The first and second generations of GW interferometric detectors

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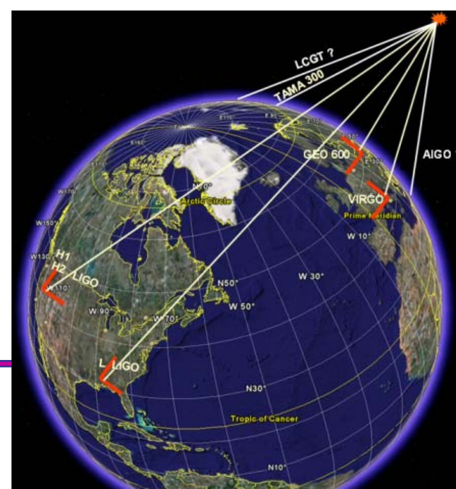
Ecole des Astroparticules, OHP

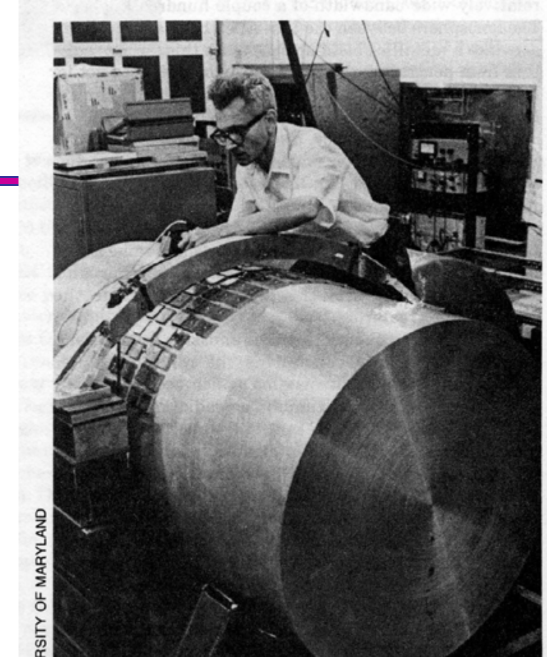


Outline

- What is a GW inteferometric detector
- How to get it running
- From first to second generation

- Remarks:
  - Talk mostly about instrumentation
  - bias view: use Virgo as example

Preamble

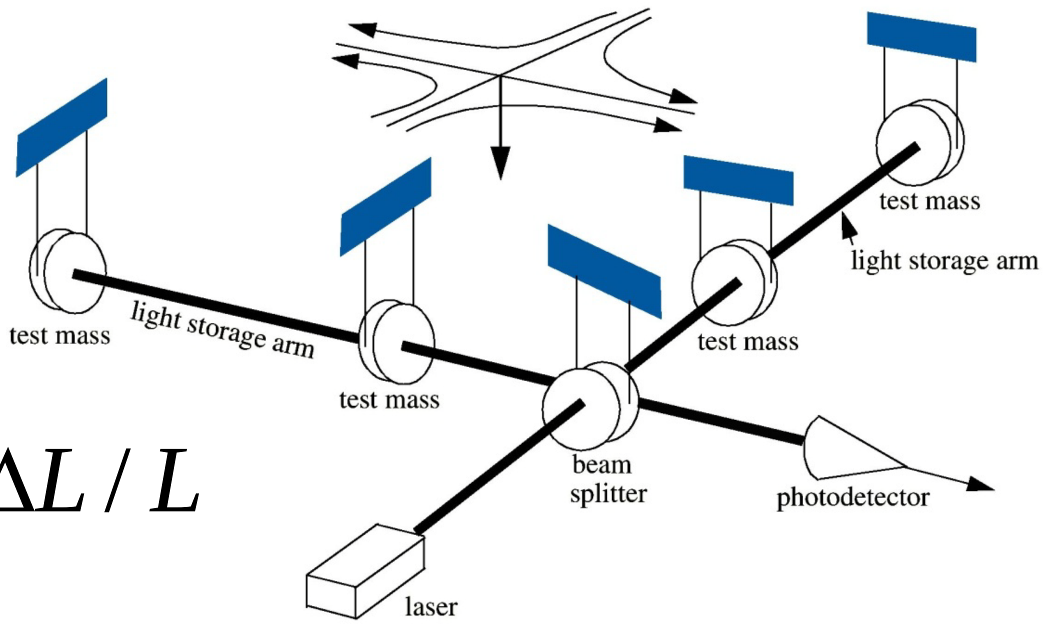


- Joseph Weber invents the bar detector
  - First claim for detection in 1968… but contested
- Evolve to cryogenic resonant bars ('80-'90)
- Bar not enough sensitivity:
  - h : few 10^{-21} 1/sqrt(Hz) @ 900Hz
- ITF started in the 70's (Rai Weiss)
  - Broad band instrument
- Few ITF prototypes in the 80's
  - MIT, Glasgow, Garching, Caltech,...
  - ~10m long
  - Not made for detection
- Jump to km scale in early 90
  - LIGO, GEO, TAMA Virgo

Principle of a GW interferometric detector

Detecting GW with an interferometer

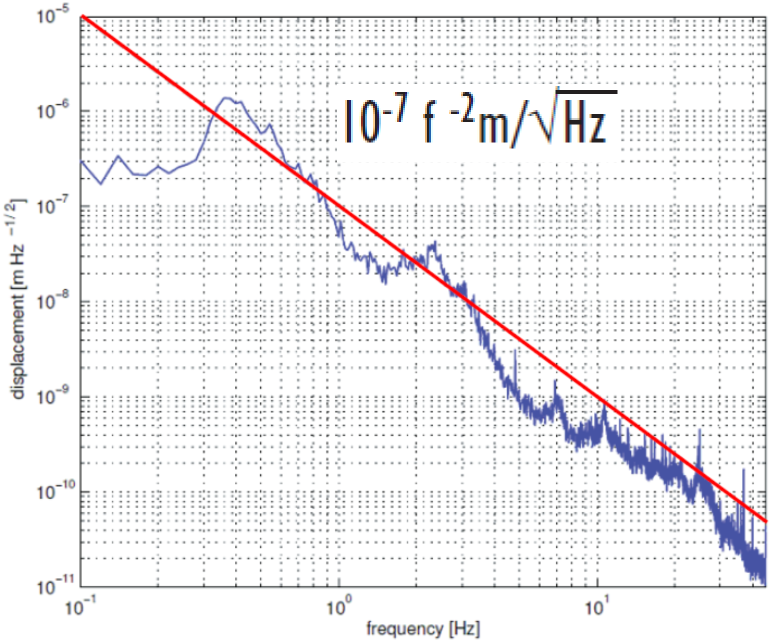
- Interferometer mirrors = test masses
  - Mirror are suspended: “free” test masses above pendulum frequency

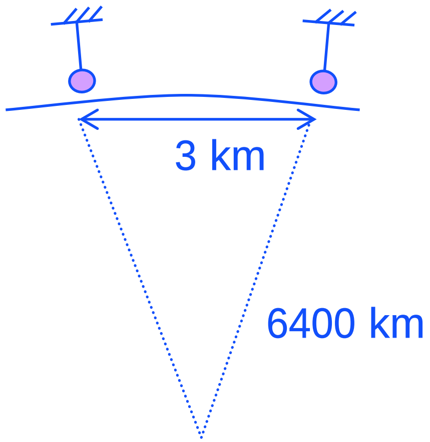


$$h = \Delta L / L$$

- **For h = ~ 10^{-22} and L = 3 km $\Rightarrow$ $\Delta L \sim 10^{-19} - 10^{-18}$ m**
- Complex seismic isolation systems required

The Seismic Noise Challenge

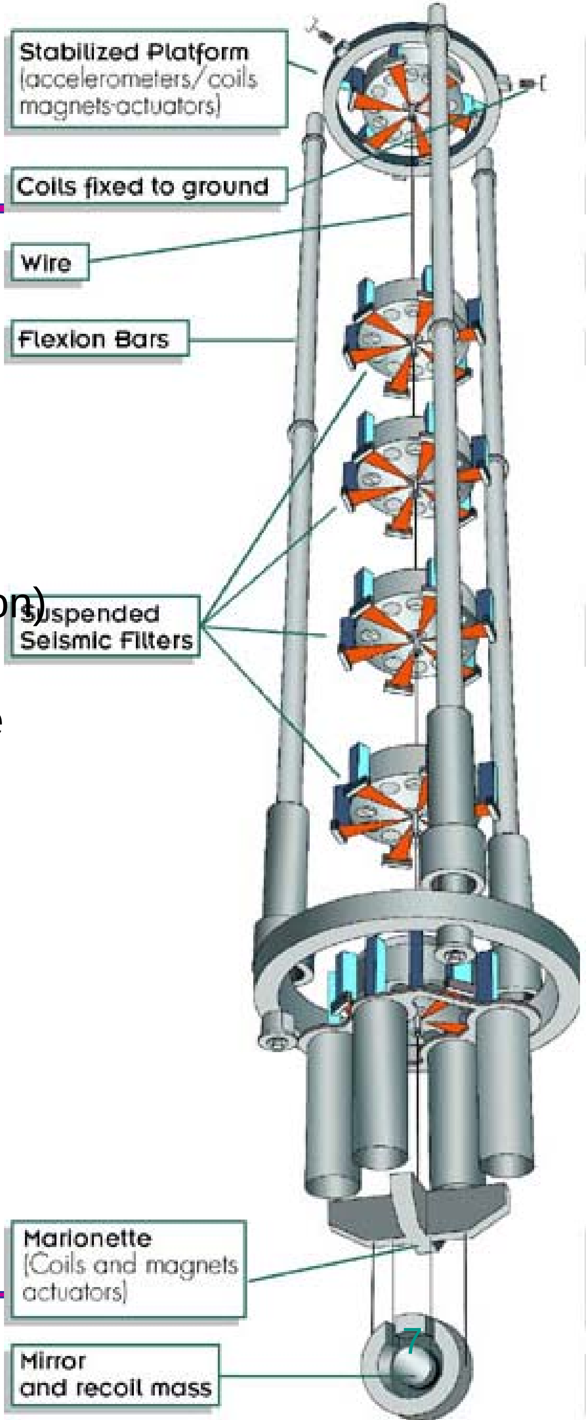




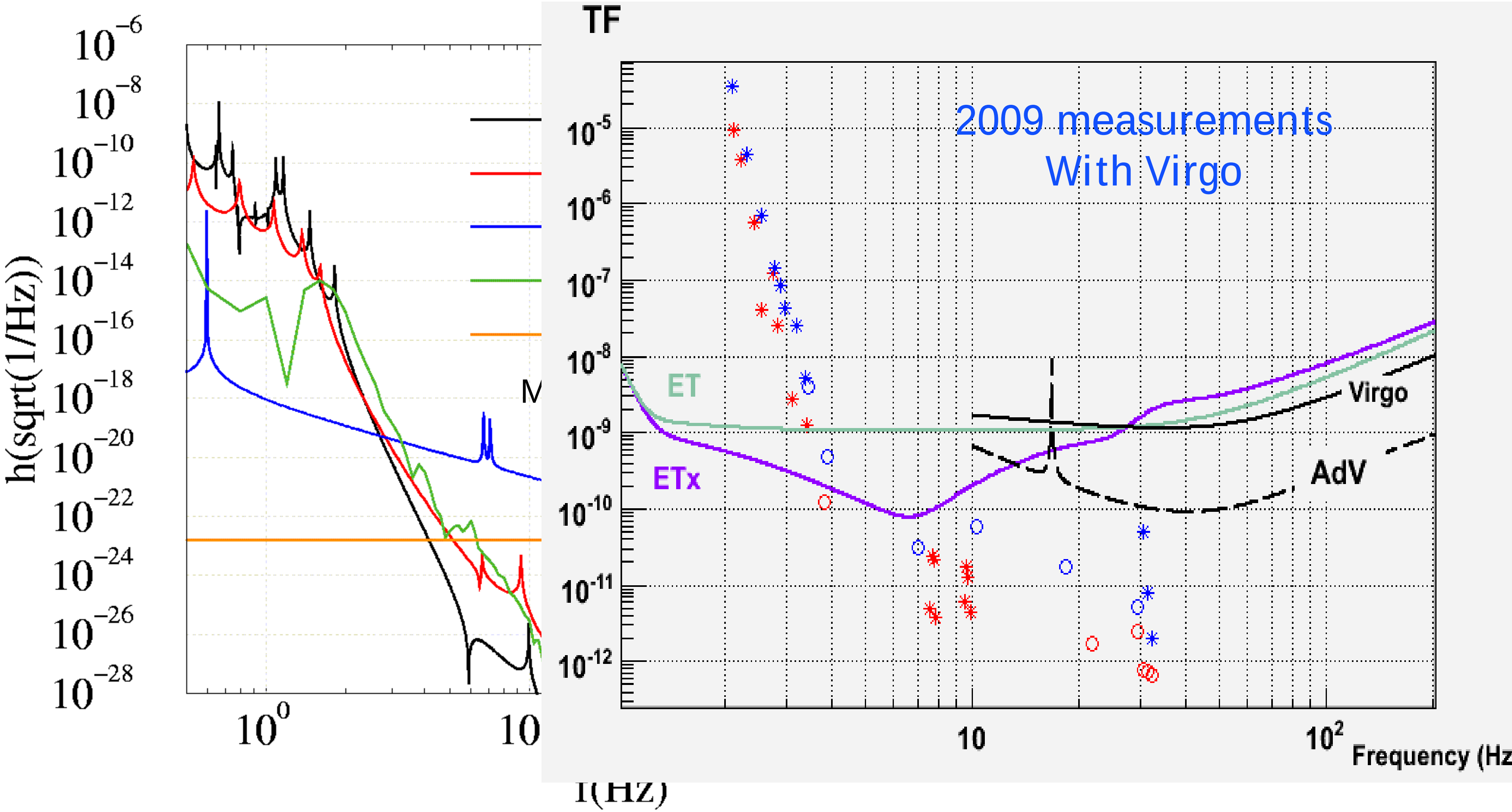
- Seismic noise at the Virgo site
  - ~ 10^{-7}m./sqrt(Hz) @ 1Hz (on a quite day: weather dependant)
- Vertical to horizontal coupling > 2 10^{-4}
- Seismic attenuation requirements:
  - Attenuation larger than 10 order of magnitude above 4Hz on 6 d.o.f.

Virgo Seismic Isolation

- A chain of mechanical filters
  - ◆ Inverted pendulum
    - » for low freq. control
  - ◆ 6 seismic filter (in all DOFs)
    - » Combine blades (vertical attenuation) and wires (pendulum)
  - ◆ 1 longitudinal-angular control stage
    - » “marionetta”
  - ◆ 1 longitudinal control stage
    - » the reference mass

