Neutron Star News and Puzzles

M. Prakash

Department of Physics & Astronomy
Ohio University, Athens, OH

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45 Years of Nuclear Theory at Stony Brook:
A Tribute to Gerald E. Brown

Nov 24-26, 2013, Stony Brook University

Memories of Gerry (Personal Perspective)

- My Association: Began in 1980 at the NBI, Copenhagen
- Mentor, colleague, in-situ father and a great friend
- A perfect “match-maker”
- Provocateur par excellence
- Generous beyond belief in personal and professional matters
- Passionate lover of physics
- Never stopped doing physics

Overview of On-Going Activities Spawned by Gerry

Neutron Star News

- Maximum and Minimum Masses
- Masses and Radii of Individual Stars
- Long-Term Cooling Points to Stellar Superfluidity
- Quiescent Cooling of Accreting Neutron Stars - Existence of Crusts
- Emerging Evidence for Binary Mergers - Site for r-process
- The Dense Matter Equation of State (EOS)

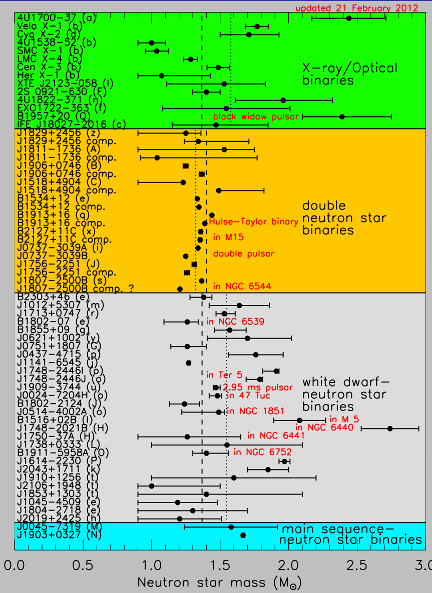
Neutron Star Puzzles

- Neutron Star or Black Hole in SN 1987A?
- Really Cold Objects - DUrca or not?
- Why don't neutron stars spin as fast as allowed?
- .....

Tasks

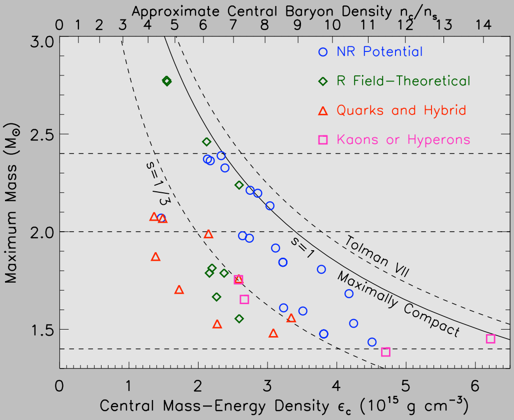
- Measure masses and radii of several individual neutron stars
- Theoretical tools in place to pin down the neutron-star EOS

Measured Neutron Star Masses



- Mean & error weighted mean in $M_\odot$
- X-ray binaries: 1.66 & 1.383
- Double NS binaries: 1.322 & 1.402
- WD & NS binaries: 1.553 & 1.367
- New masses not in figure: PSR J0348+0432: $2.04 \pm 0.04\ \mathrm{M}_\odot$ Triple system J0337+1715: 1.442, 0.198 & 0.411 $\mathrm{M}_\odot$
- G. E. Brown's Festschrift (2011); arXiv: [1012.3208].
- Updates by Lattimer in www.stellarcollapse.org

