Searching for continuous gravitational waves

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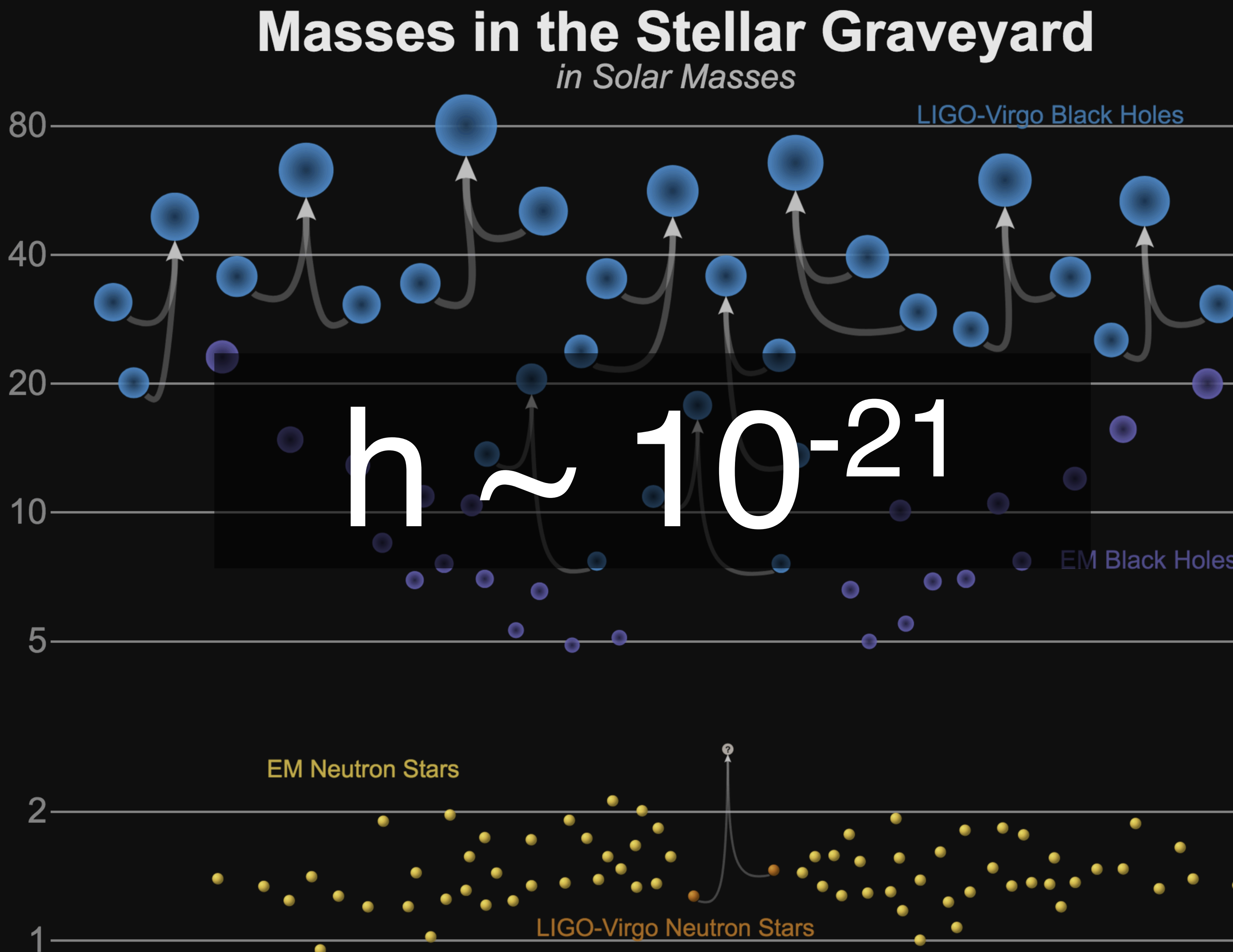
CONTINUOUS GRAVITATIONAL WAVES



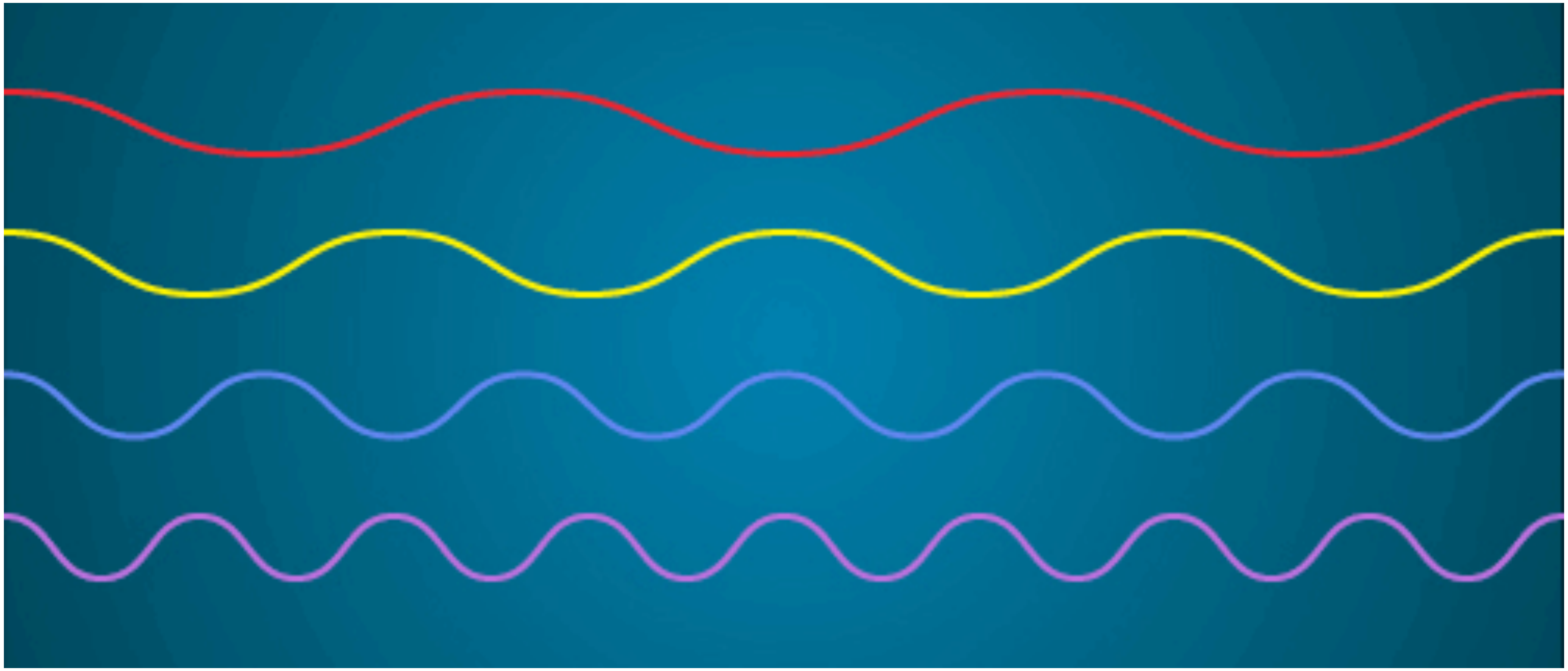
$$h \sim 10^{-21}$$

Credit: *Visualization: LIGO/Frank Elavsky/Northwestern* | *Non-LIGO Data Sources: Neutron Stars: http://xtreme.as.arizona.edu/NeutronStars/data/pulsar_masses.dat Black Holes: https://stellarcollapse.org/sites/default/files/table.pdf* | *LIGO-Virgo Data: https://www.gw-openscience.org/events/*

The (nearly) pure tone from a rotating neutron star

A very weak but omni-present continuous gravitational waves

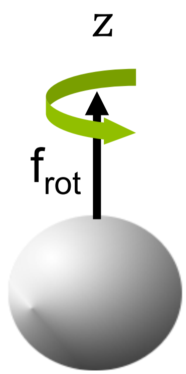
GW amplitude ≈10^{-25} compare w. GW150914 ~10^{-21}



A number of mechanisms for continuous GW emission

- If not perfectly axisymmetric
  - Non axisymmetric shape
  - Non axisymmetric motion
    - Free-precession
    - R-modes
    - Ekman flows
  - Exotic
- Predictions on GW amplitude span orders of magnitude

Deformation of a neutron star



"Bumpy" Neutron Star

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

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz}\varepsilon f_{gw}^2}{D} = 3 \times 10^{-25}$$

for:

D=1kpc

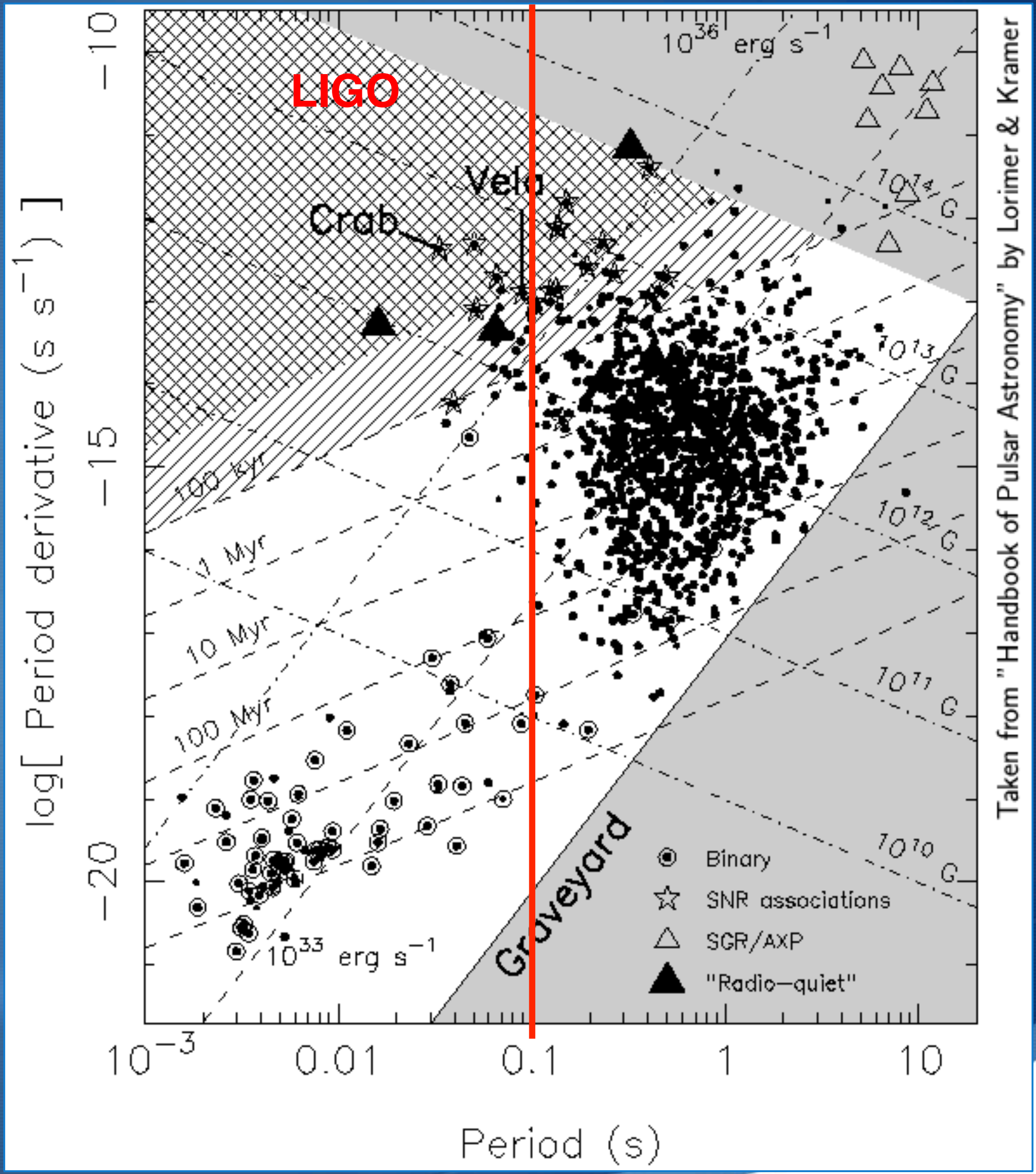
f_{gw}=1kHz

$\varepsilon = 10^{-6}$

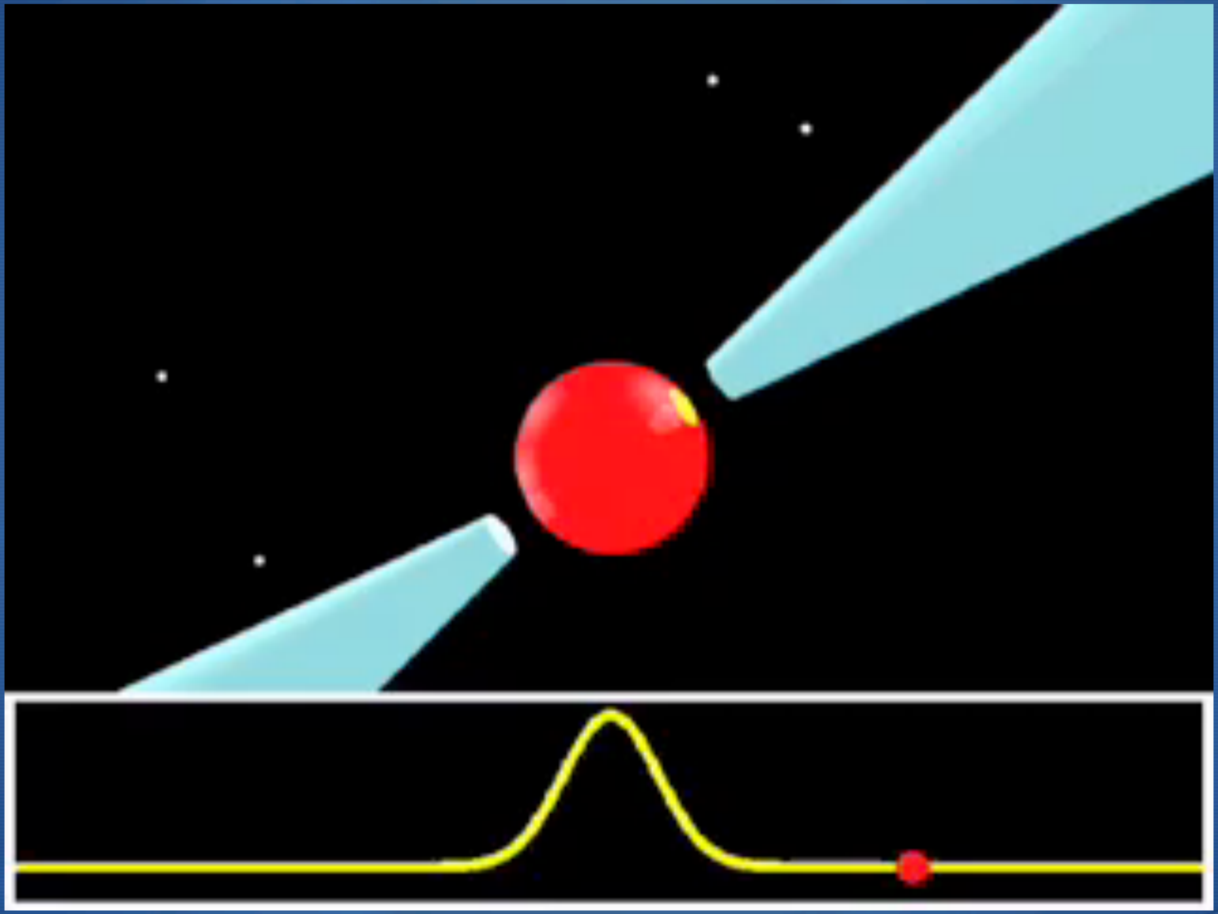
Real value of ε ? Unknown.