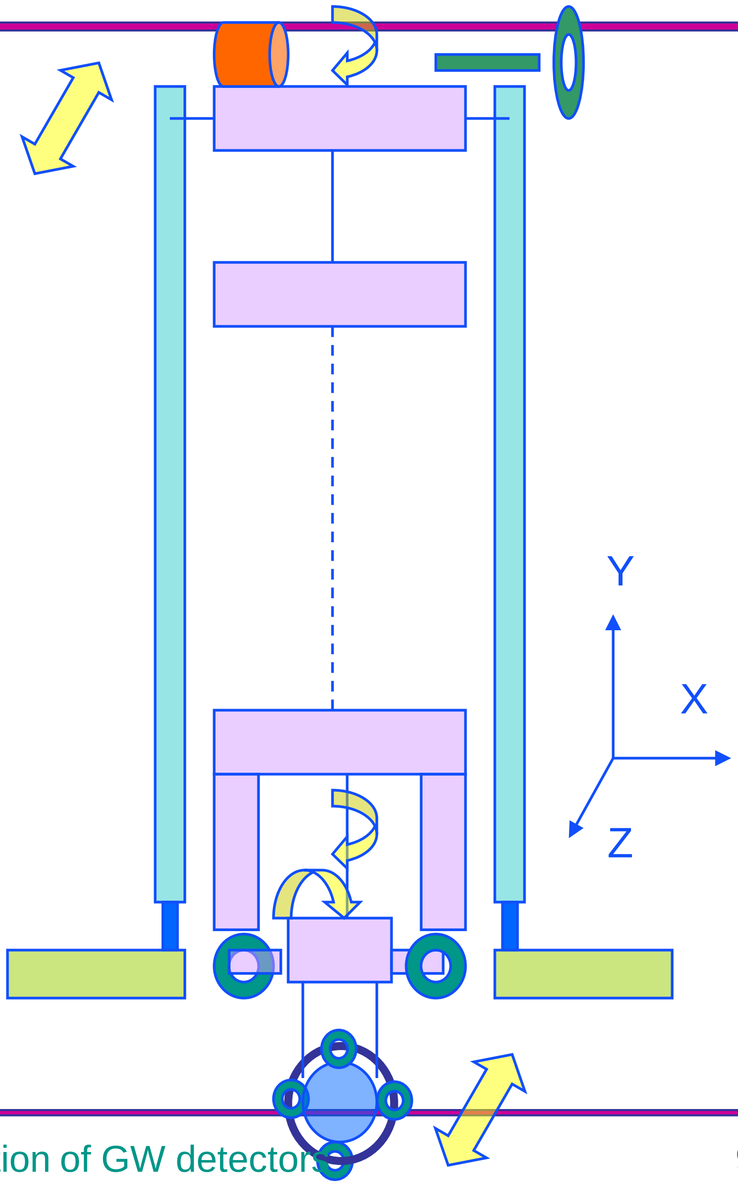


Virgo seismic isolation performances



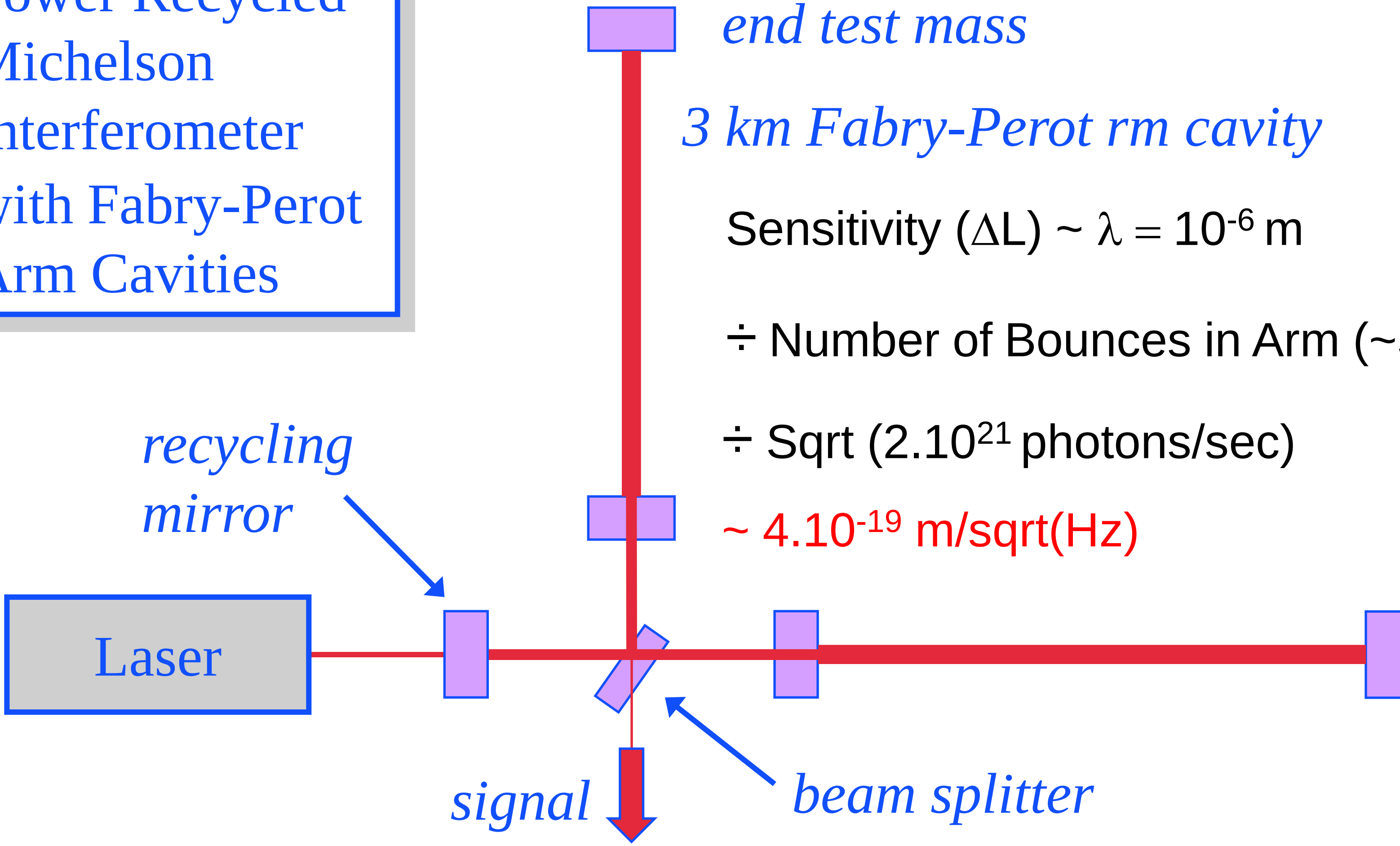
The SA as a control device

- Four Sensing devices
  - LVDT Sensor on top
  - Accelerometers on top
  - Camera and optical lever on bottom
  - The interferometer itself
- Hierarchy of noises → hierarchy of forces
  - Avoid large forces applied directly to the test-mass
- Three actuation stages
  - Below 5Hz coils on the IP
  - .01-20 Hz from the marionetta
  - above 5 Hz: reference mass



First generation: optical configuration

Power Recycled Michelson Interferometer with Fabry-Perot Arm Cavities



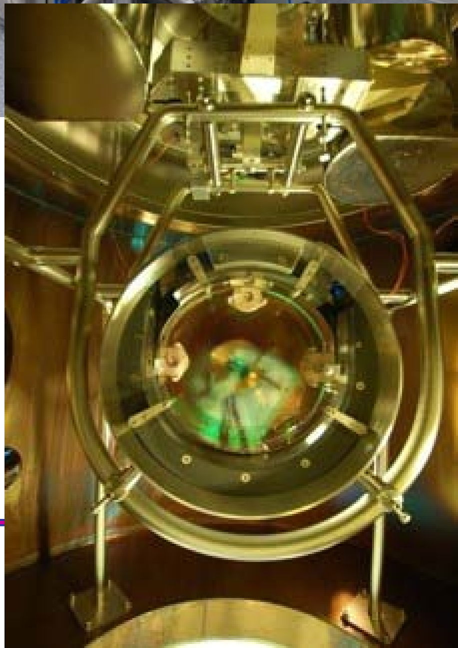
Sensitivity (ΔL) ~ $\lambda = 10^{-6}$ m

÷ Number of Bounces in Arm (~50)

÷ Sqrt (2.10^{21} photons/sec)

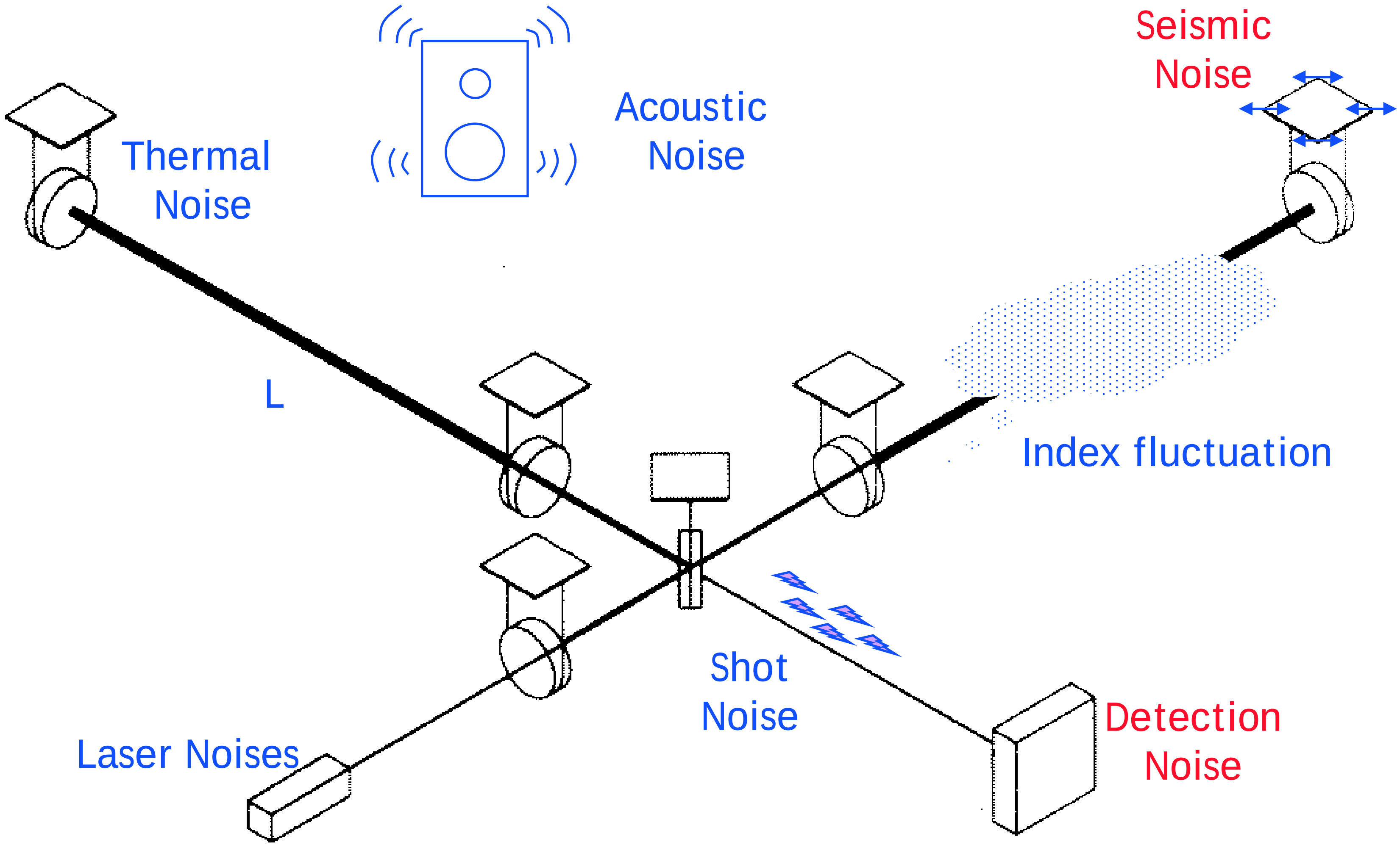
~ 4.10^{-19} m/sqrt(Hz)

Mirrors



- Low absorption fused silica
  - 35 cm diameter, 10 cm thick
  - 21 kg
- Dedicated infrastructure built in Lyon for the coatings
- Challenge of keeping them clean
  - Included when installed on the seismic isolation

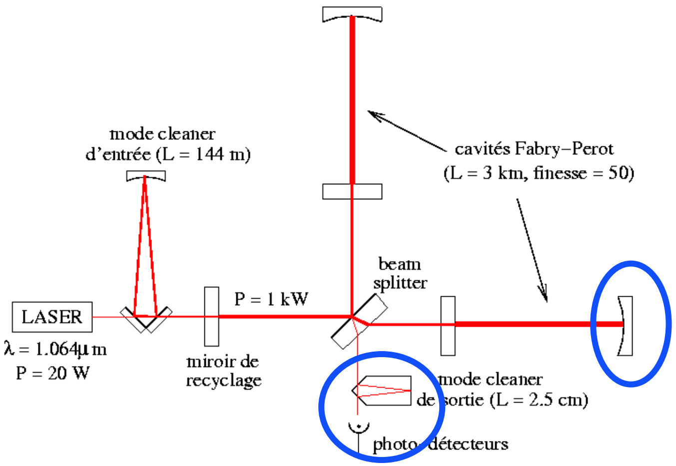
Noise sources



Vacuum system

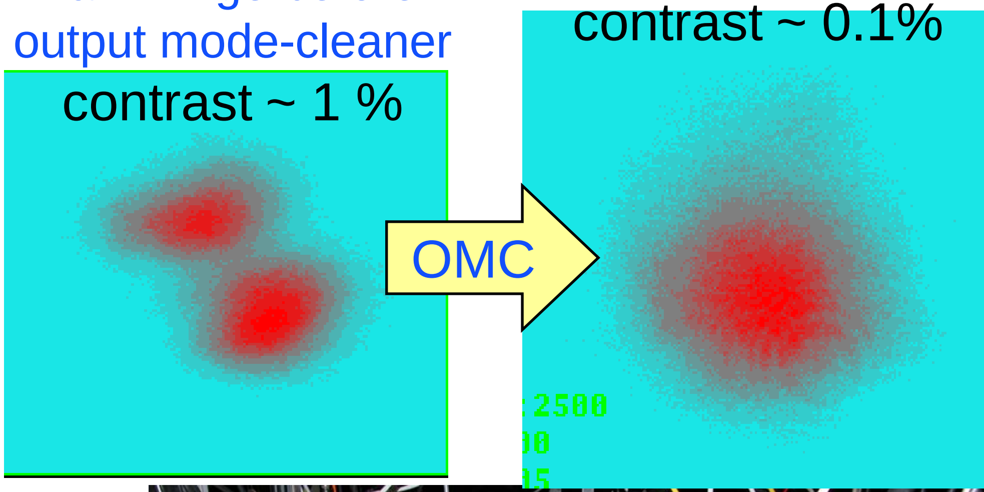
- Protect laser beam from air fluctuations
- Protect key components from acoustic noise
- 1.2m diameter beam tube
- All key mirrors under vacuum

