Title: LIGO and Virgo continuous wave searches - Overview and all-sky searches

Date: May 10, 2018 02:30 PM

URL: http://pirsa.org/18050033

Abstract: The Continuous Waves (CW) Search Group of the LIGO Scientific Collaboration and Virgo Collaboration carries out a diverse suite of searches for a diverse set of possible CW sources. Assumptions underlying these searches will be discussed, along with strategies used so far to keep our eyes wide open while also giving due attention to the most promising sources. One important assumption to date has been that fast-spinning, non-axisymmetric neutron stars are the most promising class of CW sources. If the most promising source class is, instead, black hole super-radiance from axion clouds, then current searches may not be optimal. Potential modifications to current all-sky searches to address super-radiance will be discussed.

LIGO and Virgo continuous wave searches - Overview and all-sky searches

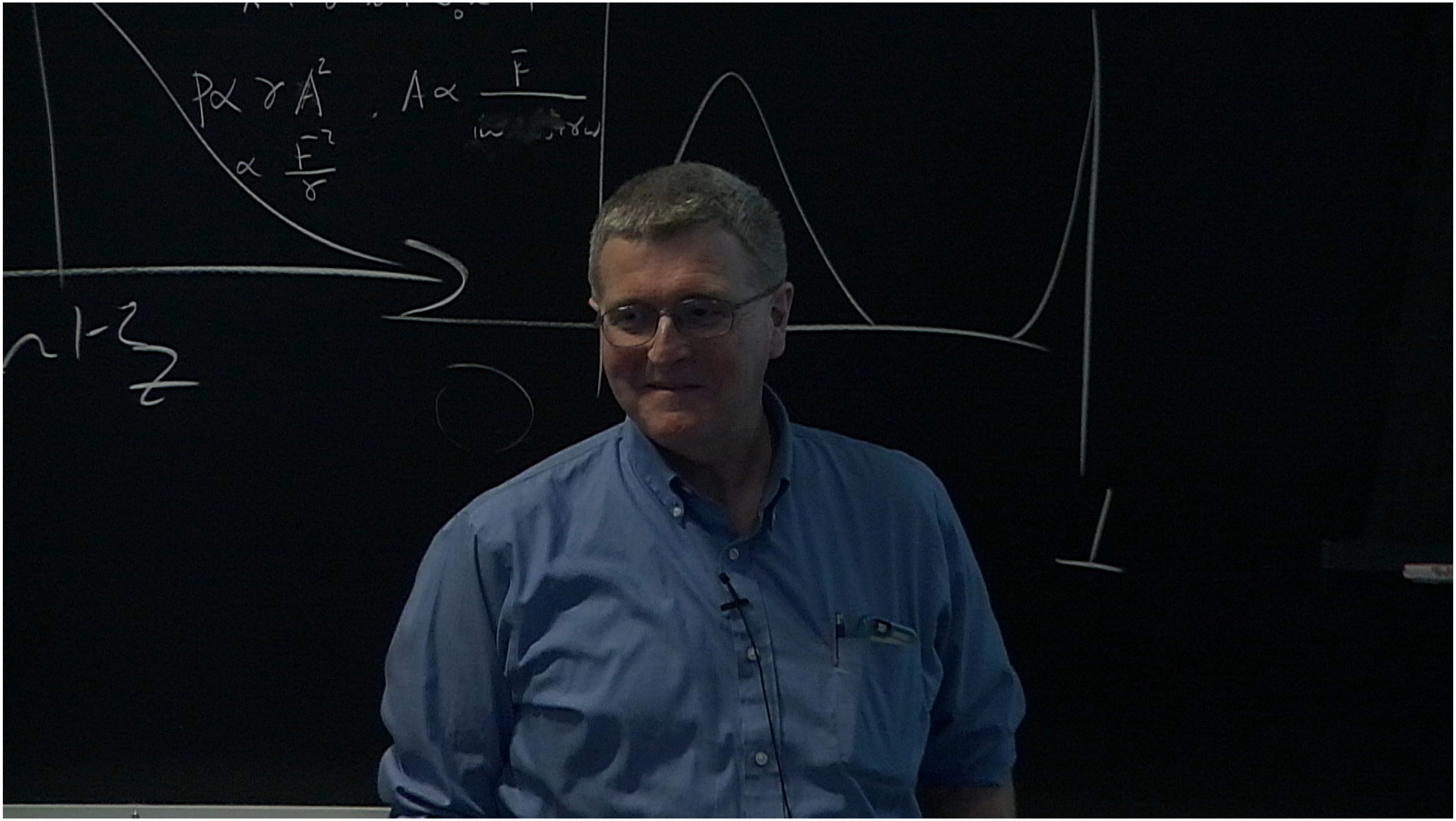
Keith Riles
University of Michigan

LIGO Scientific Collaboration
and the Virgo Collaboration

Workshop on Searching for New Particles with Black Hole Superradiance

Perimeter Institute
May 10, 2018

LIGO-G1800909


Pα γA²
Aα F
α F²/γ

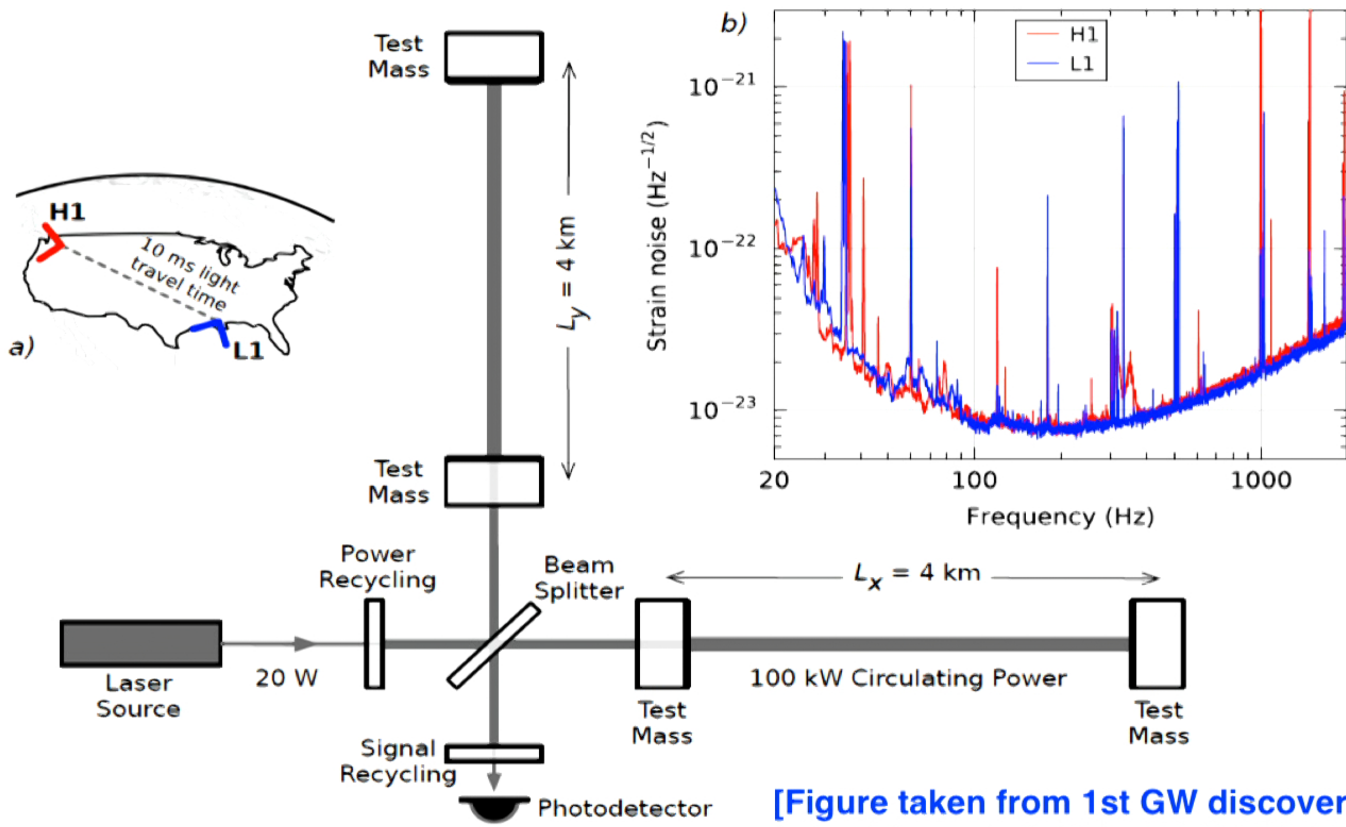
Outline

- LIGO and Virgo – Where do we stand?
  - Sensitivity progression to date
  - Prospects in near and far future

- Continuous Wave (CW) search assumptions
  - Emission mechanisms
  - Promising sources & sky directions

- CW search methods & results to date
  - Challenges – coping with unknown source parameters
  - Categories – focus on all-sky searches
  - Superradiance – what changes?

O1 Data Run (Sept 12, 2015 – January 19, 2016)



[Figure taken from 1st GW discovery paper: B.P. Abbott *et al.*, PRL 116 (2016) 061102]

Translating 1-sided amplitude spectral noise density (ASD) to GW signal amplitude sensitivity: (back of the envelope level)

Detectable signal amplitude ≈ Amplitude spectral density ÷ [Coherent observation time]$^{1/2}$ × Statistical / geometry trials factor

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BBH like GW150914:

10^{-23} Hz$^{-1/2}$ / [0.2 s]$^{1/2}$ × ~10 ≈ **several × 10^{-22}**

Actual amplitude = 10^{-21} → Very loud signal

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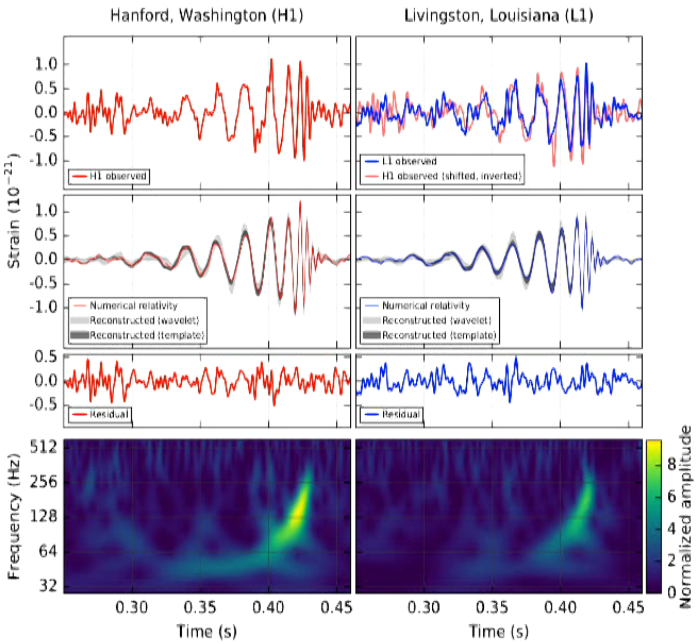
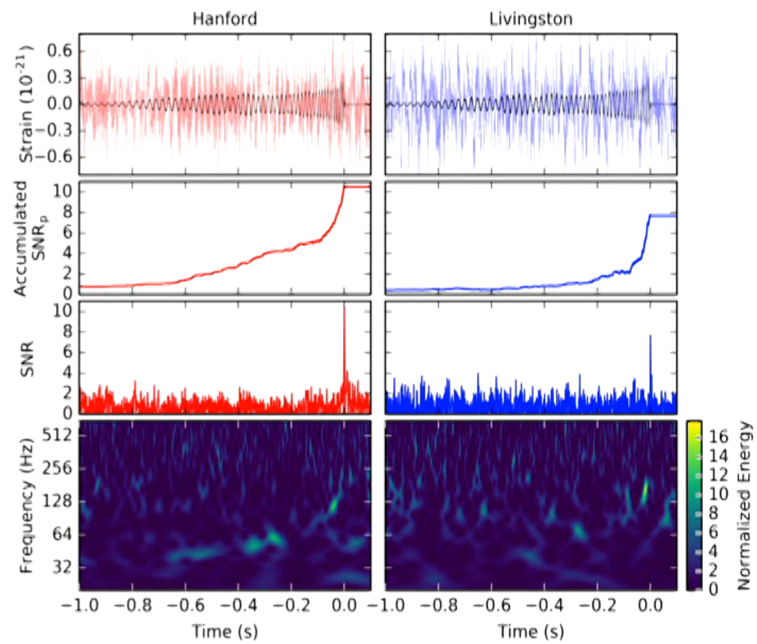
CW signal from known pulsar measured coherently over 1 year:

10^{-23} Hz$^{-1/2}$ / [3 × 10^7 s]$^{1/2}$ × ~10 ≈ **2 × 10^{-26}**

O1 "5-sigma" Detections



B.P. Abbott *et al.*, PRL 116 (2016) 061102



B.P. Abbott *et al.*, PRL 116 (2016) 241103

GW150914 **GW151226**

Two binary black hole mergers

(louder in Hanford (H1) than Livingston (L1) interferometer)

The O2 Run

After O1 completed in January 2016, both observatories began preparations for the the O2 run planned for the fall:

- Mitigate some non-fundamental noise sources seen in O1
- Raise laser powers to reduce fundamental noise and demonstrate mitigation of parametric instability (PI) associated with high power