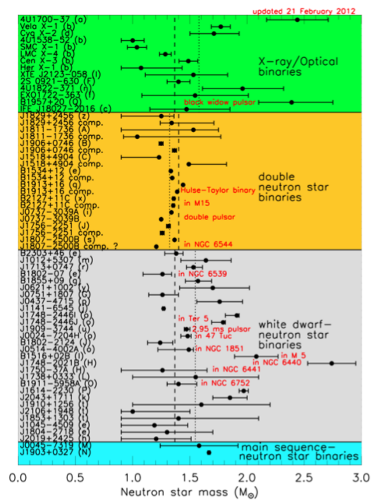
Ultimate Energy Density of Cold Matter



- Tolman VII:
  $\epsilon = \epsilon_c(1 - (r/R)^2)$
- $\epsilon_c \propto (M_\odot/M)^2$
- **Crucial to establish an upper limit to** M_{max} **.**

Lattimer & Prakash, PRL, **94** (2005) 111101;
GEB's Festschrift (2011)

Estimates of Radiation Radii



- Masses are well-measured in binary systems but radii are not precisely known

- Systems in which R_∞ was measured do not have reliable masses

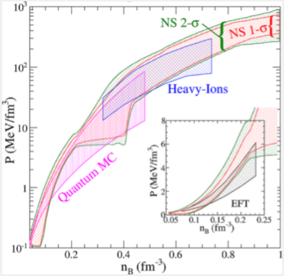
Object	R_∞ (km)	D (kpc)
M28	12.2 ± 3.0 $14.5^{+6.9}_{-3.8}$	5.0 ± 0.3
NGC 6397	$9.6^{+0.8}_{-0.6}$	2.02 ± 0.18
M13	10.8 ± 0.3 $12.3^{+1.4}_{-1.7}$ $10.6^{+0.3}_{-0.4}$	6.5 ± 0.6
ω Cen	13.7 ± 2.0 12.3 ± 0.3 $13.9^{+6.5}_{-4.5}$	4.8 ± 0.3
NGC 6304	$12.1^{+6.6}_{-4.8}$	6.22 ± 0.26
47 Tuc	$17.1^{+1.8}_{-1.5}$	4.85 ± 0.29
NGC 6553	$10.7^{+2.0}_{-1.5}$	6.0

Deconstructing a neutron star

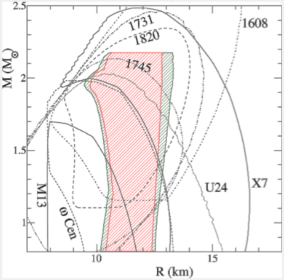
Bayesian TOV Inversion

- $\varepsilon < 0.5\varepsilon_0$: Known crustal EOS
- $0.5\varepsilon_0 < \varepsilon < \varepsilon_1$: EOS parameterized by K, K', S, γ
- $\varepsilon_1 < \varepsilon < \varepsilon_2$: Polytrope with index n_1
- $\varepsilon_2 < \varepsilon$: Polytrope with index n_2

- EOS parameters $(K, K', S, \gamma, \varepsilon_1, n_1, \varepsilon_2, n_2)$ uniformly distributed
- Choose region which encloses several models



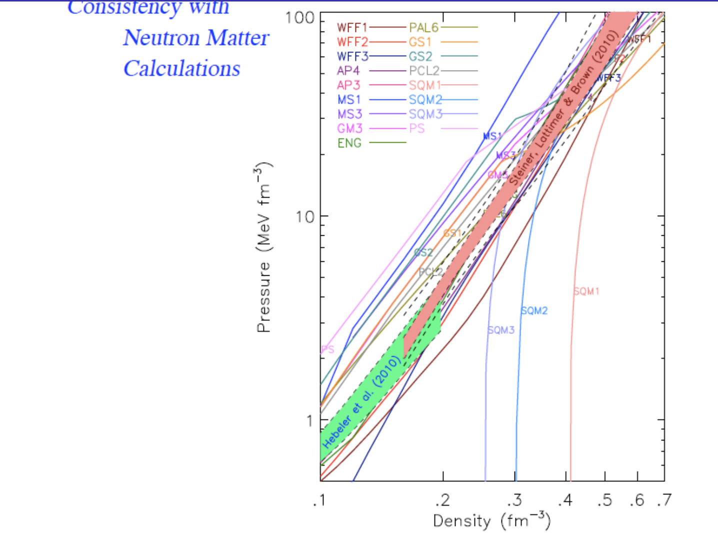
Inferred EOS



Inferred $M(R)$

Steiner, Lattimer & Brown (ApJ, 2011), Steiner & Lattimer (ApJ 2013)

