Francesco Fidecaro, JGRG 22(2012)111403

# "Virgo: design, results and perspectives"

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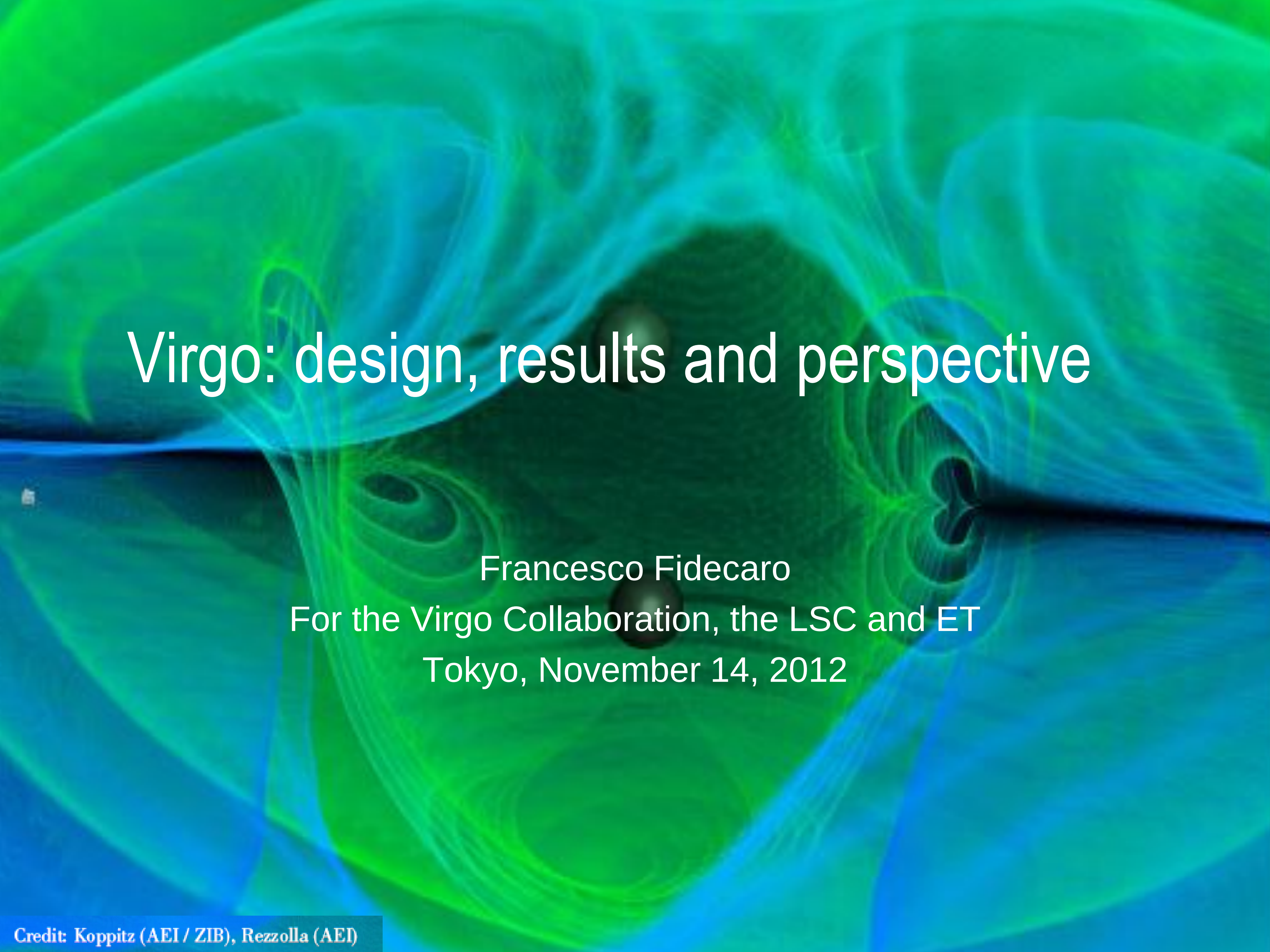
## RESCEU SYMPOSIUM ON

## GENERAL RELATIVITY AND GRAVITATION

# JGRG 22

**November 12-16 2012**

**Koshiba Hall, The University of Tokyo, Hongo, Tokyo, Japan**



# Virgo: design, results and perspective

Francesco Fidecaro
For the Virgo Collaboration, the LSC and ET

Tokyo, November 14, 2012

Credit: Koppitz (AEI / ZIB), Rezzolla (AEI)

# Outline

- GW detection peculiarities
- Gravitational wave spectrum
- The Virgo interferometer
- Some LSC-Virgo results (LSC and Virgo collaborations)
- Advanced Virgo
- The ET perspective (ET study group and science team)

# GW detection

# GW detection

- Need to measure changes in space time metric due to $T^{\mu\nu}$ variations
- The shape of the signal is given by the 2nd time derivative of $Q^{ij}$
- By measuring fields, and not energy, the signal amplitude varies as 1/R , distance from the source
- The amplitude of the detected signal depends smoothly on the incoming direction, due to the quadrupolar nature of the wave
- It scales as L, the size of the detector

## Consequences

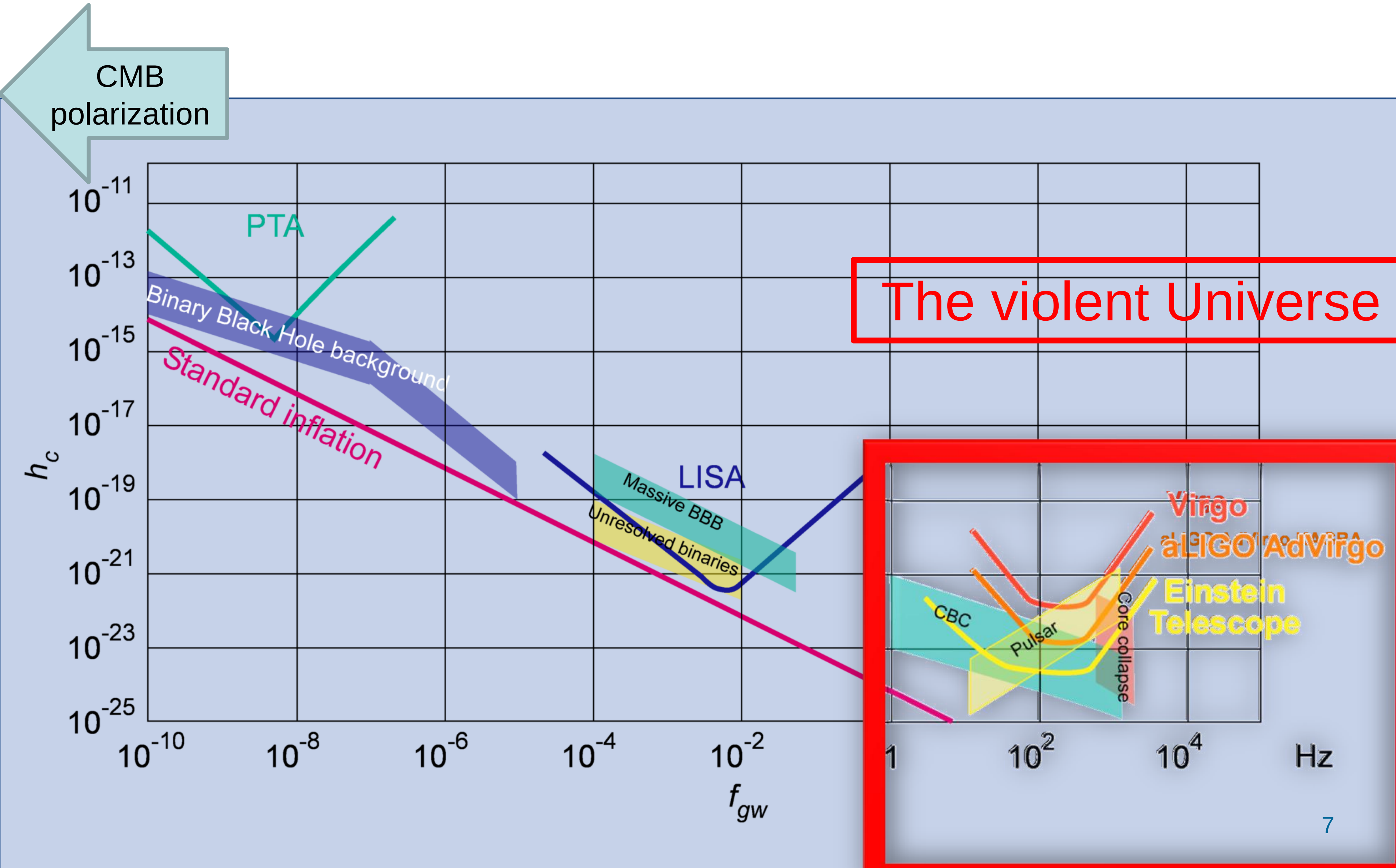
- Type of astrophysical / cosmological process identified by the signal shape (frequency components, phase)
- The number of observed sources, or recorded events, will raise as the distance (horizon) the detector is able to reach, to the 3rd power.
- Fixing the position of the source in the sky requires to measure the phase of the signal in more than one detector
- For long deterministic signals a single detector can be used (it moves !)
- The size of the detector determines the detectable GW wavelength

# The reality

- Different detectors operate in different frequency bands, making their best to reduce noise
- Looking for amplitude one prefers massive compact astrophysical objects. The heavier the slower, but also the louder
- Studying the details of the process require higher spatial resolution, this translates into high frequency
- Options (remember that effects on single masses scale as 1/L)
  - Ground based, km size
  - Space based detectors
  - Galaxy based detectors
  - Universe based
  - No scale (stochastic background)
- Correspond to different sources
  - Compact binary systems
  - Binaries, massive black holes
  - Supermassive black holes
  - Stochastic background