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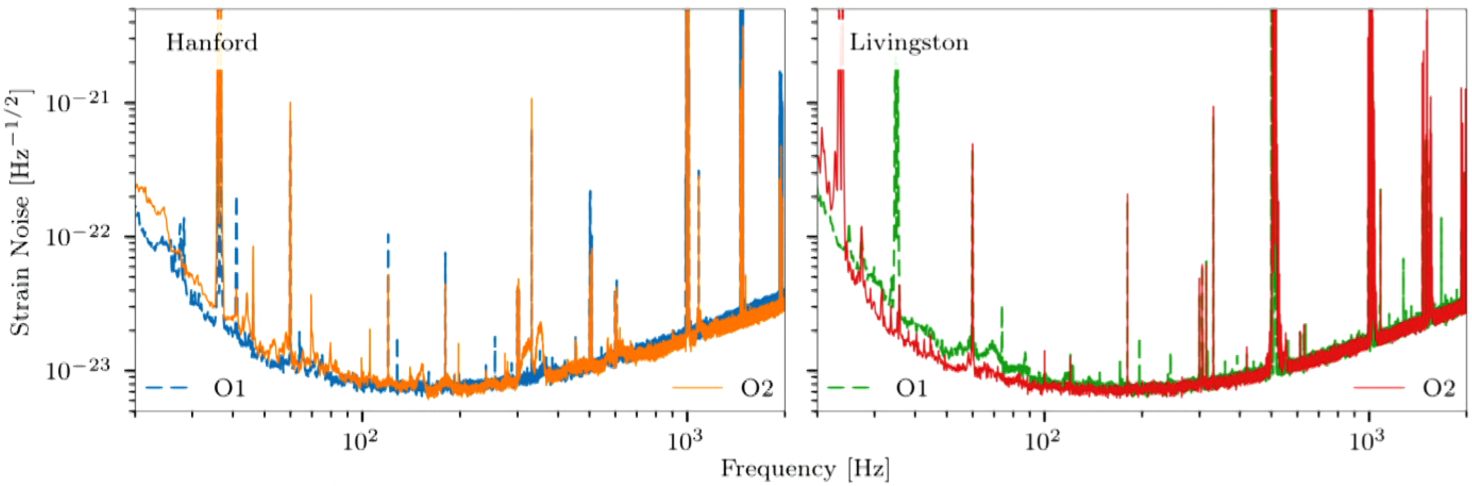
- Raise laser powers to reduce fundamental noise and demonstrate mitigation of parametric instability (PI) associated with high power

Mishap at Livingston derailed high-power plans for 2016, but other noise mitigation paid off well

Hanford learned to cope well with PIs at higher power, but encountered other technical problems at higher power and had to back off (for O2)

The O2 Run

- → Hanford less sensitive ☹
- → Livingston more sensitive in O2 than in O1 ☺



B.P. Abbott *et al*, PRL **118**, 221101 (2017)

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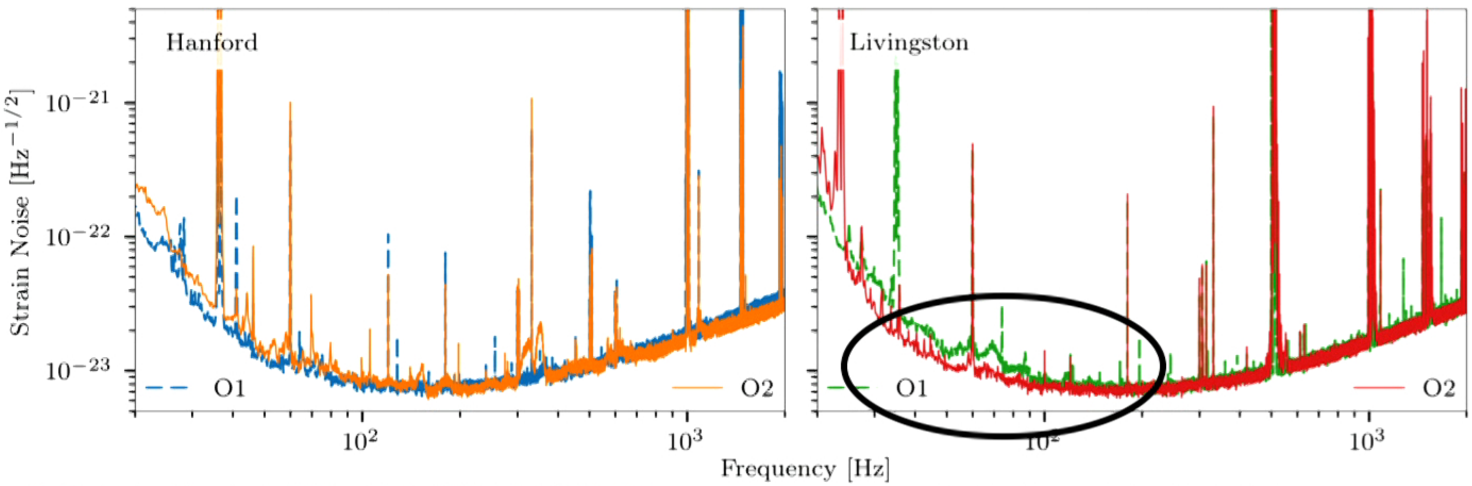


B.P. Abbott *et al*, PRL **118**, 221101 (2017)

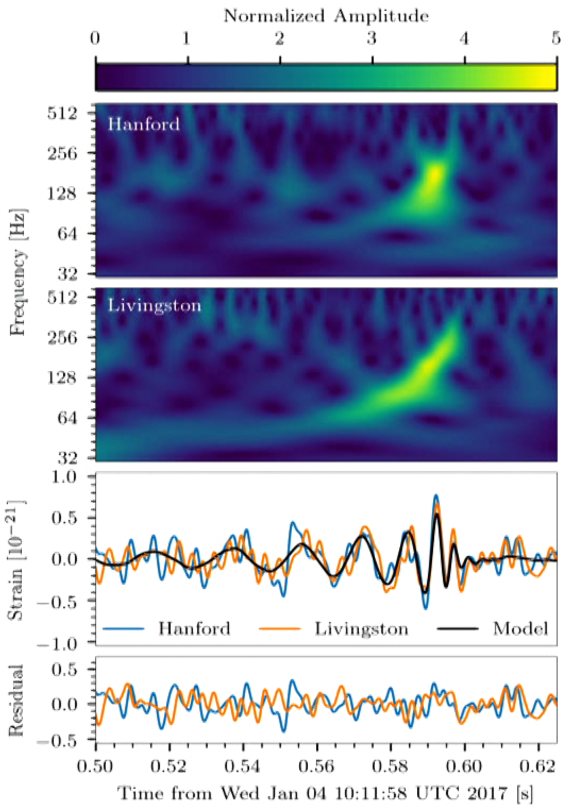
This band helpful for detecting binary black holes

– and young pulsars

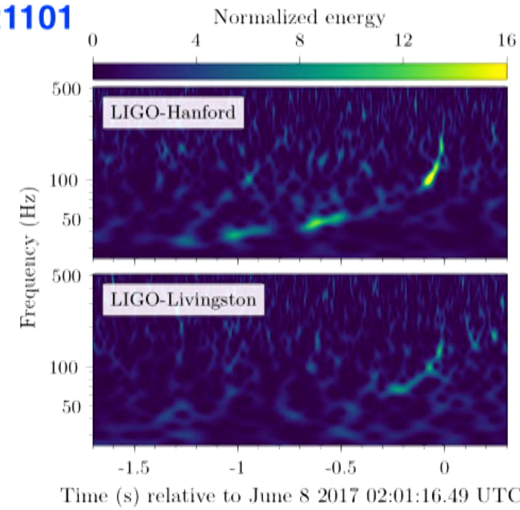
– and QCD axions?

K. Riles - Overview of CW Searches

B.P. Abbott *et al.*, PRL 118 (2017) 221101

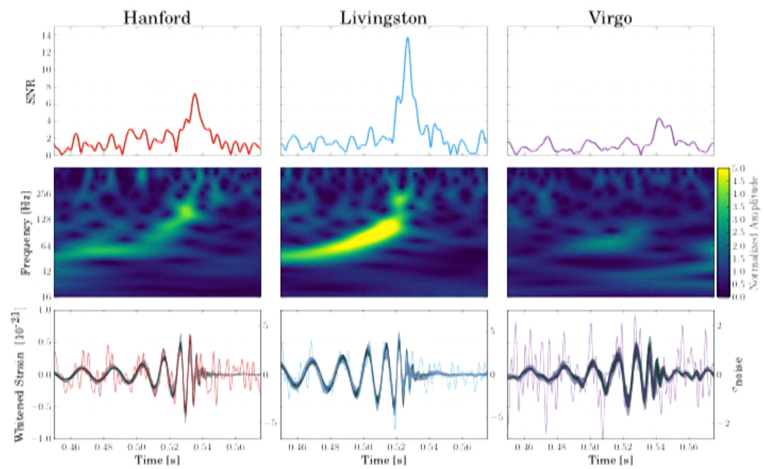


GW170104



GW170608

B.P. Abbott *et al.*, ApJL 851 (2017) L35



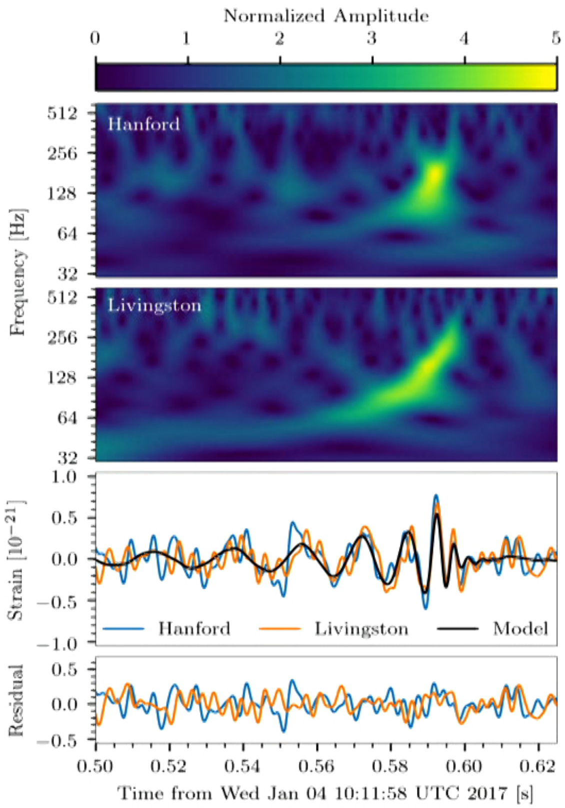
More black hole mergers

B.P. Abbott *et al.*, PRL 119 (2017) 141101

GW170814

8

B.P. Abbott *et al.*, PRL 118 (2017) 221101



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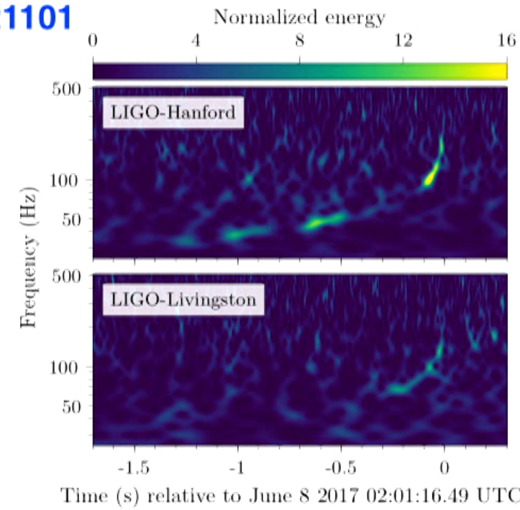

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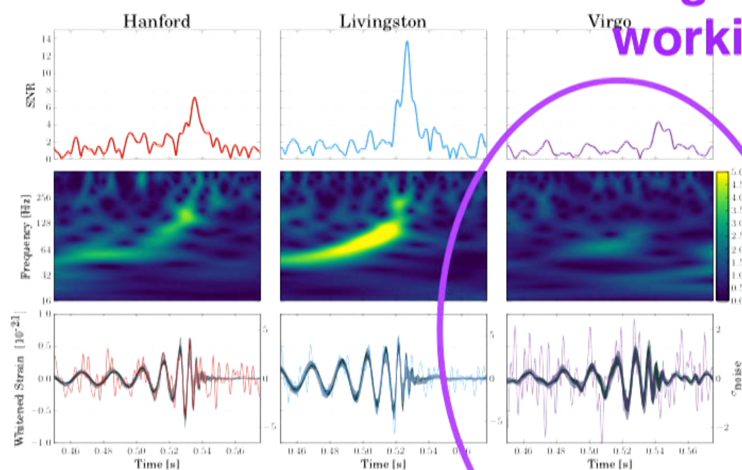
Virgo working!



