VESF School 2009:
FUTURE INTERFEROMETERS

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Some remarks ahead ...

- ‘Future interferometers’ is a very wide field ... ... and I apologise for only covering a small fraction of the most interesting topics.

- In order to reserve as much space as possible for the ‘cool future stuff’, I will build on the basics covered in previous lectures (‘Interferometers’, ‘Noise and Control’, ‘Current detectors’).

- If we come along anything you do not understand, PLEASE ASK !!!
What do I want you to take with you from this lecture?

- Get a good overview of all the exciting physics and technologies necessary for designing and building future interferometers.

- Get an intuitive understanding of the relevant technologies and underlying principles.
Today’s network of GW detectors

Today:
- Virgo, LIGO, GEO600 and Tama
- Sensitivity: $10^{-13}$ of a fringe

GEO600: measures the 600m long arms to an accuracy of 0.0001 proton diameter @ 500 Hz

Status and future of GW observatories

- **1st** generation successfully completed:
  - Long duration observations (~1yr) in coincidence mode of 5 observatories.
  - Spin-down upper limit of the Crab-Pulsar beaten!

- **2nd** generation on the way:
  - End of design phase, construction about to start (or even started)
  - 10 times better sensitivity than 1st generation. => Scanning 1000 times larger volume of the Universe

- **3rd** generation at the horizon:
  - FP7 funded design study
  - 100 times better sensitivity than 1st generation. => Scanning 1000000 times larger volume of the Universe
Overview

What do we need to change to make our instruments 2nd Generation observatories?

- Details of 2nd Generation interferometer: Example Advanced Virgo
  - Noise limits: Suspension thermal noise, Coating Brownian noise, Quantum noise
  - Important Techniques: Thermal compensation, NDRC, DC-readout
  - Sensitivity optimisation and observation prospects

- Other 2nd Generation GW Observatories
  - Advanced LIGO, LGCT, GEO-HF

What will a 3rd Generation Interferometer look like?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?
Overview

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**What will a 3rd Generation Interferometer look like?**

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  - How to reach the sensitivity?
Which are the main fundamental noise sources limiting Virgo?

![Graph showing noise sources and their contributions to the total noise level in Virgo.](http://wwwcascina.virgo.infn.it/senscurve/)
Which are the main fundamental noise sources limiting Virgo?

- Suspension thermal noise (low frequencies)

![Graph showing noise sources]

http://wwwcascina.virgo.infn.it/senscurve/
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![Graph showing noise sources limiting Virgo](http://www.cascina.virgo.infn.it/senscurve/)
Which are the main fundamental noise sources limiting Virgo?

- Suspension thermal noise (low frequencies)
- Mirror thermal noise (mid frequencies)
- Shot noise (high frequencies)

Improving these three noise contributions is the primary design task for Advanced Virgo!!

http://wwwcascina.virgo.infn.it/senscurve/
How to reduce Suspension Thermal Noise?

- Suspension thermal noise of a simple pendulum:

\[
x^2(\omega) = \frac{4k_B T \omega_0^2 \phi(\omega)}{\omega m [(\omega^2 - \omega_0^2)^2 + \omega_0^4 \phi^2(\omega)]}
\]
How to reduce Suspension Thermal Noise?

- Suspension thermal noise of a simple pendulum:
  \[
  x^2(\omega) = \frac{4k_B T \omega_0^2 \phi(\omega)}{\omega m[(\omega_0^2 - \omega^2)^2 + \omega_0^4 \phi^2(\omega)]}
  \]

- Suspension thermal noise can be reduced:
  - By cooling: proportional to sqrt(T)
  - By making the pendulum longer: proportional to w_0
  - By making the mirror heavier: proportional to sqrt(1/m)
  - By reducing the pendulum losses: proportional to sqrt(\phi)
How to improve the loss angle of a suspension?

- Example:
  Displacement noise of a single pendulum:
  - Mass = 42kg
  - Room temperature
  - 1 Hz resonance frequency

- How can we improve the loss angle?
Steel Wire Suspensions

- Steel wire suspensions: loss angle of up to 1e-6
- Fairly easy to build and to handle...
Quasi-monolithic Fused Silica Suspension

- Using thin (few hundred microns) fused silica fibers welded or clamped onto fused silica mirrors.
- Breaking stress limit of fused silica fibers (2-4e9 Pa) comparable with steel wires.
- Quasi-monolithic fused silica suspensions: loss angle of up to 1e-8

- Fused Silica Suspensions are used in GEO600 for more than 5 years and will be the baseline for all 2nd generation interferometers.
Which are the main fundamental noise sources limiting Virgo?

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- Shot noise (high frequencies)

http://wwwcascina.virgo.infn.it/senscurve/
How to decrease Coating Brownian Noise?