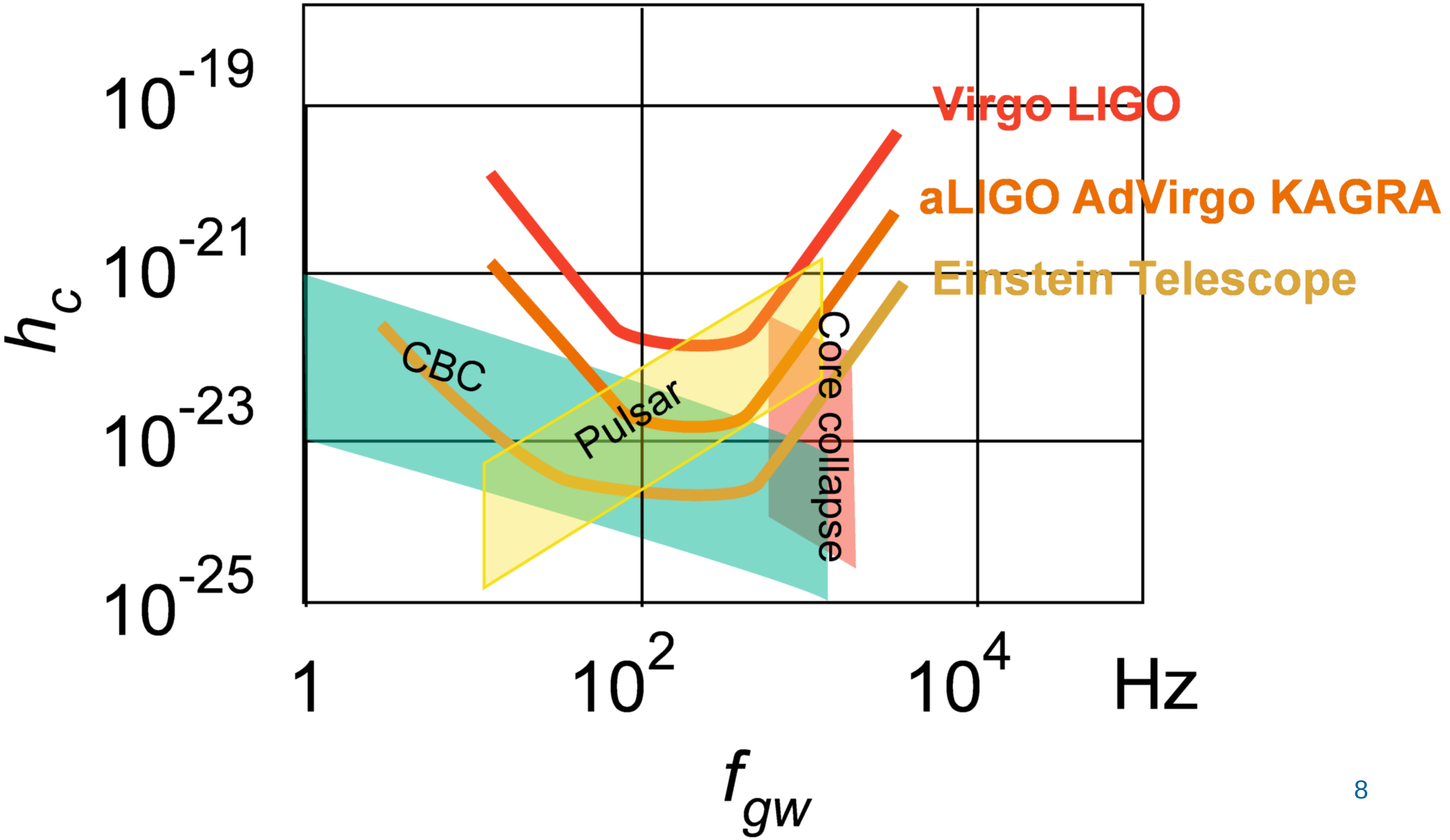
# The GW spectrum

# Gravitational wave spectrum



# The violent Universe

- Ground based km scale interferometers will listen to the violent Universe, where gravity is strong over short distances



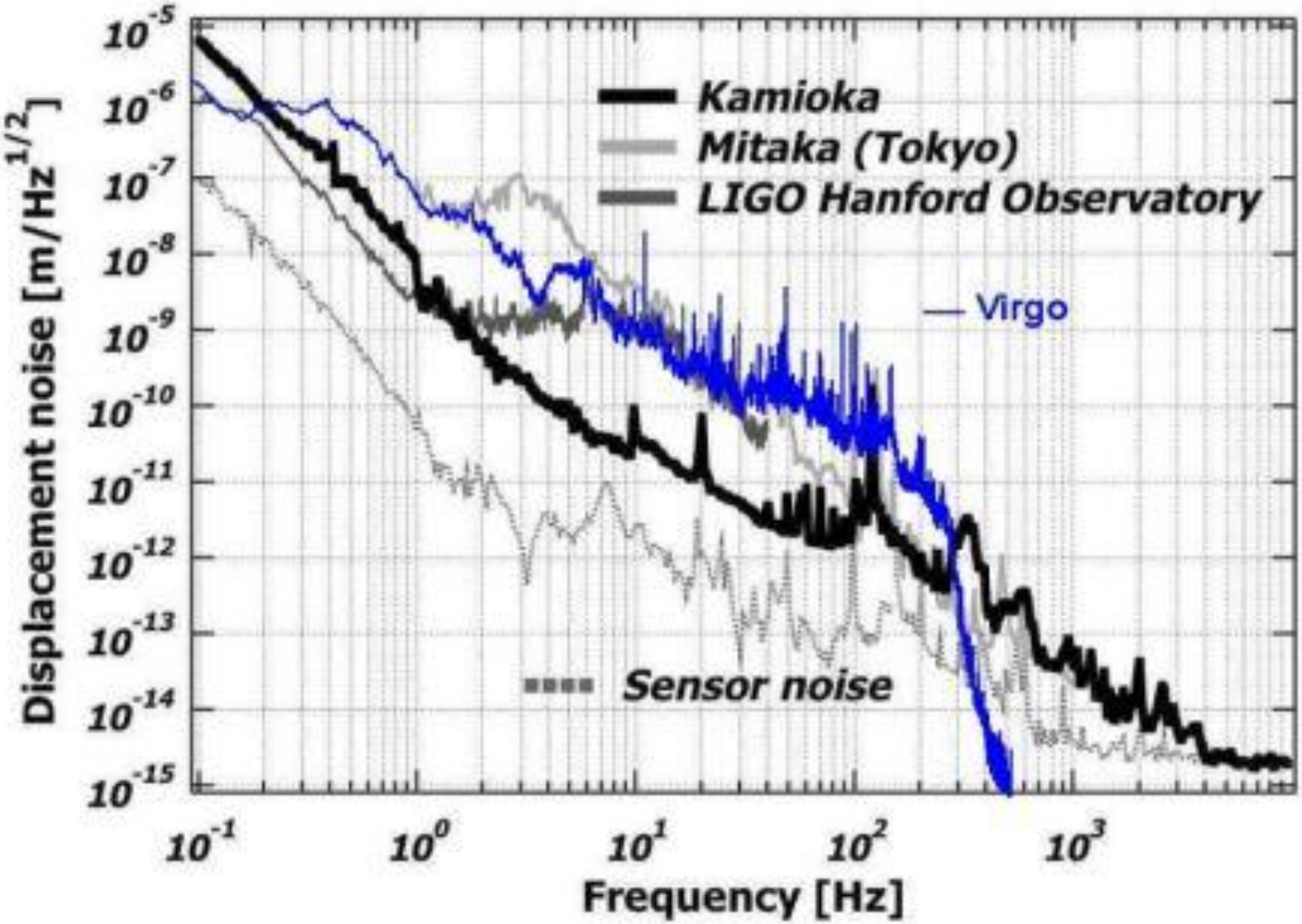
# The Virgo detector

# The Virgo Collaboration

T. Accadia[11], F. Acernese[5ac], F. Antonucci[8a], P. Astone[8a], G. Ballardin[2], F. Barone[5ac], M. Barsuglia[1], Th. S. Bauer[13a], M.G. Beker[13a], A. Belletoile[11], S. Birindelli[14a], M. Bitossi[7a], M. A. Bizouard[10a], M. Blom[13a], C. Boccara[10b], F. Bondu[14b], L. Bonelli[7ab], R. Bonnand[12], V. Boschi[7a], L. Bosi[6a], B. Bouhou[1], S. Braccini[7a], C. Bradaschia[7a], A. Brillet[14a], V. Brisson[10a], R. Budzyński[16b], T. Bulik[16cd], H. J. Bulten[13ab], D. Buskulic[11], C. Buy[1], G. Cagnoli[3a], E. Calloni[5ab], E. Campagna[3ab], B. Canuel[2], F. Carbognani[2], F. Cavalier[10a], R. Cavalieri[2], G. Cella[7a], E. Cesarini[3b], E. Chassande-Mottin[1], A. Chincarini[4], F. Cleva[14a], E. Coccia[9ab], C. N. Colacino[7a], J. Colas[2], A. Colla[8ab], M. Colombini[8b], A. Corsi[8a], J.-P. Coulon[14a], E. Cuoco[2], S. D'Antonio[9a], V. Dattilo[2], M. Davier[10a], R. Day[2], R. De Rosa[5ab], G. Debreczeni[17], M. del Prete[7ac], L. Di Fiore[5a], A. Di Lieto[7ab], M. Di Paolo Emilio[9ac], A. Di Virgilio[7a], A. Dietz[11], A. Dietz[11], M. Drago[15cd], V. Fafone[9ab], I. Ferrante[7ab], F. Fidecaro[7ab], I. Fiori[2], R. Flaminio[12], J.-D. Fournier[14a], J. Franc[12], S. Frasca[8ab], F. Frasconi[7a], A. Freise[*], M. Galimberti[12], L. Gammaitoni[6ab], F. Garufi[5ab], M. E. Gáspár[17], G. Gemme[4], E. Genin[2], A. Gennai[7a], A. Giazotto[7a], R. Gouaty[11], M. Granata[1], C. Greverie[14a], G. M. Guidi[3ab], J.-F. Hayau[14b], H. Heitmann[14], P. Hello[10a], S. Hild[**], D. Huet[2], P. Jaranowski[16e], I. Kowalska[16c], A. Królak[16af], N. Leroy[10a], N. Letendre[11], T. G. F. Li[13a], M. Lorenzini[3a], V. Loriette[10b], G. Losurdo[3a], E. Majorana[8a], I. Maksimovic[10b], N. Man[14a], M. Mantovani[7ac], F. Marchesoni[6a], F. Marion[11], J. Marque[2], F. Martelli[3ab], A. Masserot[11], C. Michel[12], L. Milano[5ab], Y. Minenkov[9a], M. Mohan[2], J. Moreau[10b], N. Morgado[12], A. Morgia[9ab], S. Mosca[5ab], V. Moscatelli[8a], B. Mours[11], I. Neri[6ab], F. Nocera[2], G. Pagliaroli[9ac], L. Palladino[9ac], C. Palomba[8a], F. Paoletti[7a,2], S. Pardi[5ab], M. Parisi[5b], A. Pasqualetti[2], R. Passaquieti[7ab], D. Passuello[7a], G. Persichetti[5ab], M. Pichot[14a], F. Piergiovanni[3ab], M. Pietka[16e], L. Pinard[12], R. Poggiani[7ab], M. Prato[4], G. A. Prodi[15ab], M. Punturo[6a], P. Puppo[8a], D. S. Rabeling[13ab], I. Rácz[17], P. Rapagnani[8ab], V. Re[15ab], T. Regimbau[14a], F. Ricci[8ab], F. Robinet[10a], A. Rocchi[9a], L. Rolland[11], R. Romano[5ac], D. Rosińska[16g], P. Ruggi[2], B. Sassolas[12], D. Sentenac[2], L. Sperandio[9ab], R. Sturani[3ab], B. Swinkels[2], A. Toncelli[7ab], M. Tonelli[7ab], O. Torre[7ac], E. Tournefier[11], F. Travasso[6ab], G. Vajente[7ab], J. F. J. van den Brand[13ab], S. van der Putten[13a], M. Vasuth[17], M. Vavoulidis[10a], G. Vedovato[15c], D. Verkindt[11], F. Vetrano[3ab], A. Viceré[3ab], J.-Y. Vinet[14a], H. Vocca[6a], M. Was[10a], M. Yvert[11]

