Searching for gravitational waves from known pulsars using LIGO S5 data

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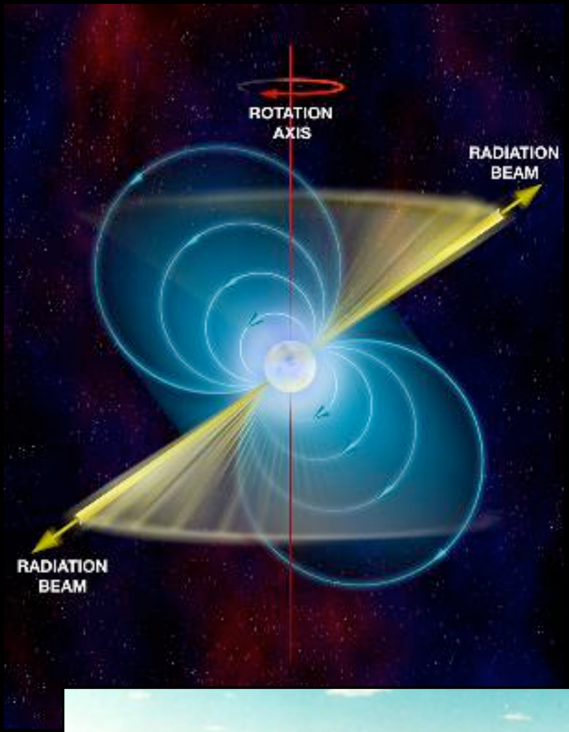
What we do

- Target known pulsars, with well defined position and phase, to allow a deep, fully coherent search for gravitational waves
- Assume triaxial neutron stars with GW emission at exactly twice the rotation frequency
- Use data from current generation of ground-based interferometric detectors LIGO, GEO600, Virgo

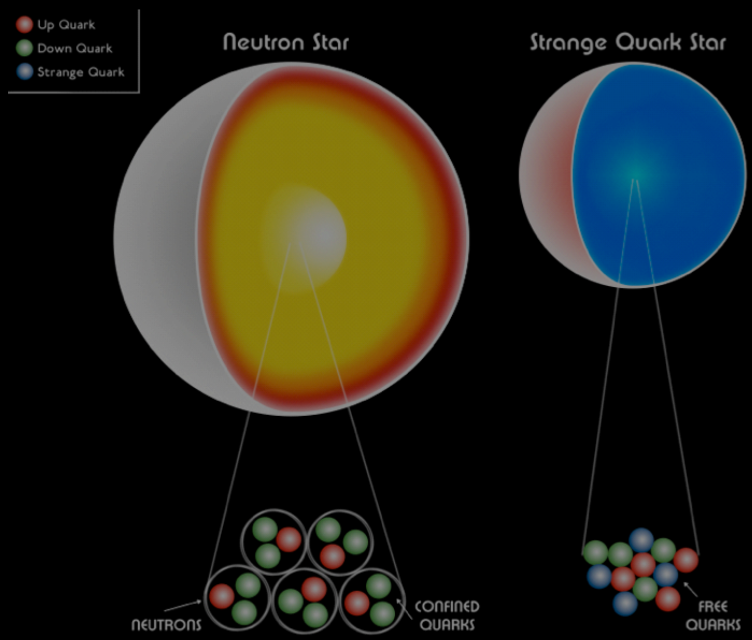


What we've done

- Used LIGO and GEO600 science (S) run data for searches
- S1 searched for 1 pulsar (J1939+2134)
- S2 searched for 28 isolated pulsars
- S3 and S4 targeted 78 known (isolated and binary) radio pulsars with spin frequencies greater than 25Hz
  - pulsar parameter data supplied specifically for this search from Jodrell and Parkes observations, and the Australia Telescope National Facility (ATNF) online catalogue
- S5 (4 Nov 2005-1 Oct 2007) produced a upper limit for the Crab pulsar using the first 9 months of data (Ap. J. Lett., 683, L45-L49, 2008)
  - single and multi-template searches
  - beat spin-down amplitude limit by a factor of ~5 and limit power in GWs to be less than 4% of spin-down limit