- Coating Brownian noise can be reduced:
  - By cooling: proportional to $\sqrt{T}$
  - By making the coating layers thinner: proportional to $\sqrt{d}$
  - By making laser beam larger: proportional to $1/r_0$
  - By reducing mechanical losses of the coating: proportional to $\sqrt{\phi}$
Can we make the coating thinner?

- **NO!** For a certain laser wavelength and coating materials the coating thickness is driven by the required reflectivities \((R)\) of the mirrors.

- Coating made of \(k\) quarter-wave stacks, formed by alternating layers of high refraction index \((n_H)\) and low refraction index \((n_L)\)

- PLEASE NOTE: If we would use different lasers the coating layer thickness would go down inverse proportional to the laser wavelength
Required coating thicknesses for the Advanced Virgo mirrors

- Input mirror: \( R = 99.3\% \)
- End mirror: \( R = 99.9995\% \)
- High refractive material: \( n = 2.04 \)
- Low refractive material: \( n = 1.45 \)

<table>
<thead>
<tr>
<th>Optic</th>
<th>Number of HLL</th>
<th>Thickness of low index material [m]</th>
<th>Thickness of high index material [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ITM, Fin = 888</td>
<td>8</td>
<td>1.83e-6</td>
<td>1.05e-6</td>
</tr>
<tr>
<td>ITM, Fin = 444</td>
<td>7</td>
<td>1.65e-6</td>
<td>0.92e-6</td>
</tr>
<tr>
<td>ETM</td>
<td>16</td>
<td>3.30e-6</td>
<td>2.09e-6</td>
</tr>
</tbody>
</table>
Can we use better coatings?

- Fortunately: **YES!**
- Coating research is one of the hot topics in the GW field.
- Standard high-refractive material is tantala.
- Doping the tantala with titania reduces the loss angle by about 30%.

G. Harry et al: ‘Titania-doped tantala/silica coatings for GW detection’  
*CQG, 2007, 24, 405-415*
Where to put the cavity waist?

- Initial Virgo has the waist on the input mirror:
  - Disadvantage: Coating noise is entirely dominated by small beam size of input mirror.
Gauss beams

\[ g_1 = 1 - \frac{L}{R_{C1}} \quad \text{and} \quad g_2 = 1 - \frac{L}{R_{C2}} \]

\[ w_1^2 = \frac{L\lambda}{\pi} \sqrt{\frac{g_2}{g_1(1 - g_1g_2)}} \quad \text{and} \quad w_2^2 = \frac{L\lambda}{\pi} \sqrt{\frac{g_1}{g_2(1 - g_1g_2)}} \]

- \( R_C \approx \infty, \quad z - z_0 \ll z_R \)
- \( R_C \approx z, \quad z \gg z_R, \quad z_0 \)
- \( R_C = 2z_R, \quad z - z_0 = z_R \)

Slide stolen from A. Freise
Where to put the cavity waist?

- Initial Virgo has the waist on the input mirror:
  - Disadvantage: Coating noise is entirely dominated by small beam size of input mirror

- Advanced Virgo will have the waist close to cavity center:
  - Disadvantage: large beams in the central IFO
  - Advantage: much lower coating Brownian noise!
What is the maximum Beam Size?

- **Sensitivity**
  - Need to make the beams as large as possible!

- **Cavity stability**
  - Large beams means pushing towards instability of the cavity.
  - Cavity degeneracy sets limit for maximal beam size

- **Mirror size**
  - The maximum coated area might also impose a limit for the beam size.
Clipping losses

- Why are clipping losses a problem?
  - Reduced power buildup.
  - Scattered light noise.

- In the ideal case a factor 2.5 (beam radius to mirror radius) seems to be fine = clipping loss of only a few ppm.

- Keep in mind: in reality
  - Mirror imperfections
  - Miscentering
  - Residual alignment fluctuations

Advanced Virgo:
Mirror diameter 35cm
Maximal beam radius = 6.5cm
Sensitivity with symmetric radii of curvature (ROC)

- With 6cm radius and 1530m ROC: Advanced Virgo obtains about 150 Mpc.

Example: cavity of 3km length and identical curvatures of input and end mirror.
Cavity Stability and Choice of ROCs

- The larger the beams the more accuracy is required for the mirror polishing!

- Account for potential manufacturing accuracy
  - AdVirgo example: L = 3000m, beam radius at ITM and ETM = 6cm => ROCs of 1531m are required.
  - Deviation of only a few ten meters can make cavity instable.

- Advanced Virgo: Believe that we can go for ROCs 2% of instability.

- Corrective coating as baseline.
Corrective Coating

- A way to improve the mirrors flatness: corrective coating

- Two ingredients
  - Robot
  - Metrology

Slide stolen from R. Flaminio
Corrective coating from LMA

Before correction (Ø120 mm)
3.3 nm R.M.S.
16 nm P.V.

