eROSITA: Factory of Gravitational Wave Source Candidates

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X-ray Observations of Isolated Neutron Stars (INSs)

- INSs are important for neutron star population studies. They are remnants of stellar evolution, and so their properties constrain natal temperatures and velocities, cooling history, as well as the NS birth rate in our galaxy.

- Searches for INSs with eROSITA will discover a population of interest to gravitational wave observatories.

Some quick Neutron Star Accounting

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- 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 =

$$\boxed{10^9}$$

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:

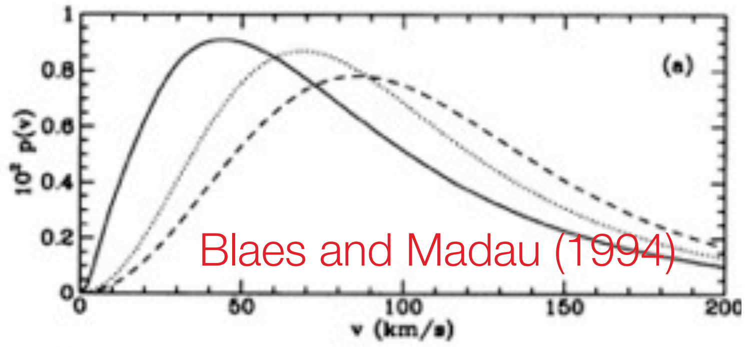
$$L_X = \dot{M}\frac{G\,M_{NS}}{R_{NS}}$$

  - 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.



Blaes and Madau (1994)

Prediction: Should detect

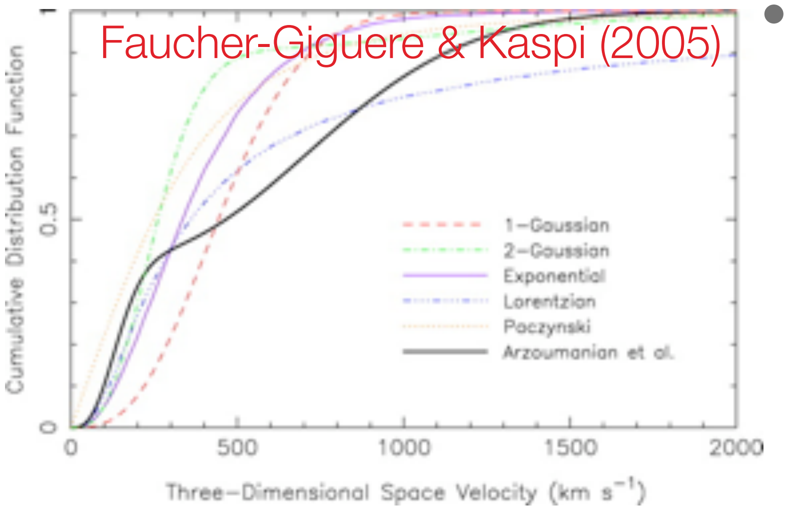
700-7000N_9

INSs in ROSAT All Sky-Survey

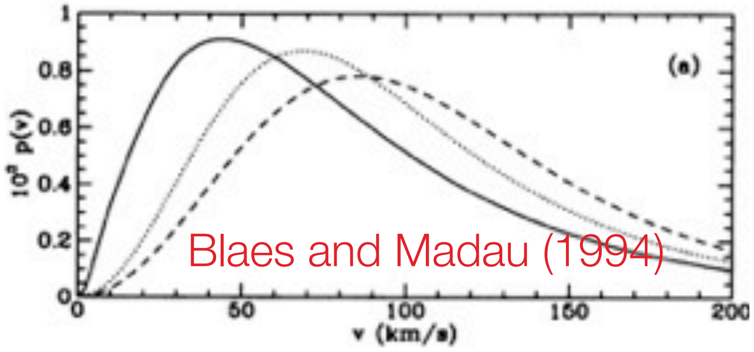
Where are all these INSs?

- Modern upper limit: <37 (non-variable) INSs in the RASS/BSC (Rutledge et al 2003, Turner et al 2010).

- Two partial explanations for this discrepancy:

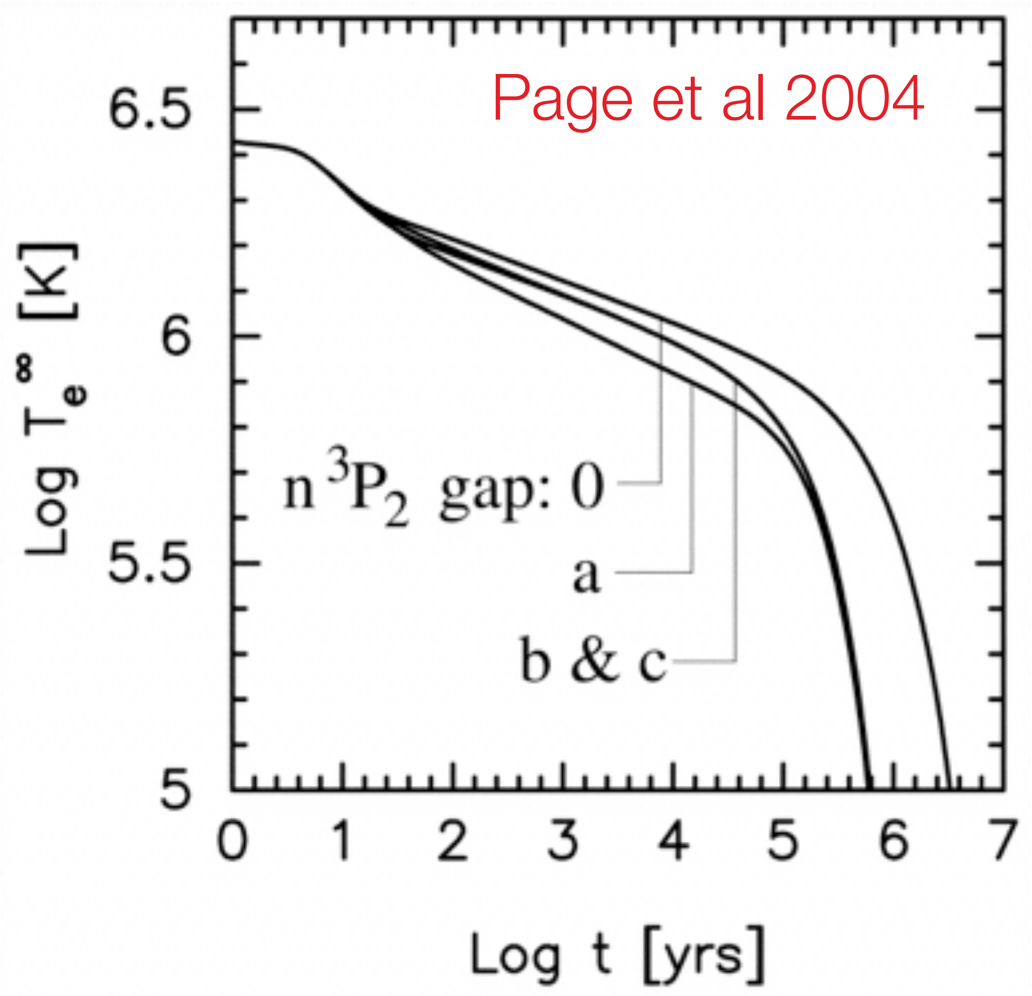

Faucher-Giguere & Kaspi (2005)

- (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!


Blaes and Madau (1994)

- (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.



- "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.
- NB: it is observationally challenging (and has not been done) to distinguish between accretion power and natal 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.

Number of Confirmed INSs Known: 9

	kT (eV)	F_X (10^{-13} CGS)	optical	Period (s)	log B
1RXS J0420.0-5022	45	5	B=26.6	3.5	13
RX J0720.4-3125	90	100	B=26.6	8.4	13.1
RX J0806.4-4123	95	2.8	B>24	11.4	<13.3
1RXS J130848.6+212708	117	45	m_50ccd=28.6	10.3	13.2
1RXS J141256.0+792204 (CALVERA)	215	12	g>26.3	0.059	<11.5
RX J1605.3+3249	91	88	B=27.2	-	-
1RXS J185635.1-375433	63.5	210	B=25.2	7.1	~13.1
1RXS J214303.7+065419 (RBS 1774)	91	87	B=27.4	9.4	~13.1
2XMM J104608.7-594306	117	1	>26	-	-

Compendium of work by: **Haberl; Schwope; Motch; Kaplan; Zampieri; Walter; RR; Van Kerkwijk; Halpern; Zane; Tetzlaf; Pires**

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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 than a completely blind all-sky search.

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

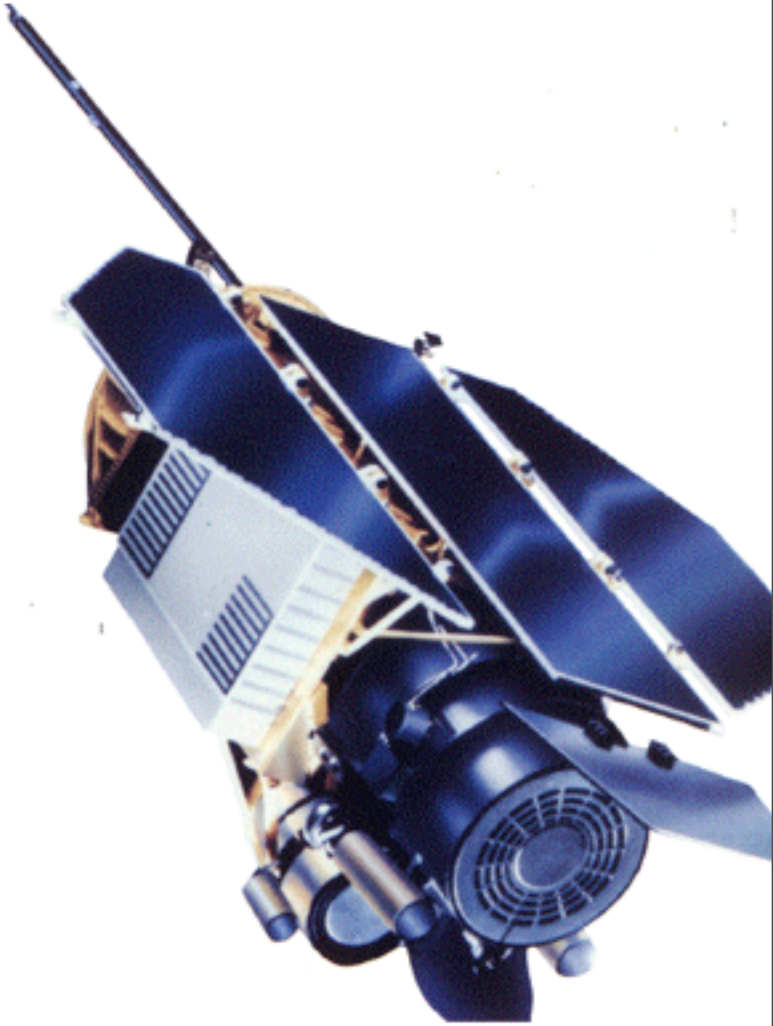
- Pro: Expected to be many of them (the entire NS population) and so they can be very nearby, compared with LMXBs and other rare compact objects (aids detection of weak sources).

