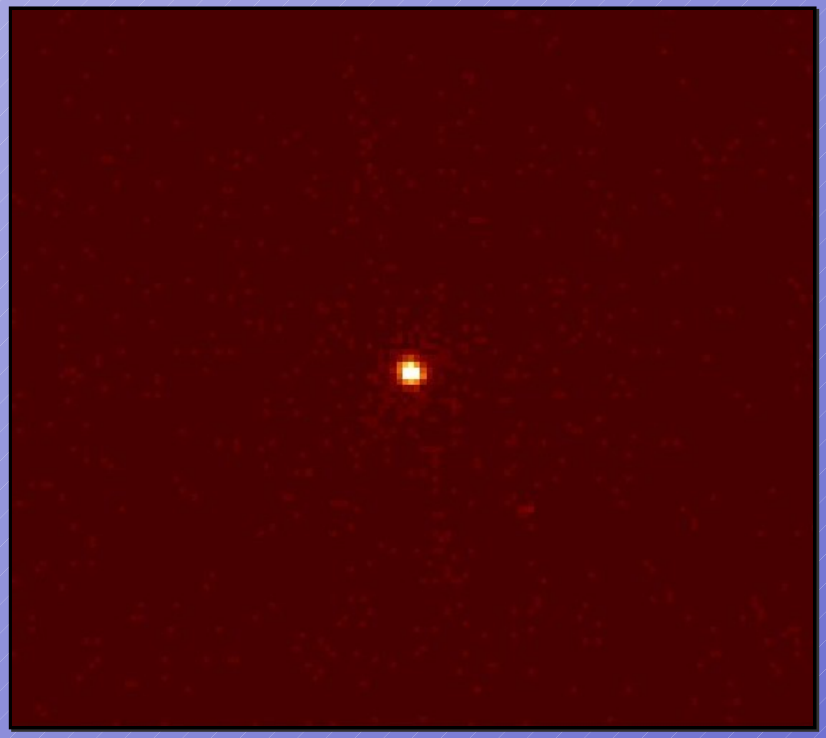
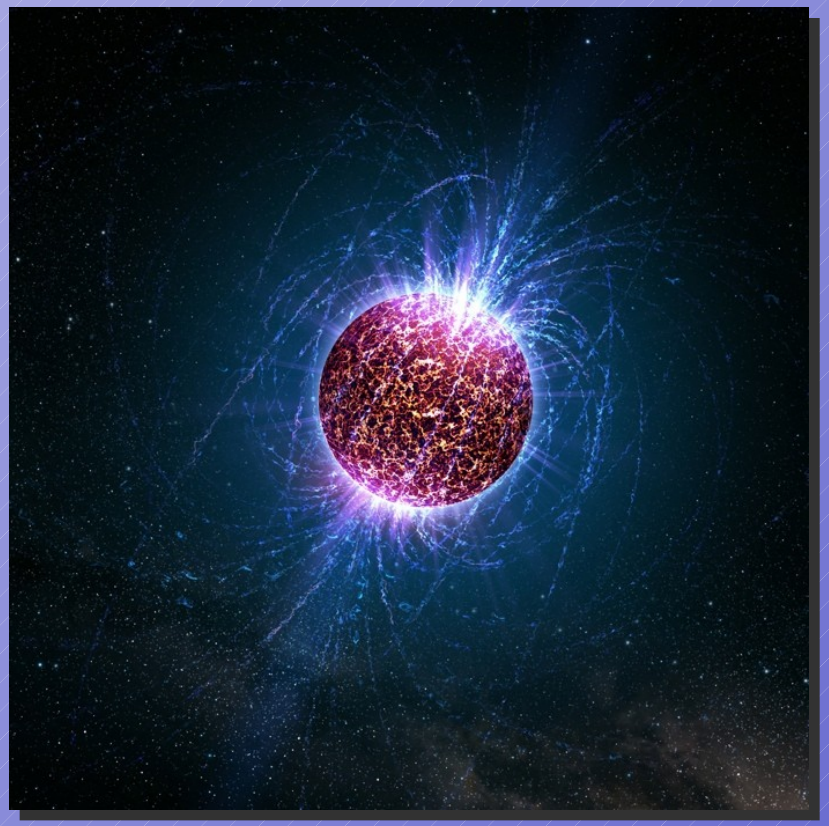
- Possible spectral feature at low energies
- No high-amplitude (rms > 8%) slow (P > 0.88 s)




