Title: Directed and targeted searches for continuous gravitational waves

Date: May 10, 2018 04:00 PM

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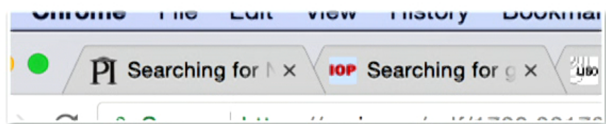
Abstract: Traditionally, searches for continuous gravitational waves have looked for neutron stars with varying mass or current quadrupoles. If information is known about the source â€" such as a sky position or even a full ephemeris â€" this information can be used to run a more sensitive search around the known parameters of that source. These directed and targeted searches have set new and ever-improving constraints on the properties of individual neutron stars. The searches can also be applied to other astrophysical sources, such as continuous waves from boson clouds that have built up around black holes due to superradiance. I will discuss the current status of directed and targeted searches for continuous gravitational waves with the advanced LIGO and Virgo detectors, and sketch out some considerations for running directed searches for boson clouds.

Directed and targeted searches for continuous gravitational waves

Sylvia J. Zhu
AEI Hannover



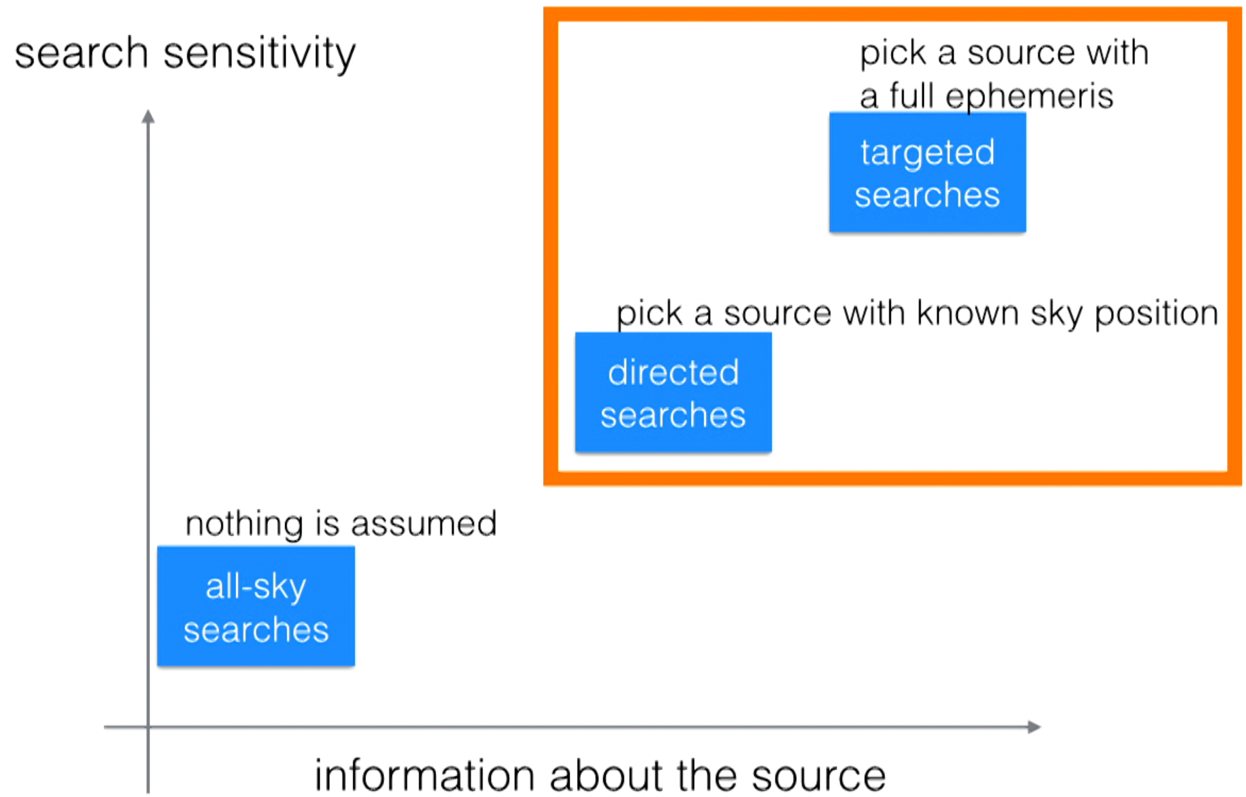
Searching for New Particles with Black Hole Superradiance
@ Perimeter Institute 10 May 2018

LIGO-G1800940

Structure of this talk

What are directed and targeted searches?
Where do we look?
How would we run a directed search for boson clouds?

types of CW searches



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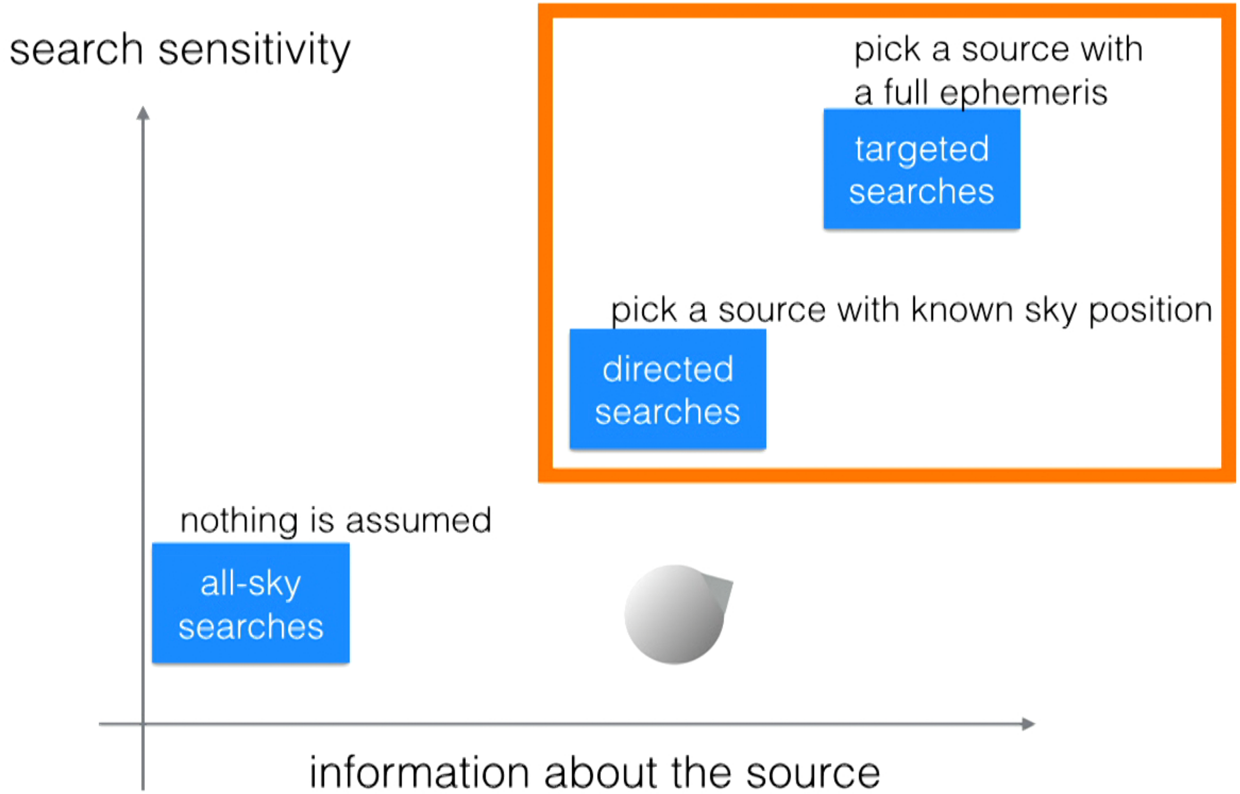

