Virgo and results from gravitational wave experiments

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On behalf of the Virgo Collaboration

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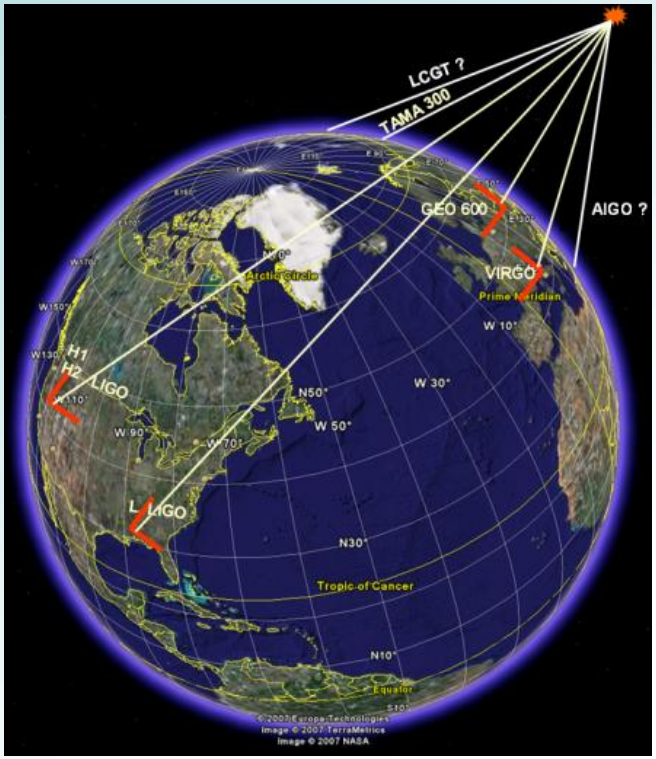
Summary

- **Virgo Science Run 2** (July 2009 – January 2010)
  - Partially in coincidence with LIGO S6 run
- Installation of monolithic suspensions (January – May 2010)
  - Followed by a commissioning period (May – July 2010)
- **Virgo Science Run 3** (August – October 2010)
  - Coincident with LIGO S6 (external triggers)
- Further interferometer commissioning (November 2010 – today)
- Future plans
  - **Virgo Science Run 4** (June – September 2011)
  - Start construction of **Advanced Virgo** (October 2011)

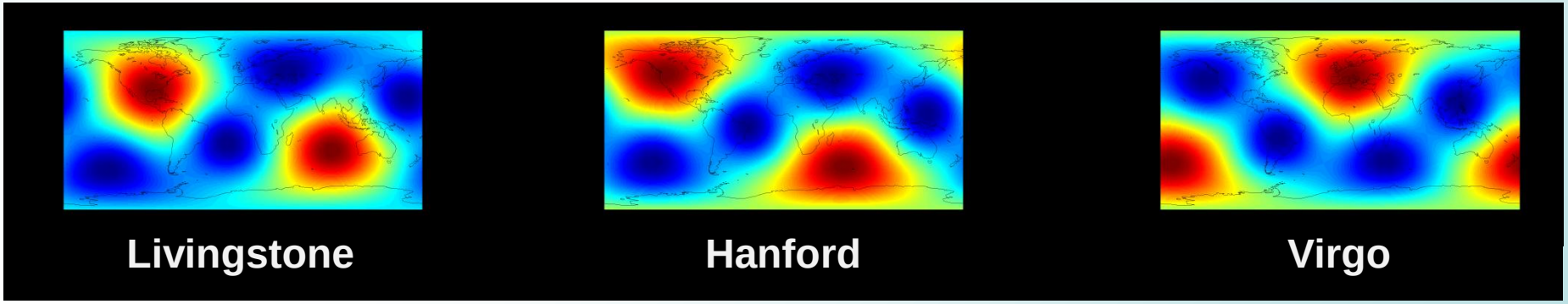
Selected results

Detector network with LSC

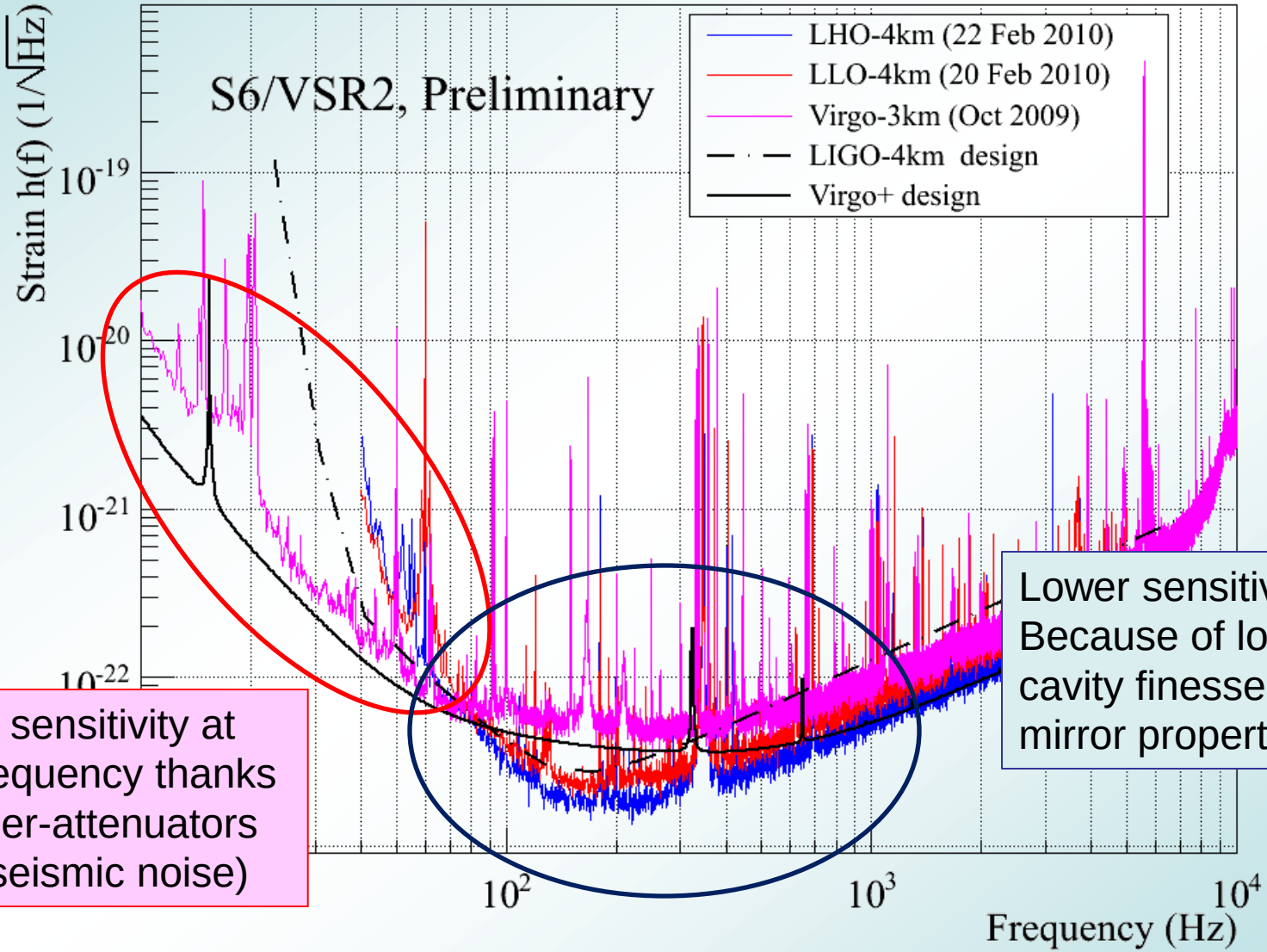


- Starting from Virgo second science run (VSR2) *MoU* to take data in coincidence with LIGO and joint run organization
- Triple coincidences to reduce background
- Better sky coverage
- Ability to reconstruct sky position with tens of square degrees accuracy