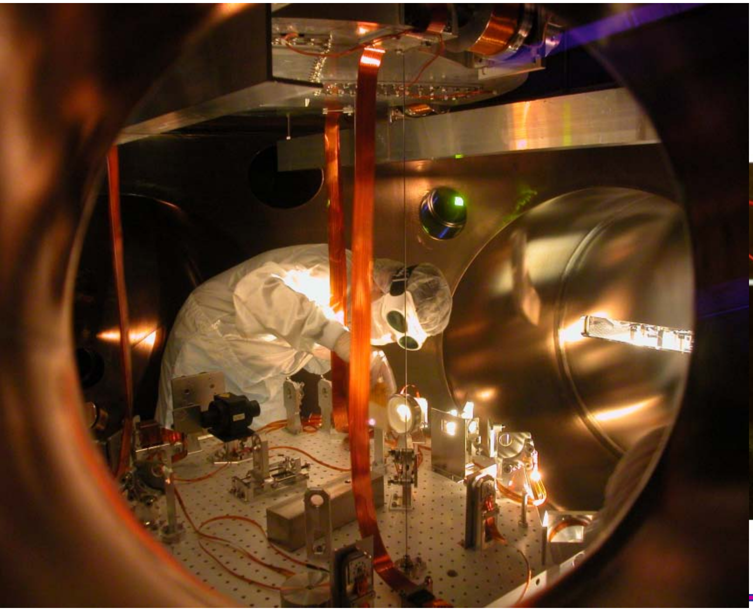
The detection system

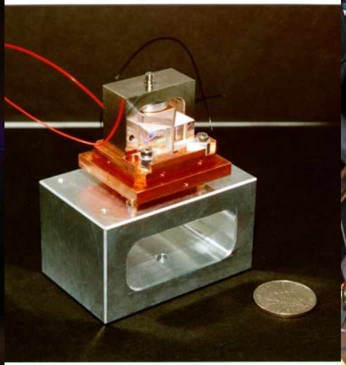


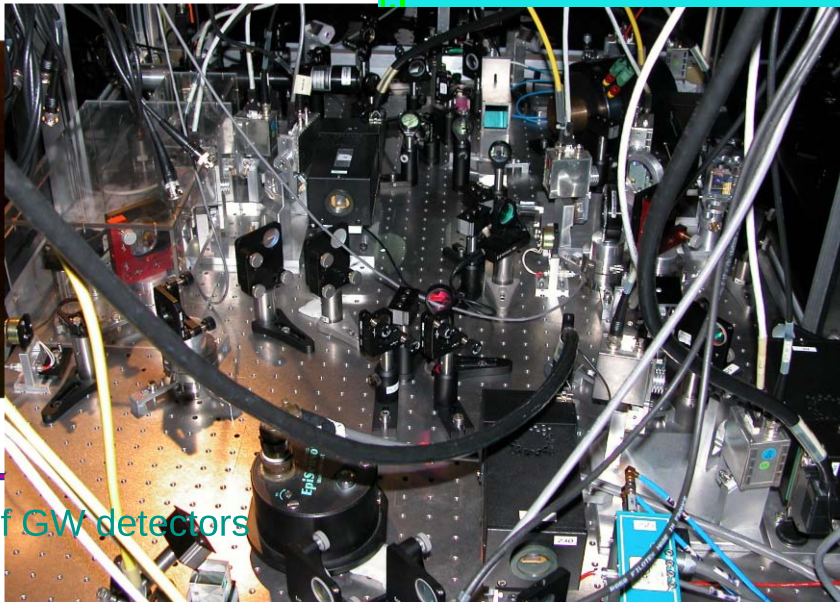
Dark fringe before
output mode-cleaner

Dark fringe after
output mode-cleaner

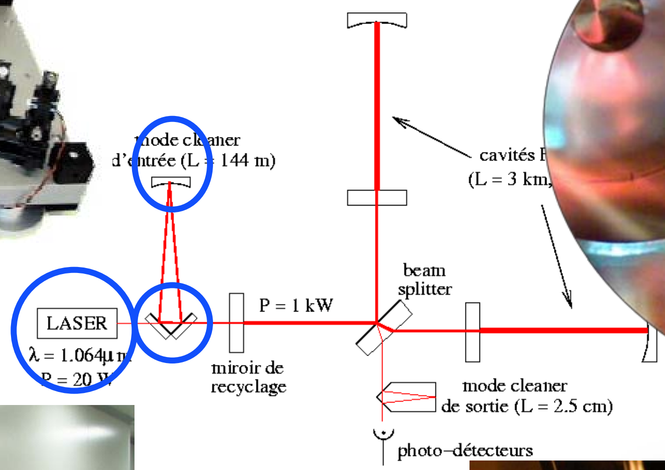


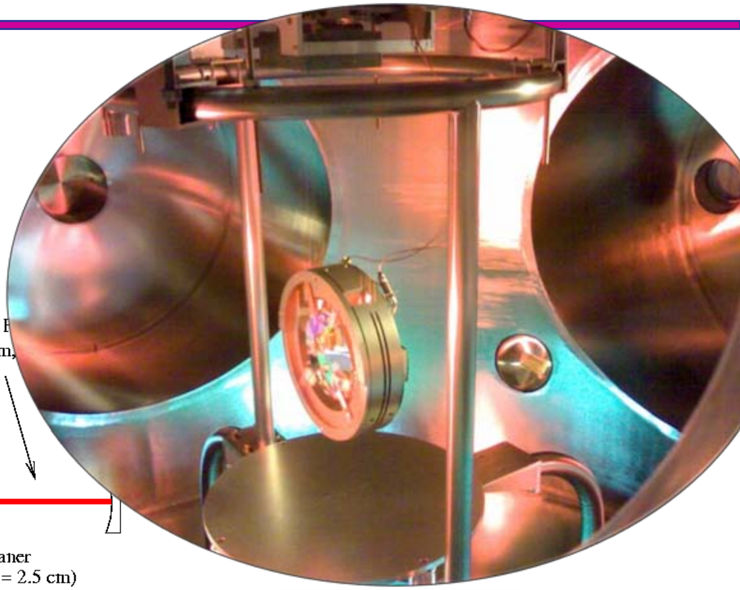


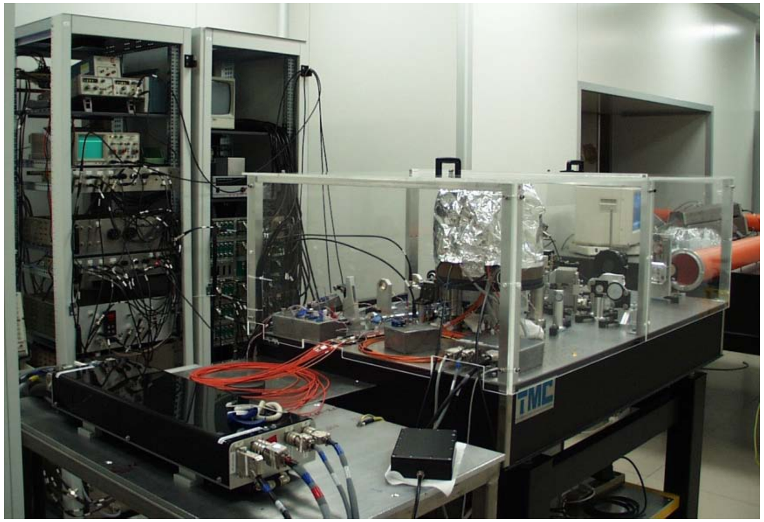


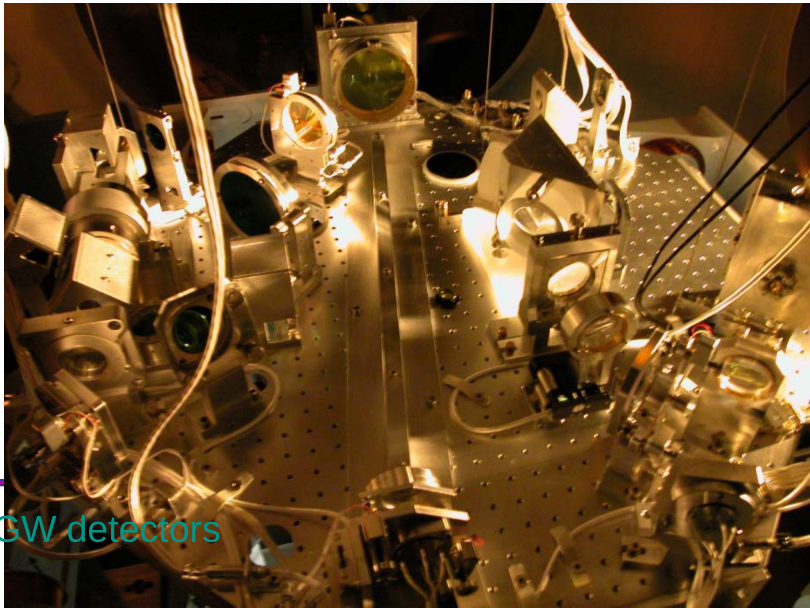


The injection system





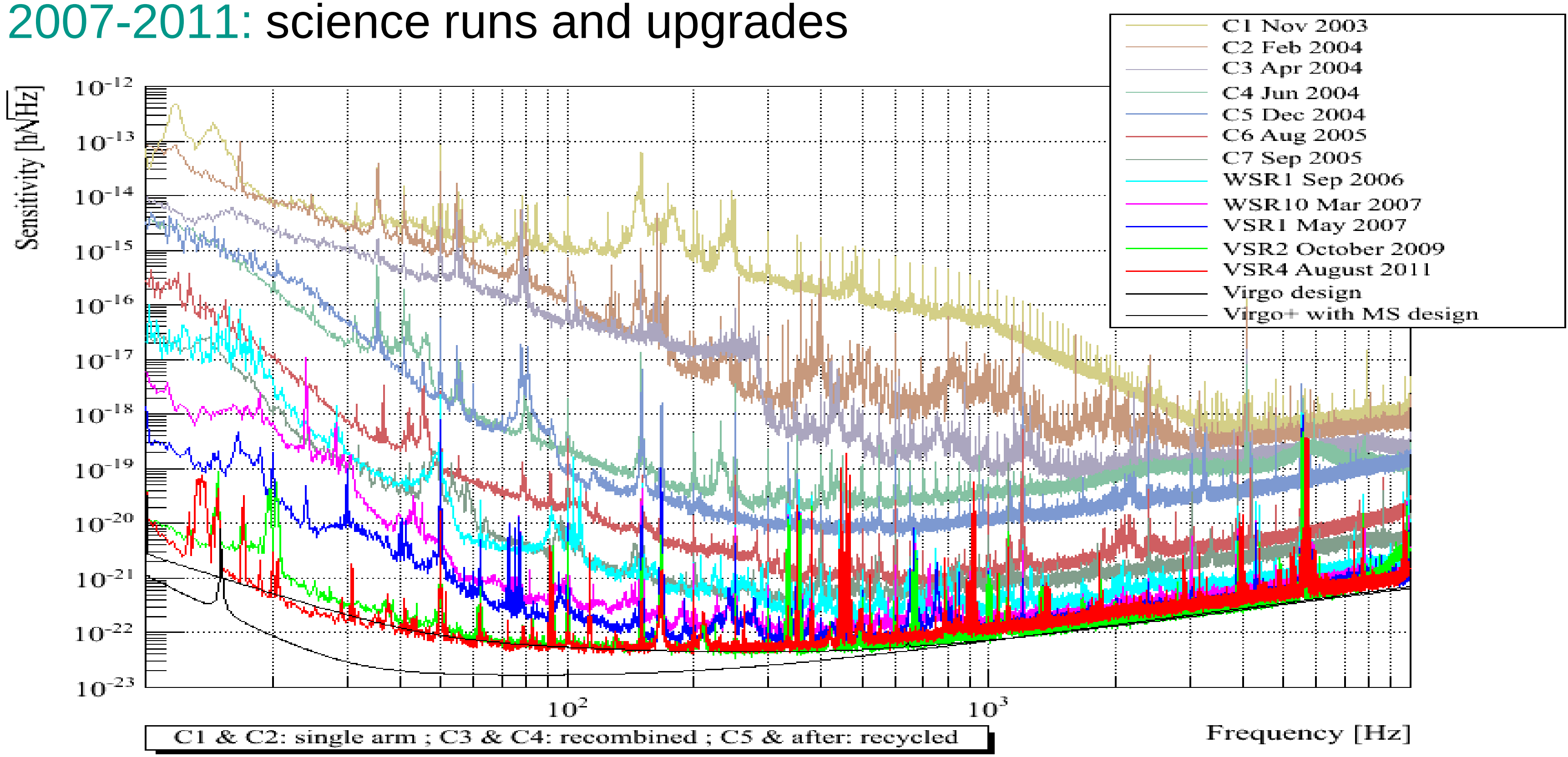




Running the first generation of GW interferometric detectors

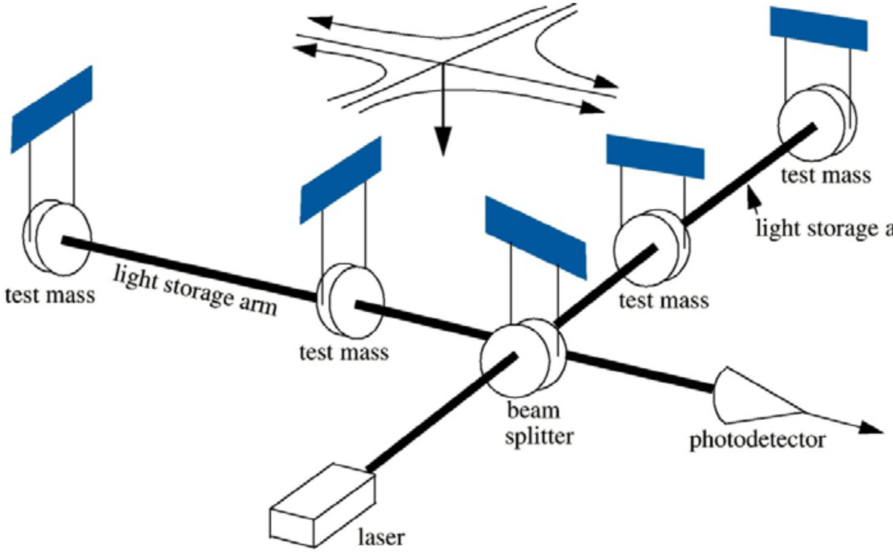
Sensitivity of Virgo: a long story

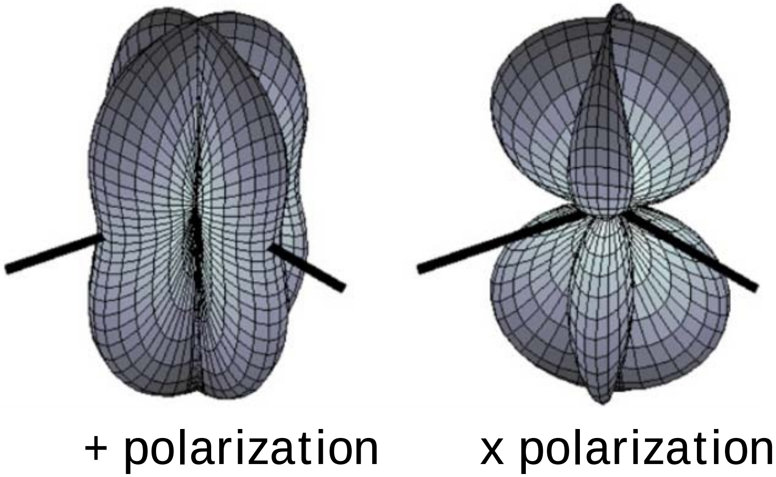
- 1998 – 2002: installation and commissioning of the central part
- 2002 – 2003: completion of the full Virgo and start of commissioning
- End 2004: control of the full interferometer at 0.8 W
- 2006: control of the full interferometer at 8 W
- End 2006 – 2007: reduction of technical noises
- 2007-2011: science runs and upgrades



Inspirale range and horizon

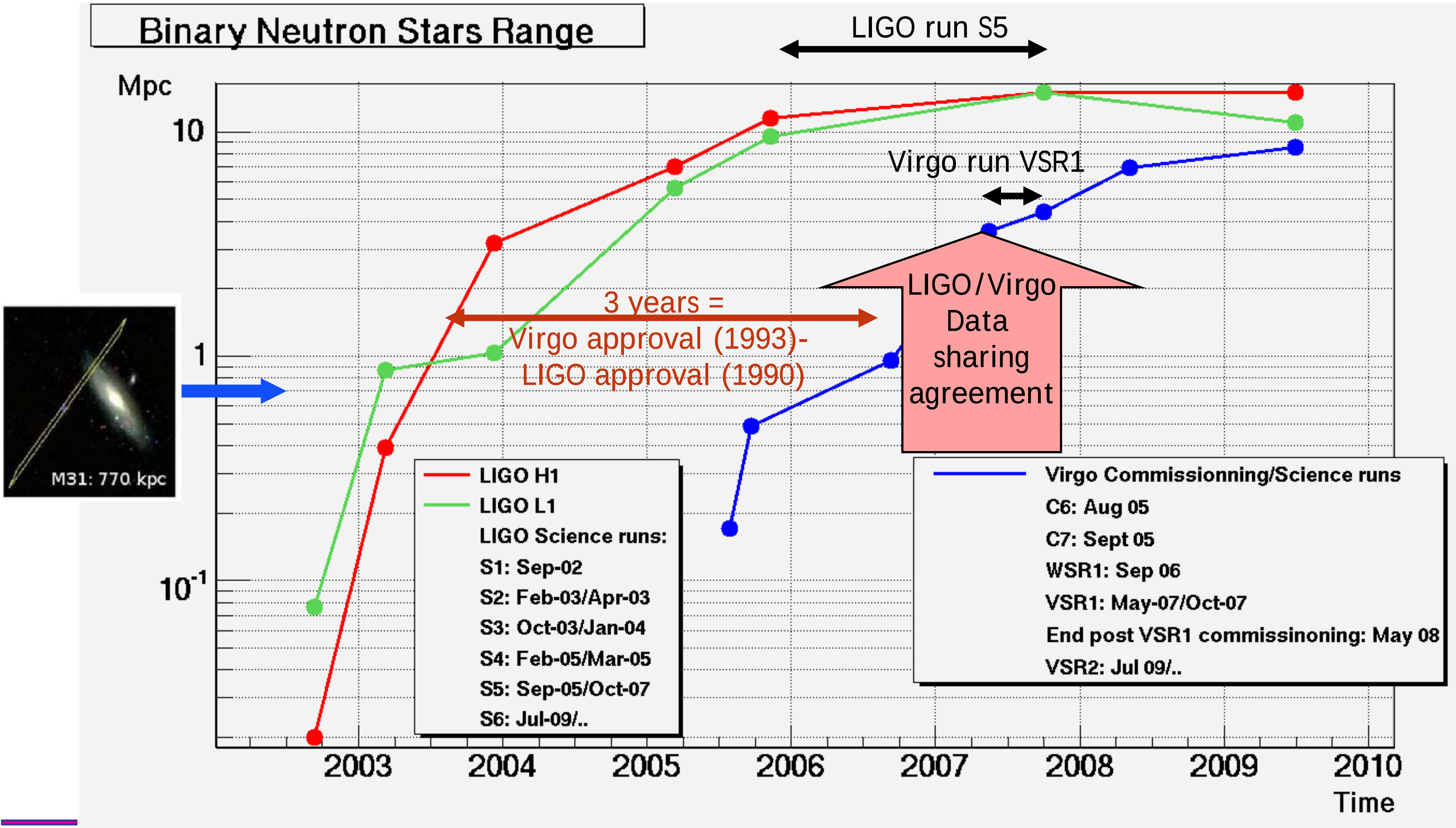
- Horizon: distance at which a source with optimal orientations is seen with SNR=8





- The ITF antenna patterns are broad
- Range: radius of a sphere of the same volume as the antenna pattern
- For BNS: horizon~2.3 range

LIGO & Virgo Sensitivity Progress

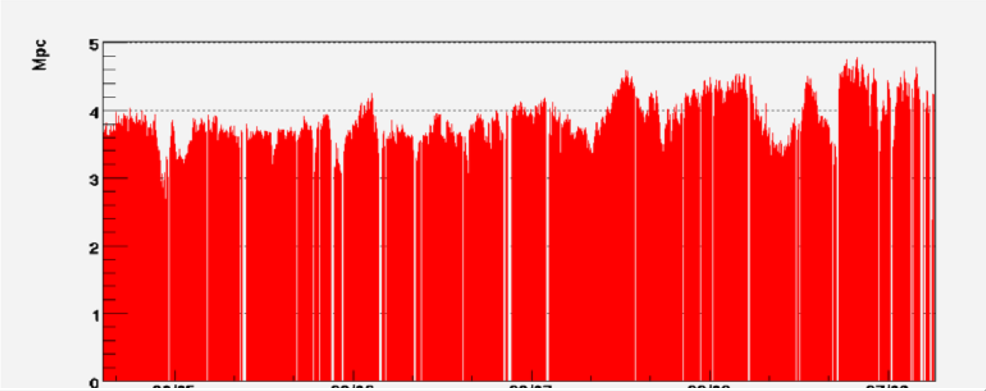


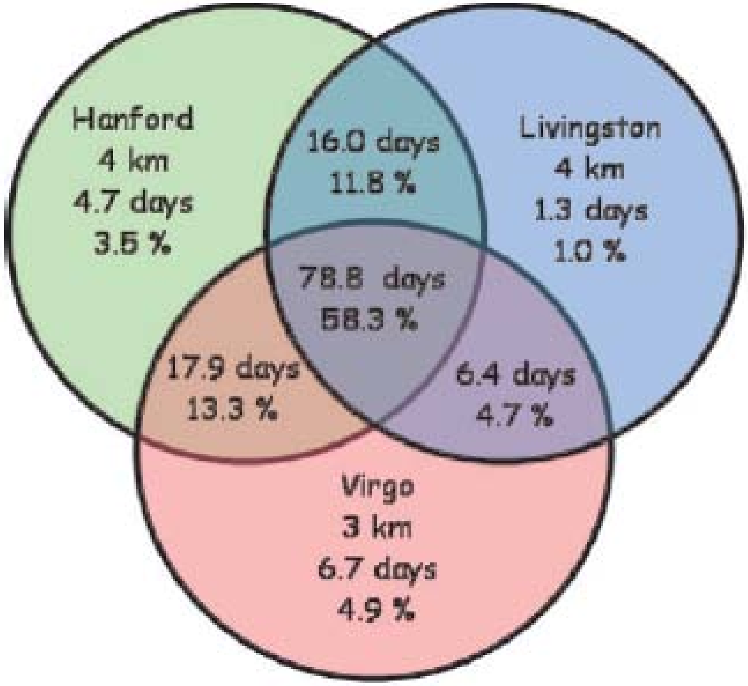
2007: LIGO-Virgo agreement

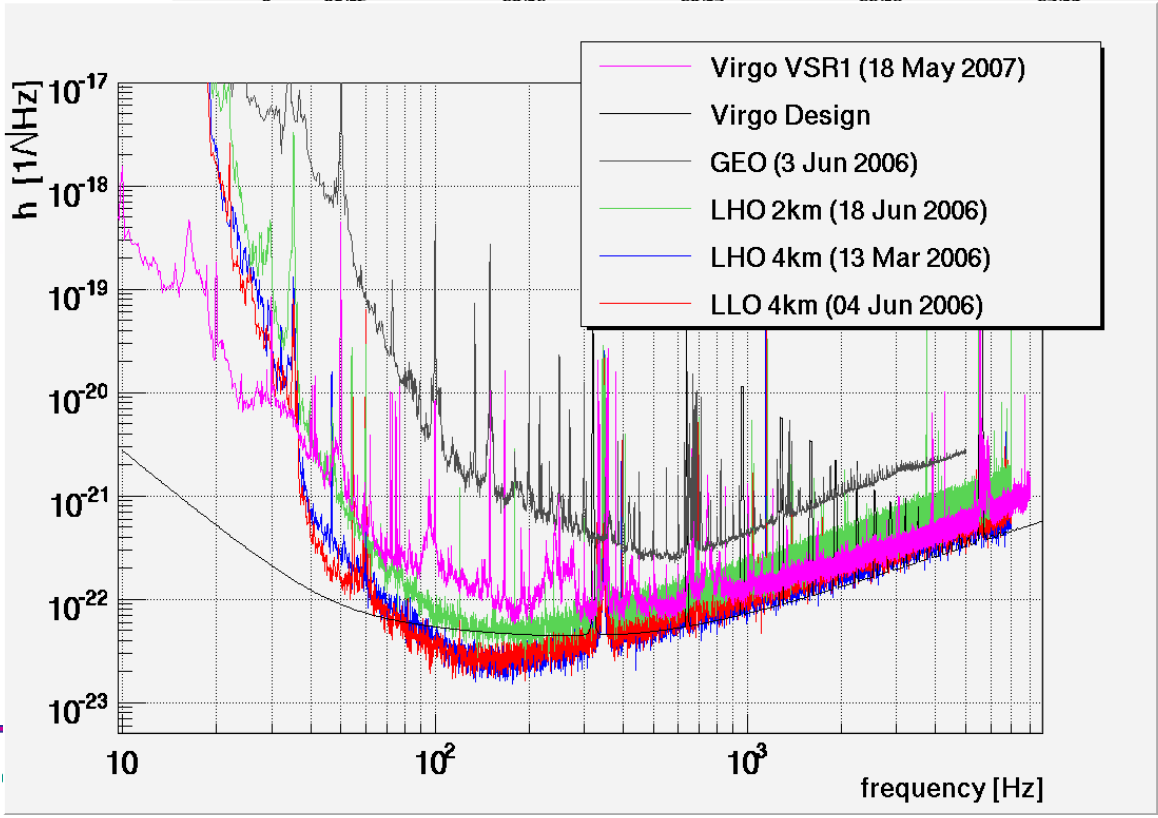
- Agreement (MoU) Virgo-LIGO
- Full data exchange and joint analysis working group
- Joint publication policy
- Science runs coordination
- Collaborative technical research
- Benefits:
  - Confidence in detection
  - Duty cycle
  - Sky coverage
  - Sky position localization

