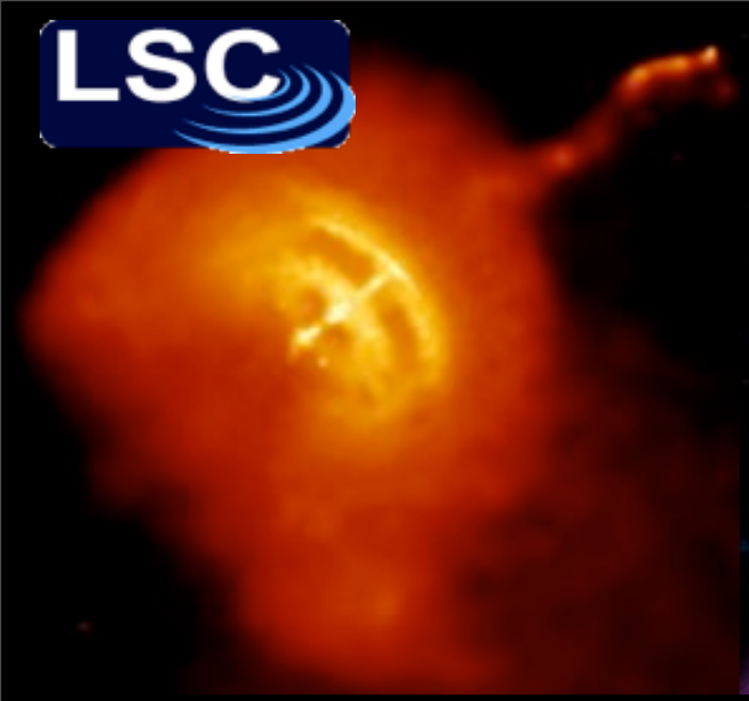
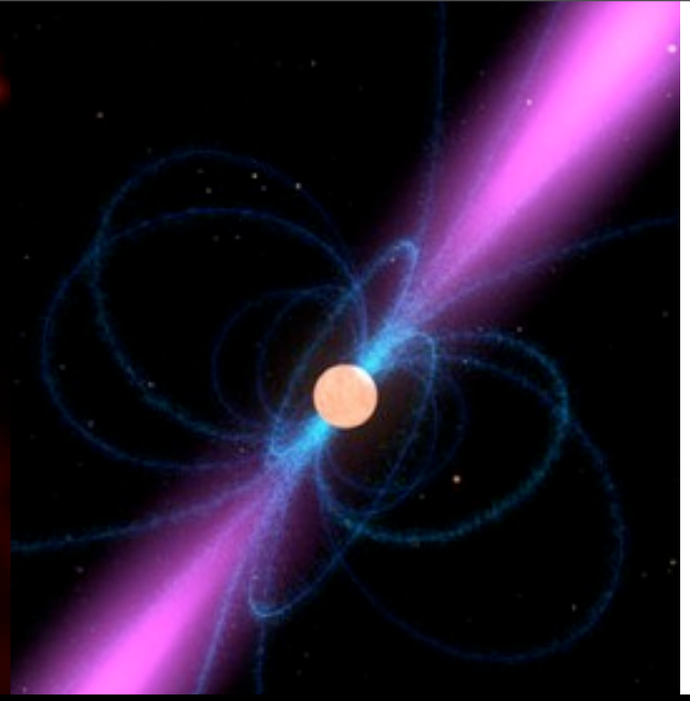




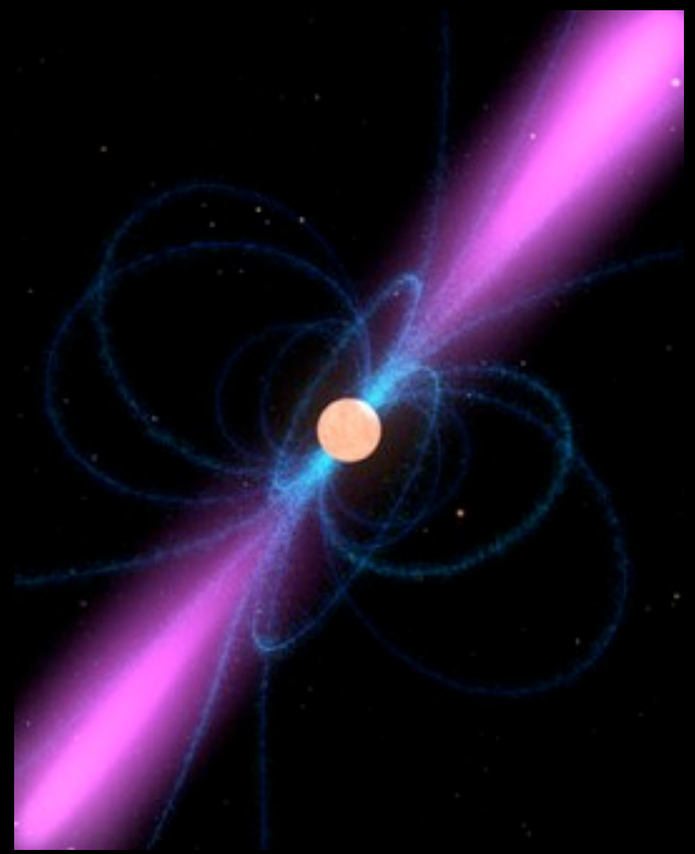
Unveiling Vela

[ET F2F] 01/09/10

James Clark

Introduction

- Pulsar glitches & gravitational radiation
- LIGO August 2006 Vela glitch search (results!)
- How well might we do with ET?



