Overview and Status of Advanced Interferometers

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On behalf of the LIGO scientific collaboration
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TAUP, Torino
11.Sept. 2015
Gravitational Waves

Distortion of space-time traveling at the speed of light
Gravitational Waves

Distortion of space-time traveling at the speed of light

...traveling at the speed of thought!!

A.S. Eddington
The Gravitational-wave Spectrum

- Primordial GWs
- Cosmic strings
- Supermassive BH binaries
- BH and NS binaries
- Binary coalescence
- Spinning NS
- Supernovae
- Inflation probe
- Pulsar timing
- Interferometers in space
- Ground-based interferometers

Hz:

- $10^{-16}$
- $10^{-8}$
- $10^{-3}$
- $10^{0}$
- $10^{3}$
Gravitational waves are hard to measure, they are small...

Virgo Cluster
50 million light-years away
(15Mpc)

\[ h = \Delta L / L \]

Inspiral signal from NS binary in Virgo cluster
\[ h_{NS} \sim 10^{-22} \]

The pioneer of the GW-detection research:

Resonant antennas: bars („Weber-bars“)
**Resonant Bar Detectors**

- **Auriga**
  - Legnaro, INFN (Italy)

- **Allegro**
  - Baton Rouge, LSU (USA)

- **Explorer**
  - Geneva, CERN, INFN (Switzerland)

- **Nautilus**
  - Frascati, INFN (Italy)

- **Niobe**
  - Perth, UWA (Australia)

- **Specifications**
  - $M \sim$ a few tons
  - $L \sim 3\; m$
  - $F \sim 900\; Hz$
Resonant Bar Detectors

M ~ a few tons
L ~ 3 m
F ~ 900 Hz

$h \sim 10^{-21}$ @ ~900 Hz

Auriga
Legnaro, INFN (Italy)

Nautilus
Frascati, INFN (Italy)

STILL RUNNING!

Allegro
Baton Rouge, LSU (USA)

Explorer
Geneva, CERN, INFN (Switzerland)

Niobe
Perth, UWA (Australia)

RETIREDE
Michelson Interferometers

Gravitational wave propagation

Mirror 1

Mirror 2

y-arm

x-arm

Beam splitter

Laser

Photodetector
Michelson (with additions)

Michelson-Morley experiment:
Accuracy: $10^{-8}$ m ($10^{-9}$ relative)

10m arm-length

Advanced Interferometer:
Accuracy: $10^{-19}$ m ($3 \times 10^{-23}$ relative), 100Hz BW

3-4 km arm-length
Michelson-Morley experiment:
Accuracy: $10^{-8}$ m ($10^{-9}$ relative)

10m arm-length

Advanced Interferometer:
Accuracy: $10^{-19}$ m ($3 \times 10^{-23}$ relative), 100Hz BW

3-4 km arm-length

Measurement limited by Heisenberg uncertainty $h \sim dx \times dp$

(40kg masses)
...and a bit closer
To reality...
Current GW – Interferometer Projects

- LIGO Hanford 4km
- GEO600 600m
- KAGRA 3km
- LIGO Livingston 4km
- VIRGO 3km
- LIGO India? 4km
Current GW – Interferometer Projects

- **LIGO Hanford**: 4km
- **GEO600**: 600m
- **KAGRA**: 3km
- **LIGO Livingston**: 4km
- **VIRGO**: 3km
- **LIGO India?**: 4km

2015
Current GW – Interferometer Projects

LIGO Hanford
4km

GEO600
600m

KAGRA
3km

LIGO Livingston
4km

LIGO India?
4km

VIRGO
3km

2015

2016
Current GW – Interferometer Projects

LIGO Hanford 4km

GEO600 600m

KAGRA 3km

LIGO Livingston 4km

VIRGO 3km

LIGO India 2015

LIGO India 2016

LIGO India 2017/18
Improving Sensitivity in Advanced Detectors
Detection range for average oriented BNS inspiral (SNR=8):

Initial: ~20Mpsec

Advanced: ~200Mpsec
TECHNOLOGIES

- Dominated by seismic noise
- Managed by suspending the mirrors from extreme vibration isolators
  - Virgo Superattenuator (from 1st generation) / 8 stages
  - LIGO active system + 4 stages
- Technical noises of different nature are the real challenge in this range
- Ultimate limit for ground based detectors: gravity gradient noise

