Gravitational wave detectors: First astrophysical results and path to next generation

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for LIGO Scientific Collaboration and Virgo collaboration

- Introduction to Gravitational Waves
- Status of LIGO and Virgo
- Astrophysical Results
- Multi-messenger effort
- Advanced generation

Gravitational Wave Physics

Emitted Power:

$$P = \frac{G}{5c^5}\left\langle \dddot{Q}_{\mu\nu}\,\dddot{Q}^{\mu\nu} \right\rangle = \varepsilon^2 \frac{c^5}{G}\frac{R_S^2}{R^2}\frac{v^6}{c^6}$$

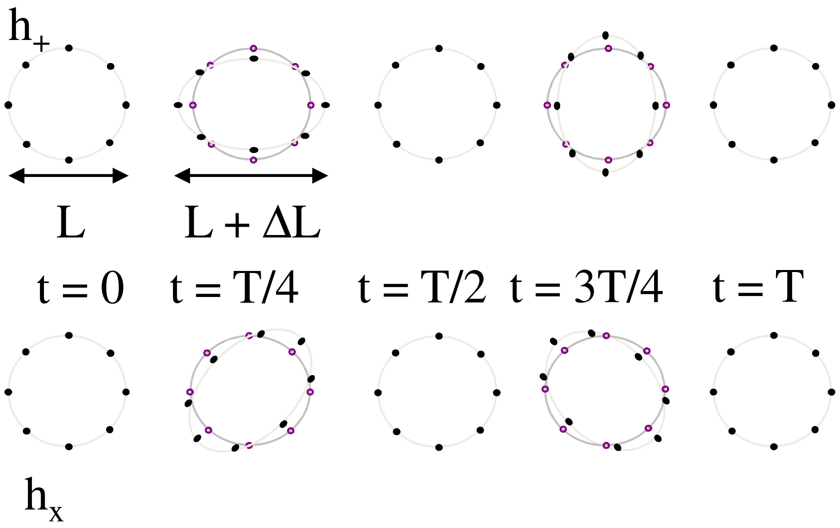
- ε source asymmetry
- R_s Schwarzschild radius of the source
- R source radius
- v typical speed of the source

⇒ **Cataclysmic Astrophysical** Phenomena needed for production of **detectable GW**

⇒ Amplitude **$h \sim 10^{-21}$** for a source at 10 Mpc

Effect of free particles:

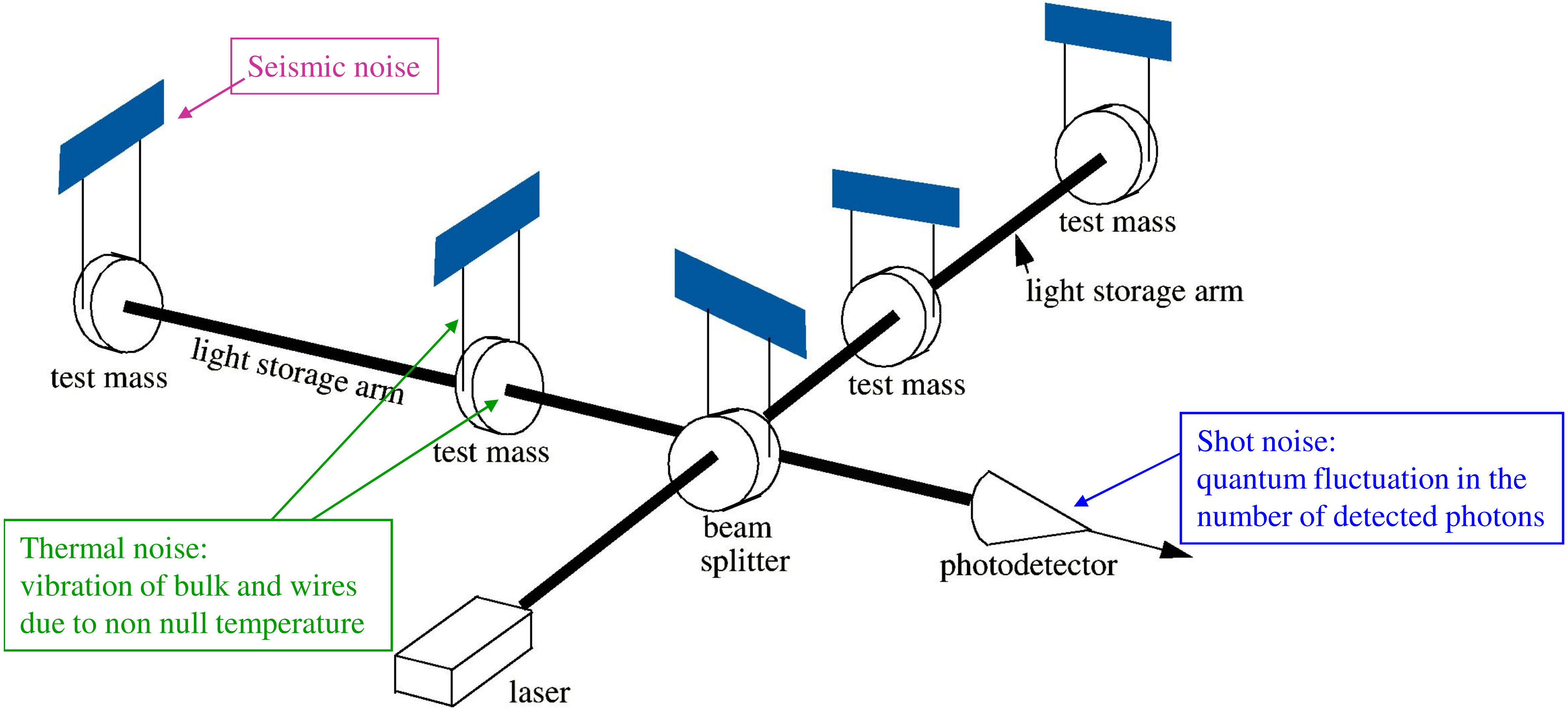
- $\Delta L/L \sim h$
- Differential effect



Interferometric Detection of GW

Measure the displacement of the test masses (mirrors) induced by the GW
⇒ light phase shift measurement
But:

- GW amplitude is small $h \sim 10^{-21}$ L=3km → $\delta L = 10^{-18}$ m
- The laser has fluctuations in phase and amplitude
- External forces push the mirrors



Seismic noise

Thermal noise:
vibration of bulk and wires
due to non null temperature

Shot noise:
quantum fluctuation in the
number of detected photons

Ground-based Detectors

LIGO Hanford : 2 ITF (4 km and 2 km)

GEO, Hannover, 600 m

Virgo, Cascina, 3 km

LIGO Livingston, 4 km

TAMA, Tokyo, 300 m
Future LCGT
in Kamioka mine

AIGO R&D
LIGO-Australia ?

