Overview of Gravitational Wave Detectors

... from initial detectors to 3rd generation

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Talk Outline

• Introduction to the Gravitational Wave (GW) search
• Gravitational wave interferometric detectors
  • Working principles
  • Current status
  • Advanced detectors
  • 3rd generation of gravitational wave observatories
    • The Einstein Telescope
• Conclusions
General Relativity and GW

- GW are predicted by the Einstein General Relativity (GR) theory
- Formal treatment of the GW in GR is beyond the scope of this talk and only the aspects important for the GW detection will be considered

Einstein field equation links the source of the space-time deformation ($T_{\mu\nu}$, Energy-impulse tensor) to the effect of the deformation ($G_{\mu\nu}$, the deformation tensor)

$$T_{\mu\nu} = -\frac{c^4}{8\pi G} G_{\mu\nu}$$

Far from the big masses Einstein field equation admits (linear approximation) wave solution (small perturbation of the background geometry)

$$g = \eta + h \text{ with } |h_{\mu\nu}| \ll 1 \Rightarrow \left(\nabla^2 - \frac{1}{c^2} \frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$
Gravitational Waves

- Gravitational waves are a perturbation of the space-time geometry.
- They present two polarizations.
- The effect of GWs on a mass distribution is the modulation of the reciprocal distance of the masses.

\[
h(z,t) = e^{i(\omega t - k z)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_x & 0 \\ 0 & h_x & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}
\]
Let quantify the “deformation”

- Should we expect this?
- Coupling constant (fundamental interactions)

<table>
<thead>
<tr>
<th>strong</th>
<th>e.m.</th>
<th>weak</th>
<th>gravity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>1/137</td>
<td>10^{-5}</td>
<td>10^{-39}</td>
</tr>
</tbody>
</table>

GW emission: very energetic events but almost no interaction

- Or “space-time” rigidity (Naïf):

\[ G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu} \implies \frac{8\pi G}{c^4} = 4.8 \cdot 10^{42} \text{ N} \]

\[ \sigma_{ij} = C_{ijkl} \varepsilon_{kl} \implies Y_{\text{Steel}} \approx 2 \times 10^{11} \text{ Pa} \]

- Very energetic phenomena in the Universe could cause only faint deformations of the space-time
Let quantify the “deformation”

- The amplitude of the space-time deformation is:
  \[ h_{\mu \nu} = \frac{2G}{c^4} \cdot \frac{1}{r} \dot{Q}_{\mu \nu} \]

- Let suppose to have a system of 2 coalescing neutron stars, located in the Virgo cluster (r~10Mpc):
  \[ h \approx 10^{-21} - 10^{-22} \]

\[ \delta L \approx \frac{h}{2} \cdot L_0 \] \[ L_0 \approx 10^3 m \]  \[ \Rightarrow \delta L \approx 10^{-18} - 10^{-19} m \]

Where \( Q_{\mu \nu} \) is the quadrupolar moment of the GW source

and \( r \) is the distance between the detector and the GW source

Extremely challenging for the detectors
But, GWs really exist?

Neutron star binary system: PSR1913+16

- Pulsar bound to a “dark companion”, 7 kpc from Earth.
- Relativistic clock: $v_{\text{max}}/c \sim 10^{-3}$
- GR predicts such a system to lose energy via GW emission: orbital period decrease

Radiative prediction of general relativity verified at 0.2% level

Nobel Prize 1993: Hulse and Taylor
GW detectors: the resonant bars

- The epoch of the GW detectors began with the resonant bars

Joseph Weber (~1960)

- Then a network of cryogenic bars has been developed in the past

Piezoelectric transducers

Resonant bar suspended in the middle
GW interferometric detectors

- A network of detectors has been active in the World in the last years

GEO, Hannover, 600 m

Virgo, Cascina, 3 km

TAMA, Tokyo, 300 m (now CLIO)
VIRGO

- LAPP – Annecy
- NIKHEF – Amsterdam
- RMKI - Budapest
- INFN – Firenze-Urbino
- INFN – Genova
- INFN – LNF

- LMA – Lyon
- INFN – Napoli
- OCA – Nice
- LAL – Orsay
- APC – Paris
- LKB - Paris

- INFN – Padova-Trento
- INFN – Perugia
- INFN - Pisa
- INFN – Roma 1
- INFN – Roma 2
- POLGRAV - Warsaw
GW interferometric detectors