LOW FREQUENCY RANGE

Adv. Virgo

Adv. LIGO
DOMINATED BY THERMAL NOISE OF
- Mirror coatings
- Suspensions

REDUCED BY:
- Improved optical configuration: larger beam spot
- Mirror coatings engineered for low losses
- Test masses suspended by fused silica fibers (low mechanical losses)
- Dominated by laser shot noise
- Improved by increasing the power: >100W input, ~1 MW in the cavities

**REQUIRES:**
- New laser amplifiers (solid state, fiber)
- Heavy, low absorption optics (substrates, coatings)
- Smart systems to correct for thermal aberrations: Ring heaters, heat projectors, scanning CO2 lasers
Advanced Virgo (AdV): upgrade of the Virgo interferometric detector of gravitational waves

Participated by scientists from Italy and France (former founders of Virgo), The Netherlands, Poland and Hungary

Funding approved in Dec 2009 (23.8 ME)

5 European countries
19 labs, ~200 authors

APC Paris
ARTEMIS Nice
EGO Cascina
INFN Firenze-Urbino
INFN Genova
INFN Napoli
INFN Perugia
INFN Pisa
INFN Roma La Sapienza
INFN Roma Tor Vergata
INFN Trento-Padova
LAL Orsay – ESPCI Paris
LAPP Annecy
LKB Paris
LMA Lyon
NIKHEF Amsterdam
POLGRAW(Poland)
RABOUD Uni. Nijmegen
RMKI Budapest
FIRST “MINITORRE BENCH” (SIB2) INTEGRATED
Status of Advanced Virgo

- Installation in progress, to be completed end of 2015
- Plan to take observational data together with LIGO in 2016!
Advanced LIGO

LIGO scientific collaboration:

17 countries,
80+ institutions
900+ members
L1 Strain Sensitivity changes over time

<table>
<thead>
<tr>
<th>Date</th>
<th>Power</th>
<th>Drive</th>
<th>Distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jun 1 2014</td>
<td>0.7 W</td>
<td>ESD drive</td>
<td>0.5 Mpc</td>
</tr>
<tr>
<td>Jun 12 2014</td>
<td>0.7 W</td>
<td>ESD drive</td>
<td>3.6 Mpc</td>
</tr>
<tr>
<td>Jun 28 2014</td>
<td>2 W</td>
<td>ESD drive</td>
<td>5.8 Mpc</td>
</tr>
<tr>
<td>Jul 24 2014</td>
<td>2 W</td>
<td>ESD drive</td>
<td>15 Mpc</td>
</tr>
<tr>
<td>Jul 31 2014</td>
<td>6 W</td>
<td>L2 drive</td>
<td>20 Mpc</td>
</tr>
<tr>
<td>Nov 27 2014</td>
<td>6 W</td>
<td>L2 drive</td>
<td>46 Mpc</td>
</tr>
<tr>
<td>Mar 03 2015</td>
<td>25 W</td>
<td>L2 drive</td>
<td>67 Mpc</td>
</tr>
</tbody>
</table>

- **Strain [strain/Hz]**
- **Frequency (Hz)**

Graph showing the L1 Strain Sensitivity over time with different power levels, drive types, and distances.
Status of Advanced LIGO

- Installation (project) completed in March 2015
- Both interferometers reached first stage sensitivity (~60Mpsec)
- First observational run (O1) of advanced detector era to start Monday (14.Sept.2015)!
Can we expect GW detections?