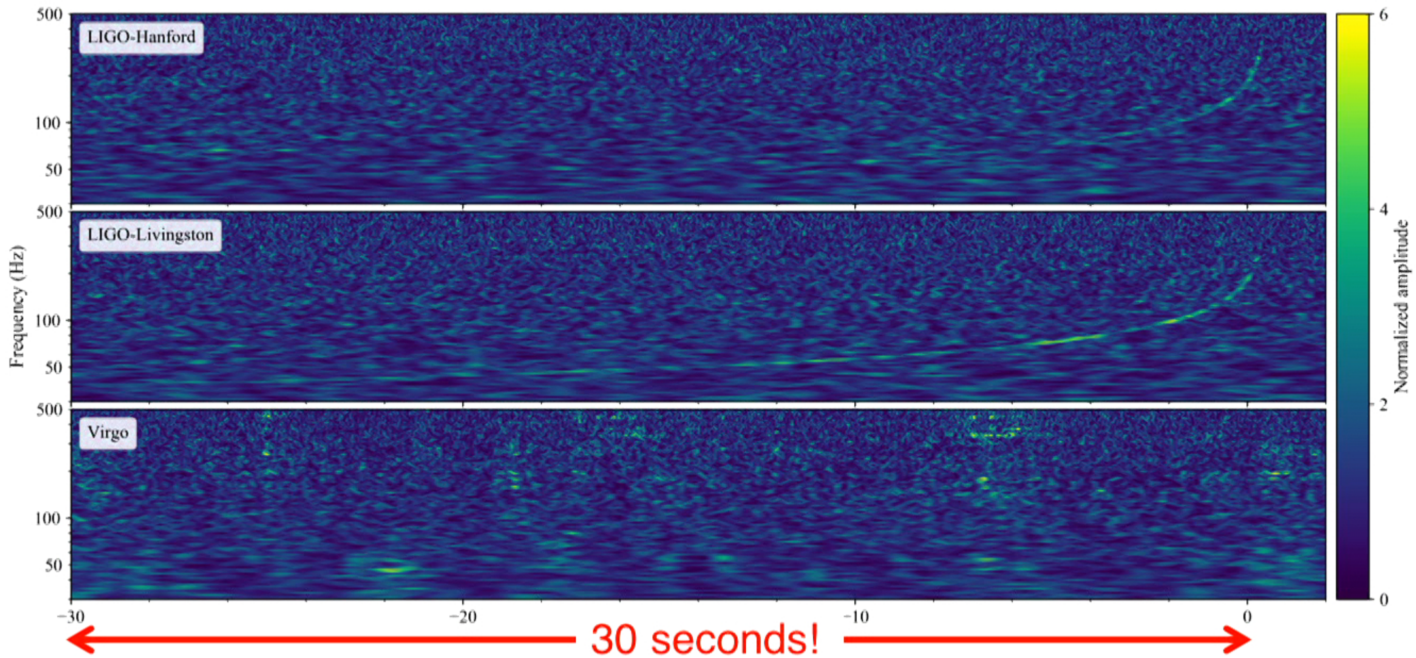
More black hole mergers

B.P. Abbott *et al.*, PRL 119 (2017) 141101

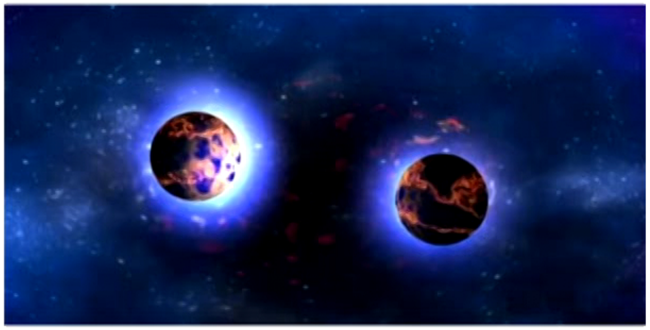
GW170814

Not to mention a binary neutron star merger...

GW170817



B.P. Abbott *et al.*,
PRL 120 (2017) 161101



CAASTRO

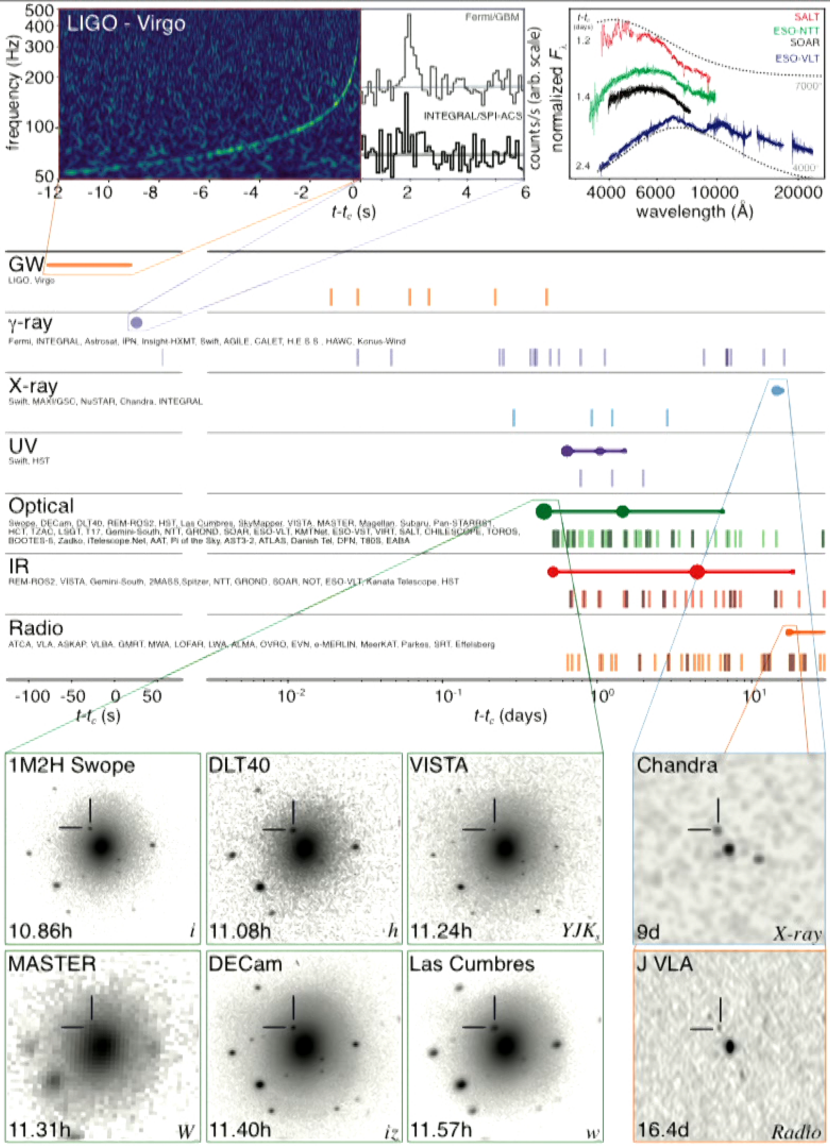


Figure from

"Multi-Messenger Observations of a Binary Neutron Star Merger"

B. Abbott et al.,
ApJL 848 (2017) L12

59-page "letter" (!)
More than 3000 authors,
~70 collaborations

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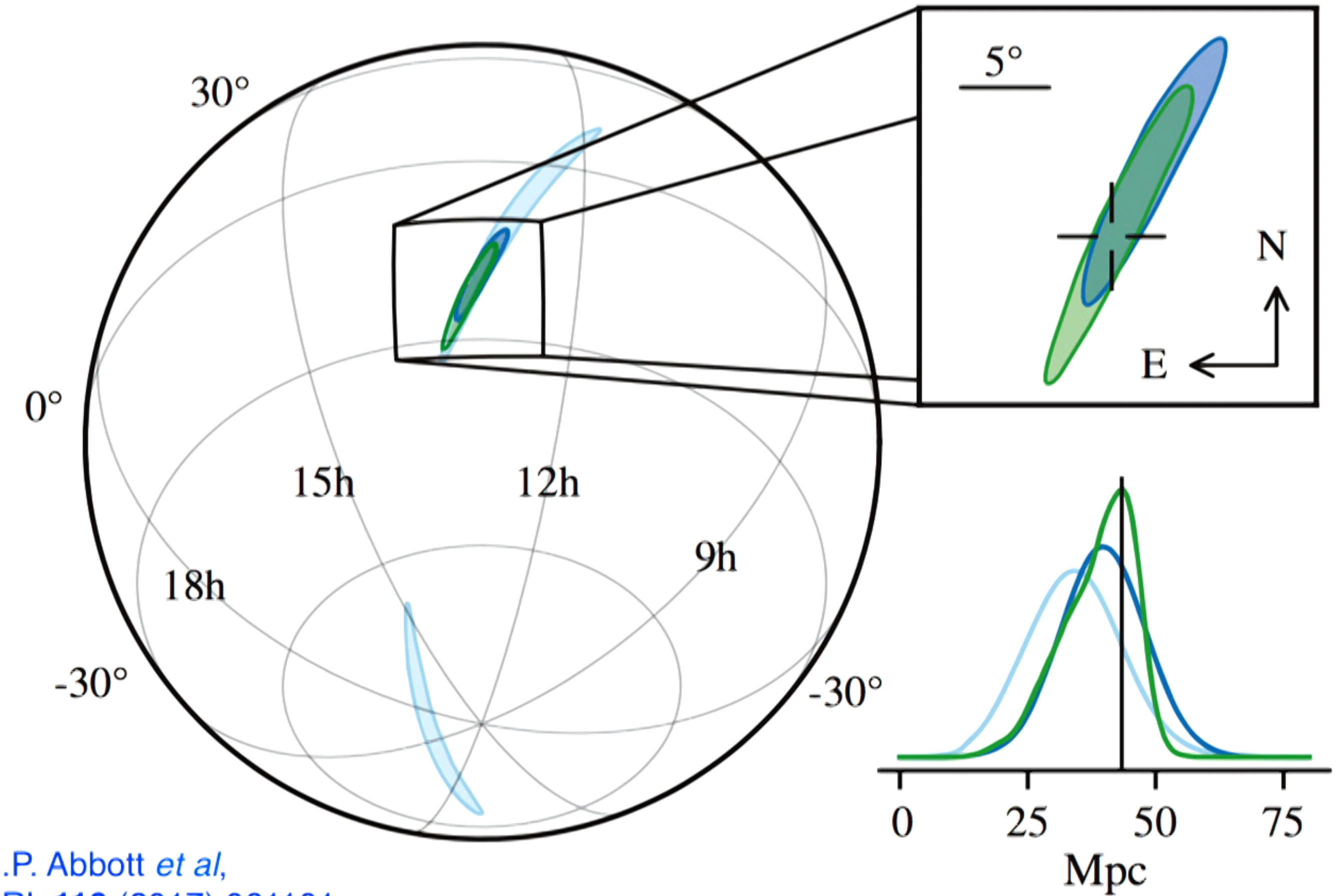

B.P. Abbott *et al*,
PRL **119** (2017) 061101

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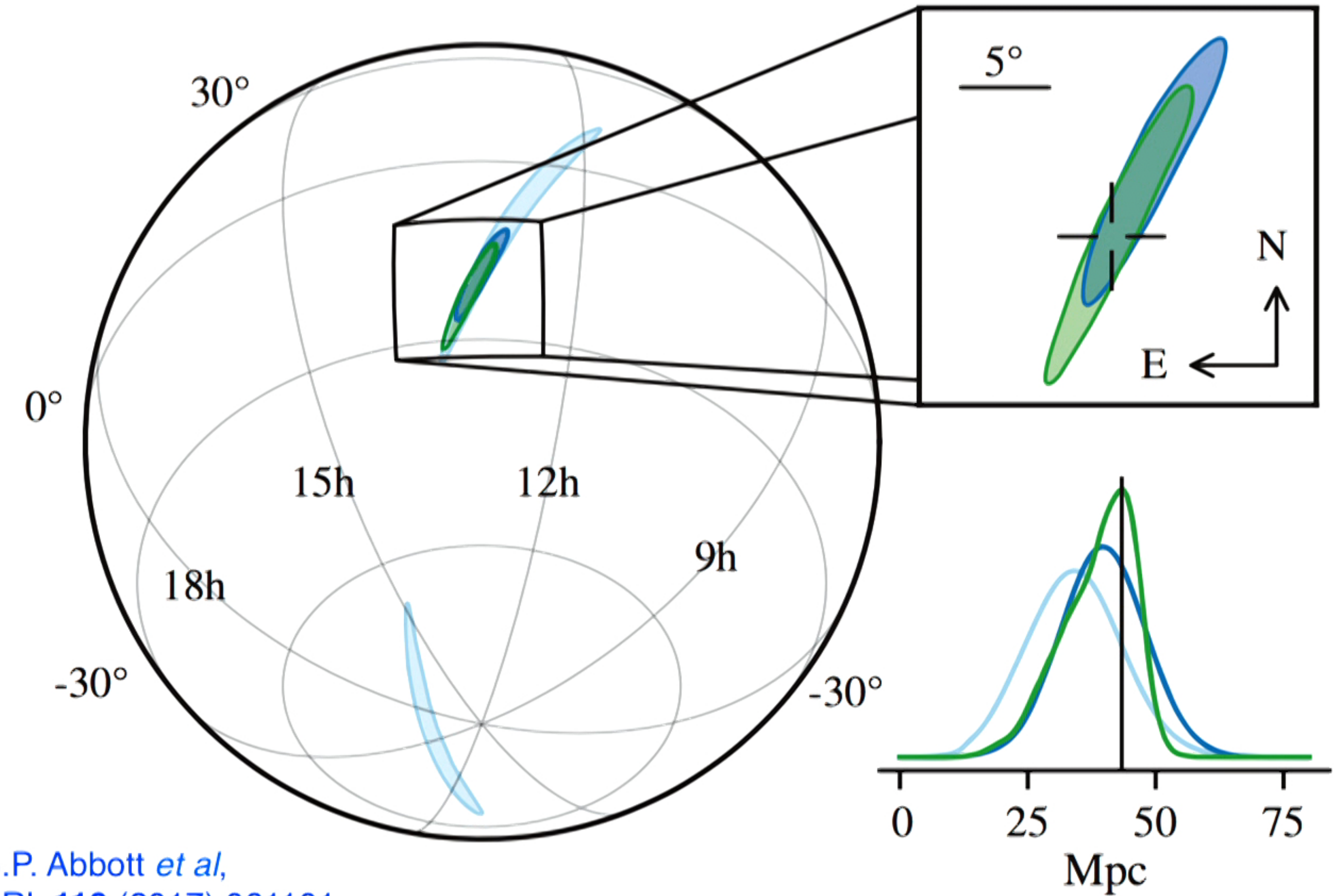
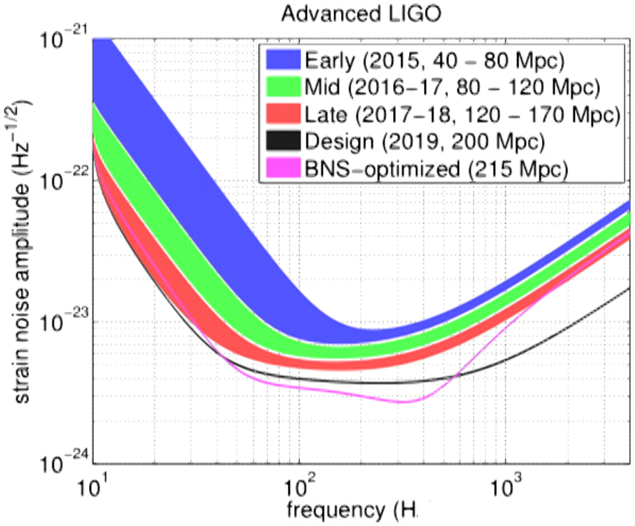


