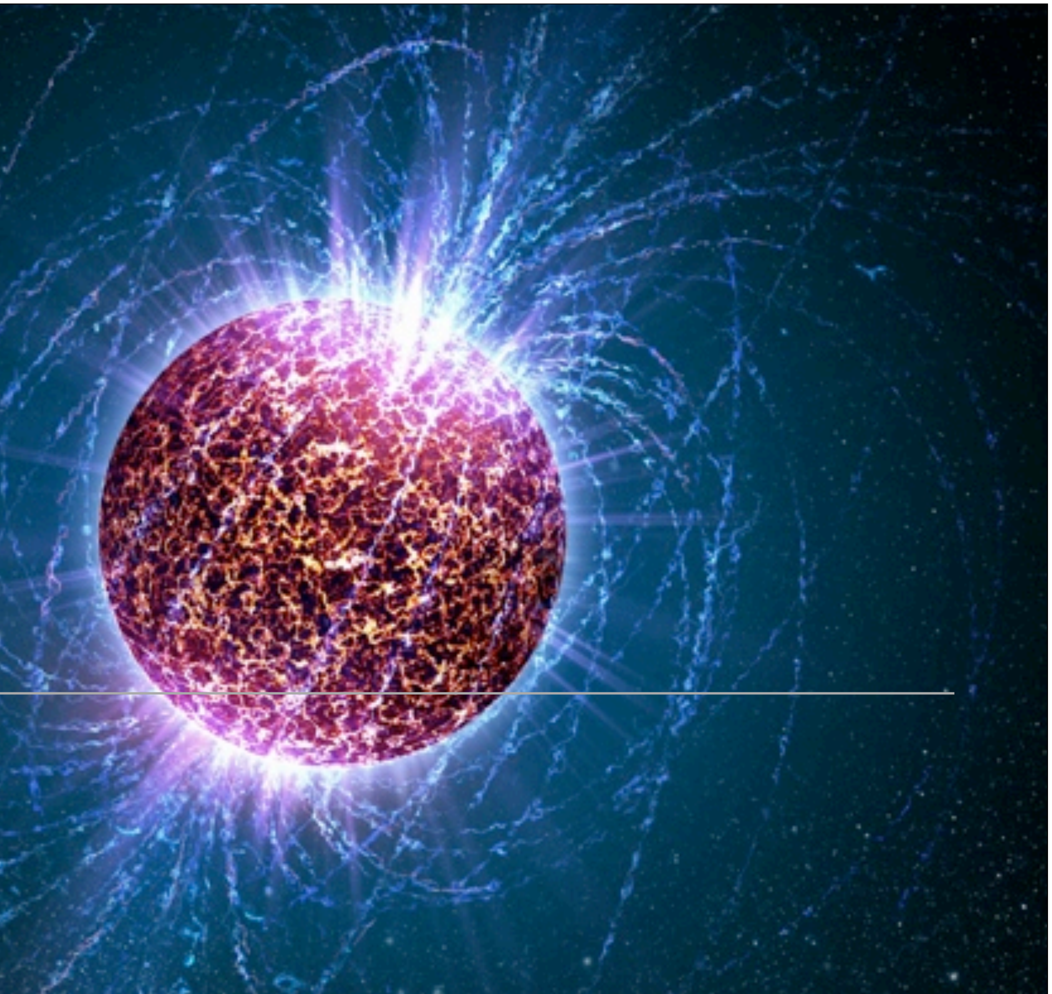
Isolated Neutron Stars: Calvera and Beyond



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X-ray Observations of Isolated Compact Objects

- Isolated Compact Objects are presumably remnants of stellar evolution.

- Isolated objects are unaffected by the evolution of a binary companion (such as in LMXBs), and they can provide a “pristine” look at the properties of “neutron stars” -- generically, the compact objects which are the result of supernovae at the end of a massive star’s H-burning lifetime.

What is an “Isolated Neutron Star”, and what does it have to do with Gravity Waves?

- Stellar Evolution gives ~ 10^9 neutron stars formed in supernovae in our galaxy over its history. Perhaps (?) 10^9 LIGO targets? Where are they all?

- Isolated Neutron Stars (INSs) are an observationally defined class of compact object:
  - Discovered in the X-ray band (kT~50-600 eV).
  - Not a radio pulsar
  - No stellar companion (evidence: no, or little optical emission)

- Summary: INSs result from detection of compact objects through thermal emission from their surface.

INSs: Promising Gravitational Wave Sources?

- Con: unlike LMXBs and radio pulsars, the spin periods are (in general) not measured initially (or at all). Thus detecting GWs from INSs is only better from a completely blind all-sky search, by having a direction.

- Pro: We don't have strong observational constraints on the birth magnetic field distibution of neutron stars. INSs are where the golden "gravitars" would be discovered .

- Pro: Expected to be many of them (the entire NS population) and so they can be very nearby compared with LMXBs and other rare compact objects (aids detection of weak sources).

- Pro: Emission is of thermal emission - unbeamed. Detectable in all directions.