Antenna pattern of the 3 km-scale interferometers



Sensitivity during VSR2 / S6

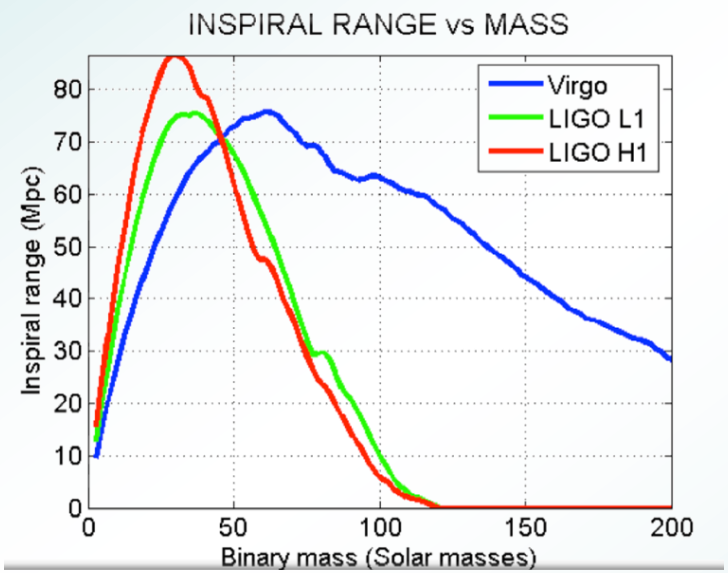


Better sensitivity at low frequency thanks to super-attenuators (less seismic noise)

Lower sensitivity Because of lower arm cavity finesse (different mirror properties)

Coalescing binary systems

- First generation detectors with ranges up to Virgo super-cluster (~15 Mpc)
- Expected detection rates still very low

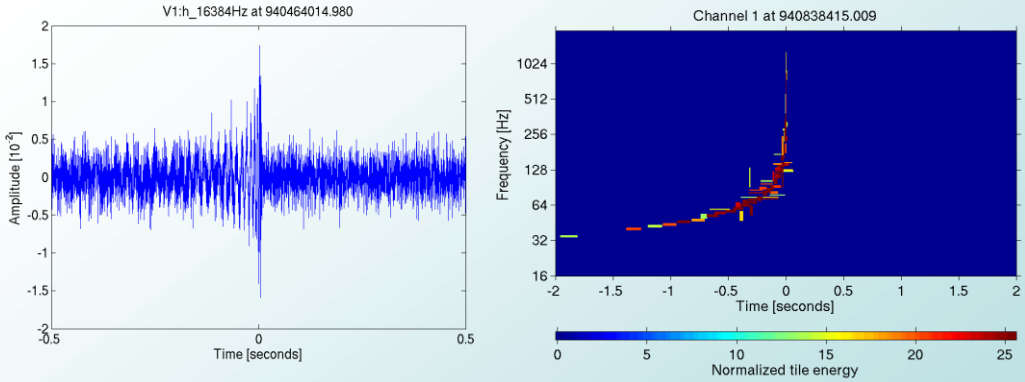


IOP Publishing — Classical and Quantum Gravity
Class. Quantum Grav. 27 (2010) 173001 (25pp) doi:10.1088/0264-9381/27/17/173001

Predictions for the rates of compact binary coalescences observable by ground-based gravitational-wave detectors

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}	$\dot{N}_{max}$ yr^{-1}
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	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]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]



Typical time and frequency shape of a signal from binary coalescence

Binary systems

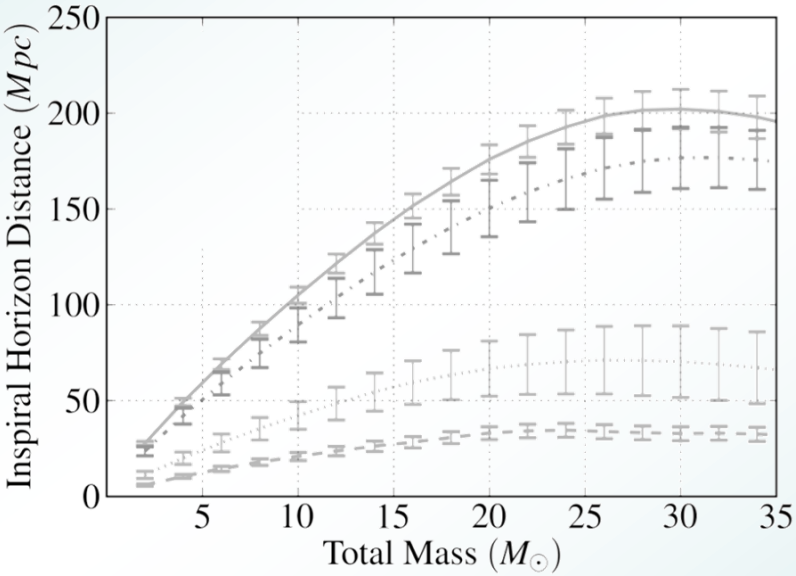
- VSR2 and VSR3 data analysis on-going

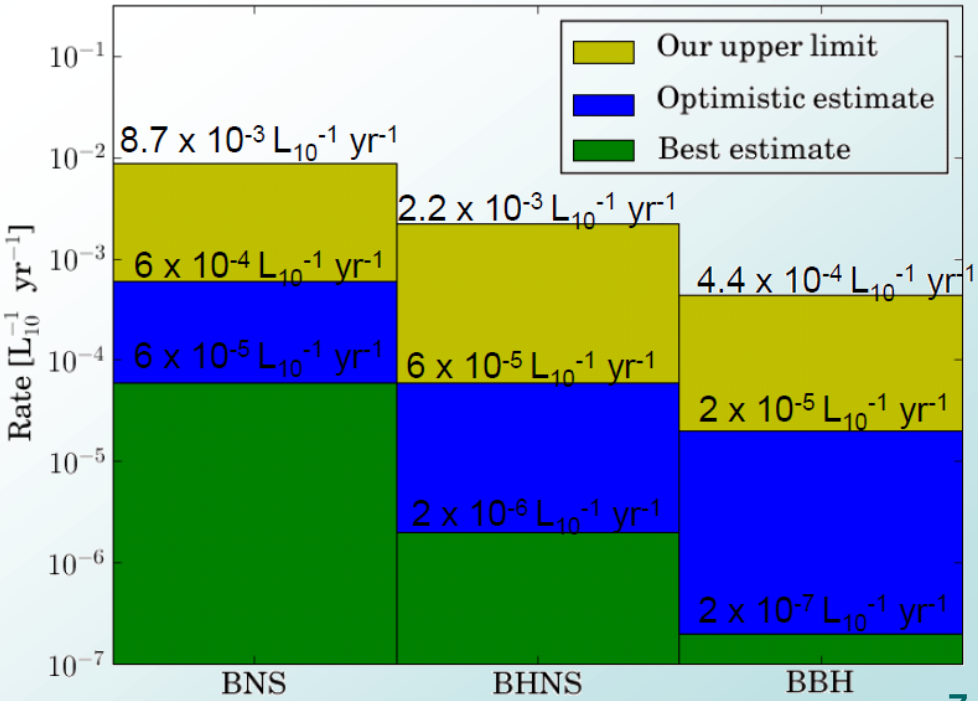
Phys. Rev. D 82, 102001 (2010) [11 pages]

