Gravitational Wave Detectors on the Earth

Piero Rapagnani

Plan of the Talk

The Global Network up to **Now**

- **Some History: The Resonant Bars**
- **The interferometric detectors:**
    - **TAMA**
    - **GEO**
    - **LIGO**
    - **Virgo**
- **The Enhanced Detectors**

The Near Future:

The **Advanced Detectors**

- Advanced LIGO
- GEO-HF
- Advanced Virgo

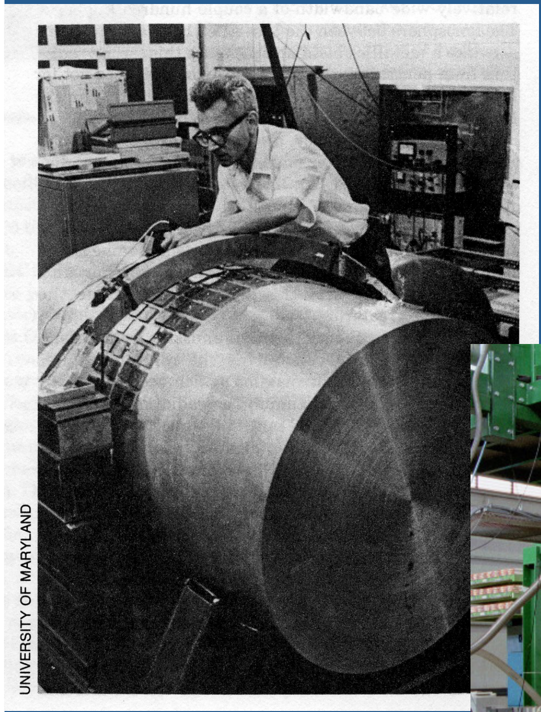
The new proposals:

- LCGT
- AIGO

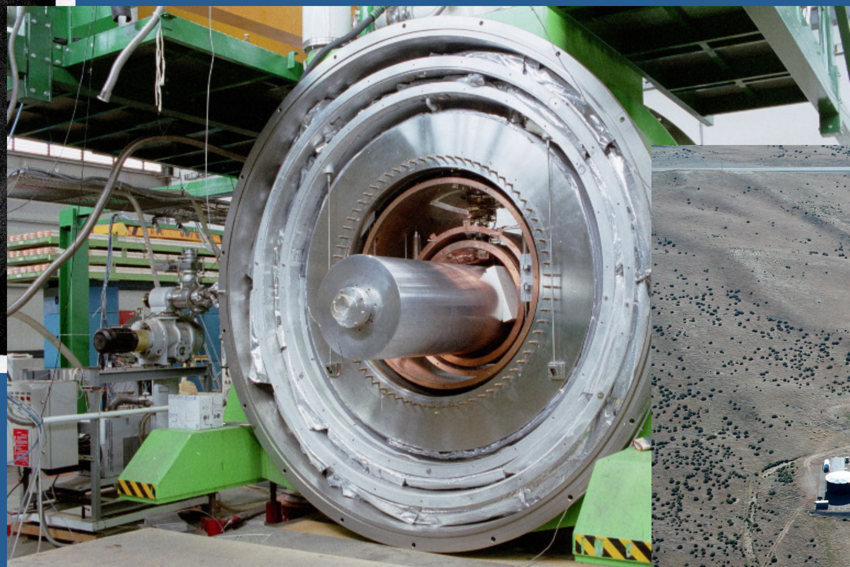
Conclusions

Some perspective: 40 years of attempts at detection:

Since the pioneering work of Joseph Weber in the '70, the search for Gravitational Waves has never stopped, with an increasing effort of manpower and ingenuity:



'70: Joe Weber pioneering work

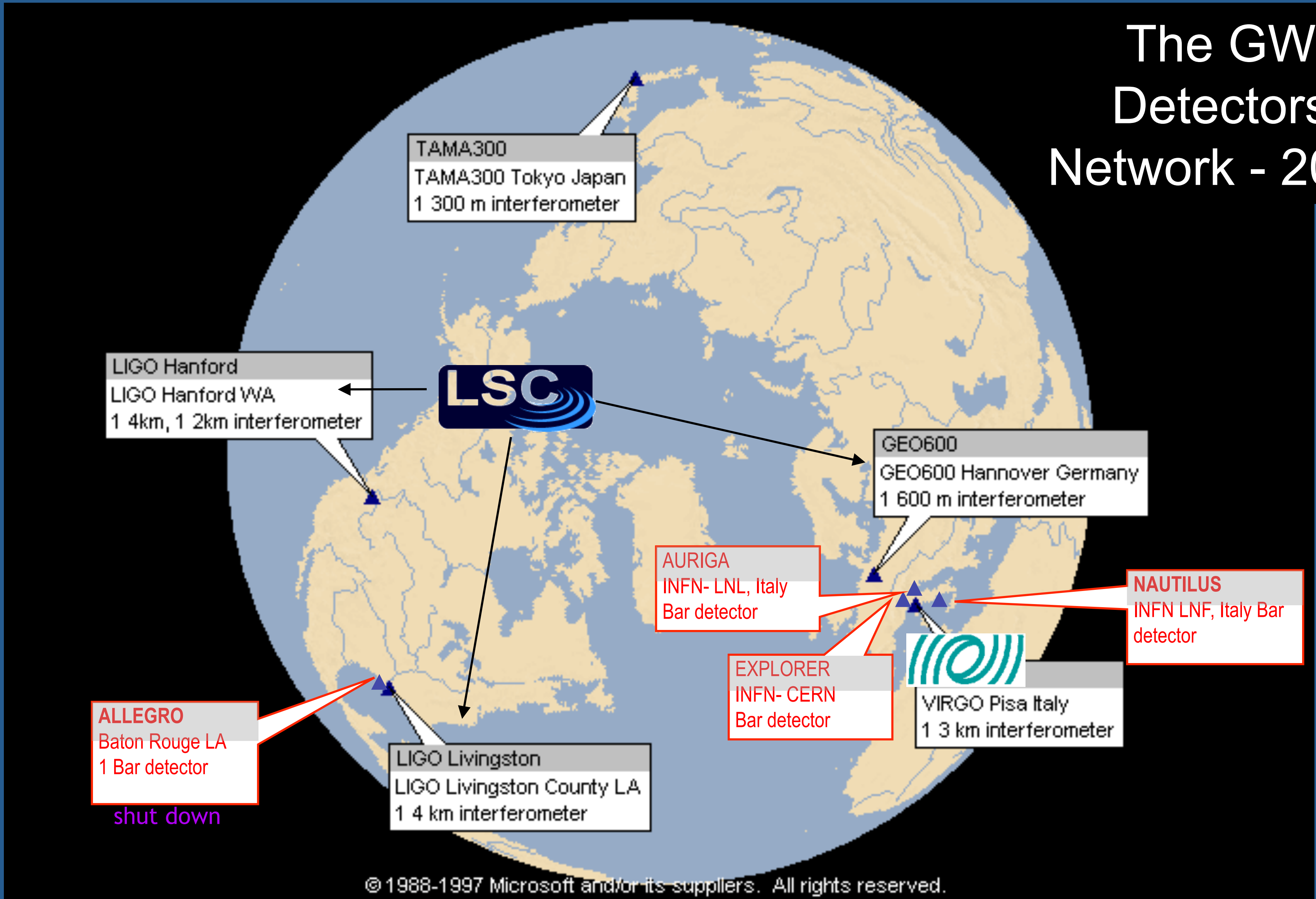


'80-'90: Cryogenic and Ultracryogenic Resonant Bars

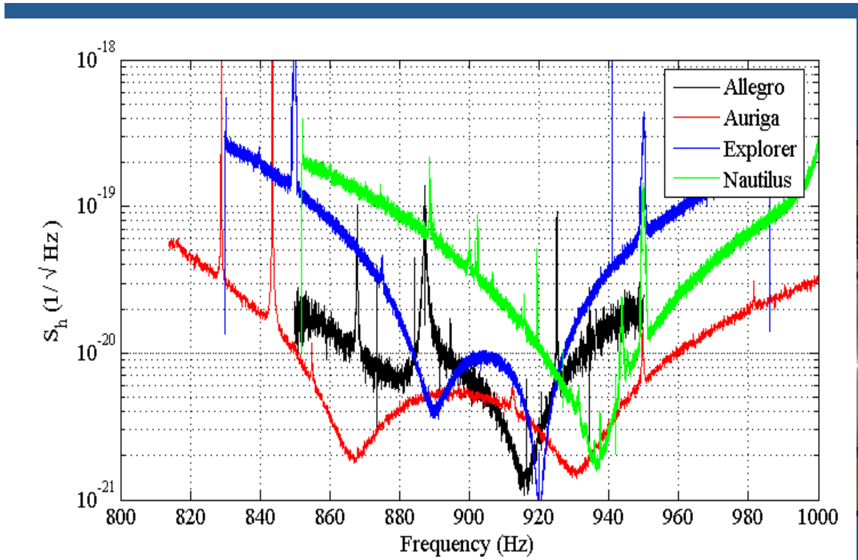
'90-Now: Large Interferometric Detectors

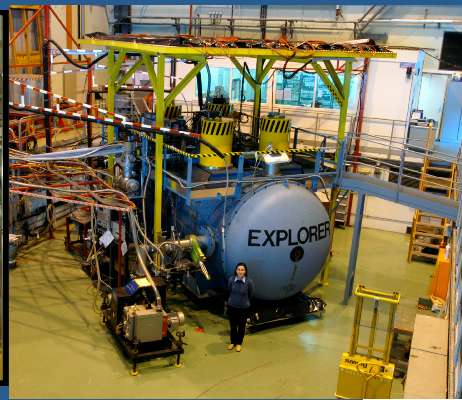
Over the years, techniques and sensitivities varied greatly, but since the start it has been clear that to detect gravitational waves we need a **NETWORK**

The GW Detectors Network - 2010



RESONANT DETECTORS





IGEC2

AURIGA

ROG ricerca onde gravitazionali gravitational wave research

AURIGA, **EXPLORER** and **NAUTILUS** in continuous operation:
⇒ **continuous search for strong galactic sources with specific attention to the periods not covered by long arm interferometers.**

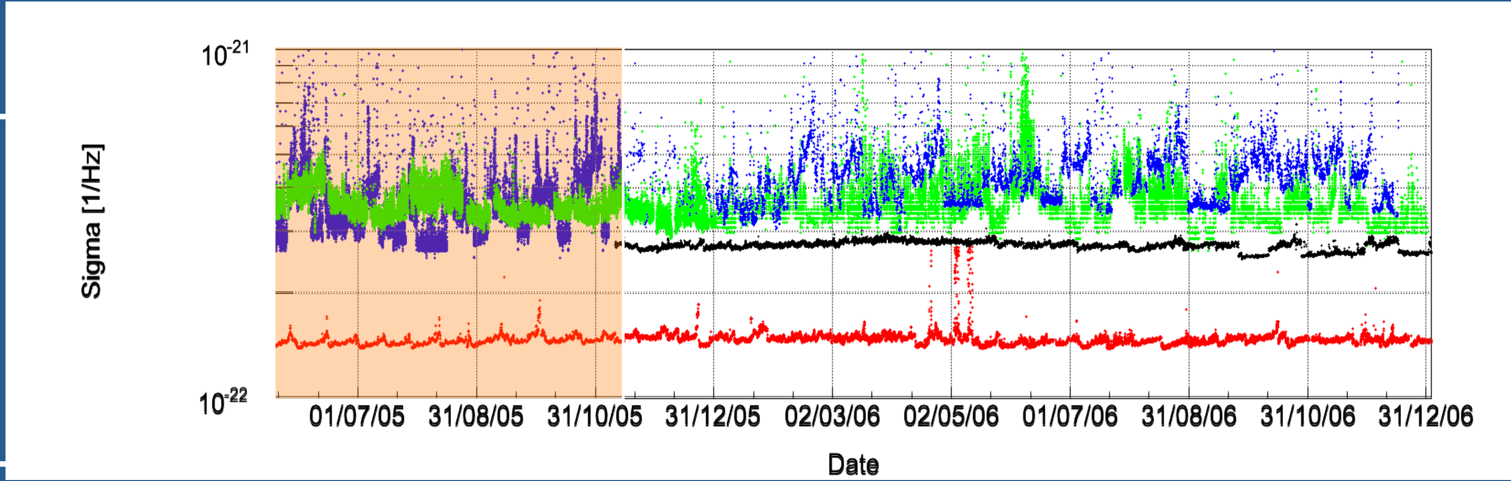
IGEC2 search for burst signals includes ALLEGRO up to march 2007:
- analysis of November 2005 – December 2006 at final tuning stage (1 false alarm/century)

fourfold coincidence 244 days (59%)
threefold coincidence 388 days (94 %)

- previous search on May-November 2005 published:
Phys.Rev.D**76** (2007) 102001 *gr-qc 0705.0688*

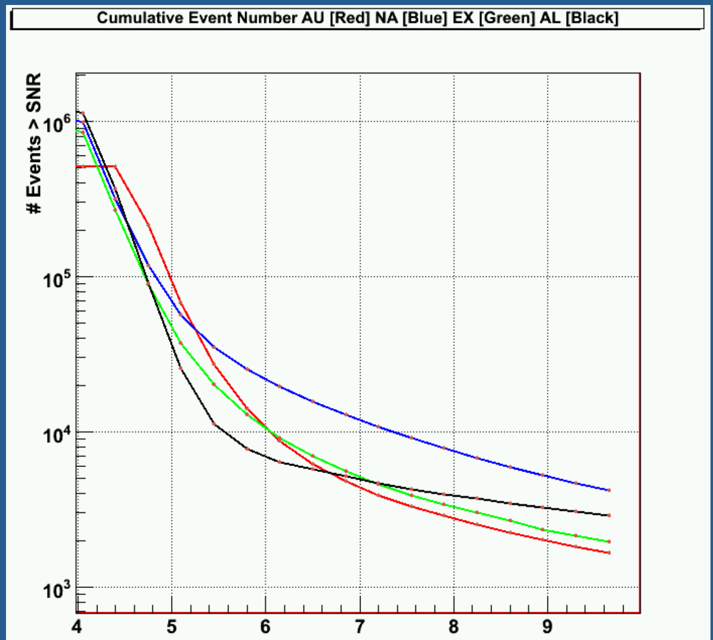
Stable performances in the long run

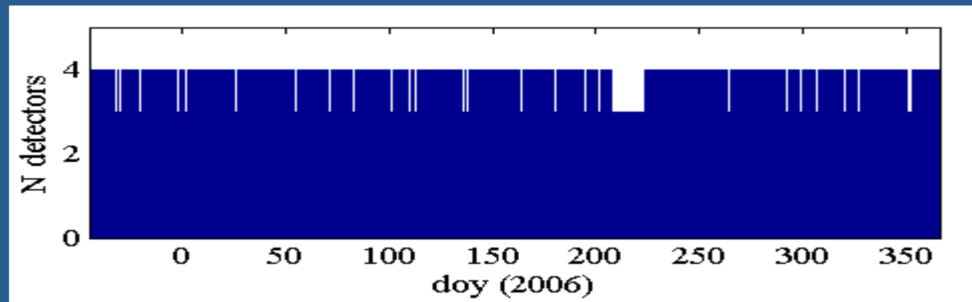
- no detector 0 days
- Single 0.98 days
- Double 21.94 days
- **Triple 144.10 days**
- **Quadruple 243.97 days**



Cumulative Event Number vs SNR

AURIGA-NAUTILUS-EXPLORER-ALLEGRO





Very low fraction of outliers SNR>10

Duty Time

	AL	AU	EX	NA
AL	**403.3**			
AU	383.2	**390.9**		
EX	319.8	309.8	**326.7**	
NA	326.1	317.5	261.7	**332.2**

98% **95%** **79 %** **81%**

The contribution of Resonant Bars has been essential in establishing the field and putting some important upper limits on the gravitational landscape around us, but now **the hope for detection is the in the Network of long arm interferometers.**

At the beginning of the '90's, the first groups to build long arm interferometric detectors were born.