First LIGO/Virgo joint data taking: 2007

- Virgo first science run (VSR1)
  - 4.5 months (May 18th - October 1st)
  - Duty cycle: 81%
  - NS-NS range from 3.6 to 4.5 Mpc



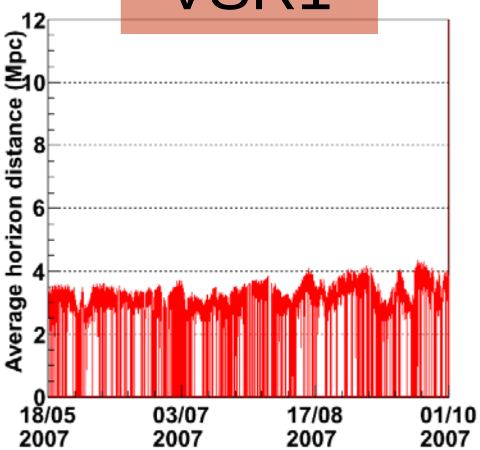




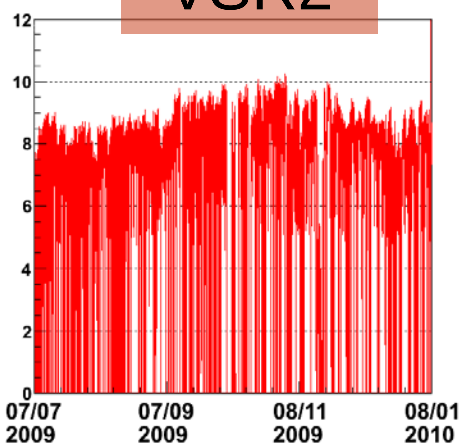
Virgo : VSR1, VSR2 runs

Virgo ➔ Virgo+
Improve laser, electronics, diffuse light, noise hunting, thermal compensation,

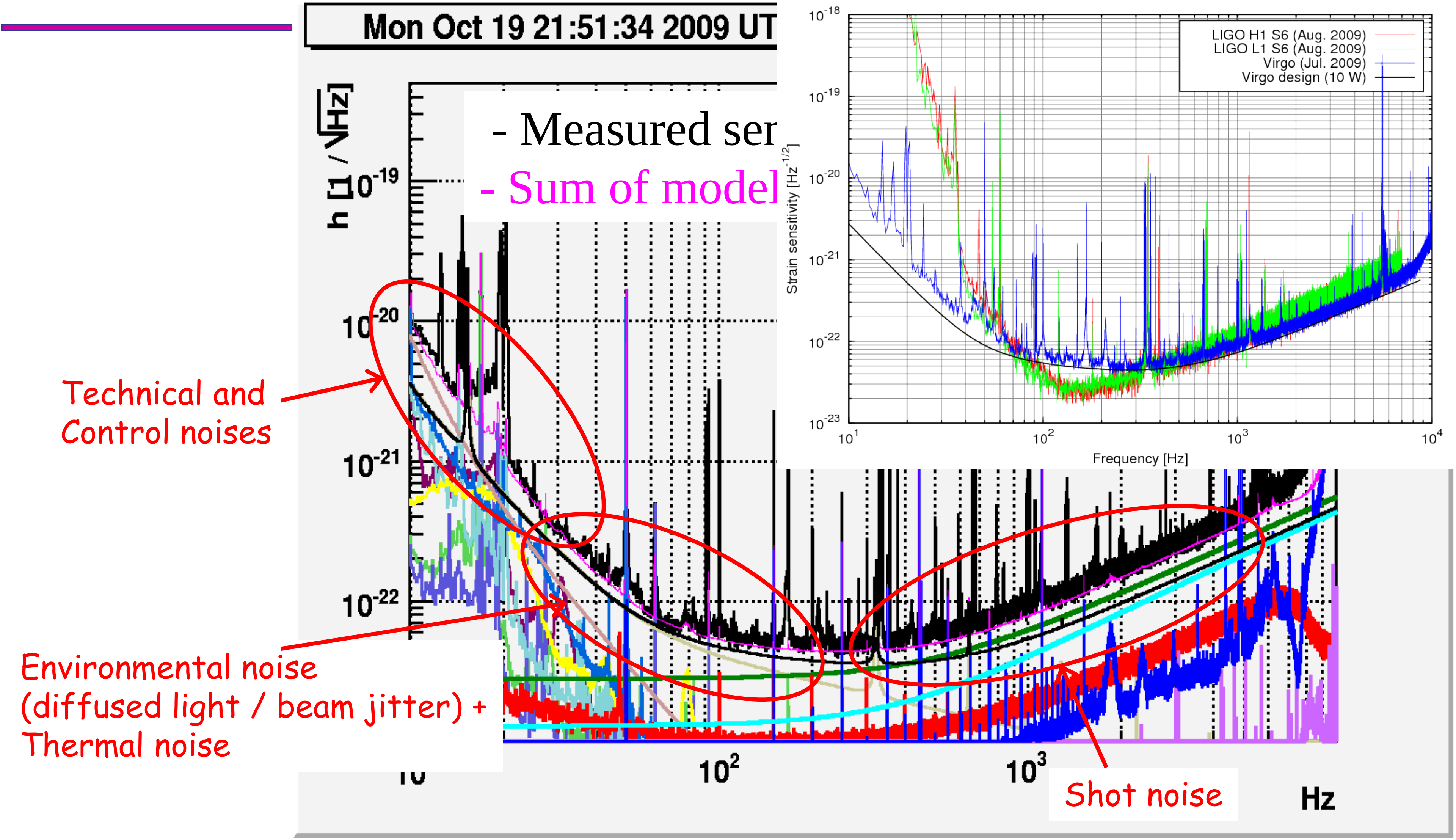
VSR1



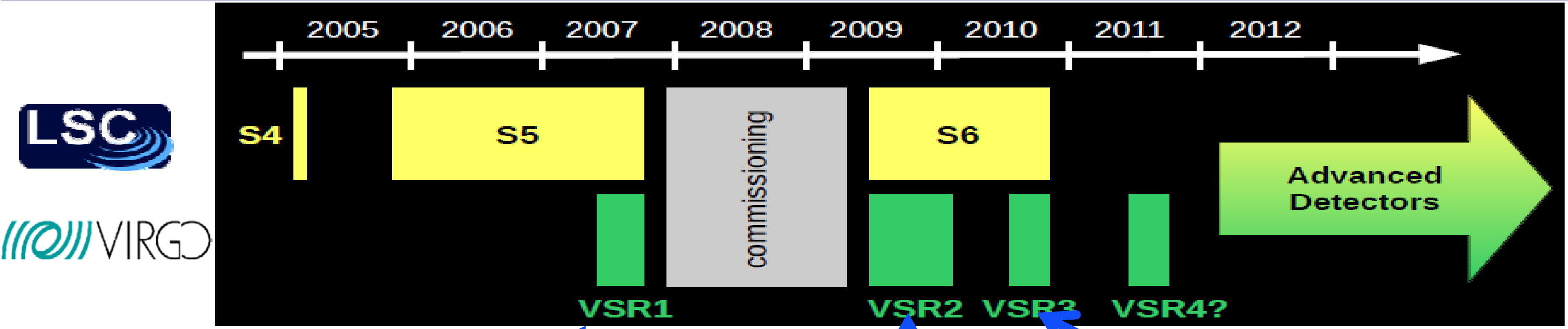
VSR2

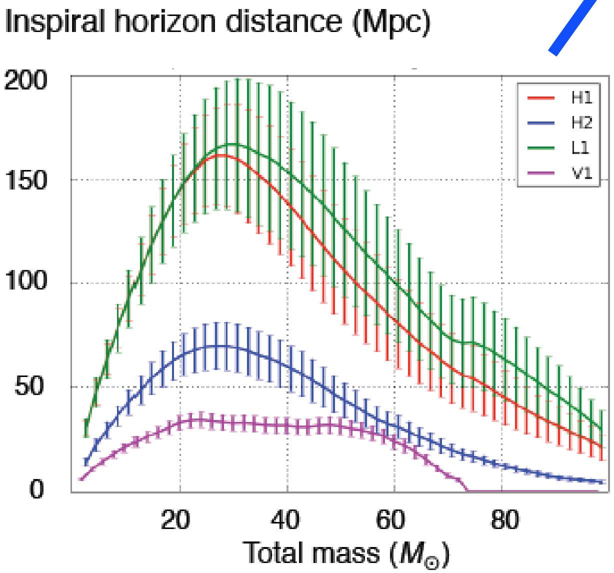


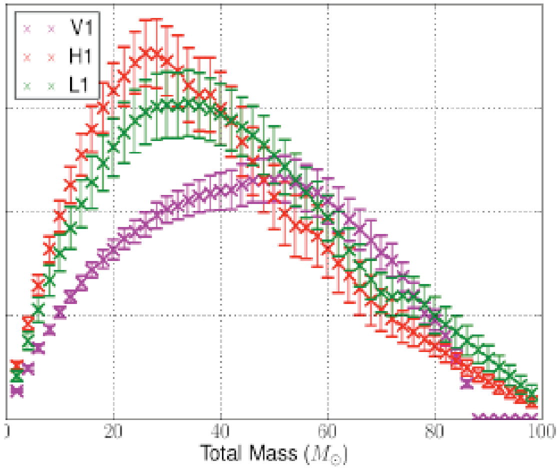
Oct. 2009 (VSR2) Virgo noise budget

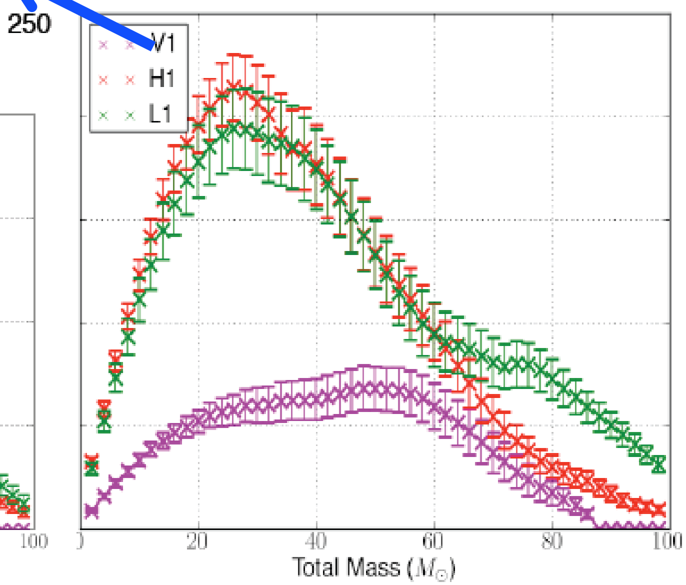


VSR3: installing monolithic suspensions…



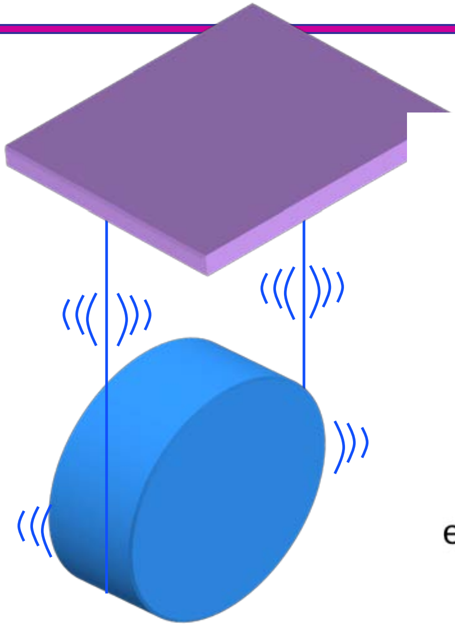


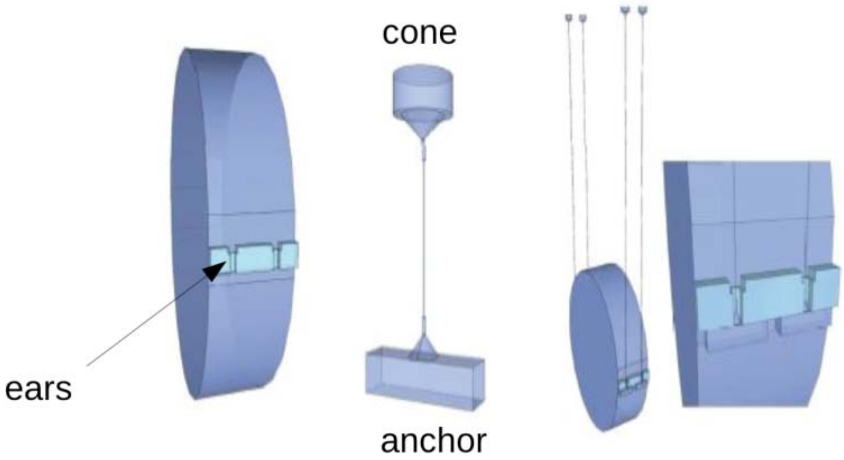


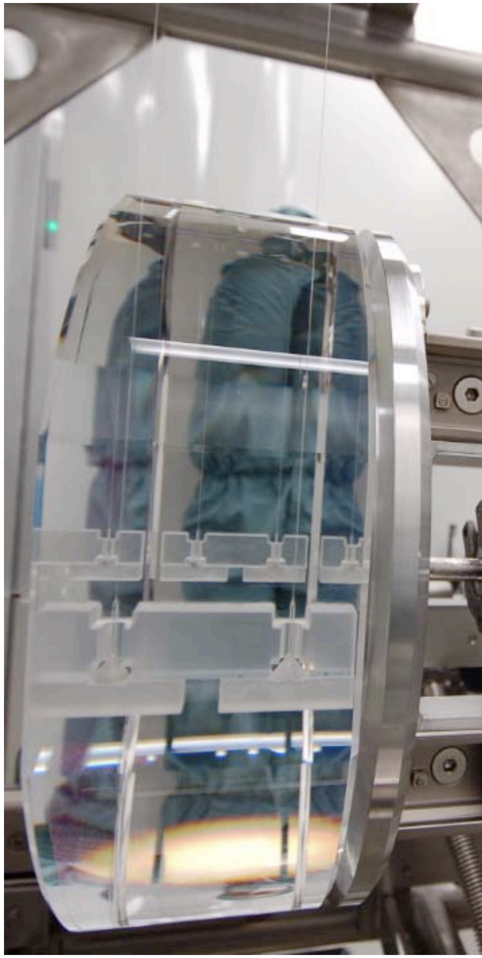


All S5 Beginning of S6/VSR2 End of S6/VSR3

2010 Virgo+ monolithic suspensions



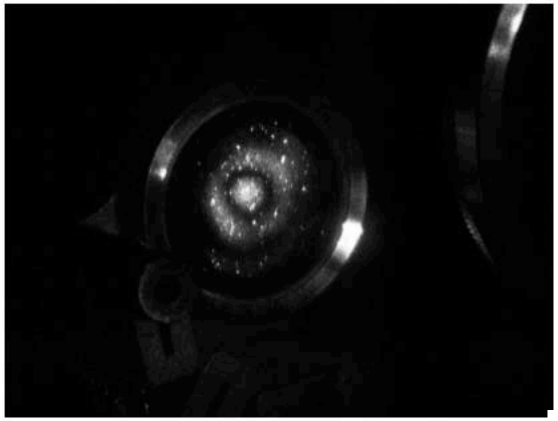


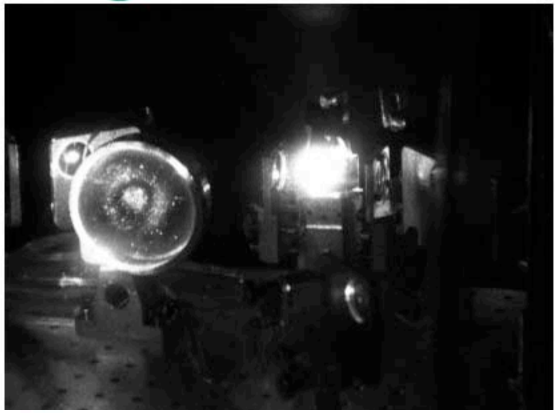


- Use of fused silica fibers to suspend the test masses
  - Replace steel wires
  - Reduction of suspensions thermal noise
  - Risk reduction for Advanced Virgo
- 4 arm-cavity mirrors installed in the spring-summer 2010
- No robustness or control problems experienced with monolithic suspensions.
- But…

