Background: NASA/JPL-Caltech/WISE Team

LIGO–Virgo–KAGRA webinar

Towards understanding neutron stars with continuous gravitational waves

24 March 2022

https://dcc.ligo.org/G22XXXX/public

Towards understanding neutron stars with continuous GWs

1. <u>Introduction</u>
   Ian Jones
   Professor
   University of Southampton (UK)

2. <u>Known pulsars</u>
   Paritosh Verma
   PhD student
   National Centre for Nuclear Research (Poland)

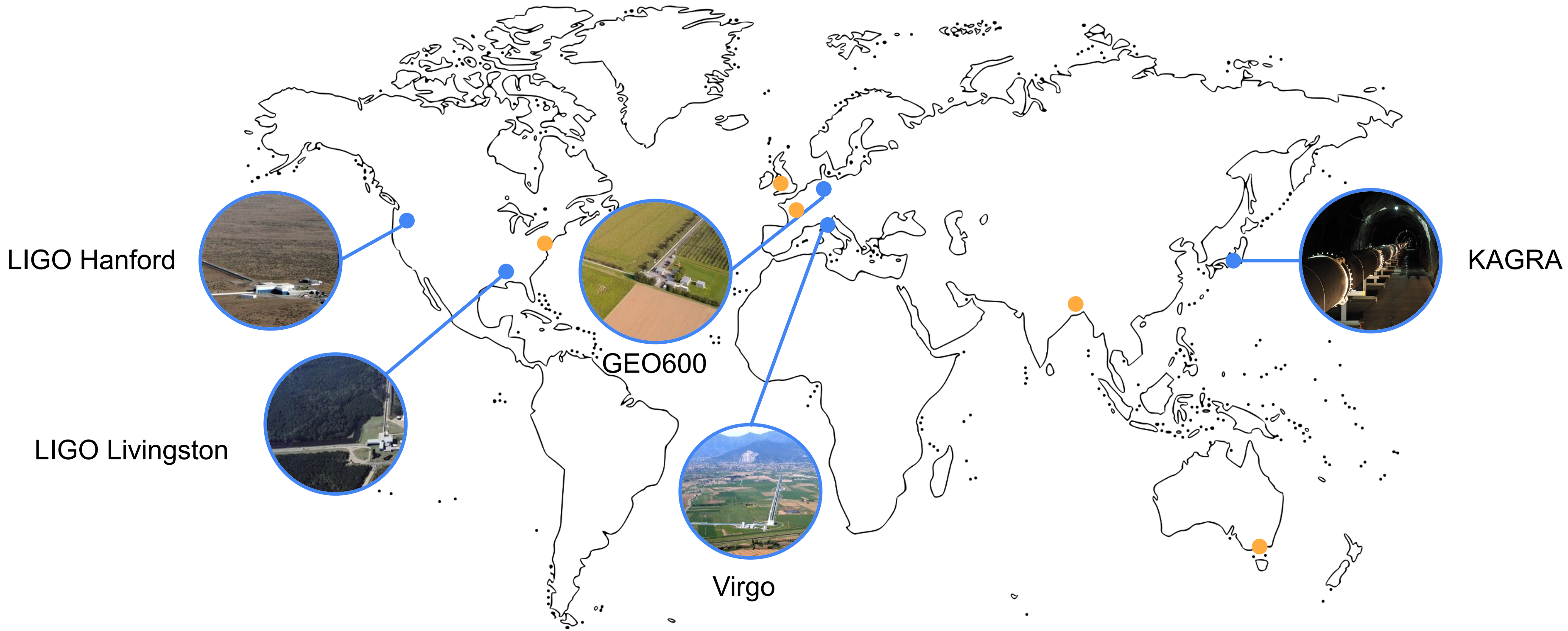
3. <u>Supernova remnants</u>
   Lucy Strang
   PhD student
   University of Melbourne (Australia)

4. <u>Accreting stars</u>
   Andrés Vargas-Sánchez
   PhD student
   University of Melbourne (Australia)

<u>Moderation:</u> Andrew Miller (Université catholique de Louvain, Belgium)

<u>Panelists:</u> Wynn Ho (Haverford College, USA), Simone Mastrogiovanni (Observatoire de Cote D'Azur, France), Arunava Mukherjee (Saha Institute of Nuclear Physics, India), Amy Hewitt (Lancaster University, UK)

Towards understanding neutron stars with continuous GWs

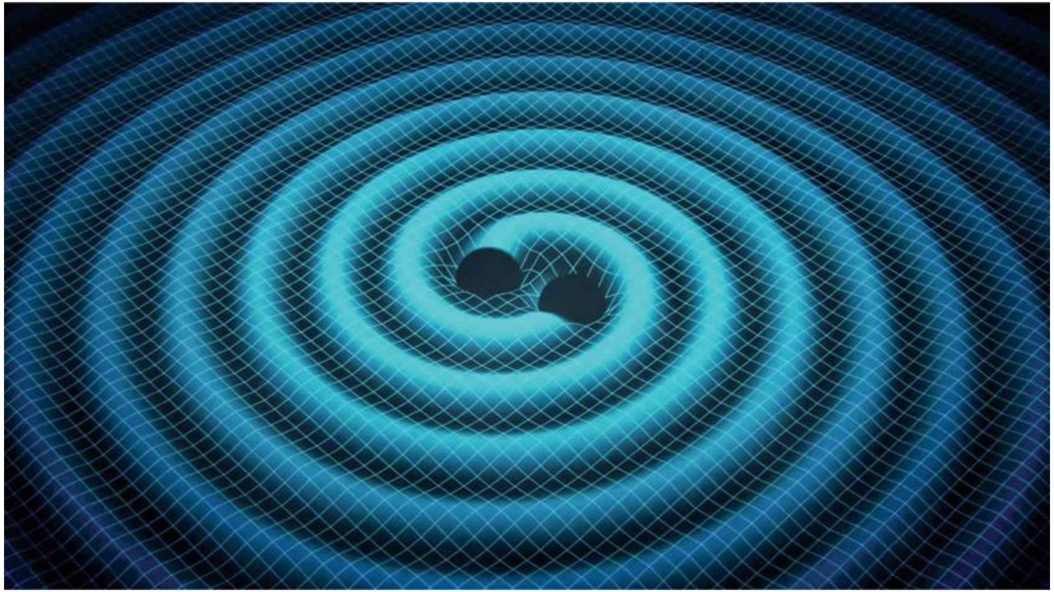


Thanks to all the people that have worked tirelessly on the detectors, computing clusters throughout the Covid-19 pandemic

Introduction

Gravitational Waves

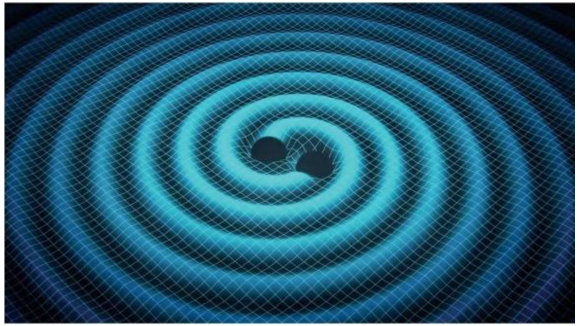
In 1916, Einstein realised that small disturbances in the gravitational field would propagate at the speed of light.



These ripples in spacetime are *gravitational waves (GWs)*.

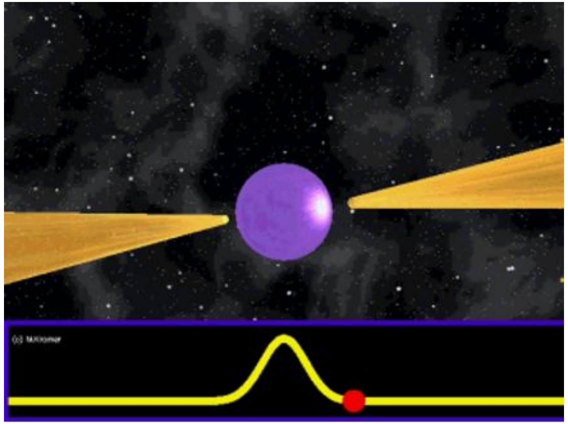
Sources of Gravitational Waves

Compact binary coalescence

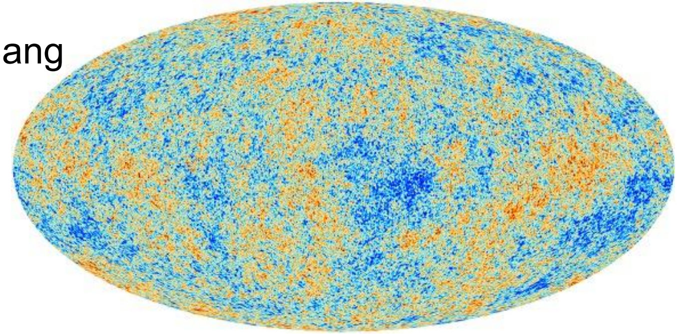


Exploding stars

Rotating neutron stars

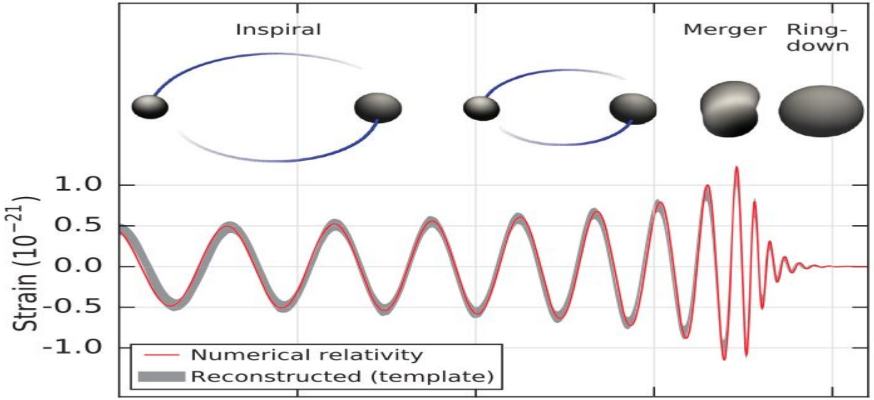


The Big Bang



Binary coalescence verses Continuous Waves

- **Compact binary coalescence**: “chirp signal”.
- Signal is short and “loud”.

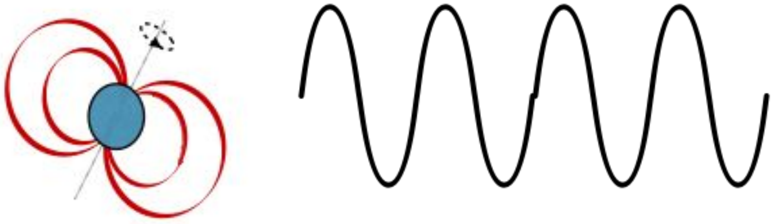


6]

- **Continuous waves (CWs)**: long lived quasi- monochromatic signals (e.g. from rotating neutron stars).

- Signals generally weaker, but signal to noise grows with observation time:

$$SNR \propto \sqrt{T}$$



Continuous wave searches

- Difficulty of search depends upon how much **prior information** we have from EM observations.

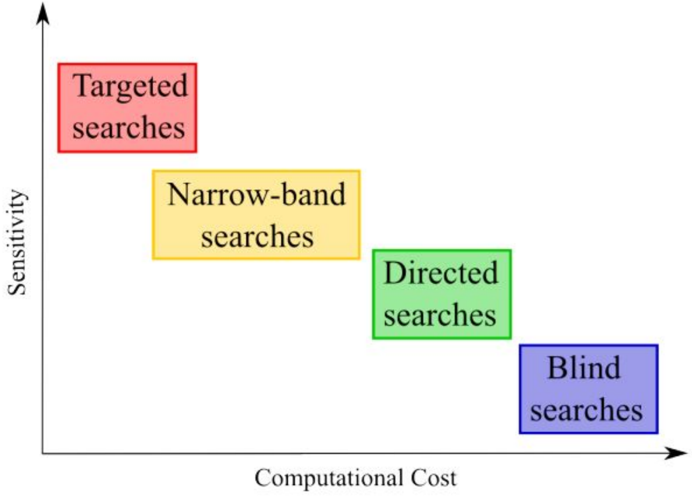
- **Targeted searches**: know sky location and frequency.

- **Narrow-band searches**: known sky location, but search over a small frequency band.

- **Directed searches**: known sky location, but frequency completely unknown.