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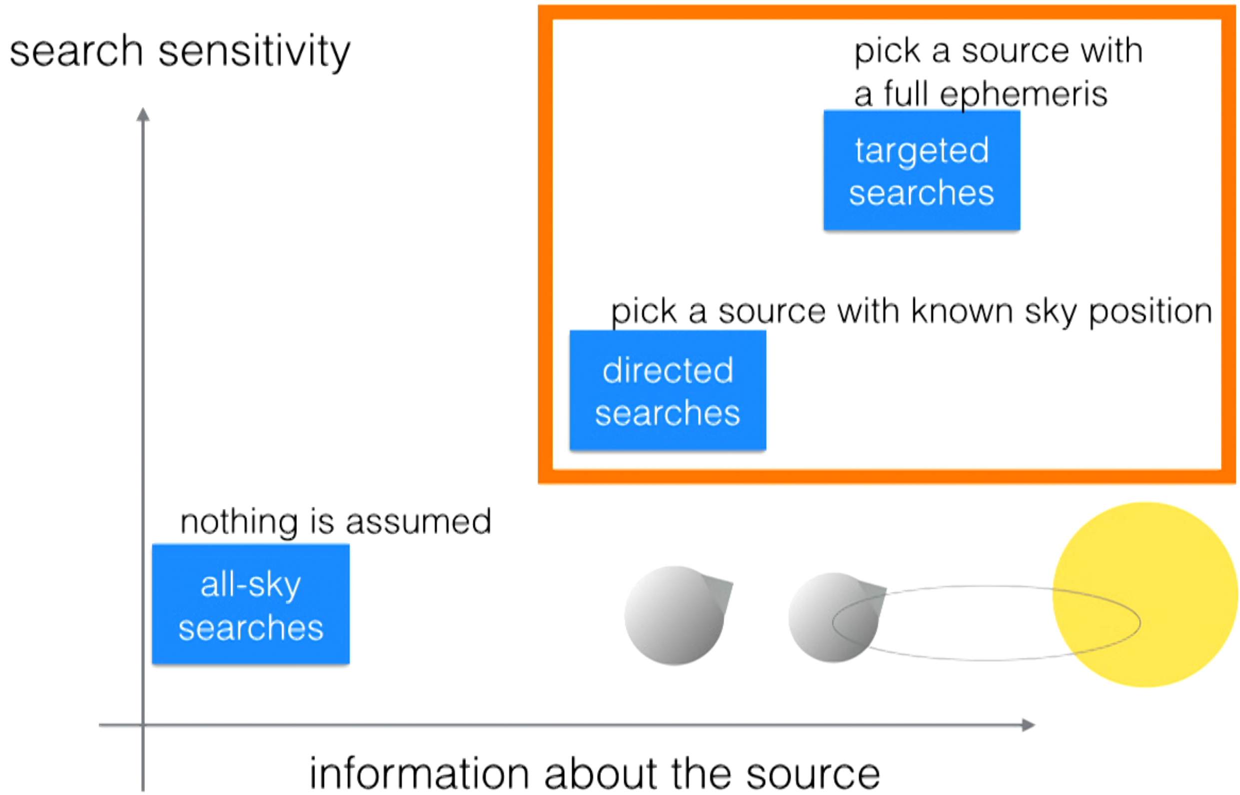
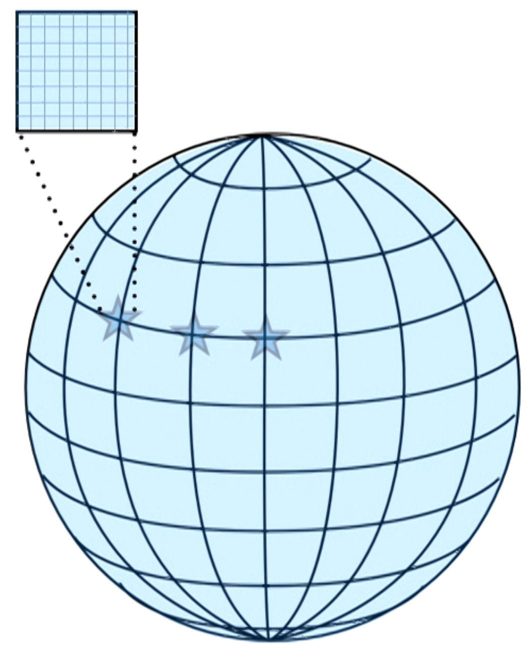


all-sky searches

no parameters assumed

[this is where you remind yourself of everything Keith talked about that you recall perfectly]



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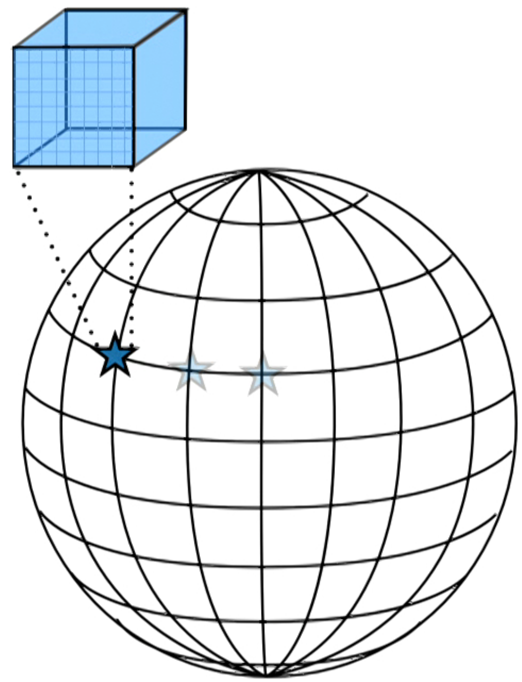
directed searches

pick a source with a known sky position but with unknown spin parameters

search can (and generally needs to) go to second order in frequency derivative for isolated neutron stars

search can accommodate orbital modulation for neutron stars in accreting binaries

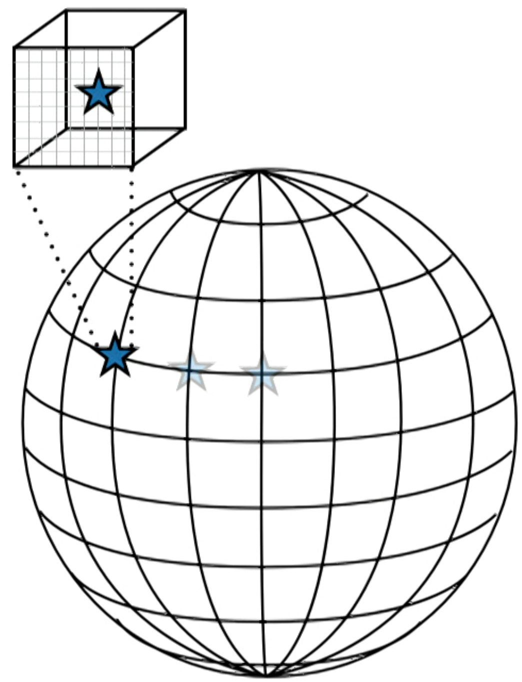


targeted searches

ephemeris is known from
observed electromagnetic pulsations

only need to search a single set of
parameters

sources could be isolated or in binaries

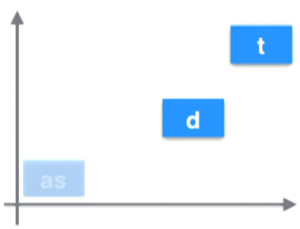


Which sources to search for?

Main consideration: Could we say something interesting?
(Could we detect something?)

Compare our (estimated) direct upper limits on CW emission to indirect upper limits from energy conservation arguments.

$$\left(\frac{dE}{dt}\right)_{\mathrm{gw}} \leq -\left(\frac{dE}{dt}\right)_{\mathrm{rot}}$$



physical upper limits

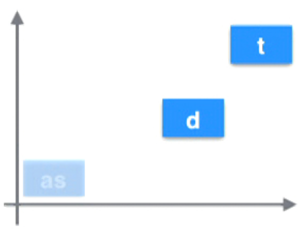
$$\left(\frac{dE}{dt}\right)_{\rm gw} \leq -\left(\frac{dE}{dt}\right)_{\rm rot}$$

spindown limit

$$\left(\frac{dE}{dt}\right)_{\rm rot} = \frac{d}{dt}\left(\frac{1}{2}\pi^2 I_{zz} f^2\right) = \pi^2 I_{zz} f \dot{f}$$

Use the observed spindown of the object to set an indirect limit on the gravitational-wave strain.

(In reality, only a small fraction of the energy is emitted in gravitational waves.)



[Wette et al., CQG, 25 (2008)]

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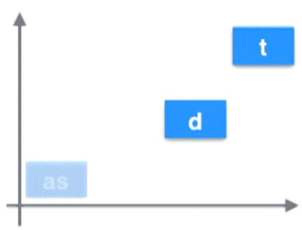
age-based limit

$$\dot{f} \propto f^n, n = 2$$

Without a measured spindown, use the age of the object and assume that its evolution is dominated by mass quadrupole emission to set an indirect limit.



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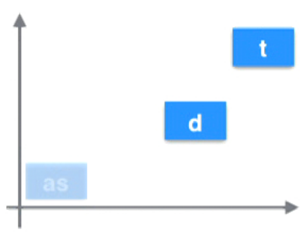
Without a measured spindown, use the age of the object and assume that its evolution is dominated by mass quadrupole emission to set an indirect limit.

torque-balance limit

For an accreting neutron star in a binary (i.e., LMXB), assume the angular momentum gained from accretion is balanced by the angular momentum lost (to gravitational-wave emission).

(This is used to explain the small range of observed spin frequencies of pulsars in LMXBs.)



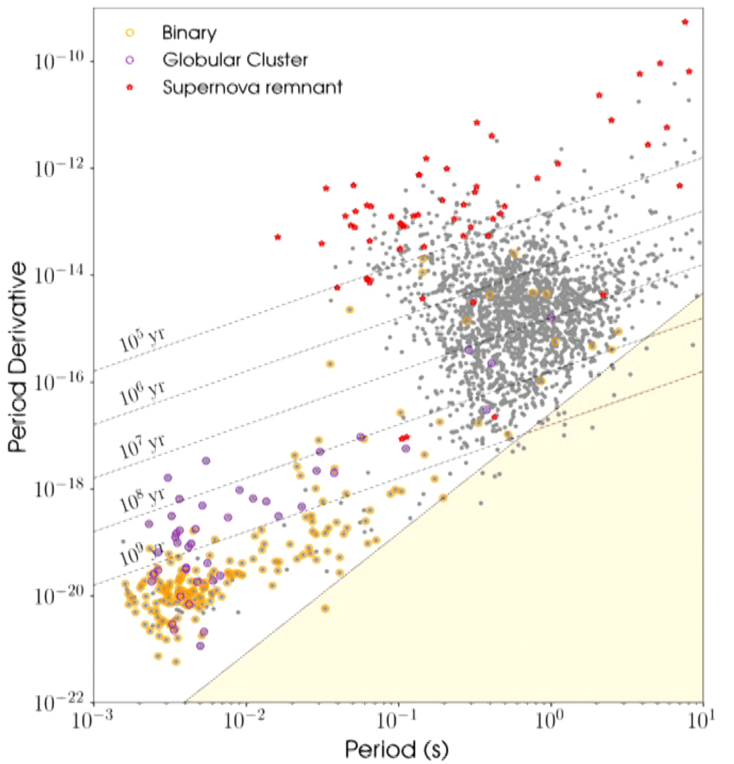
[Wette et al., CQG, 25 (2008)]

targeted searches for known pulsars

what is a good target?

