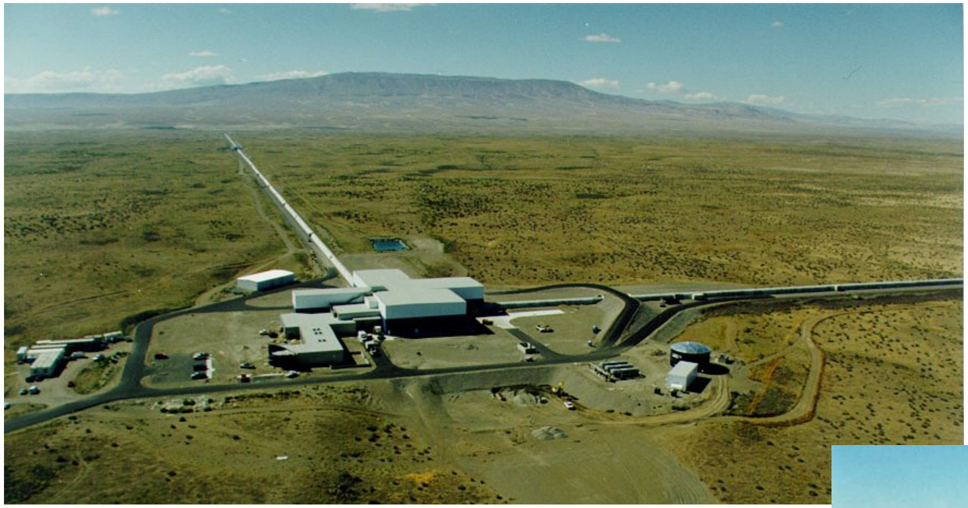
Overview of continuous gravitational waves detection methods



Keith Riles
U. Michigan

LIGO Scientific Collaboration
and the Virgo Collaboration

Astro-Solids workshop on Dense Matter, and Gravitational Waves

Institute for Nuclear Theory
University of Washington
April 16, 2018

LIGO-G1800759

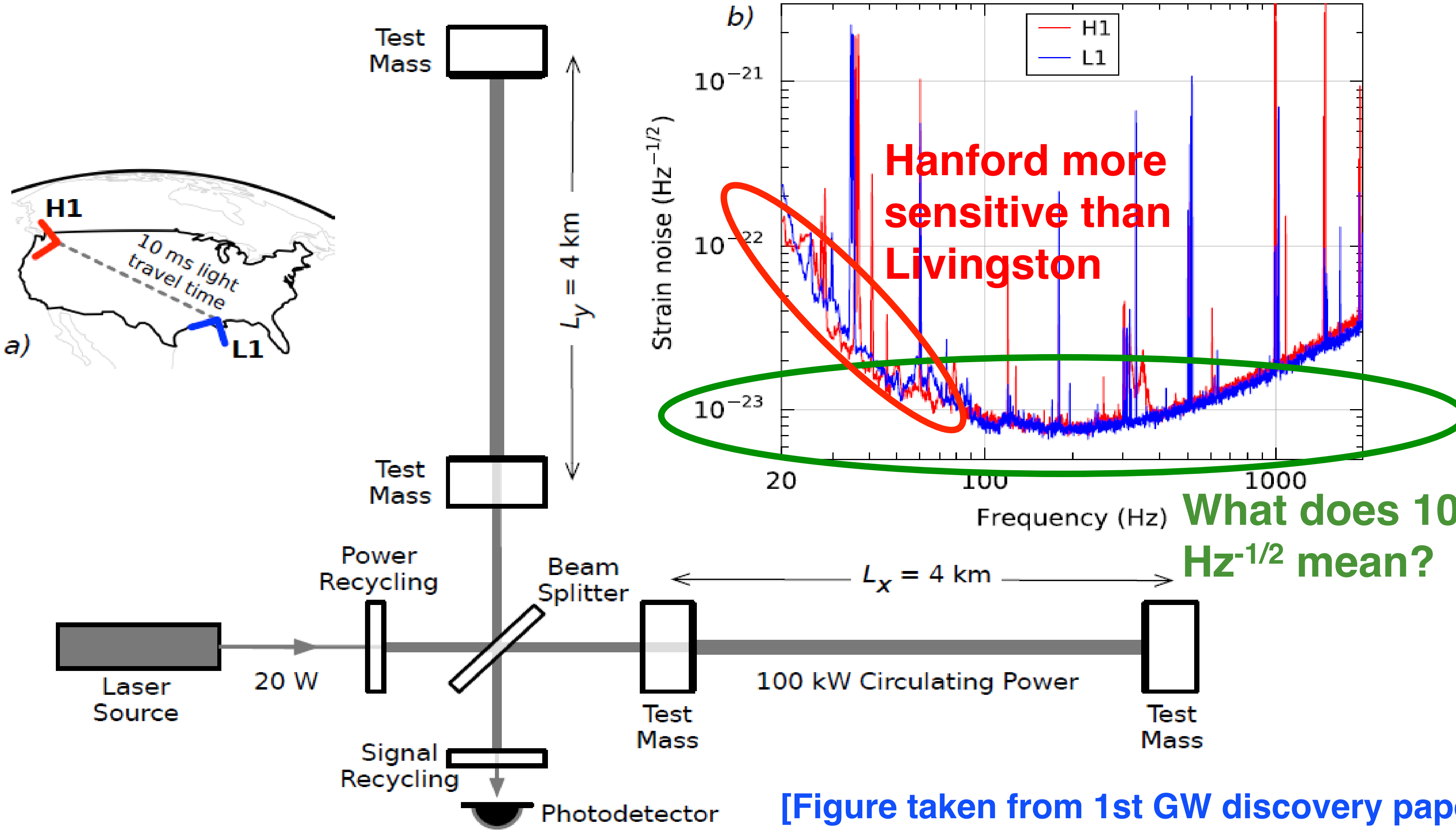
Outline

- **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**
  - **Sampling of methods and results**

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



What does 10^{-23} Hz$^{-1/2}$ mean?

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

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

Examples:

BBH like GW150914:

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

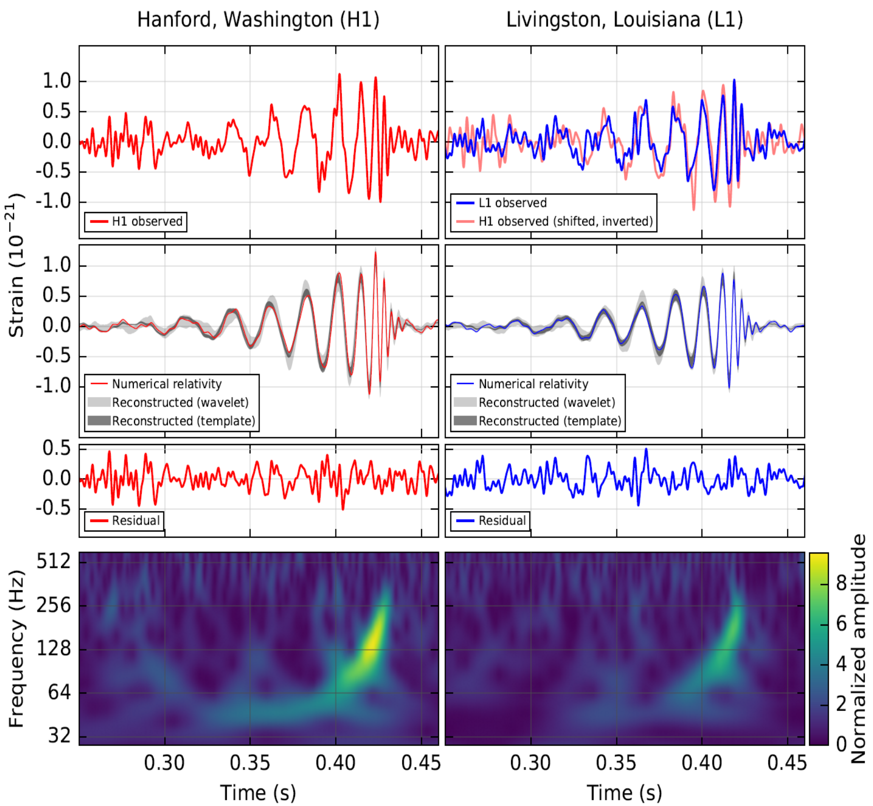
Actual amplitude = 10^{-21} → Very loud signal

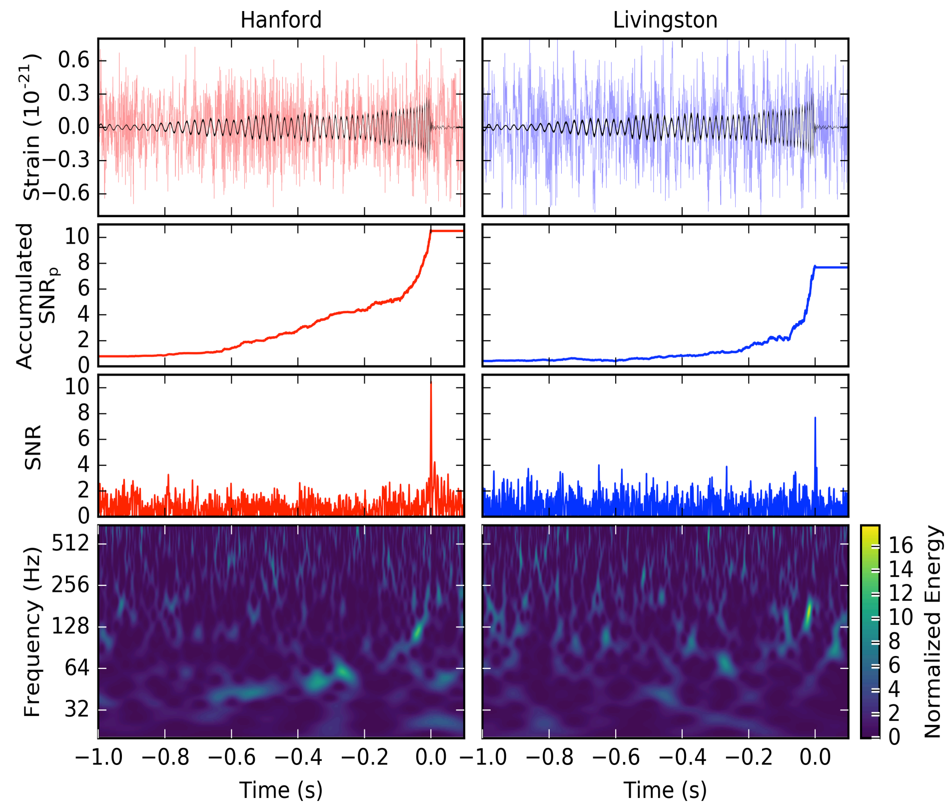
CW signal from known pulsar measured coherently over 1 year:

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

In practice, most detectable CW source amplitudes lie (currently) in **10^{-25}-10^{-24}** because of large trials factors (more later)

O1 “5-sigma” Detections





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

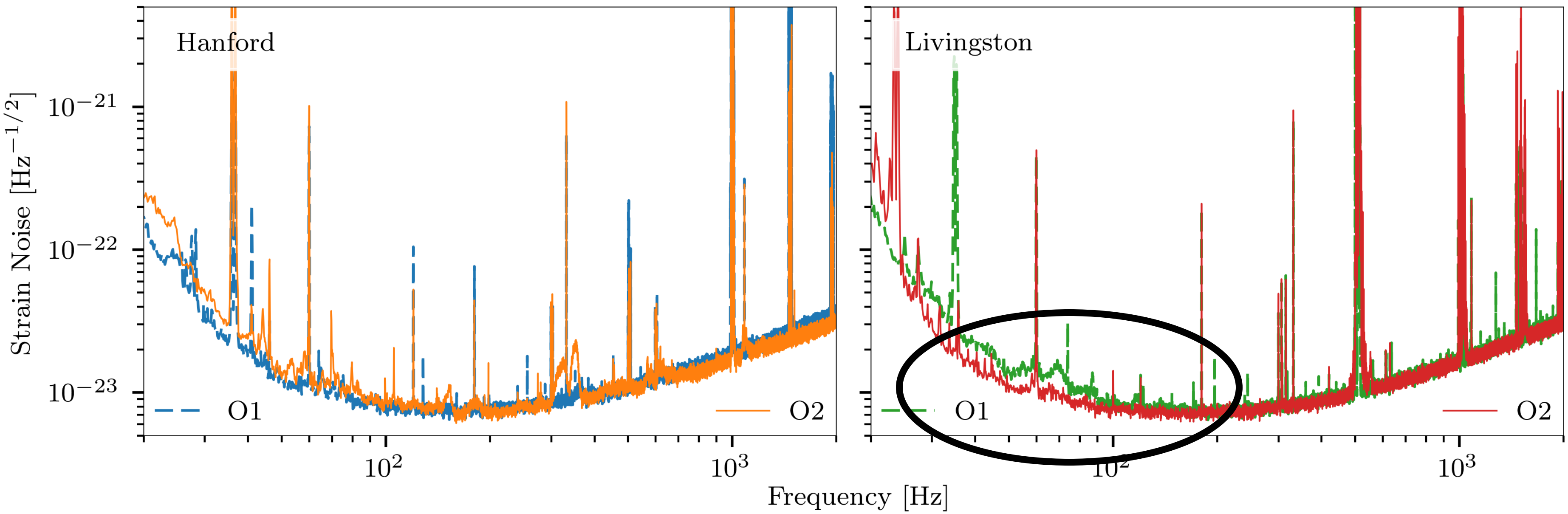
Mishap at Livingston derailed high-power plans for 2016, but other noise mitigation paid off well