Some quick Neutron Star Accounting

- Number of Neutron stars produced in SNe in our galaxy: 10^9
- Number observationally discovered as radio pulsars: ~2000
- Number observationally discovered as X-ray binaries: ~500
- Number observationally discovered as INSs: ~10
- Number remaining to be observationally discovered: 10^9-2000-500-10 =

10^9

Why search for compact objects as INSs?

- “They cannot hide”. All compact objects accrete material from the interstellar medium (“Bondi-Hoyle Accretion”). This provides a “rock bottom” luminosity, with an effective temperature in the X-ray band:

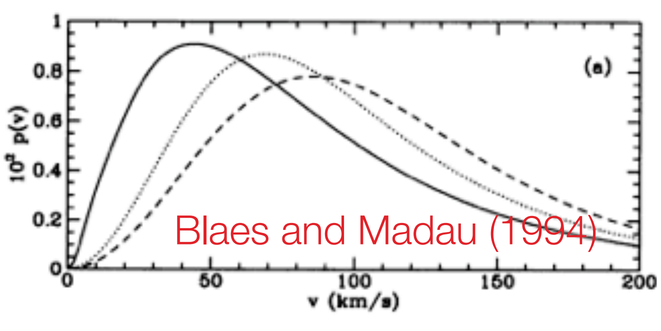
$$L_X = \dot{M} \frac{G\, M_{NS}}{R_{NS}}$$

  - Classical Bondi-Hoyle Accretion Rate:

$$\dot{M} \approx \frac{n}{v^3}$$

Set by the the amount of mass enclosed in a radius

set by the free-fall time (amount of time matter falls freely onto the NS) equal to the crossing time.



Prediction: Should detect

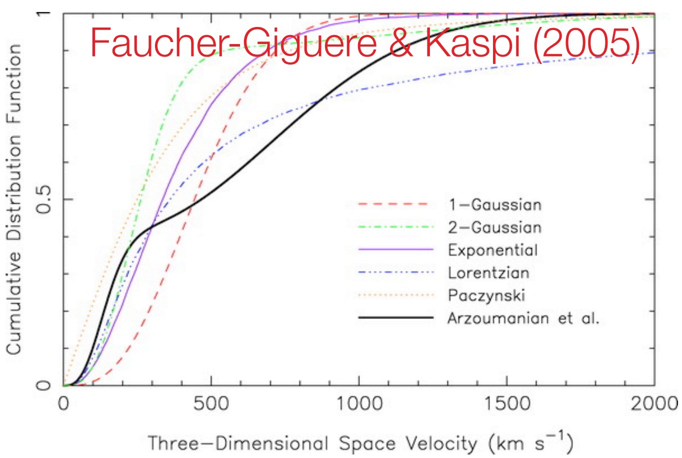
700-7000N_9

INSs in ROSAT All Sky-Survey

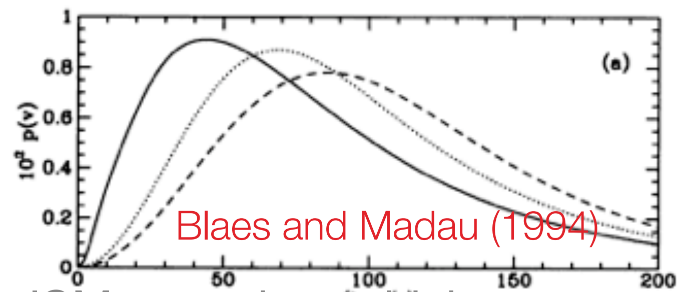
So where are all these INSs? Only 8 Detected to date

- Modern upper limit: <46 INSs in the RASS/BSC (Rutledge et al 2003, Turner et al 2009).

- Two partial explanations for this discrepancy:

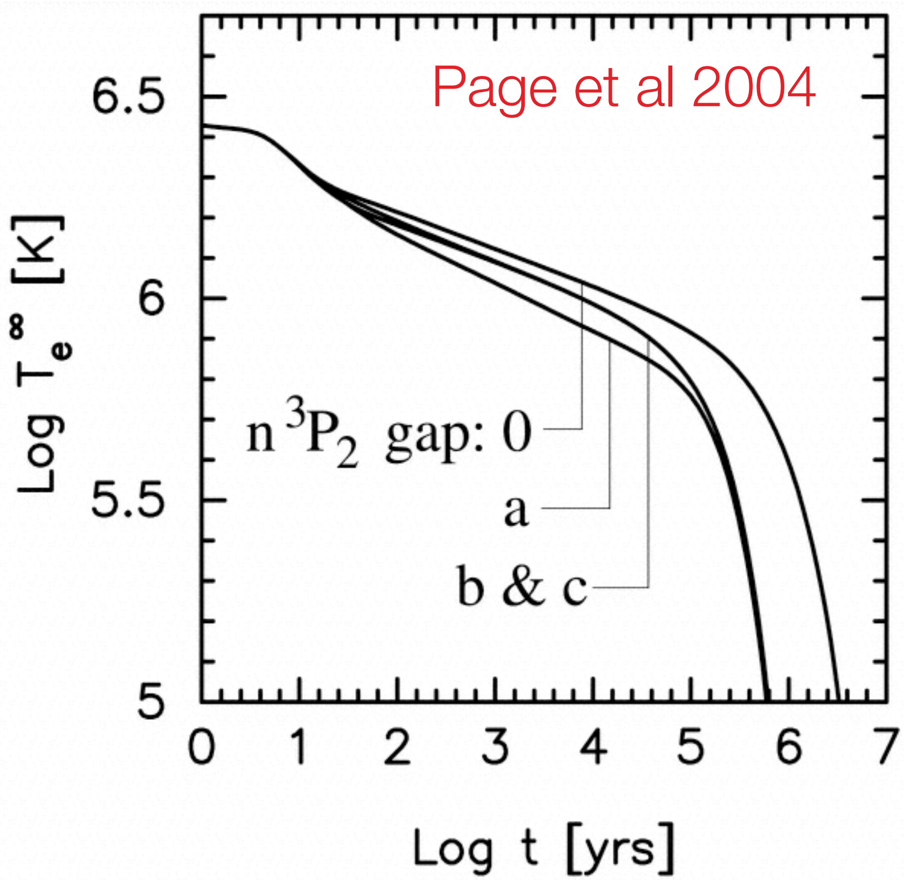


- (1) Better radio pulsar velocity measurements find typical v~380 km/s. A factor of 9 greater velocity, is a factor of 700 smaller X-ray luminosity!



- (2) MHD simulations show plasma instabilities in ISM accretion, which increases the accretion timescale dramatically from a simple “free-fall” timescale. This further decreases the accretion rate -- by ~x100. (Perna et al 2003).

Population Synthesis implies the observed INSs are not powered by accretion, but instead by natal cooling



Note: 10^6 K = 86 eV

- "Non-Exotic" neutron stars (pure beta-equalibrium core matter)
- Cools after birth in a SNe for ~10^6 yrs, at a temperature of about 10^6 K.
- However, note that it is observationally challenging (and has not been done) to distinguish between accretion power and pure cooling.
- Probably, the best evidence is that one INS -- RXJ 1856 -- has a velocity vector which would place it in a nearby open cluster ~500,000 yrs ago.
- Implication: for every 1 cooling INS, there are 10^4-10^5 powered by accretion from the ISM.

These Neutron Stars are Observed through as many different, sometimes overlapping, observational classes

- Radio pulsars (radio emission mechanism associated with the presence of a magnetic field).

- X-ray binaires (optical stellar companion, and accretion onto the compact object)

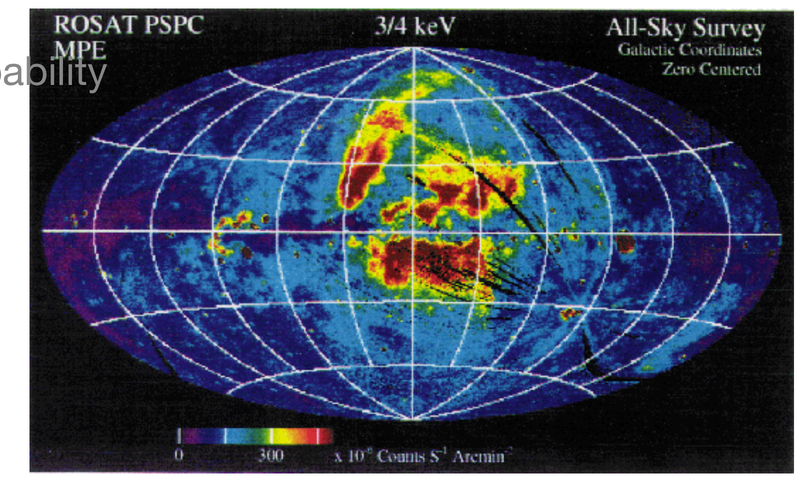
- Magnetars (processes associated with magnetic field decay).

- But what about neutron stars with weak, or no, magnetic field? Which are not in an optical binary?

- The goal of searches for INSs is to discover compact objects which are not observable any other way.

How do discover INSs: Observational Approach

- The ROSAT All-Sky-Survey observed 92% of the sky to a flux limit of 2×10^{-12} erg cm^{-2} s^{-1}
- 18,802 X-ray sources in the “Bright Source Catalog”, (<1 false source in the catalog).
- We use a statistical approach (Rutledge et al 2001; Haakonsen & Rutledge 2009) to calculate the probability of association between the X-ray sources, and nearby optical (USNO-A2), radio (NVSS), and infrared (IRAS and 2MASS) sources. “As Bright or Brighter, as Close or Closer”.
- Using this statistical approach, we calculate a probability that the X-ray source is not associated with any cataloged off-band counterpart



$$P_{\rm no-id}$$

How do discover INSs: Observational Approach

- Perform SWIFT X-ray observation of unidentified ROSAT All-Sky Survey Bright Source Catalog X-ray sources (positional uncertainties -- 13”).

