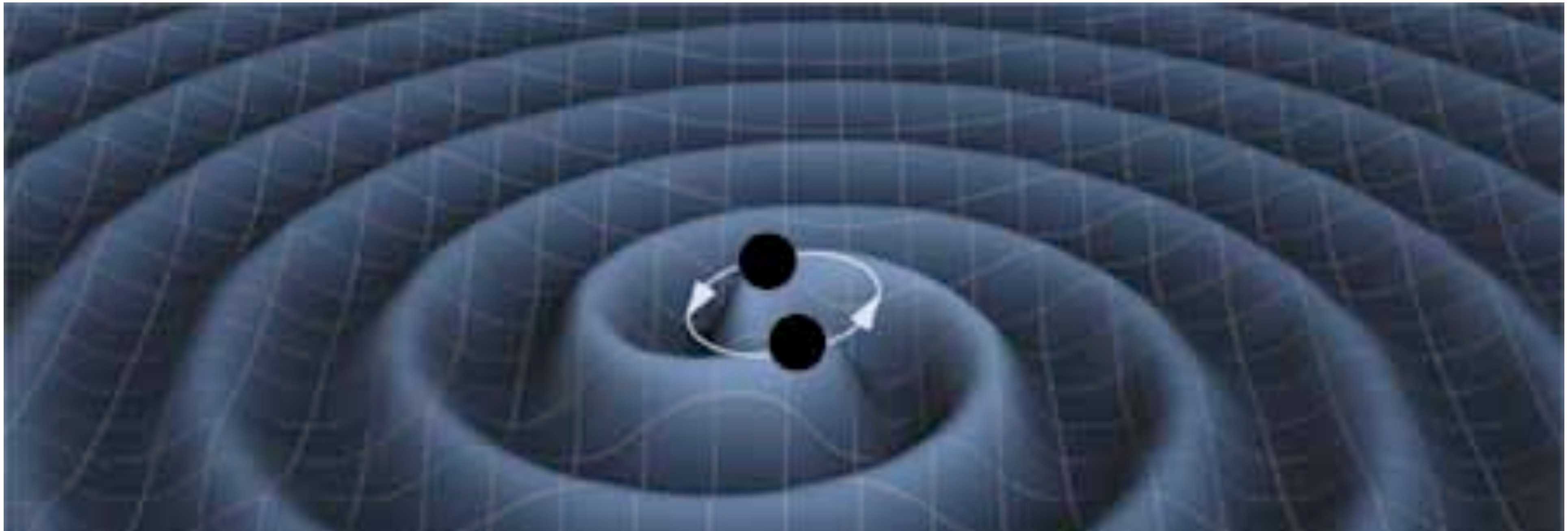


VESF School 2013
Advanced Virgo: Sensitivity and perspectives

Andrea Viceré
Università degli Studi di Urbino "Carlo Bo" & INFN Firenze

ESSENTIALS ON GRAVITATIONAL WAVES

RIPPLES IN THE COSMIC SEA

- Linearized Einstein equations admit wave solutions, as perturbations to a background geometry

$$\mathbf{G} = \frac{8\pi G}{c^4}\mathbf{T}$$

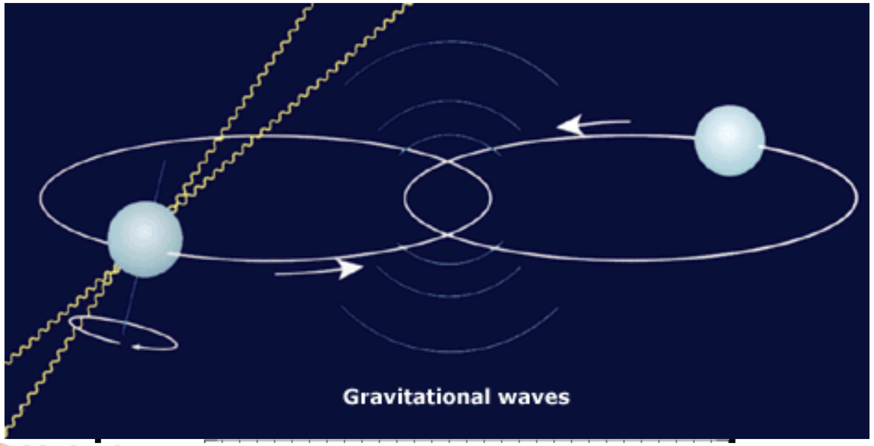
$$\mathbf{g} = \eta + \mathbf{h} \;\; \text{with} \; |h_{\mu\nu}| << 1 \;\; \Rightarrow \;\; \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

- **Gravitational Waves**:
  transverse space-time distortions propagating at the speed of light, described by 2 independent polarization

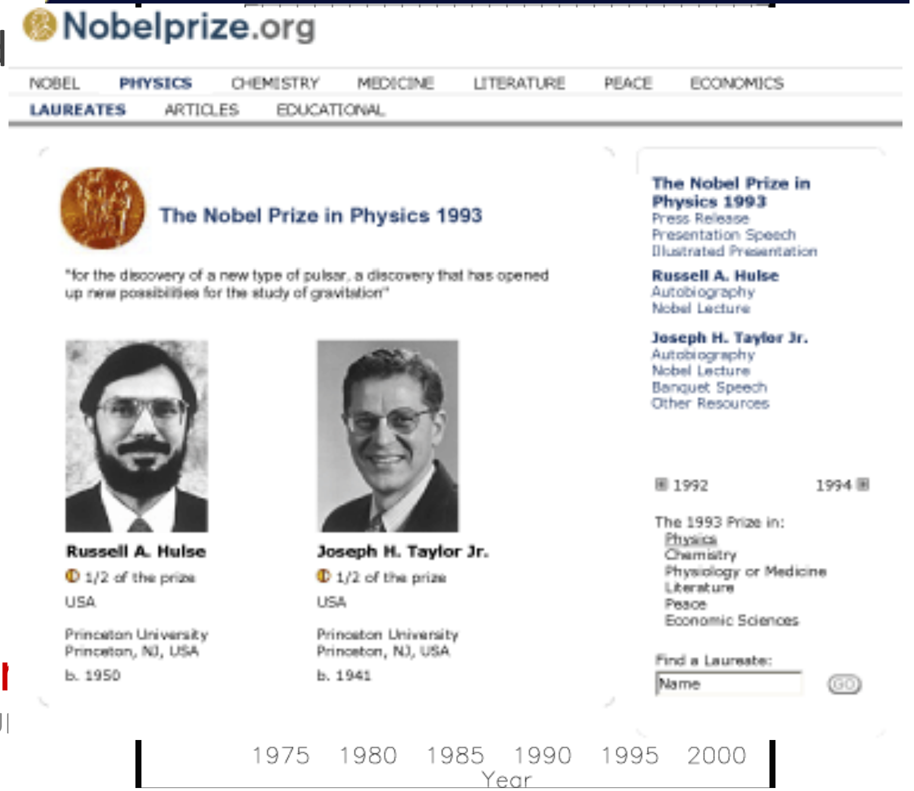
$$\mathbf{h}(z,t) = e^{i(\omega t - kz)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

PSR1913+16: GW DO EXIST

- Pulsar bound to a "dark companion", 7 kpc from Earth.
- Relativistic clock: $v_{max}/c \sim 10^{-3}$
- GR predicts such a system to lose energy via GW emission: orbital period decrease
- Prediction of general relativity verified at 0.2% level



P (s)	**27906.9807807(9)**
dP/dt	**$-2.425(10)\cdot 10^{-12}$**
$d\omega/dt$ (º/yr)	**4.226628(18)**
M_p	**$1.442 \pm 0.003\ M_{\odot}$**
M_c	**$1.386 \pm 0.003\ M_{\odot}$**



Nobel Prize 1993: Hulse and Taylor

TARGET GW AMPLITUDE

LUMINOSITY

$$P = \frac{G}{5c^5} < \dddot{Q}^{ij}\dddot{Q}_{ji} > \approx \varepsilon \frac{c^5}{G}\left(\frac{R_s}{R}\right)^2\left(\frac{v}{c}\right)^6$$

AMPLITUDE

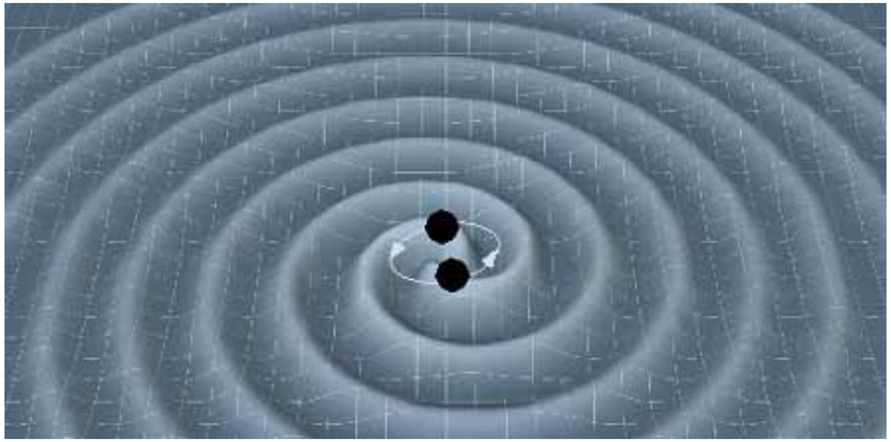
$$h_{\mu\nu} = \frac{2G}{c^4}\cdot\frac{1}{r}\ddot{Q}_{\mu\nu}$$

Compactness *C*

1	for BH
0.3	for NS
10^{-4}	for WD

Efficient sources of GW must be **asymmetric**, **compact** and **fast**

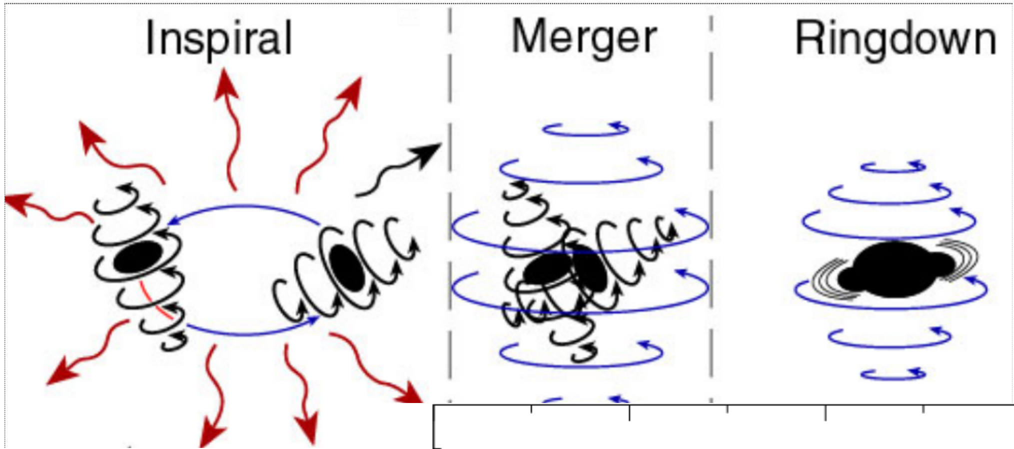
GW detectors are sensitive to amplitude $h : 1/r$ attenuation!

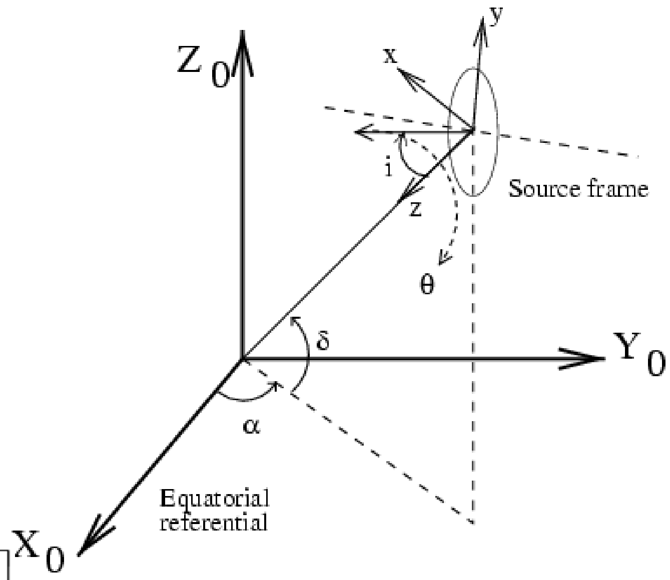


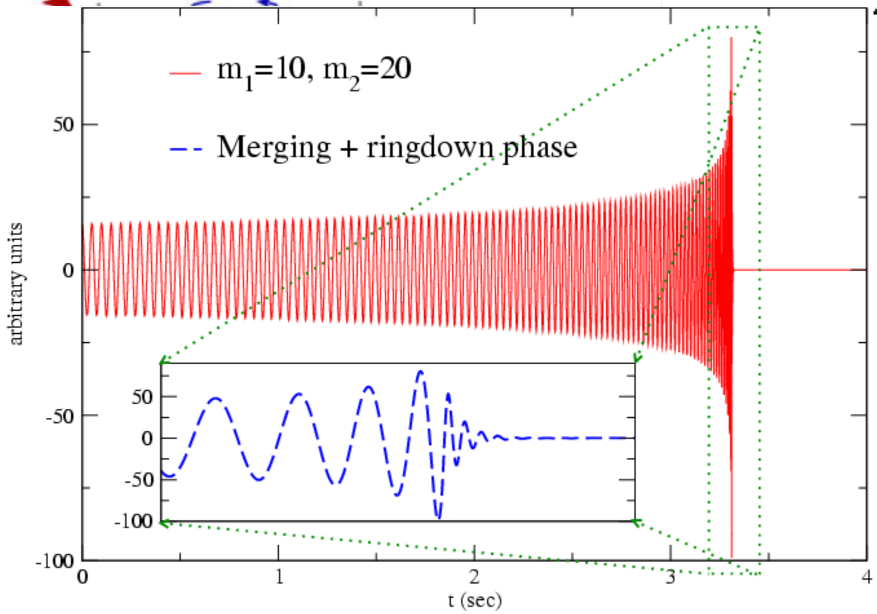
Target amplitude:
coalescing NS/NS in the Virgo cluster
(*r* ~ *10 Mpc*)

$h \sim 10^{-21}$

Example: inspiral signal





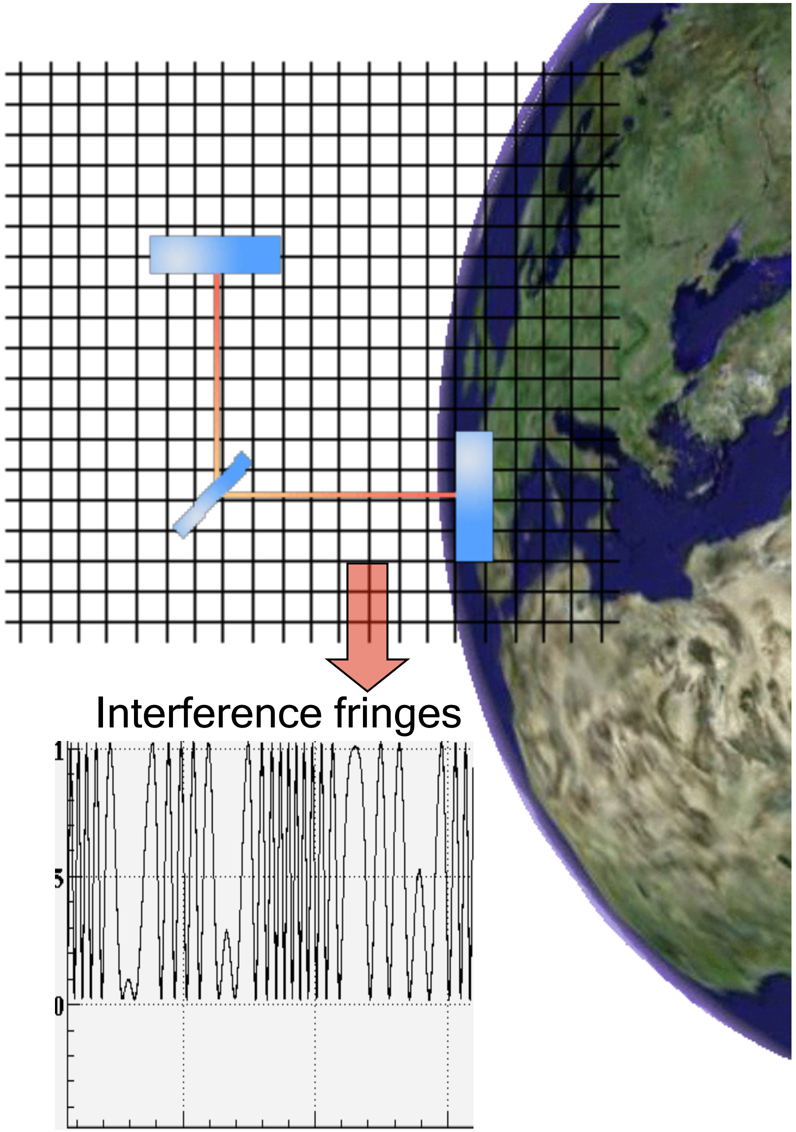


$$\begin{pmatrix} h_+ \\ h_\times \end{pmatrix} = A\left[\nu(t)\right]^{2/3} \begin{pmatrix} \cos\phi(t)\cos(2\theta)\frac{\cos^2 i+1}{2} + \sin\phi(t)\sin(2\theta)\cos i \\ \sin\phi(t)\cos(2\theta)\cos i - \cos\phi(t)\sin(2\theta)\frac{\cos^2 i+1}{2} \end{pmatrix}$$

Principle of Detection

GW induce space-time deformation

strain using light



$$\Delta L \approx \frac{1}{2} h L$$

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

Feasible L ~ 10^{3} m

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

Big challenge for experimentalists!

What does 10^{-18} m mean?

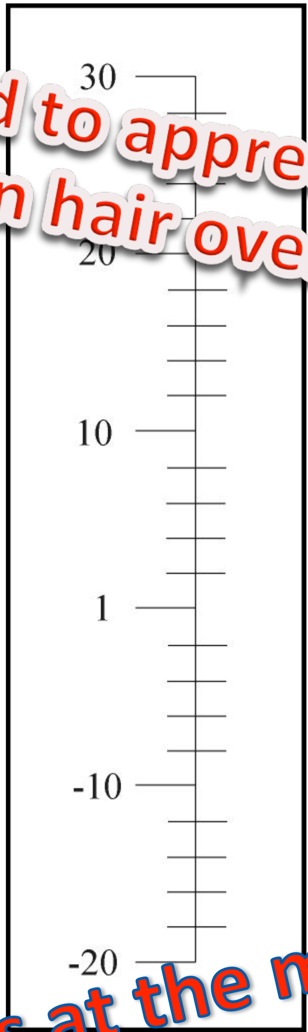
We need to appreciate the thickness of an hair over 4 light years

Distance to Virgo cluster

Size of the Universe

Distance from Galactic Center

1 lght-year



Typical wavelength of GW

Radius of a Neutron Star

Laser wavelength

Atom

Radius of a proton

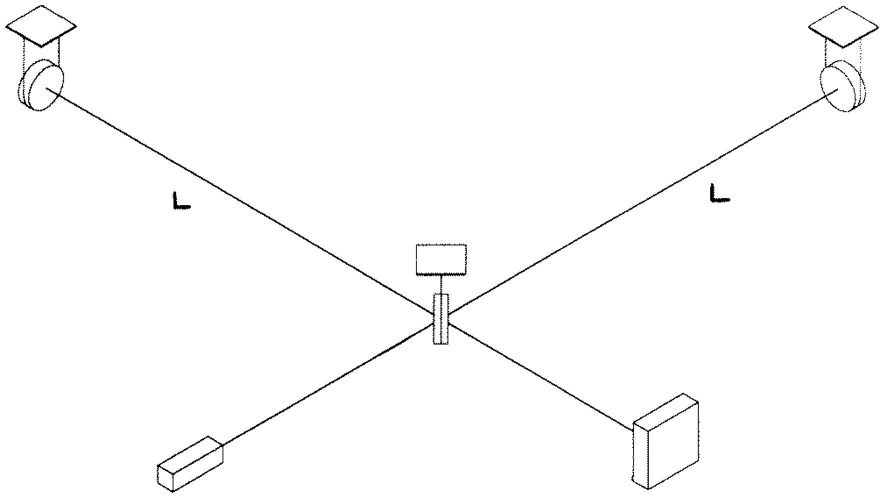
Required sensitivity!