New Neutron Stars

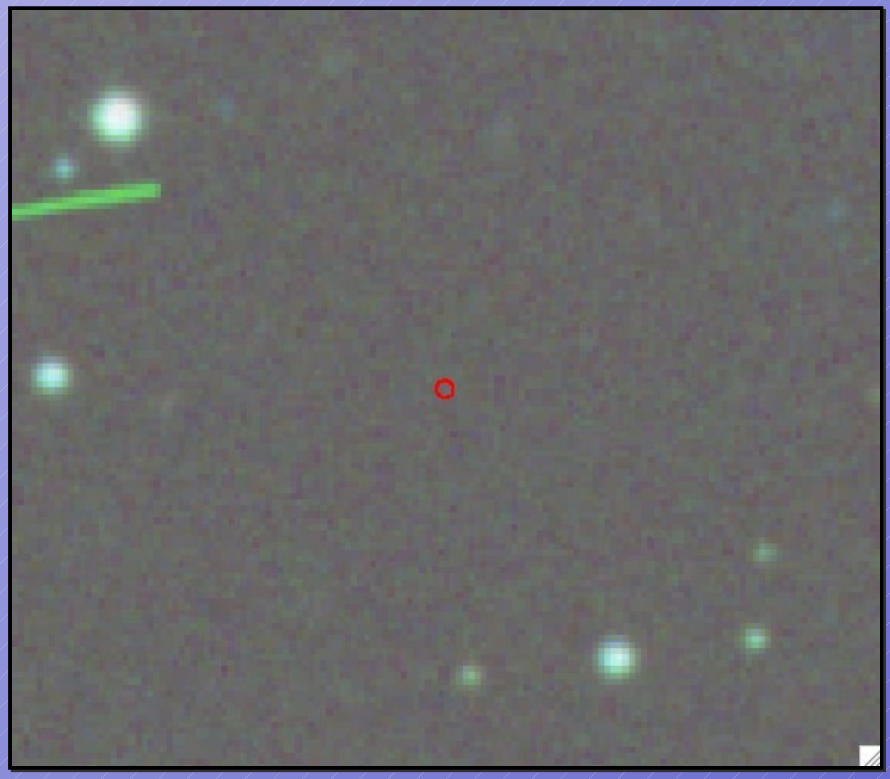
Survey Status

- 36 candidates from *Swift* survey
- One confirmed object (Calvera)
- 3 candidates observed in *XMM* Cycle 7
- 16 candidates observed in *Chandra* Cycle 10 (just finished)
- 13 targets for future X-ray rounds
- Optical follow-up underway from Gemini (N +S)
- 5 targets with subarcsec X-ray positions under evaluation



A Calvera Analogue

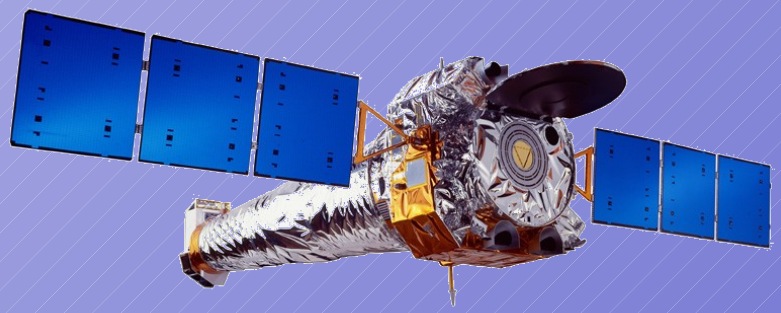
- A new high-confidence ICO from our survey
- High Galactic latitude
- Hottest yet: BB $kT_{\rm eff}$ = 330 eV
- Distance for full-surface emission: 20 kpc
- Gemini data in-hand to confirm