$$h_0 = \frac{4\pi G I_{zz}}{c^4} \frac{f_{\rm GW}^2 \epsilon}{D}$$

plot produced with psrqpy
[Pitkin, JOSS, 3(22), 538 (2018)]



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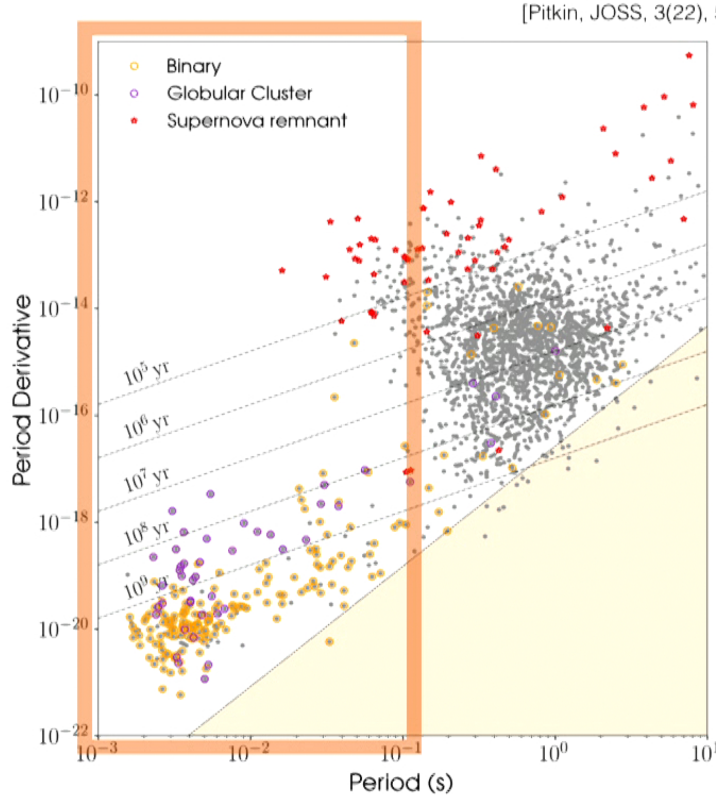

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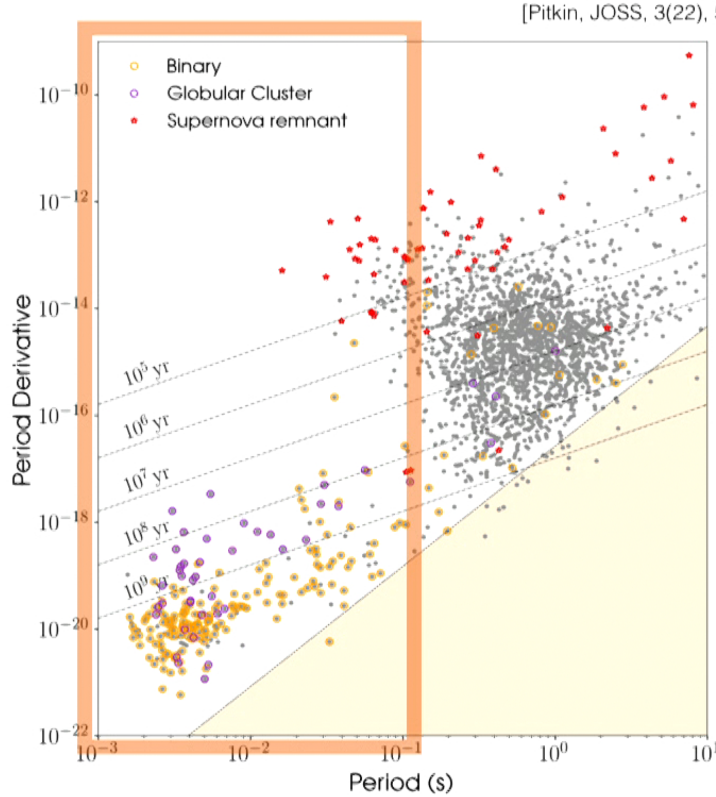

targeted searches for known pulsars

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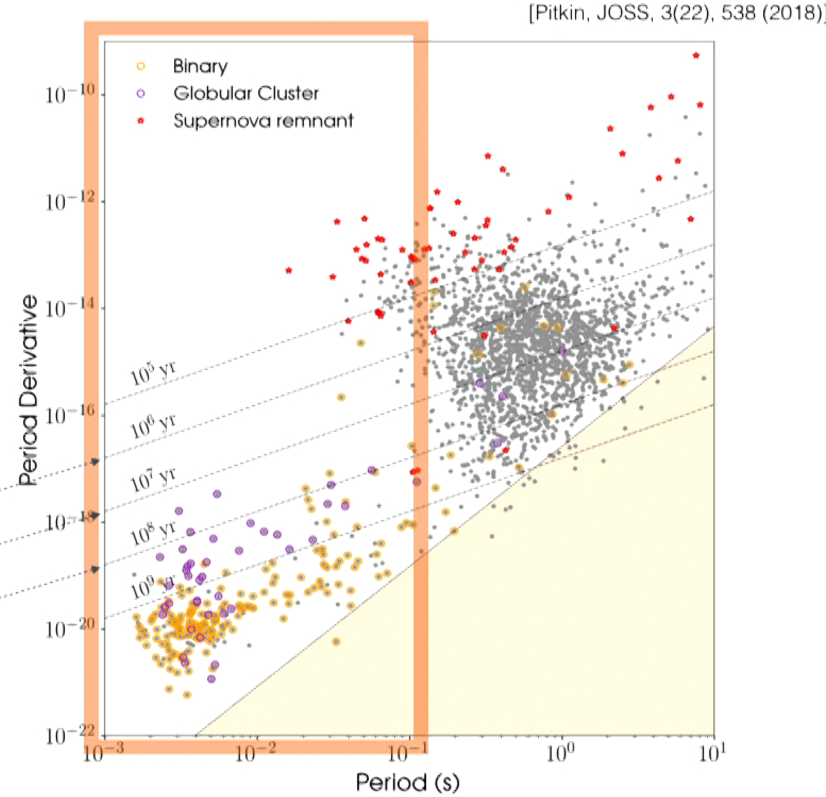
[Pitkin, JOSS, 3(22), 538 (2018)]

$$\frac{|I_{xx} - I_{yy}|}{I_{zz}}$$

$$h_0 = \frac{4\pi G I_{zz} f_{\mathrm{GW}}^2 \epsilon}{c^4 D}$$

characteristic age, calculated assuming evolution has been dominated by magnetic dipole (n=3)



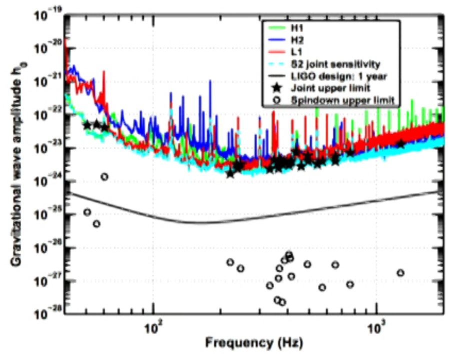
targeted searches for known pulsars

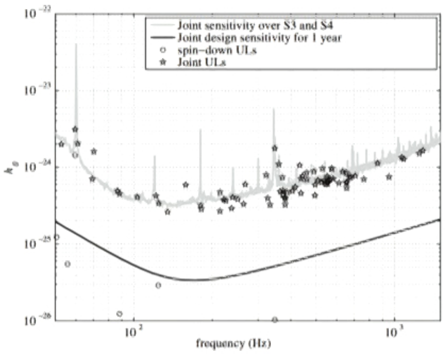
LIGO S2: 28 pulsars

[Abbott et al., PRL 94, 181103 (2005)]

LIGO S3/S4: 78 pulsars

[Abbott et al., PRD 76, 042001 (2007)]





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LIGO S3/S4: 78 pulsars
[Abbott et al., PRD 76, 042001 (2007)]
LIGO S5: 116 pulsars
[Abbott et al., ApJ, 713 (2010)]
LIGO S6 + Virgo VSR2/VSR4: 195 pulsars
[Aasi et al., ApJ, 785 (2014)]