Pulsar Glitches & Gravitational Waves

- Pulsar glitches: observed as sudden step increases in pulsar rotation frequency
- Mechanism is unclear but may be:
  - crustal rearrangement due to spin-down induced relaxation of ellipticity
  - Sudden coupling of superfluid core to solid crust
  - Combination of these or something more exotic
- Glitches may result in gravitational wave emission via (e.g.,):
  - superfluid vortex avalanche
  - quasi-normal mode excitation
  - continuous emission during recovery (Mark Bennet's talk)

Energy Scales

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

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

F-mode emission model

- Our search only considers GW emission from f-mode oscillations
- Adopt a simple ring-down waveform, characterised by a peak amplitude h_{lm}, frequency ν_0 (1-3 kHz) and decay time τ_0 (50 - 500 ms)
- Assume quadrupolar (l=2) emission dominates. For a pulsar glitch, don't know a priori which individual harmonics (m=-2, -1, 0, +1, +2) dominate, if any.

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

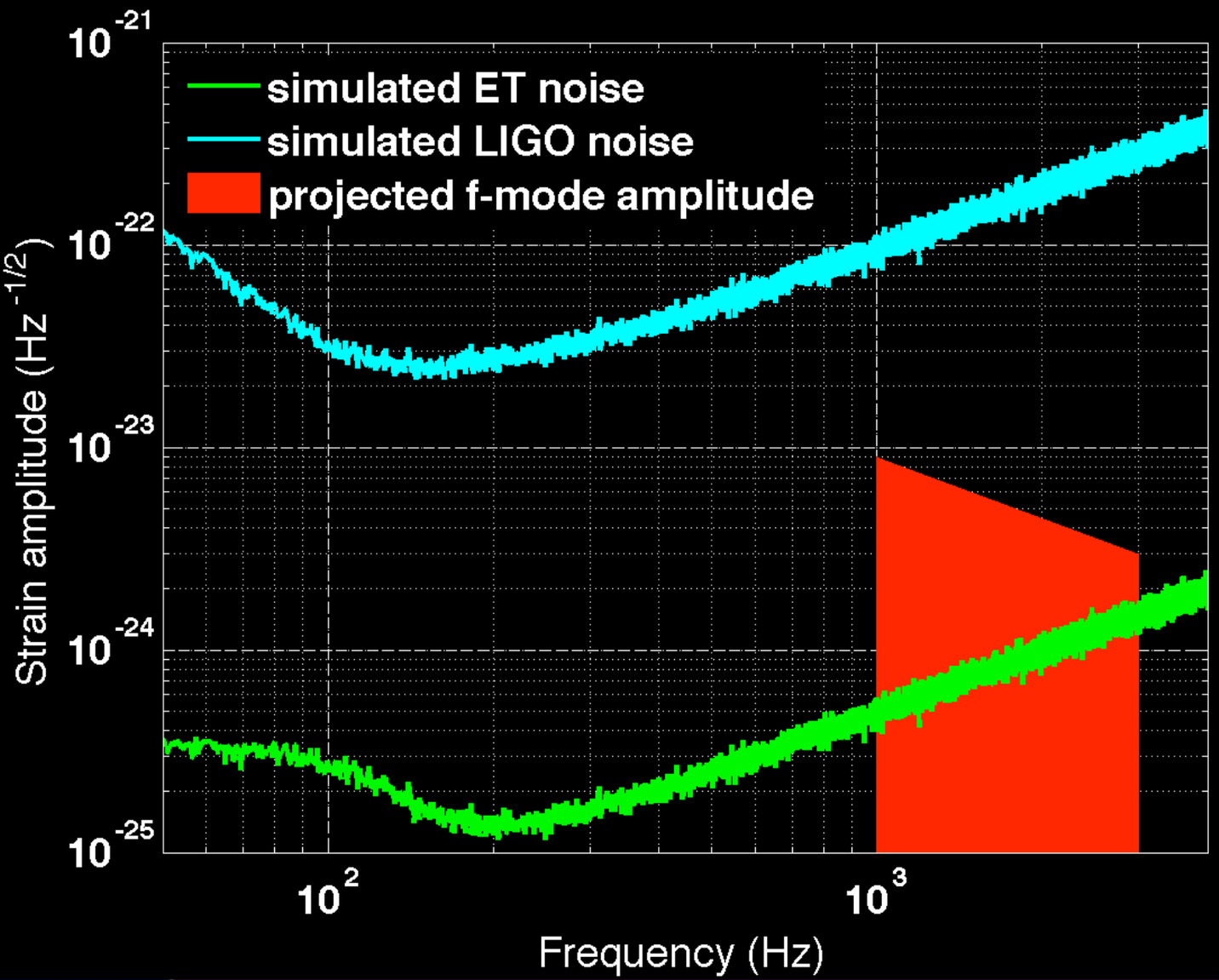
$$h_\times^{2m}(t) = \begin{cases} h_{2m}\mathcal{A}_\times^{2m}\cos(2\pi\nu_0(t-t_0)+\delta_0)e^{-(t-t_0)/\tau_0} \text{ for } t \geq t_0\ , \\ 0 \text{ otherwise.} \end{cases}$$

- If the orientation of the pulsar is known, we assume only a single harmonic is dominant and interpret amplitudes and energies in terms of that harmonic, using known inclination dependence (see Vela glitch search, slides 6-9)
- If the orientation is not known, assume isotropic emission with linear polarisation (see investigation of ET potential, slides 10-11)

Pulsar Glitches & Gravitational Waves

f-mode detection prospects

$$h_{2m} \approx 10^{-23} \left(\frac{E_{2m}}{10^{42}\,\mathrm{erg}}\right)^{\frac{1}{2}} \left(\frac{2\,\mathrm{kHz}}{\nu_0}\right) \left(\frac{200\,\mathrm{ms}}{\tau_0}\right)^{\frac{1}{2}} \left(\frac{1\,\mathrm{kpc}}{\mathcal{D}}\right)$$



- Simulated LIGO / ET noise using `ET_Mdc_v2a.c` (Regimbau, Sathyaprakash, Robinson & Rodriguez)
- Red region indicates root-sum squared range of f-mode amplitudes for energies up to 10^{42} erg
- Initial LIGO some way from probing astrophysics
- ET potentially capable of detection, given optimistic energy assumptions