Possible values: $10^{-12} - 10^{-5}$

An obvious starting point: known pulsars



Targeted searches

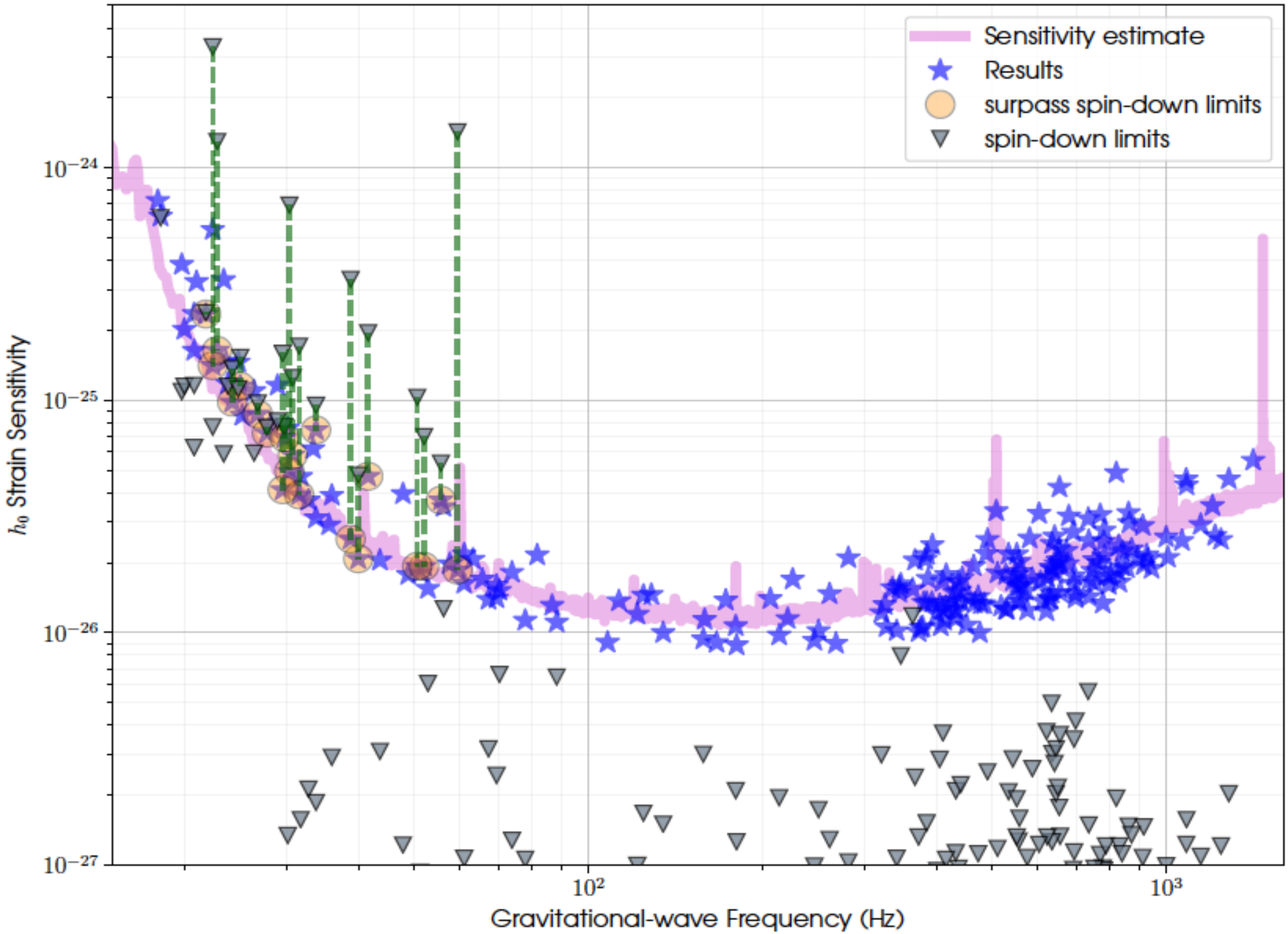


rotation period evolution known ➔ known GW waveform

With every new data set, LIGO looks

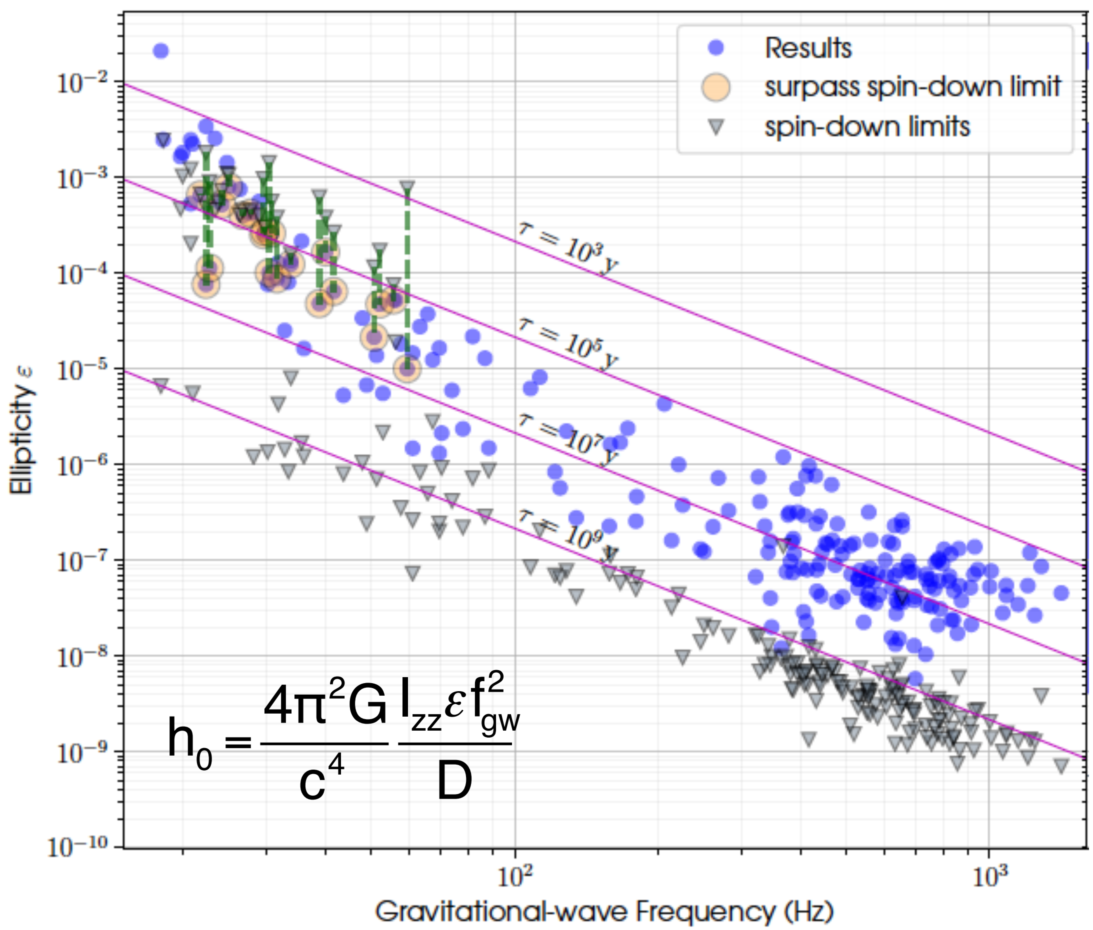
- So far no GWs from known pulsars
- Set upper limits on the GW amplitude
- Compare with indirect upper limit: the spin-down upper limit

$$h_0^{spindown} = \frac{1}{D}\sqrt{\frac{5GI}{2c^3}\frac{|\dot{f}|}{f}}$$



LIGO/Virgo Searches for Gravitational Waves from Known Pulsars at Two Harmonics in 2015-2017 LIGO Data.
ApJ 879, 10 (2019)

Ellipticity upper limits, look at dots



Most constraining e UL is 5.9 x 10^{-9} for J0636+5129

- ~ 700 Hz, 200pc, ~ a few above spindown limit

@ > 300 Hz, the bulk below 10^{-6}, well within maximum predicted values, but spindown limit is ≈ x 10 lower

spindown limit is beaten but corresponding to higher ellipticities, less likely to exist

There's more than meets the eye

Interesting regions (Galactic center)

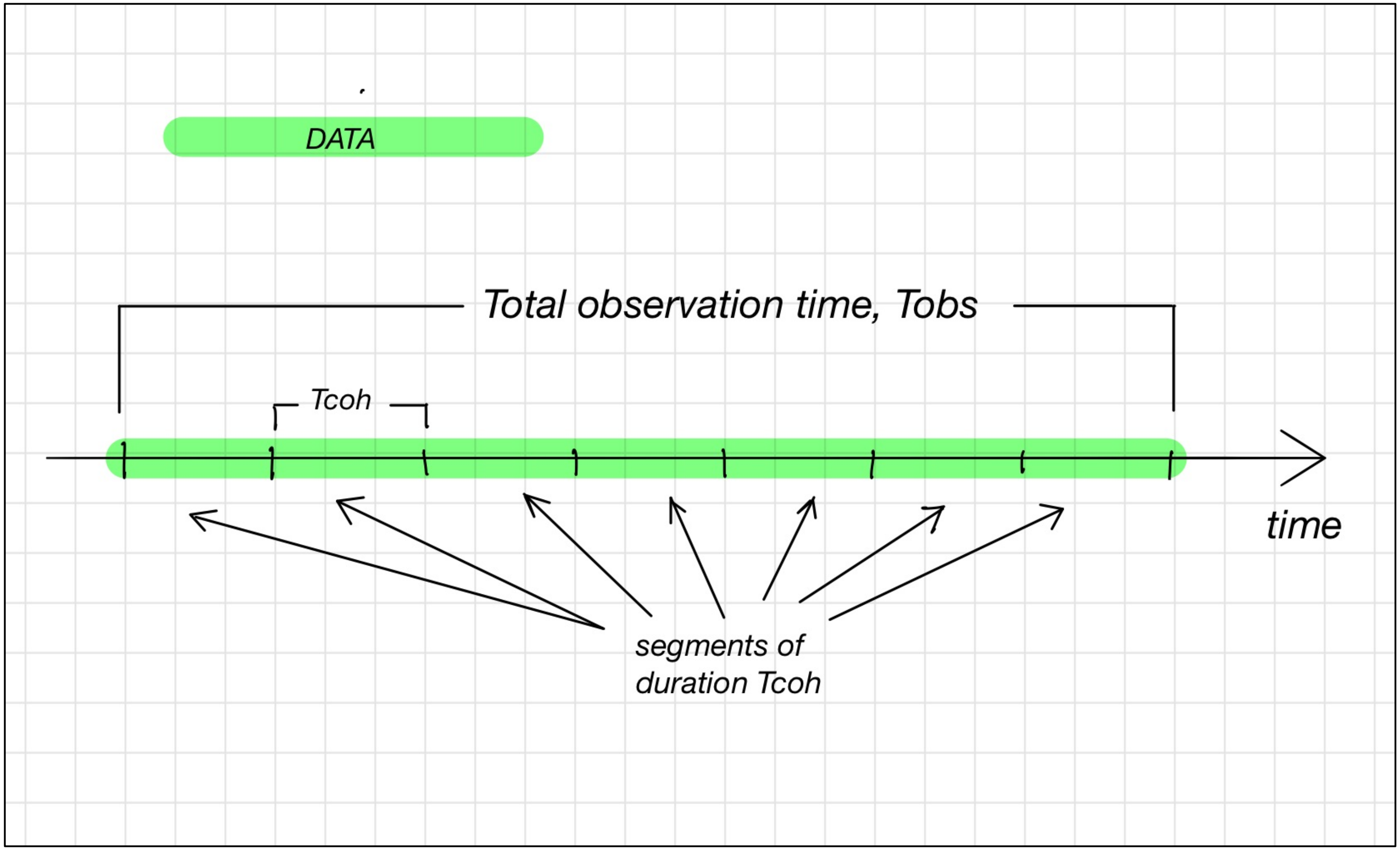
Interesting objects (e.g. CasA)

All-sky

Where's the challenge ?

