Gravitational-Wave Astronomy: Observational Results and Their Impact

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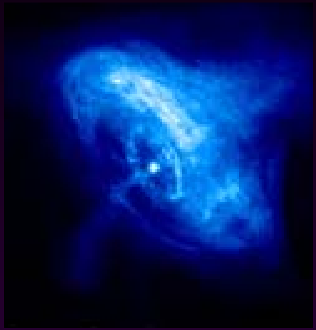
What We Have Detected So Far:

Nothing.

The Impact of Null Results Published So Far

Getting to Know our Neighbors Better

The Crab Pulsar *[Abbott et al., ApJL 683, L45]*

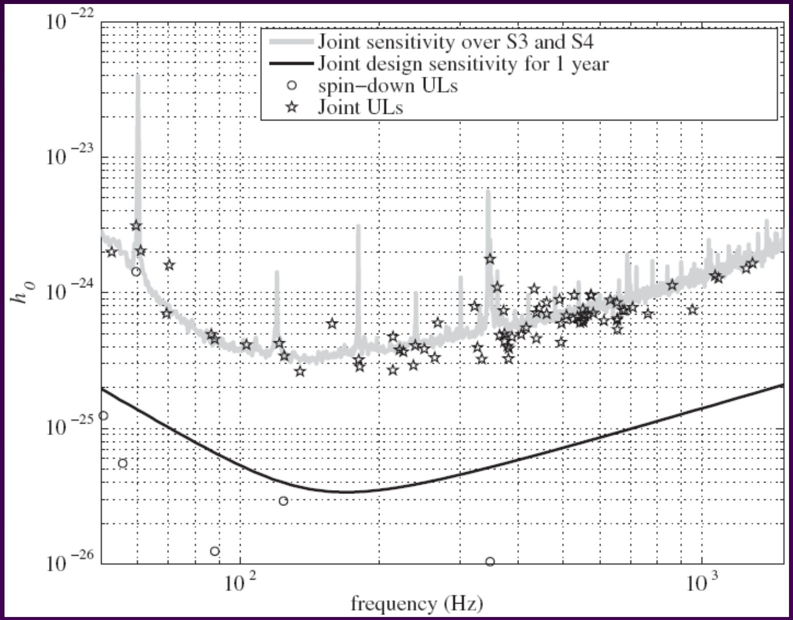


Chandra image

- Spinning down rapidly; energy loss ~ 4×10^{31} W
- A significant fraction of that could be going into GWs
- Searched for signal in first 9 months of LIGO S5 data
- Assuming that GW signal is locked to EM pulses, null search result implies that no more than **4–6%** of the spin-down energy is going into GW emission

Other known pulsars *[Abbott et al., PRD 76, 042001]*

- Searched for GW from 78 known pulsars using LIGO S3 and S4 data
- PSR J1603–7202 : $h_0 < 2.6 \times 10^{-25}$
- PSR J2124-3358 : $\varepsilon < 7 \times 10^{-7}$
- Better results from S5 are coming…



Getting to Know our Neighbors Better

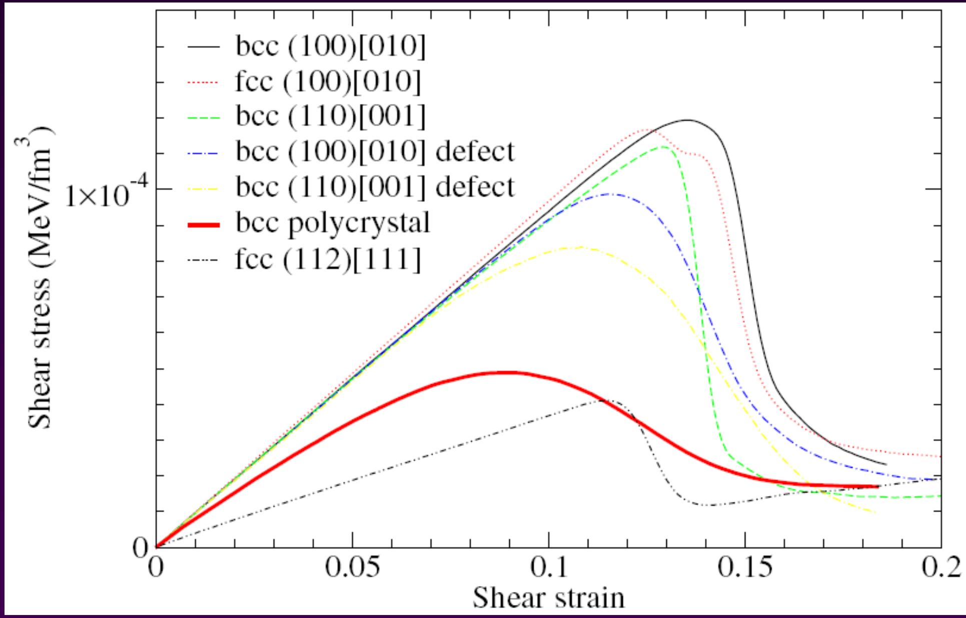
⇒ GW data shows that these neutron stars, at least, are pretty close to being symmetric

– Is that due to the material properties?