After correction (Ø120 mm)
0.98 nm R.M.S.
10 nm P.V.
Symmetric ROCs of IM and EM?

- Coating noise for ITM and ETM are different, due to their different number of coating layer:

\[
S_x(f) = \frac{4k_BT}{\pi^2fY} \frac{d}{r_0^2} \left( \frac{Y'}{Y} \phi_\parallel + \frac{Y}{Y'} \phi_\perp \right)
\]

- For equal beam size ETM has higher noise.
Optimal Waist Position

- In order to minimize the thermal noise we have to make the beam larger on ETM and smaller on ITM.

- Equivalent to moving the waist closer to ITM.

- Nice additional effect: the beam in the central area would be slightly smaller.

Symmetric ROCs = non optimal Coating noise

Asymmetric ROCs = optimal Coating noise
Cavity Stability and Choice of ROCs

- Definition of mode-non-degeneracy:
  - Gouy-phase shift of mode of order \( l+m \):
    \[
    \phi_{l+m} = (l+m) \frac{1}{\pi} \arccos \sqrt{(1 - \frac{L}{R_{c,i}})(1 - \frac{L}{R_{c,e}})}.
    \]
  - Mode-non-degeneracy for a single mode is:
    \[
    \Psi_{l+m}(L, R_{c,i}, R_{c,e}) = |\phi_{l+m} - \text{round}(\phi_{l+m})|.
    \]
  - Figure of merit for combining all modes up to the order \( N \):
    \[
    \Theta_N(L, R_{c,i}, R_{c,e}) = \frac{1}{\sqrt{\sum_{k=1}^{N} \frac{1}{\Psi_k^2}}}.
    \]
Choice of ROCs/beam size:
Sensitivity vs Mode-non-degeneracy

- In general mode-non-degeneracy and sensitivity go opposite.

- Asymmetric ROCs are beneficial:
  - For identical mode-non-degeneracy (parallel to arrows in lower plot) and even slightly increased sensitivity we can reduce the beam size in the CITF from 6 to 5.5 cm.

<table>
<thead>
<tr>
<th>beam radius [mm]</th>
<th>input mirror</th>
<th>end mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROC [m]</td>
<td>1416</td>
<td>1646</td>
</tr>
</tbody>
</table>

Table 8: Design parameter of the AdV arm cavity geometry.
Which are the main fundamental noise sources limiting Virgo?

- Suspension thermal noise (low frequencies)
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- Shot noise (high frequencies)

![Graph showing noise sources limiting Virgo](http://wwwcascina.virgo.infn.it/senscurve/)
How can we reduce the shot noise contribution?

- Shot noise is proportional to $\sqrt{\text{light power}}$
- Signal is directly proportional to light power
- In total our signal to shot noise ratio improves with $\sqrt{\text{light power}}$
- Ways to increase the light power:
  - Bigger laser: Virgo = 20W, Advanced Virgo >165W
  - Higher arm cavity finesse
  - Stored light power: Virgo = 4kw, Advanced Virgo= 760kW

Please note: Shot noise is only one of two components of the so-called quantum noise!
What is quantum noise?

- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
- The photons in a laser beam are not equally distributed, but follow a Poisson statistic.

\[
\mathcal{h}_{\text{sn}}(f) = \frac{1}{L} \sqrt{\frac{\hbar c \lambda}{2\pi P}}
\]
What is quantum noise?

- Quantum noise is comprised of **photon shot noise** at high frequencies and **photon radiation pressure noise** at low frequencies.
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\[
\begin{align*}
\hbar_{\text{sn}}(f) &= \frac{1}{L} \sqrt{\frac{\hbar c \lambda}{2\pi P}} \\
\hbar_{\text{rp}}(f) &= \frac{1}{m f^2 L} \sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}
\end{align*}
\]
The Standard Quantum Limit (SQL)

- While shot noise contribution decreases with optical power, radiation pressure level increases:

\[ h_{sn}(f) = \frac{1}{L} \sqrt{\frac{\hbar c \lambda}{2\pi P}} \]

\[ h_{rp}(f) = \frac{1}{m f^2 L} \sqrt{\frac{\hbar P}{2\pi^3 c \lambda}} \]

- The SQL is the minimal sum of shot noise and radiation pressure noise.

- Using a classical quantum measurement the SQL represents the lowest achievable noise.

V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)
The Standard Quantum Limit (SQL)

- While shot noise contribution decreases with optical power, radiation pressure level increases.

The SQL is the minimal sum of shot noise and radiation pressure noise. Using a classical quantum measurement the SQL represents the lowest achievable noise.

More on this topic: tomorrow's lecture on QND, squeezing and other eracy ideas.

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Advanced Virgo sensitivity
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What will a 3rd Generation Interferometer look like?