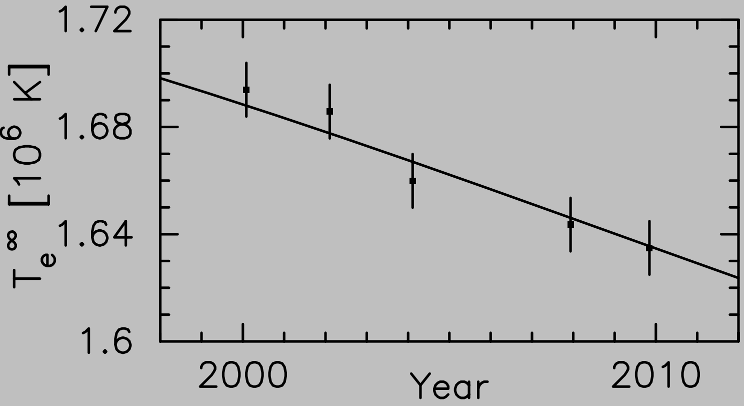
Situation Then and Now



Lattimer & Prakash, ApJ 550 (2001) 426

Ongoing work on model independent deconstruction (Postnikov, Steiner, Prakash & Lattimer)

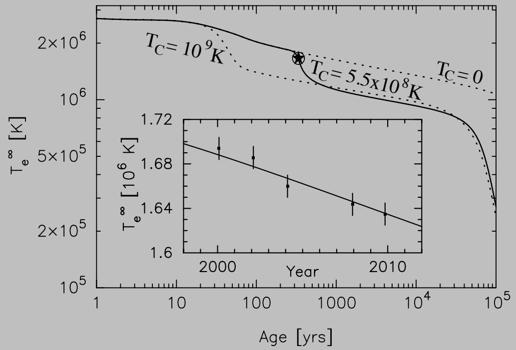
Red-shifted Surface Temperature of Cas A



Decline in surface temperature over 9 years: $3.6 \pm 0.6\%$

Archival Chandra data deemed well calibrated analyzed by Heinke & Ho, Astrophys. J. Lett. **719**, L167 (2010).

Good fit to Cas A's rapid cooling



- $1.4 M_\odot$ star from the EOS of APR.
- Light element envelope mass: $5 \times 10^{-13}\ M_\odot$
- Model $^1S_0$ gaps allow the entire core to superconduct.
- Data with 1σ errors.

Page, Prakash, Lattimer & Steiner, PRL, **106**, 081101 (2011)

Robustness of T_c

$$T_c = \max\ T_{cn}(\rho) = 10^9\ \mathrm{K}\ (\tau_{MU}/t_c)^{1/6} \sim 0.5 \times 10^9\ \mathrm{K}$$

The MU cooling time scale $\tau_{MU} = 10^9 C_9/6L_9 \sim 1\ \mathrm{yr}.$

Time $t_c \simeq (0.5 - 0.9) \times 330$ yr is somewhat smaller than Cas A's age.