TAMA, a 300 m arms interferometer at Mitaka, in Japan, started to operate in 1998.

In the same period of time, the GEO detector, a 600 m interferometer, was being built in Hannover, in Germany.

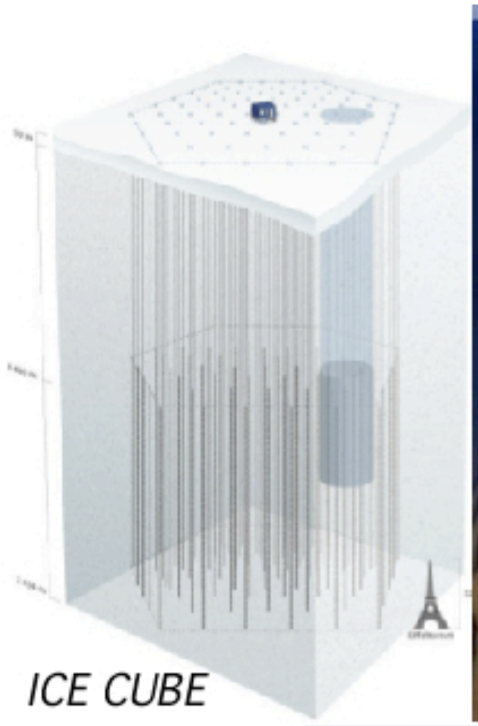
The experience gained with these machines has been useful for the development of km-size detectors: LIGO and Virgo

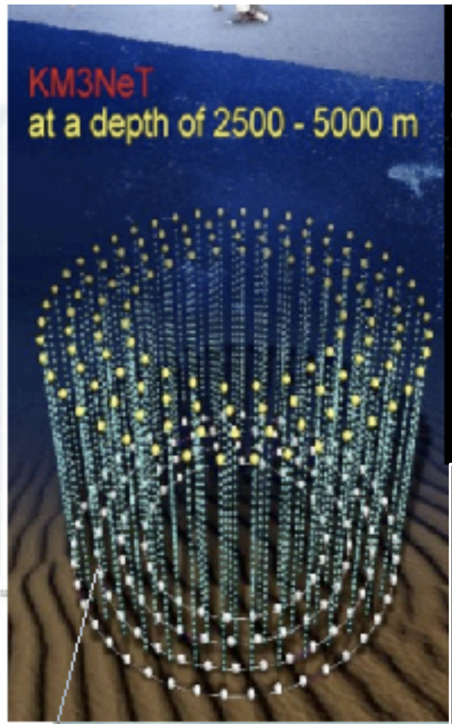

LIGO – Hanford:
One 4km arm interferometer
One 2km arm interferometer

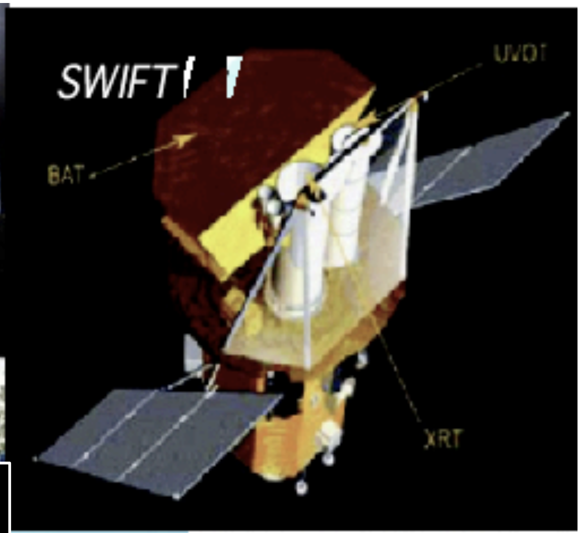

Virgo – Pisa:
One 3km arm interferometer


LIGO – Livingston:
One 4km arm interferometer

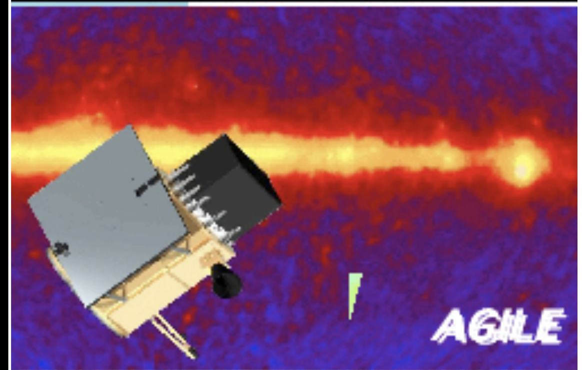
The Large Interferometer Network - 2010

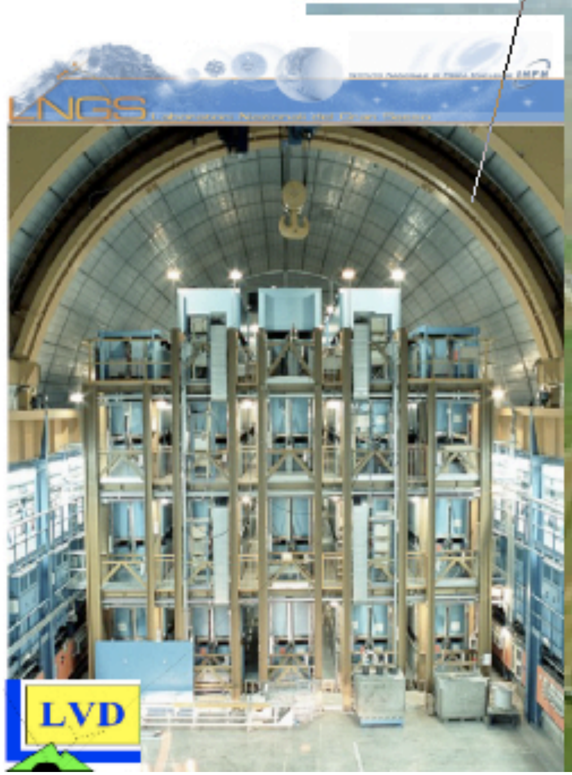


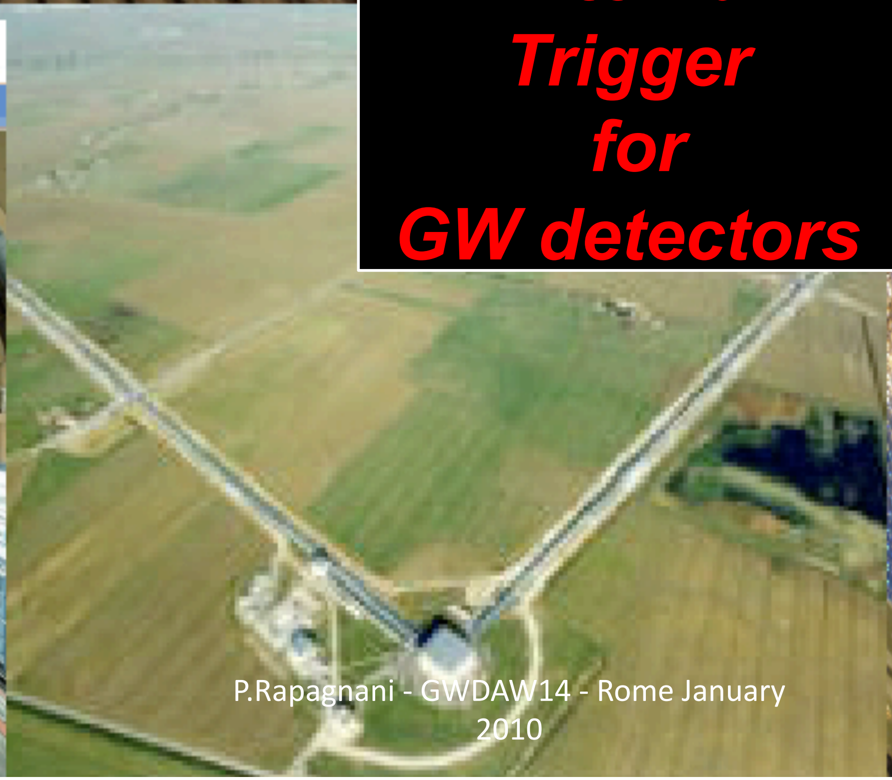




External Trigger for GW detectors







Interferometric Detectors Sensitivity Steps:

Initial configuration (2001-2008)

- Infrastructure established
- Design Sensitiviy Reached
- Data Analysis paradigms developed
- Many new upper limits, important non-detections

Enhanced Detectors: Now

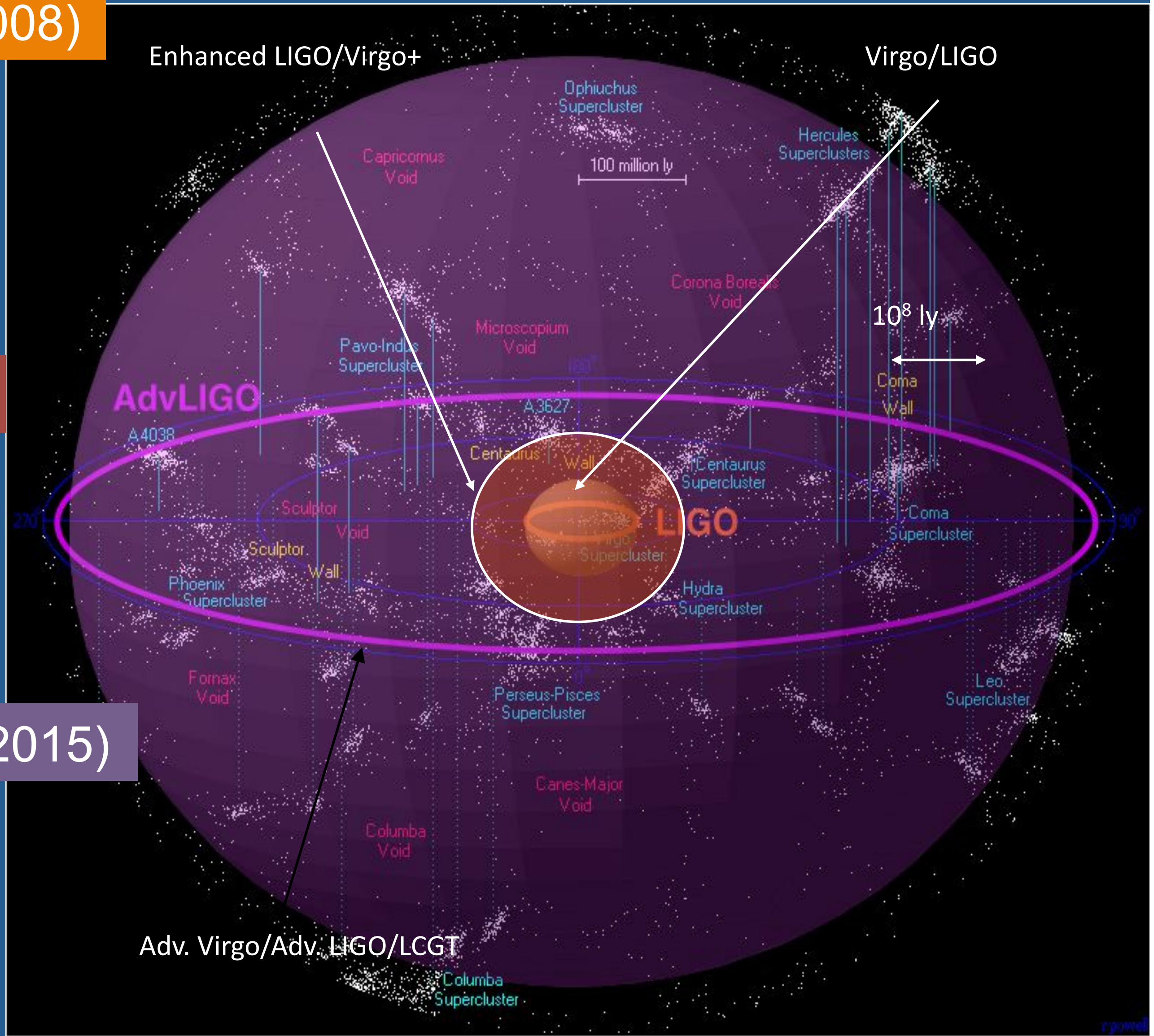
- Sensitivity improvement by a factor 2-3 using some of the Advanced Detectors technologies
- Detection still unlikely, but surprises possible.