- How to build the Einstein Telescope (ET)?
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Advanced Virgo Baseline design
Three examples of important techniques to improve the detector robustness:

- Thermal compensation
- Non-degenerate Recycling cavities
- DC-readout
Thermal compensation

- Ring heater to change the curvature of each mirror:
  - Introducing temperature gradient in mirror substrate.
  - Thermal expansion bends the mirror.

- CO$_2$ act on compensation plates:
  - Relative intensity noise (radiation pressure) prohibits to act directly on mirror.
  - Introducing additional silica plates and use the temperature dependent index of refraction to correct wavefront curvature.
Three examples of important techniques to improve the detector robustness:

- Thermal compensation
- Non-degenerate Recycling cavities
- DC-readout
Non-degenerate Recycling cavities

- **Motivation:** Thermal effects or misalignments scatter light into higher-order modes so that optical signal is lost. Non-degenerate cavities reduce this effect.

- **Commissioning experience** shows that degenerate cavities cause problems for control signals. Y. Pan showed in 2006 that also GW signal is lost.

![Graph showing non-degenerate recycling cavity](image)
A possible optical layout

- Design of Non-degenerate Recycling Cavity

- Proper design of the non-degenerate Recycling Cavity is rather complicated ...

- Here I concentrate on a single aspect: Infrastructure
Advanced Virgo Baseline design

- Folded beam to increase recycling cavity length
- PRM3 and PRM2 are (de)focusing elements.
- Infrastructure problems:
  - Need to suspend more than 1 optic per vacuum tower
  - Need large vacuum tubes to fit (larger) folded beams
  - Non perpendicular angle of incidence = losses due to astigmatism
Three examples of important techniques to improve the detector robustness:

- Thermal compensation
- Non-degenerate Recycling cavities
- DC-readout
DC-readout

- Initial Virgo uses heterodyne readout for the GW signal.
- Advanced Virgo will use DC-readout (a special case of homodyne detection).

![Heterodyne, Homodyne, DC-readout](image)
Advanced Virgo Baseline design
### Advanced Virgo: Executive Summary

#### Adv Overview, Part I

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<tr>
<th>Subsystem and Parameters</th>
<th>Adv Baseline Design</th>
<th>Initial Virgo Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensitivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Binary Neutron Star Inspiral Range</td>
<td>1.5 x 10^5 Mpc</td>
<td>11 Mpc</td>
</tr>
<tr>
<td>Anticipated Strain Sensitivity</td>
<td>3 x 10^{-24}/√Hz</td>
<td>4 x 10^{-23}/√Hz</td>
</tr>
<tr>
<td>Displacement Sensitivity</td>
<td>1 x 10^{-19} m/√Hz</td>
<td>1 x 10^{-18} m/√Hz</td>
</tr>
</tbody>
</table>

#### Instrument Topology

<table>
<thead>
<tr>
<th>Laser and Optical Powers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser Wavelength</td>
</tr>
<tr>
<td>Optical Power at Laser Output</td>
</tr>
<tr>
<td>Optical Power at Interferometer Input</td>
</tr>
<tr>
<td>Optical Power at Test Masses</td>
</tr>
<tr>
<td>Optical Power on Beam Splitter</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Test Masses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mirror Material</td>
</tr>
<tr>
<td>Main Test Mass Diameter</td>
</tr>
<tr>
<td>Main Test Mass Weight</td>
</tr>
</tbody>
</table>

#### Test Mass Surfaces and Coatings

<table>
<thead>
<tr>
<th>Coating Material</th>
<th>Ti doped Ta2O5</th>
<th>Ta2O5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roughness</td>
<td>&lt; 1 Angstrom</td>
<td>&lt; 0.5 Angstrom</td>
</tr>
<tr>
<td>Flatness</td>
<td>0.5 mm RMS</td>
<td>&lt; 0.5 mm RMS</td>
</tr>
<tr>
<td>Losses per Surface</td>
<td>3.5 ppm</td>
<td>250 ppm (measured)</td>
</tr>
<tr>
<td>Test Mass ROC</td>
<td>Input Mirror = 1416 m</td>
<td>Input Mirror = flat</td>
</tr>
<tr>
<td>Beam Radius at Input Mirror</td>
<td>56 mm</td>
<td>21 mm</td>
</tr>
</tbody>
</table>

#### Thermal Compensation

<table>
<thead>
<tr>
<th>Thermal Actuators</th>
<th>CO2 Lasers and Ring Heaters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actuation Points</td>
<td>Compensation Plates directly at Mirrors</td>
</tr>
</tbody>
</table>

#### Adv Overview, Part II

<table>
<thead>
<tr>
<th>Subsystem and Parameters</th>
<th>Adv Preliminary Design</th>
<th>Initial Virgo Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Suspension</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seismic Isolation System</td>
<td>Superattenuator</td>
<td>Superattenuator</td>
</tr>
<tr>
<td>Degrees of Freedom Inverted Pendulum Inertial Control</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>suspension Fibres</td>
<td>Fused Silica Fibres (super)</td>
<td>Steel Wires</td>
</tr>
</tbody>
</table>