Search for gravitational waves from compact binary coalescence in LIGO and Virgo data from S5 and VSR1

Received 25 June 2010; published 5 November 2010

We report the results of the first search for gravitational waves from compact binary coalescence using data from the Laser Interferometer Gravitational-Wave Observatory and Virgo detectors. Five months of data were collected during the Laser Interferometer Gravitational-Wave Observatory's S5 and Virgo's VSR1 science runs. The search focused on signals from binary mergers with a total mass between 2 and 35$M_\odot$. No gravitational waves are identified. The cumulative 90%-confidence upper limits on the rate of compact binary coalescence are calculated for nonspinning binary neutron stars, black hole-neutron star systems, and binary black holes to be 8.7×10^{-3} yr^{-1} L_{10}^{-1}, 2.2×10^{-3} yr^{-1} L_{10}^{-1}, and 4.4×10^{-4} yr^{-1} L_{10}^{-1}, respectively, where L_{10} is 10^{10} times the blue solar luminosity. These upper limits are compared with astrophysical expectations.





Binary NS < 8.7×10^{-3} yr^{-1} L_{10}^{-1}
Binary BH < 4.4×10^{-4} yr^{-1} L_{10}^{-1}

Continuous wave sources

- Sources expected mainly at low frequency
- Spin-down limit beaten for two known pulsars
  Crab - 59.56 Hz (LIGO S5)
  Vela - 22.38 Hz (Virgo VSR2)

Analysis method	95% upper limit for h_0
Heterodyne, restricted priors	$(2.1 \pm 0.1) \times 10^{-24}$
Heterodyne, unrestricted priors	$(2.4 \pm 0.1) \times 10^{-24}$
$\mathcal{G}$-statistic	$(2.2 \pm 0.1) \times 10^{-24}$
$\mathcal{F}$-statistic	$(2.4 \pm 0.1) \times 10^{-24}$
MF on signal Fourier components, 2 d.o.f.	$(1.9 \pm 0.1) \times 10^{-24}$
MF on signal Fourier components, 4 d.o.f.	$(2.2 \pm 0.1) \times 10^{-24}$

Vela (paper to be submitted to ApJ)

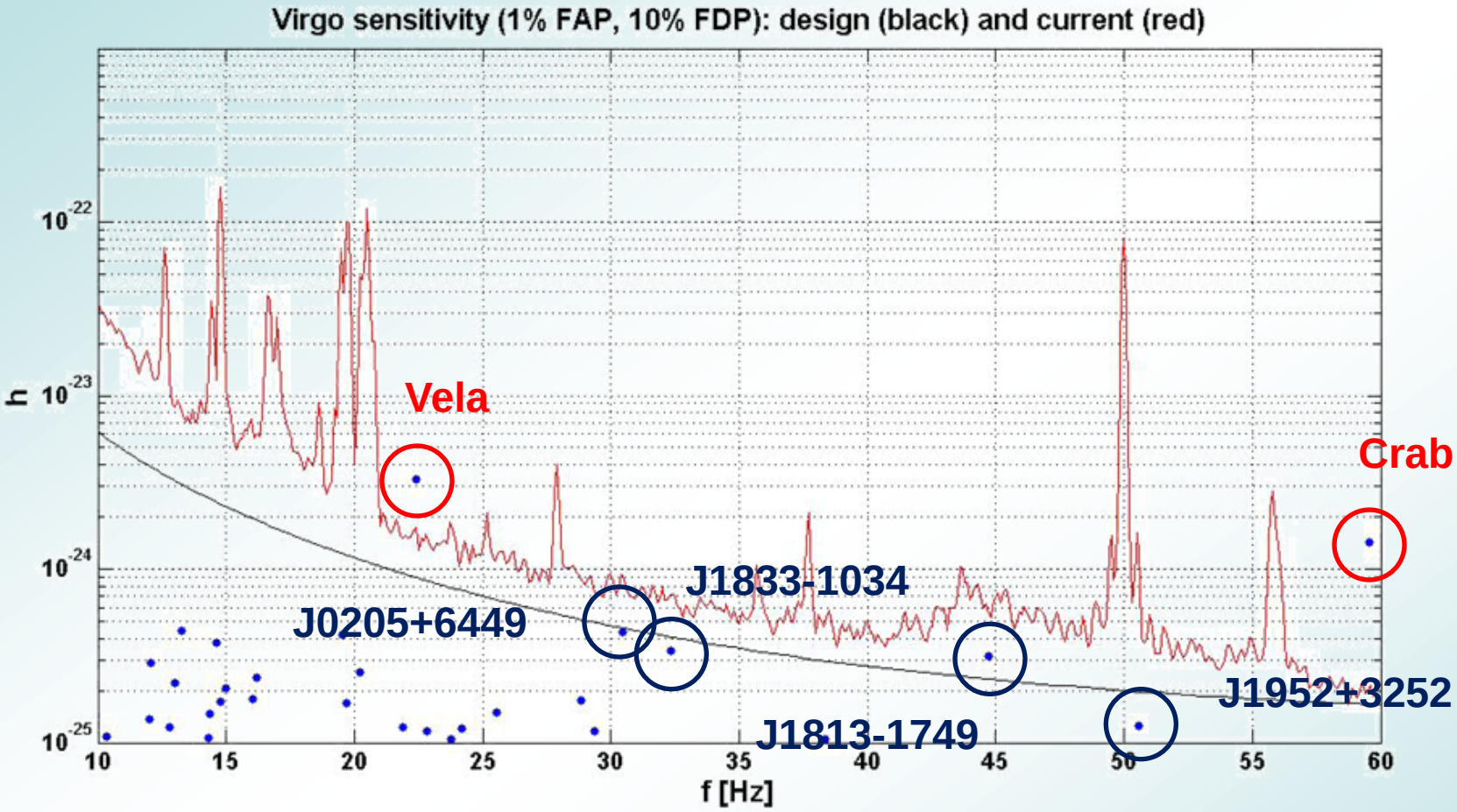
Enegy in GW < 35% spin down

Epoch	$h_0^{95\%}$		Ellipticity		$h_0^{95\%}/h_0^{sd}$	
	Uniform	Restricted[a]	Uniform	Restricted[a]	Uniform	Restricted[a]
			Crab pulsar			
Model (1)[b]	2.6×10^{-25}	2.0×10^{-25}	1.4×10^{-4}	1.1×10^{-4}	0.18	0.14
Model (2)[c]	2.4×10^{-25}	1.9×10^{-25}	1.3×10^{-4}	9.9×10^{-5}	0.17	0.13
1.	4.9×10^{-25}	3.9×10^{-25}	2.6×10^{-4}	2.1×10^{-4}	0.34	0.27
2.	2.4×10^{-25}	1.9×10^{-25}	1.3×10^{-4}	1.0×10^{-4}	0.15	0.13

