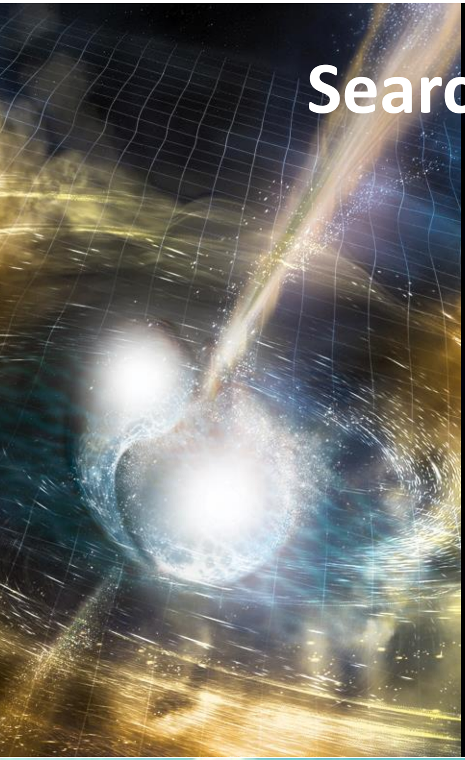
UIB Universitat de les Illes Balears | IAC3 Institute of Applied Computing & Community Code. | LSC LIGO Scientific Collaboration | VIRGO



Searches for signals from unknown or poorly known sources

Alicia M Sintes

Dept. Física & IAC3 - Universitat de les Illes Balears &

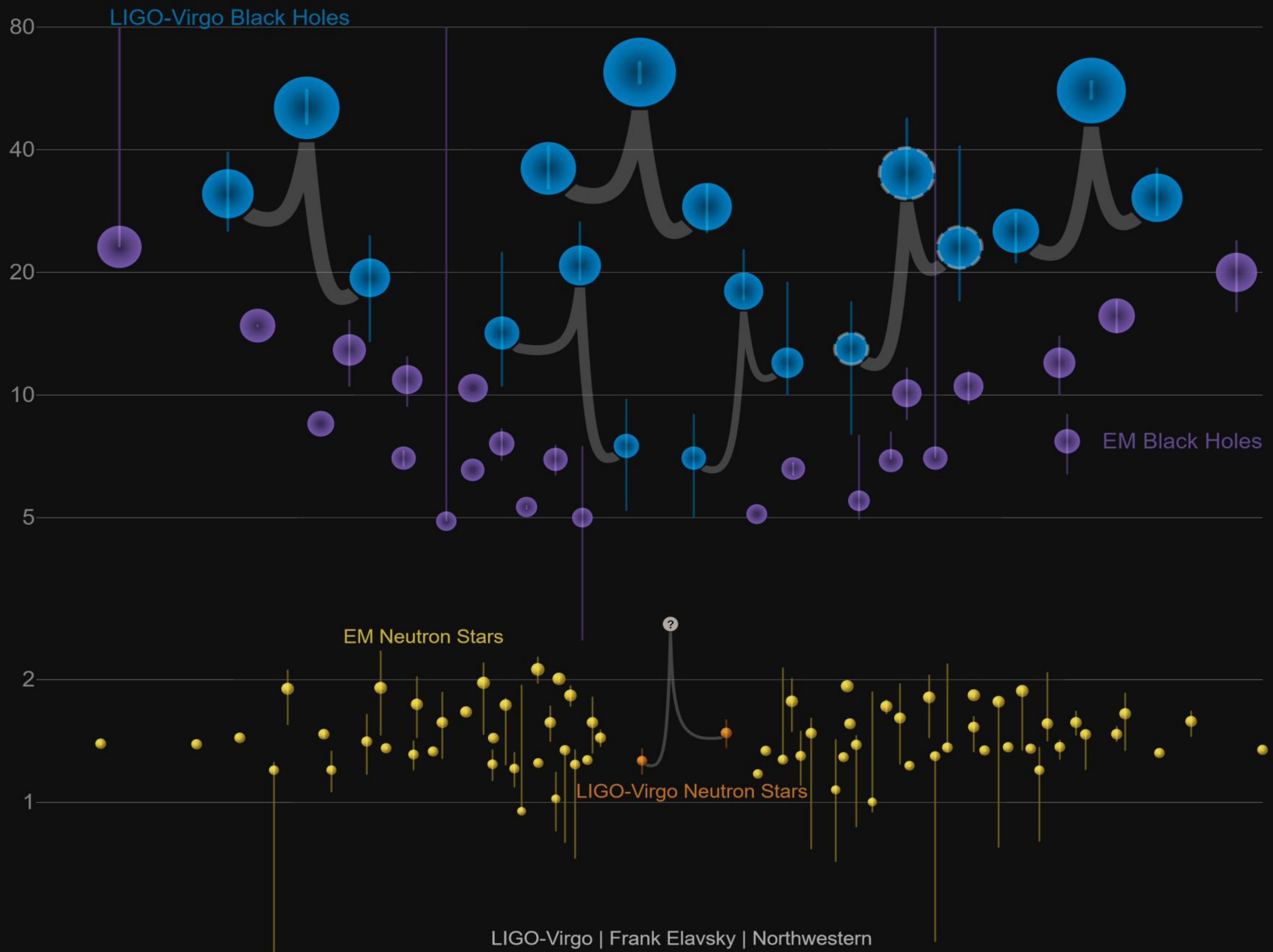
Institut d'Estudis Espacials de Catalunya (IEEC).

For the LIGO Scientific Collaboration and Virgo Collaboration

LIGO-G1800775

Masses in the Stellar Graveyard

in Solar Masses



LIGO-Virgo | Frank Elavsky | Northwestern

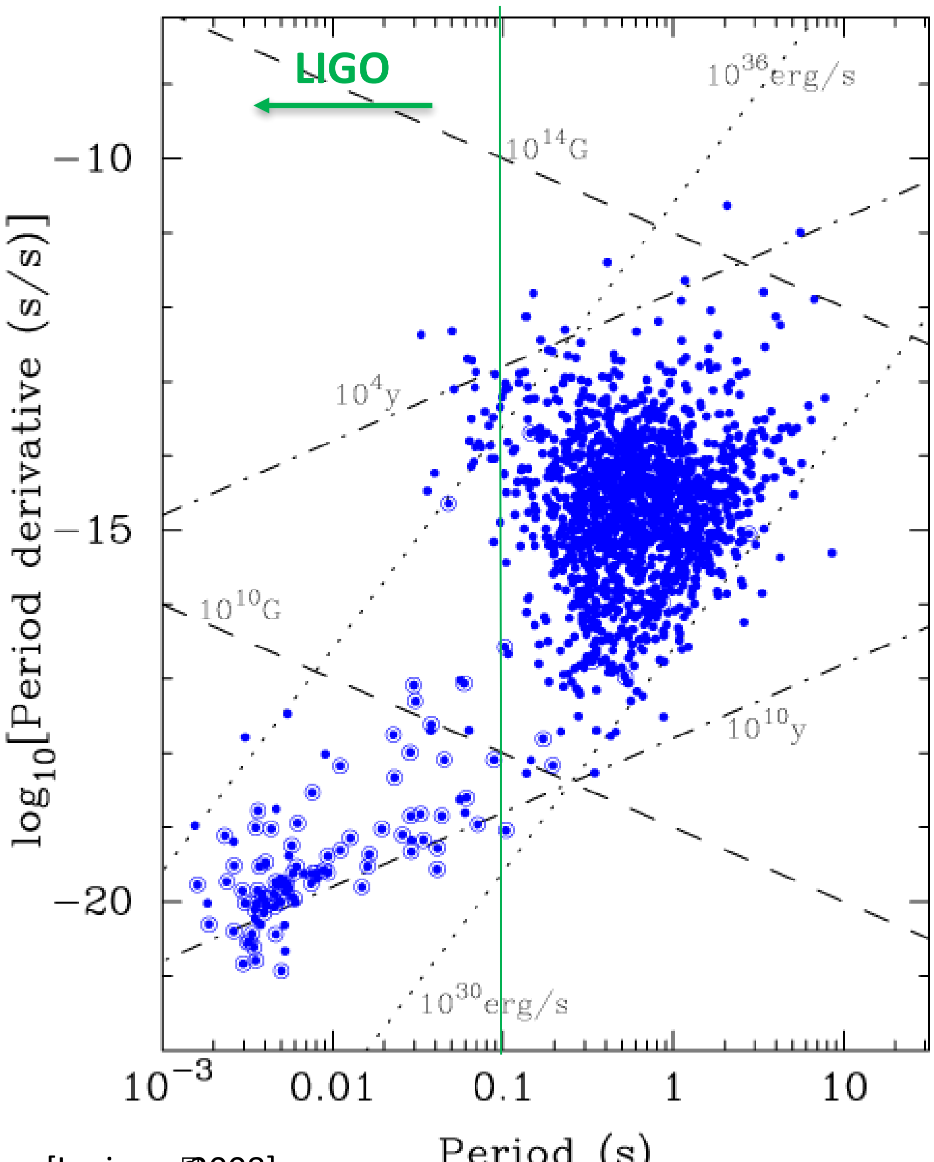
No continuous gravitational waves (CW) detected… yet!

- Source emitting nearly monochromatic sinusoidal waves
- Signal is weak, but persistent over years of data taking
- Most searches begin *after* an observing run has ended, and all the data is in
- Still analysing LIGO O1 & O2 data
- Strict emission limits have already been set from initial detector era data on signals from known and unknown neutron star sources.