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)

O2 began November 30, 2016 – ended August 25, 2017

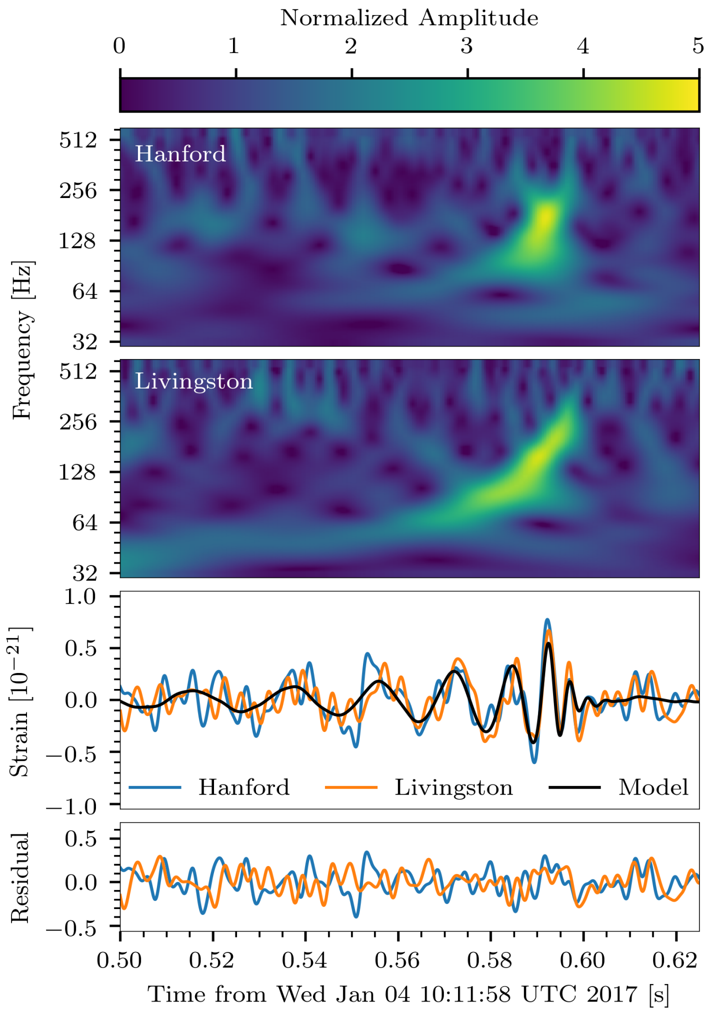
The O2 Run

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

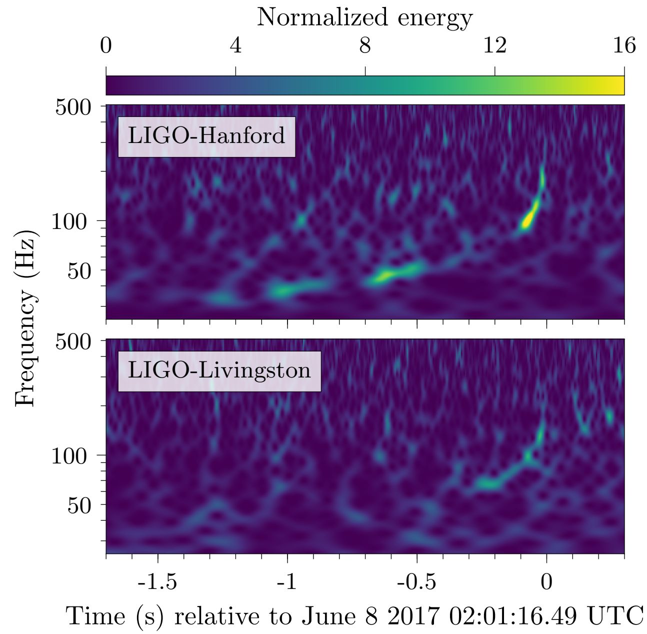


B.P. Abbott *et al*, PRL **118**, 221101 (2017)

This band helpful for detecting binary black holes – and young pulsars

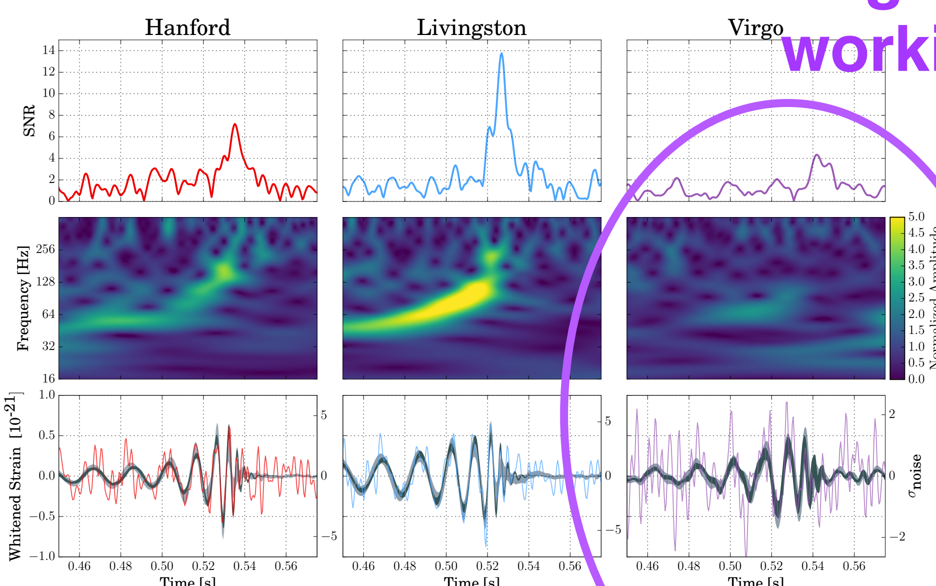


GW170104



GW170608

Virgo working!

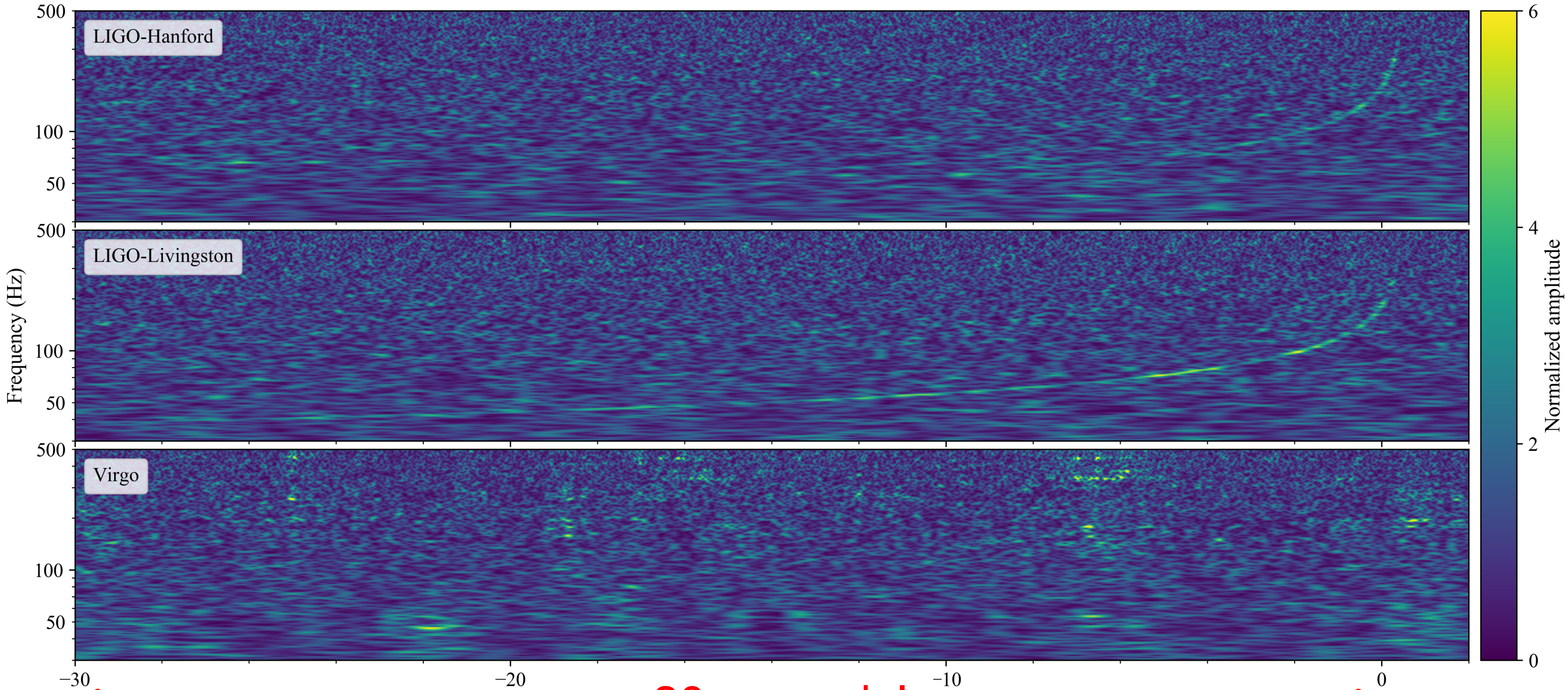


GW170814

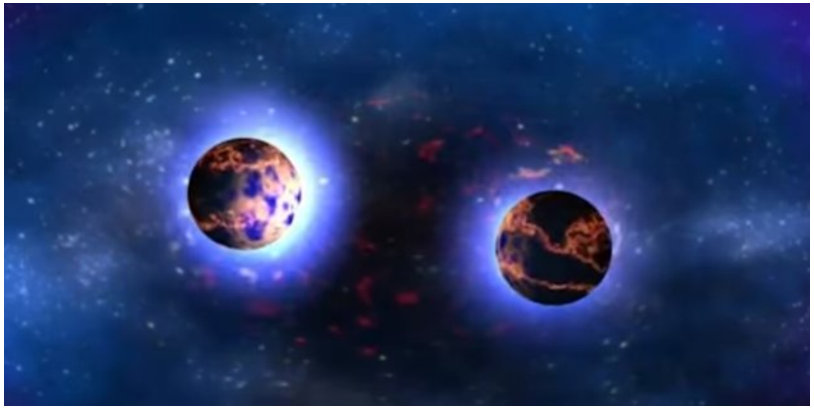
More black hole mergers

Not to mention a binary neutron star merger...

GW170817



30 seconds!