…excess of light at the ITF output

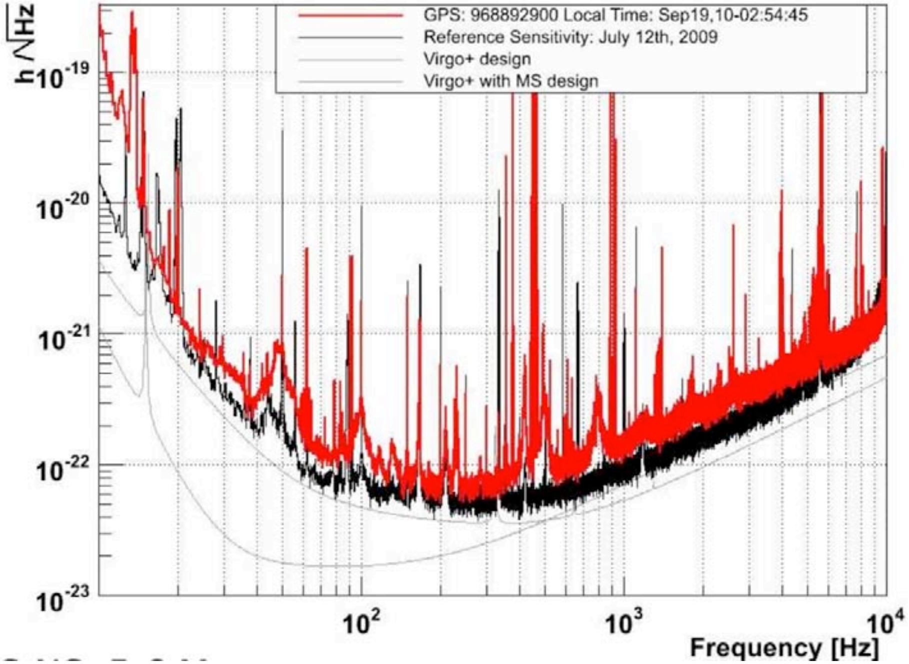
Before





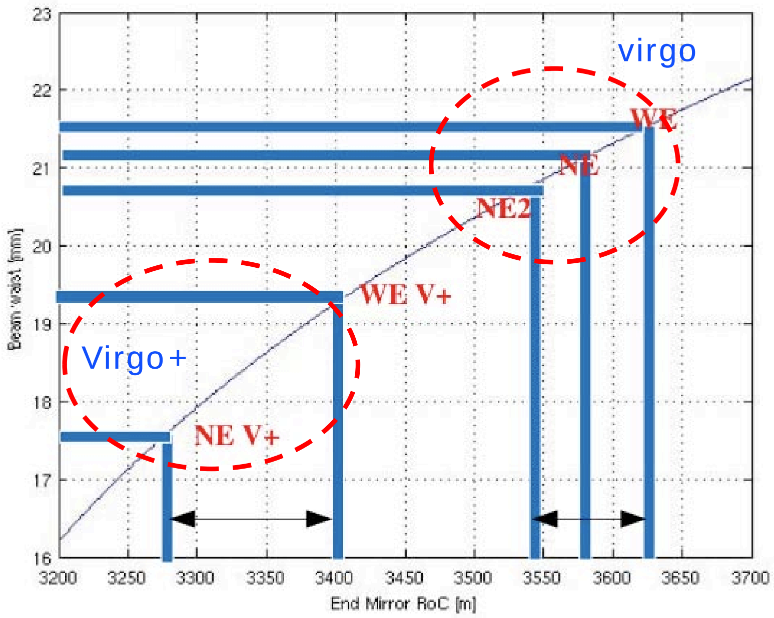
After

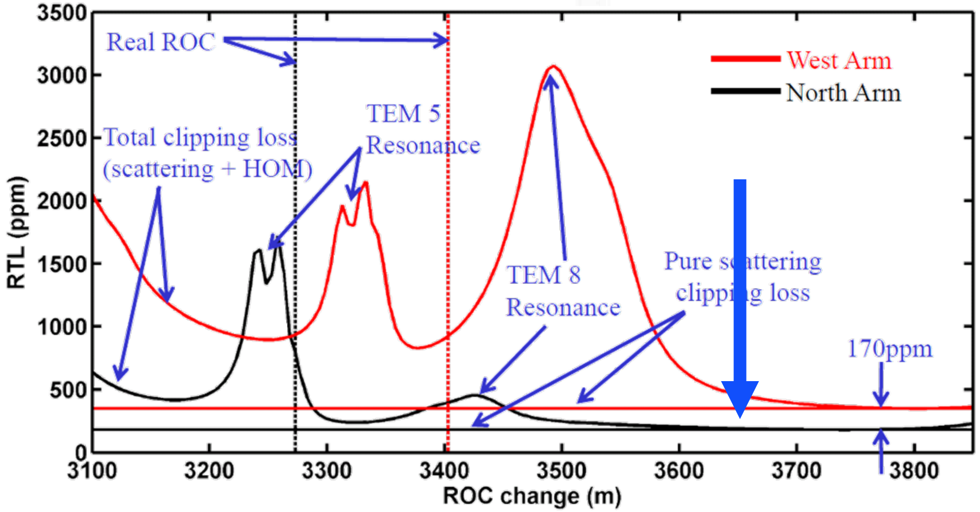
- Degradation of the interferometer contrast due to the waist mismatch (Laguerre-Gauss mode 01)
- lot of power (2-3 W)
- Scattered light on the detection optics
- VSR3 sensitivity only 5-6 Mpc
  (8-9 before monolithic suspensions)
- Part of the problem fixed with beam dumps



Problems with radii of curvature of the new end mirrors

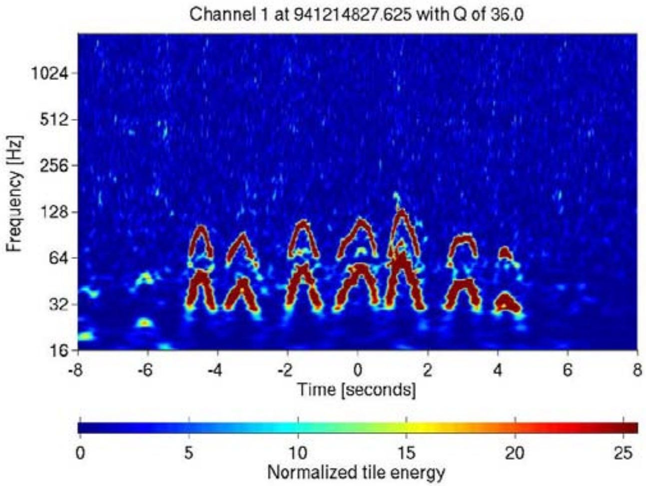
- Mirrors inside the specifications
  - 3450+-100m,
- But asymmetry and average value of the ROC changed
- Optical simulation:
  - importance of mode degeneracy inside Fabry-Perot cavities
  - not only the ROC asymmetry is important also the absolute value of the two ROCs
- Specifications not correct
- Solution: increase both ROCs by heating the center of the mirrors
  - Using a IR source
  - To minimize losses asymmetry between the two cavities



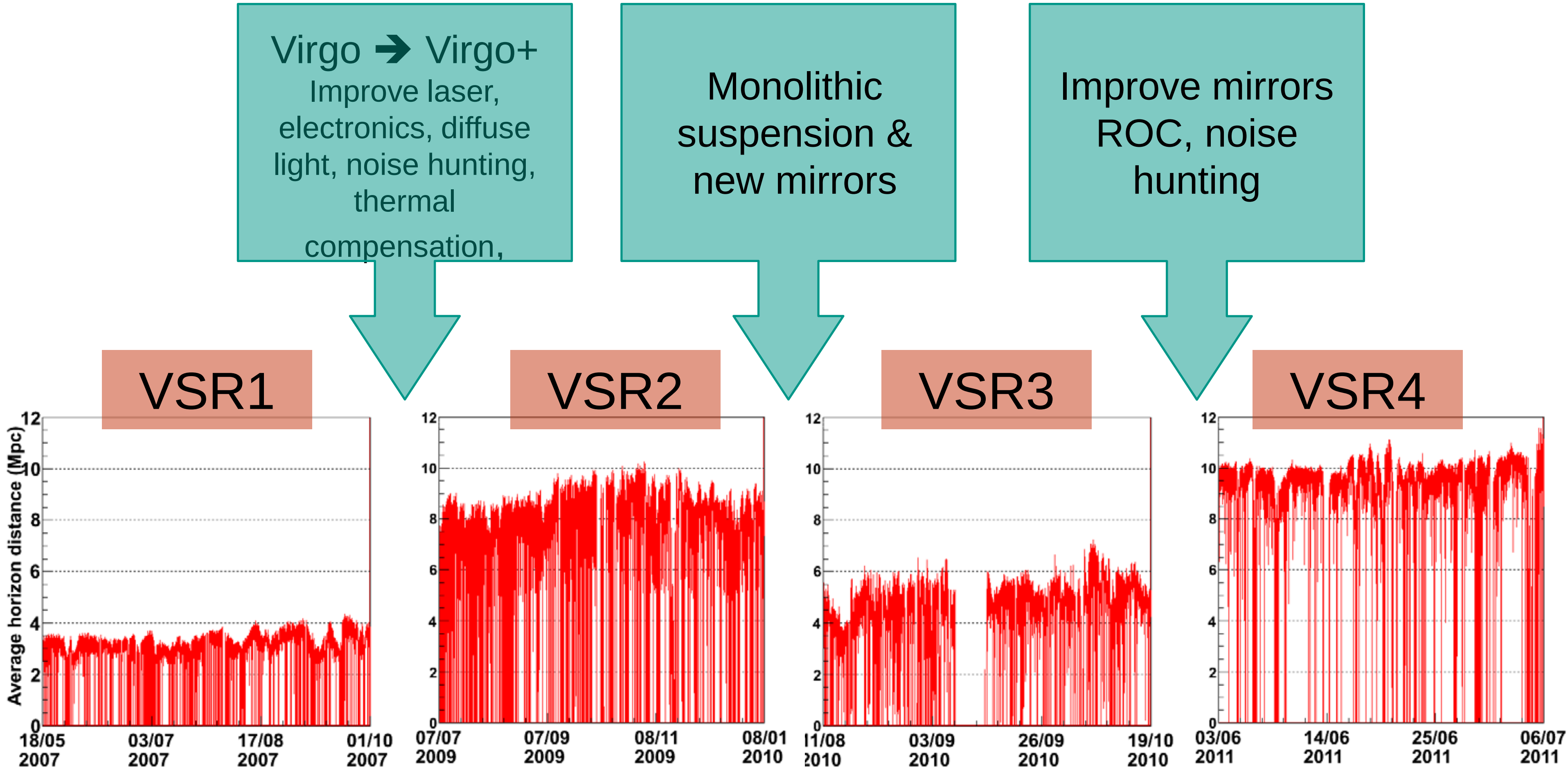


Dealing with scattered light

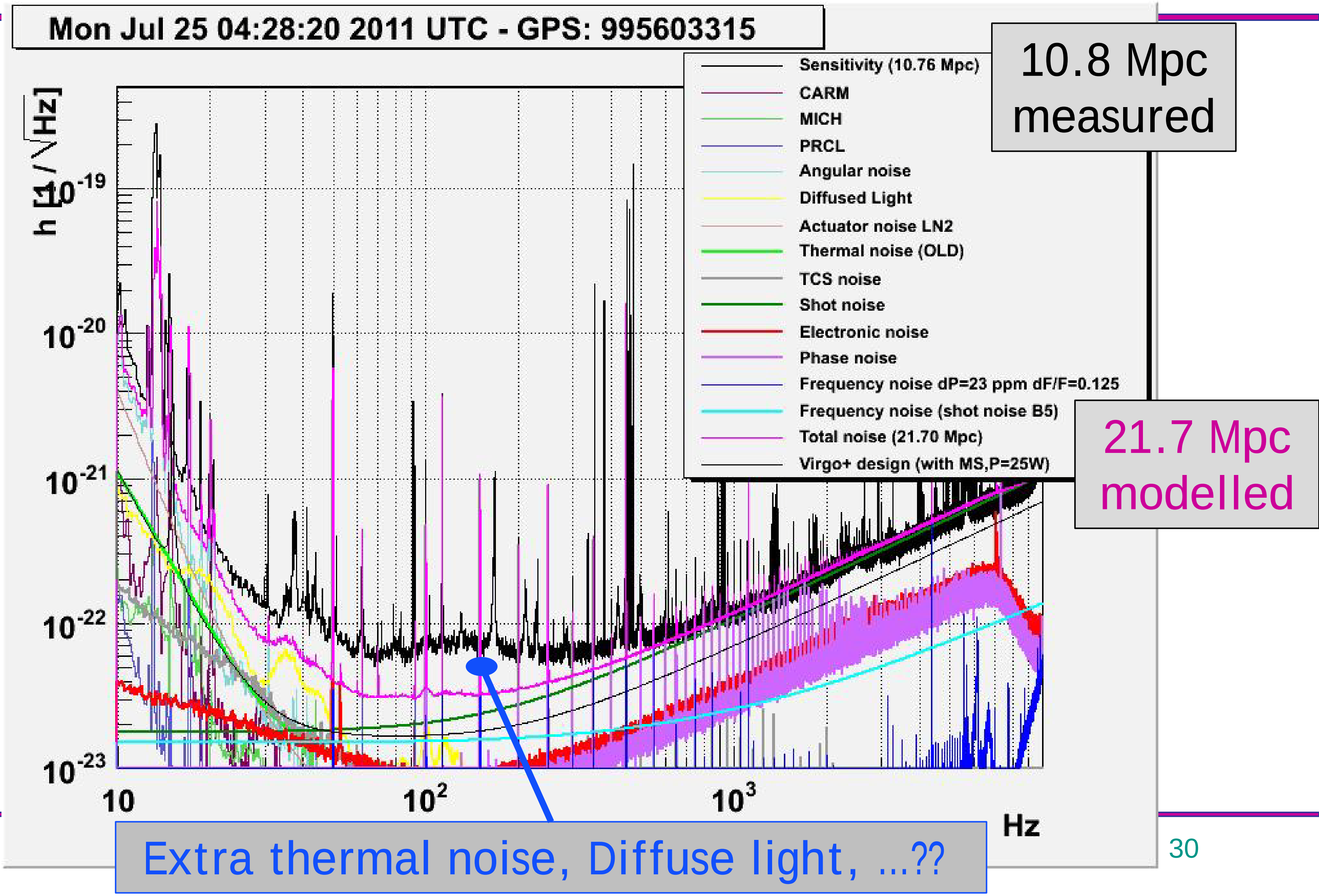
- Scattered light can couple back to main beam
  - ◆ Phase modulated by movement of scattering surface
  - ◆ Source of excess noise + non-stationary noise (glitches)
- Trap stray light
  - ◆ Baffles, beam dumps…
- Minimize coupling by seismically and acoustically isolating sensitive elements



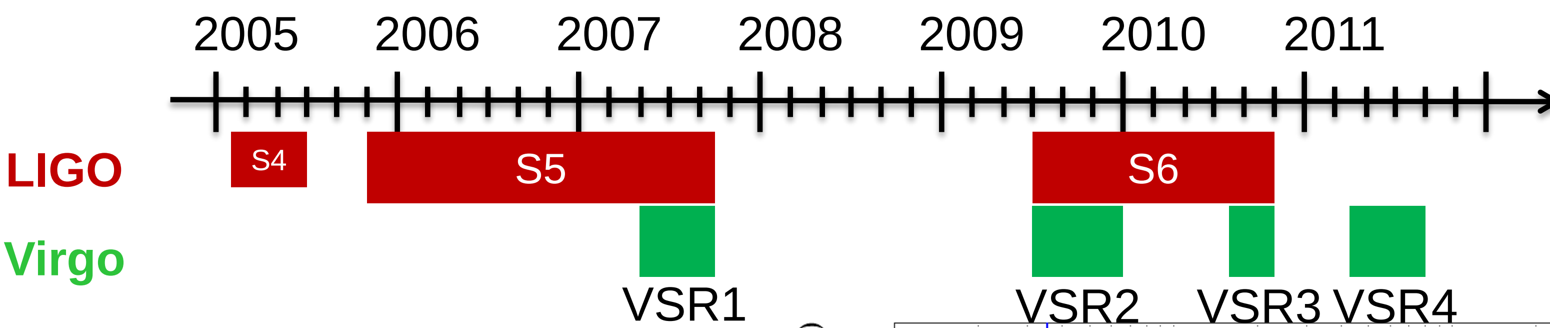
Virgo : Four science runs



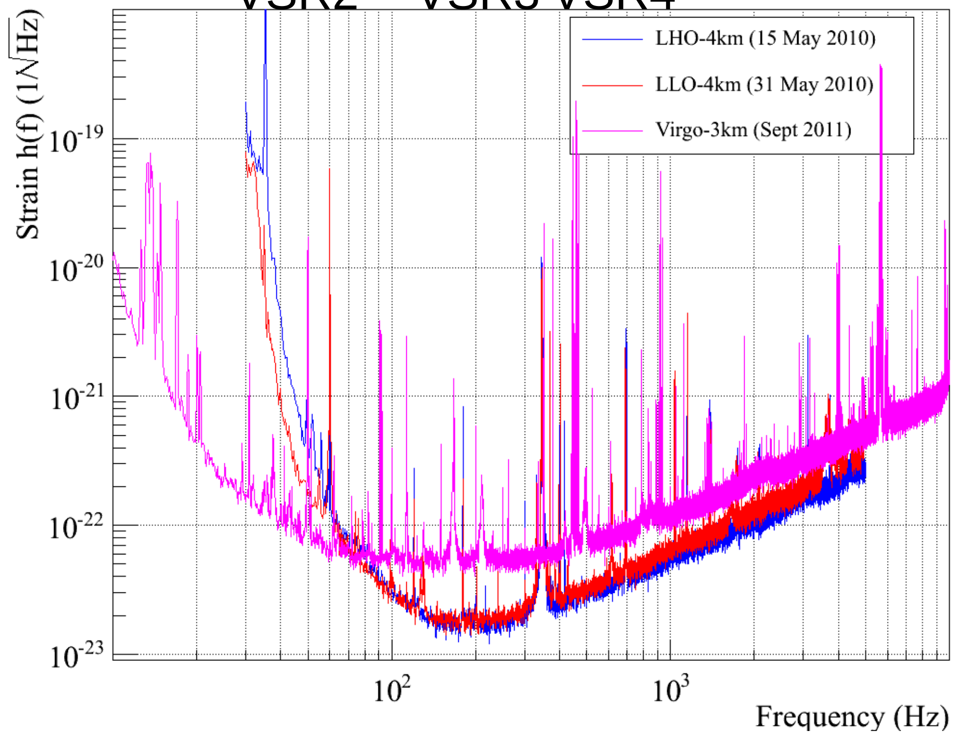
VSR4 noise budget



1st generation achievements



- Operating detectors at their nominal sensitivities took years of effort
- Long science data taking
- No detection, but some science!