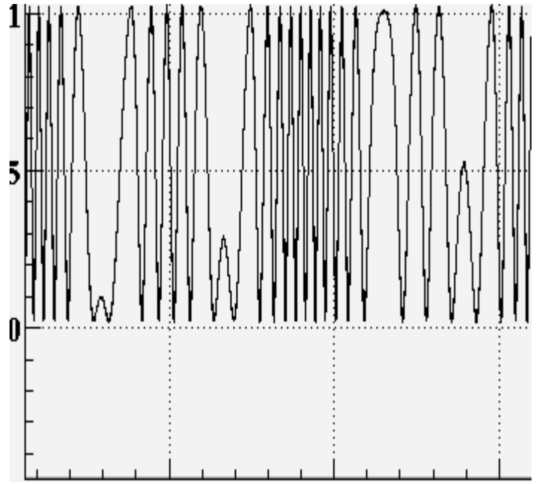
Physics at the milli-Fermi scale

$\log_{10} r$

INTERFEROMETRIC GW DETECTION

The simplest: a Michelson & Morley





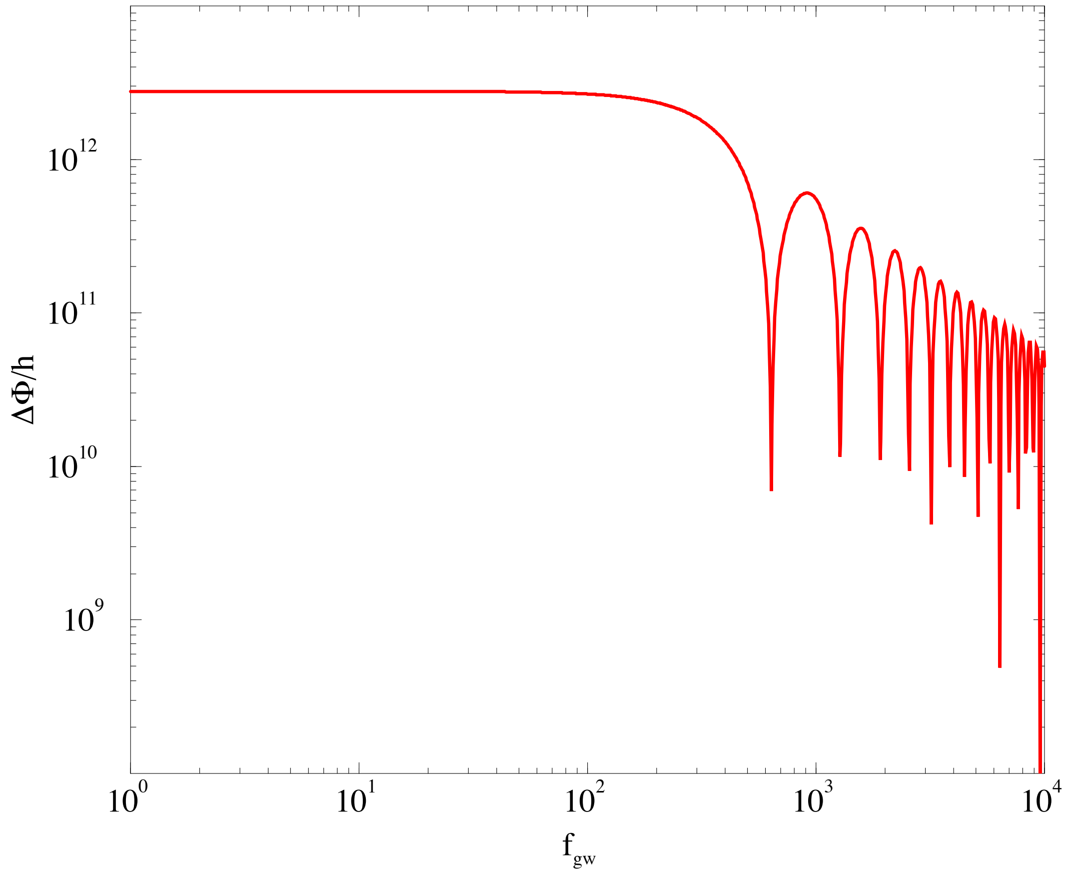
$$P_{out} = P_{in} \cos^2(\phi_0 + \phi_{GW})$$

$$\phi_{GW} = \frac{4\pi}{\lambda} L \cdot h$$

P_{out} depends also on P_{in}, l, L.

ITF sensitive to power and frequency fluctuations, displacement noises, ...

The remarkable power of interferometry



Assume L = 100 Km

Take λ = 1μm

- An interferometer is a low pass filter, with the first zero at c/(4 L)
- Even if we could afford it, L should not be too large. **But … 100 km ?**

OPTICAL READOUT NOISE

- Power fluctuations limit the phase sensitivity. Ultimate power fluctuations are associated to the quantum nature of light

- Shot noise (assuming P, l stable): $\tilde{\phi}_{shot} = \sqrt{\frac{2\hbar\omega}{P}} \Rightarrow \tilde{h}_{shot} = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{\pi \cdot P}}$

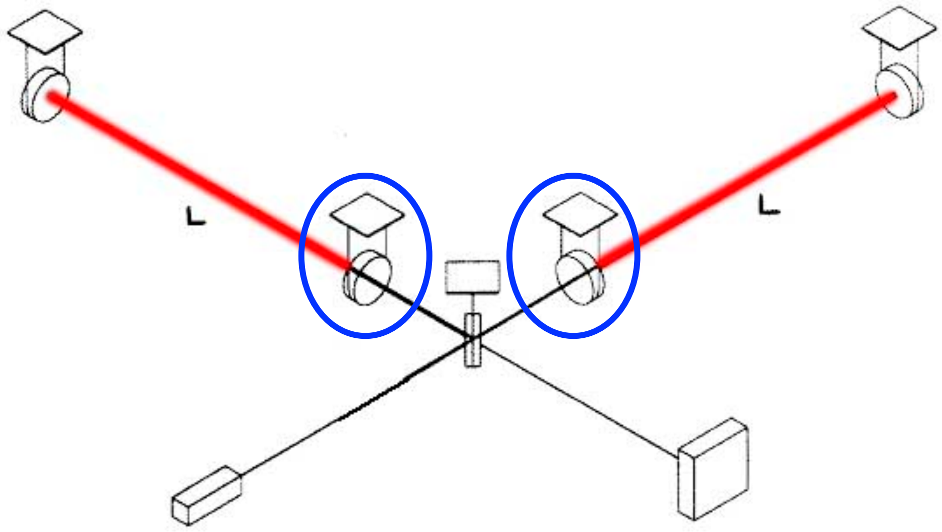
- L = 100 km, P = 1 kW → $h_{shot} \approx 10^{-21}$

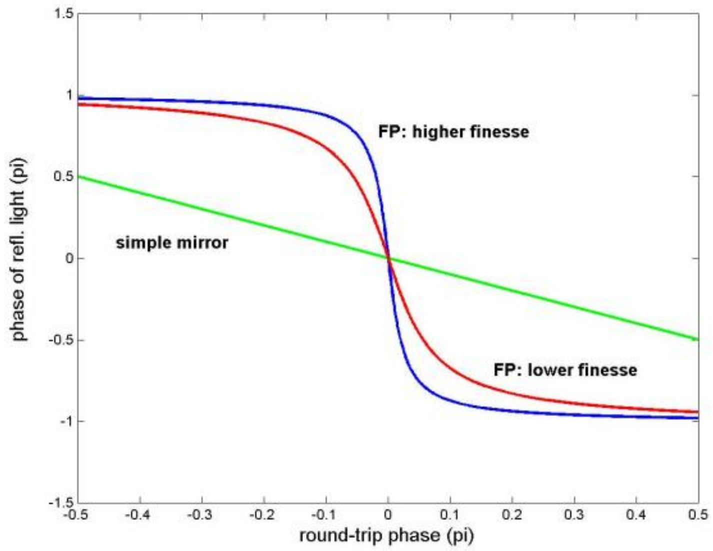
Lengthen the detector to 100 km

Increase the light power to 1 kW

HOW?

100 KM INTERFEROMETER?

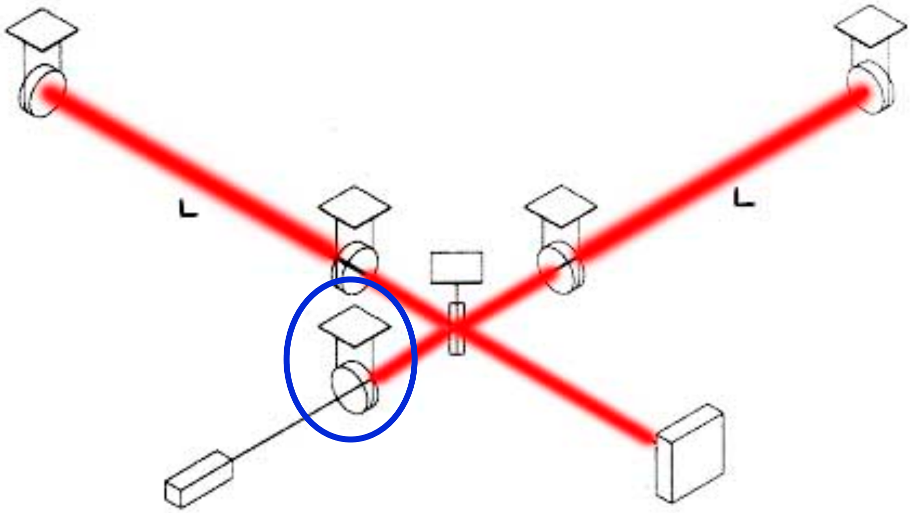


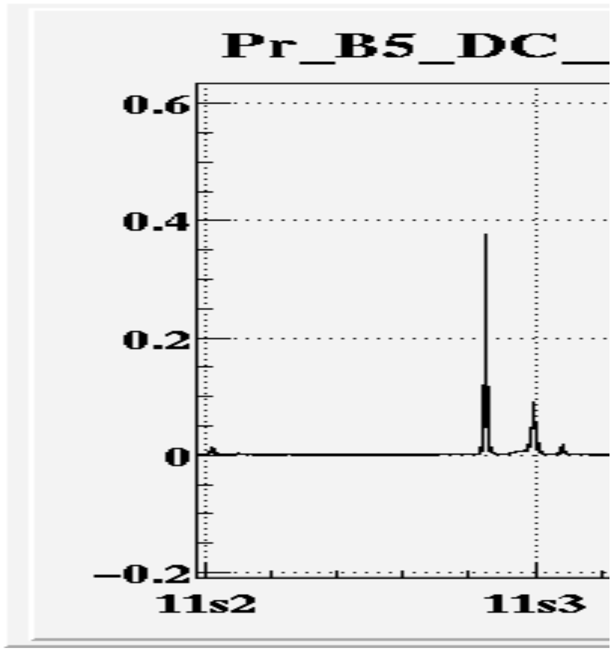


Effective length: $$L' = L \cdot \frac{2F}{\pi}$$

- **Fabry-Perot cavities:** amplify length-to-phase transduction
- **Higher finesse →** higher $d\phi/dL$
- ***Drawback:*** *requires a resonance condition to work*

1 KW POWER?





Idea: recycle the wasted light!

- *P_{eff}= Recycling factor ·P_{in}* → **20 W → 1 kW**
- **Shot noise reduced by a factor ~7**
- **But … one more cavity to be controlled**

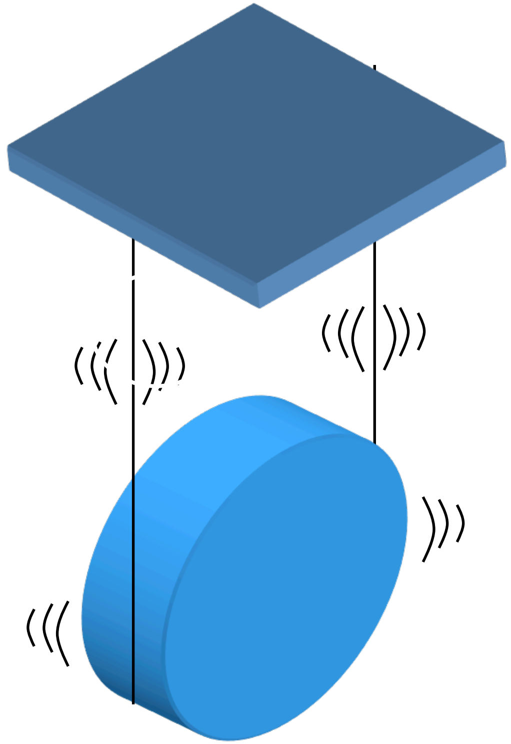
A complication: position noise

- **For instance, thermal noise.** Any DOF of the detector's components obeys to the fluctuation-dissipation theorem:

$$v(\omega) = Y(\omega) F_{ext}(\omega)$$

$$F^2_{therm}(\omega) = 4 k_B T \Re[Y^{-1}(\omega)]$$

$$x^2_{therm}(\omega) = \frac{4 k_B T}{\omega^2} \Re[Y(\omega)]$$

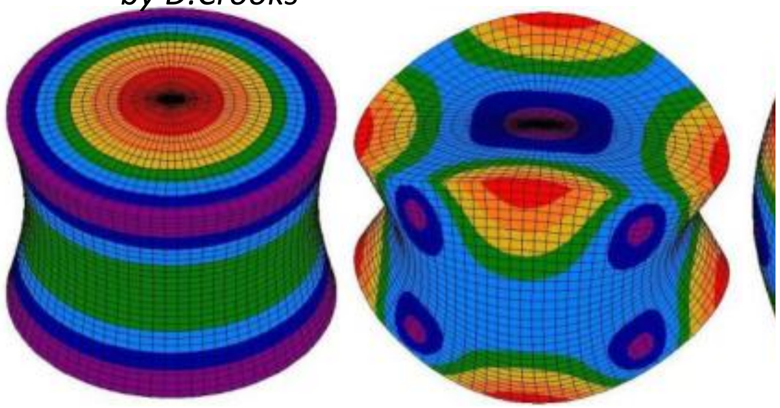


- Mirrors and wires vibrate, pendulum oscillates
- All translate into an equivalent noise for GW

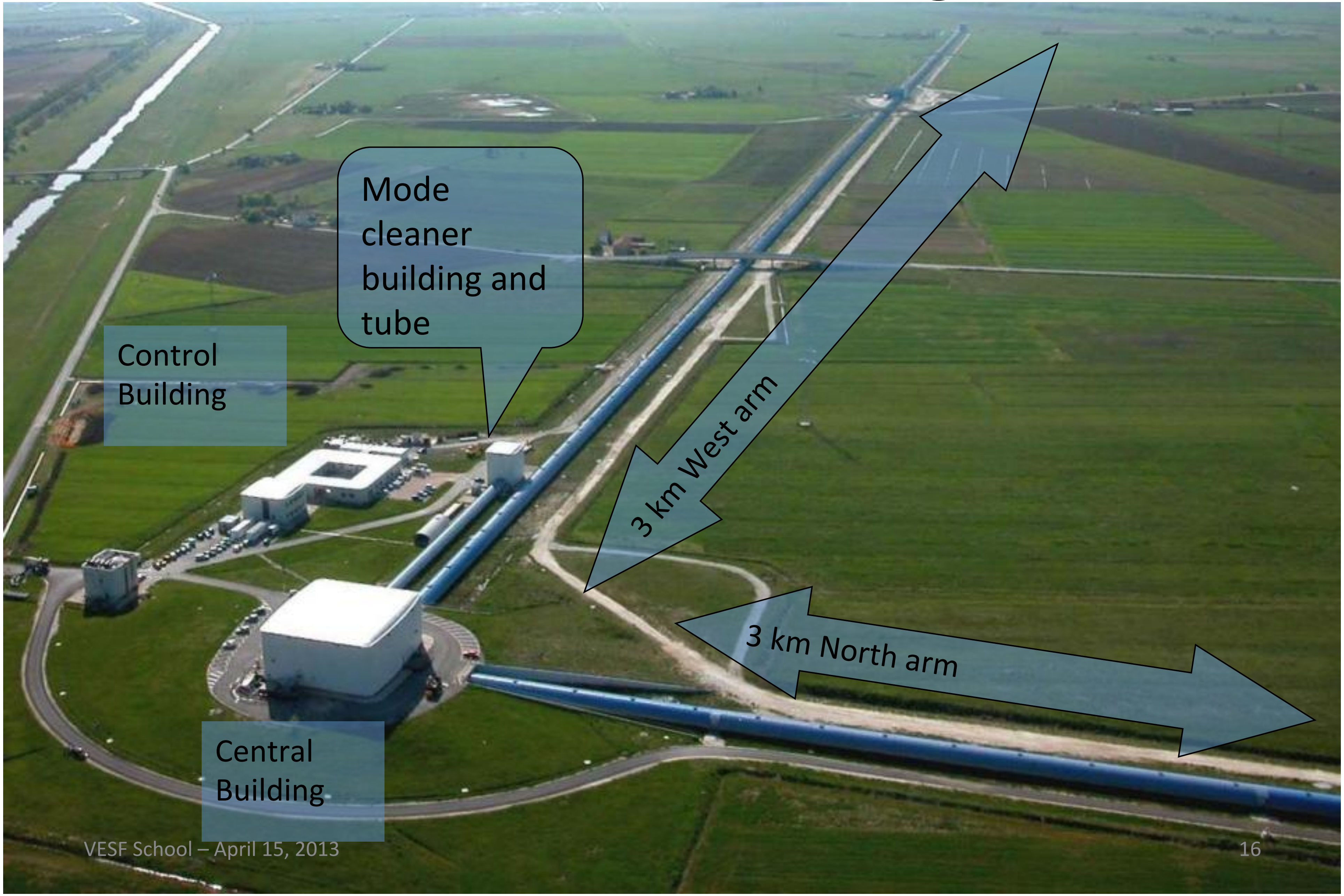
$$h_{therm}(\omega) \propto \frac{1}{L} x_{therm}(\omega)$$

- **L is the physical distance of the mirrors, not the optical length!**
- ***Possible cures: reduce the dissipation, or cool down the mirrors***