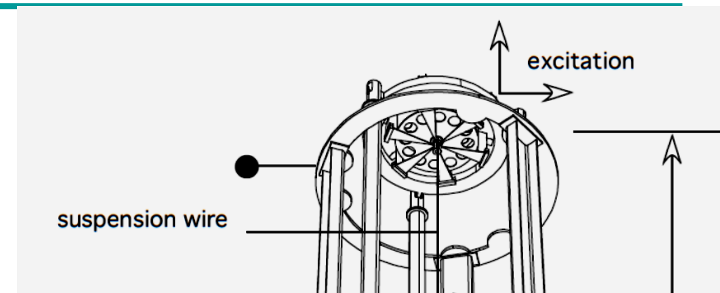
- Early efforts
  - Brillet (optics)
  - Giazotto (suspensions)
- Collaboration started in 1992
- LAPP Annecy
- EGO Cascina
- Firenze-Urbino
- Genova
- Napoli
- OCA Nice
- NIKHEF Amsterdam
- LAL Orsay
- LMA Lyon
- APC Paris – ESPCI Paris
- Perugia
- Pisa
- Roma La Sapienza
- Roma Tor Vergata
- Trento-Padova
- IM PAN Warsaw
- RMKI Budapest
- LKB Paris
- 18 groups
- About 200 authors