Advanced Detectors (2011-2015)

A factor of ~10 improvement in linear strain sensitivity over the initial instruments (h of ~3×10^{-23} in a 100 Hz bw): brings ~10^3 more candidates into reach

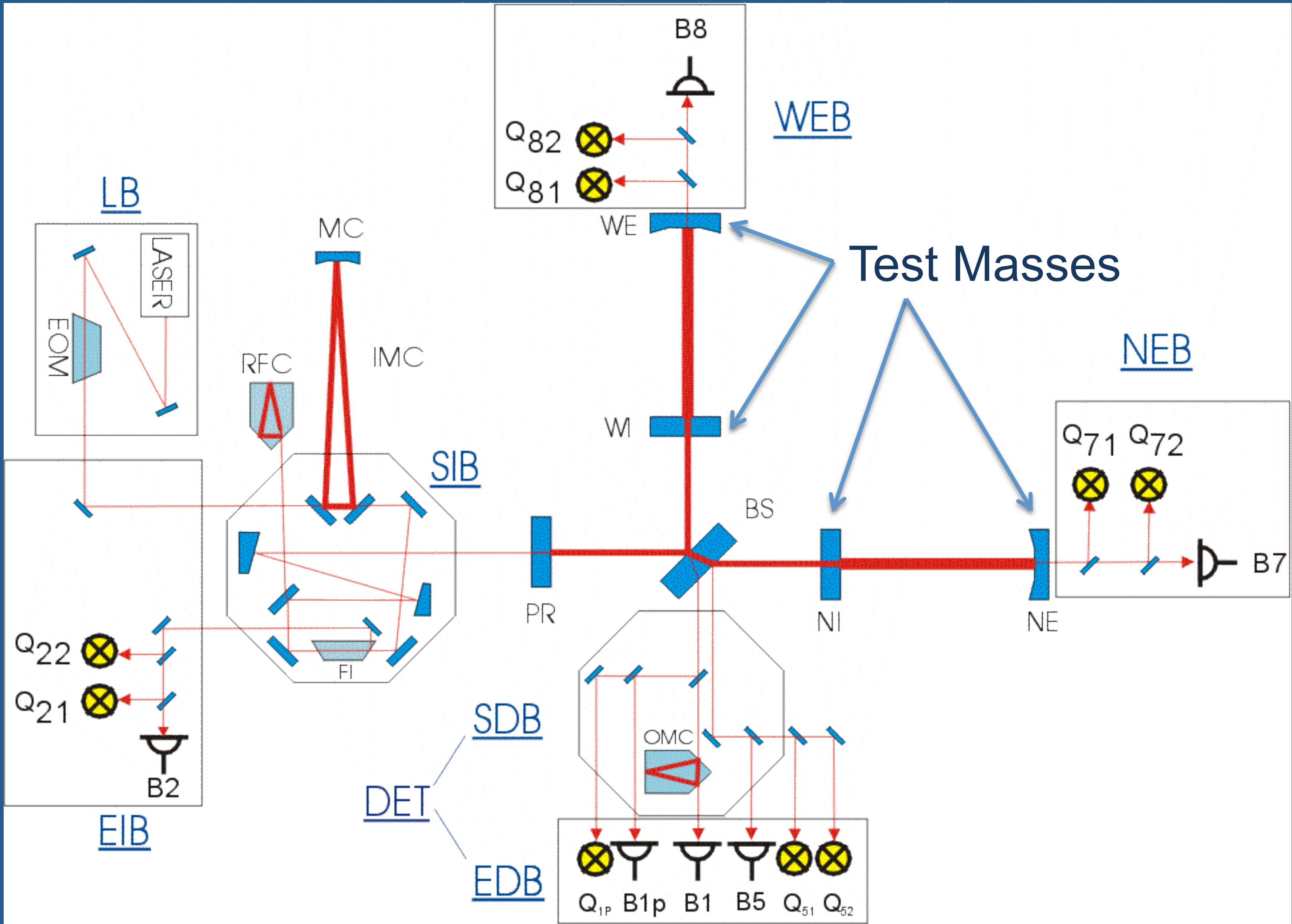
=> 10's–100's signals/ year

Improved Network allows to detect position and polarization of sources



Credit: R.Powell, B.Berger

Virgo simplified Optical Scheme



A Gravitational Interferometer Intrinsic Noise Summary

Strain Spectral Amplitude $(Hz)^{-1/2}$

Seismic

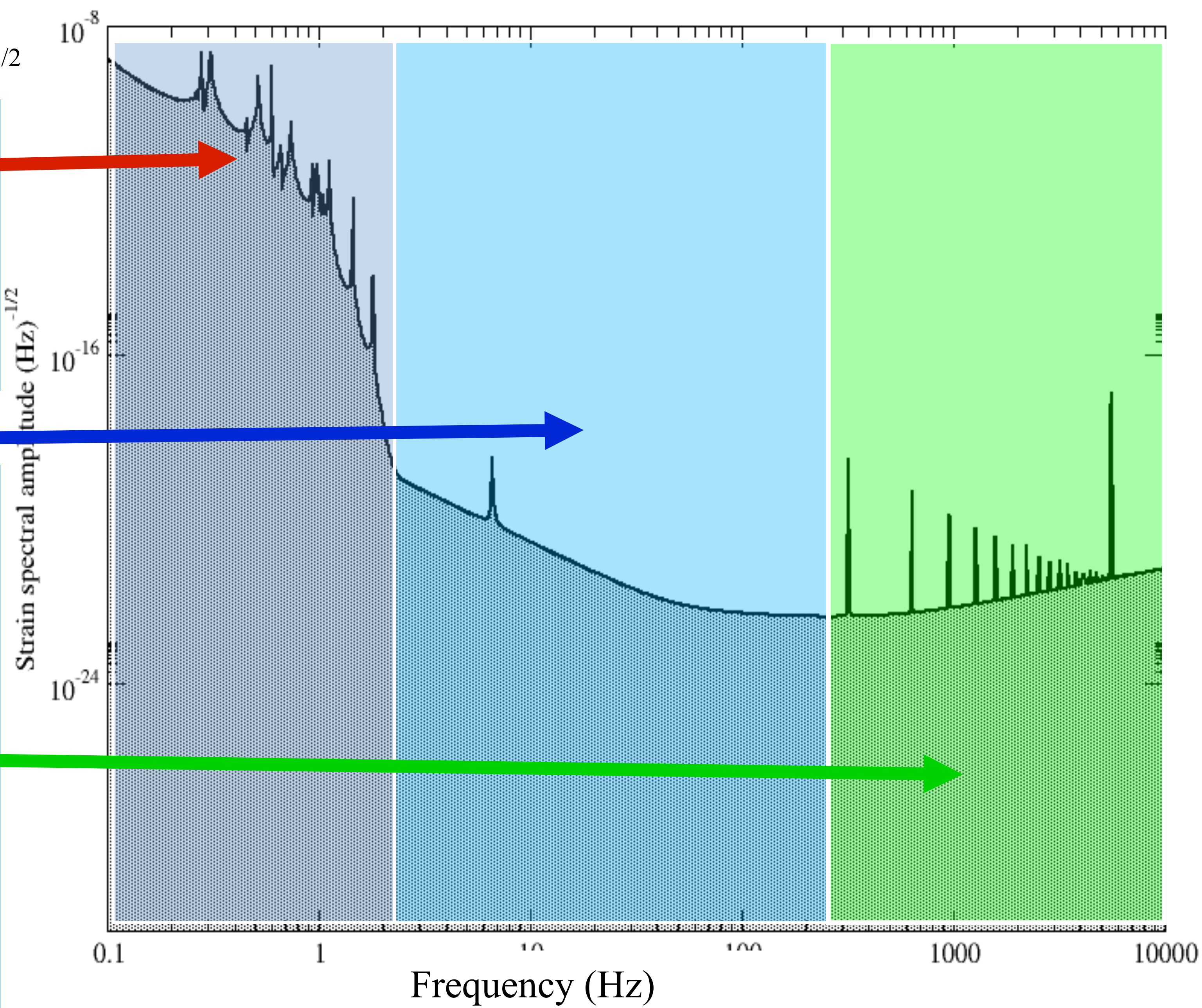
Passive and Active Attenuators

Thermal

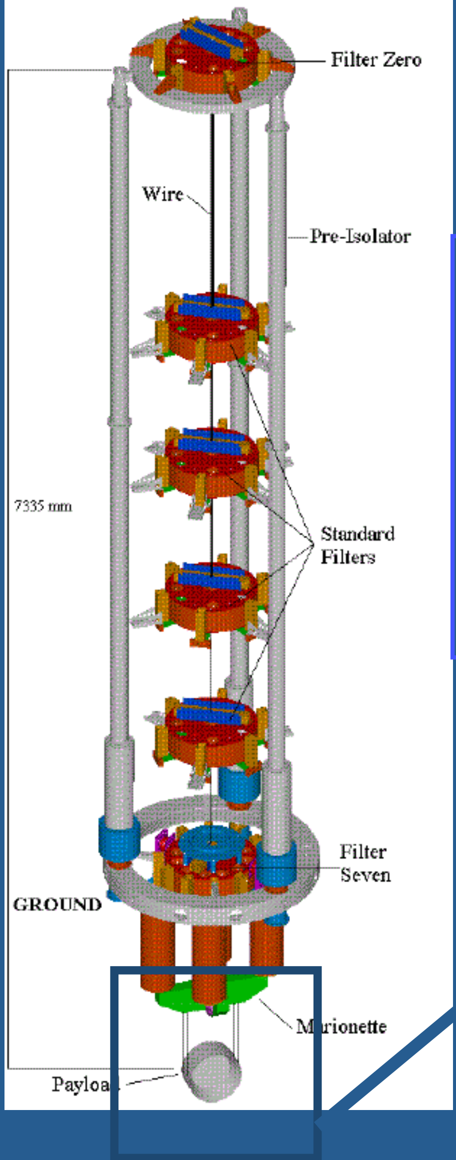
Low dissipation materials for mirrors and suspensions

Shot

High Laser Power, Signal Recycling Techniques



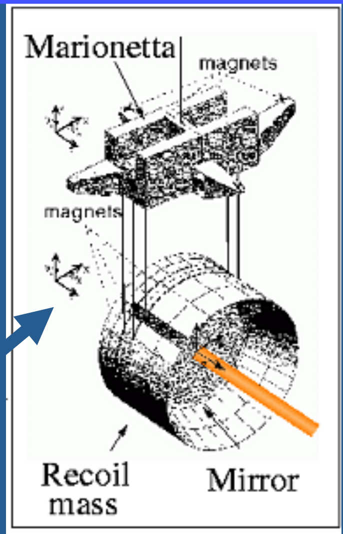
Seismic Noise

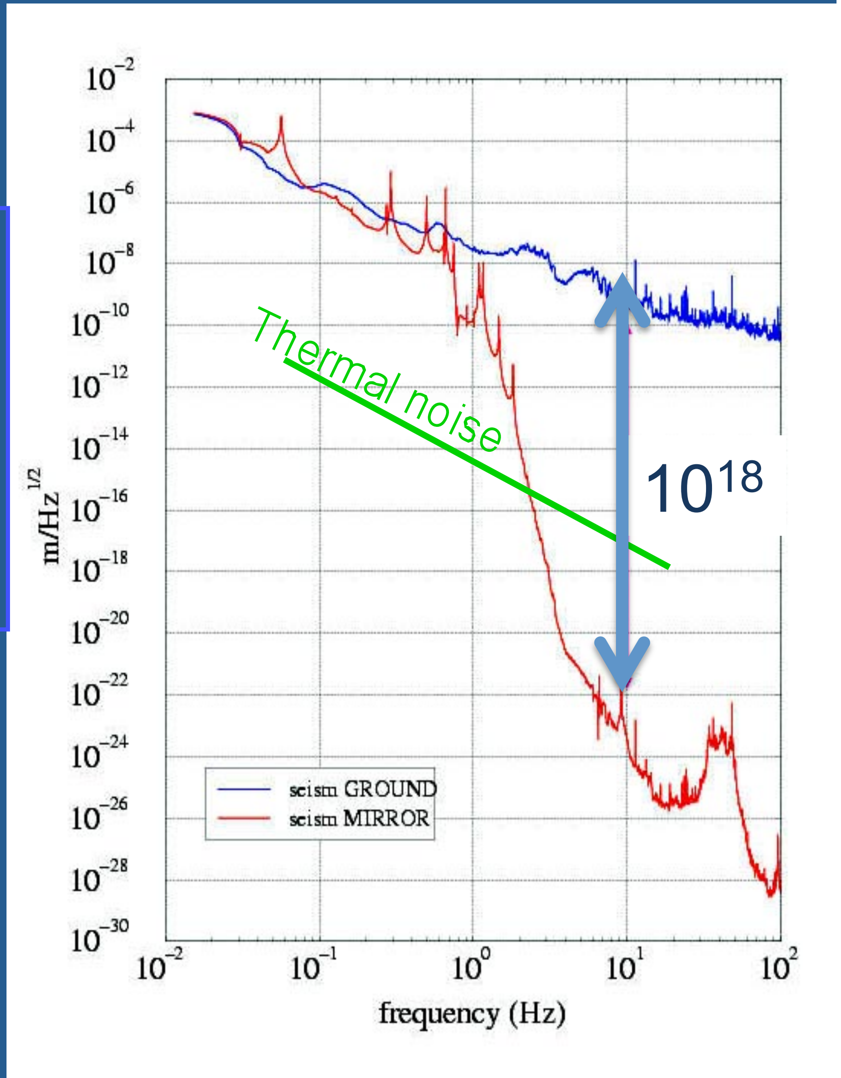


Virgo Superattenuator:

Soft isolator concept:

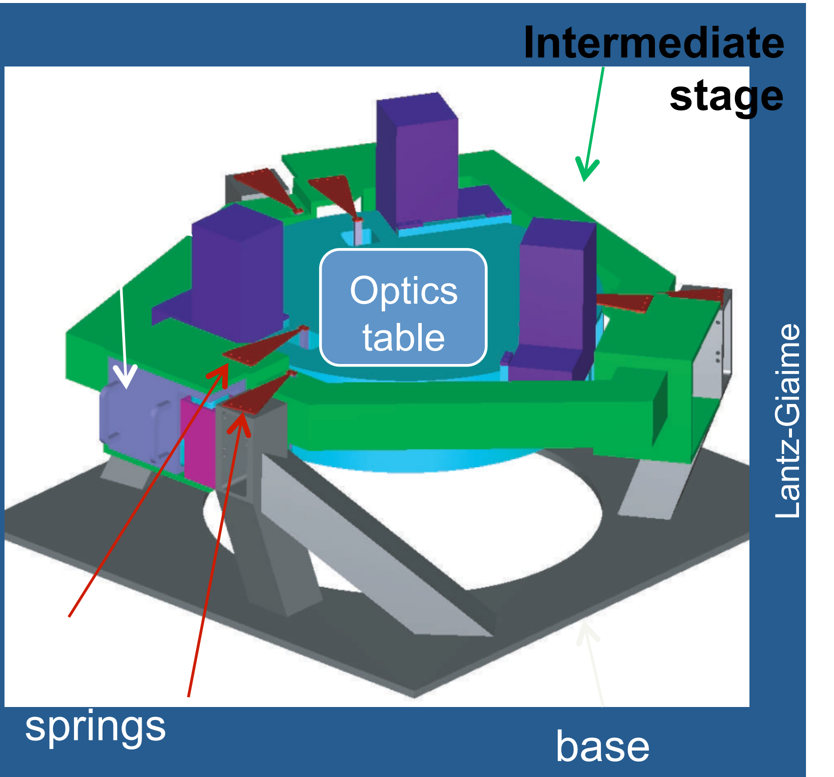
1. very efficient passive attenuation
2. active controls for normal mode damping

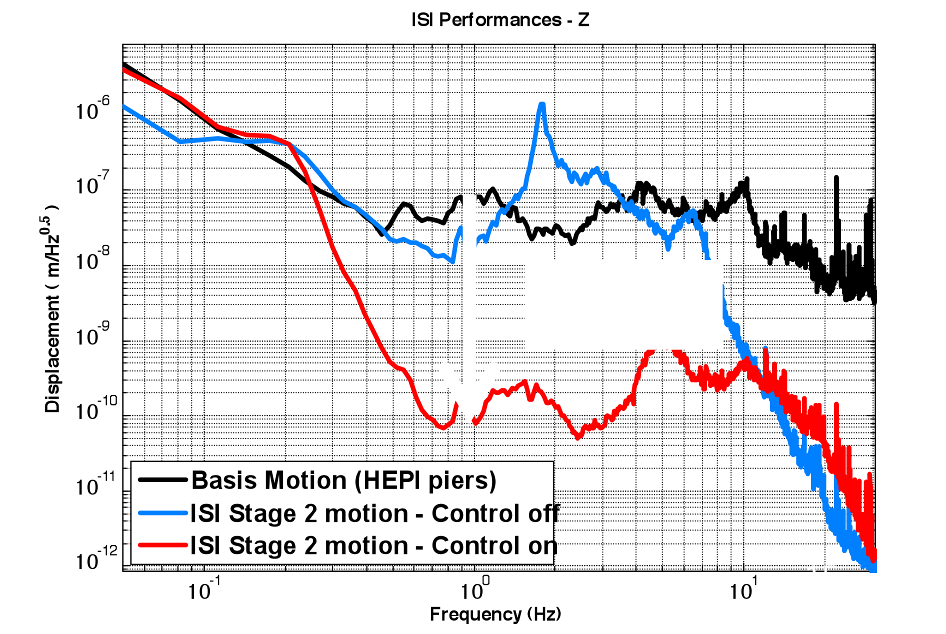




LIGO Active seismic isolation

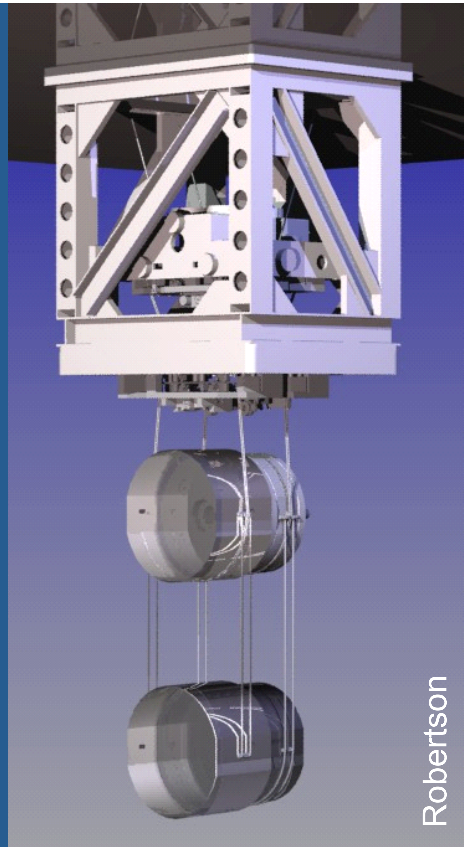
- One new approach is 'active' suppression, used in Advanced LIGO
  - Low-noise seismometers on payload detect motion in all six degrees-of-freedom
  - Actuators push on payload to eliminated perceived motion
  - Multiple 6-DOF stages to achieve desired suppression, allocation of control
- Challenges in structural resonances, sensor performance
- Nice to have a quiet table to mount lots of stuff on
- Enhanced LIGO using this approach for one chamber per interferometer
  - **Meets requirements, will remain in place for AdvLIGO**

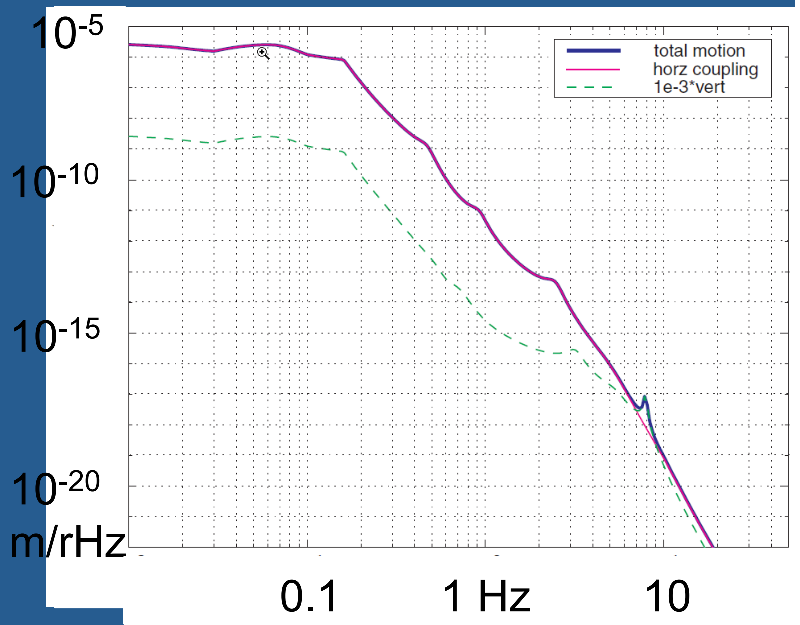




LIGO Test mass isolation and control

- Test mass suspension complements seismic isolation
- All instruments using several pendulums in series for improved isolation, staging of control forces and dynamic range
- Glasgow has championed multiple-stage pendulums, and UK Consortium has designed and is fabricating suspensions for Advanced LIGO
  - 4 stages; sensors and actuators as needed to manage forces and dynamic range
- Combined attenuation of seismic noise ~10 orders of magnitude at 10 Hz





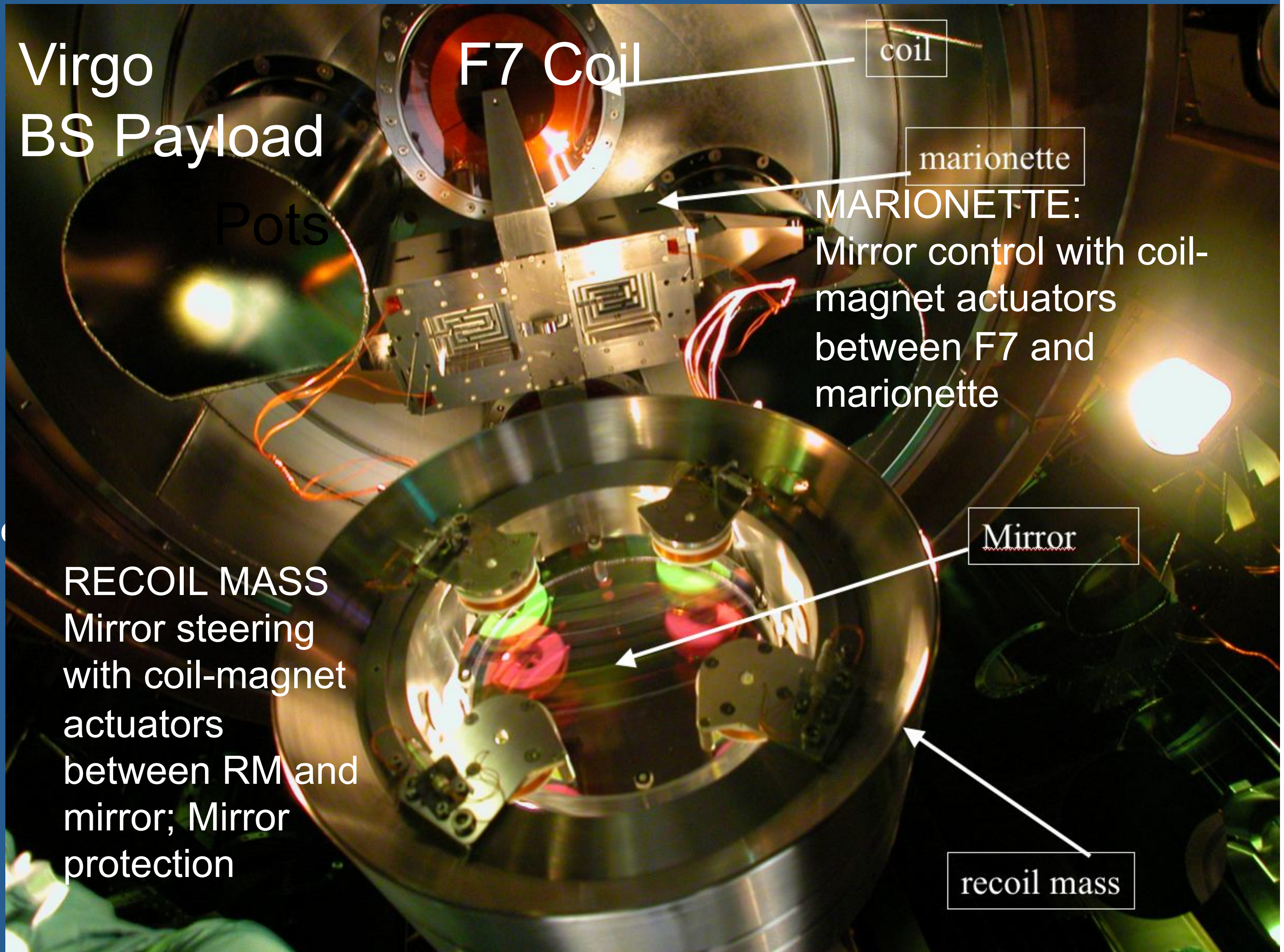
Virgo Test Mass isolation and control (Payload)

▪ *Compensates the residual seismic noise and to steer the optical components maintaining the relative position of the interferometer mirrors.*

Requirements:

Materials:
•UHV compatible;
•Amagnetic;
•No electrostatic charges;
•Internal Frequencies above Virgo bandwidth;
•Low frequencies of the system below Virgo bandwidth;

▪Compatibility with SuperAttenuator and lower part of the tower:
- ▪Weights
- ▪Shape

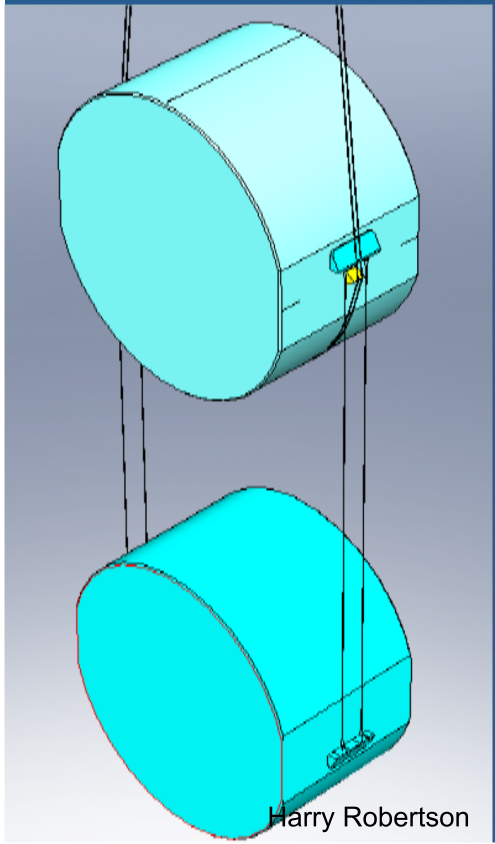


Suspension thermal noise

½ kT of energy in each mode, expressed according to the Fluctuation-Dissipation theorem