Motivation for theorists! *e.g.* these recent papers:

– Horowitz & Kadau, PRL 102, 191102 :

Normal crystalline crust can have breaking strain up to ~0.1, allowing ε to be up to ~4 × 10^{-6}



– Knippel & Sedrakian, PRD 79, 083007 : GW emission from a crystalline color-superconducting core

When the Neighbors are Disturbed…

Soft gamma repeater (SGR) flares

- Crustal cracking may excite quasinormal modes which emit GW

GW bursts at times of flares ?

[Abbott et al., PRL 101, 211102 and arXiv:0905.0005]

- For certain assumed waveforms, GW energy limits are as low as few × 10^{45} erg, comparable to EM energy emitted in giant flares
- Ioka, MNRAS 327, 639 : GW emission during a giant flare could be ~ 10^{45} to 10^{49} erg, probably mainly in ***f***- and ***p***-modes

Long-lived quasiperiodic GWs after giant flare ?

[Abbott et al., PRD 76, 062003]

- GW energy limits are comparable to total EM energy emission

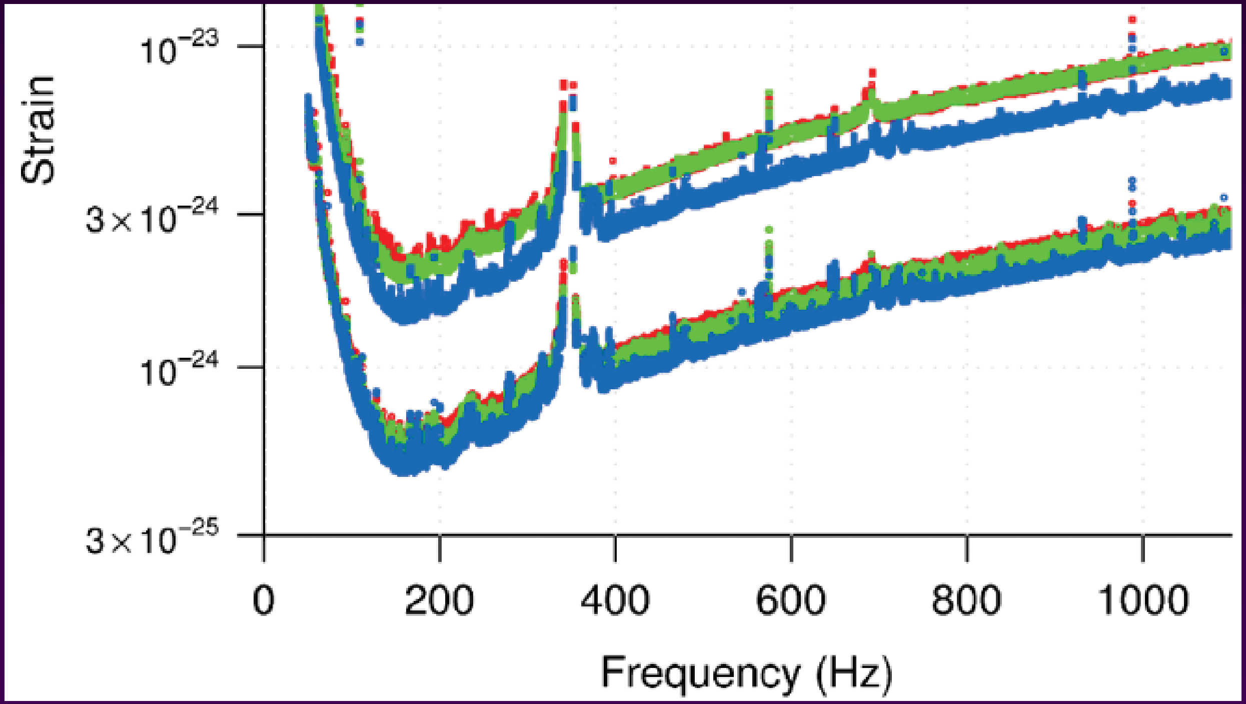
Motivation…

- for theorists to refine models
- for observers to find more giant flares and closer SGRs !

Listening for Invisible Neighbors

Search for continuous-wave GW signals from unseen neutron stars *[Abbott et al., PRL 102, 111102]*

- Searched first 8 months of LIGO S5 data with "PowerFlux" semi-coherent analysis
- Distance reach: out to hundreds of parsecs if $\varepsilon \sim 10^{-6}$
- Set upper limits on strain amplitude vs. frequency