Crab (ApJ, 713, 671, 2010)

Energy in GW < 2% spin down

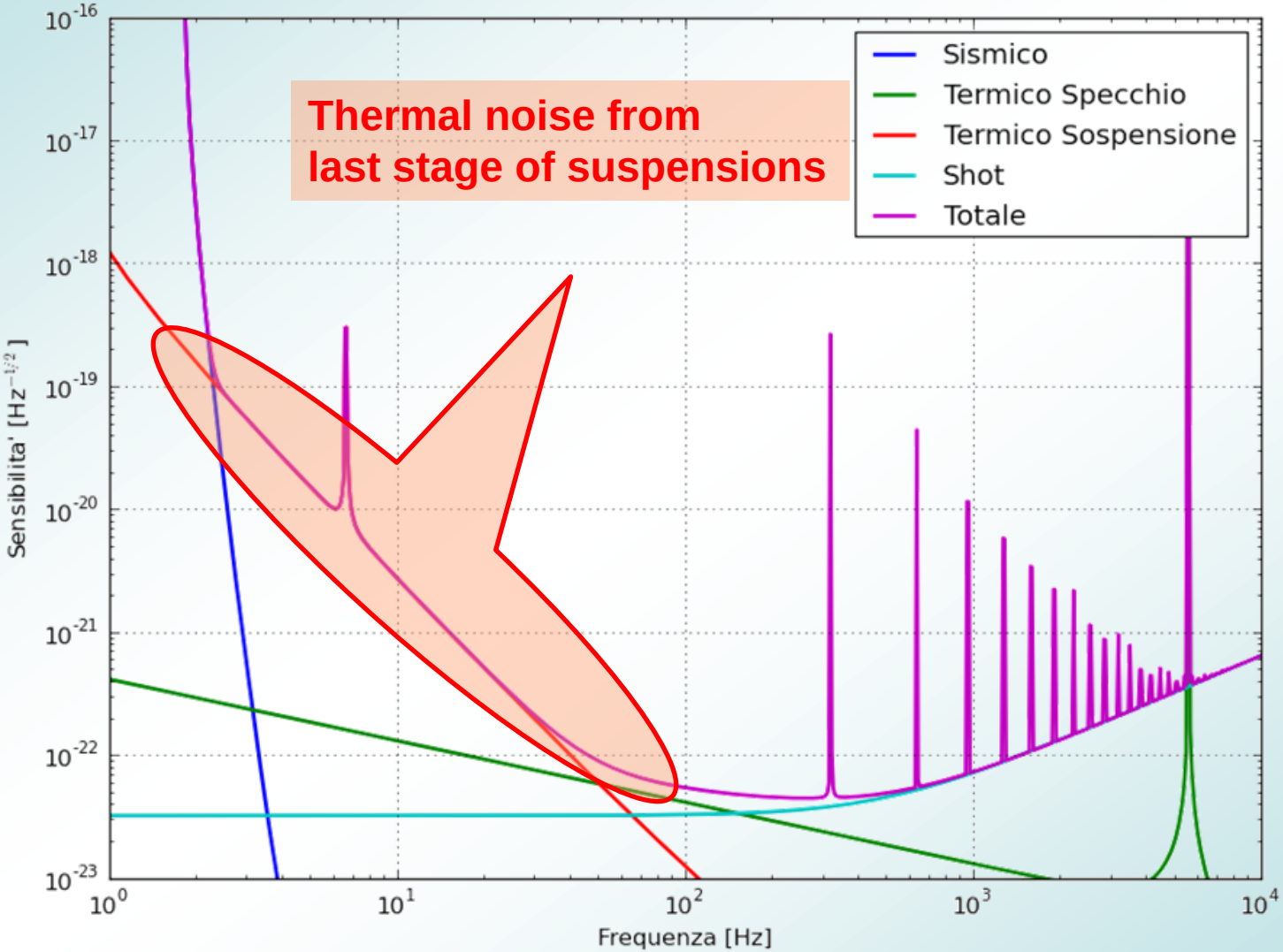
All-Sky searches



- One year integration sensitivity
- Dots are spin-down limits

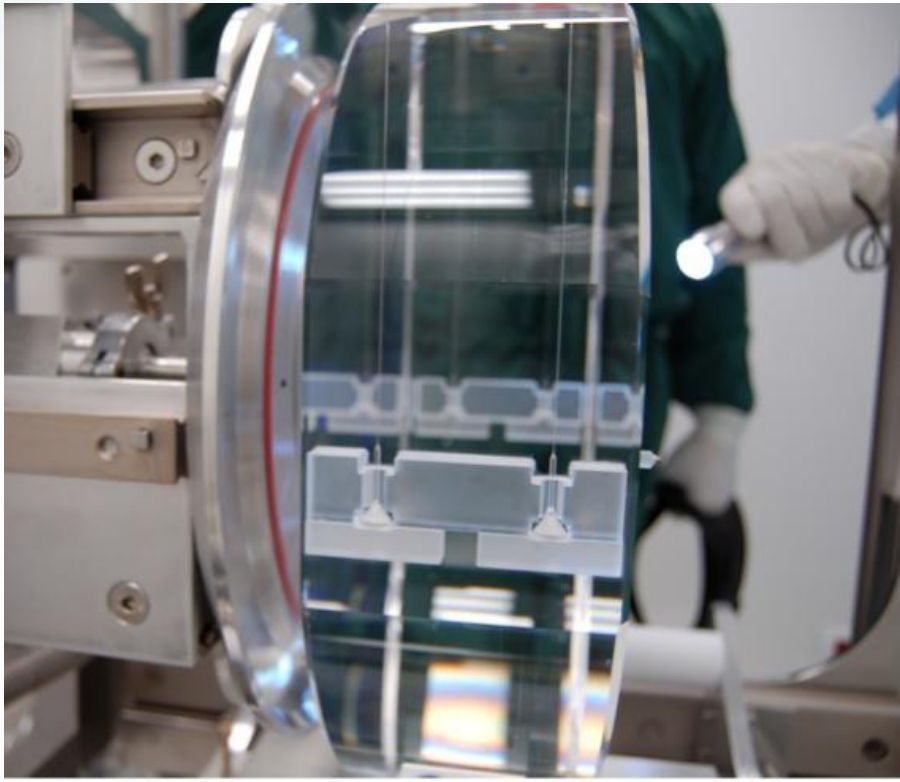
Virgo status

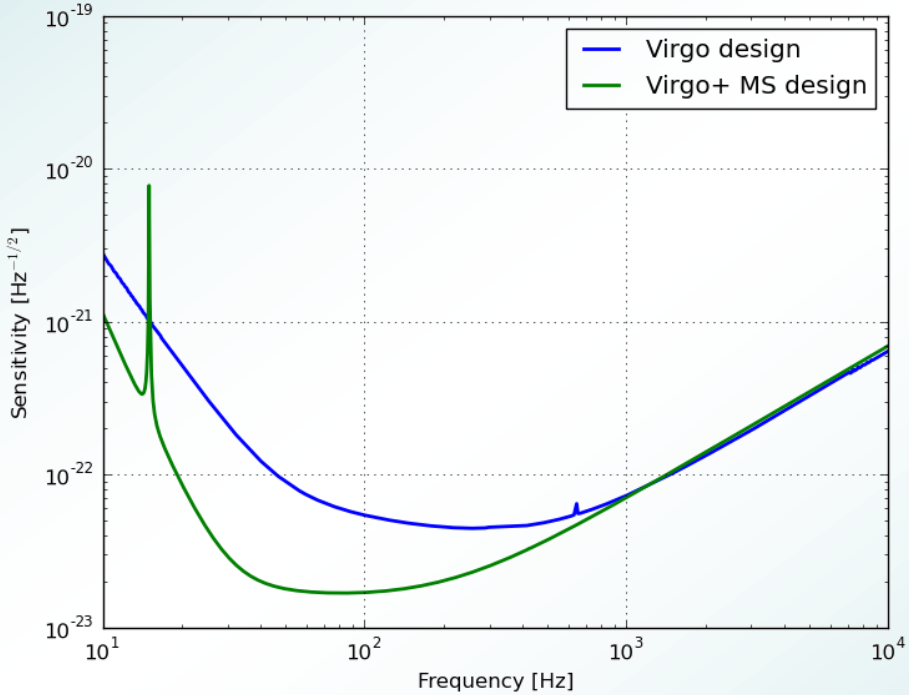
Noise sources (Virgo)



Monolithic suspensions

- Thermal noise reduced suspending the test mass with fused silica fibers, silicate bonded to the mirror
- Virgo is today the only large scale interferometer with monolithic suspensions

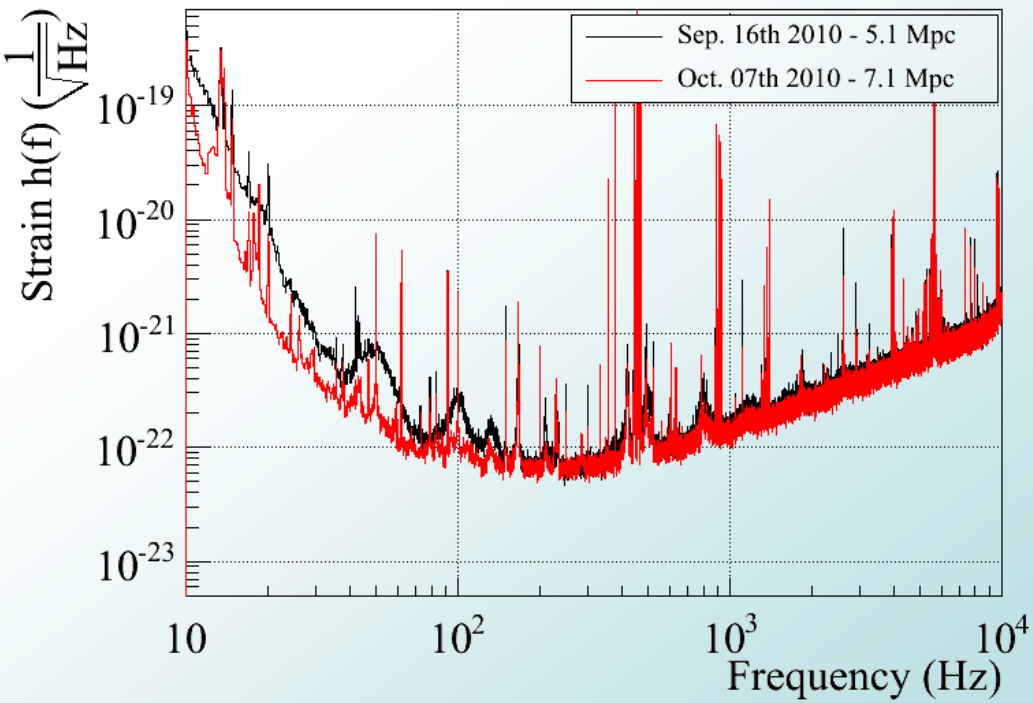




Since May 2010 in Virgo 4 test masses are suspended in this way

Virgo Science Run 3

- July 28th – October 20th 2010
- In coincidence with LIGO Hanford and LIGO Livingstone
- Real time analysis of triple coincidences to send triggers to EM observatories
- Virgo sensitivity limited by technical noises (scattered light) appeared after new mirror installations
- Some of them have been mitigated after the run
- Work still going on for others



Pipelines tests

- Blind injections: simulated signals injected at the actuator level
- During VSR3 one candidate correctly detected
  - Test of First Detection Procedure
