Gravitational waves from known pulsars: past searches and future prospects

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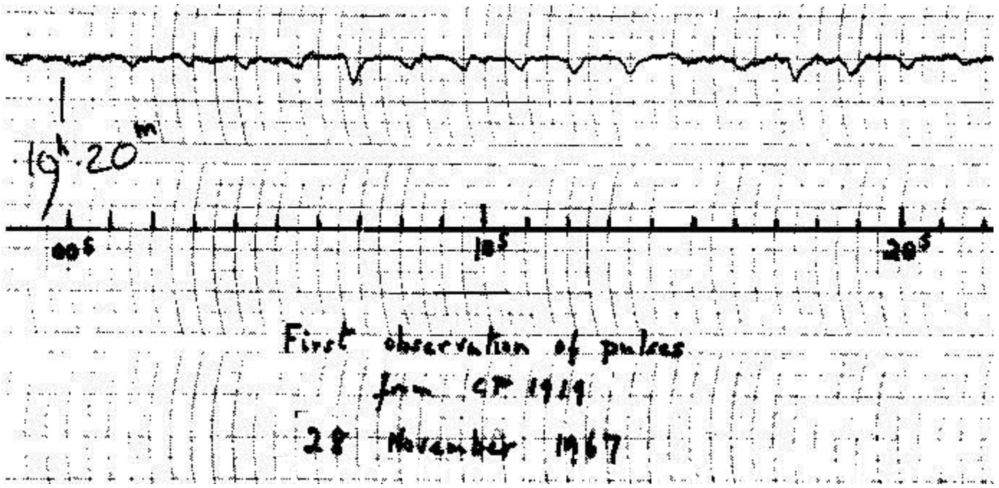
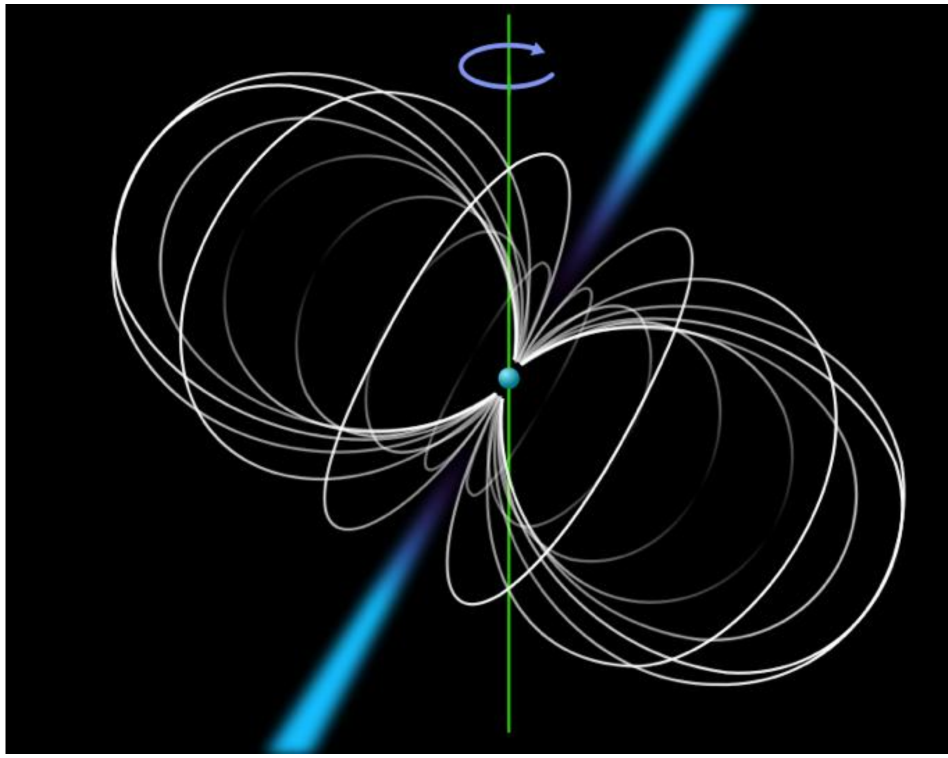
What are pulsars?

- First pulsar discovered by accident in 1967 by Bell and Hewish who were trying to study interplanetary scintillation of radio sources - period of 1.3 seconds
- Several more pulsars soon discovered including Crab pulsar with period of ~33ms [Cocke et al, et al, Nature, 221, 1969 – period seen in optical]
- Pulse period and duration suggested a very small source (smaller than white dwarfs)
    - consistent with theorised neutron stars (first proposed by Baade & Zwicky in 1934)



What are pulsars?

- Rapidly rotating neutron stars
  - beamed radiation (radio through to γ-rays) from magnetic poles
  - periods from seconds to milliseconds
  - high magnetic fields (implied from spin-down)
    - ~10^{12} gauss - normal young neutron star; ~10^{10} gauss - old neutron star; ~10^{8} gauss - recycled millisecond pulsar
  - found in:
    - Globular clusters; binary systems (with other NSs, white dwarfs, main sequence stars, planets); supernova remnants; isolated

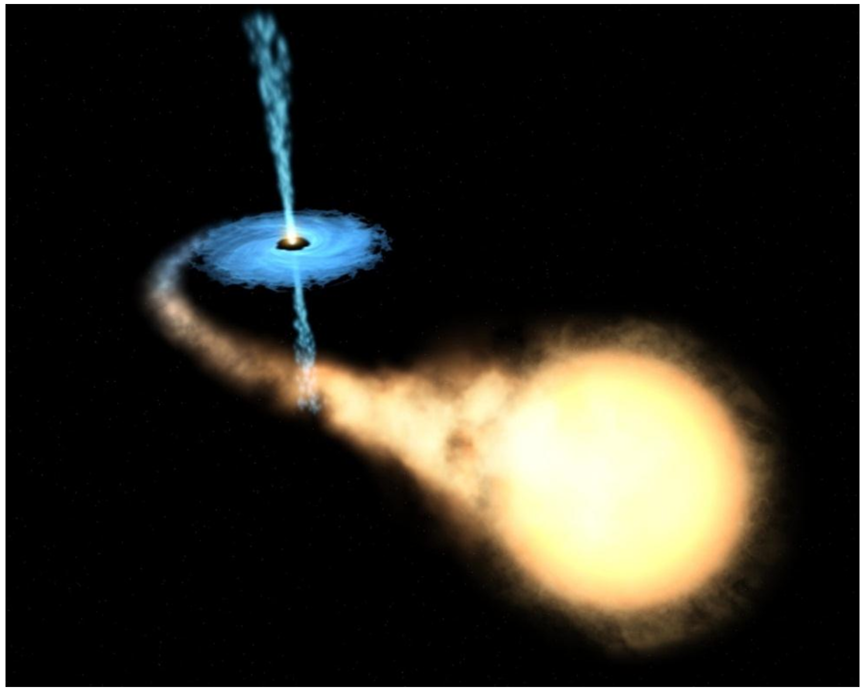


Fermi γ-ray observations of Vela pulsar. Credit: NASA/DOE/Fermi LAT Collaboration

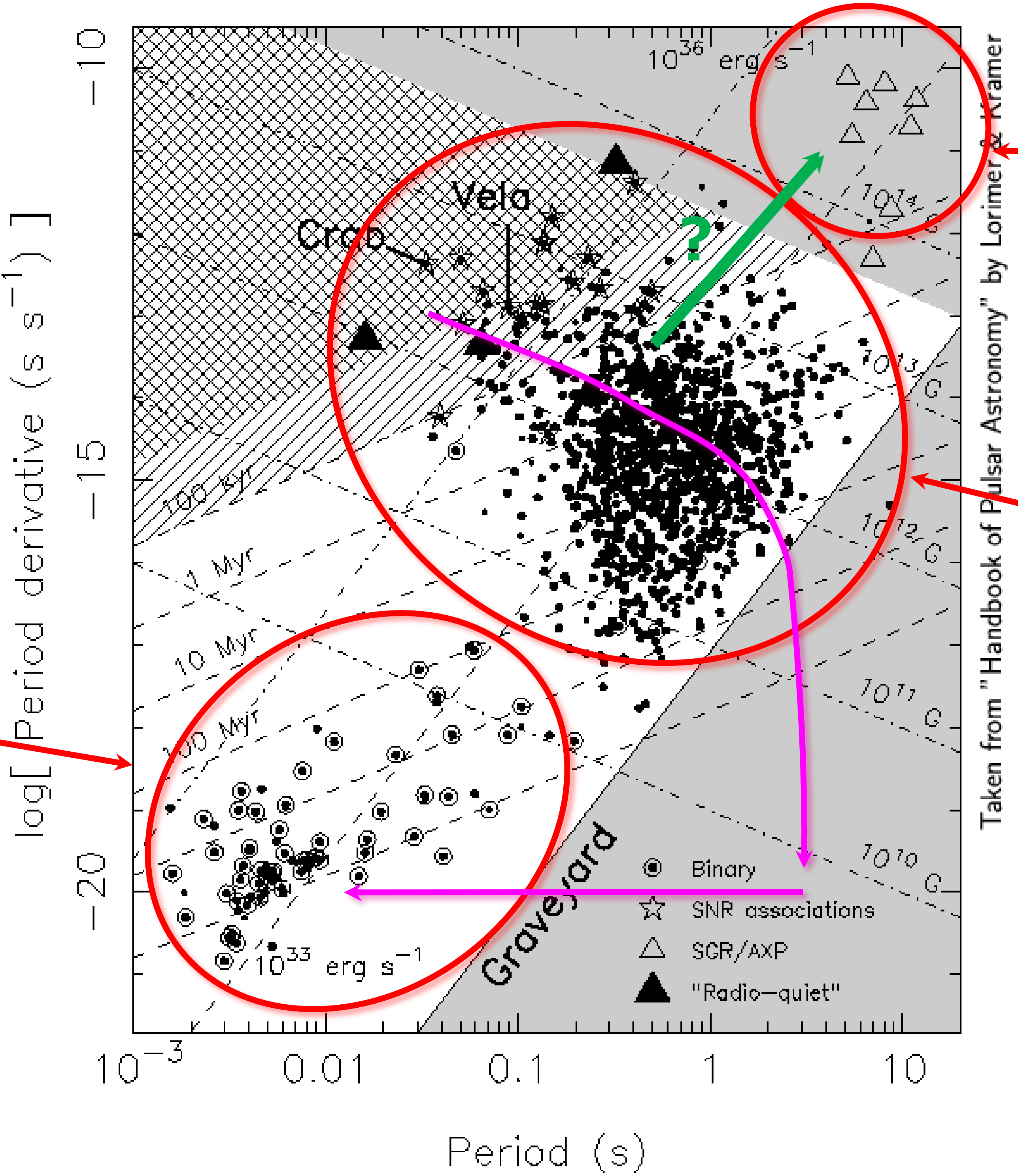
What are pulsars?

- Young pulsars have large magnetic fields
  - spin-down rapidly
    - dipole radiation (often assumed to be the main loss mechanism to infer the magnetic field)
    - particle acceleration
    - gravitational radiation
    - other?
- Old millisecond "recycled" pulsars (MPSs) (see review arXiv:0811.0762)
  - pulsars were/are part of a binary system and 'spun-up' from accreting material from companion
  - lose much of their magnetic field - spin-down slowly

Crab nebula. Credit: J. Hester (ASU), CXC, HST, NRAO, NSF, NASA



What are pulsars?



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

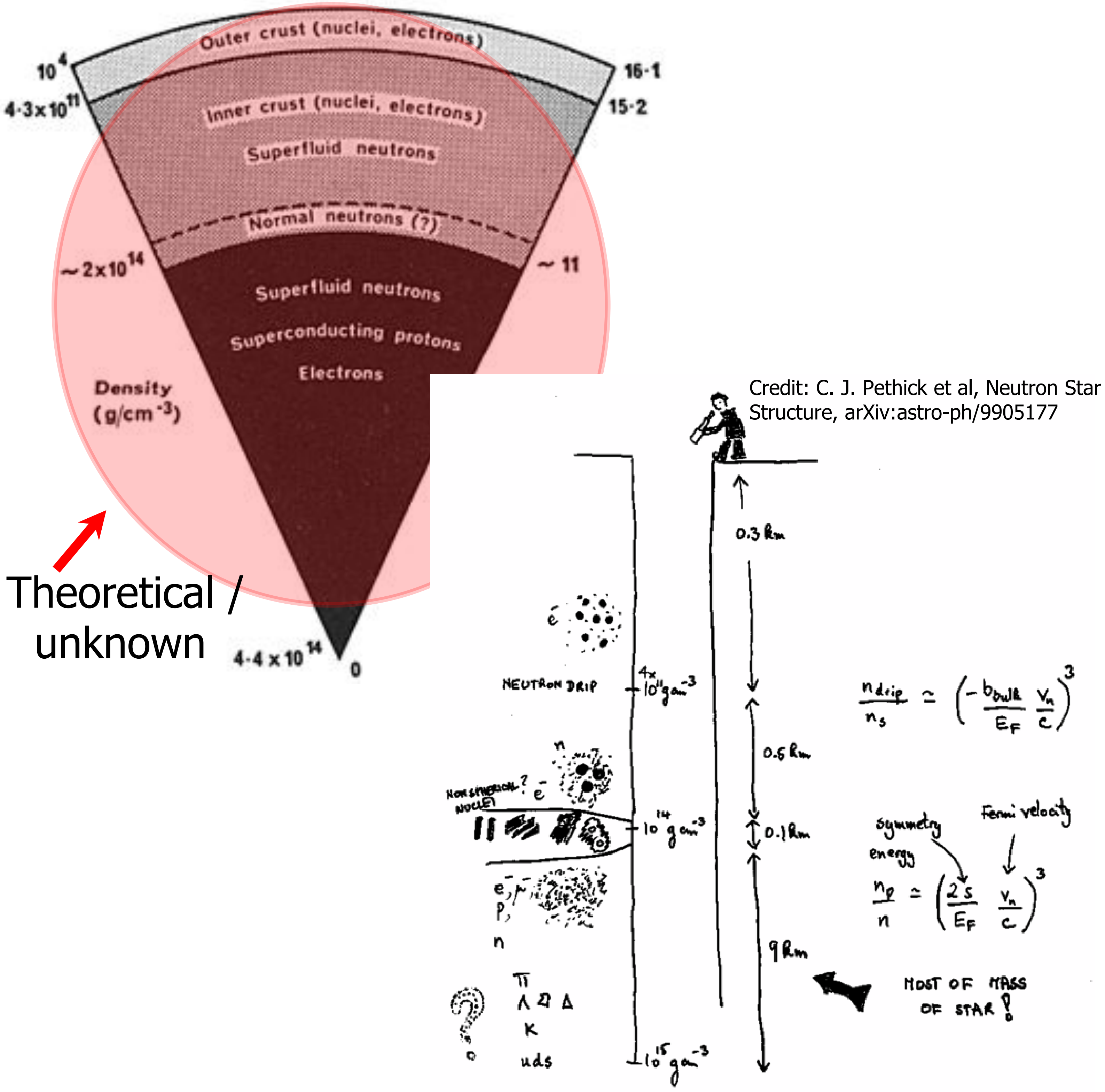
magnetars

"young" pulsars

Old recycled pulsars

What are pulsars?

