All-sky search for almost monochromatic gravitational waves using supercomputers

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Outline of this talk

★ Gravitation and gravitational waves,
★ Sources of gravitational waves,
★ Gravitational wave detectors,
★ Rotating neutron stars as sources,
  ★ Gravitational wave data analysis,
  ★ All-sky search pipeline,
  ★ Massive parallelization,
★ Current and future plans.
4 fundamental interactions, but our knowledge about the Universe is based on EM. Let’s directly probe the other long-range interaction: gravitation.
Gravitational waves

Metric

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]

Einstein’s equations

\[ G_{\mu\nu} = 8\pi G/c^4 \, T_{\mu\nu} \]

Einstein 1916:

\[ \Delta \bar{h}_{\mu\nu} = \frac{16\pi G}{c^4} \, T_{\mu\nu} \]

GW amplitude

\[ h_{ij}(t) = \frac{2G}{c^4 r} \, \frac{\partial^2}{\partial t^2} I_{ij}(t - \frac{r}{c}) \]

GW luminosity

\[ L = \frac{G}{5c^5} \left\langle \frac{\partial^3}{\partial t^3} I_{ij} \frac{\partial^3}{\partial t^3} I_{ij} \right\rangle \]

Quadrupole moment

\[ G/c^4 = 8.3 \cdot 10^{-50} \quad [s^2/(kg \cdot m)] \]
How to make a gravitational wave

Case #1: Try it in your own lab!

$$M = 1000 \text{ kg}$$
$$R = 1 \text{ m}$$
$$f = 1000 \text{ Hz}$$
$$r = 300 \text{ m}$$

$$h \approx \frac{32\pi^2 G M R^2 f_{\text{orb}}^2}{r c^4}$$

$$h \sim 10^{-35}$$
How to make a gravitational wave that might be detectable!

- Case #2: A 1.4 solar mass binary neutron star pair
  - \( M = 1.4 \, M_\odot \)
  - \( R = 20 \, \text{km} \)
  - \( f = 1000 \, \text{Hz} \)
  - \( r = 10^{23} \, \text{m} \)

\[ h \sim 10^{-20} \]

Credit: T. Strohmayer and D. Berry
Sources of gravitational waves

- **Periodic sources**
  - Binary Pulsars, Spinning neutron stars, Low mass X-ray binaries

- **Coalescing compact binaries**
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown
  - Numerical relativity will be essential to interpret GW waveforms

- **Burst events**
  - e.g. Supernovae with asymmetric collapse

- **Stochastic background**
  - Primordial Big Bang ($t = 10^{-22}$ sec)
  - Continental of sources

*The Unexpected!*
Some Questions Gravitational Waves May Be Able to Answer

**Fundamental Physics**
- Is General Relativity the correct theory of gravity?
- How does matter behave under extreme conditions?
- What equation of state describes a neutron star?
- Are black holes truly bald?

**Astrophysics, Astronomy, Cosmology**
- Do compact binary mergers cause GRBs?
- What is the supernova mechanism in core-collapse of massive stars?
- How many low mass black holes are there in the universe?
- Do intermediate mass black holes exist?
- How bumpy are neutron stars?
- Is there a primordial gravitational-wave residue?
- Can we observe populations of weak gravitational wave sources?
- Can binary inspirals be used as “standard sirens” to measure the local Hubble parameter?
Michelson-Morley type interferometric detector

Gravitational wave is registered by measuring temporal change in arms’ length (changes in the interferometric pattern):

\[ h(t) = h_+(t) \cdot F_+(t; \psi) + h_\times(t) \cdot F_\times(t; \psi), \]

\[ h = \Delta L/L \ll 10^{-18} \]
Gravitational wave detectors’ network: LIGO (USA), GEO600 (UK, Germany), Virgo (France, Italy, Hungary, Netherlands and Poland), KAGRA (Japan), LIGO India...

Polgraw group in Virgo project and LIGO-Virgo consortium:

- IMPAN, CAMK, OAUW, NCBJ, UZg, UwB.
- Theory, data analysis, large-scale computation, detector engineering.
LIGO (US, Hanford & Livingston) and Virgo detectors (FR+IT+NL+HU+PL, Pisa) have reached the desired initial sensitivity (2002-2011).

Currently ongoing - the Advanced Detector Era (2015 - . . . )

Two LIGO detectors (Livingston & Hanford) began O1 observational run on September 18th 2015 (end of run: January 12th 2016).
Sensitivity of AdLIGO and AdVirgo increased by an order of magnitude → distance reach ×10 (sensitivity ∝ 1/r - detection of amplitude, not energy of the wave!)
Neutron stars = very dense, magnetized stars

🌟 The most relativistic, material objects in the Universe: compactness $M/R \approx 0.5$. 

\[
\begin{align*}
P \left[ \text{s}^{-1} \right] & \quad B > B_{\text{crit}} = 4.4 \cdot 10^{13} \text{ G} \\
P \left[ \text{s} \right] & \quad 10^{-9} \quad 10^{-8} \\
P \left[ \text{s} \right] & \quad 10^{-7} \quad 10^{-6} \\
B \left[ \text{G} \right] & \quad 10^9 \quad 10^{10} \\
B \left[ \text{G} \right] & \quad 10^{11} \quad 10^{12} \\
B \left[ \text{G} \right] & \quad 10^{13} \quad 10^{14} \\
\end{align*}
\]
The mystery of neutron star interiors

Dense matter in conditions impossible to obtain on Earth!
Continuous GWs from spinning neutron stars

Characteristics:

1. Long-lived: \( T > T_{\text{obs}} \)

2. Nearly periodic: \( f_{\text{GW}} \sim \nu \)

Generation mechanisms (we need a time varying quadrupole moment):

1. Mountains
   (elastic stresses, magnetic fields)
2. Oscillations
   (r-modes)
3. Free precession
   (magnetic field)
4. Accretion
   (drives deformations from r-modes, thermal gradients, magnetic fields)

Courtesy: B. J. Owen
Courtesy: McGill U.
Example: weak monochromatic signals hidden in the noise

In this case Fourier transform is sufficient to detect the signal (a matched filter method):

$$F = \int_0^{\frac{T_0}{T_0}} x(t) \exp(-i\omega t)dt$$

Signal-to-noise

$$SNR = h_0 \frac{\sqrt{T_0}}{\sigma_{noise}}$$
In reality: signal is modulated

Since the detector is on Earth, influence of planets and Earth’s rotation changes the signal’s amplitude and phase.