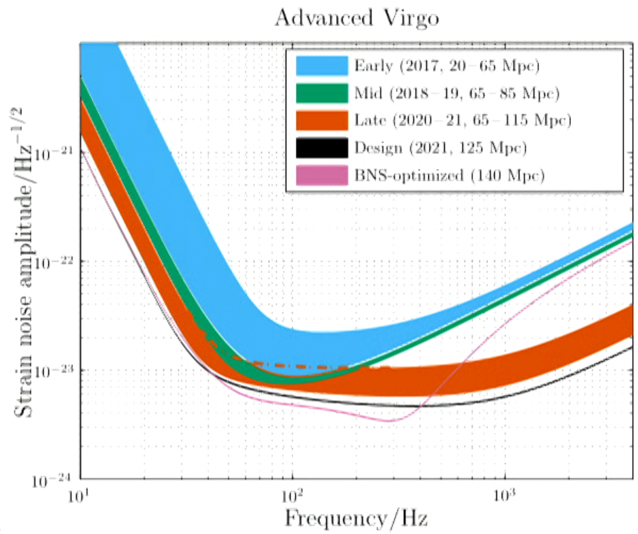
B.P. Abbott *et al*,
PRL **119** (2017) 061101

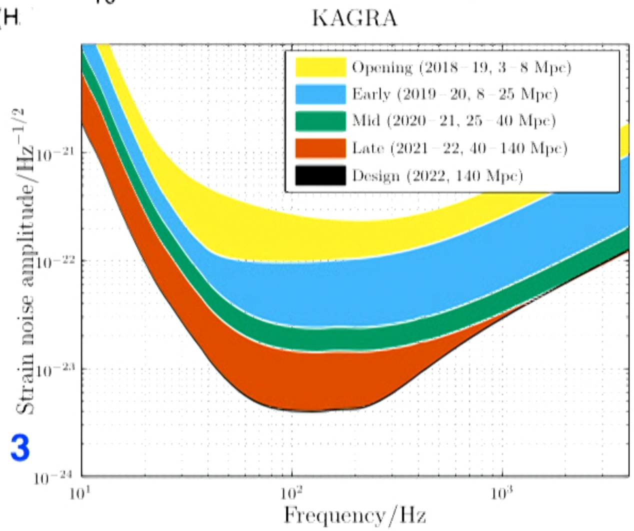
A CW detection could give far better localization – sub-arcsec

(Aperture of detector is Earth's orbit for a 1-year observation) 11

Looking Ahead







B.P. Abbott *et al.*,
Liv. Rev. Rel. 21 (2018) 3

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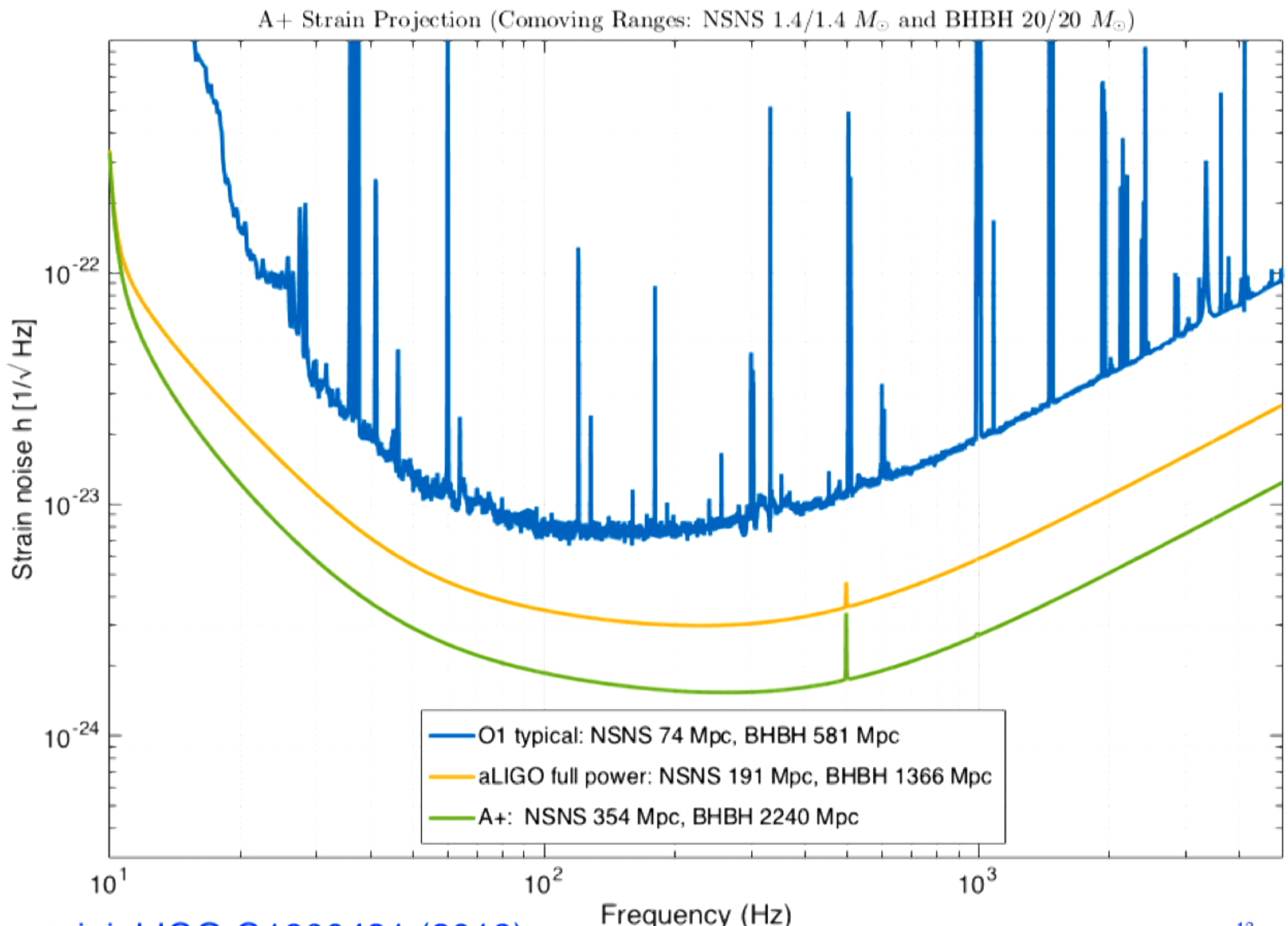

A. Lazzarini, LIGO G1800431 (2018)

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CW Search Assumptions

The LIGO and Virgo joint CW search group fields a diverse suite of programs to cover various source scenarios

Diversity applies to source types:

- Isolated neutron stars
- Neutron stars in binary systems
- Neutron stars undergoing accretion
- Newborn neutron stars (including BNS post-merger remnants)
- Glitching neutron stars

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- **Black hole super-radiance**

Diversity applies to algorithms:

- Matched filters
- Time domain heterodynes
- Semi-coherent power sums
- "Loose coherence" power sums
- Hough transforms
- Viterbi dynamical programming
- Sideband summing in orbital systems
- Double-Fourier Spectra

CW Search Assumptions – Emission Mechanisms

- Radiation generated by quadrupolar mass movements:

$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}\left[I_{\mu\nu}\right]$$

($I_{\mu\nu}$ = quadrupole tensor, r = source distance)

15

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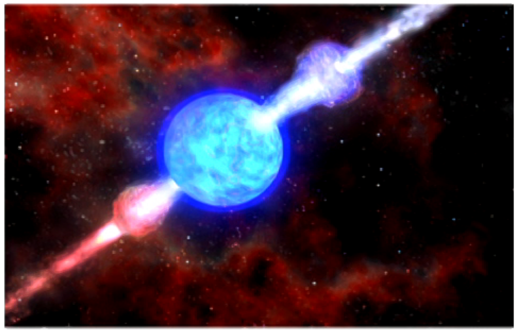

Courtesy: U. Liverpool

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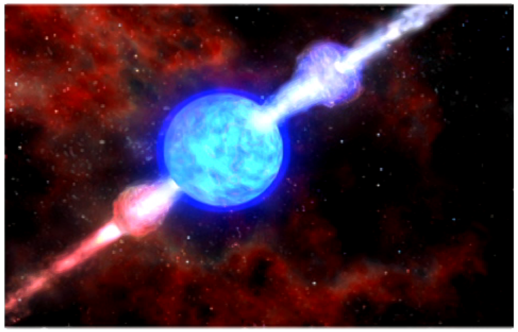

Courtesy: U. Liverpool

gives a strain amplitude h ($f_{GW} = 2 \bullet f_{Rot}$):

$$h = 1.1\times 10^{-24}\left[\frac{kpc}{r}\right]\left[\frac{f_{GW}}{kHz}\right]^2\left[\frac{\varepsilon}{10^{-6}}\right]\left[\frac{I_{zz}}{10^{38}\ \mathrm{kg}\cdot\mathrm{m}^2}\right]$$

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Gravitational CW mechanisms

- **Equatorial ellipticity** (e.g., – mm-high "bulge"):

$$h \propto \varepsilon_{\text{equat}} \quad \text{with} \quad f_{GW} = 2 f_{\text{rot}}$$

- **Poloidal ellipticity** (natural) **+ wobble angle** (precessing star):

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→ **Precession due to different L and Ω axes**

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N. Andersson, ApJ 502 (1998) 708

S. Chandrasekhar, PRL 24 (1970) 611

J. Friedman, B.F. Schutz, ApJ 221 (1978) 937

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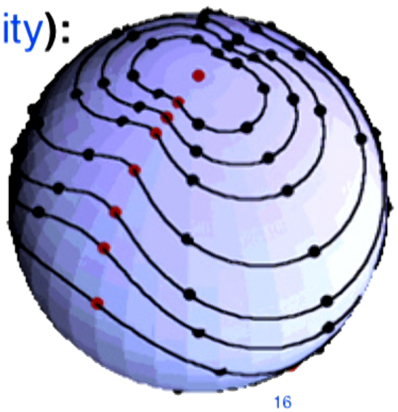

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C. Hanna & B.J. Owen

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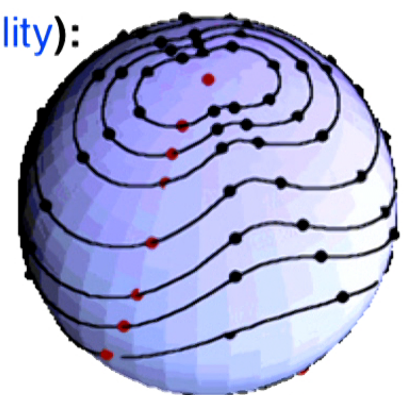

C. Hanna & B.J. Owen[16]

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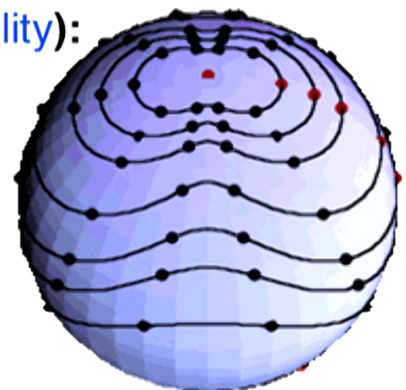

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C. Hanna & B.J. Owen

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Assumption we (LSC, Virgo) have usually made to date:

Bulge is best bet for detection
→ Look for GW emission at twice the EM frequency

e.g., look for Crab Pulsar (29.6 Hz) at 59.3 Hz
(troublesome frequency in North America!)

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What is allowed for $\boldsymbol{\varepsilon_{equat}}$?