- Signal is weak <~ 10^{-25} and we don't know its frequency or may not know where it is coming from
  - To dig it out of noise: coherently search data against signal waveforms for long periods of time
  - **Can resolve *many* (≈ 10^{17}) different waveforms (cf. aperture synthesis for radio telescopes)**
  - **Naïve approach is computationally unfeasible**

Semicoherent searches



Semicoherent searches

- $\text{SNR} \approx \frac{h_0}{\sqrt{S_h}} \sqrt{T_{coh}} \sqrt[4]{N_{seg}}$

- Comp-Cost $\propto T_{coh}^{\alpha}$ with typically $\alpha \geq 5$

- longer T_{coh} : more sensitive
  more expensive
  less robust

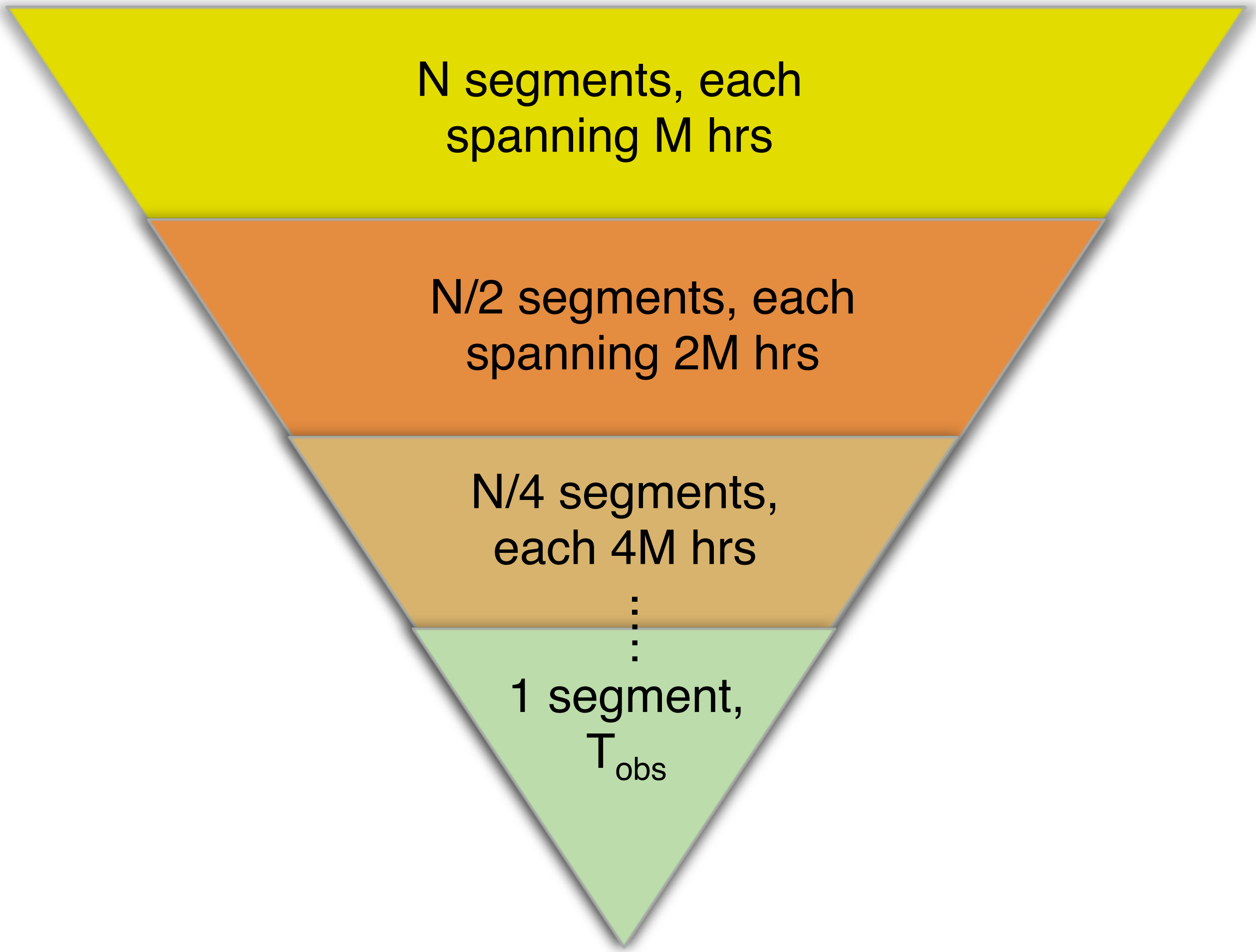
Two different types of surveys

- Broad, fast-turn around, robust, short Tcoh

- More limited in breadth, deepest, long Tcoh

volunteer computing

Hierarchical schemes



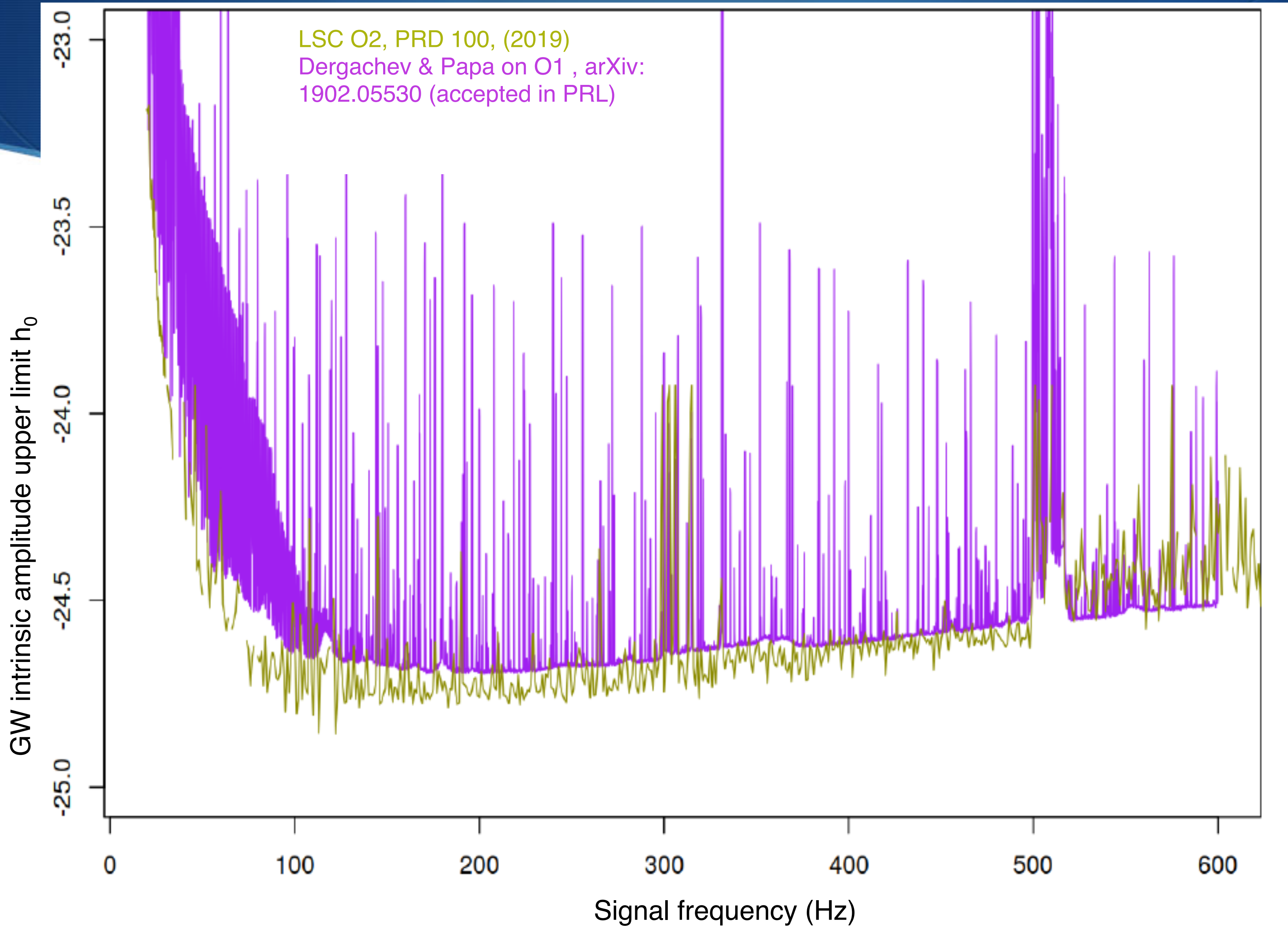
Hierarchical schemes

- At each stage more noise is rejected
- The significance of a signal-candidate is increased from one stage to the next, as is the uncertainty in the signal parameters
- Complex methods

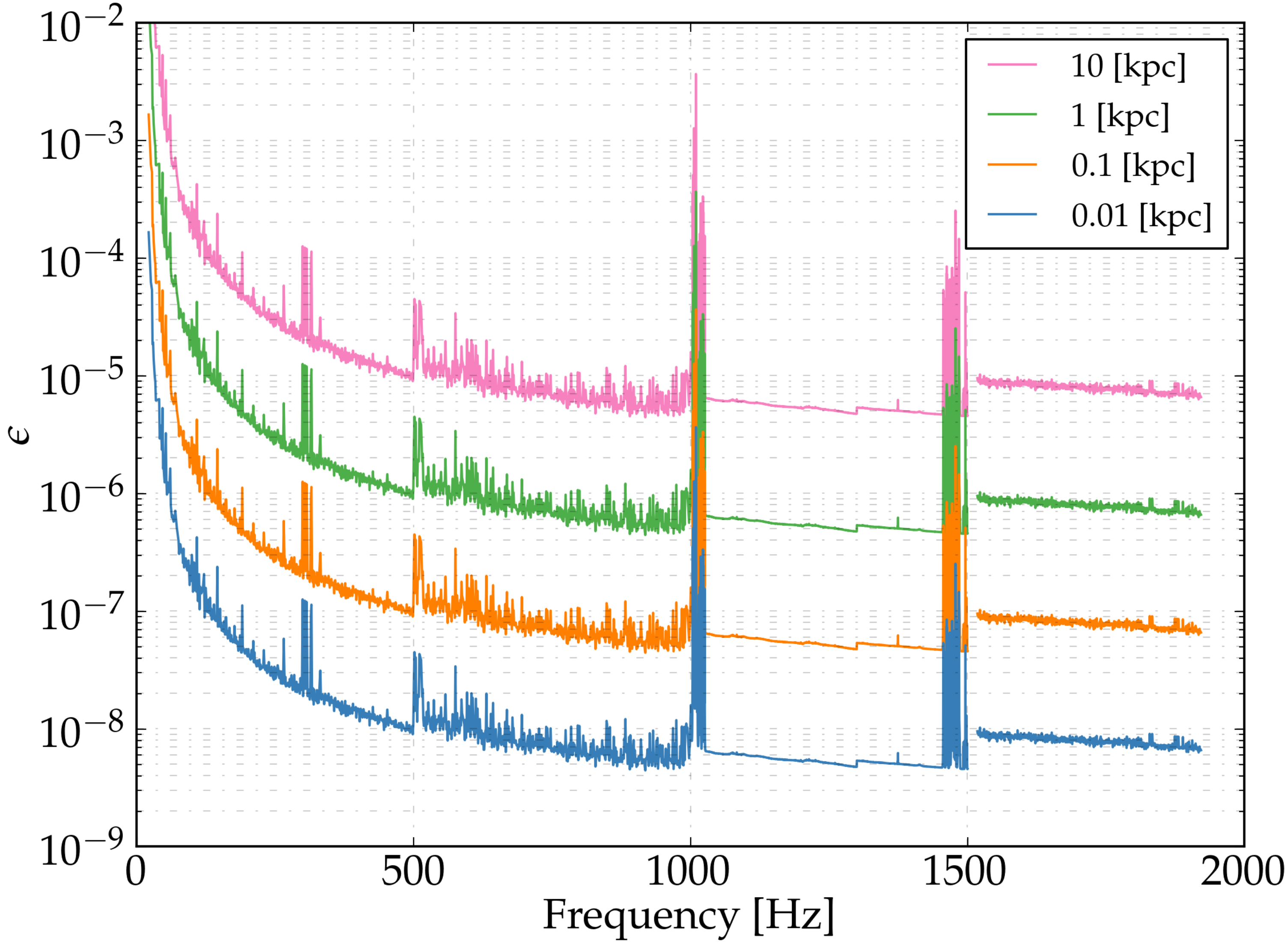
First such search: *M.A. Papa et al , “Hierarchical follow-up of subthreshold candidates of an all-sky Einstein@Home search for continuous gravitational waves on LIGO sixth science run data”, PRD 94 , 122006, (2016)*