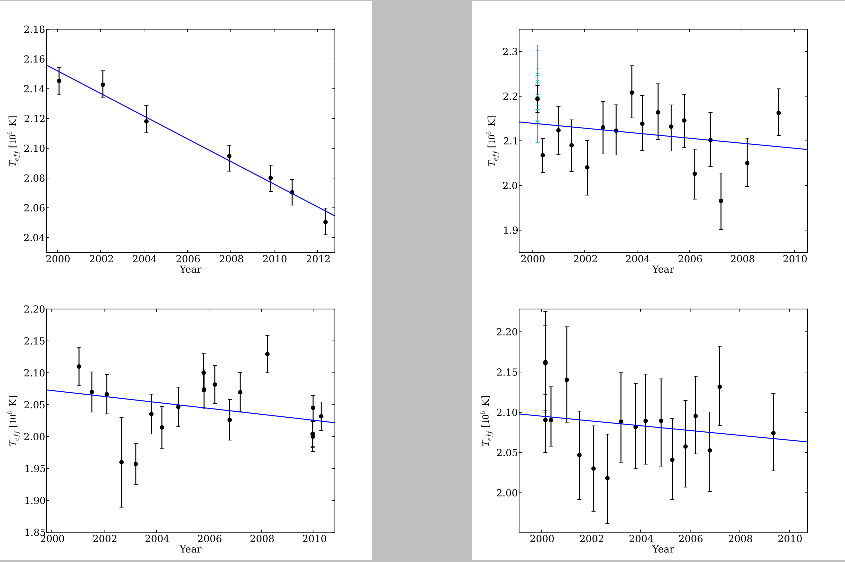
Many numercial trials, changing all important ingredients, give $T_c \sim 0.5 \times 10^9$ K.

- The robustness of T_c is mostly determined by t_c which, given the briefness of the transit phase, cannot be much smaller than the age of Cas A.
- The rapidity of cooling, i.e., the slope, is predominantly controlled by proton superconductivity reflected in the suppression of L_{MU}. If the proton ${}^1S_0$ gap extends to vey high densities, as in Shternin et al. (2011), T_c can reach 10^9 K.

Conclusions of independent investigations

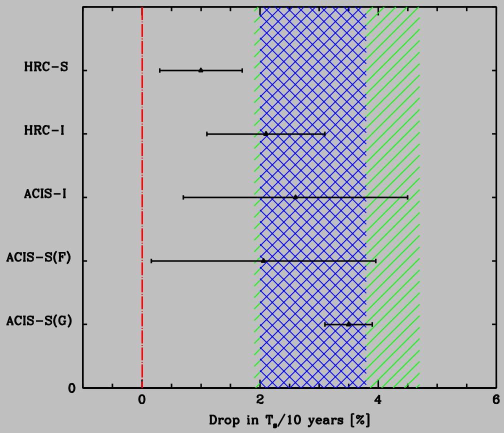
- The rapid cooling of the neutron star in Cas A is likely due to neutrino emission from the onset of the breaking and formation of neutron Cooper pairs in the $^3\mathrm{P}_2$ channel.
- The deduced value of $T_c > 0.5 \times 10^9$ K is compatible with the requirement of minimal cooling established earlier than Cas A's reported cooling rate. This is the first direct evidence that superfluidity and superconductivity occur at supranuclear densities within neutron stars.
- Shternin et al. (2011) reach similar conclusions as ours with $T_c \simeq (0.7 - 0.9)$ K, laregely due to differences in the uncertain proton pairing gaps used.