Science achieved with 1st generation

- All sky searches
  - Compact coalescing binaries
  - Burst sources
    - » Supernovae, cosmic strings…
  - Continuous waves (spinning neutron stars) :
  - Stochastic background
- Targeted searches
  - Known pulsars
  - Neutron star oscillations
    - » SGR flares, pulsar glitches
  - Gamma ray bursts
    - » Long & short
  - High energy neutrinos
- Search for electromagnetic counterparts to GW

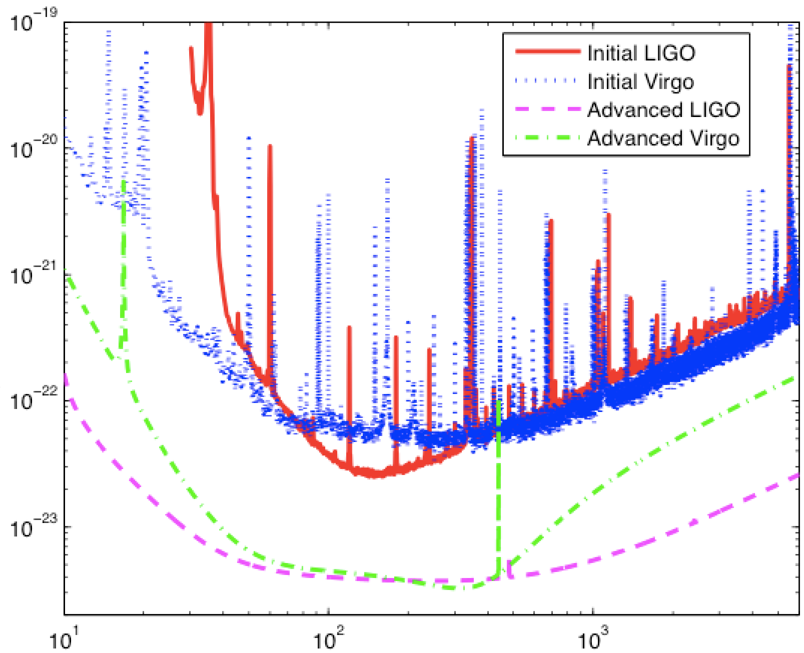
Gravitational waves

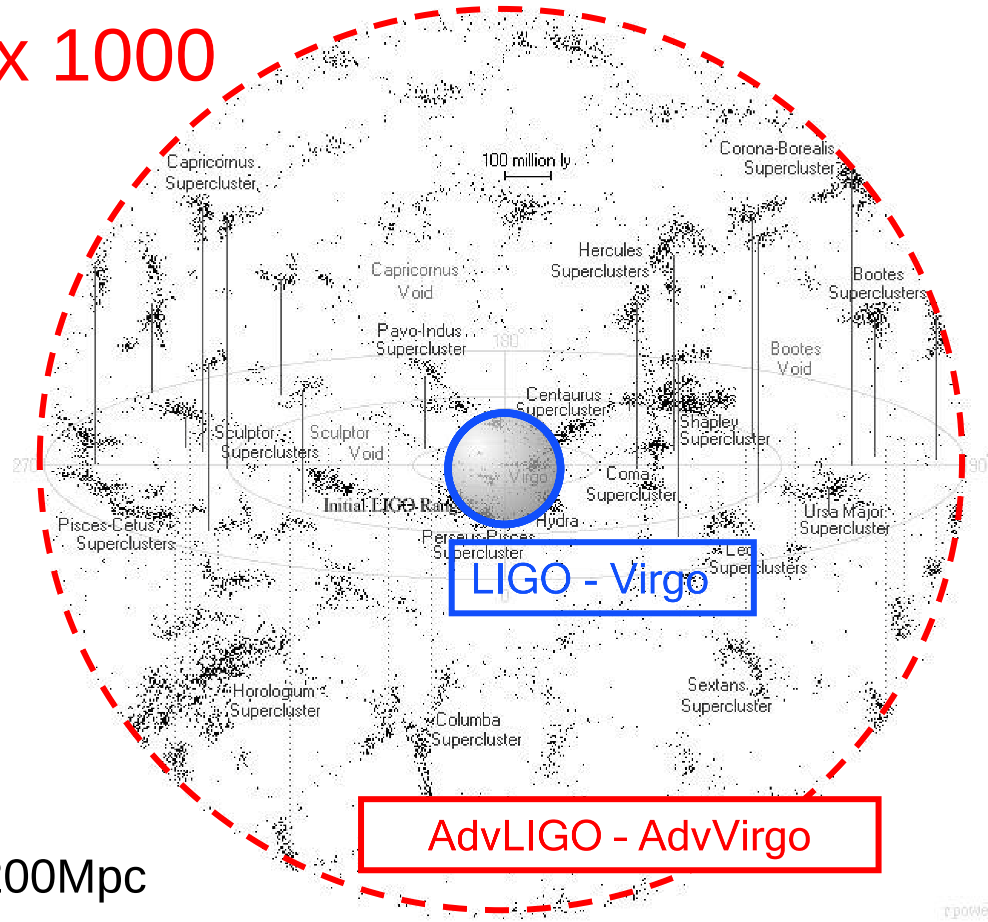
Other messengers

From first to second generation

Advanced Virgo & Advanced LIGO

Sensitivity x10 = Volume x 1000





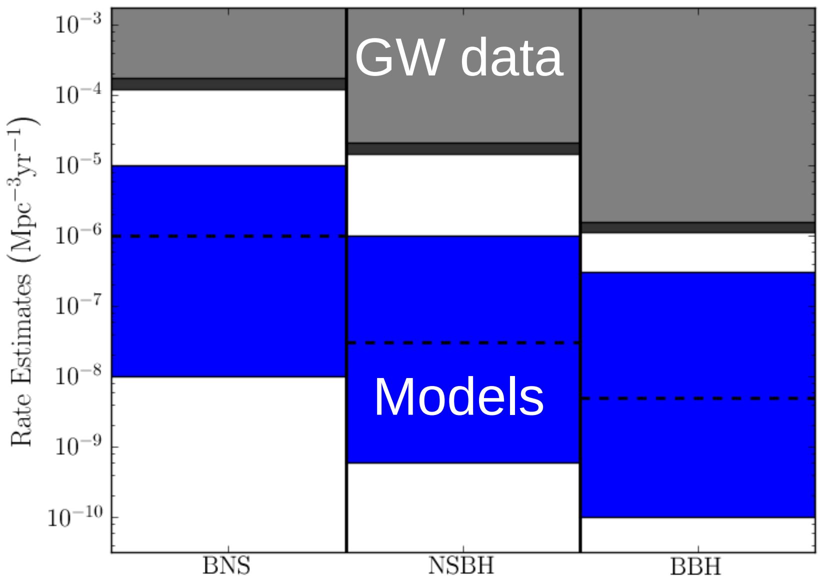
Very likely detection:

- ◆ BNS : ~ 40/year, typical range: 200Mpc
- ◆ BBH : ~ 20/year, typical range 1Gpc ➔ Start cosmology

- Planning: commissioning 2013-15, first data taking 2015/16

CBC: initial detector rates

IFO	Source[a]	$N_{\rm low}$ $\rm yr^{-1}$	$N_{\rm re}$ $\rm yr^{-1}$	$N_{\rm pl}$ $\rm yr^{-1}$	$N_{\rm up}$ $\rm yr^{-1}$
	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			$10^{-4\,d}$	$10^{-3\,e}$



- Rate upper limits from LIGO-S6/Virgo-VSR2-3 data
- ~1 order of magnitude above optimistic estimates

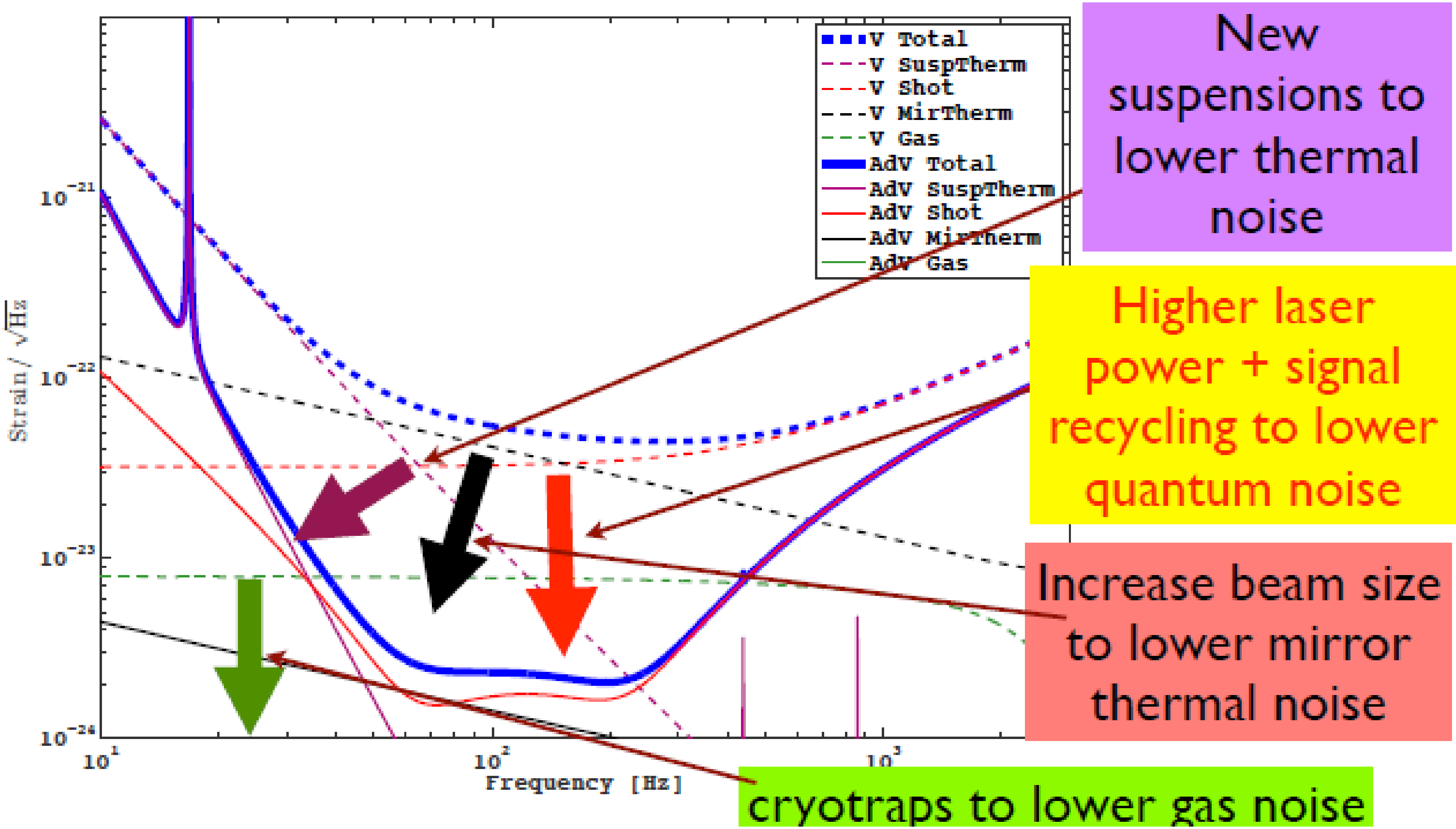
CBC: advanced detector rates

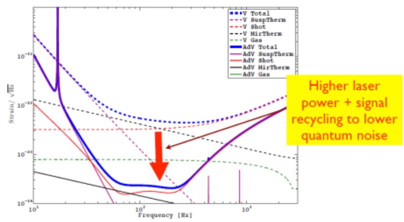
IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm pl}$ yr^{-1}	$\dot{N}_{\rm up}$ yr^{-1}
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

Realistic rates do get substantial for advanced detectors

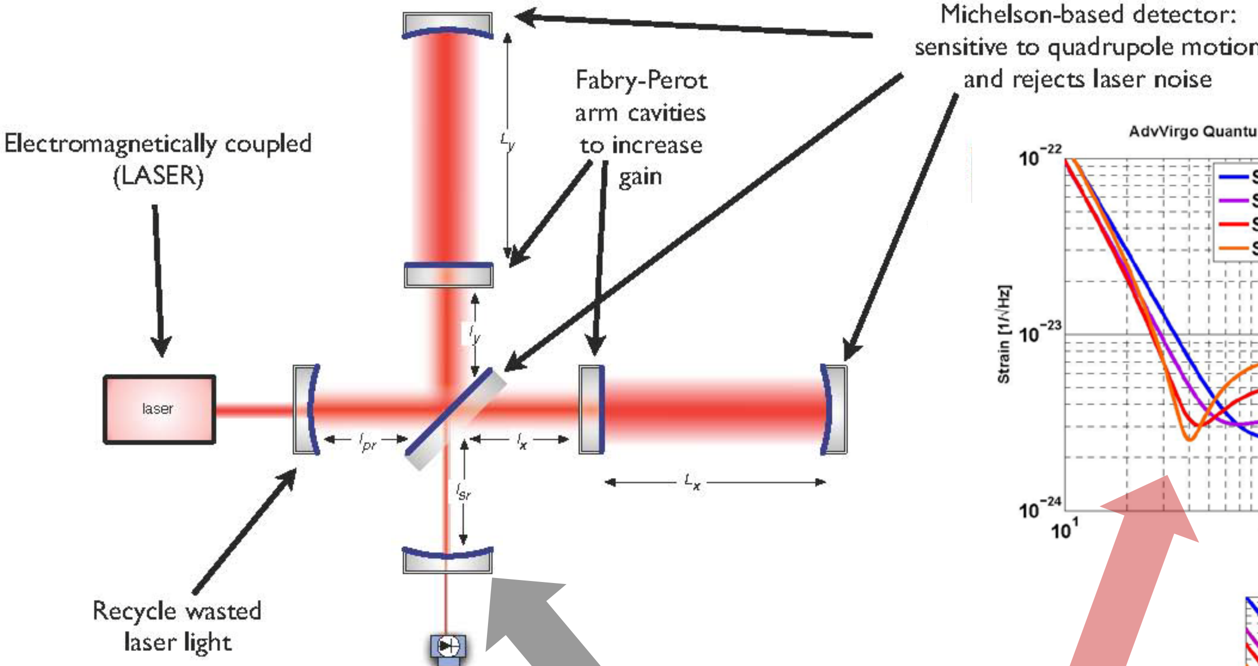
BBH visible up to a few Gpc

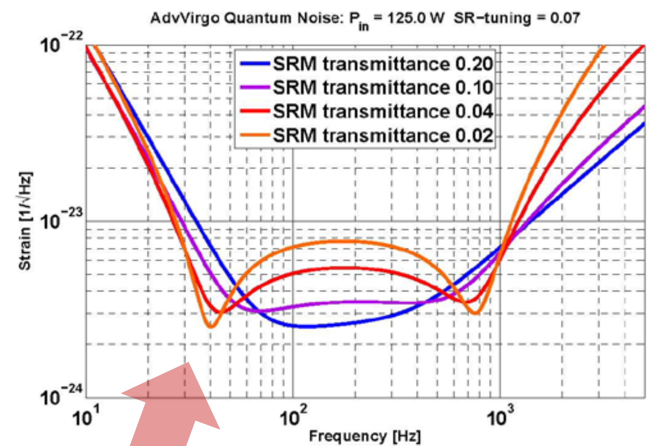
Sensitivity x 10: How?

