Virgo: sensibilité et résultats actuels

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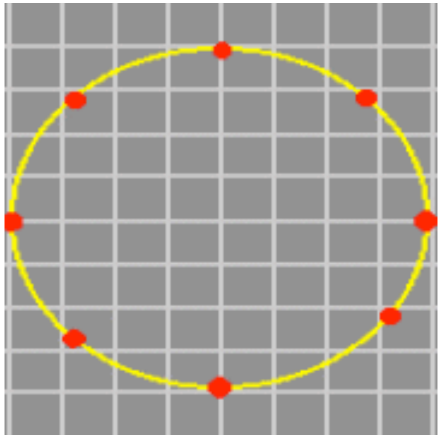
Conseil Scientifique de l'IN2P3

The gravitational waves (GW)

- Perturbations of the space-time metrics

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

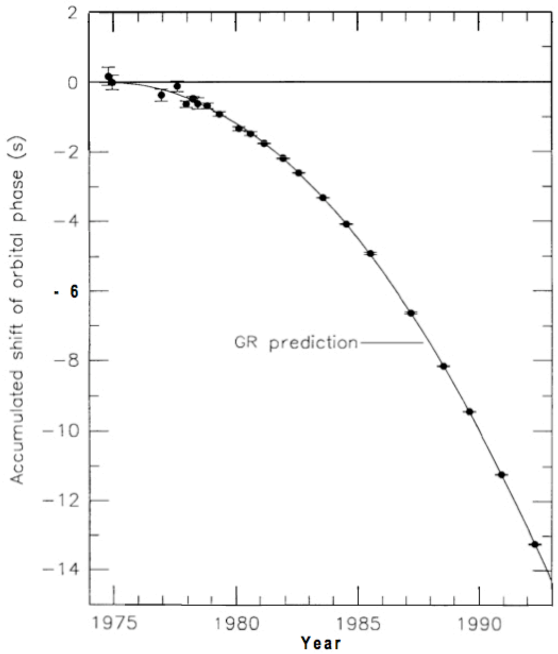
- Propagation at the speed of light
- Tranverses, 2 polarisations at 45 degrees ("+" et "x")
- Generated by mass quadrupole acceleration



- Order of magnitude: coalescence of neutron star of 1.4 Msun at 15 Mpc

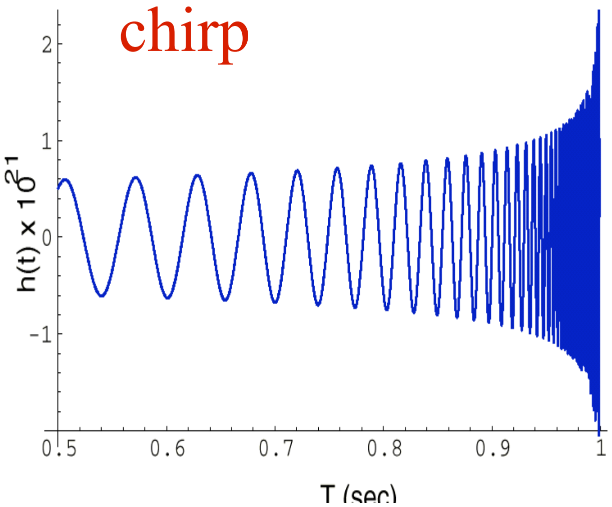
$$h \approx 10^{-21}$$

- No direct detection
- Indirect detection: decrease of orbital period of PSR1913+16 (and other similar systems)



Coalescing binaries (CBC)

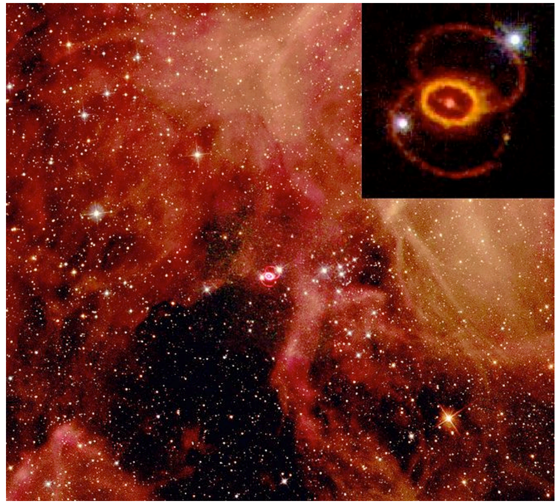
- Final evolution stage of compact stars
  - Two neutron stars
  - Two black holes
  - A black hole + a neutron star
- Waveforms can be predicted



- Scientific potential - some examples
  - *Cosmology*: distance of the source can be inferred by the waveform (Independent measurement of Hubble constant)
  - *Test of General Relativity*: accurate measurements of inspiral waveform can test gravity in the strong field regime (test alternative theories of gravity)
  - *Nuclear Physics*: Waveform depend on the equation of state of the star
  - *Astrophysics:* coalescence of compact objects is the best candidate for short gamma ray bursts (confirmation of the progenitor)

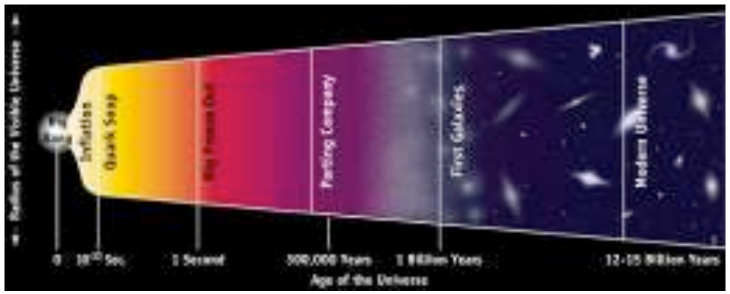
Other GW sources

- Spinning neutron stars
  - GW at a frequency = 2 f_rotation + Doppler effect
  - Amplitudes unknown, depend on star asymmetry
  - SNR can be increased by integration
  - A billion of pulsar expected in the galaxy, about a thousand known



- Supernovae
  - GW from non spherical collapse
  - GW amplitudes difficult to model
  - 1/century in the galaxy - 10/year in the Virgo cluster
  - Much higher amplitudes expected when Virgo was built

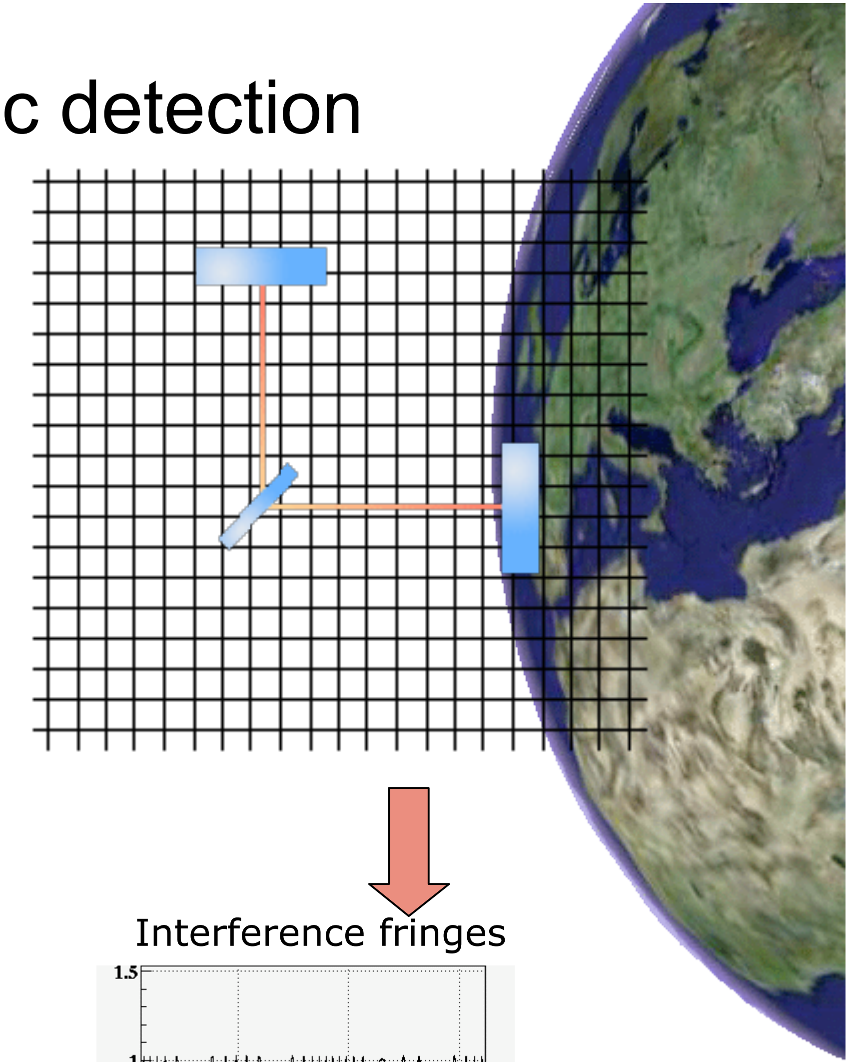
- Cosmological GW background
  - Predicted by standard inflation and by some string models



The interferometric detection

GW induce space-time deformation

Measure space-time strain using light



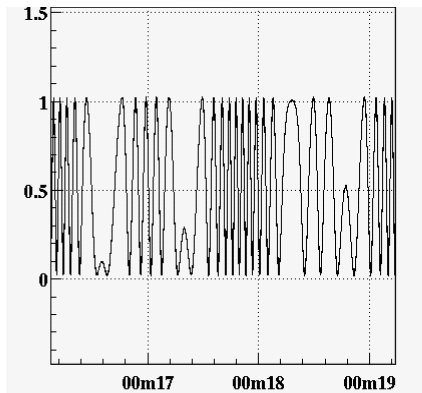
$$\Delta L \approx hL$$

Target h ~ 10^{-21}
(NS/NS @Virgo Cluster)

L ~ 10^{3} m

Need to measure: $\Delta L \sim 10^{-18}$ m

Interference fringes



The Virgo Collaboration

- **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

Goals

- First direct detection of gravitational waves
- Study of the gravity
- **New *window* to observe the Universe**