A bit of history

First generation (2001-2008)

- Infrastructure setup
- **Design sensitivity** has been **reached**
- **Upper limits** on event rates
- **No detection**

Enhanced Detectors (2009-2011)

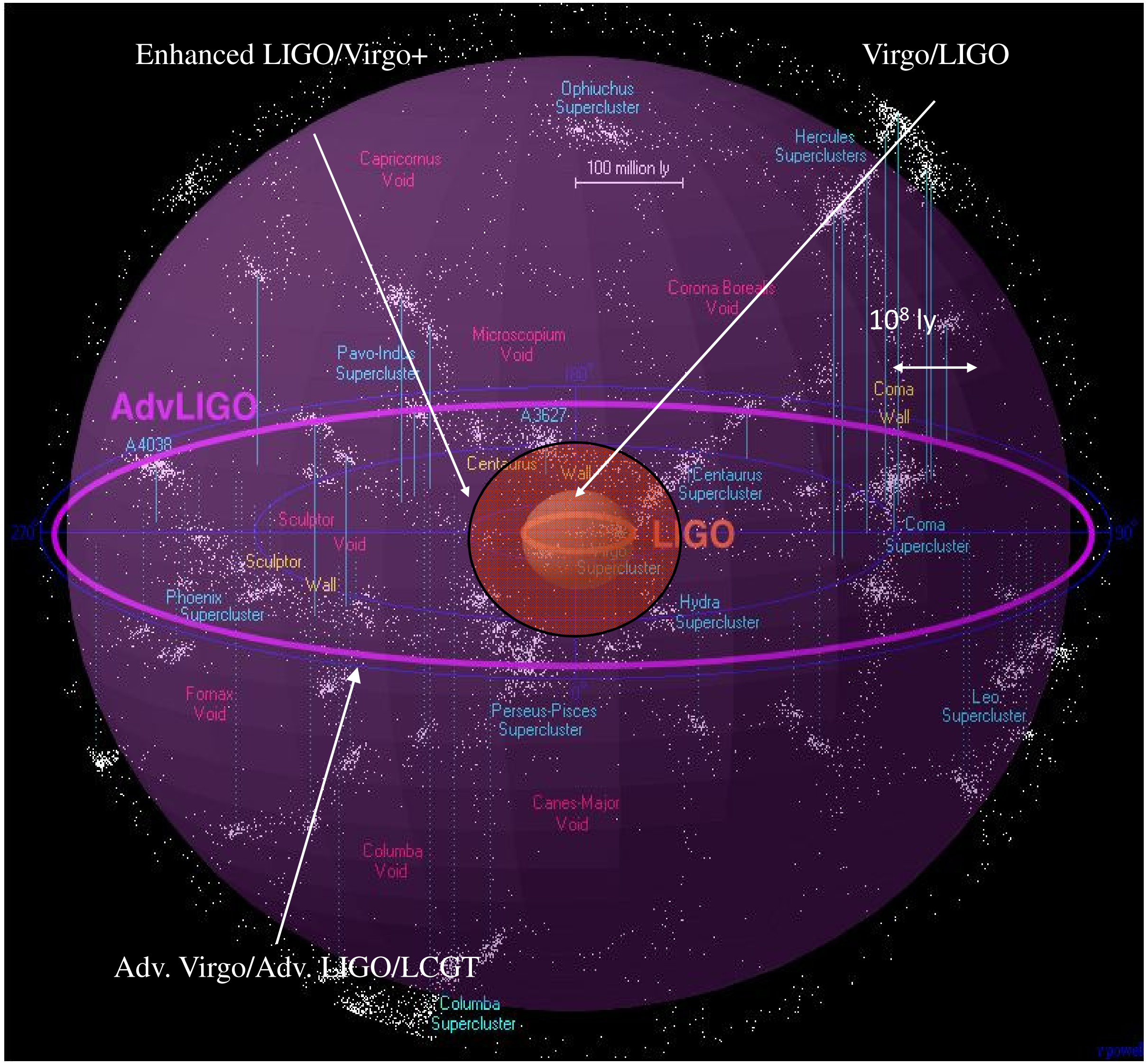
- **Sensitivity increased** by a factor **2-3**
- Use of some Advanced detector technologies
- **Detection still unlikely** but surprises are always possible

Advanced Detectors (2011-2020)

- **Sensitivity gain** by factor **10** compared to first generation
- Visible **Universe volume** increased by **1000**
- **10-100 events per year** ?

Third Generation (>2017)

- **Gain** by factor **100** compared to first generation



Credit: R.Powell, B.Berger

The LSC-Virgo collaboration

- **Full sharing** of data since **May 2007** (S5 second year - VSR1)
- Joint Data Analysis groups
- Joint run **S6-VSR2 July 2009-Jan.2010** (stop of Virgo for Virgo+ upgrade), S6 still going on
- **S6-VSR3** will start **beginning August 2010**