Why we do it

- Gravitational wave strain for a neutron star is directly proportional to the star quadrupole moment (principal moment of inertia times ellipticity)
- Measuring this quantity allows potential constraints on star's equation of state
  - large ellipticity - solid quark star?
  - ellipticity sustained by internal magnetic field?
  - quantify the energy budget of the star's spin-down



Credit: Illustration: CXC/M.Weiss

Theoretical expectations

- Exotic forms of crystalline quark matter *could* sustain ellipticities of 10^{-4} (Owen 2005; Lin 2007; Haskell et al 2007; Knippel & Sedrakian 2009)
- Or, could be sustained by internal toroidal magnetic fields of order 10^{16}G (dependent on configuration and equation of state of star) (Cutler 2002; Akgun & Wasserman 2007; Colaiuda et al 2008)
- Recent work (Horowitz and Kadau 2009) has suggested that normal neutron star crusts may sustain ellipticities of up to 10^{-5}
- This suggests stars *could* be emitting gravitational waves near currently detectable level, **but** upper limits alone cannot constrain these various possibilities - stars may just be intrinsically smooth

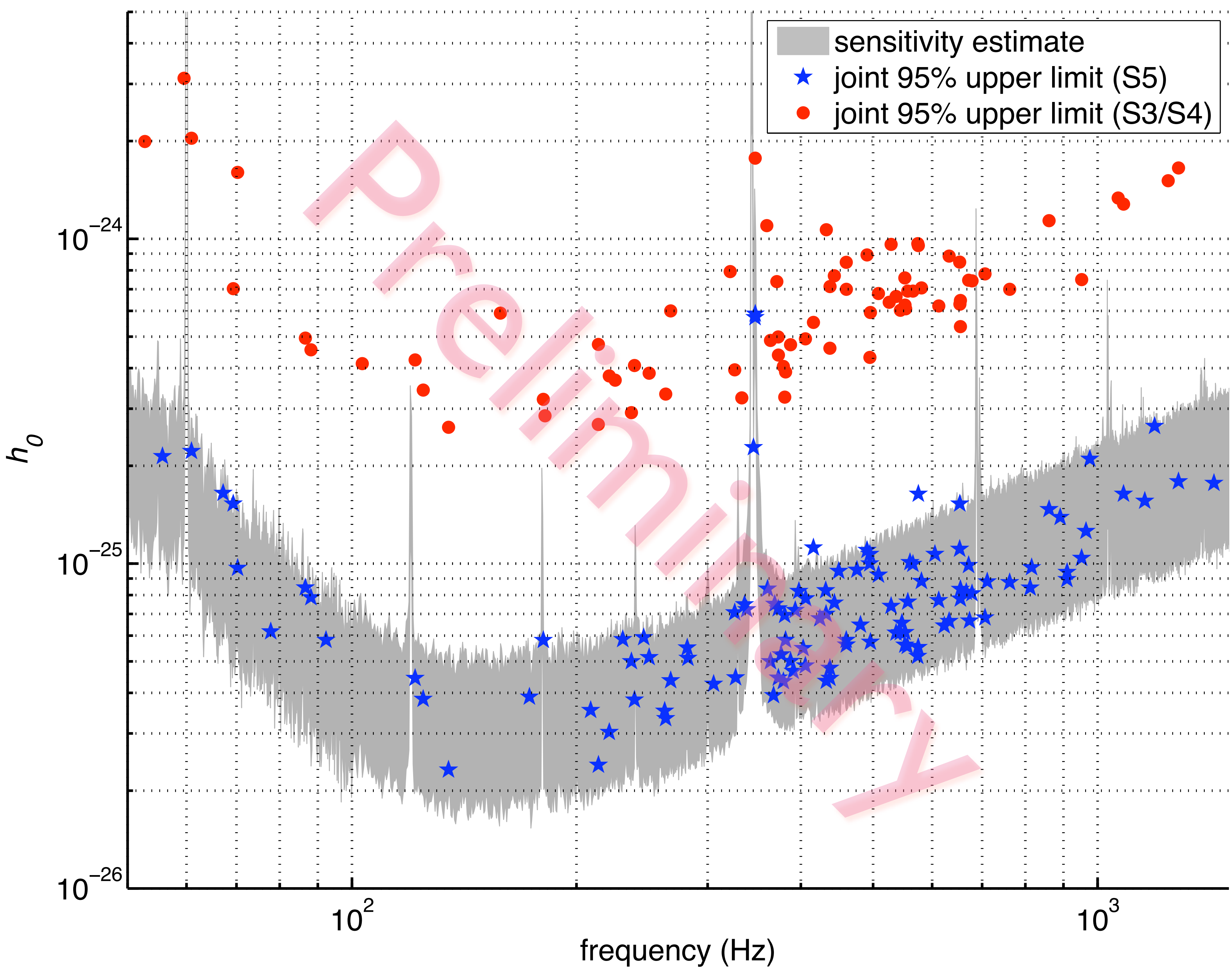
The current search

- ~200 known pulsars with spin frequencies greater than 20Hz (LIGO sensitive band)
- Have parameters fit to radio observations of 115 pulsars (isolated, binaries and in globular clusters) covering all, or part, of S5 run
  - Jodrell Bank Observatory (e.g. Crab, etc)
  - Green Bank Observatory (Ter5, M28)
  - Parkes Telescope (e.g. PPTA)
- Perform a targeted search for these pulsars using all S5 LIGO data
- For one pulsar, J0537-6910, only have RXTE X-ray observations, covering entire run
  - Six glitches during this period