Content

- ❖ **Blind all-sky Searches**
- ❖ **Search for signal of post-merger remnant from GW170817**

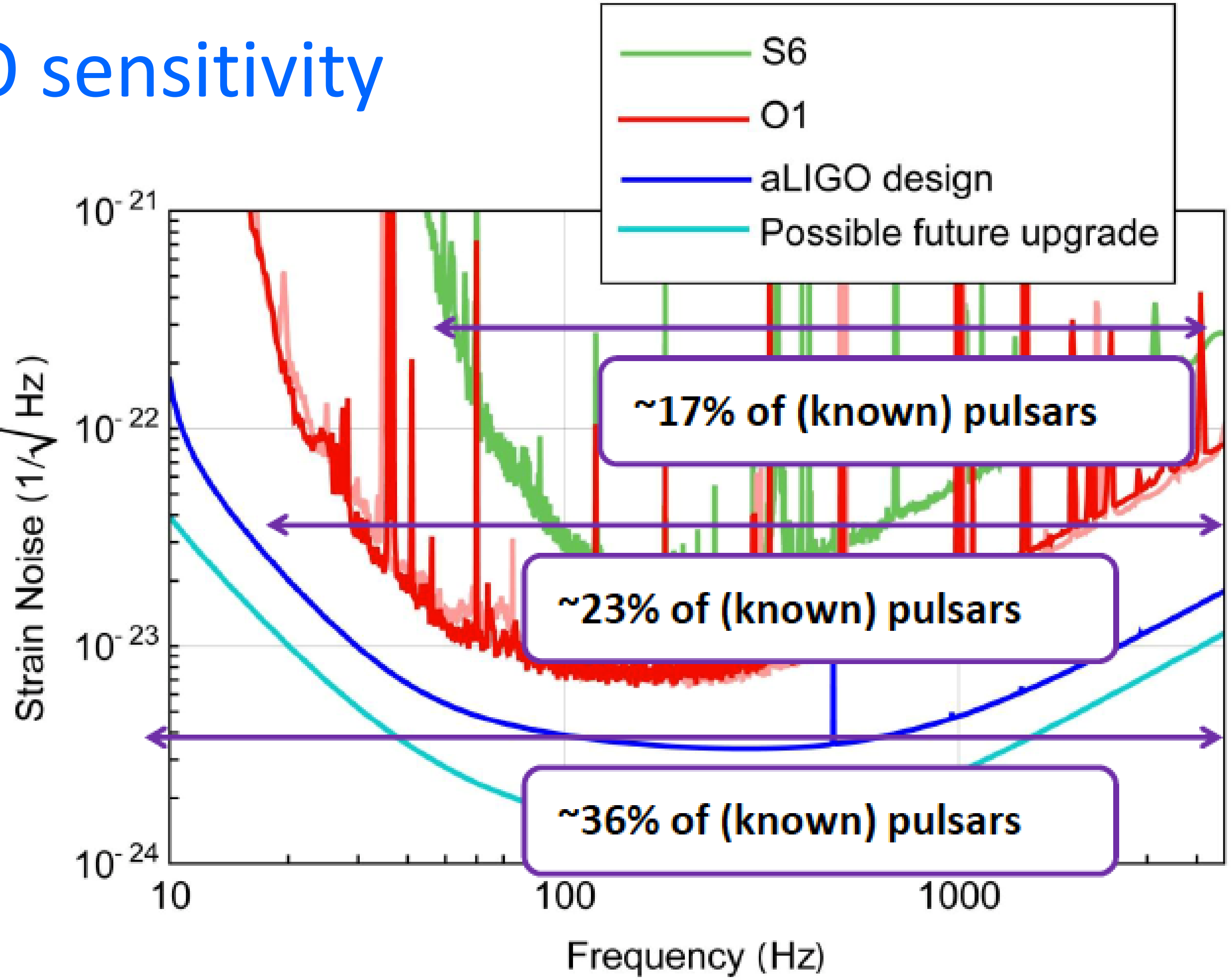
Searching CW signals



[Lorimer, 2008]

- There are a few thousand known pulsars
- 40,000 millisecond pulsars in our galaxy [Lorimer, Living Rev. Relativity, 11 2008]
- O(10^6 – 10^7) undiscovered EM quiet NS within 5kpc [Narayan. *ApJ*, 1987]
- Potential to discover off-axis pulsars or gravitars

aLIGO sensitivity



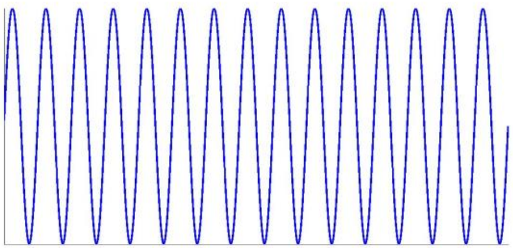
B.P. Abbott et al., *PRL* **116**:131103 (2016)

We have no idea how many signal detections to expect in first years of aLIGO/AdV.

Advocate for better modeling of neutron star deformation to enhance science case?

The Signal from a NS

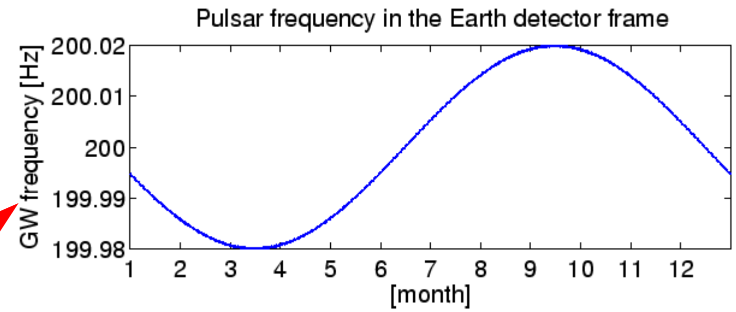
At the source

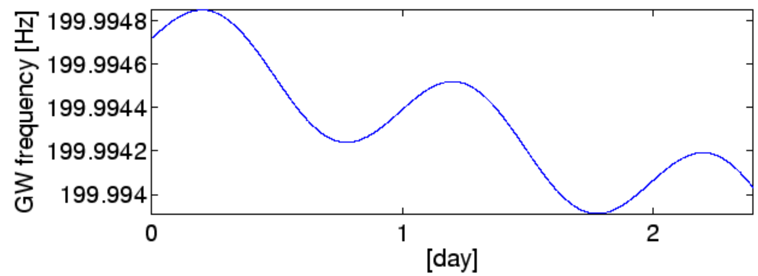


Spin-down ⇒ phase evolution

- Annual variation: up to ~10^{-4}
- Daily variation: up to ~10^{-6}

At the detector





Frequency modulation + amplitude modulation

… more complications for GW signals from pulsars in binary systems

Additional Doppler shift due to orbital motion of neutron star

Varying gravitational red-shift if orbit is elliptical

Shapiro time delay if GW passes near companion

Continuous Waves Searches (1)

These searches have several parameters:

May be known, used in the search:

position

frequency,

frequency derivatives

orbital parameters

Not explicitly searched for:

initial phase

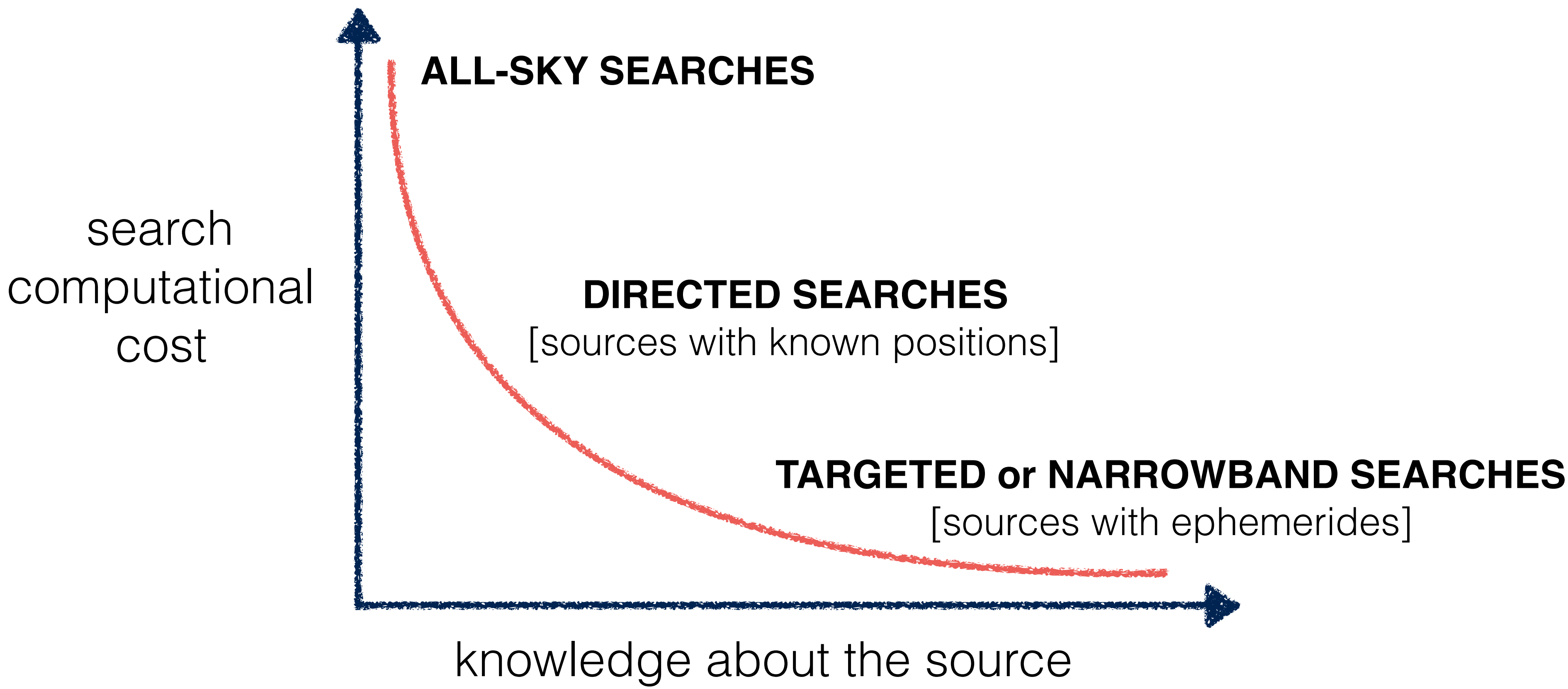
inclination angle

polarization

amplitude

Different algorithms have been developed, depending on what we know about the source: source parameters knowledge, waveform knowledge, isolated or binary system sources etc.

Types of CW searches



Continuous Waves Searches (2)

- Detection of signals from a single target :
  - Compute correlation with known waveform. Analyze significance.

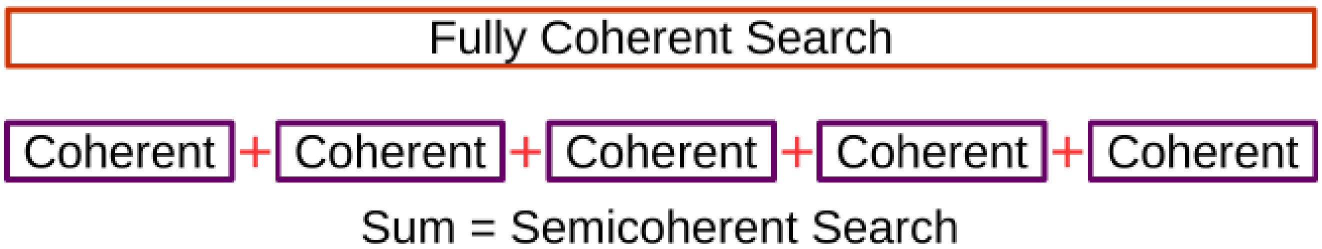
  This procedure is not computationally limited

- Blind search of large datasets:
  - *Sweep large area of parameter space*
  - Use *carefully chosen algorithm* for signal detection
    - **Number of distinct sky location scales like $f^2 T_{coh}^2$**
    - **For isolated NS computing cost scales as T_{coh}^{6+} without 2nd frequency derivative!**
    - **Limits Coherent *F*-Statistic** (T_{coh} ~ 1-few days)
  - Pure Gaussian noise triggers events at 6σ level. Real data produces >7σ artifacts
  - Computation efficiency becomes as important as statistical efficiency.
  - **All-sky survey at full sensitivity not possible**

- The cornerstones of CW searches are:
  - sensitivity
  - robustness with respect to signal uncertainties and instrumental noise
  - computational load

Semi-Coherent Methods

split data of length T into N_{seg} segments of length T_{seg}
+ combine coherent results by summing:



less sensitive for same amount of data, but much faster!