  - Went on up to preparation of paper to be submitted to journal

Evidence for the Direct Detection of Gravitational Waves from a Black Hole Binary Coalescence

The LIGO Scientific Collaboration[1] and The Virgo Collaboration[2]

[1]*The LSC*
[2]*Virgo*

(RCS Id: detection.tex,v 1.81 2011/03/09 19:03:31 ajw Exp ; compiled 9 March 2011)

We report the observation of a gravitational-wave signal in data from a joint science run of the LIGO, Virgo and GEO 600 detectors. The signal exhibits the characteristic chirp waveform expected from a compact binary coalescence, and its form indicates a source with component masses $5.4 - 10.5\,M_\odot$ and $2.7 - 5.6\,M_\odot$ at a distance of less than 60 Mpc. There is strong evidence that the more massive component is a black hole with significant spin. The estimated false alarm rate for this event is 1 in 7 000 y, and detailed checks show no evidence that it is an instrumental artifact.

PACS numbers: 04.80.Nn, 04.25.dg, 95.85.Sz, 97.80.-d

WARNING: BLIND TEST

Virgo today

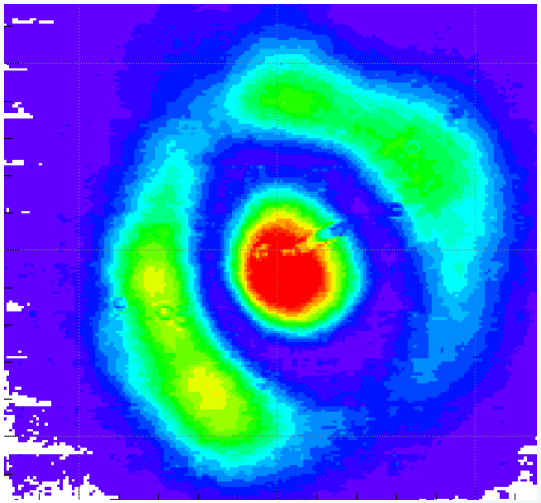


Image from the output port of the interferometer (dark fringe), dominated by high order transverse modes created by asymmetries