August 2006 Vela Glitch

Electromagnetic Observations:

- HartRAO (Hartesbeesthoek Radio Observatory): 25 year old Vela monitoring program with 26m dish
- Between 12th Aug 14:51:22 and 13th Aug 04:26:05 Vela was below HartRAO's horizon
- When it emerged the frequency had undergone a fractional jump of 2.62×10^{-6}
- Follow-up by Sarah Buchner places the glitch epoch at Aug 12th, 22:31:35.7 +/- 17.3 s
- We take on-source: Glitch Epoch +/- 60 seconds for ~3-sigma window
- Use position angle & inclination from Ng, Romani (2003) [Chandra]
- Distance = 287 pc, from Dodson et al (2003) [Hubble]

LIGO status:

- Glitch occurred during LIGO's 5th science run (S5)
- All three detectors operating at the time but only co-located Hanford detectors had sufficient high quality data for analysis
- Analysis uses co-located Hanford detectors (4km and 2km)
- Search paper in preparation...

August 2006 Vela Glitch: GW analysis

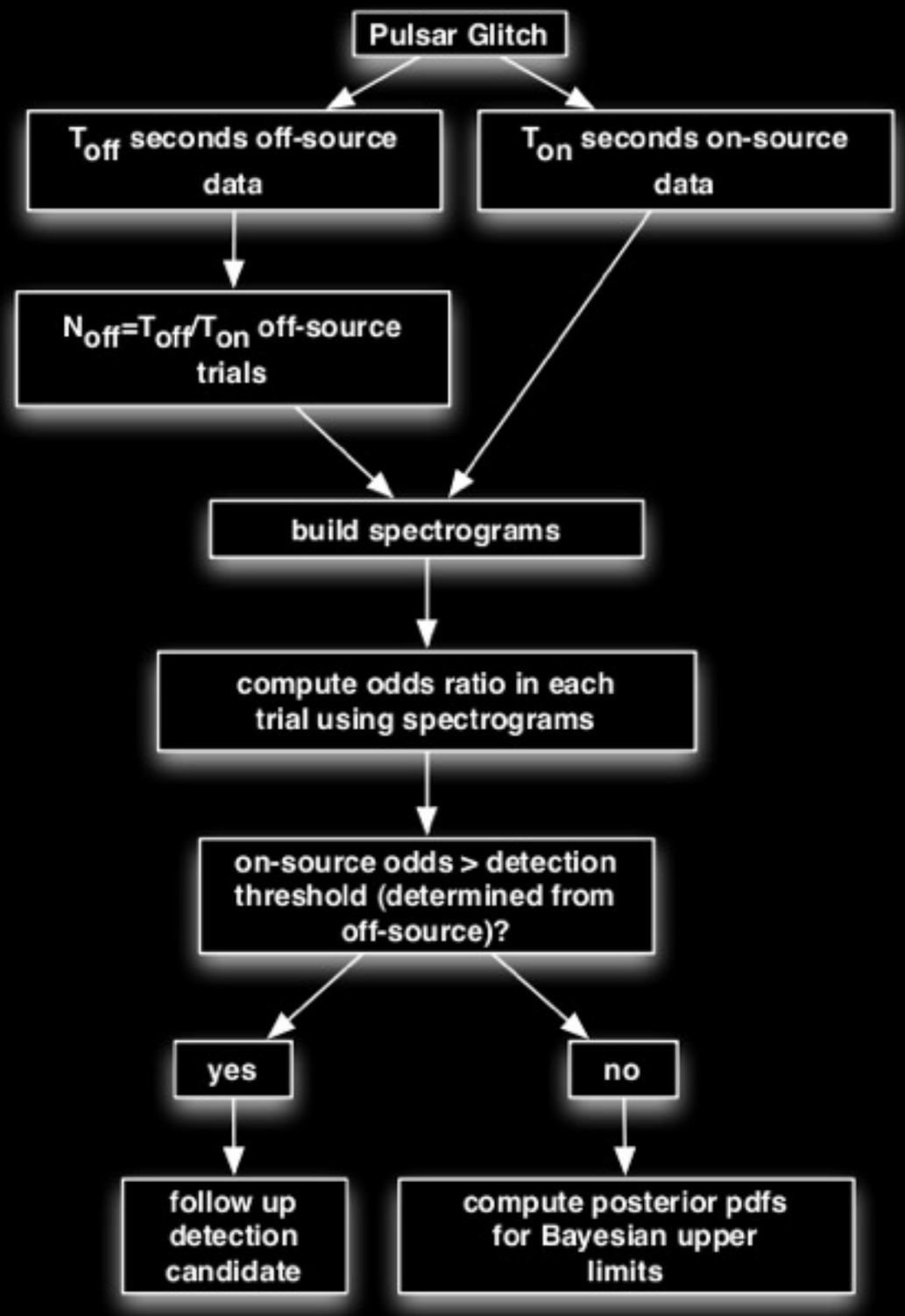
- Search method deploys Bayesian odds ratio as detection statistic:

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

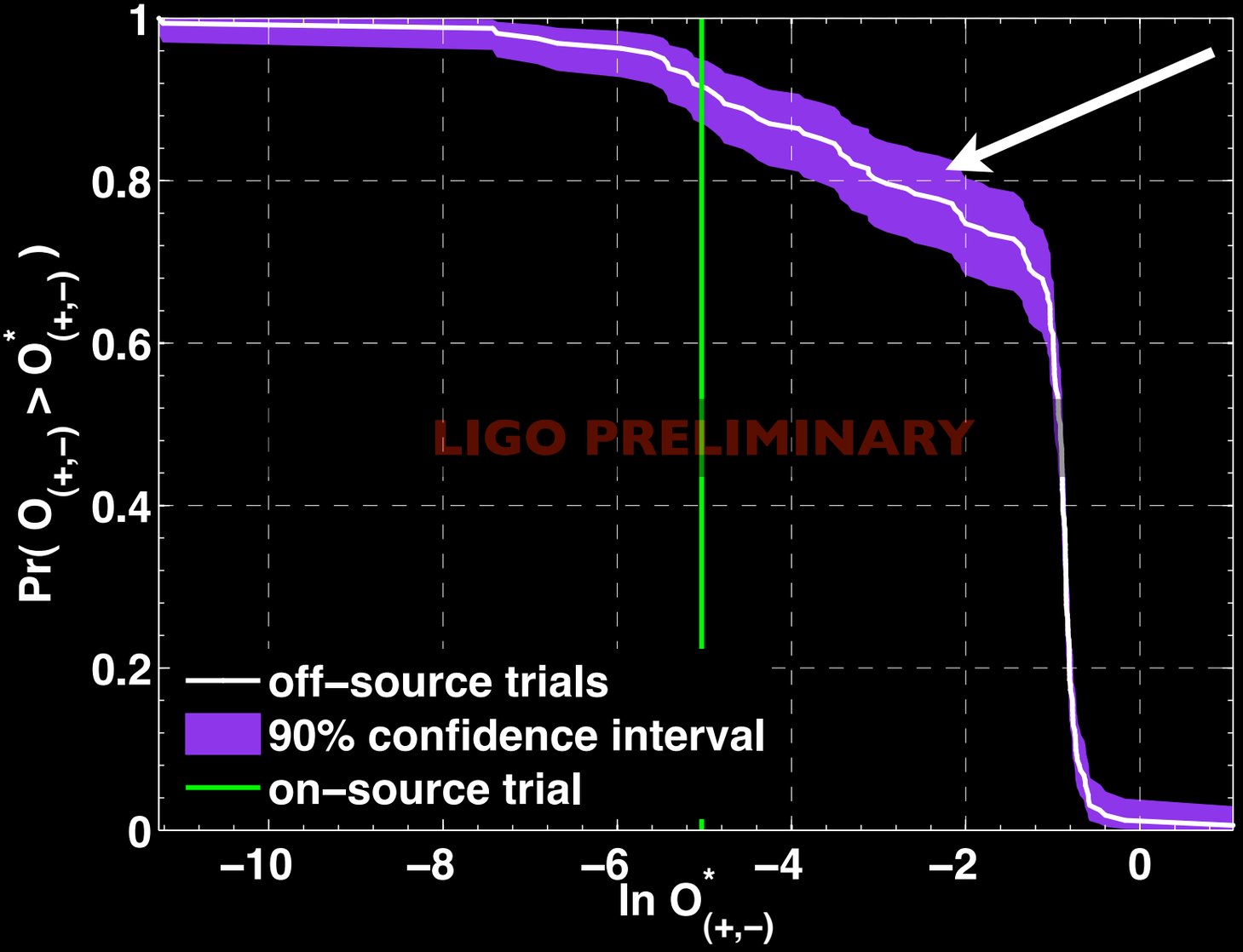
- choose between two models: detection (i.e., ring-down signal) or null-detection (Gaussian noise **OR** ring-down signals independent across detectors):

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

- do multiple off-source trials, single on-source trial
- 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