- Neutron stars (big nuclei!):
  - –mass ~1.4 M$_\odot$
  - –radius ~10km
  - –mean density few 10^{17} kg/m^3
  - –quark stars?
    - harder equation of state
    - thinner crust

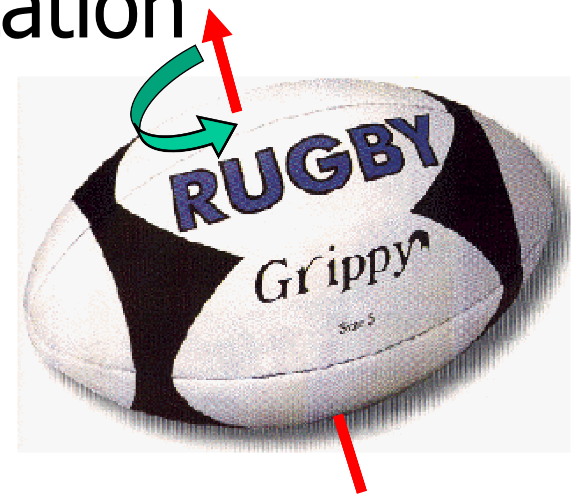


Theoretical / unknown

Credit: C. J. Pethick et al, Neutron Star Structure, arXiv:astro-ph/9905177

Gravitational waves from neutron stars

- For GW emission NS must have a time varying quadrupole moment i.e. be deformed/aspherical:
  - triaxial - have a bump/mountain (emit at 2x rotation frequency) [**continuous emission**]:
    - from formation; from magnetic field (e.g. magnetic mountains); from stresses during relaxation



  - vibrational modes
    - fundamental mode (first resonant mass quadrupolar mode)
      - excited by glitch/nuclear explosion/SGR burst/impact(?)
    - r-modes (Rossby waves) wave-like mode (from the mass current quadrupole) in hot young/accreting NS
  - precession

GWs from neutron stars

- Emission estimates:
  - triaxial star

rotation frequency (but GW signal will be at twice this value)

$$h \sim 4.2 \times 10^{-26}\left(\frac{\varepsilon}{10^{-6}}\right)\left(\frac{I_{zz}}{10^{38}\mathrm{kg\ m}^2}\right)\left(\frac{f}{100\ \mathrm{Hz}}\right)^2\left(\frac{1\ \mathrm{kpc}}{r}\right)$$

quadrupole moment

ε = equatorial ellipticity

$$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$$

Ellipticity also depends on *equation of state* and allowable sustainable crust breaking strains

I_{zz} = principle moment of inertia

$$I_{zz} \approx \frac{2MR^2}{5}$$

uniform density sphere

Moment of inertia depends on *equation of state* - mass and radius

Theoretical expectations

- Exotic forms of crystalline quark matter could sustain ellipticities of 10^{-4} [arXiv:astro-ph/0503399; arXiv:0708.2965; arXiv:0708.2984; arXiv:0901.4637]
- Or, could be held up by (internal) magnetic fields of order 10^{16}G (dependent on configuration and equation of state of star) [e.g. arXix:astro-ph/9602107, arXiv:gr-qc/0206051; arXiv:0705.2195; arXiv:0712.2162, arXiv:1204.3781]
- Horowitz and Kadau [arXiv:0904.1986] suggest that normal neutron star crusts may sustain ellipticities of up to 10^{-5}
- 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

Pulsars: spin-down limit

- Pulsars lose energy and slow down:
  - Magnetic dipole radiation
  - Particle acceleration
  - Gravitational radiation
- Braking index n: $\dot{f} = k f^n$ $\quad n = \dfrac{f\,\ddot{f}}{\dot{f}^2}$
  - 3 for pure magnetic dipole
  - 5 for pure gravitational radiation
- Pulsars with measurable braking indices (only 4 or 5 objects) have $n<3$ suggesting some combination of processes

Pulsar	n
Crab pulsar	2.51±0.01
B0540-69	2.28±0.02
B1509-58	2.837±0.001
Vela pulsar	1.4±0.2

from Palomba, *A&A*, **354**, 2000

Pulsars: spin-down limit

- Assuming spin-down is all due gravitational waves we can set the so-called ‘spin-down limit’

spin-down luminosity = gravitational wave luminosity

$$h_{\text{spin-down}} \sim \left(\frac{5}{2} \frac{G\, I_{zz} |\dot{f}|}{c^3 r^2 f} \right)^{1/2}$$

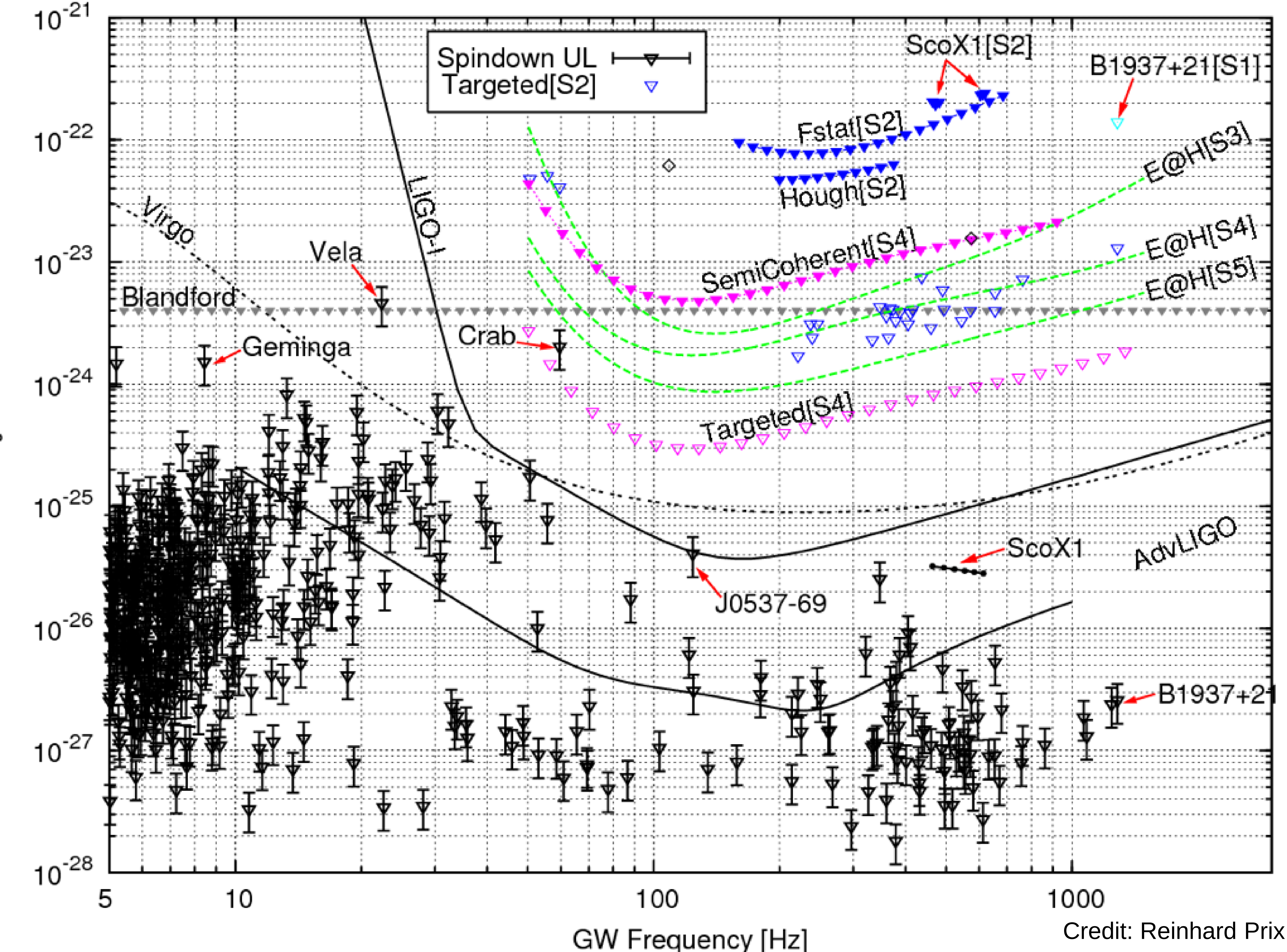
spin-down rate

spin frequency

distance to pulsar

$$h_{\text{spin-down}} \sim 2.5 \times 10^{-25} \left(\frac{I_{zz}}{10^{38} \text{kg m}^2} \right)^{1/2} \left(\frac{|\dot{f}|}{10^{-11} \text{Hz s}^{-1}} \right)^{1/2} \left(\frac{100 \text{ Hz}}{f} \right)^{1/2} \left(\frac{1 \text{ kpc}}{r} \right)$$

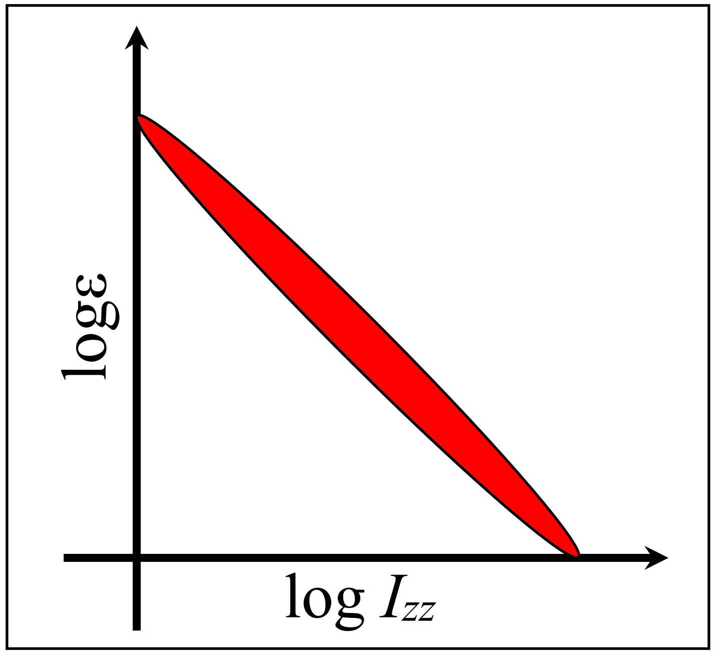
- For most millisecond pulsars (with very small spin-downs) this number is small and well below current sensitivities (but not future observatories)
- For several young pulsars we can approach, or beat this limit



Credit: Reinhard Prix

Neutron star physics

- What can we learn from direct observations (of continuous waves from a triaxial star)?
- Direct observation would constrain the quadrupole moment:
  - – Ellipticity
    - breaking strain of neutron star matter
      - – large ellipticity - solid quark star?);
    - magnetic fields
  - – Moment of inertia
    - neutron star equation of state



- Unfortunately these parameters are highly degenerate
  - – need input from theory/other observations to constrain individual parameters
- Quantify energy budget of star’s spin-down

Data analysis: model

- What does the signal model look like?
- For a simple rigidly rotating triaxial star:

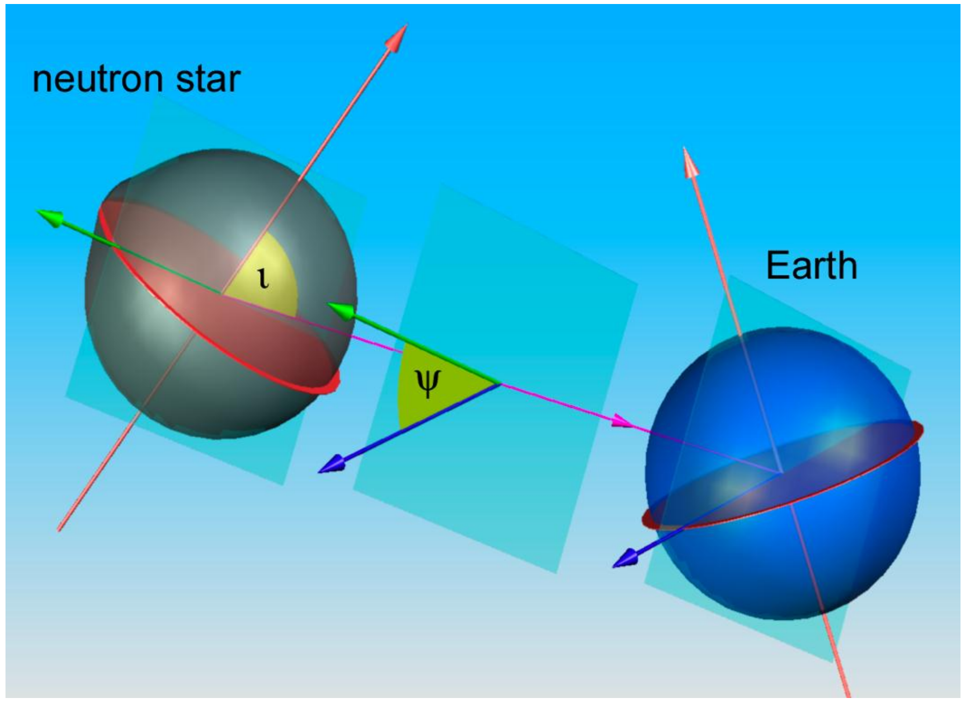
+ and x polarisation antenna response for a given detector

$$h(t) = F_{+}(t,\psi)\frac{h_0}{2}(1+\cos^2\iota)\cos 2\phi(t) + F_{\times}(t,\psi)h_0\cos\iota\sin 2\phi(t)$$

Polarisation angle

Inclination angle

Spin phase evolution



Data analysis: model

- Phase model:

$$\phi(t) = \phi_0 + 2\pi \left\{ f(t+\Delta t) + \frac{\dot{f}}{2}(t+\Delta t)^2 + \frac{\ddot{f}}{6}(t+\Delta t)^3 + \cdots \right\}$$

  - Doppler shift in signal due to detector motion
    - Earth's orbital motion and rotation (depends on pulsar position)
    - pulsar motion w.r.t. the solar system barycentre (SSB) (e.g. if pulsar's in a binary system)
    - relativistic effects (e.g. Shapiro delay, gravitational redshift)
  - Take this into account as a time delay (same at all frequencies)

Data analysis: model

- Phase model:

$$\Delta t(t) = \Delta t(t)_{\mathrm{Roemer}} + \Delta t(t)_{\mathrm{Shapiro}} + \Delta t(t)_{\mathrm{Einstein}} + \Delta t(t)_{\mathrm{Binary}}$$

Position vector of Earth w.r.t. the SSB

Shapiro delay

Gravitational redshift and time dilation

Binary system time delay

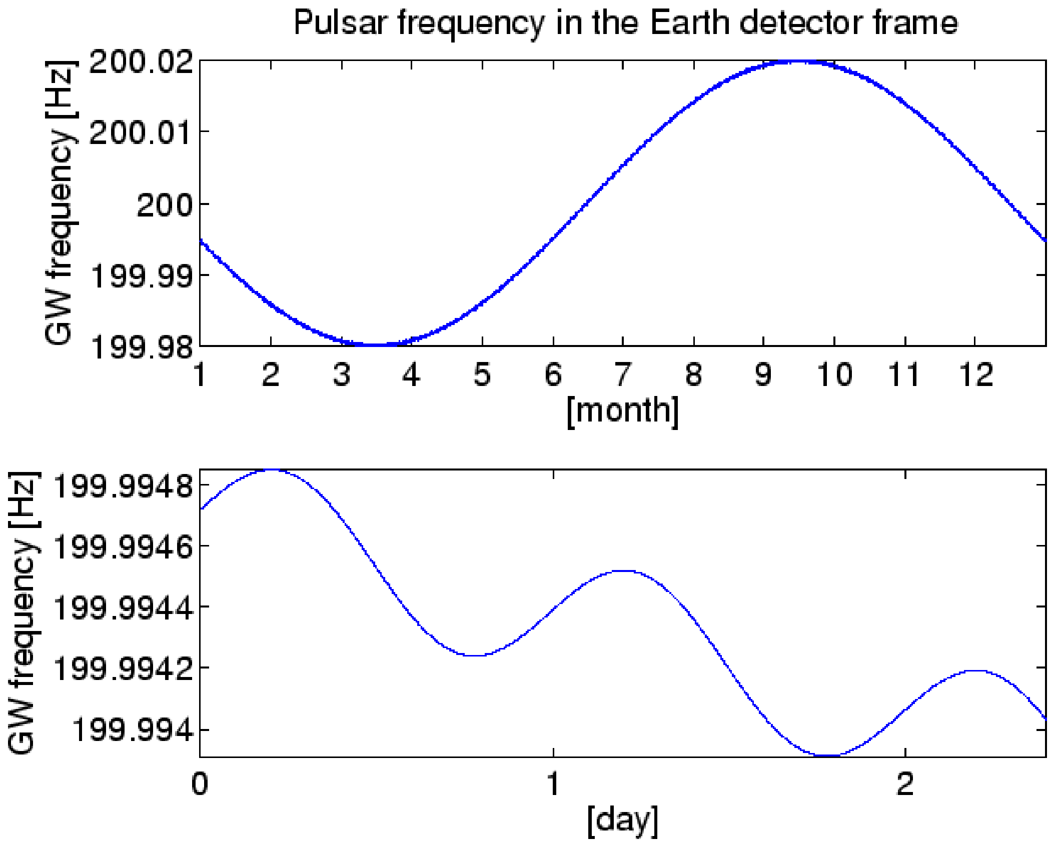
$$\Delta t(t)_{\mathrm{Roemer}} = \frac{r(t) \cdot \hat{n}(\alpha, \delta)}{c}$$

Propagation time across orbit e.g. doppler delay

Unit vector towards the pulsar

If ***r*** and ***n*** stay close to orthogonal get minimum time delay

Maximum solar system doppler shift ~1x10^{-4}f Hz



Pulsar frequency in the Earth detector frame

Data analysis

- For known pulsars we know: sky position; spin frequency evolution; binary parameters
  - Phase model completely defined, so can perform coherent analysis of all data
- We have a GW model defined by a set of 4 unknown parameters:

$$\boldsymbol{a} = \{h_0, \iota, \psi, \phi_0\}$$

- Given a set of data we evaluate the (Gaussian) likelihood over the parameters

data model

likelihood

$$p(\{d_i\}|\boldsymbol{a}_i, I) \propto \prod_i \exp\left[-\frac{(d_i^2 - h(\boldsymbol{a}_i))^2}{2\sigma_i^2}\right]$$

noise variance

log likelihood

$$\ln p(\{d_i\}|\boldsymbol{a}_i, I) = L \propto \sum_i -\frac{(d_i - h(\boldsymbol{a}_i))^2}{2\sigma_i^2}$$

Data analysis

- Frequentist method:
  - Maximum likelihood (find values of $\mathbf{a}$ that maximise the (log) likelihood ratio) - some parameters can be maximised analytically:

$$\left.\frac{\partial L}{\partial \boldsymbol{a}}\right|_{h_0,\iota,\phi_0,\psi} = 0$$

  - With such a statistic and a given false alarm/false dismissal rate you can define a detection criterion
    - to produce an upper limit you need to perform many Monte Carlo simulations on different realisations of noise
  - More suitable for wider parameter spaces - maximisation can be cheaper than marginalisation

Data analysis

- Bayesian method (used in LSC known pulsar searches):
  - natural way of parameter estimation and setting upper limits
  - produce posterior from likelihood and priors

$$p(\boldsymbol{a}_i|\{d_i\},I) \propto p(\{d_i\}|\boldsymbol{a}_i,I) \times p(\boldsymbol{a}_i|I) \longleftarrow \text{Priors}$$

  - generally use uniform independent priors for all parameters
  - marginalise over 3 unwanted parameters to create a posterior probability density for the wanted parameter h_0