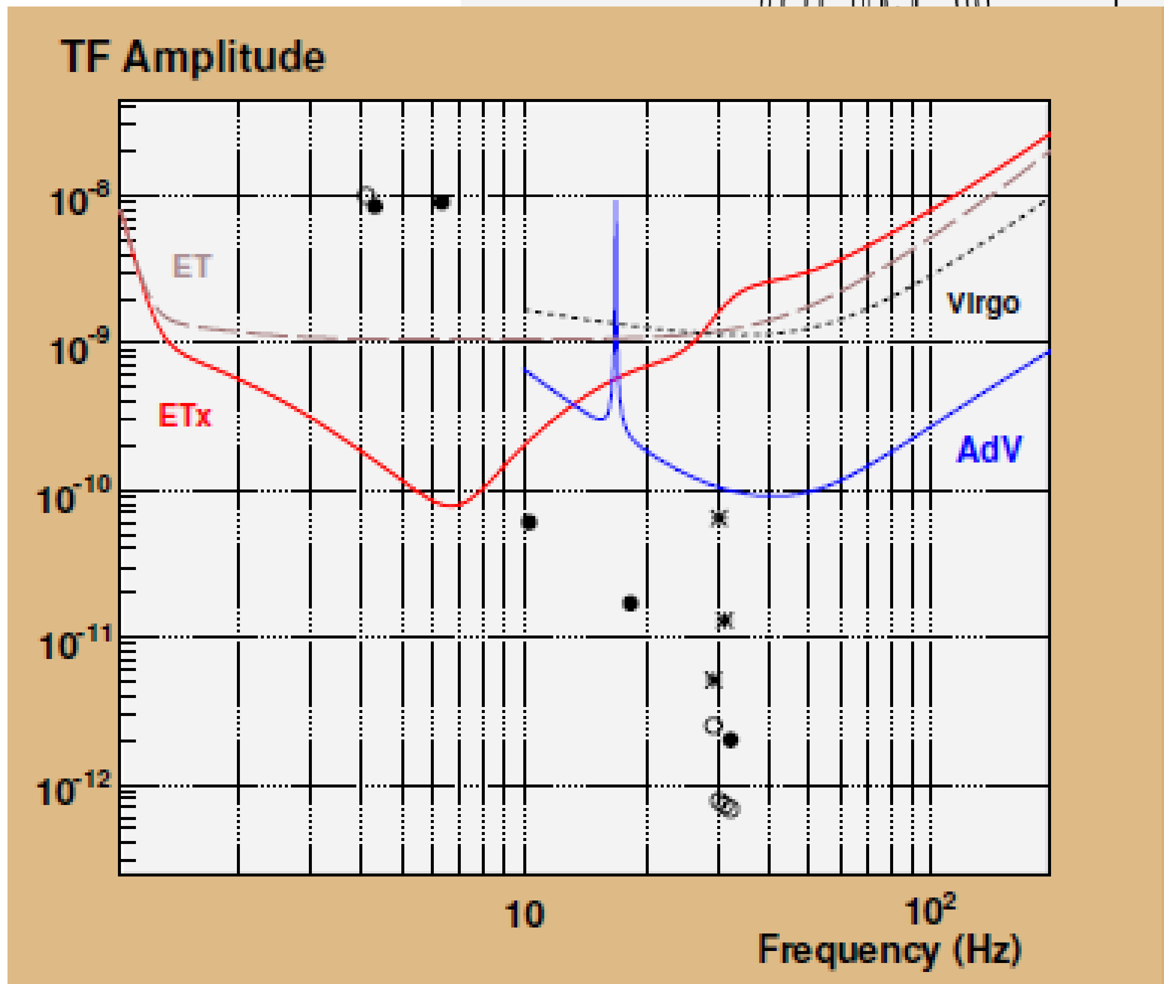
# Noise in mass position



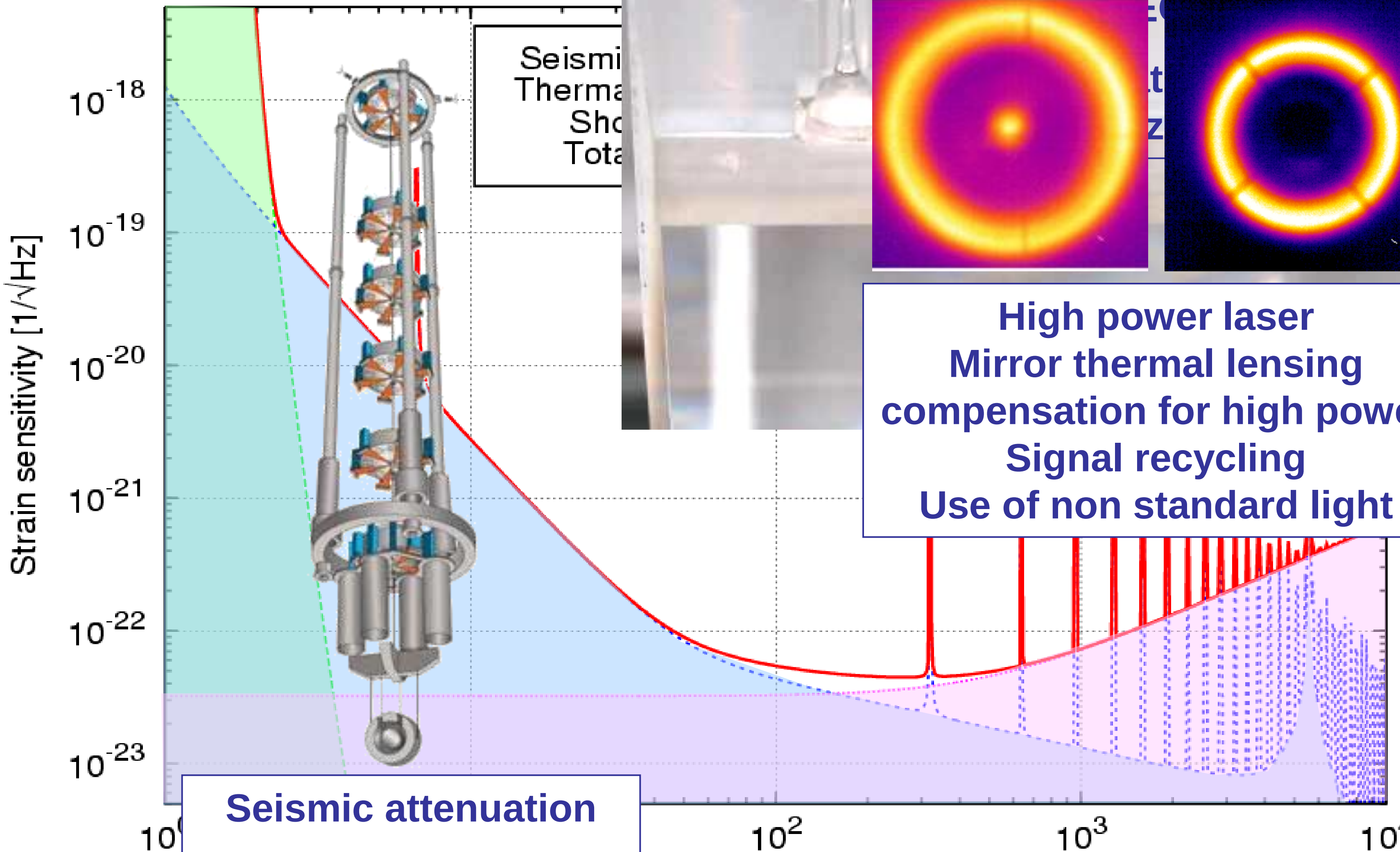
# Superattenuator performance

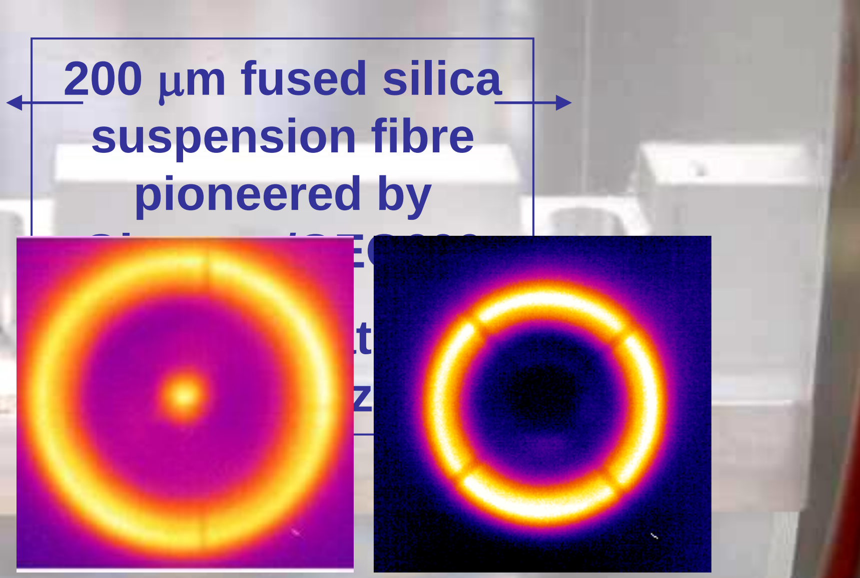
- Excitation at top
- Use Virgo sensitivity and stability
- Integrate for several hours
- Upper limit for TF at 32 Hz:1,7 $10^{-12}$
- In some configurations a signal was found, but also along a direction perpendicular to excitation: compatible with magnetic cross talk



# Issues in ser



200 μm fused silica suspension fibre pioneered by

**High power laser**
**Mirror thermal lensing compensation for high power**
**Signal recycling**
**Use of non standard light**

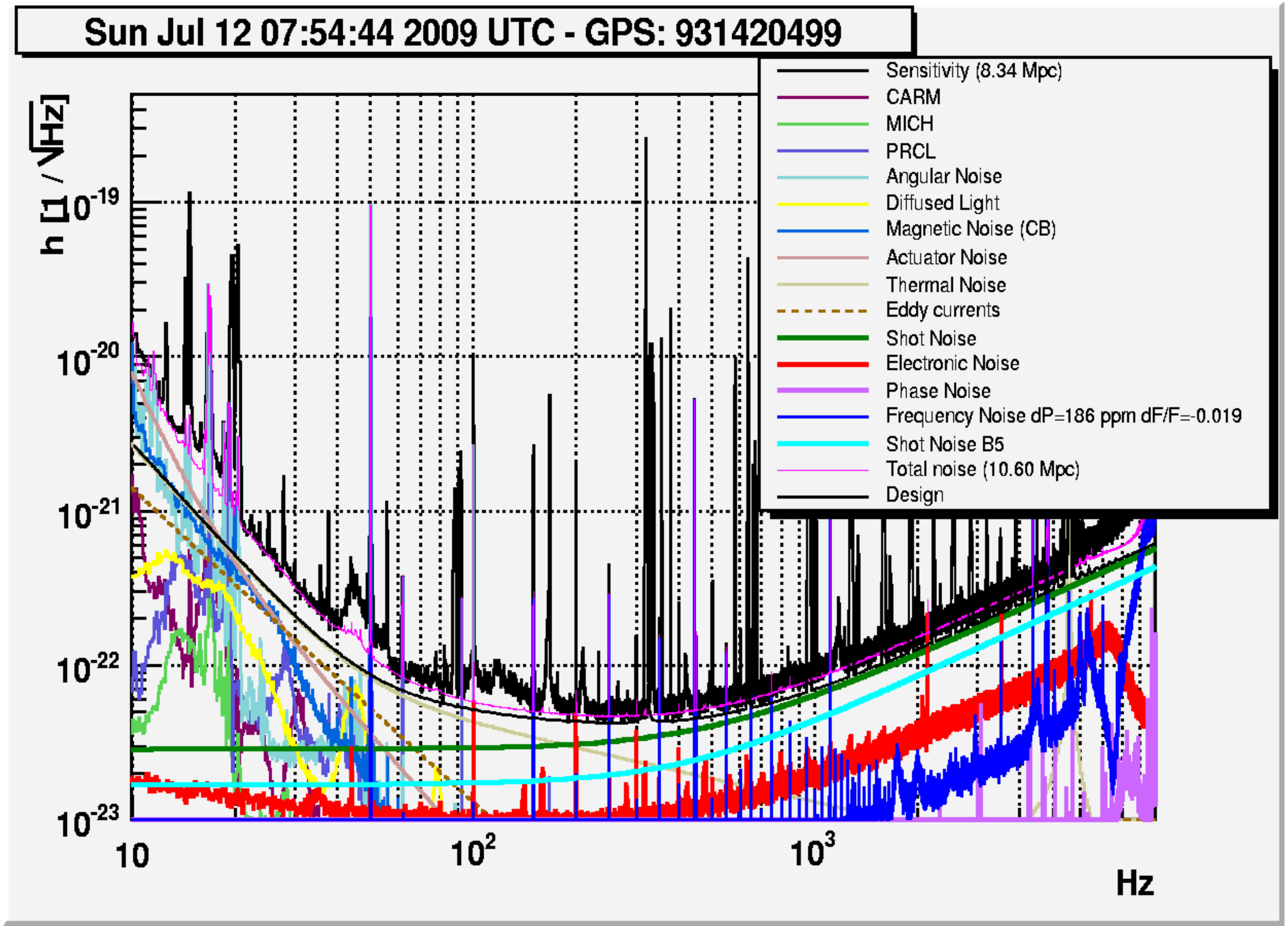
**Seismic attenuation**

**Local gravity fluctuations**

# Virgo site in Cascina

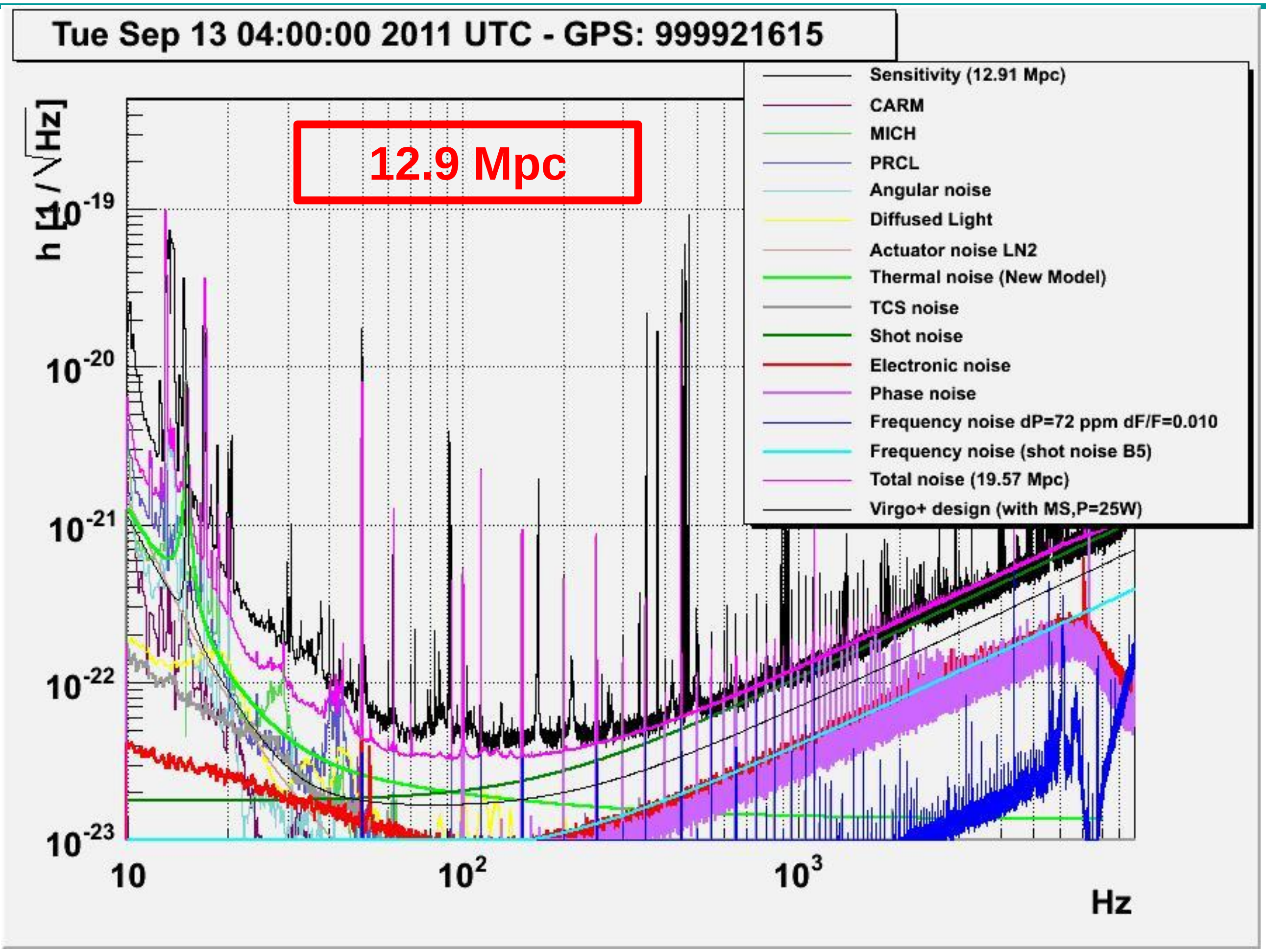
# Noise understanding

- Noise sources and coupling are well understood
- Low frequency shows more structures
- Noise reduction in advanced detectors achieved with proper design



# The noise budget

Lines
10.28 & arm (NI)
13-14 Cal
14.8 vert_rm
17 Mich
18.6 Env_Inj
20.1 Tz_rm
37 DET
78-82 Dihedron
130 (?)
166 Bs_violin
166 M1
210 M2




*The noise budget. For frequency lower than about 300 Hz the sensitivity calculated as the quadratic sum of all noises - violet curve - does not explain the actual sensitivity - black curve.*