CAASTRO

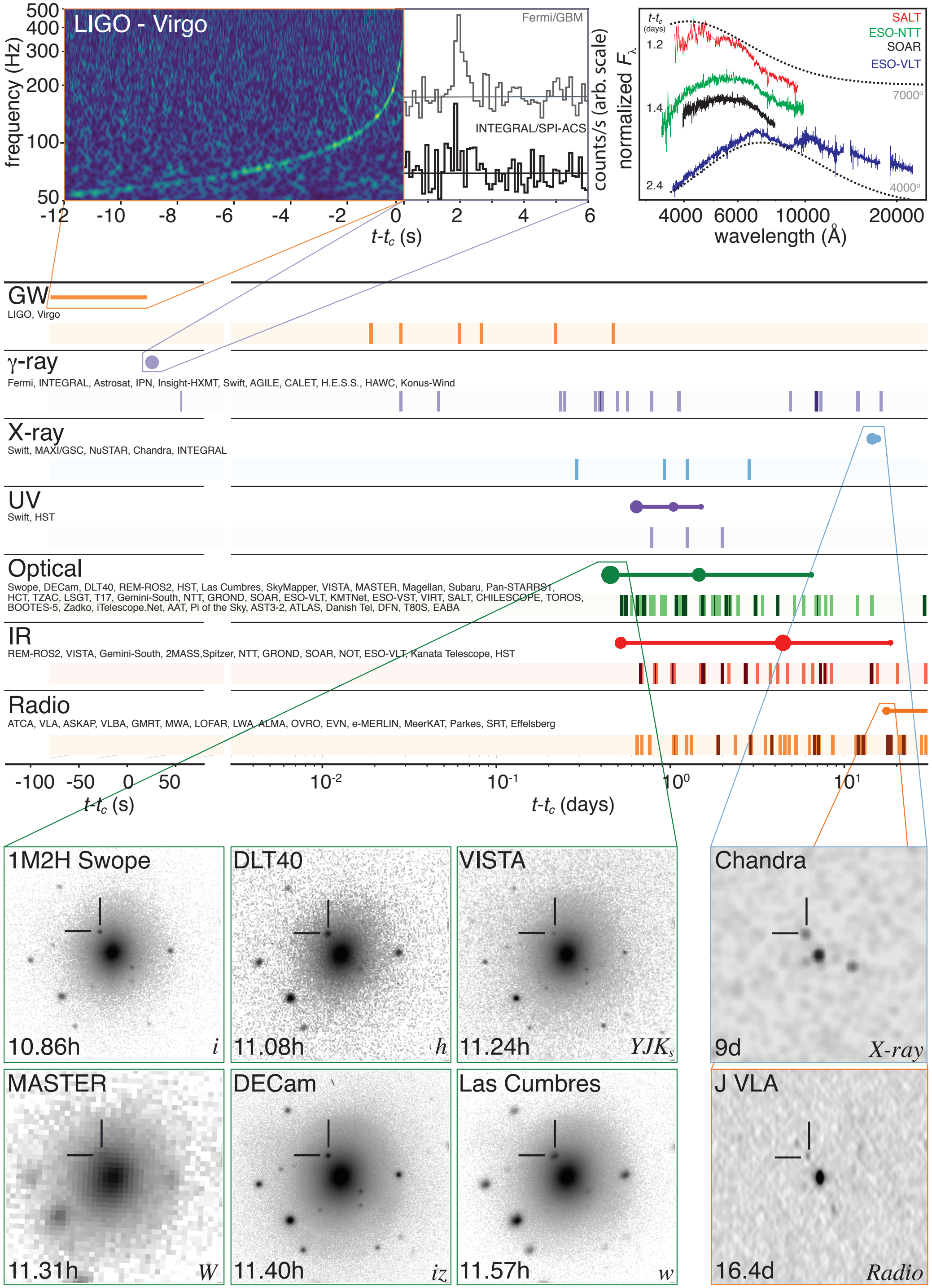


Figure from

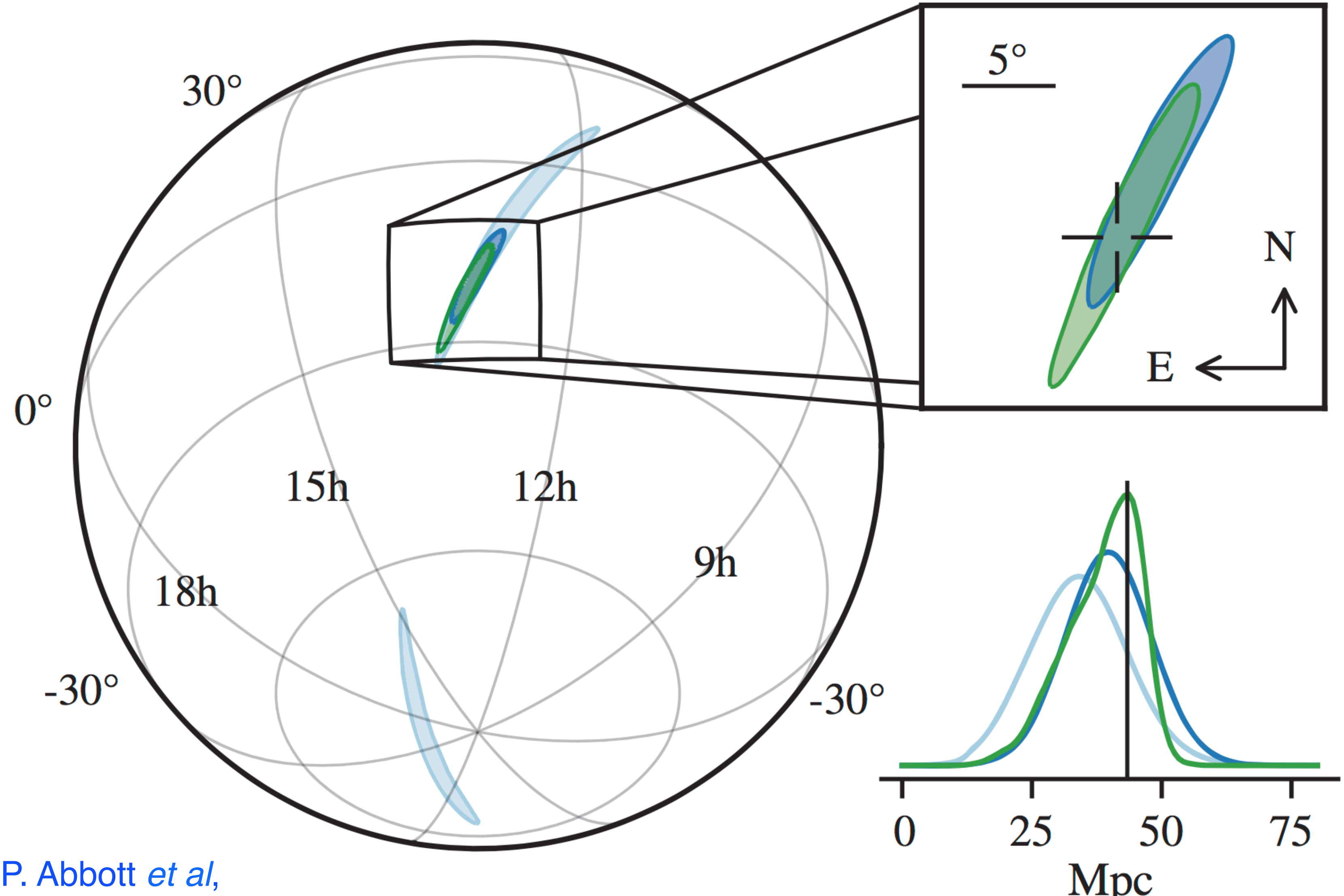
"Multi-Messenger Observations of a Binary Neutron Star Merger"

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

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

At this point we CW searchers have acute "source envy"

[See Graham Woan's talk on potential joint CWGW/EM observations]

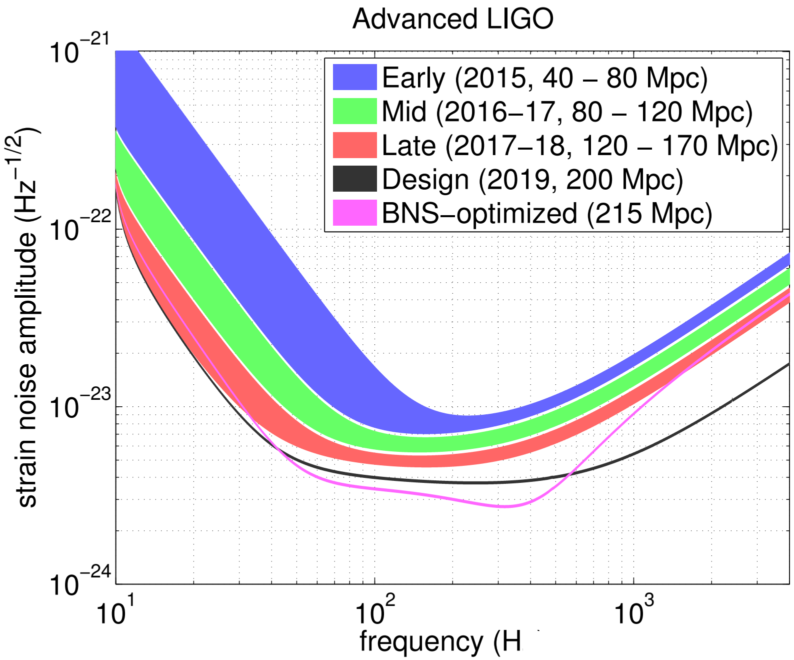


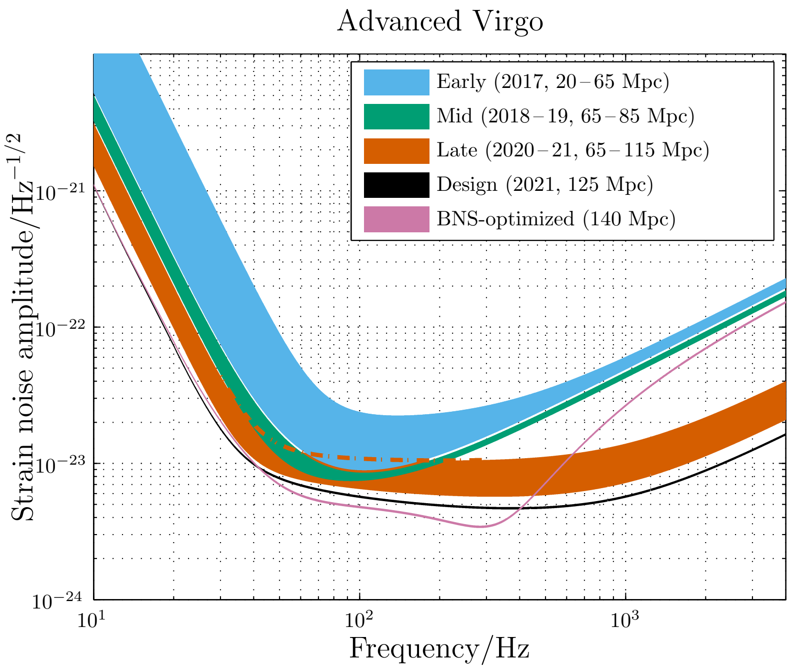
B.P. Abbott *et al*,
PRL **119**, 061101 (2017)

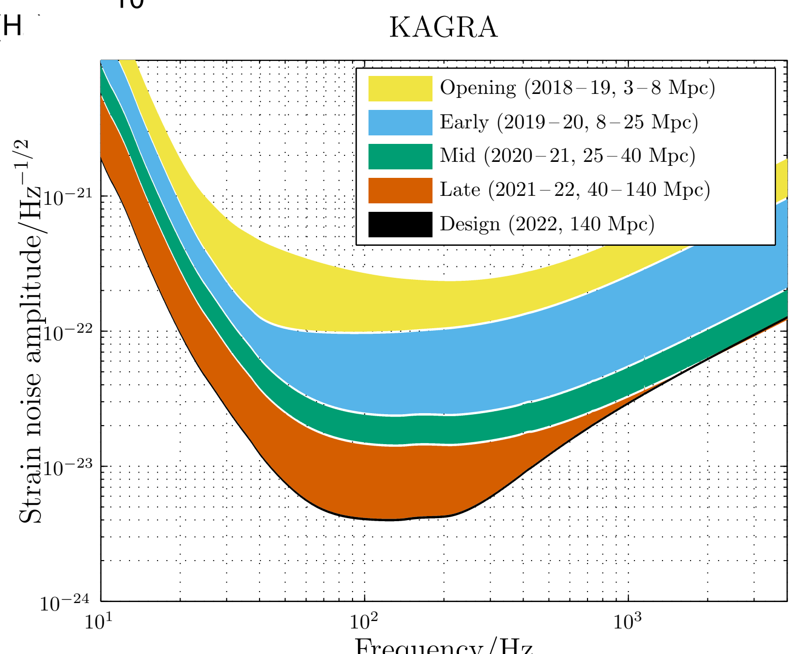
A CW detection could give far better localization − sub-arcsec

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

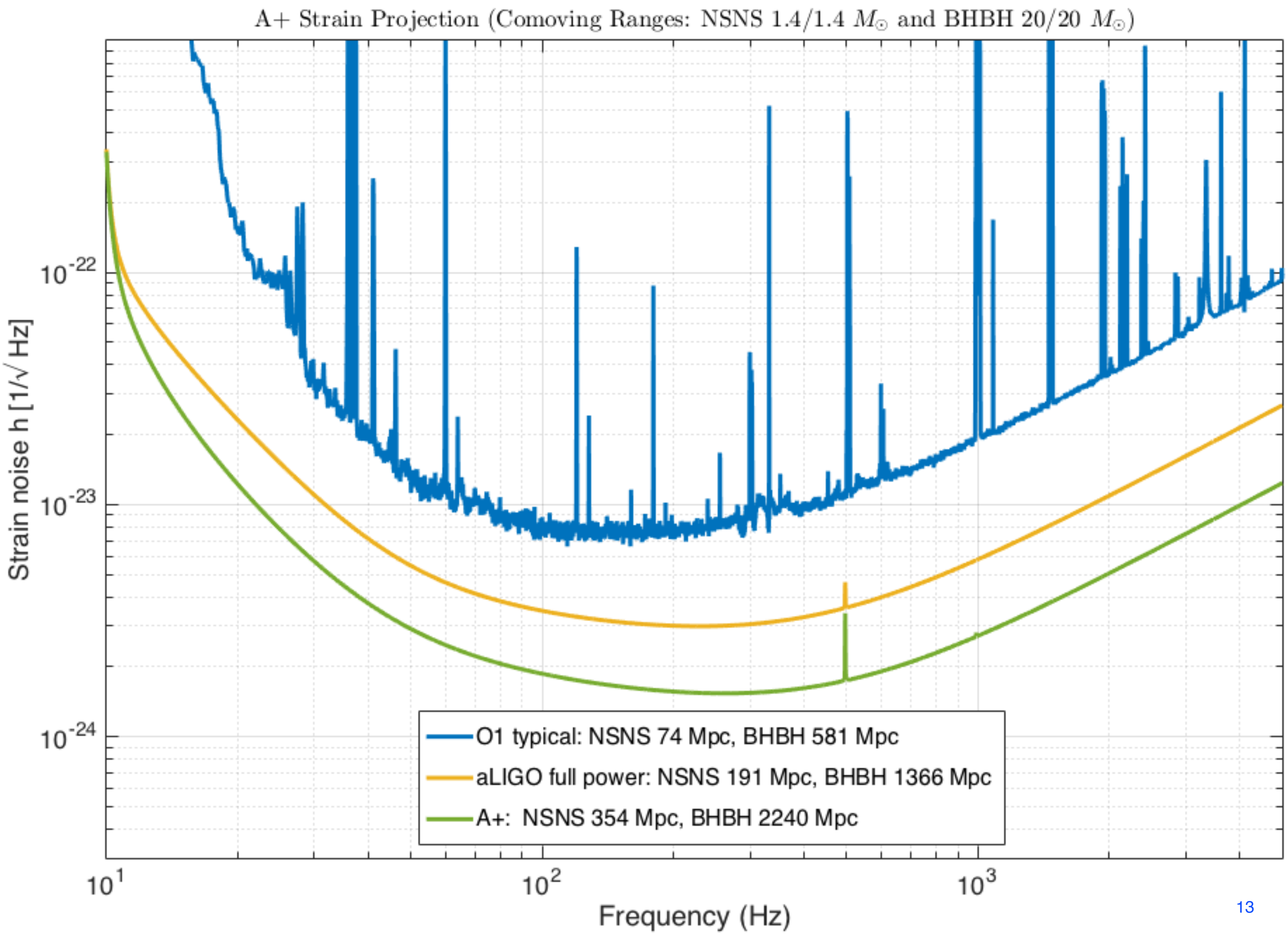
Looking Ahead







Looking Ahead



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
- Even 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

So we're all set, right?