Data with ALL detectors on Chandra



Elshamouty et al., arXiv: 1306.3387v1 [astro-ph.HE] 14 Jun 2013

Decline in temperature from ALL detectors on Chandra

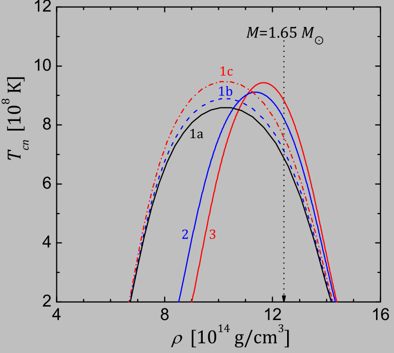


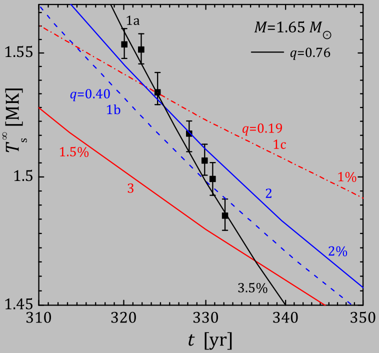
- 1σ errors for each instrument are statistical
- Blue region shows best estimate from all detectors
- Green region includes systematic errors
- Best estimate of decline in $T_S/10$ years: $2.9 \pm 0.9_{stat.}\,{}^{+1.6}_{-0.3}{}_{sys.}\,\%$

All is fair in love and war, and statistics !?!

Elshamouty et al., arXiv: 1306.3387v1 [astro-ph.HE] 14 Jun 2013

Reckoning with the new data



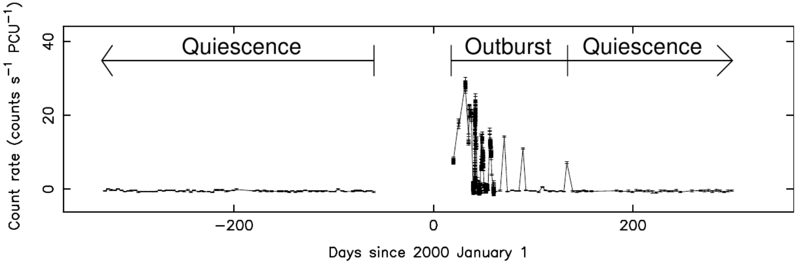


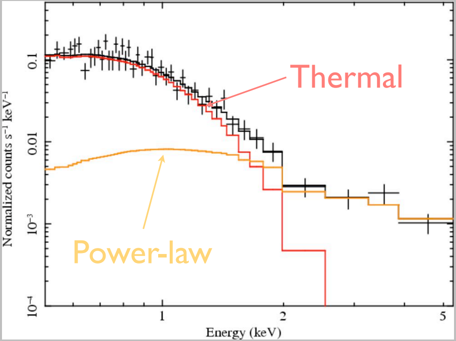
Left: Models for the critical temperature of triplet-state neutron pairing

Right: Cooling curves for the models on the left (q is the reduction factor for the PBF ν-emission by many-body effects).

Elshamouty et al., arXiv: 1306.3387v1 [astro-ph.HE] 14 Jun 2013
Posselt et al., arXiv:1311.0888 [astro-ph.HE] 4 Nov 2013

Thermal Emission Following X-Ray Outburst Activity





Cooling in Quiescent Periods

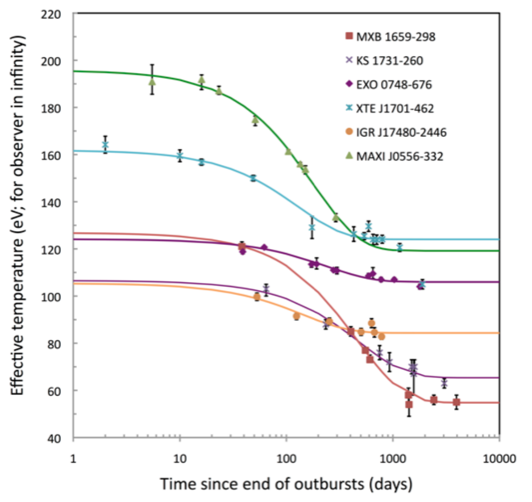
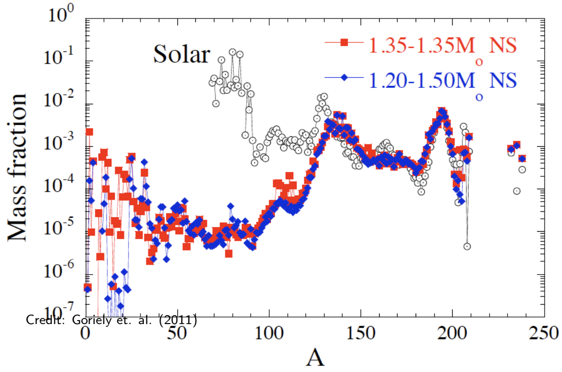


Figure courtesy Ed Cackett.