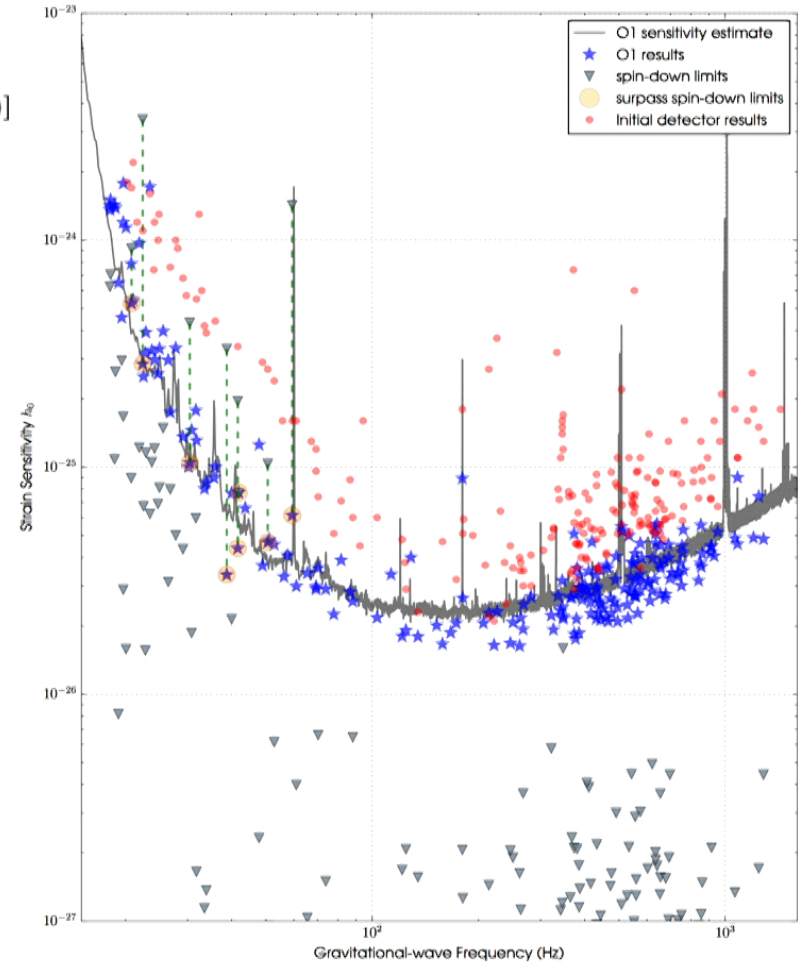
aLIGO O1: 200 pulsars
[Abbott et al., ApJ, 839 (2017)]

targeted searches for known pulsars

O1 search [Abbott et al., ApJ, 839 (2017)]

200 known pulsars
78 for the first time
including 11 “high priority”

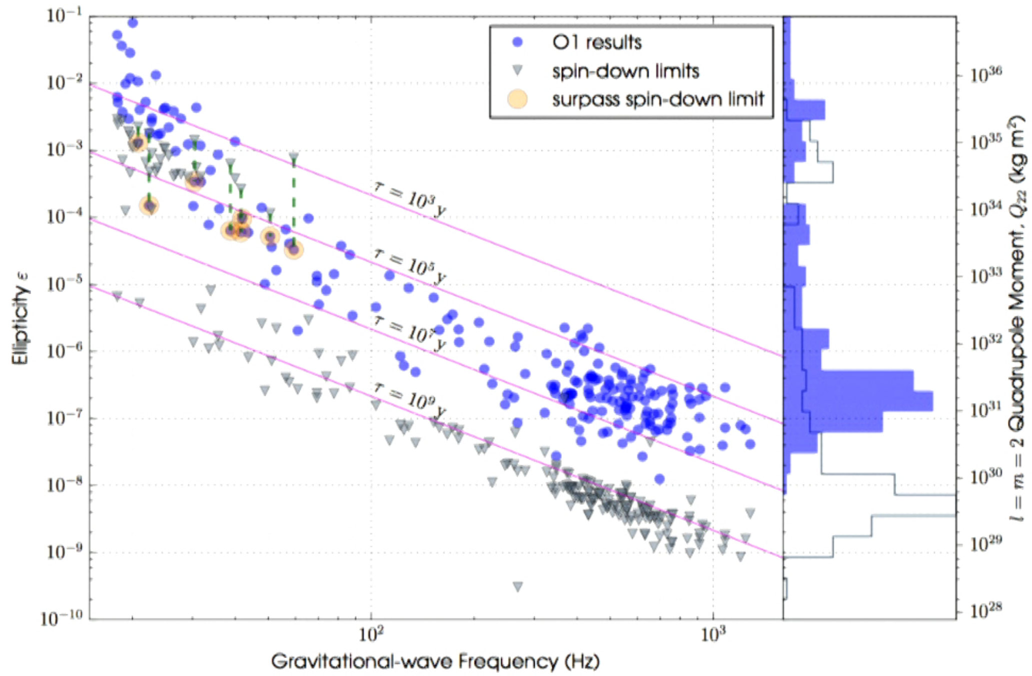
beat spindown limit for
eight pulsars (prev: two)



targeted searches for known pulsars

use the distance to translate strain into ellipticity

$$h_0 = \frac{4\pi G I_{zz}}{c^4}\frac{f_{\rm GW}^2 \epsilon}{D}$$



targeted searches for known pulsars

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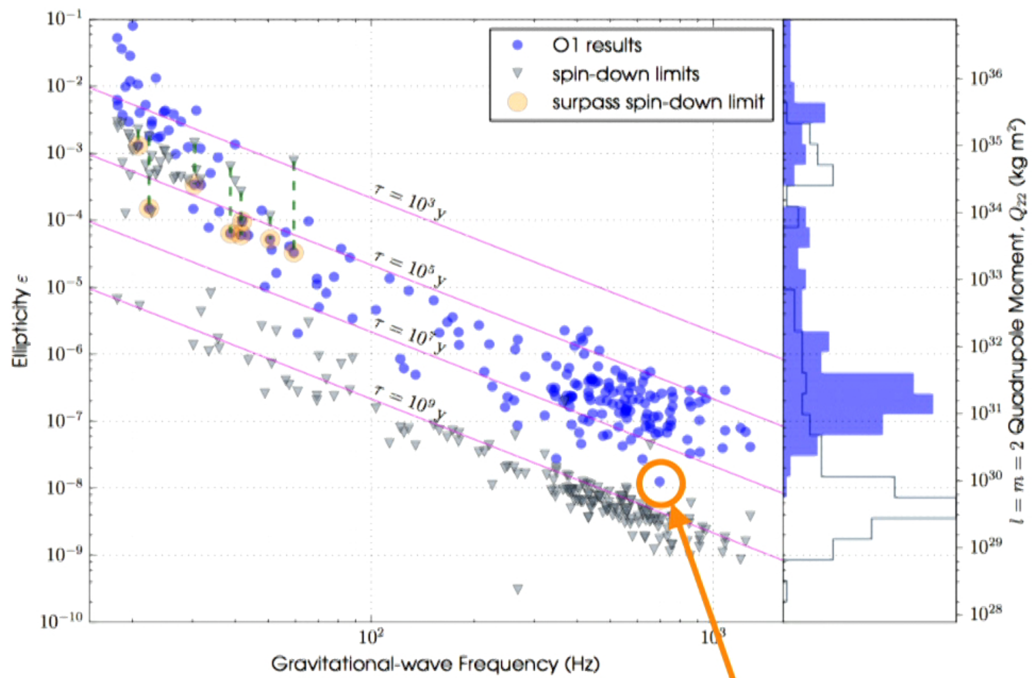
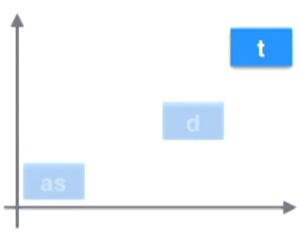
$$h_0 = \frac{4\pi G I_{zz} f_{\mathrm{GW}}^2 \epsilon}{c^4 \, D}$$



most stringent limit
on ellipticity (<1.2e-8)



narrowband searches

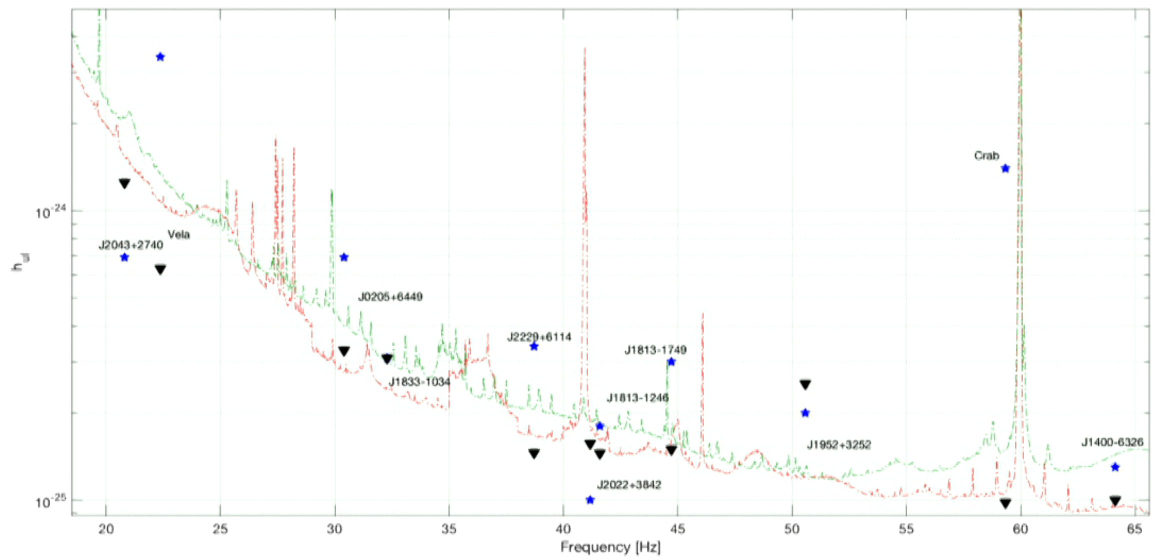
allow for some mismatch between electromagnetic and gravitational-wave parameters by searching over a range (e.g., +/- 0.01% to 0.1%) in frequency, spindown

LIGO S5: Crab
[Abbott et al., ApJL 683 (2008)]
Virgo VSR4: Crab, Vela
[Aasi et al., PRD 91, 022004 (2015)]

aLIGO O1: 11 pulsars
[Abbott et al., PRD 96, 122006 (2017)]