- A network of detectors has been active in the World in the last years

- LIGO Hanford, 4 km: 2 ITF on the same site!
- LIGO Livingston, 4 km
- GEO, Hannover, 600 m
- Virgo, Cascina, 3 km
- TAMA, Tokyo, 300 m (now CLIO)
GW interferometric detectors

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Working principle

- The quadrupolar nature of the GW makes the Michelson interferometer a “natural” GW detector

\[ \delta L \approx \frac{h}{2} \cdot L_0 \]

10^2 \leq L_0 \leq 10^4 \text{ m in terrestrial detectors}

\[ E_{out}(t) = E_1(t) + E_2(t) = \]
\[ = \frac{E_{in}}{2} \{ \cos[\omega t - k L_1(t)] + \cos[\omega t - k L_2(t)] \} = \]

Interference term

\[ = E_{in} \cdot \cos \left[ k \frac{L_2(t) - L_1(t)}{2} \right] \cos \left[ \omega t - k \frac{L_2(t) + L_1(t)}{2} \right] \]

\[ P_{out}(t) = \frac{P_{in}(t)}{2} \left\{ 1 + \cos \left[ \frac{2\pi n(t)}{\lambda_{laser}(t)} \cdot L \cdot h(t) \right] \right\} \]

\[ \phi_{GW} = \frac{4\pi}{\lambda} L_0 \cdot h \]

\( \Delta P \) Power fluctuations
\( \Delta n \) Index fluctuations

\{ Noise sources \}
Power fluctuation

- Power fluctuation? Shot noise!

\[
\frac{\sigma_N}{N} = \frac{1}{\sqrt{N}} \quad \Rightarrow \quad \tilde{\phi}_{\text{shot}} = \sqrt{\frac{2\hbar \omega}{P}}
\]

\[
\tilde{h}_{\text{shot}} = \frac{\lambda}{4\pi} \frac{1}{L} \tilde{\phi}_{\text{shot}} = \frac{1}{2L} \sqrt{\frac{\hbar \lambda c}{\pi P}}
\]

To allow the GW detection, the shot noise should be smaller than the expected signal (h~10^{-21}-10^{-22})

Try the intuitive numbers: \( P \leq 100\text{W}, L \sim 10^3 \):

\[ h_{\text{shot}} \sim 10^{-20} \quad \text{It works!} \]

If we try \( P \sim 1\text{kW}, L \sim 10^5\text{m} \):

\[ h_{\text{shot}} \sim 10^{-23} \quad \text{It doesn't work!} \]
Fabry-Perot cavities

- We need a “trick” to build ~100km long detectors on the Earth

Effective length:

\[ L' = L_0 \times \frac{2F}{\pi} \]

\[ I(t) = I_0 \cdot e^{\frac{t}{\tau_s}}, \quad \tau_s \approx \tau_{rt} \frac{F}{2\pi}, \quad F = \frac{\pi \sqrt{r_1 r_2}}{1 - r_1 r_2} \]

- Fabry-Perot cavities: amplify the length-to-phase transduction
- Higher finesse: higher \( df/dL \)
- Drawback: works only at resonance
Power recycling

- We need a “trick” to realize a 1000W CW laser
- GW interferometers work near the dark fringe:
  - Huge power wasted at the input port:
    - Recycle it

\[ P_{\text{eff}} = \text{Recycling factor} \cdot P_{\text{in}} \]

20 W \approx 1 \text{ kW}

Shot noise reduced by a factor \approx 7

One more cavity to be controlled
Typical earth crust tidal strain: $\sim 10^{-4}$ m
Allowed mirror rms motion: $\sim 10^{-14}$ m
The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity. Seismic filtering in Virgo pendulum chains to reduce seismic motion by a factor $10^{14}$ above 10 Hz.
Detector sensitivity

The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity.

Optimization of the payload design to minimize the mechanical losses.
Detector sensitivity

The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity.