All-sky searches on O2 data: nothing seen

All-sky

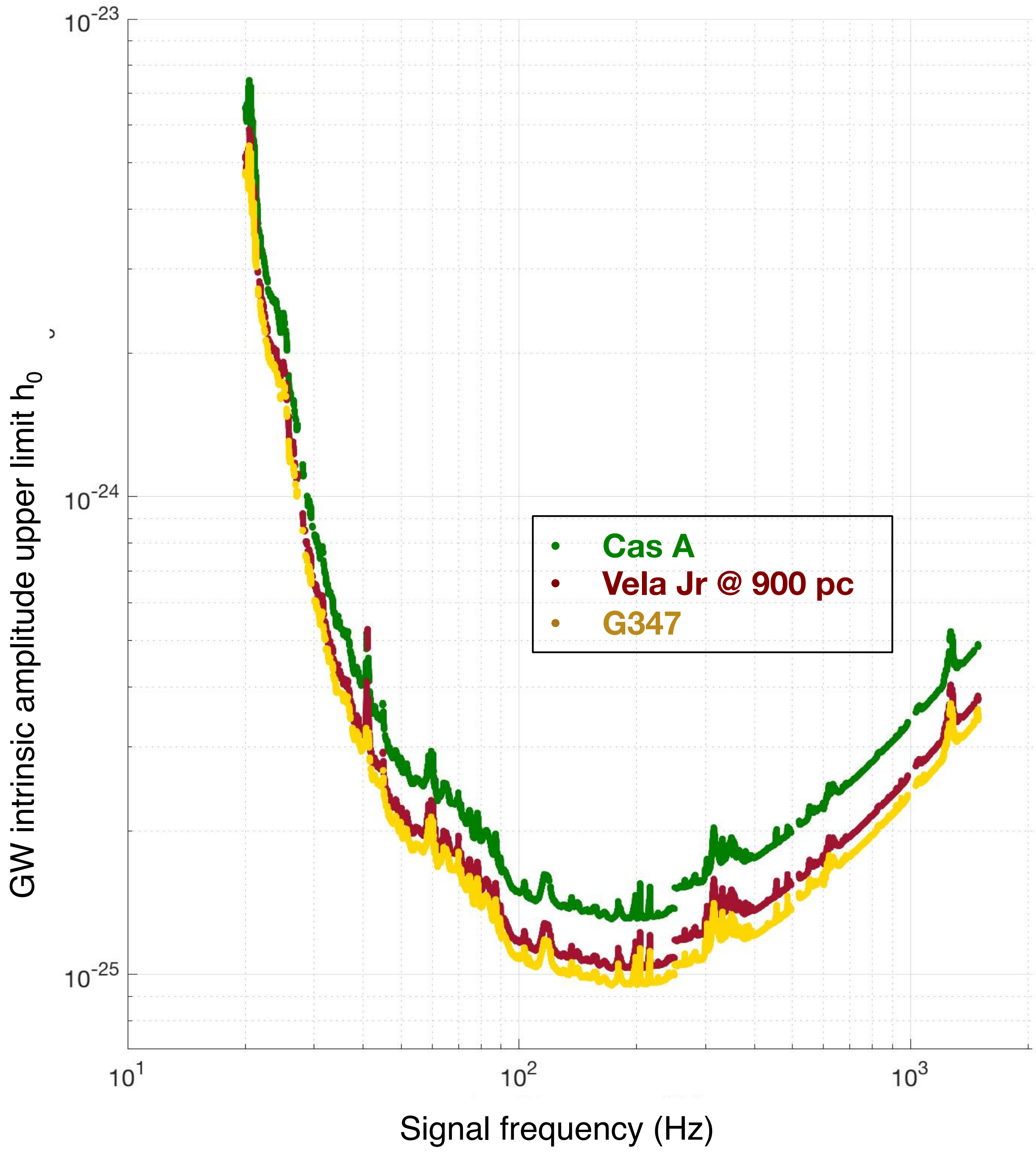

LSC O2, PRD 100, (2019)
Dergachev & Papa on O1 , arXiv: 1902.05530 (accepted in PRL)
GW intrinsic amplitude upper limit h_0
-23.0
-23.5
-24.0
-24.5
-25.0
0
100
200
300
400
500
600
Signal frequency (Hz)

Ellipticity upper limits



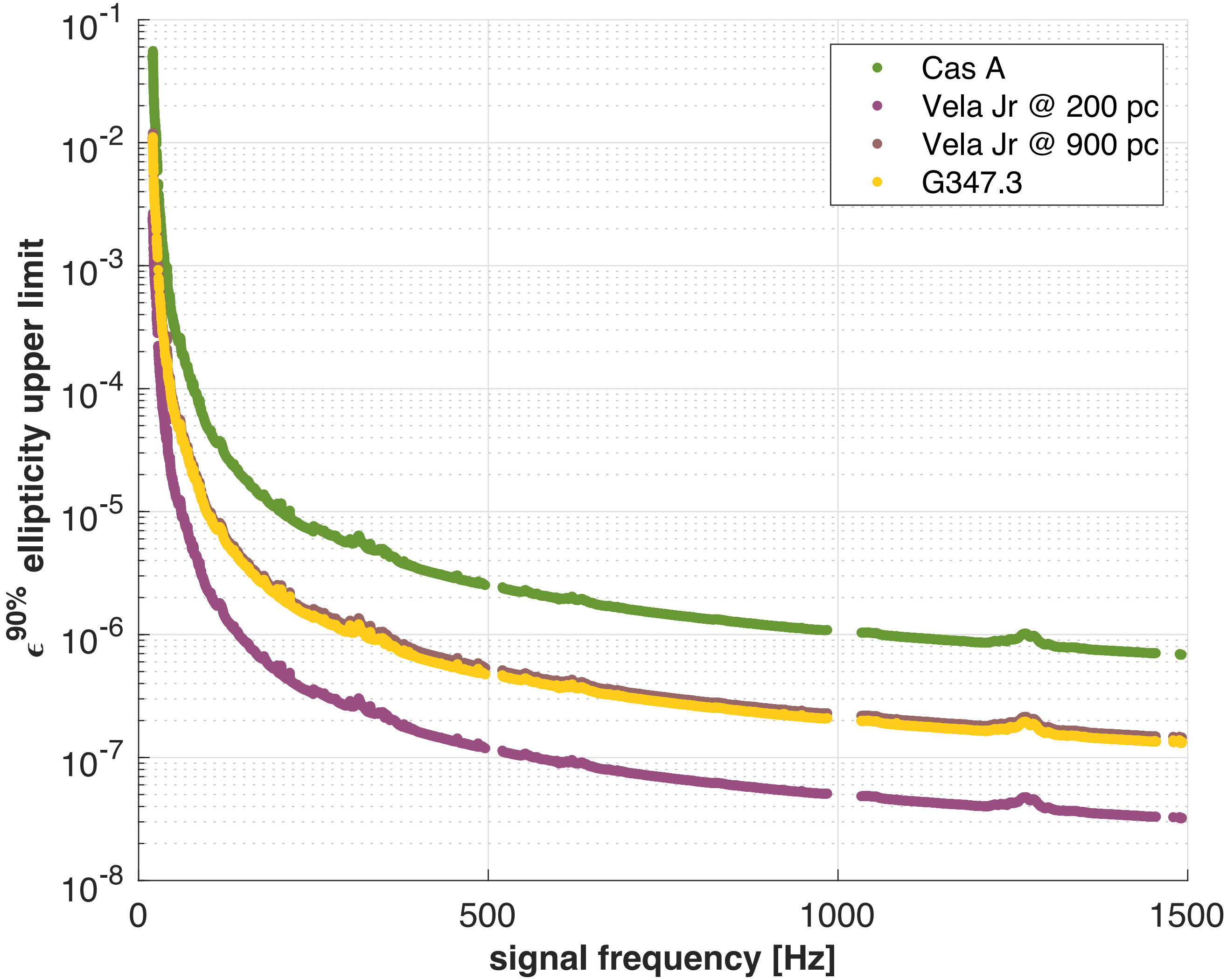
Directed searches

Directed searches



J.Ming, M.A.Papa et al, PRD 100, 2 (2019)