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Recent re-evaluation: $\varepsilon_{equat} < 10^{-5}$
N.K. Johnson-McDaniel & B.J. Owen, PRD 88 (2013) 044004

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CW Search Assumptions – Promising sources

Three broad categories of searches have dominated analysis:
→ See Sylvia Zhu's talk for details on 1st two categories

Targeted searches for known pulsars using radio / X-ray / γ-ray ephemerides
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(unknown / poorly known frequencies)

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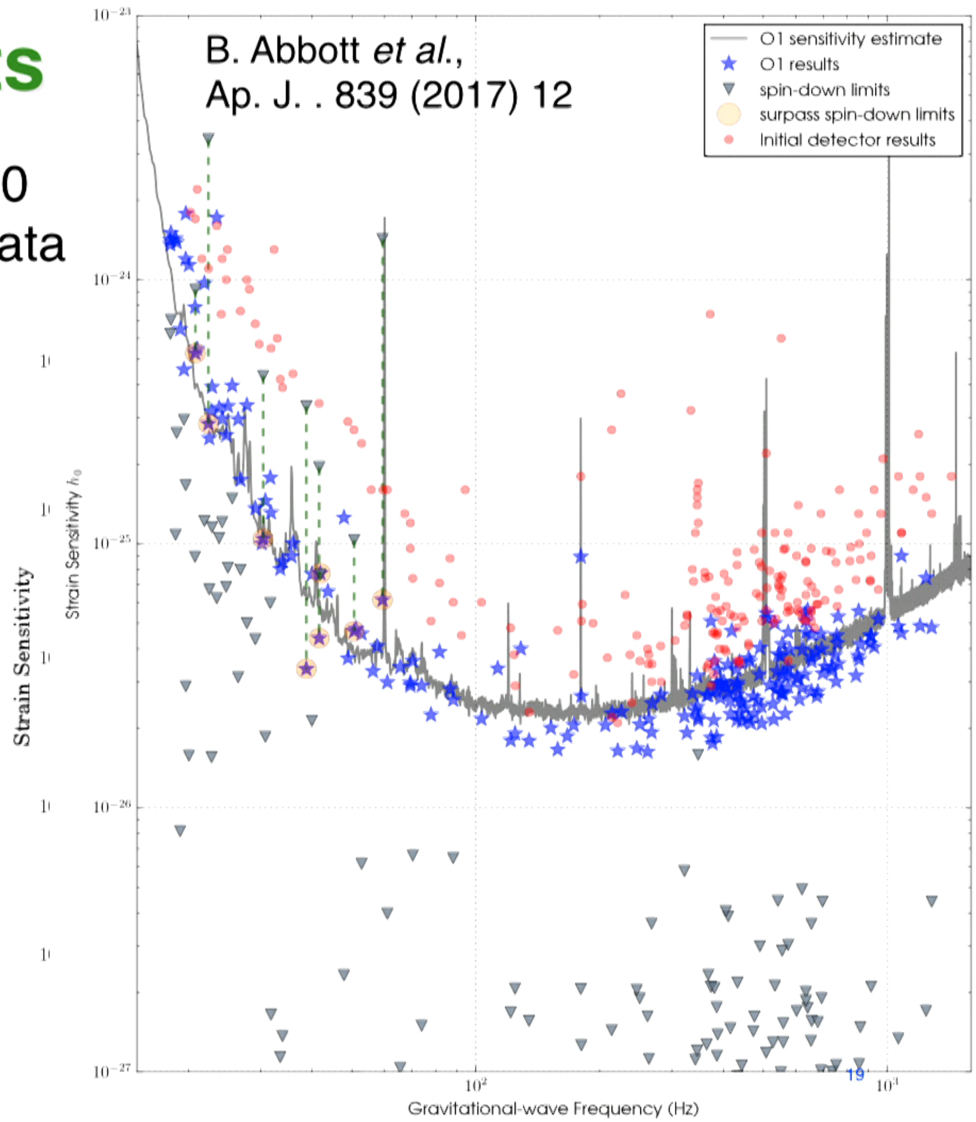
All-sky searches for unknown sources
- Isolated and binary sources treated separately (binary esp. challenging)
- Semi-coherent searches over full data runs

Recent results

Targeted search for 200 known pulsars in O1 data



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Lowest (best) upper limit on strain:

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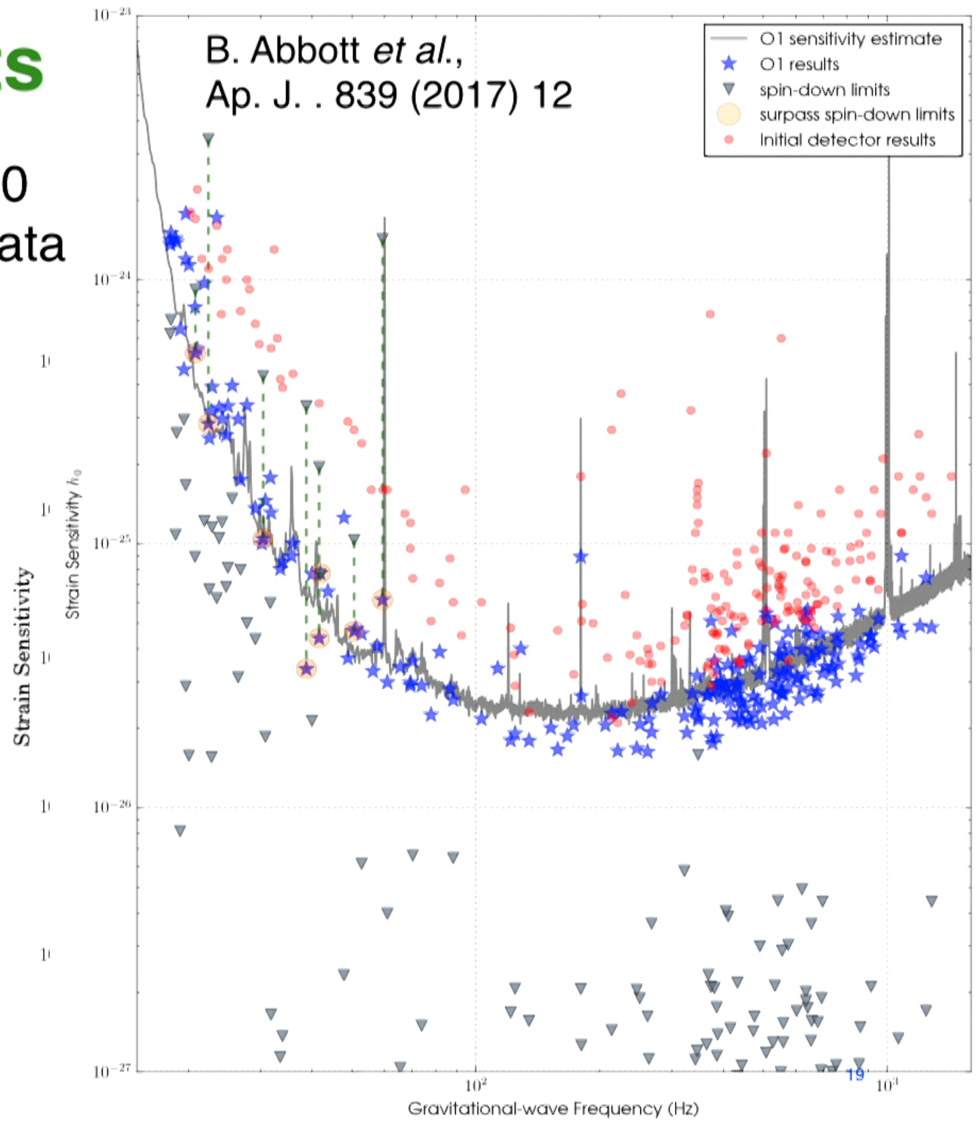

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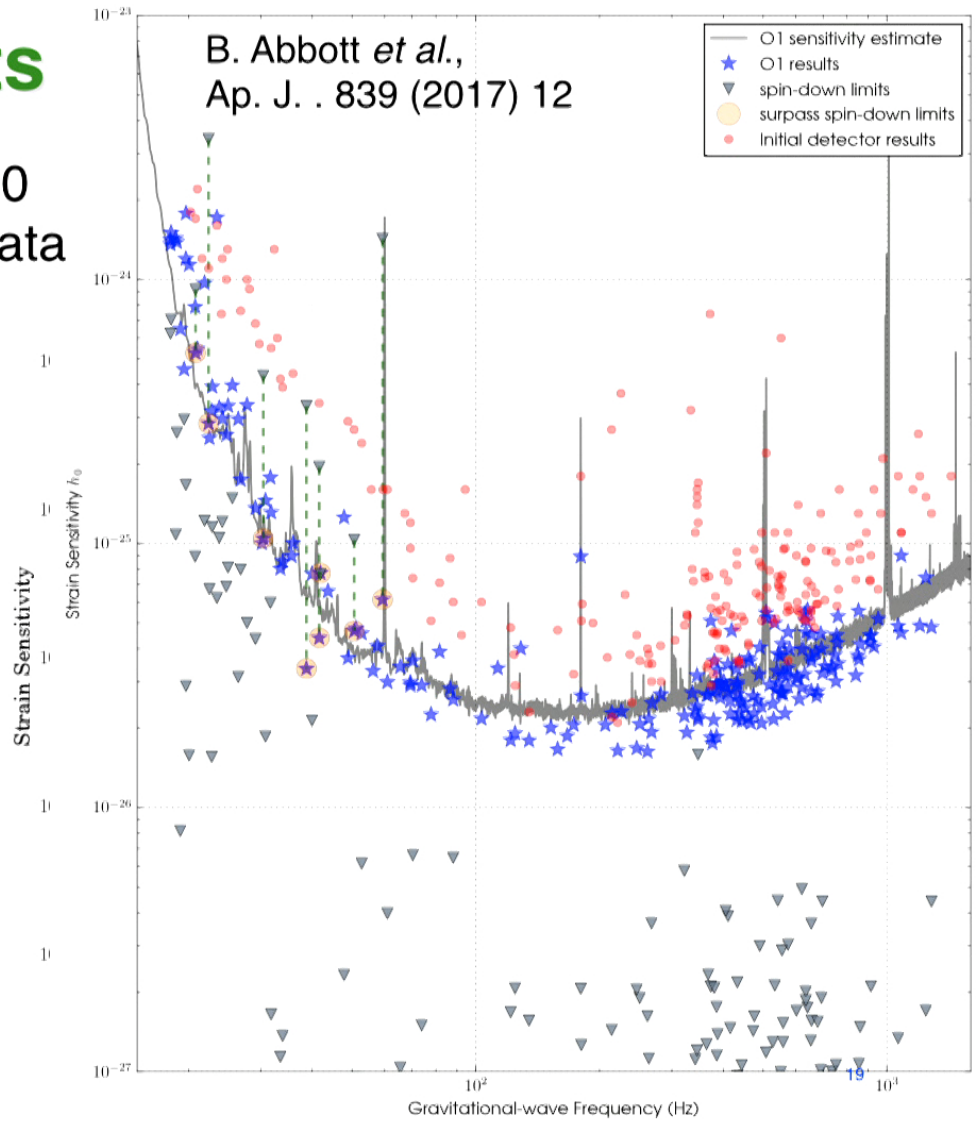

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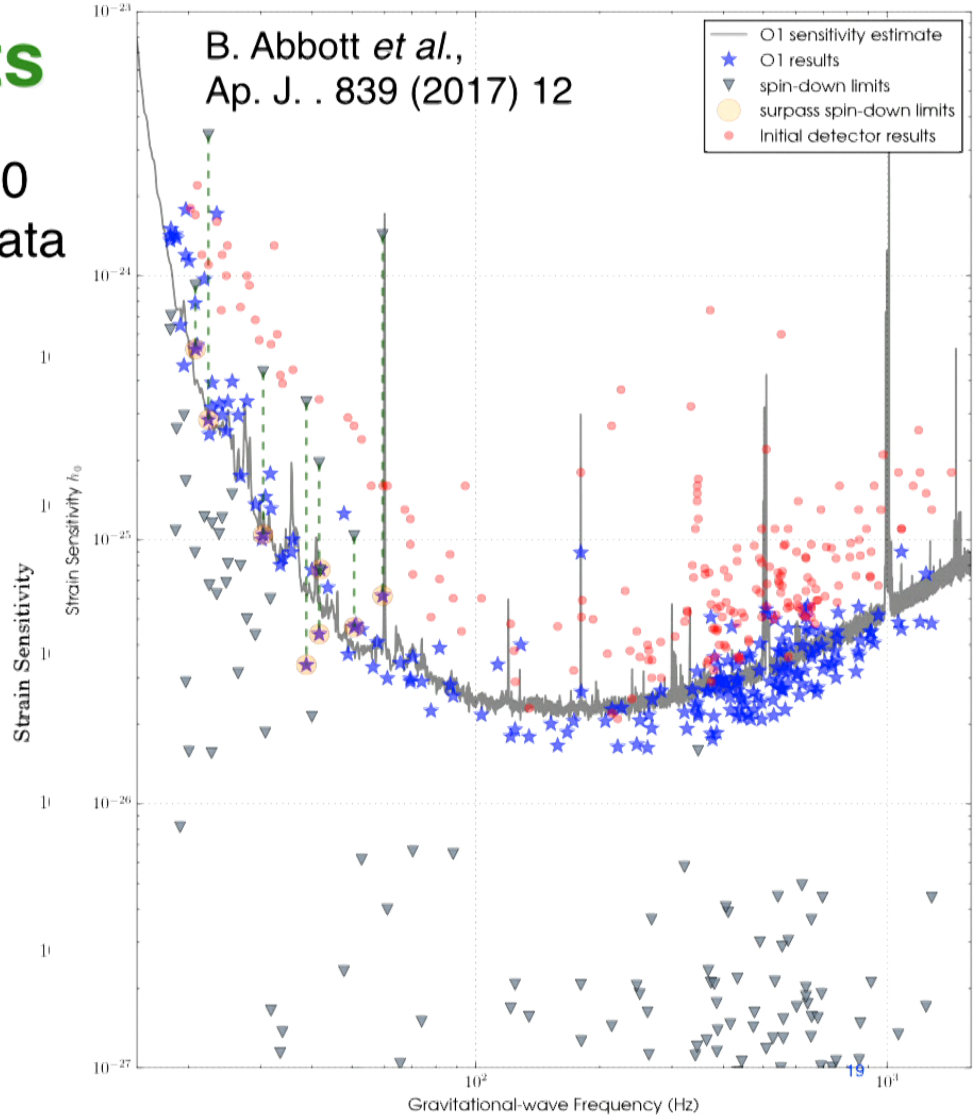
Crab limit at 0.2% of total energy loss
(beats "spindown limit")