# Environmental noises studies

Investigations to understand the sources and the path to dark fringe

⇒ Coupling (paths) to dark fringe

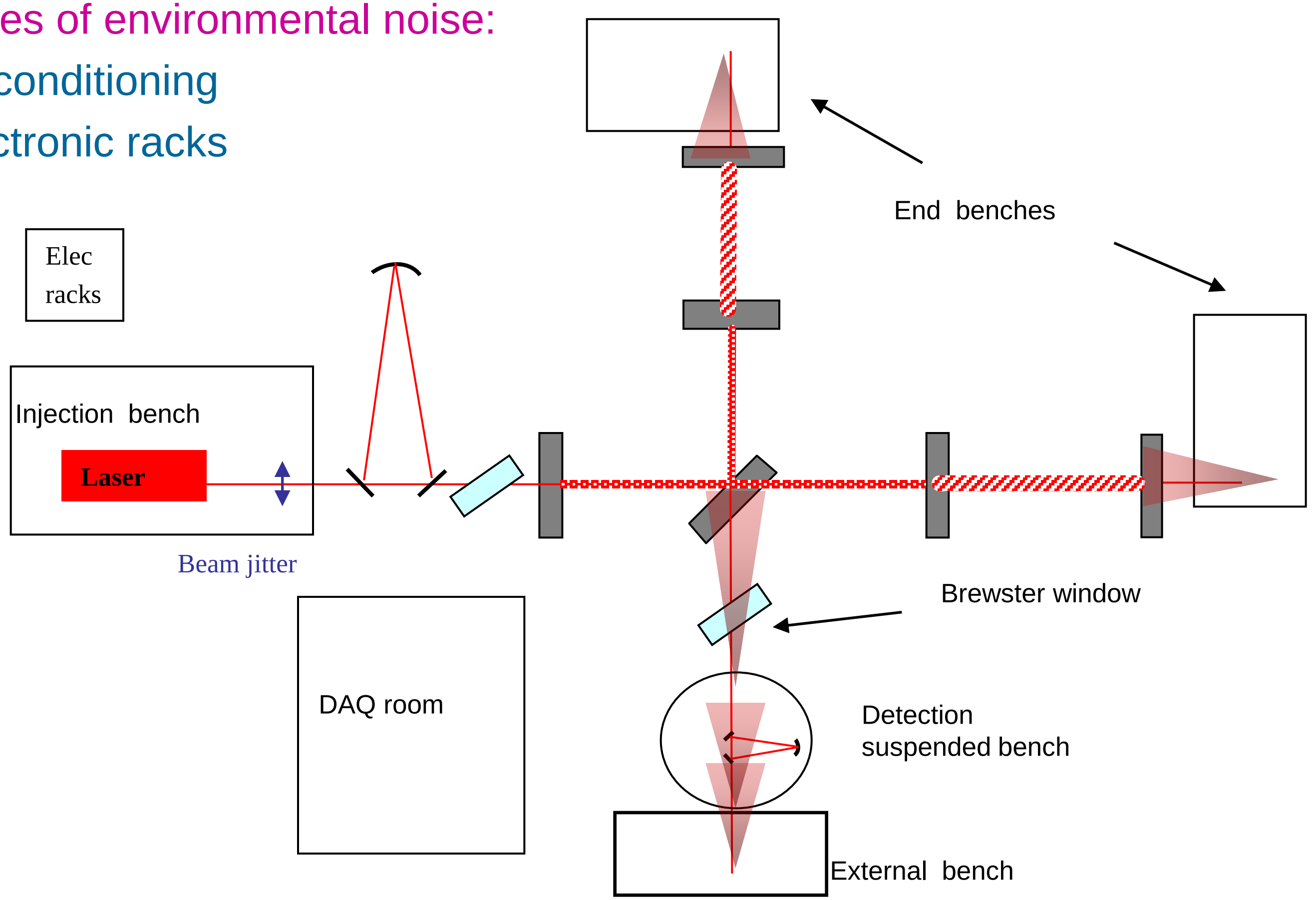
- diffused light from in air optical benches
- diffused light related to Brewster window
- beam jitter on injection bench

⇒ Sources of environmental noise:

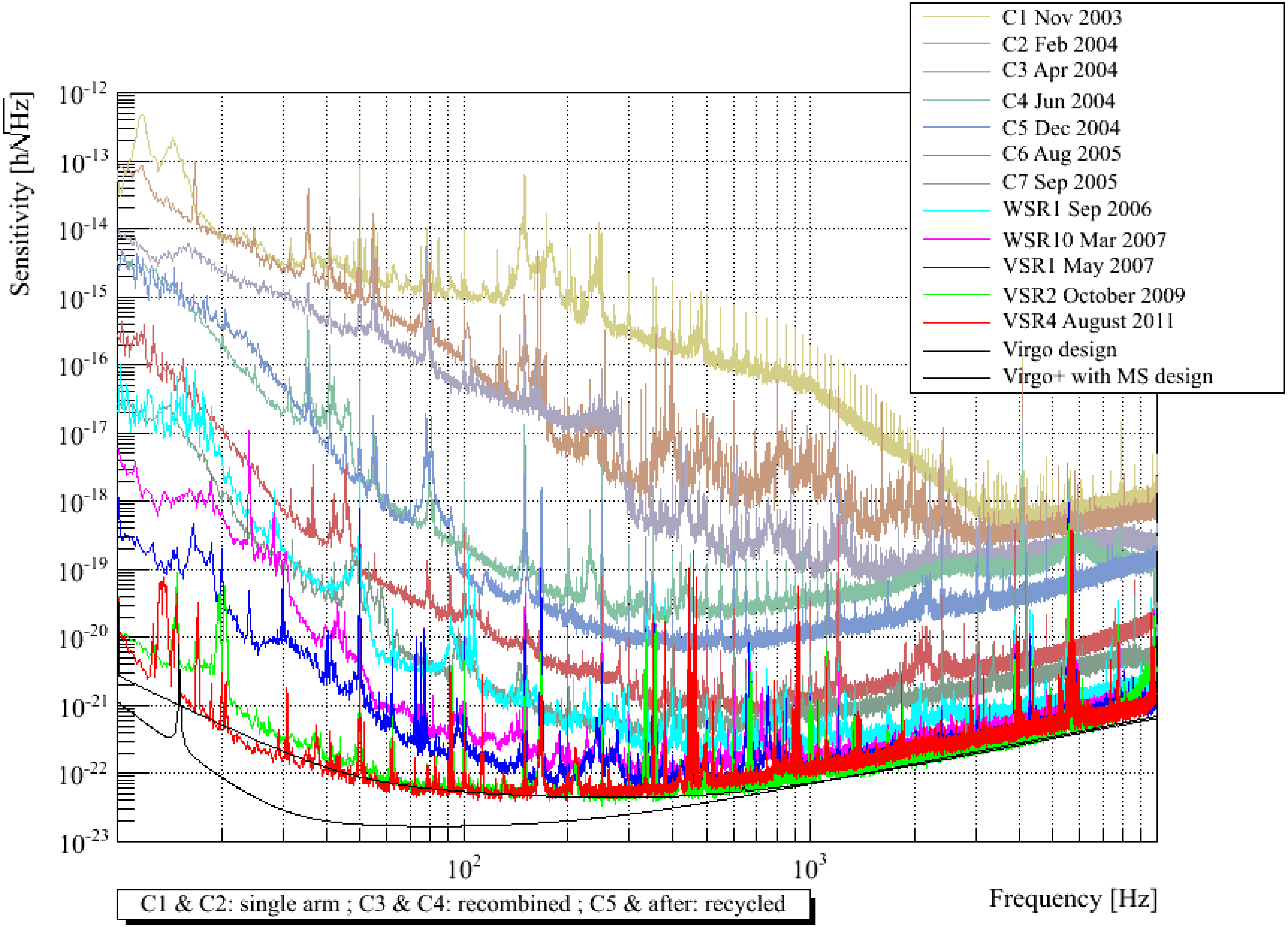
- air conditioning
- electronic racks

Need to work both on:

- reduction of coupling
- reduction of environmental noise

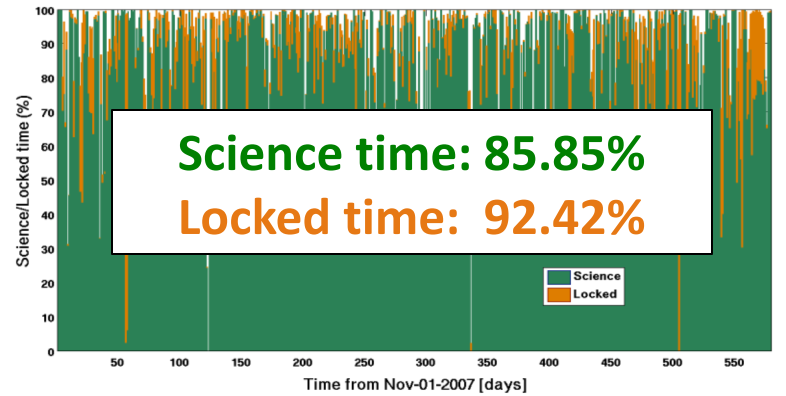


# Virgo sensitivity progress

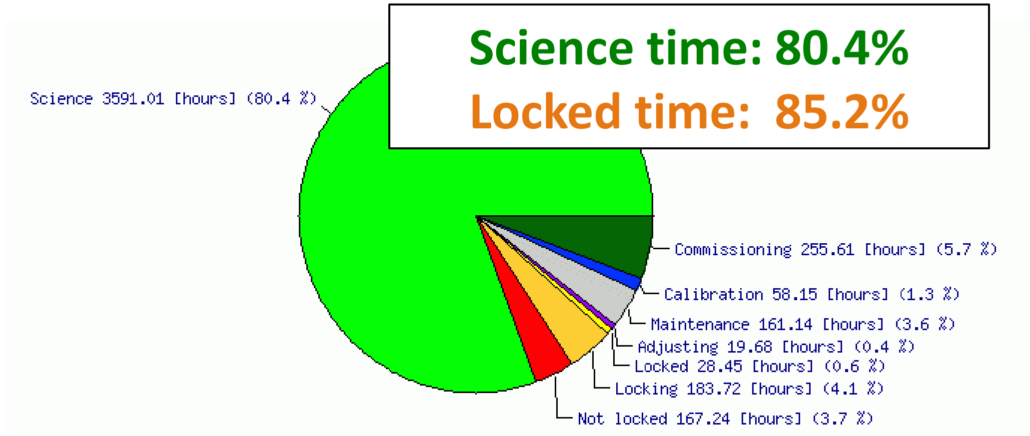


# ROBUSTNESS

- 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

# The global network

# Motivation for a Global GW Detector Network

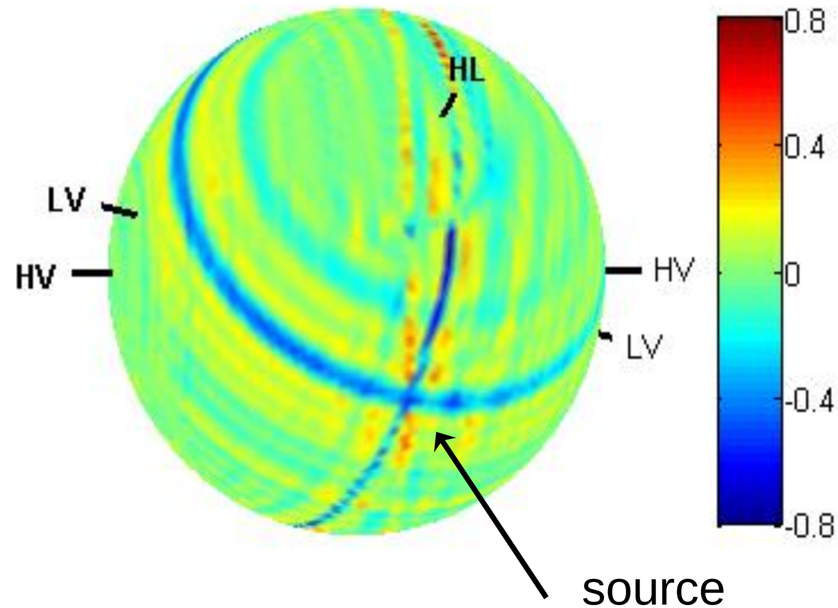
- *Source location*:
  - Ability to triangulate (or 'N-angulate') and more accurately pinpoint source locations in the sky
  - More detectors provides better source localization → *Multi-messenger astronomy*

- *Network Sky Coverage:*
  - GW interferometers have a limited antenna pat maximal sky coverage

- *Detection confidence*:
  - Redundancy – signals in multiple detectors

- *Maximum Time Coverage - 'Always listening'*:
  - Ability to be 'on the air' with one or more detect

- *Source parameter estimation:*
  - More accurate estimates of amplitude and phas
  - Polarization - array of oriented detectors is sen:




- *Coherent analysis*:
  - Combining data streams coherently leads to better sensitivity 'digging deeper into the noise'
  - Also, optimal waveform and coordinate reconstruction

# World wide GW network: LV agreement

- “Among the **scientific benefits** we hope to achieve from the collaborative search are:
  - better confidence in detection of signals, better duty cycle and sky coverage for searches, and better source position localization and waveform reconstruction. In addition, we believe that the intensified sharing of ideas will also offer additional benefits.”
- Collaborations keep their identities and independent governance

# LV Agreement (I)

- “All data analysis activities will be open to all members of the LSC and Virgo Collaborations, in a spirit of cooperation, open access, full disclosure and full transparency with the goal of best exploiting the full scientific potential of the data.”

- Joint committees set up to coordinate data analysis, review results, run planning, and computing. The makeup of these committees decided by mutual agreement between the projects.

- Joint publication of observational data whether data from Virgo, or LIGO (GEO) or both

# Some results from L-V

# Horizon and event rate

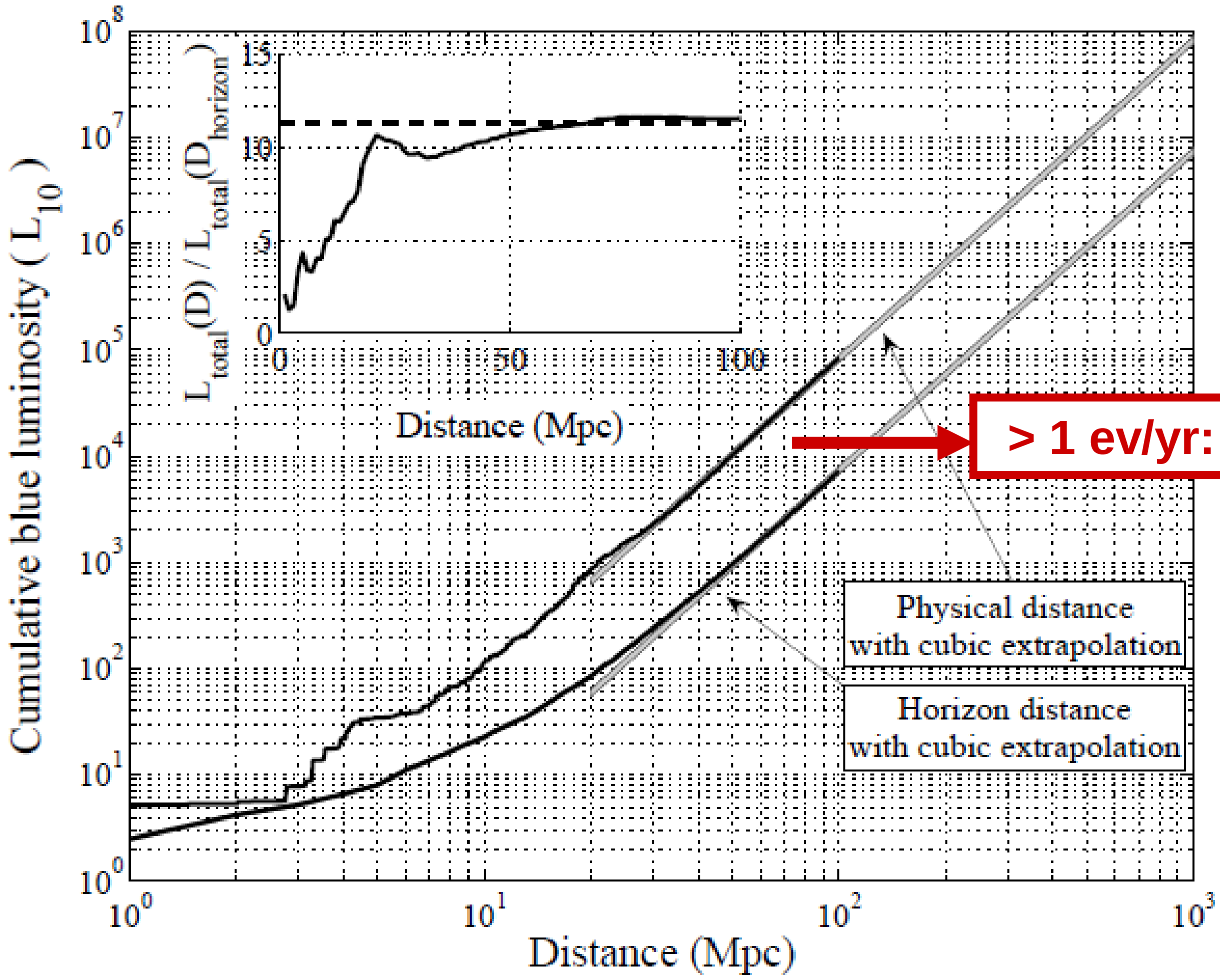


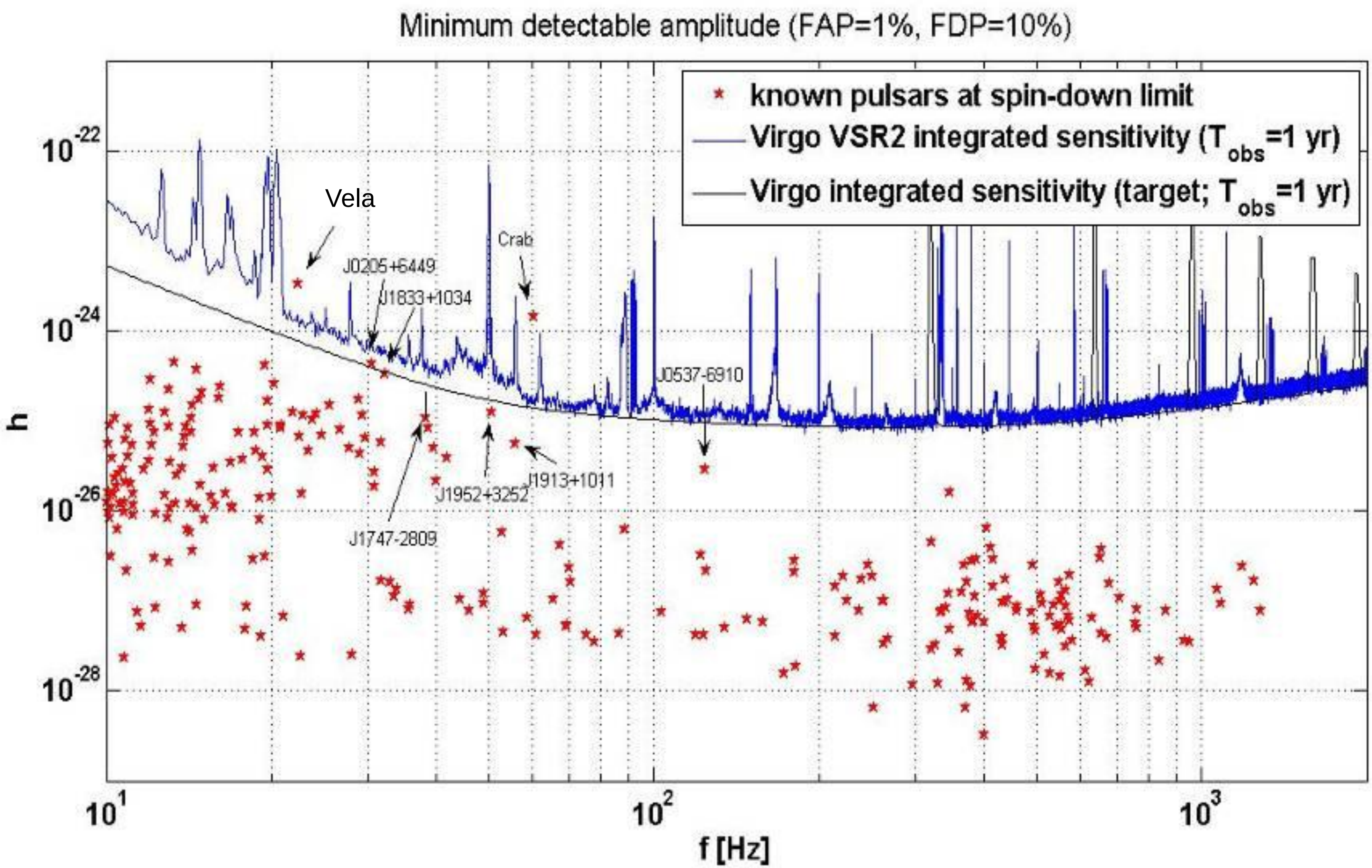

FIG. 1: The total blue-light luminosity within a sphere of a given radius (top curve) and the accessible blue-light luminosity for a given horizon distance $D_{\text{horizon}}$, taking location and orientation averaging into account (bottom curve). Gray shaded lines are cubic extrapolations. The inset shows the ratio between the top and bottom curves, which asymptotes to $2.26^3$, as discussed in the text. Reproduced from [15] by permission of the AAS.