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

How to 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).
- Almost 2/3 of these are not identified with >90% confidence (Haakonsen & RR 2009).
- We use a statistical approach (RR et al 2001; Haakonsen & RR 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

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



How to identify INS Candidates

(RR et al 2000, Haakonsen & RR 2010)

Likelihood Ratio

$$LR_i = \frac{\exp\left(\frac{-r_i^2}{2\sigma^2}\right)\exp\left(-\rho\pi r_i^2\right)}{2\pi\sigma^2 N(< m_{J,i})}.$$

- We included in our analysis 150 “control sources”, placed randomly on the sky, which mimic INSs.

RR et al (2001)

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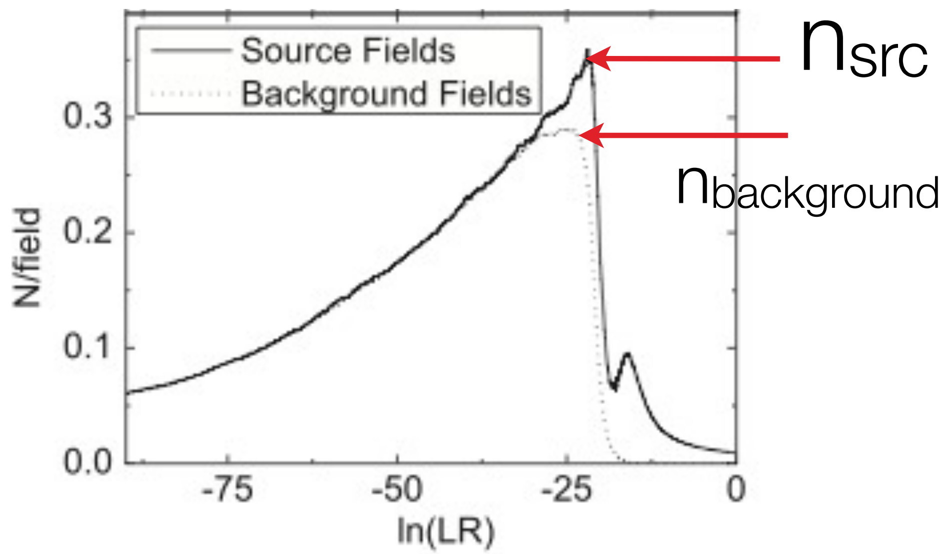

Reliability

$$R(LR) \approx \frac{n_{\text{source}}(LR) - n_{\text{background}}(LR)}{n_{\text{source}}(LR)}.$$

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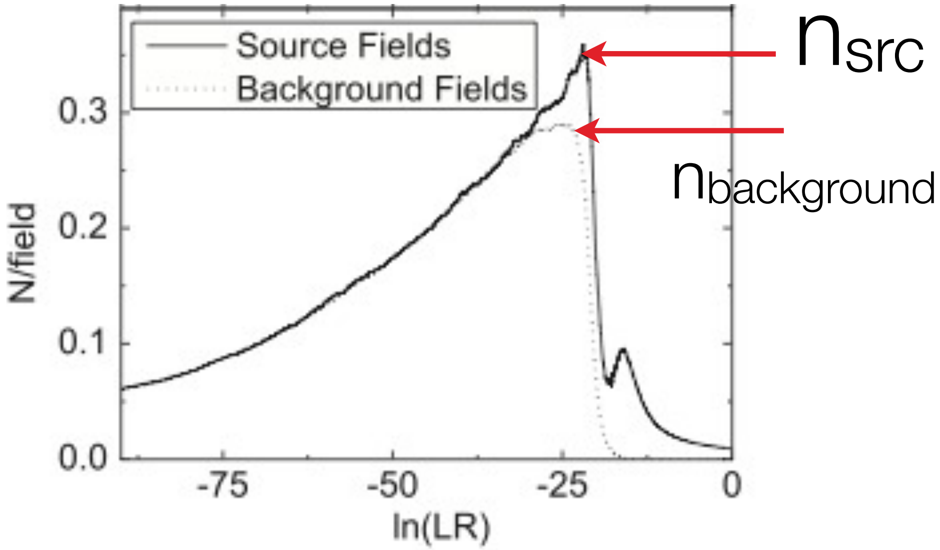