#### Vacuum System

| Pressure | 2 x 10^{-9} mbar | 2 x 10^{-7} mbar |

#### Injection System

| Input mode cleaner throughput | >90% | 85% (meas.) |

#### Detection System

<table>
<thead>
<tr>
<th>GW Signal Readout</th>
<th>DC-Readout</th>
<th>Heterodyne (RF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Mode Cleaner</td>
<td>RF Sidebands and Higher Order Modes</td>
<td></td>
</tr>
<tr>
<td>Suppression</td>
<td>Higher Order Modes</td>
<td></td>
</tr>
<tr>
<td>Main Photo Diode Environment</td>
<td>in Vacuum</td>
<td>in Air</td>
</tr>
</tbody>
</table>

#### Lengths

| Arm Cavity Length | 3 m | 3 m |
| Input Mode Cleaner | 144 m | 144 m |
| Power Recycling Cavity | 28 m | 10 m |
| Signal Recycling Cavity | 28 m | n.a. |

#### Interferometric Sensing and Control

| Lock Acquisition Strategy | Auxiliary Lasers (different wavelength) | Main Laser |
| Number of RF Modulations | 3 | 1 |
| Schuapp Asymmetry | 4 cm | 8 cm |
| Recycling Cavity Design | Non-degenerate | Marginally stable |

#### Signal Recycling Parameter

| Signal Recycling Mirror Transmittance | 11% | n.a. |
| Signal Recycling Tuning | 0.15 rad | n.a. |
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Signal Recycling: Possibility for tunable GW microphones
How to listen to the Universe?

- Advanced Virgo is a hyper-sensitivity microphone to listen to the Universe.
- Each astrophysical source has its own sound or tone.
- This microphone can be tuned ‘similar’ to a radio receiver.
Fundamental noise limits for Advanced Virgo

- Advanced Virgo will be limited by quantum noise at nearly all frequencies of interest.

- **GOAL:** Optimise quantum noise for maximal science output.
Our optimisation is limited by Coating thermal noise and Suspension thermal noise.

Quantum noise to be optimised!
In order to understand the ‘Resonant Sideband Extraction’ of Advanced Virgo it is useful to first have a look at a simpler example:

**Signal Recycling in GEO600**

- GEO600 is so far the only detector using Signal Recycling.
- Signal Recycling can beat the SQL.
- All advanced interferometers will use Signal Recycling !!
- Signal Recycling is easy to understand if you just think of it as an additional resonator for the GW-signal inside the interferometer.
Signal-Recycling in short

An additional recycling mirror (MSR) at the dark port allows:

- enhancing the GW signal
- shaping the detector response

Two main parameters:

- **Bandwidth** (of the SR resonance)
  - broadband
  - narrowband

- **Tuning** (Fourier frequency of the SR resonance)
  - tuned
  - detuned

Short Excursion: Signal recycling in GEO600
The tuning of the Signal-Recycling resonance is determined by the microscopic position of the Signal Recycling mirror.

Shot noise for GEO600 with a light power of 1.8 kW @ beam splitter

- $T_{MSR} = 2^\circ$, tuning: 0 Hz
- $T_{MSR} = 2^\circ$, tuning: 300 Hz
- $T_{MSR} = 2^\circ$, tuning: 700 Hz
- $T_{MSR} = 2^\circ$, tuning: 1500 Hz
The bandwidth of the Signal-Recycling resonance is determined by the reflectivity of the Signal Recycling mirror.
We have three knobs available for optimisation:

- **knob 1**: microscopic position of SRM1 (nm scale)
- **knob 2**: optical transmittance of SRM1
- **knob 3**: input light power

**Quantum noise knobs in Advanced Virgo**
Optimization Parameter 1: Signal-Recycling (de)tuning

- Frequency of pure optical resonance goes down with SR-tuning.
- Frequency of opto-mechanical resonance goes up with SR-tuning

Advanced Virgo, Power = 125W, SR-transmittance = 4%

- Photon radiation pressure noise
- Photon shot noise
- Pure optical resonance

Opto-mechanical Resonance (Optical spring)

knob 1

Photon radiation pressure noise
Photon shot noise
Pure optical resonance
Optical Springs & Optical Rigidity

- Detuned cavities can be used to create optical springs.

- Optical springs couple the mirrors of a cavity with a spring constant equivalent to the stiffness of diamond.