- Use better localization (5” with XRT, and <1” if there is a UVOT counterpart) to identify UV, optical, or infrared counterpart (in UVOT image, or 2MASS catalog, or DSS).

- X-ray sources with high F_X/F_UVOT, and no 2MASS or DSS counterparts.

- To date, we have observed ~200 X-ray sources, identifying mostly low-mass stars, a few AGN, but also 3 new X-ray clusters. (Shevcuk et al, in prog; Letcavage et al, in prog).

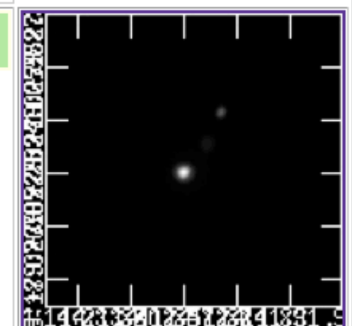
Observations of Calvera

- First detection (1992) in the ROSAT All-Sky Survey as 1RXS J141256.0+792204.
- We observed with SWIFT/XRT in August 2006, obtained a 5” error circle which excluded all nearby counterparts (DSS, 2MASS, NVSS). No UVOT counterpart (UVM2>21m).
- In Dec 2006, we obtained deep Gemini-North imaging (DDT time) in g-band (1 hour integration)

1RXSJ141256.0+792204 A

New Spectral Analysis

OBJ	XRT F S	UVOT	No 2MASS Counterpart	No USNO Counterpart
INS_fom: 119.3	RA: 14:12:56.88	# Srcs (<300"): 11	log F_X/F_J > 0.8	
35561.141256	Dec: +79:22:07.11	M_(UVM2) > 21.08		
00035561001	R_RASS: 4"	T_obs (s): 1880		
Objid: 2567	I (c/ksec): 33.43 +/-4.23	log F_{UVOT}/F_J: -		
Bore Corr: Y (12*s)	T_obs (s): 1893			
d_RA: -0"	Start: 2006-08-25T01:25:21			
d_Dec: -0.3"				



ObsIDs Used
00035561001

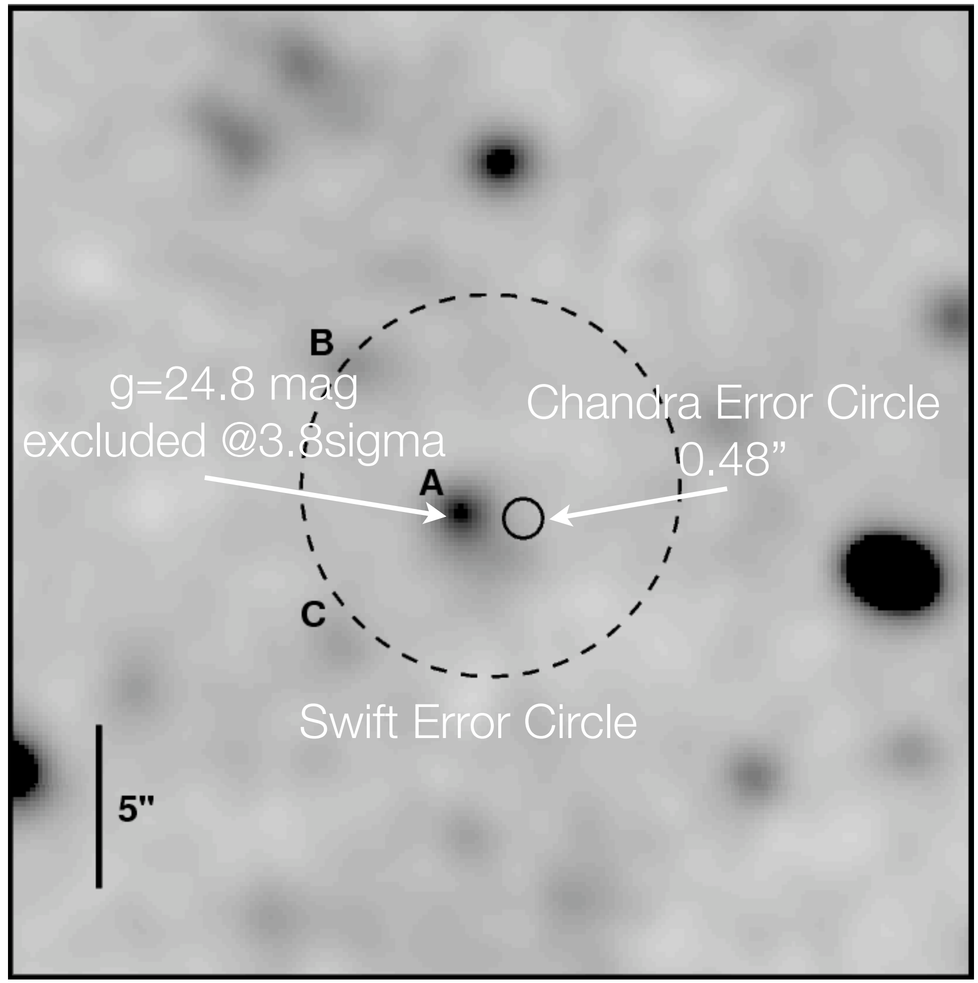
Power-Law	
Alpha:	$2.46^{+0.29}_{-0.28}$
NH (1e22 cm-2):	0.0296
C-stat:	192.33