Globular cluster Terzan 5

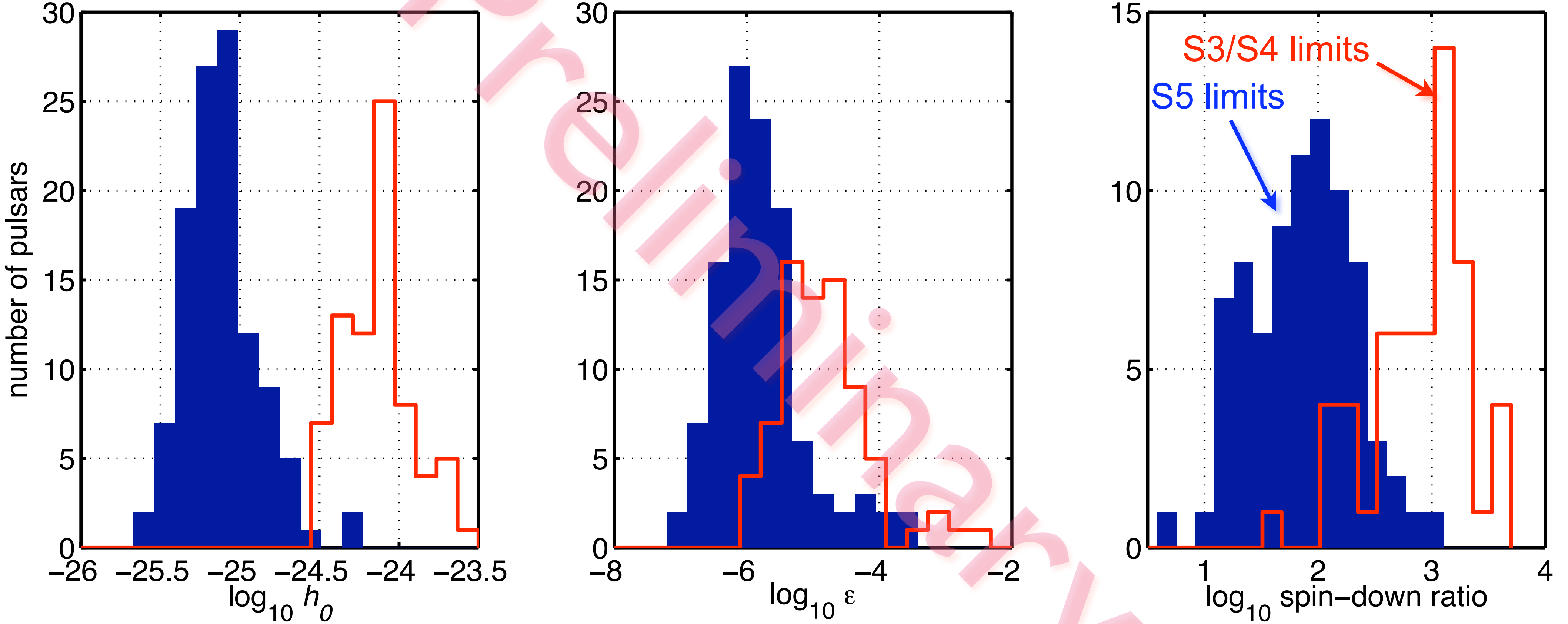
Preliminary S5 results

- ~527 days H1, 535 days H2, 405 days L1 data
- No signal seen for any pulsar
- Highlights:
  - Lowest amplitude upper limit: 2.3×10^{-26} for J1603-7202 at 135 Hz and distance 1.6 kpc
  - Lowest ellipticity limit: 7×10^{-8} for J2124-3358 at 406 Hz and distance 0.2 kpc
  - Lowest amplitude relative to spin-down:
    - *millisecond recycled* pulsar: 10 times spin-down for J2124-3358
    - *non-glitching young* pulsar: 4 times spin-down for J1913+1011
    - *glitching young* pulsar: 0.18 times spin-down for Crab
