A search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar

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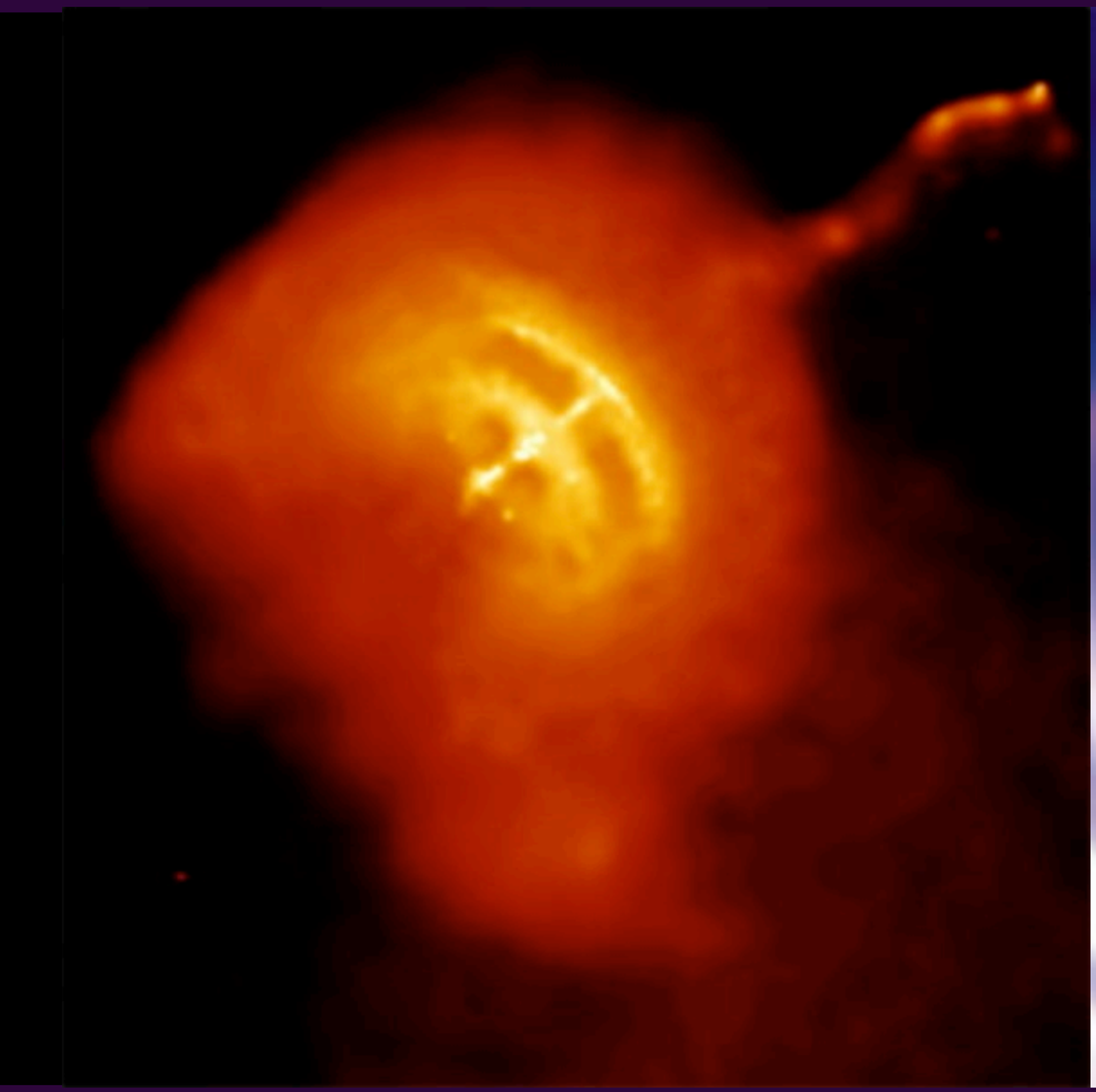