- Signal is almost monochromatic: pulsars are slowing down,
- To analyze, we have to demodulate the signal (detector is moving),
  → precise ephemerids of the Solar System used.
Calculation of the F-statistic

To estimate how well the model matches with the data $x(t)$, we calculate $\mathcal{F}$,

$$\mathcal{F} = \frac{2}{S_0 T_0} \left( \frac{|F_a|^2}{\langle a^2 \rangle} + \frac{|F_b|^2}{\langle b^2 \rangle} \right)$$

where $S_0$ is the spectral density, $T_0$ is the observation time, and

$$F_a = \int_0^{T_0} x(t) a(t) \exp(-i\phi(t)) dt, \quad F_b = \ldots$$

and $a(t)$, $b(t)$ are amplitude modulation functions (depend on the detector location and sky position of the source),

$$h_1(t) = a(t) \cos \phi(t), \quad h_2(t) = b(t) \cos \phi(t),$$

$$h_3(t) = a(t) \sin \phi(t), \quad h_4(t) = b(t) \sin \phi(t),$$

related to the model of the signal ($h_i, i = 1, \ldots, 4$)

$$h(t) = \sum_{i=1}^{4} A_i h_i(t).$$

For triaxial ellipsoid model: dependence on the extrinsic ($h_0, \psi, \nu, \phi_0$) and intrinsic ($f, \dot{f}, \alpha, \delta$) parameters.
Methods of data analysis

Computing power $\propto T_0^5 \log(T_0)$. Coherent search of $T_0 \approx 1$ yr of data would require zettaFLOPS ($10^{21}$ FLOPS) $\rightarrow$ currently impossible $
abla$

Solution: divide data into shorter length time frames ($T_0 \approx 2$ days)

$$f_{i,j} \quad (i,j) \quad (i,j+1) \quad (i-1,j)$$

$n$ narrow frequency bands - sampling time $\delta t = 1/2B$,
number of data points $N = T/\delta t \rightarrow N = 2TB$

$\rightarrow$ feasible on a petaFLOP computer.

Example search space (Virgo Science Run 1).
Red: no data, yellow: bad data, green: good data.
Typical all-sky search: parameter space

- Narrow (1 Hz) frequency bands \( f \): \([100 - 1000]\) Hz,
- Spin-down \( f_1 \) range proportional to \( f \):
  \[ [-1.6 \times 10^{-9} \frac{f}{100\text{Hz}}, 0] \text{ Hz s}^{-1} \]
- All-sky search: number of sky positions \( \alpha(f), \delta(f) \propto f \).

In our astrophysical applications, the 4-dim parameter space \((f, \dot{f}, \alpha, \delta)\) is big (in VSR1 \(\sim 10^{17}\) F-statistic evaluations)
All-sky pipeline

- Input data generation (Raw time domain data \( \sim PB \))
- Pre-processing \( \rightarrow \sim TB \) (input time series, detector ephemerids and grid of parameters),
- Stage 1: F-statistic search for candidate GW signals (the most time-consuming part of the pipeline)
  \( \rightarrow 10^{10} \) candidates/detector, 100 TB of output.
- Stage 2: Coincidences among candidate signals from different time segments,
- Stage 3: Followup of interesting coincidences - evaluation of F-statistic along the whole data span.
Most expensive part: search for candidate signals

- Suitable algorithms that allow for Fast Fourier Transforms,
- Optimized grid of parameters - minimum number of operation to reach desired sensitivity,
  → partial demodulation before the inner spindown loop (only once per sky position),
- Sky positions completely independent of each other
  → "Embarasingly parallel problem"
First level of parallelization: over the sky positions

Sky positions (here in parameter grid coordinates) are independent → Round-robin scheduling.
Second level: massive parallelisation with MPI

Internal MPI scheduling algorithm to run multiple instances of parallel all-sky search as one massively parallel computation:

- Initialization and estimation of the available and necessary parallel resources,
- Construction of different tasks as groups for requested frequencies,
- Size of Group of tasks estimated using frequency scaling,
- Distribution and decomposition of groups,
- Bookkeeping.
Amount of computation scales well with the band frequency.

SkyFarmer was tested up to 50k CPU tasks.

- Scalability is good, but not optimal:
  - communication per task starts to dominate,
  - suboptimal domain decomposition due to simplified scheduling
Current and future plans

★ CPU SkyFarmer will be used to analyze the incoming O1 data (40 - 2000 Hz, 4 months), using data divided in 2 day segments

→ \( \approx 5 \times 10^6 \) CPU-hours needed,

→ For better sensitivity with 6-day segments, we need \( \approx 10^8 \) CPU-hours.

★ Scaling higher for future exaFLOP computers - hybrid code with GPU.

→ single-GPU code already exists - CUDA cuFFT allowing for considerable speedup (\( > 50\times \)).

★ Analysing data from future runs: O2, O3, ... until 2020 and beyond,

★ 3 detectors (LIGO + Virgo) or more (+KAGRA, LIGO India...)

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