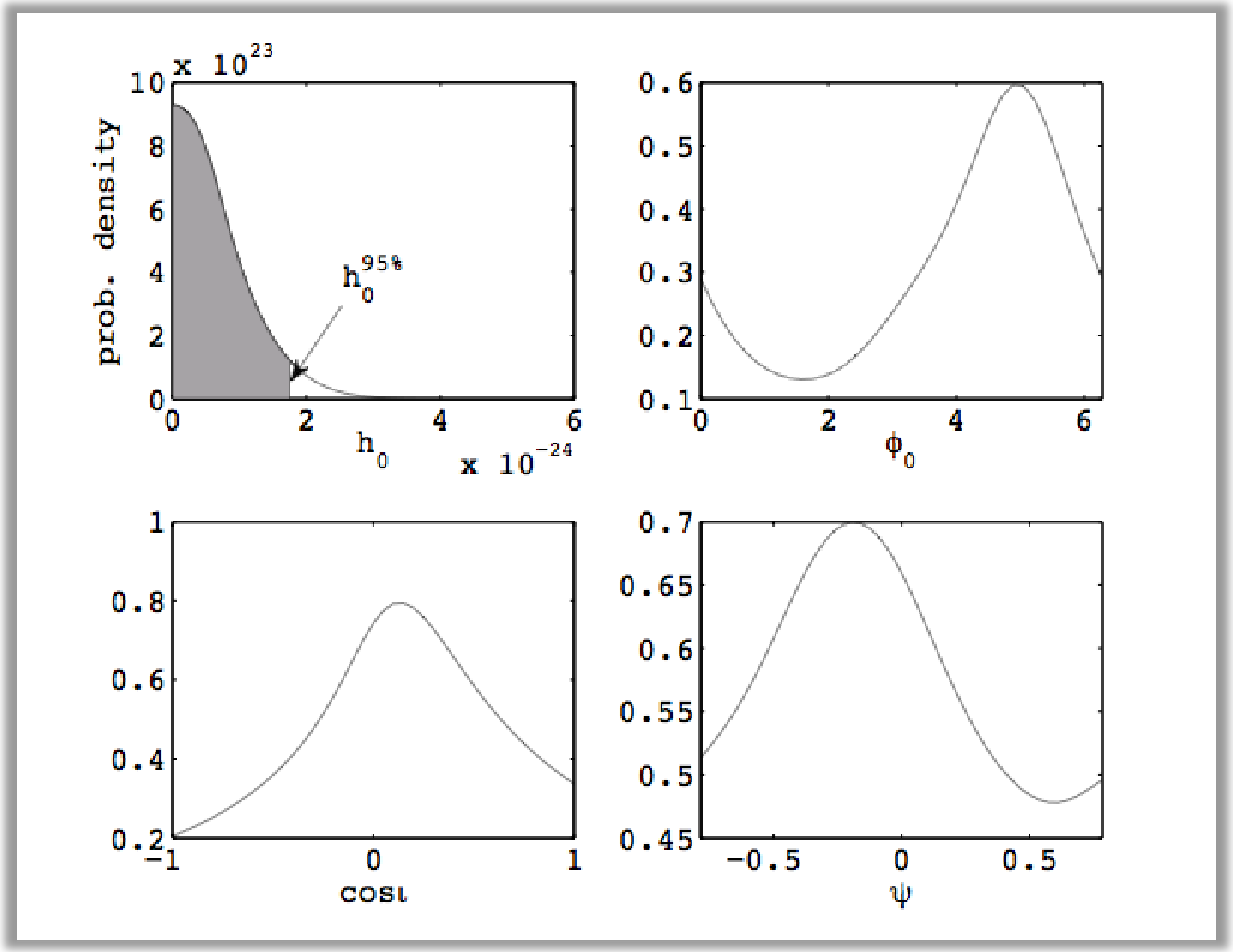
$$p(h_0|\{d_i\},I) \propto \int_{-\frac{\pi}{4}}^{\frac{\pi}{4}} \mathrm{d}\psi \int_0^{2\pi} \mathrm{d}\phi_0 \int_{-1}^{1} \mathrm{d}\cos\iota \, p(\{d_i\}|\boldsymbol{a}_i,I) \times p(\boldsymbol{a}_i|I)$$

    - can combine likelihoods from multiple detectors
    - marginalise over amplitude to get model evidence

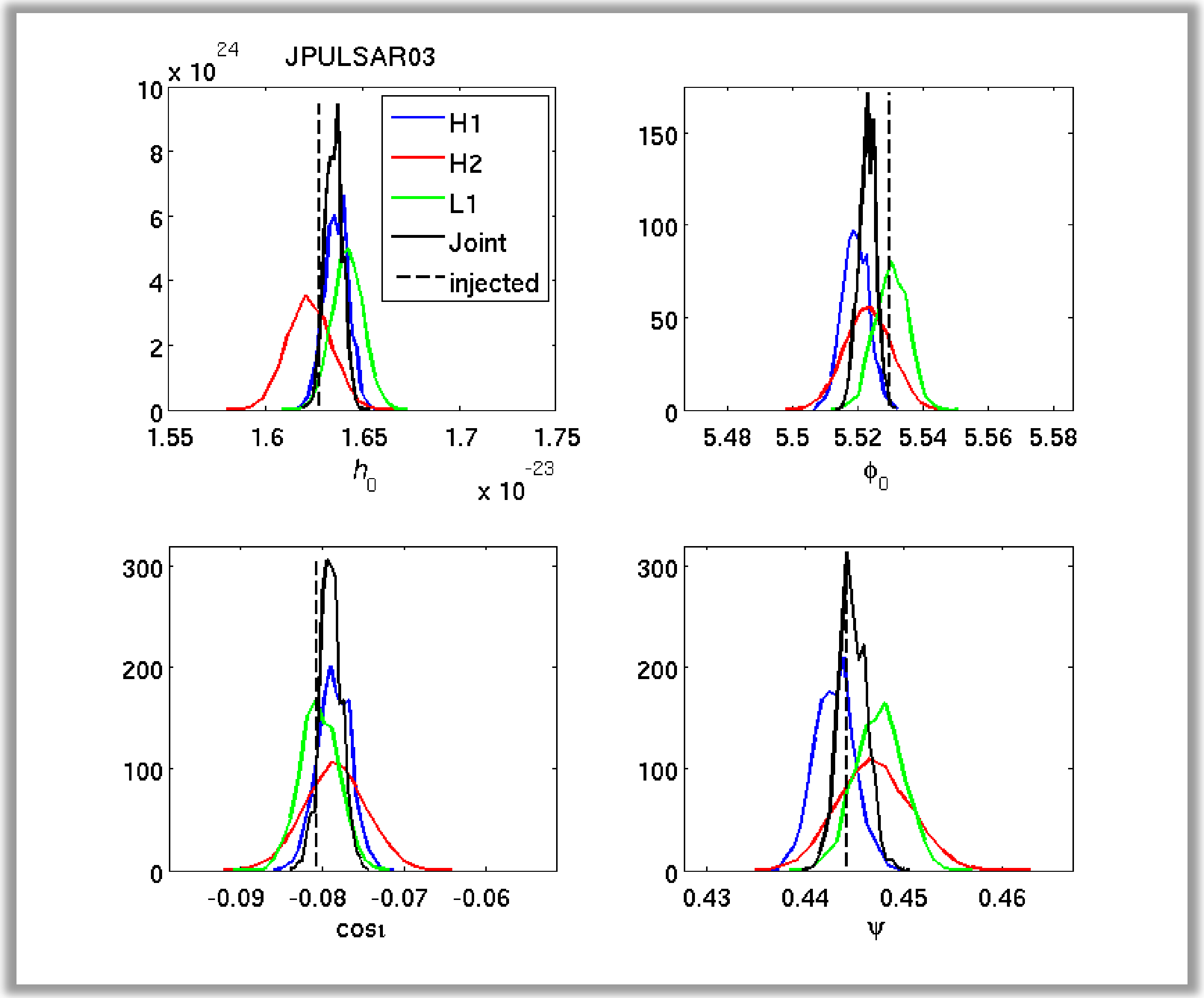
Data analysis: method

- If no signal is seen we can use posterior to set an upper limit e.g. 95% degree of belief

$$0.95 = \int_0^{h_0^{95\%}} p(h_0|\{d_i\}, I)\,\mathrm{d}h_0$$



Simulated signal



Data analysis

- In future use Bayesian hypothesis testing as a detection statistic:
  - Calculate evidence ratio for signal versus noise/incoherent signal between detectors
  - $\mathcal{B}$-statistic [arXiv:0907.2569]
    - Marginalisation with uniform priors rather than maximisation with unphysical priors
- Calculate evidence ratio between different signal models:
  - E.g. purely rigid triaxial star with emission at 2f vs. star with emission also at 1f [arXiv:0909.4035]

Known pulsar GW search history

- Searches for GWs from pulsars did not begin with LIGO:
  - Looking for GWs from the Crab pulsar (optical pulsations at ~30Hz discovered in 1969 [Cocke et al, Nature, 221, Feb 1969]):
    - 1972 – Levine and Stebbins (PRD, **6**, 1972) [National Bureau of Standards and JILA] used a 30m laser interferometer (single arm Fabry-Perot cavity)
    - 1978 – Hirakawa *et al* (PRD, **17**, 1978 and PRD, **20**, 1979) [Tokyo] searched for the Crab - specially designed ~1000kg aluminium quadrupole antenna with resonant frequency at 60.2 Hz

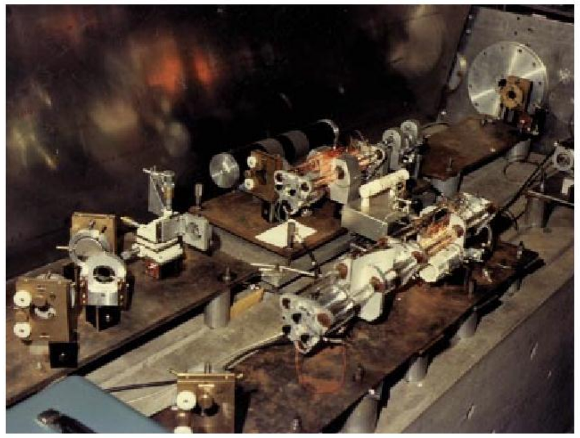


Fig. 2. Laser table, in next room, to left and behind camera position of Fig. 1. Methane-stabilized laser (longer laser in foreground) heterodynes with interferometer-cavity length-stabilized laser, to provide frequency-based length control or readout information (~1971).

Fig. 1. View of 30-m interferometer in Poorman's Relief Gold Mine, with a colleague adjusting a mirror at the far end.

30 m interferometer at Poorman's Relief Gold-mine, Boulder, CO.
Credit: J. L. Hall, "Optical Frequency Measurement: 40 years of Technology Revolutions", *IEEE Journal on Selected Topics in Quantum Electronics*, Vol. **6**, No. 6, 2000

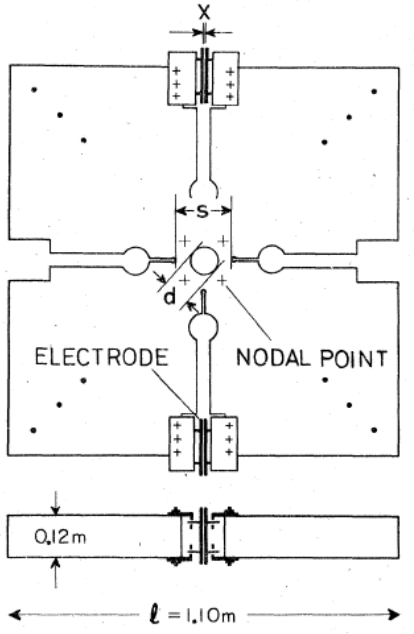
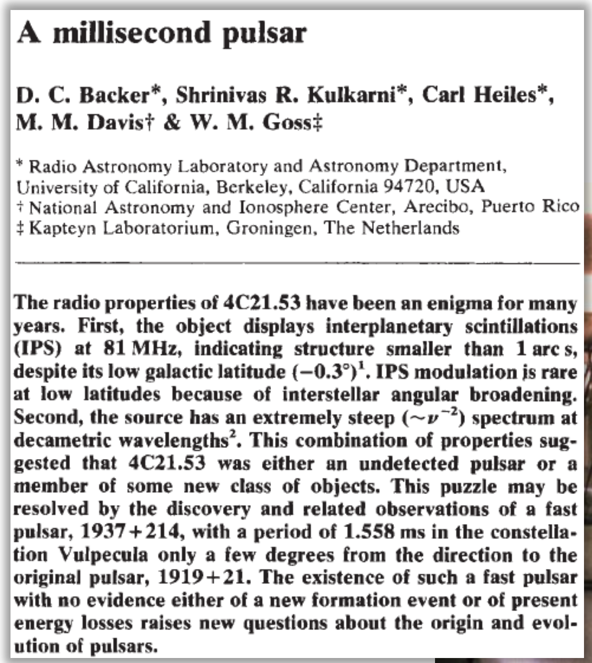


FIG. 1. 400-kg quadrupole antenna for gravitational radiation (GR) at 60.2 Hz. Machined from a square aluminum plate $l = 1.10$ m, it has cuts on each side, $s = 0.14$ m, $d = 0.08$ m. Four electrode plates are mounted in the cuts to form a pair of capacitors.

Hirakawa et al,
PRD, **17**, 1978

Known pulsar GW search history

- Other interferometer and bar detector searches:
  - Then fastest millisecond pulsars PSRJ1939+2134 (~642 Hz)
    - 1983 – Hereld [PhD thesis] at Caltech using 40 m interferometer
    - 1983 – Hough *et al* [Nature, **303**, 1983] at Glasgow using split bar detector



A millisecond pulsar

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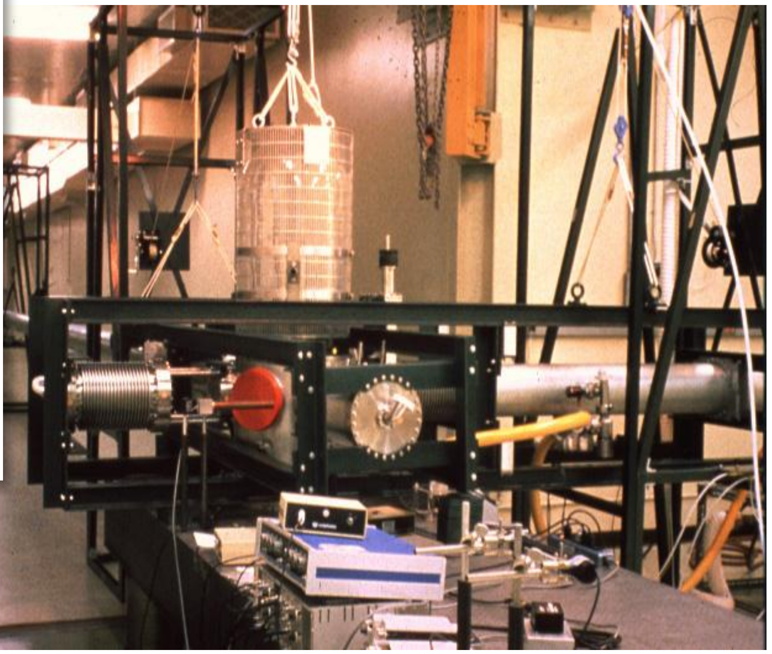
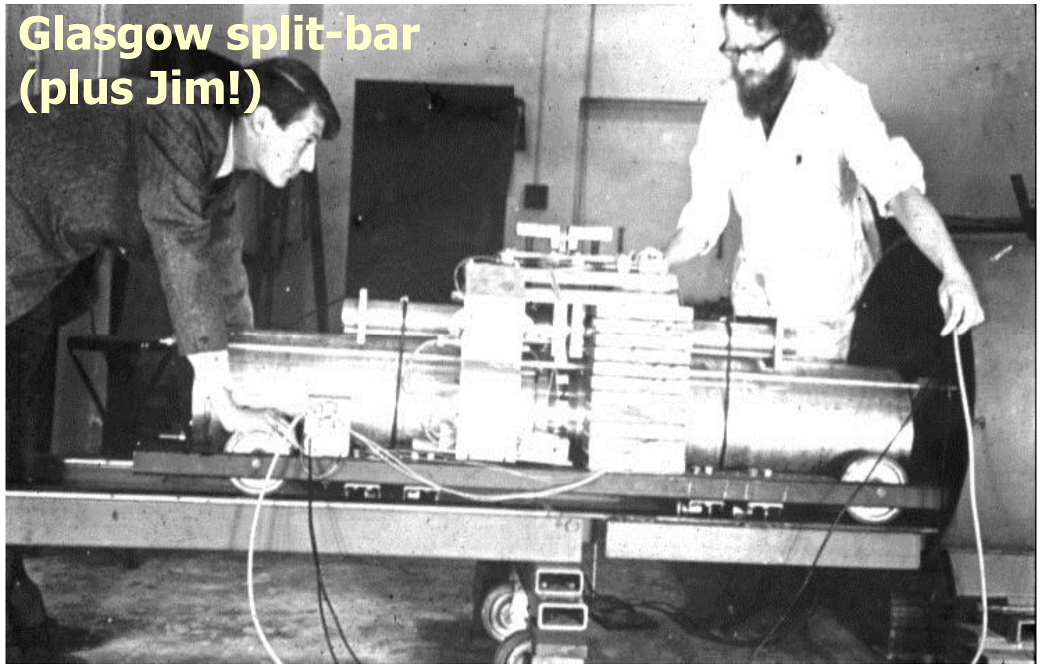
† National Astronomy and Ionosphere Center, Arecibo, Puerto Rico
‡ Kapteyn Laboratorium, Groningen, The Netherlands

The radio properties of 4C21.53 have been an enigma for many years. First, the object displays interplanetary scintillations (IPS) at 81 MHz, indicating structure smaller than 1 arc s, despite its low galactic latitude (−0.3°)[1]. IPS modulation is rare at low latitudes because of interstellar angular broadening. Second, the source has an extremely steep ($\sim\nu^{-2}$) spectrum at decametric wavelengths[2]. This combination of properties suggested that 4C21.53 was either an undetected pulsar or a member of some new class of objects. This puzzle may be resolved by the discovery and related observations of a fast pulsar, 1937+214, with a period of 1.558 ms in the constellation Vulpecula only a few degrees from the direction to the original pulsar, 1919+21. The existence of such a fast pulsar with no evidence either of a new formation event or of present energy losses raises new questions about the origin and evolution of pulsars.