Worst-case pulsar orientation

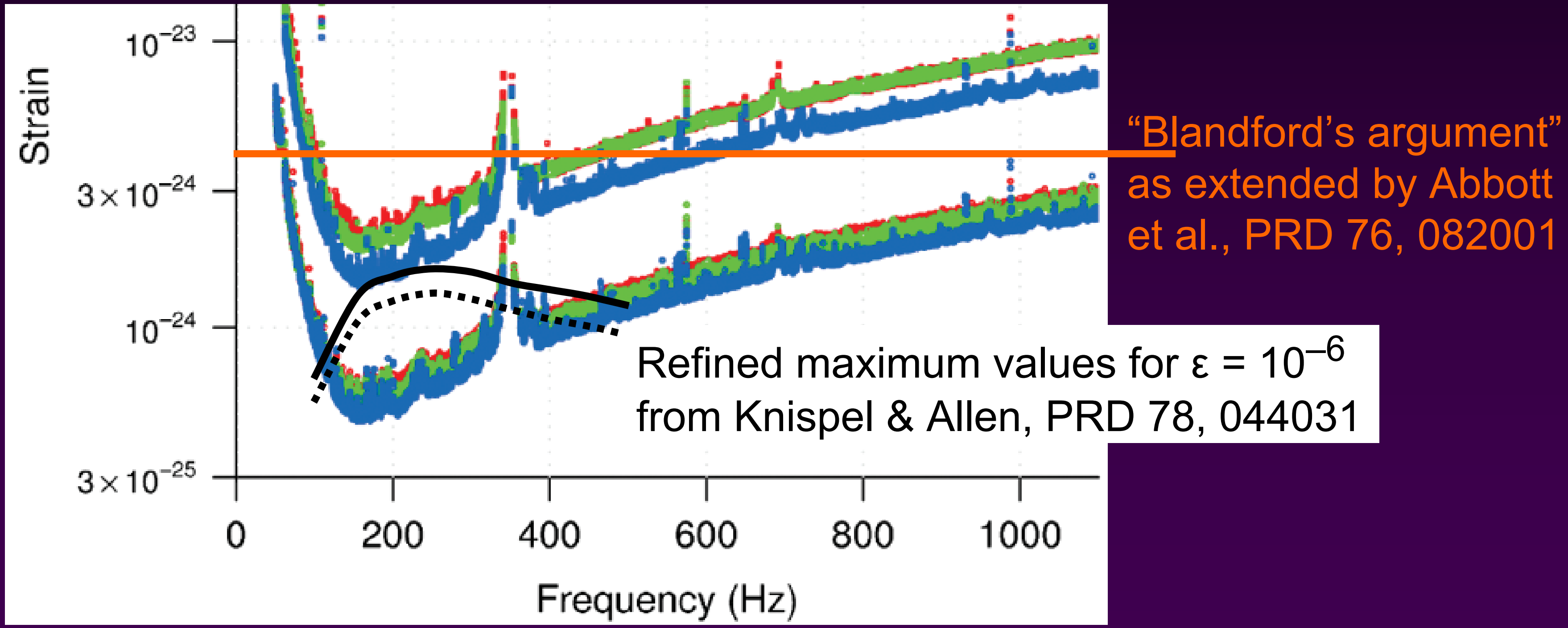
Best-case pulsar orientation

Each maximized over sky position within a given declination band

Listening for Invisible Neighbors

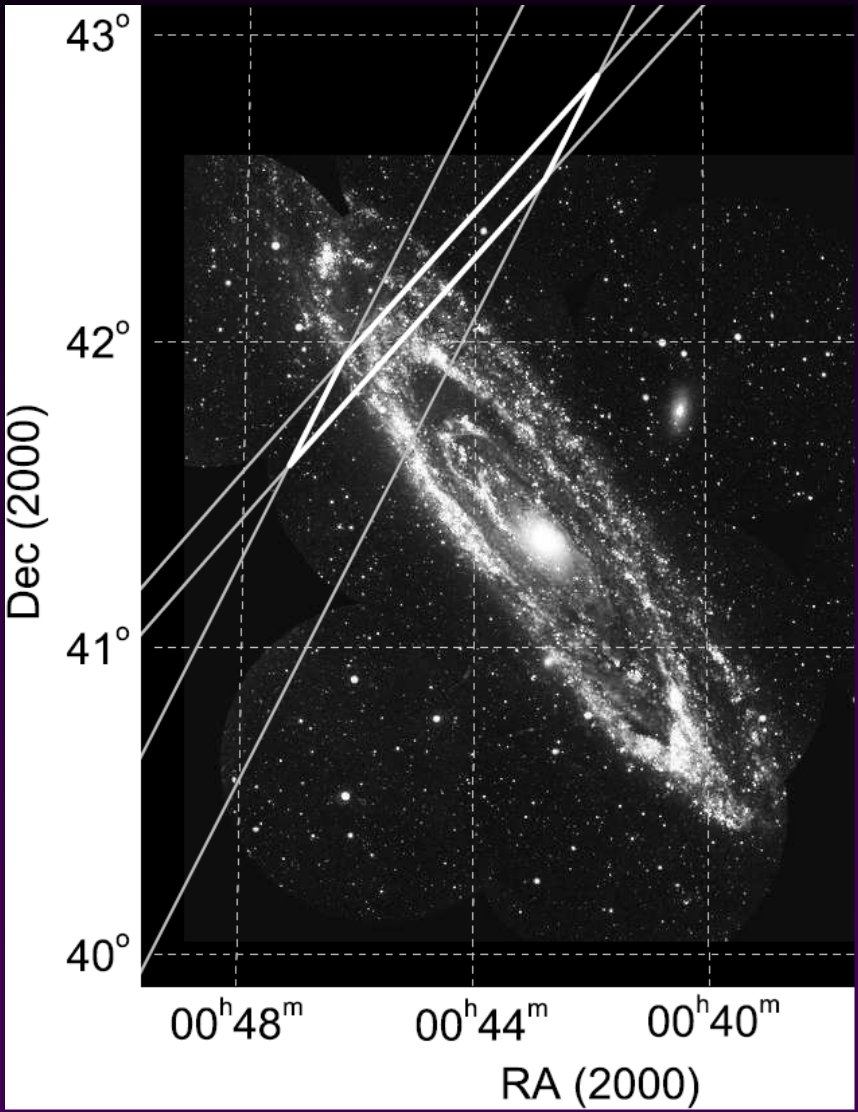
? Is the lack of a detected signal significant ?