Not necessarily...

Most searches must make tradeoffs – sensitivity vs computing cost (more later)

Analysts too make choices on where to spend their own time

We may not be making the optimum choices (sources, algorithms, time)

Will walk through assumptions we make now and where focus has been

→ This workshop can (ideally) make upcoming choices better informed

CW Search Assumptions – Emission Mechanisms

- Radiation generated by quadrupolar mass movements:

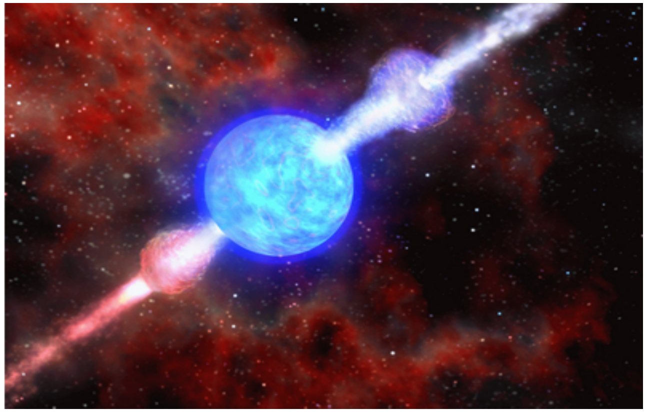
$$h_{\mu\nu} = \frac{2G}{rc^4}\frac{d^2}{dt^2}\left[I_{\mu\nu}\right]$$

→ No GW from axisymmetric object rotating about symmetry axis

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

- Spinning neutron star with equatorial ellipticity ε_{equat}

$$\varepsilon_{\text{equat}} = \frac{|I_{xx} - I_{yy}|}{I_{zz}}$$



Courtesy: U. Liverpool

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

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

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):**

$$h \propto \varepsilon_{poloidal} \times \theta_{\text{wobble}} \quad \text{with} \quad f_{GW} = f_{\text{rot}} \pm f_{\text{precess}}$$

→ Precession due to different L and Ω axes

[See Ian Jones' talk on free precession and magnetic stars]

- **Two-component (crust+superfluid) →** $f_{\text{GW}} = f_{rot}$ and $2 f_{\text{rot}}$

- **r modes** (rotational oscillations – CFS-driven instability):

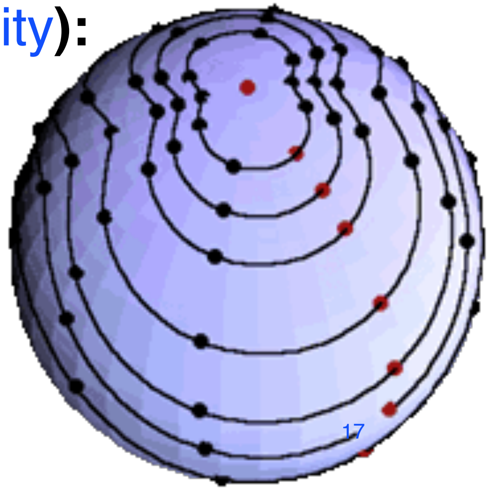
N. Andersson, ApJ 502 (1998) 708

S. Chandrasekhar, PRL 24 (1970) 611

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

$$h \propto \alpha_{\text{r-mode}} \quad \text{with} \quad f_{GW} \cong \frac{4}{3} f_{\text{rot}}$$

[See Ben Owen's talk on r-mode searches]



Gravitational CW mechanisms

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 (29.7 Hz) at 59.5 Hz
(troublesome frequency in North America!)

What is allowed for ε_{equat} ?

Old maximum (?) $\approx 5 \times 10^{-7}$ $[\sigma/10^{-2}]$ ("ordinary" neutron star)
with σ = breaking strain of crust
G. Ushomirsky, C. Cutler & L. Bildsten, MNRAS 319 (2000) 902

More recent finding: $\sigma \approx 10^{-1}$ supported by detailed numerical simulation
C.J. Horowitz & K. Kadau, PRL 102, (2009) 191102

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

Gravitational CW mechanisms

Strange quark stars could support much higher ellipticities

[B.J. Owen, PRL 95 (2005) 211101;
N. Johnson-McDaniel & B.J. Owen, PRD 88 (2013) 044004]

Maximum $\varepsilon_{equat} \approx 10^{-1}$ (!)

But what $\boldsymbol{\varepsilon}_{\mathbf{equat}}$ is realistic?

What could drive $\boldsymbol{\varepsilon}_{\mathbf{equat}}$ to a high value (besides accretion)?

Millisecond pulsars have spindown-implied values lower than 10^{-9}–10^{-6} ☹

CW Search Assumptions – Promising sources

Three broad categories of searches have dominated analysis:

Targeted searches for known pulsars using radio / X-ray / γ-ray ephemerides

→ Exact phase tracking over O(years) – low trials factor (3 methods)

→ Variation ("narrowband") allows for EM/GW $\Delta f \sim O(10^{-3})\, f_{EM}$

Directed searches for known sources / locations
(unknown / poorly known frequencies)

- Isolated and binary sources treated separately
- Fully coherent searches over days/weeks
- Semi-coherent searches over full data runs

All-sky searches for unknown sources

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

CW Searches – The main challenge

Two other categories receiving more attention:

Searches for "CW transients" (e.g., enhanced CW emission following known neutron star glitch) –
[See Reinhard Prix's talk on "not-quite-continuous" waves]
→ Challenge: fewer constraints available to establish detection

Searches for newborn known neutron stars
(including short-lived post-BNS-merger remnants)
[See Paul Lasky's talk on newborn objects]

→ Challenge: rapid and poorly known frequency evolution
(conventional Taylor expansion methods break down)
→ Advantage: turn-on of signal well defined

Computing Challenges – Directed Searches

CW searches could saturate Earth's computing – Why?

Assume a GW phase model using a Taylor expansion (source frame):

$$\Phi(t) = \phi_0 + 2\pi[f(T - T_0) + \frac{1}{2}\dot{f}(T - T_0)^2 + \frac{1}{6}\ddot{f}(T - T_0)^3 + \ldots]$$

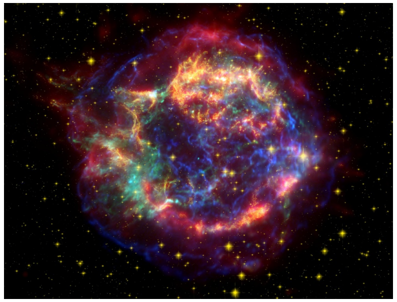
where f is the nominal signal frequency at reference time T_0 in the source frame, and T is the time of arrival of the GW signal at the solar system barycenter (SSB):

$$T = t + \delta t = t - \frac{\vec{r}_d \cdot \hat{k}}{c} + \Delta_E - \Delta_S$$

Where $\mathbf{r_d}$ is the detector position w.r.t. the SSB, $\mathbf{k}$ is the wave vector, Δ_E is the Einstein delay, and Δ_S is the Shapiro delay

Computing challenges – Directed Searches

Consider a coherent directed search for a precisely known location but unknown frequency, e.g., Cassiopeia A (isolated X-ray source at center of supernova remnant)



To avoid cumulative phase mismatch $\Delta\Phi$ greater than, say, 0.5 radians, search templates used must have correct frequency parameters to within about

$$\Delta f \approx \frac{1}{T_{\mathrm{COH}}}, \qquad \Delta \dot{f} \approx \frac{2}{T_{\mathrm{COH}}^2}, \qquad \Delta \ddot{f} \approx \frac{6}{T_{\mathrm{COH}}^3}, \qquad \text{etc.}$$

Hence a search with long enough T_{COH} to require multiple steps in $\ddot{f}$ has a computational cost that scales as $(T_{\mathrm{COH}})^7$

→ Cost of search rises rapidly for long T_{COH} and young objects
→ Limits coherence time to O(10 days) for 300-year-old Cas A

It gets worse…

Computing challenges – All-sky Searches

Serious technical difficulty: Doppler frequency shifts

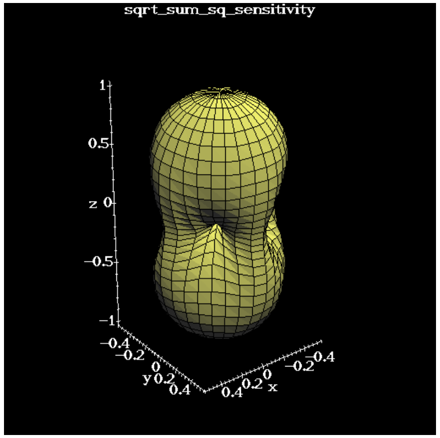
- Frequency modulation from earth's rotation ($v/c \sim 10^{-6}$)
- Frequency modulation from earth's orbital motion ($v/c \sim 10^{-4}$)

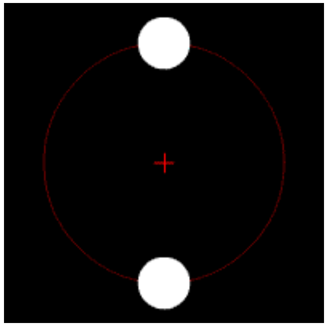
→ Coherent integration of 1 year gives frequency resolution of 30 nHz

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

Additional, related complications:

Daily amplitude modulation of antenna pattern
(polarization dependent)
Still have frequency derivatives to address...





Orbital motion of sources in binary systems

Computing challenges – All-sky Searches

Modulations / drifts complicate analysis enormously:

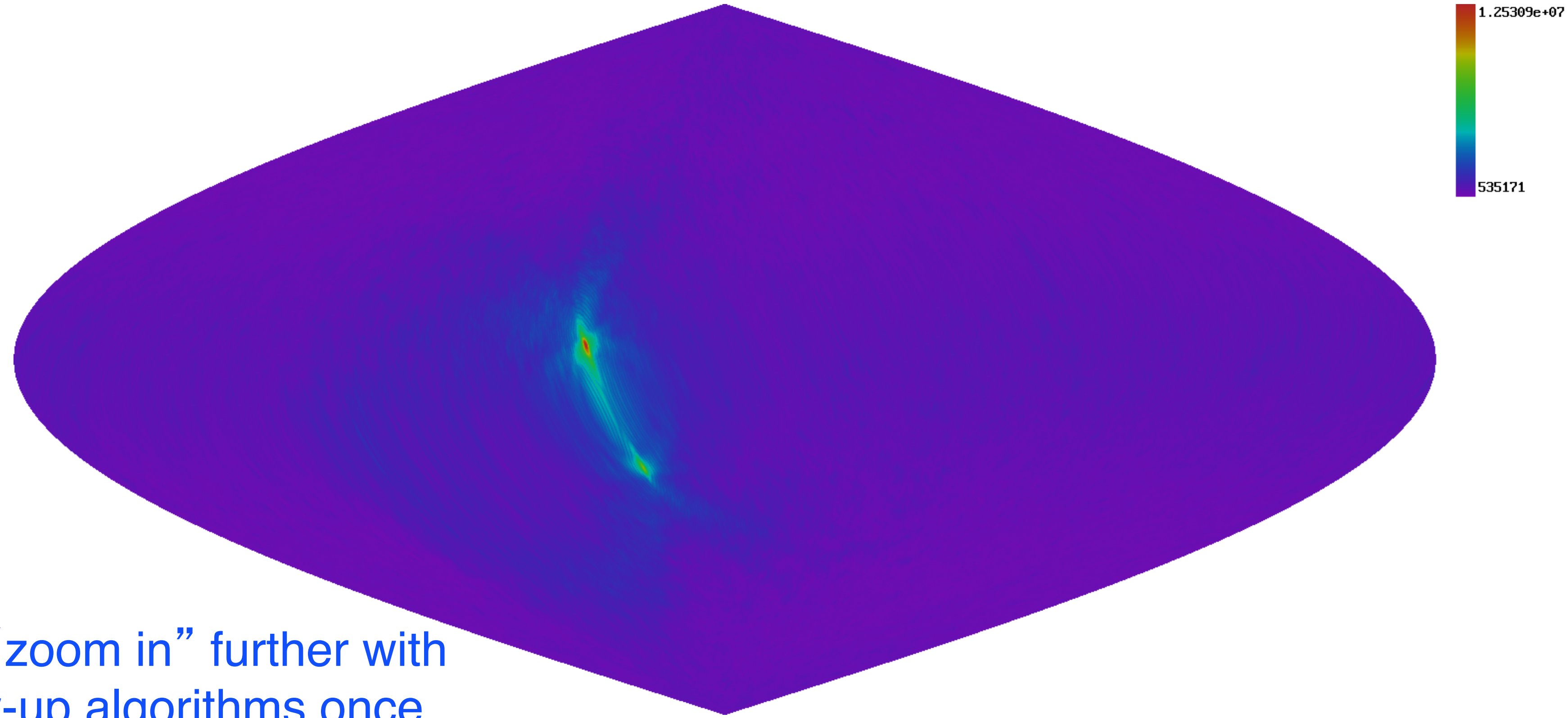
- Simple Fourier transform inadequate
- Every sky direction requires different demodulation
- →Number of distinct sky location scales like $f^2 T^2_{\mathrm{COH}}$
- →Computing cost scales as $(T_{\mathrm{COH}})^6$ without 2nd frequency derivative!
- All-sky survey at full sensitivity not possible (at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