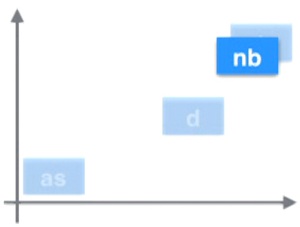
narrowband searches

11 pulsars where the search could beat or approach spindown limit



-- Hanford
-- Livingston

★ spindown limit
▼ upper limit



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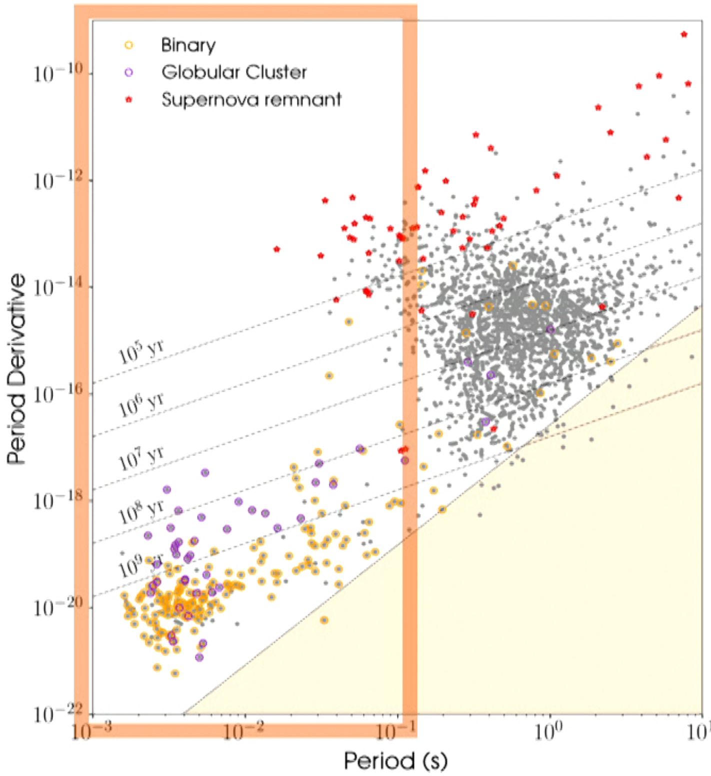
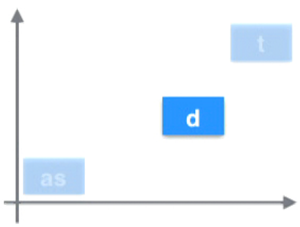
promising sources

$$h_0 = \frac{4\pi G I_{zz}}{c^4} \frac{f_{\mathrm{GW}}^2 \epsilon}{D}$$





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Which sources to search for?

Main consideration: Could we say something interesting?

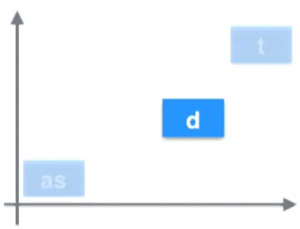
$$h_0 = \frac{4\pi G I_{zz}}{c^4} \frac{f_{\rm GW}^2 \epsilon}{D}$$

For a directed search, promising sources are:

young objects,
accreting objects

nearby sources

regions of high (stellar) density



directed searches: supernova remnants

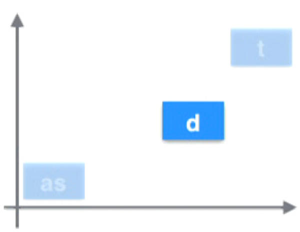
e.g., Cassiopeia A

central object is likely a neutron star [Ho and Heinke, Nature 462 (2009)]

only ~300 years old

~3.4 kpc away

$$f, \dot{f}, \ddot{f}$$



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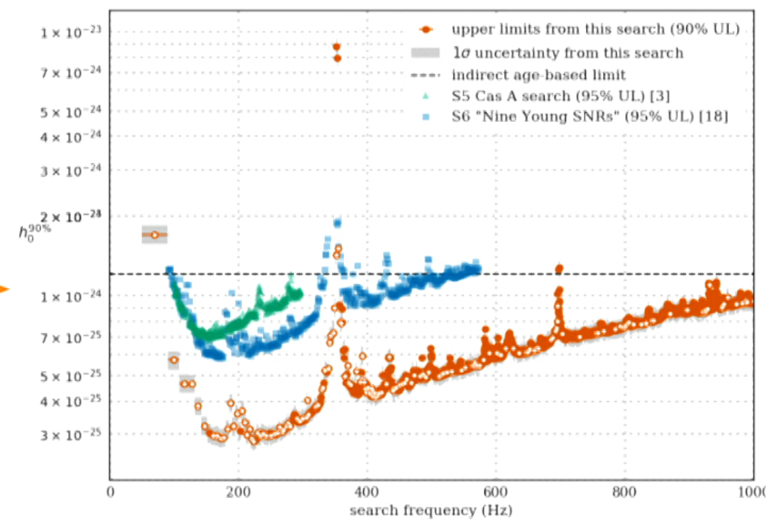
LIGO S5
[Abadie et al., ApJ, 722:1504-1513 (2010)]
LIGO S6 (with 8 other SNRs)
[Aasi et al., ApJ, 813:39 (2015)]
LIGO S6
[S. J. Zhu et al., PRD 94, 082008 (2016)]



searches using advanced
detector data are forthcoming

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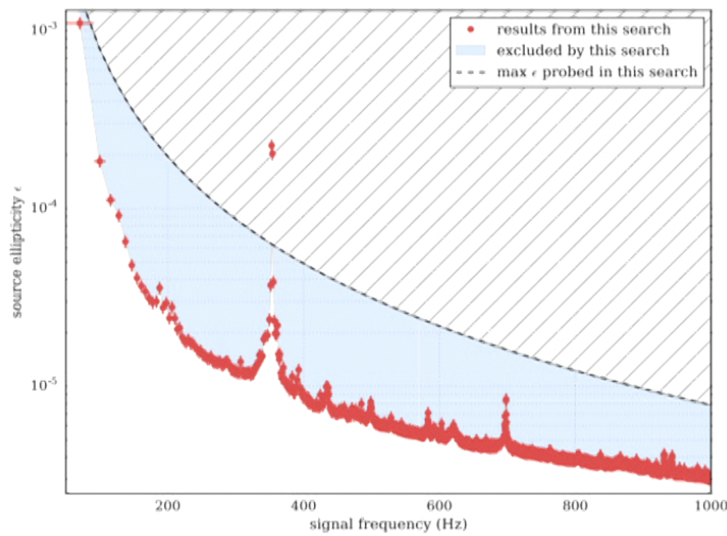

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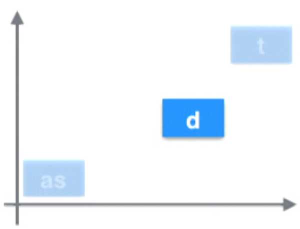
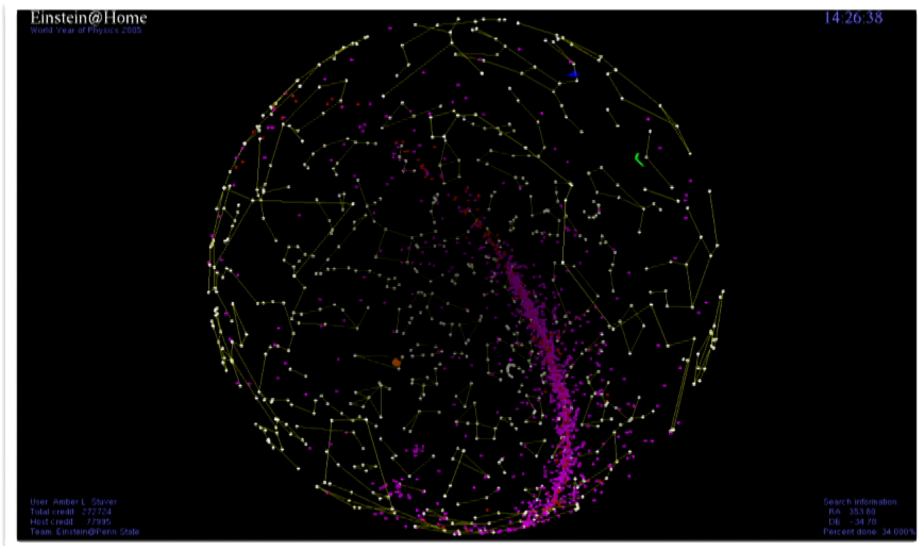


Pause for an advertisement

We make a lot of decisions based on how promising a source is because searches are very computationally €x₱€₦$iv€.