- Sensitivity limited by optical imperfection of newly installed mirrors
  - End mirrors have different radii of curvature
  - Power losses due to scattering (micro roughness) are high and asymmetric
- Interferometer asymmetries
  - Couple laser technical noise (frequency noise, frontal modulation phase noise, etc…) to the main output signal
  - Increase the power reaching the output port worsening scattered light problems
- Activity concentrated in development and commissioning of correction systems

Radii of curvature

- End mirrors must be curved to be matched to laser beam
- New mirrors have a large relative difference in RoCs (~100 m)
- CHRoCC (Central Heating for Radius of Curvature Change): heat the center of the mirrors to increase radius by thermal dilatation
- Installed and working sine January
  - Can change Roc of about 500-600 m
- Today work concentrated on searching the best operating point

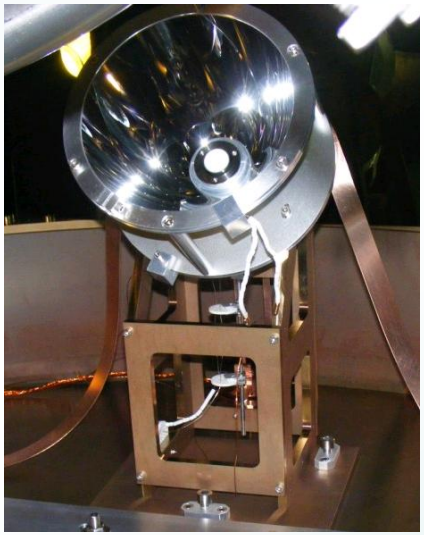
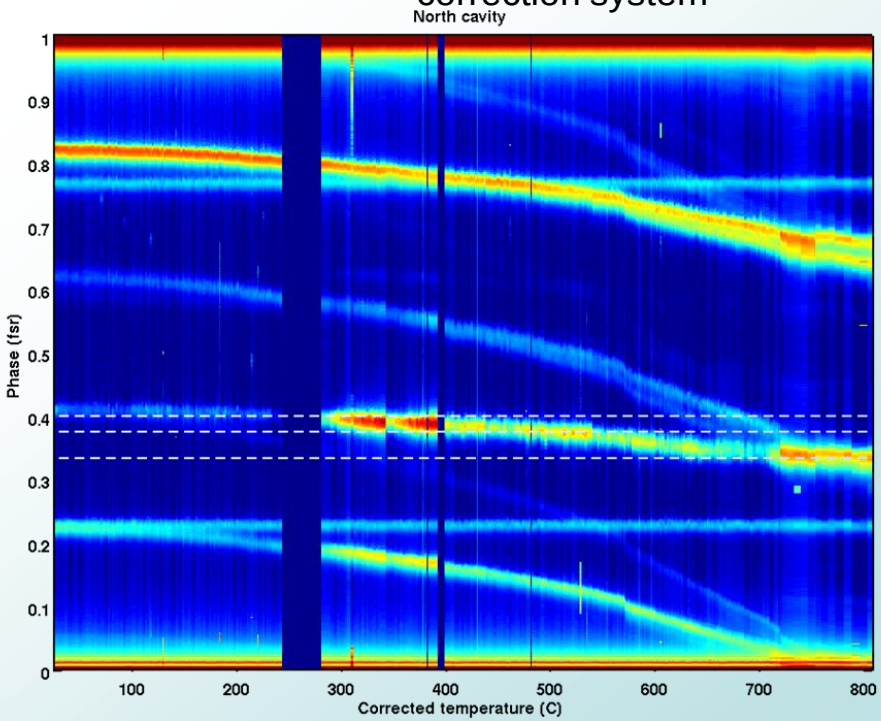


Image of Radius of Curvature correction system

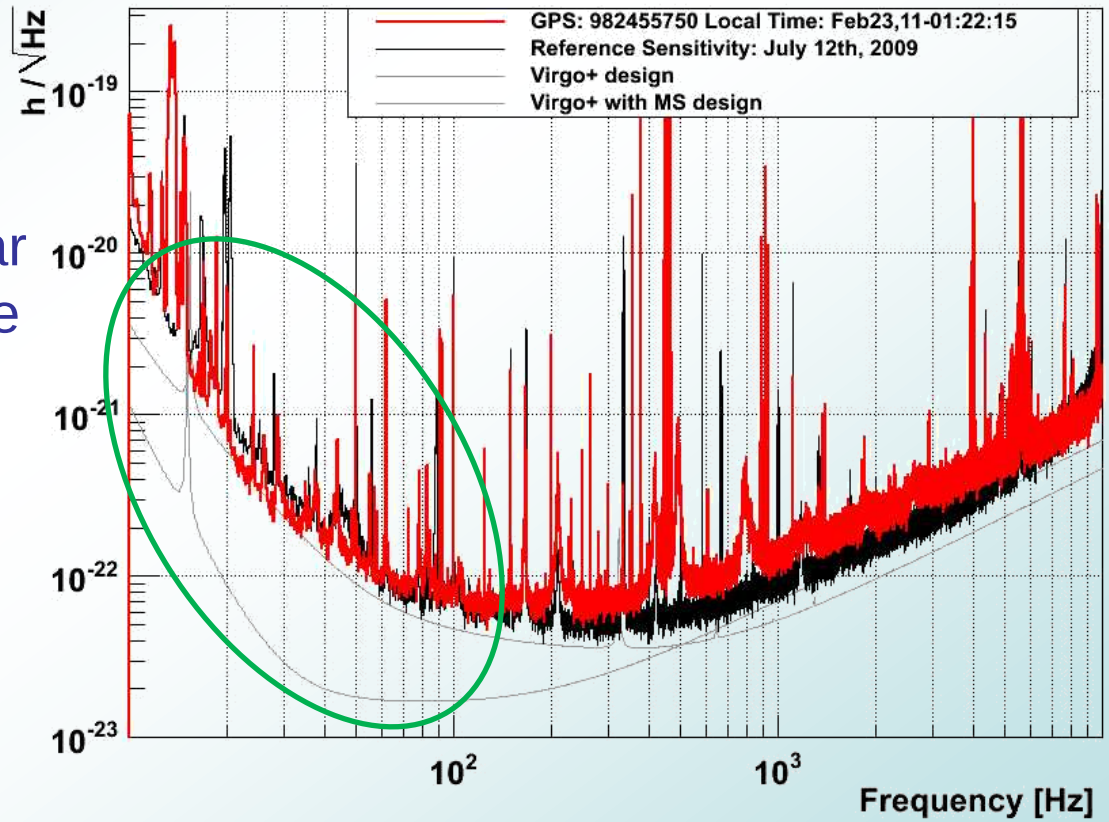


Variation of the mirror radius of curvature as a function of the correction system temperature. As seen by 3km long cavity high order mode positions.