Nature, **300**, Dec 1982



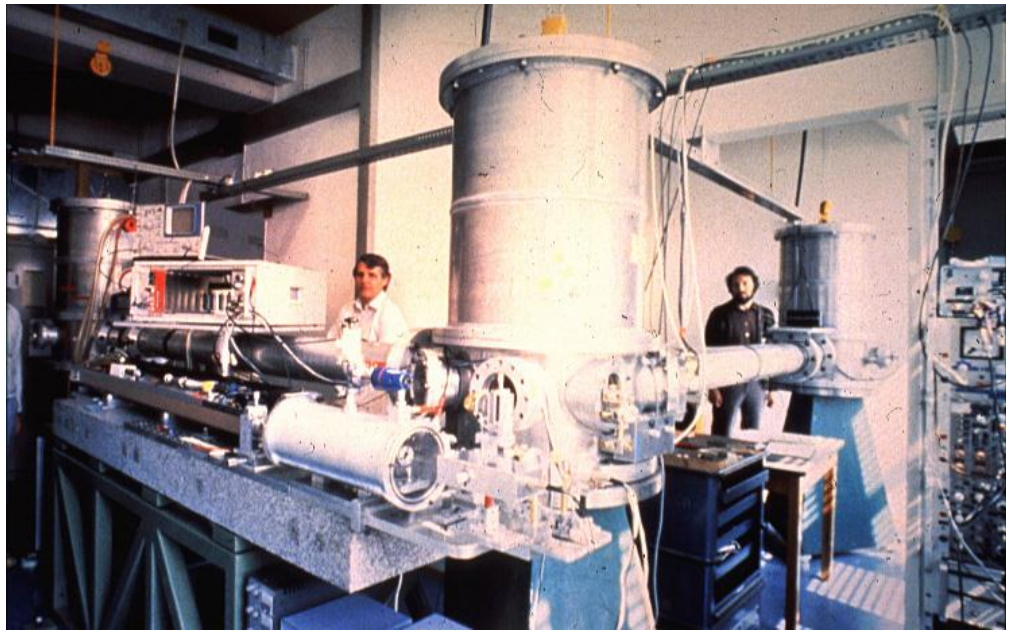
Caltech 40m proto-type



Glasgow split-bar (plus Jim!)

Known pulsar GW search history

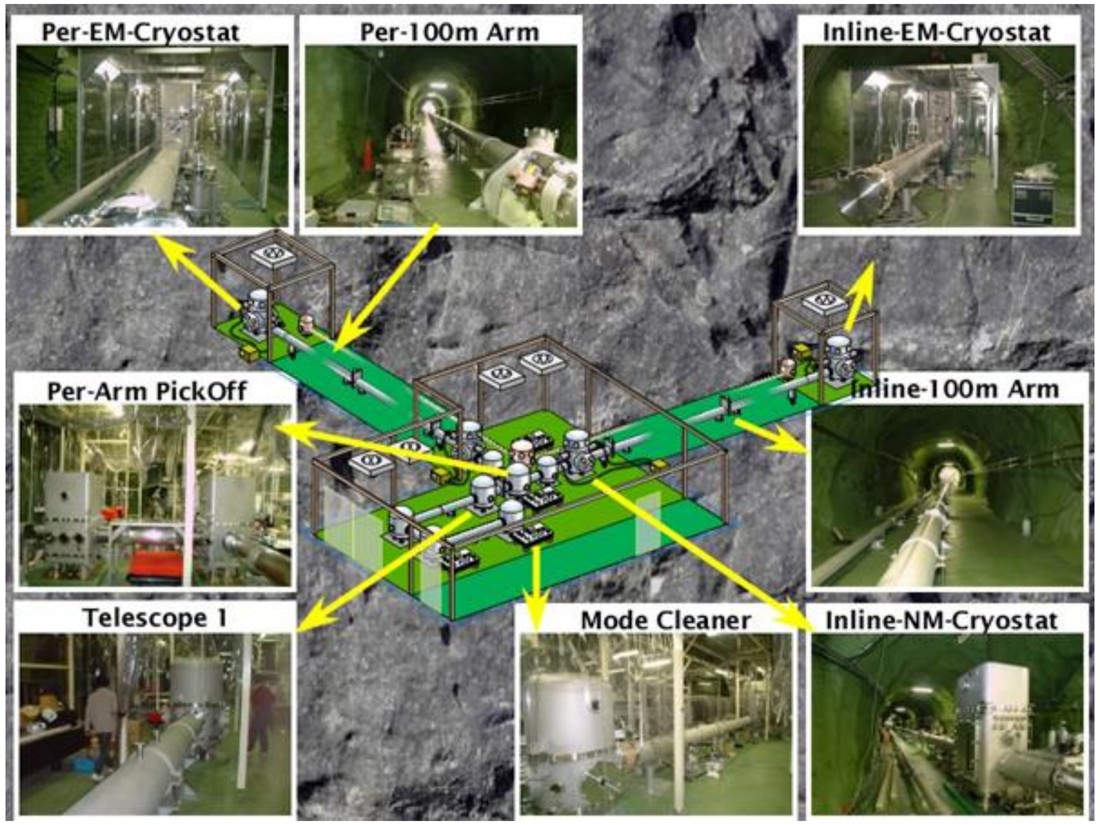
- The 90s:
  - 1993 – Niebauer et al [*PRD*, **47**, 1993] searched for GWs from a possible NS remnant of SN1987A using Garching 30m interferometer (100 hrs of data from 1989; searching around 2 and 4kHz): $h_0 < 9 \times 10^{-21}$
  - 1986-1995 – Tokyo group Crab pulsar search using torsion-type antenna Owa *et al* [1986mgm..conf..571O, 1988egp..conf..397O] using cooled (4.2K) 74 kg antenna, Suzuki [1995gwe..conf..115S] using cooled (4.2K) 1200kg antenna: $h_0 < 2 \times 10^{-22}$ (~140 times greater than spin-down limit)



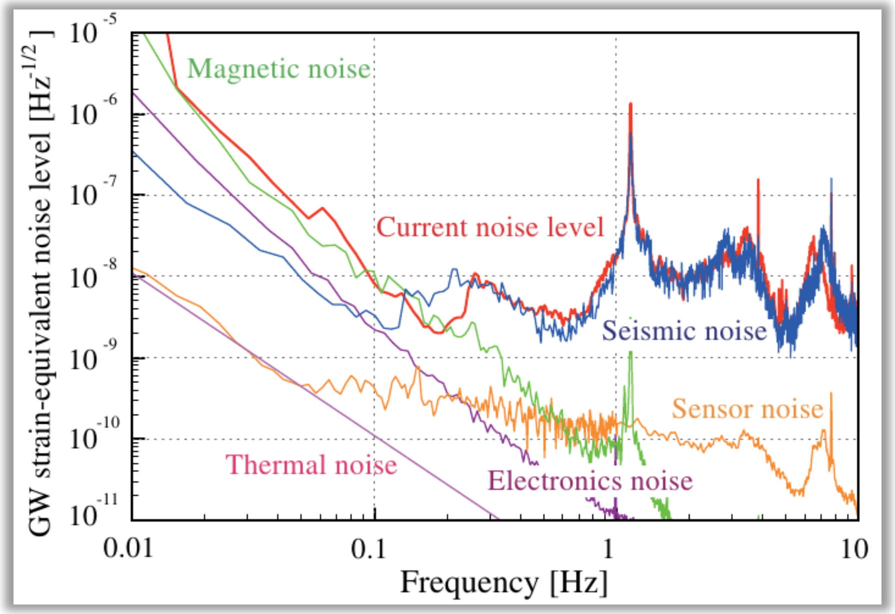
Garching 30m proto-type

Known pulsar search history

- Non-LVC searches (2000s):
  - 2008 – CLIO search for GWs from Vela [Akutsu *et al*, *CQG*, **25**, 2008]: $h_0 < 5.3 \times 10^{-20}$ at 99.4% CL
  - 2010 – Tokyo proto-type low-frequency mag-lev torsional bar antenna search for slowest pulsar (PSR J2144-3933 at $f_{\mathrm{rot}} \sim 0.1\ \mathrm{Hz}$) [Ishidoshiro, *PhD thesis*, University of Tokyo]: $h_0 < 8.4 \times 10^{-10}$ (Bayesian 95% UL with 10% calibration errors)
- Various narrow-band all-sky, and galactic centre, *blind* searches have been performed using EXPLORER and AURIGA bar detectors [arXiv:gr-qc/0011072, arXiv:gr-qc/0304107]

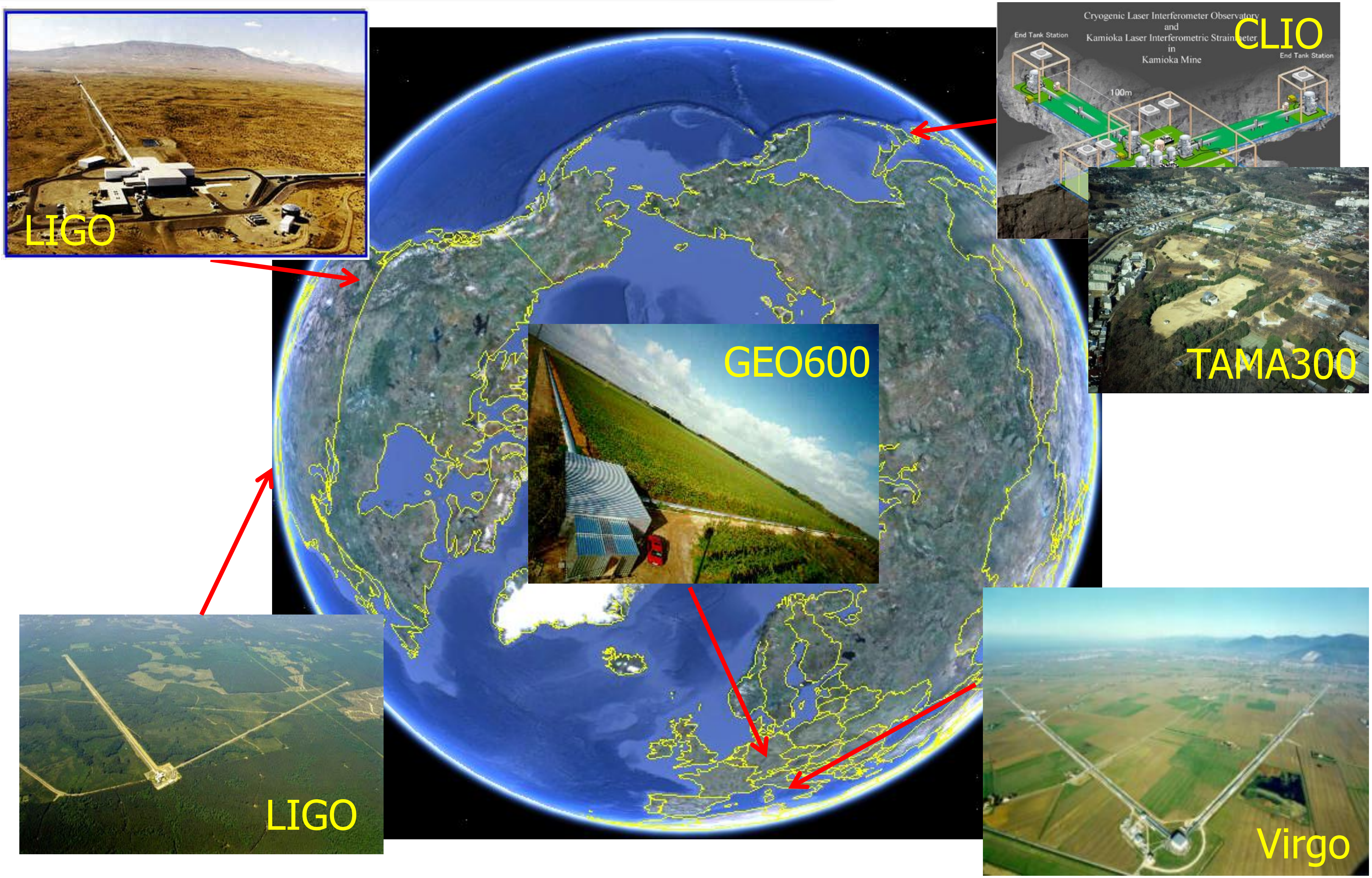


Credit: http://www.icrr.u-tokyo.ac.jp/gr/clio/CLIOALL.jpg



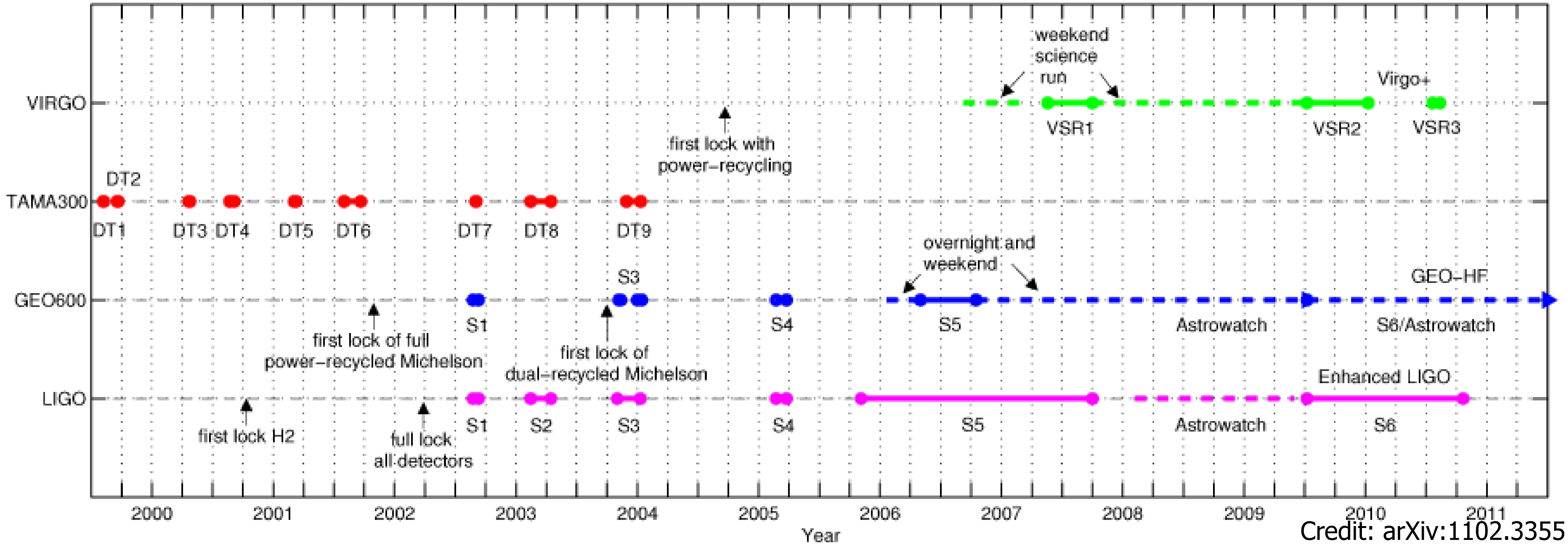
Sensitivity of TOBA arXiv:1103.0346

Gravitational wave detector network



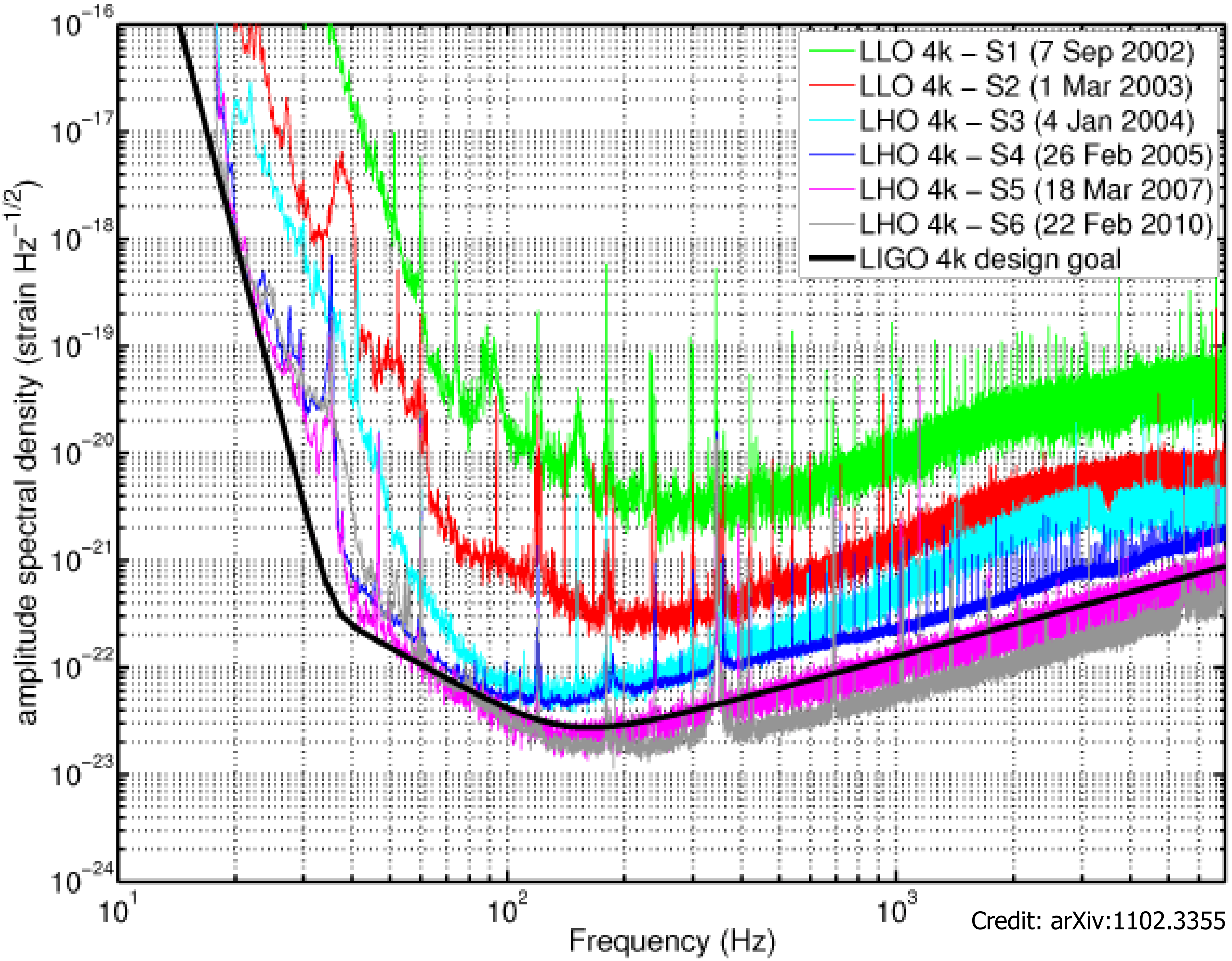
LVC Science runs

- Since 2001 interferometric detectors have been through periods of science data taking
- LIGO and GEO600 data have been analysed as part if the LIGO Scientific Collaboration
  - some joint analyses with TAMA and Virgo
- In 2007 Virgo joined forces with the LSC for joint analyses
- 6 major science runs producing astrophysical results with data up to 2011