Sign up for Einstein@Home! (Like SETI@Home but with fewer aliens)



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directed searches: Galactic Center

Instead of one source (e.g., a single supernova remnant), search a region that is densely populated.

directed searches: Galactic Center

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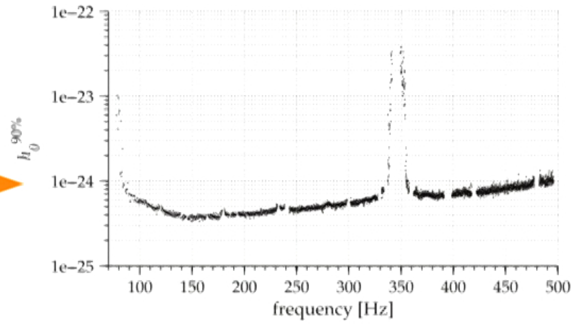
LIGO S5
[Abadie et al., PRD 107, 271102 (2011)]
LIGO S5
[Aasi et al., PRD 88, 102002 (2013)]



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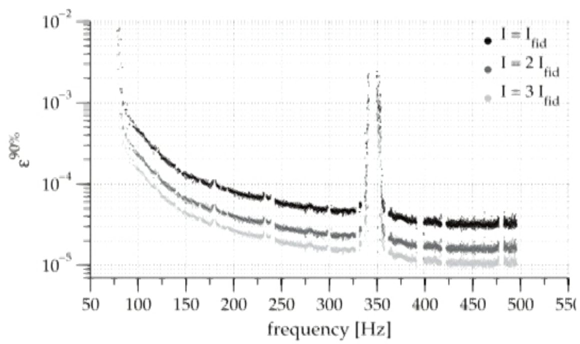

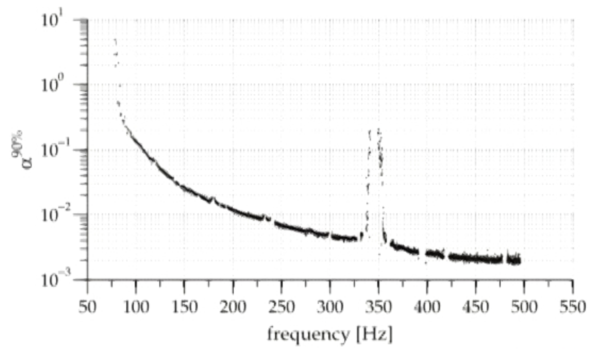

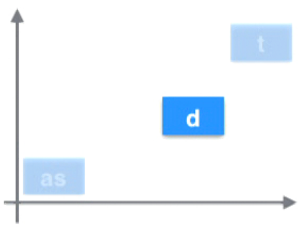

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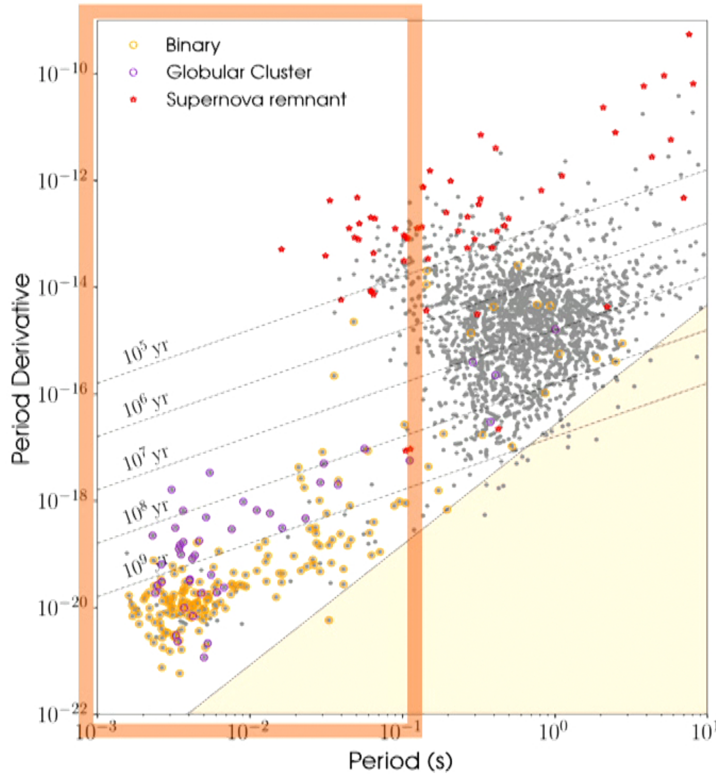
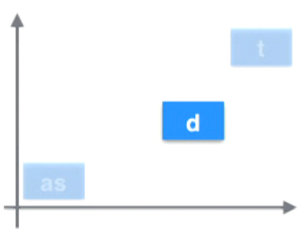
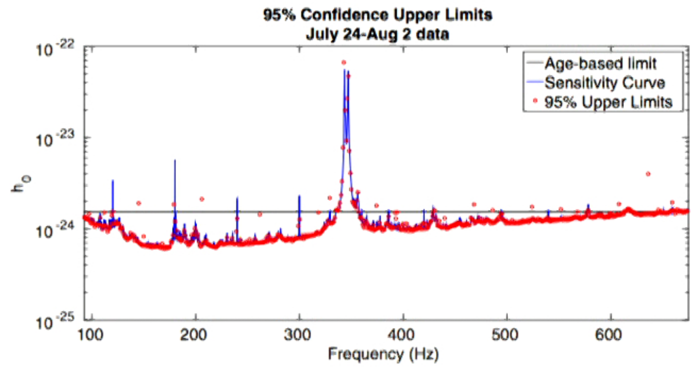




directed searches: globular clusters

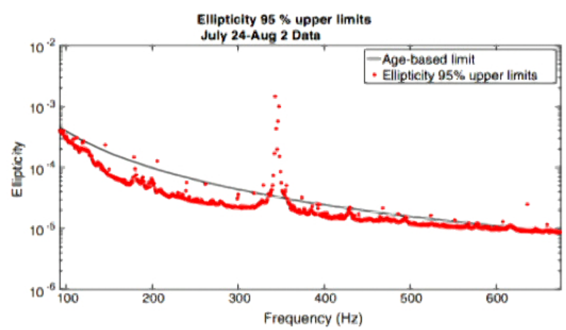
Instead of one source (e.g., a single supernova remnant), search a region that is densely populated.

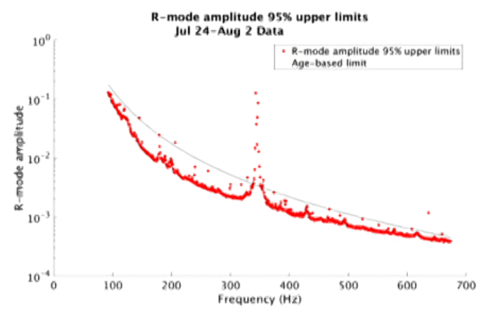
NGC 6544



LIGO S6

[Abbott et al., PRD 95, 082005 (2017)]





directed searches: binaries

torque-balance limit

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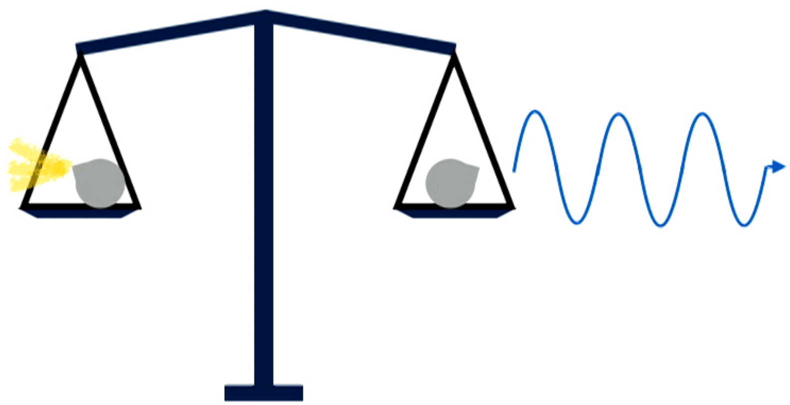
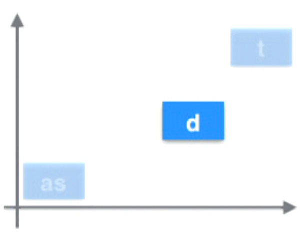
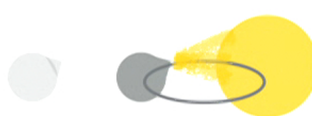
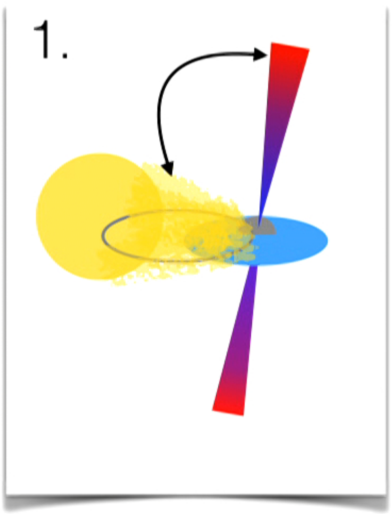
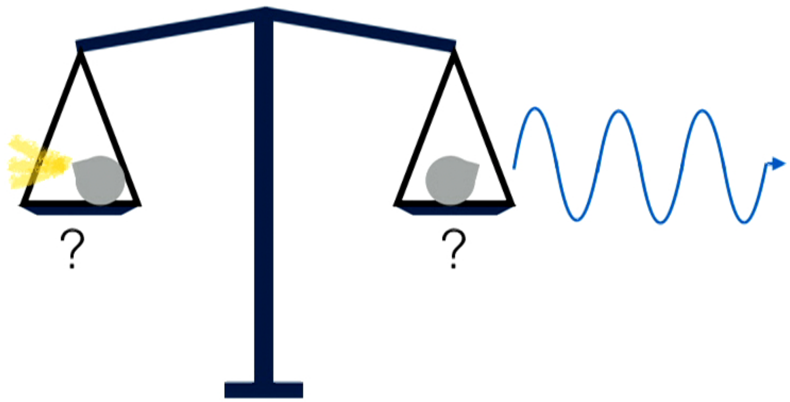