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$$LR_i = \frac{\exp\left(\frac{-r_i^2}{2\sigma^2}\right)\exp\left(-\rho\pi r_i^2\right)}{2\pi\sigma^2 N(< m_{J,i})}.$$

Reliability

$$R(LR) \approx \frac{n_{\rm source}(LR) - n_{\rm background}(LR)}{n_{\rm source}(LR)}.$$

P_no-id

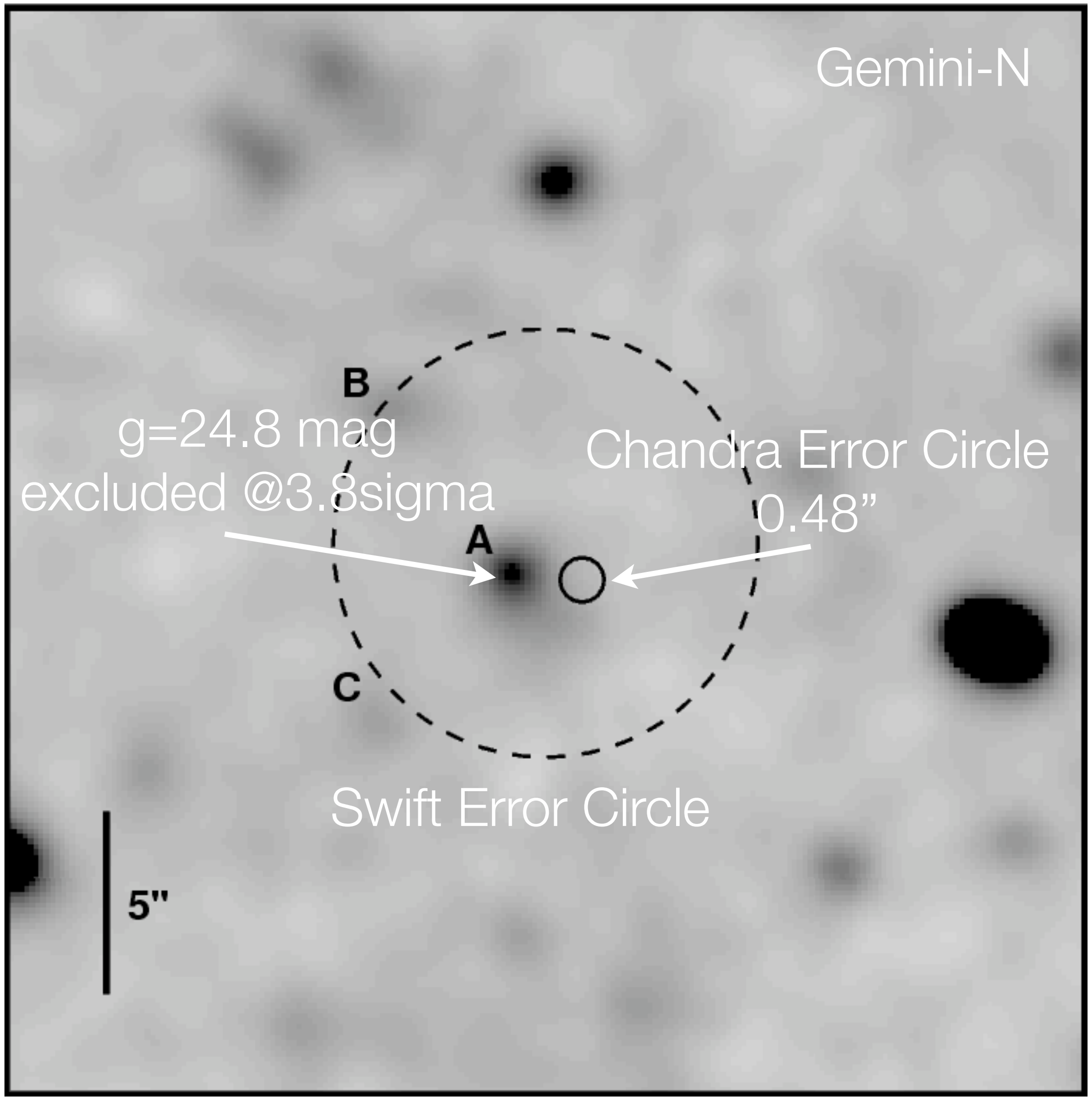
$$P_{\rm no-id} = \frac{1}{1 + \sum_{j=1}^{M} \frac{R_j}{1-R_j}},$$

- We included in our analysis 150 “control sources”, placed randomly on the sky, which mimic INSs.