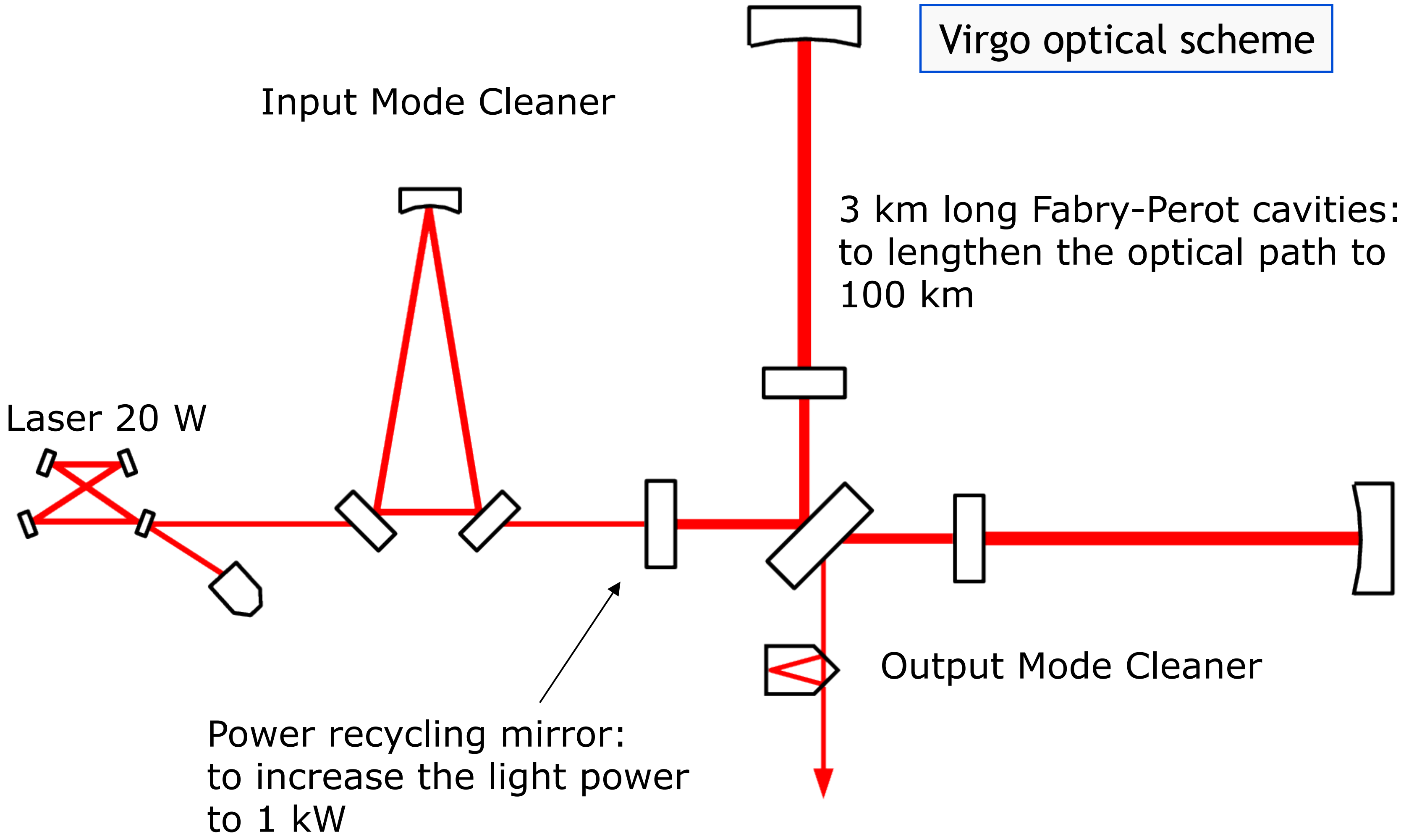
by D.Crooks



A real detector: Virgo

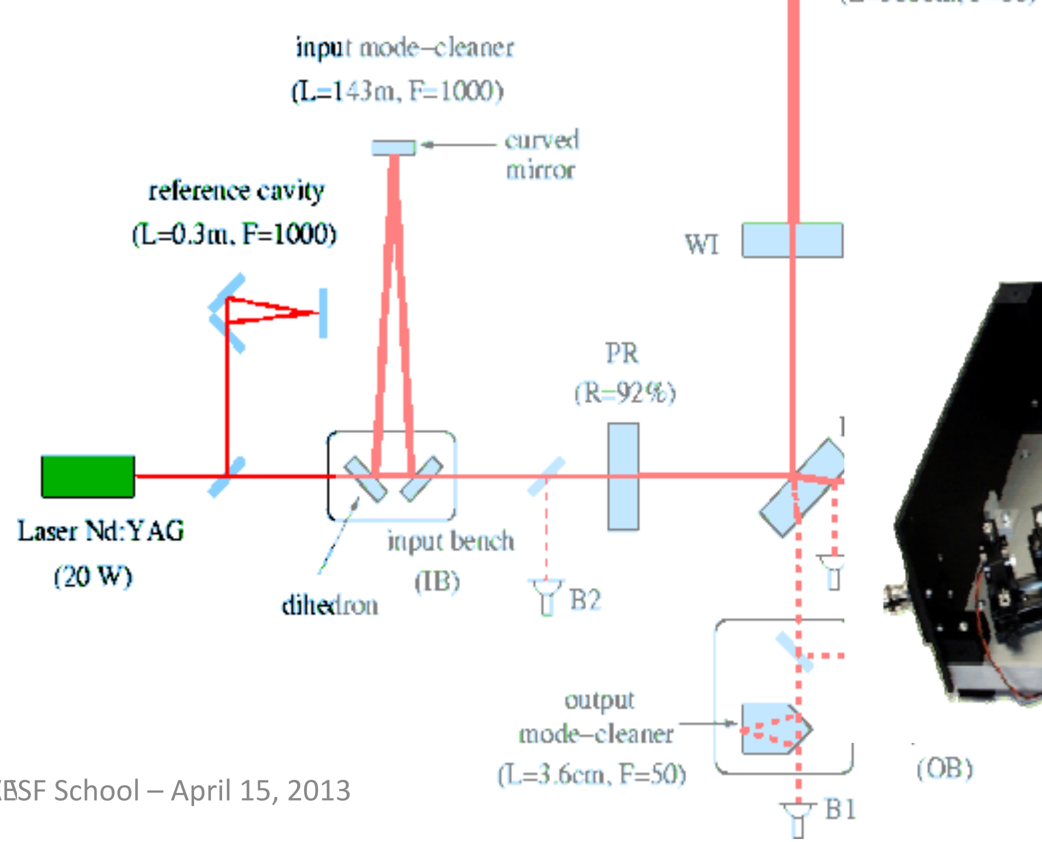


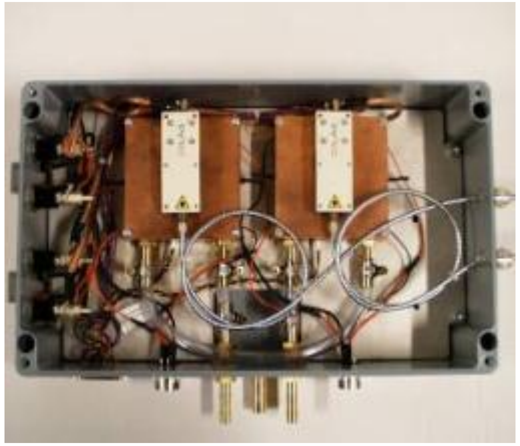
Scheme of Virgo (rather similar to LIGO I)

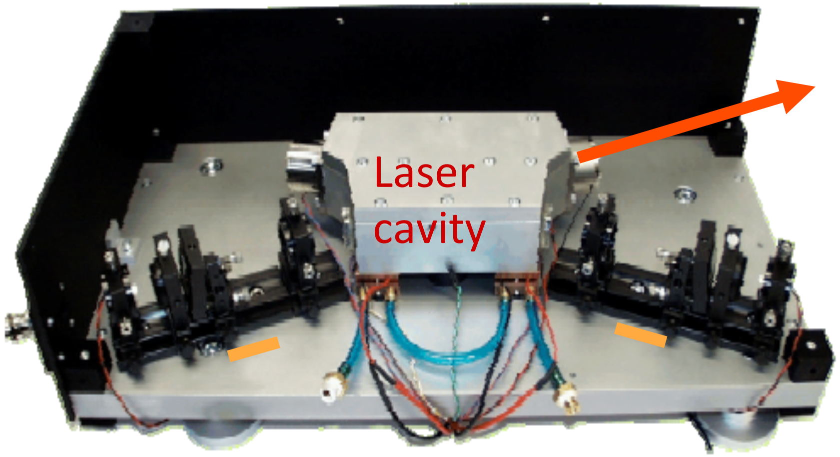


Laser

- 20 W, Nd:YVO_4 laser, two pumping diodes
- Injection locked to a 0.7 W Nd:YAG laser
- Required power stability: $\delta P/P \sim 10^{-8}\ Hz^{-1/2}$
- Required frequency stability: $10^{-6}\ Hz^{1/2}$

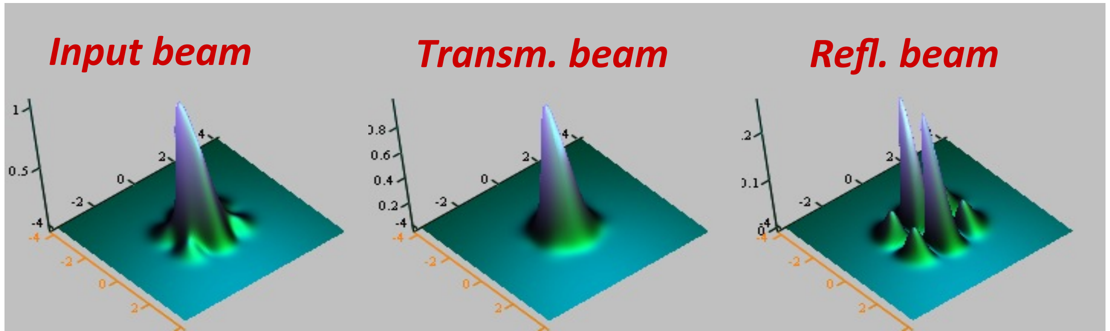


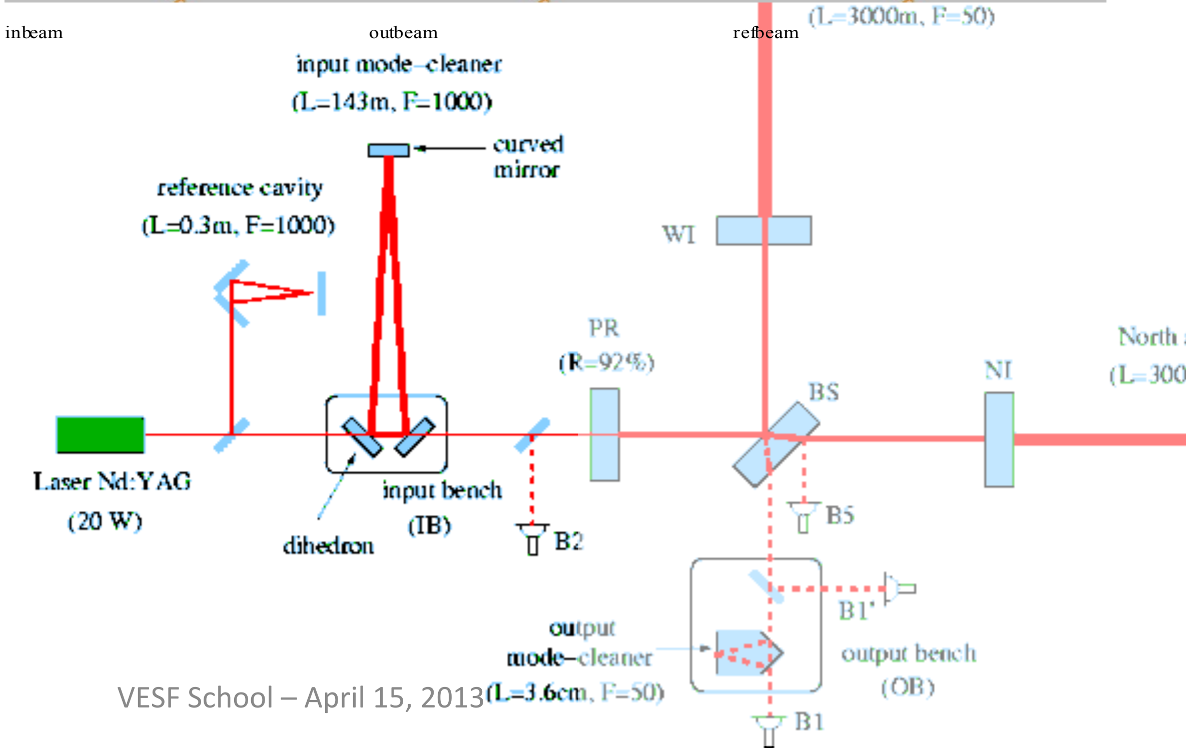


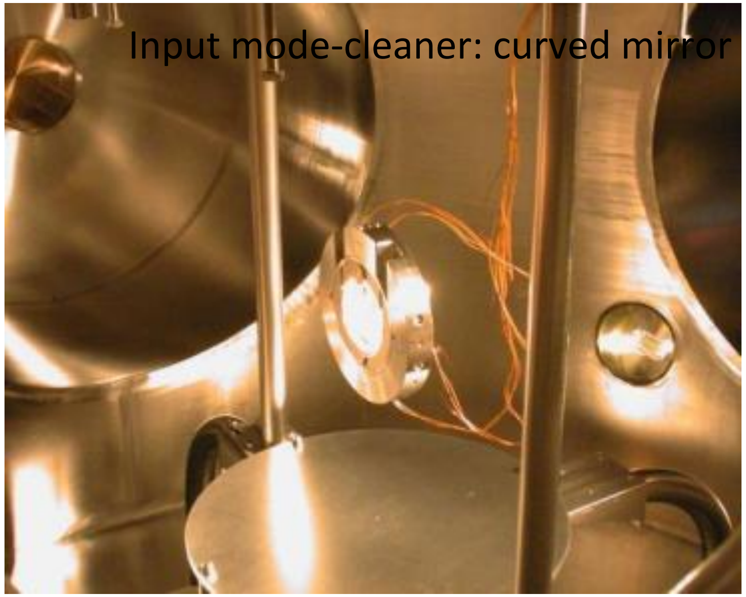


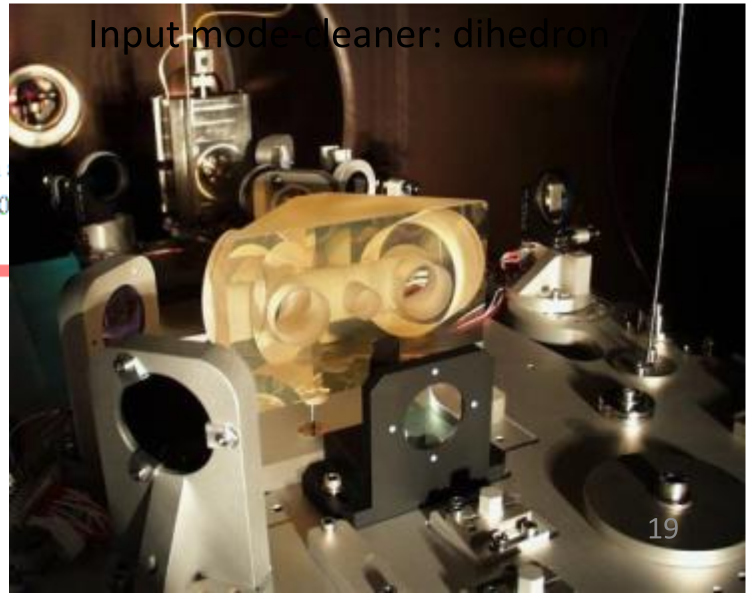
Input Mode Cleaner

- Mode cleaner cavity: filters laser



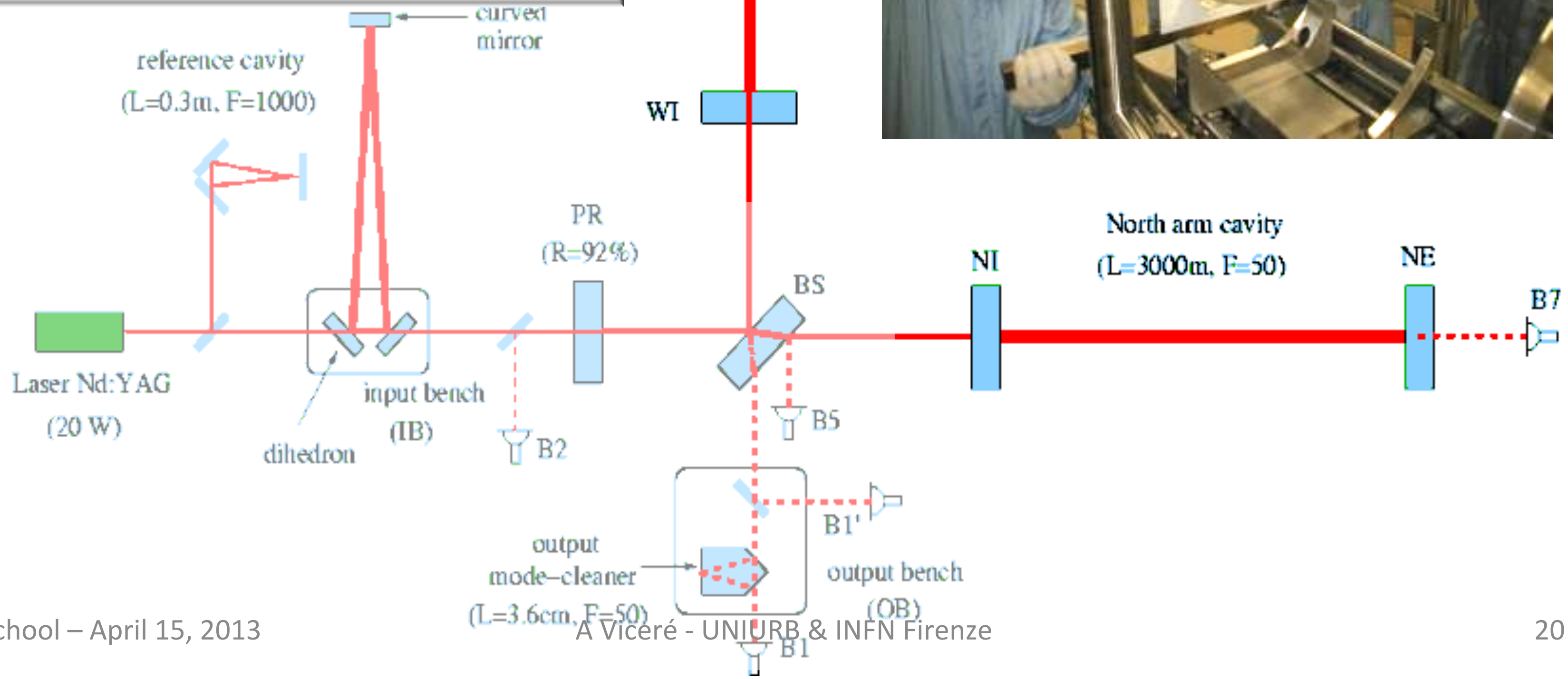






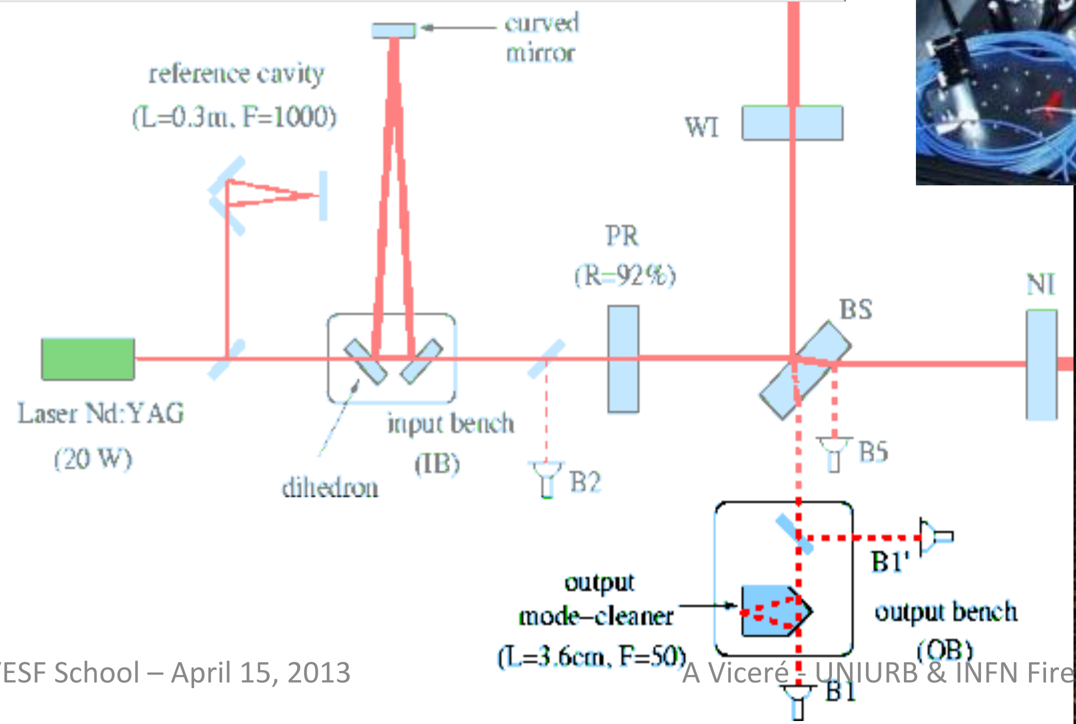
Mirrors

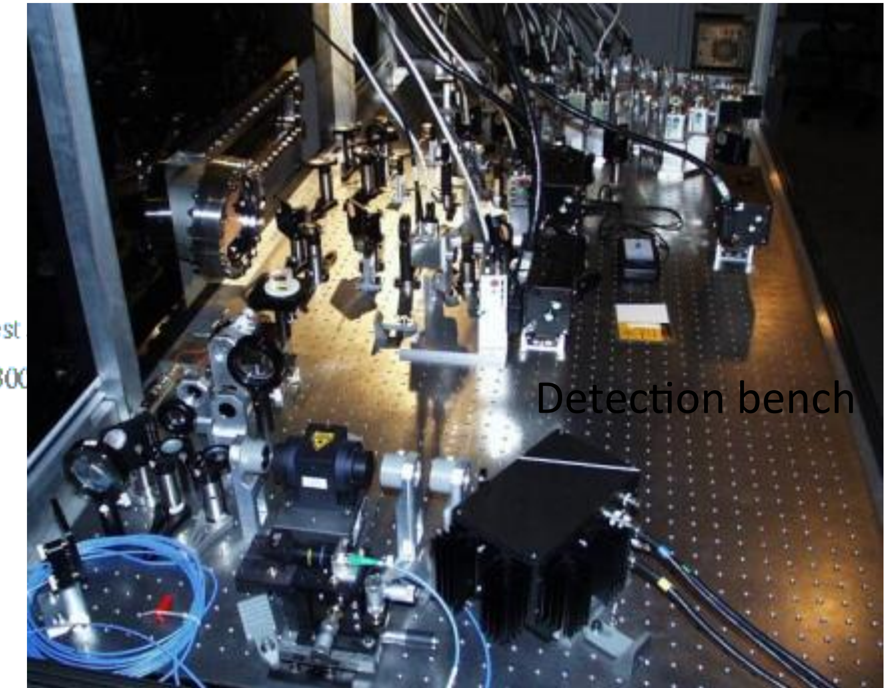
- High quality fused silica mirrors
- 35 cm diameter, 10 cm thickness, 21 kg mass
- Figures:
  - Substrate losses: 1 ppm
  - Coating losses: <5 ppm
  - Surface deformation: λ/100