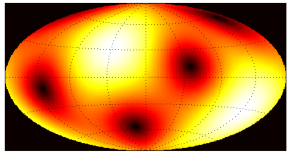
⇒ **Reduction** of **false alarm** rate

⇒ **Increase** of probability **detection**

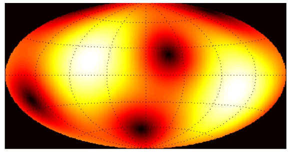
⇒ Reconstruction of **source location**

⇒ Reconstruction of **waveform**

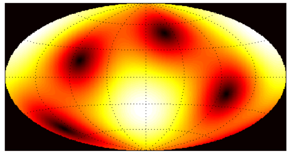
Antenna pattern



Hanford

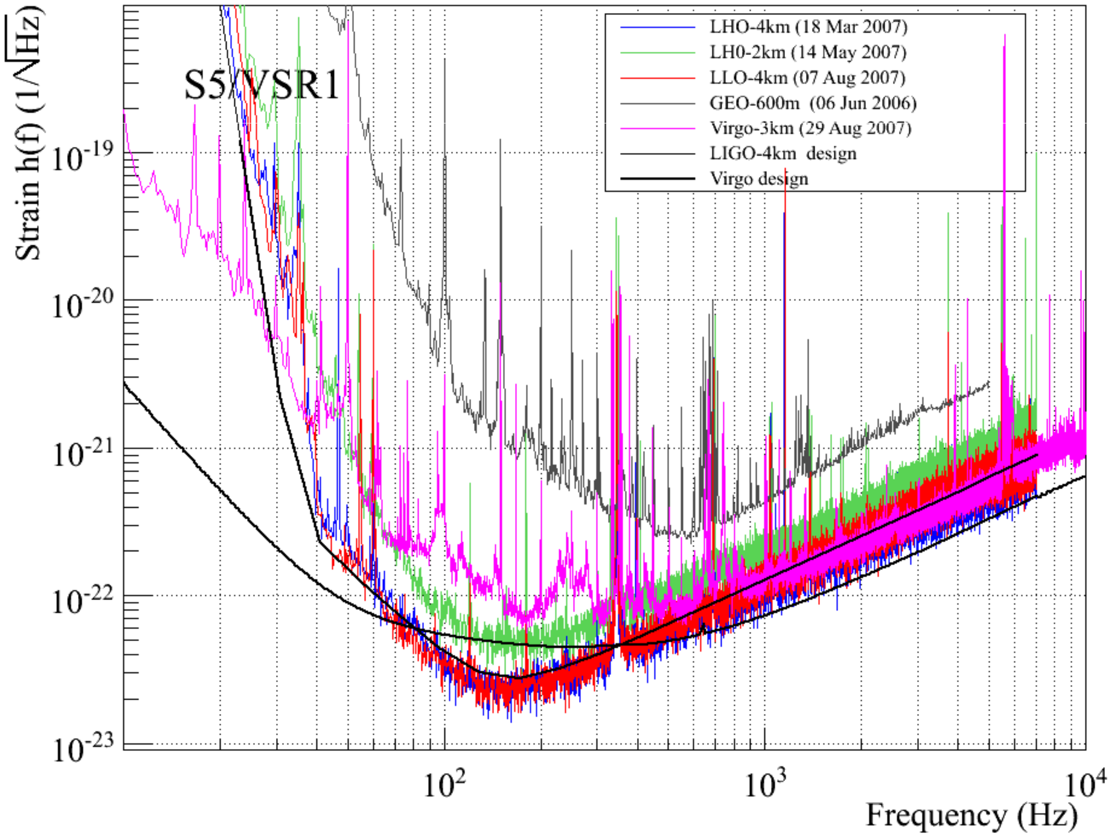


Livingston



Virgo

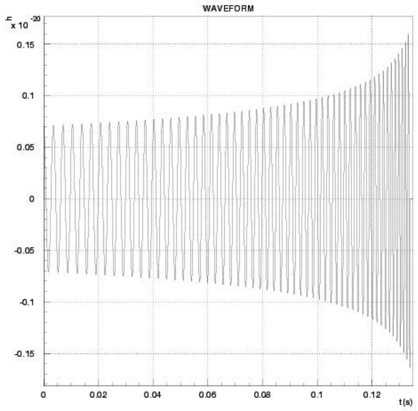
Sensitivities for S5-VSR1

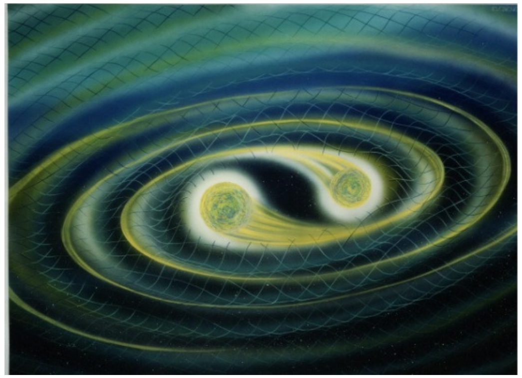


Coalescing Binaries

- Neutron Star-Neutron Star
- Neutron Star-Black Hole
- Black Hole-Black Hole

Precise theoretical prediction of the **waveform**
⇒ detection by **matched filtering**





Limits on Rates

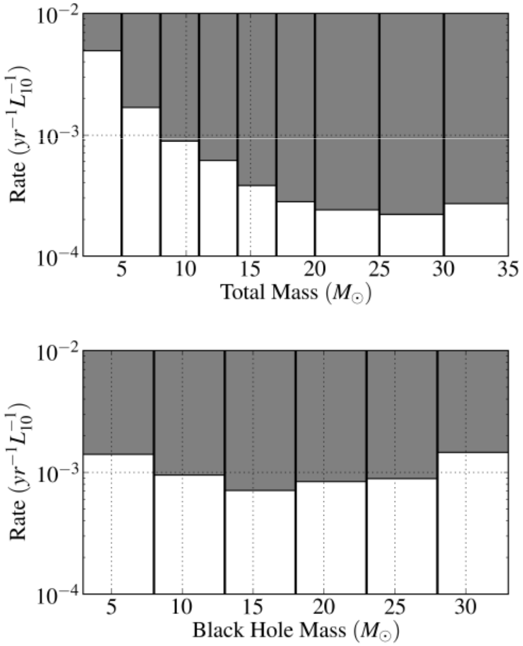
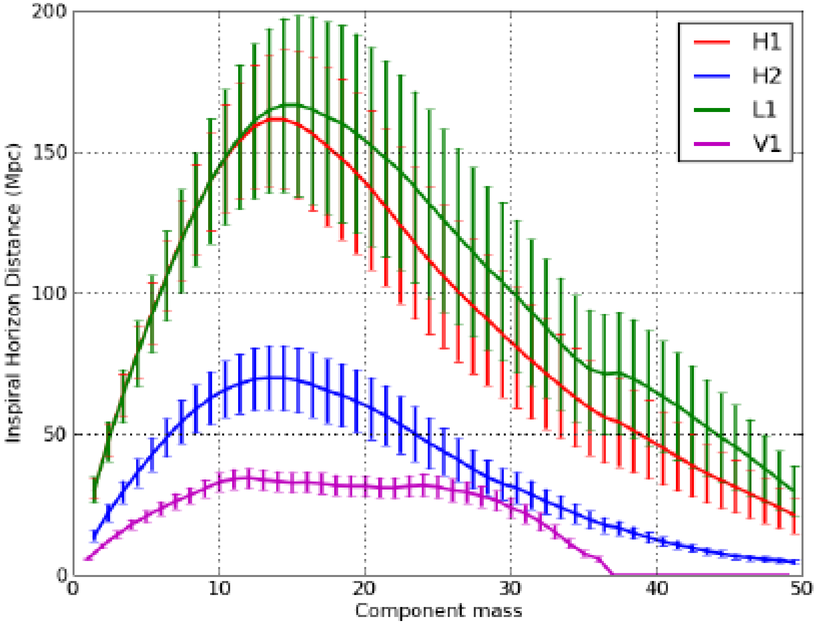


FIG. 4: The 90% rate upper limits as a function of mass. The first figure gives the upper limit on the rate of coalescence from BBH system as a function of the total mass of the system. The second figure gives the BHNS upper limit as a function of black hole mass, assuming a fixed neutron star mass of 1.35 $M_\odot$.