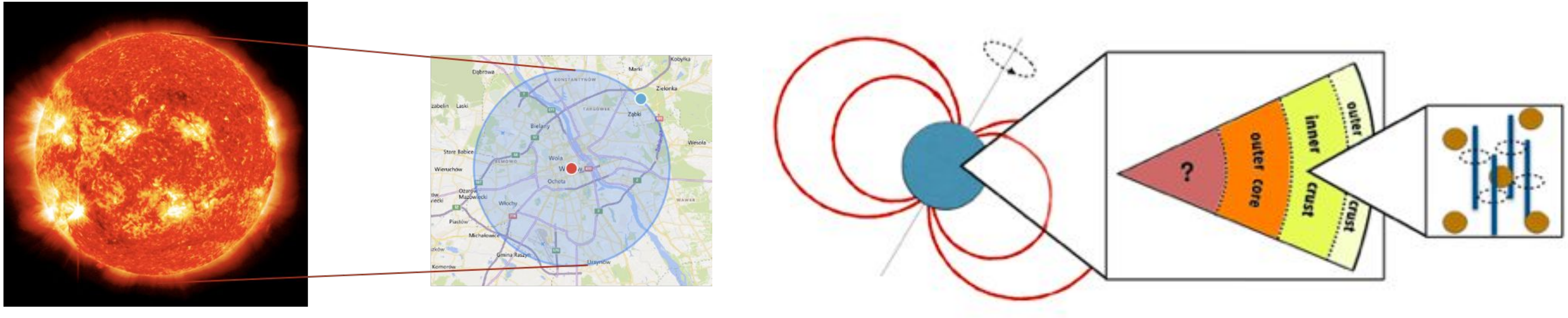
- **Blind searches**: don't know anything! See [recent webinar.]()

- Analysing long segments of data coherently is **computationally challenging**. *Semicoherent* strategies must be adopted to compensate the loss in sensitivity.



[Sieniawska & Bejger, Universe 5, 11217, 2019]

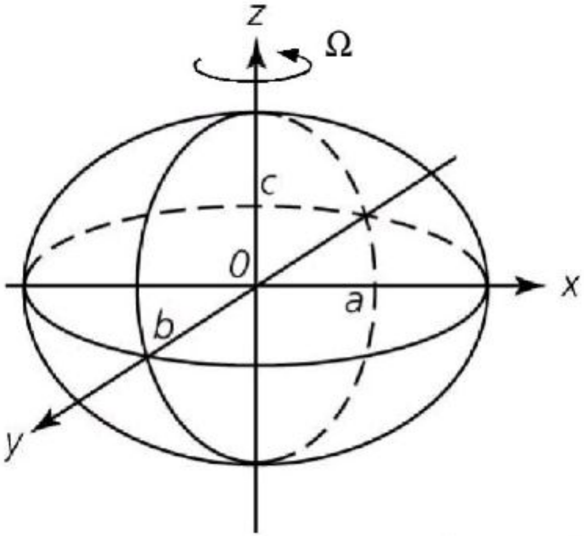
Neutron star structure



- The strong gravity of a Neutron Star ensures it is *almost* a perfect sphere.
- Crustal strains and magnetic fields can support small deformations.
- A deformation in a rotating star can lead to GW emission.

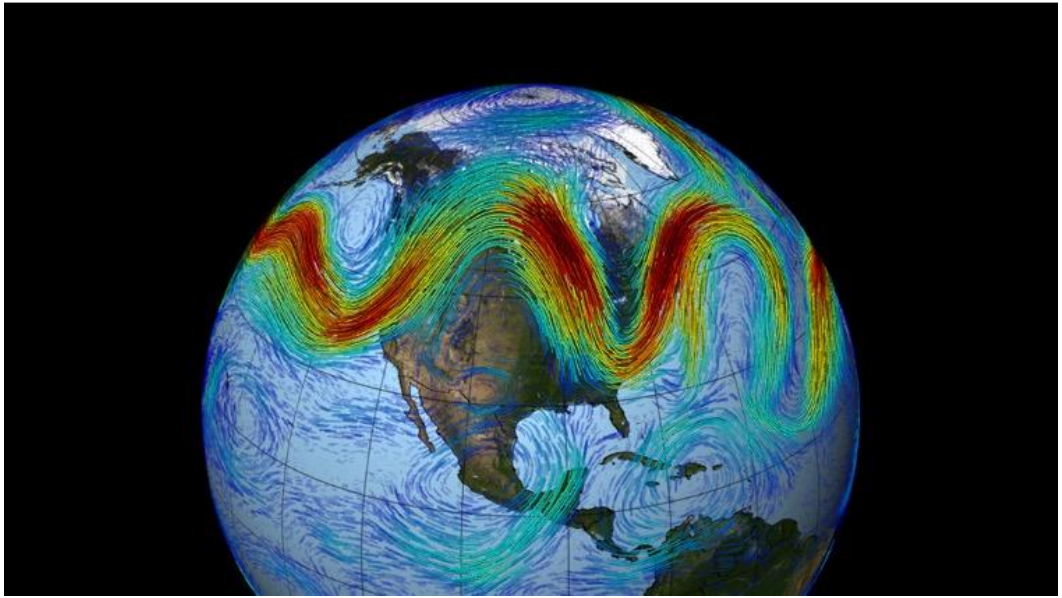
CWs from Neutron Stars

- Mountain size described in terms of ellipticity: $\epsilon = \dfrac{I_{xx} - I_{yy}}{I_{zz}}$
- Theoretical limits on the size: $\epsilon \lesssim 10^{-6}$
- Strongest emission at frequency $\omega = 2\Omega$
- We expect to be sensitive to sources in our galaxy.
- Gravitars: spun down entirely by GWs, ‘dark’ in EM.



CWs from stellar oscillations

Could also get CW emission from stellar oscillations.

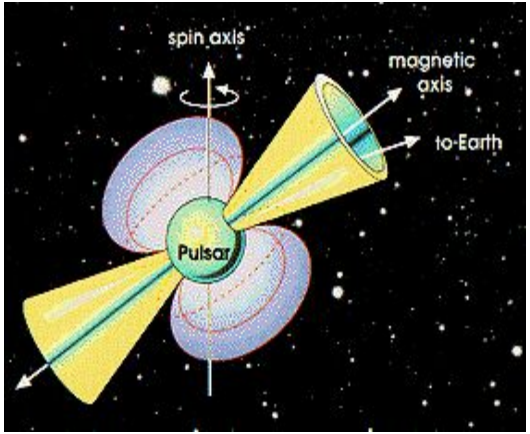


In close analogy with geophysics and solar physics, e.g. Rossby waves.

Gravitational waves from known pulsars

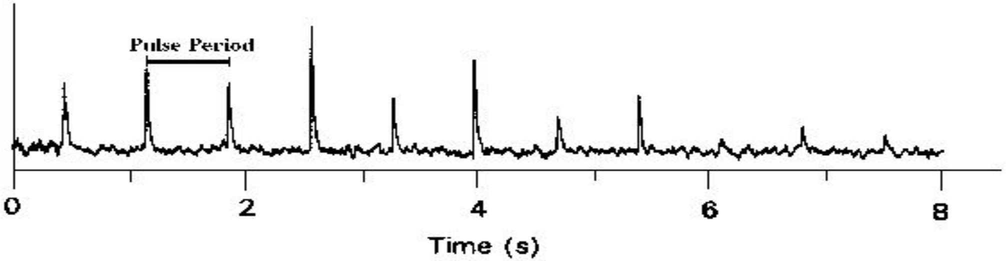
Introduction to Pulsars

- Pulsars are a special kind of neutron stars
- They emit a beam of radiation, which we observe as a periodic pulse as the beam sweeps over us once per rotation.



Courtesy: *Imagine the Universe!* at *NASA/GSFC*

Particles accelerated along strong magnetic field lines produce beam of radiation. If magnetic field not aligned along the spin axis, this gives lighthouse effect.

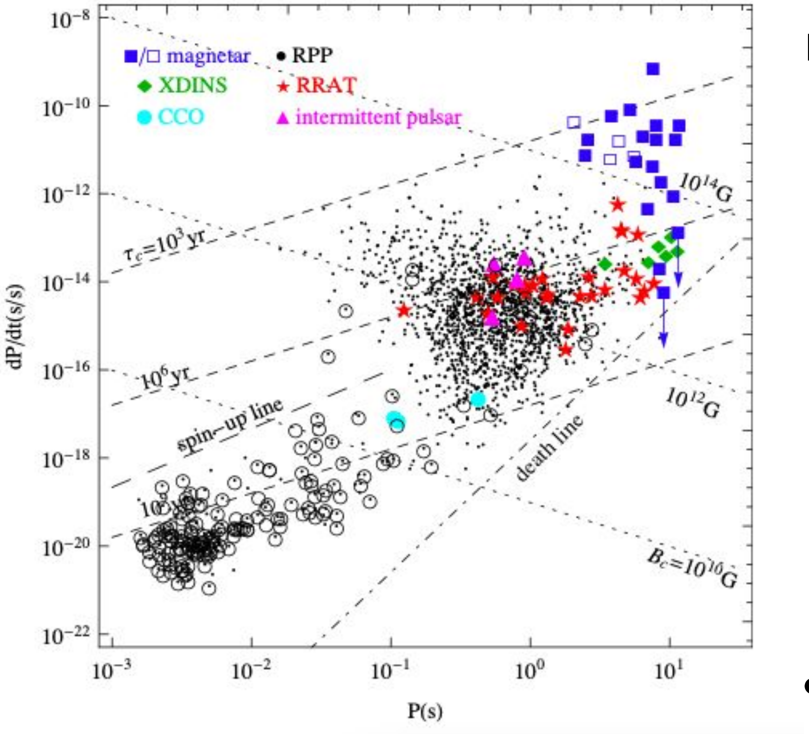


Courtesy: Manchester, R.N. and Taylor, J.H., Pulsars, Freeman, 1977.

1934: Walter Baade and Fritz Zwicky predicted the existence of NS.

1967: First pulsar was discovered by Jocelyn Bell and Anthony Hewish.

Introduction to Pulsars



arXiv:1508.03115

Estimated magnetic field: $B = 3.2 \times 10^{19}\sqrt{P\dot{P}} \quad G$

Standard pulsar: $B \approx 10^{12}G$

Accreting pulsar: $B \approx 10^{8}G$

Magnetar: $B \approx 10^{15}G$

A rough approximation of pulsar's age: $\tau_c = \dfrac{P}{2\dot{P}}$

- Young and strongly magnetized: top right hand corner
- Old and weakly magnetized: bottom left

Introduction to Pulsars

Pulsars are observed across all parts of the electromagnetic spectrum from radio waves to gamma-rays.

Lovell telescope, Jodrell Bank Observatory (Courtesy: Wikipedia)

Parkes radio telescope (Courtesy: Wikipedia)

Fermi satellite (Courtesy: Wikipedia)

GWs from Pulsars

Continuous GW: A signal with duration longer than the typical observation time of a detector.

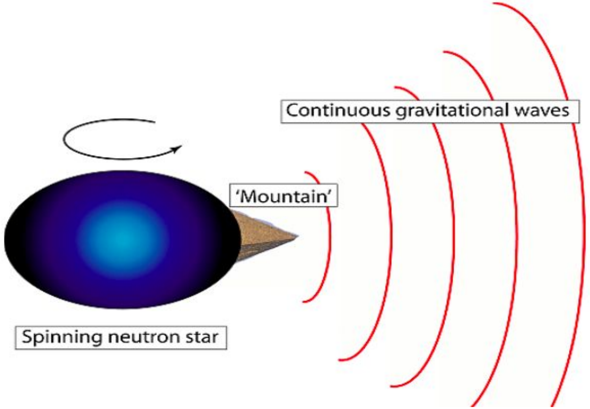
- It is believed that the Milky Way contains about a billions of neutron stars, more than 3000 (mostly pulsars) have been detected so far using EM observations.
- A fraction of these emit in the sensitivity band of GW interferometers.

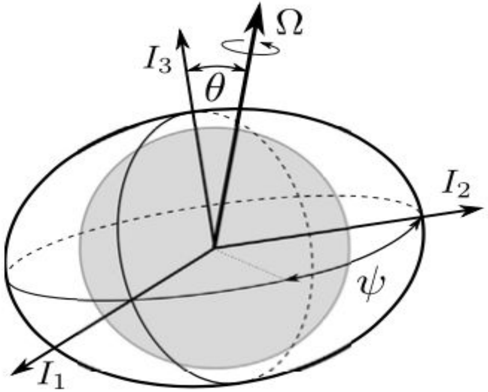
  ❏ These signals are feeble but always present.
  ❏ Therefore, possible to implement procedure to increase the SNR.
  ❏ SNR increases with the observation time.

