UCLouvain

Continuous gravitational waves as probes of neutron stars and dark matter

Andrew Miller

Université catholique de Louvain

22 June 2020

Outline

1. Overview
2. Neutron stars
3. Dark matter around black holes

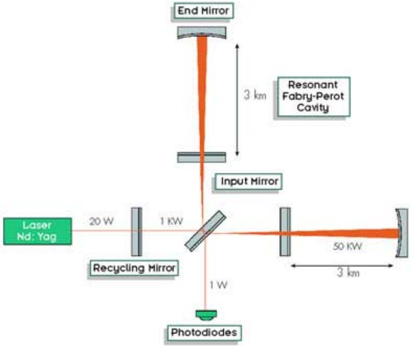
Who makes up the Belgian Virgo group?

- Joined Virgo in July 2018; group has grown to 16 members, many young people
- Weekly meetings, strong collaboration
- VUB has applied to join Virgo

Ongoing activities

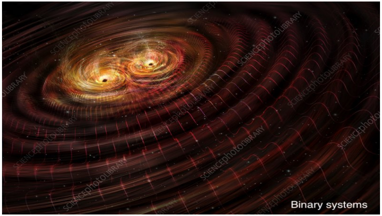
- Broadband isotropic and directional stochastic gravitational wave searches
- Searches for (subsolar) primordial black hole mergers with CW and matched filter methods, and from a stochastic GW background
- Analysis of Schumann resonances
- Long gravitational wave transient (burst) searches
- Detecting binary systems before merger with deep learning
- Absolute calibration of the Virgo antenna
- Computing - CPUs and GPUs at UCLouvain center within the LIGO/Virgo computing infrastructure
- Instrumentation: mirror coating research, optics commissioning and development, Einstein Telescope preparation (mirror seismic isolation)
- Probing dark matter with gravitational wave detectors

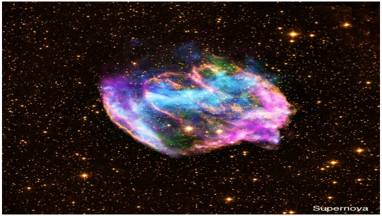
Laser interferometry

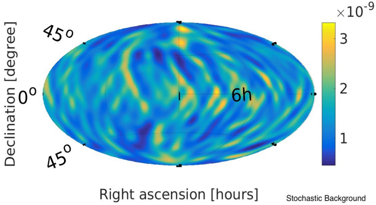


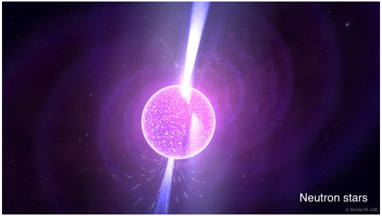
- The mirrors move differently in response to passing GWs that induce a differential strain on the detector
- The phase ϕ is measured: $\phi = \frac{\Delta L}{L} = \int f(t)dt$

Sources of gravitational waves



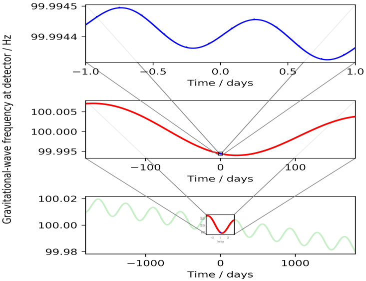


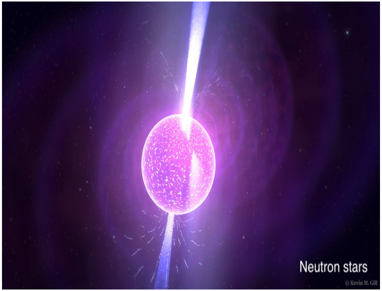




- Four major sources that LIGO/Virgo search for

Focus here on continuous waves

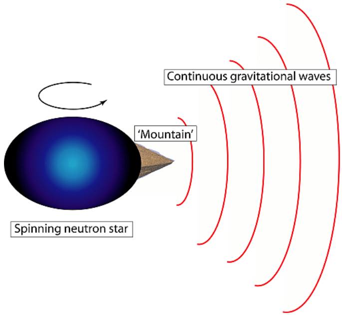




- Quasi-monochromatic, quasi-infinite duration
- Searches are computationally demanding: template searches difficult