Estimate the strongest signal expected, on average, assuming that all pulsars spin down by GW emission



⇒ Null result still excludes the most optimistic scenario

Listening to the Galaxy Next Door



IPN 3-sigma error region from Mazets et al., ApJ 680, 545

GRB 070201

- Short, hard gamma-ray burst
- Consistent with being in M31
- Leading model for short GRBs: binary merger involving a neutron star

Looked for a GW signal in LIGO

[Abbott et al., ApJ 681, 1419]

- Searched for both inspiral and burst signals
- No plausible GW signal found

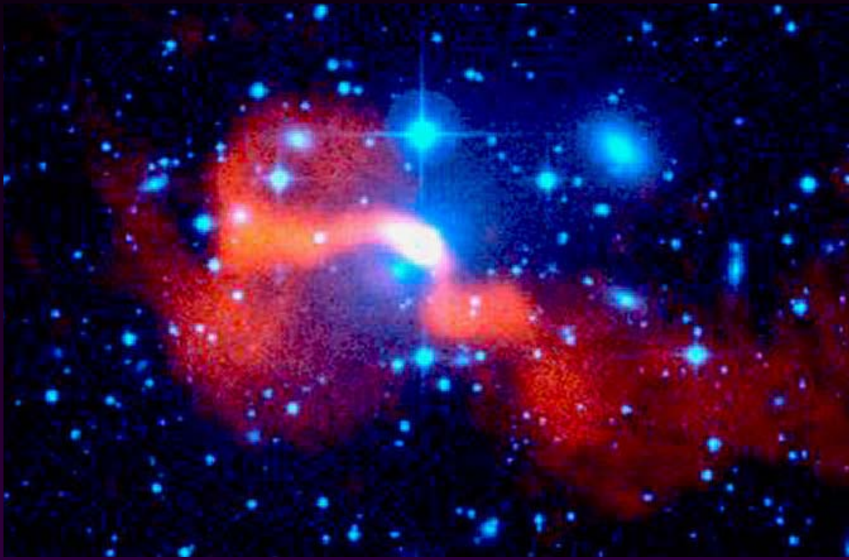
Conclusion: it was most likely an SGR giant flare in M31

- Mazets et al., ApJ 680, 545
- Ofek et al., ApJ 681, 1464

Black Hole Binary in 3C66B ?

Bright radio galaxy with jets

- Distance ~90 Mpc
- Sudou et al., Science 300, 1263 : observed motion of radio core consistent with elliptical orbit with period of 1.05 year
- Suggestive of a supermassive black hole binary



Blue: *Digitized Second Palomar Sky Survey*
Red: VLA 1.45 GHz
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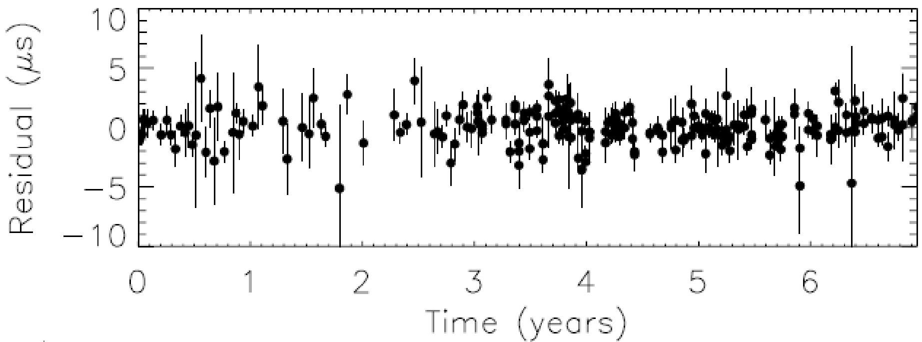
Used pulsar timing data to check

[Jenet, Lommen, Larson and Wen, ApJ 606, 799 (2004)]

- Looked at PSR 1855+09 arrival times in archival Arecibo data
- No variation seen – rules out black hole binary hypothesis



Catching a Merger Anywhere in the Sky

Low-mass inspirals *[Abbott et al., PRD 79, 122001]*

- Searched LIGO data from the first year of S5
- Systems with total mass up to 35 Msun
- Set upper limits on event rates, using a population model
  - Binary neutron star systems: < 0.039 per year per L_{10}
  - Black hole – neutron star systems: < 0.011 per year per L_{10}
  - Binary black hole systems: < 0.0025 per year per L_{10}
- Still far from expected rates