August 2006 Vela Glitch Search: Results

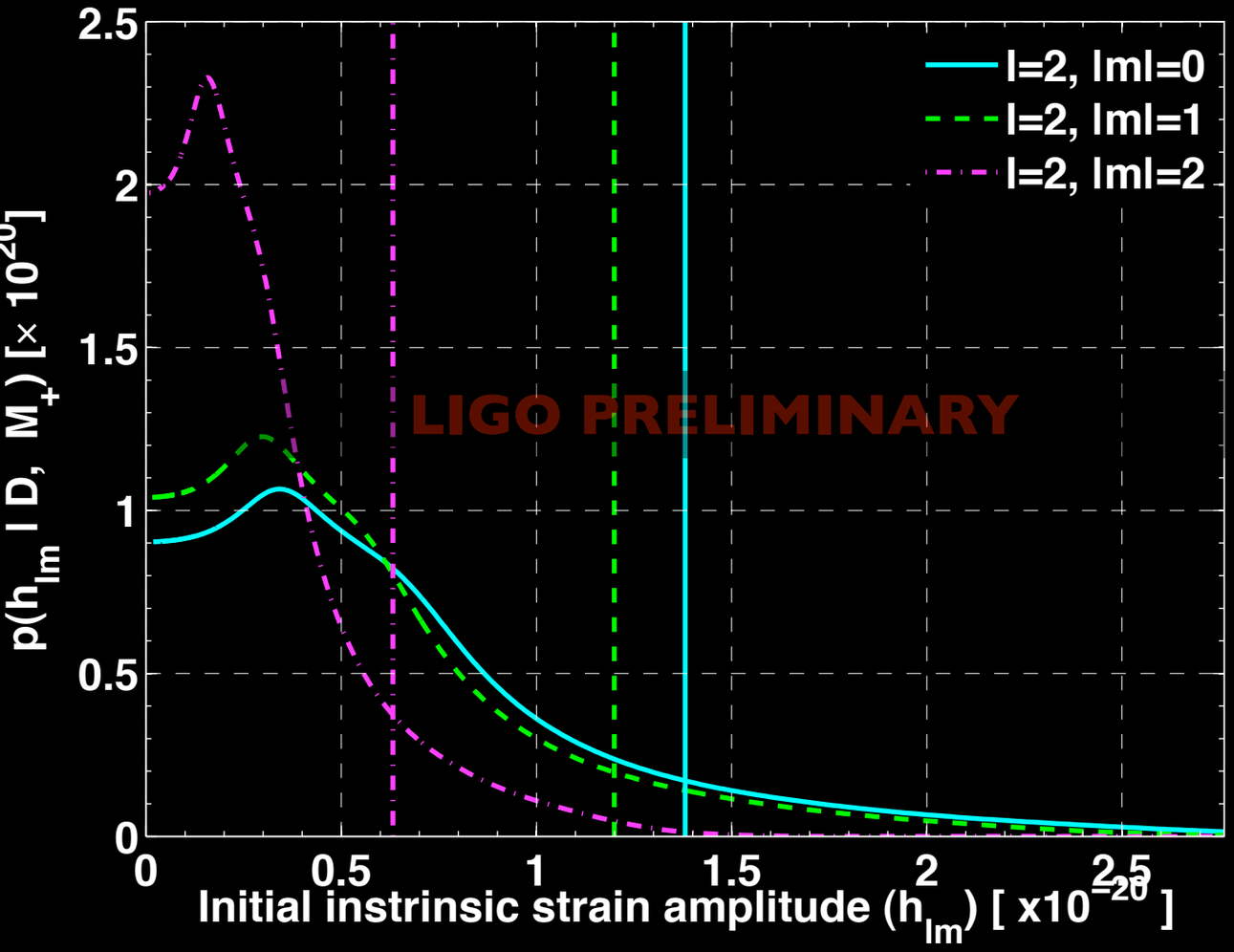


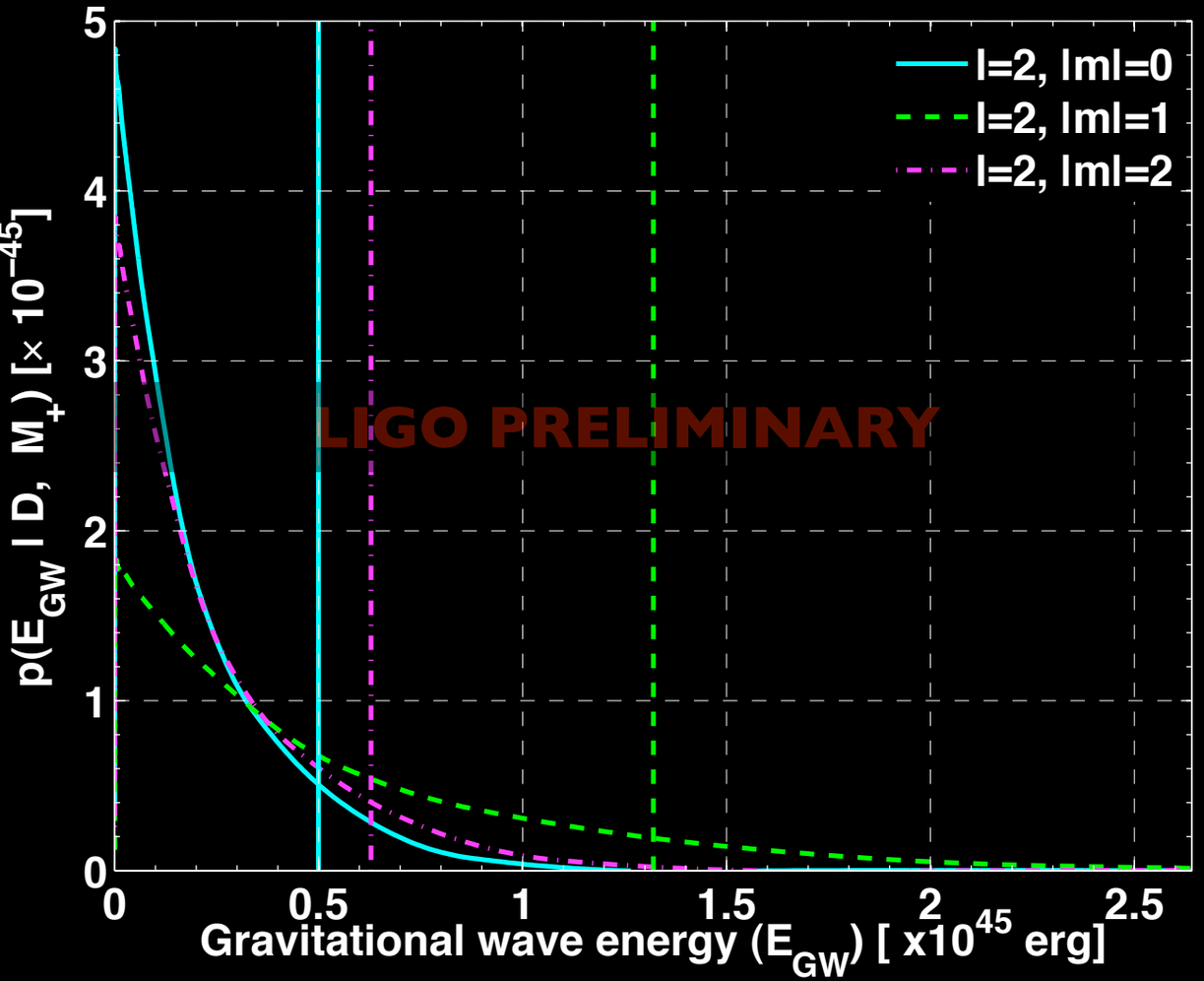
- Use **161** off-source segments of 120 s to estimate background distribution of odds ratio
- Estimate probability of obtaining an odds ratio greater than or equal to the value found in the on-source segment
- We find:
  - log on-source odds ratio = -5.03
  - max off-source log odds = 1.07
  - min off-source log odds = -11.26
- **Probability of obtaining odds >= on-source from background = 0.92**

Conclusion: no evidence in favour of gravitational wave signal associated with Vela August 2006 Glitch

August 2006 Vela Glitch Search: LIGO Results

Upper Limits From Marginal Posteriors:





Spherical Harmonic Indices	$h_{2m}^{90\%}$	$E_{2m}^{90\%}$ (erg)
$l=2,\ m=0$	1.4×10^{-20}	5.0×10^{44}
$l=2,\ m=\pm1$	1.2×10^{-20}	1.3×10^{45}
$l=2,\ m=\pm2$	6.3×10^{-21}	6.3×10^{44}