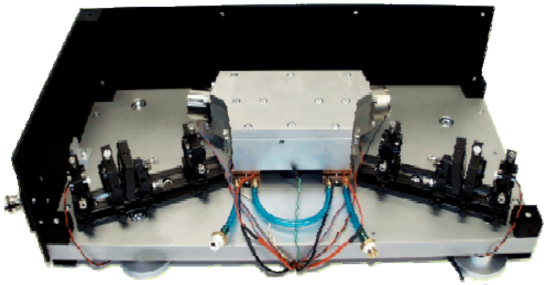
Virgo chronology

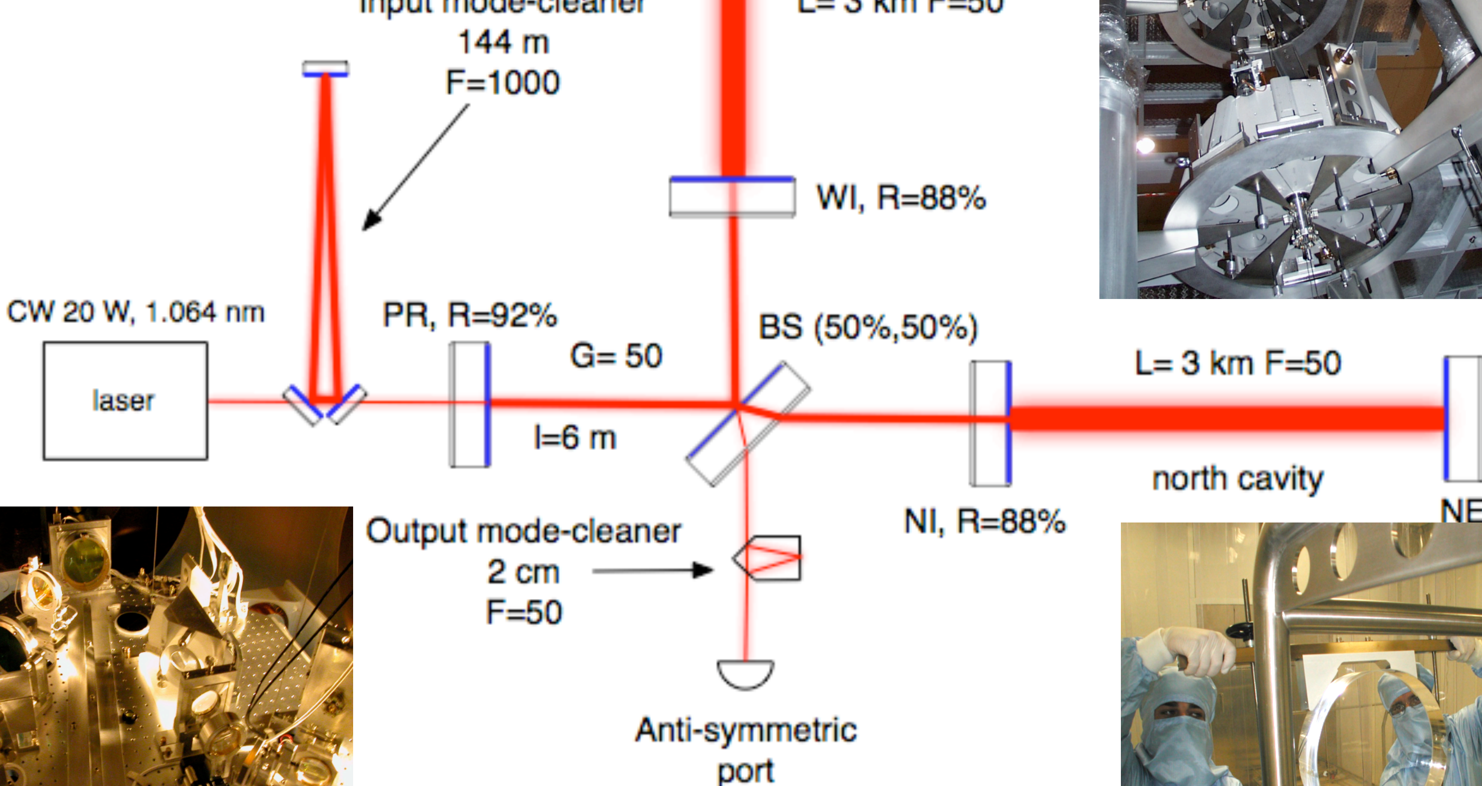
- 1993 Virgo approval
- 2003 end of the Virgo construction

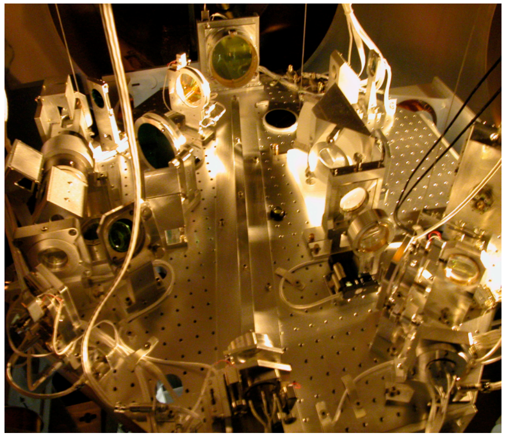
- commissioning
- **2007 data taking (VSR1)**
- Commissioning
- 2008 upgrade to Virgo+ (first part)
- **End 2009 data taking (VSR2)**
- Commissioning
- 2010 upgrade to Virgo+ (second part: monolithic suspensions)
- Commissioning
- **Summer 2010 data taking (VSR3)**
- Commissioning
- **Summer 2011 data taking (VSR4)**

- Fall 2011 shutdown, start of Advanced Virgo construction

Virgo optical scheme & detector highlights



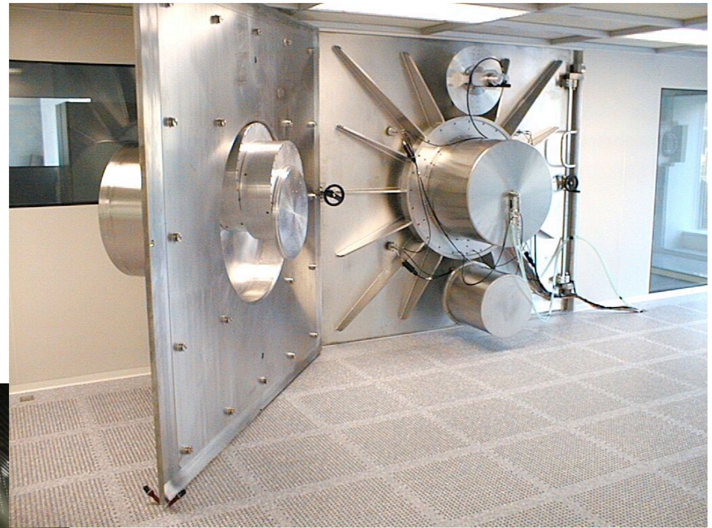


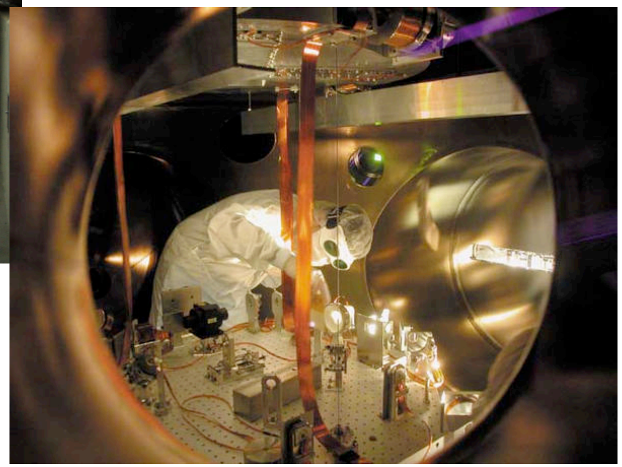


IN2P3 contributions- construction

(the contributions to Advanced Virgo will be described by R.Flaminio)

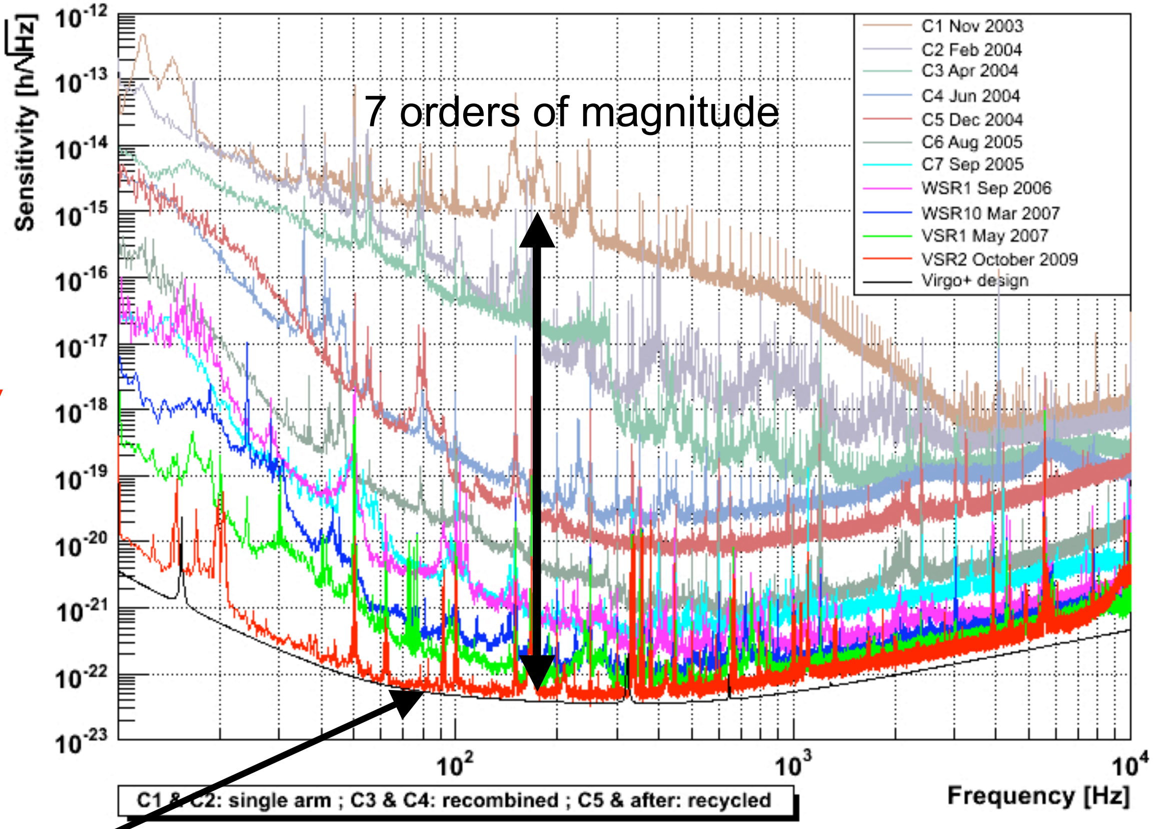
- APC (new group>2008)
- LAL
  - Vacuum tube
  - Global control & locking
  - Software
- LAPP
  - Vacuum towers bases
  - Detection system
  - DAQ
  - Software
- LMA
  - Coatings
  - Optical metrology