- In a full Michelson interferometer detuned Signal Recycling causes an optical spring resonance.
Optimization Parameter 2:
Signal-Recycling mirror transmittance

Resonances are less developed for larger SR transmittance.
Optimization Parameter 3: Laser-Input-Power

- High frequency sensitivity improves with higher power (Shotnoise)
- Low frequency sensitivity decreases with higher power (Radiation pressure noise)
Figure of merit: Inspiral

- Inspiral ranges for BHBH and NSNS coalescence:

- Parameters usually used:
  - NS mass = 1.4 solar masses
  - BH mass = 10 solar masses
  - SNR = 8
  - Averaged sky location

\[
d = \frac{m_5^6}{\rho_0 \pi^{2/3}} \left( \frac{5\eta}{6} \right)^{1/2} \left[ \int_{f_{\text{iso}}}^{f_{\text{low}}} df \frac{f^{-7/3}}{S_h(f)} \right]^{1/2}
\]


Detector sensitivity

Frequency of last stable orbit (BNS = 1570 Hz, BBH = 220 Hz)

Spectral weighting = \( f^{-7/3} \)
Example: Optimizing 2 Parameters

- Inspiral ranges for free SR-tuning and free SRM-transmittance, but fixed Input power

NSNS-range

BHBH-range
Example: Optimizing 2 Parameters

- Different source usually have their maxima at different operation points.
- It is impossible to get the maximum for BNS AND BBH both at the same time!
Example: Optimizing 3 Parameter for Inspiral range

- Scanning 3 parameter at the same time:
  - SR-tuning
  - SR-trans
  - Input Power

- Using a video to display 4th dimension.
Optimal configurations

Curves show the optimal sensitivity for a single source type.
Which is the most promising source?

**Binary neutron star inspirals:**

Based on observations of existing binary stars

Based on models of binary star formation and evolution

<table>
<thead>
<tr>
<th>Model</th>
<th>merger rate (Myr$^{-1}$MWE$^{-1}$)</th>
<th>detection rate (yr$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>empirical</td>
<td>3 - 190</td>
<td>0.4 - 26</td>
</tr>
<tr>
<td>A</td>
<td>12 - 19</td>
<td>1.6 - 2.6</td>
</tr>
<tr>
<td>B</td>
<td>7.6 - 12</td>
<td>1 - 1.6</td>
</tr>
<tr>
<td>C</td>
<td>68 - 101</td>
<td>9.2 - 14</td>
</tr>
</tbody>
</table>

Expected event rates seen by Advanced Virgo: ~1 to 10 events per year.

Binary neutron star inspirals are chosen to be the primary target for Advanced Virgo.

**Binary black hole inspirals:**

<table>
<thead>
<tr>
<th>Model</th>
<th>$\mathcal{M}/M_\odot$ range</th>
<th>$d_{\text{eff–sight}}$Mpc</th>
<th>merger rates Myr$^{-1}$</th>
<th>AdV detection rate yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5 – 8</td>
<td>613</td>
<td>0.02 – 0.03</td>
<td>0.2 – 0.3</td>
</tr>
<tr>
<td>C</td>
<td>2.5 – 8.5</td>
<td>545</td>
<td>7.7 – 11</td>
<td>52 – 75</td>
</tr>
</tbody>
</table>

C.Kim, V.Kalogera and D.Lorimer: “Effect of PSRJ0737-3039 on the DNS Merger Rate and Implications for GW Detection”, astro-ph:0608280

When Advanced Virgo and Advanced LIGO come online \textbf{WE WILL SEE GRAVITATIONAL WAVES!}

... if not, then something is completely \textbf{wrong} with our understanding of \textbf{General Relativity}.
Overview

What do we need to change to make our instruments 2nd Generation observatories?

- Details of 2nd Generation interferometer: Example Advanced Virgo
  - Noise limits: Suspension thermal noise, Coating Brownian noise, Quantum noise
  - Important Techniques: Thermal compensation, NDRC, DC-readout
  - Sensitivity optimisation and observation prospects

- Other 2nd Generation GW Observatories
  - Advanced LIGO, LGCT, GEO-HF

What will a 3rd Generation Interferometer look like?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?

What else is around in other parts of the world?
Specialties of other 2nd generation instruments

- **Advanced LIGO:**
  - 3 instruments of 4km length
  - Construction already started!!
  - Design pretty similar to Advanced Virgo, apart from seismic isolation: 4 stage pendulums (boosted GEO design)

- **LGCT:**
  - Cryogenic temperatures (reduce thermal noises)
  - Underground location in Kamioka mine.

- **GEO-HF:**
  - Quantum noise reduction by means of squeezed light injection.
Overview

What do we need to change to make our instruments 2nd Generation observatories?

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What will a 3rd Generation Interferometer look like?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?
  - What else is around in other parts of the world?
- Start around 2020(?)
- Underground location
- ~30km integrated tunnel length (?)

- Myriads of new possibilities and challenges !!