Credit: arXiv:1102.3355

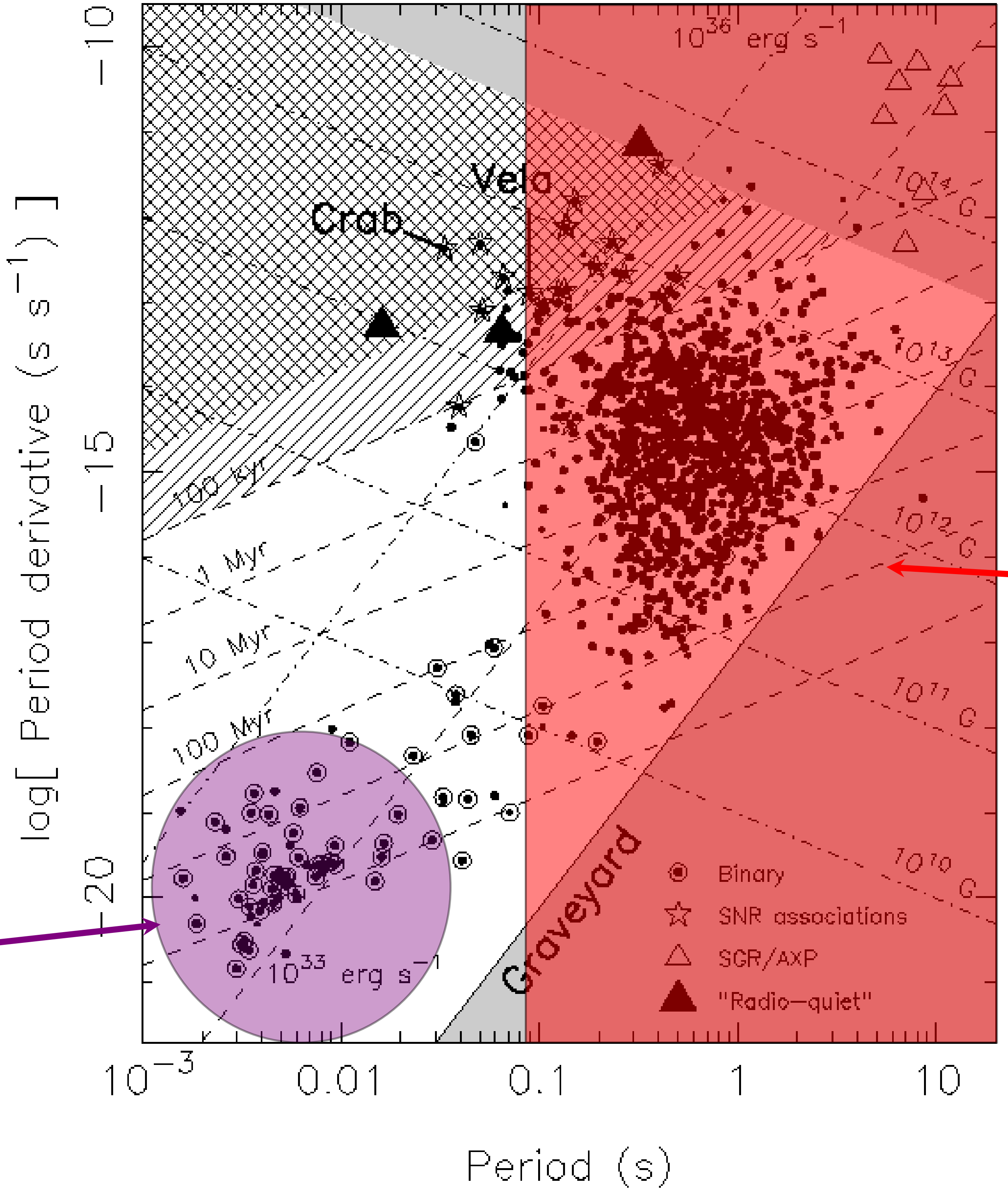
LIGO Science runs



Credit: arXiv:1102.3355

The best strain sensitivities from the LIGO science runs S1 through S6

Pulsars in LVC searches



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

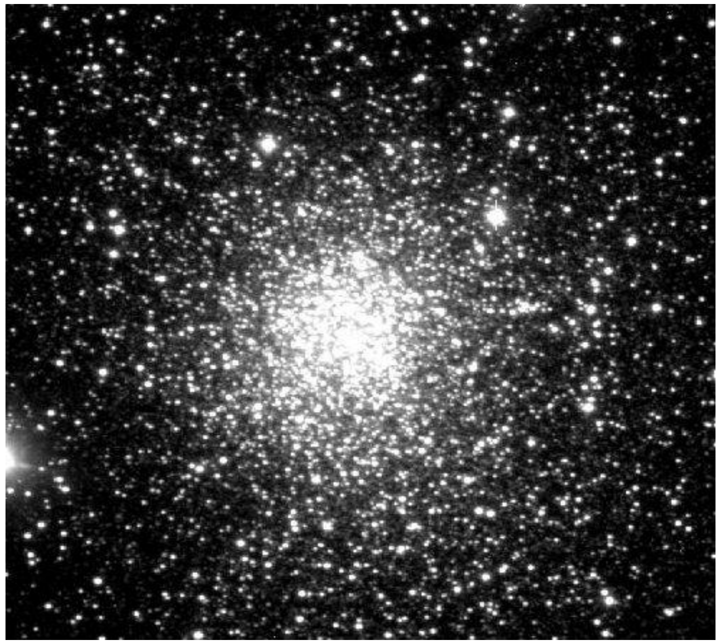
Region excluded from current searches due to lack of detector sensitivity

Old millisecond pulsars

LSC searches

- Used LIGO and GEO600 science (S) run data for searches
- S1 search for 1 pulsar (then fastest - J1939+2134) [arXiv:gr-qc/0308050]
- S2 search for 28 isolated pulsars [arXiv:gr-qc/0410007]
- S3 and S4 targeted 78 known (isolated and binary) radio pulsars with spin frequencies greater than 25Hz [arXiv:gr-qc/0702039]
  - 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 [arXiv:0805.4758]
  - 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

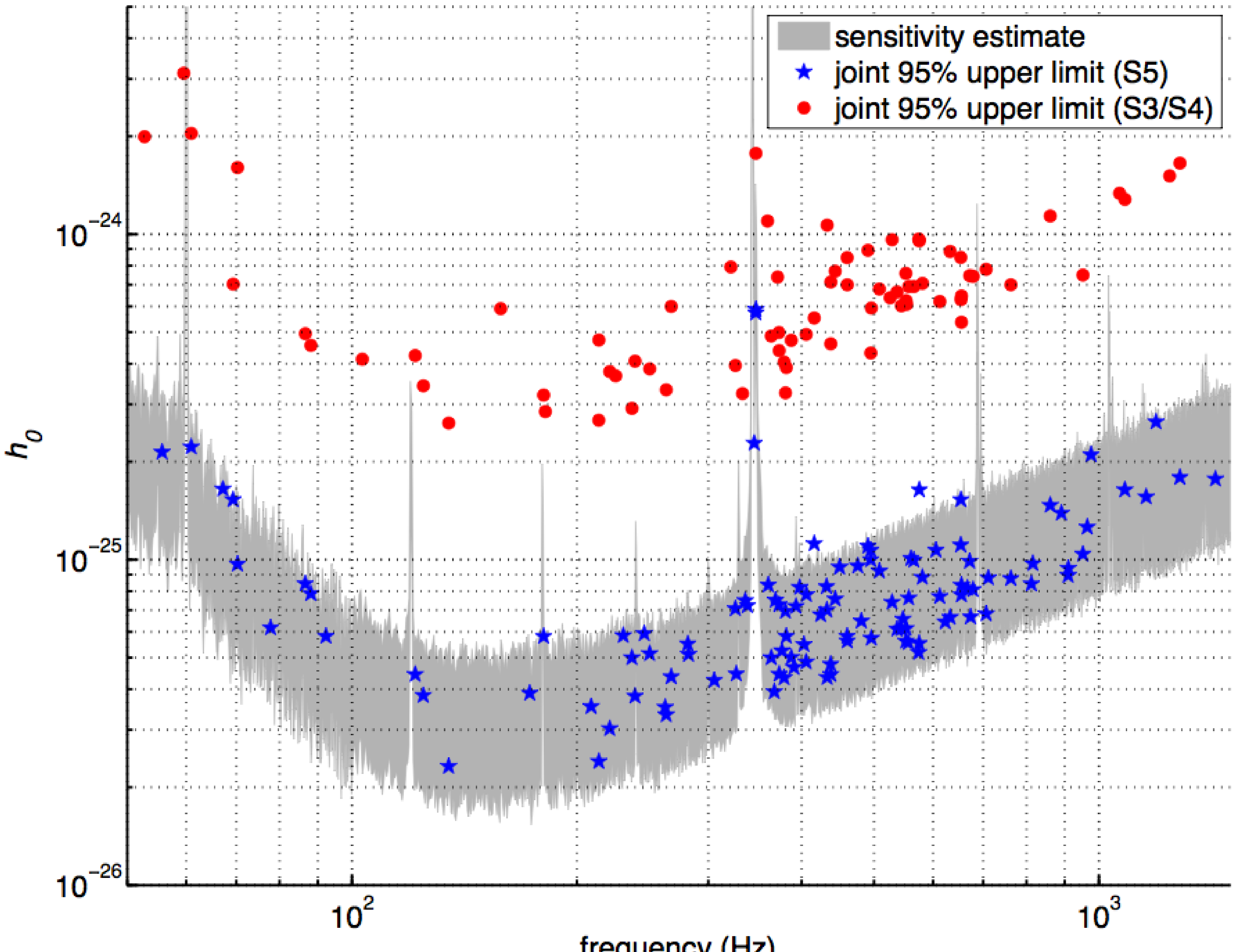
Searches: S5



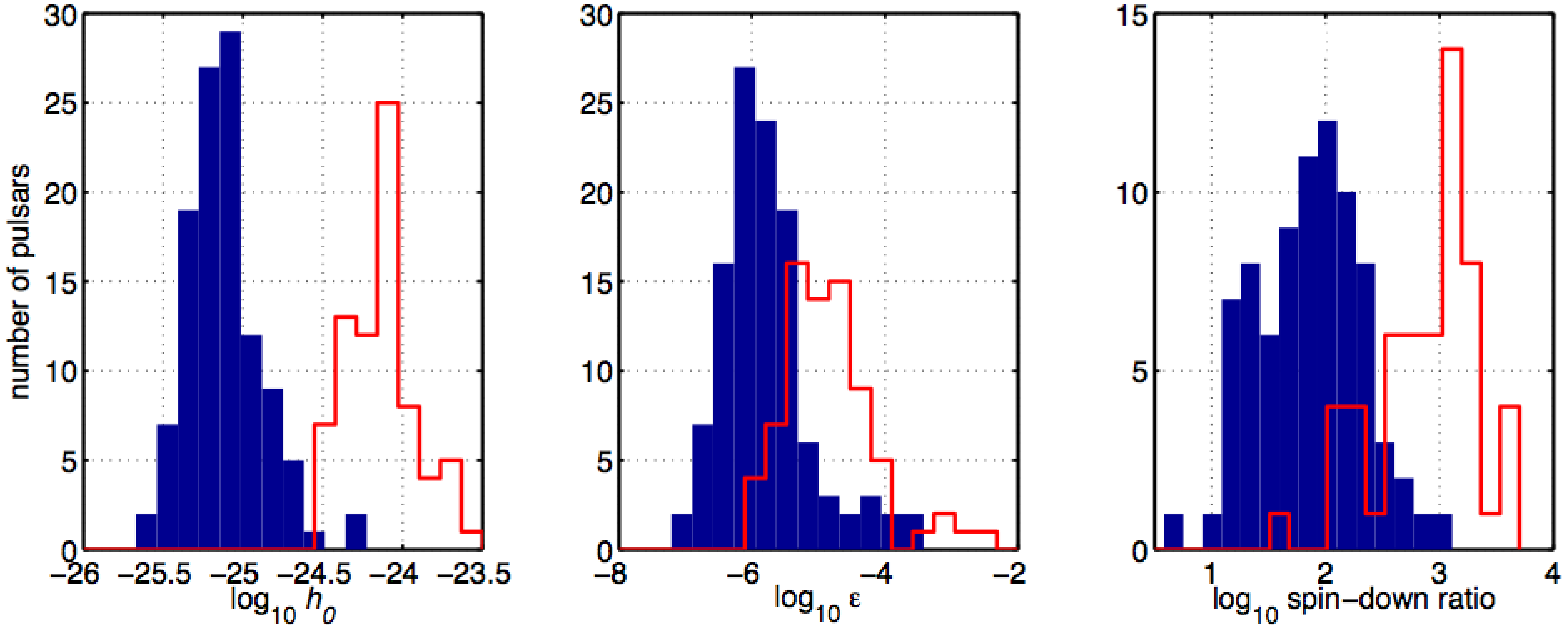
- ~200 known pulsars with spin frequencies greater than 20Hz (LIGO sensitive band)
- Have parameters fit to radio observations of 115 pulsars (isolated, binaries and in globular clusters) covering all, or part, of S5 run
  - Jodrell Bank Observatory (e.g. Crab, etc)
  - Green Bank Observatory (Ter5, 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

Searches: S5 results

- ~527 days H1, 535 days H2, 405 days L1 data
- No signal seen for any pulsar (arXiv:0909.3583)
- 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 (for moment of inertia of 10^{38} kgm^2)
  - 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)
h_0
10^{-24}
10^{-25}
10^{-26}
10^2
10^3
frequency (Hz)

Searches: S5 results

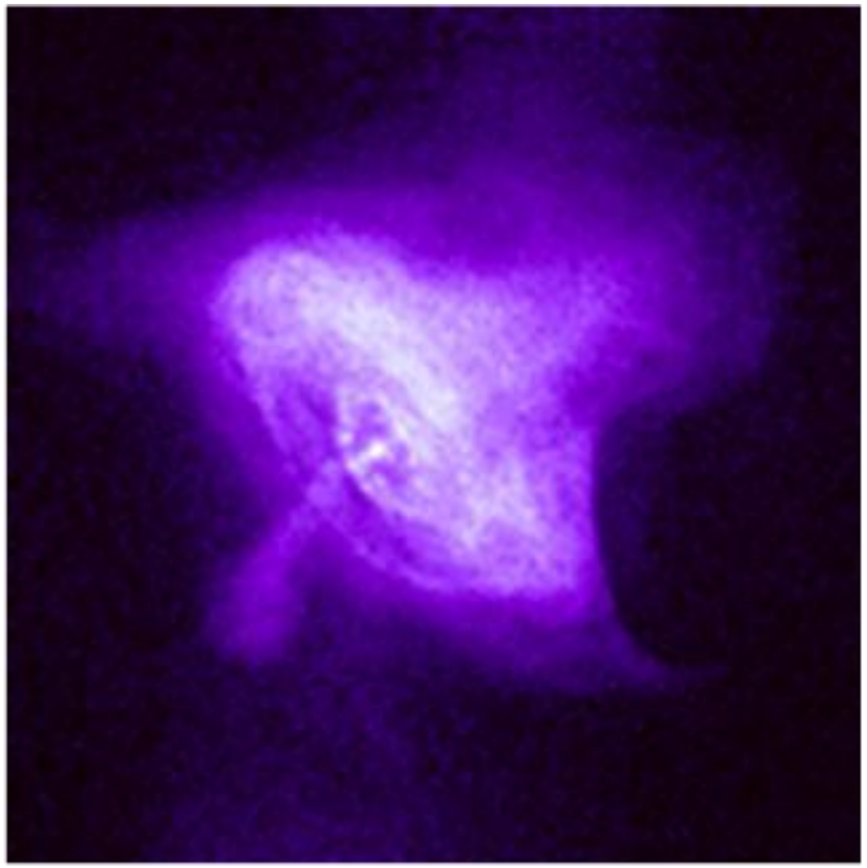


Glitching pulsars

- Three young pulsars seen to glitch during S5
  - Crab pulsar - 1 glitch
  - J0537-6910 - 6 glitches
  - J1952+3252 - 1 glitch
- Three scenarios:
  - Fully coherent signal over entire run (most likely case)
  - Glitch causes phase offset between EM and GW signals, so add as extra parameter
  - Perform independent coherent searches on stretches of data between glitches