Sensitivity Depth

Different search algorithms use different fractions of available data from a run and have different scalings of sensitivity with observation time [e.g., $(T_{OBS})^{1/2}$, $(T_{OBS})^{1/4}$]

Sensitivity Depth

Examples: (current algorithms)

• Targeted search over 1 year:	~500
• "Narrowband" search over 4 months:	~100-150
• Directed isolated search over 10 days:	~30
• Semi-coherent directed isolated search over 1 year:	~60
• Cross-correlation directed Sco X-1 search over 4 months:	~80
• All-sky isolated search over 4 months:	~25
• All-sky binary search over 1 year:	~3

These depths affect how we choose to focus resources on searches (computational, human)

Computing challenges – All-sky Searches

Serious technical difficulty: Doppler frequency shifts

- Frequency modulation from earth's rotation ($v/c \sim 10^{-6}$)
- Frequency modulation from earth's orbital motion ($v/c \sim 10^{-4}$)

→ Coherent integration of 1 year gives frequency resolution of 30 nHz

→ 1 kHz source spread over 6 million bins in ordinary FFT!

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Daily amplitude modulation of antenna pattern

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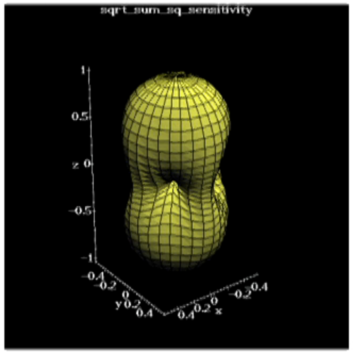

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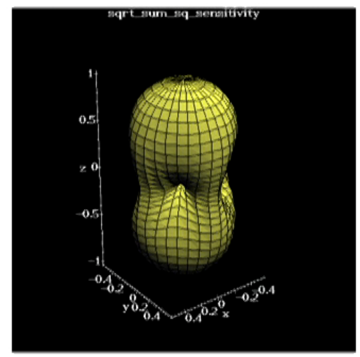

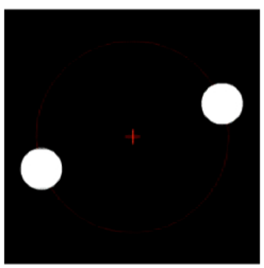

Orbital motion of sources in binary systems

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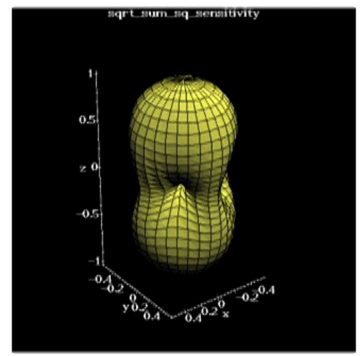

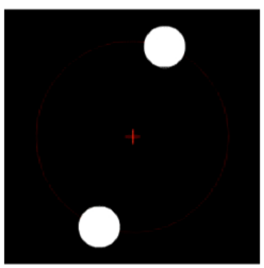

Orbital motion of sources in binary systems

K. Riles - Overview of CW Searches

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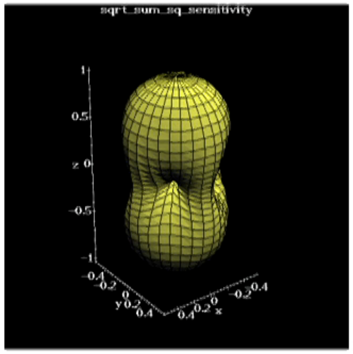

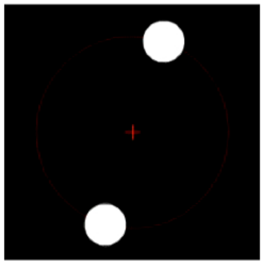

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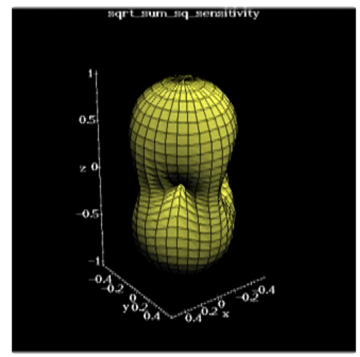

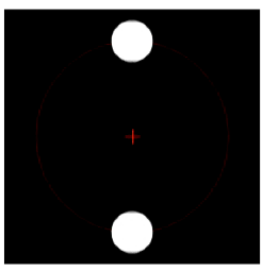

Orbital motion of sources in binary systems

Computing challenges – All-sky Searches

Modulations / drifts complicate analysis enormously:

- Simple Fourier transform inadequate
- Every sky direction requires different demodulation
- →Number of distinct sky location scales like $f^2T^2_{\mathrm{COH}}$
- →Computing cost scales as $(T_{\mathrm{COH}})^6$ without 2nd frequency derivative!
- All-sky survey at full sensitivity not possible **(at this time)**

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Tradeoffs to cope with astronomical computing costs:

- Restrict T_{COH} < several days for all-sky search
  → Compute demodulated spectra (e.g., "F-Statistic")
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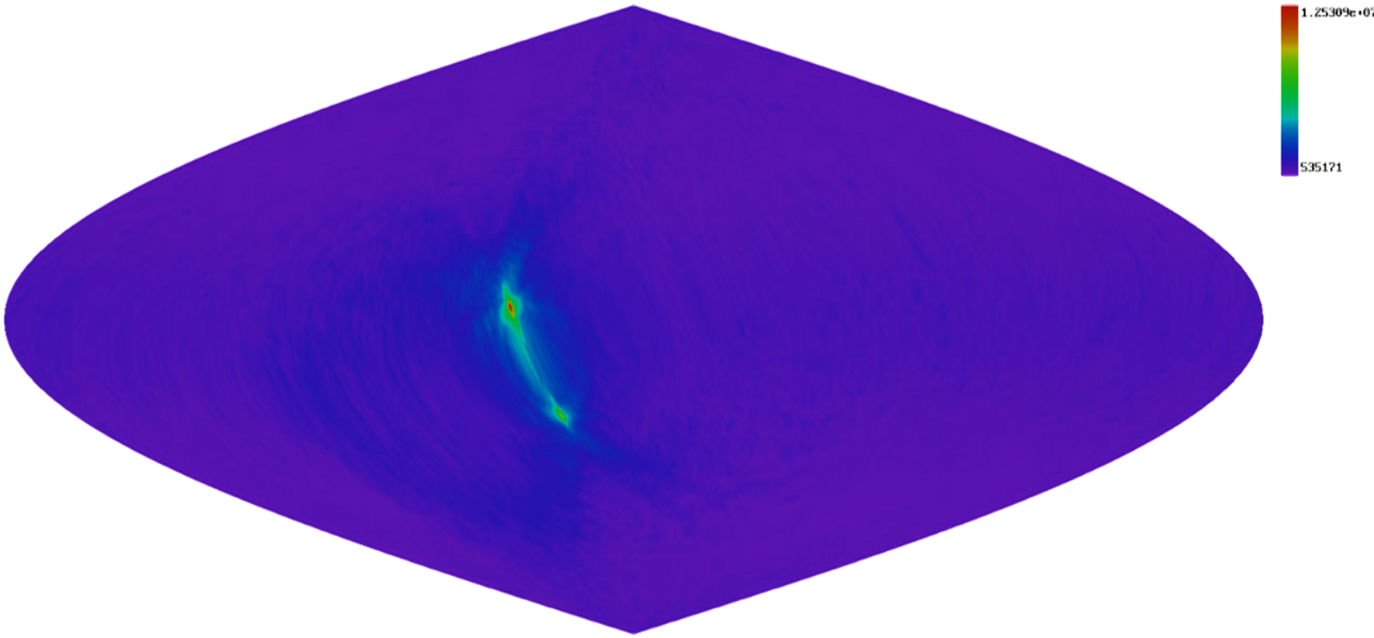
- Semi-coherent stacking ($N_{\mathrm{stack}} = T_{\mathrm{OBS\text{-}RUN}} / T_{\mathrm{COH}}$)
  - Raw / weighted spectral powers (T_{COH} ~ 0.5-2.0 hours)
  - Thresholded powers – Hough transforms
  - Demodulated spectra – F-Statistic
    → Sensitivity improves only as $(N_{\mathrm{stack}})^{1/4}$

But three substantial benefits from Doppler modulations:

- Reality of signal confirmed by need for corrections
- Corrections give precise direction of source
- Single interferometer can make definitive discovery



Example sky map of strain power for signal injection (semi-coherent search)

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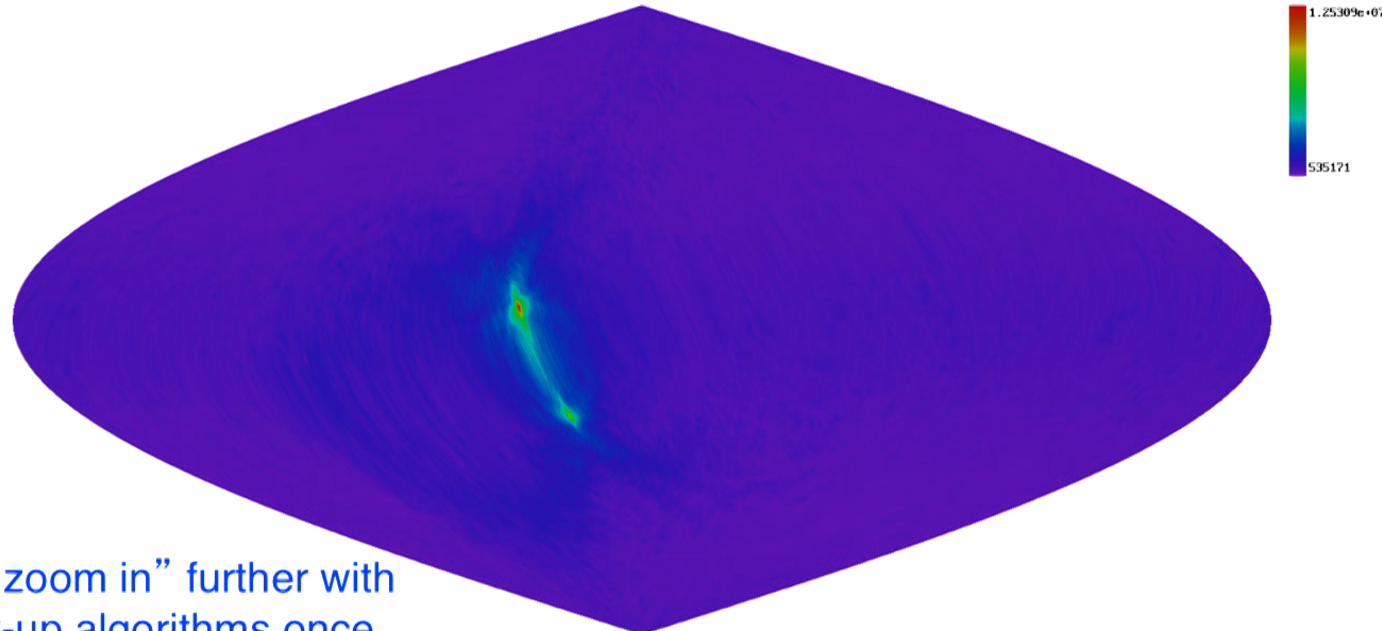

Can "zoom in" further with follow-up algorithms once we lock on to source

Example sky map of strain power for signal injection (semi-coherent search)

V. Dergachev, PRD 85 (2012) 062003
M. Shaltev & R. Prix, PRD 87 (2013) 084057
A. Singh *et al.*, PRD 96 (2017) 082003

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All-sky Searches for Unknown Isolated Stars

Search methods used in Initial LIGO data:

- Coherent *F*-Statistic (T_{COH} = 10 hours)
  [P. Jaranowski, A. Krolak & B. Schutz, PRD 58 (1998) 063001;
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- Stacked power spectra ("stack-slide" & variants) (Tcoh = 0.5-2.0 hours]
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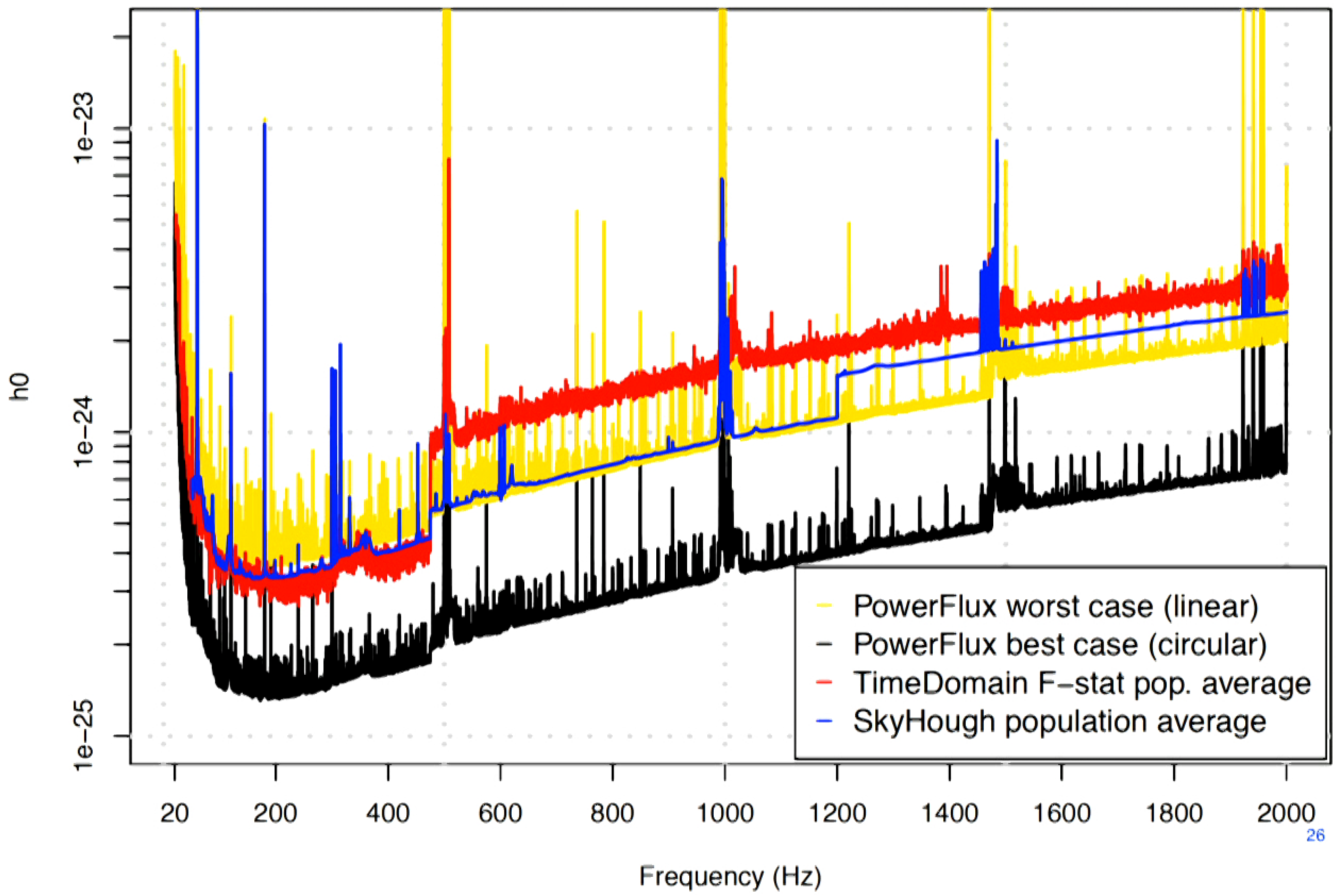
    [P. Astone *et al.*, PRD 82 (2010) 022005; J. Aasi *et al.*, CQG 31 (2014) 165014]
  - Stacked *F*-Statistic (Einstein@Home)
    [R. Prix, PRD 75 (2007) 023004; H.J. Pletsch & B. Allen, PRL 103 (2009) 181102;
    K. Wette & R, Prix, PRD 88 (2013) 123005; D. Keitel, PRD 93 (2016) 084024;
    M. Shaltev *et al.*, PRD 89 (2014) 124030; M.A. Papa *et al.*, PRD 94 (2016) 122006]

Recent results – All-sky search

B. Abbott *et al.*, arXiv:1802.05241, Feb 2018



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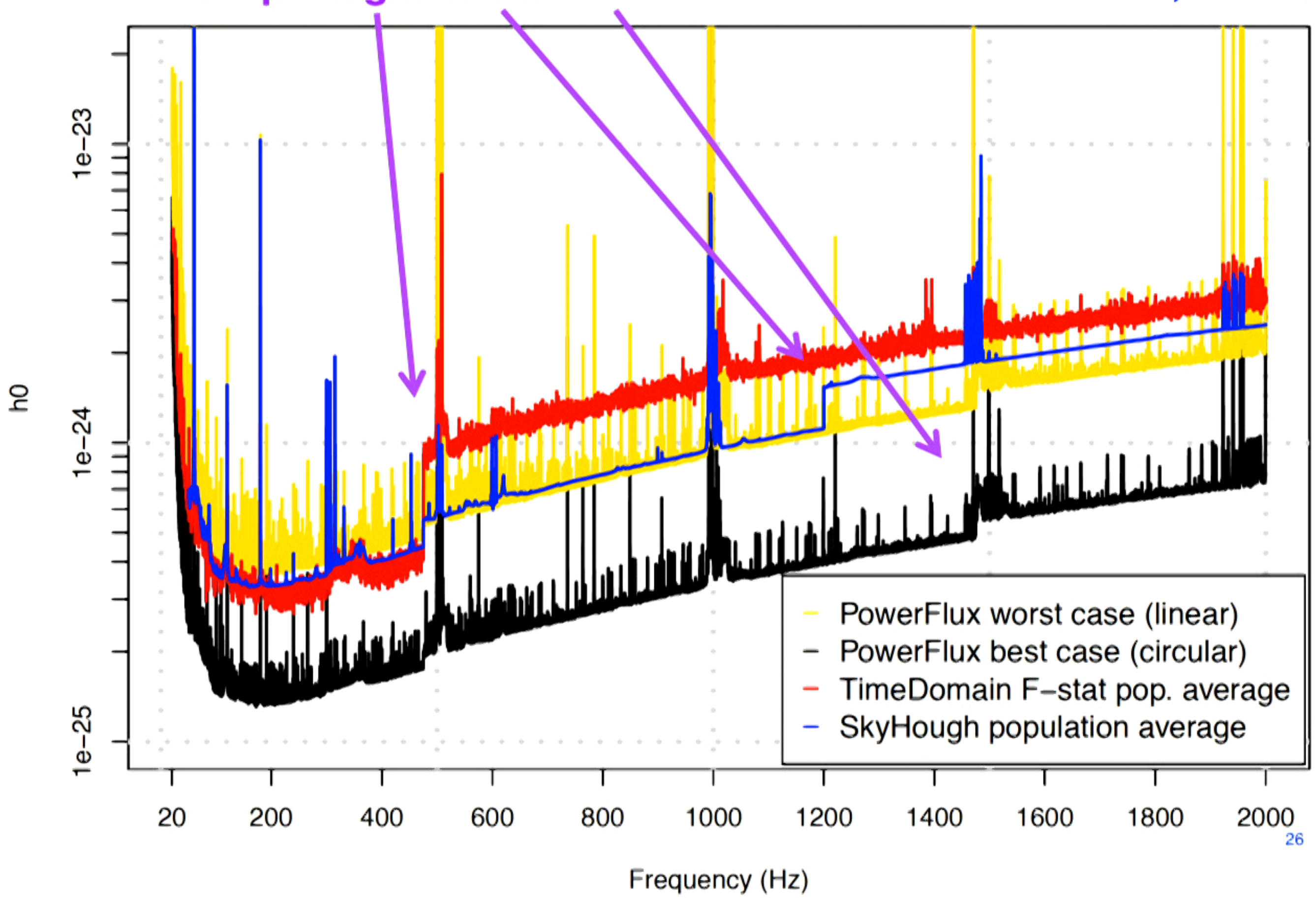
Recent results – All-sky search

Sensitivity steps come from computing tradeoffs

B. Abbott *et al.*, arXiv:1802.05241, Feb 2018



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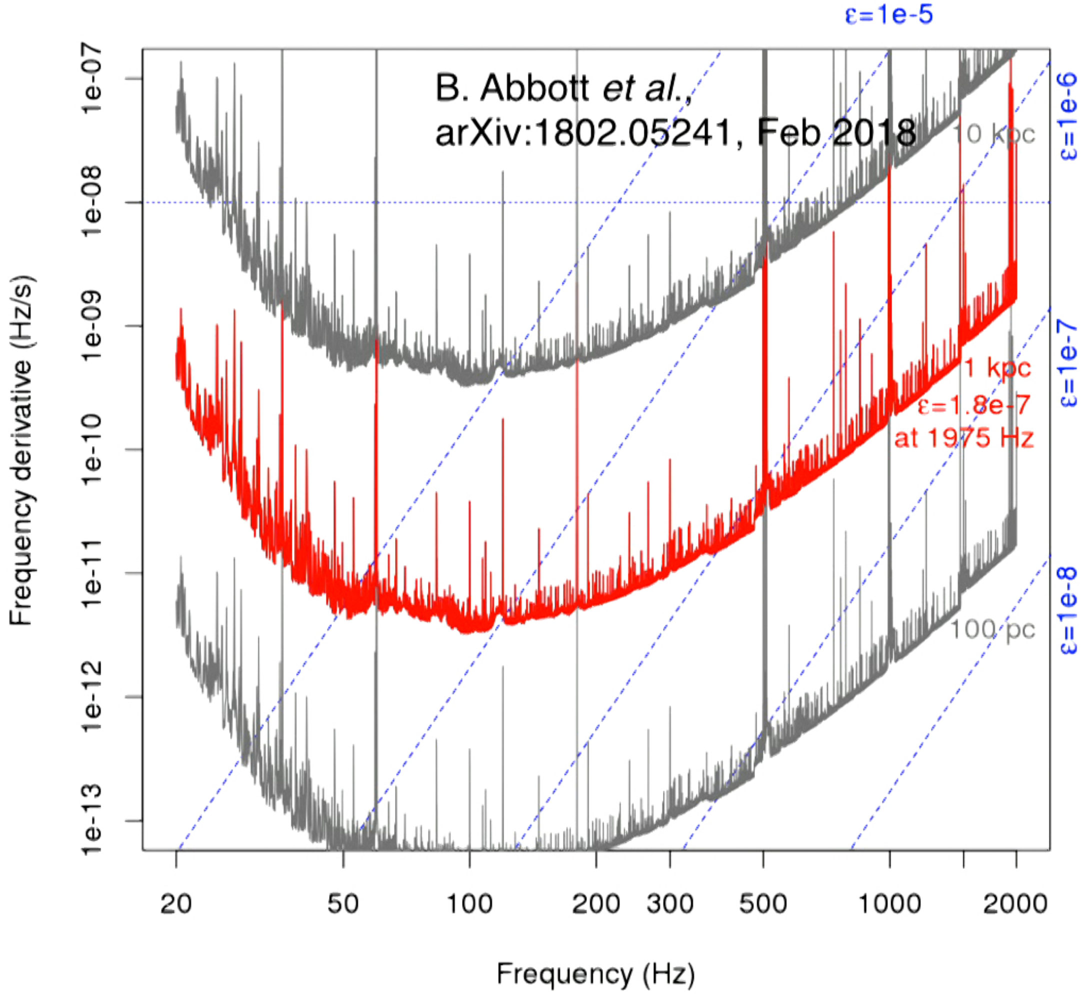
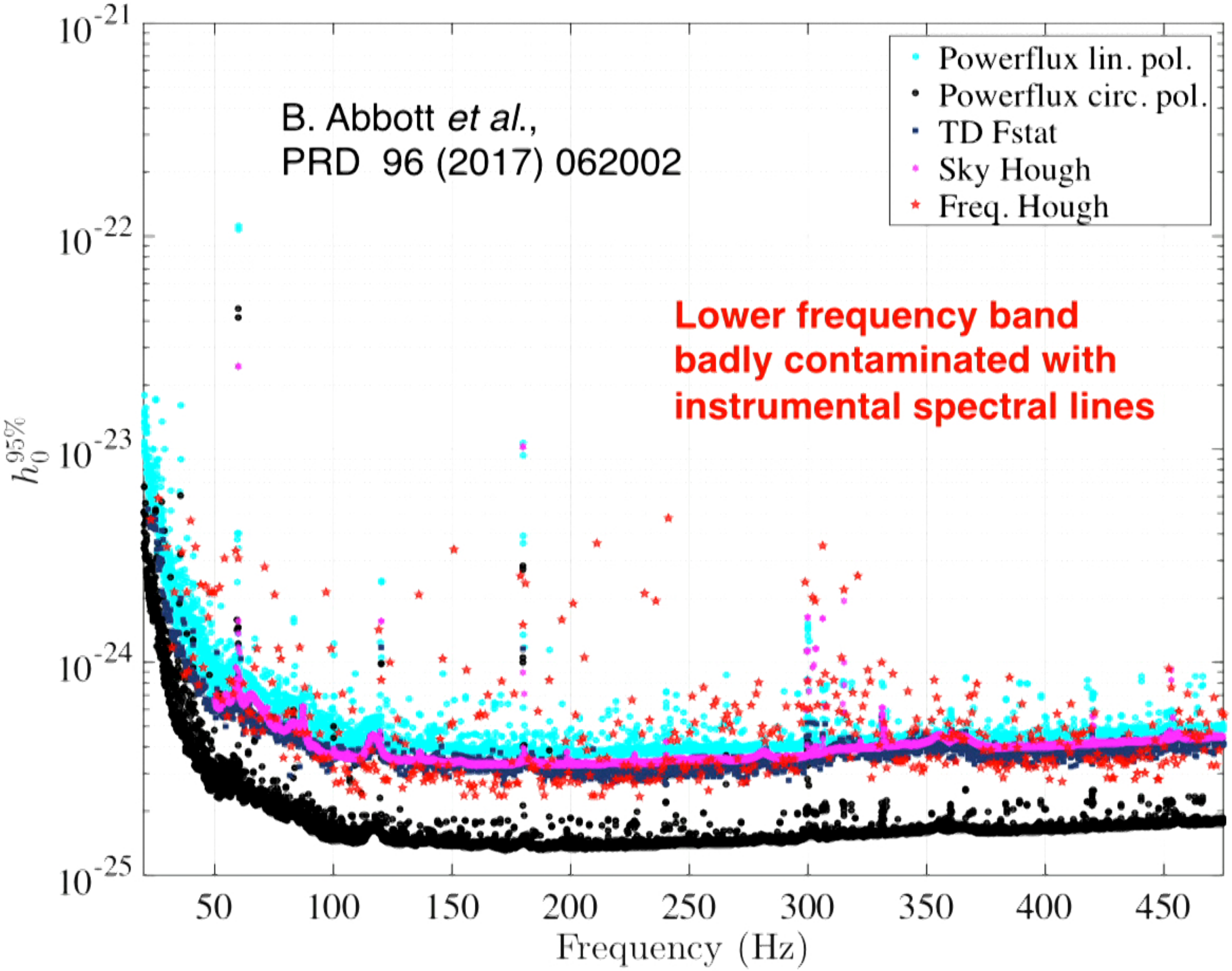