Deformed neutron stars

- Small deformation and rotation → gravitational waves (GWs)
- Rotate at $\sim 10 - 1000$ Hz [10]
- Model: $f = f_0 + \dot{f}(t - t_0)$ [4]
- $\dot{f}$: [-1×10^{-8}, 2×10^{-9}] Hz/s
- Mechanisms of deformation
  - Crustal strain (starquake, formed at birth)
  - Strong *internal* magnetic field buried during accretion (MSPs) [8]



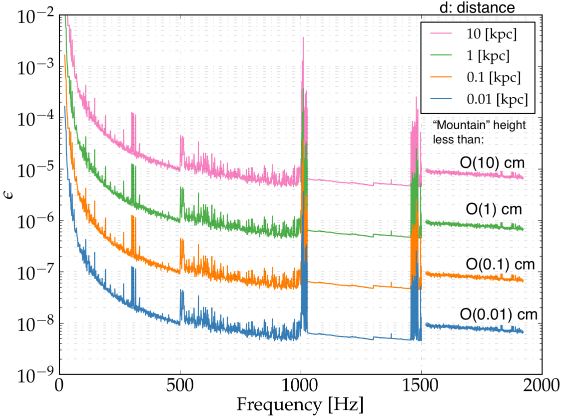
Types of searches

Search type	Description	Sources
targeted	known $\alpha, \delta, f_0, \dot{f}$	Crab, Vela, MSPs
directed	known α, δ	galactic center
all-sky	nothing known	any

α: right ascension
δ: declination
f_0: pulsar rotation frequency at a reference time t_0
$\dot{f}$: spindown

- Targeted/directed searches can be fully coherent
- All-sky searches are semicoherent: the Doppler shift causes $O(10^{-4} f)$ Hz modulations and affects the Fast Fourier Transform time T_{FFT}
- We “point” to specific locations when analyzing the data

Existing constraints from an all-sky search



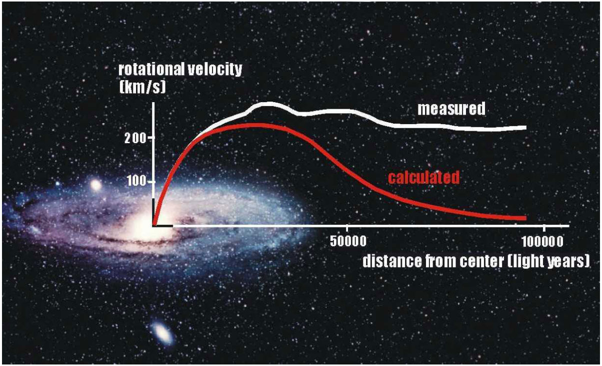
- These are upper limits: the minimum deformation, or ellipticity ϵ, we can see at 95% confidence
- $I_{zz} = 10^{38}$ kg $\cdot$ m^2, constraints possible on $\frac{I_{zz}\epsilon}{d}$ [2]
- Deformations with smaller ϵ are easier to form

Prospects for LIGO/Virgo's next run (O3)

- All-sky search for isolated sources and sources in binary systems
- Known pulsars search
- Search for GWs from young supernova remnants

The dark matter problem

- New particles and modifications to gravity have been proposed
- Dark matter can take many forms ($10^{-22} - 10^{50}$ eV)
- GWs can probe nature of ultralight dark matter
  - A cloud of bosons can form around BHs and deplete its energy over time in the form of GWs

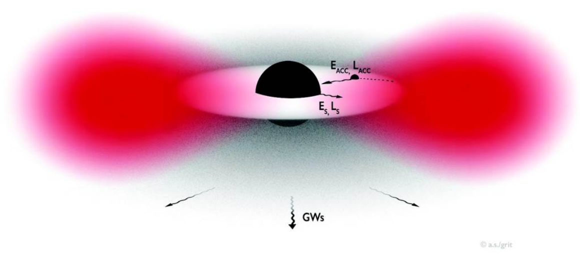


Black hole (BH) superradiance

- Near a BH, quantum fluctuations → bosons pop into existence
- Many bosons fall in, but if $\lambda_c \sim R_{BH}$, bosons can scatter off the BH
- Greater effect for BHs with higher spins χ
- Energy (mass/spin) extracted from the BH by scattering bosons → outgoing boson amplitude boosted
- Unlike photons, bosons are massive, so they tend to be bound to the BH → successive scatterings possible
- A boson “cloud” can form [7]
- Focus here is on scalar bosons, but clouds composed of vector/tensor bosons are possible [3]