arXiv:1005.4655

Inspiral Horizon Distance during S5/VSR1



arXiv:1003.2481

Pulsars-Rotating neutron stars

- Periodic signal
- Need for ellipticity

Spin-down limit reached for 3 pulsars

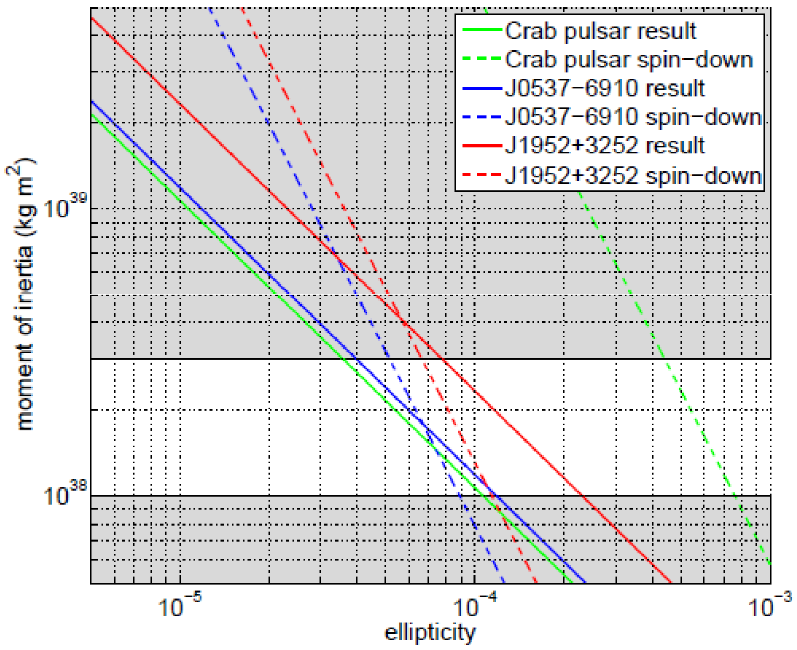


Fig. 5.— The results of the Crab pulsar, J0537−6910 and J1952+3252 analyses, and the spin-down limits, plotted on the moment of inertia–ellipticity plane. The results used are those from model i) and with restricted priors on the angular parameters for the Crab pulsar and J0537−6910. Areas to the right of the diagonal lines are excluded. The shaded regions are those outside the theoretically predicted range of moments of inertia I_{38} =1–3.

Astrophys. J. 713 (2010) 671

Stochastic background

- Incoherent sum of sources
- Signal from early Universe

First significant **upper bounds**

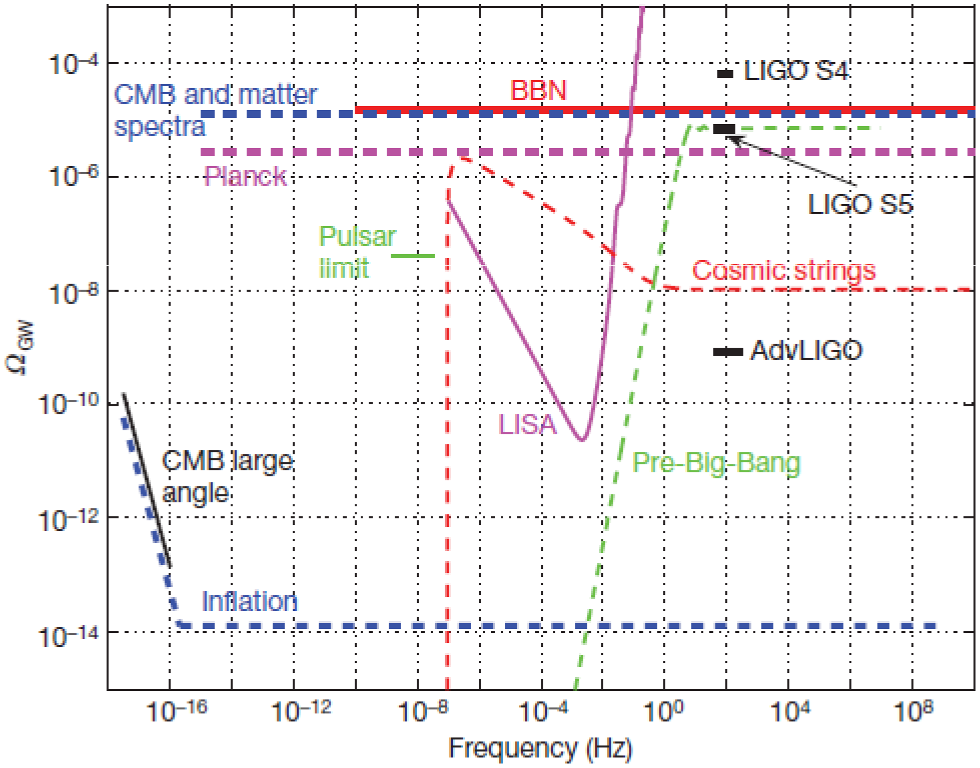


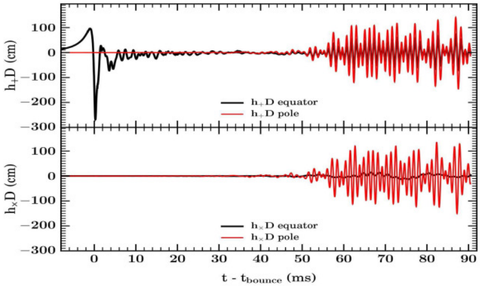
Figure 2 | Comparison of different SGWB measurements and models. The 95% upper limit presented here, $\Omega_0 < 6.9\times10^{-6}$ (LIGO S5), applies in the frequency band 41.5–169.25 Hz, and is compared to the previous LIGO S4 result[22] and to the projected Advanced LIGO sensitivity[25]. Note that the corresponding S5 95% upper bound on the total gravitational-wave energy density in this band, assuming frequency independent spectrum, is 9.7×10^{-6}. The indirect bound due to BBN[1,6] applies to $\Omega_{\rm BBN} = \int \Omega_{\rm GW}(f)\,d(\ln f)$ (and not to the density $\Omega_{\rm GW}(f)$) over the frequency band denoted by the corresponding horizontal line, as defined in equation 3. A similar integral bound (over the range 10^{-15}–10^{10} Hz) can be placed using CMB and matter power spectra[7]. Projected sensitivities of the satellite-based Planck CMB experiment[7] and LISA gravitational-wave detector[26] are also shown. The pulsar bound[27] is based on the fluctuations in the pulse arrival times of millisecond pulsars and applies at frequencies around 10^{-8} Hz. Measurements of the CMB at large angular scales constrain the possible redshift of CMB photons due to the SGWB, and therefore limit the amplitude of the SGWB at largest wavelengths (smallest frequencies)[6]. Examples of inflationary[9,10], cosmic strings[4,5,15,16], and pre-Big-Bang[11–13] models are also shown (the amplitude and the spectral shape in these models can vary significantly as a function of model parameters).