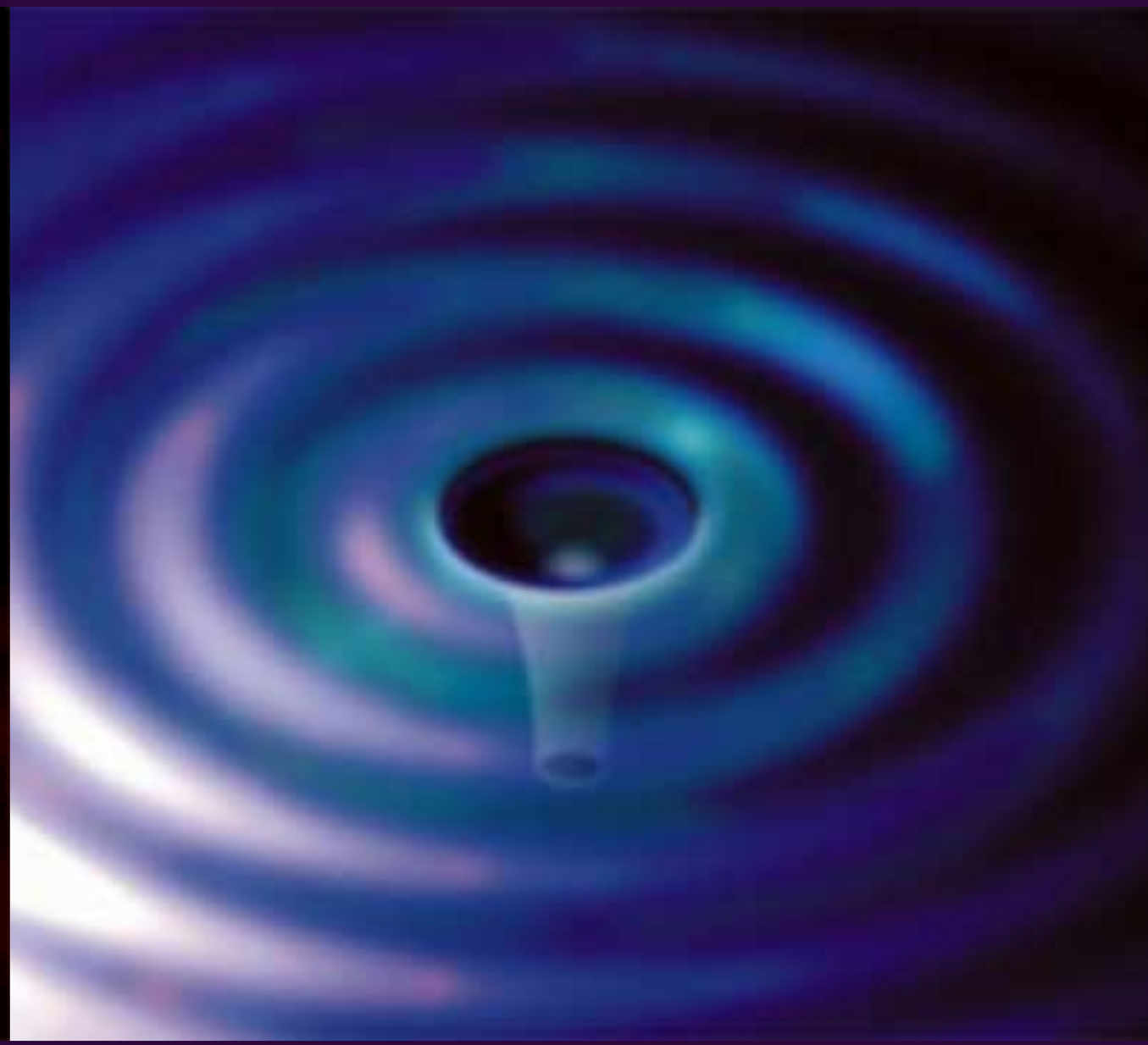

James Clark For The LSC

LIGO-G1100010-v3

Introduction

- **This talk: first search for GWs associated with pulsar timing glitch:**
  - **Pulsar glitches & gravitational radiation**
  - **LIGO August 2006 Vela glitch search**

Full details:

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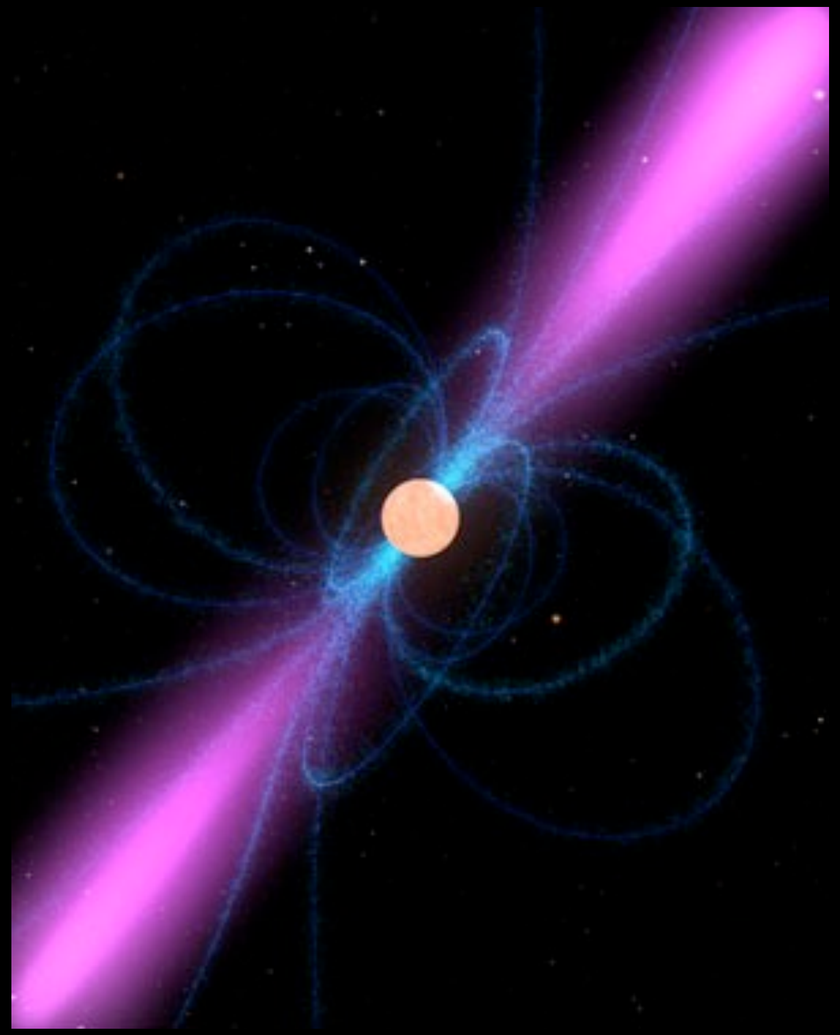
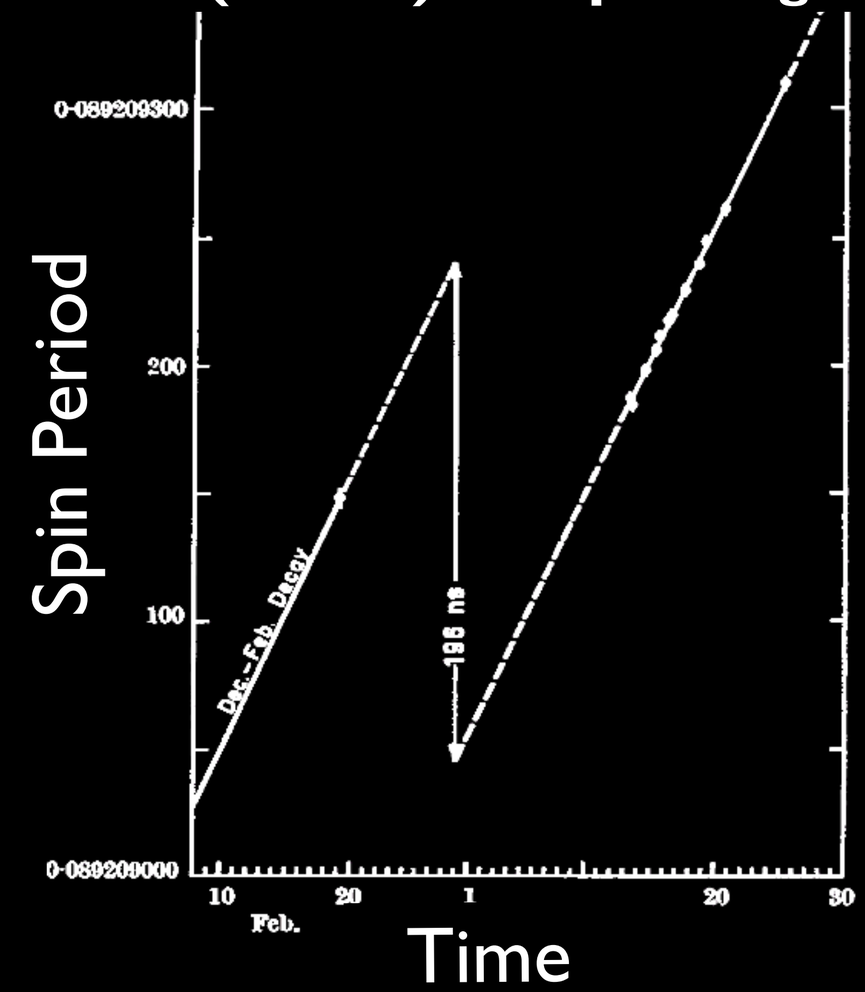


Pulsar Glitches

- Occassional (for e.g., Vela I every ~2 years) sudden step increases observed in spin-frequency
- Sudden leap (drop) in spin freq (period) is followed by exponential recovery to ~pre-glitch spin on timescales of days-weeks
- Fitting for the recovery time-scale τ allows estimation of glitch epoch.