Spin-down: The rotation frequency of the pulsar, and hence the GW frequency slowly decreases due to the loss of energy in the form of radiation.

Spin-down limit: Rate of change of rotational kinetic energy = Power emitted in GWs

Models





$$f_{GW} = 2f_{rot}$$

$$f_{GW} = 2f_{rot} \quad \& \quad f_{GW} = f_{rot}$$

There has also been a search for gravitational dipole radiation using Brans-Dicke theory of gravity. The dipole radiation originates at the spin frequency of the star.

$$f_{GW} = f_{rot}$$

Analysis and results (Targeted)

Analysis

- We searched for continuous GWs from O2 and O3 runs at two frequencies
- Total 236 known pulsars
- 168 of them are in the binary system
- 161 with frequency > 100 Hz

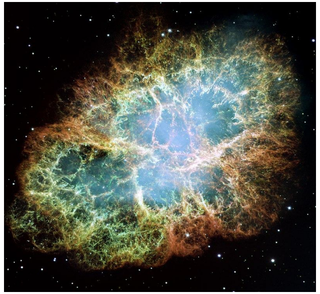
Results

- No evidence of GWs are found both in GR and BD theory
- Improved the upper limits on signal amplitudes
- 23 pulsars surpassed the spin down limit (Younger pulsars)
- Obtained stringent limits on the height of mountains

https://arxiv.org/abs/2111.13106

Analysis and results (Targeted)

Crab Pulsar



Credit: Hubble space telescope

Glitch occurred

High spin-down

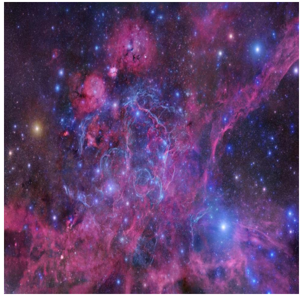
GWs contributes < 0.009% of the spin-down

$$h_0^{95\%} = 1.3(1.2) \times 10^{-26}$$ at d = 2 kpc

$$Q_{22}^{95\%} = 5.6(5.0) \times 10^{32}\ kg - m^2$$

$$\epsilon^{95\%} = 7.2(6.5) \times 10^{-6}$$

Vela Pulsar



Credit: NASA

No glitch occurred

Very High spin-down

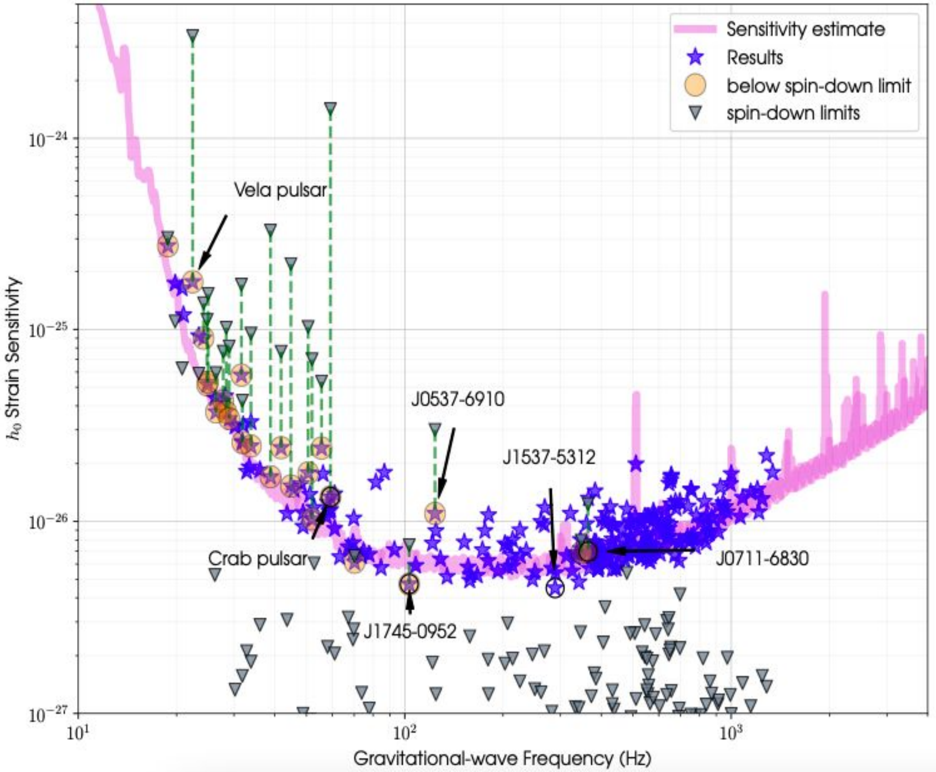
GWs contributes < 0.27% of the spin-down

$$h_0^{95\%} = 1.8(1.7) \times 10^{-25}$$ at d = 0.28 kpc

$$Q_{22}^{95\%} = 7.2(7.1) \times 10^{33}\ kg - m^2$$

$$\epsilon^{95\%} = 9.3(9.2) \times 10^{-5}$$

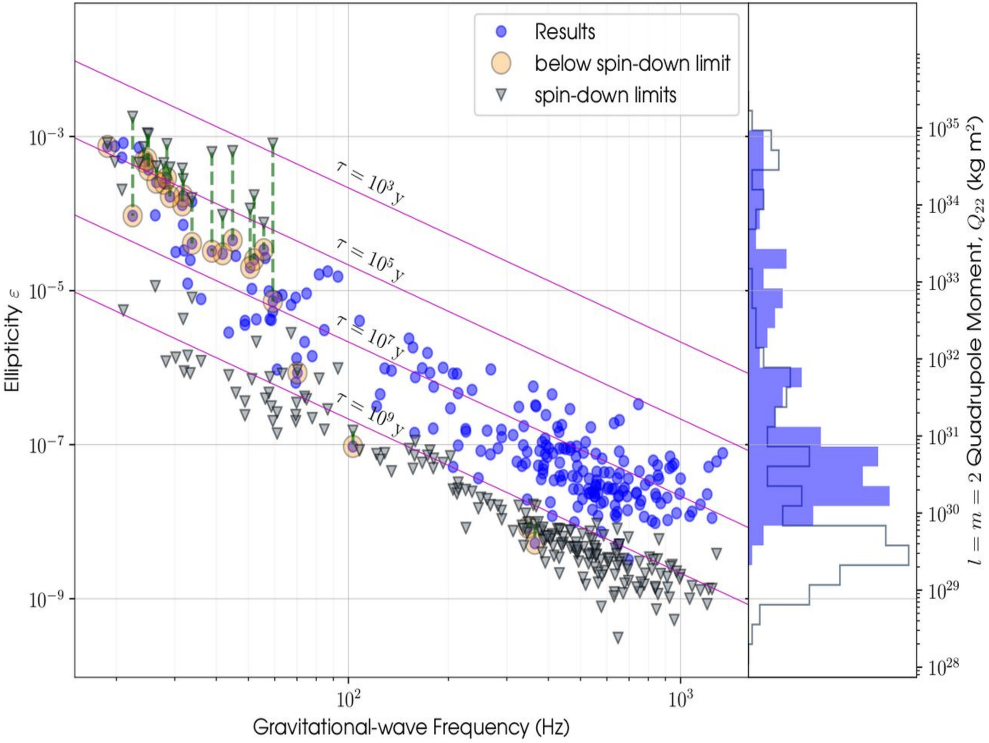
Analysis and results (Targeted)



$$h_0 \approx 4.23 \times 10^{-26} \left(\frac{1\ \text{kpc}}{\text{d}}\right) \left(\frac{I_{zz}^{fid}}{10^{38}\ \ kg\ m^2}\right) \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{f_{rot}}{100\ Hz}\right)^2$$

- Blue stars: 95% credible upper limit for GW amplitudes.
- Grey triangle: spin-down limit for each pulsar.
- Shaded circles: h0 for pulsars which surpass spin-down limits.
- Green dotted line: if upper limit is less than spin-down limit
- Solid line: Joint detector estimate for O3

Analysis and results (Targeted)

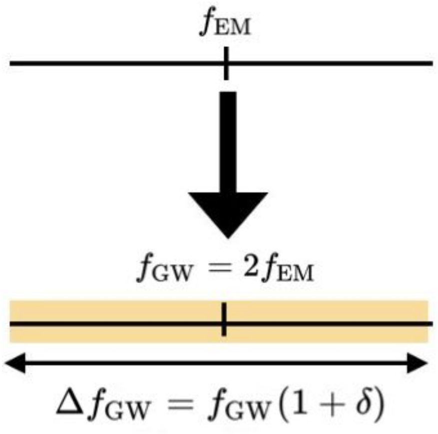


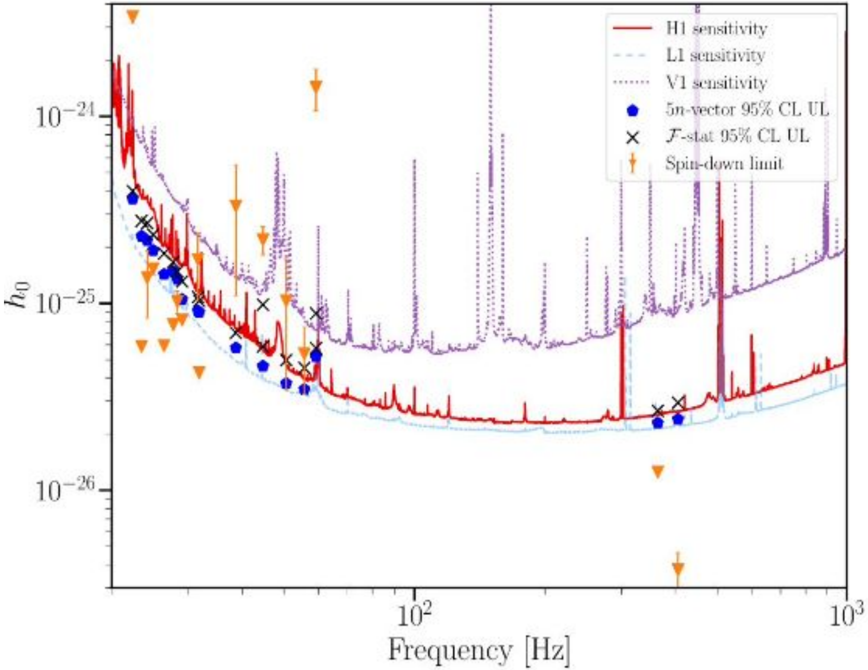
$$\epsilon \approx 2.36 \times 10^{-6} \left(\frac{h_0}{10^{-25}}\right)\left(\frac{d}{1\ kpc}\right)\left(\frac{100\ Hz}{f_{rot}}\right)^2\left(\frac{10^{38}\ kg\ m^2}{I_{zz}^{fid}}\right)$$

- Limit on mass quadrupole moment which in turn places limit on ellipticity.
- Result from single harmonic Bayesian analysis.

Narrowband search

Narrow band searches: Similar to targeted search, but allowing some uncertainty in the frequency and spin-downs around the EM values.





arxiv.org/abs/2112.10990

(Astrophysical Journal accepted)

Two main pipelines:

- 5n-vector search (used for O2, Abbott + PRD99,122002)
- Search using F-stat (new for narrowband)

Transient search

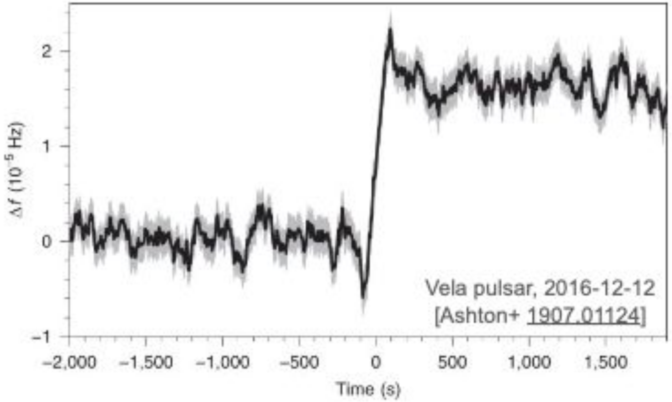
Pulsars slowly spin down over time due to emission of radiation. But sometimes they suddenly spin up! This is known as pulsar **glitch**.