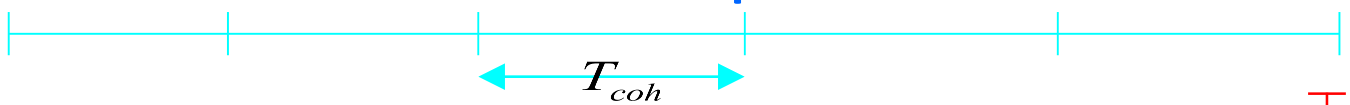
☞ allows analysing all the data

☞ more sensitive at fixed computing cost if $\Delta(\text{sky}, f, \dot{f}, \ldots) > 0$

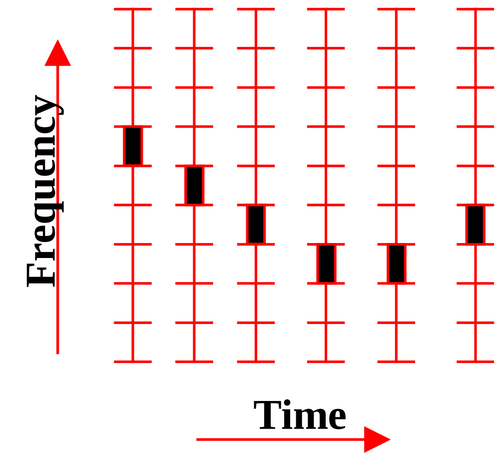
[+] maximize sensitivity (template banks, N_{seg}, T_{seg}) at fixed cost

[+] maximize computing power: clusters, GPUs, Einstein@Home

Semi-coherent power-sum methods



- The idea is to perform a search over the total observation time using a *semi-coherent* (sub-optimal) method.
- Several methods have been developed to search for cumulative excess power from a hypothetical periodic gravitational wave signal:



Stacked power spectra

- Based on FT each segment (T_{coh} ~ 0.5-2.0 hours) from h(t),
- Examining successive spectral estimates, tracking the frequency drifts due to Doppler modulations and df/dt as the incoherent step.
  - **Raw spectral powers:**
    Stack-slide (Radon transform),
    Power-flux, Loose coherence
  - **Thresholded powers** (Robust pattern detection technique)
    Frequency Hough transform ,
    Sky Hough transform

$$\mathrm{SNR} \propto \frac{h_o}{\sqrt{S_n}} \mathrm{T_{coh}}^{\frac{1}{2}} \mathrm{N_{seg}}^{\frac{1}{4w}},$$

$w(N_{seg}, pFA)$ range [1, ↑ 3.5]

[Prix & Shaltev, PRD85, 2012]

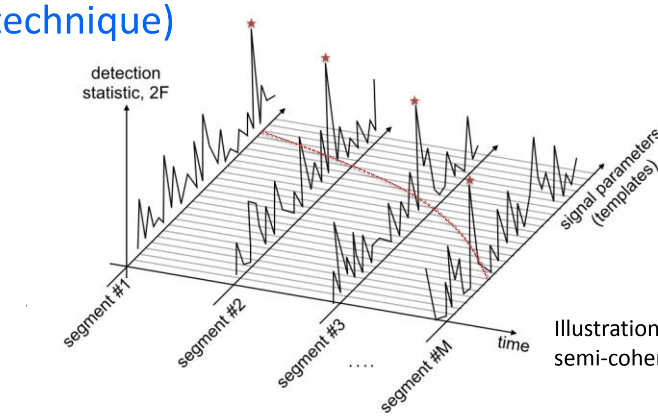
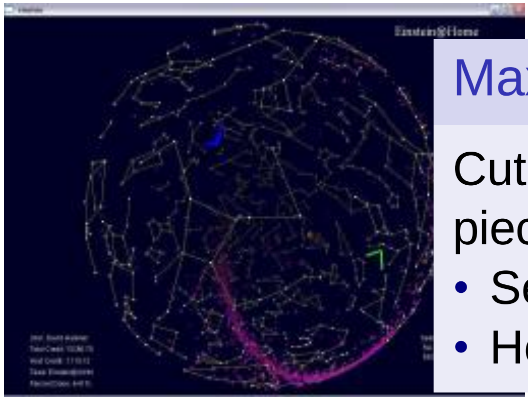


Illustration of stack-slide semi-coherent method

Multi-segment Demodulated spectra – F-Statistic
(T_{coh} ~ 1-few days)

- Coincident *F*-Statistic
- Stacked *F*-Statistic (Einstein@Home)



Maximize available computing power

Cut parameter-space $\Delta(\text{sky}, f, \dot{f}, \ldots)$ into small pieces

- Send these “workunits” to participating hosts
- Hosts return finished work and request next

- Public distributed computing project, launched Feb. 2005
- $\sim$100,000 participants, $\sim$5 PFlop/s (24x7)
- All-sky and directed CW searches
- Workunits run $\sim 6 - 12\,\text{h}$ on hosts
- Typical search runs $\sim 3 - 12$ months on E@H

\+ You can sign up and help! https://einsteinathome.org

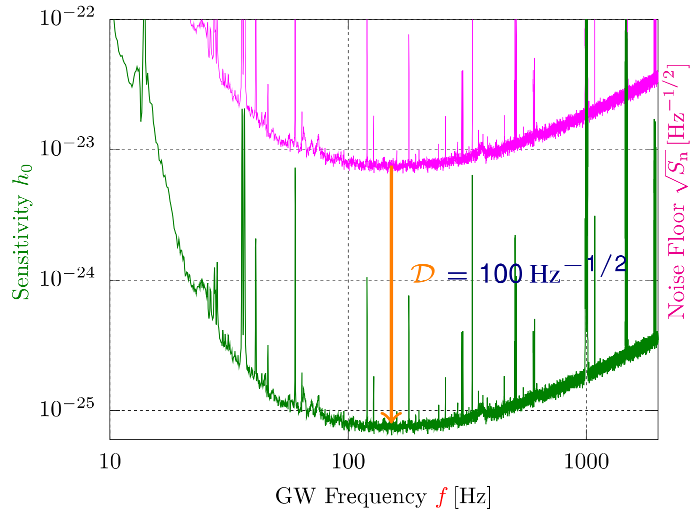
Sensitivity Depth $\mathcal{D}$ of a CW search

Sensitivity / Upper Limit $\equiv$ Smallest detectable $h_0|_{\text{p-value}=1\%}^{\text{confidence}=90\%}$

Depends on

- data quality: PSD $S_n(f)$
- search method ☞ constant sensitivity depth $\mathcal{D}$

$$h_0(f) = \frac{\sqrt{S_n(f)}}{\mathcal{D}}$$



Examples:

- Fully-coherent search, 2 years of data from 2 detectors: ☞ $\mathcal{D} \sim 1000\,\text{Hz}^{-1/2}$
- Semi-coherent all-sky search over $f, \dot{f}$: ☞ $\mathcal{D} \sim 20 - 50\,\text{Hz}^{-1/2}$

O1 all-sky searches

Fast turnaround, broad, robust

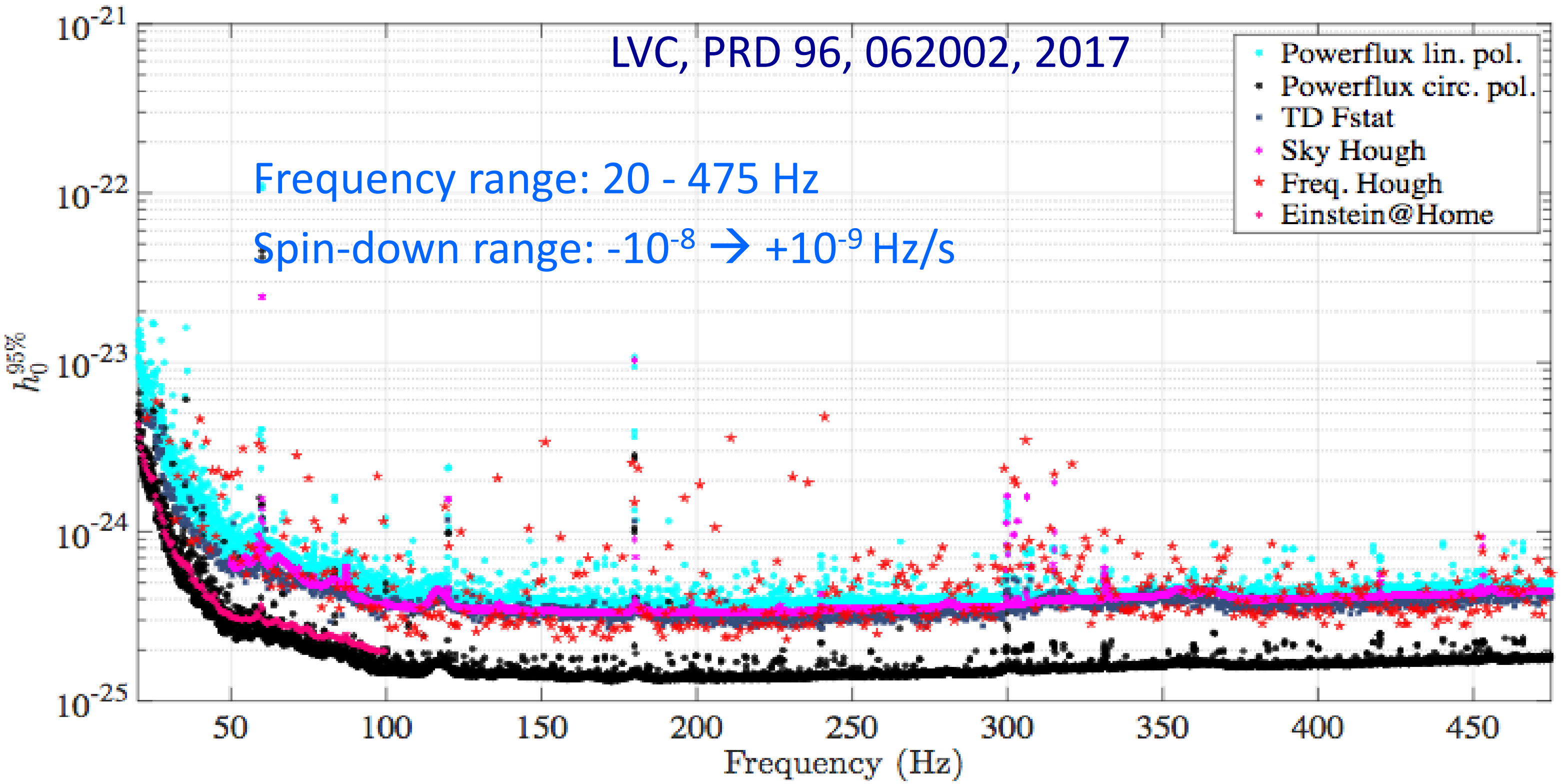
- Two searches: 20 – 475 Hz , 475 – 2000 Hz
  [-10,+1] x 10^{-9} Hz/s
- Four pipelines: PowerFlux, time- domain F-statistic, Sky Hough and Frequency Hough