Commissioning - Sensitivity evolution (2003-2009)

- September 2003: beginning of commissioning
- Set-up and tune all the interferometer **control systems** (~ 100)
- Reach the design sensitivity (maintaining stability): identify and reduce the technical noises ("noise hunting")
- Difficulties
  - Sub-systems very interconnected
  - First kilometric gravitational wave detector



$$10^{-22} 1/\sqrt{Hz} \Rightarrow 3 \cdot 10^{-19} m/\sqrt{Hz}$$

- LIGO experienced the same timeline

IN2P3 contributions - spokesperson/commissioning

Spokesperson

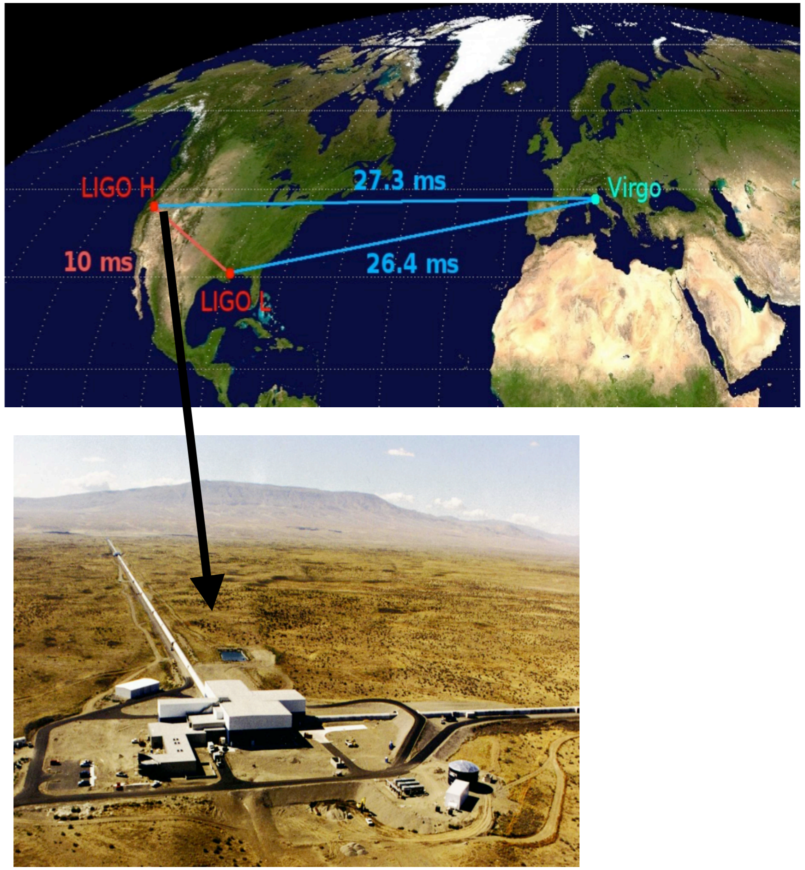
- B.Mours (2005-2008)

Commissioning

- Commissioning coordinators
  - R.Flaminio, M.Barsuglia, E.Tournefier
- Weekly coordinators
- Detector support
  - DAQ, global control, detection system
  - Automation, calibration, monitoring
- Transversal commissioning activities
  - Locking
  - noise budgets
  - optical characterization

2007: Virgo - LSC agreement

- Ligo Scientific Collaboration (LSC)
- 4 interferometers (2 LIGO 4km, 1 LIGO 2 km, 1 GEO)
- ~500 scientists, ~40 institutions

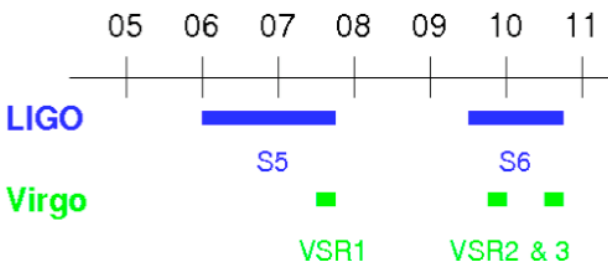


Agreement (MoU) Virgo-LSC

- Full data exchange and analysis joint publication policy
- Science runs coordination
- Collaborative technical research

Benefits:

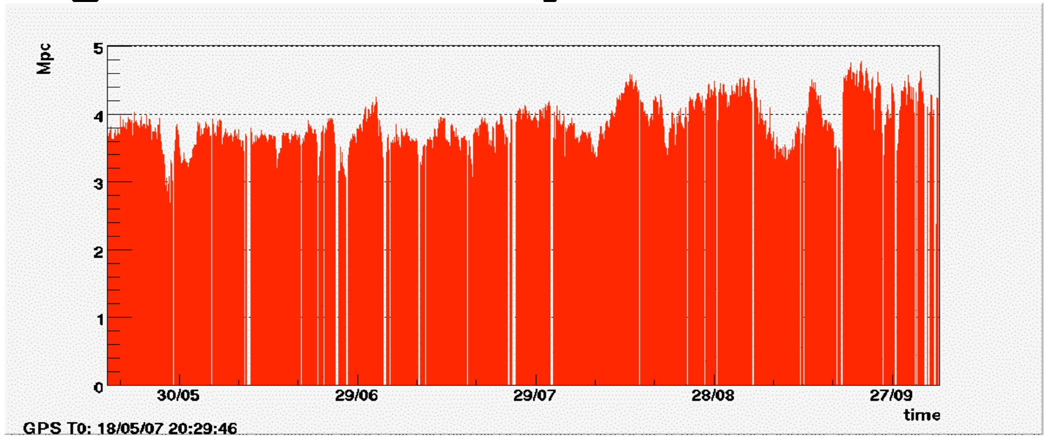
- Confidence in detection
- Sky coverage
- Duty cycle
- Sky position localization

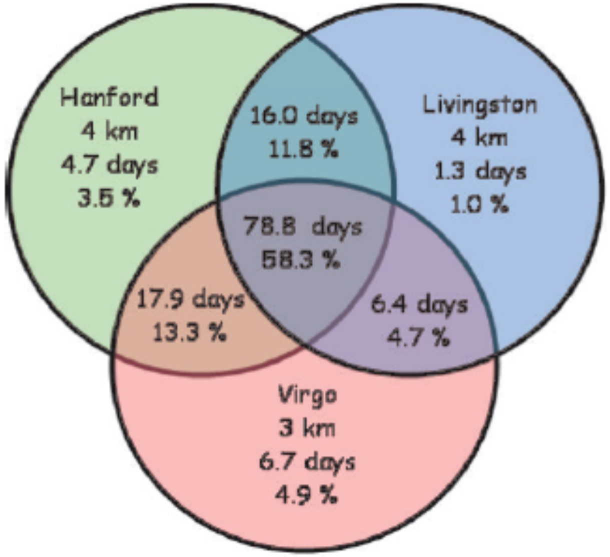


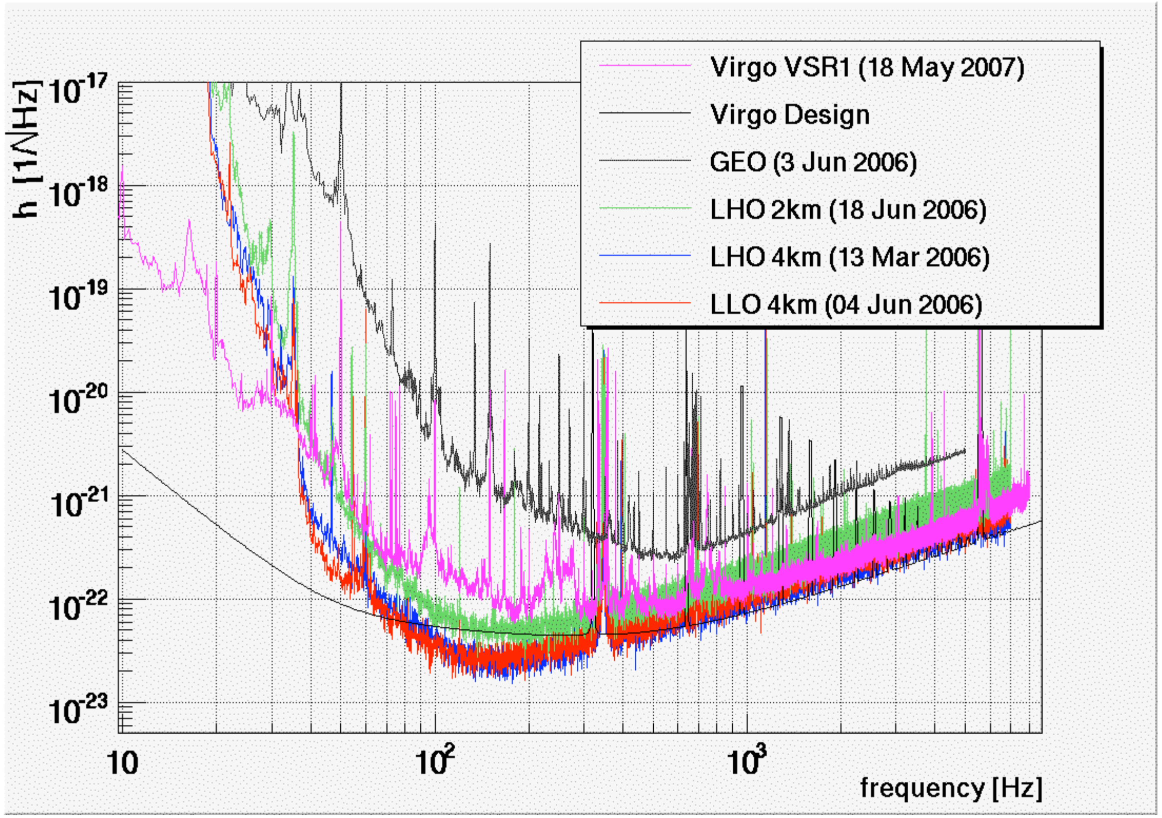
First scientific data taking - VSR1 - May/Oct 2007