- NS's have crusts:
  M. Ruderman
  (Nature: 1969)
- Pertinent observations:
  Wijnands, Rutledge, Cackett et. al.,
- Recent interpretation:
  Page & Reddy (2013)
  arXiv:1307.4455
- Cooling times depend on amount of mass accreted, specific heat, thermal conductivity, nuclear heating & neutrino cooling rates at relevant layers

Nucleosynthesis from Ejecta in Binary Mergers

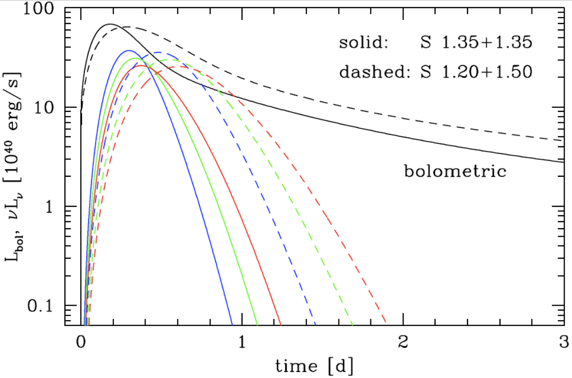


Credit: Goriely et. al. (2011)

- Predicts synthesis of 2^{nd} & 3^{rd} peaks
- Light curve?

- Hydrodynamic simulations of NS-NS merger leading to kilo nova
- $E_{eject} \cong 10^{50} ergs$
- 1000 times brighter than novea (thus kilo novea)
- Abundances from r-process nucleosynthesis

Light curves from kilo nova models (Goriely et. al.)

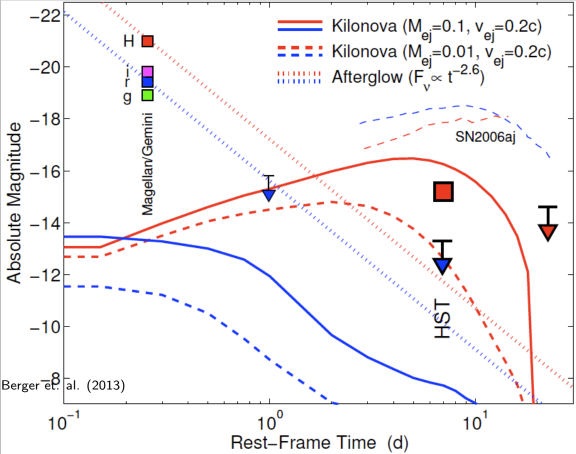


Credit: Goriely et. al. (2011)

- band - λ
- blue - 445 nm
- visual - 551 nm
- red - 658 nm

- No tail in r band
- Short duration provides a method to distinguish from SN

SGRB 130603B Light Curve



Berger et. al. (2013)

- 25 times too bright for afterglow
- 5 mag too dim to be a type I & wrong color
- Consistent with kN radioactive tail

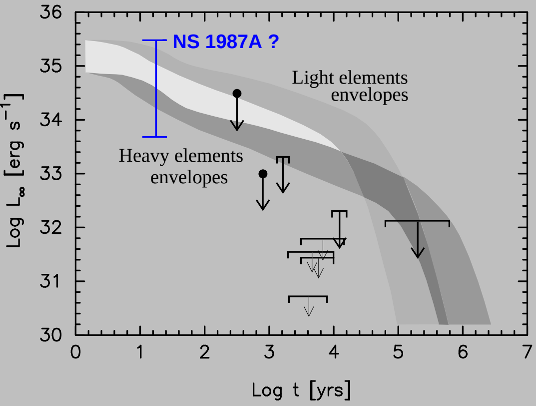
- HST: $V - H \gtrsim 1.9$ mag
- kN: $B - J = 12$

A Neutron Star or a Black Hole in SN 1987A?