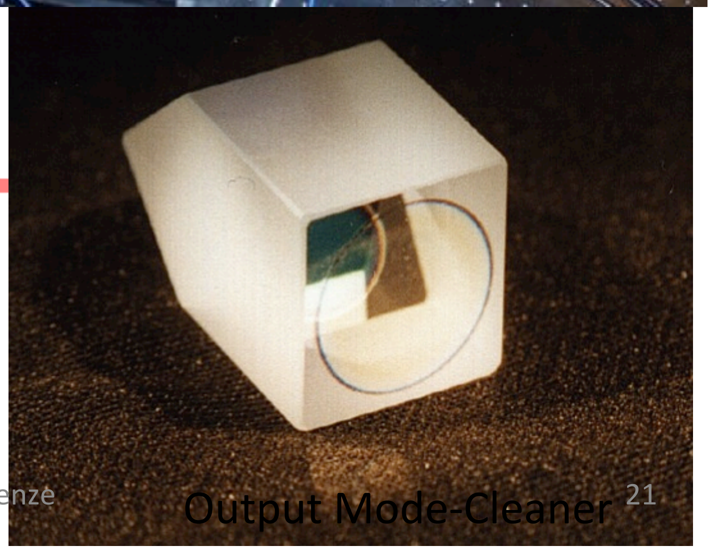


Output Optics

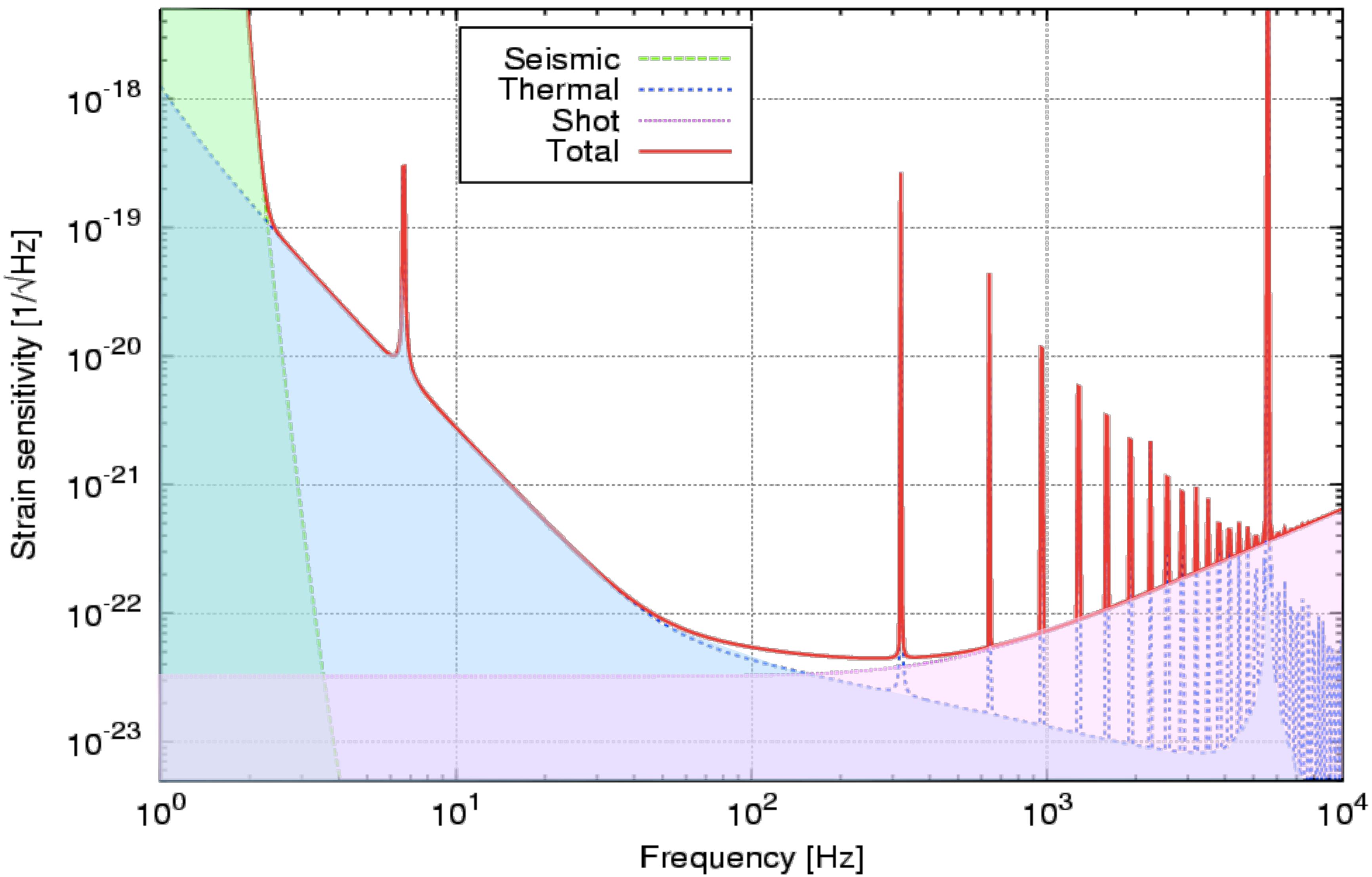
- Light filtering: output mode cleaner, 3.6 cm long monolithic cavity
- Light detection: InGaAs photodiodes, 3 mm diameter, 90% quantum efficiency
- Suppression of TEM_{01} by a factor of 10
- Length control via temperature (Peltier cell)



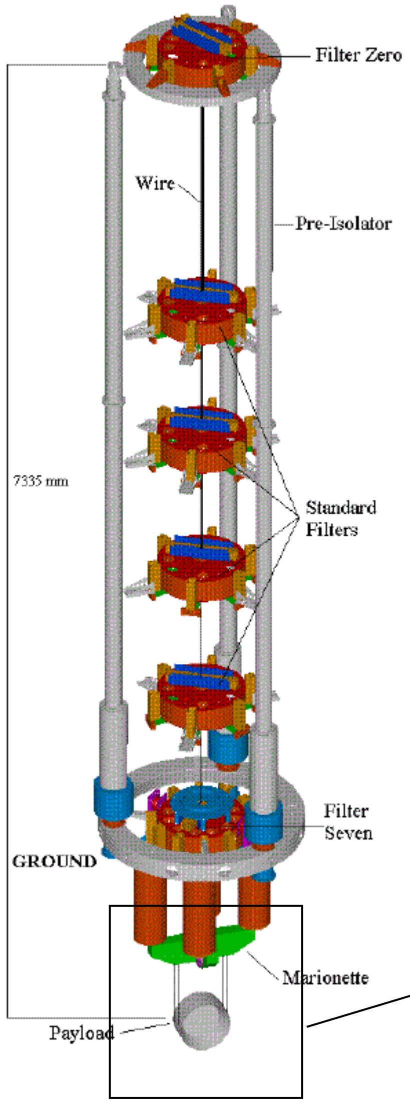




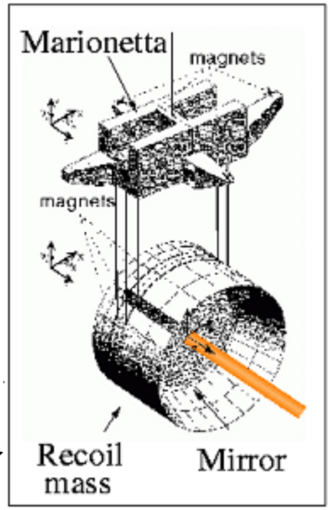
VIRGO DESIGN SENSITIVITY

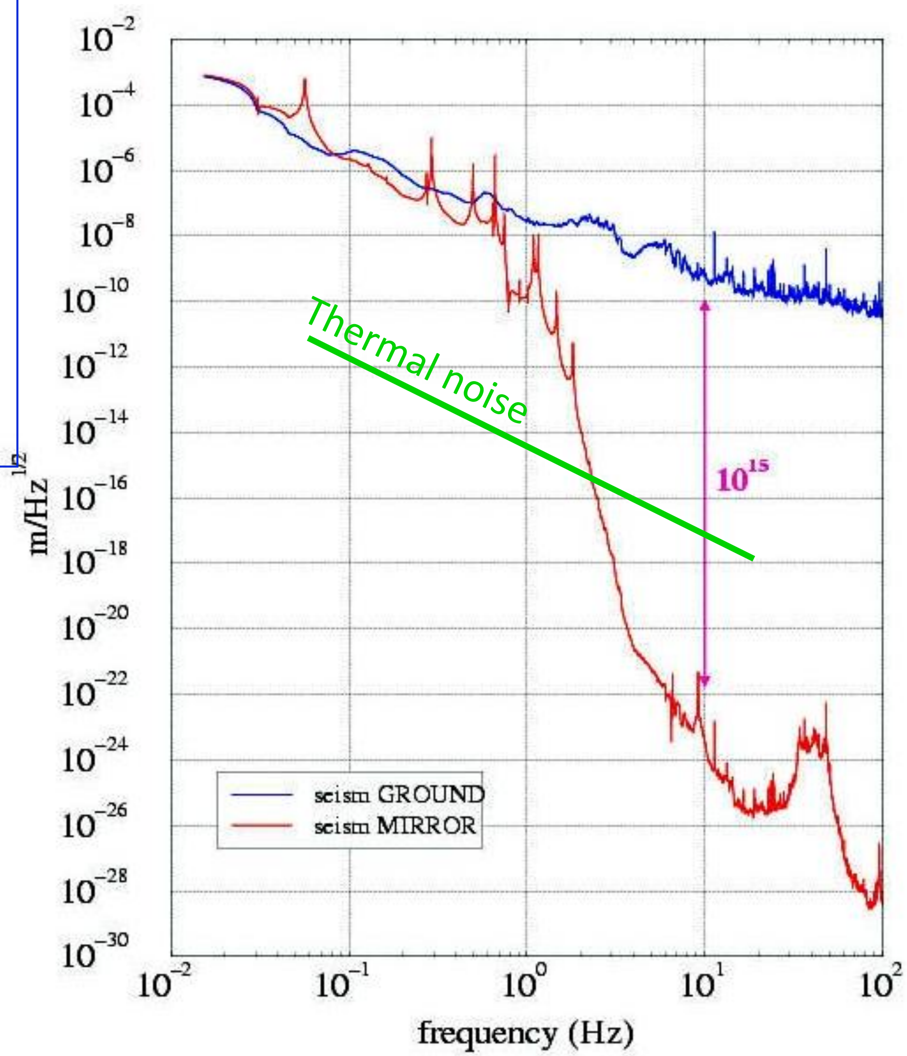


At *all* frequencies, seism *would be* king

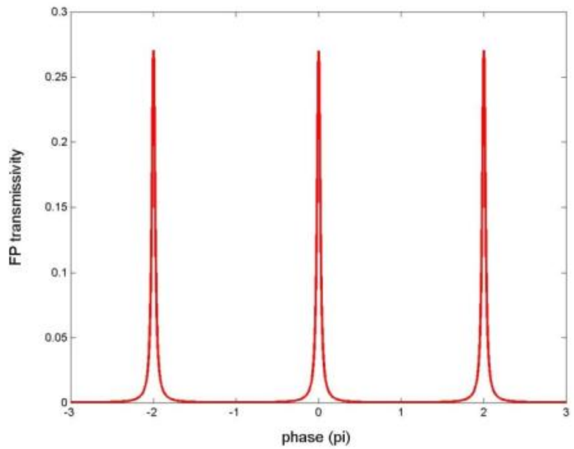


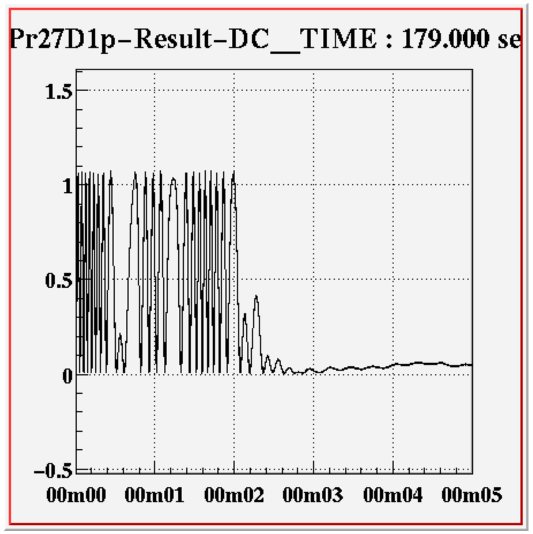
Superattenuator: A chain of pendula in all DOF, filtering the seismic noise in all directions.
Without it we would be 15 orders of magnitude from the goal !!!





ITF Operation Conditions

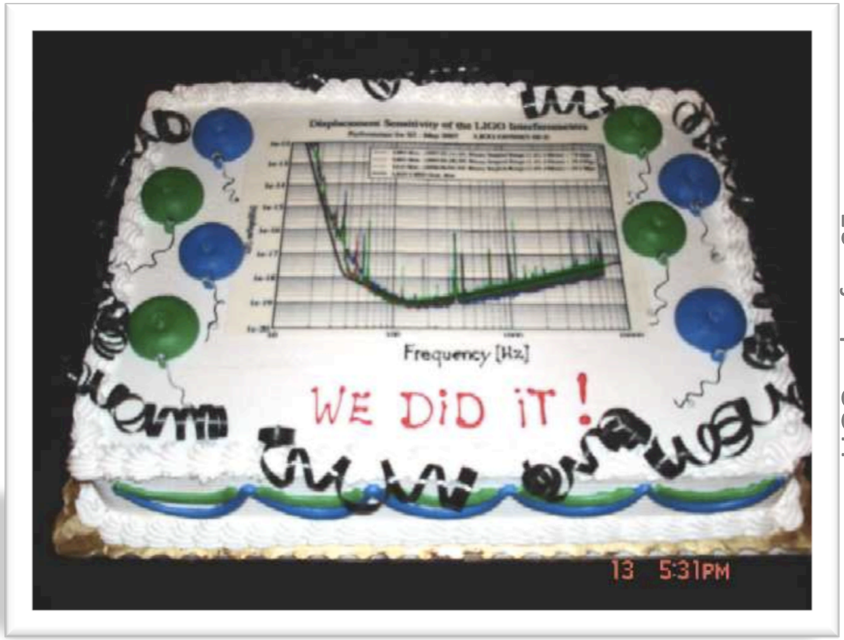




- Keep the FP cavities in resonance
  - Maximize the phase response
- Keep the PR cavity in resonance
  - Minimize the shot noise
- Keep the output on the “dark fringe”
  - Reduce the dependence on power fluctuations

LOCKING

Keep the armlength constant within 10^{-12} m !

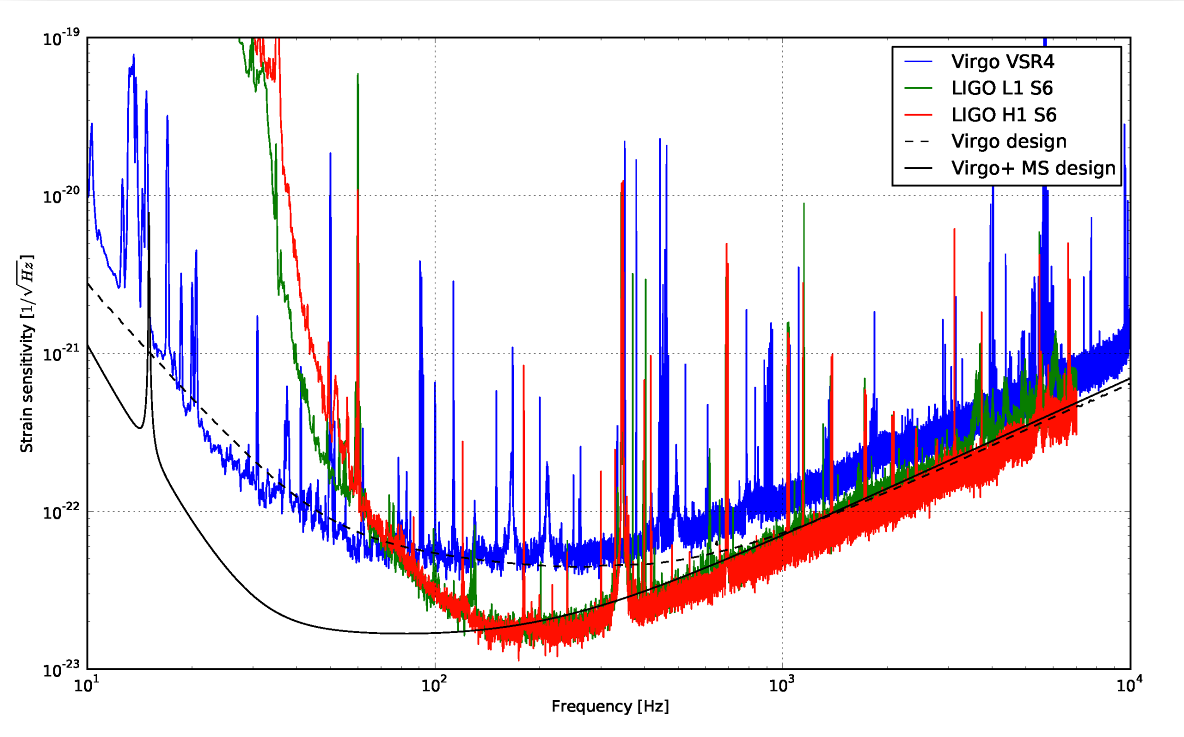


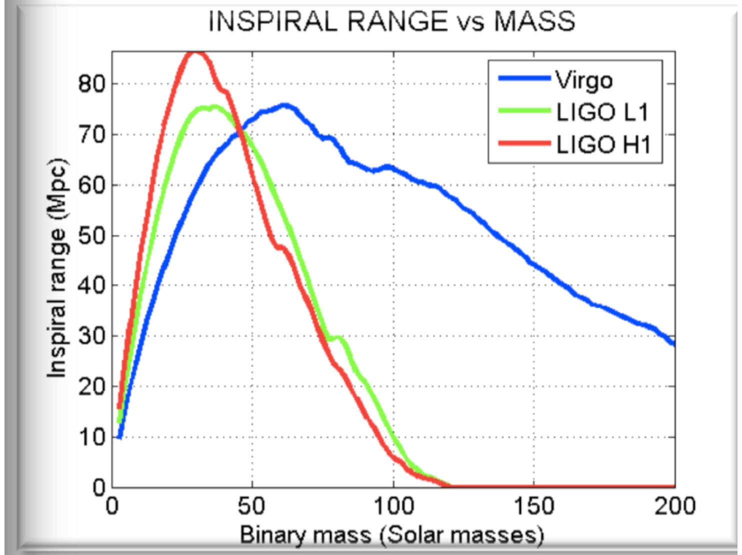
LIGO cake for S5 run

THE LEGACY OF THE 1ST GENERATION DETECTORS

The technology has been demostrated …

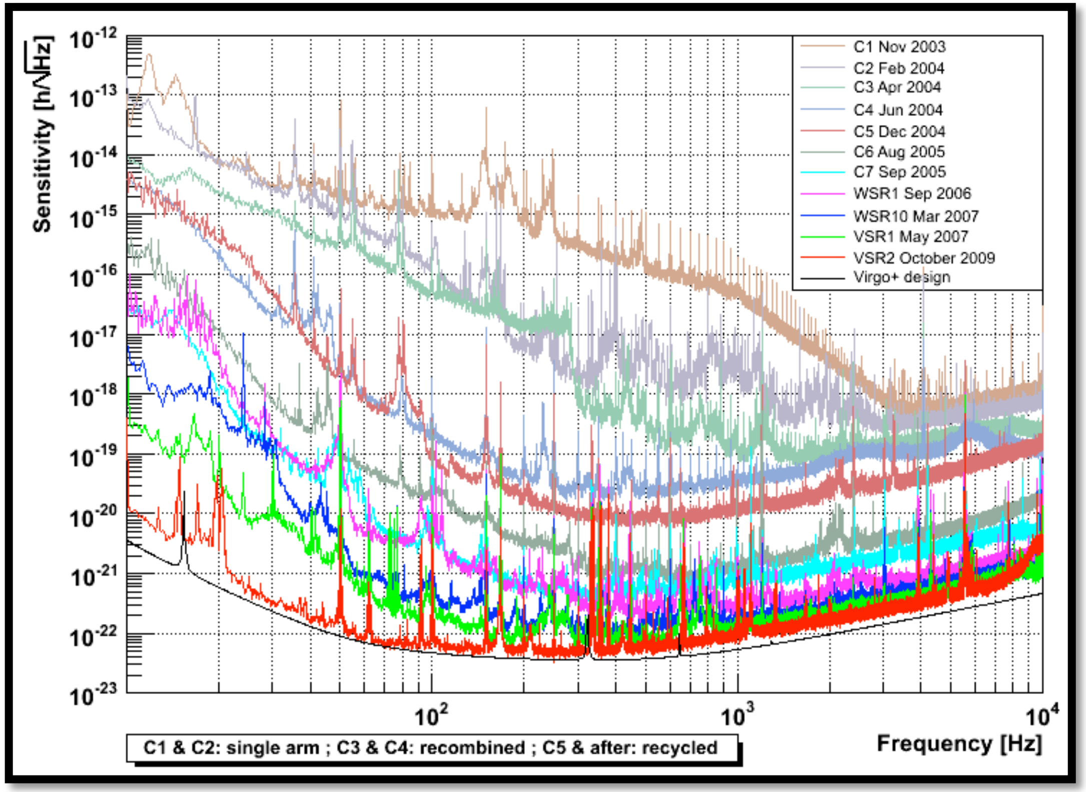
- LIGO and Virgo have reached the design sensitivity
- An important achievement! Highly non trivial …