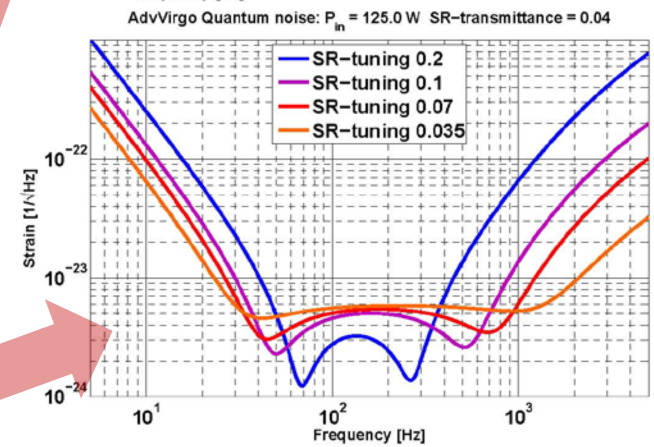




Signal recycling







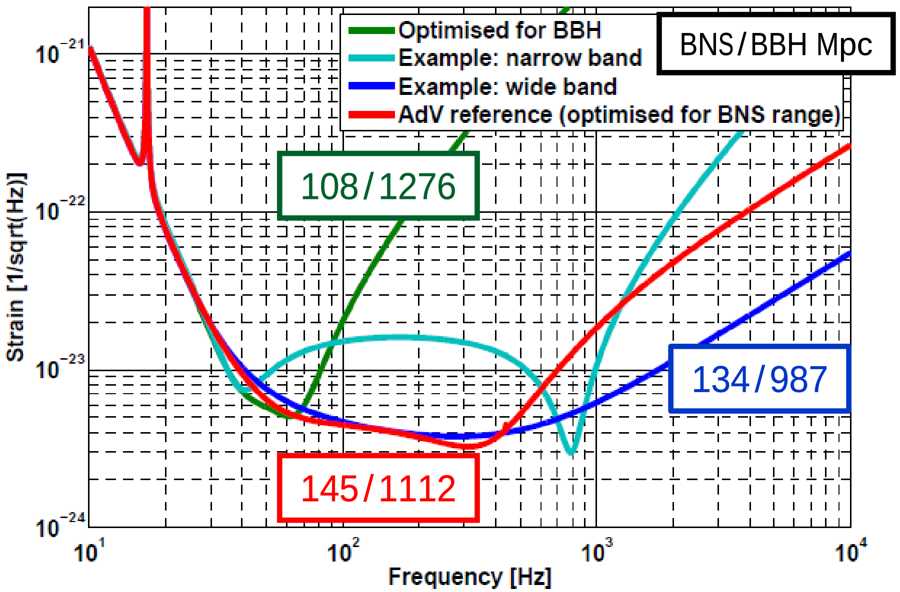
Signal recycling

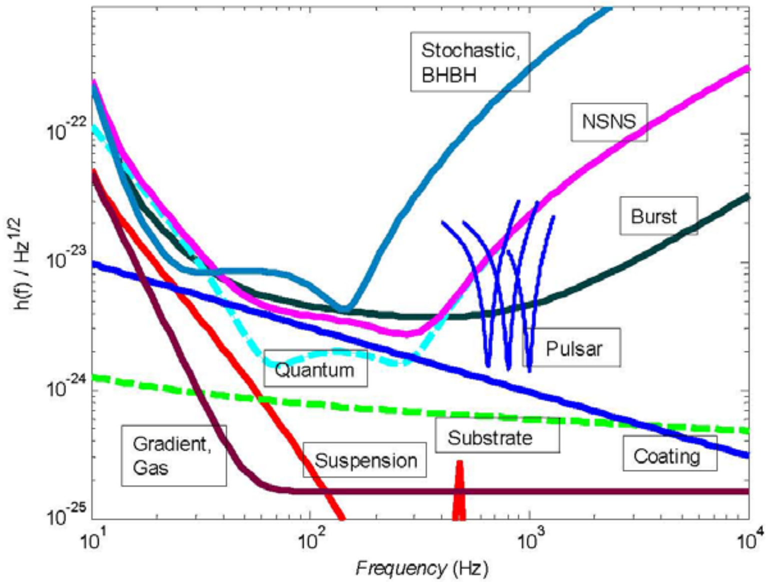
Shape the signal frequency response

SR mirror transmittance ➔ bandwidth

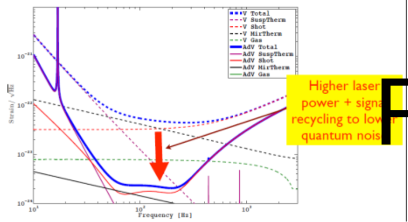
SR mirror tuning ➔ peak sensitivity frequency

Sensitivity tunability

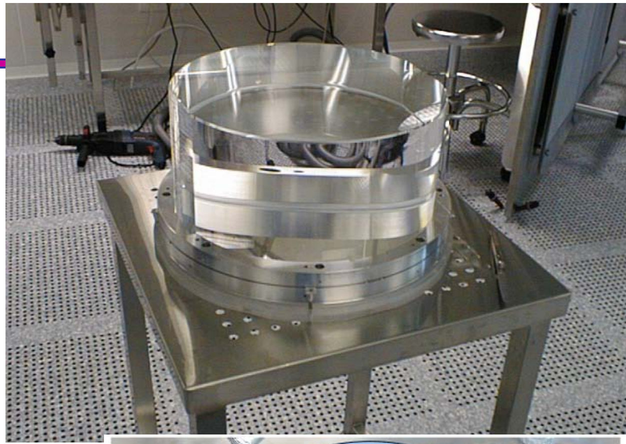




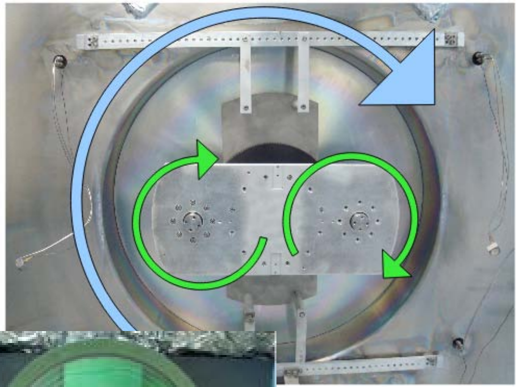
- Some degrees of freedom in the advanced detectors sensitivity curves
  - some contingencies too…
- Can be tuned to detect/study various sources



Reduce the shot noise: New mirrors



- Increased the arm cavity finesse
- Mew mirrors with better flatness
  - Reduces the power loss by large angle diffusion
  - Goal: less than 50ppm per round trip
- Low absorption, high Q mirrors
- Super-polished surface
  - RoC tolerance: 1% (6% for initial Virgo)
  - All Roc within 0.2% (new)
  - Surface flatness: 0.5nm RMS (8nm for Virgo)
  - Absorption HR: < 0.5ppm (<5ppm for initial Virgo)
  - 0~ 0.3nm RMS on 150cm diameter
- Improved coating
  - New tools for better uniformity
  - New material to reduce coating thermal noise



Laser

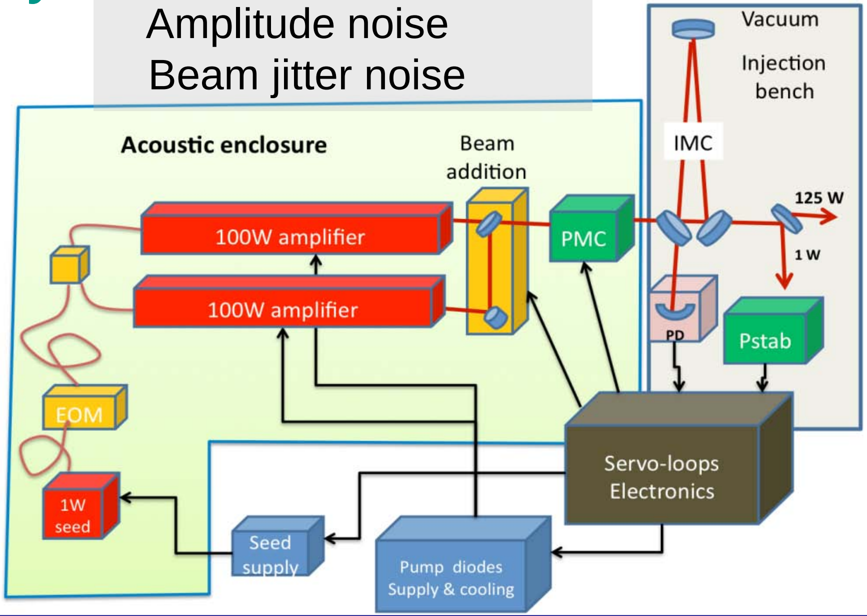
Initial detectors ~10 W input power → Enhanced detectors ~50 W → Advanced detectors ~200 W

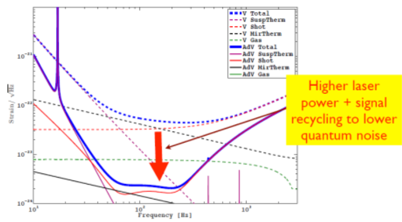
- Reduce shot noise

→ Improve high frequency sensitivity

- Cope with high power
  - Radiation pressure noise
  - Mirror thermal lensing
  - High power through input optics
- Requires new developments
  - Heavier mirrors
  - Improved thermal compensation
  - High power, low noise, input optics

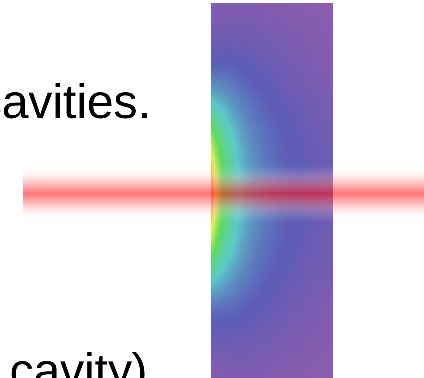
Other requirements
- Beam quality
- Frequency noise
- Amplitude noise
- Beam jitter noise



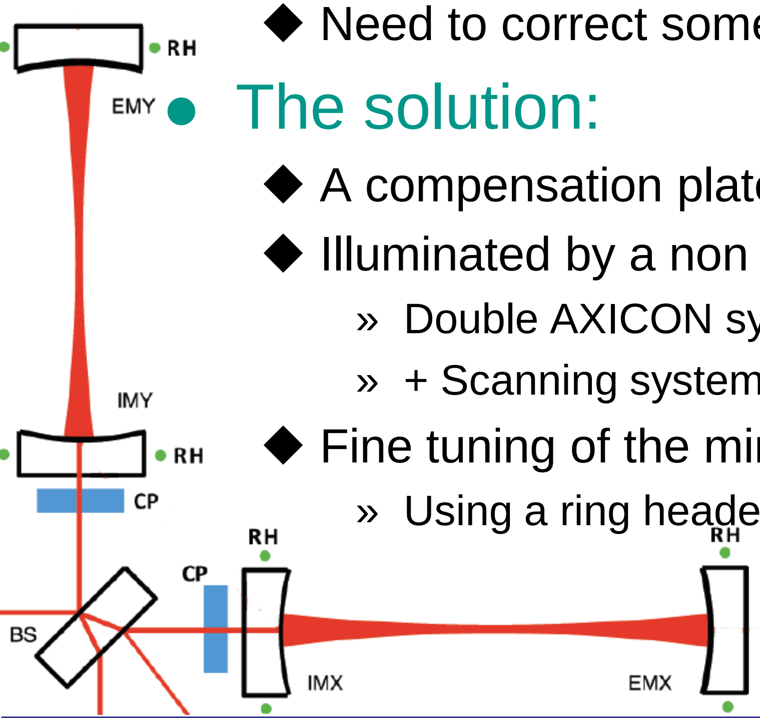


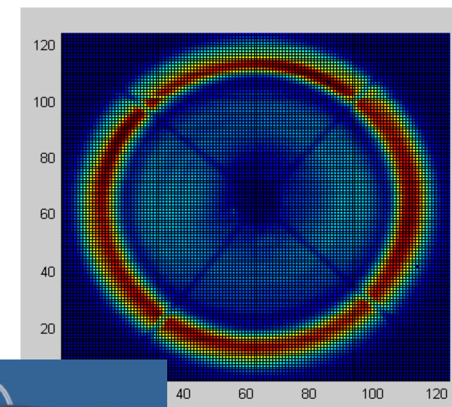
Thermal Compensation system

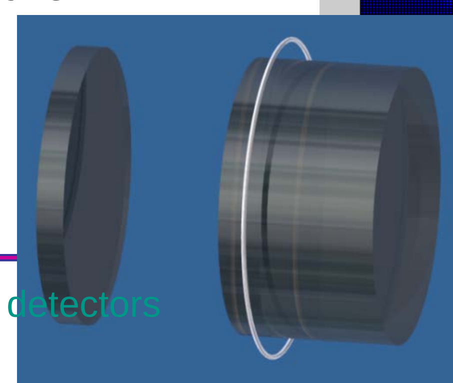
- **The main issue:**
  - The optics absorb some (O(ppm)) power stored in the cavities.
    - » Few kW on BS, ~MW in the arms for Advanced detectors
  - A thermal gradient is established in the substrate.
  - This create a thermal lensing: (dn/dT≠0, O(ppm/K)).
  - Need to correct some "cold" defects (unstable recycling cavity)



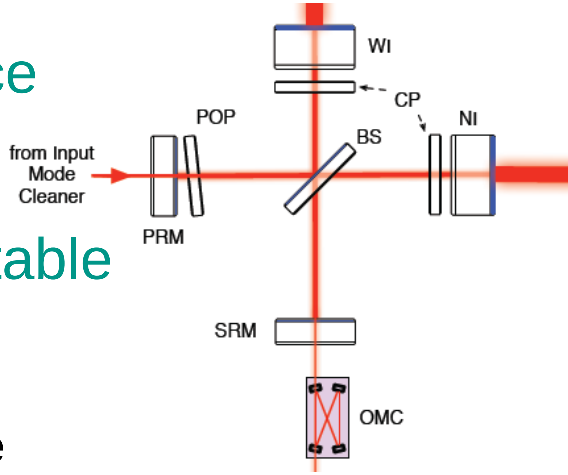
- **The solution:**
  - A compensation plate is added
  - Illuminated by a non uniform CO_2 laser
    - » Double AXICON system for accurate compensation
    - » + Scanning system
  - Fine tuning of the mirror radius of curvature
    - » Using a ring header around the mirror



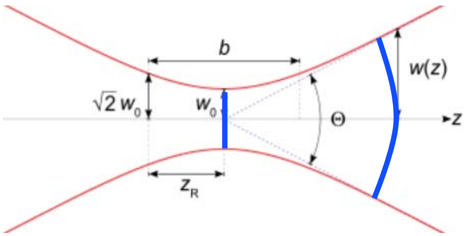




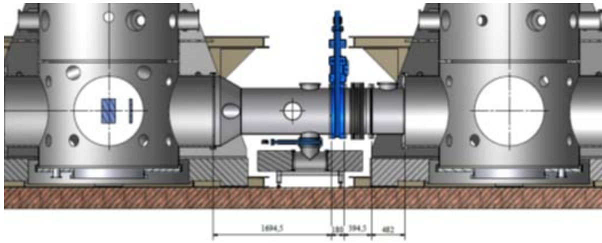
Increase beam size

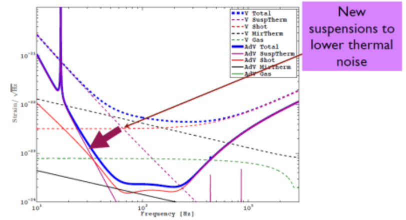


- Average coating thermal noise on a larger surface
  - Reduce thermal density load → reduces power induced aberrations
- Drawback: recycling cavity becomes (more) unstable
  - A laser beam always diverge
  - Propagation is different for the various modes
  - For a too short cavity, all modes resonate at the same time
  - Option of a “long” stable recycle cavity not selected by Virgo
  - Therefore Virgo need
    - “Perfect optics” to avoid problem
    - Tools to measure deformations: Hartman wave front sensors
    - Tools to correct them: thermal compensation system



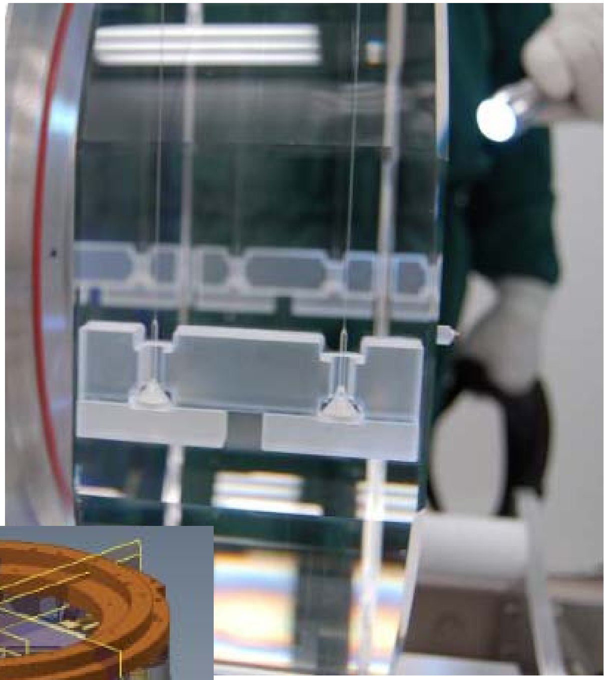
- Changes in the central area:
  - Larger vacuum tube / valve
  - Larger beam:
    - more complex mode matching telescopes
    - More difficult to isolate pickoff beams

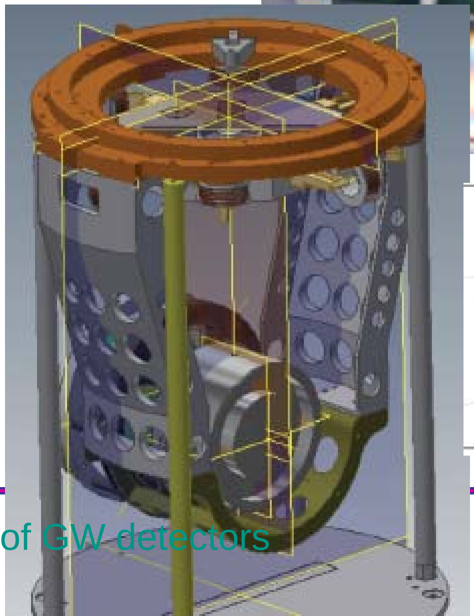


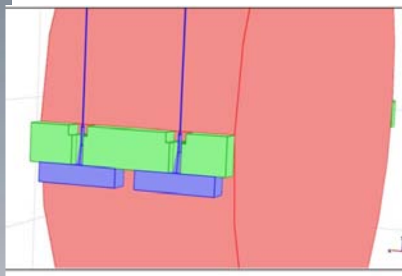


New monolithic suspensions

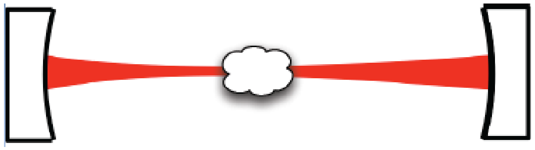
- Main optics are suspended from fused silica fiber
  - ◆ Low loss/ high Q system
  - ◆ Reduce the thermal noise effect
  - ◆ Improve the low frequency
- Installed in Virgo for VSR3
  - ◆ Some low Q factor observed
  - ◆ Improved design
- Heavier mirrors
  - ◆ From 21 to 42 kg
  - ◆ Reduce thermal noise effect
  - ◆ Reduce the radiation pressure effect
- Full new “payload”
  - ◆ Compensation plate added