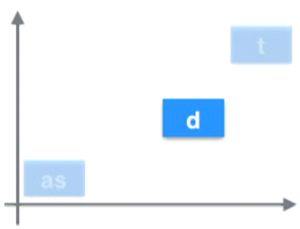




directed searches: binaries







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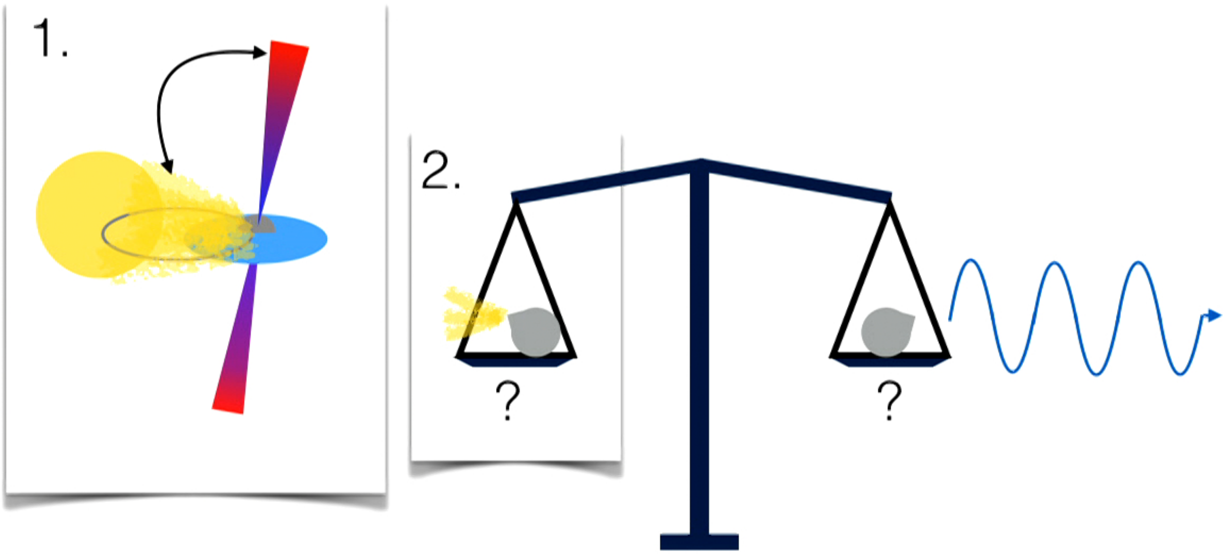
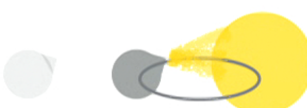


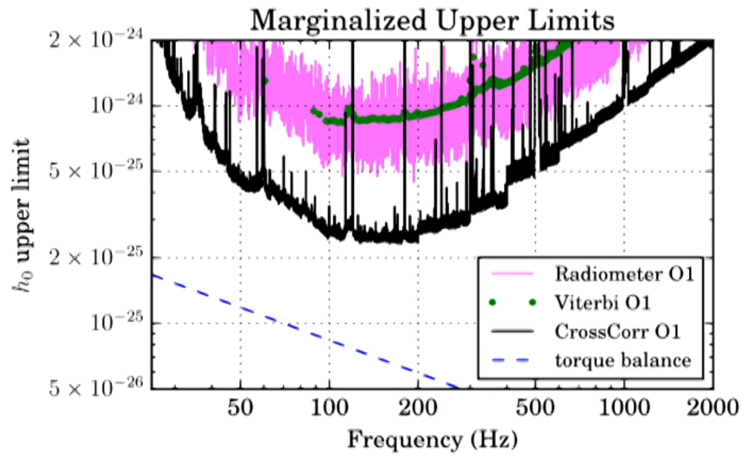


directed searches: binaries

Sco-X1

LIGO S2
[Abbott et al., PRD 76, 082001 (2007)]
LIGO S5
[Aasi et al., PRD 91, 062008 (2015)]
LIGO S6
[G. D. Meadors et al., PRD 95, 042005 (2017)]

aLIGO O1 (“Radiometer O1”)
[Abbott et al., PRL 118, 121102 (2017)]
aLIGO O1 (“Viterbi O1”)
[Abbott et al., PRD 95, 122003 (2017)]
aLIGO O1 (“CrossCorr O1”)
[Abbott et al., ApJ, 847:47 (2017)]



directed searches for boson clouds?

CW searches:

constraints on strain => constraints on source properties

Main consideration: Could we say something interesting?

Pros: Better sensitivity than an all-sky search, and you *know* a black hole is there

Cons: Limited in how much of the parameter space you can probe (you're only looking at one object); unclear if your source has developed the cloud

What are some potential sources?

directed searches for boson clouds?

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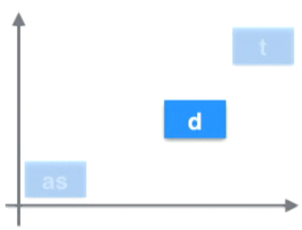
directed searches for boson clouds?

Known black holes	comments
LIGO-Virgo binary merger remnants	stellar mass, tens to hundreds of Mpc, spin known



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directed searches for boson clouds?

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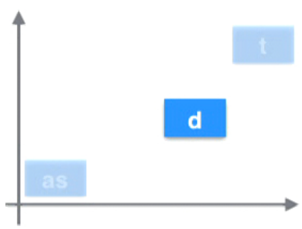

directed searches for boson clouds?

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These all require **very short timescales** for cloud formation.

Notes:
[1] short GRBs from binary mergers, long GRBs from core collapses; slightly different population properties
[2] infer spin with arguments about sustained emission, GRB existence?
[3] different types, different distances, different central objects
[4] but see [Chan et al., ApJL, 852 (2018)]

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directed searches for boson clouds?

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Sgr A* (and others)	supermassive, 8 kpc or >Mpc, spin known

LISA regime, but worth thinking about now.

Isolated source, well observed, well constrained properties.

This could probably be a narrowband (or mediumband) search => cheap!

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directed searches for boson clouds?

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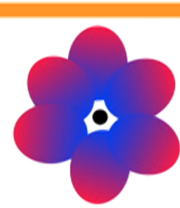
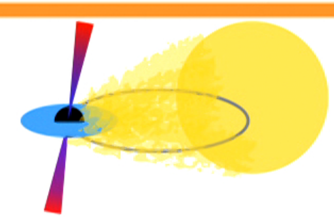
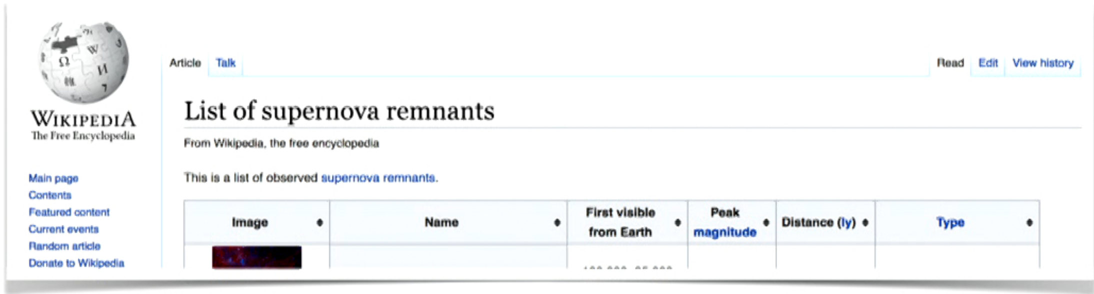
supernova remnants with black holes

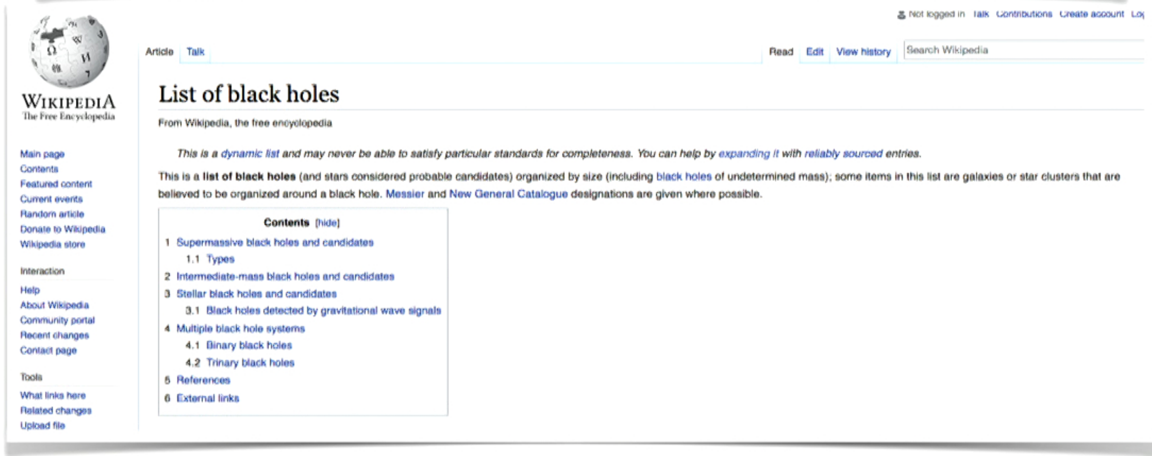
stellar-mass black holes in electromagnetically detected binaries (phew)





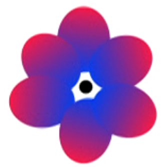
directed searches for boson clouds?