Unlike CWs, the transient signal has a definite start-time and a finite effective lifetime, and the signal amplitude can be modulated by a window function.

In addition to phase and amplitude parameters:

$$\lambda = \{\alpha, \delta, f, \dot{f}, \ddot{f} \dots\}$$

$$\mathscr{A} = \{h_0, \cos\iota, \psi, \phi_0\}$$



Vela pulsar, 2016-12-12
[Ashton+ 1907.01124]

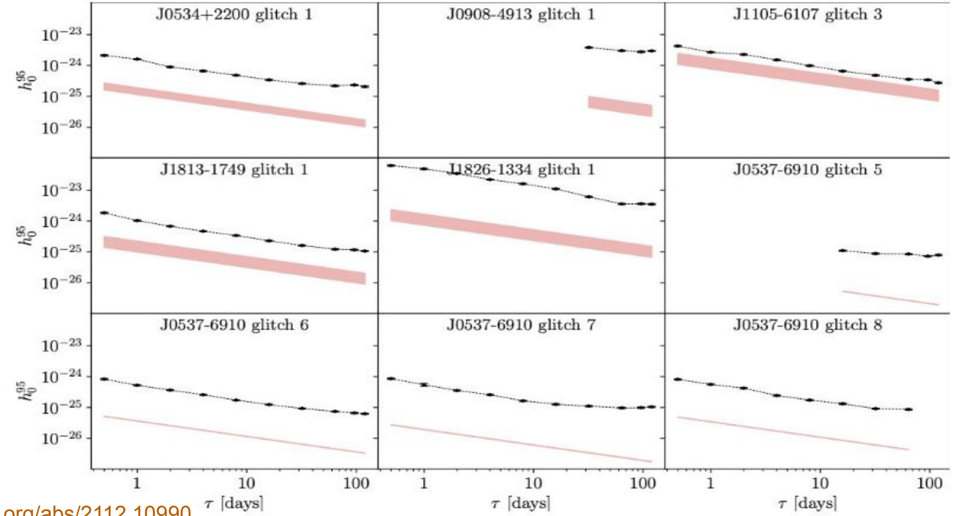
we consider a set of transient parameters: the start time and duration of the signal.

Credit: L.M.Modafferi/D.Keitel (UIB/IAC3)

Transient search results

Glitching pulsars are rare, so we target all during O3 with decent f_{GW} regardless of energy constraint.

J0534+2200 **“the Crab”**	**J0537-6910** **“big glitcher”**	**J0908-4913**	**J1105-6107**	**J1813-1749**	**J1826-1334**
f_{GW} ~ 60 Hz	f_{GW} ~ 123 Hz	f_{GW} ~ 19 Hz	f_{GW} ~ 31 Hz	f_{GW} ~ 45 Hz	f_{GW} ~ 20 Hz
glitched on 2019/07/23	4 glitches for O3, ± (3–8) days	glitched ~ 2019/10/09 ± 4.5 days	glitched ~ 2019/04/09 ± 2 days	glitched ~ 2019/08/03 ± 1 day	glitched ~ 2020/01/31 ± 21 days



arxiv.org/abs/2112.10990

Transient search: upper limit results

🟥 glitch excess energy

-‡- ULs from injection recovery

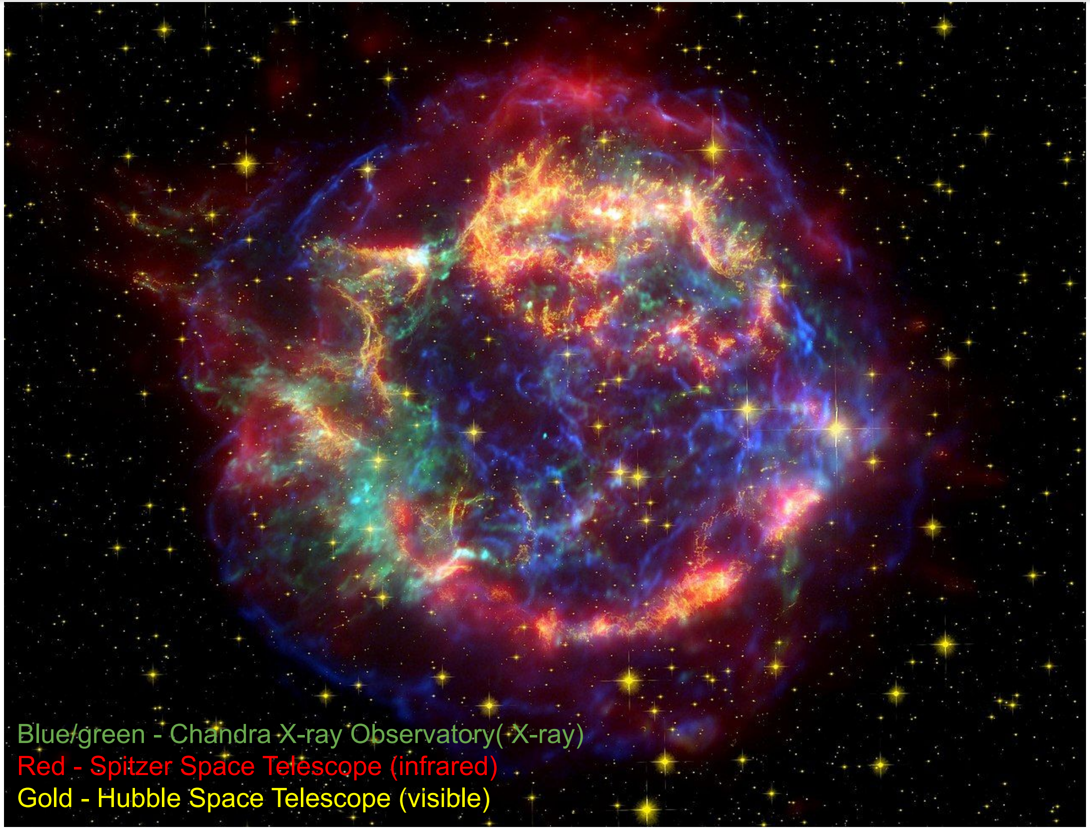
$$h_0 \le \frac{1}{d}\sqrt{\frac{5G}{2c^3}\frac{I}{\tau}\frac{\Delta f_{gl}}{f}}$$

Glitch excess energy
(Prix + 1104.1704)

Gravitational waves and supernova remnants

Supernova remnants

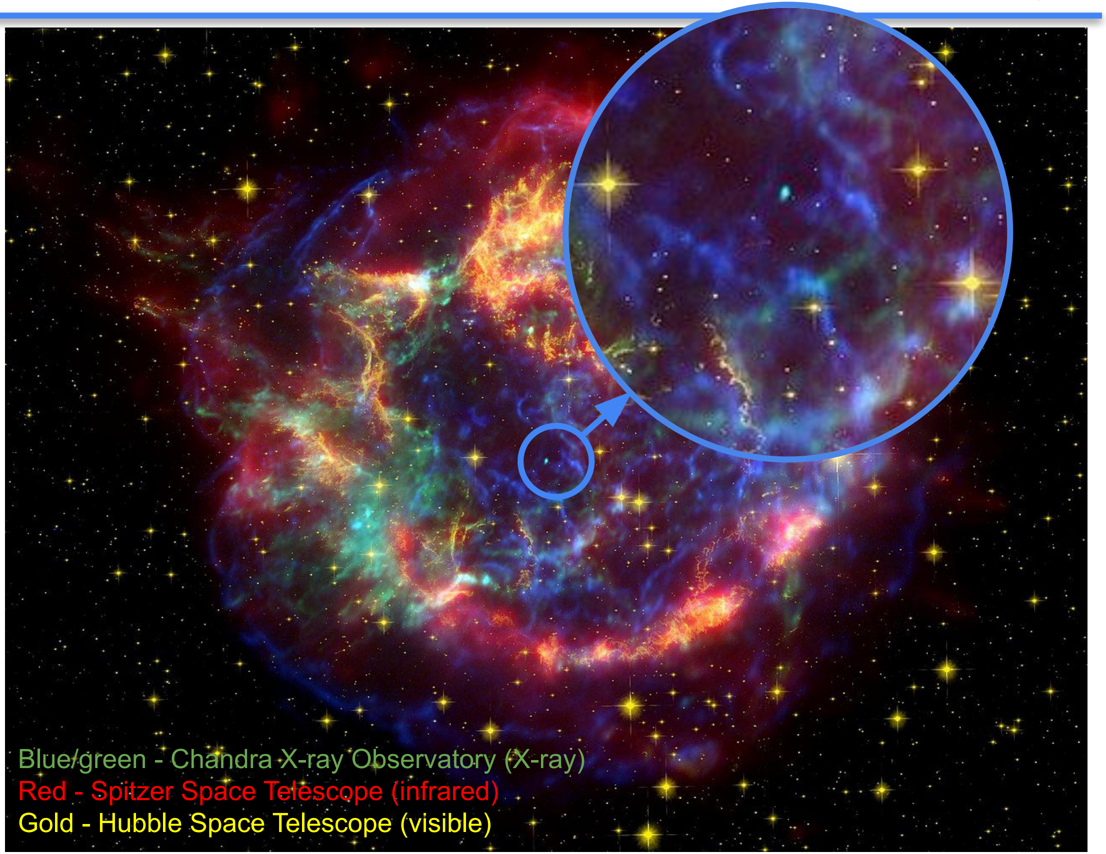
- Core-collapse supernovae mark the deaths of massive stars
- The light, outer layers of the star are blown off as supernova ejecta and the dense core remains as a neutron star


Blue/green - Chandra X-ray Observatory(X-ray)
Red - Spitzer Space Telescope (infrared)
Gold - Hubble Space Telescope (visible)

Courtesy NASA/JPL-Caltech

Supernova remnants

- Core-collapse supernovae mark the deaths of massive stars
- The light, outer layers of the star are blown off as supernova ejecta and the dense core remains as a neutron star
- Non-pulsating neutron stars in supernova remnants observed as steady X-ray sources
- Searches targeting supernova remnants are **directed searches**



Blue/green - Chandra X-ray Observatory (X-ray)
Red - Spitzer Space Telescope (infrared)
Gold - Hubble Space Telescope (visible)

Courtesy NASA/JPL-Caltech

Recent work

- A recent LVK analysis used three pipelines to search for CWs from 15 young supernova remnants in O3a data
- *f* unknown, so we have to search between 10 Hz – 2000 Hz
- Exact signal is unknown, so repeat the search with three different models/search pipelines to maximize probability of detection

Searches for continuous gravitational waves from young supernova remnants in the early third observing run of Advanced LIGO and Virgo