Tradeoffs to cope with astronomical computing costs:

- Restrict T_{COH} < several days for all-sky search
  → Compute demodulated spectra (e.g., "F-Statistic")
  → Exploit coincidence among different time segments
  → Sensitivity scales like $(T_{\mathrm{COH}})^{1/2}$
- Semi-coherent stacking ($N_{\mathrm{stack}} = T_{\mathrm{OBS\text{-}RUN}} / T_{\mathrm{COH}}$)
  - Raw 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**



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

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

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

Targeted Searches

Targeted searches use ephemerides from radio, X-ray, γ-ray pulsar astronomers (informal consortium of observers who co-author GW papers)

Three methods used to date:

- Time-domain heterodyne with Bayesian parameter estimation applied to 200 pulsars in O1 data
  [R. Dupuis & G. Woan, PRD 72 (2005) 102002]

- Matched-filter with marginalization over unknowns (F-Statistic & G-Statistic) applied to O(10) "high-value" known isolated pulsars
  [P. Jaranowski, A. Krolak & B. Schutz, PRD 58 (1998) 063001;
  P. Jaranowski & A. Krolak, CQG 27 (2010) 94015]

- Fourier-domain "5-vector" method exploiting carrier and amplitude-modulation sidebands applied to high-value targets
  [P. Astone et al., CQG 27 (2010) 194016;
  P. Astone et al., JPCS 363 (2012) 012038]

What is the "direct spindown limit"?

It is useful to define the "direct spindown limit" for a known pulsar, under the assumption that it is a "gravitar", i.e., a star spinning down exclusively due to gravitational wave energy loss

Unrealistic for known stars, but serves as a useful benchmark

Equating "measured" rotational energy loss (from measured period increase and reasonable moment of inertia) to GW emission gives:

$$h_{SD} = 2.5 \times 10^{-25} \left[\frac{kpc}{d}\right] \sqrt{\left[\frac{1kHz}{f_{\mathrm{GW}}}\right]\left[\frac{-df_{\mathrm{GW}}/dt}{10^{-10}\,Hz/s}\right]\left[\frac{I}{10^{45}\,g\cdot cm^2}\right]}$$

Example:

Crab → $\mathbf{h_{SD} = 1.4 \times 10^{-24}}$

(d=2 kpc, f_{GW} = 59.5 Hz, $df_{GW}/dt = -7.4 \times 10^{-10}$ Hz/s)

Recent results

Targeted search for 200 known pulsars in O1 data

Lowest (best) upper limit on strain:

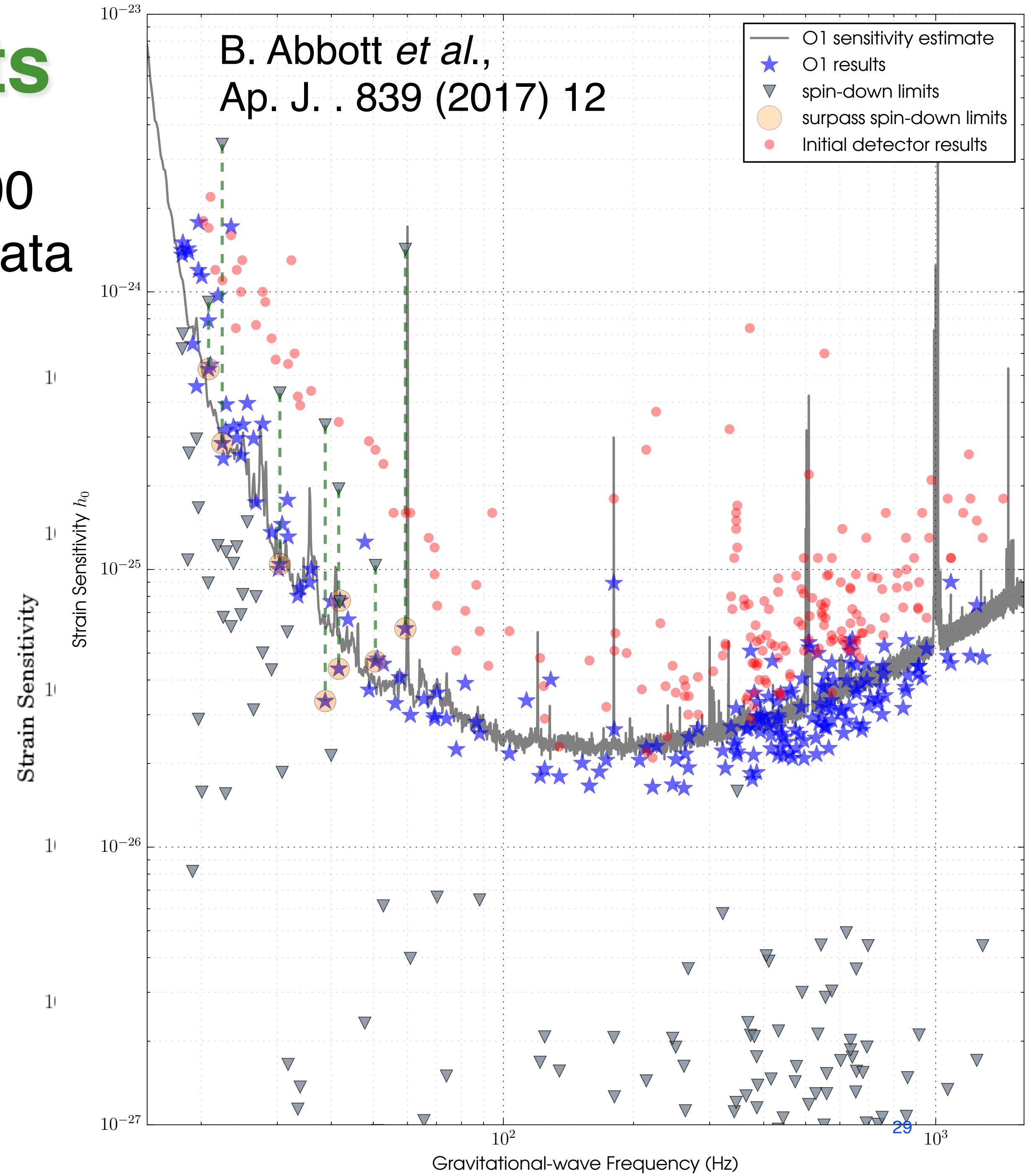
$h_0 < 1.6 \times 10^{-26}$

Lowest (best) upper limit on ellipticity:

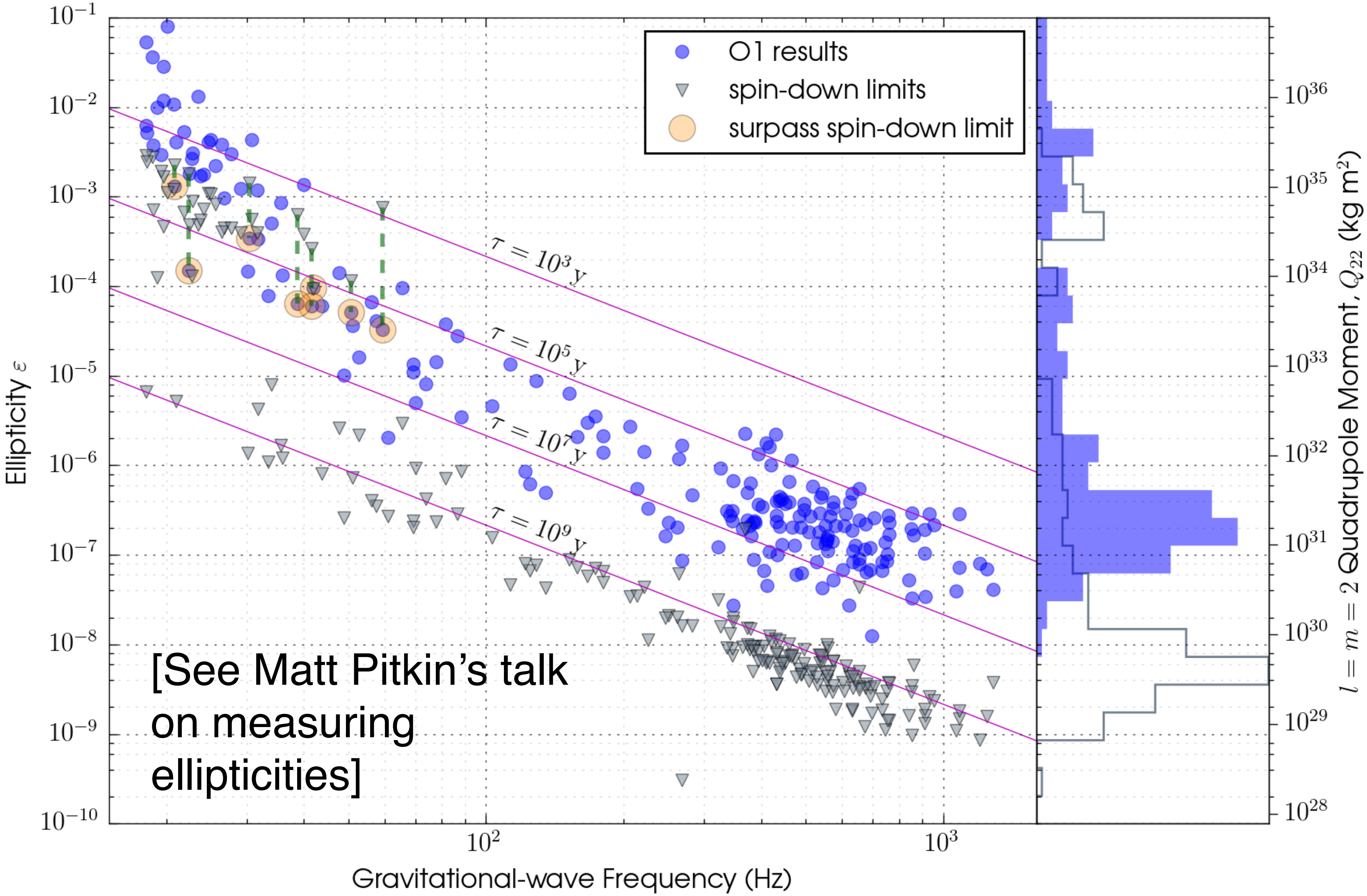
$\varepsilon < 1.3 \times 10^{-8}$

Crab limit at 0.2% of total energy loss

(beats "spindown limit")



Another take on the 200*



[See Matt Pitkin's talk on measuring ellipticities]

*Also looked for non-tensorial polarizations – none seen – B. Abbott *et al*, PRL 120 (2018) 031104

“Narrowband” Searches

Narrowband searches also use ephemerides from radio, X-ray, γ-ray pulsar astronomers, but allow for slight mismatch between EM and GW phase, e.g., from differential rotation

Used in initial LIGO & Virgo searches with both *F*-Statistic and 5-vector methods

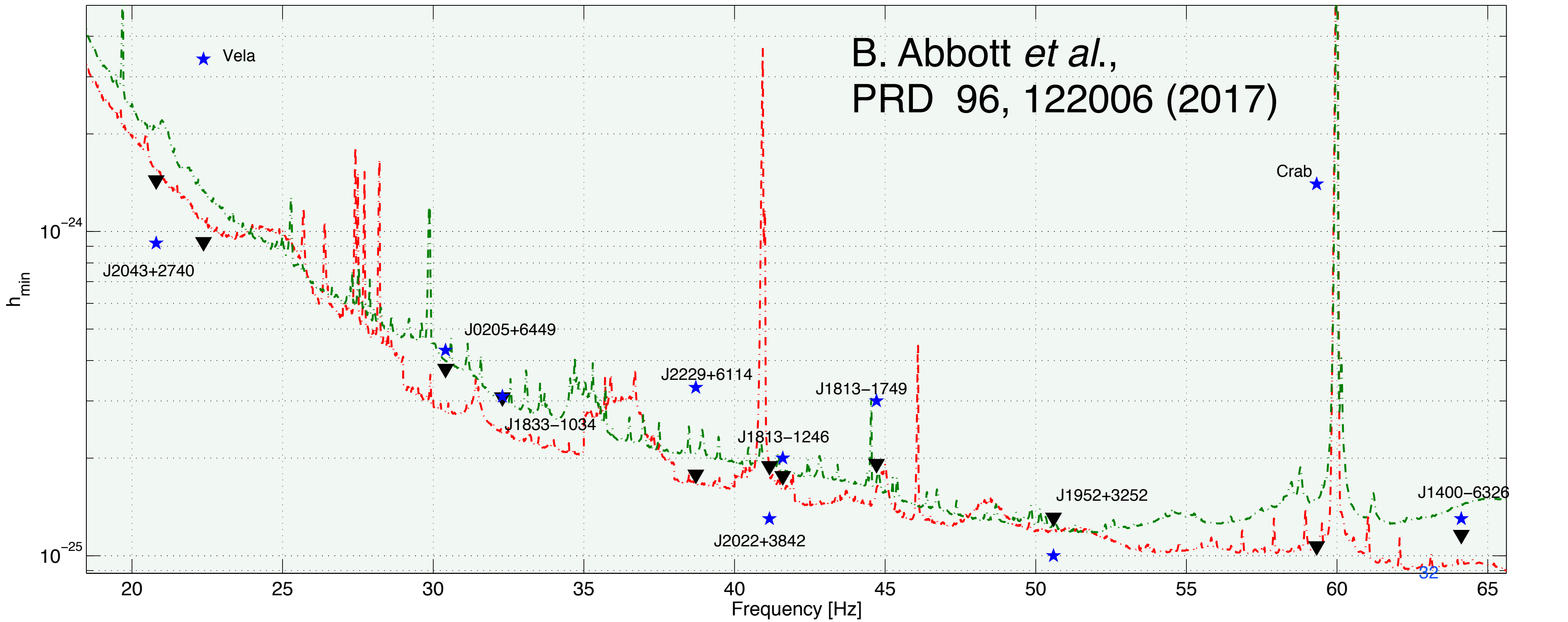
O1 narrowband search used 5-vector method and allowed $O(10^{-3})$ relative frequency mismatch in targeting high-value young pulsars at low frequencies

Recent results – Narrowband Search

Targeted search assumes exact agreement between EM and GW phase, but differential rotation can lead to slight mismatch

Despite larger trials factor, O1 search still beat spindown limit for handful of pulsars

Question: Is O(10^{-3}) relative frequency mismatch enough?