### Table 5. Detection rates for compact binary coalescence sources.

<table>
<thead>
<tr>
<th>IFO</th>
<th>Source</th>
<th>( \dot{N}_{\text{low yr}^{-1}} )</th>
<th>( \dot{N}_{\text{re yr}^{-1}} )</th>
<th>( \dot{N}_{\text{high yr}^{-1}} )</th>
<th>( \dot{N}_{\text{max yr}^{-1}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>NS–NS</td>
<td>( 2 \times 10^{-4} )</td>
<td>0.02</td>
<td>0.2</td>
<td>0.6</td>
</tr>
<tr>
<td></td>
<td>NS–BH</td>
<td>( 7 \times 10^{-5} )</td>
<td>0.004</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH–BH</td>
<td>( 2 \times 10^{-4} )</td>
<td>0.007</td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td>&lt;0.001(^b)</td>
<td></td>
<td>0.01(^c)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMBH-IMBH</td>
<td>( 10^{-4} )(^d)</td>
<td></td>
<td>( 10^{-3} )(^e)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>NS–NS</td>
<td>0.4</td>
<td>40</td>
<td>400</td>
<td>1000</td>
</tr>
<tr>
<td>Advanced</td>
<td>NS–BH</td>
<td>0.2</td>
<td>10</td>
<td>300</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BH–BH</td>
<td>0.4</td>
<td>20</td>
<td>1000</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IMRI into IMBH</td>
<td>( 10 )(^b)</td>
<td></td>
<td></td>
<td>( 300 )(^c)</td>
</tr>
<tr>
<td></td>
<td>IMBH-IMBH</td>
<td>0.1(^d)</td>
<td></td>
<td></td>
<td>1(^e)</td>
</tr>
</tbody>
</table>

Class. Quant. Grav., 27 (2010) 173001
Observing prospects

Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories

KAGRA Project

Cryogenic and Underground Gravitational-wave detector

Host: U of Tokyo ICRR

Co-host: NAOJ, KEK

~230 collaborators from ~60 universities
Kamioka site

CRYOGENIC, UNDEGROUND interferometer

KAGRA Office

KAGRA

Entrance

KAMIOKA

CLIO (GW)

XMASS (dark matter)

KamLand (Neutrino)

Super-Kamiokande (Neutrino)
Cryostat Design

- 2.6 diameter, 3.6m high, 10 ton
- 8K an 80K
- 4 pulse tube cryo-coolers for each cryostat
• Both 3 km arm vacuum tubes (800mm d) and 125 baffles were jointed and leak tested → no leak!
• Cryostats installed
Project Started in 2010
1 yr delay due to the earthquake

- Simple 3-km Michelson ifo
- Room temperature
- Simplified suspensions

iKAGRA

- Simple 3-km Michelson ifo
- Room temperature
- Simplified suspensions

bKAGRA

- Dual-recycled FP MI ifo
- Cryogenic temperature
- VIRGO-type big suspensions
Smaller-scale detector run as prototype observatory.
Development and test of new technologies.
Example: Control and long-term application of squeezed light.
Squeezed light at GEO: 3.7 dB reduction of read-out noise
Beyond Advanced Interferometers

- Upgrades with squeezed light planned for LIGO and Virgo
- LIGO: likely suspension/mirror upgrade, perhaps new detector in same facility on intermediate timescale (10y). Perhaps new facility
- ET (Europe): New facility, 10x more sensitive than advanced IFOs (design study completed)
Summary

- Gravitational waves as new tool for astronomy, just around the corner...
- Advanced Interferometers (Virgo, LIGO, KAGRA) progressing nicely, on schedule
- LIGO starting 1\textsuperscript{st} observational run (O1) next week, Virgo to join O2 in 2016, KAGRA 2017/18
- Expect 1\textsuperscript{st} detections within few years...
Limiting Noise

- Radiation pressure
- Vacuum fluctuations entering dark port
- Shot noise
- Technical noises (not shown):
  - Laser amp/freq
  - Backscatter
  - Residual gas
  - Angular
  - Newtonian
  - Electronics
  - ...
Vacuum fluctuations in interferometers

Diagrams credit: L. Barsotti, K. Dooley
Vacuum fluctuations in interferometers

Squeezing the phase quadrature of the vacuum field entering the anti-symmetric port reduces the readout noise.

Diagrams credit: L. Barsotti, K. Dooley
AURIGA & NAUTILUS continuously on the air ~ 90% (combined) with noise close to Gaussian (~ 20 outliers/day at SNR>6) until LIGO/Virgo resume operation

AUNA: “astrowatch” of AURIGA & NAUTILUS under triggers from SN neutrinos, giant X-rays flares, etc