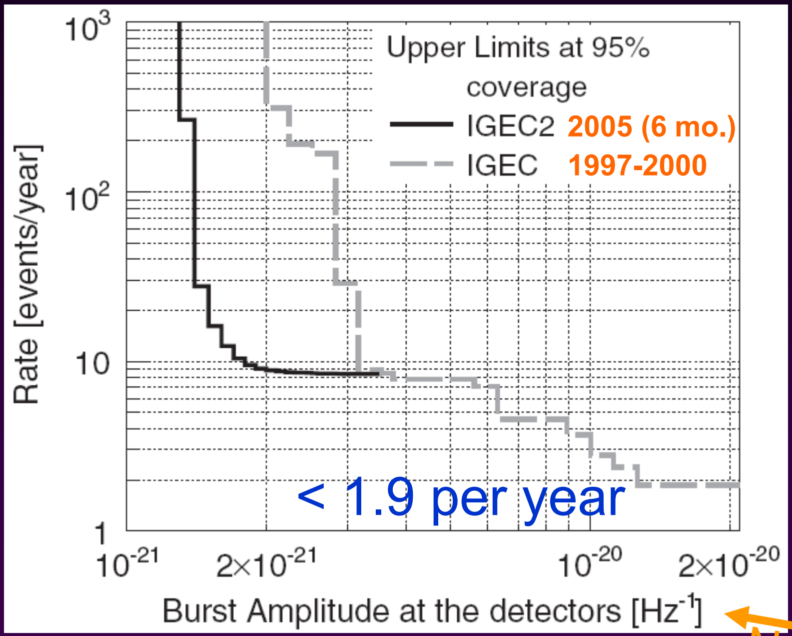
Motivates improved waveform modeling

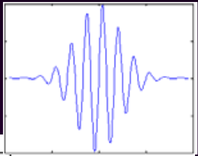
- Numerical relativity simulations
- Hybrid waveforms

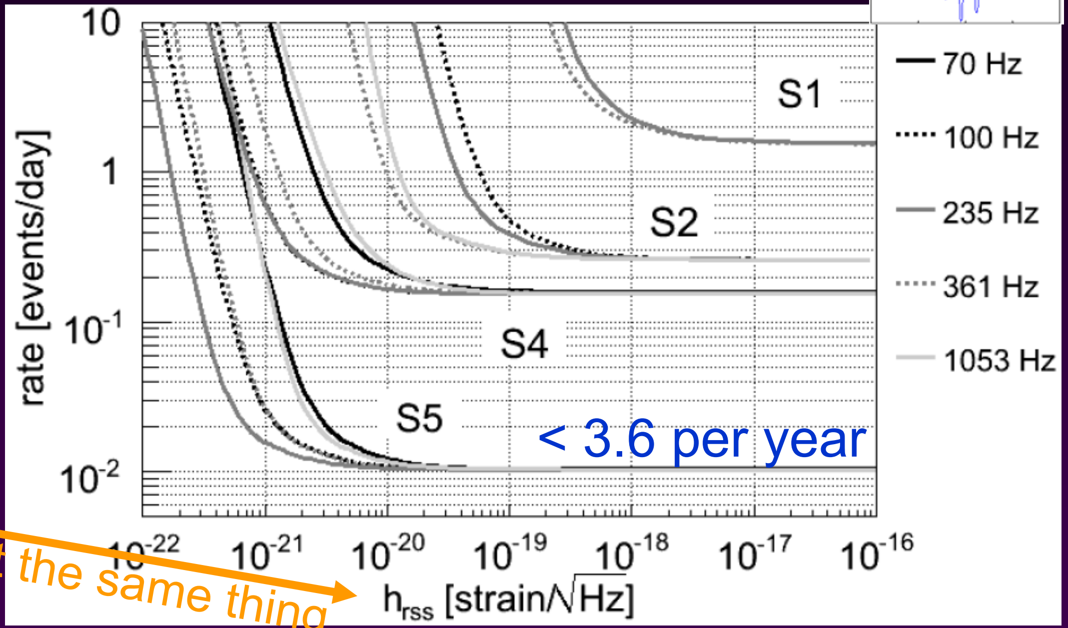
Being Vigilant for Arbitrary Bursts

Observation time champion: IGEC

[Astone et al., PRD 68, 022001 and PRD 76, 102001]







Not the same thing

Sensitivity champion: LIGO [Abbott et al., arXiv:0905.0020]

At least we know there are few, if any, GW bursts arriving with these strengths

Tuning In to Spacetime Shivering

Search for an isotropic stochastic background of GWs

[Jenet et al., ApJ 653, 1571]

- Pulsar timing analysis using 7 pulsars over time spans of at least a few years
- Placed limits on energy density of GW, assuming different power-law distributions as a function of frequency
- Derived limits on:
  - Mergers of supermassive binary black hole systems at high redshift
  - Relic gravitational waves (model by Grishchuk)
  - Cosmic superstrings (parameters of the population)
- For the cosmic superstring network,
  upper limit on string tension $G\mu$ depends on characteristic loop size ε and reconnection probability p