Astrophysical reach for most favorable inclination
-> **Circular Polarization**

Recent results – All-sky search



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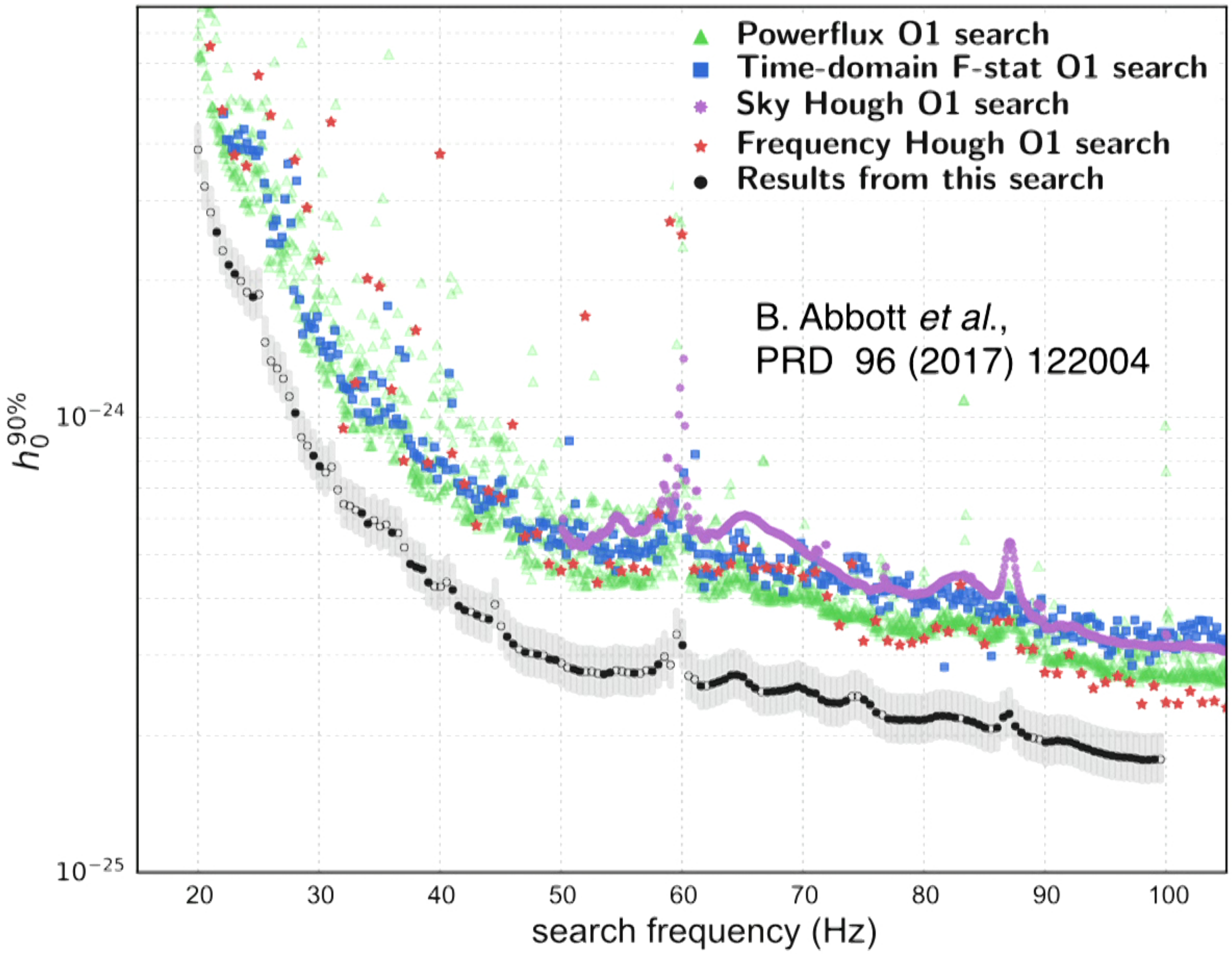

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All-sky Searches for Unknown Binary Stars

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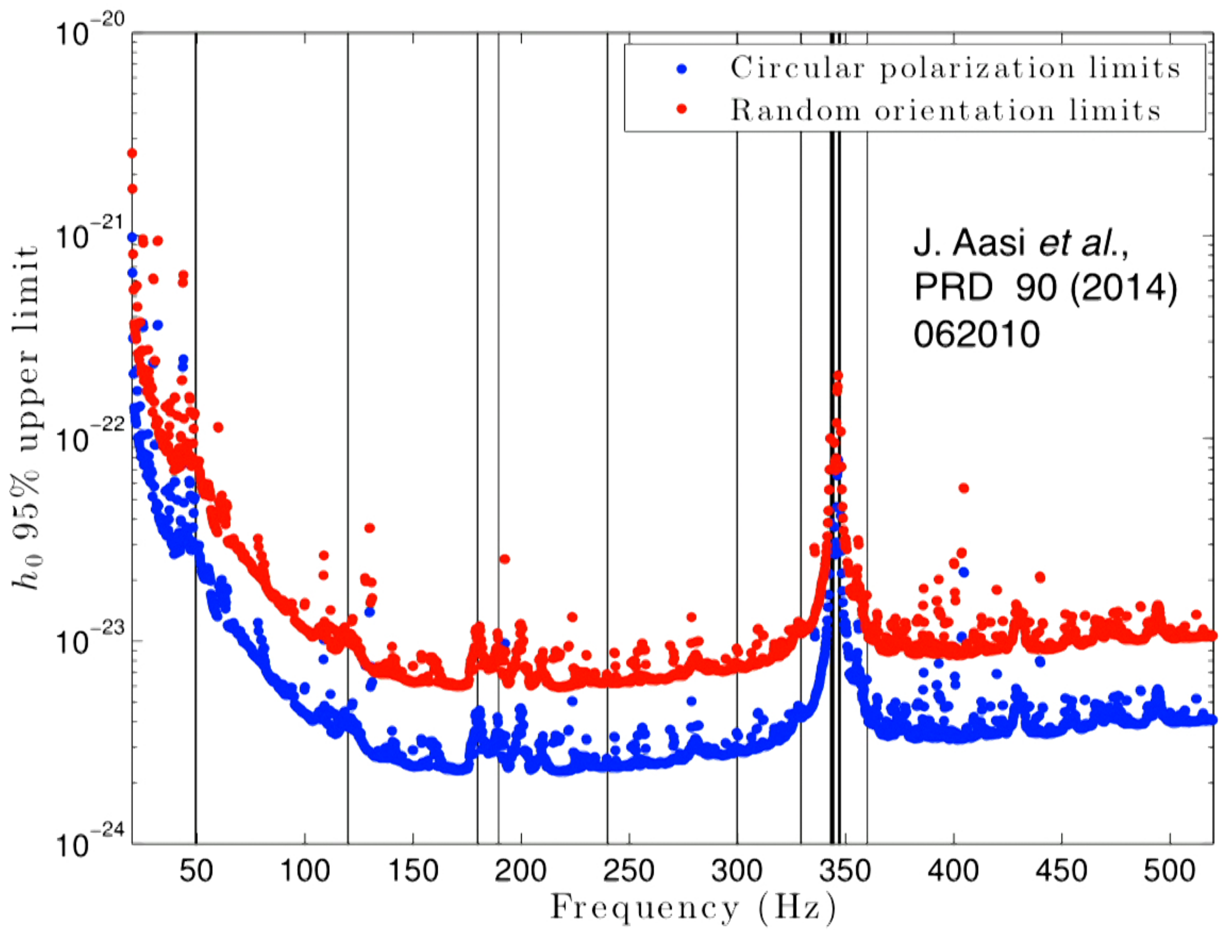
  [A. Vicere & M. Yvert, CQG 33 (2016) 165006]

Initial LIGO results – All-sky binary search



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What changes when searching for superradiance?

Different models have (somewhat) different consequences:

- String axion

  [Arvanitaki et al., PRD 81 (2010) 123530;
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Will focus here on QCD scenario (weak self-interactions)

What changes when searching for superradiance?

Level transition emission

[**1×10^{-11} – 6×10^{-11} eV/c^2** in nominal LIGO/Virgo CW 10-2000 Hz band for ABH-favored 6*g* → 5*g* transition and $M_{BH} = 10M_{\odot}$]

→ Signal frequency determined by axion mass, but also by self-interaction and varying (black hole mass)^2
(still must deal with Doppler modulations)

- Spin**up** parameter space small but non-zero

$$\frac{df}{dt} \approx 10^{-11}\,\frac{\text{Hz}}{\text{s}}\left(\frac{f}{90\text{ Hz}}\right)\left(\frac{M}{10M_{\text{Sun}}}\right)\left(\frac{10^{17}\text{ GeV}}{f_a}\right)\left(\frac{5\text{ yr}}{T_{\text{Signal}}}\right)$$

- Rare events (ABH) – once per stellar lifetime for ~10 years

What changes when searching for superradiance?

Annihilation emission – Splendid long-lived source!

[**2×10^{-14} – 4×10^{-12} eV/c^2** in nominal LIGO/Virgo CW 10-2000 Hz band]

→ Signal frequency determined by fixed axion mass, but with small quadratic corrections in $(M/10M_\odot)^2$ (still must deal with Doppler modulations)

- Spin**up** parameter space nearly vanishes
  → Especially helpful for long observation times

- Stochastic GW searches could see superposition of multiple, incoherent sources in narrow band (detection of closest source likely first?)

Some Questions

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- Is there theoretical consensus on QCD rates / strengths? (analytical and numerical agree well now?)
- Are unknown isolated black holes or known black hole binaries better bets? (all-sky comes "for free"; searches for specific binaries impose non-trivial computing and analysis costs)
- Which binaries are most promising? (Ideal: close & medium-spin)

Some Questions

- Just how narrow is the signal band for annihilation?

$$f_{\rm GW} = \frac{2\mu_a c^2}{h}\left(1 - \frac{\alpha^2}{2n^2}\right) \quad \Rightarrow \quad \frac{\Delta f_{\rm GW}}{f_{\rm GW}} = \frac{\Delta(\alpha^2)}{2n^2}$$

$$\alpha = \frac{G M_{\rm BH}\mu_a}{\hbar c} = (0.075)\left(\frac{M_{\rm BH}}{10 M_{\rm Sun}}\right)\left(\frac{\mu_a}{10^{-12}\ {\rm eV/c^2}}\right)$$

→ If band extremely narrow, must be careful about source confusion in following up all-sky outliers (we wish!)

- Should CW searches go above 290 Hz? ($\mu_a > 6\times10^{-13}$ eV/c^2)
  [excluded for QCD axions; what about stringy axions?]
- If so, should CW searches go above 2000 Hz?
  [very costly for all-sky searches]

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CW searches are diverse in both targets and algorithms
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But we do make choices on where to spend computing resources and analyst time

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→ Trying to keep our eyes wide open

But we do make choices on where to spend computing resources and analyst time

Have mainly assumed galactic neutron star is prime source and that BH superradiance comes for free in all-sky searches – at some sensitivity

If superradiance gives stable frequencies, we should be safe

But if boson self-interactions give significant spin wandering, we could miss the signal with current CW searches
(but still catch extra-galactic signal from stochastic signal?)
→ How much should we worry about this?

Should we focus on particular black hole binaries?

Guidance is welcome!