Growth of boson clouds

- Clouds are formulated as solutions to Schrodinger-like equations for a scalar field in the Kerr metric: “gravitational Hydrogen atom”
- The lowest, fastest growing state is $l = 1$, $m = 1$



- Superradiance (instability) condition: $\omega_{axion} < m\Omega_{BH}$
- No limit on the number of bosons in each state [6]

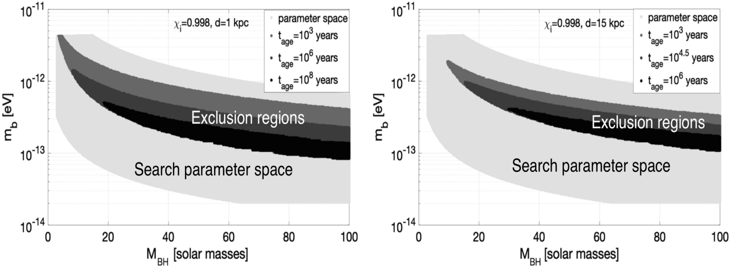
Depletion of boson clouds

- Assume bosons couple to gravity and annihilate into gravitons [5]
- GWs are emitted from one energy level at a time $\rightarrow$ monochromatic up to small spinup due to classical self-gravity
- Timescale of depletion $>>$ timescale of cloud growth
- Consider boson mass range $[10^{-14}, 10^{-11}]$ eV

We expect *continuous* gravitational waves!

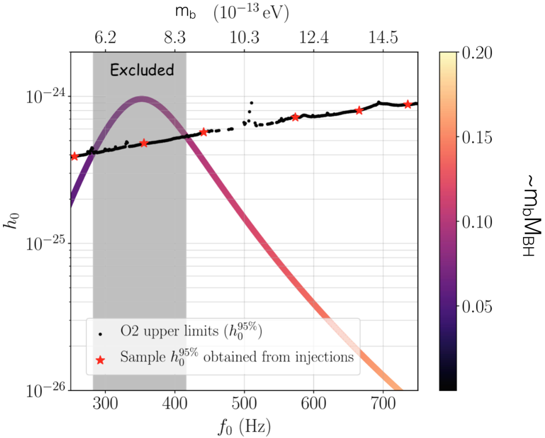
Constraints from an all-sky search

- Reinterpretation of upper limits on ϵ from slide 8: $\epsilon \propto h_0$, the GW amplitude [9]
- $h_0, f \rightarrow m_b$ and M_{BH} constraints with assumptions on BHs' spins χ, distances d, and ages t_{age}



- More combinations of m_b and M_{BH} excluded for younger systems (small t_{age}) than older ones
- Darker colors are constraints on older systems

Directed search for Cygnus X-1



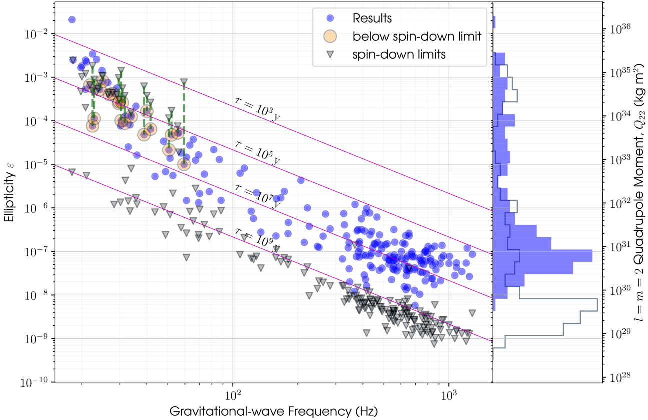
- Binary parameters and mass/spin known
- Viterbi method used to find the optimal signal path [11]

Prospects for the next observing run

- All-sky search for scalar boson clouds
- Directed search for vector boson clouds around binary systems
- Future detectors most likely needed to probe merger remnants
- Other probes of dark matter: dark photons directly interacting with the mirrors
  - Not GWs, but cause similar signatures
- This is new territory for CW analyses