Tuning In to Spacetime Shivering

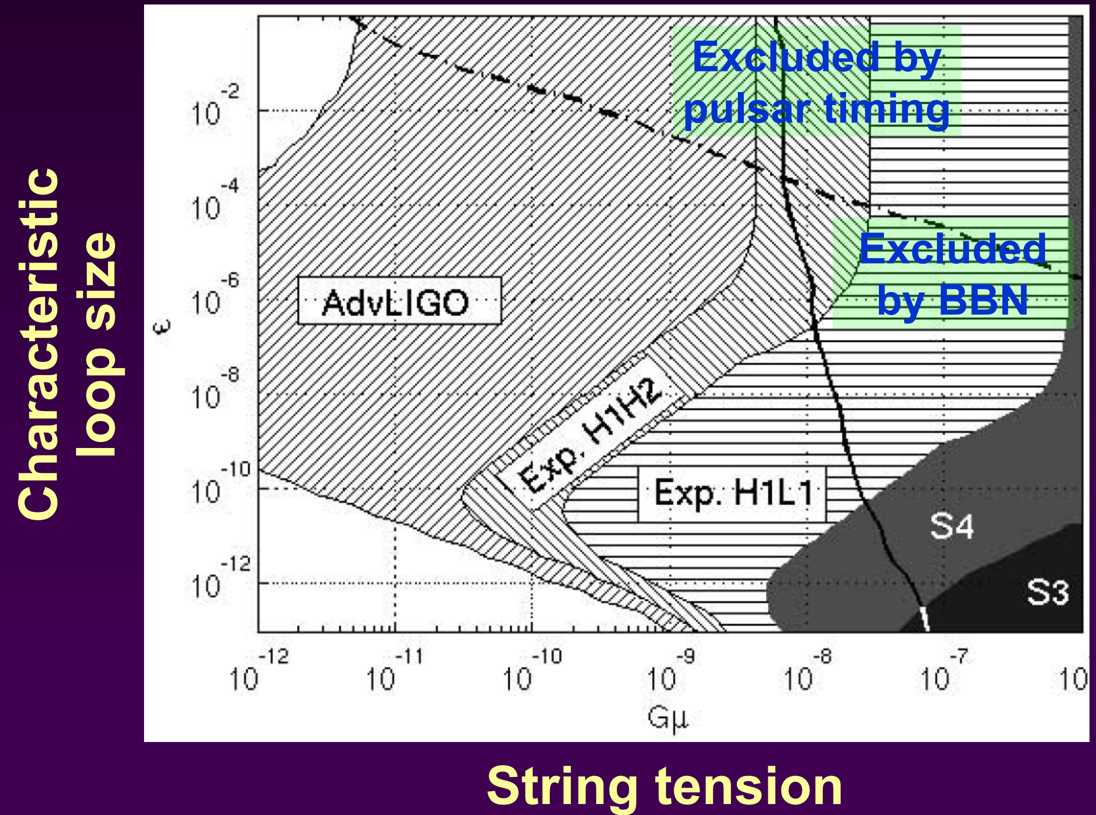
Search for an isotropic stochastic background of GWs

[Abbott et al., ApJ 659, 918]

- Analyzed LIGO S4 data
- Placed limit on GW energy spectral density: $\Omega_0 < 6.5 \times 10^{-5}$
- Constrains parameters of cosmic superstring population:

  (This plot assumes reconnection prob. $p = 10^{-3}$)

- Expect better results soon from S5 data



Summary: Impact of Null Results

GW searches are now placing meaningful constraints on:

- Individual objects and events
- Source populations (real or imagined)
- Total energy density in GWs

Still, null results will never be as interesting as a detection…

The Impact of (Future) Positive Observational Results

What We Will Learn…

… depends on what signal(s) we detect, of course

- See, for example, Sathyaprakash & Schutz, "Physics, Astrophysics, and Cosmology with Gravitational Waves", Living Reviews in Relativity, March 2009 – http://relativity.livingreviews.org/Articles/lrr-2009-2/

Here is one way it might play out…

A Wild Guess at the Future

August 2010: LIGO and Virgo record a BH-NS candidate

- Detected by inspiral search with false alarm rate of 1 per 160 years; masses 8.2 and 1.46 Msun
- Also a candidate in burst search, but not the strongest
- Reconstructed position is consistent with galaxies within 50 Mpc
- Weak optical transient seen in an elliptical galaxy in the field
- Published as cautious evidence for a GW signal
- Many improved upper limits extracted from S6/VSR2 data

A Wild Guess at the Future

Spring 2015: AdvLIGO, AdVirgo, GEO-HF first science run

- Two BH-NS candidates found in the 8-month run, with expected background of 0.02 . Also two NS-NS candidates, with background of 0.03, one followed up promptly with radio and found to have a clear afterglow. These are published as first detection of GWs.
- Strong limits set on non-GR polarization states
- One outlier burst candidate is seen with central frequency 330 Hz and duration 0.21 s, unlike most background events. Two other similar candidates are in the noise tail. Described in a paper, but not claimed to be certain GW signals.
- Continuous-wave signal candidate found in a search aimed at the Galactic bulge; looks real, but not significant enough to claim as a detection
- Strongly improved CW emission limits for known pulsars and for stochastic signals, but no detections yet

2015: Greatly improved limits published from pulsar timing

A Wild Guess at the Future

2016-2018: Next science run of AdvLIGO and AdVirgo, joined in 2017 by LCGT and AIGO

- Collect 15 NS-NS candidates with a background of 2.2 . Two of them correspond to short-hard GRBs, one of which is localized in a galaxy with a measured redshift of 0.07 .
- 18 BH-NS candidates with a background of 4.1 . Two of these correspond to GRBs, one also with a high-energy neutrino event.
- 6 BH-BH candidates with a background of 1.7 . Masses and spins measured, start to get a picture of their distributions
- Comparison of GW inspiral times with GRB times confirms that GWs travel at the speed of light.
- Samples of NS-NS and BH-NS are consistent with all being in high-mass galaxies. BH-BH candidates may be too, but it isn't clear.
- 4 burst events found with background of 0.15 . One of them, with central frequency 310 Hz, corresponds to a weak long GRB with no measured redshift. The other 3 have central freqs around 120 Hz.