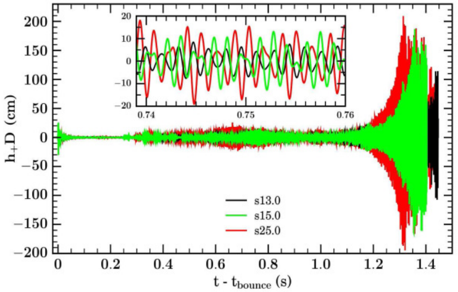
Nature 460 (2009) 990

Burst Searches

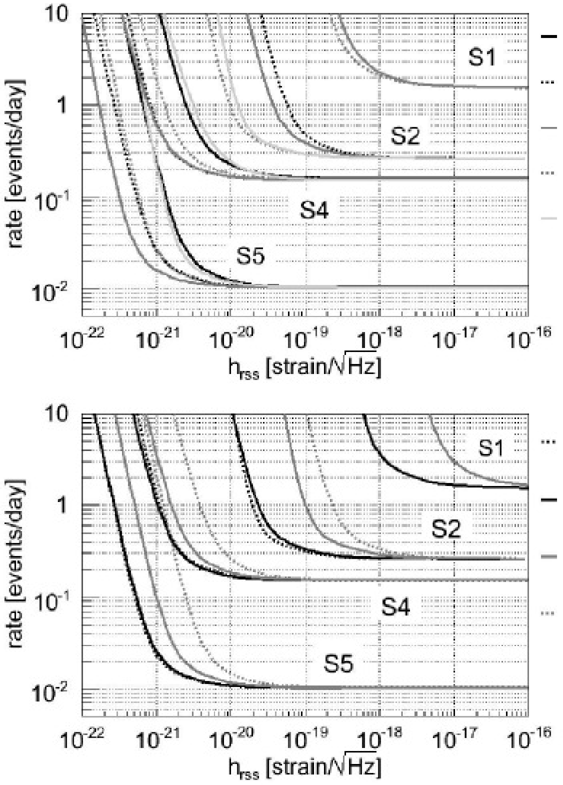
- Supernovae
- Black hole formation and ringdown
- Cosmic cusps
- …

Typical Duration : few milliseconds





Upper limit on rates



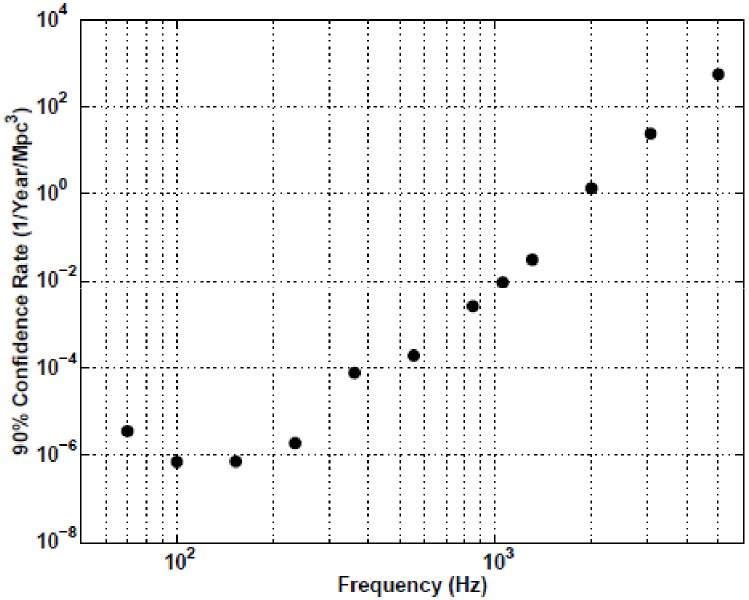
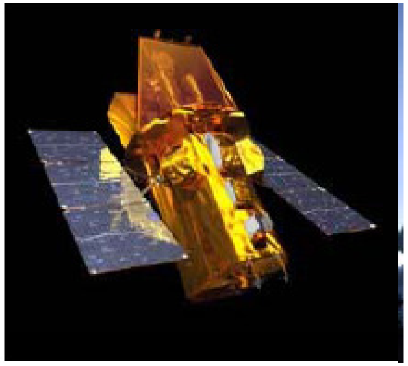


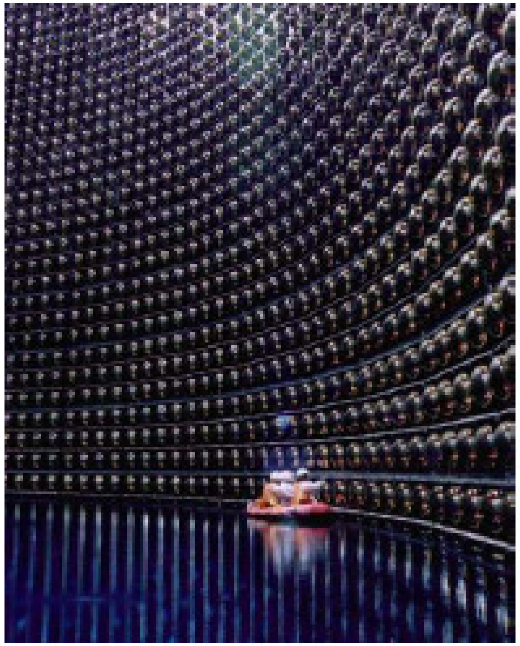
FIG. 7: Rate limit per unit volume at the 90% confidence level for a linearly polarized sine-Gaussian standard-candle with $E_{\rm GW} = M_\odot c^2$.

FIG. 8: Selected exclusion diagrams showing the 90% confidence rate limit as a function of signal amplitude for Q=9 sine-Gaussian (top) and Gaussian (bottom) waveforms for the results in this paper (S5) compared to the results reported previously (S1, S2, and S4).

Phys. Rev. D 81 (2010) 102001

Multi-messenger Strategy

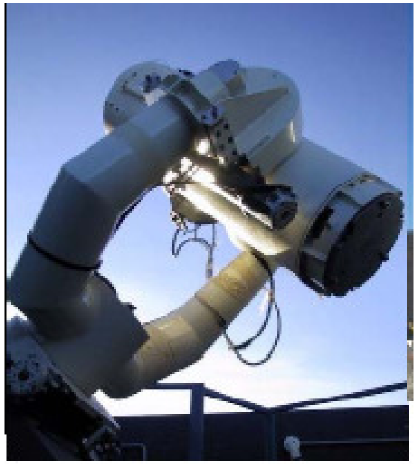




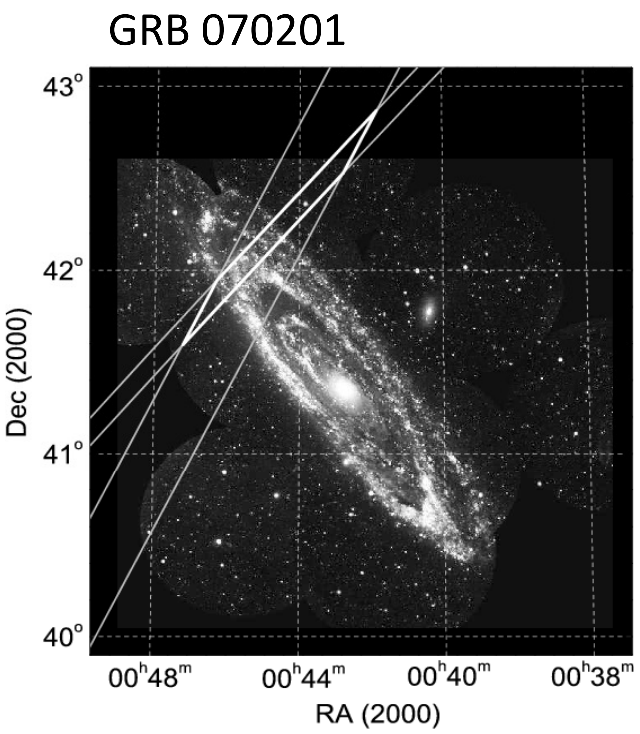
- **To** GW detectors: use **triggers** delivered by **EM** telescopes or satellites and **ν** detectors