… after a long commissioning

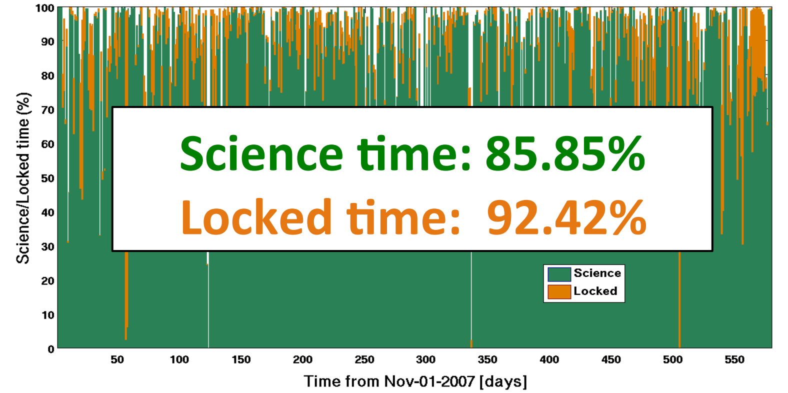
- All detectors went through a long commissioning/learning phase
  - Asymptotic process. It slows down when approaching the design curve
- Many common troubles: great benefits from reciprocal exchanges (to be continued in the advanced detectors era)



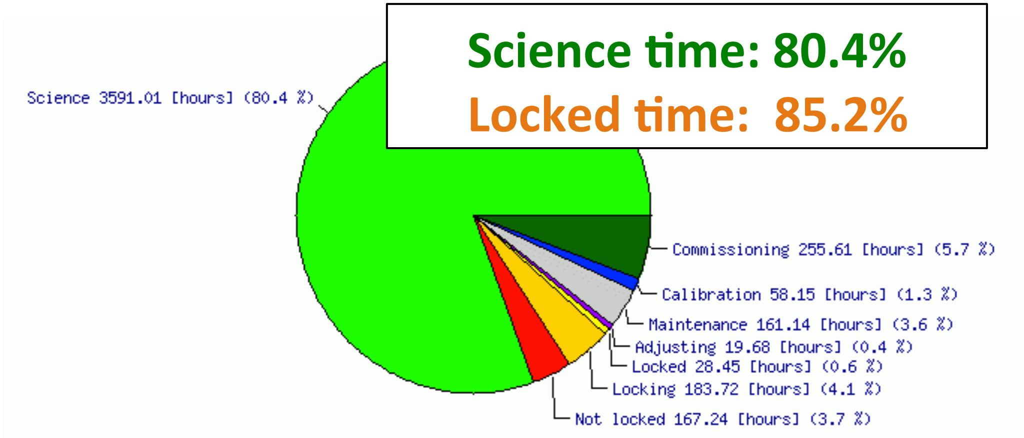
- **Lessons we had to learn:**
  - operating controls
  - coping with increasing complexity of the optical configuration
  - coping with thermal effects
  - coping with scattered light
  - identifying unknown noise
  - fix detector bugs
  - …and many others

ROBUSTNESS

- Excellent robustness (and very good duty cycles) obtained by 1st generation detectors
- Not just sensitive instruments, but reliable ones!



GEO: Nov 07 – Jun 09



Virgo: Jul 09 – Jan 10

INFRASTRUCTURES

- The infrastructures of km-scale interferometers were established
- The same ones will be used for the next generation of LIGO, Virgo and GEO
- New ones will be needed for LCGT in Japan and for a new detector in the southern hemisphere: LIGO-India

EXTERNAL COLLABORATIONS

LSC/VIRGO are starting external collaborations, first step towards MULTI-MESSENGER science:

- NEUTRINO DETECTORS
  - IceCube and ANTARES MOUs are signed
  - Super-K MOU on hold
- WIDE-FIELD OPTICAL FOLLOWUPS
  - All have been approved as part of LOOC-UP
  - TAROT, QUEST, ROTSE signed
  - Pi of the Sky, Skymapper, Palomar Transient Factory in process
- NASA SATELLITE MISSIONS
  - RXTE, Swift, Fermi LAT and GBM working through the signature process
  - Long standing existing MOU with RXTE for Sco-X1 work
- RADIO TELESCOPES
  - Arecibo, LOFAR, Green Bank
- NUMERICAL RELATIVITY
  - NINJA2 MOU

nature Vol 460|20 August 2009|doi:10.1038/nature08278

SCIENCE SO FAR… (A SELECTION)

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved gravitational-wave sources of astrophysical and cosmological origin. It should carry unique signatures from the earliest epochs in the evolution of the Universe, inaccessible to standard astrophysical observations[1]. Direct measurements of the amplitude of this background are therefore of fundamental importance for understanding the evolution of the Universe when it was younger than one minute. Here we report limits on the amplitude of the stochastic gravitational-wave background using the data from a two-year science run of the Laser Interferometer Gravitational-wave Observatory[2] (LIGO). Our result constrains the energy density of the stochastic gravitational-wave background normalized by the critical energy density of the Universe, in the frequency band around 100 Hz, to be $<6.9 \times 10^{-6}$ at 95% confidence. The data rule out models of early Universe evolution with relatively large equation-of-state parameter[3], as well as cosmic (super)string models with relatively small string tension[4] that are favoured in some string theory models[5]. This search for the stochastic background improves on the indirect limits from Big Bang nucleosynthesis[1,6] and cosmic microwave background[7] at 100 Hz.

According to the general theory of relativity, gravitational waves

mirrors[2] is well suited to measure this differential strain signal due to gravitational waves. Over the past decade, LIGO has built three such multi-kilometre interferometers, at two locations[2]: H1 (4 km) and H2 (2 km) share the same facility at Hanford, Washington, USA, and L1 (4 km) is located in Livingston Parish, Louisiana, USA. LIGO, together with the 3 km interferometer Virgo[19] in Italy and GEO[20] in Germany, forms a network of gravitational-wave observatories. LIGO has completed science run S5 (between 5 November 2005 an[illegible] 2007), [illegible]quiring [illegible] yea[illegible] of data [illegible]incident am[illegible] H1 [illegible] at the in[illegible] sensitivities (Fig. 1).

The search for the SGWB using LIGO data is performed by cross-correlating str[illegible] from pai[illegible] interferometers[illegible]. In the fre-quency (f) do[illegible], the cross-correlation between two interferom-eters is multiplied by a filter function $\tilde{Q}(f)$ (Supplementary Information):

$$\tilde{Q}(f) = N \frac{\gamma(f)\Omega_{GW}(f)H_0^2}{f^3 P_1(f) P_2(f)} \quad (2)$$

Some science papers

PHYSICAL REVIEW D **85**, 082002 (2012)

Search for gravitational waves from low mass compact binary coalescence in LIGO's sixth science run and Virgo's science runs 2 and 3

THE ASTROPHYSICAL JOURNAL, 760:12 (18pp), 2012 November 20 doi:10.1088/0004-637X/760/1/12

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SEARCH FOR GRAVITATIONAL WAVES ASSOCIATED WITH GAMMA-RAY BURSTS DURING LIGO SCIENCE RUN 6 AND VIRGO SCIENCE RUNS 2 AND 3

PHYSICAL REVIEW D **85**, 122007 (2012)

All-sky search for gravitational-wave bursts in the second joint LIGO-Virgo run

THE ASTROPHYSICAL JOURNAL, 737:93 (16pp), 2011 August 20 doi:10.1088/0004-637X/737/2/93

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BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE VELA PULSAR

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LETTERS

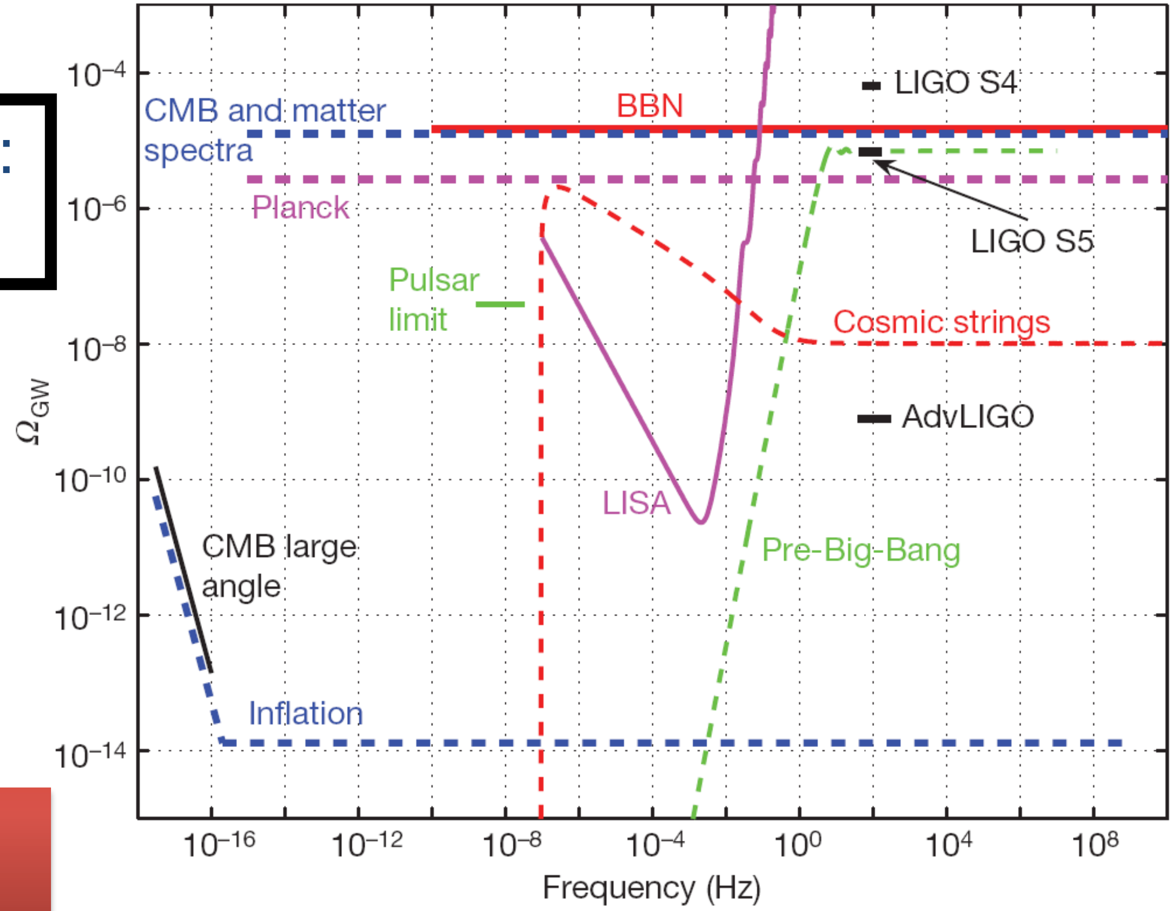
An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

COSMOLOGICAL BACKGROUND

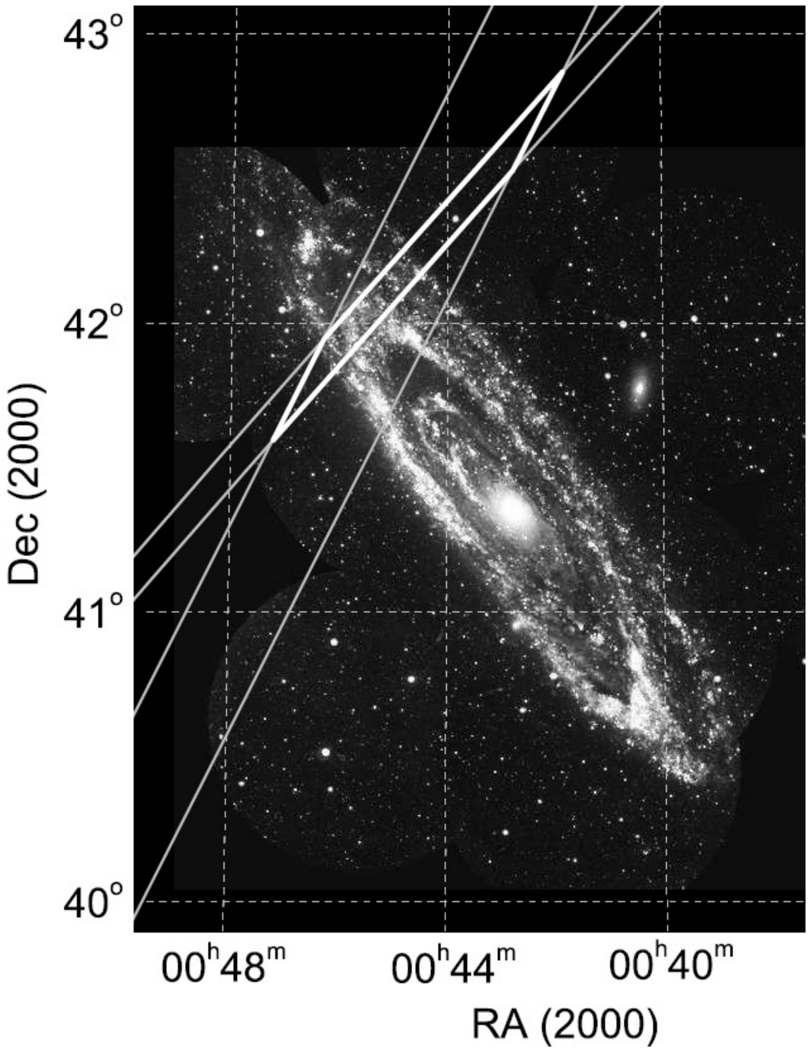
LIGO S5 limit surpasses indirect limit from Big Bang nucleosynthesis

LIGO S5 result:
$\Omega_0 < 6.9 \times 10^{-6}$



Abbott, et al. (LSC and Virgo), Nature., V460: 990 (2009)

GRB070201

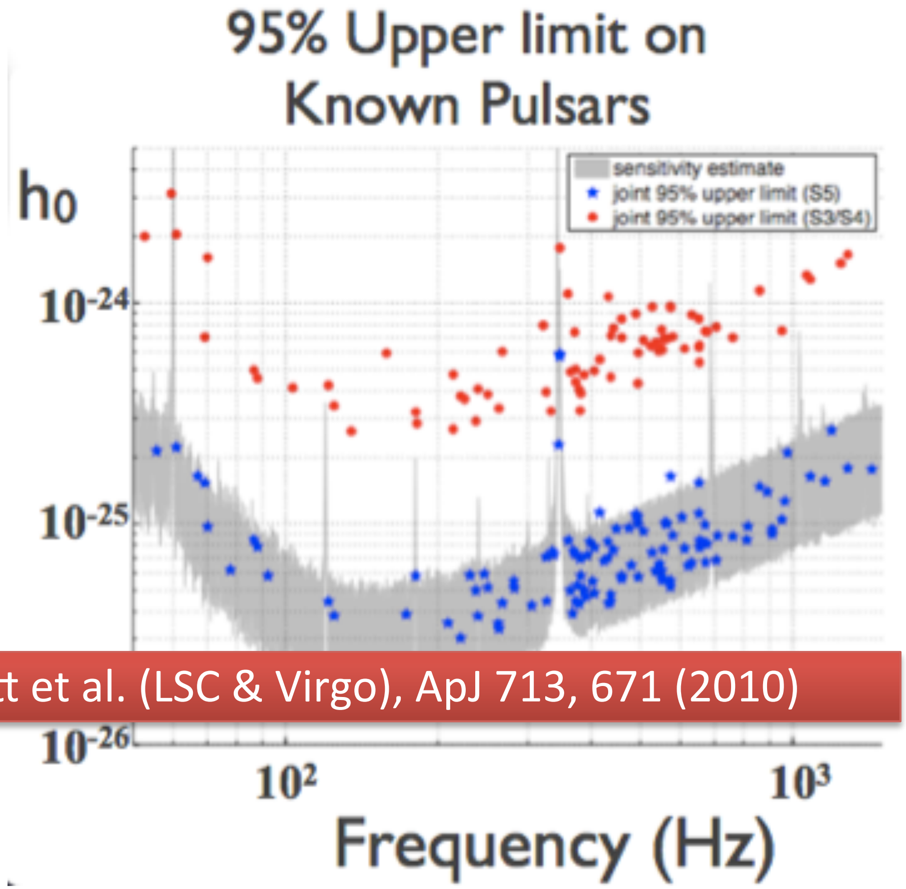


- GRB070201
  - Short, hard gamma-ray burst
  - Consistent with being in M31
  - Leading model for short GRBs: binary merger involving a neutron star
- Looked for a signal in LIGO data
  - searched for both inspiral and burst signals
  - No plausible GW signal found [1]
- CONCLUSION: probably a merger farther out, or a SGR giant flare in M31 [2,3]

[1] Abbott et.al., ApJ 681, 1419 (2008)
[2] Mazets et.al., ApJ 680, 545 (2008)
[3] Ofek et.al., ApJ, 681, 1464 (2008)

PULSARS

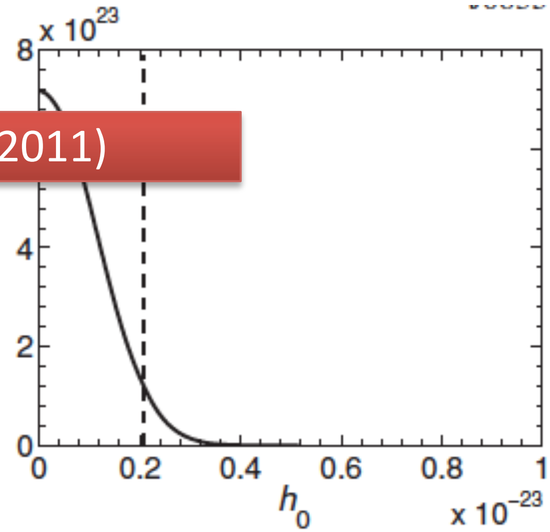
- Strength of emitted GW depends on ellipticity ε
- Radio observations of Crab pulsar constrain $\varepsilon < 10^{-3}$
- LIGO-Virgo non detection of GW constrains Crab's $\varepsilon < 10^{-4}$
- Vela spin-down limit beaten (Virgo data), $\varepsilon < 10^{-3}$
- For *some* pulsars, $\varepsilon < 10^{-7}$



Abbott et al. (LSC & Virgo), ApJ 713, 671 (2010)