Computational intensive, more sensitive

- 20 – 100 Hz
  [-2.6, 0.3] x 10^{-9} Hz/s
- Einstein@Home

Spindown range implies limit on ages searched

O1 all-sky fast turnaround searches



Four pipelines: PowerFlux, time-domain F-statistic, Sky Hough and Frequency Hough

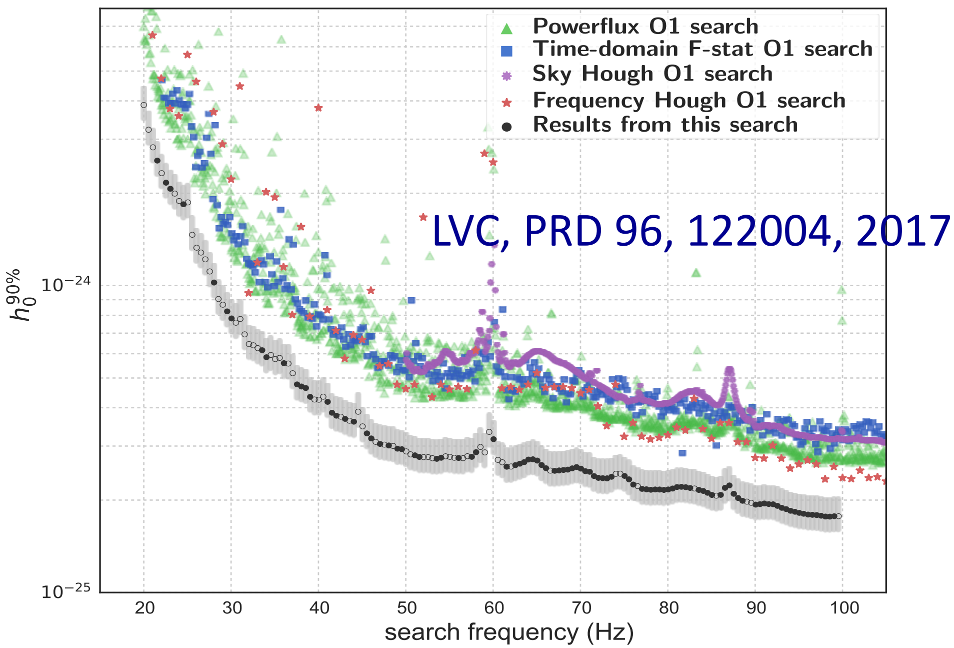
No candidate survived the follow-up.

Significant improvement in the ULs with respect to past analyses (> 3x)

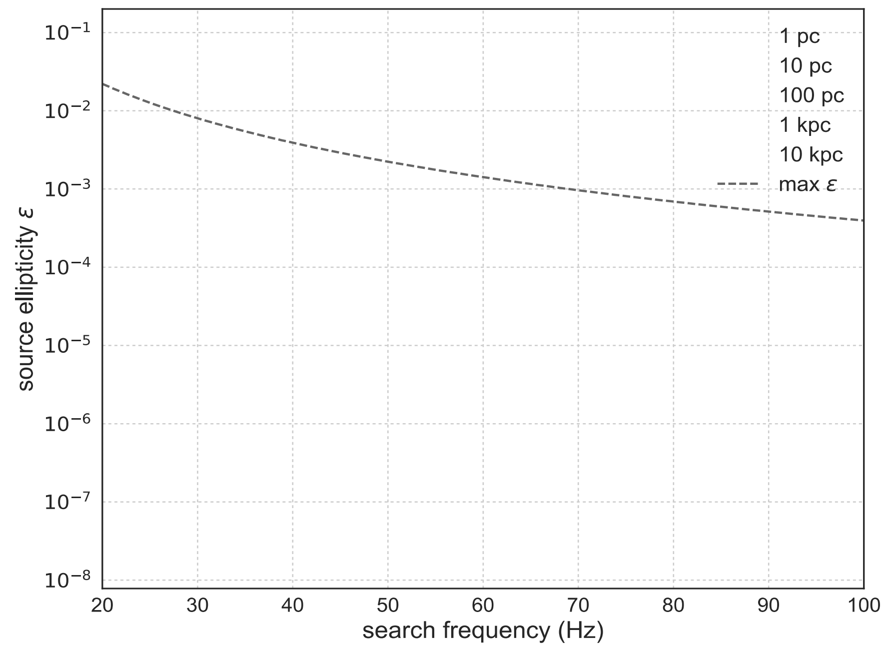
Best limits on h_0 of 1.5×10^{-25} (optimal source spin orientation) near 170 Hz

At 475 Hz sensitive to NS with ellipticity $\varepsilon > 8 \times 10^{-7}$ as far as 1kpc, for optimal spin orientation

O1 all-sky Einstein@Home search



LVC, PRD 96, 122004, 2017



Search ranges: f : [20, 100] Hz, spin-down: [-2.6, 0.3] x 10^{-9} Hz/s

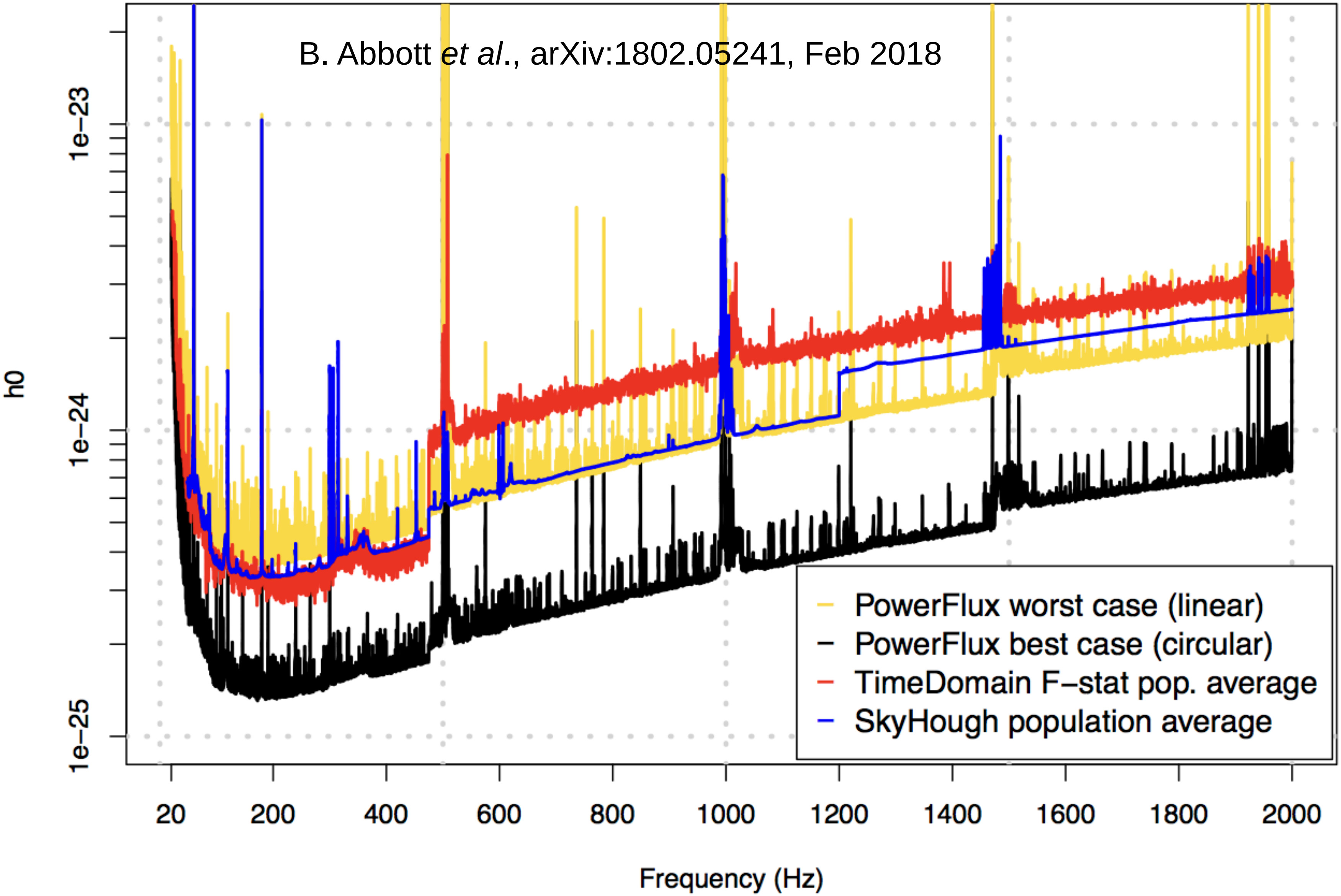
N_{seg}=12, T_{coh}= 210h= 8.8 d ☞ 3x10^{17} templates