- **From** GW detectors: **trigger** EM **observations** (telescope or satellite)

⇒ Event localization (time and space)
⇒ Increase of confidence detection
⇒ Progenitor information



Coïncidences with GRB



- **Short GRB** (usually associated with binary mergers)
- Position consistent with **M31** (D=760 kpc)
- GW binary signal **easily detectable**

⇒ **ruled out at 99 %**

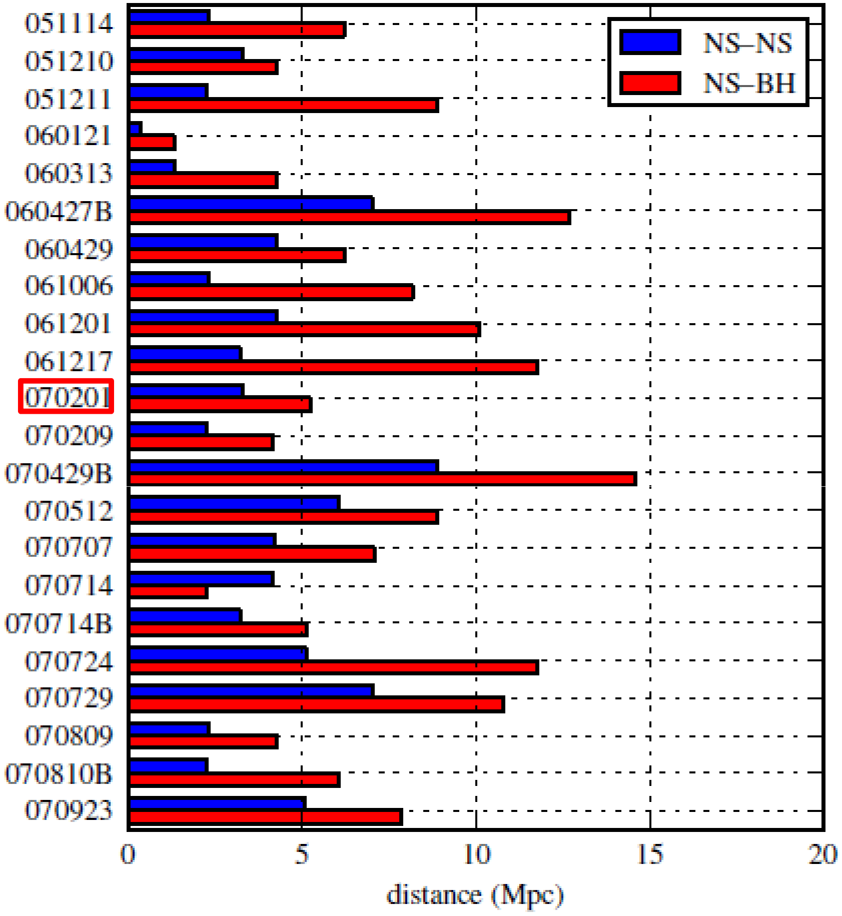
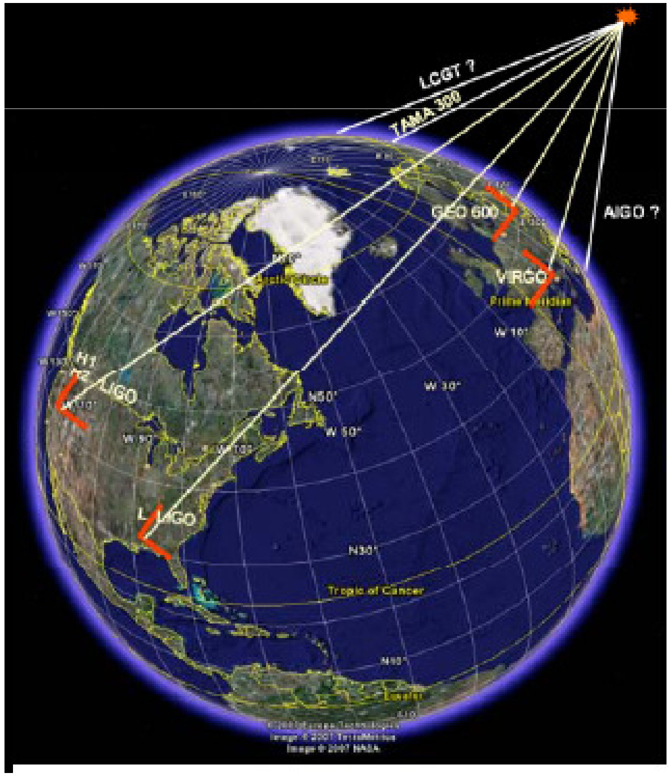


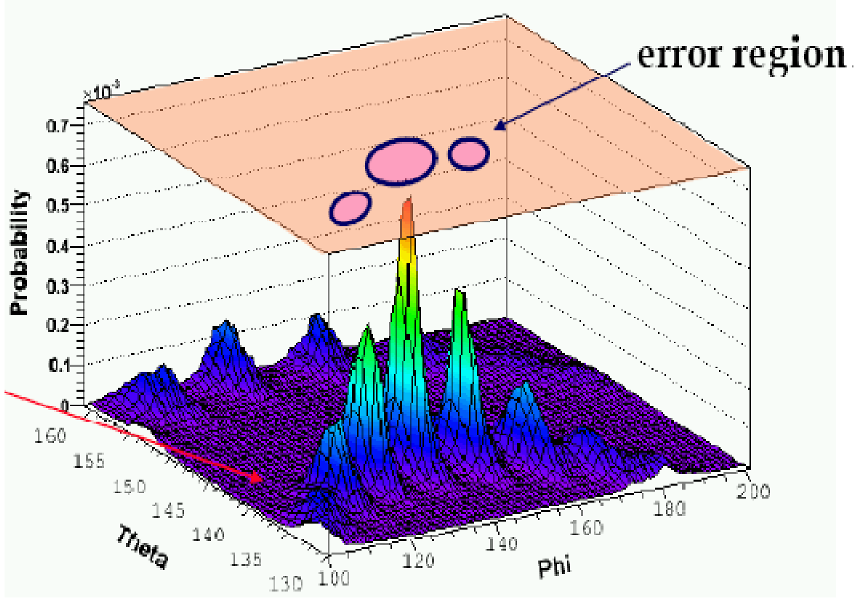
Figure 2. Lower limits on distances at 90% CL to putative NS–NS and NS–BH progenitor systems, as listed in Table 2 and explained in Section 3.2.