R. Abbott,[1] T. D. Abbott,[2] S. Abraham,[3] F. Acernese,[4,5] K. Ackley,[6] A. Adams,[7] C. Adams,[8] R. X. Adhikari,[1]
V. B. Adya,[9] C. Affeldt,[10,11] D. Agarwal,[3] M. Agathos,[12,13] K. Agatsuma,[14] N. Aggarwal,[15] O. D. Aguiar,[16]
L. Aiello,[17,18,19] A. Ain,[20,21] P. Ajith,[22] T. Akutsu,[23,24] K. M. Aleman,[25] G. Allen,[26] A. Allocca,[27,5] P. A. Altin,[9]
A. Amato,[28] S. Anand,[1] A. Ananyeva,[1] S. B. Anderson,[1] W. G. Anderson,[29] M. Ando,[30,31] S. V. Angelova,[32]
S. Ansoldi,[33,34] J. M. Antelis,[35] S. Antier,[36] S. Appert,[1] Koya Arai,[37] Koji Arai,[1] Y. Arai,[37] S. Araki,[38]
A. Araya,[39] M. C. Araya,[1] J. S. Areeda,[25] M. Arène,[36] N. Aritomi,[30] N. Arnaud,[40,41] S. M. Aronson,[42]
K. G. Arun,[43] H. Asada,[44] Y. Asali,[45] G. Ashton,[6] Y. Aso,[46,47] S. M. Aston,[8] P. Astone,[48] F. Aubin,[49]
P. Aufmuth,[10,11] K. AultONeal,[35] C. Austin,[2] S. Babak,[36] F. Badaracco,[18,19] M. K. M. Bader,[50] S. Bae,[51]
Y. Bae,[52] A. M. Baer,[7] S. Bagnasco,[53] Y. Bai,[1] L. Baiotti,[54] J. Baird,[36] R. Bajpai,[55] M. Ball,[56] G. Ballardin,[41]
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R. Bhandare,[81] A. V. Bhandari,[3] D. Bhattacharjee,[82] S. Bhaumik,[42] J. Bidler,[25] I. A. Bilenko,[83] G. Billingsley,[1]
R. Birney,[84] O. Birnholtz,[85] S. Biscans,[1,67] M. Bischi,[86,87] S. Biscoveanu,[67] A. Bisht,[10,11] B. Biswas,[3]
M. Bitossi,[41,20] M.-A. Bizouard,[88] J. K. Blackburn,[1] J. Blackman,[89] C. D. Blair,[90,8] D. G. Blair,[90] R. M. Blair,[63]
F. Bobba,[91,92] N. Bode,[10,11] M. Boer,[88] G. Bogaert,[88] M. Boldrini,[93,48] F. Bondu,[94] E. Bonilla,[69] R. Bonnand,[49]
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M. Caesar,[103] G. Cagnoli,[28] C. Cahillane,[1] H. W. Cain III,[2] J. Calderón Bustillo,[104] J. D. Callaghan,[66]
T. A. Callister,[105,106] E. Calloni,[27,5] J. B. Camp,[107] M. Canepa,[108,80] M. Cannavacciuolo,[91] K. C. Cannon,[31]
H. Cao,[78] J. Cao,[109] Z. Cao,[110] E. Capocasa,[23] E. Capote,[25] G. Carapella,[91,92] F. Carbognani,[41] J. B. Carlin,[111]
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G. Castaldi,[116] S. Caudill,[50,117] M. Cavaglià,[82] F. Cavalier,[40] R. Cavalieri,[41] G. Cella,[20] P. Cerdá-Durán,[118]
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F. Chiadini,[127,92] C-Y. Chiang,[128] R. Chierici,[129] A. Chincarini,[80] M. L. Chiofalo,[21,20] A. Chiummo,[41] G. Cho,[130]
H. S. Cho,[131] S. Choate,[103] R. K. Choudhary,[90] S. Choudhary,[3] N. Christensen,[88] H. Chu,[126] Q. Chu,[90]
Y-K. Chu,[128] S. Chua,[96] K. W. Chung,[132] G. Ciani,[72,73] P. Ciecielag,[76] M. Cieślar,[76] M. Cifaldi,[114,115]
A. A. Ciobanu,[78] R. Ciolfi,[133,73] F. Cipriano,[88] A. Cirone,[108,80] F. Clara,[63] E. N. Clark,[134] J. A. Clark,[102]
L. Clarke,[135] P. Clearwater,[111] S. Clesse,[136] F. Cleva,[88] E. Coccia,[18,19] P.-F. Cohadon,[96] D. E. Cohen,[40]
L. Cohen,[2] M. Colleoni,[137] C. G. Collette,[138] M. Colpi,[60,61] C. M. Compton,[63] M. Constancio Jr.,[16] L. Conti,[73]
S. J. Cooper,[14] P. Corban,[8] T. R. Corbitt,[2] I. Cordero-Carrión,[139] S. Corezzi,[71,70] K. R. Corley,[45] N. Cornish,[74]

Case study: G189.1+0.3

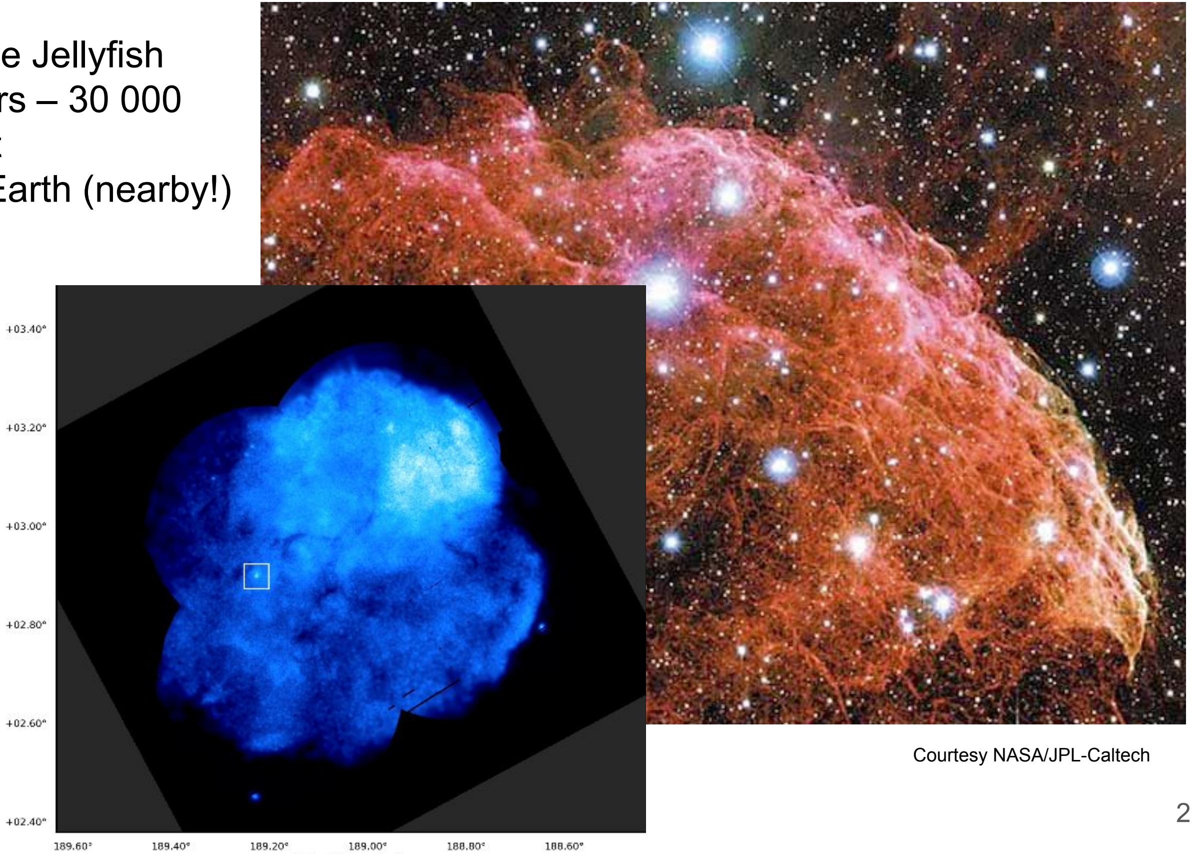
- G189.1+0.3, also known as the Jellyfish nebula, is a young (3 000 years – 30 000 years old) supernova remnant
- About 5 000 light years from Earth (nearby!)

- Contains compact X-ray source, i.e. a likely neutron star!
- No observed pulsations, so we have to search many frequencies

$$h_{\mathrm{age}} \leq \frac{1}{D}\sqrt{\frac{5GI_{zz}}{8c^3\tau}}$$

5000 light years

3000 years

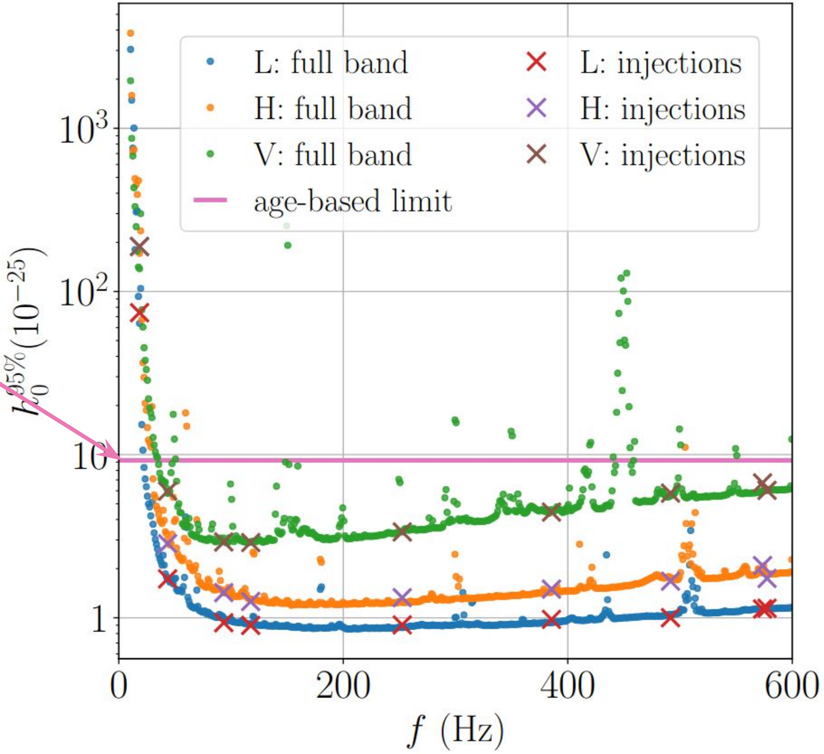


Courtesy NASA/JPL-Caltech

Case study: G189.1+0.3

- First step: estimate the maximum h_0 from the age of the supernova remnant

$$h_{\rm age} \leq \frac{1}{D}\sqrt{\frac{5GI_{zz}}{8c^3\tau}}$$

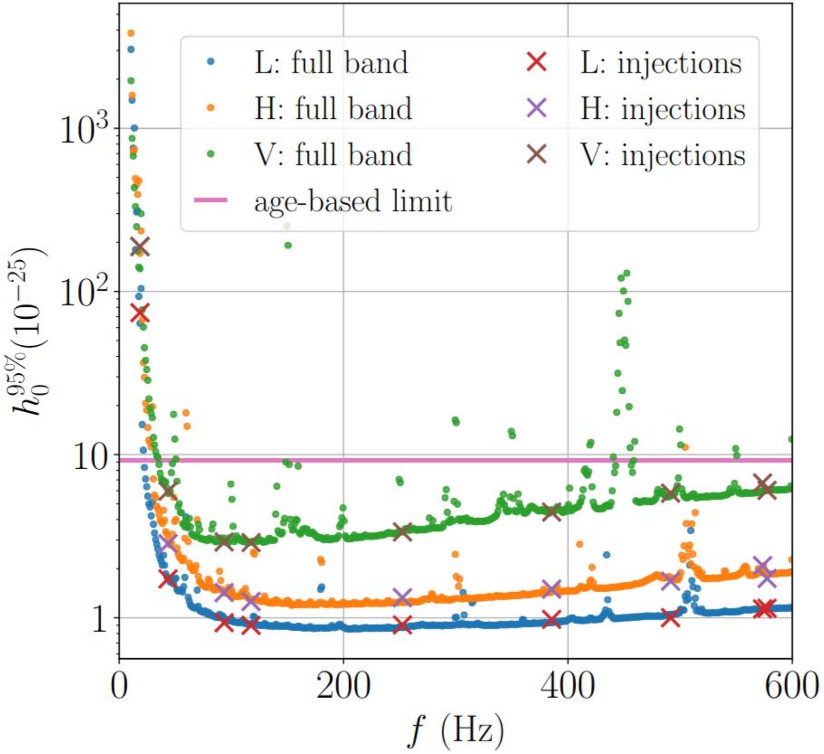


Case study: G189.1+0.3

- First, estimate the maximum h_0 from the age of the supernova remnant

$$h_{\text{age}} \leq \frac{1}{D}\sqrt{\frac{5GI_{zz}}{8c^3\tau}}$$

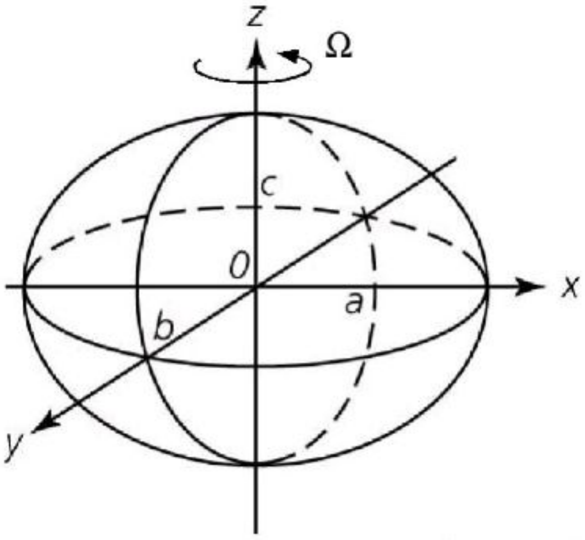
- Second, inject fake signals and set upper limits on h_0
- Finally, estimate the sensitivity across the full band