- gather noise power into a narrow band around suspension resonances, via…

Use of very high quality factor (low loss) materials



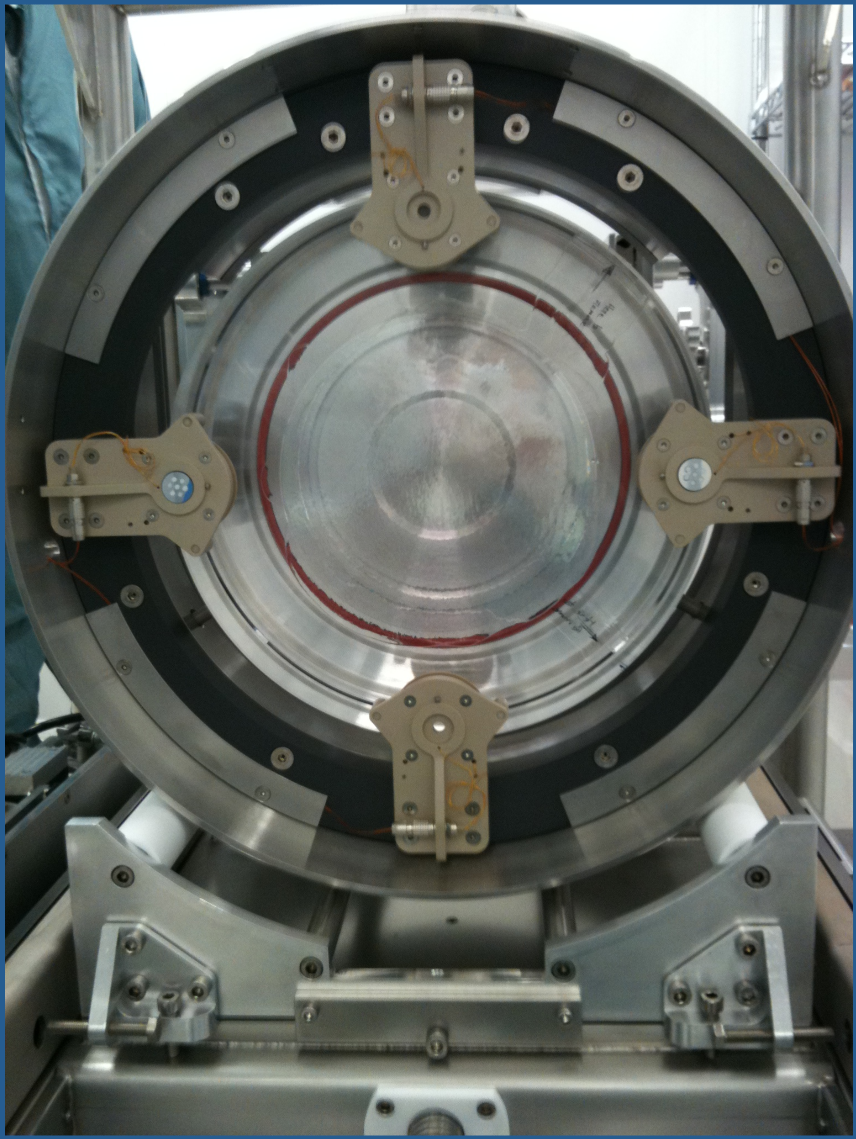
Fused Silica suspension fibers, as pioneered by GEO (Glasgow) in the GEO600 instrument

Advanced LIGO: as the final stage of suspensions delivered by the UK consortium

In Advanced Virgo, using somewhat different connection approaches, same principle

In Virgo+ -- as early as January 2010

January 22nd 2009: The first Virgo Monolithic Payload being assembled in EGO Clean Room



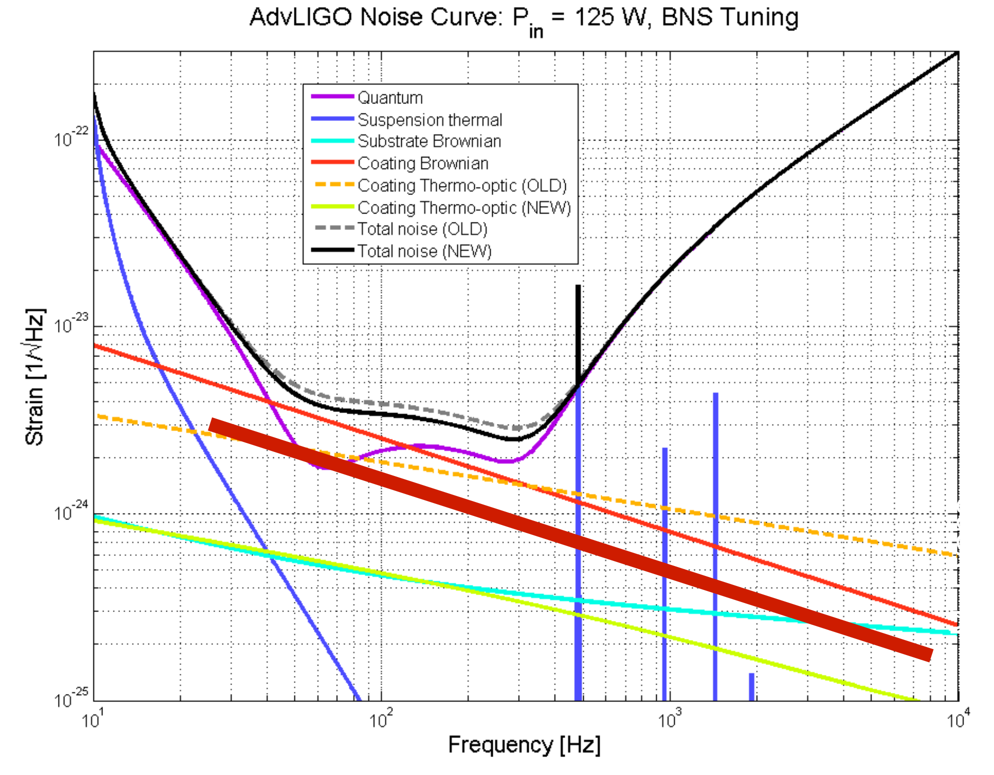
Test Mass and Coating thermal noise

- Again, thermal energy of mechanical modes of the optic substrate which serves as the test mass cause motions of surface
- Most instruments using fused silica as the substrate material as for initial instruments
  - Virgo+, AdvVirgo, eLIGO, AdvLIGO, GEO600
  - Loss values of ~10^{-8} …

  Substrate thermal noise not a problem

- **Mirror coatings: loss values of ~10^{-4}**
- **THE dominant mid-range noise**
- Meets 10x improvement, barely

Continuing work needed



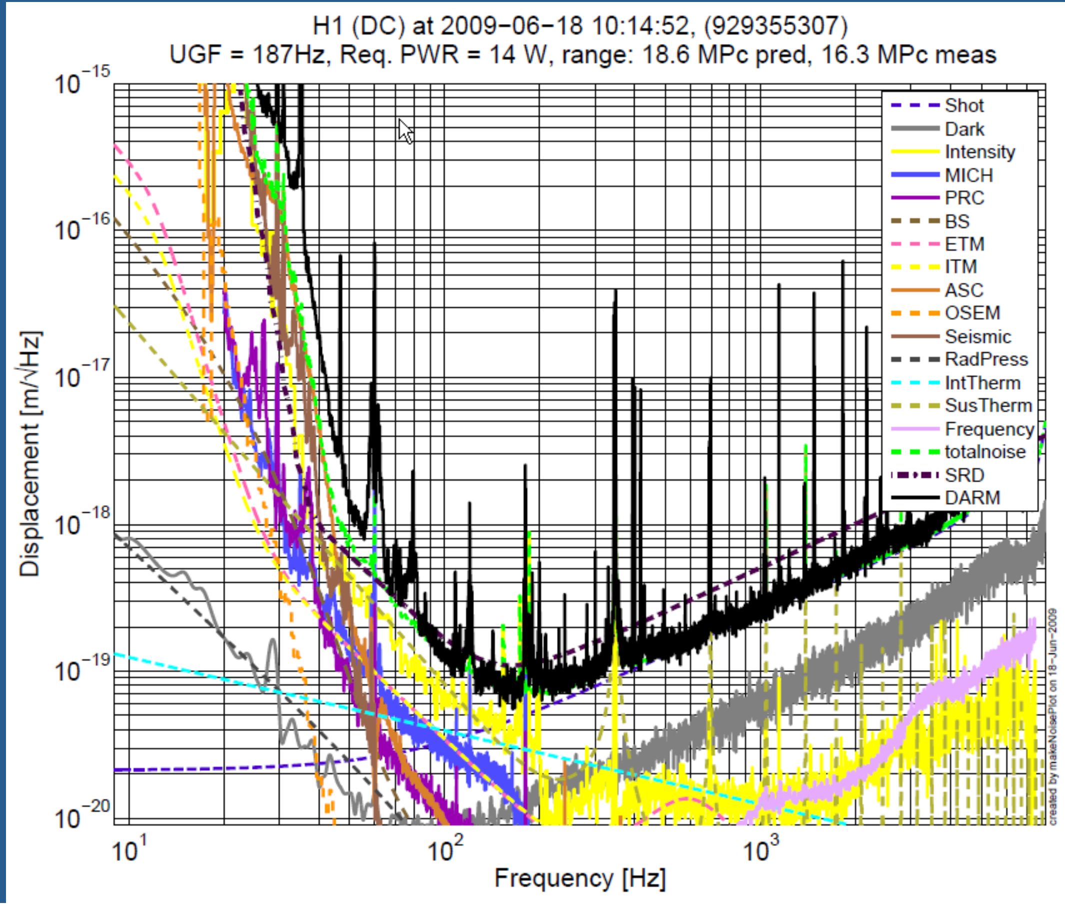
Shot Noise: Laser light sources

- **Initial power**: 8 – 10 W
- **Intermediate step**: **eLIGO –> 35W front end laser** **Virgo+ -> 17 W laser**
- Advanced Detectors:

GEO-HF, **Adv LIGO** - 150-200W Nd-Yag lasers

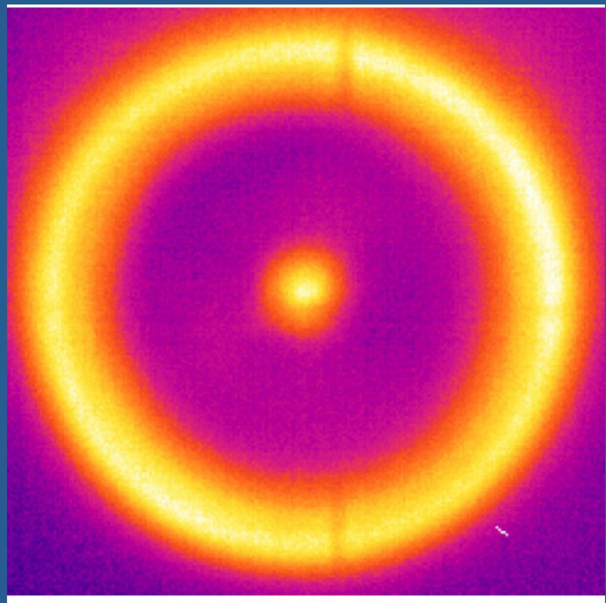
- – Max Planck Hannover-developed solution for the laser for several projects
- – modulators, isolators, thermal compensation schemes are advanced for a factor ten

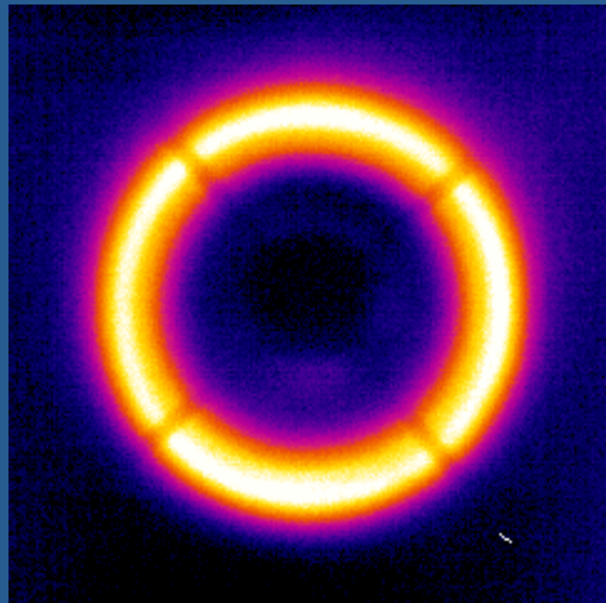
Adv Virgo – keeping option of a fiber laser open



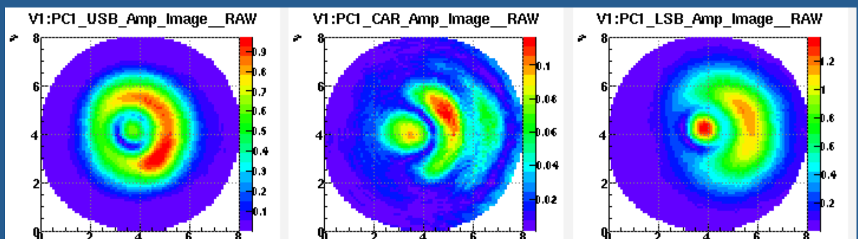
Shot Noise: Laser light sources

Increasing the input laser power, it is Essential for compensating thermal lensing in input mirrors

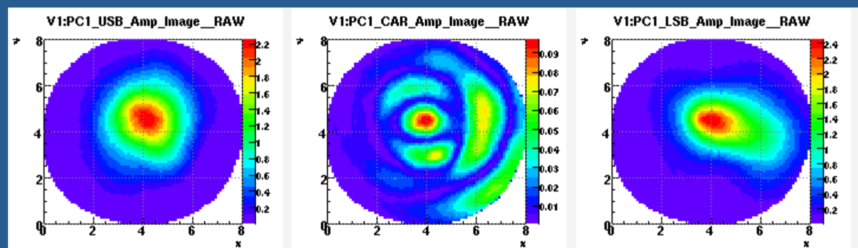




Annulus and central spot from CO2 laser on both input mirrors in Virgo+ with 17 W