Crab pulsar search

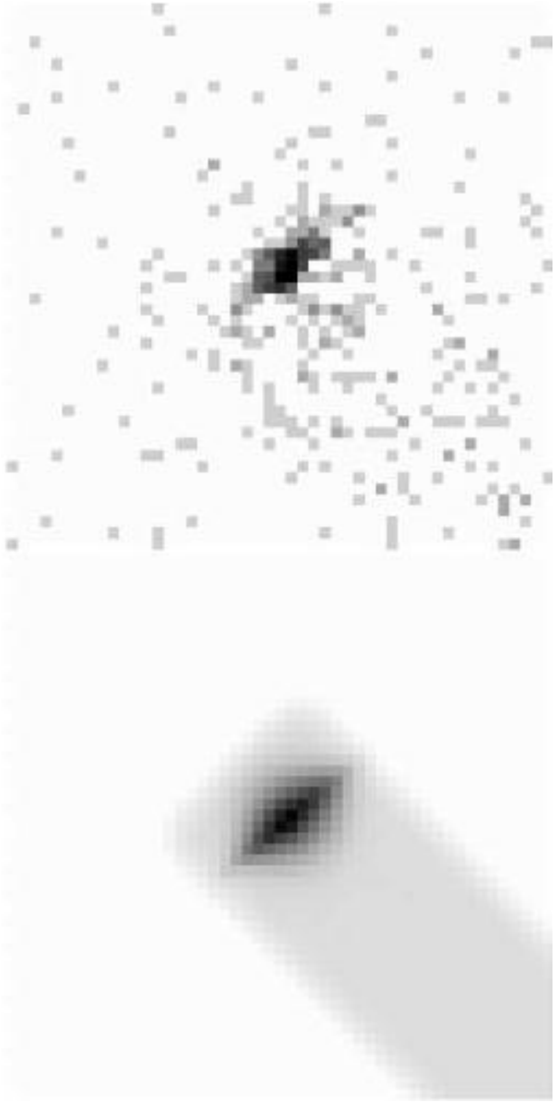
- Priors on polarisation and orientation angles from Pulsar Wind Nebula (PWN) observations ψ = 125.16±1.36°, ι = 62.17±2.20° [arXiv:0710.4168]
- For scenario i) with priors as above we get:
  - h_0 upper limit 2.0×10^{-25}
  - ellipticity upper limit 1.1×10^{-4}
  - ratio to spin-down amplitude of 7
- 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, r = 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$^{\mathrm{o}}$, ι = 92.8±0.9$^{\mathrm{o}}$ (non-optimal orientation)
- PSR J1952+3252 (f_{gw} = 50.6 Hz, r = 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

Results

- For J0537-6910 scenario i) gives (using orientation angle priors):
  - h_0 upper limit 4.4×10^{-26}
  - ellipticity limit 1.3×10^{-4}
  - Amplitude ratio to spin-down: ~1.5x spin-down (moment of inertia $10^{38}\mathrm{kg\,m}^2$)
  - 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: ~2.5x spin-down

Crab multi-template search

- Pulsar GW phase model may not be at precisely twice EM phase
  - free precession
  - two component model (EM and GW components spinning separately, but coupled by some torque)
- Causes a small offset in frequency and spin-down (so perform a “fuzzy” search)
  - for long observation times (months/years) require a search over many different signal templates - a single phase model would not stay coherent with the signal
  - use the maximum likelihood frequentist search method

$$f_{gw} = 2f(1+\delta)$$

$$\delta \sim \alpha \frac{(I_{zz} - I_{xx})}{I_{xx}}$$

$$\delta \sim \frac{\tau_{\text{coupling}}}{\tau_{\text{spin-down}}}$$

$$\boxed{|\delta| = 10^{-4}}$$

~ maximum δ for free precession

$$\tau_{\text{spin-down}} \sim 2500 \text{ years}$$

spin-down timescale for Crab pulsar

$$\tau_{\text{coupling}} \sim 10^{-4} \tau_{\text{spin-down}}$$

typical recovery timescale after glitches

Crab multi-template search

- For S5 search [arXiv:0805.4758] had:

$$\delta f = \pm 6 \times 10^{-3}\,\mathrm{Hz}$$
$$\delta \dot{f} = \pm 1.5 \times 10^{-13}\,\mathrm{Hz\,s^{-1}}$$

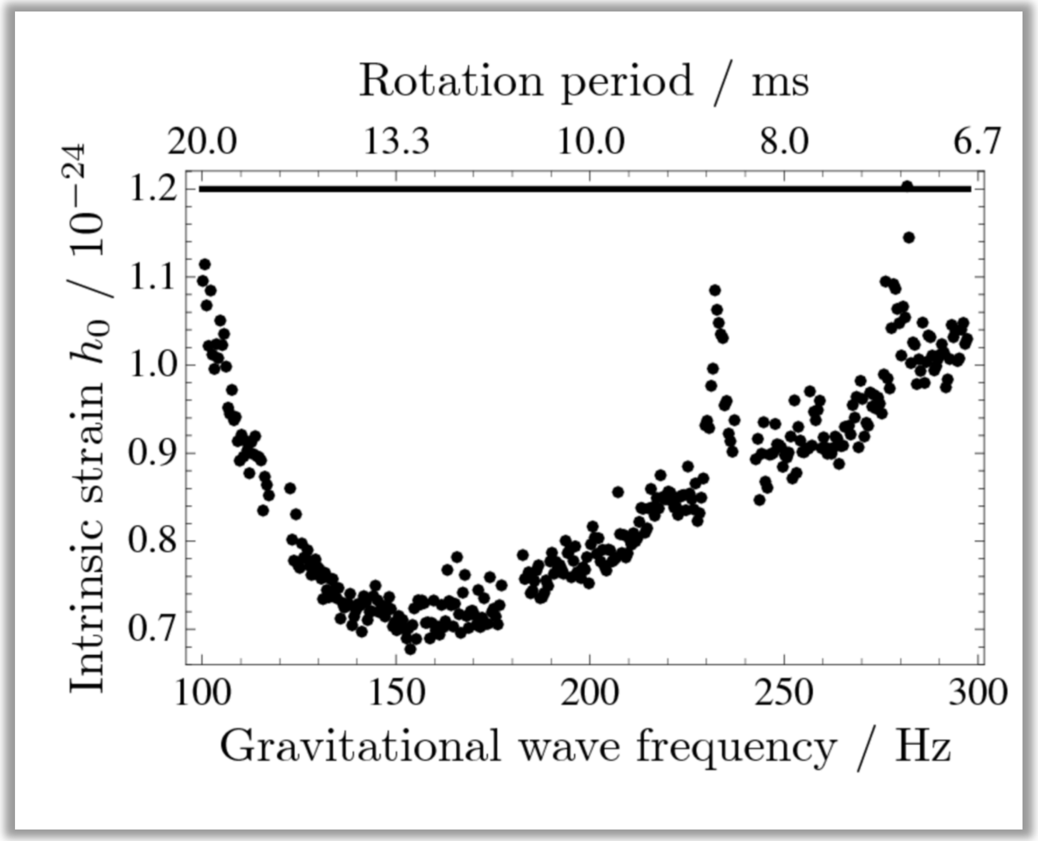
  - Number of phase templates 3×10^{7} (ensuring only 5% loss between templates)
- Results (with observational priors):
  - h_0 upper limit 1.2×10^{-24}
  - ~0.8x spin-down limit

Cas A search

- Cas A supernova remnant contains the youngest known neutron star (331 years old) [arXiv:1006.2535]
  - no spin period known
  - Set age-based limit on GWs

Age ~ spin-down age $-(1-n)^{-1} f/\dot{f}$

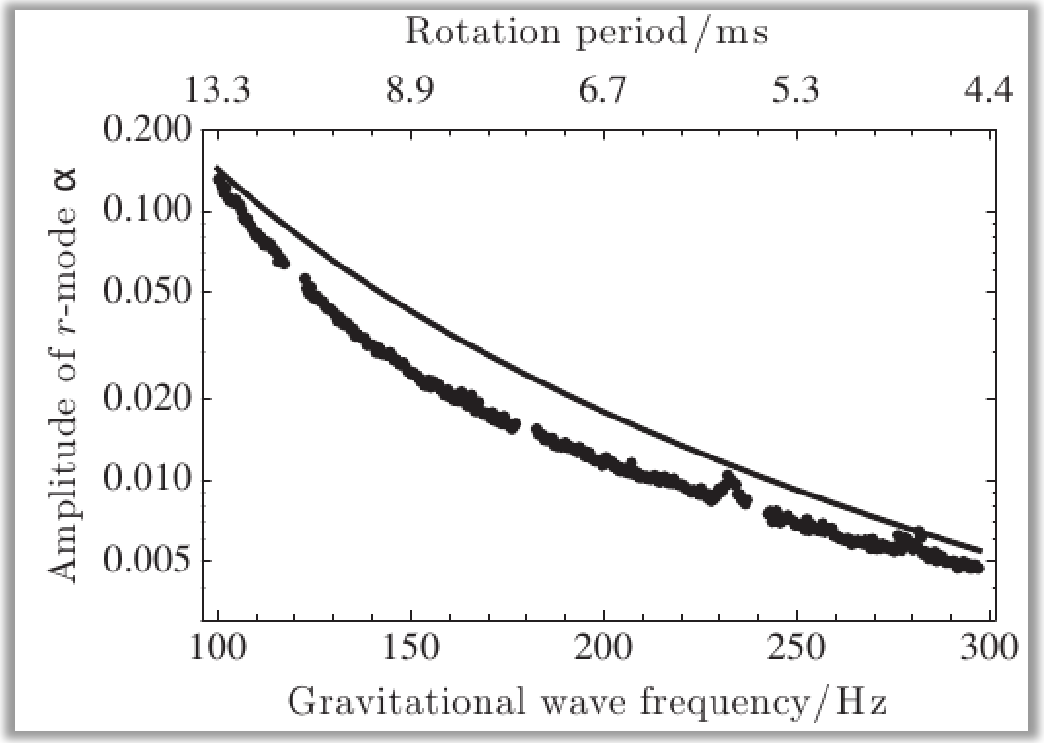
$$h_{sd} = 1.2 \times 10^{-24} \left(\frac{3.4\ \mathrm{kpc}}{r}\right) \left(\frac{I}{10^{38} \mathrm{kg\ m}^2}\right) \left(\frac{300\ \mathrm{yr}}{\tau}\right)^{1/2}$$



- Search 12 days of S5 data coherently:
  - Between 100-300Hz
  - Spin-down range based on 2< n <7
- Upper limit on r-mode amplitude

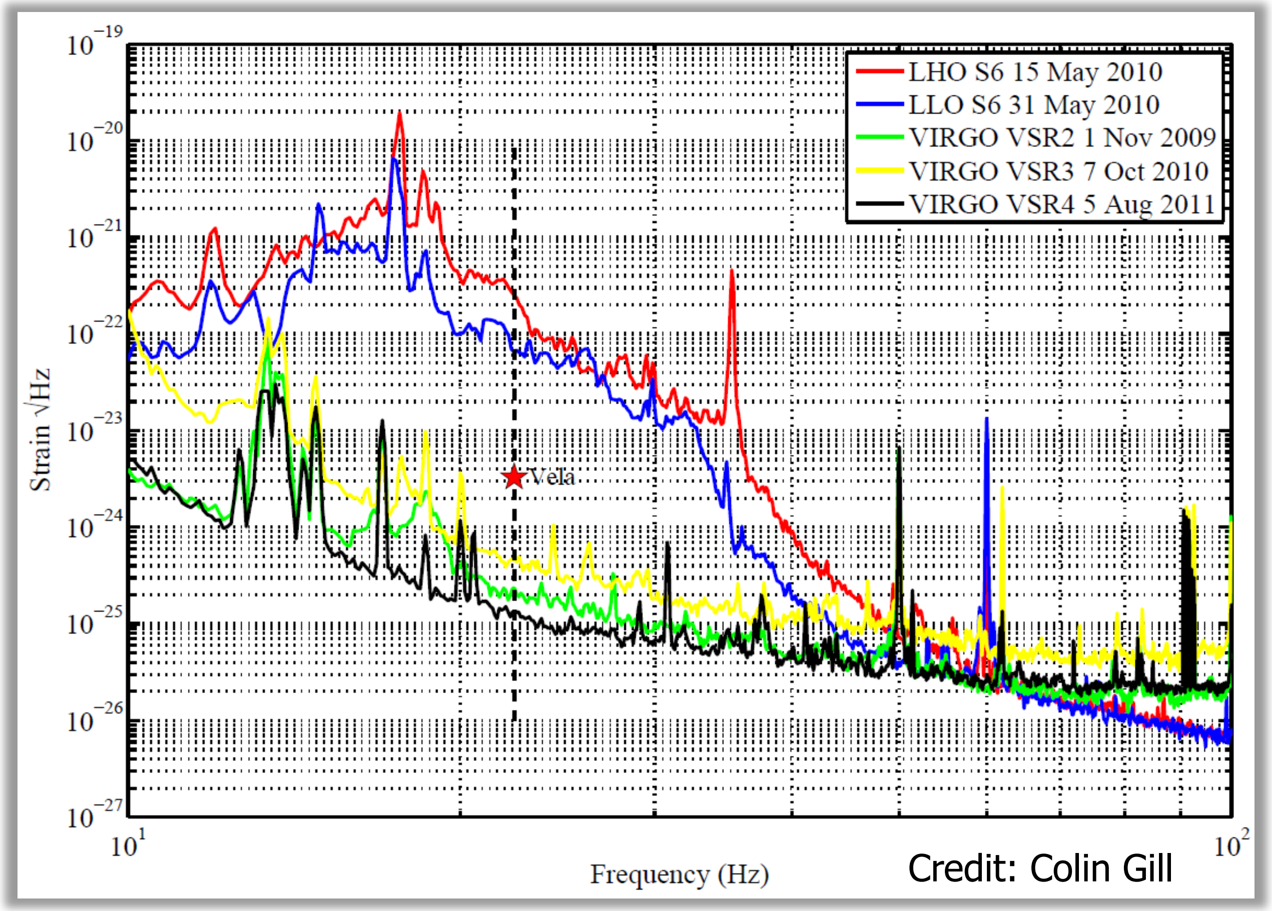
$$\alpha = 0.14 \left(\frac{300\ \mathrm{yr}}{\tau}\right)^{1/2} \left(\frac{100\ \mathrm{Hz}}{f_{\mathrm{r\text{-}mode}}}\right)^{3}$$

4/3 rotation frequency



Vela search

- Low frequency sensitivity of Virgo allowed search for the Vela pulsar (~22Hz) in VSR2 data [arXiv:1104.2712]
  - VSR2: 7 Jul 2009 – 8 Jan 2010
- Search used 3 methods:
  - 1 using time domain data and Bayesian PE
  - 2 using frequency domain and frequentist detection statistics and UL estimators
- Assumed known orientation angles



Credit: Colin Gill

$$h_{\text{spin-down}} = 3.3 \times 10^{-24}$$

$$h_0^{95\%} \approx 2 \times 10^{-24}$$

$$\varepsilon \approx 1.1 \times 10^{-3}$$

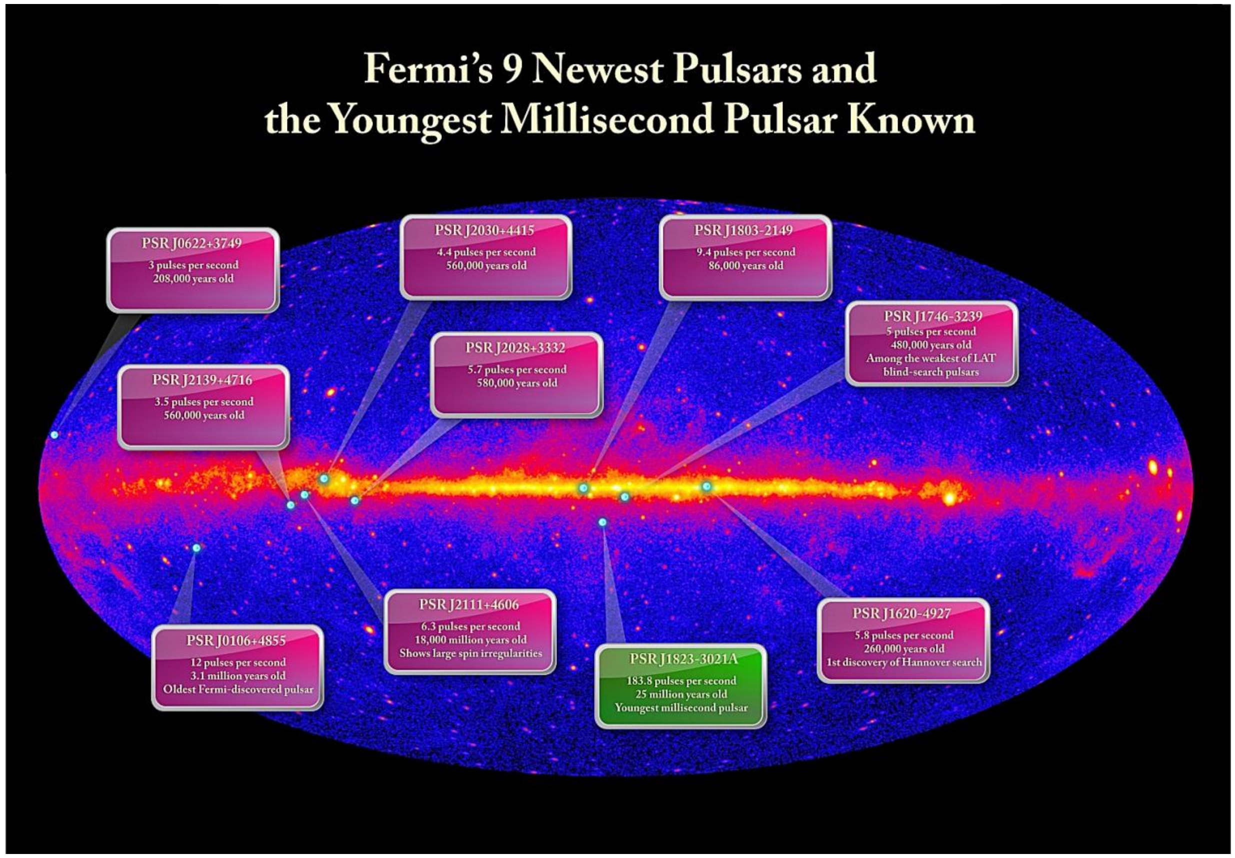
~0.6x spin-down limit, or less than ~ 40% of spin-down energy in GWs