Ellipticity upper limits



J.Ming, M.A.Papa et al, PRD 100, 2 (2019)

List of young supernova remnants

LIGO/Virgo, ApJ 875, 122 (2019)

SNR (G name)	parameter space	Other name	RA+dec (J2000)	D (kpc)	a (kyr)
1.9+0.3		—	174846.9−271016	8.5	0.1
15.9+0.2		—	181852.1−150214	8.5	0.54
18.9−1.1		—	182913.1−125113	2	4.4
39.2−0.3		3C 396	190404.7+052712	6.2	3
65.7+1.2		DA 495	195217.0+292553	1.5	20
93.3+6.9		DA 530	205214.0+551722	1.7	5
111.7−2.1		Cas A	232327.9+584842	3.3	0.3
189.1+3.0	wide	IC 443	061705.3+222127	1.5	3
189.1+3.0	deep	IC 443	061705.3+222127	1.5	20
266.2−1.2	wide	Vela Jr.	085201.4−461753	0.2	0.69
266.2−1.2	deep	Vela Jr.	085201.4−461753	0.9	5.1
291.0−0.1		MSH 11−62	111148.6−603926	3.5	1.2
330.2+1.0		—	160103.1−513354	5	1
347.3−0.5		—	171328.3−394953	0.9	1.6
350.1−0.3		—	172054.5−372652	4.5	0.6
353.6−0.7		—	173203.3−344518	3.2	27
354.4+0.0	wide	—	173127.5−333412	5	0.1
354.4+0.0	deep	—	173127.5−333412	8	0.5

Decisions, decisions …

- Which ones ?
  - Youngest ?
  - Closest ?
- What signal frequency range ?
- What spindown spindown range ?
- Search
  - What frequency and frequency-derivative grid spacings ?
  - What search set-up (Tcoh) ?

Decisions, decisions …

An example of the *knapsack/backpack problem*

My backpack problem

- Pick among different targets and different search set-ups including ranges of searched signal parameters
  - Computing cost
  - Detection probability

- Want to maximize detection probability at fixed computing budget
  - most difficult part: priors on signal parameters

- Started with simplest broad parameter space search, i.e. the directed one

- J.Ming, M.A.Papa et al, Phys. Rev. D 97, 024051 (2018)
- J.Ming, M.A. Papa et al, Phys. Rev. D 93, 064011 (2016)

Astrophysics > High Energy Astrophysical Phenomena

Searches for Continuous Gravitational Waves from Fifteen Supernova Remnants and Fomalhaut b with Advanced LIGO

The LIGO Scientific Collaboration, the Virgo Collaboration: B. P. Abbott, R. Abbott, T. D. Abbott, S. Abraham, F. Acernese, K. Ackley, C. Adams, R. X. Adhikari, V. B. Adya, C. Affeldt, M. Agathos, K. Agatsuma, N. Aggarwal, O. D. Aguiar, L. Aiello, A. Ain, P. Ajith, G. Allen, A. Allocca, M. A. Aloy, P. A. Altin, A. Amato, A. Ananyeva, S. B. Anderson, W. G. Anderson, S. V. Angelova, S. Antier, S. Appert, K. Arai, M. C. Araya, J. S. Areeda, M. Arène, N. Arnaud, K. G. Arun, S. Ascenzi, G. Ashton, S. M. Aston, P. Astone, F. Aubin, P. Aufmuth, K. AultONeal, C. Austin, V. Avendano, A. Avila-Alvarez, S. Babak, P. Bacon, F. Badaracco, M. K. M. Bader, S. Bae, P. T. Baker, F. Baldaccini, G. Ballardin, S. W. Ballmer, S. Banagiri, J. C. Barayoga, S. E. Barclay, B. C. Barish, D. Barker, K. Barkett, S. Barnum, F. Barone, B. Barr, L. Barsotti, M. Barsuglia, D. Barta, J. Bartlett, I. Bartos, R. Bassiri, A. Basti, M. Bawaj, J. C. Bayley, M. Bazzan, B. Bécsy, M. Bejger, I. Belahcene, A. S. Bell, D. Beniwal, B. K. Berger, G. Bergmann, S. Bernuzzi, J. J. Bero, C. P. L. Berry, D. Bersanetti, A. Bertolini, J. Betzwieser, R. Bhandare, J. Bidler, I. A. Bilenko, S. A. Bilgili, G. Billingsley, J. Birch, R. Birney, O. Birnholtz, S. Biscans, S. Biscoveanu, A. Bisht, M. Bitossi, M. A. Bizouard, J. K. Blackburn et al. (1031 additional authors not shown)

(Submitted on 31 Dec 2018 (v1), last revised 4 Jan 2019 (this version, v2))

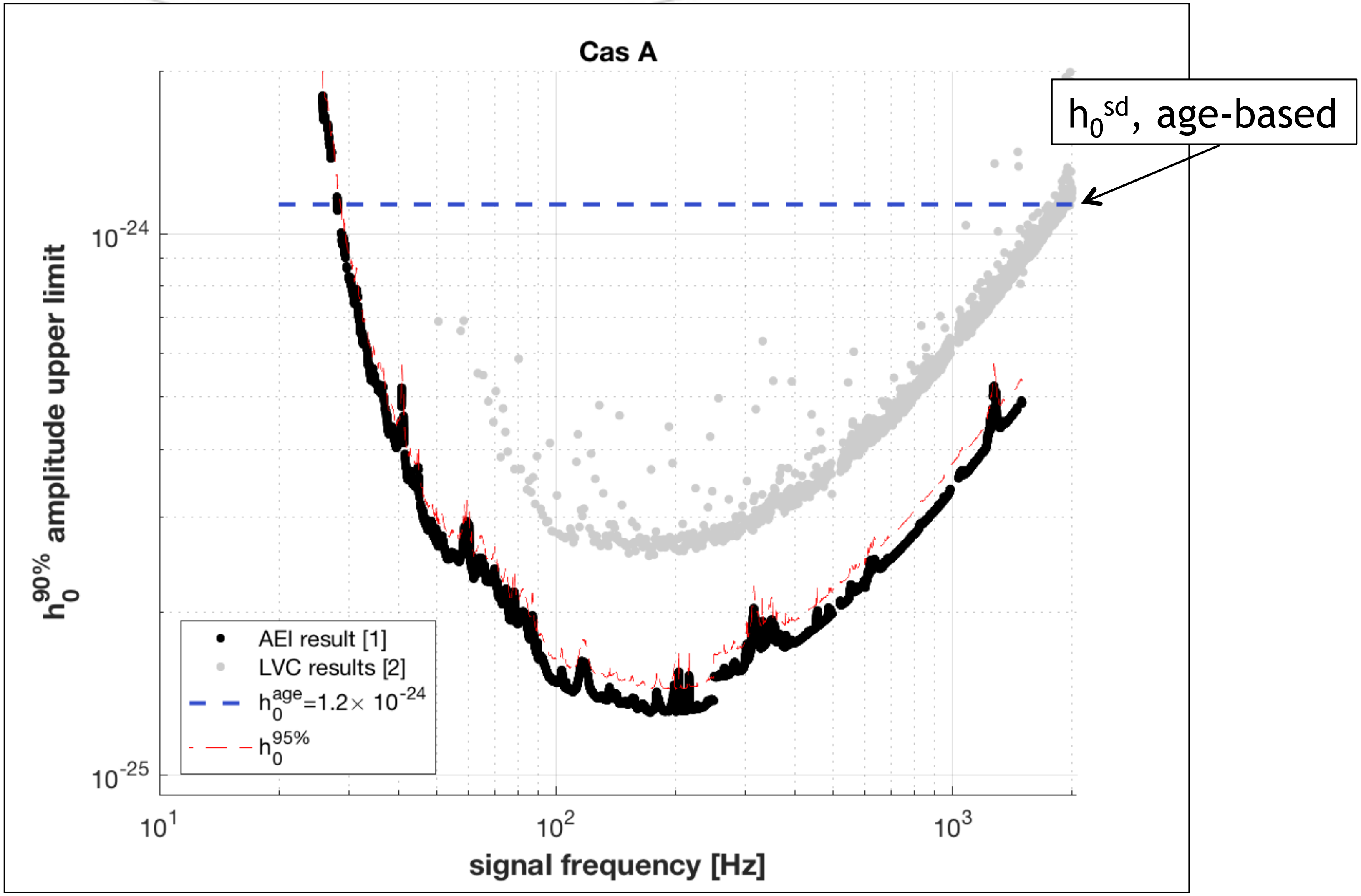
General Relativity and Quantum Cosmology

Results from an Einstein@Home search for continuous gravitational waves from Cassiopeia A, Vela Jr. and G347.3

Jing Ming, Maria Alessandra Papa, Avneet Singh, Heinz-Bernd Eggenstein, Sylvia J. Zhu, Vladimir Dergachev, Yi-Ming Hu, Reinhard Prix, Bernd Machenschalk, Christian Beer, Oliver Behnke, Bruce Allen