Best limits on h_0 of 1.8 x 10^{-25} (marginalised) near 100 Hz

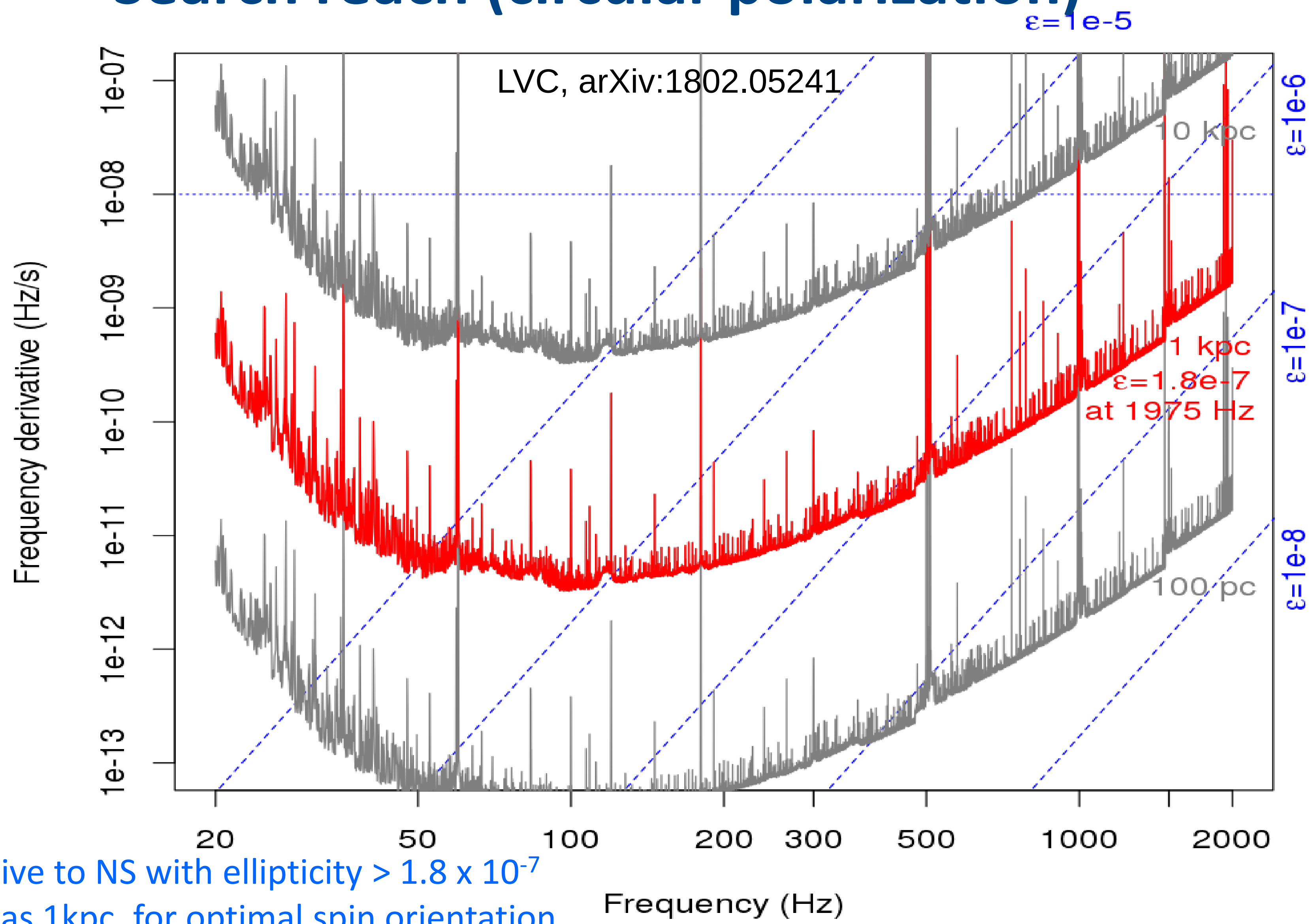
Sensitivity Depth *D*~49 Hz^{-1}

At 55Hz, exclude sources with ellipticity above 10^{-5} within 100pc

O1 full band all-sky search



Search reach (circular polarization)



Sensitive to NS with ellipticity > 1.8×10^{-7}
as far as 1kpc, for optimal spin orientation

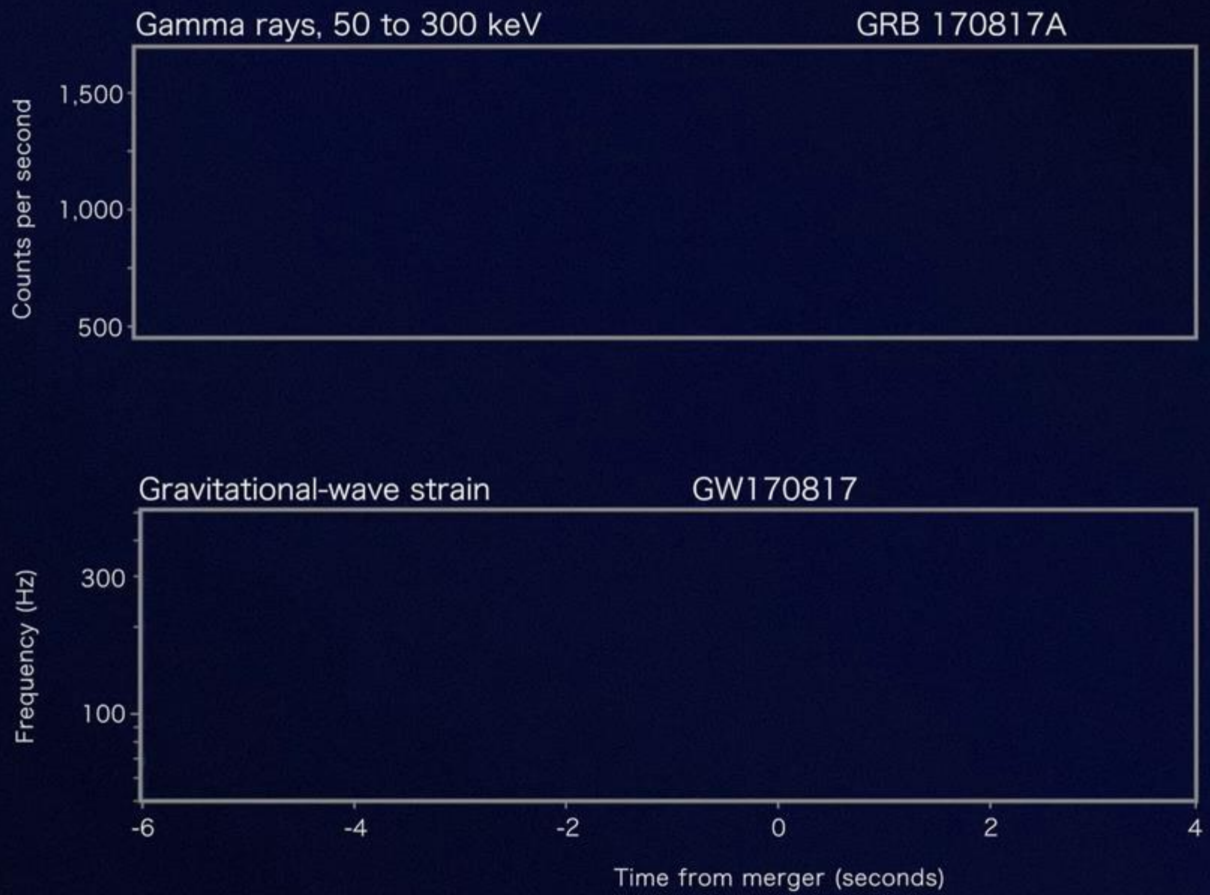
GRB 170817A - GW170817:

Coincident Detection with Gravitational Waves and Gamma Rays.

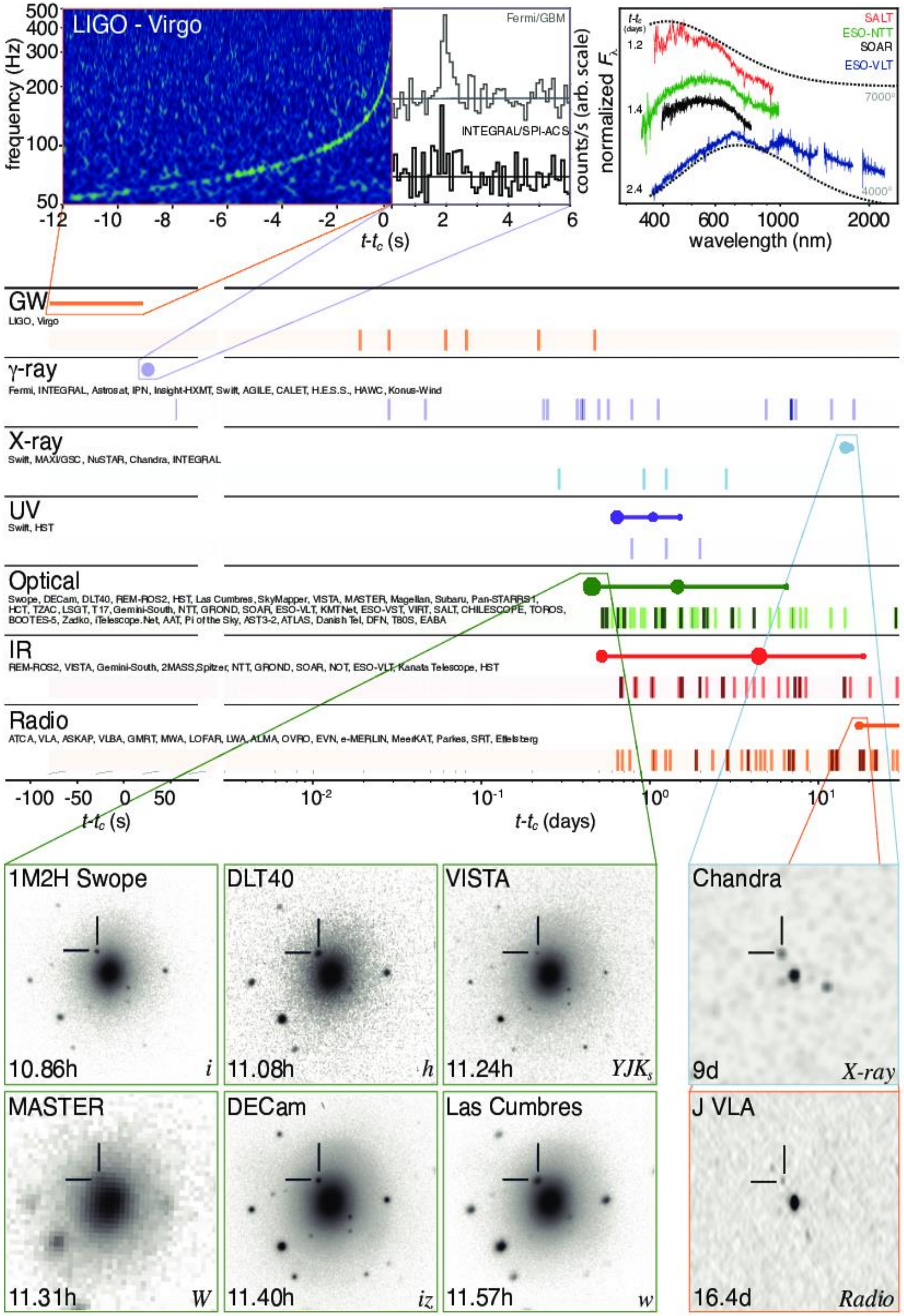
LIGO and Virgo and partners make first detection of gravitational waves and light produced by colliding neutron stars

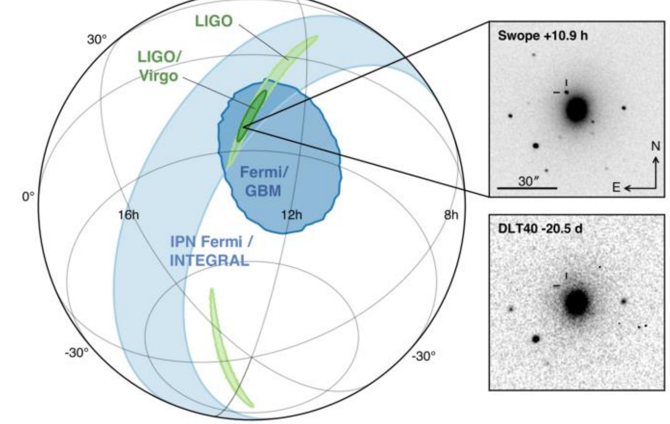
Fermi

LIGO



Credit: NASA GSFC & Caltech/MIT/LIGO Lab





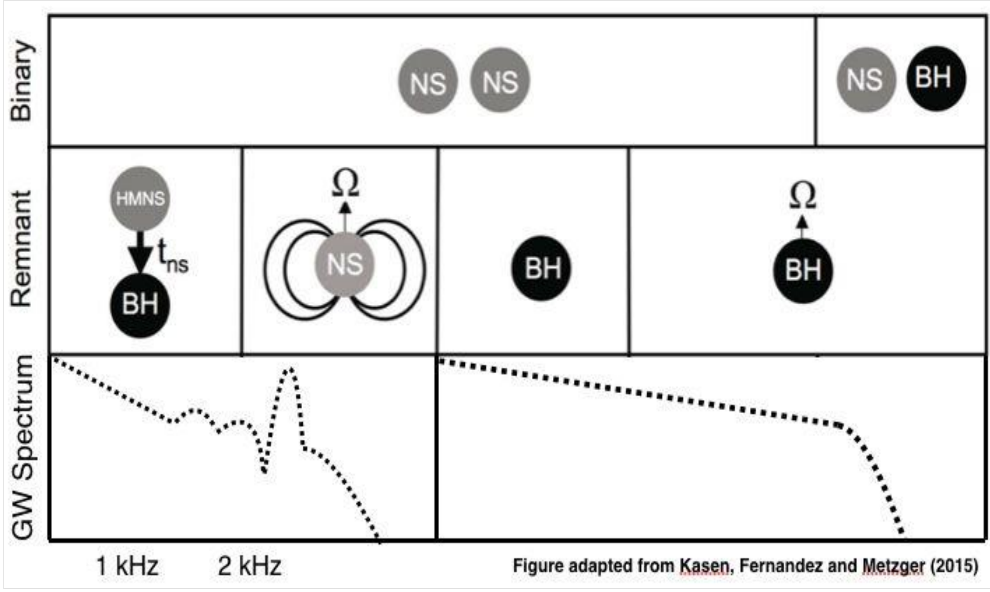
Post-merger remnant from GW170817

Challenges for longer-duration search:

- Unknown GW emission frequency and (rapid) signal evolution
- Distance is far for traditional CW searches $d = 40^{+8}_{-14}\,\mathrm{Mpc}$

Detection unlikely, but worth developing the searches, verify expectations & determine future prospects.

Post-merger Scenarios



Theoretically, the end-product of a BNS merger can be (depending on the remnant mass and EOS):

- Prompt collapse to a BH (BH ringing >6 kHz)
- Unstable hypermassive NS, supported by differential rotation and thermal pressure
  → Collapse after 10-100 ms
- Supramassive, metastable NS, supported by centrifugal force
  → Collapse after O(10-10000 s)
- **Stable remnant NS** (t_{GW}~100 ms, minutes-weeks+)

GW emission from the remnant

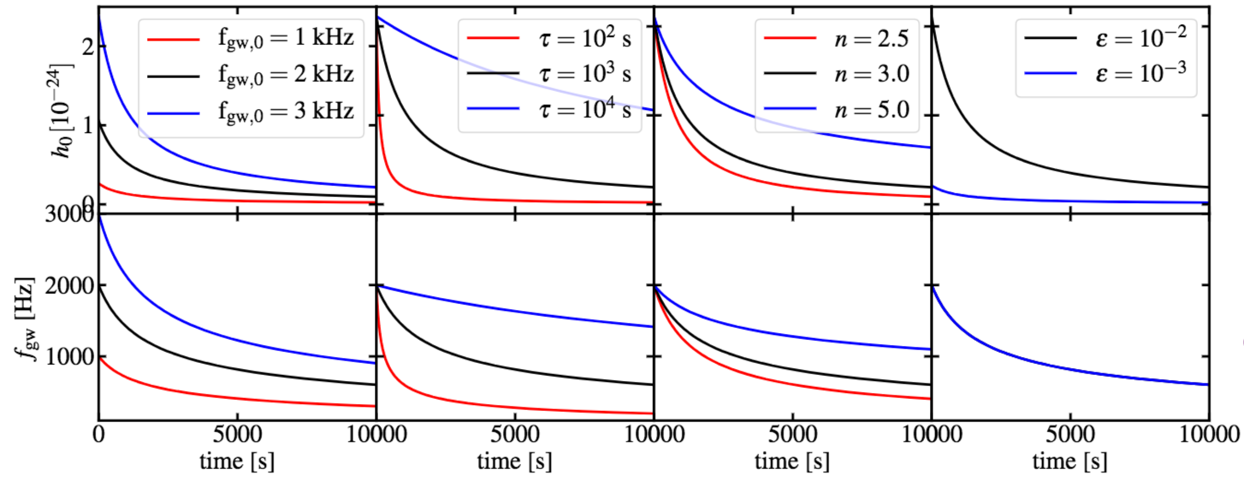
The newborn NS may emit a "transient" GW signals due to:

- the formation of a millisecond magnetar
  (e.g. Giacomazzo+, 2013, 2014; Dall'Osso+, 2012; Lü+, 2015; Rowlinson+, 2013; Gompertz+, 2013, 2014)

- the development of dynamical or secular instabilities, like r-modes or bar-modes
  (e.g. Andersson, 1998; Lindblom, 1998; Corsi+, 2009; Passamonti+, 2013; Doneva+, 2015)

- ?

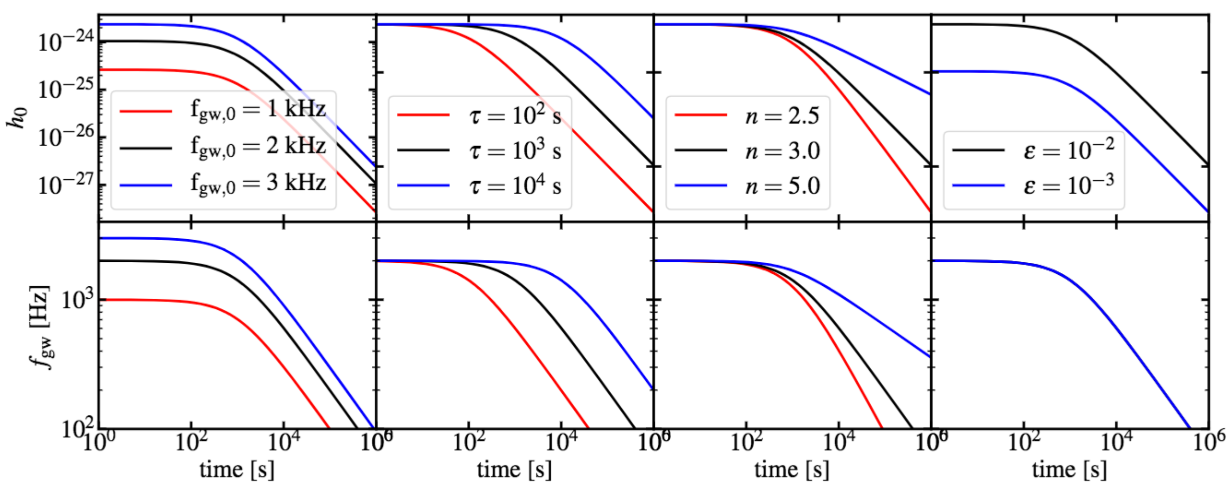
Magnetar-like emission waveform examples



Periodic signal with power law frequency evolution

$$\dot{\Omega} = -k\Omega^n$$

depending on the braking mechanisms



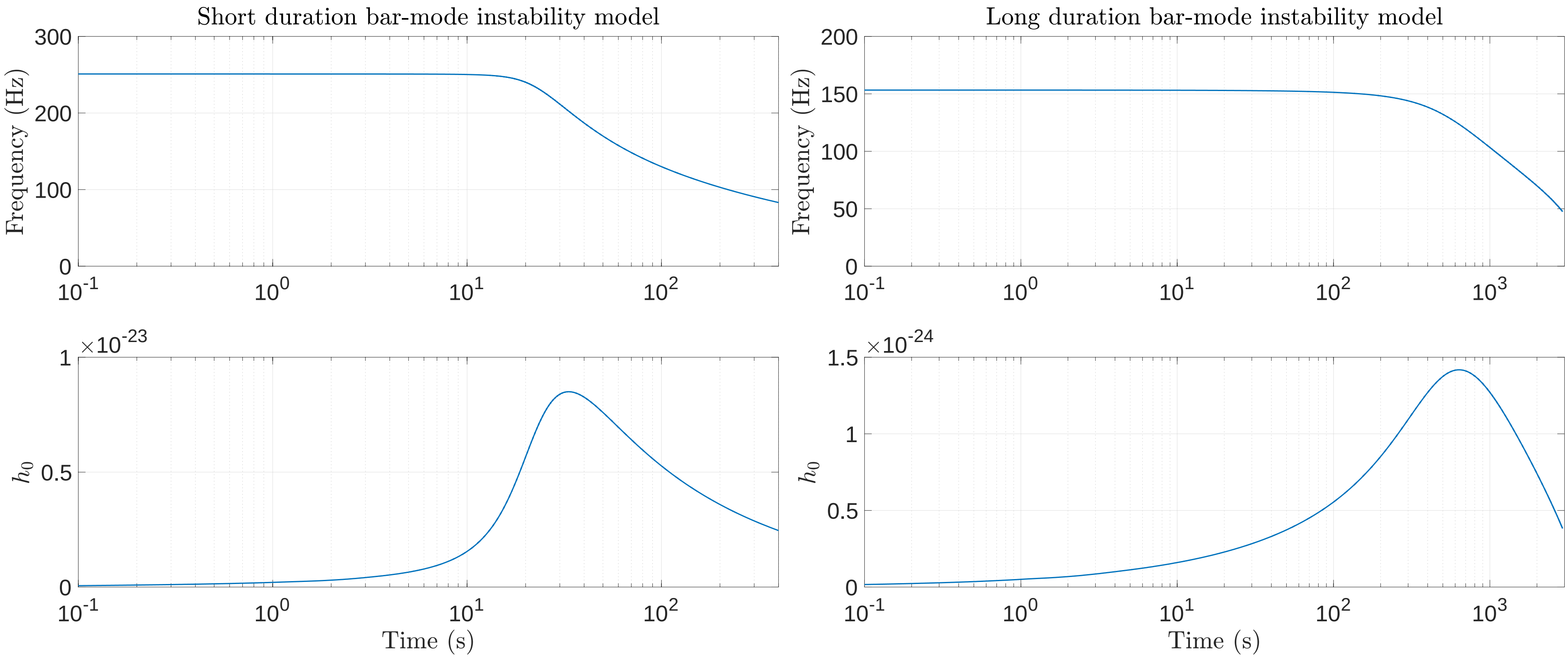
GW contribution to the spin-down cannot be excluded

Due to fast spin-down the GW signal frequency may become too small after hours-days

Lasky, et al., LIGO-T1700408

Bar-mode instability model waveform examples

Dynamical and secular, with different time scales, depending on the ratio between kinetic and gravitational binding energy