RR et al (2001)

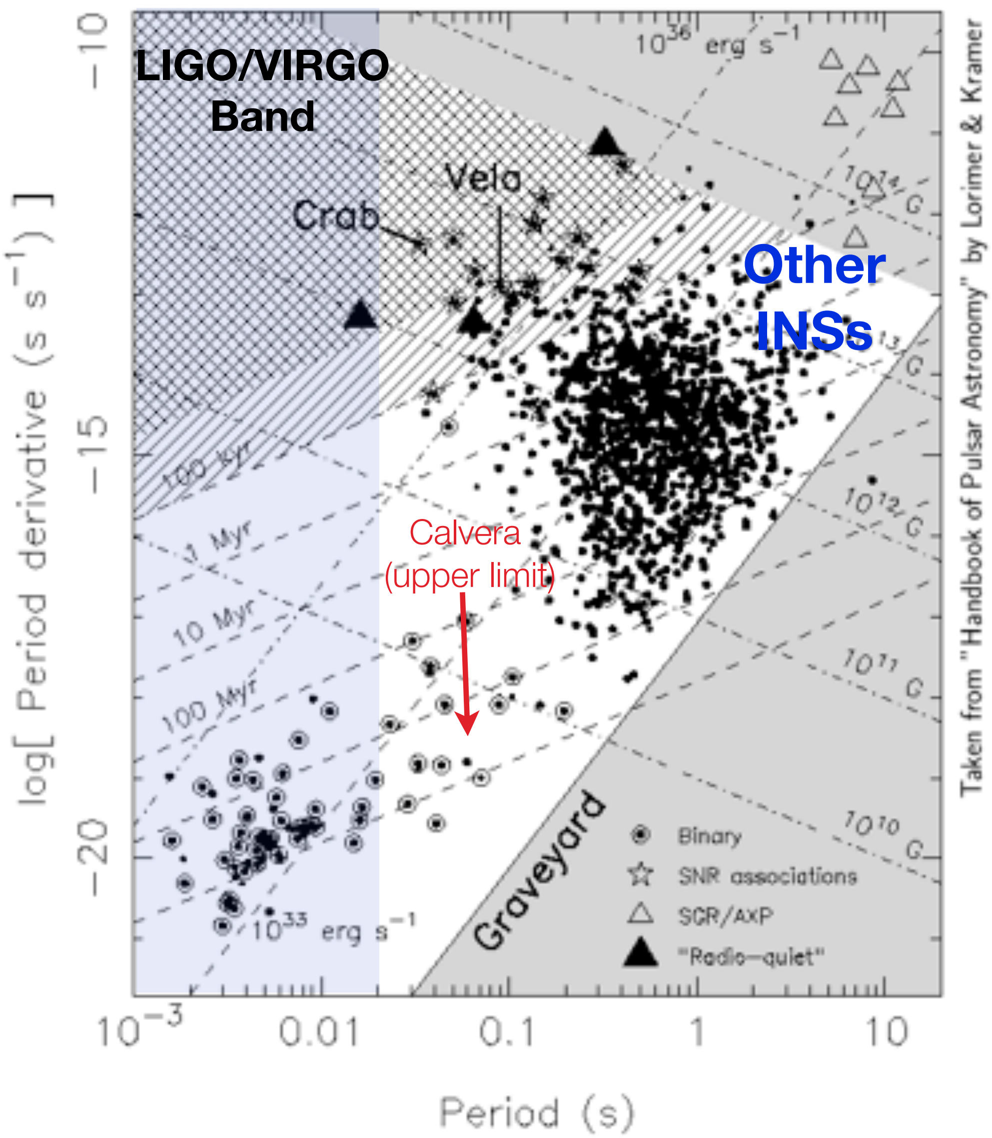
Identification of Calvera as an INS

- A high P_no-id led to SWIFT, Chandra, and Gemini imaging. (Plate limit: g>26.3, 3 sigma).
- 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).
- However, source properties indicated it was likely not a "classic" INSs (low T, high B).