Directed Searches for Isolated Stars

Coherent directed searches for known sources / locations with unknown or poorly known frequencies carried out in initial and advanced LIGO data using the F-Statistic with optimized templating
[K. Wette *et al.*, CQG 25 (2008) 235011]

Applied in final initial LIGO S6 and advanced LIGO O1* runs to nine supernova remnants [J. Aasi *et al.*, ApJ 813 (2015) 39] and with barycenter-resampled *F*-Statistic (quicker) to core of globular cluster NGC 6544 [B. Abbott *et al.*, PRD 95 (2017) 082005]

Semi-coherent directed searches using stacked *F*-Statistic carried out in initial LIGO data for galactic center [J. Aasi *et al.*, PRD 88 (2013) 102022] and for Cas A [S.J. Zhu *et al.*, PRD 94 (2016) 082008]

→ Semi-coherent searches using full data set now carried out on Einstein@Home
→ Achieve O(2) sensitivity improvement over quicker coherent searches

*Result from O1 under review

What is the "age-based spindown limit"?

If a star's age is known (e.g., historical SNR), but its spin is unknown, one can still define an indirect spindown upper limit by assuming gravitar behavior has dominated its lifetime:

$$\tau = \frac{f}{4\,(df\,/\,dt)}$$

And substitute into h_{SD} to obtain
[K. Wette *et a*l., CQG 25 (2008) 235011]

$$h_{ISD} = 2.2\times10^{-24}\left[\frac{kpc}{d}\right]\sqrt{\left[\frac{1000\,yr}{\tau}\right]\left[\frac{I}{10^{45}\,g\cdot cm^2}\right]}$$

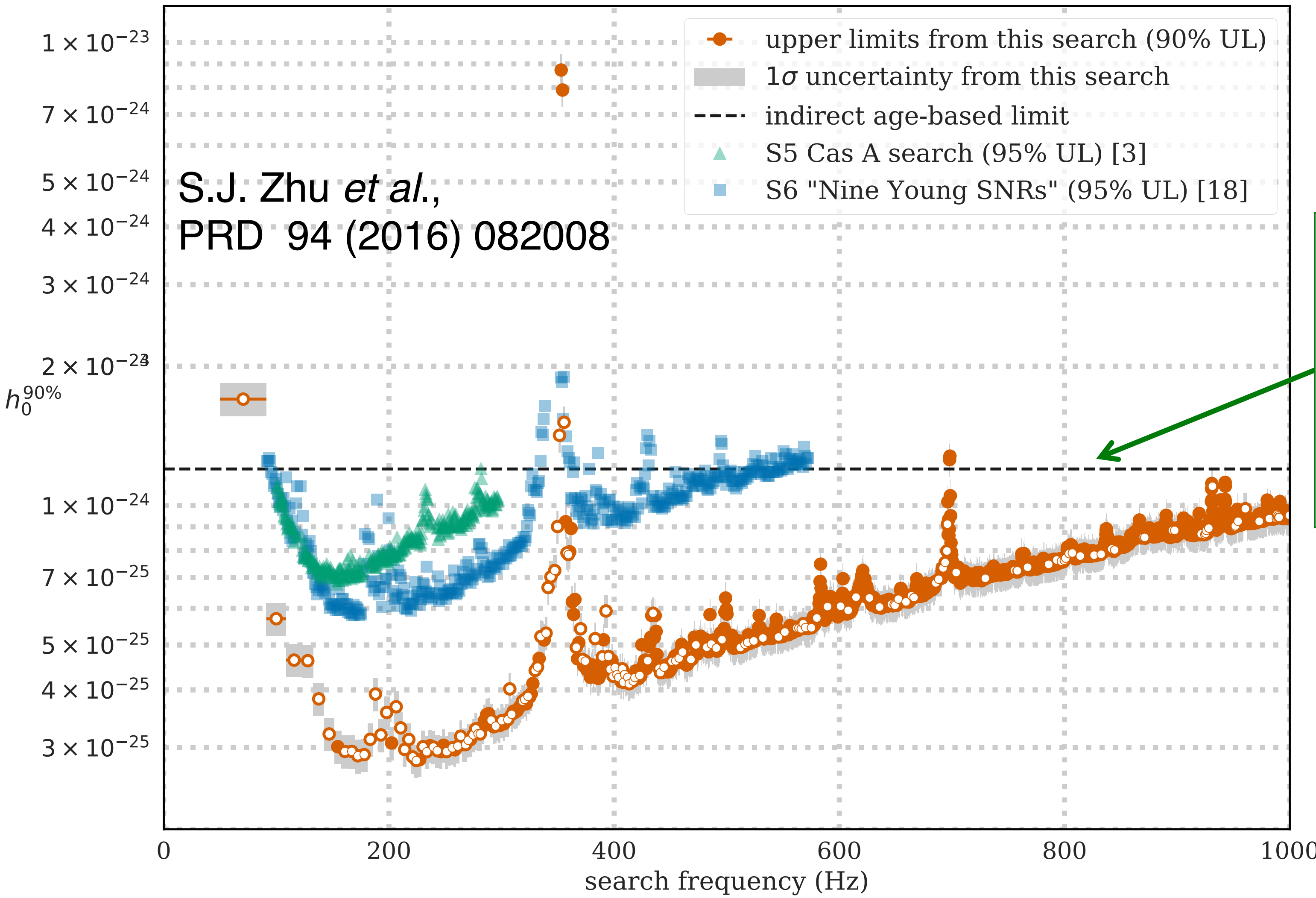
Example:

Cassiopeia A → **$h_{ISD} \approx 1.1 \times 10^{-24}$**

(d ~ 3.4 kpc, τ ~ 340 yr)

Initial LIGO results – Directed Search

Search for Cassiopeia A – Young age (~340 years) requires search over 2nd derivative



indirect upper limit

(based on age, distance)

Directed Searches for Binary Stars

The prospect of detecting Scorpius X-1 (X-ray-bright LMXB) in Advanced LIGO / Virgo data has spurred renewed algorithm development in recent years to detect CW sources in binary systems.

Sco X-1's spin frequency unknown, but

- Orbital period known precisely, time of ascending node known well
- Projected semi-major axis bounded

Search methods used in Initial LIGO data:

- Coherent *F*-Statistic (T_{COH} = 6 hours)
  [P. Jaranowski, A. Krolak & B. Schutz, PRD 58 (1998) 063001;
  B. Abbott *et al*., PRD 76 (2007) 082001]
- Radiometer stochastic radiation search
  [S.W. Ballmer, CQG 23 (2006) S179; B. Abbott *et al*., PRL 118 (2017) 121102]
- *F*-Statistic sideband summing ("Sideband") (T_{COH} = 10 days)
  [C. Messenger & G. Woan, CQG 24 (2007) S469; L. Sammut *et al*., PRD 89 (2014) 043001;
  B. Abbott *et al*. PRD 91 (2015) 062008]
- Double Fourier spectra ("TwoSpect")
  [G.D. Meadors, E. Goetz & K. Riles, CQG 33 (2016) 105017;
  G.D. Meadors *et al*., PRD 95 (2017) 042005]

Directed Searches for Binary Stars

Mock data challenge carried out comparing these algorithms and new one based on cross-correlation with signal frequency demodulation
→ **Clear winner was demodulated cross-correlation**
[C. Messenger *et al.*, PRD 92 (2015) 023006]

Cross-correlation allows tuning of performance via effective coherence time as short Fourier transforms are combined from different interferometers and observation intervals ("CrossCorr")
[S. Dhurandhar *et al.*, PRD 77 (2008) 082001;
J.T. Whelan *et al.*, PRD 91 (2015) 102005;
B. Abbott *et al.*, ApJ 841 (2017) 47]

Recent improvement to F-Statistic sideband summing: combining multiple 10-day segments with Viterbi tracking ("Viterbi Sideband")
[S. Suvorova *et al.*, PRD 93 (2016) 123009; B. Abbott *et al.*, PRD 95 (2017) 122003]

More algorithms on near horizon:

- Sideband with orbital phase tracking [S. Suvorova et al., PRD 96 (2017) 102006]
- Stacked *F*-Statistic [P. Leaci & R. Prix, PRD 91 (2015) 102003]

Next mock data challenge will include stochastic spin-wandering
[A. Mukherjee, C. Messenger & K. Riles, PRD 97, 043016 (2018)]

What is the "torque-balance limit"?

For an LMXB, equating accretion rate torque (inferred from X-ray luminosity) to gravitational wave angular momentum loss (steady state) gives: **[R.V. Wagoner, ApJ 278 (1984) 345; J. Papaloizou & J.E. Pringle, MNRAS 184 (1978) 501; L. Bildsten, ApJ 501 (1998) L89]**

$$h_0 \sim 7\times10^{-27}\sqrt{\left[\frac{600\ \mathrm{Hz}}{f_{Signal}}\right]\left[\frac{F_{\text{X-ray}}}{10^{-8}\ \mathrm{erg\ cm^{-2}\ s^{-1}}}\right]}$$

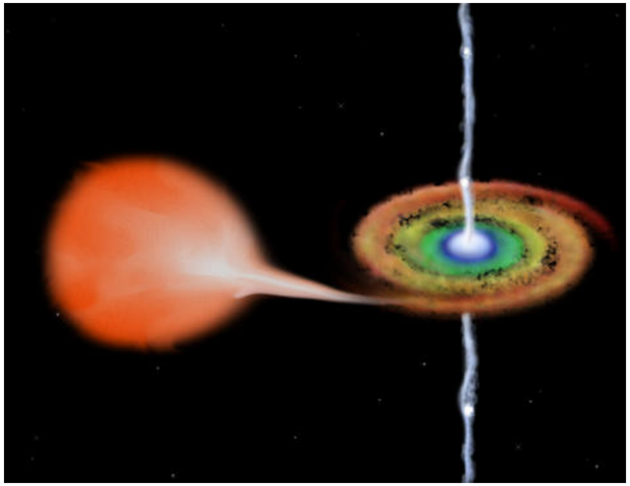
"GW Speed limit" for LMXBs?
[D. Chakrabarty *et al*., Nat 424 (2003) 42; A. Patruno, B. Haskell, N. Andersson, ApJ 850 (2017) 106]

More mundane speed limit from magnetosphere?
[P. Ghosh & F.K. Lamb, ApJ 234 (1979) 296; B. Haskell & A. Patruno, ApJL 738 (2011) L14]