Astrophys. J. 715 (2010) 1453

EM Followup

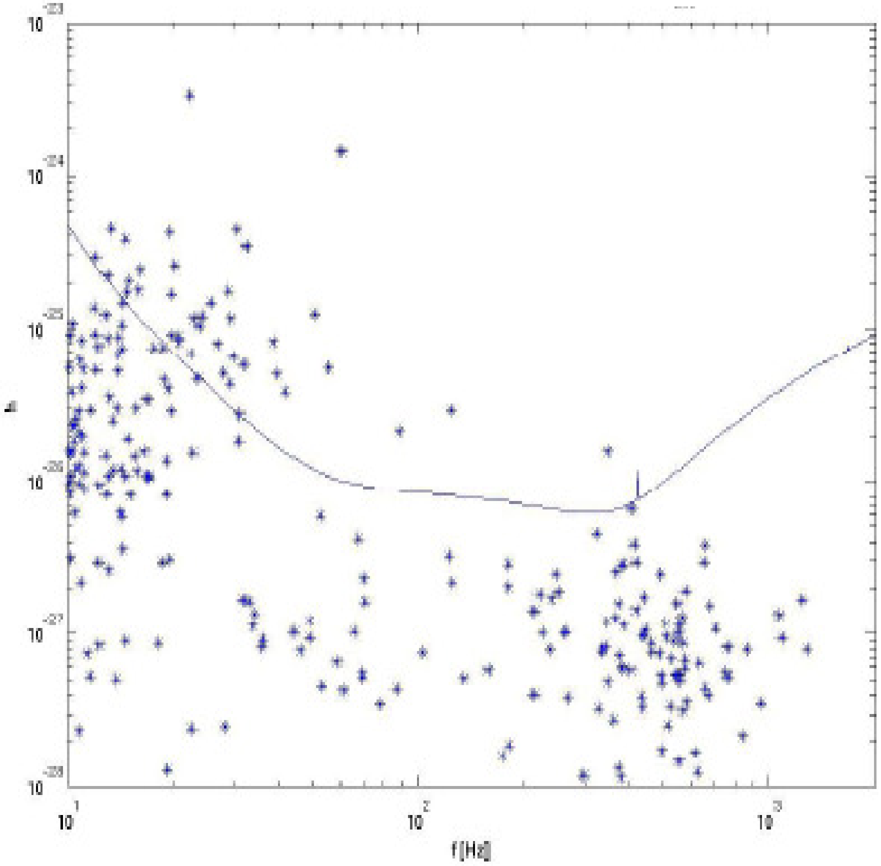
- **Online** data analysis with ~**10 minutes latency**
- Error regions in the sky about **several degrees**
- Alerts sent to:
  - **Wide-field telescopes** :TAROT, Pi of the Sky, QUEST, …
  - **Satellite**: Swift
- Successfully **tested** in **December 2009** before Virgo stop
- **New campaign** during **S6-VSR3** (August-October 2010)





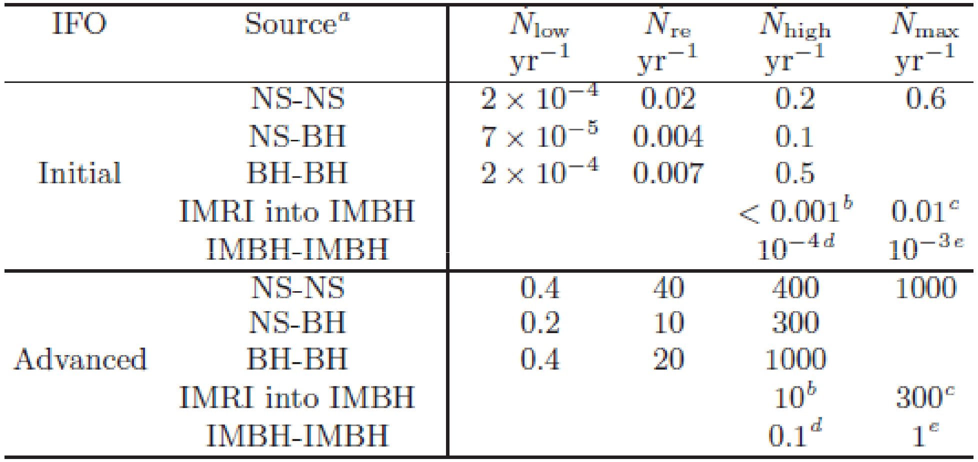
Physics for Advanced Detectors (some examples)

Pulsars



Line: Minimal detectable h for continuous source after one year of data taking
Stars: current upper limit on known pulsars

Coalescing Binaries



IFO	Source[a]	N_{low} yr^{-1}	N_{re} yr^{-1}	N_{high} yr^{-1}	N_{max} yr^{-1}
Initial	NS-NS	2×10^{-4}	0.02	0.2	0.6
	NS-BH	7×10^{-5}	0.004	0.1	
	BH-BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			$< 0.001^{b}$	0.01^{c}
	IMBH-IMBH			$10^{-4\,d}$	$10^{-3\,e}$
Advanced	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