1st (known) Vela pulsar glitch



Pulsar Glitches & Gravitational Waves

- **Mechanism is unclear but may be:**
  - **star-quake (crustal rearrangement)**
  - **internal superfluid vortex un-pinning**
- **Glitches & GWs:**
  - **superfluid vortex avalanche (short ~1ms white noise burst)**
  - **global oscillations (f-modes: 1-3 kHz, 50-500ms ring-downs)**
  - **longer emission from r-modes, internal fluid motion (hours - days)**

Energy Scales

$$\Delta E_{\rm quake} \approx 10^{42}\,{\rm erg}\left(\frac{I_*}{10^{38}\,{\rm kg\,m^2}}\right)\left(\frac{\Omega}{20\pi\,{\rm rad\,s^{-1}}}\right)^2\left(\frac{\Delta\Omega/\Omega}{10^{-6}}\right)$$

$$\Delta E_{\rm vortex} \approx 10^{38}\,{\rm erg}\left(\frac{I_c}{10^{37}\,{\rm kg\,m^2}}\right)\left(\frac{\Omega}{20\pi\,{\rm rad\,s^{-1}}}\right)^2\left(\frac{\Delta\Omega/\Omega}{10^{-6}}\right)\left(\frac{\Omega_{\rm lag}/\Omega}{5\times10^{-4}}\right)$$

Oscillation Model

- Assume glitch *somehow* excites f-mode oscillations (i.e., frequencies 1-3 kHz)
- Decompose fluid oscillations into spherical harmonics of degree *l*, order *m*.
- We're interested in the quadrupole mode (l=2) with superposition of m=-2,-1,0,+1,+2 modes
  - m=0: rotational symmetry - natural connection with build-up of superfluid lag or decreasing centrifugal force
  - |m|=1: glitch begins at one point in star and moves out (vortex avalanche)
  - |m|=2: glitch inherits symmetry of magnetic dipole field
- Which, if any, dominates dictated by UNKNOWN behaviour in stellar interior

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GW model

- **Simplifying assumptions:**
  - **only a single m dominates, spin unimportant**
- **Plus, cross waveform polarisations:**

$$h_+^{2m}(t) = \begin{cases} h_{2m}\mathcal{A}_+^{2m}\sin[2\pi\nu_0(t-t_0)+\delta_0]e^{-(t-t_0)/\tau_0} \text{ for } t \geq t_0, \\ 0 \text{ otherwise.} \end{cases}$$

$$h_\times^{2m}(t) = \begin{cases} h_{2m}\mathcal{A}_\times^{2m}\cos[2\pi\nu_0(t-t_0)+\delta_0]e^{-(t-t_0)/\tau_0} \text{ for } t \geq t_0, \\ 0 \text{ otherwise.} \end{cases}$$

Spherical Harmonic Indices	$\mathcal{A}_+^{2m}$	$\mathcal{A}_\times^{2m}$
$l=2,\ m=0$	$\sin^2\iota$	0
$l=2,\ m=\pm1$	$\sin 2\iota$	$2\sin\iota$
$l=2,\ m=\pm2$	$1+\cos^2\iota$	$2\cos\iota$

- **Inclination affects relative amplitudes through A+, Ax:**
- **If we have inclination (and polarisation) info, we have a good handle on the *intrinsic* GW amplitudes**

(Note that the data analysis pipeline works with power spectral densities so is insensitive to the sign of m)

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August 2006 Vela Glitch: GW analysis

- Search method deploys Bayesian odds ratio as detection statistic:

$$\mathcal{O}_{(+,-)} = \frac{\Pr(M_+|D)}{\Pr(M_-|D)} = \frac{\Pr(M_+)}{\Pr(M_-)}\frac{\Pr(D|M_+)}{\Pr(D|M_-)}$$