Virgo: the first science run (VSR1)

- 4.5 months (May 18th - October 1st)
- Duty cycle: 81%
- NS-NS range from 3.6 to 4.5 Mpc

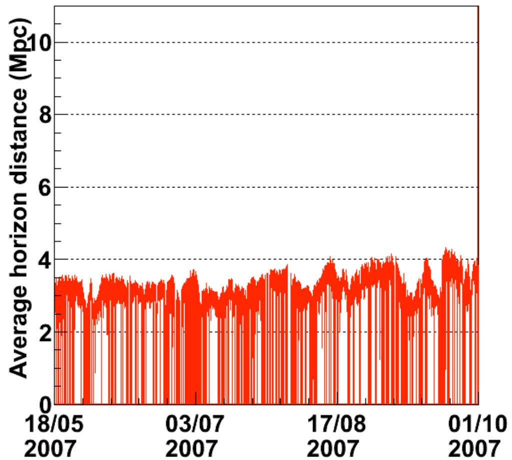






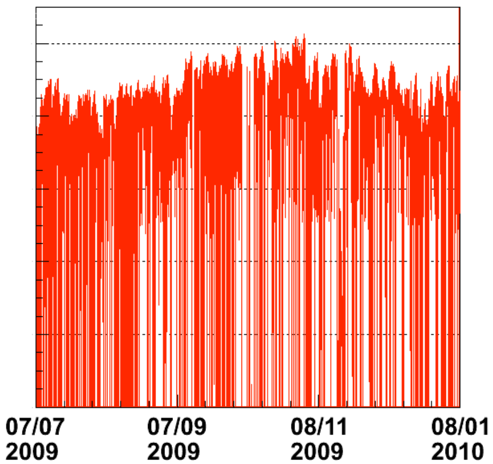
After VSR1: from Virgo to Virgo+

VSR1



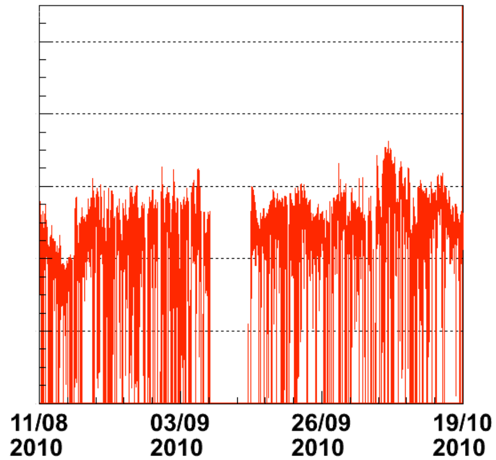
Virgo → Virgo+

VSR2



Virgo+ → Virgo+ with monolithic suspensions

VSR3

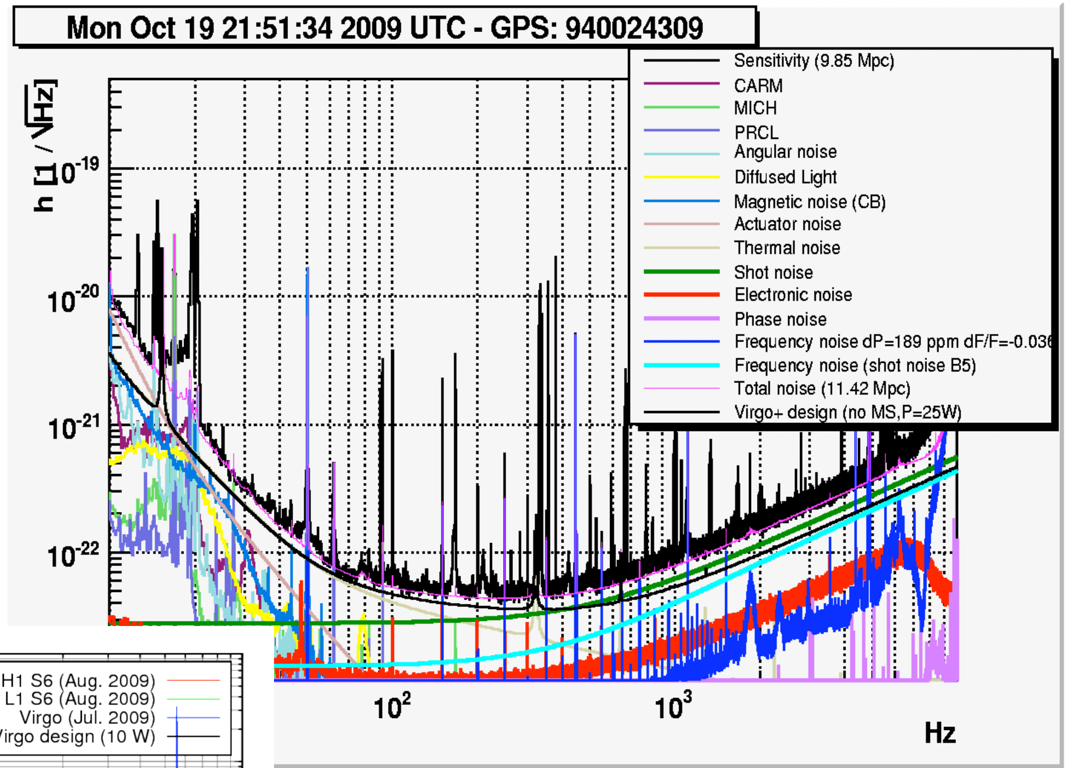


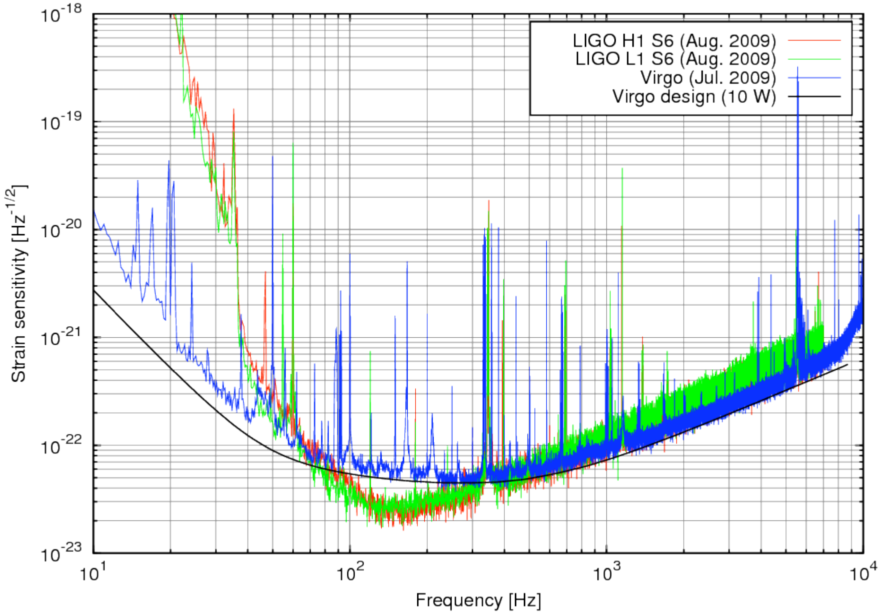
- ❑ Increase laser power
- ❑ Improve the electronics
- ❑ Install thermal compensation system
- ❑ Damp diffused light
- ❑ Noise hunting

- ❑ Increase finesse of the arms
- ❑ Monolithic suspensions

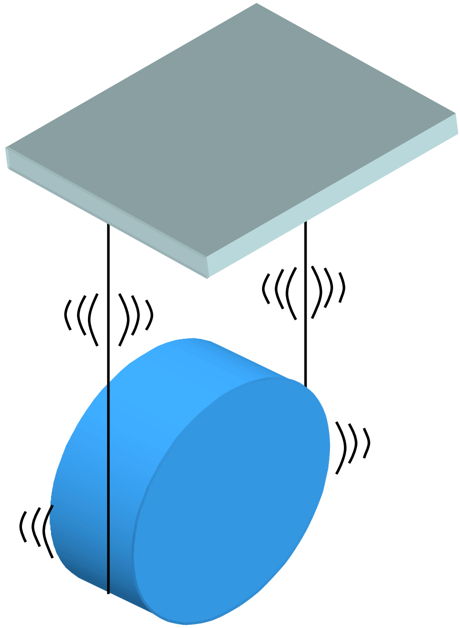
Oct 2009: VSR2 sensitivity

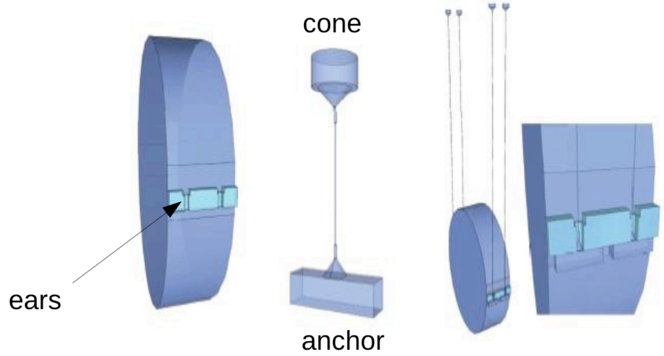
- Detection horizon for NS-NS = 9 Mpc
- Noise understood