Predictions for the rates of compact binary coalescences observable … CQG, 10.1088/0264-9381/27/17/173001

# VSR2 sensitivity for CW searches

Targeted searches.



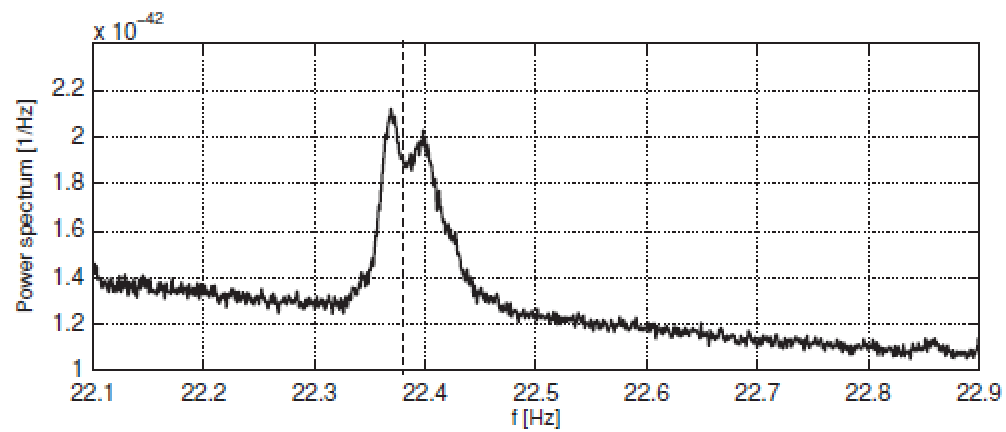
# Vela pulsar spin down limit

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


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

J. ABADIE[1], B. P. ABBOTT[1], R. ABBOTT[1], M. ABERNATHY[2], T. ACCADIA[3], F. ACERNESE[4,5], C. ADAMS[6], R. ADHIKARI[1],

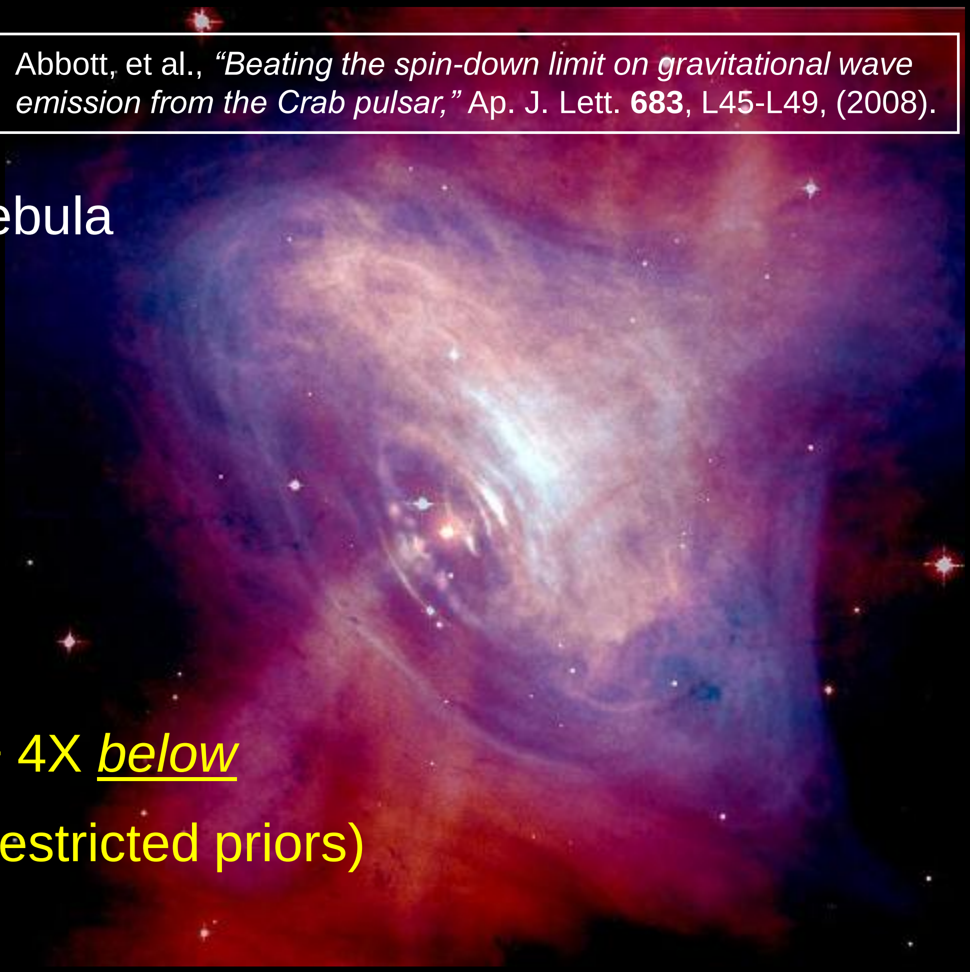
- Spin down limit amplitude: 3.3 $10^{-24}$ for VSR2
- Upper limit (known period, phase, orientation) < 2.2 $10^{-24}$ 95% CL
- Local vibration disturbance (laser cooling pump)
- Improvements expected with VSR3 and VSR4



# The Crab Pulsar: *Beating the Spin Down Limit!*

- Remnant from supernova in year 1054
- Spin frequency $\nu_{EM}$ = 29.8 Hz

  → $\nu_{gw} = 2\ \nu_{EM}$ = 59.6 Hz



Abbott, et al., *"Beating the spin-down limit on gravitational wave emission from the Crab pulsar,"* Ap. J. Lett. **683**, L45-L49, (2008).

- observed luminosity of the Crab nebula

accounts for < 1/2 spin down power

- spin down due to:
  - electromagnetic braking
  - particle acceleration
  - *GW emission?*

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- early S5 result: $h < 3.9 \times 10^{-25}$ → ~ 4X *below*

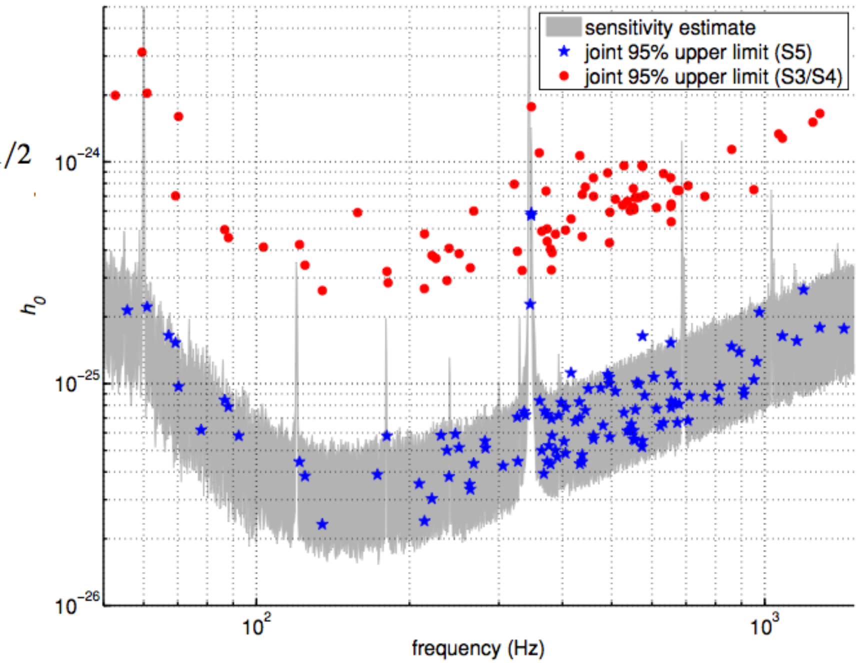
  the spin down limit (assuming restricted priors)
- ellipticity upper limit: $\varepsilon < 2.1 \times 10^{-4}$
- GW energy upper limit < 6% of radiated energy is in GWs

# Searches for GWs from known pulsars

- Continuous gravitational-wave emission due to asymmetry rotation axis
  - elastic deformations of the solid crust or core
  - Distortion an extremely strong misaligned magnetic field
  - Weak emitters
- Spin-down limit:

$$h_{\mathrm{sd}} = \left(\frac{5}{2}\frac{G I_{zz}|\dot{\nu}|}{c^3 r^2 \nu}\right)^{1/2}$$

- Crab pulsar (using LIGO data):
  - $h_0 < h_{sd}/7$, $E_{GW} < 0.02$
- Vela pulsar (using Virgo data):
  - $h_0 < 0.66 h_{sd}$, $E_{GW} < 0.45 E_{total}$
- S5 search of 116 pulsars
  - Lowest upper-limit $h_0$: 2.3 x $10^{-26}$ (PSR J1603-7202)
  - Lowest upper-limit ellipticity: 7 x $10^{-8}$ (PSR J212




LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Crab pulsar*", Astrophys. J. Lett. 683 (2008) 45

LIGO Scientific and Virgo Collaborations, "*First search for gravitational waves from the youngest known neutron star*", Astrophys. J. 722 (2010) 1504

LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Vela pulsar,*" Astrophys. J. 737 (2011) 93

LIGO Scientific and Virgo Collaborations, "*Searches For Gravitational Waves From Known Pulsars With Science Run 5 LIGO Data*", Astrophys. J. 713 (2010) 671