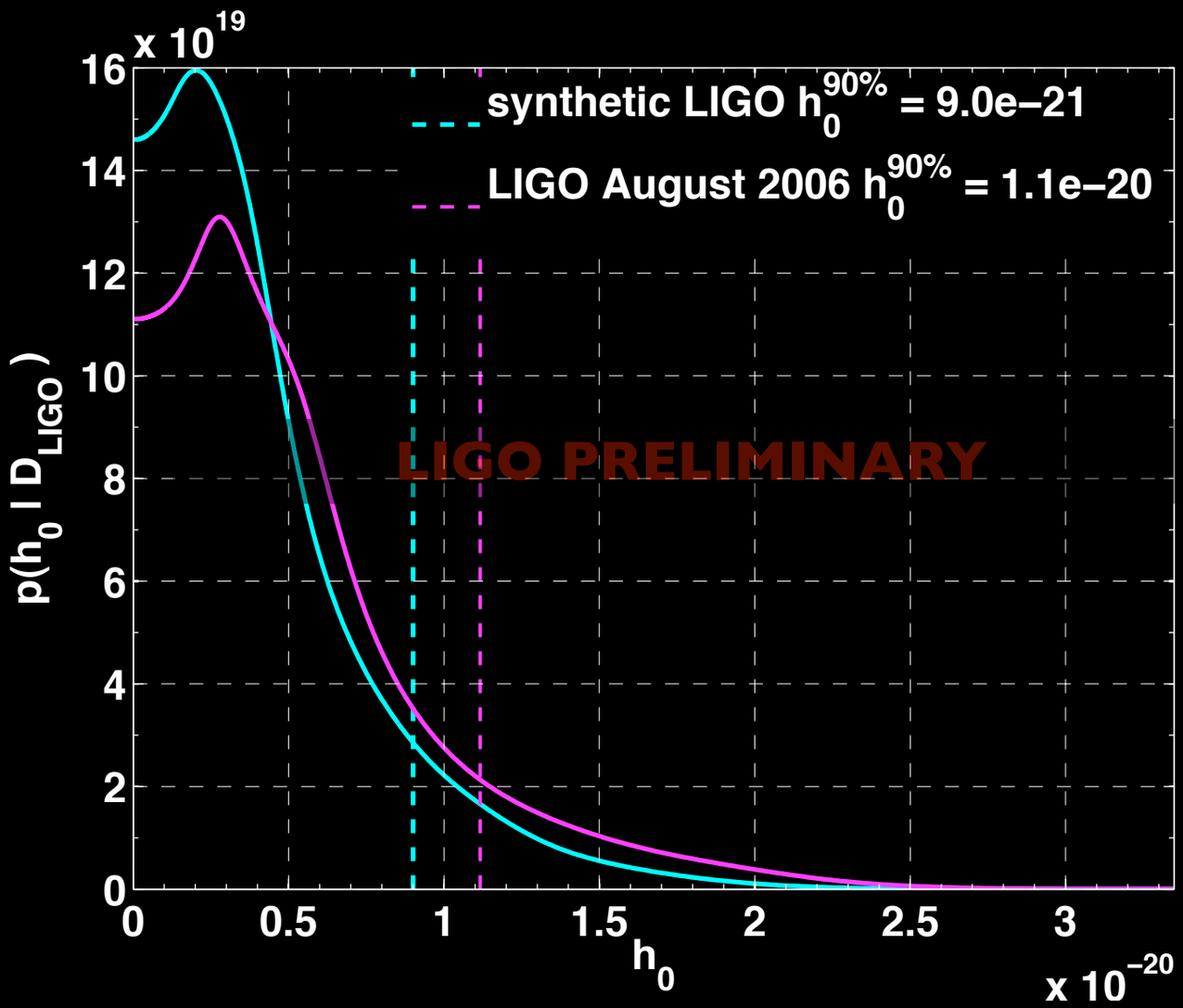
Comparison with simulated ET data

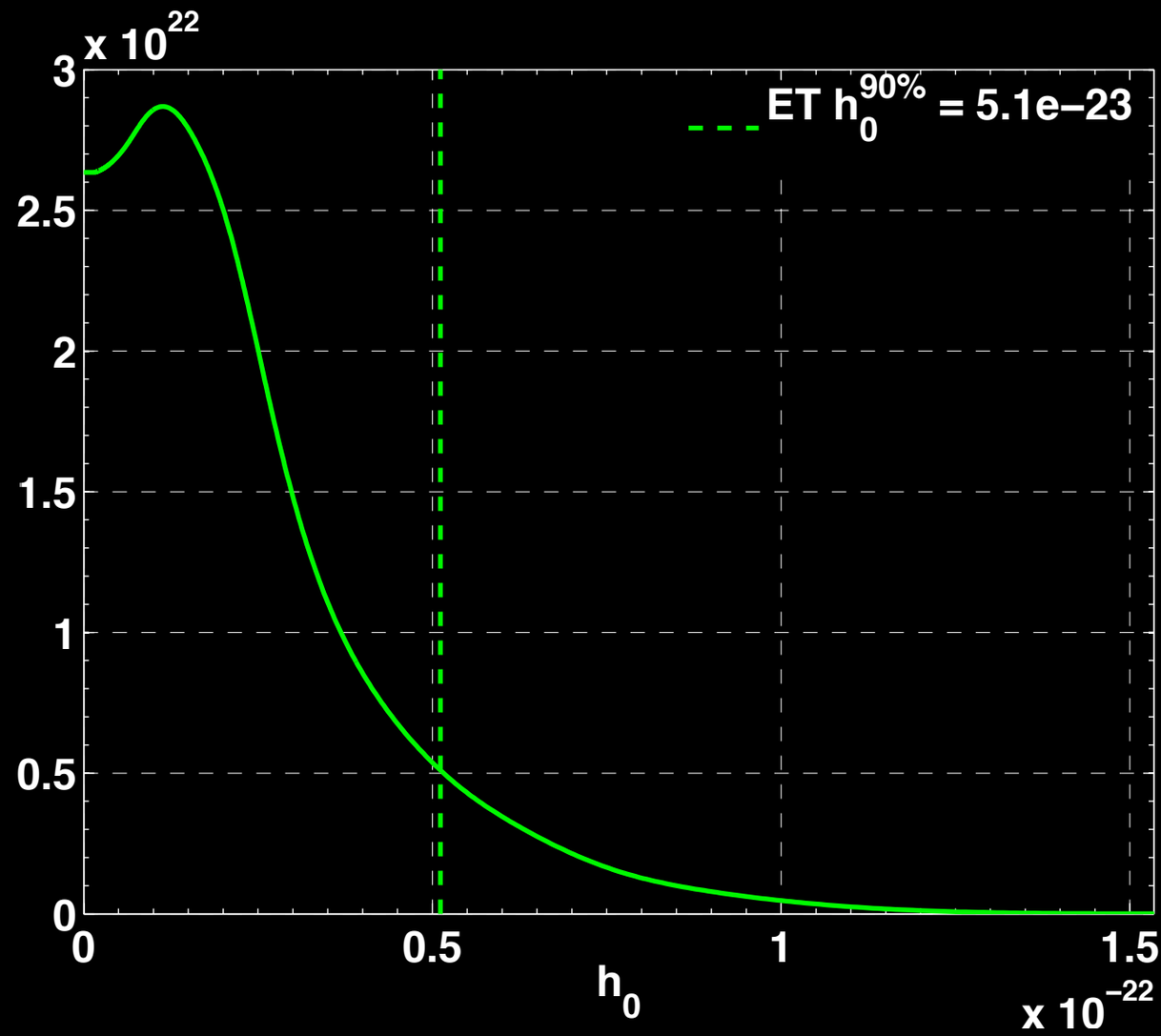
Thought Experiment

- Suppose we had performed this type of search using ET
- What strain amplitudes and GW energies could we probe down to?
- We compare upper limits from marginal posteriors using the simulated ET noise from `ET_Mdc_v2a.c` (Regimbau, Sathyaprakash, Robinson & Rodriguez)
- For fairness / realism, assume isotropic emission, source distance 1kpc, ET site @ Cascina, LIGO Hanford site and average detector antenna responses for both

GW Strain Amplitude Upper Limits

Now we reinterpret upper limits assuming isotropic emission & average detector response and compare Vela 2006 glitch upper limits with those obtained from simulated (initial) LIGO & ET data