Blackbody	
kT (eV)	222^{+34}_{-27}
NH (1e22 cm-2)	0.0296
C-stat:	177.81

Fluxes (0.5-10 keV; erg cm-2 s-1)	
Observed:	7.6329e-13
Unabsorbed:	8.4533e-13

Gemini North Multi-Object Spectrograph.

- SWIFT Error circle (90% confidence) contained 1 g=24.8, and two other much fainter (B&C) objects. (Plate limit: g>26.3, 3 sigma).
- In early 2007, Chandra/HRC-S DDT observation (2ksec) localized the X-ray source to an error ellipse which excluded all infra-red objects.
- Chandra positional uncertainty dominated by statistical uncertainty in Calvera's position, using relative astrometry with a 2' off-axis source.
- FX/F_V > 8700 -- excludes all known source classes other than isolated neutron stars (INSs).



$$L_x = 4\pi\, R_{\rm bb}^2\, \sigma T_{\rm eff}^4$$

What Type of Source is Calvera?

- The observational approach (arcsec localization, followed by deep optical imaging, to produce high FX/F_V limit) was chosen to find new INSs, like RX J1856.5-3754.
- No counter examples of high FX/F_V limit objects selected in this way which are not INSs exist in the literature; but clearly it is possible to find other types of compact objects.
- Basis for comparison: assume blackbody spectra (almost certainly not physically true!) and compare bbody spectral parameters.
- Note: to say *anything* about the properties of the source, one must compare either R_bb or L_x with those of a known class. This directly implies a distance to Calvera.
- For INSs -- assume Rbb are all identical to RXJ 1856, and a distance to RXJ 1856 of 170 pc (cf. Kaplan et al 2007).

Summary of Properties of SWIFT J1412+7922

- Uncertainty radius (here) includes 0.14” Gemini-USNOB registration uncertainty.
- Effective temperature is the highest among the INSs (215 eV, vs. 117 eV for J1308).

Parameters confirmed with recent, higher S/N Chandra Observations (Shevchuck et al, in prog)

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	
$kT_{\rm eff}$	215±25 eV
Normalization	$7.2^{+2.4}_{-1.8}$ $(R_{\rm km}/D_{\rm 10kpc})$
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

Galactic Distribution of X-ray “Dim” Isolated Neutron Stars (INS), if Calvera is like them.

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

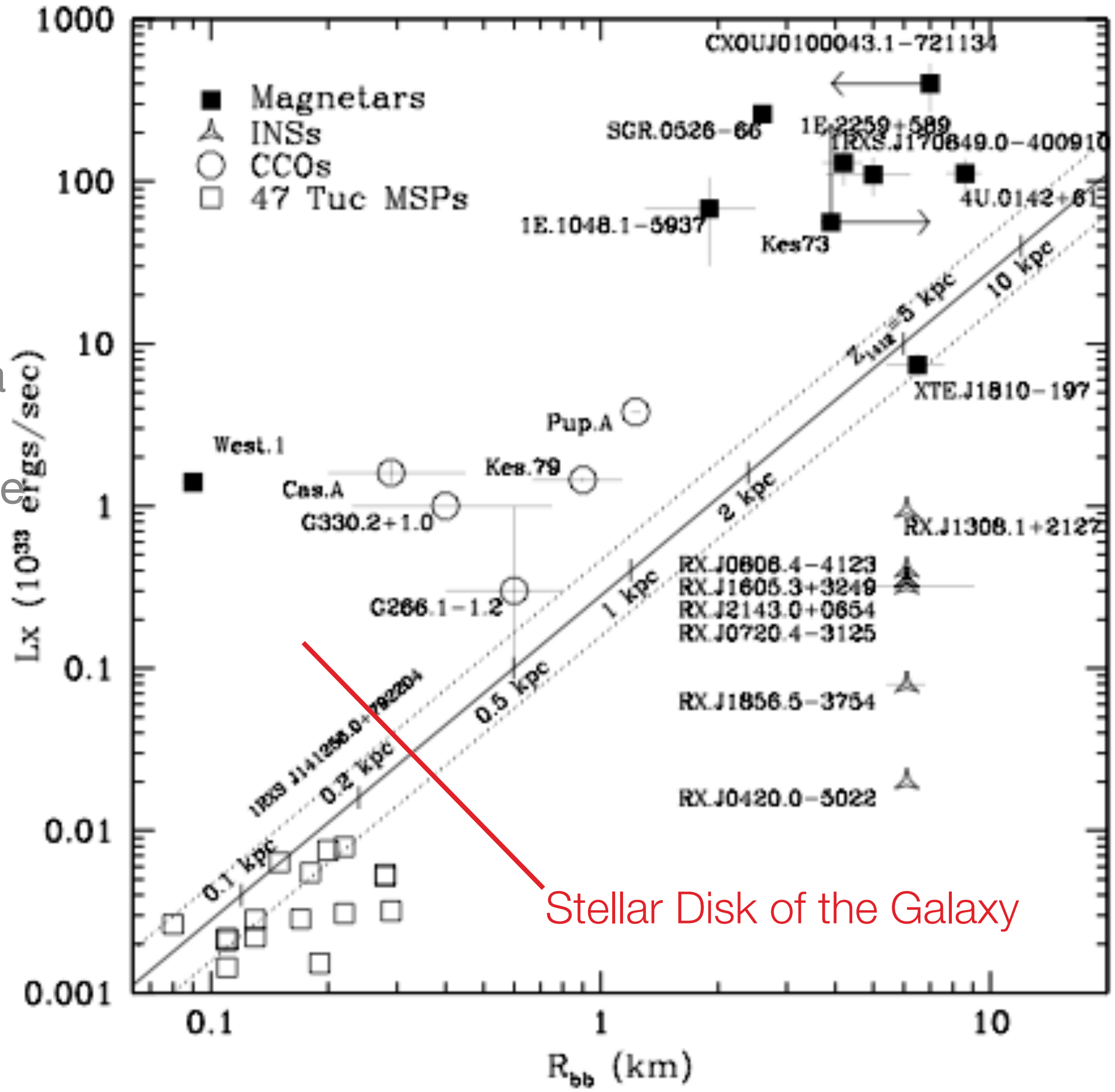
Source	$kT_{\rm eff}$ (eV)	F_X	(l,b) (deg,deg)	X (kpc)	Y (kpc)	Z (kpc)	d (kpc)	R_c (kpc)	Refs.
1RXS J0420.0−5022	45	5	258, -44	-0.36	8.58	-0.35	0.51	8.59	1
RXJ0720.4−3125	90	100	244, -8	-0.45	8.72	-0.07	0.50	8.73	2
RXJ0806.4−4123	95	2.8	257, -5	-3.29	9.26	-0.30	3.39	9.83	3
1RXS J130848.6+212708	117	45	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 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)