Next future

Toward VSR4

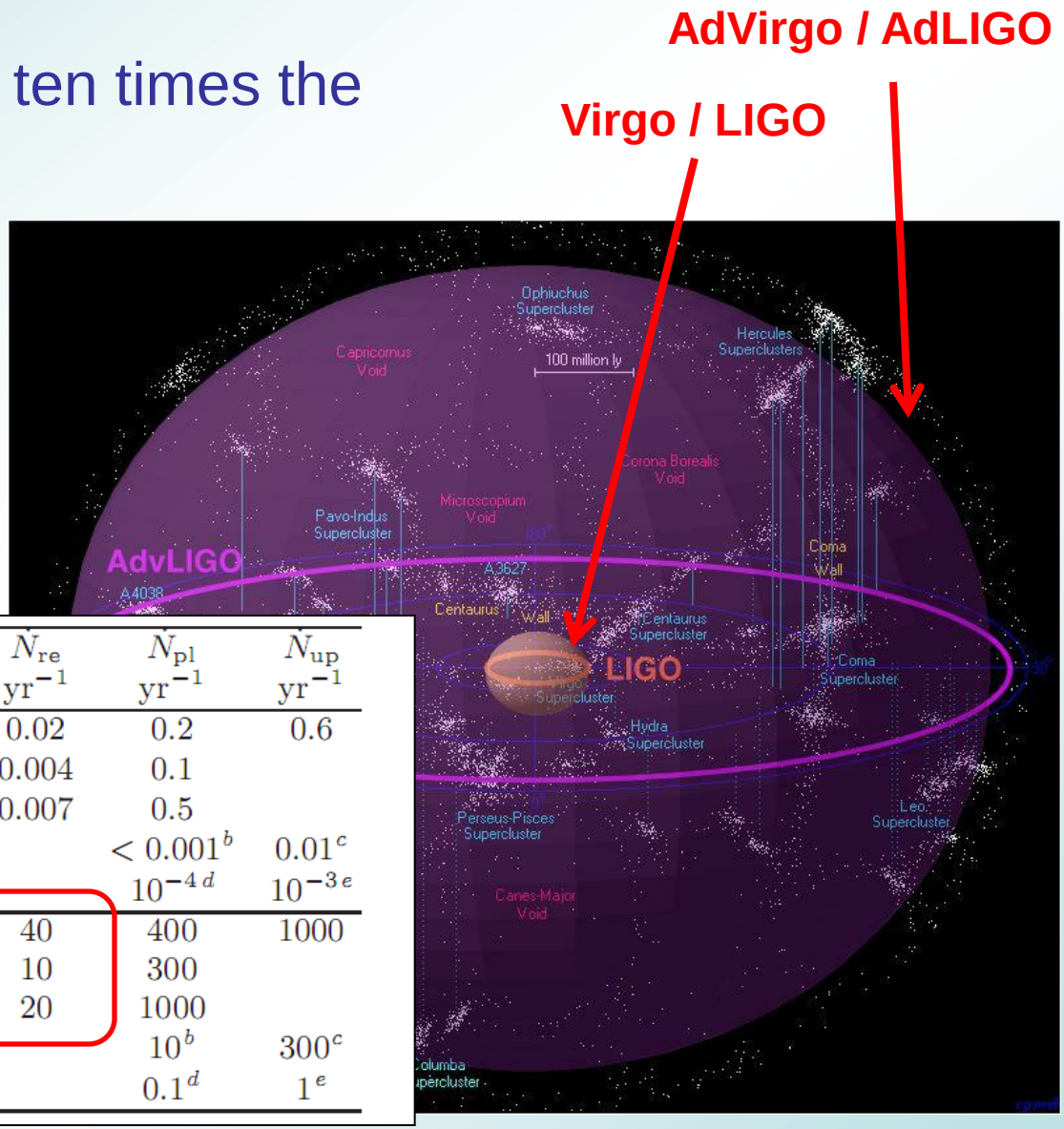
- Monolithic suspension have reduced thermal noise
- Great improvement at low frequency expected (<50 Hz)
- Up to now only small but promising results
- Efforts toward the next run concentrated at low frequency
- Improvements of sensitivity at Vela pulsar frequency could provide improvements on emission limit



Comparison of the best VSR2 sensitivity and actual low frequency improvements

Advanced Detectors

- Goal is to improve by ten times the sensitivity
- According to realistic rate estimates this means few tens of events per year



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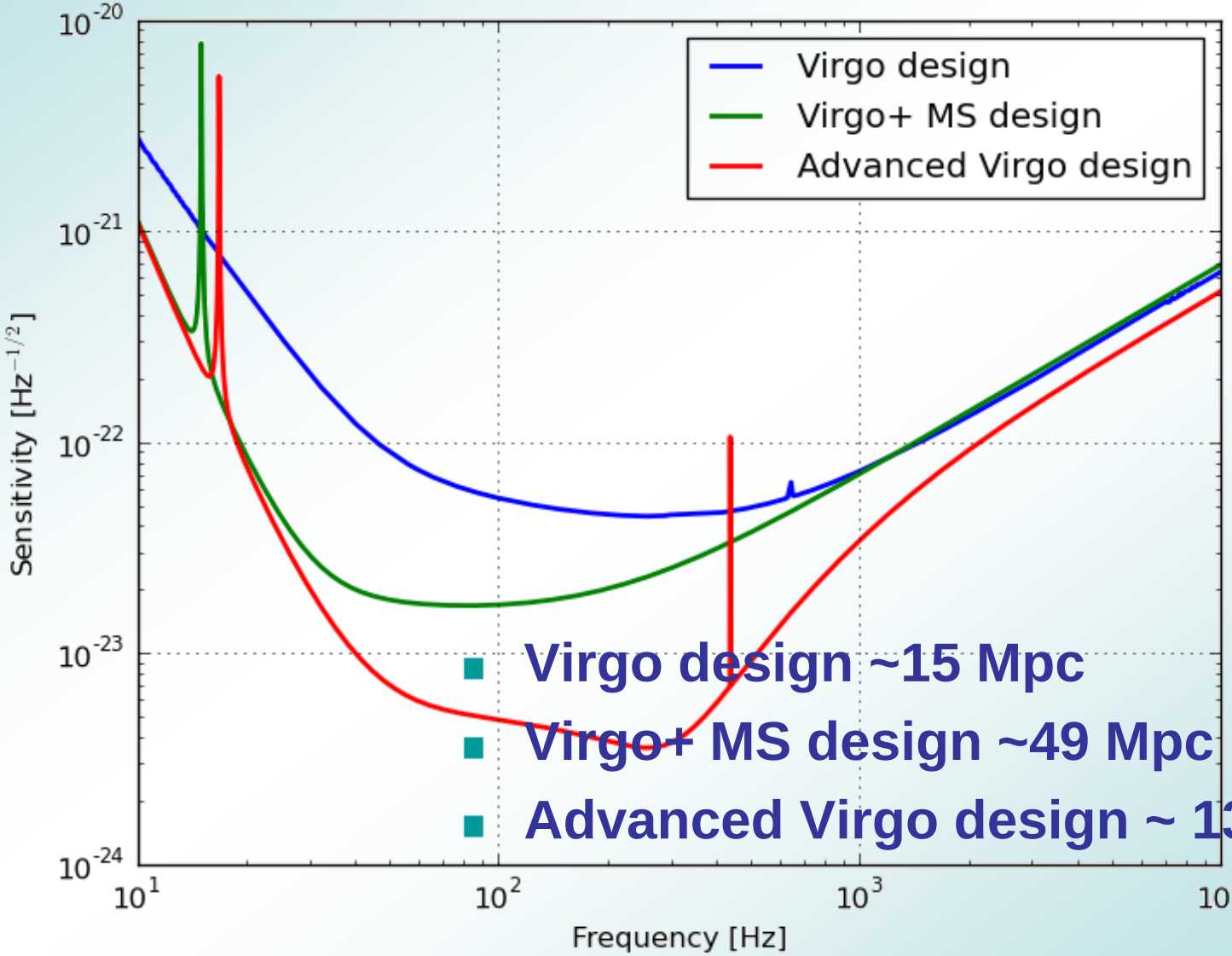
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^{b}	300^{c}
	IMBH-IMBH			0.1^{d}	1^{e}