Maximization of the injected laser power, to minimize the shot noise.
Virgo+ noise budget example

- Sensitivity (7.75 Mpc)
- CARM
- MICH
- PRCL
- Angular noise
- Diffused Light
- Magnetic noise (CB)
- Actuator noise
- Thermal noise
- Shot noise
- Electronic noise
- Phase noise
- Frequency noise dP=181 ppm dF/F=0.011
- Frequency noise (shot noise B5)
- Total noise (10.08 Mpc)
- Virgo+ design (no MS, P=25W)
GW interferometer past evolution

- Evolution of the GW detectors (Virgo example):

Proof of the working principle

- Infrastructure realization and detector assembling
- Commissioning & first runs

Same infrastructure

2003
2008

GW detectors

COMPSTAR 2011: GW detectors

C1 & C2: single arm ; C3 & C4: recombined ; C5 & after: recycled

Sensitivity [Hz/Hz]

Frequency [Hz]

10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}

C1 Nov 2003
C2 Feb 2004
C3 Apr 2004
C4 Jun 2004
C5 Dec 2004
C6 Aug 2005
C7 Sep 2005
WSR1 Sep 2006
WSR10 Mar 2007
WSR1 May 2007
VSRQ May 2007
VSRQ October 2008
Virgo+ design
Sensitivities

- Both the LIGO and Virgo detectors confirmed the working principle substantially reaching the design sensitivity
Evolution of the GW interferometer past evolution:

**Evolution of the GW detectors (Virgo example):**

- **2003**: Infrastructure realization and detector assembling.
- **2008**: Commissioning & first runs.
- **25**: Upper Limit physics.
- **Search for gravitational waves associated with GRB 050915a using the Virgo detector**.

**Search for gravitational waves from known pulsars with science run 5 LIGO data.**
GW sources: BS

- Binary systems of massive and compact stellar bodies:
  - NS-NS, NS-BH, BH-BH
- Source of crucial interest:
  - We are able to model (roughly) the signal using the (post) Newtonian physics
Network of GW detectors

- The search for GW signal emitted by a binary system (of neutron star) asks for a network of (distant) detectors

- Event reconstruction
  - Source location in the sky
  - Reconstruction of polarization components
  - Reconstruction of amplitude at source and determination of source distance (BNS)

- Detection probability increase
- Detection confidence increase
- Larger uptime
- Better sky coverage
Binary systems of massive and compact stellar bodies:

- NS-NS, NS-BH, BH-BH

**1st Generation Interferometers could detect a NS-NS coalescence as far as Virgo cluster (15 Mpc)**

Low expected event rate: 0.01-0.1 ev/yr (NS-NS)
Scientific runs

- A series of runs have been performed by the GW network
- As expected, no BS detection so far!

But, upper limit physics exploited!
**GW source: Isolated NS**

- Not-axisymmetric rotating neutron stars (pulsars) are expected to emit GW at frequency double of the spinning one

\[
h \approx \frac{G}{r c^4} \varepsilon \cdot I_{zz} \cdot \Omega^2
\]

\[
I_{zz} \approx 10^{38} \text{kg} \cdot \text{m}^2
\]

\[
\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}
\]

- The periodicity of the signal allows to increase the SNR integrating for a long time
  - But Doppler effect correction needed because of the Earth motion determines a computational obstacle to a full blind search
- Detection of GW from a NS gives info on the internal structure of the star (\(\varepsilon\) limit is related to the superfluid/strange matter nature of the star, to the magnetic field, …)
GW sources: Crab

About $10^5$ pulsars in the Galaxy, few hundreds in the frequency range of GW detectors

- Many of them show a measurable time derivative of the period: spin-down

Upper limit for the energy lost in GW emission

$$\dot{E} = 4\pi^2 I_{zz} \dot{\nu}$$

Spin-down limit of known NS vs integrated sensitivities

Know Pulsar spin down limit

Virgo nominal sensitivity

iLIGO nominal sensitivity

Crab pulsar in the Crab nebula (2kpc)

LIGO-S5 upper limit: $\sim2\%$ of the SD limit in energy

$\varepsilon \sim 1.3 \times 10^{-4}$

B. Abbot et al (LSC collaboration), Astrop. Jour. 683(2008), L45

B. Abbot et al (LSC and Virgo collaborations), Astrop. Jour. 713 (2010), 671

Credits: C. Palomba
GW sources: Vela

- Only Virgo has currently access to the frequency ($2 \times 11.19$ Hz) of the GW signal potentially emitted by the Vela pulsar ($r=0.3\text{kpc}$)
- VSR2 data have been analyzed and results are under publication (arXiv:1104.2712v2 [astro-ph.HE])