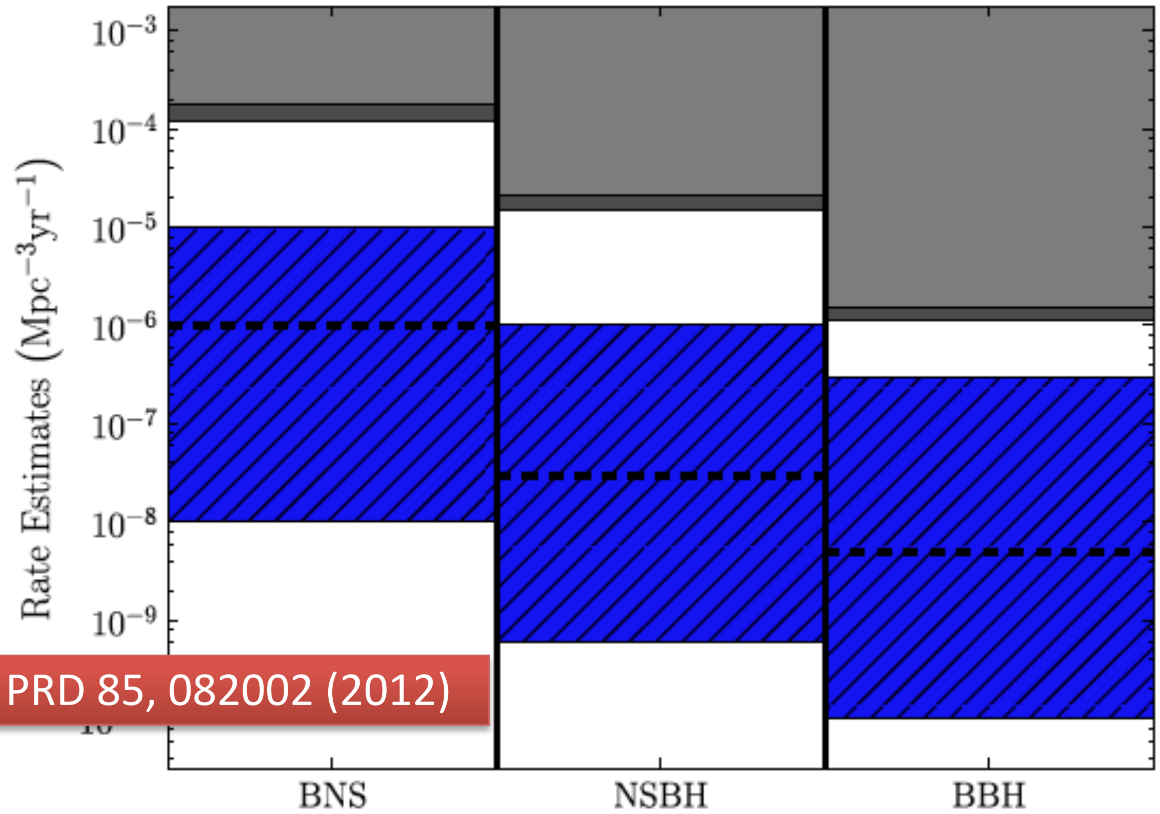
Abadie et al. (LSC & Virgo), ApJ 737:93 (2011)

$$h_0^{\rm sd} = 8.06 \times 10^{-19}\, I_{38}\, d_{\rm kpc}^{-1} \sqrt{\frac{|(\dot{f}_{\rm rot}/{\rm Hz\,s^{-1}})|}{(f_{\rm rot}/{\rm Hz})}},$$



Binary coalescences

- Upper limits on the rates now about a factor 10 above **optimistic** rates, and about a factor 100 above *plausible* rates

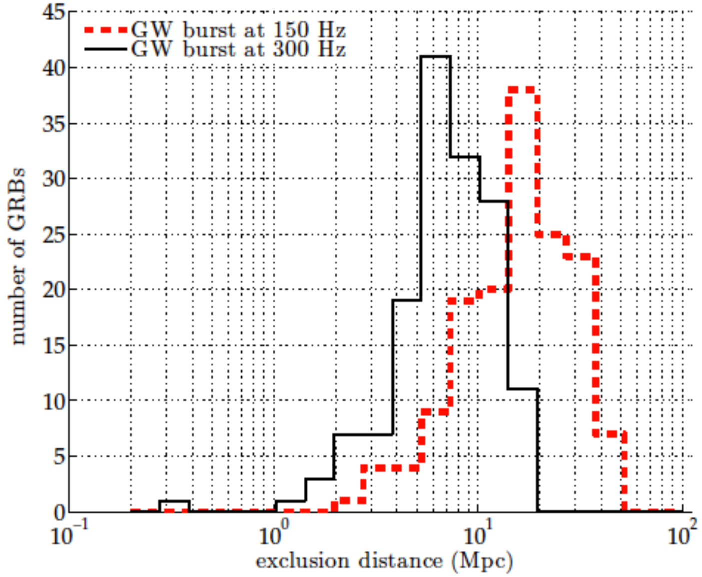


Abadie et al. (LSC & Virgo), PRD 85, 082002 (2012)

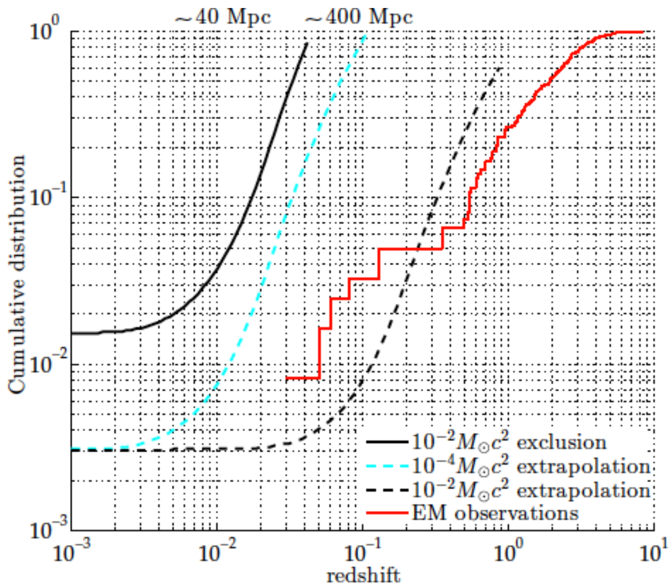
System	BNS	NSBH	BBH
Component masses ($M_\odot$)	1.35/1.35	1.35/5.0	5.0/5.0
D_{horizon} (Mpc)	40	80	90
Nonspinning upper limit (Mpc^{-3} yr^{-1})	1.3×10^{-4}	3.1×10^{-5}	6.4×10^{-6}
Spinning upper limit (Mpc^{-3} yr^{-1})	···	3.6×10^{-5}	7.4×10^{-6}

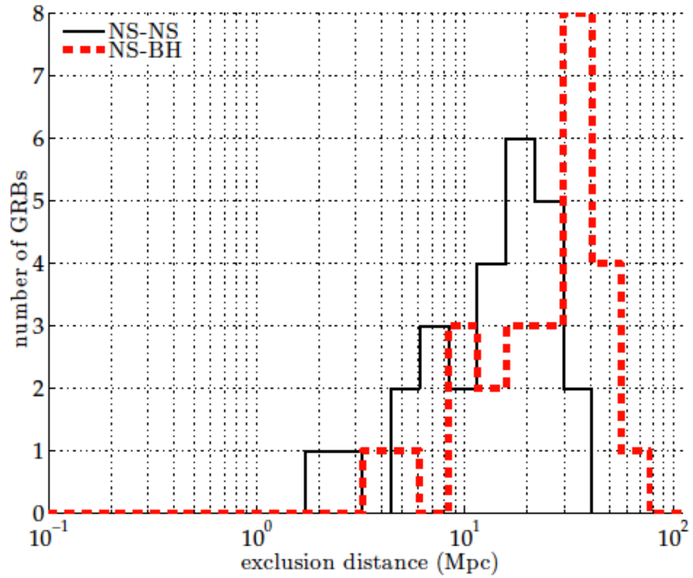
S6/VSR2,3 GRB TRIGGERED SEARCHES

- 154 GRBs analyzed (26 short-hard)
- Non-detection -> exclusion distances: had there been a GW in coincidence, we would have seen it if closer than..



Abadie et al. (LSC & Virgo), ApJ 760:12 (2012)





Advanced Virgo
Technical Design Report

The Virgo Collaboration

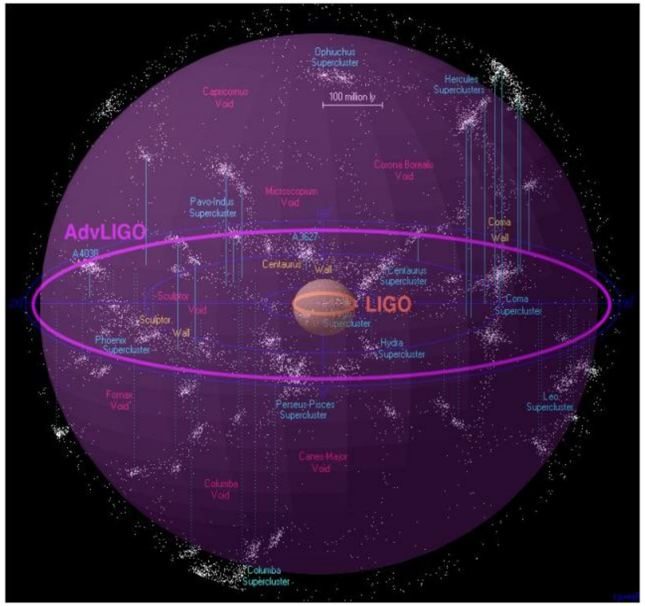
VIR–0128A–12

April 13, 2012

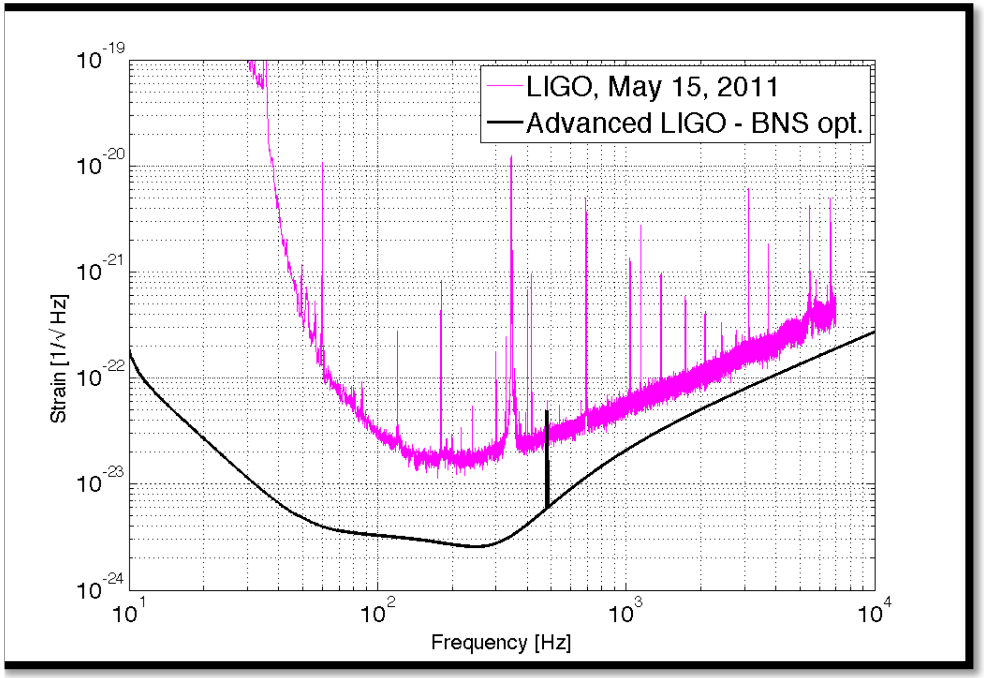
ADVANCED DETECTOR'S TECHNOLOGIES

What can we shoot for?

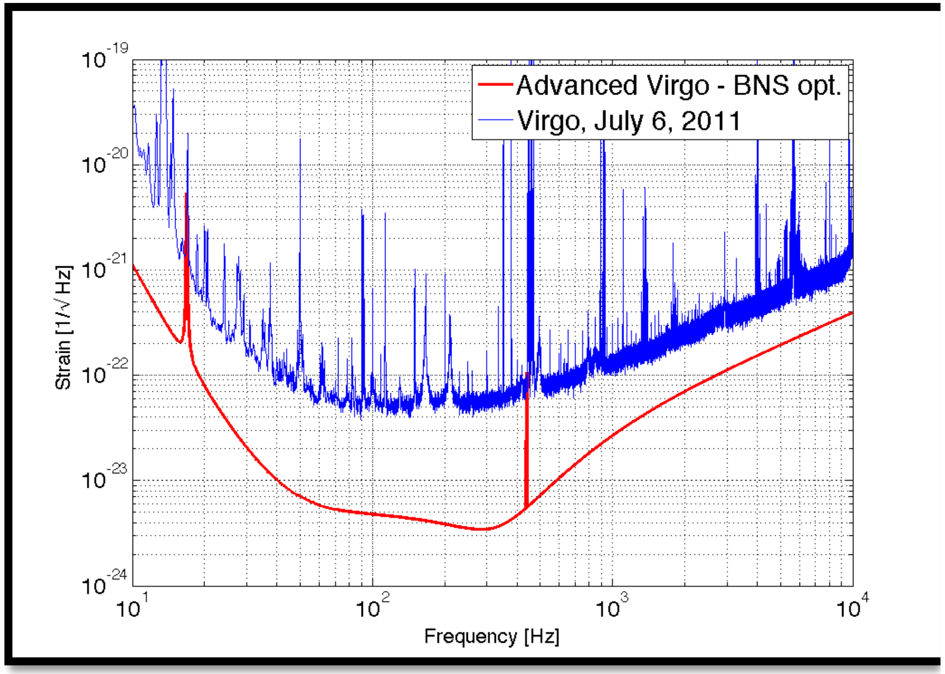
- We possess *now* the technology to aim at **tenfold** sensitivity improvement



Measured spectrum from
http://www.ligo.caltech.edu/~jzweizig/distribution/LSC_Data/



Measured spectrum courtesy of the Virgo Coll.



Will it suffice? Expected BNS rates

- Initial detectors: ~15 - 20 Mpc inspiral range. One event/50 years
- Advanced detectors: 200 Mpc insp. range (aLIGO at its best). 40 ev/yr!
- Detections expected in the near future
  - …but reaching the design sensitivity will be a long process

[CQG 27 (2010) 173001]

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}
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]

ADVANCED LIGO

- Funding in place (approved by NSF: 4/08)
- Total budget (equipment, personnel, travels): 240 M$ (including UK, D contributions)
- Installation in advanced state
- First lock expected: April 2014
- 3rd interferometer to be shipped to India (LIGO-India)

KAGRA

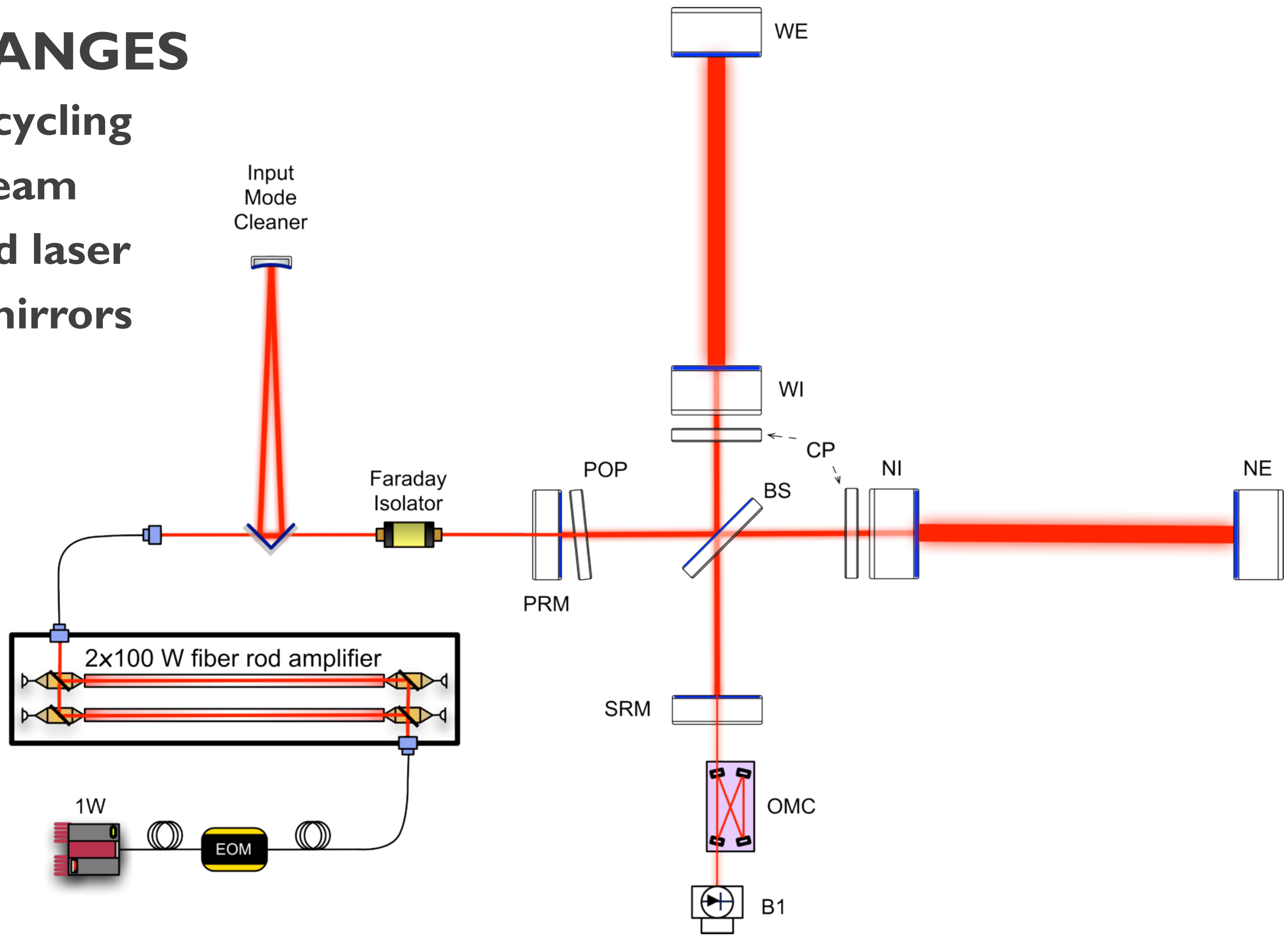
- **Underground detector in the Kamioka mine**
  - **3km length**
  - **Cryiogenic mirrors in the 2nd phase**

ADVANCED VIRGO – ID CARD

- **Advanced Virgo: upgrade of the Virgo interferometric detector of gravitational waves**
- **Goals:**
  - **improve the detection rate by ~1000**
  - **Participate to the early detections**
  - **Start the GW astronomy**
- **Funded by INFN, CNRS, EGO, Nikhef in Dec 2009: 23.8 ME**
  - **With some contributions from Poland and Hungary**
- **First light expected: fall 2015**