Current search

- Search underway using LIGO S6 and Virgo VSR2/3/4 for more pulsars
  - Getting pulsar ephemerides from radio groups, Fermi and RXTE (more young high spin-down objects particularly in Virgo band)
  - Vela should get factor 1.5 improvement
  - Search for GWs at rotation frequency and twice rotation frequency
  - Perform narrow-band search for all pulsars (like S5 Crab analysis)
    - Enables us to include pulsars without up-to-date, or precise, ephemerides

New pulsars

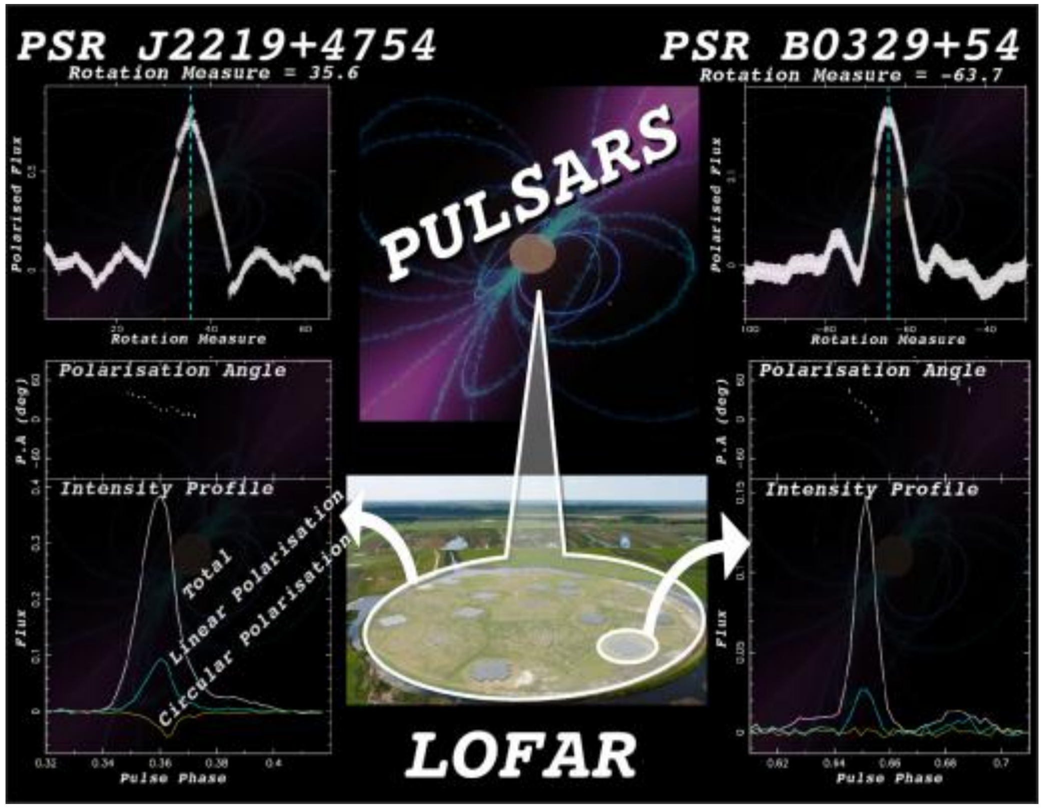
- Fermi pulsars:
  - – Detected 100 pulsars, 31 γ-ray only (radio quiet) pulsars [e.g. arXiv:1111.0523] – several young pulsars in GW band including youngest MSP (184 Hz)!
  - – Now searching with Einstein@home blind pulsar search
- New surveys:
  - – HTRU (High Time Resolution Universe) N/S surveys discovering more pulsars with Parkes [e.g. arXiv:1109.4193] (12 new MSPs to date)
  - – Searches of PALFA Arecibo data with Einstein@home – a few new MSP sources



Credit: NASA/DOE/Fermi LAT Collaboration

New pulsars

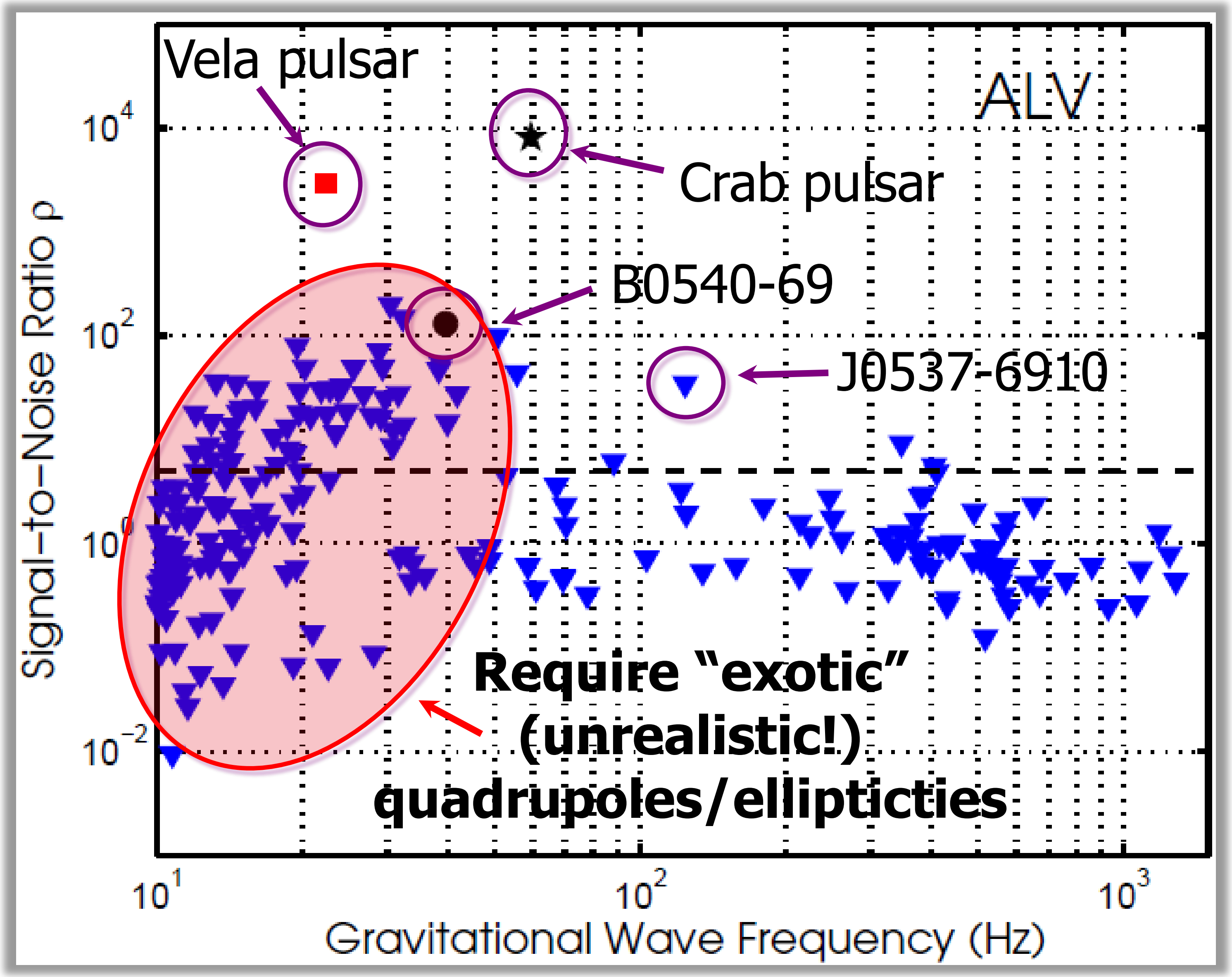
- LOFAR:
  - LOFAR stations are coming online and the first pulsars have been observed (not new ones though)
  - Expect to discover ~1000 new pulsars (all Northern hemisphere observable objects within 2kpc) [arXiv:0905.5118, arXiv:1104.1577]
  - High sensitivity to millisecond pulsars
- SKA:
  - Expect to observe 14000 normal pulsar and 6000 millisecond pulsars [arXiv:0811:0211]

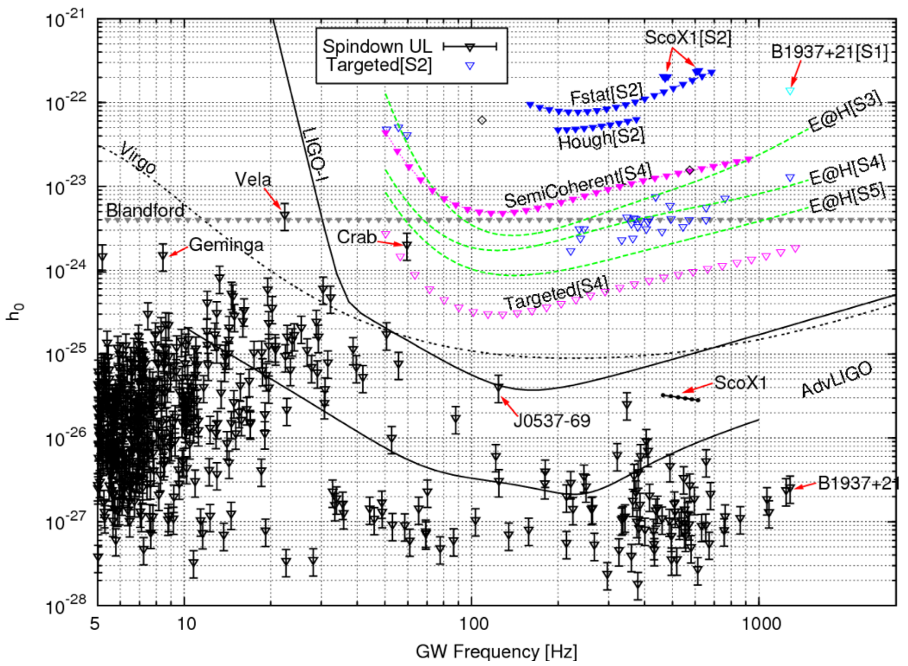


Copyright: ASTRON

Prospects for future searches

- Advanced LIGO/Advanced Virgo (upgrade of most detector systems for 2015)
  - ~10 times increasing in sensitivity over initial LIGO/Virgo

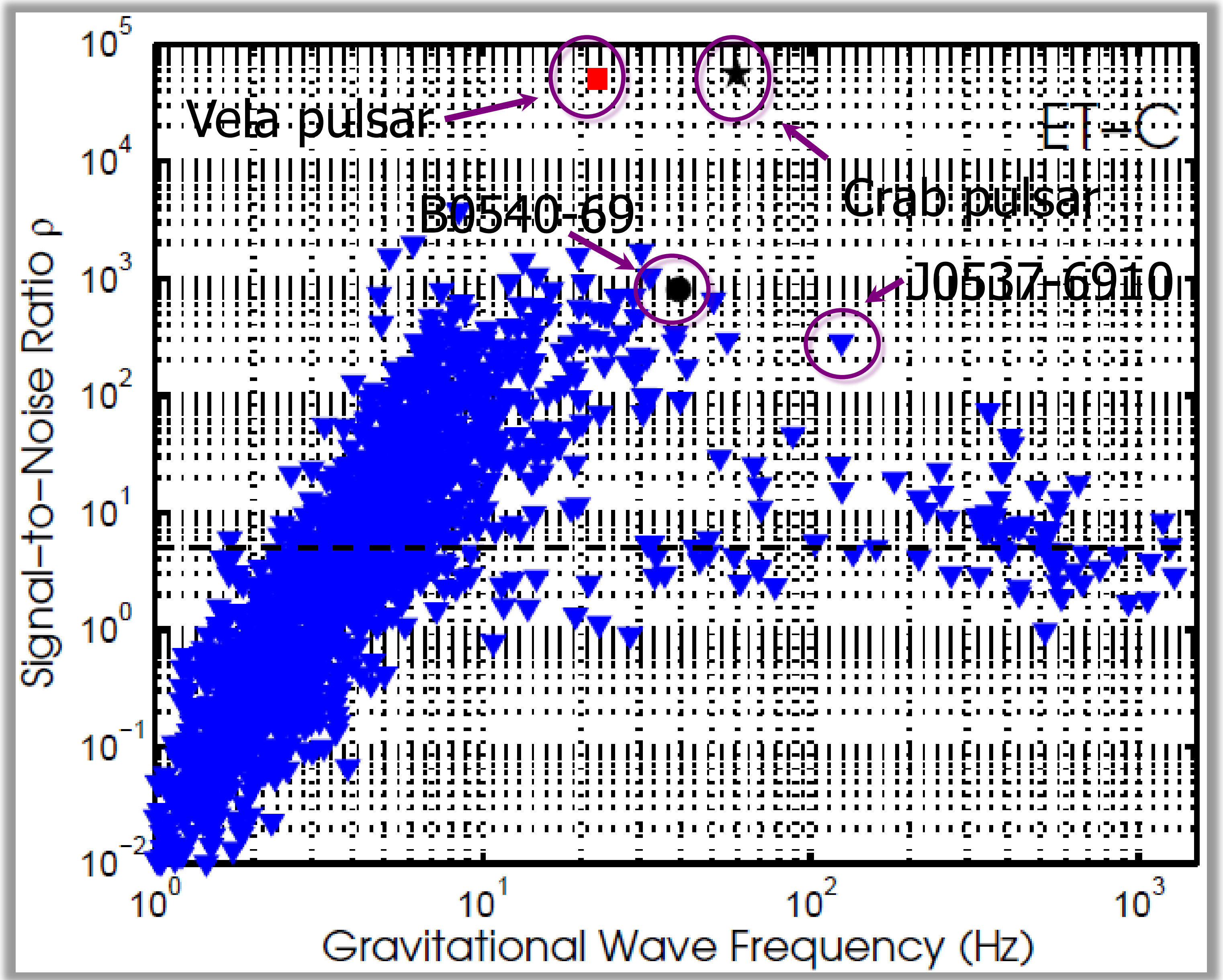




Estimate of signal-to-noise ratio for known pulsars if emitting at spin-down limit for 3 aLIGO+AdVirgo detectors observing for 1 year. Plot shows orientation and polarisation angle averaged values [arXiv:1103.5867]

Prospects for future searches

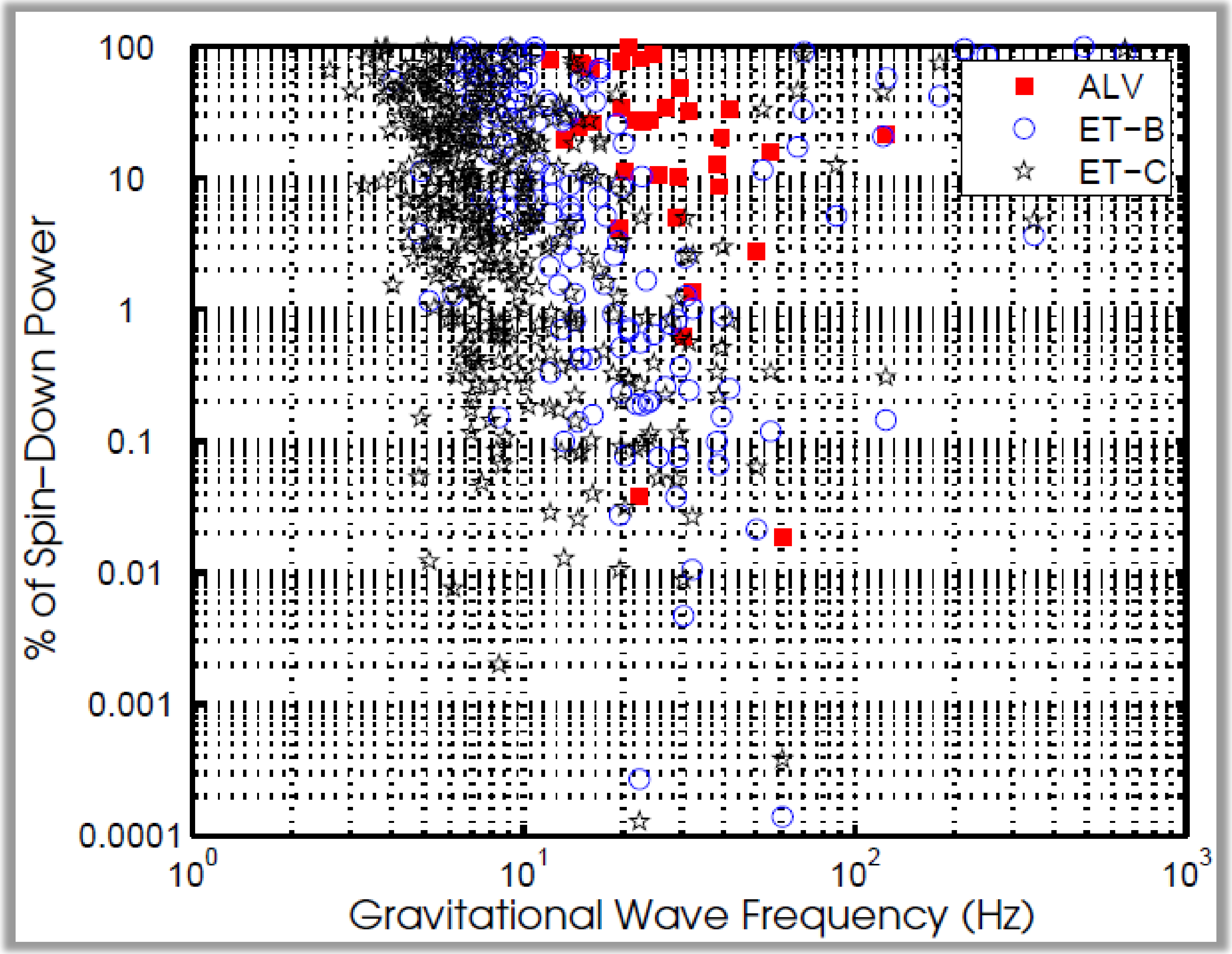
- Einstein Telescope (ET)
  - proposed European 3rd generation GW telescope another 10 times more sensitive than AdvLIGO



Estimate of signal-to-noise ratio for known pulsars if emitting at spin-down limit for 3 ET-C (xylophone configuration) detectors observing for 1 year. Plot shows orientation and polarisation angle averaged values [arXiv:1103.5867]

Prospects for future detectors

- Assume that pulsars can be detected at signal-to-noise ratio (SNR) of 5
  - Scaling from the spin-down limit SNR what % of the spin-down power would be required to observe the pulsars?
  - We know a (triaxial) Crab is emitting < 2% of spin-down power in GWs, but for MSPs?