- Three young pulsars glitched during the run



sensitivity estimate
joint 95% upper limit (S5)
joint 95% upper limit (S3/S4)
Preliminary
h_0
frequency (Hz)
10^{-24}
10^{-25}
10^{-26}
10^{2}
10^{3}

Preliminary results



Glitching pulsars

- Three young pulsars seen to glitch during S5
  - Crab pulsar - 1 glitch
  - J0537-6910 - 6 glitches
  - J1952+3252 - 1 glitch
- Three scenarios:

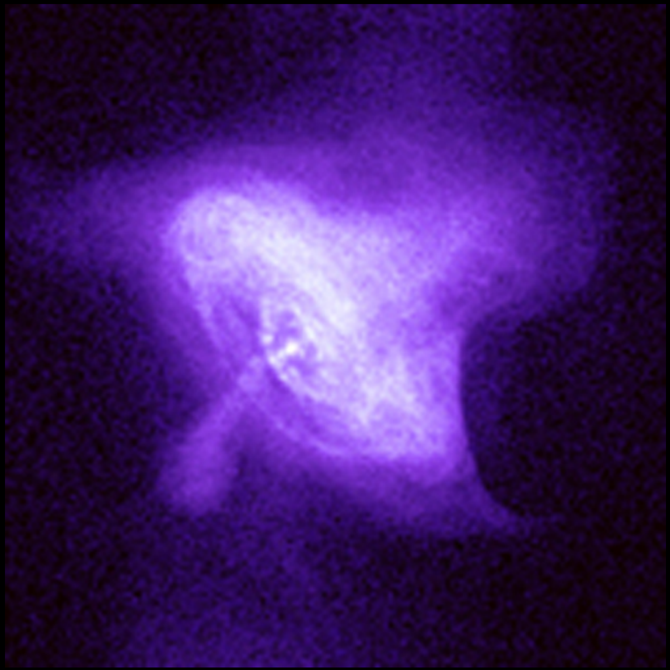
  i) Fully coherent signal over entire run (most likely case)

  ii) Glitch causes phase offset between EM and GW signals, so add as extra parameter