DSS B/R/I

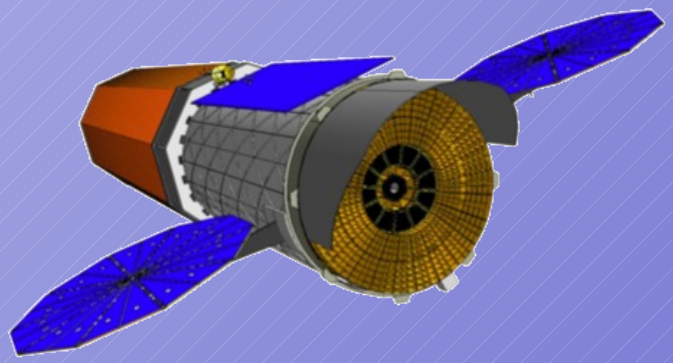
Neutron Stars Now

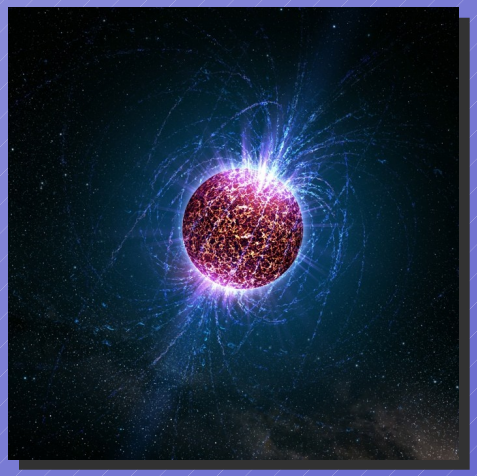
- Original “Magnificent Seven” observed for 3.4 Msec to-date
- 500 ksec per object
- Calvera & friends: A new class of isolated compact object
- Likely partial-surface emitters (X-ray pulsars)
- X-ray spectroscopy: Atmosphere models, discrete features
- X-ray timing: Ages, *B* fields, LIGO
- Parallax / proper motion studies



Neutron Stars in the Future

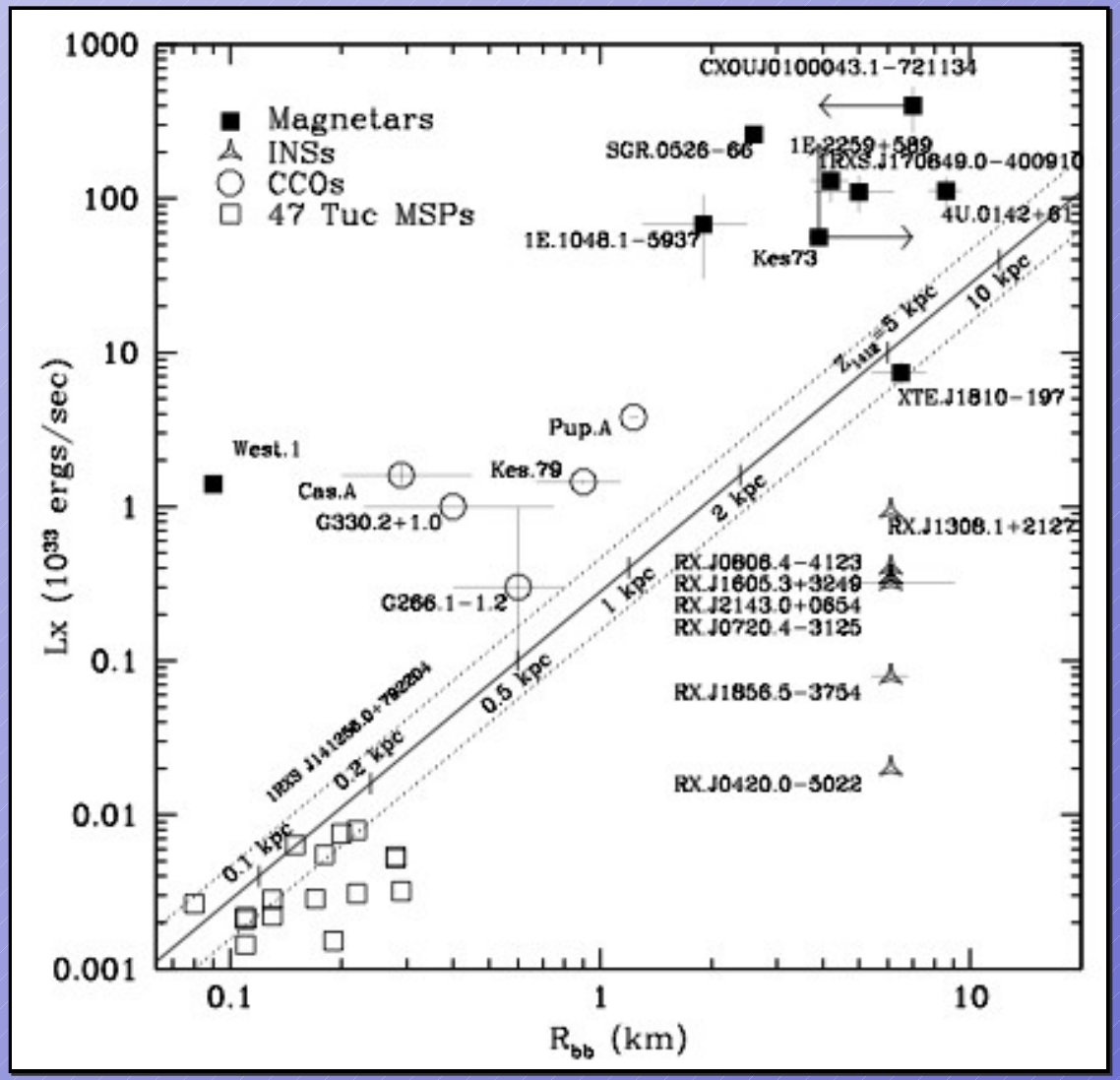
- "Behavior of Matter Under Extreme Conditions" white paper for Astro2010 (Paerels +09, arxiv:0904.0435)
- Constrain nuclear equation of state via X-ray observations
- X-ray bright neutron stars as one approach among several
  - Measured parallaxes resolve R/D
  - Atmospheric effects break M/R
- Gravitational-Wave Connection
  - Fast rotators & Advanced LIGO sensitivity
- Rich harvest of INS and