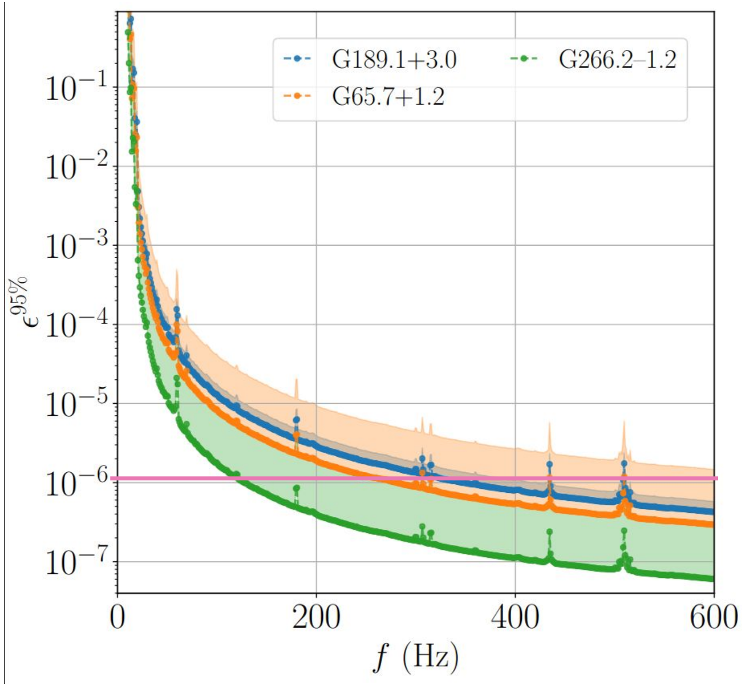


G189.1+0.3 & ellipticity

- Turn constraints h_0 into limits on ellipticity via

$$\epsilon = 9.46 \times 10^{-5}\left(\frac{h_0}{10^{-24}}\right)\left(\frac{D}{1\ \mathrm{kpc}}\right)\left(\frac{100\ \mathrm{Hz}}{f}\right)^2$$



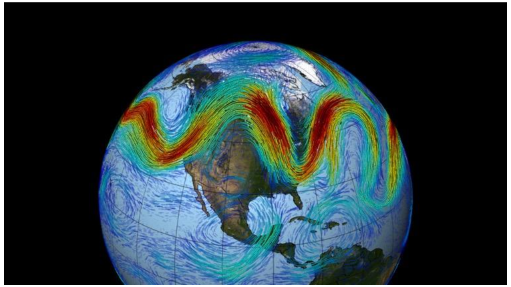


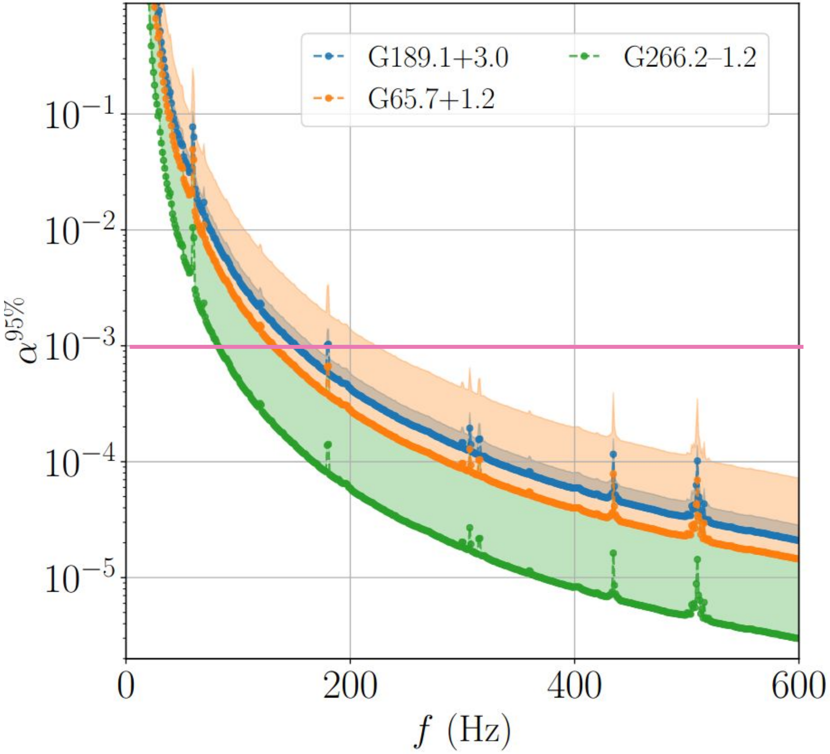
G189.1+0.3 & *r*-modes

- Turn constraints h_0 into limits on *r*-mode amplitudes via

$$\alpha \simeq 0.028\left(\frac{h_0}{10^{-24}}\right)\left(\frac{D}{1\ \mathrm{kpc}}\right)\left(\frac{100\ \mathrm{Hz}}{f}\right)^3$$

Theoretical limits predict $\alpha < 10^{-3}$ at $f > 150$ Hz





Supernova remnant summary

- Search for CWs from 15 young supernova remnants in O3a reports no CW candidates
- First search to set limits using three different models
- Searches directed at neutron stars in supernova remnants must cover a wide range of frequencies
- Future data will increase the probability of a detection – stay tuned for O4!

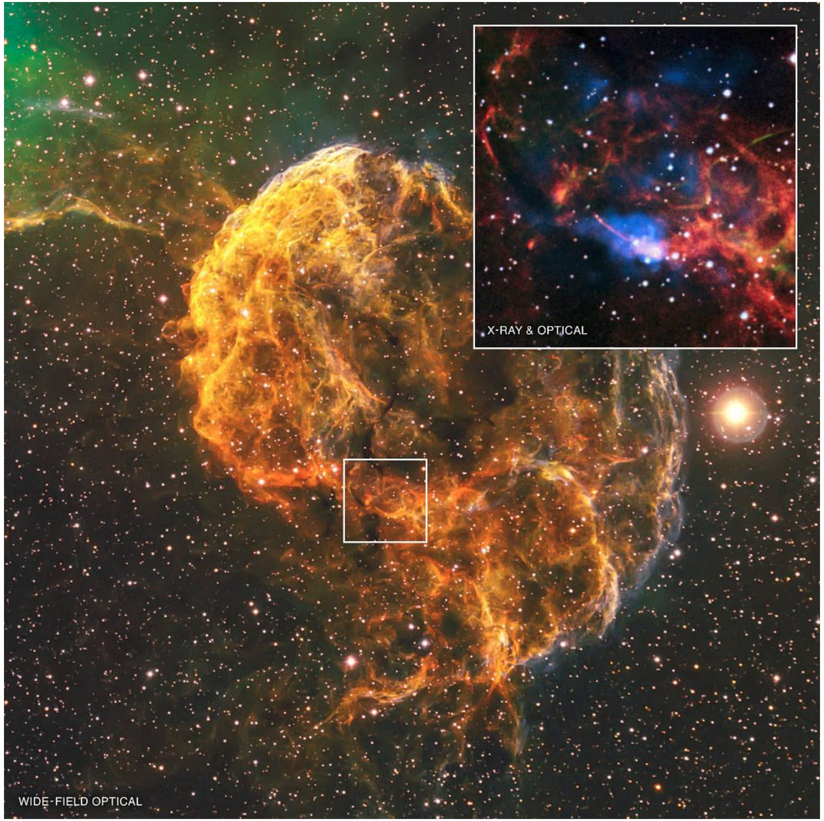
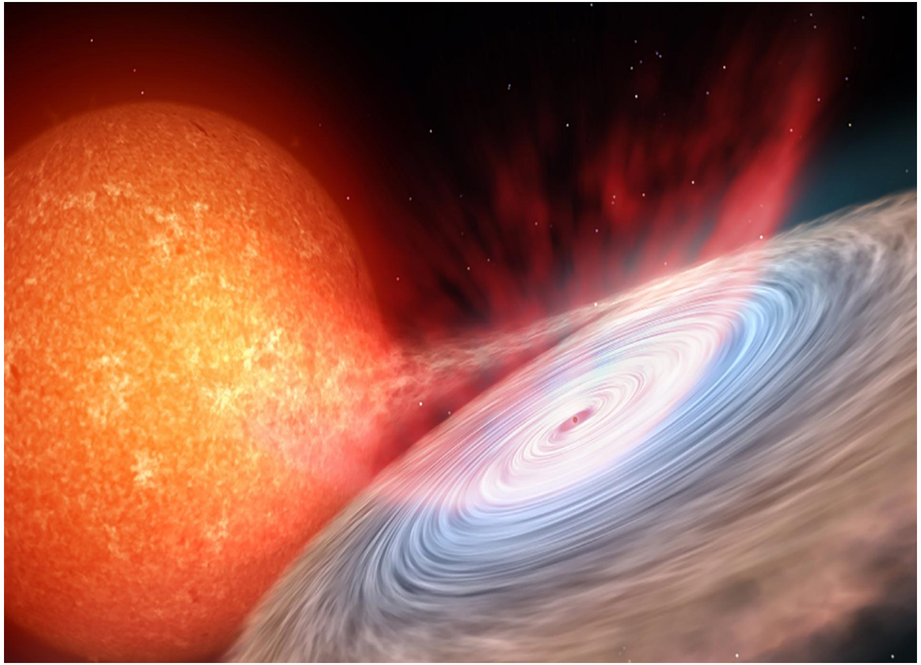


Image credit: Wide Field Optical: Focal Pointe Observatory/B.Franke, Inset X-ray: NASA/CXC/MSFC/D.Swartz et al, Inset Optical: DSS, SARA

Gravitational waves from accreting neutron stars

Low mass X-ray binaries (LMXBs)

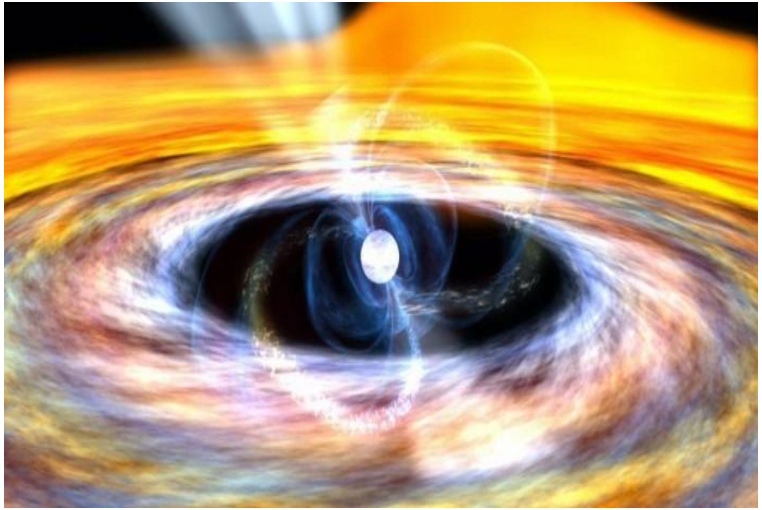
- Accretion is the accumulation of matter, generally gas, due to gravitational interaction.
- The infalling matter releases gravitational potential energy as X-rays.
- LMXBs are binary systems composed by a *donor* which accretes matter unto its companion, generally a compact object like a neutron star, a black hole, etc…



Artistic representation of a neutron star accreting matter from its companion's envelope. Credit: Gabriel Pérez Díaz, SMM (IAC)

Accretion and gravitational waves generation

- The influx of material, via accretion, creates a *spin-up* torque, which unchecked could *break* a Neutron star due centrifugal forces.
- Yet, observations of such systems suggest the spin-frequency of Neutron stars in LMXBs, $f_\star$,are far from the breaking frequency , f_{break} .
- Gravitational wave emission may be the mechanism that balances the accretion torque. This is referred to as ***torque-balance***.