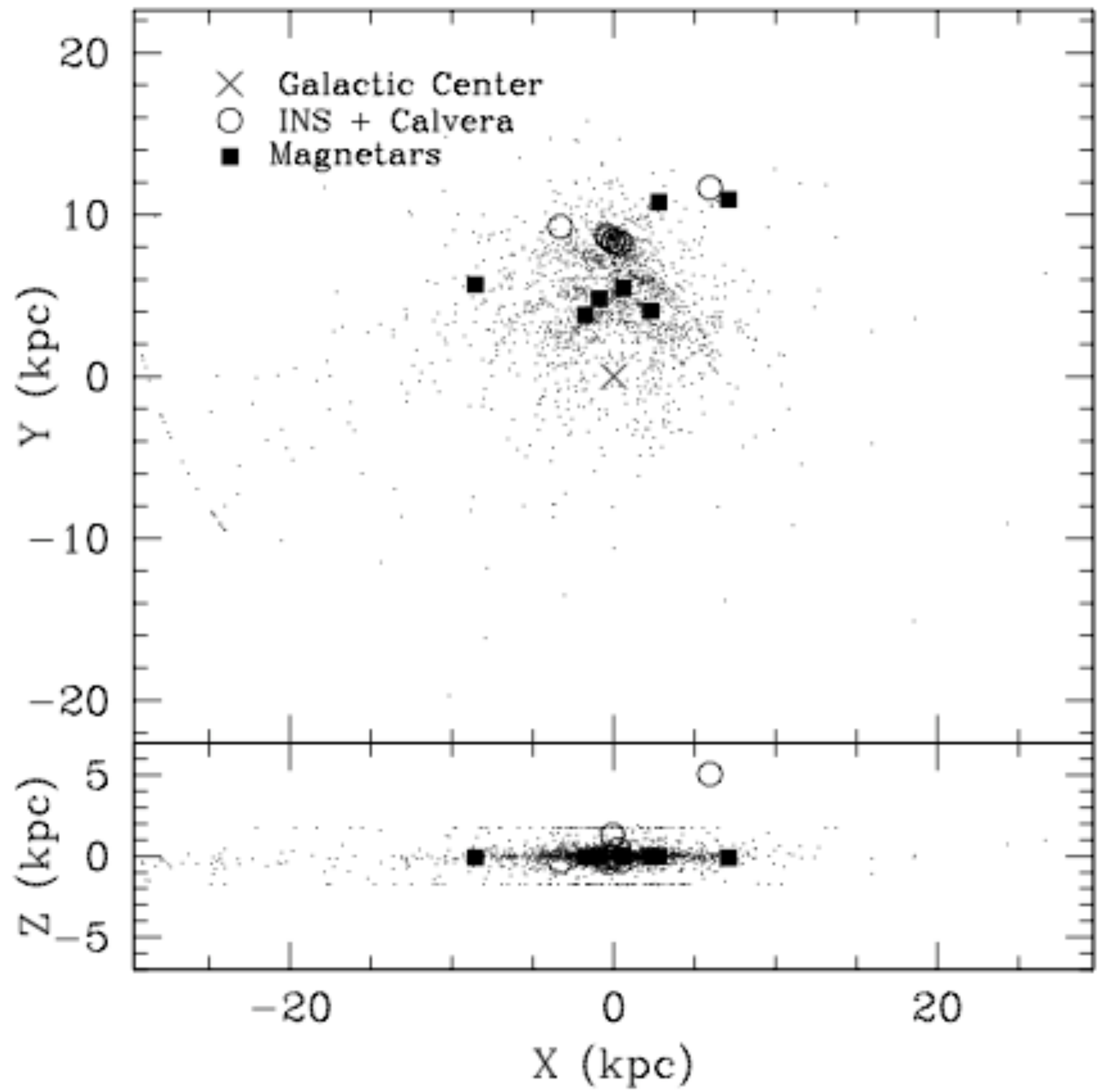
R_bb vs. Lx

- R_bb is a function of distance (which is unknown).
- If R_bb is comparable to RX J1856, this requires a large distance -- d=8.4 kpc, which implies a large z=5.1 kpc.