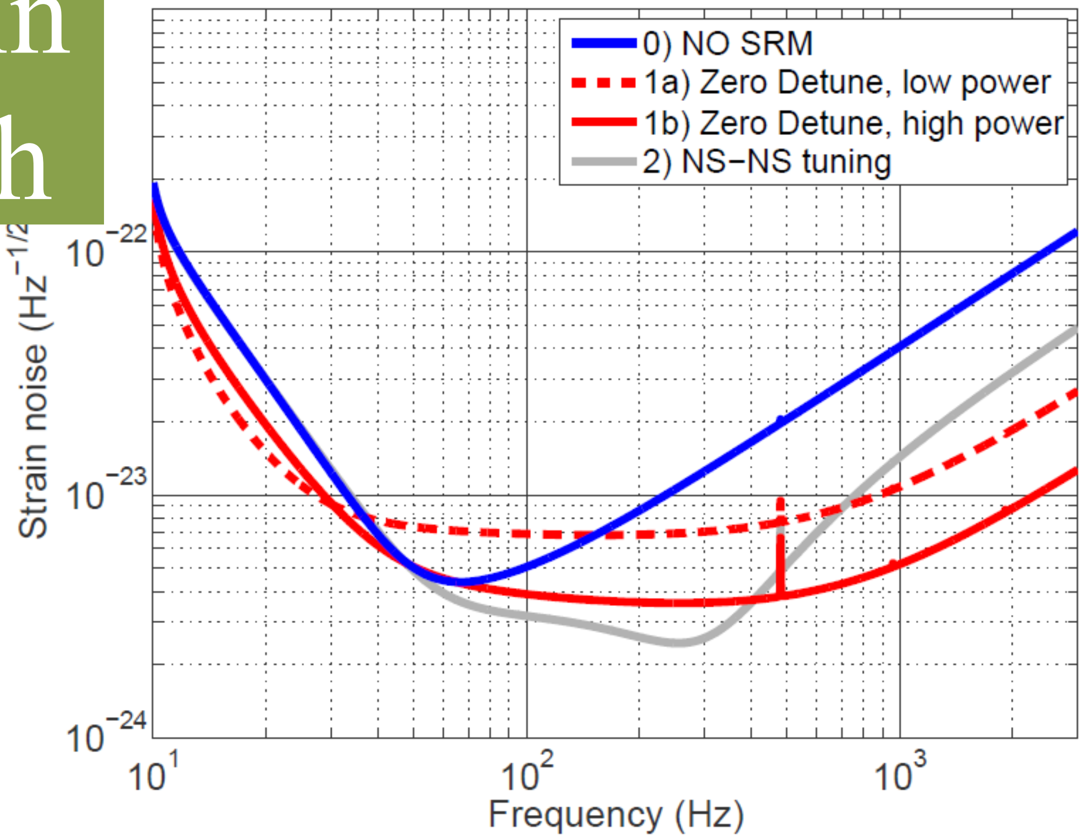


without TCS



with TCS

Shot Noise: Strain sensing approach

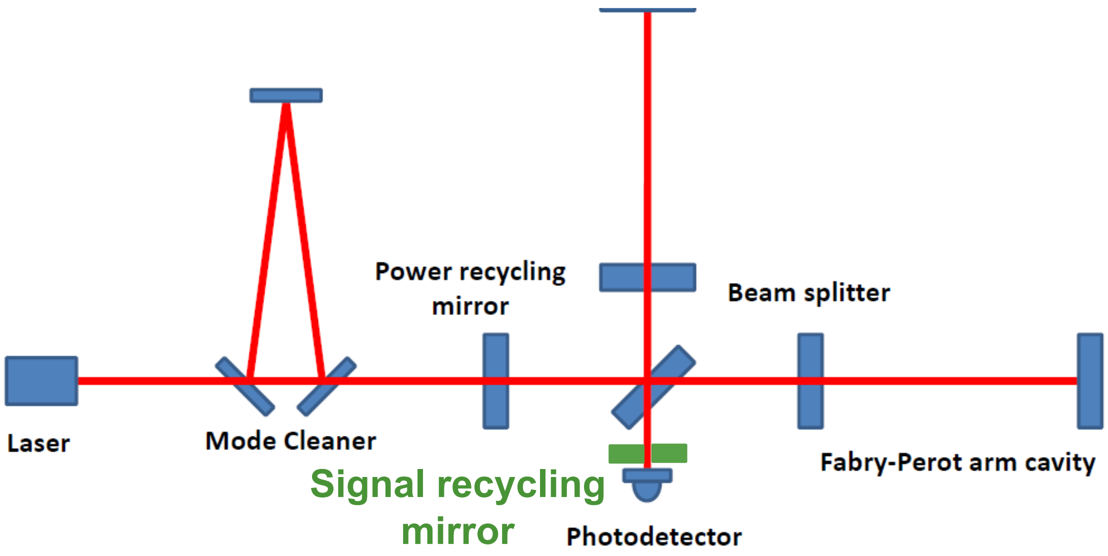


Adv Virgo, AdvLIGO, signal recycling,
Pioneered in GEO600

Allows some tuning, used to balance technical limitations and astrophysical signatures

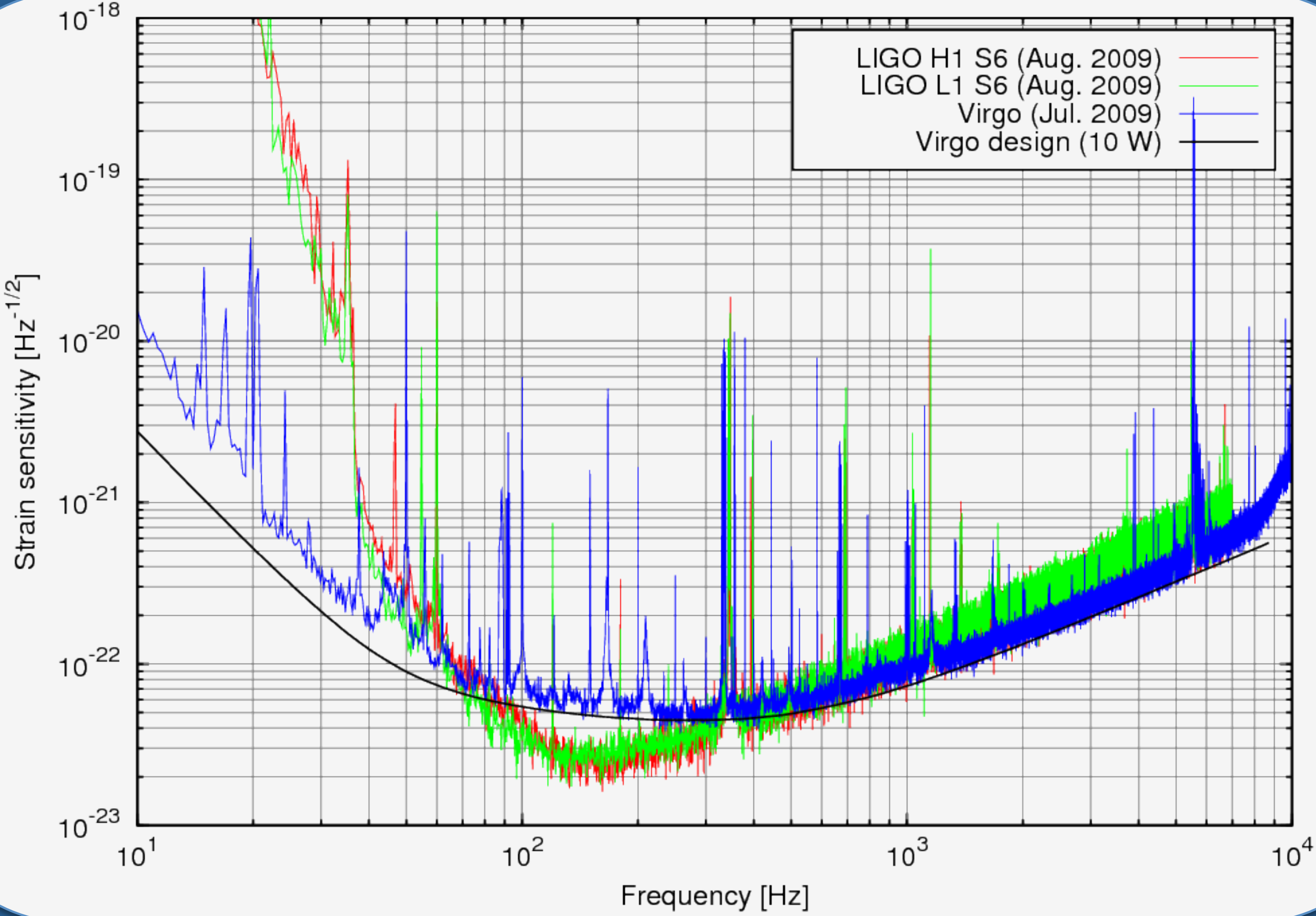
GEO-HF – will use squeezed light

- **Can achieve e.g., same sensitivity for less light power**
- **pathfinding for 3rd Generation (or 2.5 or 2.3….)**
- **May test in LIGO/eLIGO/AdvLIGO…**