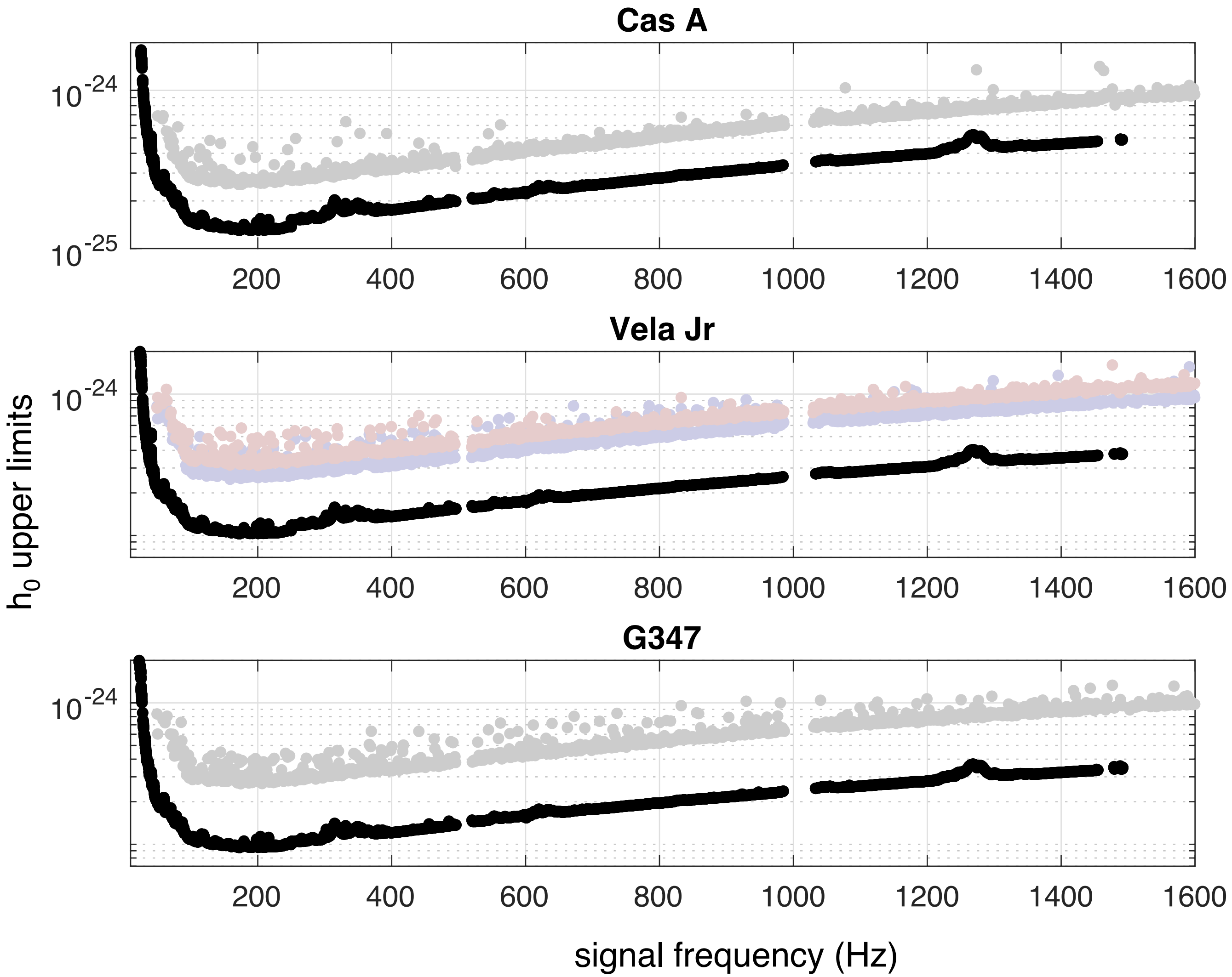
(Submitted on 21 Mar 2019)

Cas A results



Ming et al. PRD 100, 2 (2019) LIGO/Virgo, ApJ 875, 122 (2019)

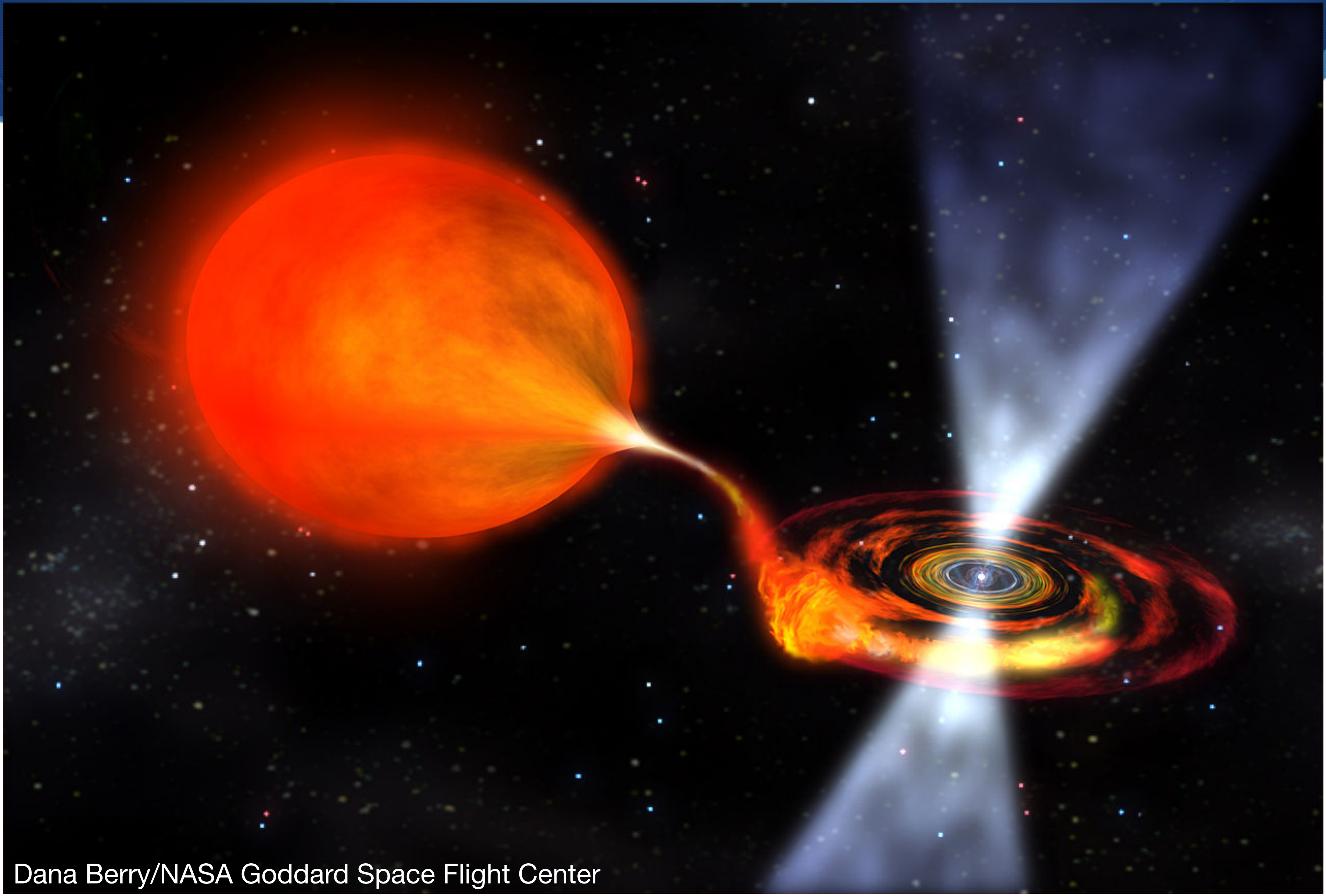
All three targets



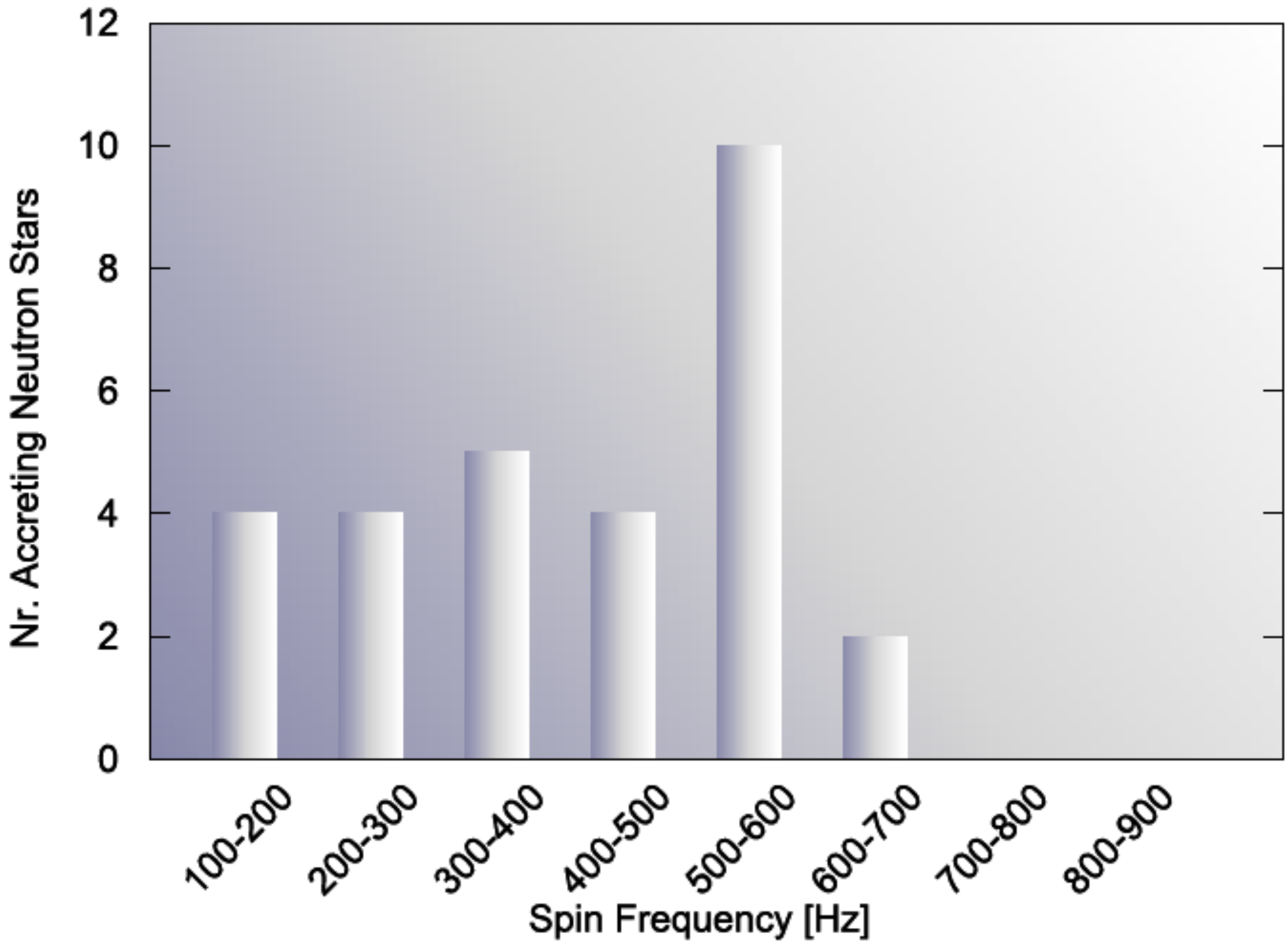
- Ming et al, PRD 100, 2 (2019)