- If L_X is comparable to magnetars (1e35 ergs/sec), d=66 kpc!



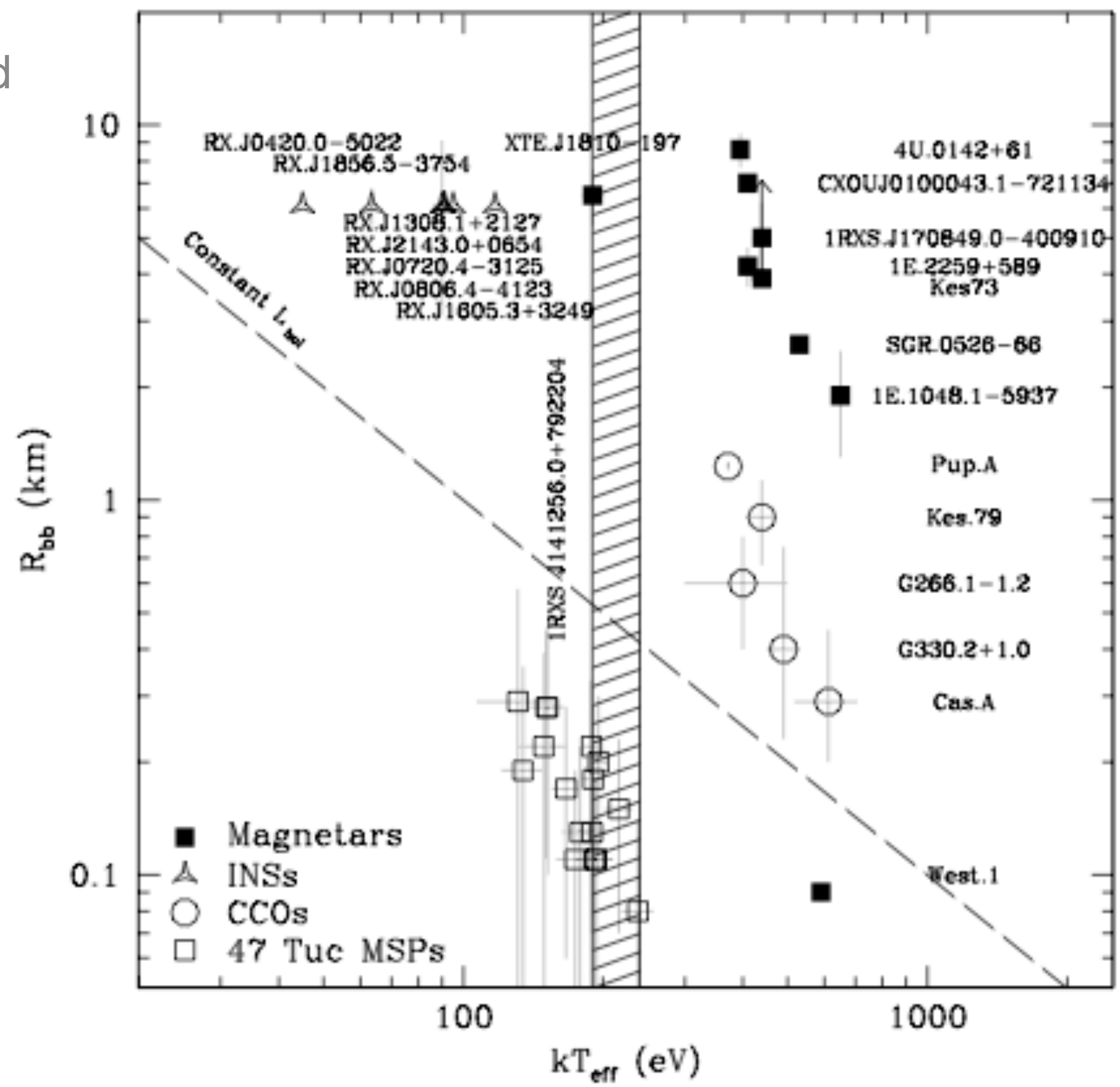
Galactic Distribution of X-ray “Dim” Isolated Neutron Stars, if Calvera is like them.