![Graph showing spin-down limit of known NS vs integrated sensitivities](image)

**Spin-down limit beated by 41% (33% for unknown orientation of the star)**

**Ellipticity upper limit set to $1.1 \times 10^{-3}$ ($1.2 \times 10^{-3}$ for unknown orientation)**
GW sources: GRB

- Gamma ray bursts are subdivided in 2 classes:
  - Long (>2s duration): SNe generation mechanism
  - Short (<2s): BNS coalescence mechanism → GW

B.P. Abbot (LSC and Virgo coll), Astr. Jour. 715 (2010), 1438

- A series (137) of GRB occurred during the LIGO-S5/Virgo-VSR1 run
- No detection occurred, but lower limit for the distance of each GRB event

GRB mainly detected by Swift satellite
Similarly to the microwave background (CMB), we are immersed in a stochastic GW background caused by the random superposition of several unresolved sources:

- **COSMOLOGICAL**: Left over of the early universe, analogous to Cosmic Microwave Background Radiation
- **ASTROPHYSICAL**: due to overlapping signals from many astrophysical objects / events relatively recent (within few billion years)
Stochastic GW background

- SGWB is characterized by a GW spectrum:

\[ \Omega_{GW}(f) = \frac{f}{\rho_c} \frac{d\rho_{GW}}{df} \]

Energy density of GW radiation contained in the frequency range \( f - f + df \)

Critical energy density of the universe

- LIGO detectors correlation set an upper limit on the GW spectrum more stringent than the one set by Big Bang nucleosynthesis (BBN)

GW interferometer present evolution

- Evolution of the GW detectors (Virgo example):
  - 2003: Infrastruct 
  - 2008: Proof of the working principle
  - 2011: Test of "advanced" techs
  - 2017: First detection

Upper Limit physics
- 2003: Upper Limit physics
- 2011: Enhanced detectors
- 2017: Advanced detectors

Commissioning & first runs
- 2008: Commissioning & first runs
- 2011: Enhanced detectors

First detection
- 2011: Initial astrophysics
- 2017: First detection

Advanced detectors
- 2017: First detection

Detection distance (a.u.)

year

COMPSTAR 2011: GW detectors
Advanced detectors

- The upgrade to the advanced phase (2nd generation) is just started (LIGO) or will start within this year (Virgo). The detectors should be back in commissioning in 2014.
- Advanced are promising roughly a factor 10 in sensitivity improvement:

This allows a detection distance for coalescing BNS of about 150-200Mpc.
Advanced detectors: BNS detection rates

- The detection rate follows the sight distance with a roughly cubic law:
  - A BNS detection rate of few tens per year with a limited SNR: detection is assured

<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>$10^{-4d}$</td>
<td>$0.01^c$</td>
<td>$10^{-3e}$</td>
</tr>
<tr>
<td></td>
<td>IMBH–IMBH</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td>NS–NS</td>
<td>0.4</td>
<td></td>
<td>400</td>
<td>1000</td>
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<tr>
<td></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>
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<tr>
<td></td>
<td>IMRI into IMBH</td>
<td></td>
<td>$10^b$</td>
<td>$300^c$</td>
<td></td>
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<tr>
<td></td>
<td>IMBH–IMBH</td>
<td></td>
<td>$0.1^d$</td>
<td>$1^e$</td>
<td></td>
</tr>
</tbody>
</table>

Abadie et al. (LSC & Virgo), arXiv:1003.2480; CQG 27, 173001 (2010)
Better sensitivities, especially at low frequency, will allow to beat the spin-down limit for many pulsars.

Advanced Virgo integrated sensitivity over $t_{\text{obs}} = 1$ yr (1% FAP, 10% FDP)

Credits: C. Palomba
Advanced detectors: technologies

- Advanced detectors are based on technologies having already proved their effectiveness in laboratory or in partial installation in the enhanced detectors

- Low frequency (10-100Hz):
  - Target BH-BH coalescence, pulsars
  - Reduction of residual seismic noise (adv.LIGO, through active seismic filtering)
  - Reduction of suspension thermal noise:
    - Monolithic fused silica suspensions, pioneered by GEO600, currently installed in Virgo+ (enhanced)
  - Reduction of radiation pressure noise (heavier test masses)
Advanced detectors: technologies