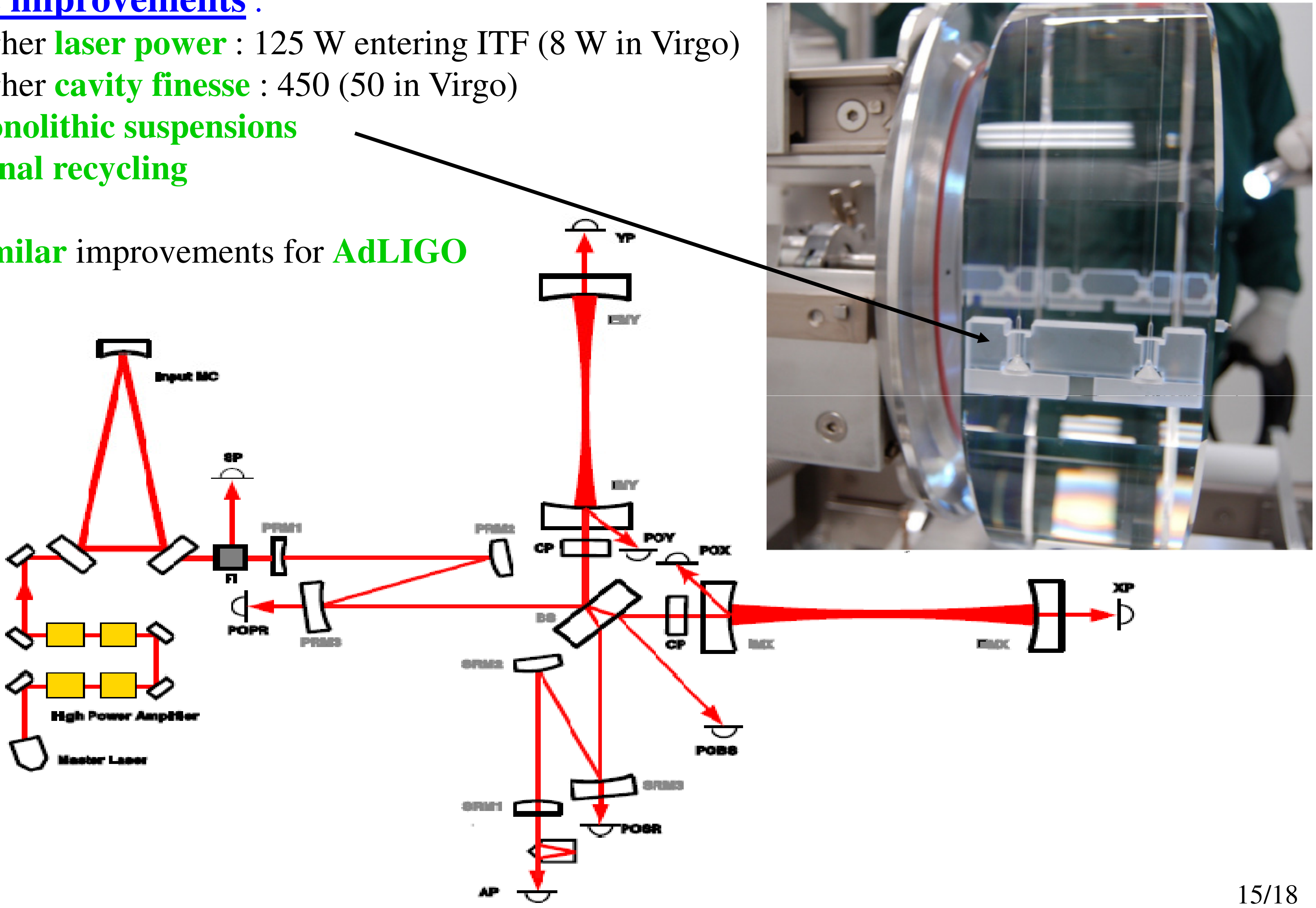
Class. Quantum Grav. 27 (2010) 173001

Advanced Virgo Layout

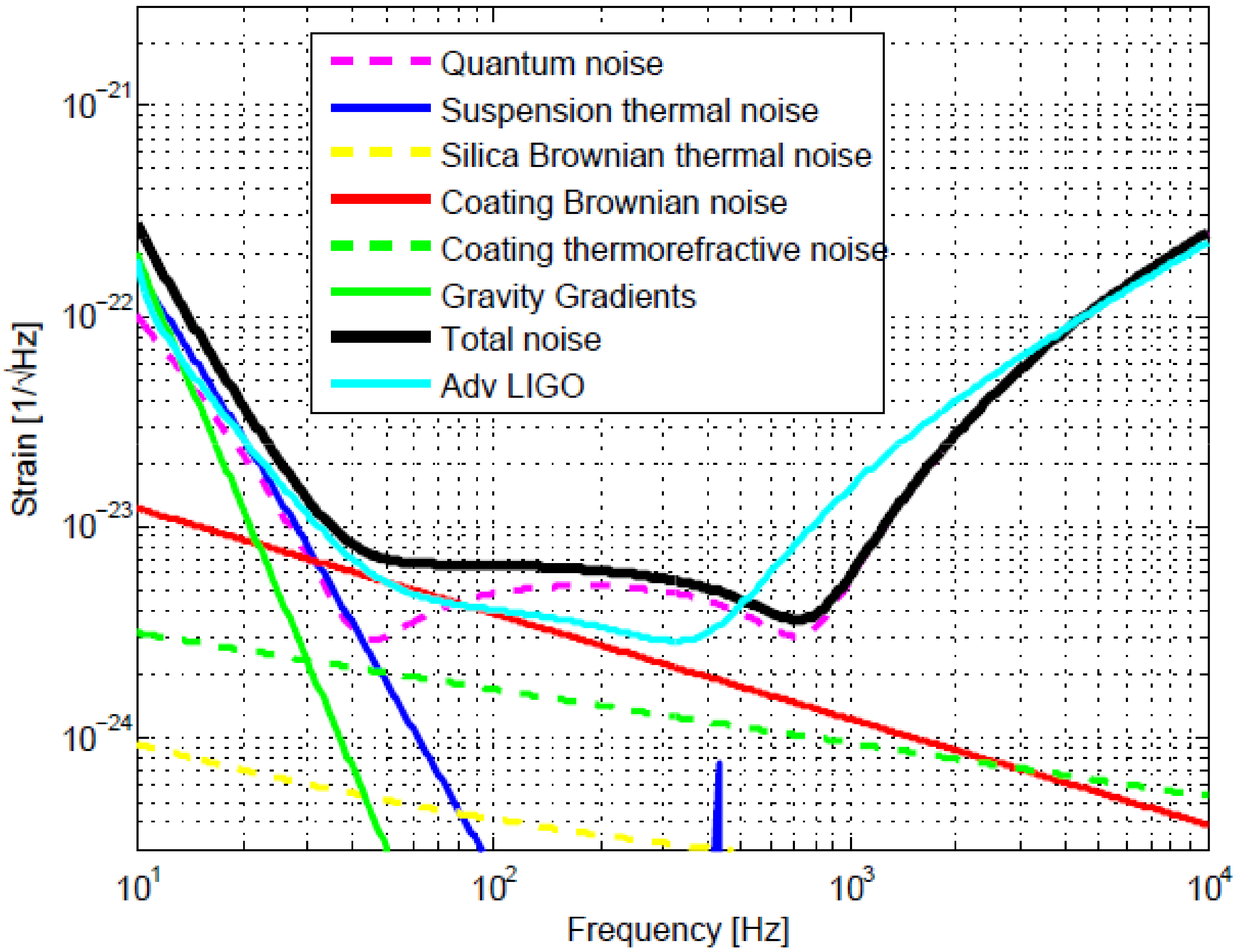
The improvements :

- higher **laser power** : 125 W entering ITF (8 W in Virgo)
- higher **cavity finesse** : 450 (50 in Virgo)
- **monolithic suspensions**
- **signal recycling**

- **Similar** improvements for **AdLIGO**



Advanced Detector Sensitivities



Planning for Advanced Generation

- Advanced LIGO approved in April 2008
- Advanced Virgo approved in December 2009
- Several sub-systems have been tested in eLIGO and Virgo +
- Project LCGT in Japan just approved one month ago
- 3rd ITF LIGO in Australia ?

Virgo Planning

- July 2011: start of installation
- 2014: full interferometer and start of commissioning
- 2015: first scientific run

LIGO Planning

- Start installation end 2010
- July 2012: first ITF installed
- June 2013: engineering runs, detector characterization
- 2014: ITF 2 and 3 running
- 2015: first scientific run

Conclusion

- **First generation** has reached the **design sensitivity**

- **Long science runs** (S5-VSR1, S6-VSR2) have been done

  - **First astrophysical results** have been published using S5-VSR1 data
  - **S6-VSR2** under analysis

- **S6/VSR3** will start in few days

- **Follow-up** with **telescopes** under **tests**

- **Advanced LIGO** and **Virgo** being **constructed**

- **First science run** foreseen in **2015** with a **sensitivity** increased by a factor **10**

- Hope for **first detection** and birth of **gravitational astronomy**