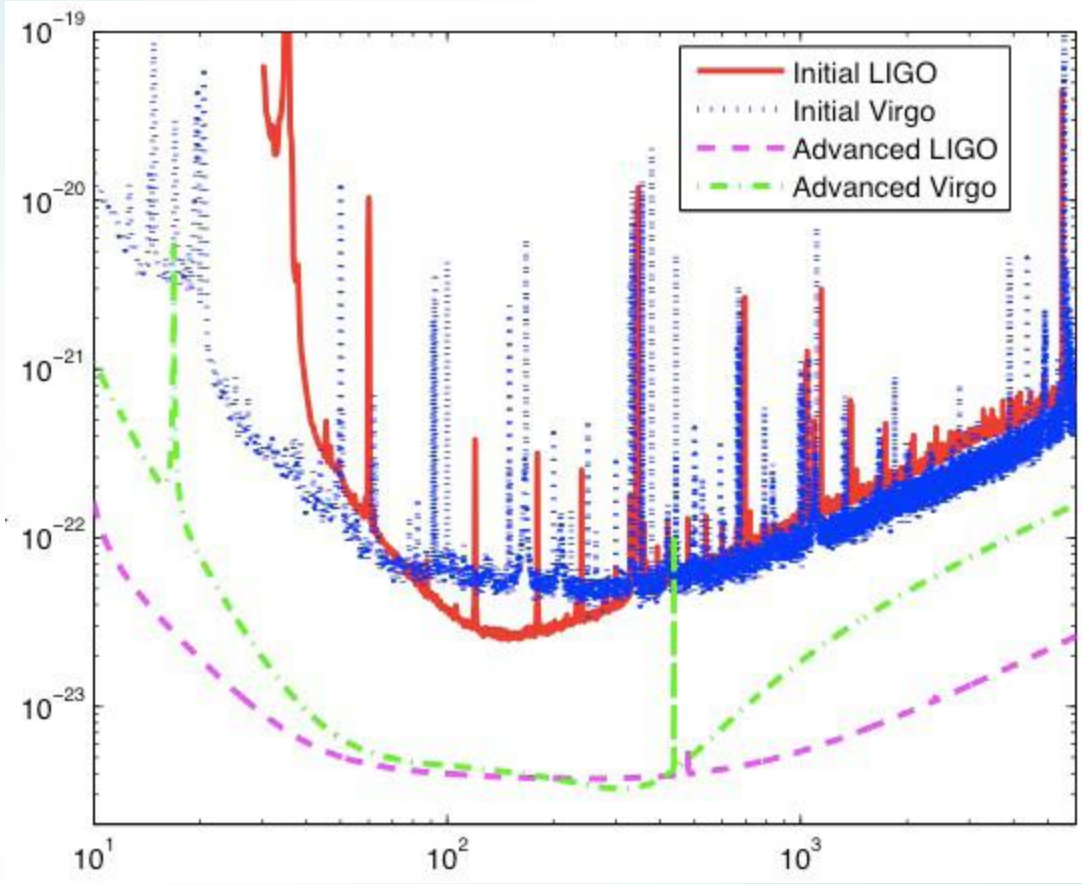
Advanced Virgo sensitivity



- **Virgo design ~15 Mpc**
- **Virgo+ MS design ~49 Mpc**
- **Advanced Virgo design ~ 135 Mpc**

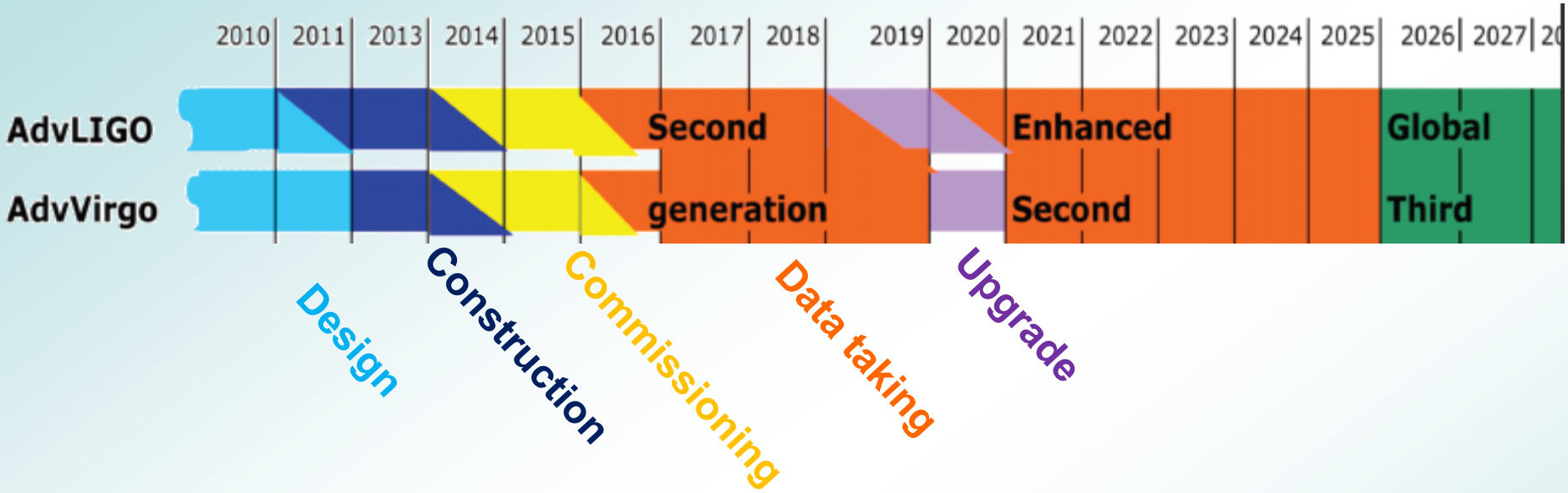
Advanced Detectors

- **Increase laser power** (20 -> 125 W)
- **Bi-concave geometry** of arm cavities to reduce mirror thermal noise
- **Monolithic suspension** to reduce suspension thermal noise
- **Signal-recycling** to increase detector optical gain and made interferometer response tunable



Presently finalization of optical and mechanical design. Strat of construction foreseen for end of year.
First scientific runs in 2015 together with Advanced LIGO

Next years



- Final review of Advanced Virgo design in ~ month
- Start construction end of year
- First “brief” runs in 2015 together with Advanced LIGO


THE END