A Wild Guess at the Future

2016-2018 science run results continued:

- GW detected from Crab pulsar, corresponding to 0.12% of spin-down energy; tests models of asymmetry freeze-in at birth
- Sco X-1 detected at the expected level during 3-month narrowband running period
- CW signals detected from 5 unseen neutron stars; get rough distributions of frequencies, spindowns, sky positions
- Stochastic search severely limits cosmic string models
- Stochastic point-source search detects signals from two LMXBs besides Sco X-1

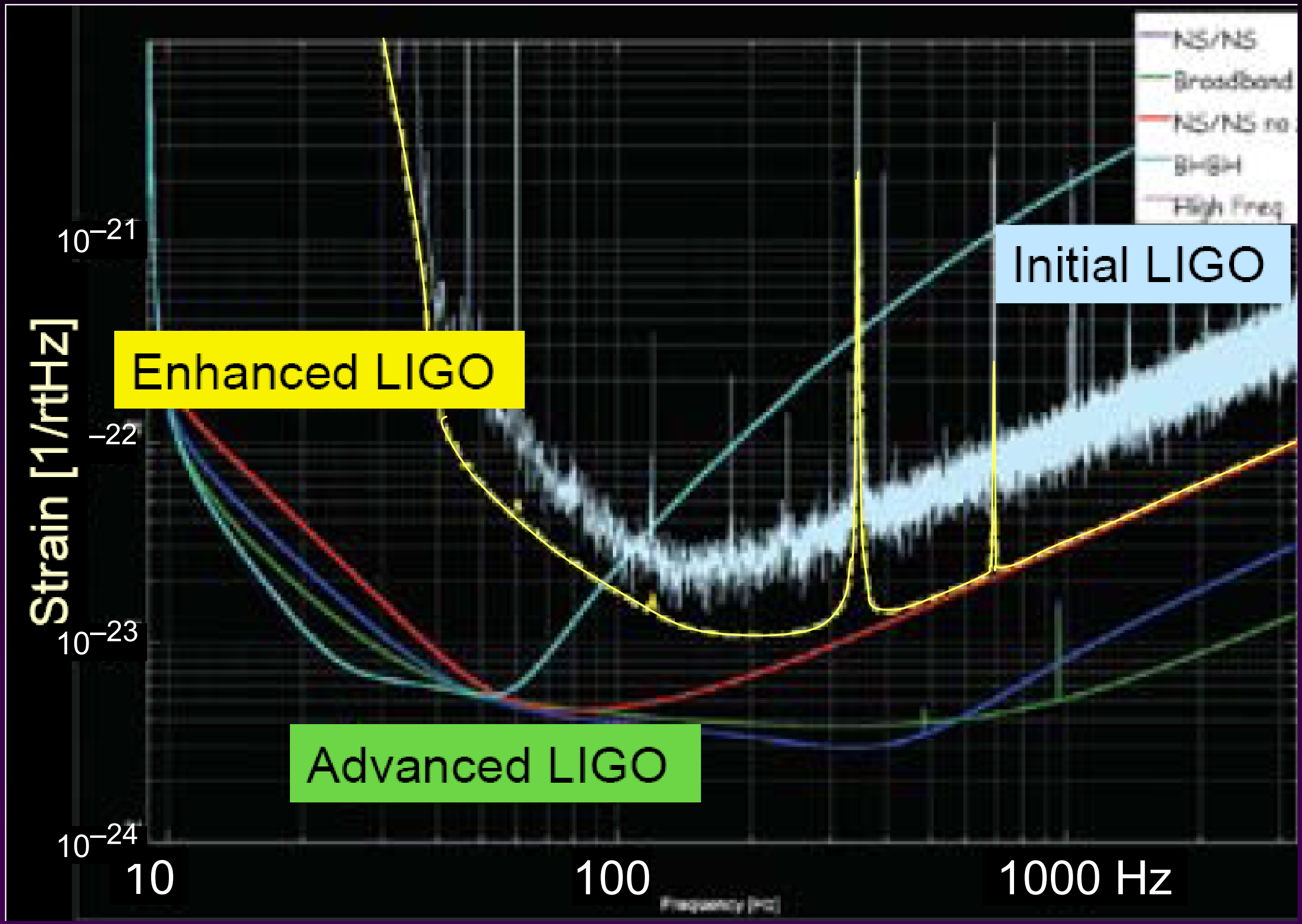
2020: Pulsar timing results

- Aided by several pulsars discovered by SKA, GWs are detected from supermassive BH binaries in two galaxies
- Large-epsilon region of cosmic string models effectively ruled out

Also: LISA and DECIGO launched, detect <u>lots</u> of signals

The Impact of Positive Observational Results on our Field

Tuning Choices for Advanced Detectors



Plus narrowband options, and possible detector redesign?

Support for Additional Detectors

- Motivation for additional detectors
  - If not already approved
  - On the ground: LCGT, AIGO, China, India, ET, other 3rd-gen
  - LISA, DECIGO, other space-based?
- Design choices
  - Frequency band(s), bandwidths
  - Locations