- choose between two models: detection (i.e., ring-down signal) or null-detection (Gaussian noise OR ring-down signals independent across detectors):

$$\mathcal{O}_{(+,-)} = \frac{\Pr(D|M_+)}{\Pr(D|T) + \Pr(D|N)}$$

- automatically rejects many instrumental transients, BUT incapable of distinguishing correlated instrumental transients
- compare on-source value to background distribution from off-source
- if on-source value > loudest off-source value, have detection *candidate*, meriting follow-up.
- otherwise, form marginal posteriors on GW amplitude & energy to form Bayesian upper limits

A Glitch In PSR B0833 (Vela)

- 12th August 2006: large glitch observed in PSR B0833 (Vela Pulsar) by S. Buchner, C. Flanagan of Hartesbeesthock Radio Astronomy Observatory (HartRAO)

- HartRAO (originally Deep Space Station 51) 26m radio telescope located ~50 km west of Johannesburg. Perform daily monitoring of Vela for glitches

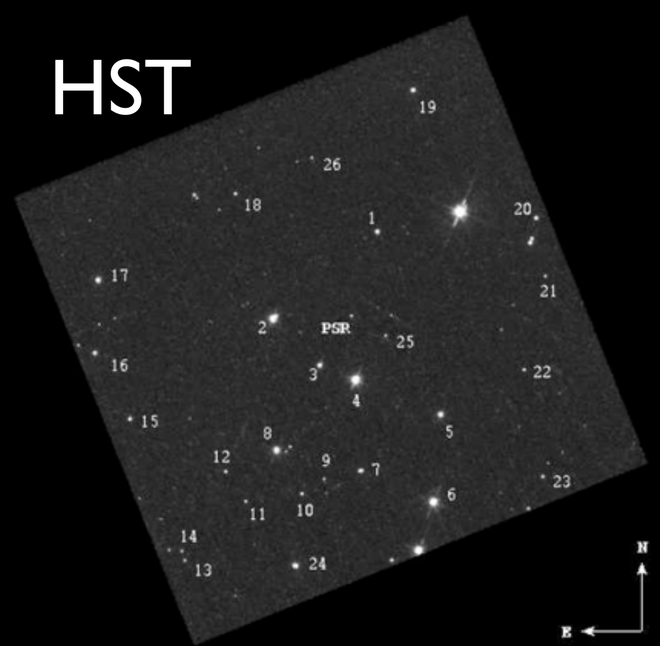
- August glitch was during the fifth LSC science run (S5)

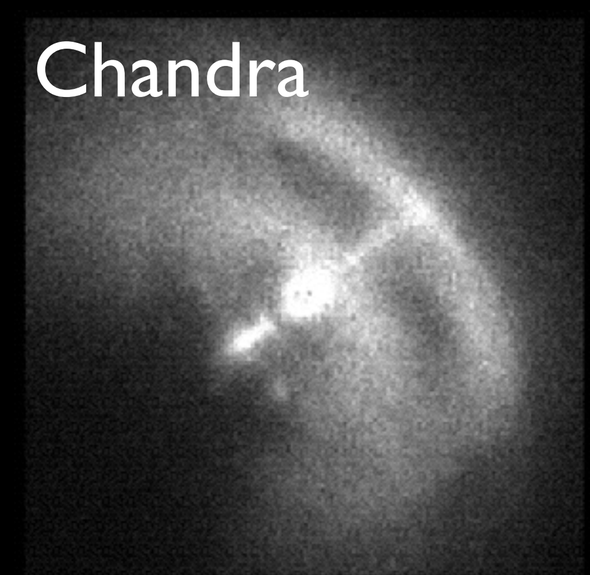
- all 3 LIGO detectors operating at design sensitivity

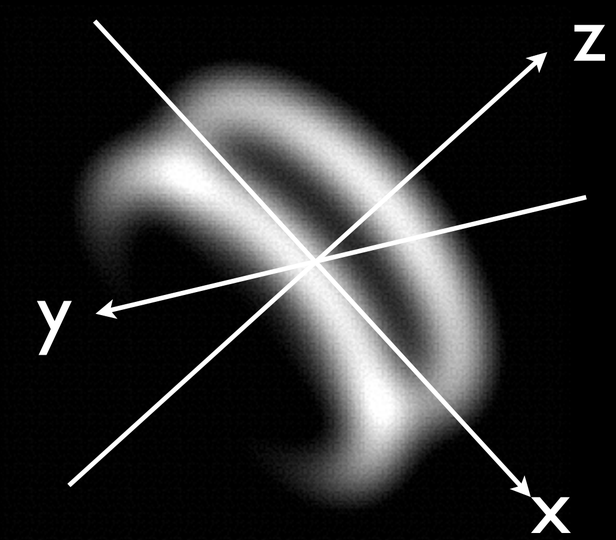
  - only the 2 Hanford detectors have contiguous science quality data during the entire glitch epoch (L1 data suffers degradation in quality)