  iii) Perform independent coherent searches on stretches of data between glitches

Crab pulsar search

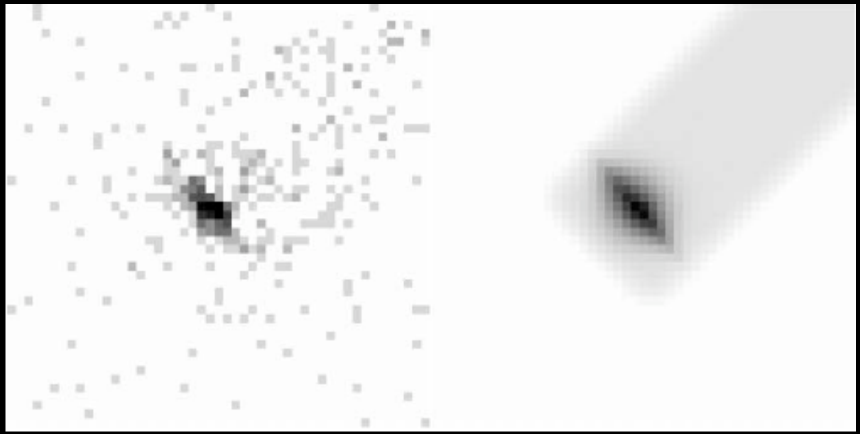
- Priors on polarisation and orientation angles from Pulsar Wind Nebula observations ψ = 125.16±1.36°, ι = 62.17±2.20° (Ng and Romani, Ap. J., 673, 2008)
- For scenario i) with priors as above we get:
  - h_0 upper limit 2.0×10^{-25}
  - ellipticity upper limit 1.1×10^{-4}
  - ratio to spin down amplitude of 7
- Assuming uniform priors increases upper limit by ~1.3 times (orientation given by priors is favourable)
- Limit power in gravitational waves to less than ~2% of that available from spin-down



Credit: NASA/CXC/SAO

J0537-6910 and J1952+3252

- PSR J0537-6910 (f_{gw} = 124.0 Hz, dist = 49.4 kpc)
  - Have RXTE 7 ephemerides for pulsar over whole of S5 (glitchy pulsar, with large timing noise)
  - Six glitches in this time – perform analysis in same scenarios as for the Crab
  - Priors on polarisation and orientation angles from Pulsar Wind Nebula observations ψ = 131.0±2.2°, ι = 92.8±0.9° (non-optimal orientation)
- PSR J1952+3252 (f_{gw} = 50.6 Hz, dist = 2.5 kpc)
  - Observed to glitch once between 1-12th Jan 2007 - have timing solutions for the two epochs
  - No observational constraints on orientation



X-ray image (left) and best fit (right) of the Pulsar Wind Nebula around J0537-6910, Ng and Romani, Ap. J. 2009

Preliminary results

- For J0537-6910 scenario i) gives (using orientational angle priors):
  - h_0 upper limit 4.4×10^{-26}
  - ellipticity limit 1.3×10^{-4}
  - amplitude ratio to spin-down 2/3 (assuming moment of inertia of 10^{38} kgm^2)
  - using uniform priors gives improvements of about 1.4 - PWN gives unfavourable orientation
- For J1952+3252 scenario i) gives:
  - h_0 upper limit 2.9×10^{-25}
  - ellipticity limit 2.7×10^{-4}
  - amplitude ratio to spin-down ~2/5

S6 search

- Enhanced LIGO S6 and Virgo+ VSR2 will begin soon
- For LIGO 4k detectors sensitivity is anticipated to be greater than S5
- Search could be done coherently with S5 data, or use S5 as prior - could give *at least* $\sqrt{2}$ increase in sensitivity
- We want to again search for as many pulsars as possible - radio observations will be vital
  - RXTE life extended for another year, so J0537-6910 observable for most of S6 - beat spin-down limit!
- Certain young pulsars close to spin-down limit are most enticing candidates and require observations: e.g. J1952+3252 (f_{gw}=50.6 Hz), J1913+1011 (f_{gw}=55.6 Hz)
  - see http://www.tapir.caltech.edu/~teviet/KnownPulsars/

Conclusions

- Have preliminary S5 results for 116 pulsars
  - Analysis review in progress
  - draft paper near completion
- S6/VSR2 should allow us to reach/beat spin-down limits for several more pulsars
  - need radio observation of these
- Include Virgo data (better low frequency sensitivity - look for Vela pulsar) - *see talk by Sergio Frasca*