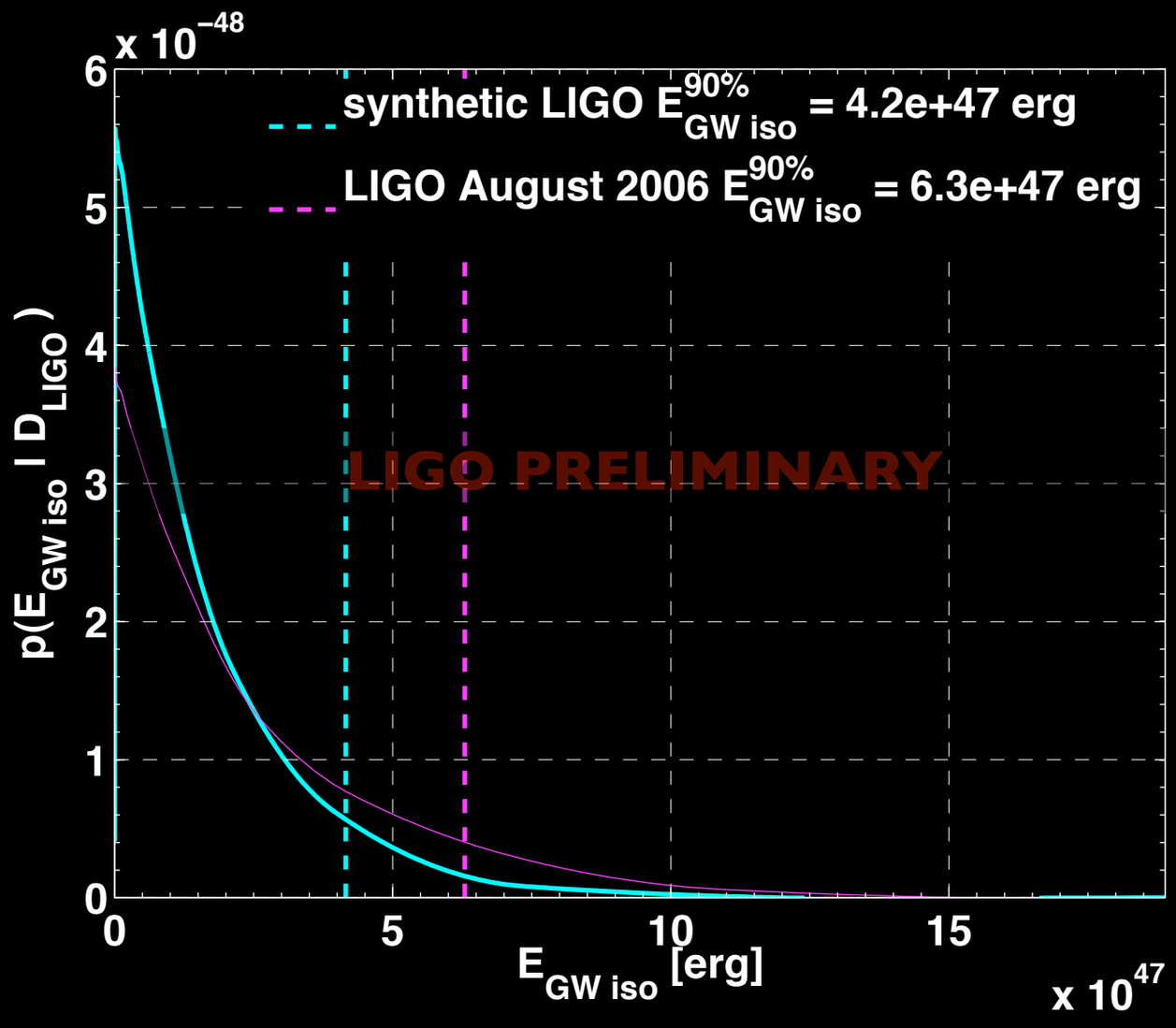


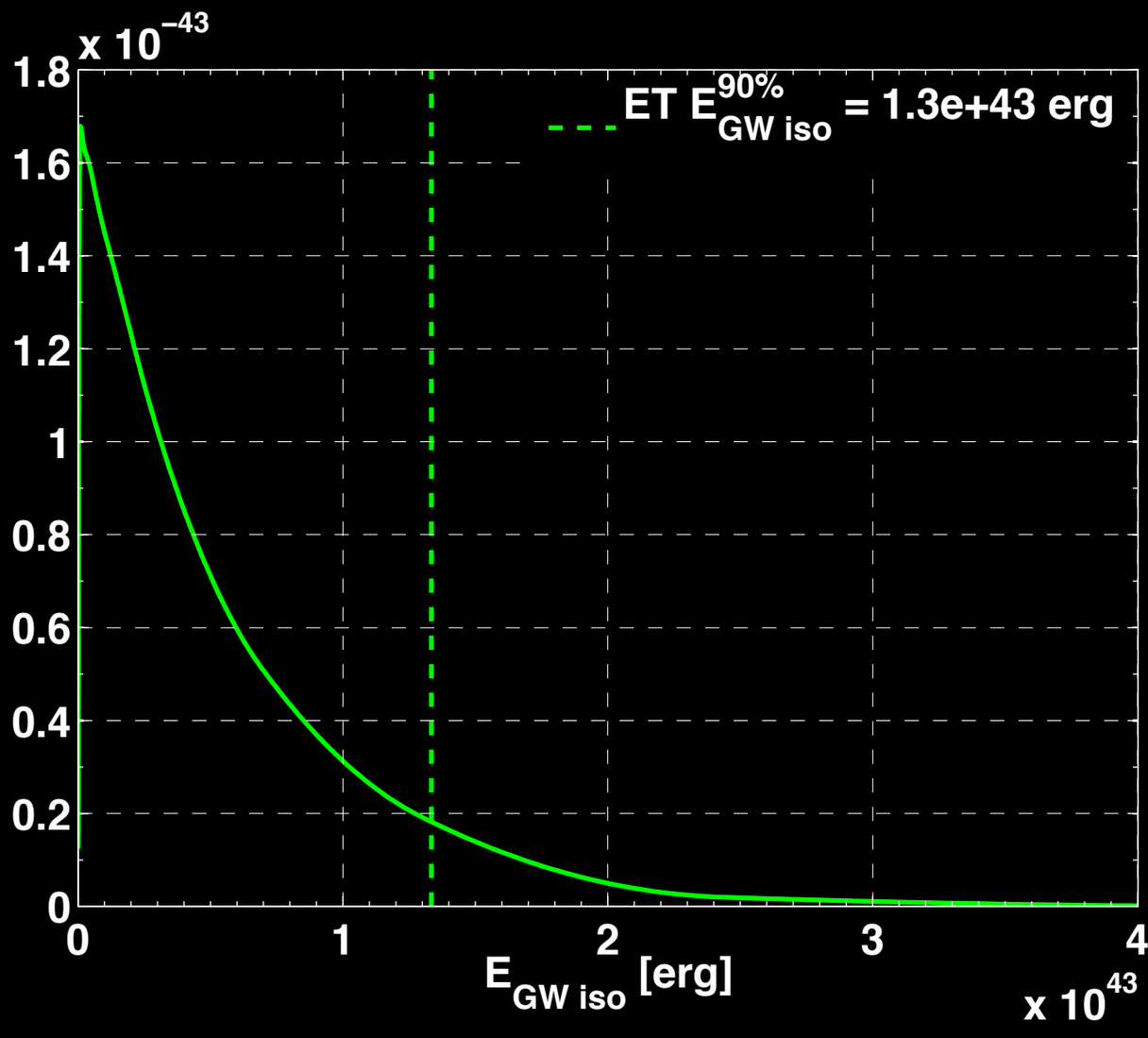


ET provides expected 2 orders of magnitude improvement in strain upper limits

GW Energy Upper Limits

Now we reinterpret upper limits assuming isotropic emission & average detector response and compare Vela 2006 glitch upper limits with those obtained from simulated (initial) LIGO & ET data





ET provides expected 4 orders of magnitude improvement in energy upper limits

Discussion

- 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} **LIGO PRELIMINARY**
  - total GW energy 90% confidence limits = 5.0×10^{44} - 6.3×10^{44} erg **LIGO PRELIMINARY**
- 'Average' sky-location and re-interpreting these upper limits in terms of an isotropic emission model @ **1kpc**, we find:
  - LIGO S5 Vela glitch upper limits peak strain = 1.1×10^{-20}, energy = 6.3×10^{47} erg
  - simulated LIGO upper limits: peak strain = 9.0×10^{-21}, energy = 4.2×10^{47} erg
  - simulated ET upper limits: peak strain = 5.1×10^{-23}, energy = 1.3×10^{43} erg

Conclusions

- **ET should detect nearby pulsar glitch f-mode ring-downs, depending on glitch mechanisms and associated energies.**
- **In a null-detection scenario, will begin to be able to probe astrophysically interesting energies (interesting = 1e38 - 1e42 erg) for nearby glitches**