EM observations: orientation

- Inclination and polarisation angle of Vela is well constrained from Chandra X-ray observations
- Distance to Vela (used to estimate energy upper limits from measured GW amplitude upper limits) is well constrained by HST (293 pc)

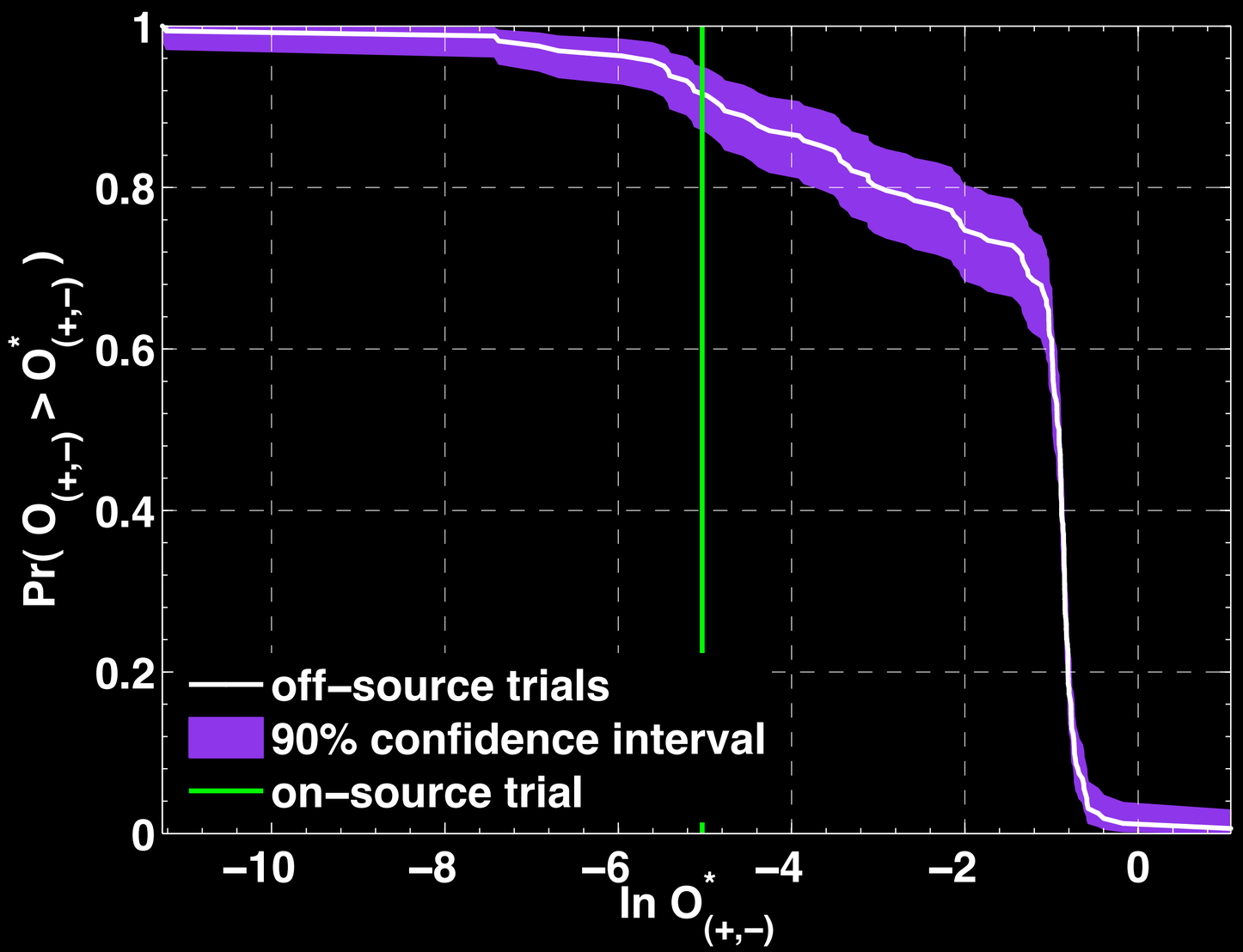






Gravitational wave search result...