Backup slides

Existing constraints, targeted searches

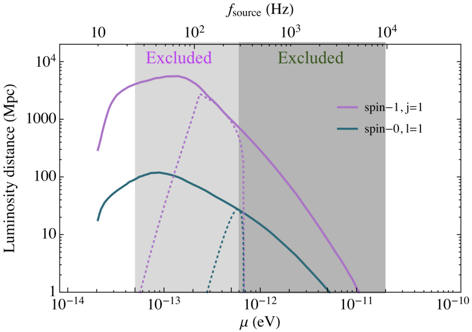


- $I_{zz} = 10^{38}$ kg $\cdot$ m^2, constraints possible on $I_{zz}\epsilon$ [1]
- The diagonal lines show the ϵ that would be required if a star had a particular characteristic age τ and was losing energy purely through GWs.

Vector bosons

- Emit GWs with higher amplitudes, but on shorter timescales, than those from scalar bosons
- For shorter signals, spinup becomes important
- Parameter space mostly composed of “transient” continuous wave signals
- Possible targets: merger remnants, x-ray binaries
- Interplay between instability and depletion timescales important

Distance reach



- Assumes monochromatic signal
- BH mass chosen as a function of particle mass to give the strongest GW signal
- Dotted line: $M_{BH} = 64 M_{sun}$

equations

Ellipticity:

$$\epsilon \equiv \frac{|I_{xx} - I_{yy}|}{I_{zz}}, \tag{3.1}$$

Amplitude of CW:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I_{zz}\epsilon f_{\mathrm{rot}}^2}{d}, \tag{3.2}$$

Spindown limit:

$$h_{0,\mathrm{sd}} = \frac{1}{d} \left(\frac{5 G I_{zz}}{2c^3} \frac{|\dot{f}_{\mathrm{rot}}|}{f_{\mathrm{rot}}} \right)^{1/2}, \tag{3.3}$$

References I

[1] Abbott, B., Abbott, R., Abbott, T., Abraham, S., Acernese, F., Ackley, K., Adams, C., Adhikari, R., Adya, V., Affeldt, C., et al. (2019a). Searches for gravitational waves from known pulsars at two harmonics in 2015–2017 ligo data. *The Astrophysical Journal*, 879(1):10.

[2] Abbott, B. et al. (2019b). All-sky search for continuous gravitational waves from isolated neutron stars using Advanced LIGO O2 data. *Physical Review D*, 100(2):024004.

[3] Arvanitaki, A., Baryakhtar, M., and Huang, X. (2015). Discovering the qcd axion with black holes and gravitational waves. *Physical Review D*, 91(8):084011.

[4] Astone, P., Colla, A., D'Antonio, S., Frasca, S., and Palomba, C. (2014). Method for all-sky searches of continuous gravitational wave signals using the Frequency-Hough transform. *Physical Review D*, 90(4):042002.

[5] Baumann, D., Chia, H. S., and Porto, R. A. (2019). Probing ultralight bosons with binary black holes. *Physical Review D*, 99(4):044001.

[6] Brito, R., Cardoso, V., and Pani, P. (2015). Black holes as particle detectors: evolution of superradiant instabilities. *Classical and Quantum Gravity*, 32(13):134001.

[7] Isi, M., Sun, L., Brito, R., and Melatos, A. (2019). Directed searches for gravitational waves from ultralight bosons. *Physical Review D*, 99(8):084042.

[8] Lasky, P. D. et al. (2017). The braking index of millisecond magnetars. *The Astrophysical Journal Letters*, 843(1):L1.

[9] Palomba, C., D'Antonio, S., Astone, P., Frasca, S., Intini, G., La Rosa, I., Leaci, P., Mastrogiovanni, S., Miller, A. L., Muciaccia, F., et al. (2019). Direct constraints on the ultralight boson mass from searches of continuous gravitational waves. *Physical Review Letters*, 123(17):171101.

[10] Prix, R. (2009). Gravitational Waves from Spinning Neutron Stars. In Becker, W., editor, *Neutron Stars and Pulsars*, volume 357 of *ASSL*, chapter 24, pages 651–685. Springer Berlin Heidelberg.

[11] Sun, L., Brito, R., and Isi, M. (2019). Search for ultralight bosons in cygnus x-1 with advanced ligo. *arXiv preprint arXiv:1909.11267*.