- Advanced detectors are based on technologies having already proved their effectiveness in laboratory or in partial installation in the enhanced detectors
  - Intermediate frequency (80-500Hz)
    - Target BS-BS coalescence, pulsars
    - Reduction of “mirror” thermal noise:
      - Heavier test masses, larger beams, lower mechanical dissipation coatings
      - Higher finesse in the Fabry-Perot cavities
Advanced detectors: technologies

- Advanced detectors are based on technologies having already proved their effectiveness in laboratory or in partial installation in the enhanced detectors
  - High frequency (300-10000Hz)
    - Target BNS-BNS coalescence, NS normal modes
  - Reduction of quantum (shot) noise:
    - High laser power
      - Solid state (aLIGO)
      - Fiber laser (aVirgo)
      - Low absorption optics and TCS to reduce the thermal lensing
    - Signal recycling to tune sensitivity in frequency (GEO600 pioneered technology)
New players?

- **aLIGO South**
  - Possibility to move aLIGO-H2 to Australia to improve pointing capabilities of the GW detector network

- **LCGT**
  - A 2.5 generation detector, partially funded by Japan, that should implement new (3G) underground and cryogenic technologies in a 3km long site in Kamioka
• Evolution of the GW detectors (Virgo example):

- 2003: Infrastructure realization and detector assemblin
- 2008: Proof of the working principle
- 2011: Upper Limit physics
- 2017: Advanced detectors
- 2022: First detection, Initial astrophysics

Limit of the current infrastructures

Same Infrastructure
(≥20 years old for Virgo, even more for LIGO & GEO600)
E.M. Astronomy

- Current e.m. telescopes are mapping almost the entire Universe
- Keywords:
  - Map it in all the accessible wavelengths
  - See as far as possible
    - Galaxy UDFy-38135539 in Ultra Deep Field image (Hubble Telescope) \( \sim 13.1 \) Gly

M. Trenti, Nature 467, 924–925 (21 October 2010)
GW Astronomy?

- Enlarge as much as possible the frequency range of GW detectors
  - Pulsar Timing Arrays
    - $10^{-9}$-$10^{-6}$ Hz
  - Space based detectors (LISA, DECIGO)
    - $10^{-5}$-$10^{-1}$ Hz
  - Ground based detectors
    - $1$-$10^4$Hz
- Improve as much as possible the sensitivity to increase the detection volume (rate) and the observation SNR

COMPSTAR 2011: GW detectors
LISA

- 3 satellites in heliocentric orbit
- 5M km arms, addressed to low frequencies (hypermassive objects)
- Crucial evolution moment (NASA budget constrains, ESA full support)
- Tests soon in LISA Pathfinder
Beyond Advanced Detectors

- GW detection is expected to occur in the advanced detectors. The 3rd generation should focus on observational aspects:
  - **Astrophysics:**
    - Measure in great detail the physical parameters of the stellar bodies composing the binary systems
      - NS-NS, NS-BH, BH-BH
    - Constrain the Equation of State of NS through the measurement
      - of the merging phase of BNS
      - of the NS stellar modes
      - of the gravitational continuous wave emitted by a pulsar NS
    - Contribute to solve the GRB enigma
  - **Relativity**
    - Compare the numerical relativity model describing the coalescence of intermediate mass black holes
    - Test General Relativity against other gravitation theories
  - **Cosmology**
    - Measure few cosmological parameters using the GW signal from BNS emitting also an e.m. signal (like GRB)
    - Probe the first instant of the universe and its evolution through the measurement of the GW stochastic background
  - **Astro-particle:**
    - Contribute to the measure the neutrino mass
    - Constrain the graviton mass measurement
Let suppose to gain a factor 10 in sensitivity wrt advanced detectors in a wide frequency range: [~1Hz, 10 kHz]

It will be possible to observe binary systems of massive stars:
- At cosmological detection distance
- Frequently, with high SNR
Red shift of the GW signal

- Hence, through the detection of the BNS gravitational signal, by a network of detectors, it is possible to reconstruct the luminosity distance $D_L$ by only using GW detectors.
- But advanced and mainly 3G observatories will detect GW at cosmological distance: Red Shift of the GW frequency!

$$\omega \Rightarrow \frac{\omega}{(1+z)}$$

Mass reconstruction ambiguity $M_c \Rightarrow M_c (1+z)$

For red-shifted distances $D_L \Rightarrow D_L (1+z)$
BNS & Gamma Ray Bursts

- The red-shift ambiguity requires an E.M. counterpart (GRB) to identify the hosting galaxy and then the red-shift $z$.