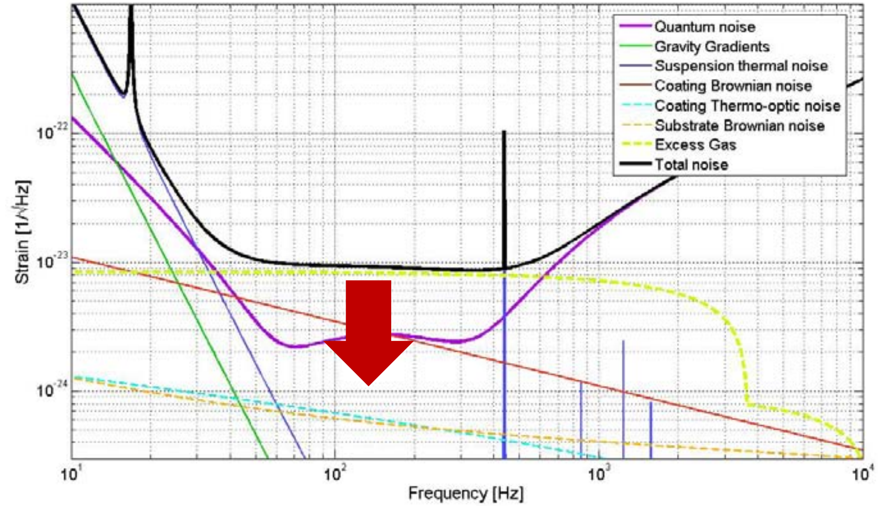




Vacuum

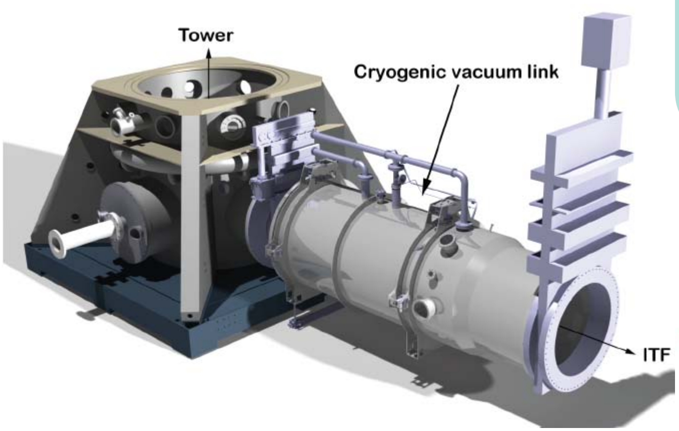


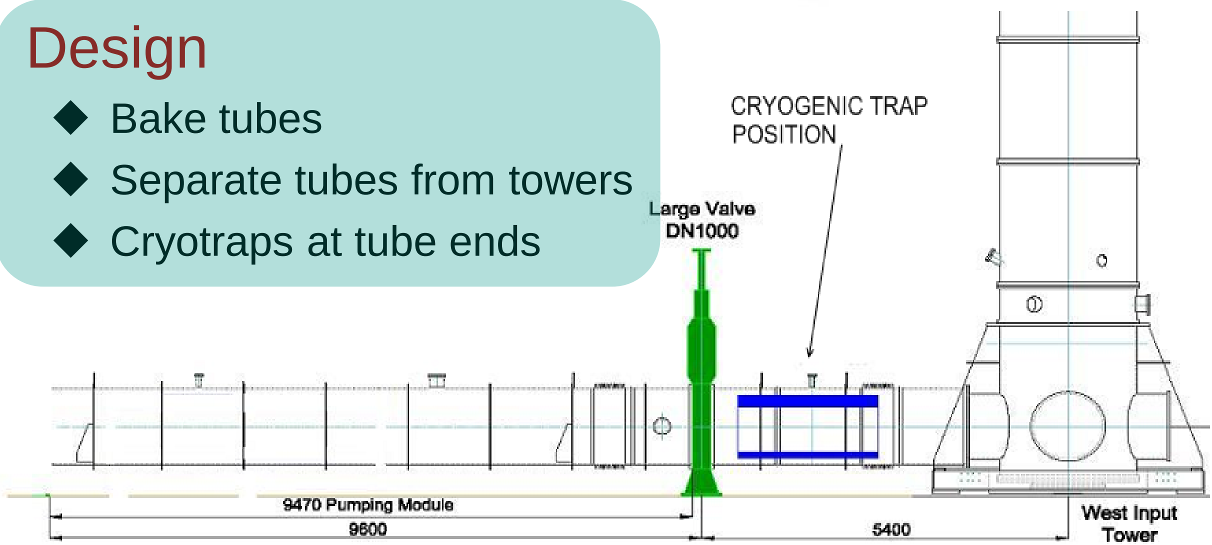
- Goal
  - Reduce noise due to index of refraction fluctuations
- Residual pressure in Virgo tubes
  - Current pressure ~ 10^{-7} mbar
  - /100 reduction required

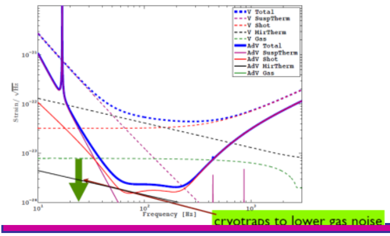


Design

- Bake tubes
- Separate tubes from towers
- Cryotraps at tube ends



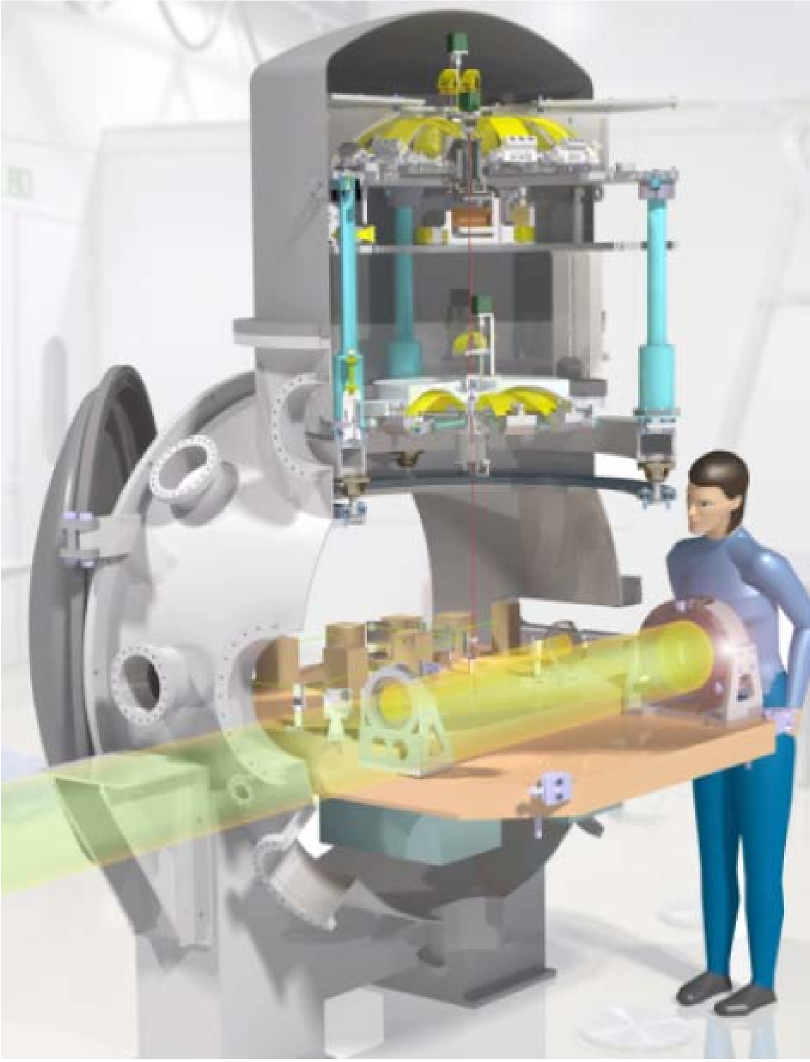




And more improvements…

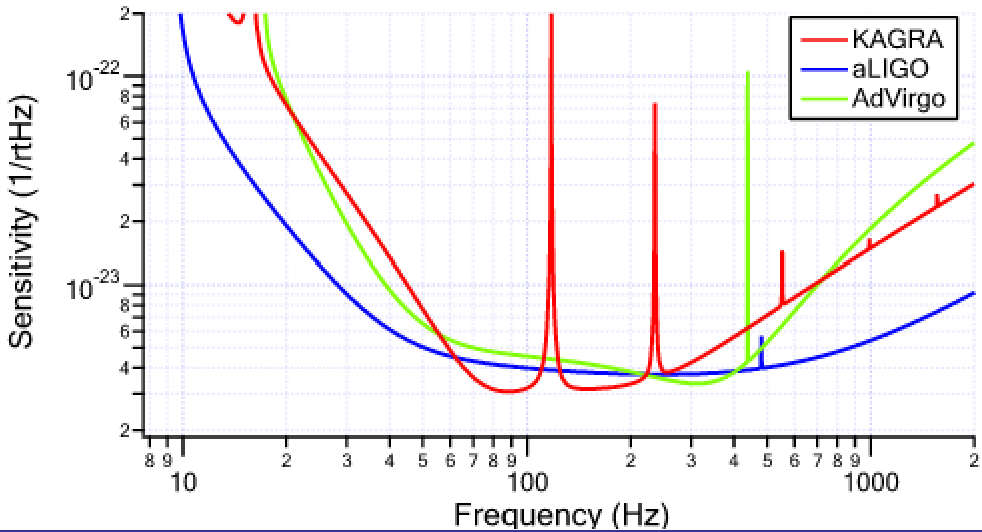
- High power optics:
  - ◆ Faraday isolator, Electro Optic Modulator, Photodiodes…
- New optical bench suspended under vacuum
- DC readout
  - ◆ New output mode cleaner

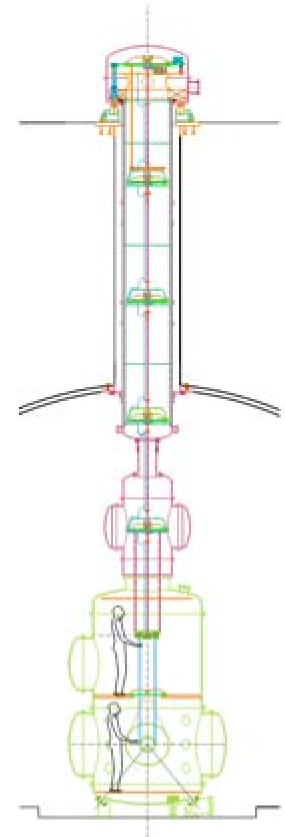
…



KAGRA Japan

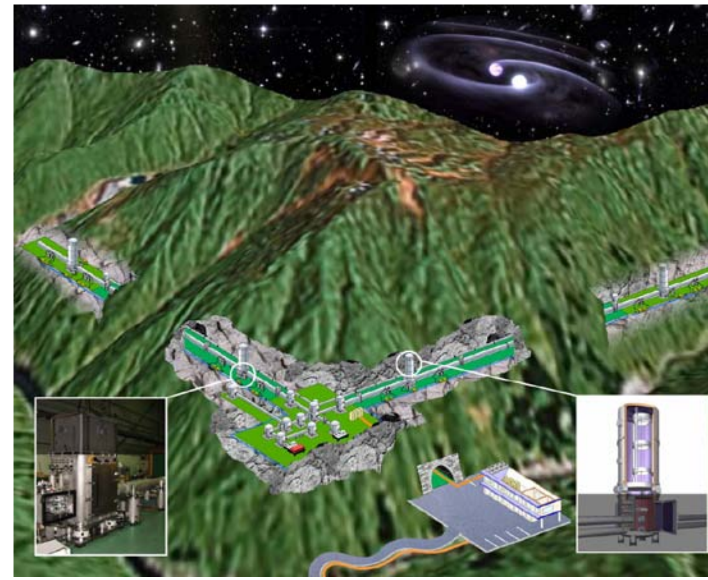
- 3km arm length
- Underground; Kamioka mine
- Approved in 2010
- Construction ongoing
- First step « warm » (2015) then cryogenic…

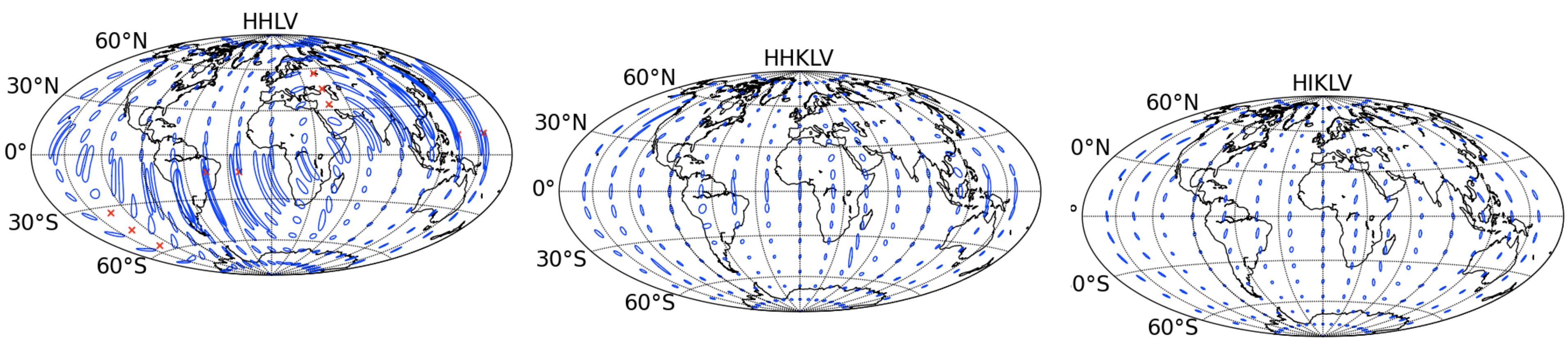




Toward an extended 2nd generation network

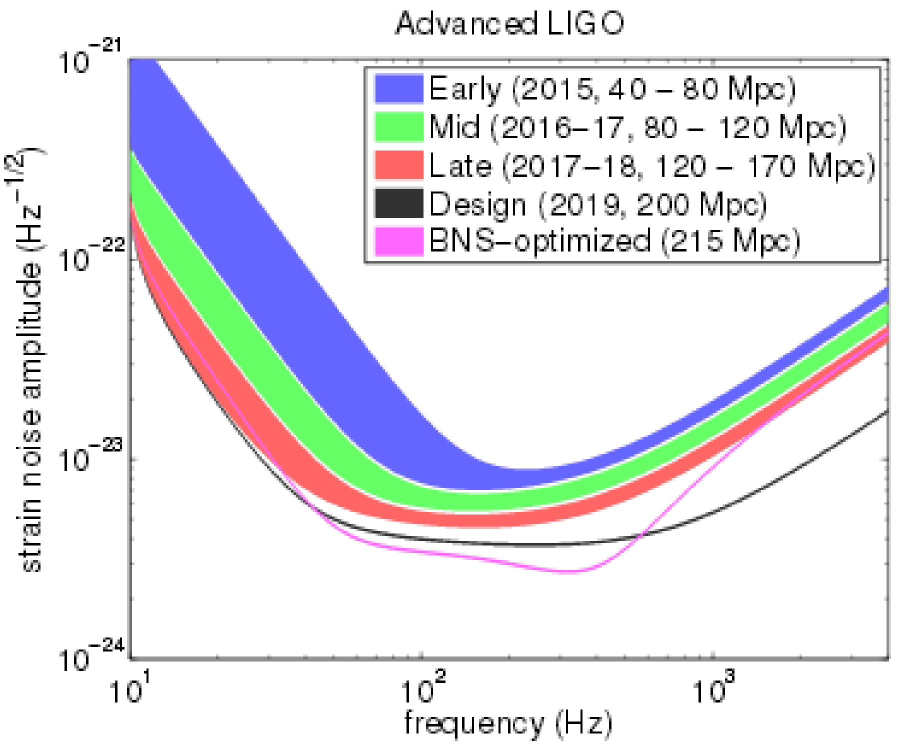
- KAGRA in Japan
- Third LIGO detector expected to go to India
- Duty cycle
  - ~80% at best for one detector
  - ~50% for three detectors in coincidence
- Sky coverage
- Source localization capability

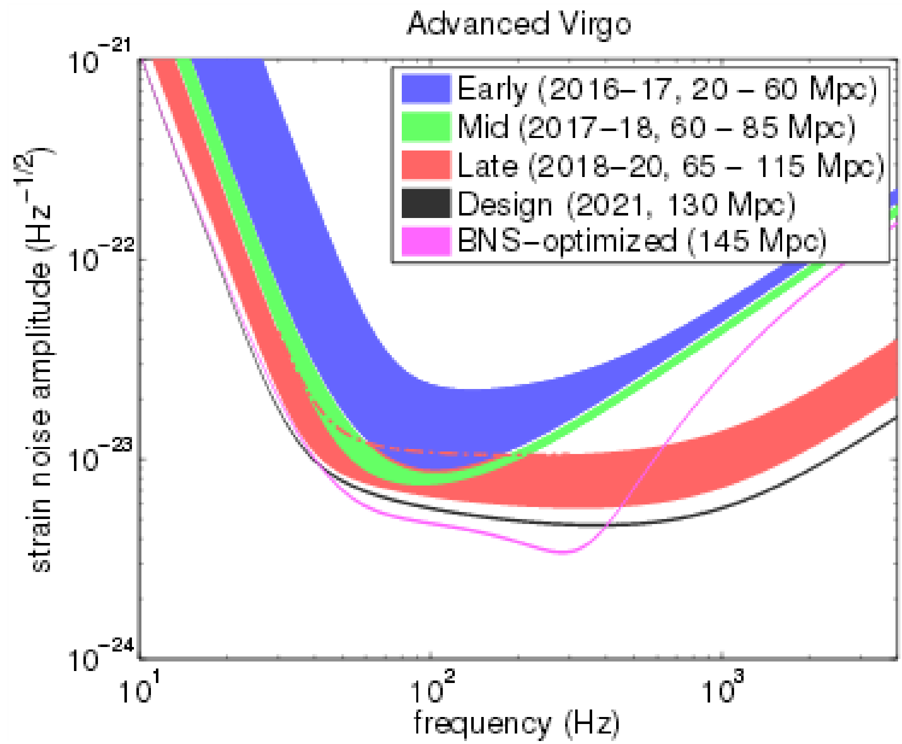




aLIGO and AdVirgo schedule?

- A current estimate:





…but commissioning usually does not go as you expect…..

Conclusion

- First generation GW interferometric detectors
  - Reached their designed sensitivity
  - Collect data as a world wide network
  - Start to give astrophysical limits & multimessenger activity
  - Field & community matured with 1st generation detectors
- Second generation ("Advanced") detectors
  - Upgrades well advanced
  - Should begging collecting data in 2015
  - Extended network
  - Are very likely to open the GW astronomy