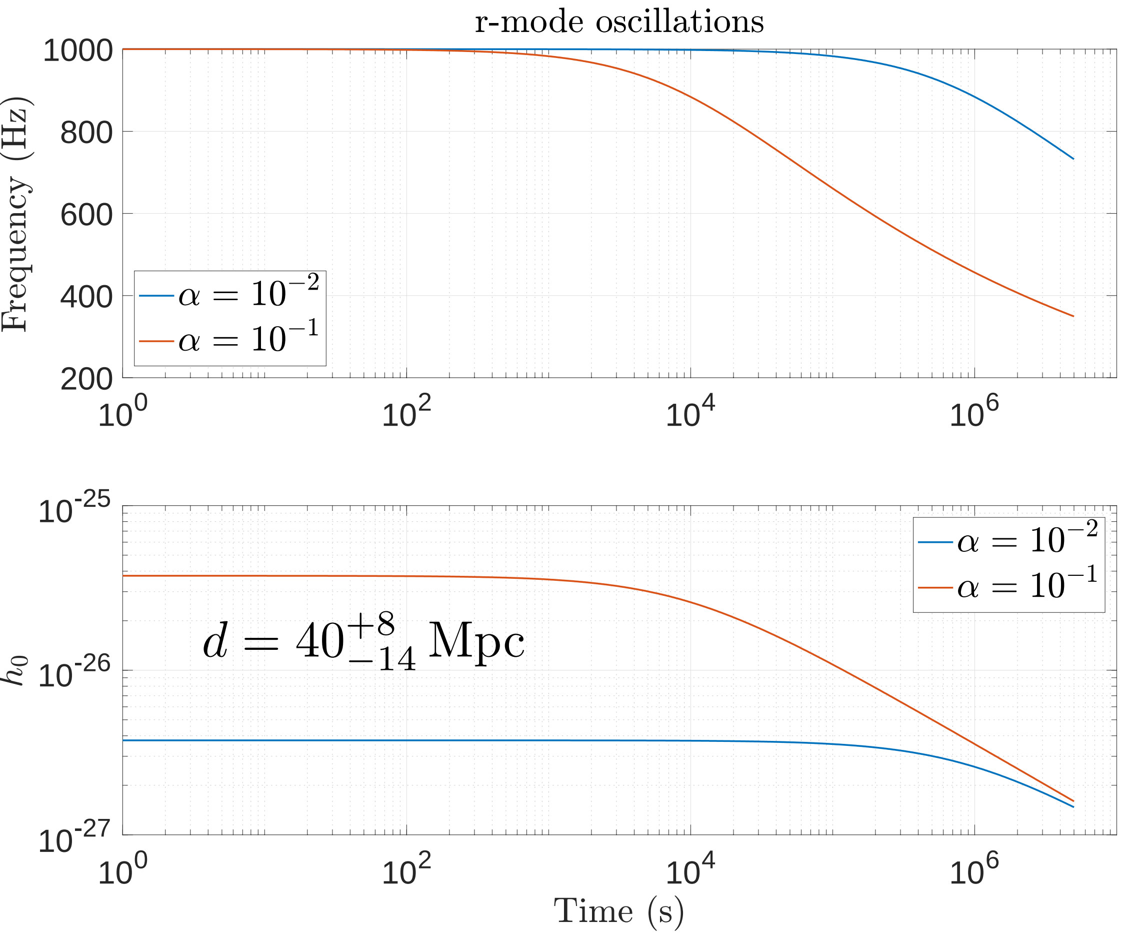
"Typical" GRB magnetar: 1.4 Msun, 20 km radius, 1e14 G, n = 1

Corsi & Meszaros 2009

Coyne et al. 2016

R-mode instability

(e.g. Haskell, 2016 for a review)



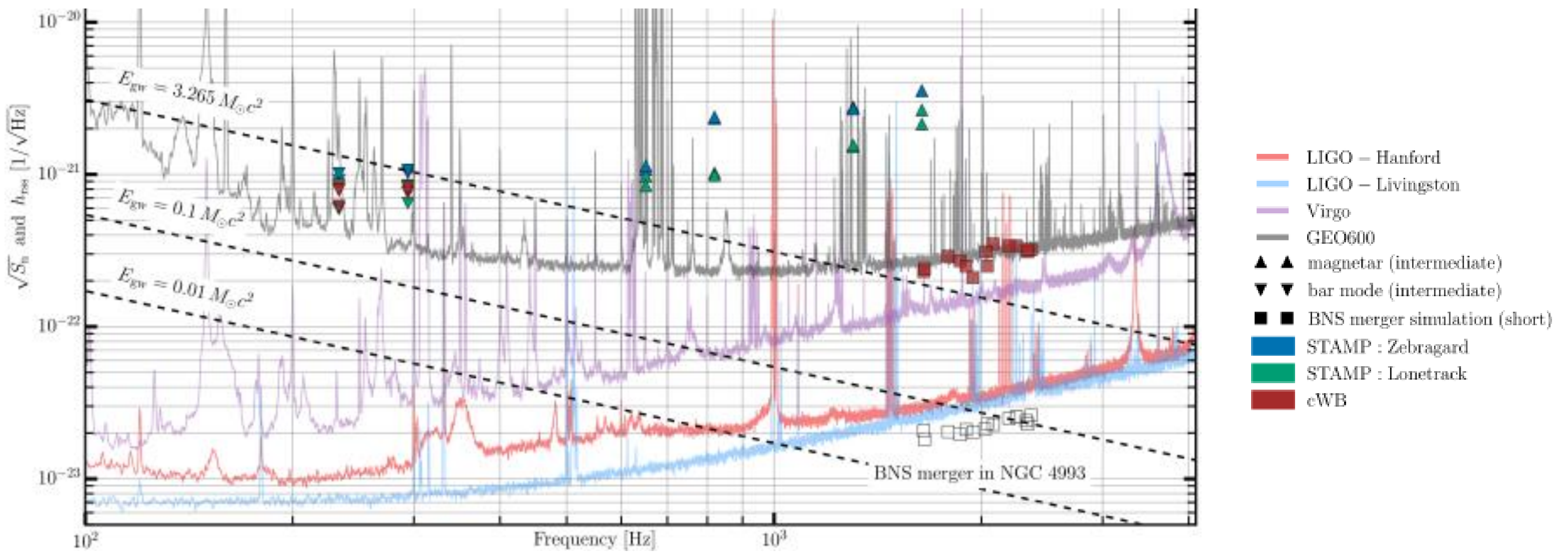
- GW frequency ~4/3 f_{rot}.
- Frequency evolution described by a power law with braking index n=7;
- r-mode saturation amplitude depends on NS EOS
- GW signal time scale O(hours-days)

Mytidis, et al. 2015 ApJ 210 27

Short-duration remnant searches

LVC, ApJL 851 (2017) sets upper limit for short (<1 s) and intermediate (<500 s) duration post-merger signals for GW170817

- Two pipelines (cWB, STAMP), based on excess power in time-frequency:
  - cWB burst analysis (. 1s 1–4 kHz HL and . 1000s 24–2048 Hz HLV)
  - STAMP directional stochastic analysis (500 s maps, 24–4000 Hz HL)



- CW pipelines not involved
- At least a factor of 10 above model predictions

Long-duration remnant searches

- Predictions rule of thumb: "Signals detectable up to ~20-25 Mpc in Advanced LIGO-Virgo detectors, **assuming matched filtering**".
- In general, of course, we cannot use matched filtering as we do not know signal parameters in advance.
- We must rely on semi-coherent or un-modeled methods, which are less sensitive.
- **EM observations crucial to reduce parameter space and to improve detection significance**
- $t \gg 500$ s fall within CW + stochastic groups' remit
- Available data: from GW170817 coalescence to end of O2: 8.5 days
- Main physical model: power law spindown ('ms magnetar')

$$\dot{\Omega} = -k\Omega^n$$

$$f_{\rm gw}(t) = f_{\rm gw,0}\left(1+\frac{t}{\tau}\right)^{\frac{1}{1-n}} \qquad \tau = \frac{-\Omega_0^{1-n}}{k(1-n)}$$

Long-duration remnant searches

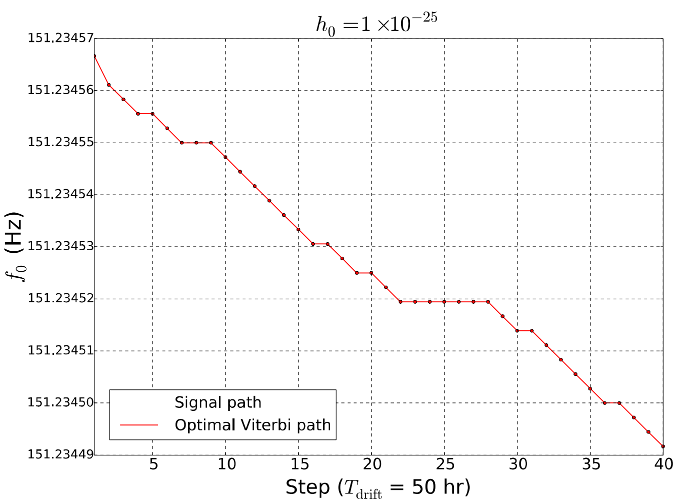
Broadly speaking, two kinds of searches are being considered for the search of very long transient signals from the remnant of GW170817:

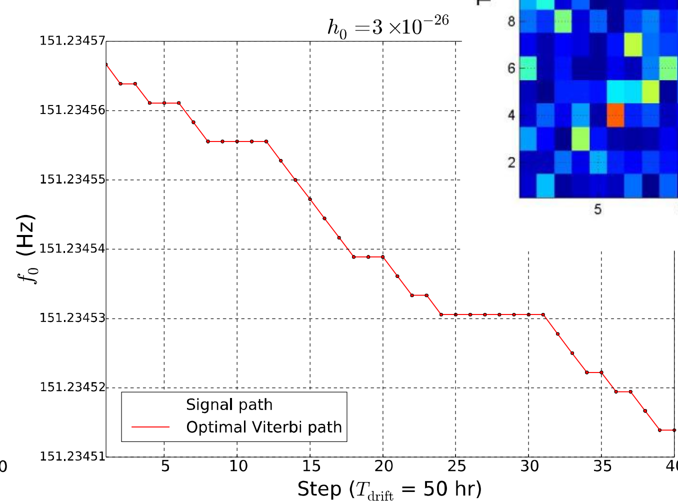
- Unmodelled search (10^2 to 10^4s intermediate duration)
  - **STAMP-VLT** (stochastic search) based on excess power in spectrograms (Thrane+, 2013)
  - hidden-Markov **Viterbi** tracking , previously used for Sco X-1, young SNRs [Suvorova et al PRD 96 (2016) 102006, Sun et al, PRD 97 (2018) 043013]
    - →More robust against fluctuations and transient instrumental glitches
      Require short tracking step size (1 s)
      Optimal observing time ~ spin-down time-scale
- Model-based searches (hours/days duration)
  - based on variations of methods used for standard continuous wave searches: **SkyHough** and **FrequencyHough:** previously used for all-sky searches [LVC, PRD 96 (2017) 062002]
    - → Allow to estimate signal parameters (in case of detection)
- 4 pipelines: 2 'unmodelled', 2 semi-coherent with grid over parameter space