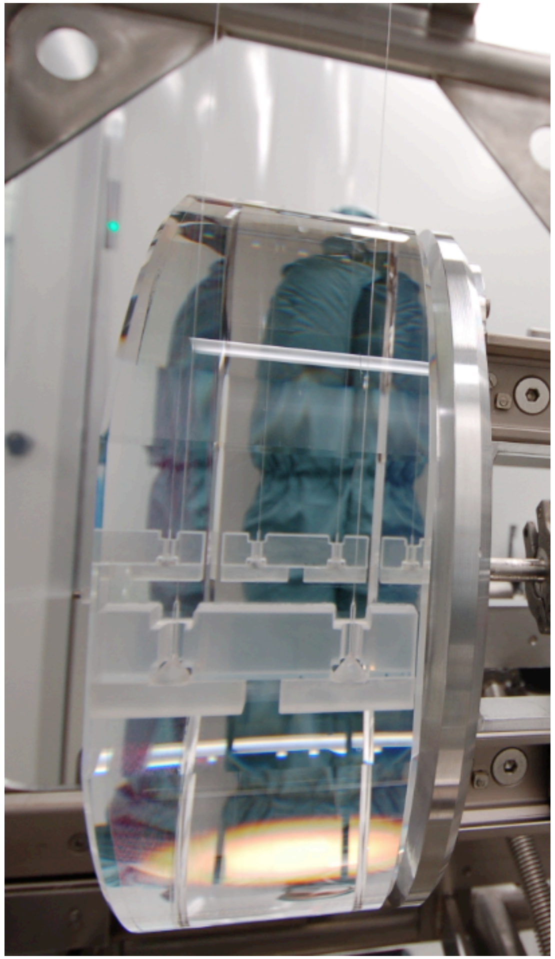




2010: monolithic suspensions

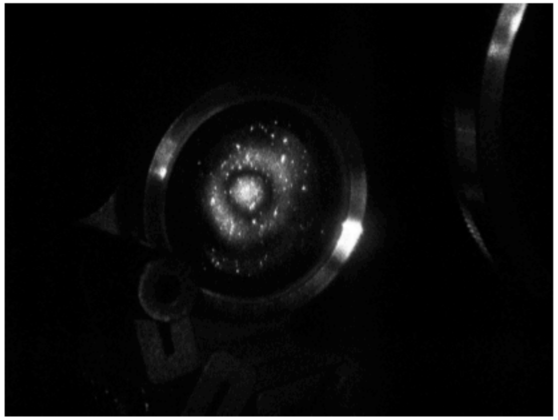


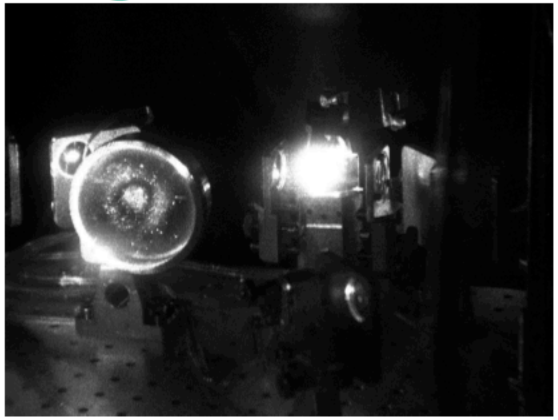




- In order to reduce the thermal noise the dissipation should be reduced: from steel to monolithic fused silica suspensions
- 4 arm-cavity mirrors installed in the spring-summer 2010
- No robustness or control problems experienced with monolithic suspensions.

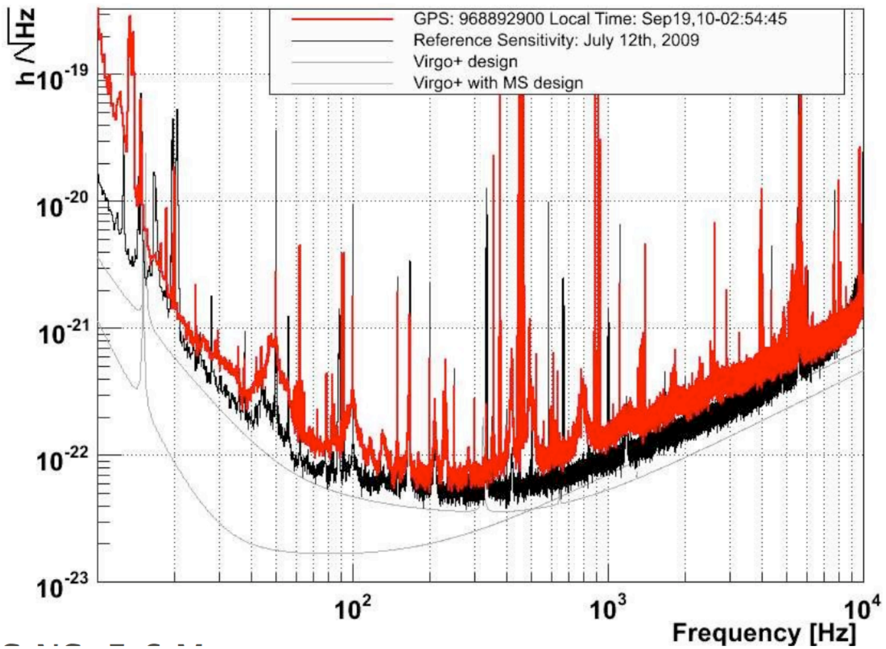
Problem of excess of light at the interferometer output





- ❑ Degradation of the interferometer contrast due to the waist mismatch (presence of Laguerre-Gauss mode 01)
- ❑ lot of power (2-3 W)
- ❑ Scattered light on the detection optics

- ❑ VSR3 sensitivity only 5-6 Mpc (8-9 before monolithic suspensions)

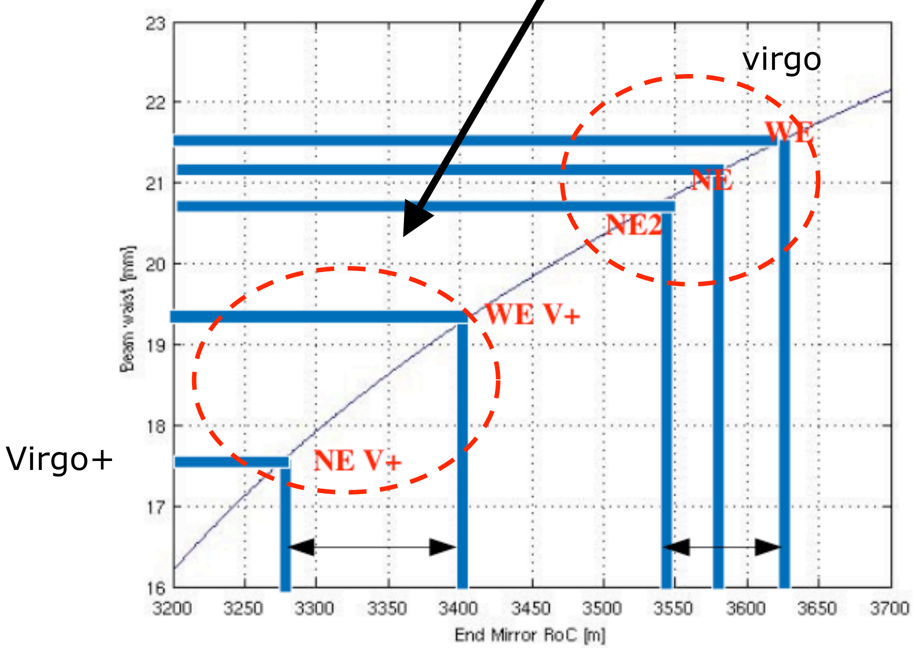


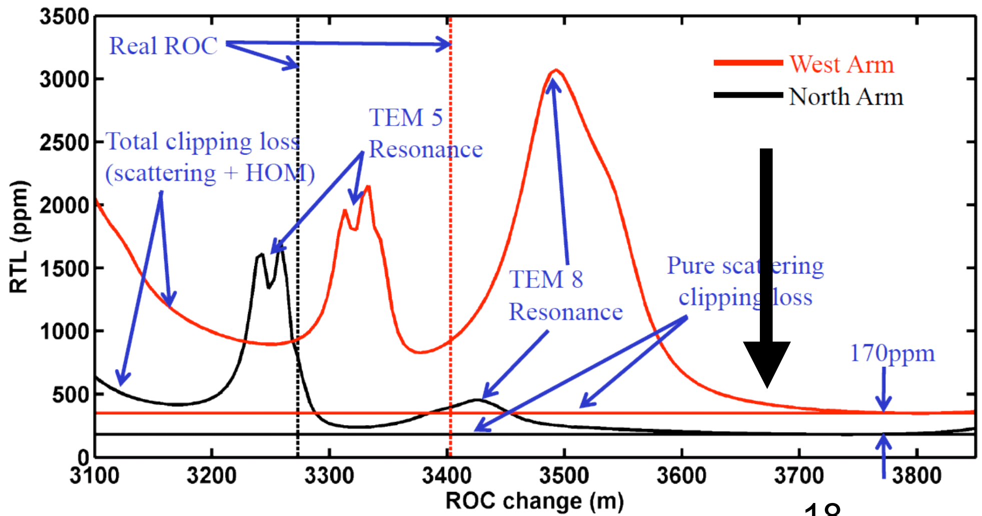
Problems with radii of curvature of the new end mirrors

	ROC before coating (m)	ROC after coating (m)
Specification	3450 +- 100	
North End	3368	3273
West End	3496	3403

- ❑ Mirror were inside the specifications, but asymmetry and average value of the ROC changed
- ❑ Optical simulation: importance of **mode degeneracy inside Fabry-Perot cavities**
- ❑ *not only the ROC asymmetry* is important also the absolute value of the two ROCs
- ❑ Specifications not correct

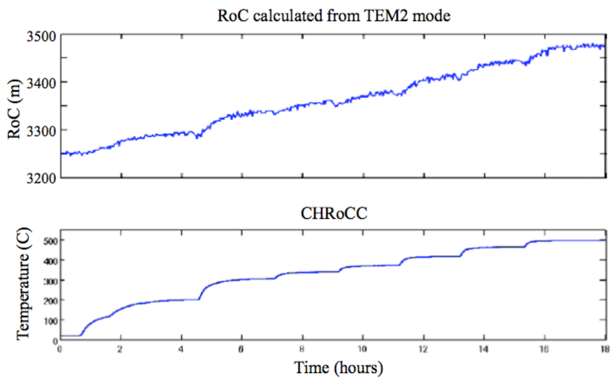
➡ Need to increase both the ROCs, in order to minimize losses asymmetry between the two cavities