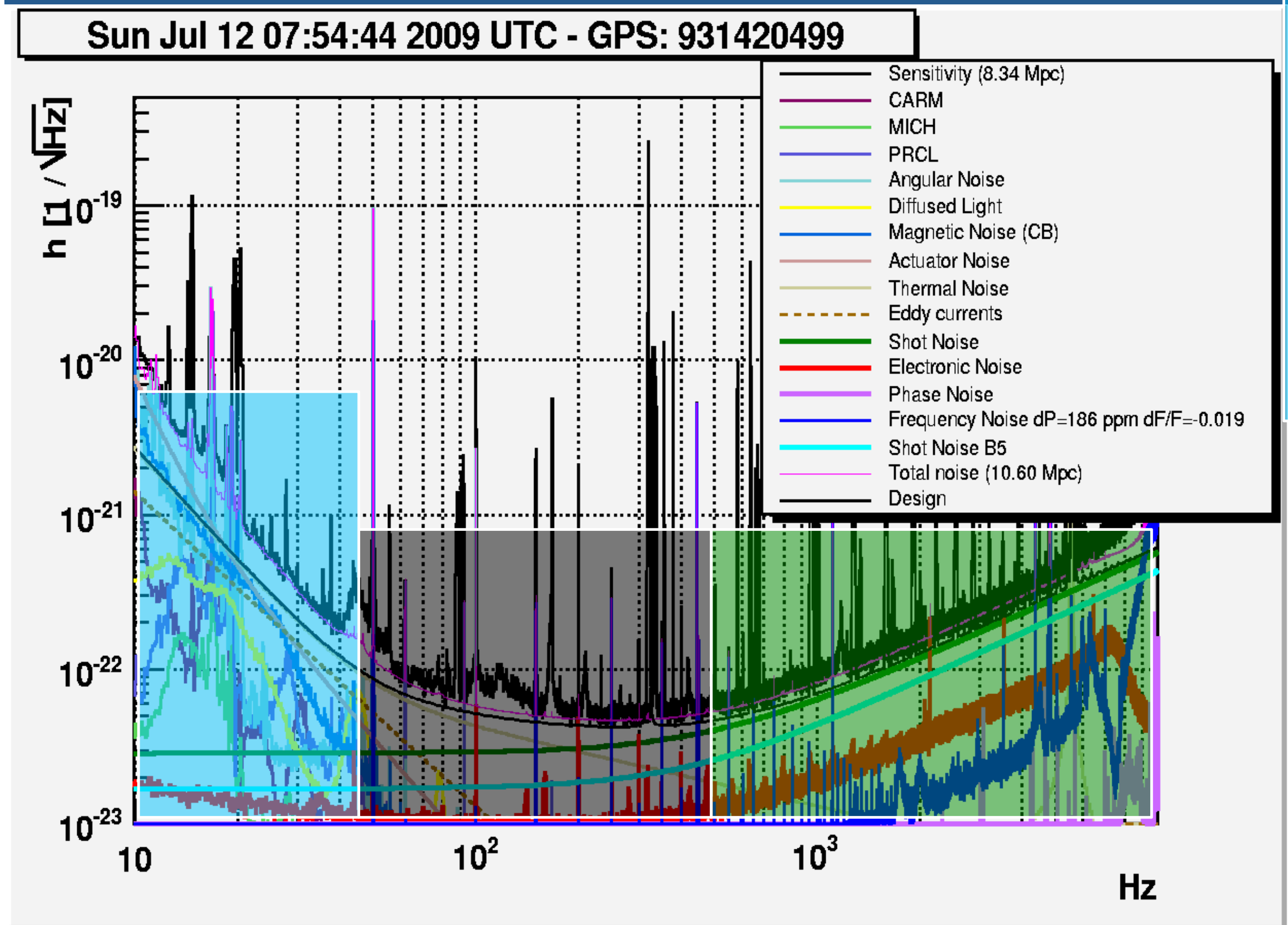


eLIGO & VIRGO+

VSR2-S6 Run

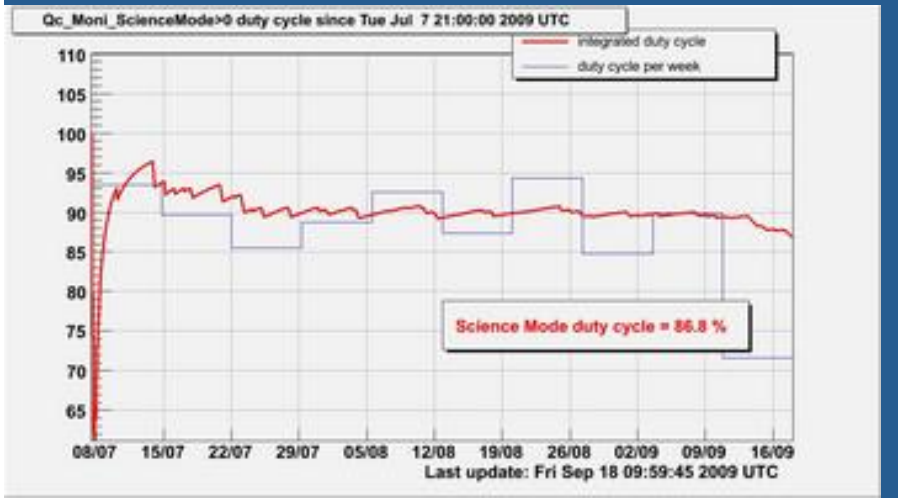


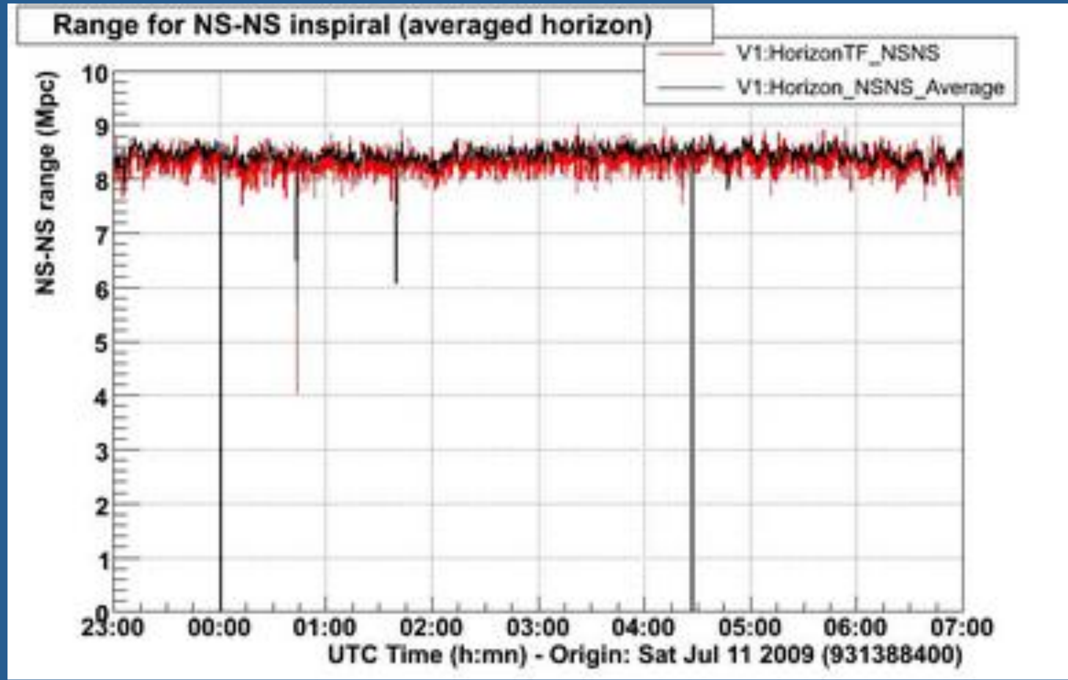
Virgo+ Noise budget



- Low frequency
  - Some environmental
  - Some scattering
  - Laser bench resonances
  - Actuator noise
  - No control noise!
- Medium frequency
  - Mirror thermal noise
  - Shot noise
  - Detection bench resonances
  - TCS radiation pressure?
- High frequency
  - Shot noise

VSR2-S6 Summary





Robust interferometer

~85% Science Mode duty cycle

Good sensitivity

Stable horizon:

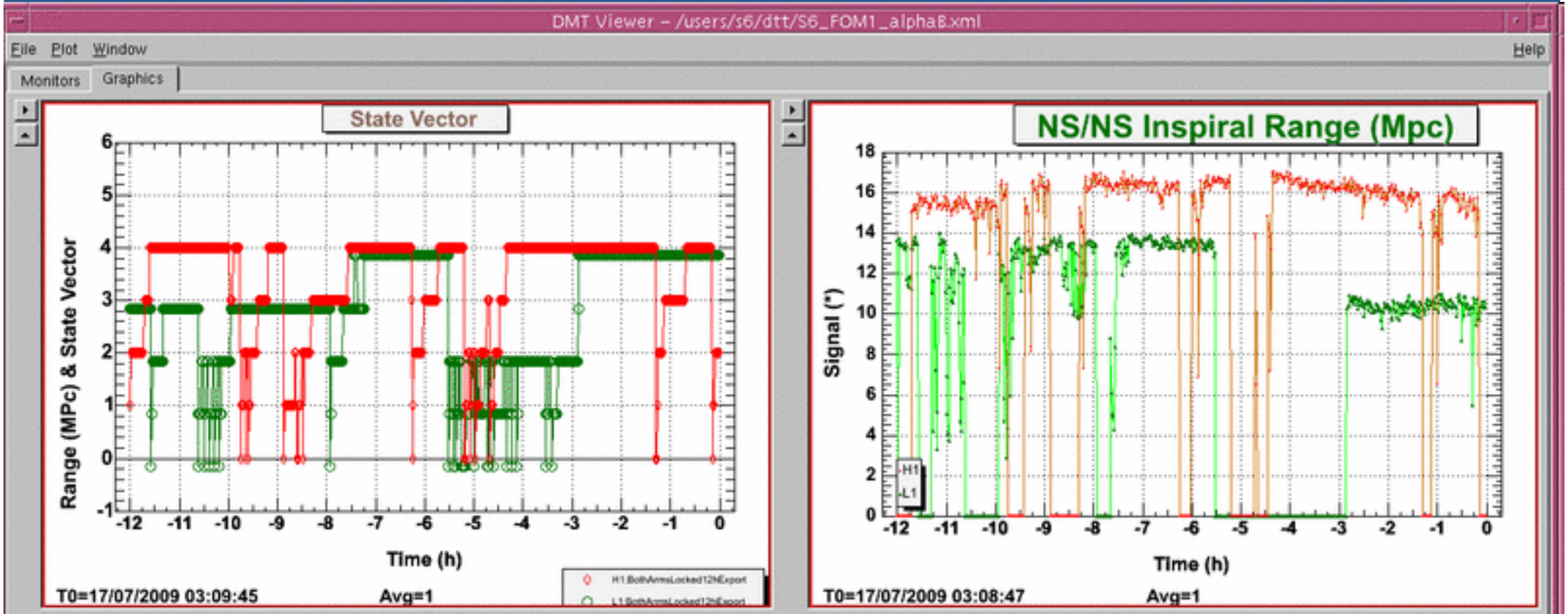
8.5-9.0 Mpc (1.4-1.4 Ns-Ns) - averaged

42-44 Mpc (10-10 BH-BH) - averaged

fluctuating with input mirror etalon effect

Low glitch rate: factor 10 lower than VSR1

Some “Typical” S6a Observing Time



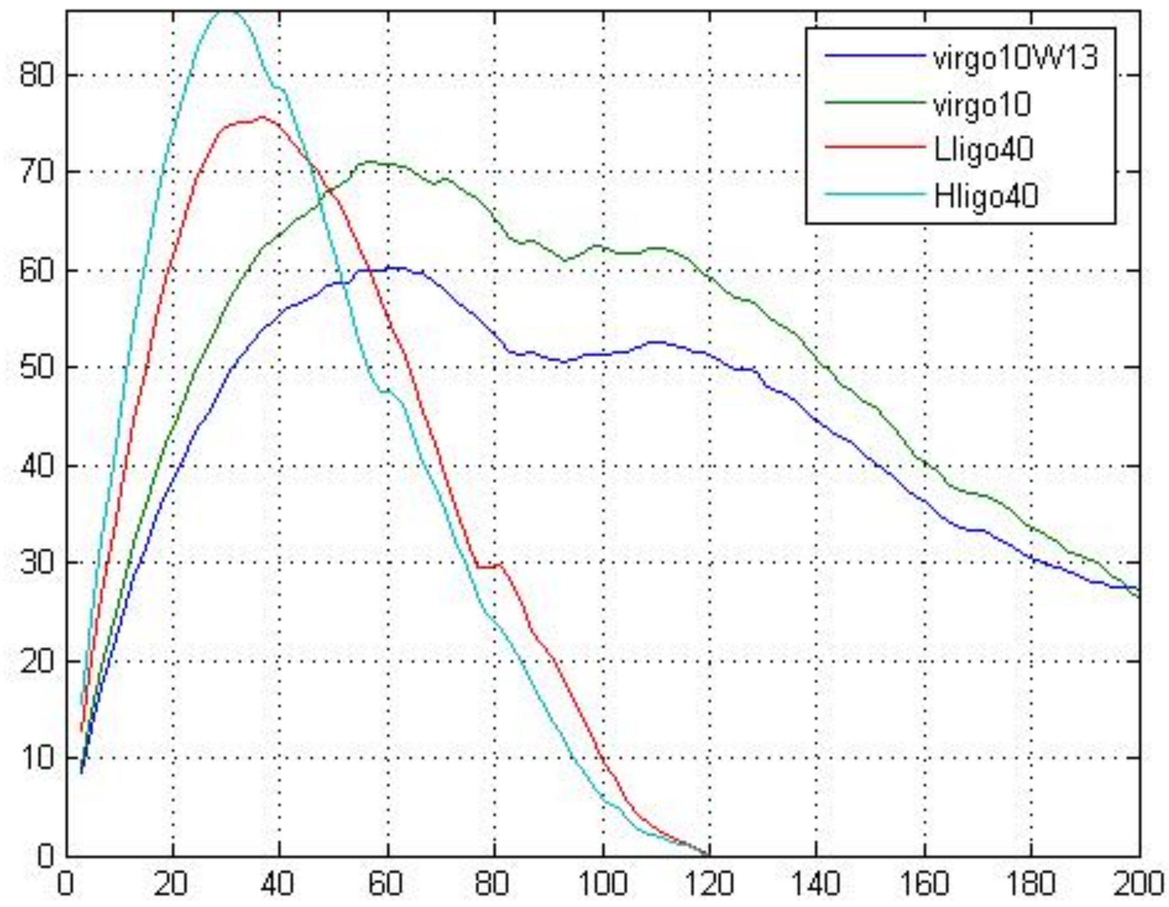
- 10 pm CST July 16 – 10 am July 17 (Thur-Fri, 10 days into the run)

L1 and H1 started with 50% better sensitivity than they had at the beginning of S5

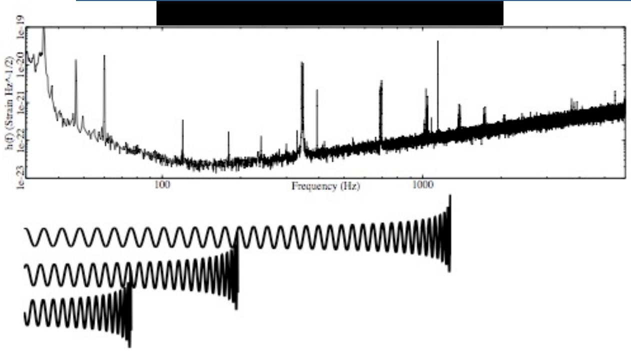
AdvLIGO subsystems and techniques have been tested and **confirmed**!

VSR2 – S6 science target

$f_{ultimate} = 4397.2*(1+0.3155\eta)(M_S/M)$ [Hz]



M_S = solar mass
M = total mass
$\eta = (m_1*m_2)/(m_1 + m_2)^2$



Comparison of LIGO and VIRGO horizon (equal masses – WSR13)

- Improvement of about 10 Mpc in the 40→120 solar masses
- About 25 Mpc for 200 solar masses

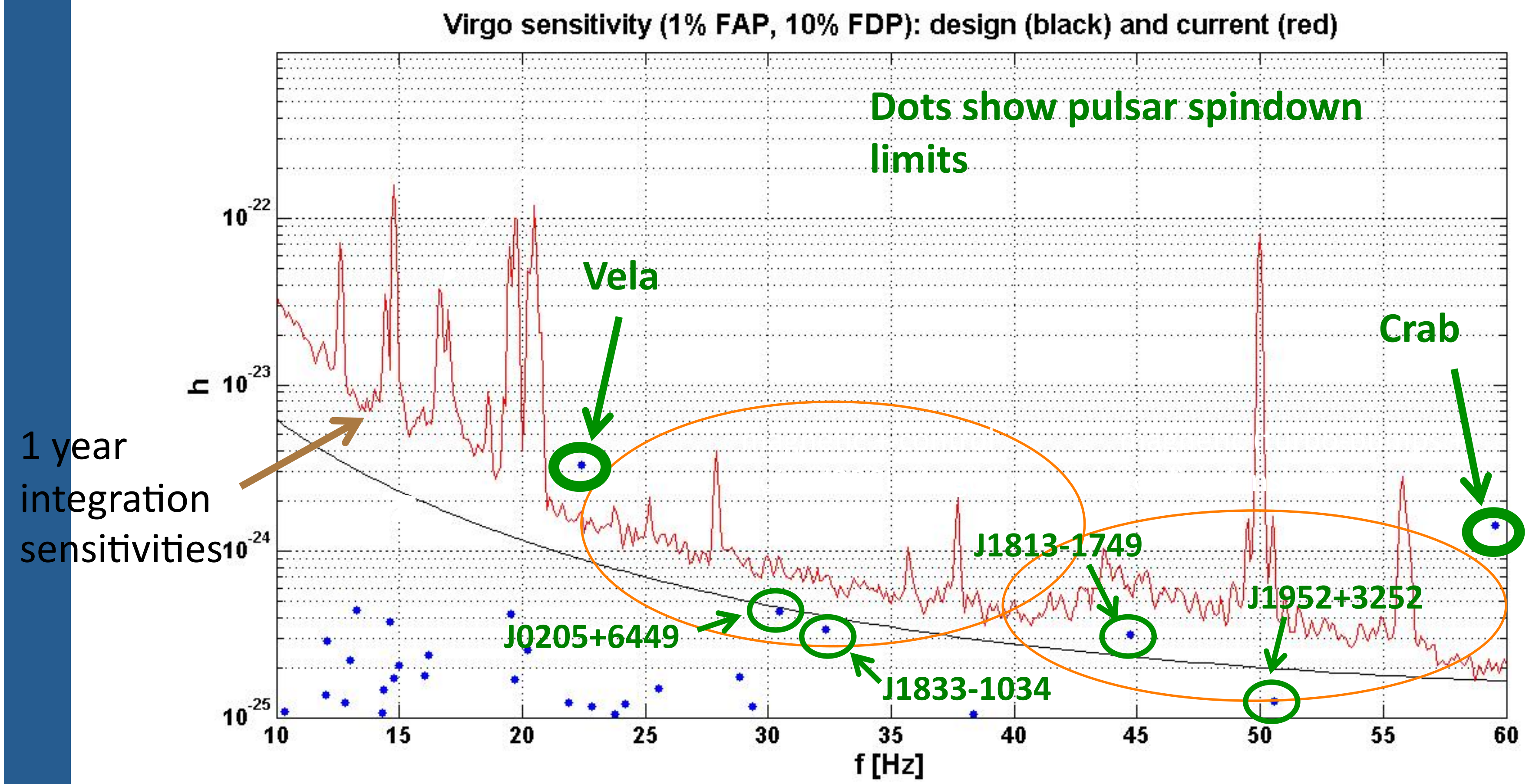
CW search targets

Blind search: ALL the frequencies in the range ~20Hz-2kHz are interesting!