- Plenty of new Science...
Main driver for going underground:
Gravity Gradient noise

Surface (Pisa)

\[
\text{about } 1 \cdot 10^{-7} \text{ m/f}^2 \text{ for } f > 1 \text{ Hz}
\]

Underground (Kamioka)

\[
\text{about } 5 \cdot 10^{-9} \text{ m/f}^2 \text{ for } f > 1 \text{ Hz}
\]
What will be the shape of ET?

**Figure 2.** A comparison of several geometries for future ground-based detectors: (A) A simple Michelson interferometer is sensitive only to a linear combination of the two polarization amplitudes. (B) Two co-aligned Michelson interferometers provide redundancy and the possibility to generate a null-stream (and as for case A are sensitive only to a linear combination of the two polarization amplitudes). (C) Two Michelson interferometers rotated by 45° with respect to each other can fully resolve both polarization amplitudes. (D) Three rotated Michelson interferometers provide redundancy and the possibility to generate a null-stream. They also can measure both polarizations (the geometries shown as C and D feature intersection tubes. Similar geometries in which the Michelson interferometers do not overlap might be more practical, depending on the properties of the detector site, see [14]). (E) A LISA-like triangular configuration, in which the interferometer arms are single cavities and there is no optical recombination. (F) A triple Michelson interferometer configuration consisting of three individual Michelson interferometers.
What will be the shape of ET?

Both solutions have an integrated tunnel length of 30 km, they can resolve both GW polarisations, feature redundant interferometers and have equivalent sensitivity.

The triangle reduces the number of end stations and the enclosed area!
(Possibly, better vetos or noise reductions are possible in the triangle)
Shape independent of actual interferometer configuration

- All different interferometer types can be formed into L-shape
Shape independent of actual interferometer configuration

- All different interferometer types can be formed into L-shape

More on QND topologies: tomorrow’s lecture on QND, squeezing and other crazy ideas
Overview

What do we need to change to make our instruments 2nd Generation observatories?

- Details of 2nd Generation interferometer: Example Advanced Virgo
  - Noise limits: Suspension thermal noise, Coating Brownian noise, Quantum noise
  - Important Techniques: Thermal compensation, NDRC, DC-readout
  - Sensitivity optimisation and observation prospects

- Other 2nd Generation GW Observatories
  - Advanced LIGO, LGCT, GEO-HF

What will a 3rd Generation Interferometer look like?

- How to build the Einstein Telescope (ET)?
  - Geometry and shape
  - How to reach the sensitivity?
    - Brute Force Approach?
    - Xylophone?
The starting point

- We consider:
  - Michelson topology with dual recycling.
  - One detector covering the full frequency band.
  - A single detector (no network).

- Start from a 2nd Generation instrument.

- Each fundamental noise at least for some frequencies above the ET target.

=> OUR TASK: All fundamental noises have to be improved!!
Step 1: Increasing the arm length

**DRIVER:** All displacement noises

**ACTION:** Increase arm length from 3km to 10km

**EFFECT:** Decrease all displacement noises by a factor 3.3

**SIDE EFFECTS:**
- Decrease in residual gas pressure
- Change of effective Signal recycling tuning
Step 2: Optimising signal recycling

**DRIVER**: Quantum noise

**ACTION**: From detuned SR to tuned SR (with 10% transmittance)

**EFFECTS**:  
- Reduced shot noise by ~ factor 7 at high freqs  
- Reduced radiation pressure by ~ factor 2 at low freqs  
- Reduced peak sensitivity by ~ factor $\sqrt{2}$  

---

Stefan Hild  
VESF School, Pisa, May 2009  
Slide 88
Step 3: Increasing the laser power

**DRIVER:** Shot noise at high frequencies

**ACTION:** Increase laser power (@ ifo input) from 125W to 500W

**EFFECT:** Reduced shot noise by a factor of 2

**SIDE EFFECTS:** Increased radiation pressure noise by a factor 2
Step 4: Quantum noise suppression

**DRIVER:** Shot noise at high frequencies

**ACTION:** Introduced 10dB of squeezing (frequency depend angle)

**EFFECT:** Decreases the shot noise by a factor 3

**SIDE EFFECTS:** Decreases radiation pressure noise by a factor 3
Increasing the beam size to reduce Coating Brownian noise

Increasing the beam size at the mirrors reduces the contribution of Coating Brownian.