- Z=5.1 kpc! (d=8.4 kpc)
- This requires a spatial velocity of >5100 km s-1.
- Or, it requires a cooling time >13 Myr (kT remains 215 eV -- still higher than any known INS.)

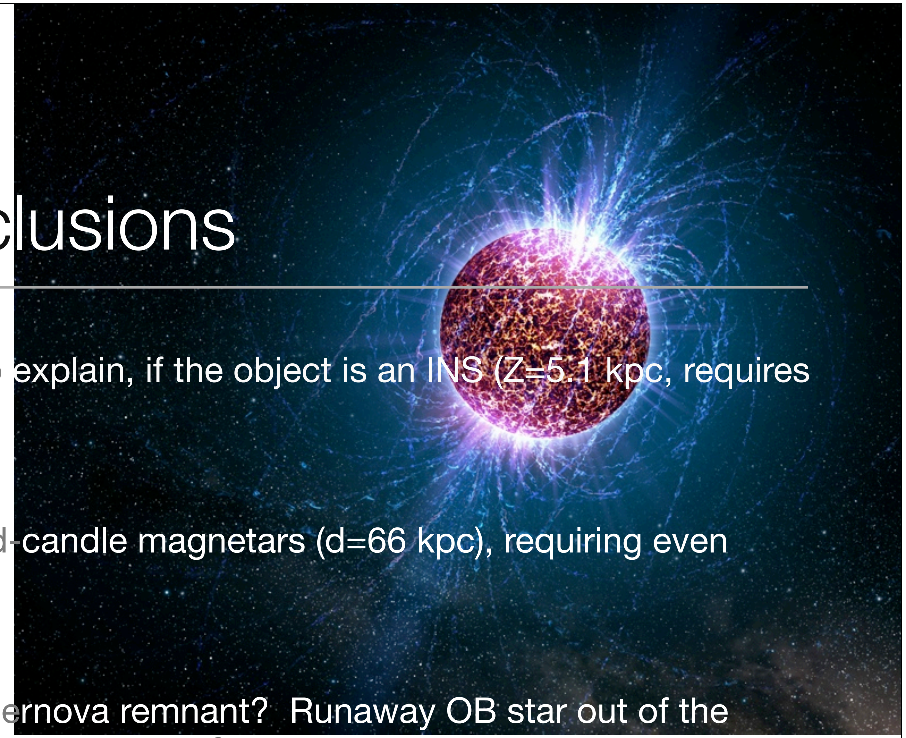


kTeff vs. R_bb

- kTeff is lower than CCOs and magnetars.
- kTeff is greater than INSs
- But, comparable to MSPs in 47 Tuc.
- Comments on kTeff vs. Rbb for CCOs and Magnetars.



Calvera: Observational Conclusions



- X-ray properties of Calvera are seriously challenging to explain, if the object is an INS (Z=5.1 kpc, requires a very high spatial velocity, or very long cooling time).
- X-ray properties are even more challenging to standard-candle magnetars (d=66 kpc), requiring even higher spatial velocity or longer cooling time.
- Could be a Compact Central Object, but without a supernova remnant? Runaway OB star out of the disk? So what is a CCO? Simply a Compact object of arbitrary size?
- Object is *most* consistent with being a nearby (80-260 pc) radio pulsar. ***However, it is undetected in a 1.4 GHz pulsar search with Westerbork (Hessels et al, 2007, in press),*** implying it is in the lowest 1% of radio pulsar luminosity distribution. Thus, it would have to be an off-beam radio pulsar -- such objects must exist.
- If it is an MSP, it is (tied for) X-ray brightest MSP in the sky, is the closest Northern MSP at <260 pc -- an interesting X-ray target, potentially useful for LIGO.
- If the object is *not* a radio pulsar, then it is highly uncertain what type of compact object this is.

A few, but not many, more where that came from!

- We included in our analysis 150 “control sources”, placed randomly on the sky, which mimic INSs.
- Of these, ~50 satisfied the P_noid selection criterion. This means, for every 1 INS in our selected sample, there are 3 INS in the RASS/BSC.
- After determining how many INSs there are in our selected sample (~10), this permits us to place an upper-limit on the number of INSs in the RASS/BSC, of <46 (90% confidence).
- At present, we are following up on ~10 promising INS candidates which resulted from the SWIFT work.
- Based on present limits, INSs will be discovered in the upcoming eROSITA (launch 2011) all-sky survey, which, based on the present 8-50 INSs limits in the RASS/BSC, will discover 240-1500 INSs. Results beginning 2013.