Prime target: Scorpius X-1

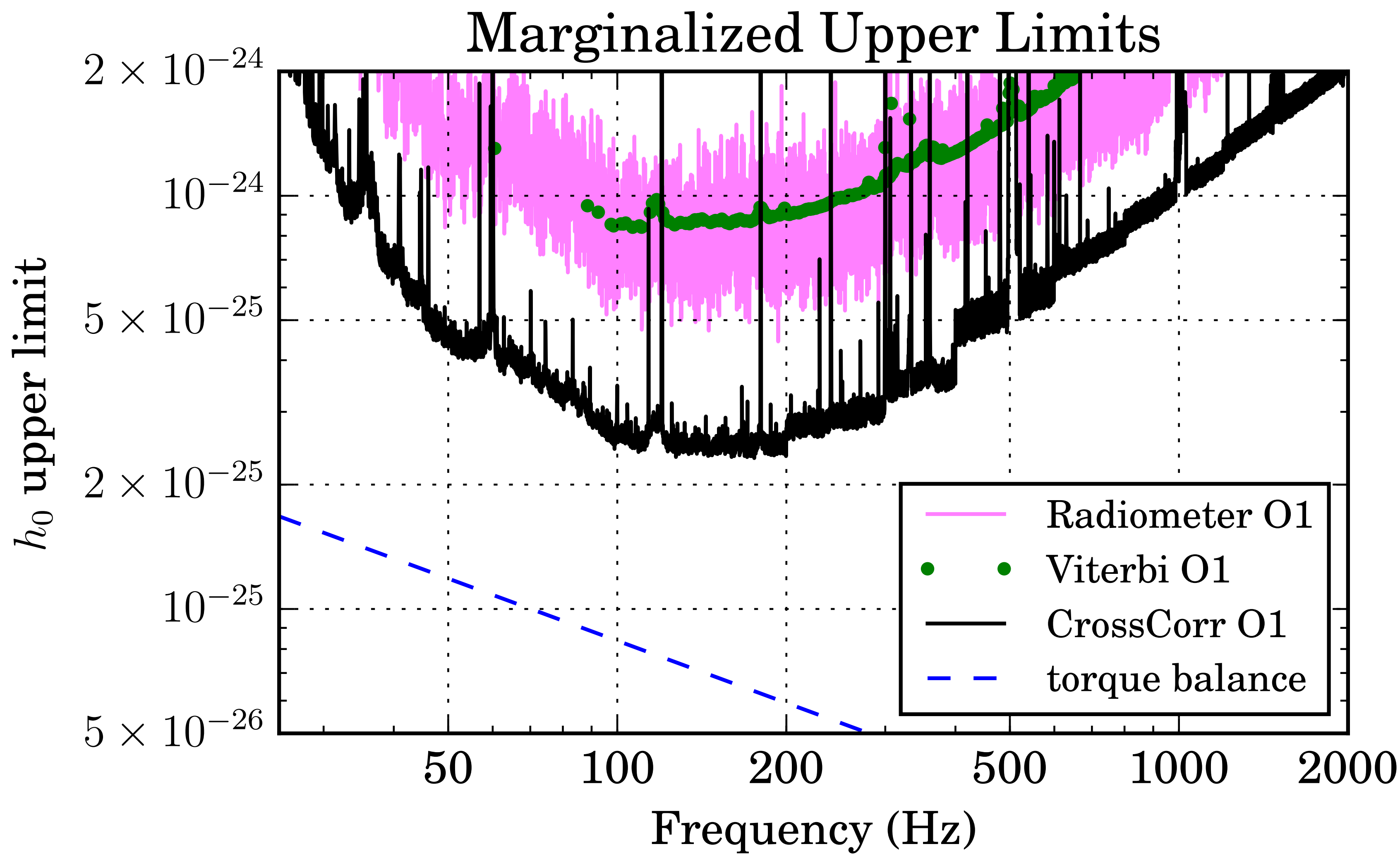
→ $\mathbf{h_0 \approx 3.5 \times 10^{-26}}$ $[600\ \mathrm{Hz} / f_{sig}]^{1/2}$

$(F_{\text{X-ray}} = 2.5 \times 10^{-7}\ \mathrm{erg\cdot cm^{-2}\cdot s^{-1}})$



Courtesy: McGill U.

Recent results – Scorpius X-1



B. Abbott *et al.*,
PRD 96, 122006 (2017)

All-sky Searches for Unknown Isolated Stars

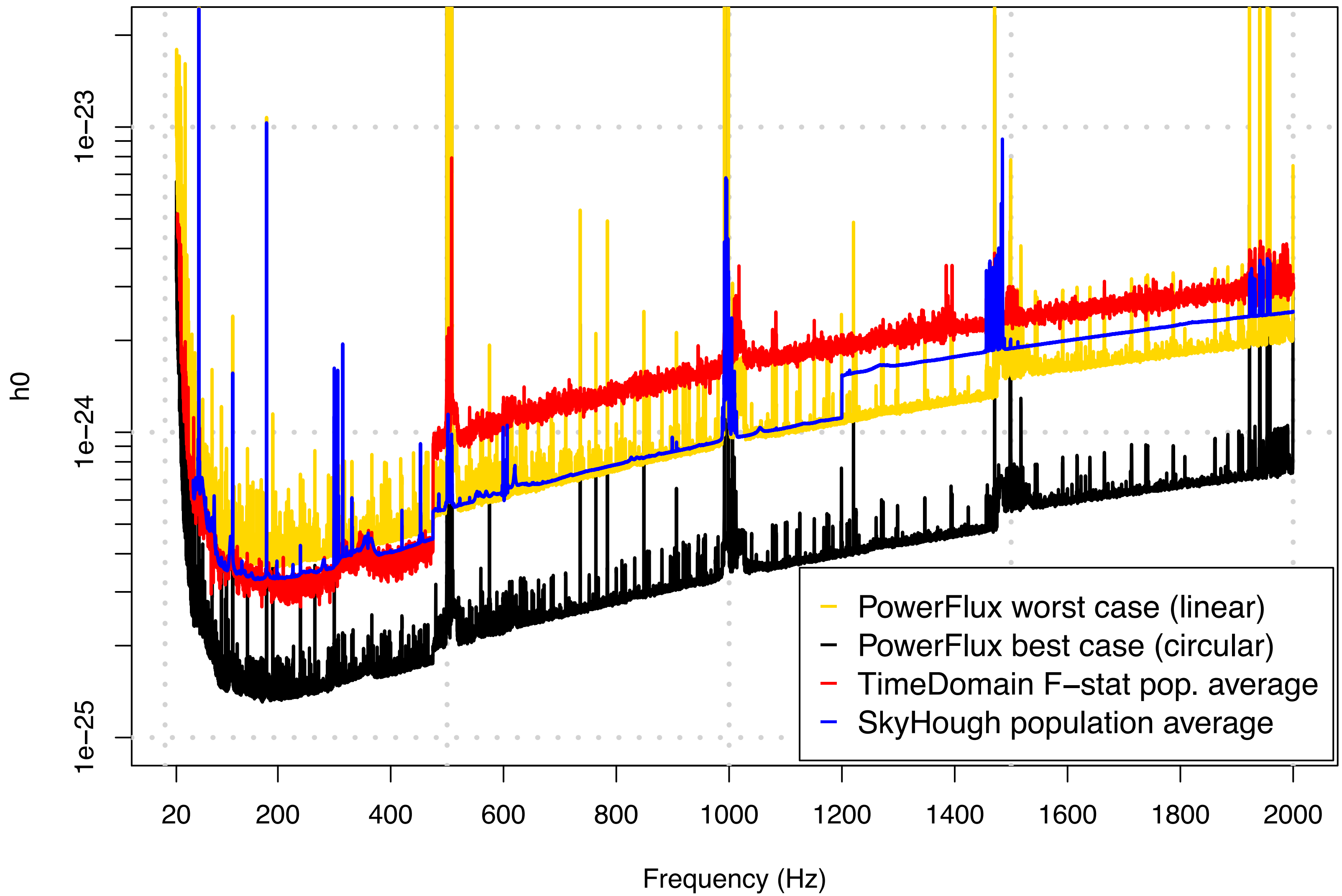
Search methods used in Initial LIGO data:

- Coherent *F*-Statistic (T_{COH} = 10 hours)
  [P. Jaranowski, A. Krolak & B. Schutz, PRD 58 (1998) 063001;
  B. Abbott *et al*., PRD 76 (2007) 082001]
- Stacked power spectra ("stack-slide" & variants) (Tcoh = 0.5-2.0 hours]
  - Stack-slide [P. Brady *et al*., PRD 57 (1998) 2101; P. Brady & T. Creighton, PRD 61 (2000) 082001; B. Abbott *et al*, PRD 77 (2008) 022001]
  - Sky Hough transform [A.M. Sintes & B. Krishnan, JPCS 32 (2006) 206]
  - PowerFlux / Loose coherence [B. Abbott *et al*, PRD 77 (2008) 022001;
    V. Dergachev, CQG 27 (2010) 205017]
  - Frequency Hough transform [P. Astone *et al*., PRD 90 (2014) 042002]
- Multi-segment *F*-Statistic (T_{COH} ~ 1-few days)
  - Coincident *F*-Statistic
    [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]

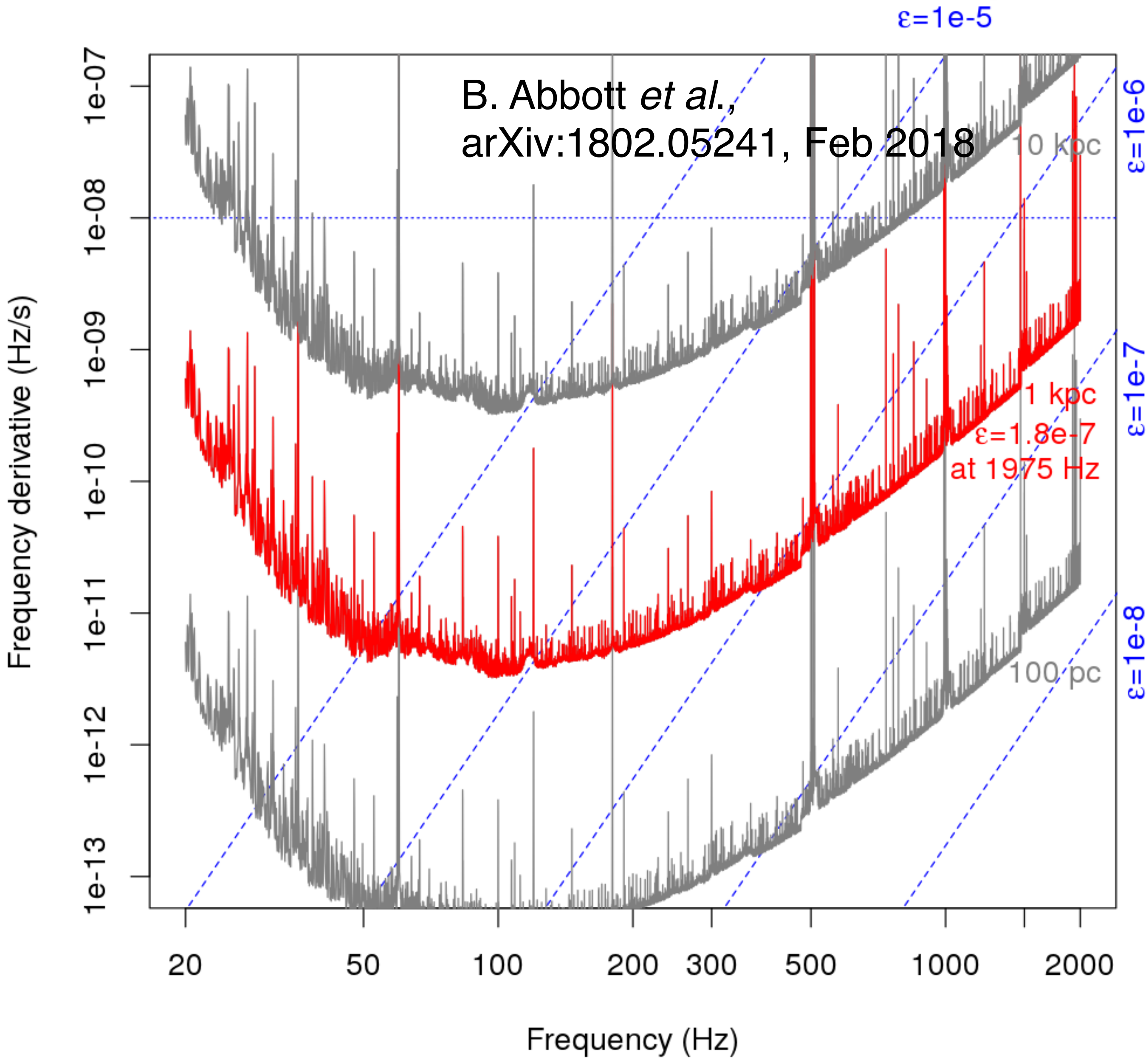
Recent results – All-sky search

[See Alicia Sintes' talk for more details;
& Greg Ashton's talk on outlier follow-up]