Targeted search: we are mainly interested at the frequency of the pulsars for which the spin-down limit could be beaten in a reasonable time.

Beating the spin-down limit means starting to constrain the degree of deformation of the pulsar (ellipticity).

Any sensitivity gain of a factor K, reduces the observation time needed to overcome the spin-down limit by a factor K^2 (or, for a fixed observation time, it reduces the upper limit on the ellipticity by K).



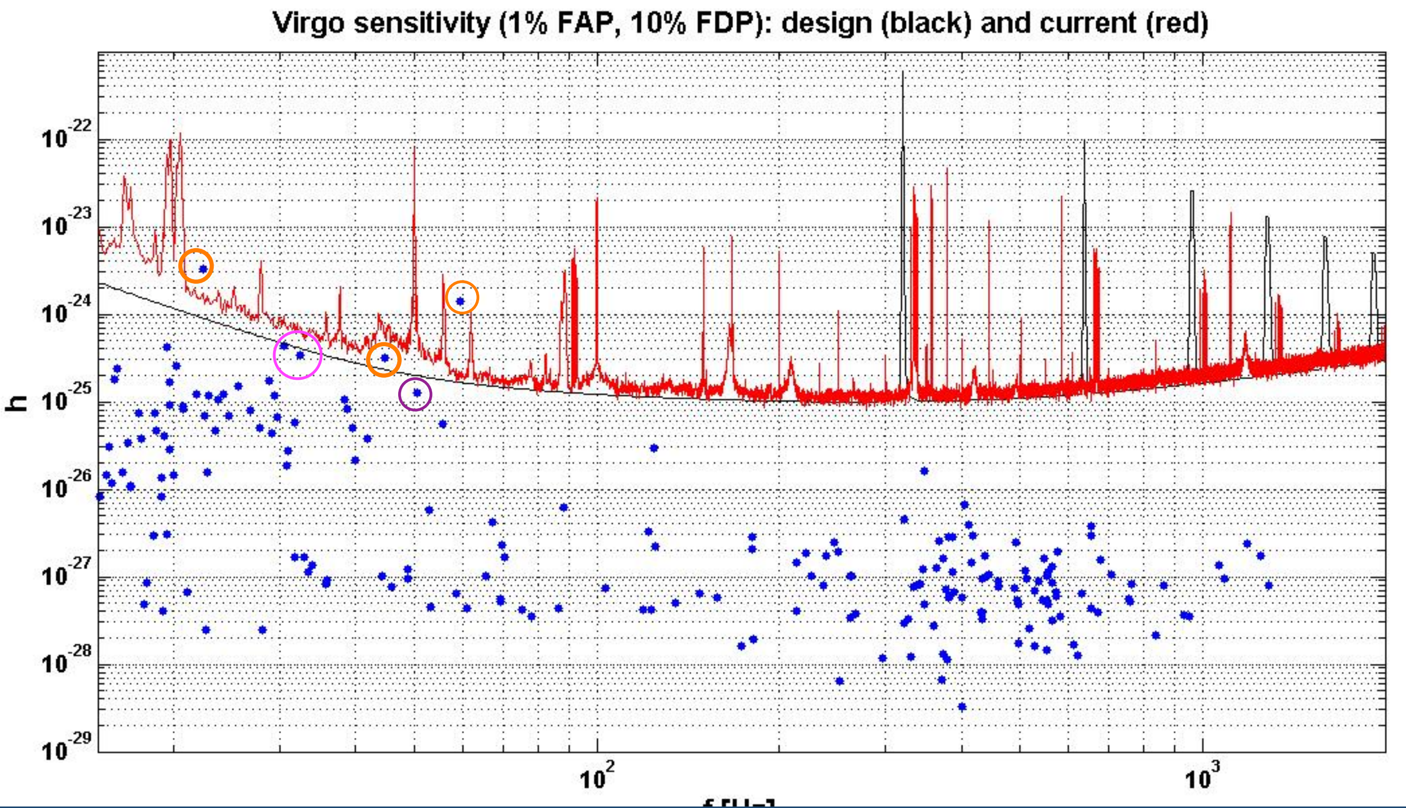
With the current Virgo+ sensitivity the spindown limit will be surely beaten for:

J0835+4510 (Vela): 22.38 Hz (before the break in January)

J0534+2200 (Crab): 59.56 Hz (~1 yr of data needed to beat LIGO current limit)

Likely it will be beaten for:

J1813-1749: 44.74 Hz (in a few months if the noise bump is removed!)



These curves can be used to estimate (conservatively) the observation time needed to beat the spin-down limit. Also pulsars which are 'slightly' below the solid curve must be considered

Possibly it will be beaten (with the full run) also for

J0205+6449*: 30.44 Hz* J1833-1034*: 32.33 Hz* and J1952+3252*: 50.59 Hz*

(provided the noise level is reduced in the corresponding band)

At the frequencies where LIGO and Virgo sensitivities are very similar, we will gain by analyzing the data all together (see for example the Crab case).

Several gamma-ray pulsars are being found by the Fermi LAT (both normal and millisecond).

Some potentially interesting objects:

Name	f [Hz]	fdot [Hz/s]	tau [kyr]
J1418-6058	18.09	-2.69e-11	10.3
J1459-60	19.38	-2.40e-12	64.0
J1813-1246	41.60	-7.61e-12	43.3
J1826-1256	18.14	-1e-11	14.4
J1907+06	18.75	-7.68e-12	19.4

What is happening now?

- On January 8th Virgo+ has started a commissioning break to install new mirrors with monolithic suspensions: the new FP cavities finesse will increase: 50 ->150
- Planning is to resume operation before summer 2010 to continue the run in coincidence with eLIGO, until LIGO shutdown in fall 2010 to start AdvLIGO construction.
- The Virgo+ Run with Monolithic Suspensions will continue until the start of AdVirgo construction in summer 2011

The Advanced Detectors in the near Future

- AdvLIGO has been approved in april 2008
- AdVirgo has been approved in december 2009

Both projects are progressing at full speed towards construction start: experience of key components in eLIGO and Virgo+MS will be essential

Preliminary AdvLIGO schedule:

- July 2012 – first interferometer installation completed; test, commission
  - First data chunks – auxiliary channels, maybe a few minutes of DARM
- 2013 – First Interferometer Acceptance as early as June '13
  - **Time for the LSC to be engaged in DetChar, E-runs**
- 2014 – Second, third IFO acceptance earliest Jan '14, April '14
  - …or the third interferometer acceptance might be a bit later, and somewhere in Australia!
- 2015 on – Observe with AdL, interleaving with further tuning

Preliminary AdVirgo schedule:

- July 2011 – Start of interferometer installation
- 2014 – Interferometer completed, start of commissioning
- 2015 – First data

Extending the NETWORK:
The proposals of LCGT in Japan and AIGO in Australia

We hope that with the Advanced Detectors Gravitational Wave Astronomy will start:

An Extended Network will be necessary to identify position and polarization of the sources.

All efforts of other countries to build new advanced detectors should be strongly encouraged by the community.

LCGT: Long Cryogenic Gravitational Telescope

3km Fabry-Perot ITF with power recycling and broadband RSE.

Main mirrors made of sapphire are cooled at 20K.

It is built at underground site in Kamioka Mine.

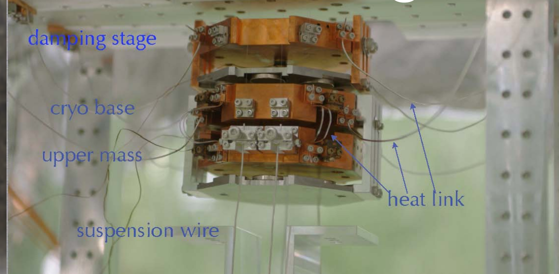
Two independent interferometers are installed.

The main target is the coalescence of Binary Neutron Stars at 180Mpc.

150 M$

CLIO: 100 m Cryogenic Prototype for LCGT

CLIO Cooling Link



AIGO: an Australian Gravitational Wave Detector

Could be AdvLIGO third interferometer?

From the AIGO project site:

(http://www.aigo.org.au/aigores.php)

*“**The west coast of Australia is the best location for the southern hemisphere detector given the current locations of the northern ones.***

Advantages come from the fact that this location is roughly opposite the northern detectors, and their relative alignment is almost optimum. Thus all the detectors see the same gravitational wave signals with roughly the same strength.

The AIGO site was contributed by the Western Australian Government. It was carefully chosen for the following reasons: easy access from the city, flatness, isolation and its pure silica sand which is ideal for seismic wave attenuation. Located in the Wallingup Plain: State Forrest 65, west of Gingin, Western Australia, the site was granted in 1998. It has been under development since 2000, with an 80m arm-length interferometer.”

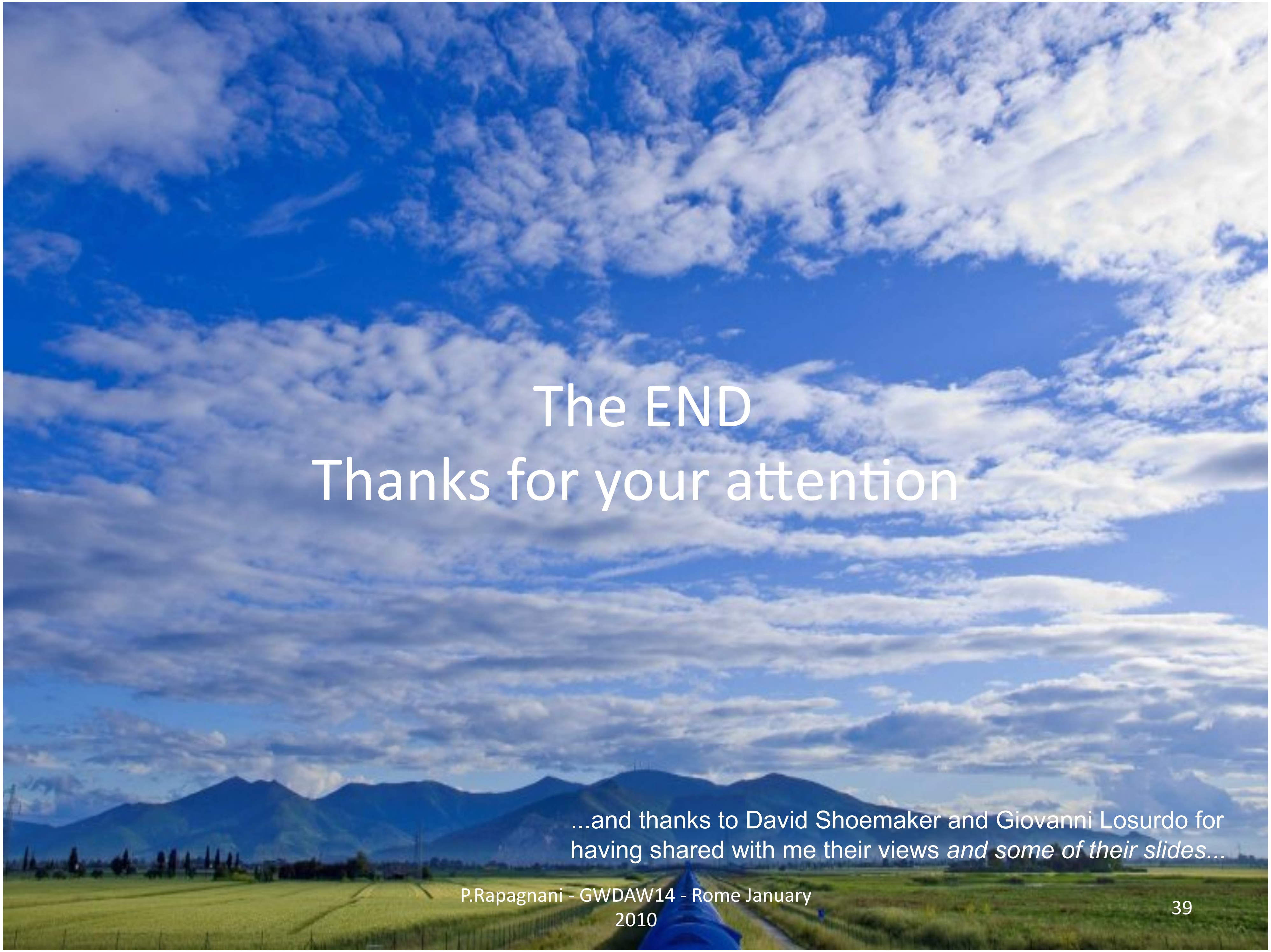
The performance of the Network would improve significantly

Conclusions

After 40 years of progress, expectations are growing high:
in the near future Advanced Detectors should detect for the first time Gravitational Waves.

Though unlikely, surprises could come also from the data of current enhanced detectors.

I hope that, in some years from now, one of the next GWDAW's will deal with the first real signals found by these new instruments.



The END
Thanks for your attention

...and thanks to David Shoemaker and Giovanni Losurdo for having shared with me their views *and some of their slides...*