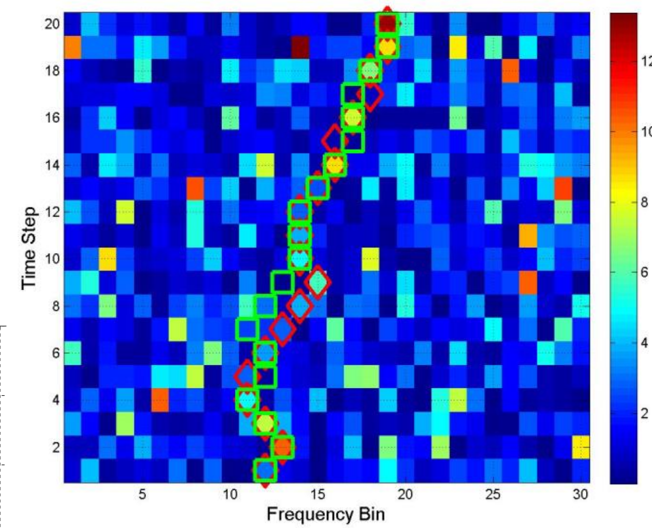
Hidden Markov model and Viterbi

Tracking rapidly spin-down CW signals with timing noise

- $\dot{f}_{0\,\mathrm{inj}} \sim 10^{-11}\ \mathrm{Hz\,s^{-1}}$, $\gg$ spin-down $\gg$ timing-noise
- $\cos\iota \sim 0.7$, $\sqrt{S_h} = 4 \times 10^{-24}\ \mathrm{Hz^{-1/2}}$
- $h_0 = 1 \times 10^{-25}$ (left) and $h_0 = 3 \times 10^{-26}$ (right)



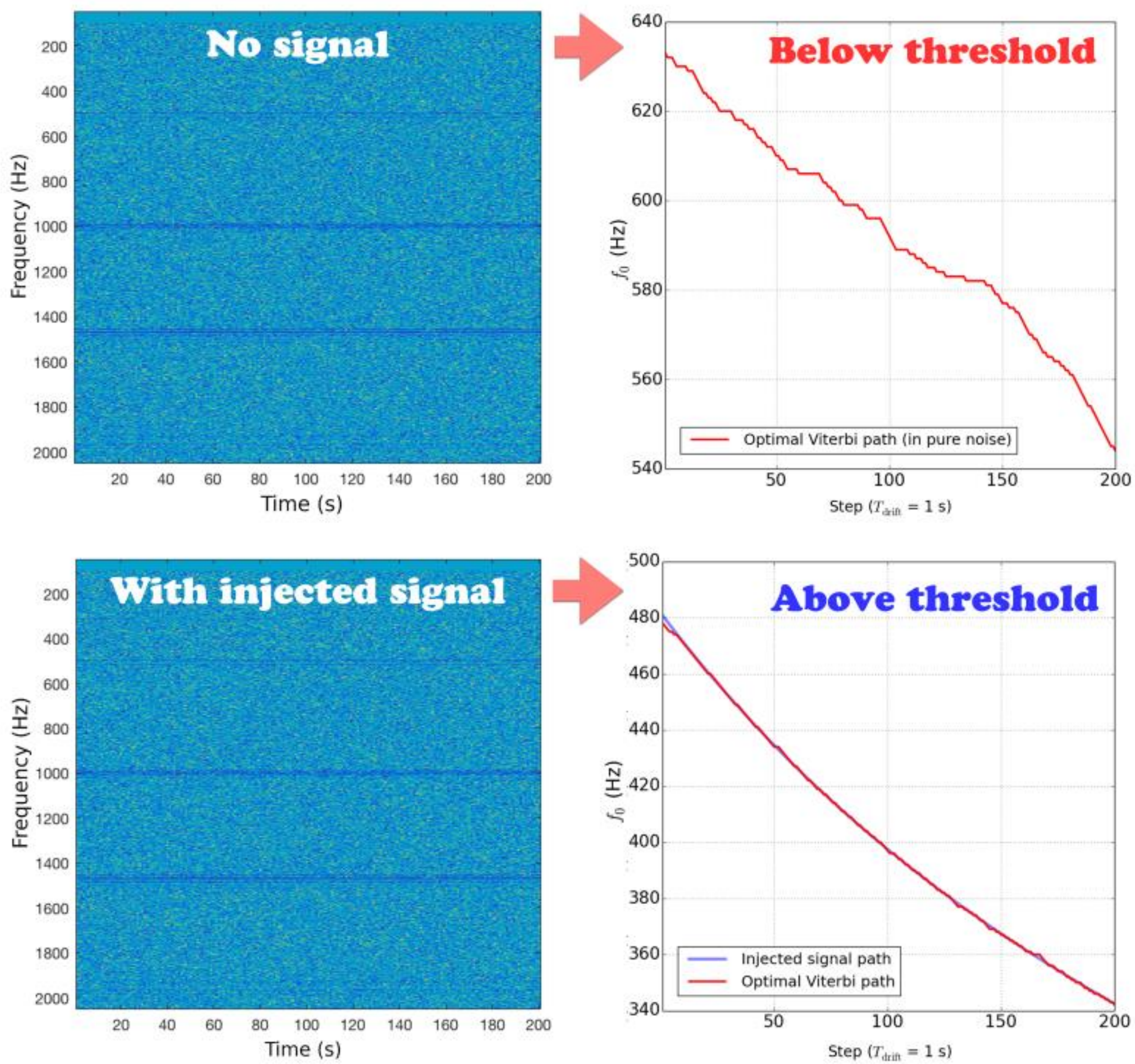




Sun et al., PRD 97, 043013 (2018)

Example: Tracking a millisecond magnetar signal

Viterbi



Generalizing the FrequencyHough

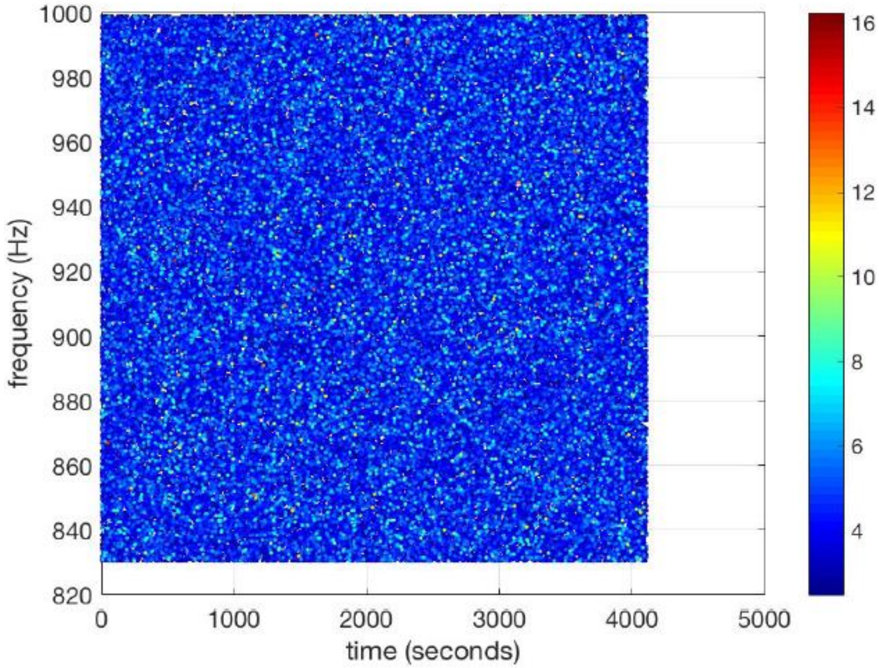
- Assumes a power law for the frequency evolution:

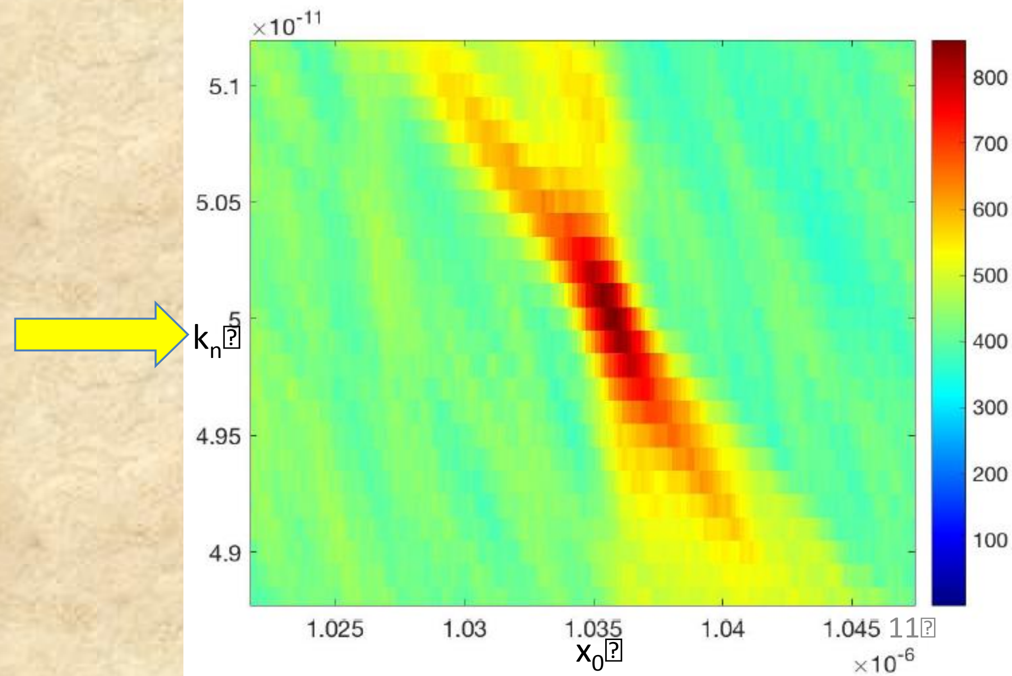
$$f(t)=f_0\left(1+(n-1)\frac{\dot{f}_0}{f_0}(t-t_0)\right)^{-1/(n-1)}$$

- Peaks in time-frequency plane are mapped into straight lines in the transformed x_0/k_n plane

$$x_0 = f_0^{1-n}, \quad k_n = \dot{f}_0/f_0$$

- The search is done over a grid built on the parameter space: f_0, k_n, n





Magnetar case (n = 3)

Search plan

- Grid over braking index $n \rightarrow$ we search over all possibilities of emission mechanisms (and combinations)
- 1 Hough per braking index
- f_0: [500, 2000] Hz
- n: [2.5, 7]
- $\dot{f}$: $[-\frac{1}{2^2}, -\frac{1}{16^2}]$ Hz/s
- Looking for sources lasting at most 1 day
- Beginning the search about 1 hour after the merger
  - Signal immediately after merger is very complicated
  - Less frequency variation later because spindown is smaller
  - Improve sensitivity because we use longer FFTs
- Search with varying T_{FFT} (2,4,8 s) in different portions of the parameter space to maximize sensitivity
- Computation cost: O(days)

- Detection of long-transient signals from GW170817 is unlikely, but it is important to setup analysis methods.
- Detection of GWs from the post-merger would provide a wealth of information on the remnant.

Conclusions

- LIGO and Virgo Collaborations have set forth a robust program to detect continuous gravitational waves
- Detecting one source would provide rich laboratory – including post-merger remnant searches!
- Critically important: improved detectors, sensitive, robust and faster algorithms, and continued collaboration with EM partners
- No guaranteed future CW detections, but . . .

. . . we are entering very interesting territory!