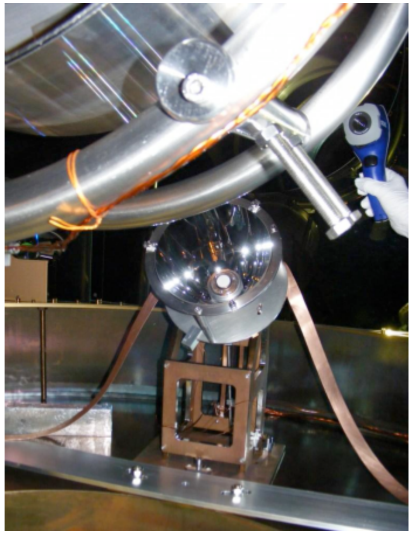


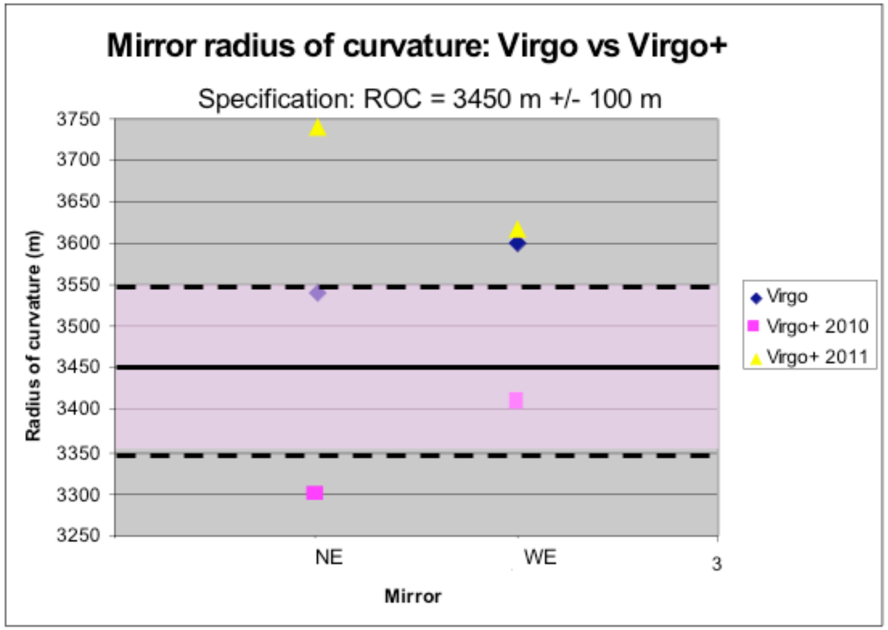


Correction of the radius of curvature

- Use of a central heater (source IR + parabolic reflector) to heat the center of the mirror in order to increase its ROC



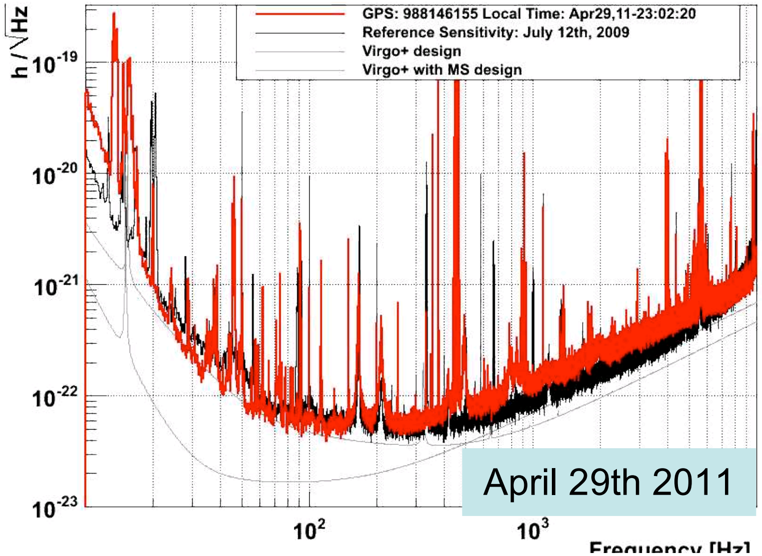




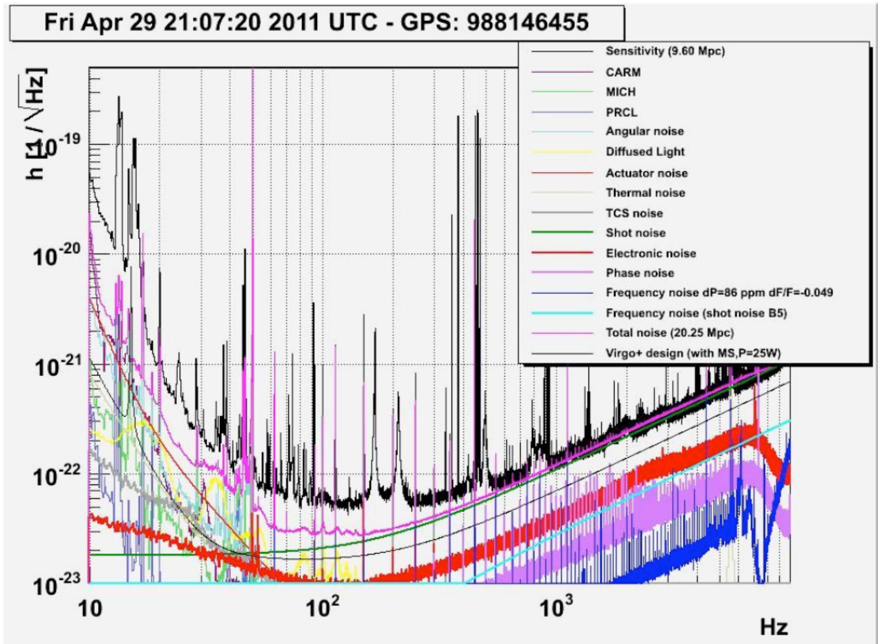
- A new "working point" of the interferometer has been found, the ROC asymmetry is higher than before, but the average value of the ROC is not in a *dangerous zone*
- *Important experience for Advanced Virgo*

Present status and plans until Advanced Virgo

- ❑ Interferometer back in good optical conditions
- ❑ VSR2 sensitivity recovered
- ❑ Detection horizon for NS-NS 9 Mpc (same as VSR2)
- ❑ *Noise hunting*



- ❑ During the summer a joint data taking (VSR4) with GEO is planned
- ❑ Shutdown to start the Advanced Virgo installation planned in the fall 2011 (exact date TBD)
- ❑ A few months of commissioning remains to increase the sensitivity in the mid-low frequency region of the spectrum



IN2P3 contributions - data analysis

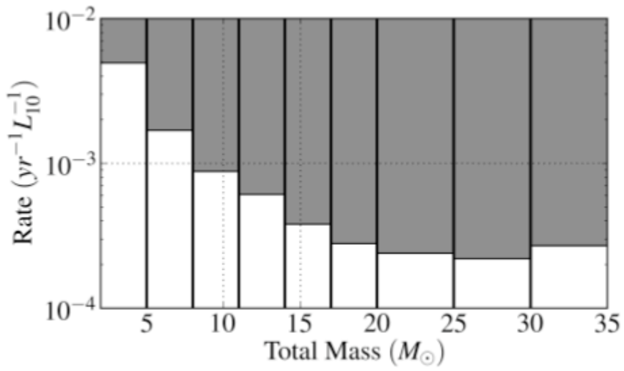
- Data analysis coordinators
  - F.Cavalier, M.A.Bizouard
- Physics group chairs
  - P.Hello (bursts)
  - M.A.Bizouard (CBC)
  - F.Marion (CBC)
  - D.Verkindt (Data quality)
- Data-analysis review chairs
  - R.Flaminio (Bursts)
  - D.Buskulic (CW)

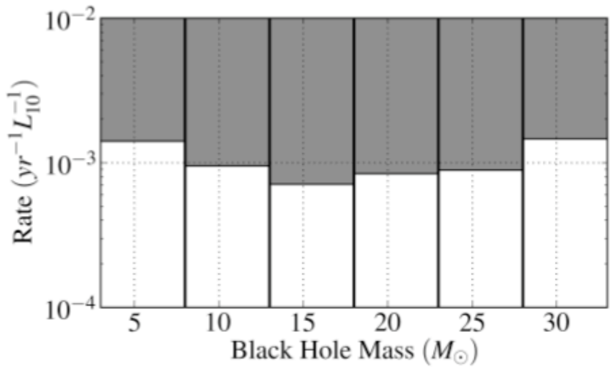
- APC (new group, >2008)
  - Multi-messenger searches
- LAL
  - Bursts
  - Data quality
- LAPP
  - CBC (Compact binary coalescences)
  - Calibration & reconstruction
  - Data quality
- LMA

  Burst review

A sample of the Virgo/LSC results: low mass binaries

- Data from LIGO S5 and Virgo VSR1 runs
- Mass of the system from 2 to 35 solar masses
- *Search for Gravitational Waves from Compact Binary Coalescence in LIGO and Virgo Data from S5 and VSR1*, PRD 82 (2010) 102001
- Previous searches using LIGO S5 data
- Upper limits on the rates of NSNS, BHNS and BBH coalescences
- Upper limit more than an order of magnitude larger than optimistic astrophysical expectations