- LIGO/Virgo, ApJ 875, 122 (2019)

LMXBs, e.g. Scorpius X-1

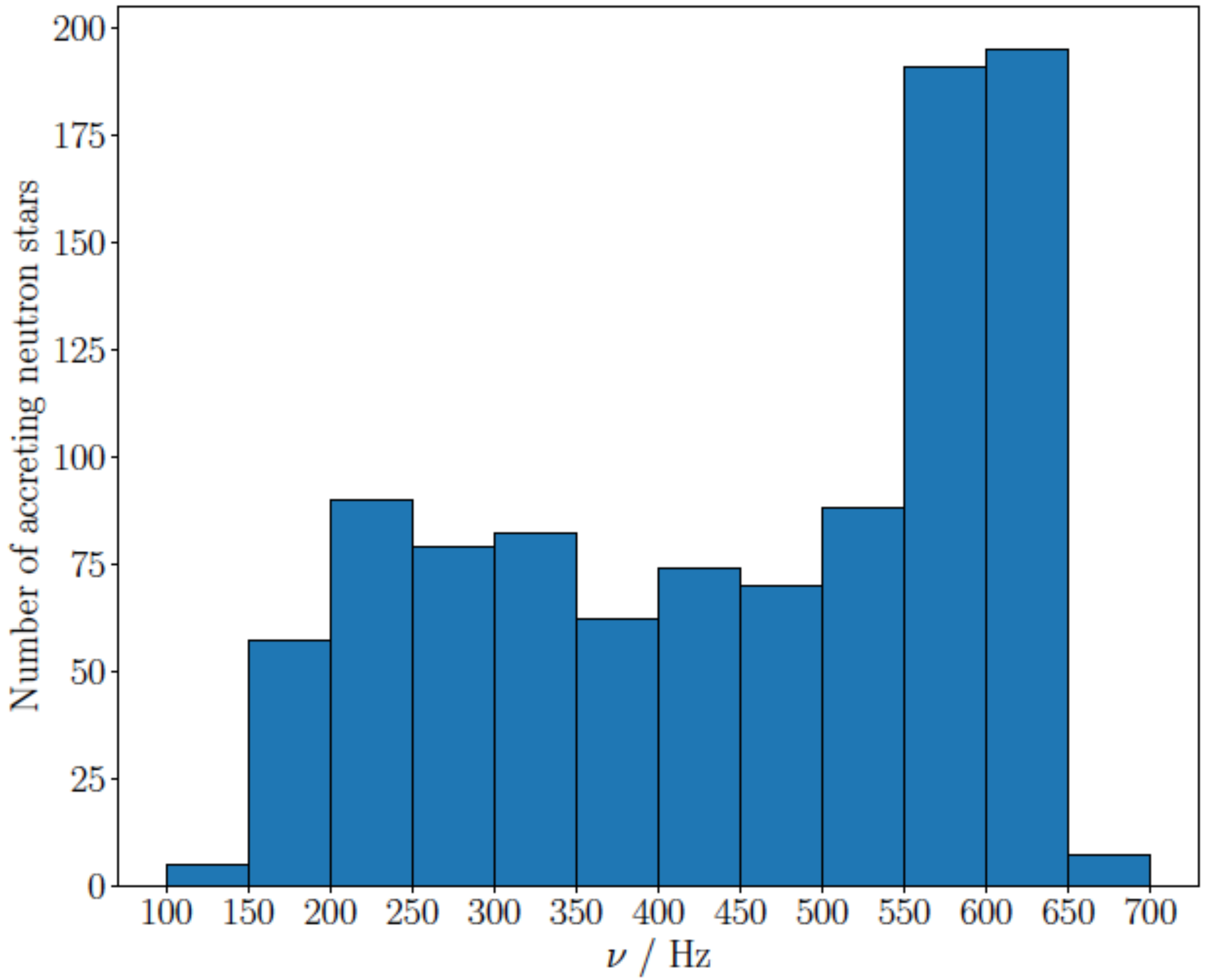


Two sub-populations of Neutron stars in LMXBs



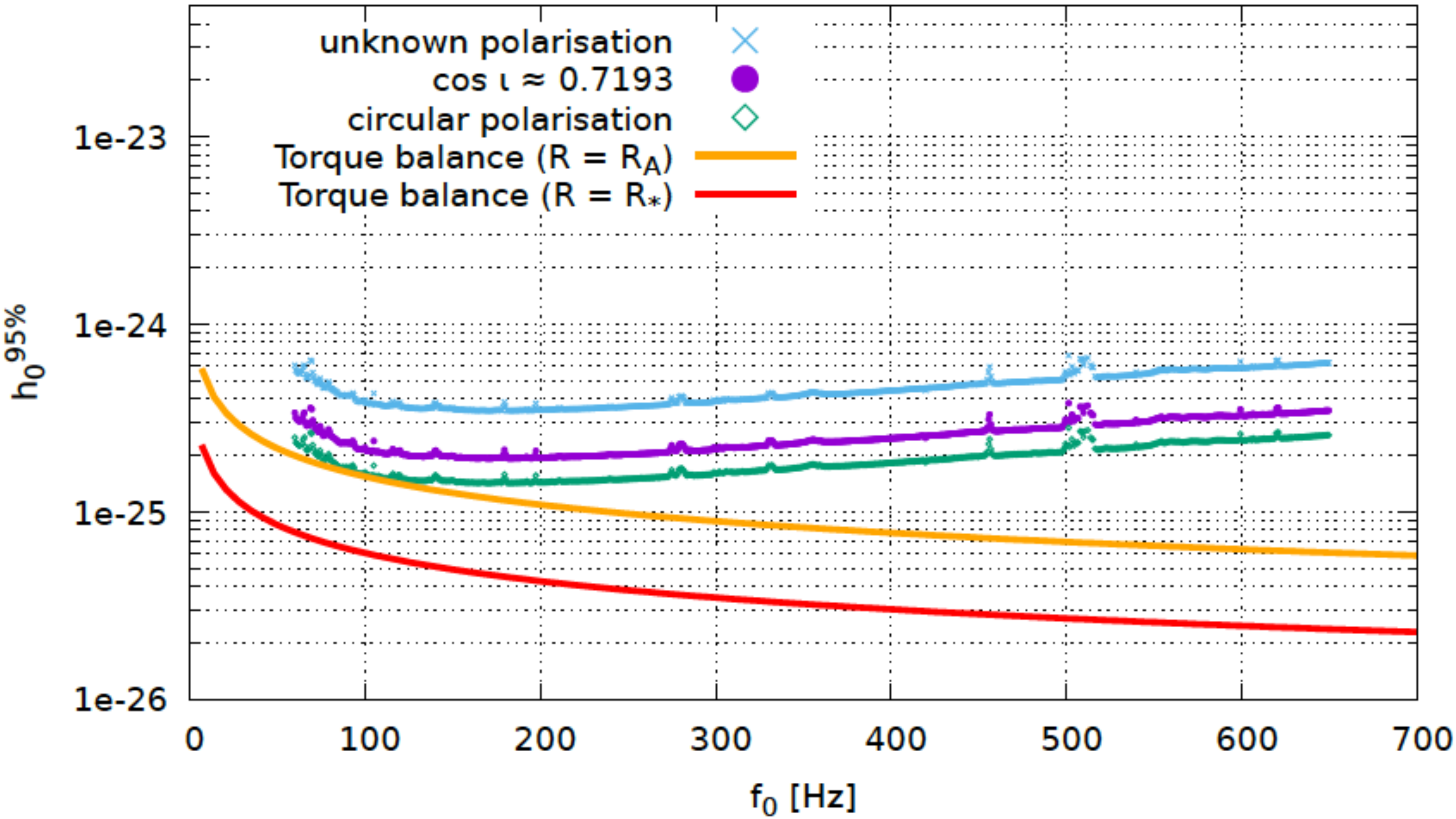
Patruno Haskell Andersson, ApJ 850 (2017)

Population synthesis of accreting neutron stars emitting GWs



F. Gittins, N. Andersson, arxiv:1811.00550

Results from Scorpius X-1



LVC, arxiv:1906:12040 on O2 data

Conclusions

- Major efforts to detect continuous GWs
- From continuous waves we will learn more about neutron stars: what they are and their history
- Broad searches are computationally challenging but interesting values of physical parameters are being probed
    - Volunteer distributed computing project E@H devotes significant resources to this problem
    - It is important to ponder how to use the computing power and match the search strategy with the most likely target
- Sadly, access to data outside of LVC is much delayed
    - the most sensitive searches cannot be performed in a timely manner

https://www.aei.mpg.de/continuouswaves

Thank you !

CONTINUOUS
GRAVITATIONAL
WAVES