August 2006 Vela Glitch: Results



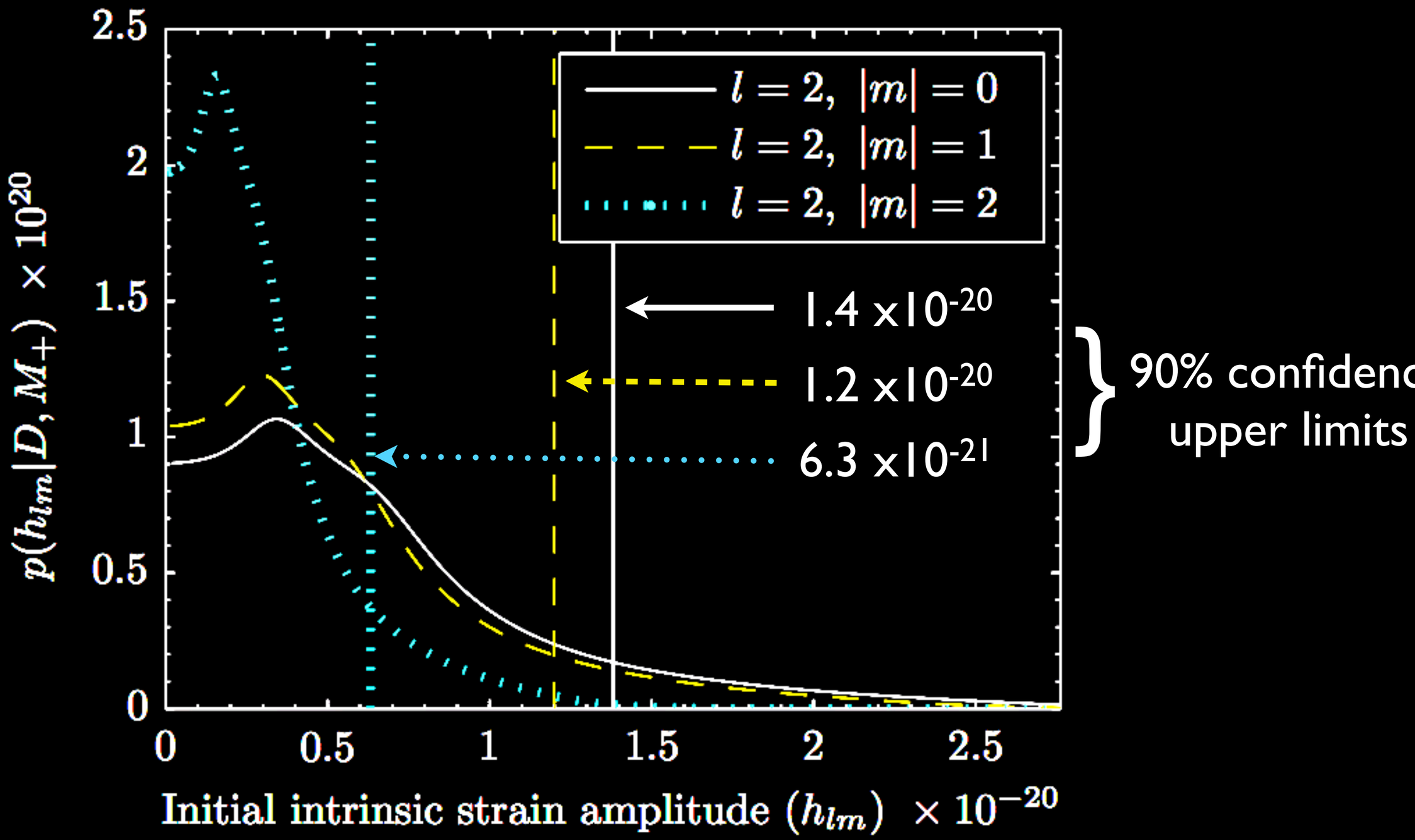
- Use **161** off-source segments of 120 s to estimate background distribution of detection statistic (odds ratio)

- Estimate probability of obtaining an odds ratio greater than or equal to the value found in the on-source segment