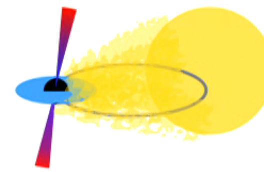




directed searches for boson clouds?

pick your source





Galactic SNRs: Summary Data

2017 June version

D. A. Green

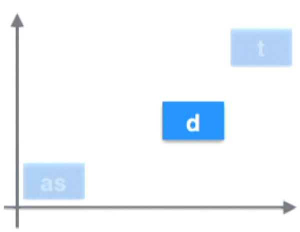
Cavendish Laboratory
19 J. J. Thomson Avenue
Cambridge CB3 0HE
UNITED KINGDOM

Please also see the documentation for notes on the entries for each SNR in the catalogue, and for details of many possible and probable SNRs not listed in the catalogue. Also see the cross-reference list of other names used for these SNRs.

l	b	RA (J2000.0) hh mm ss	Dec dd mm	size/ arcmin	type	1-GHz flux/ Jy	spectral index	other name(s)
0.0	+0.0	17 45 44	-29 00	3.5x2.5	S	100?	0.8?	Sgr A East
0.3	+0.0	17 46 15	-28 38	15x8	S	22	0.6	
0.9	+0.1	17 47 21	-28 09	8	C	18?	varies	
1.0	-0.1	17 48 30	-28 09	8	S	15	0.6?	
1.4	-0.1	17 49 39	-27 46	10	S	2?	?	
1.9	+0.3	17 48 45	-27 10	1.5	S	0.6	0.6	
3.7	-0.2	17 55 26	-25 50	14x11	S	2.3	0.65	
3.8	+0.3	17 52 55	-25 28	18	S?	3?	0.6	
4.2	-3.5	18 08 55	-27 03	28	S	3.2?	0.6?	
4.5	+6.8	17 30 42	-21 29	3	S	19	0.64	Kepler, SN1604, 3C358

Stellar black holes and candidates [edit]

- 4U 1543-475/IL Lupi
- A0620-00/V616 Mon (currently thought to be the closest
- CXOU J132527.6-430023 A candidate stellar mass blac
- Cygnus X-1
- Cygnus X-3
- GRO J0422+32 (smallest black hole yet discovered)[citat
- GRO J1655-40/V1033 Sco (at one time considered the s
- GRS 1124-683/GU Mus
- GRS 1915+105/V1487 Aql
- GS 2000+25/QZ Vul
- GX 339-4/V821 Ara
- IGR J17091-3624 (candidate smallest stellar black hole)
- M33 X-7 (most massive stellar-mass black hole known, i
- MACHO-96-BLG-5
- MACHO-96-NLG-5
- MACHO-98-BLG-6
- MACHO-99-BLG-22
- SN 1997D (in NGC 1536)
- SS 433
- V404 Cyg
- XTE J1118+480/KV UMa
- XTE J1550-564/V381 Nor
- XTE J1650-500 (at one time considered the smallest bla
- XTE J1819-254/V4641 Sgr



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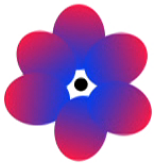
directed searches for boson clouds?

pick your method: isolated sources



In general, these are all based on the **F-statistic** matched filter search
[Jaranowski, Królak, and Schutz, PRD 58, 063001 (1998)]

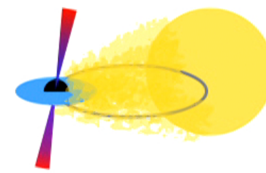
coherent F-statistic — Calculate F-statistic using entire observation time
[e.g., Wette et al., CQG 25, 235011 (2008) | Aasi et al., ApJ 813, 39 (2015) | Abbott et al., PRD 95, 082005 (2017)]

semicoherent F-statistic — Incoherently combine coherent F-statistic from different segments
[e.g., Aasi et al., PRD 88, 102022 (2013) | Zhu et al., PRD 94, 082008 (2016)]

Note that these are only the methods that have historically been used!
Many other search pipelines have been or could be applied to directed searches

directed searches for boson clouds?

pick your method: sources in binaries



Polynomial search — Models the signal with an empirical phase model
[e.g., van der Putten et al., J. Phys Conf Ser 228, 012005 (2010)]

Radiometer — Cross-correlates data from pairs of detectors
[e.g., Abbott et al., PRD 76, 082003 (2007)]

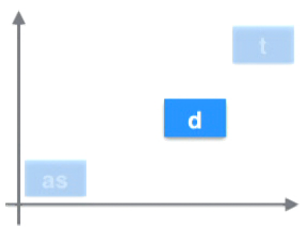
Sideband search — Searches for comb-like structure due to binary orbital modulation
[e.g., Messenger and Woan, CQG 24 (2007)]

CrossCorr — Cross-correlates data with an adjustable coherence time
[e.g., Dhurandhar et al., PRD 77, 082001 (2008)]

TwoSpect — Searches for orbital modulation using double Fourier spectra
[e.g., Goetz and Riles, CQG 28, 215006 (2011)]

F-statistic — Matched-filter search over a template grid
[e.g., Abbott et al., PRD 76, 082001 (2007)]

Viterbi — Looks for tracks in frequency-time plane with a Hidden Markov Model
[e.g., Suvorova et al., PRD 93, 123009 (2016)]



see also [Messenger et al., PRD 92, 023006 (2015)]

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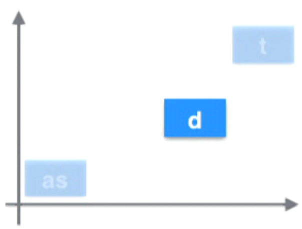
directed searches for boson clouds?

pick your method

How much computational time do you want to spend?
For how long do you expect the signal to be coherent?
What parameter space are you interested in?
Is your signal affected by any other properties of the source (e.g., accretion)?
Will you need to consider any other parameters we currently don't?
Other questions … ?



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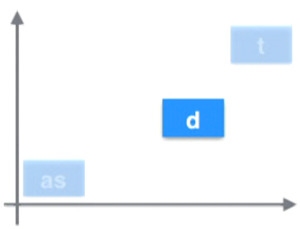
Non-zero spin-up?

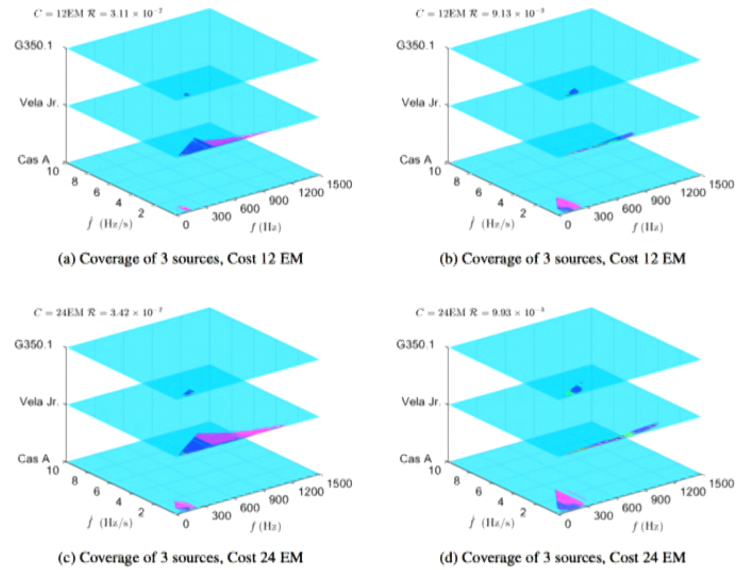


directed searches for boson clouds?

What parameter space are you interested in?

Given a set of priors to define
the detection probability
over the parameter space
plus a computational budget,
we have a method to determine
the optimal search setup
which maximizes the detection
probability.

[Ming et al., PRD 97, 024051 (2018)]



(a) Coverage of 3 sources, Cost 12 EM

(b) Coverage of 3 sources, Cost 12 EM

(c) Coverage of 3 sources, Cost 24 EM

(d) Coverage of 3 sources, Cost 24 EM

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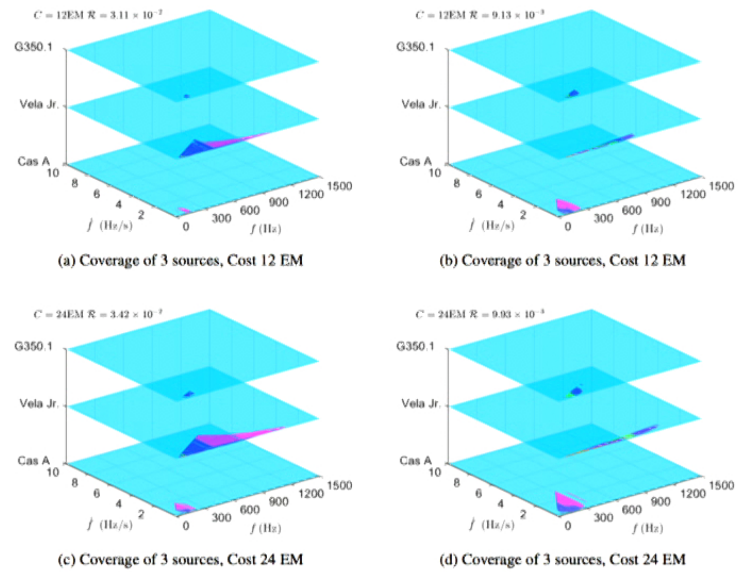

(a) Coverage of 3 sources, Cost 12 EM
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einstein@home

Take-home messages

Besides all-sky searches, we also perform **directed** and **targeted** searches for the most promising CW sources.

Many analysis methods have been developed to tackle both isolated and in-binary neutron stars, and they each have their own strengths.

Our traditional sources are neutron stars, but there's no reason we can't run searches for boson clouds around black holes.