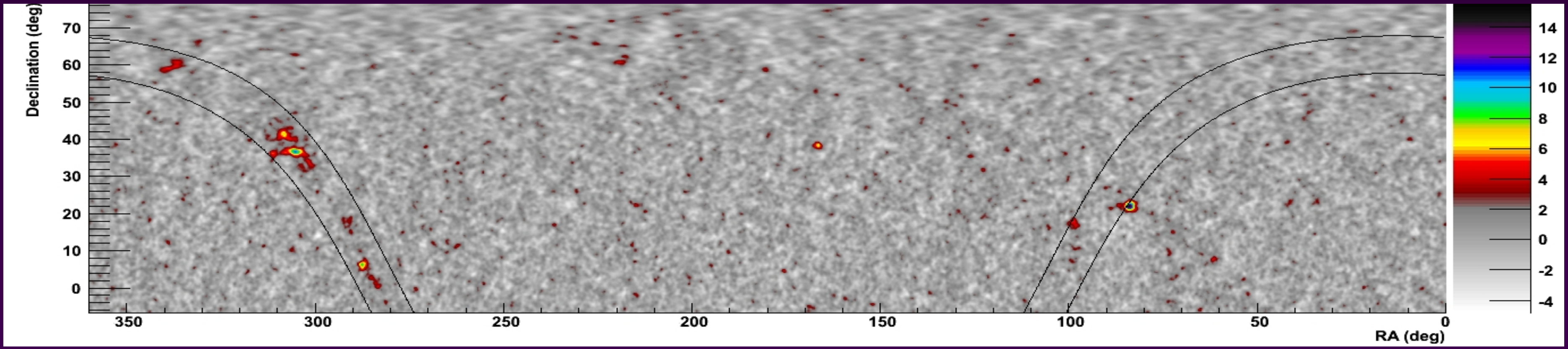
Changes in Philosophy

High-confidence detection of some signals will give us more belief in other candidates

At some point, in a sample of candidates, *most* of them will be assumed to be real

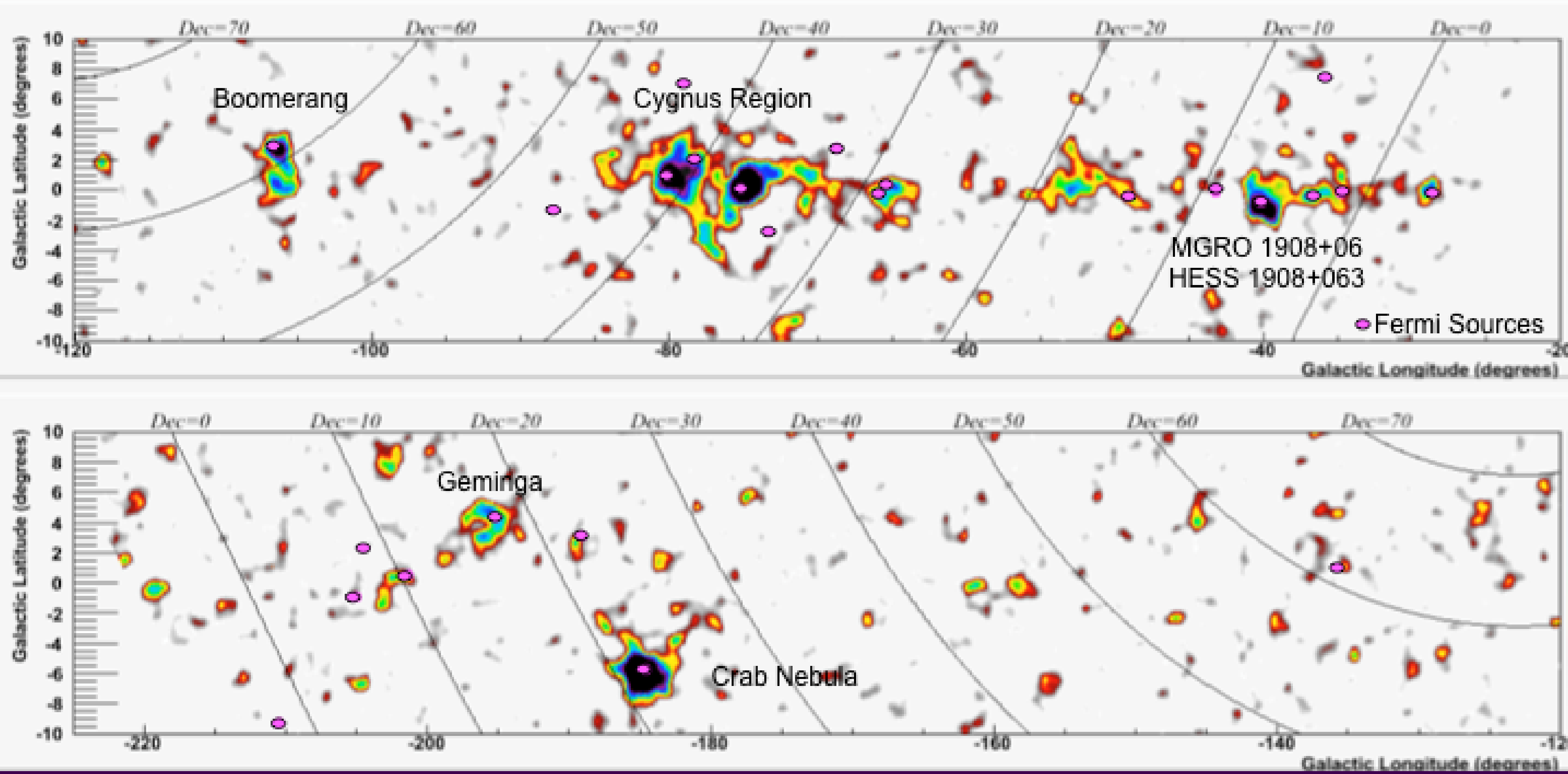
- And if a few of them aren't, who cares !

Example from another field: Milagro TeV air shower array



Milagro Sky Map – courtesy of Jordan Goodman

Milagro and Fermi Sources



There's now more reason to think that many Milagro "noise fluctuations" are real point sources !