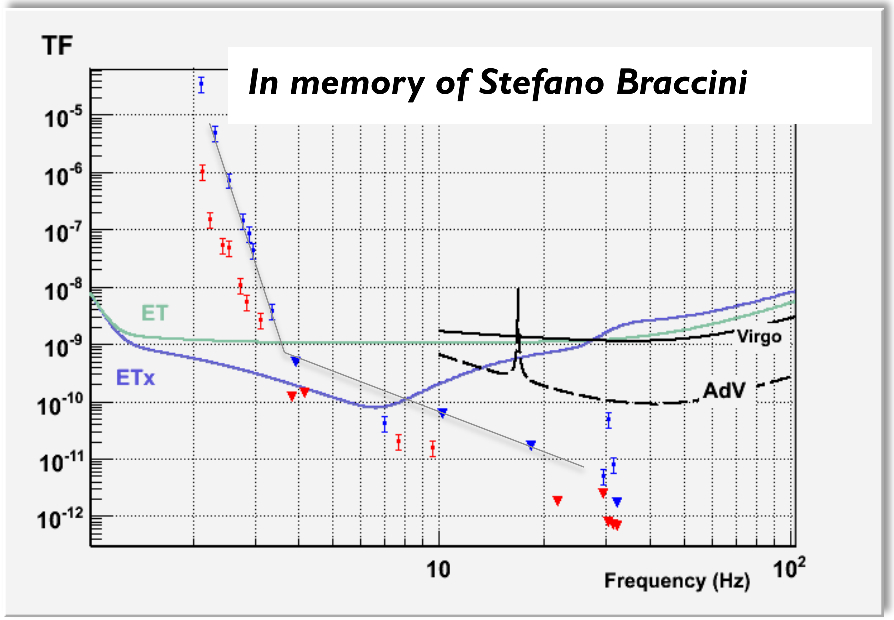
OPTICAL LAYOUT

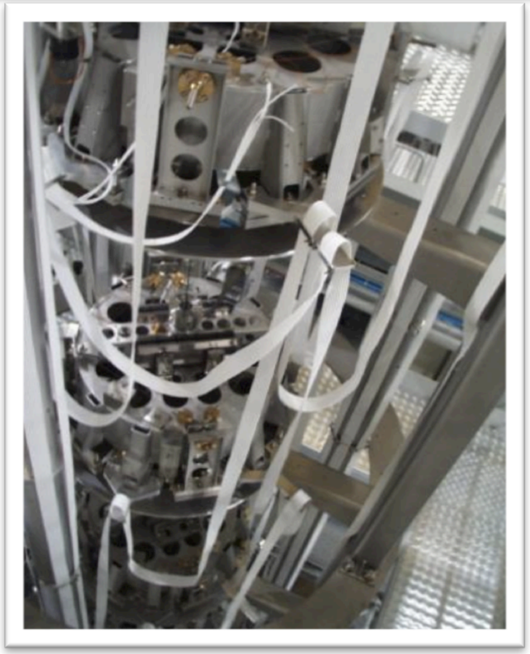
- **MAIN CHANGES**
  - Signal recycling
  - Larger beam
  - 200W rod laser
  - heavier mirrors



Vibration isolation

- aLIGO to extend bandwidth down to 10 Hz
  - active seismic isolation (1/2 stages) + triple/ quadruple pendulum
  - low frequency cutoff: 40→10 Hz
- AdV will still use the Virgo superattenuators
  - direct measurements proved isolation to be compliant with AdV requirements



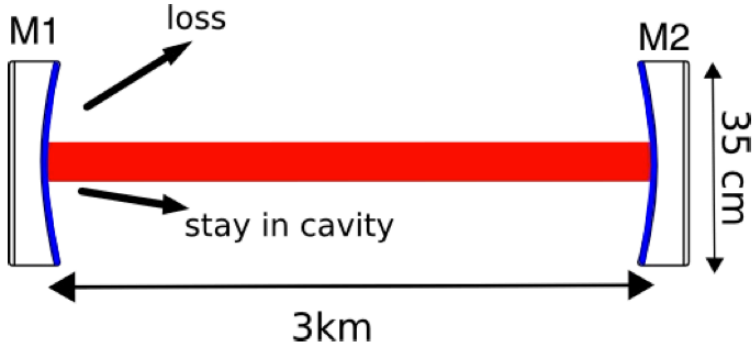


MIRRORS – SUBSTRATES

- Large high quality mirrors: 35cm diameter, 10 →20cm thick, 21 → 42 kg
- Large beam splitter: 55cm diameter
- Manufacturer = **HERAEUS** (like in VIRGO), leader in low absorption silica
- New fused silica grade (Suprasil 3002):
  - **Better bulk absorption** (0.2 ppm/cm measured at LMA): better for thermal lensing
  - Good mechanical properties (High quality factor, > 10^7)

POLISHING

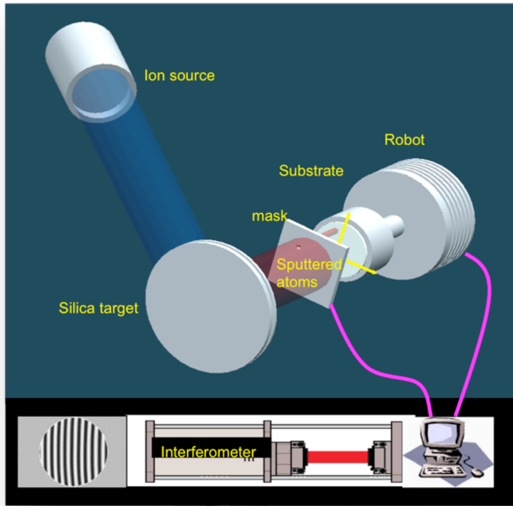
- Optical losses must be minimized to
  - Maximize the circulating power (and thus the sensitivity)
  - Minimize the scattered light (and the associated noise…)

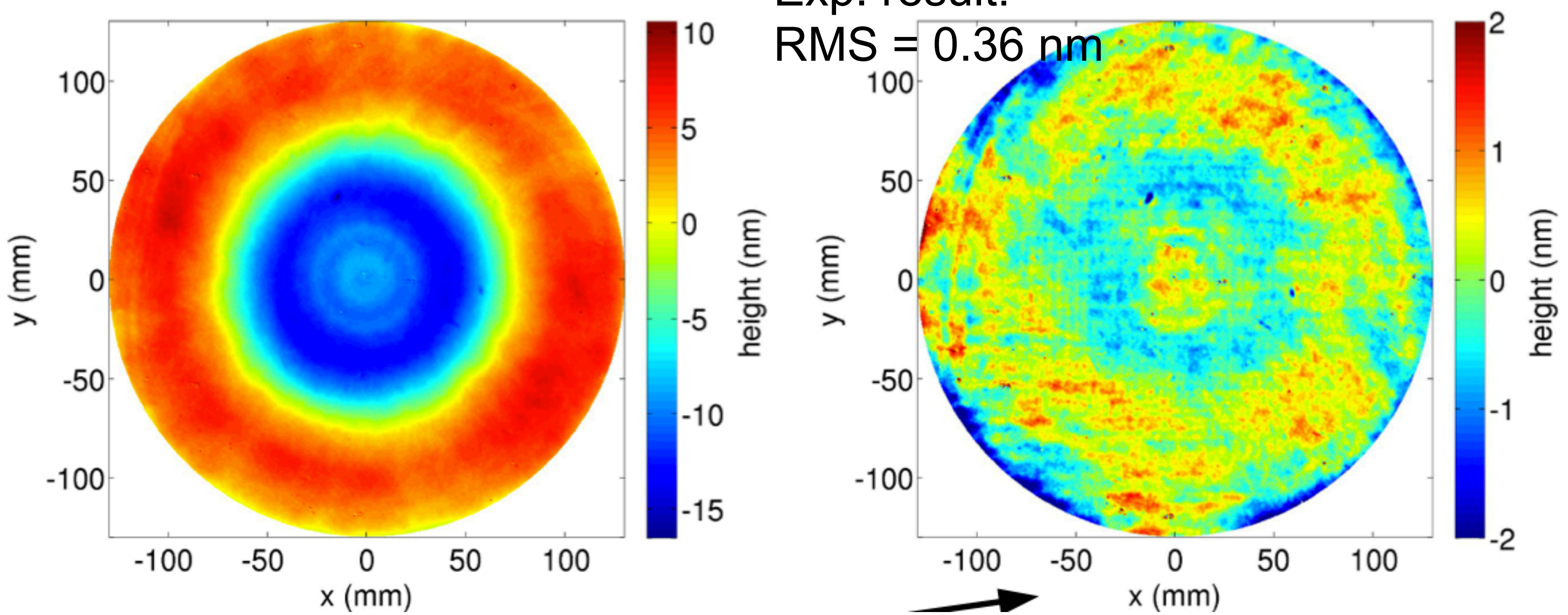


- AdV requirement: round-trip losses <50ppm →
  → mirror flatness < 0.5 nm rms
- Standard polishing may achieve flatness ~2 nm rms
- To reach specifications we apply "corrective coating" to polished mirrors

CORRECTIVE COATING

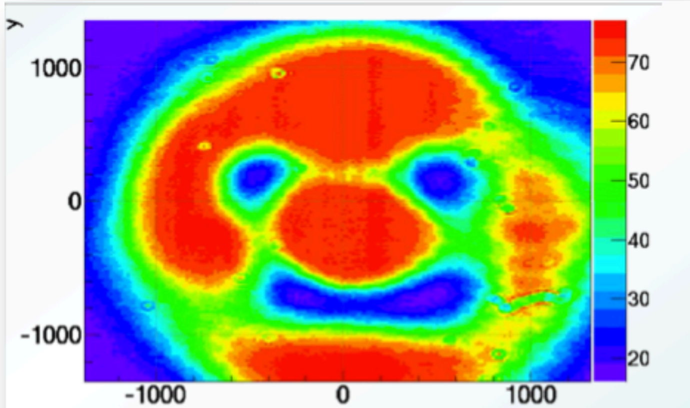
- Interferometric sensing of surface imperfections and correction by sputtering of silica molecules
- Mirror moved with respect to the silica beam by a robot (42kg mirror positioned with accuracy ~200 um)



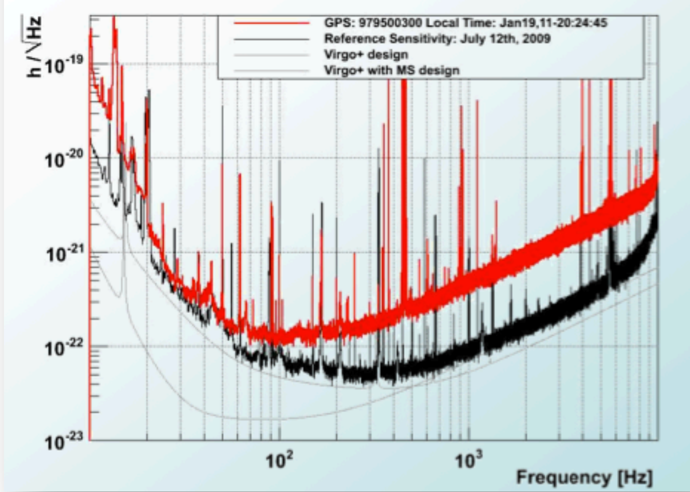


THERMAL COMPENSATION

- Aberrations (intrinsic mirror defects or thermal deformations of the mirrors) spoil the beam quality
- A set of sensors and thermal actuators has been conceived to get an "aberration free" interferometer

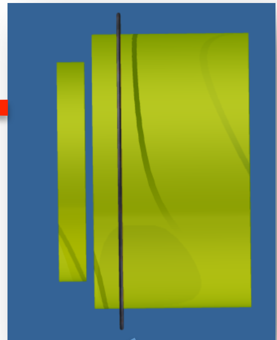


Dark fringe beam with high order modes



Effect of RoC asymmetry in Virgo+

CO2 laser

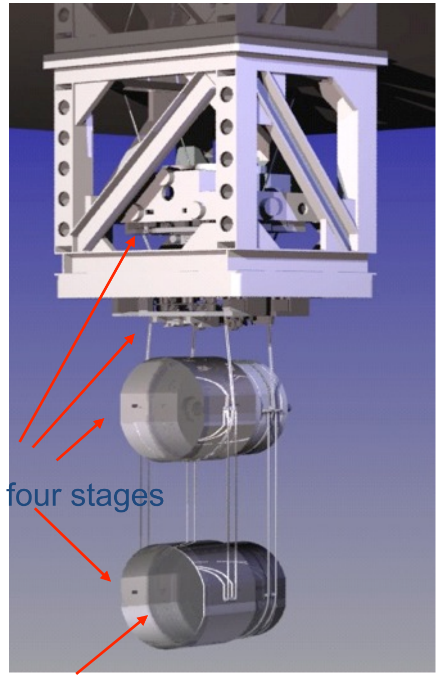


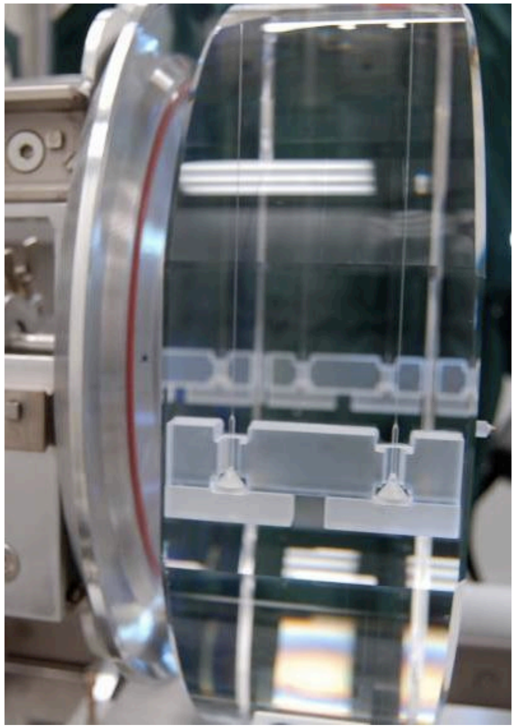
CO2 laser shined on the mirror: heat deposition where needed to compensate for aberrations

Heating rings around mirrors to tune RoC (accuracy: ~1m over 1500m)

Payload suspensions

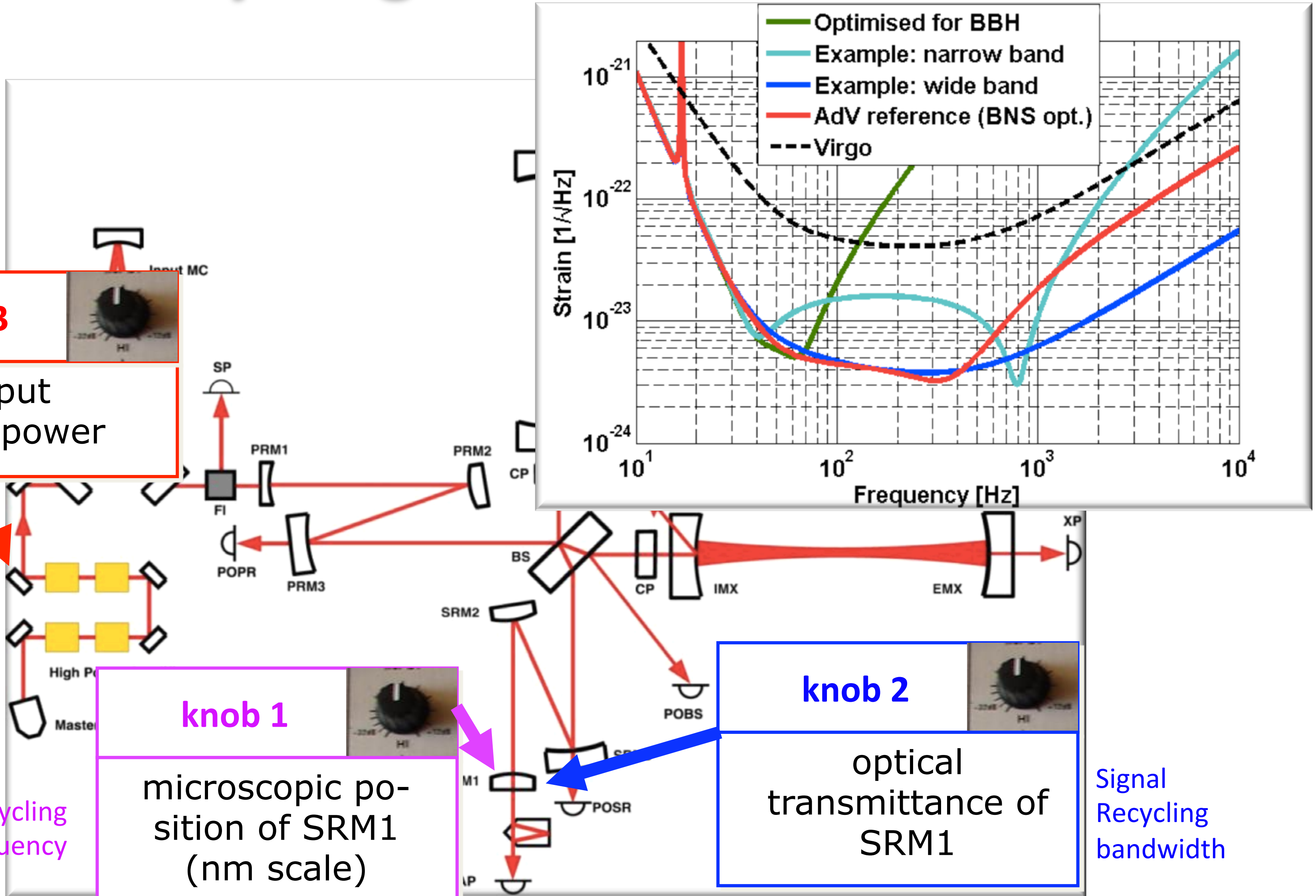
- "Monolithic" suspensions (silica fibers + silicate bonding) used in aLIGO and AdV
  - pendulum Q: 10^5 (steel) → ~10^8
- aLIGO "quad" designed and contributed by UK





- Monolithic payloads integrated in Virgo (the so called Virgo+ upgrade)
- Similar design for AdV

Signal recycling



knob 3

Input
Light power

knob 1

microscopic po-
sition of SRM1
(nm scale)

Signal Recycling
resonance frequency

knob 2

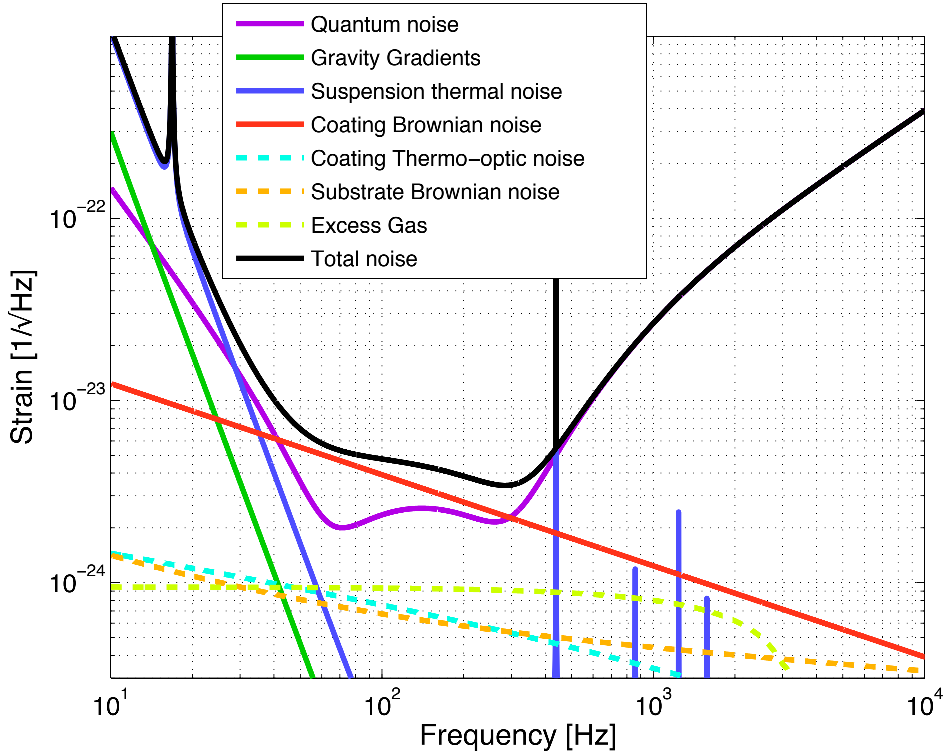
optical
transmittance of
SRM1

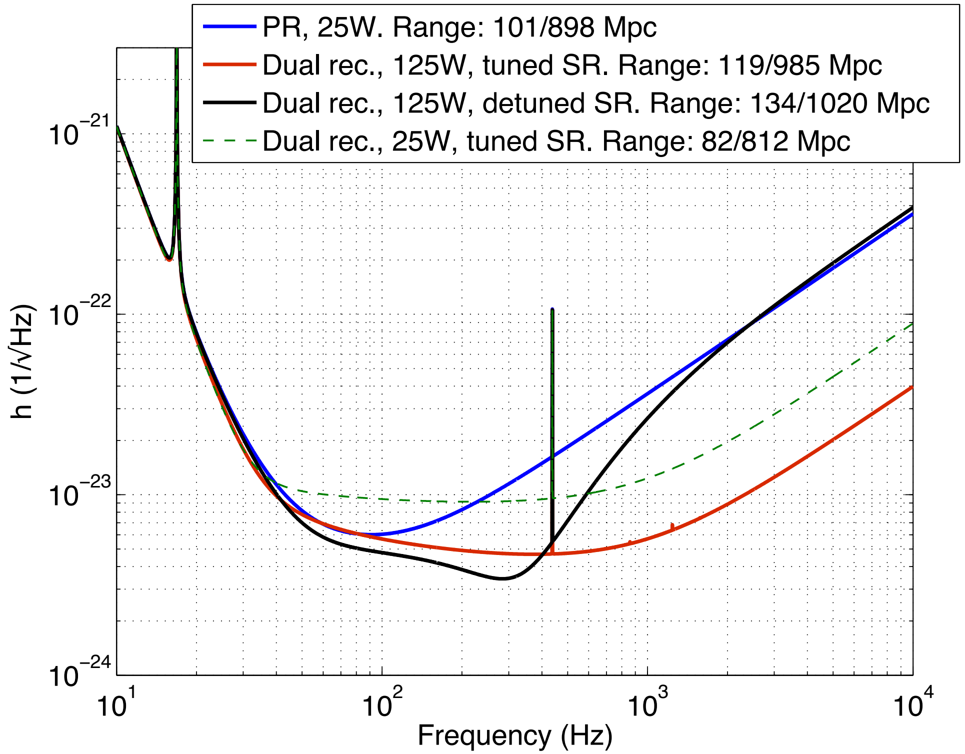
Signal
Recycling
bandwidth

OBSERVATIONAL PERSPECTIVES

SENSITIVITY GOAL(s)