The End

Implications



Implications

Table 2. Galacto-centric Positions of INSs and Calvera in an INS Interpretation

Source	$kT_{\rm eff}$ (eV)	F_X	(l,b) (deg,deg)	X (kpc)	Y (kpc)	Z (kpc)	d (kpc)	R_c (kpc)	Refs.
1RXS J0420.0−5022	45	5	258, -44	-0.36	8.58	-0.35	0.51	8.59	1
RXJ0720.4−3125	90	100	244, -8	-0.45	8.72	-0.07	0.50	8.73	2
RXJ0806.4−4123	95	2.8	257, -5	-3.29	9.26	-0.30	3.39	9.83	3
1RXS J130848.6+212708	117	45	339, 83	-0.06	8.35	1.29	1.30	8.45	4
Calvera	215	12	118, 37	5.9	11.66	5.08	8.43	14.04	present
1RXS J1605.3+3249	91	88	53, 48	0.30	8.27	0.42	0.56	8.29	5
1RXS J185635.1−375433	63.5	210	359, -17	0.00	8.34	-0.05	0.167	8.34	6
1RXS J214303.7+065419	91	87	63, -33	0.42	8.29	-0.31	0.56	8.30	7

Note. — Galactic positions of the seven INSs, plus Calvera, under the assumption all have the same $R_{\rm bb}$ as 1RXS J185635.1−375433 at a distance of 167 pc (see text). Reading across the columns, we give the source name, the measured effective temperature, the X-ray flux in units of 10^{-13} erg cm^{-2} s^{-1} $(0.1-2.4\,{\rm keV})$; the galactic longitude and latitude (l,b); the resulting galactic three dimensional coordinates X, Y, and Z, where (0,0,0) is Galactic Center, and (0,8.5,0) is the Sun's location (Taylor & Cordes 1993); the source's distance from the Sun d; and galacto-centric distance R_c, with the relevant references. These positions are plotted in Fig. 4.

References. — 1, Haberl et al. (2004); 2, Haberl et al. (2006); 3, Haberl et al. (2004); 4, Schwope et al. (1999); 5, Motch et al. (1999); 6, Burwitz et al. (2003); Kaplan et al. (2007); 7, Zampieri et al. (2001)