Coating Brownian noise of one mirror:

\[ S_x(f) = \frac{4k_B T}{\pi^2 f Y} \frac{d}{r_0^2} \left( \frac{Y'}{Y} \phi_\parallel + \frac{Y}{Y'} \phi_\perp \right) \]

Please note: a beam radius of 12cm requires mirrors of 60 to 70cm diameter
Step 5: Increasing the beam size

**Driver:** Coating Brownian noise

**Action:** Increase of beam radius from 6 to 12cm

**Effect:** Decrease of Coating Brownian by a factor 2

**Side Effects:**
- Decrease of Substrate Brownian noise (~factor 2)
- Decrease of Thermo-optic noise (~factor 2)
- Decrease of residual gas pressure noise (~10-20%)
Step 6: Cooling the test masses

**DRIVER:** Coating Brownian noise

**ACTION:** Reduce the test mass temperature from 290K to 20K

**EFFECT:** Decrease Brownian by ~ factor of 4

**SIDE EFFECTS:**
- Decrease of substrate Brownian
- Decrease of thermo-optic noise
Seismic Isolation / Suspension

Virgo Superattenuator (height ~ 8 meter)

Virgo Superattenuator

5 Stages of each 10 m height

corner freq = 0.158Hz

Suspension point

Step 7: Longer Suspensions

**DRIVER:** Seismic noise

**ACTION:** Build 50m tall 5 stage suspension (corner freq = 0.158 Hz)

**EFFECT:** Decrease seismic noise by many orders of magnitude or pushes the seismic wall from 10 Hz to about 1.5 Hz
Tackling Gravity Gradient noise: going underground

**Figure 7.** Low seismic noise environment at the Kamioka site. Displacement noises at Kamioka, TAMA site, Tokyo, Black Forest Geophysical Observatory (Germany) and a low noise model (a hybrid spectrum of quiet sites in the world) are described.

**Surface (Cascina)**

- about $1 \cdot 10^{-7} \text{m/sqrt(}Hz)$ for $f > 1 \text{Hz}$

**Underground (Kamioka)**

- about $5 \cdot 10^{-9} \text{m/sqrt(}Hz)$ for $f > 1 \text{Hz}$
Step 8: Going underground

**DRIVER:** Gravity gradient noise

**ACTION:** Go from the surface to underground location

**EFFECT:** Decrease gravity gradients by a factor 20

**SIDE EFFECTS:** Decrease in seismic noise by a factor 20
Step 9: Gravity gradient suppression

**DRIVER:** Gravity gradient noise

**ACTION:** Active subtraction of the gravity gradients

**EFFECT:** Decrease gravity gradient noise by a factor 50.
Step 10: Heavier mirrors

DRIVER: Quantum noise at low frequencies

ACTION: Increase test mass weight from 42 kg to 120 kg

EFFECT: Decrease of radiation pressure noise
### Advanced Detector vs Potential ET Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Advanced Detector</th>
<th>Potential ET Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arm length</td>
<td>3 km</td>
<td>10 km</td>
</tr>
<tr>
<td>SR-phase</td>
<td>detuned (0.15)</td>
<td>tuned (0.0)</td>
</tr>
<tr>
<td>SR transmittance</td>
<td>11%</td>
<td>10%</td>
</tr>
<tr>
<td>Input power (after IMC)</td>
<td>125 W</td>
<td>500 W</td>
</tr>
<tr>
<td>Arm power</td>
<td>0.75 MW</td>
<td>3 MW</td>
</tr>
<tr>
<td>Quantum noise suppression</td>
<td>none</td>
<td>10 dB</td>
</tr>
<tr>
<td>Beam radius</td>
<td>6 cm</td>
<td>12 cm</td>
</tr>
<tr>
<td>Temperature</td>
<td>290 K</td>
<td>20 K</td>
</tr>
<tr>
<td>Suspension</td>
<td>Superattenuator</td>
<td>5 stages of each 10 m length</td>
</tr>
<tr>
<td>Seismic</td>
<td>1 \cdot 10^{-7} m/f^2 for f &gt; 1 Hz (Cascina)</td>
<td>5 \cdot 10^{-6} m/f^2 for f &gt; 1 Hz (Kamioka)</td>
</tr>
<tr>
<td>Gravity gradient reduction</td>
<td>none</td>
<td>factor 50 required (cave shaping)</td>
</tr>
<tr>
<td>Mirror masses</td>
<td>42 kg</td>
<td>120 kg</td>
</tr>
<tr>
<td>BNS range</td>
<td>150 Mpc</td>
<td>2650 Mpc</td>
</tr>
<tr>
<td>BBH range</td>
<td>800 Mpc</td>
<td>17700 Mpc</td>
</tr>
</tbody>
</table>
Motivation for Xylophone observatories

- Due to residual absorption in substrates and coatings, high optical power (3MW) and cryogenic test masses (20K) don’t go easily together.

- IDEA: Split the detection band into 2 or 3 instruments, each dedicated for a certain frequency range. All ‘xylophone’ interferometer together give the full sensitivity.

- Example of a 2-tone xylophone:
  - Low frequency: low power and cryogenic
  - High frequency: high power and room temperature
Xylophone: More than one detector to cover the full bandwidth

Low Frequency IFO: low optical power, cryogenic test masses, sophisticated low frequency suspension, underground, heavy test masses.

High Frequency IFO: high optical power, room temperature, surface location, squeezed light
END