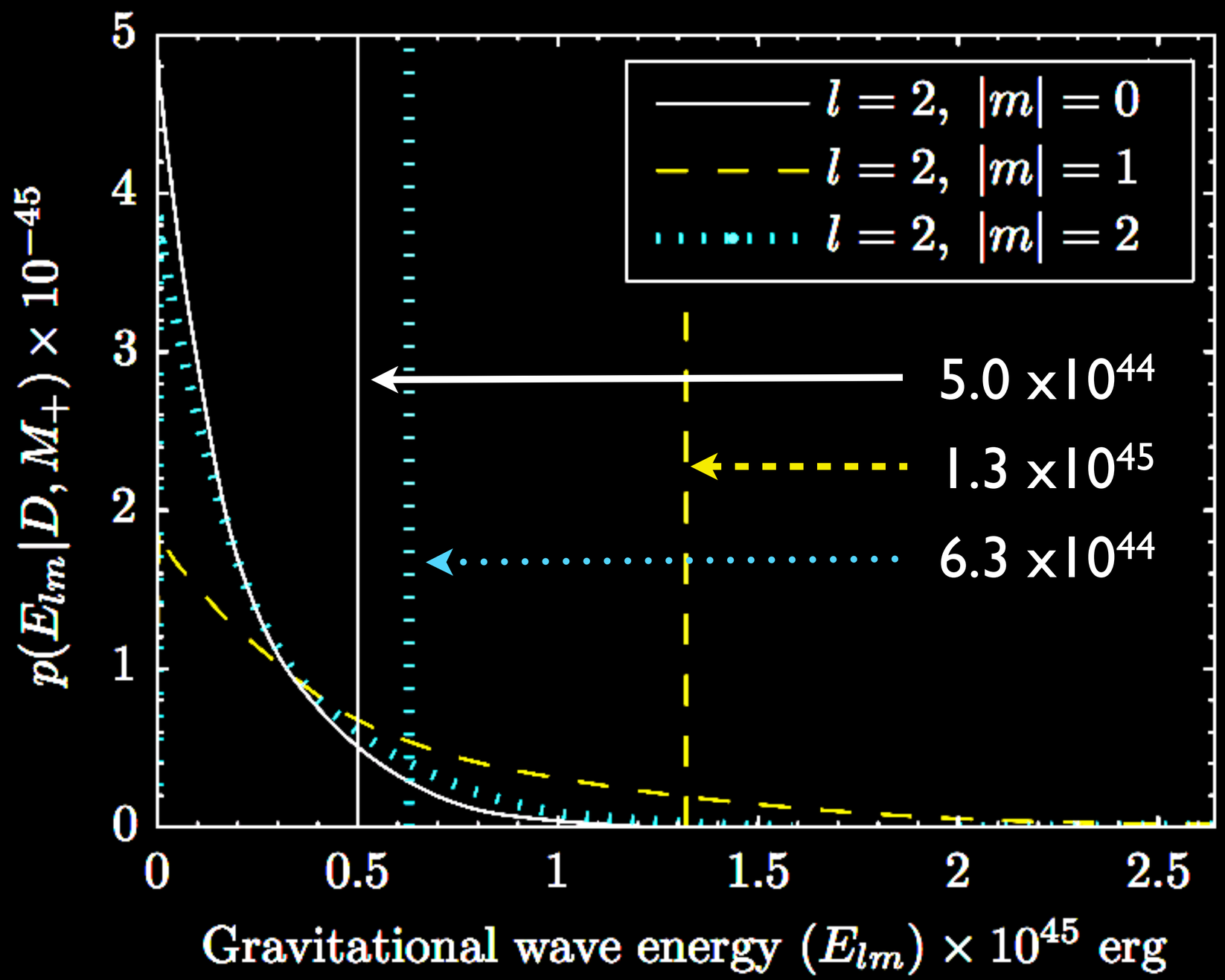
- **Probability of obtaining on-source data for no GW present = 0.92**

Conclusion: no evidence for ring-down gravitational wave signal associated with Vela August 2006 Glitch

August 2006 Vela Glitch Search: Amplitude Posteriors



August 2006 Vela Glitch Search: Energy Posteriors



90% confidence upper limits

Summary

- Pulsar glitches may lead to f-mode excitation with frequencies 1-3 kHz, durations 50-500 ms
- A search for f-mode ring-down signals associated with the August 2006 Vela glitch resulted in no detection candidates but upper limits:
  - peak strain 90% confidence limits = 6.3×10^{-21} - 1.4×10^{-20}
  - total GW energy 90% confidence limits = 5.0×10^{44} - 6.3×10^{44} erg
- Average sky-location, isotropic emission @ 10 kpc, we find:
  - LIGO S5 Vela glitch energy upper limit = 1.3×10^{48} erg
- Advanced LIGO x10 improvement in strain sensitivity = x100 improvement in energy
  - will *begin* to probe interesting (~10^{42} erg) energy limits for pulsar glitches
  - orientation / inclination information crucial to upper limit interpretation

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