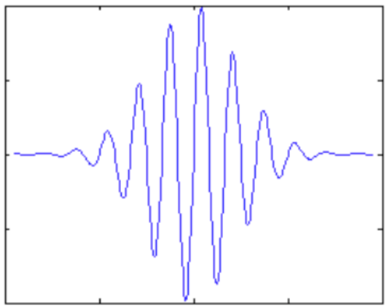


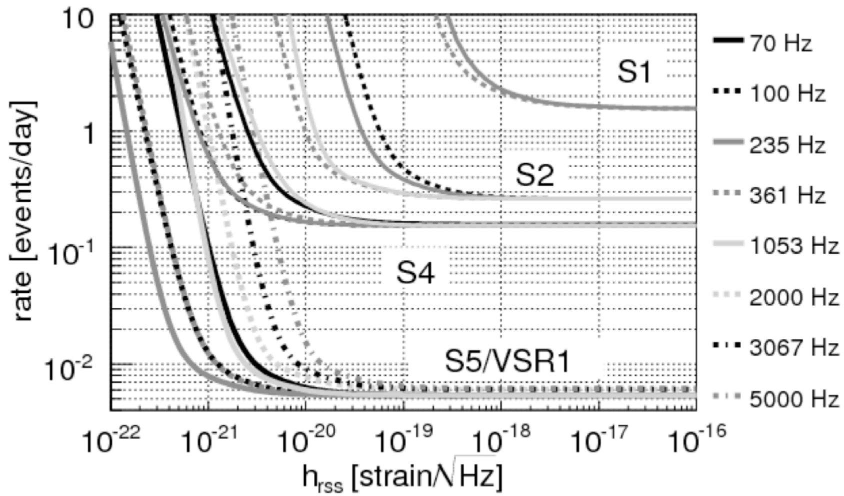


	BNS	BHNS	BBH
Component Masses $(M_\odot)$	1.35/1.35	5.0/1.35	5.0/5.0
Horizon Distance (Mpc)	~ 30	~ 50	~ 90
Cumulative Luminosity (L_{10})	370	1600	8300
Calibration Error	13%	14%	14%
Monte Carlo Error	17%	17%	18%
Waveform Error	19%	18%	16%
Galaxy Distance Error	−16%	−13%	−13%
Galaxy Magnitude Error	29%	30%	31%
Non-spinning Upper Limit $(\mathrm{yr}^{-1}L_{10}^{-1})$	8.7×10^{-3}	2.2×10^{-3}	4.4×10^{-4}
Spinning Upper Limit $(\mathrm{yr}^{-1}L_{10}^{-1})$	...	2.7×10^{-3}	5.3×10^{-4}

A sample of the Virgo/LSC results: bursts search

- Data from LIGO S5 and Virgo VSR1 runs
- Burst un-triggered search
- Waveform sine-gaussian and gaussian
- Upper limit:
  - for 153 Hz, Q = 9, sine-Gaussians, h_rss= 6e–22 1/sqrt(Hz)
  - Assuming isotropic emission at a distance of 10 kpc, this corresponds to an energy of 1.8e–8 solar Masses

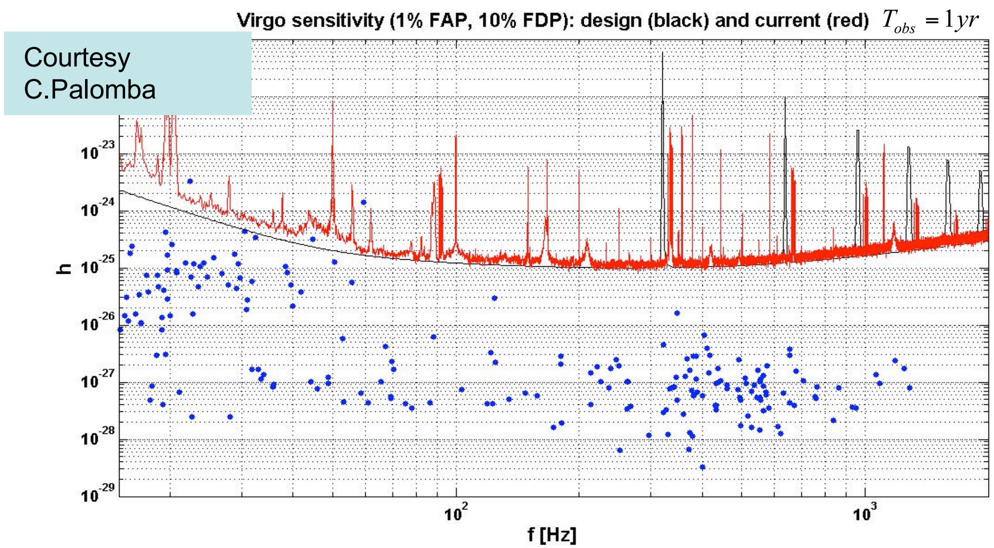




All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run, Phys. Rev. D 81, 102001 (2010)

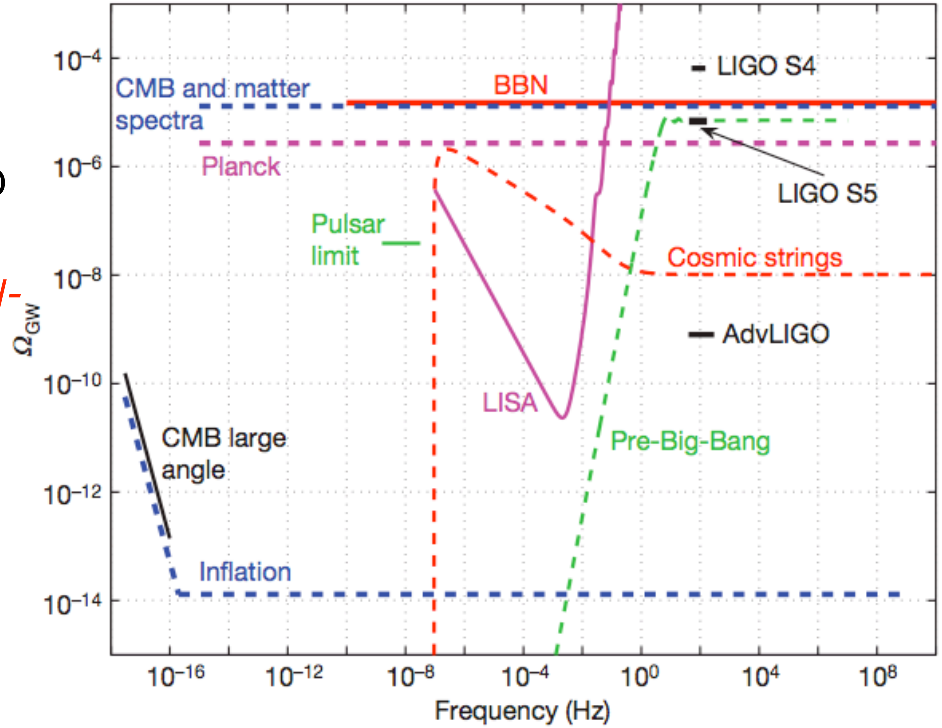
A sample of the LSC/Virgo results : pulsars

- Upper limits on GW energy release by pulsar, and on pulsar ellipticity
- 100 pulsars analyzed by LIGO
- Spin-down beaten for Crab (~60 Hz), using LIGO data
- Spin-down beaten for Vela (~20 Hz), using Virgo data, *Beating the spin-down limit on gravitational wave emission from the Vela pulsar* arXiv: arXiv:1104.2712v3
    - Ellipticity ~ 1e-3 (<35% of the energy is GW)
    - Ellipticity still far above the values allowed by standard equation of state but compatible with some exotic modes
    - Next run (VSR4, summer 2011) can decrease further this limit



A sample of the LSC/Virgo results: stochastic background

- Correlation between detectors
- Upper limit below BBN using Data from LIGO S5 (pre-VSR1)
- *An upper limit on the stochastic gravitational-wave background of cosmological origin,* Nature 460 (2009) 990
- Current analysis: Virgo increases the sensitivity at high frequency (900 Hz)



Multi-messenger observations

Motivations:

- GW comes from very energetic astrophysical processes, likely sources of EM radiation or high-energy particles
- correlate in time & direction observation by GW and other messengeres

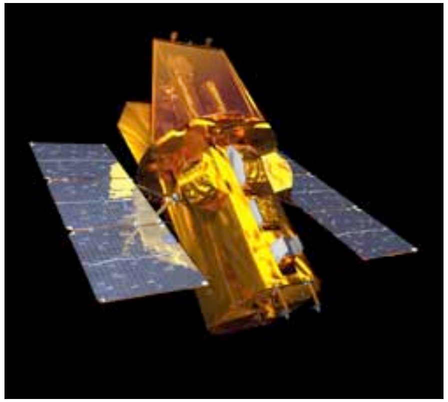
Benefits:

- Increase confidence in the astrophysical origin of the GW event
- lower threshold, increase observational horizon
- More information (host galaxy, distance) leads to more stringent constraints on source model

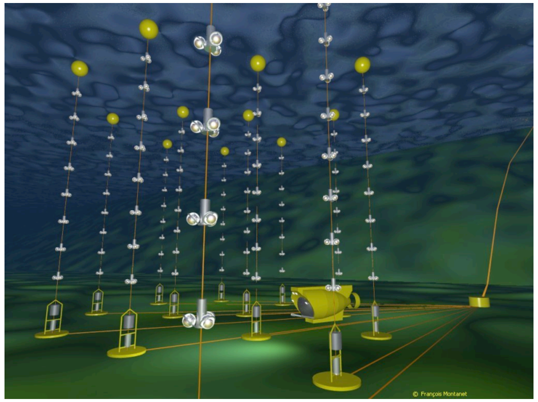
Two approaches:

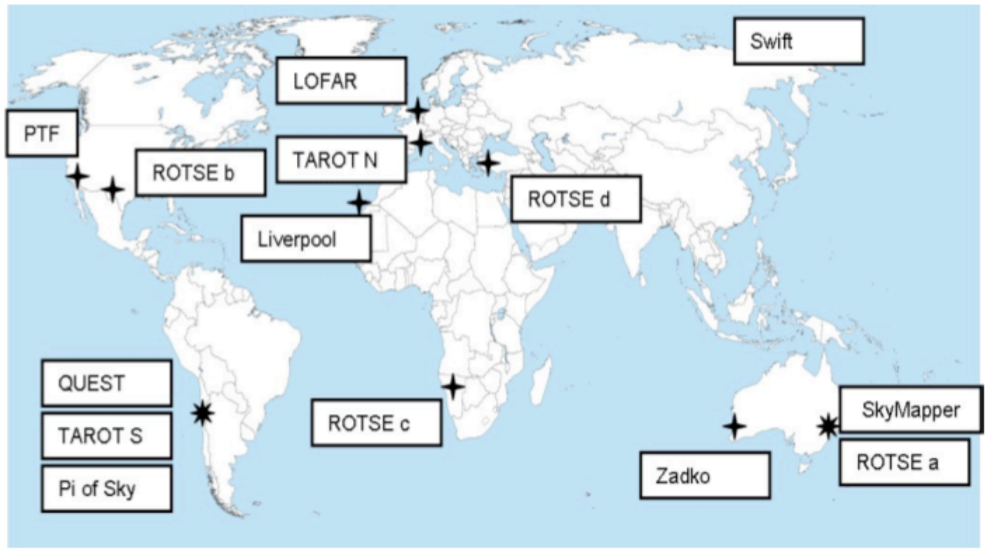
- *Other telescopes* → *GW (e.g. GRB alerts)*
- *GW* → *other telescopes (e.g. robotic telescopes)*
  - Low latency searches during VSR3 (summer 2010)