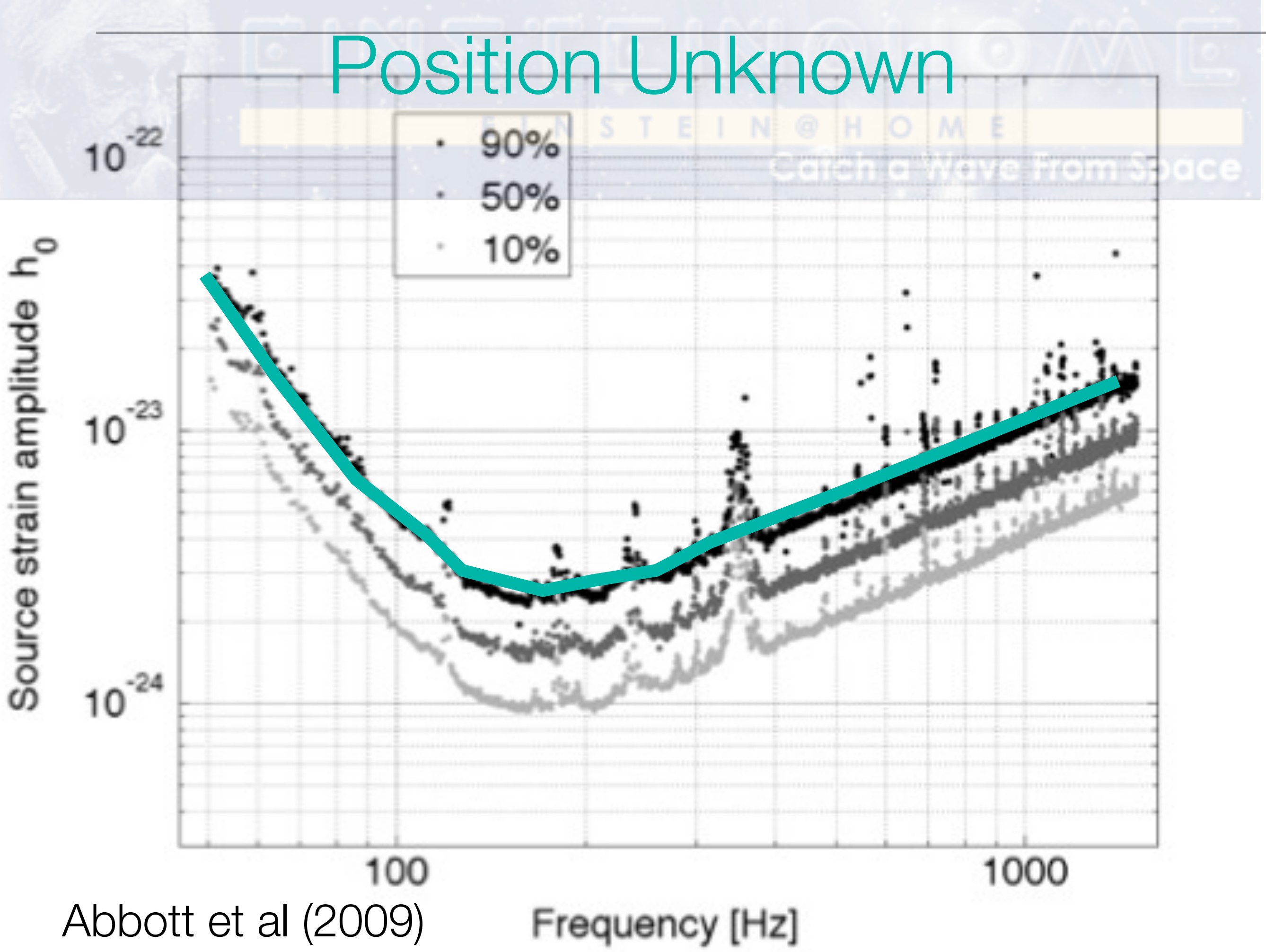
Calvera: a 59 ms off-beam radio pulsar (Zane et al 2010)

- X-ray Flux implies distance 80-260 pc (in analogy with MSPs in 47Tuc).
- Calvera: A nearby, low B-field, *perhaps* recycled pulsar.
- Deep radio observations finds no pulsed emission at the known period (lowest 0.5% radio luminosity of the *observed* pulsars; Hessels et al 2009).
- While Calvera spins too slow for LIGO/VIRGO, the population it belongs to provides candidate gravitational wave sources to LIGO/ VIRGO.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