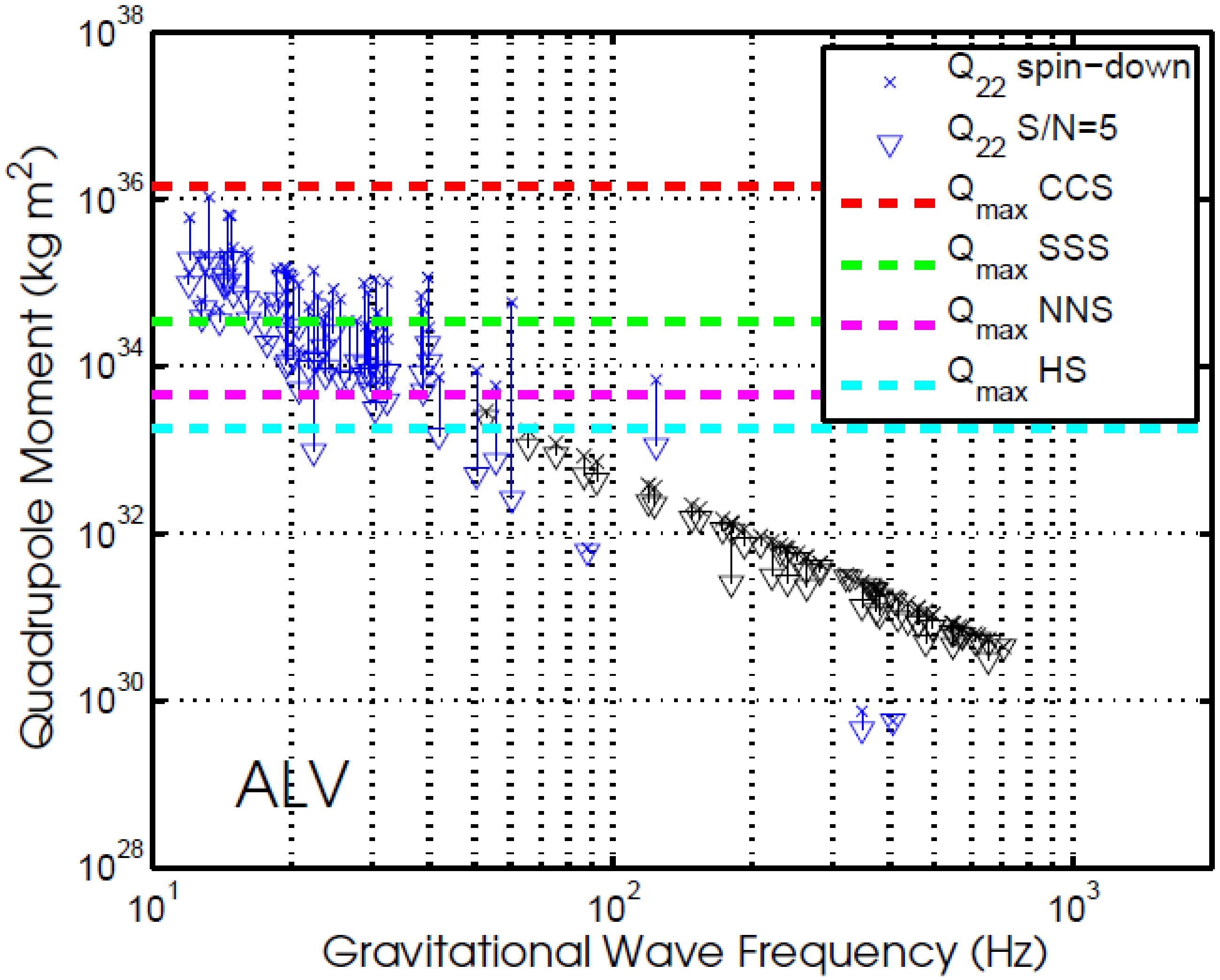


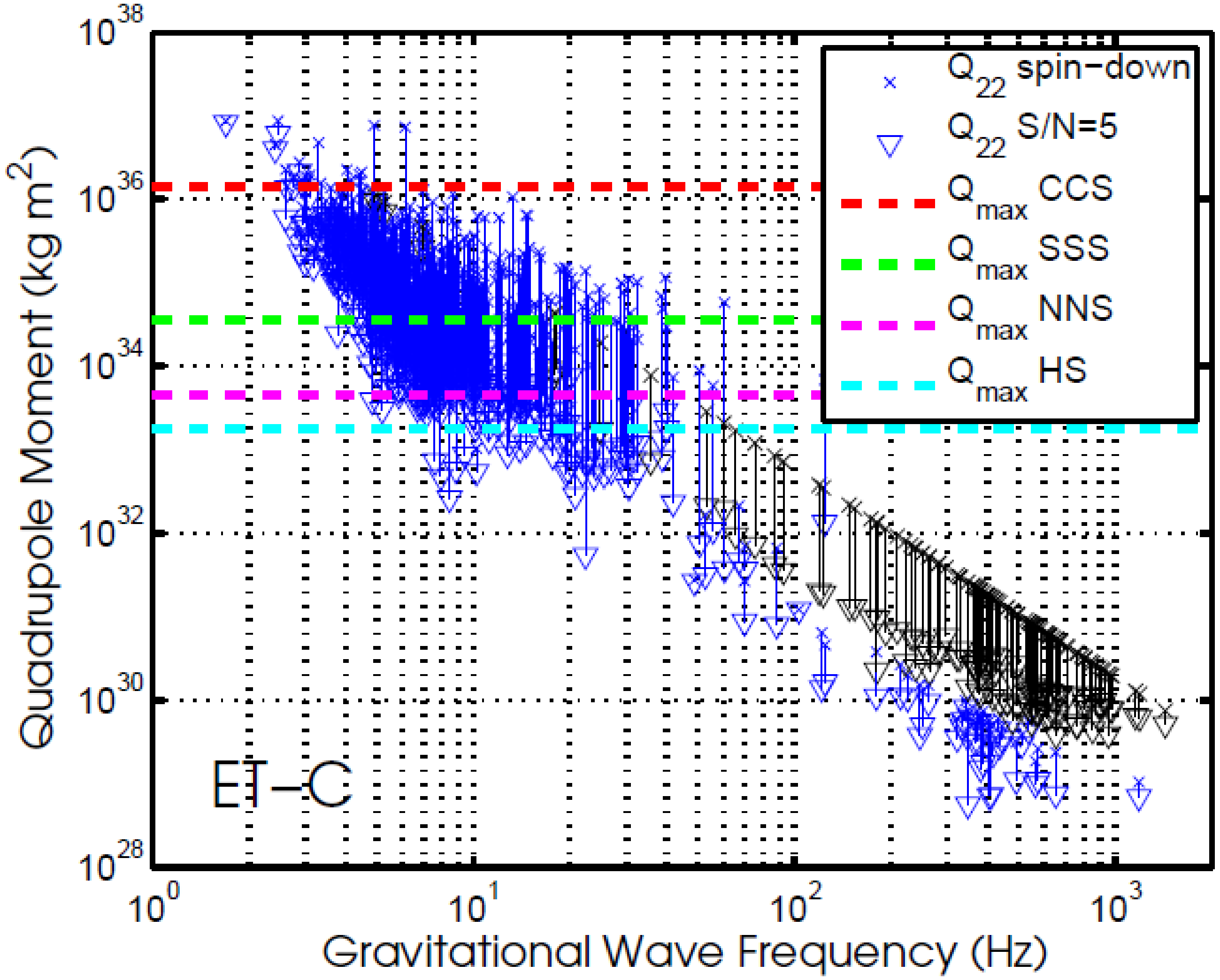
Quadrupole constraints

- Constraints on quadrupole moment Q_{22}:

$$\varepsilon = \sqrt{\frac{8\pi}{15}\frac{Q_{22}}{I_{zz}}}$$

Maximum theoretical Q_{22}			
Normal Neutron Star (NNS)	Hybrid Crystaline Colour Superconducting star (CCS)	Strange solid quark star (SSS)	Hybrid meson condensate stars (HS)
3.1×10^{33} kg m^2	1.4×10^{36} kg m^2	3.5×10^{34} kg m^2	1.8×10^{33} kg m^2

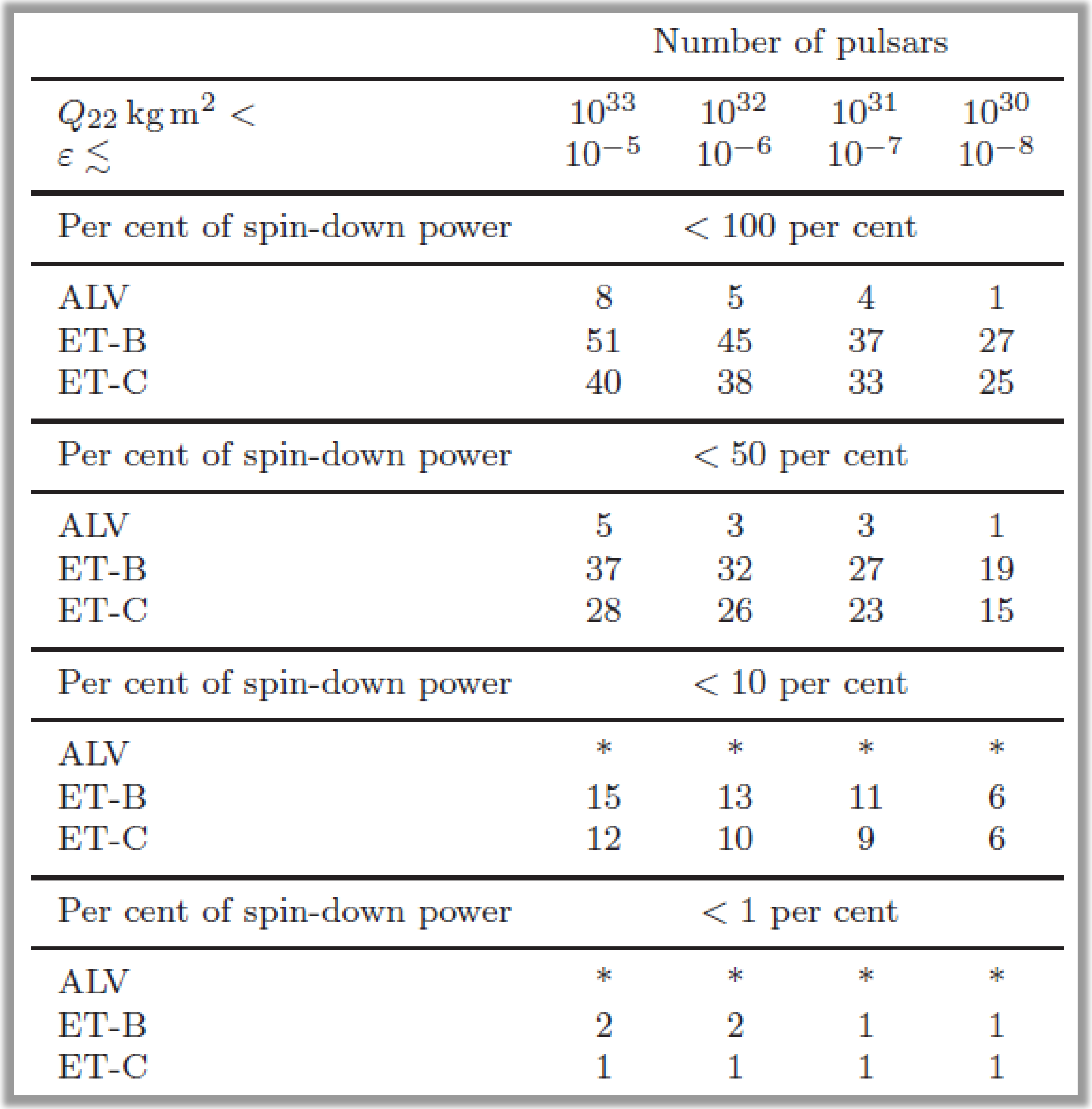




Quadrupole constraints

- Numbers of potentially detectable pulsars (at SNR ≥ 5):

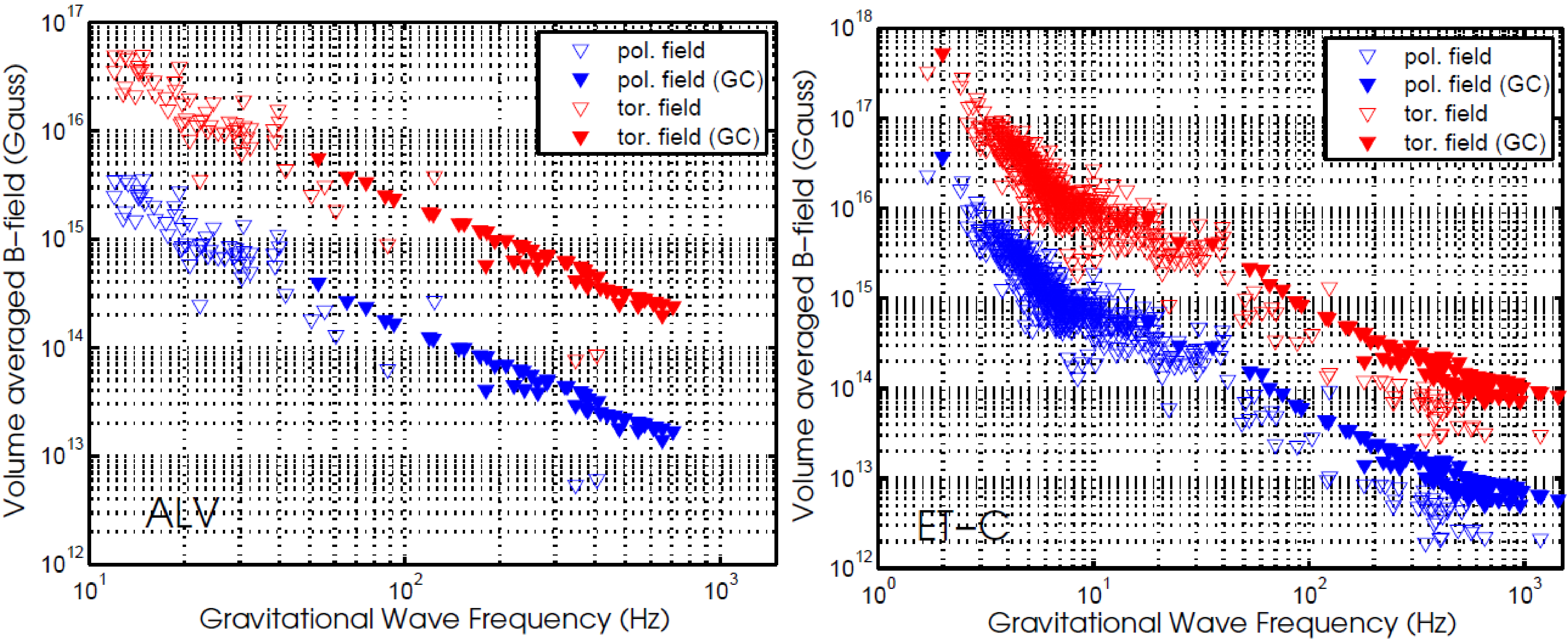
With SKA ~30 times more MSPs – 10s of detectable pulsars with realistic quadrupoles/ellipticities!



	Number of pulsars			
$Q_{22}\,\mathrm{kg\,m^2} <$	10^{33}	10^{32}	10^{31}	10^{30}
$\varepsilon \lesssim$	10^{-5}	10^{-6}	10^{-7}	10^{-8}
Per cent of spin-down power	$<$ 100 per cent			
ALV	8	5	4	1
ET-B	51	45	37	27
ET-C	40	38	33	25
Per cent of spin-down power	$<$ 50 per cent			
ALV	5	3	3	1
ET-B	37	32	27	19
ET-C	28	26	23	15
Per cent of spin-down power	$<$ 10 per cent			
ALV	*	*	*	*
ET-B	15	13	11	6
ET-C	12	10	9	6
Per cent of spin-down power	$<$ 1 per cent			
ALV	*	*	*	*
ET-B	2	2	1	1
ET-C	1	1	1	1

Magnetic field constraints

- Constraints on internal poliodal and toriodal magnetic fields:



Conclusions

- Searches for GWs from known neutron stars are well established
- Currently (mainly) assume GWs and EM signals are phase locked and neutron star is triaxial rigid body emitting at twice the rotation frequency
  - expand upon these assumption:
    - perform searches at the rotation frequency
    - carry out more “fuzzy” multi-template searches
    - search at r-mode frequencies
- Searches starting on S6/VSR4 data
  - improve spin-down limit for Vela, Crab et al
  - Newly found young pulsars (e.g. Fermi) being included
- New detectors and extra pulsars promise far more!
  - detection and parameter estimation