- No news yet of a neutron star in SN 1987A.
- How long does it take for a neutron star to be revealed after a core-collapse supernova explosion?
- Did SN 1987A end up as a black hole?
  If so, was it upon fall-back-accretion (Brown - Bethe), or, after the deleptonization stage (Prakash - Lattimer)?

Really Cold Isolated Objects

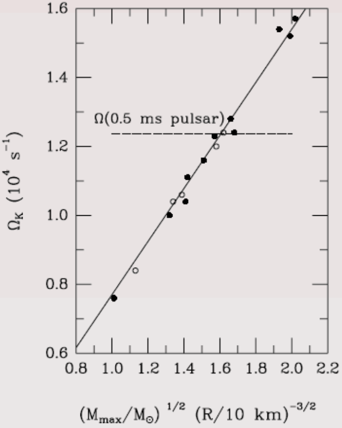
Several cases fall below the "Minimal Cooling" paradigm & point to enhanced cooling, if these objects correspond to neutron stars.



Page, Lattimer, Prakash & Steiner, ApJS **155**, 623 (2004).

Neutron Star Spins

How fast can rotation be?



General Relativity:

$$\Omega_K = 7.7 \times 10^3\,\mathrm{s}^{-1} \times SF\,.$$

$$SF = \left(\frac{M_{max}}{M_\odot}\right)^{1/2} \left(\frac{R_{max}}{10\ \mathrm{km}}\right)^{-3/2}$$

Maximum radius:

$$R_{max} = 10.3\ \mathrm{km} \times \left(\frac{1\ \mathrm{kHz}}{\nu}\right)^{2/3} \left(\frac{M}{M_\odot}\right)^{1/3}$$

M: Star of given mass

M_{max} and R_{max} refer to the spherical configuration.

Lattimer & Prakash , Science **304**, 536 (2004).

Why don't NS's spin up to the theoretically allowed limit?

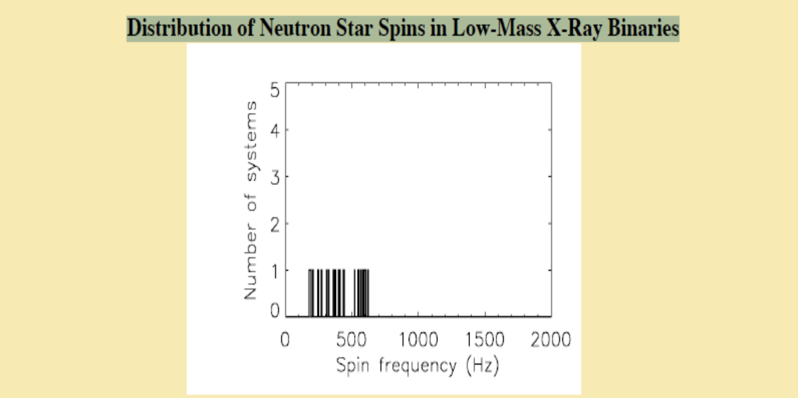


Figure courtsey Deepto Chakraborty; Nature, 424, 42 & arxiv.org/abs/0809.4031

Theory: $\nu_K = (2\pi)^{-1}\,\Omega_K = 1045\ \mathrm{Hz}\ (M/M_\odot)^{1/2}\ (10\ \mathrm{km}/R)^{3/2}$ for a star of mass M (not close to the maximum mass) and radius R.
Lattimer & Prakash, Science **304**, 536 (2004).

My Tribute to Gerry

- Tusind tak.
- I miss you! A lot!!
- Love and regards from Manju, Ellen and, particularly, Smita.