- Advanced detectors will be tunable, to be optimized for different sources
- Typical benchmarks include BNS and 10+10 BBH



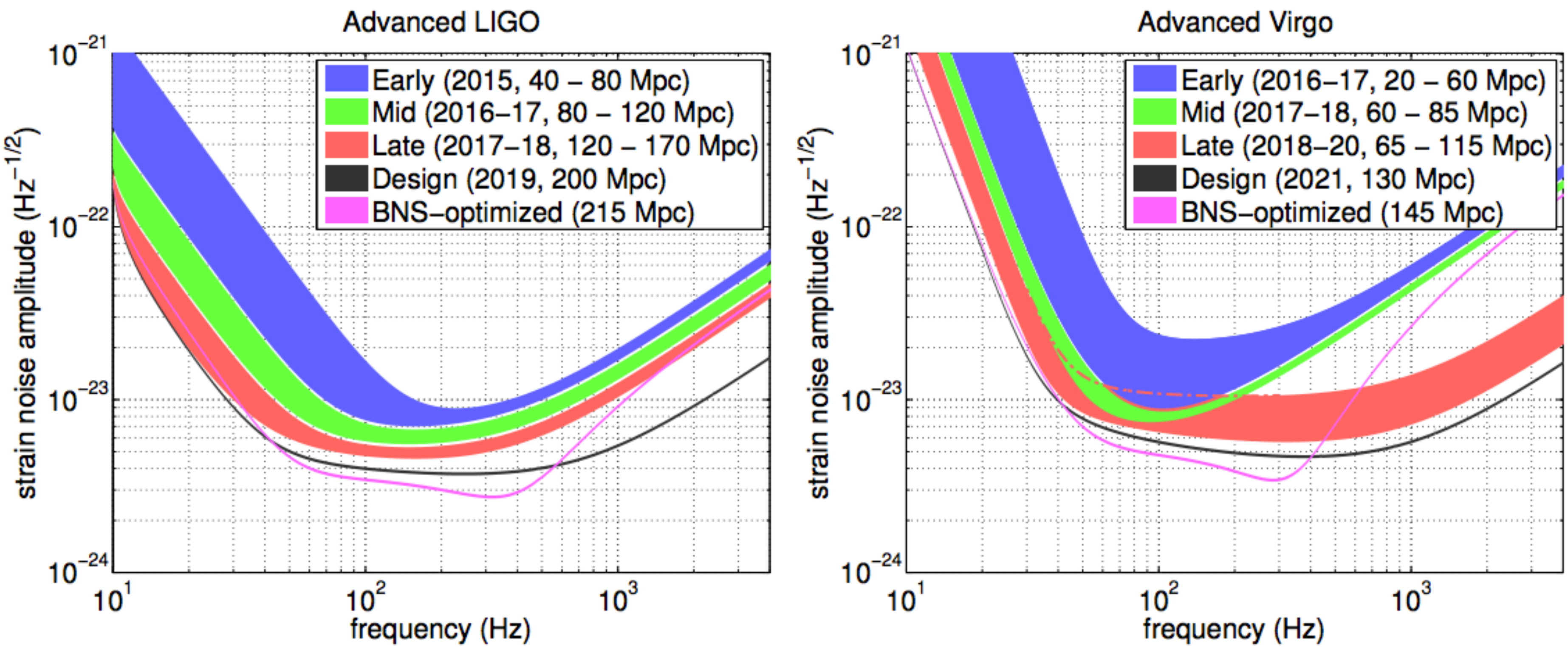


Plausible run schedule

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

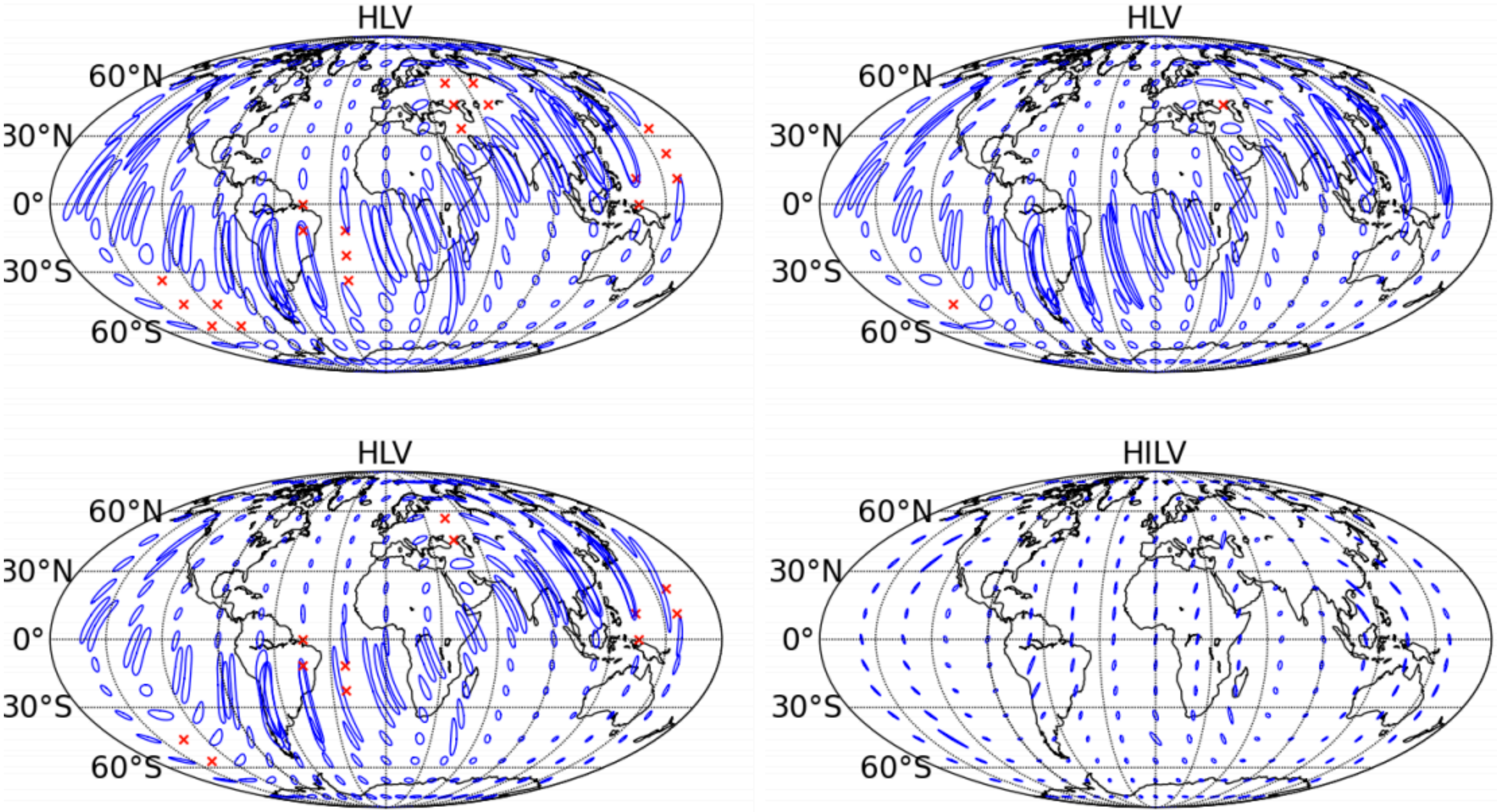
- Recently published paper on arXiv: http://arxiv.org/abs/1304.0670 *Prospects for Localization of Gravitational Wave Transients by the Advanced LIGO and Advanced Virgo Observatories*
- Official information about prospective observation schedules and associated sensitivities
- A **live** document: to be updated as our understanding progresses
- All numbers should be taken with several grains of salt …

Plausible sensitivity evolution



- Educated guess, on the basis of current detector's status, and past experiences.
- Note that Virgo lags behind LIGO by about 1.5 – 2 yrs

Sky localization capabilities



- Top left: 2016-17 ; top right: 2017-18
- Bottom left: 2019+ ; Bottom right: 2022 (with India)

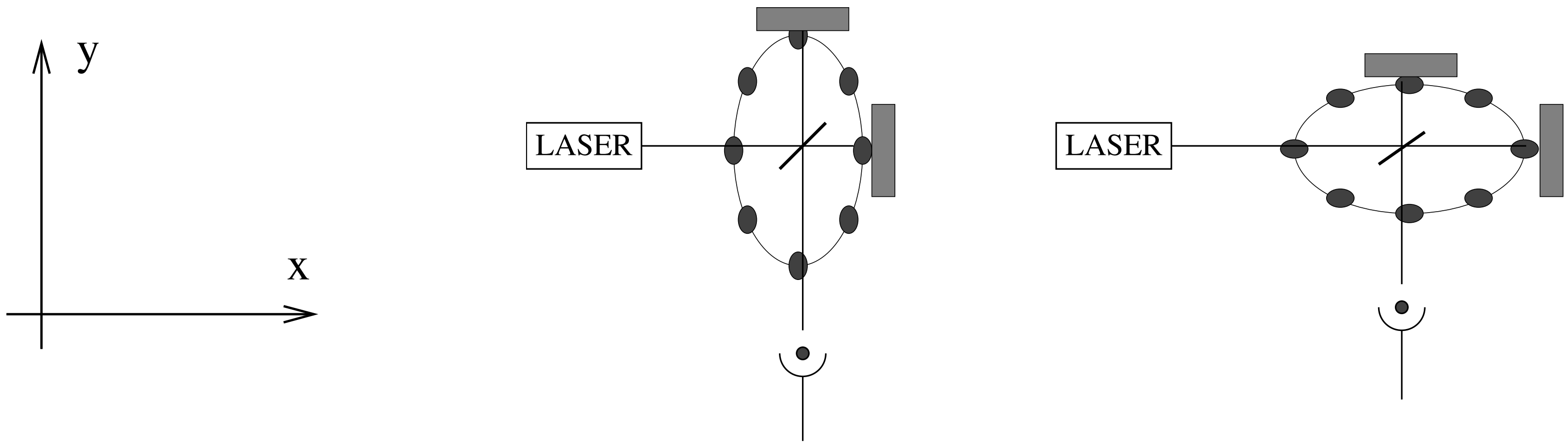
AdV and aLIGO science in one slide

- Range for BNS or BBH expanded by 10 → rate by 1000
- Amplitude sensitivity improved by 10 → same factor improvement of UL (or detection) of signals from galactic NS: allow to probe ellipticities down to ~ 10^{-9}
- Detection of impulsive events in our Galaxy with energies as small as $10^{-9}\ M_{\odot}c^2$ → likely detection of next supernova
- Limits on stochastic background, for instance on Ω_{GW}, improved by a factor 100
- Localization of BNS events improved as sensitivity progresses and all detectors come on line: from only 2% of the events localized within 5 deg^2, up to about 20% (and about 50% within 20 deg^2)
- **But it will take time: please be patient!**

The end

Thank you for the attention

A Michelson-Morley sensitive to GW? Why?



- Freely falling masses (in the TT gauge) sit on the geodesics of the metric perturbed by the presence of gravitational waves
- But the speed of light remains the same, hence

$$ds^2 = 0 = [\eta_{\mu\nu} + h_{\mu\nu}]\, dx^\mu dx^\nu$$

considering an element dx along the axis x of the interferometer

$$c^2 dt^2 = [1 + h_{11}(2\pi f_{gw} t - \mathbf{k} \cdot \mathbf{x})]\, dx^2$$

- A ray of light takes therefore a time τ_x to go from the beam splitter to the end mirror and back again *(in the following, I mean taking real part)*

$$\tau_x = \frac{2L}{c} + \frac{h}{4\pi i f_{gw}}\left[e^{i2\pi f gw 2L/c} - 1\right]$$

- With a GW wave in + polarization, a similar formula holds for light propagating along the y axis: at recombination they are off by a time

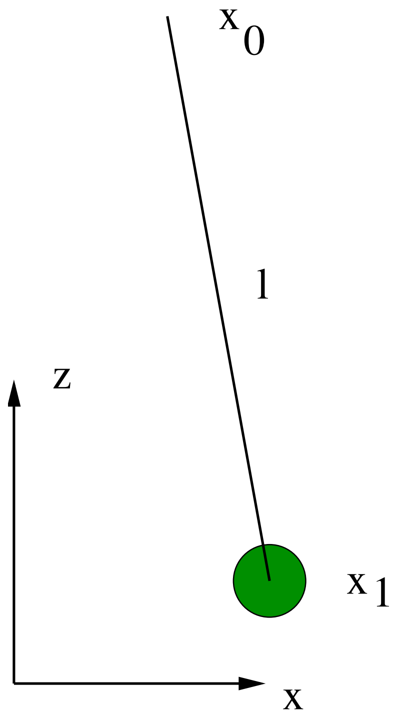
$$\Delta\tau(t) = h(t)\tau_{rt}e^{i\pi f_{gw}\tau_{rt}}\frac{\sin\left(\pi f_{gw}\tau_{rt}\right)}{\pi f_{gw}\tau_{rt}}$$

- That is, by a phase (t_{rt} is the round-trip time in the Michelson)

$$\Delta\phi(t) \;=\; \frac{4\pi L}{\lambda}h(t)e^{i\pi f_{gw}\tau_{rt}}\mathrm{sinc}(\pi f_{gw}\tau_{rt})$$

relating the GW amplitude h(t) with a phase shift in the interferometer

Wait: freely falling masses???



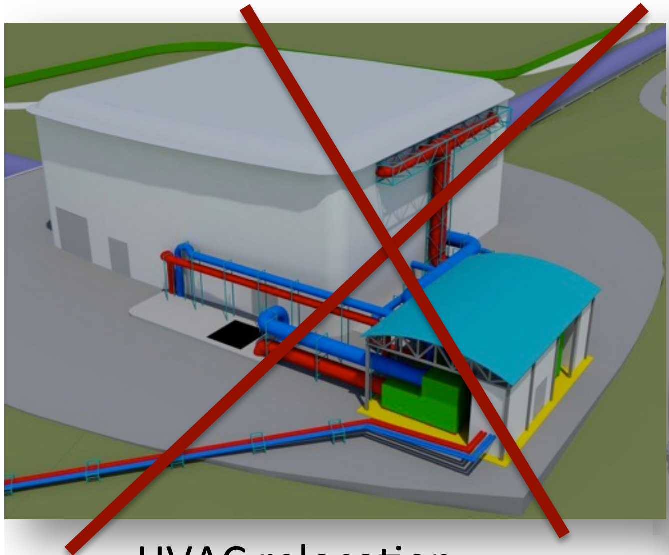
$$\ddot{x}_1 + \frac{g}{l}(x_1 - x_0) = F_{ext}/m$$

$$\tilde{x}_1(\omega) = \frac{\omega_0^2 \tilde{x}_0(\omega) + \tilde{F}_{ext}(\omega)/m}{\omega_0^2 - \omega^2}$$

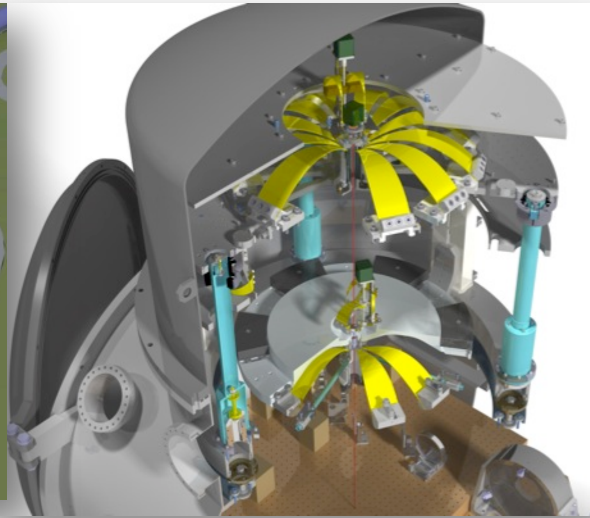
$$\omega^2 m \tilde{x}_1(\omega) + F_{ext} \simeq 0$$

- Well above a pendulum resonance, the attached mass responds like a free mass to an external force acting on it
- This force could also be (in an appropriate gauge) the *Riemann force* driving the deviation of the geodesics.

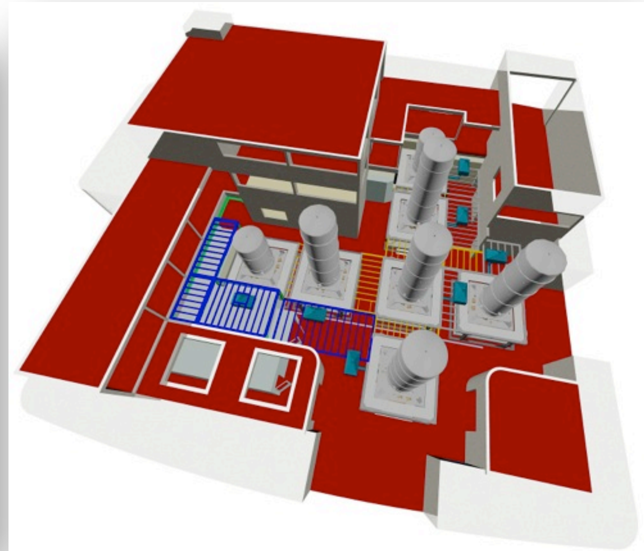
STRAY LIGHT MITIGATION



HVAC relocation

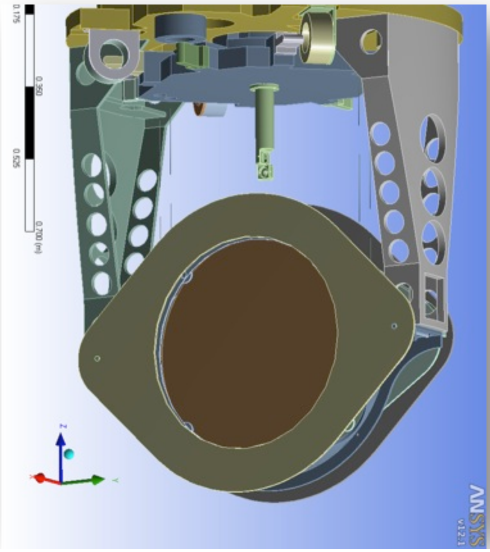


All photodiodes
seismically isolated
and In vacuum

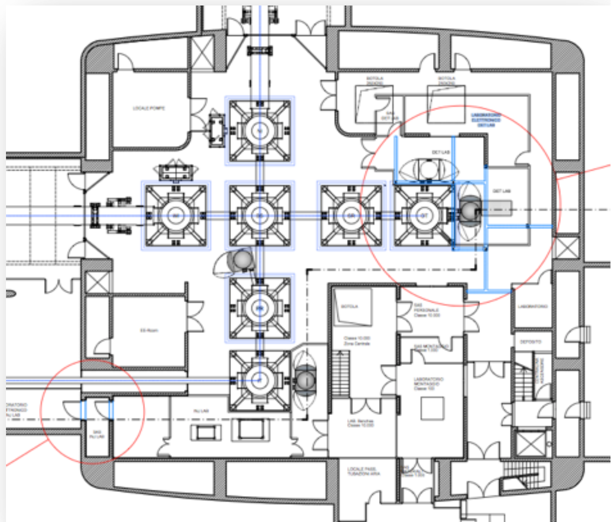


halls re-arrangements
for hosting minitowers

large suspended baffles



+ payloads/superattenuators/
vacuum modifications
for the large baffles suspension
+ superpolished optics on
suspended benches
+ …



A detail… vacuum!

- Requirements:
  - 10^{-9} mbar for H_2
  - 10^{-14} mbar for hydrocarbons
- Vacuum pipe:
  - 1.2 m diameter
  - Baked at 150 °C for 1 week or more