LIGO searches INSs for gravitational wave sources

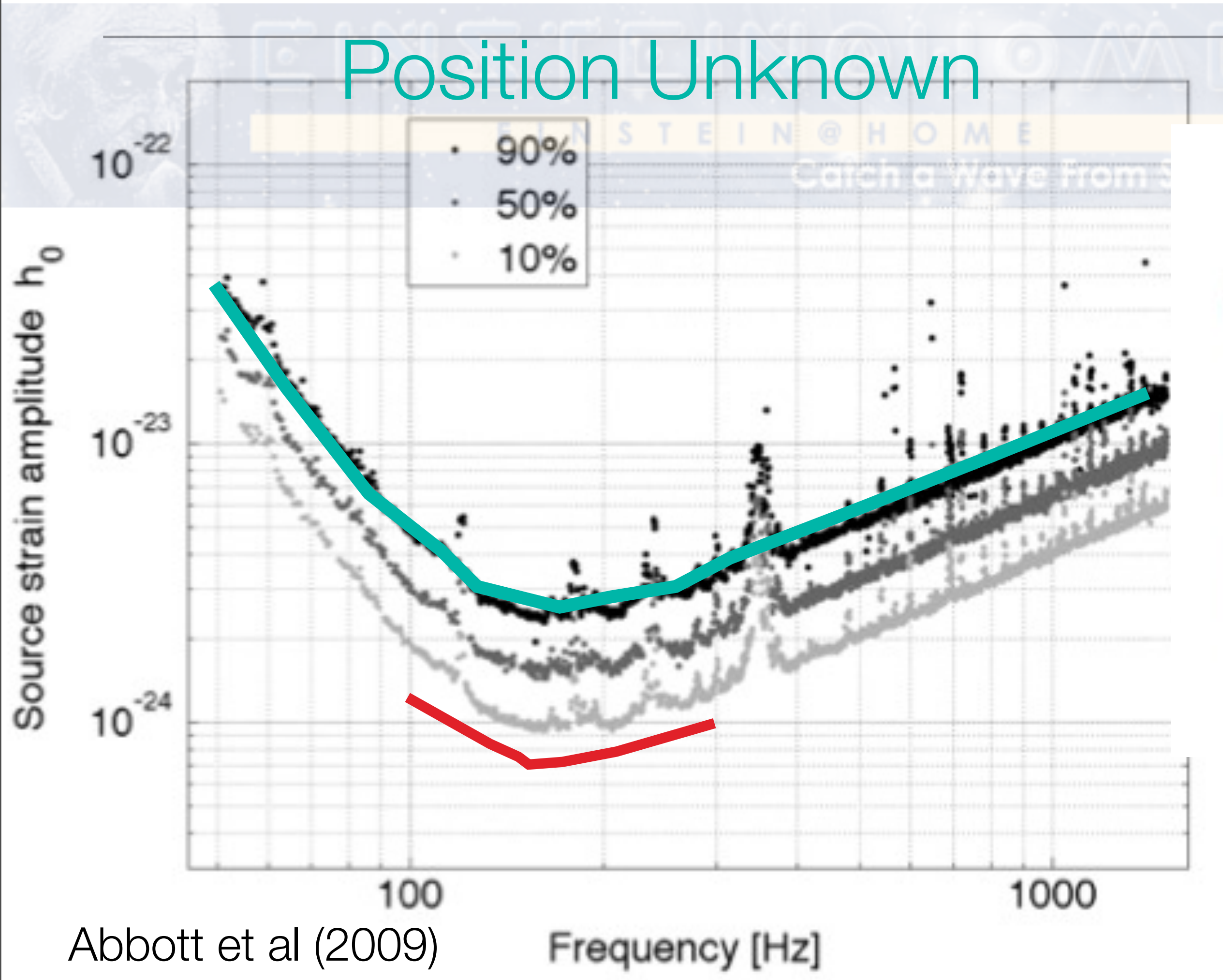


Abbott et al (2009)

Knowing a position provides a x4 increase in sensitivity for LIGO

LIGO searches INSs for gravitational wave sources

Position Unknown



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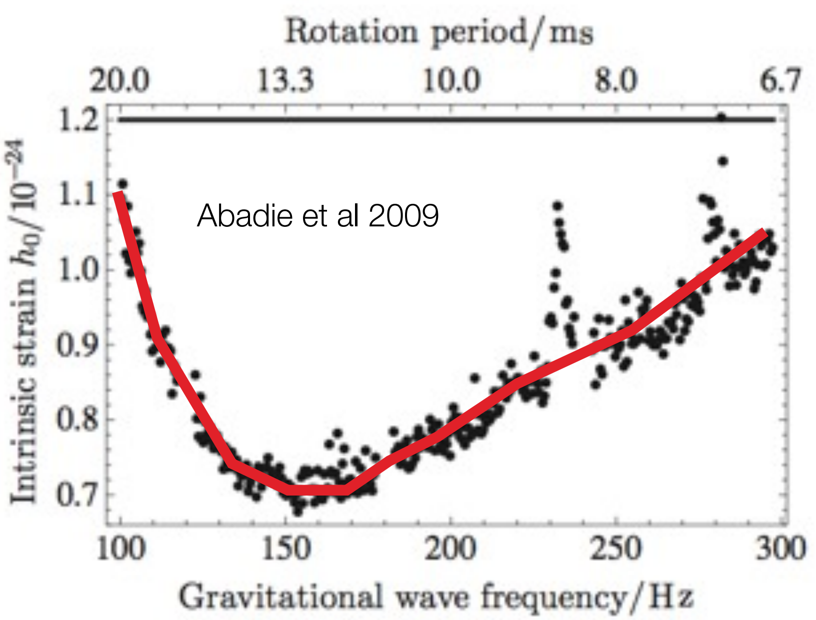