- Knowing $D_L$ and $z$ it is possible to probe the adopted cosmological model:

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^3(1+w)]^{1/2}}$$

- $\Omega_M$: total mass density
- $\Omega_\Lambda$: Dark energy density
- $H_0$: Hubble parameter
- $w$: Dark energy equation of state parameter
Cosmology with 3G

- Cosmology measurements have been proposed combining the Plank CMB measurement with the SNAP* Universe expansion.
- SNe are standard candles, but they need for “calibration” (Cosmic Distance Ladder).

*SNAP: SuperNova Acceleration Probe (JDEM)
Cosmology with 3G

- In the detection volume of ET about $10^5$ BNS evt/year are expected. Considering the strong beaming of GRB, we could expect to have a small fraction of simultaneous GRB and GW-BNS detections. Considering about $10^3$ simultaneous detections (in a period of 3 years) the measurement errors of the cosmological parameters have been evaluated (Sathyaprakash 2009, see table).

- The level of accuracy in the measurement of these parameters using CMB (Plank)+GW (ET) is similar to what is feasible with CMB+SNe, but without any need of Cosmic Distance Ladder.

| Free parameters | $\sigma_{\Omega_{\Lambda}} / \Omega_{\Lambda}$ | $\sigma_{\Omega_M} / \Omega_M$ | $\sigma_w / |w|$ |
|-----------------|---------------------------------|-------------------------------|----------------|
| 3               | 4.2% 3.5%                       | 18% 14%                       | 18% 15%        |
| $\Omega_{\Lambda} = 0.73$ | 9.4% 8.1%                       | 7.6% 6.6%                     |
| $\Omega_{\Lambda} = 0.73$ | $\Omega_M = 0.27$               | 1.4% 1.1%                     |
High SNR events

- We have seen an example of the importance to have a “cosmological” sight distance
- What about the advantages to see (frequent) events with very high SNR?
Numerical Relativity test bench

- PN approximations fails close to the plunge/merging phase (large v/c):
  - BBH Hybrid templates

- But the PN component of the hybrid template it is still source of error (Santamaria et al., PRD2010), marginally detectable in the advanced detectors (small SNR) but probably dominant in ET

- Parameters reconstruction asks for better PN approx, longer NR simulation, better cross-matching

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Supernova Explosions

- Mechanism of the core-collapse SNe still unclear
  - Shock Revival mechanism(s) after the core bounce TBC

GWs generated by a SNe should bring information from the inner massive part of the process and could constrain on the core-collapse mechanisms
SNe rates with 3G

- Expected rate for SNe is about 1 evt / 20 years in the detection range of initial to advanced detectors
  - Our galaxy & local group
- To have a decent (0.5 evt/year) event rate about 5 Mpc must be reached
- ET nominal sensitivity can promise this target

Ando et al. 2005

![Graph showing SN rate versus distance](image)
Neutrinos from SNe

- SNe detection with a GW detector could bring additional info:
  - The 99% of the $10^{53}$ erg emitted in the SNe are transported by neutrinos

- But looking at the detection range of existing neutrino detectors (<Local group limited) is discouraging

- Some promising evaluation has been made (Ando 2005) for the next generation of Megaton-scale detectors
The Einstein Telescope project is currently in its conceptual design study phase, supported by the European Community FP7 with about 3M€ from May 2008 to July 2011.
Targets of the Design Study

- Evaluate the science reaches of ET
- Define the sensitivity and performance requirements
  - Site requirements
  - Infrastructures requirements
  - Fundamental and (main) technical noise requirements
  - Multiplicity requirements
- Draft the observatory specs
  - Site candidates
  - Main infrastructures characteristics
  - Geometries
    - Size, L-Shaped or triangular
  - Topologies
    - Michelson, Sagnac, …
  - Technologies
- Evaluate the (rough) cost of the infrastructure and of the observatory
ET design study

- The ET design study document will be publically presented the 20\textsuperscript{th} of May, 2011:
  - http://www.et-gw.eu/events/dspresentation
- Description of the results is beyond the scope of this talk, hence I would like to conclude with a short series of images of the ET observatory infrastructure concepts