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

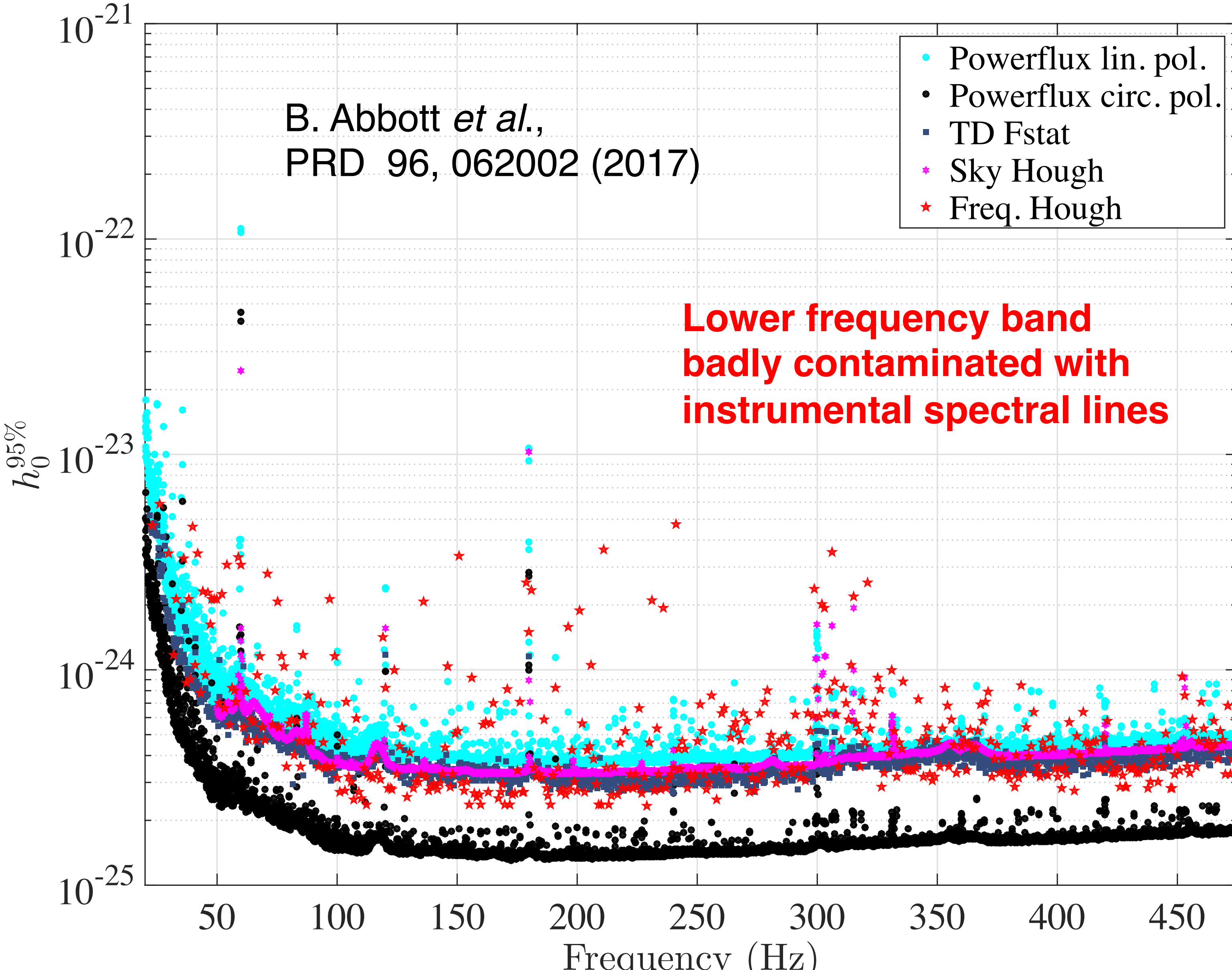


Recent results – All-sky search

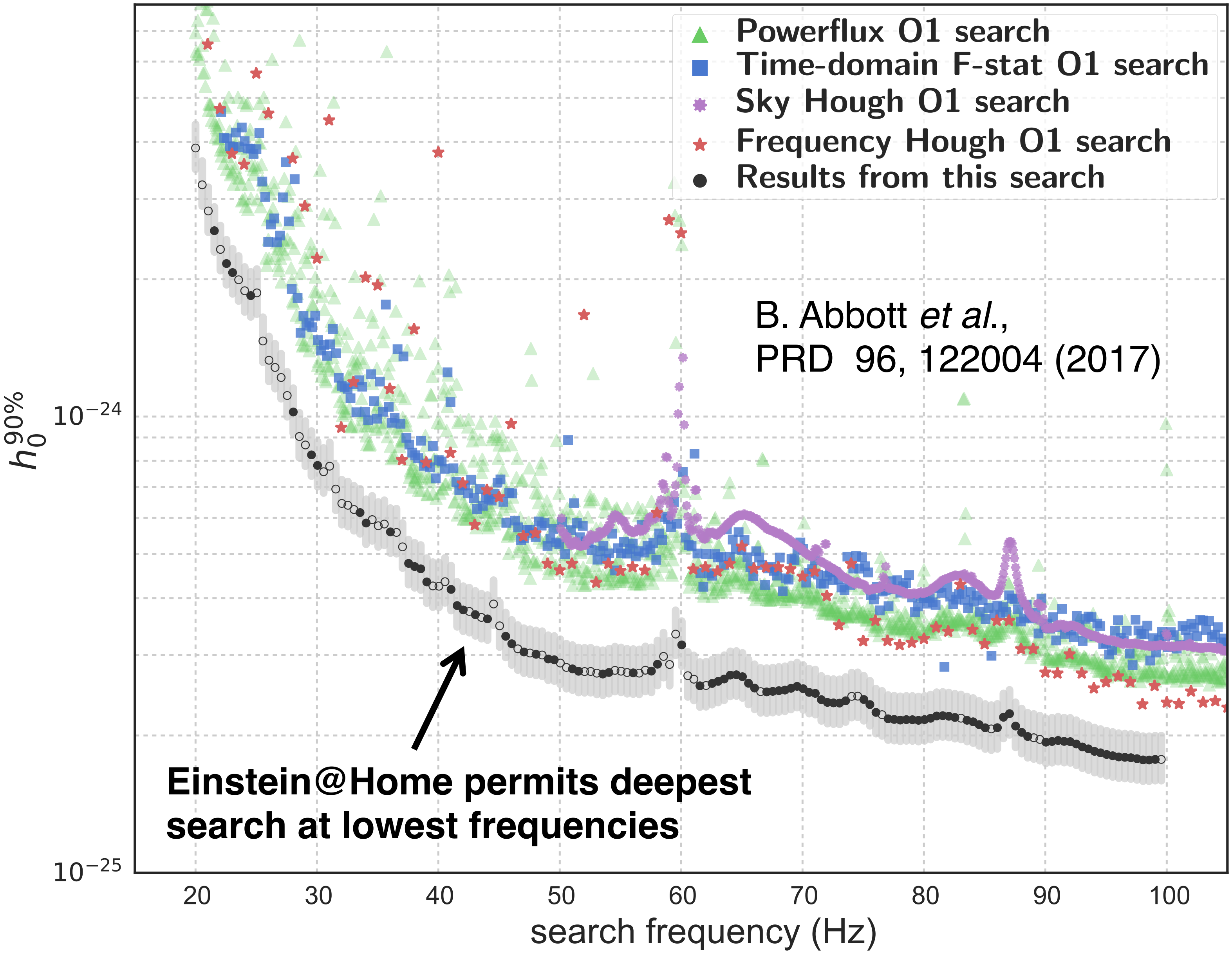


Astrophysical reach for most favorable inclination
-> **Circular Polarization**

Recent results – All-sky search



Recent results – All-sky search



All-sky Searches for Unknown Binary Stars

Search method used in Initial LIGO data:

Double Fourier spectra ("TwoSpect") − similar to semicoherent PowerFlux
[E. Goetz & K. Riles, CQG 28 (2011) 215006;
J. Aasi *et al*., PRD 90 (2014) 062010]

→ Sensitivity tradeoff to cover enormous parameter space is severe

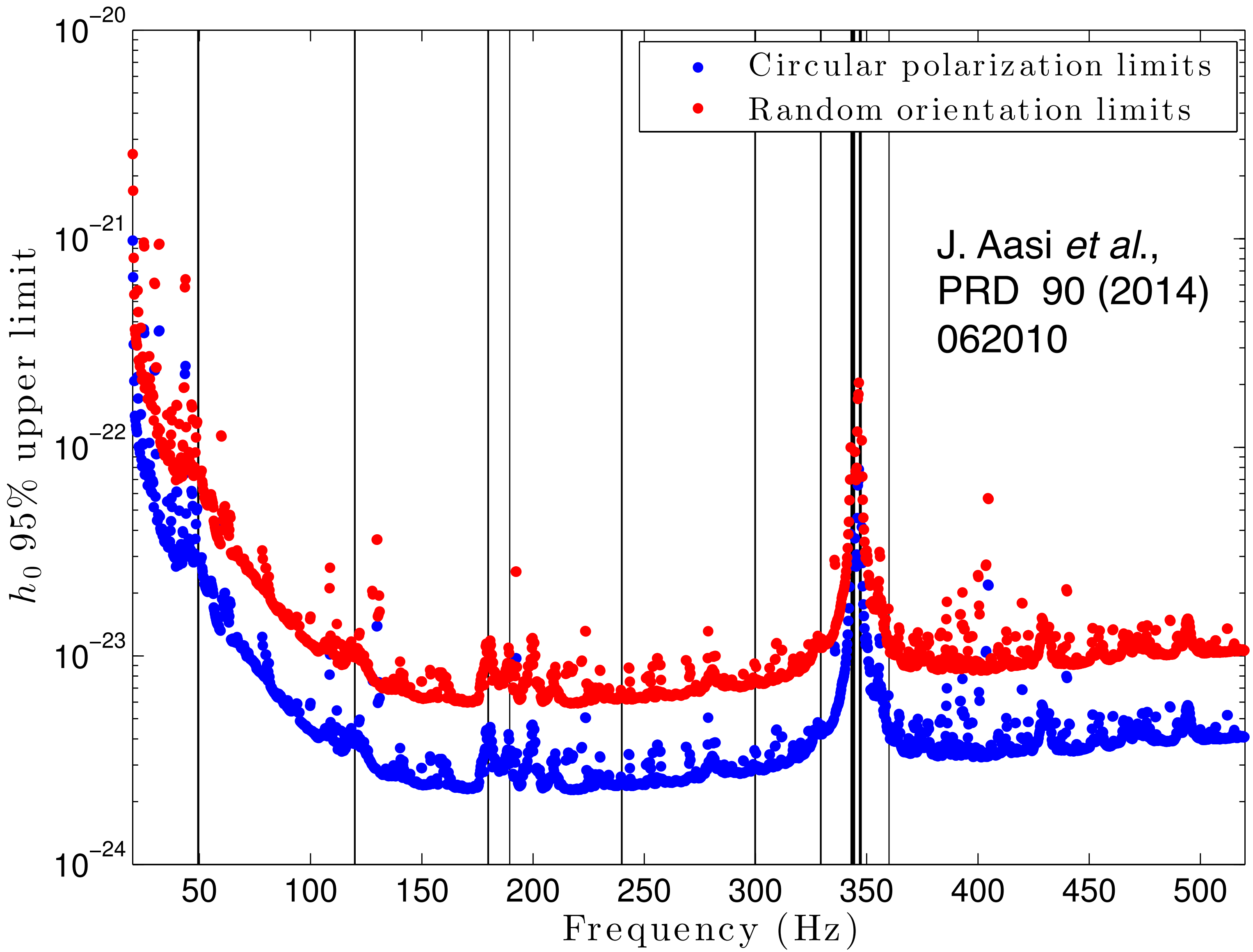
Other algorithms on near horizon or under development

- Radiometer method with sidereal-folded data
  [E. Thrane *et al*., PRD 91 (2017) 124012]

- "Polynomial" method using short-T_{COH} filters and coincidence
  [S. van der Putten *et al*., JPCS 228 (2010) 012005]

- Autocorrelation of spectograms
  [A. Vicere & M. Yvert, CQG 33 (2016) 165006]

Initial LIGO results – All-sky binary search



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., $(T_{OBS})^{1/2}$, $(T_{OBS})^{1/4}$]

Detector sensitivities vary by orders of magnitude over detection band

To make rule-of-thumb comparisons across different searches easier, the CW search group has adopted the notion (R. Prix) of "sensitivity depth"

→ Gives "bottom line" sensitivity of search over given data set w.r.t. noise floor at given frequency:

$$\text{Depth} = [\ h_0\ (95\%\ \text{CL})\ /\ \text{ASD}\ (f)\ ]^{-1} \qquad \text{(Units: Hz}^{1/2}\text{)}$$

→ Sensitive searches have greater depth

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 binary search over 4 months: ~80
- All-sky isolated search over 4 months: ~25
- All-sky binary search over 1 year: ~3

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

Summary

CW searches are diverse in both targets and algorithms
→ Trying to keep our eyes wide open

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

No sure-fire sources known, but some are no-brainers to focus on (Crab, Sco X-1)

Are we missing something entirely?

Badly mis-allocating resources?
(e.g., see Maria Alessandra Papa's talk on allocating computing time more systematically)

Your advice is welcome!

EXTRA SLIDES

Questions from organizers – Monday

- What is the minimum, typical, and maximum ellipticity one should expect? What is the strength (breaking strain) of the crust?
- How does strain evolve in the crust and how does it break?
- What are the implications of observed upper limits on the ellipticity?
- At what point do upper limits become “interesting” (e.g. constrain theory)?
- What are possible mountain building mechanisms (such as asymmetric accretion, temperature gradients, magnetic stress...)?

Questions from organizers – Tuesday

- What are the possible high density solid phases? Which of these are more "likely"? - How would such exotic solids form
- What might their shear modulus and breaking strain be?
- How are the relevant parameters constrained by EM observations?
- How do we use this information to guide CW searches?

Questions from organizers – Wednesday

- What stabilizes r-modes (or saturates the r-mode amplitude at a very low value)? Can the r-mode amplitude be large enough to detect?
- Are there constraints from other observations, e.g. involving too much heating?
- What sets the limit on the spin period of neutron stars in LMXBs?
- What are the best ways to search accreting systems for continuous gravitational waves?
- Do glitches have a gravitational-wave signature?
- How do you sensitively search for systems that may have unknown (spin) glitches?

Questions from organizers – Thursday

- What is the initial spin period of a neutron star?
- Do some kinds of (rare?) SN produce much faster initial spins
- What are young energetic neutron star doing during their first years? Decades? Centuries of life?
- What is the internal magnetic field configuration and how does it evolve?
- What does this tell us about the “minimum” deformation?
- Do neutron stars precess? What implications might this have for gravitational waves?

Questions from organizers – Friday

- What are the ultimate limits of sensitivity (ellipticity) for searches with aLIGO?
- What may be achieved by 3G instruments?
- What are promising directions for nuclear physics and for astrophysics to support continuous GW searches?