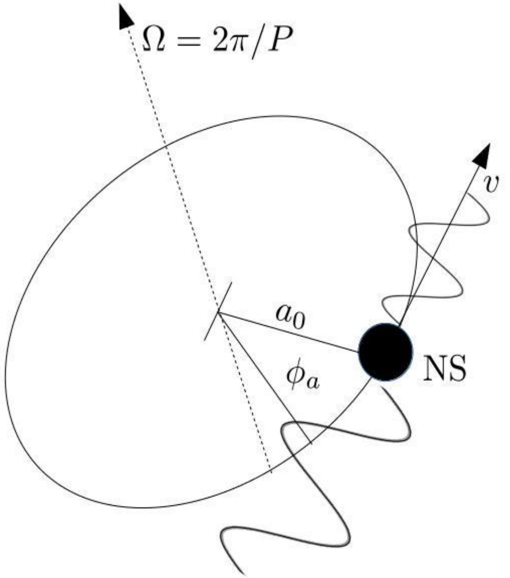


Artist's impression of a neutron star and its surrounding accretion disk.
NASA / Goddard Space Flight Center/ Danna Berry

Accretion and gravitational waves generation. Courtesy of: Mark Myers, OzGrav, Swinburne University.

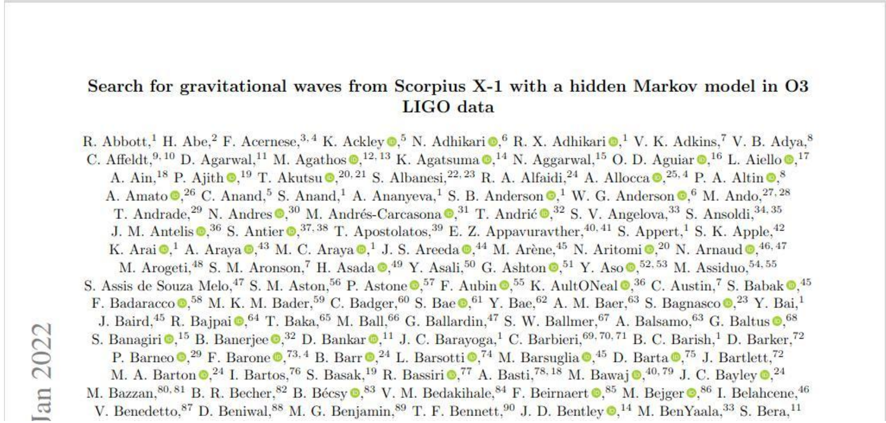
Choosing where to search

- Gravitational waves are emitted at certain multiples of the spin-frequency, i.e. $f \propto f_\star$.
- Signal amplitude, h_0, assuming **torque-balance**, depends on :
    - X-ray flux ($h_0 \propto F_X^{1/2}$)
    - spin-frequency ($h_0 \propto f_\star^{-1/2}$)
- Ideal search-candidates either have a measured $f_\star$, a considerable X-ray flux, or a combination of both. As the sky position are known, this are **directed searches.**
- Given the chaotic nature of accretion, the gravitational wave frequency is expected to wander slightly throughout the search.
- When using LMXBs as sources, searches take into account the binary motion of the system, using the orbital parameters of,
    - the projected semi-major axis a_0
    - the time of ascension T_{asc}
    - the system orbital period P



Neutron star (NS), and relevant orbital parameters.

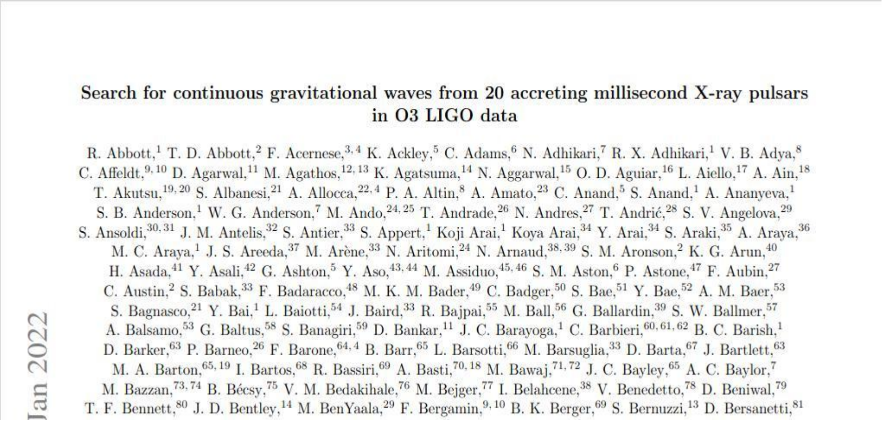
Recent searches for accreting systems



Jan 2022

Search for gravitational waves from Scorpius X-1 with a hidden Markov model in O3 LIGO data

R. Abbott,[1] H. Abe,[2] F. Acernese,[3,4] K. Ackley,[5] N. Adhikari,[6] R. X. Adhikari,[1] V. K. Adkins,[7] V. B. Adya,[8]
C. Affeldt,[9,10] D. Agarwal,[11] M. Agathos,[12,13] K. Agatsuma,[14] N. Aggarwal,[15] O. D. Aguiar,[16] L. Aiello,[17]
A. Ain,[18] P. Ajith,[19] T. Akutsu,[20,21] S. Albanesi,[22,23] R. A. Alfaidi,[24] A. Allocca,[25,4] P. A. Altin,[8]
A. Amato,[26] C. Anand,[5] S. Anand,[1] A. Ananyeva,[1] S. B. Anderson,[1] W. G. Anderson,[6] M. Ando,[27,28]
T. Andrade,[29] N. Andres,[30] M. Andrés-Carcasona,[31] T. Andrić,[32] S. V. Angelova,[33] S. Ansoldi,[34,35]
J. M. Antelis,[36] S. Antier,[37,38] T. Apostolatos,[39] E. Z. Appavuravther,[40,41] S. Appert,[1] S. K. Apple,[42]
K. Arai,[1] A. Araya,[43] M. C. Araya,[1] J. S. Areeda,[44] M. Arène,[45] N. Aritomi,[20] N. Arnaud,[46,47]
M. Arogeti,[48] S. M. Aronson,[7] H. Asada,[49] Y. Asali,[50] G. Ashton,[51] Y. Aso,[52,53] M. Assiduo,[54,55]
S. Assis de Souza Melo,[47] S. M. Aston,[56] P. Astone,[57] F. Aubin,[55] K. AultONeal,[36] C. Austin,[7] S. Babak,[45]
F. Badaracco,[58] M. K. M. Bader,[59] C. Badger,[60] S. Bae,[61] Y. Bae,[62] A. M. Baer,[63] S. Bagnasco,[23] Y. Bai,[1]
J. Baird,[45] R. Bajpai,[64] T. Baka,[65] M. Ball,[66] G. Ballardin,[47] S. W. Ballmer,[67] A. Balsamo,[63] G. Baltus,[68]
S. Banagiri,[15] B. Banerjee,[32] D. Bankar,[11] J. C. Barayoga,[1] C. Barbieri,[69,70,71] B. C. Barish,[1] D. Barker,[72]
P. Barneo,[29] F. Barone,[73,4] B. Barr,[24] L. Barsotti,[74] M. Barsuglia,[45] D. Barta,[75] J. Bartlett,[72]
M. A. Barton,[24] I. Bartos,[76] S. Basak,[19] R. Bassiri,[77] A. Basti,[78,18] M. Bawaj,[40,79] J. C. Bayley,[24]
M. Bazzan,[80,81] B. R. Becher,[82] B. Bécsy,[83] V. M. Bedakihale,[84] F. Beirnaert,[85] M. Bejger,[86] I. Belahcene,[46]
V. Benedetto,[87] D. Beniwal,[88] M. G. Benjamin,[89] T. F. Bennett,[90] J. D. Bentley,[14] M. BenYaala,[33] S. Bera,[11]



Jan 2022

Search for continuous gravitational waves from 20 accreting millisecond X-ray pulsars in O3 LIGO data

R. Abbott,[1] T. D. Abbott,[2] F. Acernese,[3,4] K. Ackley,[5] C. Adams,[6] N. Adhikari,[7] R. X. Adhikari,[1] V. B. Adya,[8]
C. Affeldt,[9,10] D. Agarwal,[11] M. Agathos,[12,13] K. Agatsuma,[14] N. Aggarwal,[15] O. D. Aguiar,[16] L. Aiello,[17] A. Ain,[18]
T. Akutsu,[19,20] S. Albanesi,[21] A. Allocca,[22,4] P. A. Altin,[8] A. Amato,[23] C. Anand,[5] S. Anand,[1] A. Ananyeva,[1]
S. B. Anderson,[1] W. G. Anderson,[7] M. Ando,[24,25] T. Andrade,[26] N. Andres,[27] T. Andrić,[28] S. V. Angelova,[29]
S. Ansoldi,[30,31] J. M. Antelis,[32] S. Antier,[33] S. Appert,[1] Koji Arai,[1] Koya Arai,[34] Y. Arai,[34] S. Araki,[35] A. Araya,[36]
M. C. Araya,[1] J. S. Areeda,[37] M. Arène,[33] N. Aritomi,[24] N. Arnaud,[38,39] S. M. Aronson,[2] K. G. Arun,[40]
H. Asada,[41] Y. Asali,[42] G. Ashton,[5] Y. Aso,[43,44] M. Assiduo,[45,46] S. M. Aston,[6] P. Astone,[47] F. Aubin,[27]
C. Austin,[2] S. Babak,[33] F. Badaracco,[48] M. K. M. Bader,[49] C. Badger,[50] S. Bae,[51] Y. Bae,[52] A. M. Baer,[53]
S. Bagnasco,[21] Y. Bai,[1] L. Baiotti,[54] J. Baird,[33] R. Bajpai,[55] M. Ball,[56] G. Ballardin,[39] S. W. Ballmer,[57]
A. Balsamo,[53] G. Baltus,[58] S. Banagiri,[59] D. Bankar,[11] J. C. Barayoga,[1] C. Barbieri,[60,61,62] B. C. Barish,[1]
D. Barker,[63] P. Barneo,[26] F. Barone,[64,4] B. Barr,[65] L. Barsotti,[66] M. Barsuglia,[33] D. Barta,[67] J. Bartlett,[63]
M. A. Barton,[65,19] I. Bartos,[68] R. Bassiri,[69] A. Basti,[70,18] M. Bawaj,[71,72] J. C. Bayley,[65] A. C. Baylor,[7]
M. Bazzan,[73,74] B. Bécsy,[75] V. M. Bedakihale,[76] M. Bejger,[77] I. Belahcene,[38] V. Benedetto,[78] D. Beniwal,[79]
T. F. Bennett,[80] J. D. Bentley,[14] M. BenYaala,[29] F. Bergamin,[9,10] B. K. Berger,[69] S. Bernuzzi,[13] D. Bersanetti,[81]

Scorpius X-1 (Sco X-1)

Pipelines Involved:
- Viterbi (hidden Markov model ; HMM)

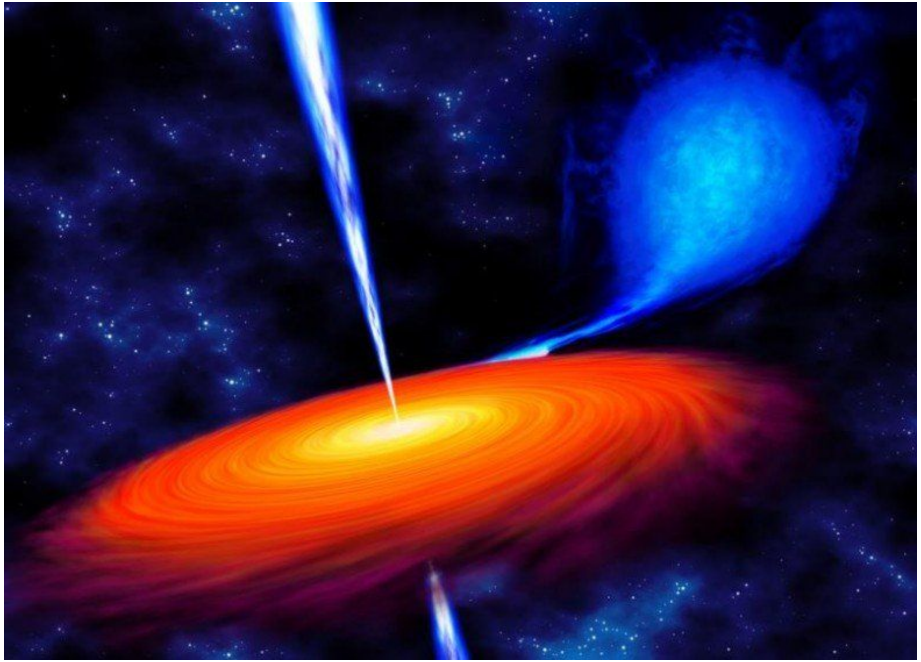
- Cross-Correlation (future paper)