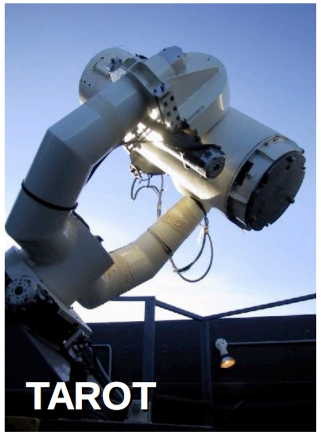
Multi-messenger projects



- Electromagnetic follow-up
  - SWIFT (gamma, X), LOFAR (radio)
  - Wide field optical telescope
    - ROTSE, TAROT, SkyMapper, Pi of the Sky, PTF
  - Narrow-field telescopes
    - Liverpool telescope, Zadko
- High-energy neutrinos
  - Exchange of triggers with Antares and IceCube

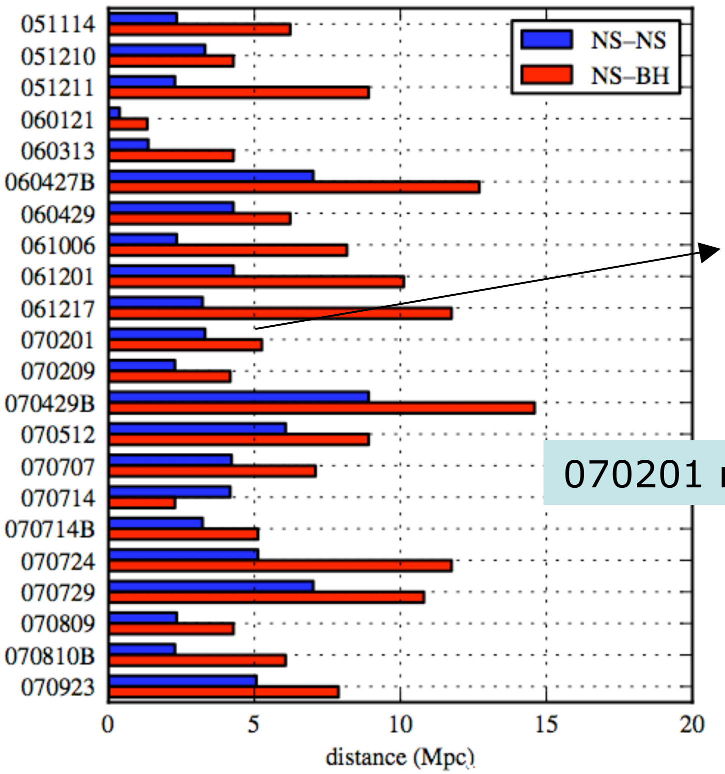


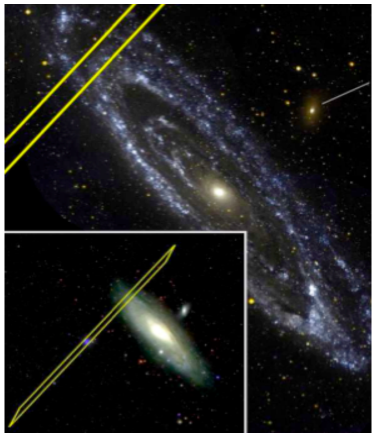




Multi-messenger searches: GRBs

- GRB very energetic phenomena, likely emit GW
- Progenitor scenarios for short gamma-ray bursts (short GRBs) include NS-NS or NS-BH coalescence
- Search data around times of GRBs observed by γ-Xray satellite based instruments
- During S5/VSR1 hundreds GRB studied
- NO GW detection, derive upper limits on the distance

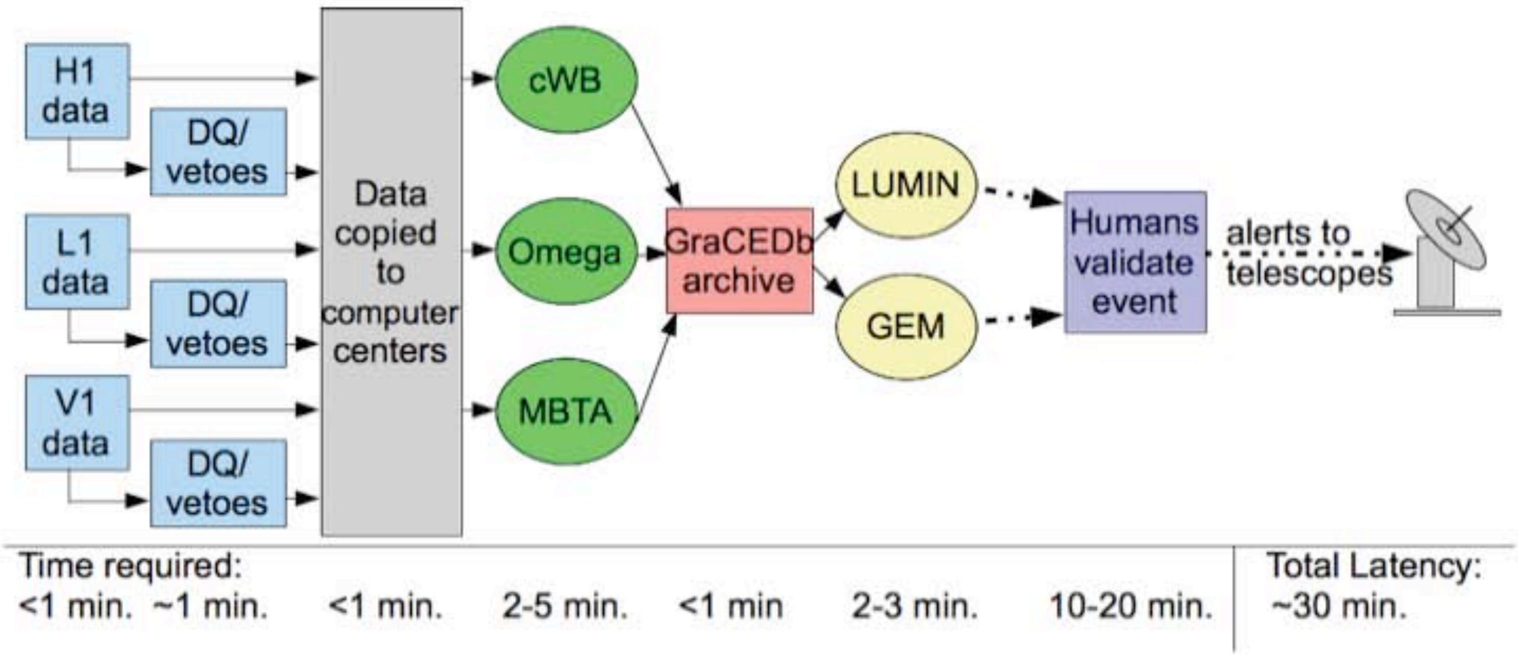




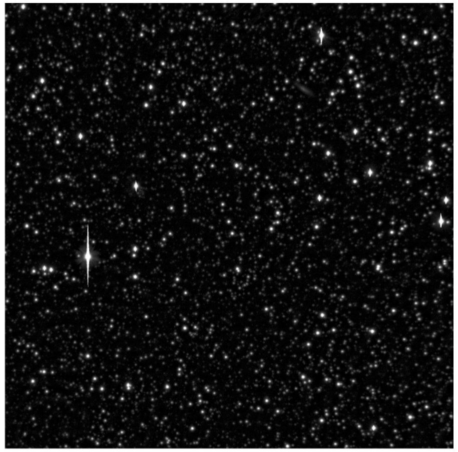
070201 not a merger in M31

- *Search for gravitational-wave inspiral signals associated with short Gamma-Ray Bursts during LIGO fifth and Virgo first science run* , Astrophys. J. 715, 1453 (2010)
- Search for gravitational-wave inspiral signals associated with short Gamma-Ray Bursts during LIGO fifth and Virgo first science run, Astrophys. J. 715, 1438 (2010)

Low latency searches during VSR3



- 6 candidate GW triggers communicated
- 4 observed by telescopes
- Several hundreds of images collected



Zadko test image

Summary/1

- Virgo
  - Commissioning of the first kilometric detector Sept 2003- May 2007
  - 2007 first data taking: Inspiral range 4 Mpc, Duty cycles ~80%
- Upgrade to Virgo+
  - Several hardware upgrades (diffused light, laser power, compensation of thermal effects,...)
  - Sensitivity increase in the first phase of Virgo+ VSR2 = 8-9 Mpc
  - **Design sensitivity level - noise understood - technologies behind the first generation demonstrated**
  - Monolithic suspensions installed (key technology for Advanced Virgo)- no robustness or control problems observed
  - Problem with mirrors radii of curvature now understood. Good experience for Advanced Virgo
  - Now detector optically good and stable. Not yet improvements in sensitivity with respect to Virgo, but still a few months of commissioning

Summary/2

- International context
  - MoU with LSC - full data exchange and common publication policy
  - Virgo/LSC comparable sensitivity (LIGO better in the 100 Hz region, Virgo better at low frequency)
  - Virgo very important in the network: confidence in detection, localization of the source in the sky
- Astrophysical searches
  - Data analysis pipelines - methods - data quality - ready for a detection
  - **Upper limits for various GW sources published**
  - Multi-messenger astronomy started - low latency telescope pointing - exchange of triggers with neutrino observatory

- Leading role of IN2P3 groups in all the activities (construction, commissioning, astrophysical searches), several responsibilities at different levels

The *big-dog* story

- 16/09/2010 (VSR3/S6): Significant trigger detected by on-line burst analyss
  - Observation by optical and X telescopes
- Evolution in the time-frequency plot typical of a chirp
- Search of coalescence signal: Double coincidence (H1,L1), false alarm rate 1/7000 year
- Paper written for PRL, but...
- It was an **hardware blind injection** (envelope opened last march)