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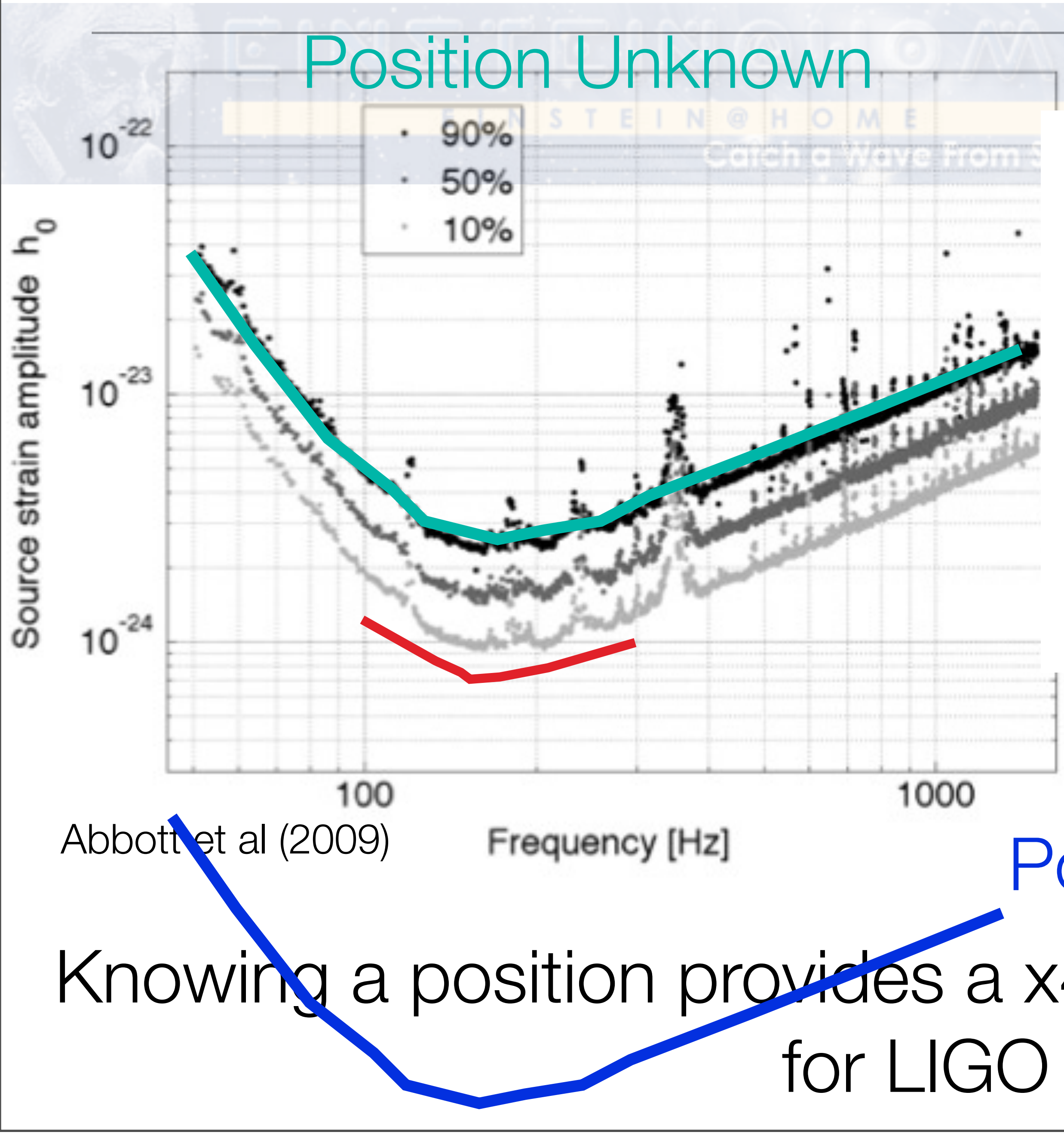

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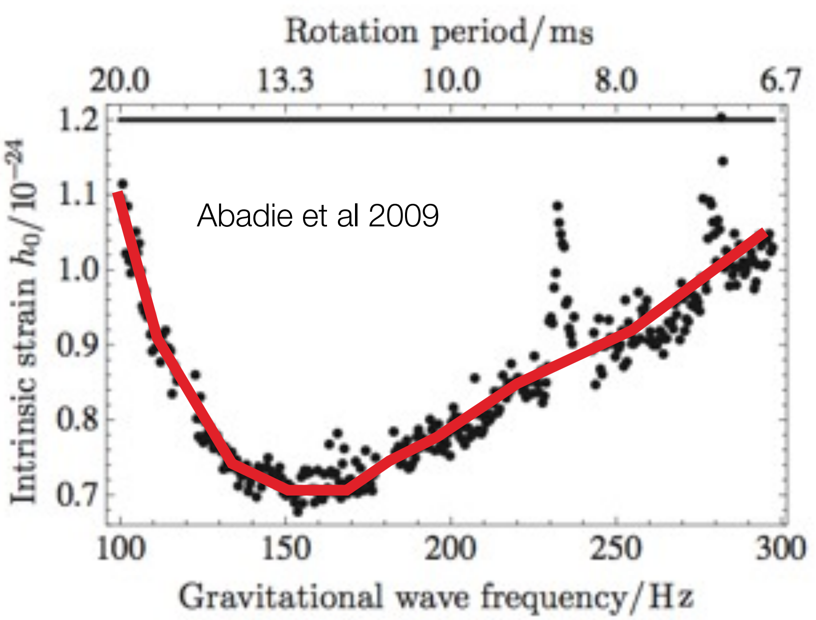

Abadie et al 2009

Position+Period Known

Knowing a position provides a x4 increase in sensitivity for LIGO

Conclusions

- eROSITA will discover 240-1500 new Isolated Neutron Stars, based on the known INS population (8-37 INSs). This will provide strong constraints on the natal and evolutionary properties of neutron stars.

- If ~12% of these are MSPs, then eROSITA will discover 30-180 gravitational wave source candidates.

- eROSITA science team should contact LIGO/VIRGO team to collaboratively provide candidate INSs from early survey. Strategically: place high priority to search for pulsar periods from INSs, since this dramatically increases GW-search sensitivity.

- Perhaps, the first detected source of gravitational waves will be named “eROSITA JXXXX.XX+XXXXX”.