20 Accreting millisecond X-ray pulsars (AMXPs)

Pipelines Involved:
- Viterbi (hidden Markov model ; HMM)

HMM Search for Sco X-1

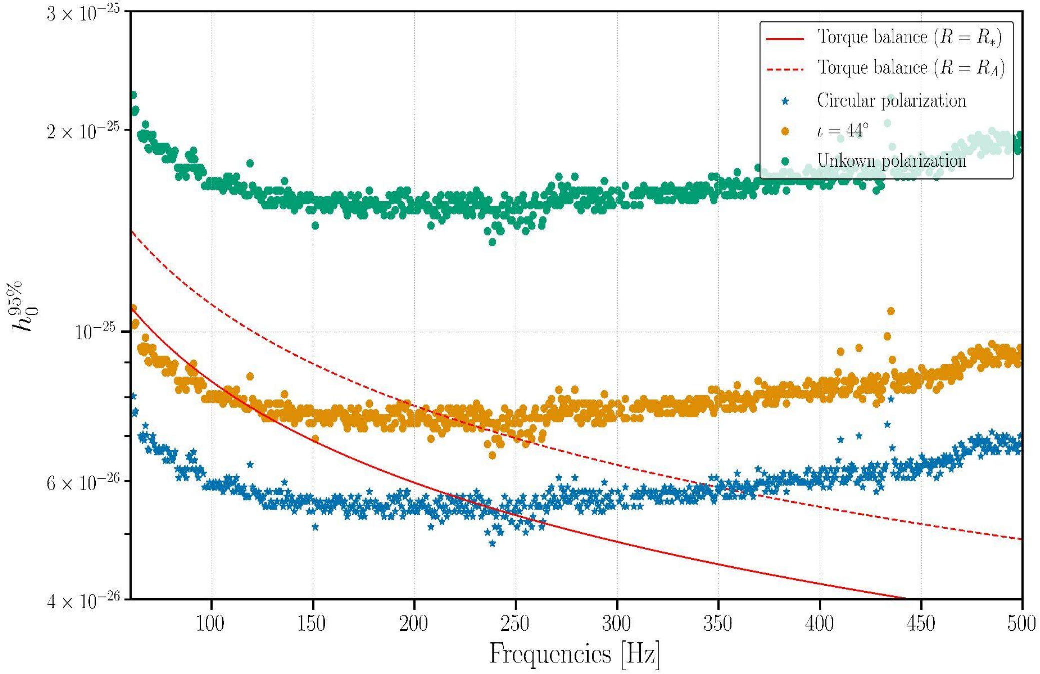
- Sco X-1 is the brightest source of X-rays, apart from the sun, in the sky.
- Following the idea of torque-balance, it should emit strong gravitational waves.
- The *caveat:* no spin-frequency has been measured for this source. Additionally, its orbital parameters have considerable uncertainties. This means the search is **computationally challenging**! -It took 6 months, in a super computer, to finish!
- We used a *binary* hidden Markov model pipeline, which allows for spin-wandering in the gravitational wave emission frequency.



An artist's impression of the Sco X-1 LMXB system. (Courtesy of Ralf Schoofs)

HMM Search for Sco X-1

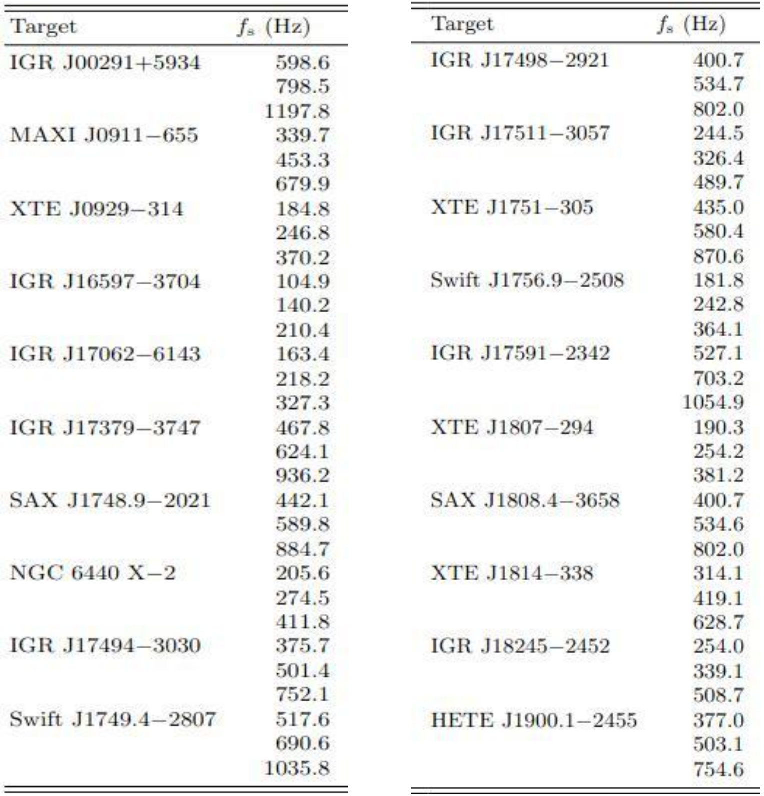
- The search was conducted from 60-500 Hz to *find* a possible gravitational wave candidate.
- The search yielded 35 candidates. None of them survived the vetoing procedure.
- We calculated upper-limits estimates on the signal amplitude h_0 .
- This is the most sensitive search for Sco X-1, using an HMM, to date.



Upper-limits estimates on the signal amplitude, for several possible wave polarizations. The red line represent the torque-balance theoretical estimates for two torque lever arms: the star and Alfvén radii. Figure 4 in the paper.

Search for 20 AMXPs

- The search featured 20 AMXPs, with well measured spin-frequency and orbital parameters.
- Three narrow sub-bands, centered at {1,2,4/3} $f_\star$, are searched for each target..
- Some of the included AMXPs had never been searched before!
- The search included an additional target-of-opportunity, SAX J1808.4-3658, which was in outburst during one month of the observing run.



Target	f_s (Hz)
IGR J00291+5934	598.6
	798.5
	1197.8
MAXI J0911−655	339.7
	453.3
	679.9
XTE J0929−314	184.8
	246.8
	370.2
IGR J16597−3704	104.9
	140.2
	210.4
IGR J17062−6143	163.4
	218.2
	327.3
IGR J17379−3747	467.8
	624.1
	936.2
SAX J1748.9−2021	442.1
	589.8
	884.7
NGC 6440 X−2	205.6
	274.5
	411.8
IGR J17494−3030	375.7
	501.4
	752.1
Swift J1749.4−2807	517.6
	690.6
	1035.8

Target	f_s (Hz)
IGR J17498−2921	400.7
	534.7
	802.0
IGR J17511−3057	244.5
	326.4
	489.7
XTE J1751−305	435.0
	580.4
	870.6
Swift J1756.9−2508	181.8
	242.8
	364.1
IGR J17591−2342	527.1
	703.2
	1054.9
XTE J1807−294	190.3
	254.2
	381.2
SAX J1808.4−3658	400.7
	534.6
	802.0
XTE J1814−338	314.1
	419.1
	628.7
IGR J18245−2452	254.0
	339.1
	508.7
HETE J1900.1−2455	377.0
	503.1
	754.6

Candidates searched. Excerpt of Table II in the paper.

Search for 20 AMXPs

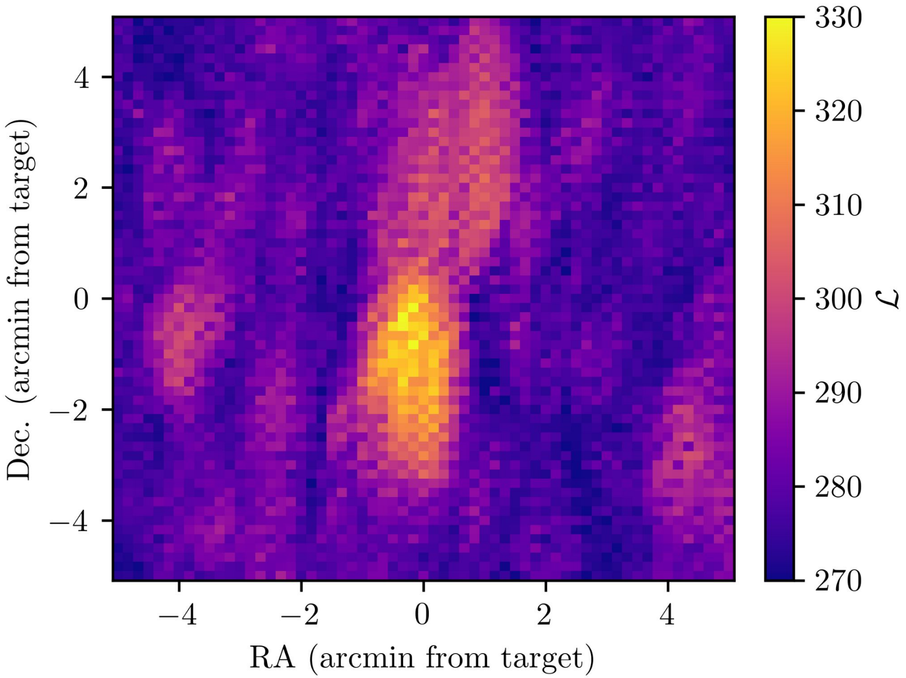
- This novel search resulted in 16 candidates, non that survived the vetoing procedure.

- Upper-limit estimates, for the signal amplitude h_0 , were obtained per target.

- Using the Upper-limit estimates, the search set limits on:

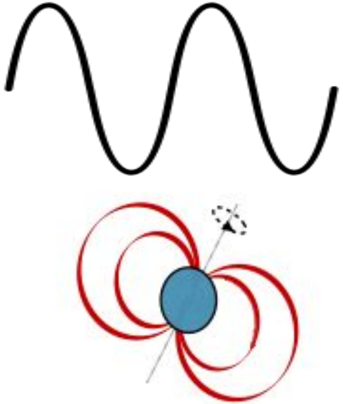
    - The ellipticity, ε, of the neutron star. Assuming asymmetries in said star are the emission mechanism.

    - The strength of r- modes, parametrized as α. Assuming this rotational modes are the emission mechanism.

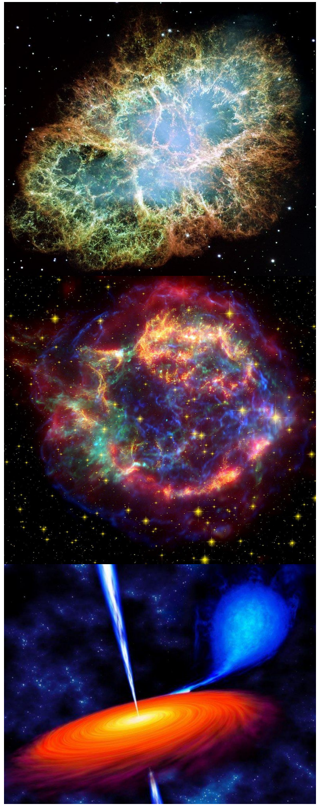


Log-likelihood, $\mathcal{L}$, represented by the color of each pixel, for a 100 arcmin^2 patch of sky, centered on IGR J18597-3704 candidate. This candidate survived the usual vetoes. But did not behave as a true signal when analyzed at different sky positions.

Summary



- Spinning/oscillating neutron stars may emit long-lived gravitational waves.
- We have targeted many likely candidates, but no detections yet.
- O4 run will start at the end of this year.



- O3a supernova remnant search
  arxiv.org/abs/2105.11641| https://www.ligo.org/science/Publication-O3aDirectedSNR
- O3 search for Cassiopeia A and Vela Jr
  arXiv:2111.15116 | www.ligo.org/science/Publication-O3CasAVelaJr/index.php
- Full O3 20 AMXBs: Phys. Rev. D 105, 022002
  arxiv.org/abs/2109.09255 | https://www.ligo.org/science/Publication-O3LMXBsAMXPs/index.php
- Full O3 Sco X-1 Viterbi
  arxiv.org/abs/2201.10104 | https://www.ligo.org/science/Publication-O3ScoX1HMM/
- Full O3 Known Pulsars
  arxiv.org/abs/2111.13106 | https://www.ligo.org/science/Publication-O3LMXBsAMXPs/index.php
- Full O3 Narrowband
  arxiv.org/abs/2112.10990 | https://www.ligo.org/science/Publication-O3NarrowbandCW/