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

LETTERS

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

The LIGO Scientific Collaboration* & The Virgo Collaboration*

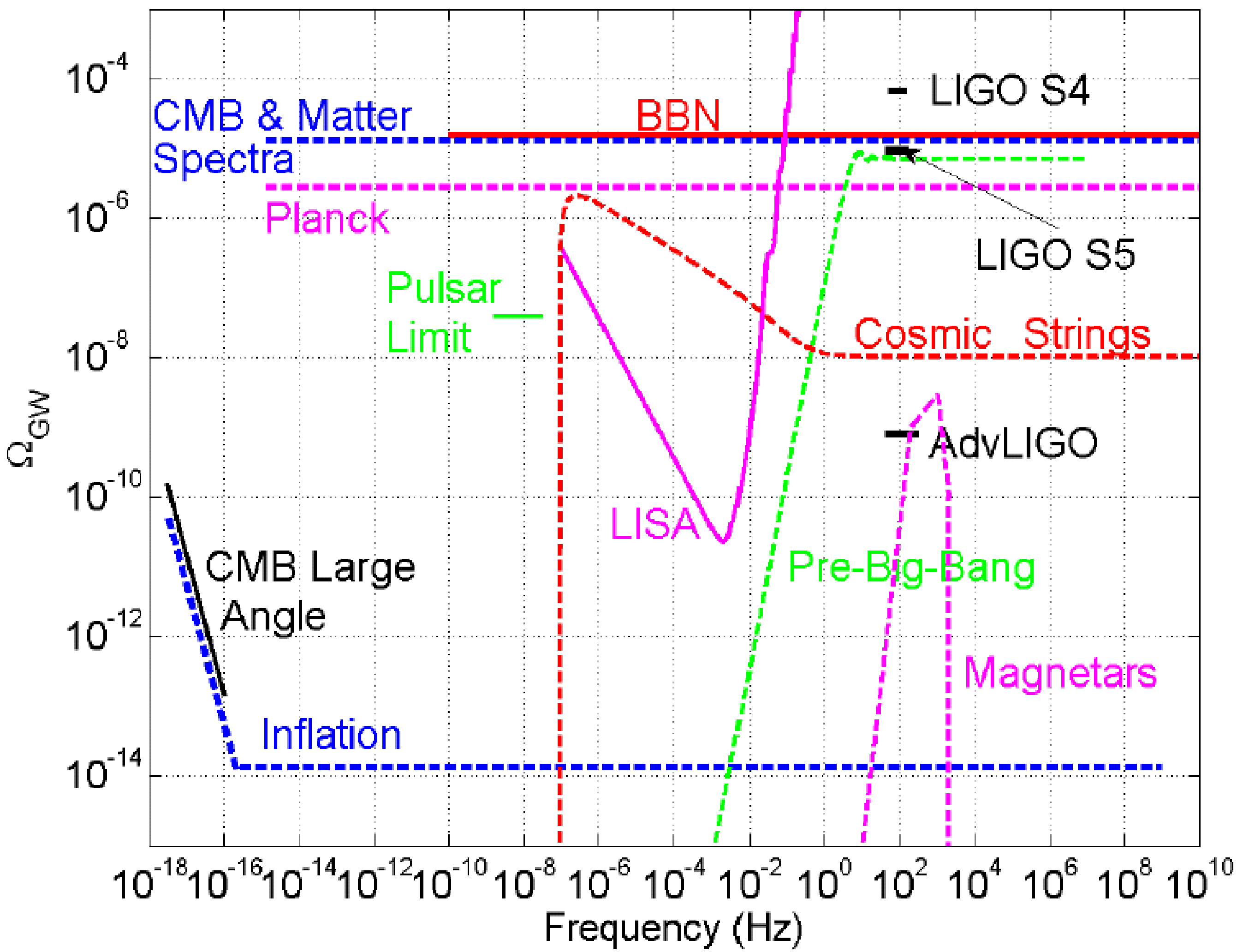
A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved gravitational-wave sources of astrophysical and cosmological origin. It should carry unique signatures from the earliest epochs in the evolution of the Universe, inaccessible to standard 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

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 and 30 September 2007), acquiring one year of data coincident among H1, H2 and L1, at the interferometer design sensitivities (Fig. 1).

The search for the SGWB using LIGO data is performed by cross-correlating strain data from pairs of interferometers[8]. In the frequency ($f$) domain, the cross-correlation between two interferom-

# Isotropic search: results

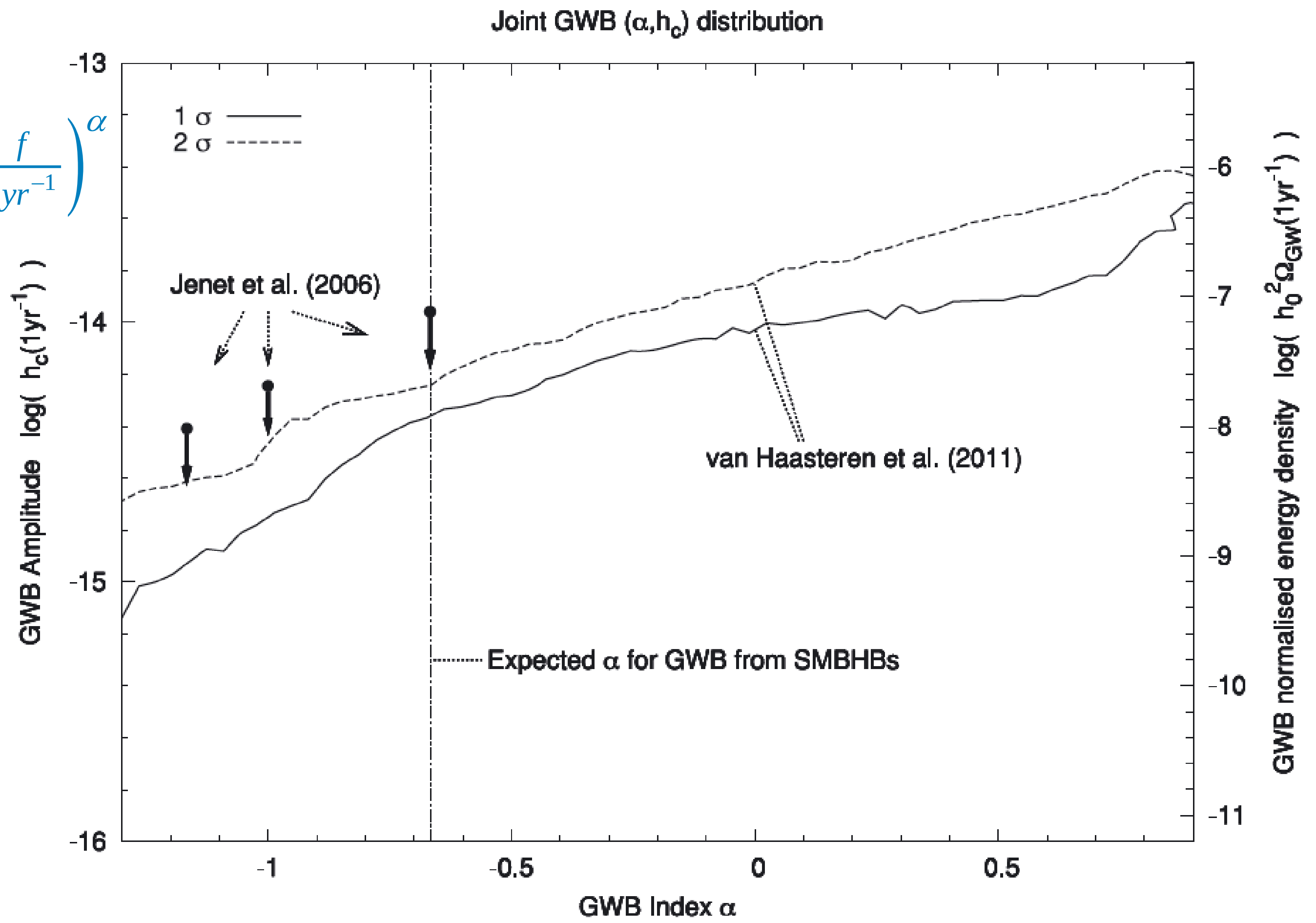
- Now we are beyond indirect BBN and CMB bounds
- We are beginning to probe models



# Pulsar Timing Array

## Placing limits on the stochastic gravitational - wave background using European Pulsar Timing Array data (2011 GWIC prize thesis)

$$h_c(f) = A\left(\frac{f}{1yr^{-1}}\right)^{\alpha}$$





**Monthly Notices of the Royal Astronomical Society**
Volume 414, Issue 4, pages 3117-3128, 20 APR 2011 DOI: 10.1111/j.1365-2966.2011.18613.x
http://onlinelibrary.wiley.com/doi/10.1111/j.1365-2966.2011.18613.x/full#f5

# Advanced Virgo

Slides by PL Giovanni Losurdo

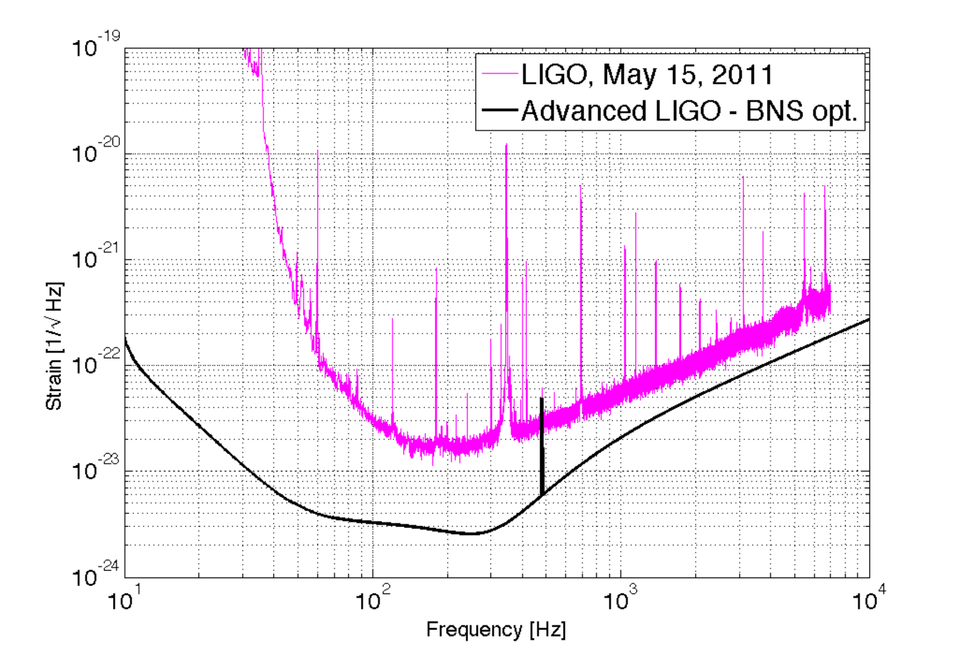
# ADVANCED VIRGO – ID CARD

- **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**

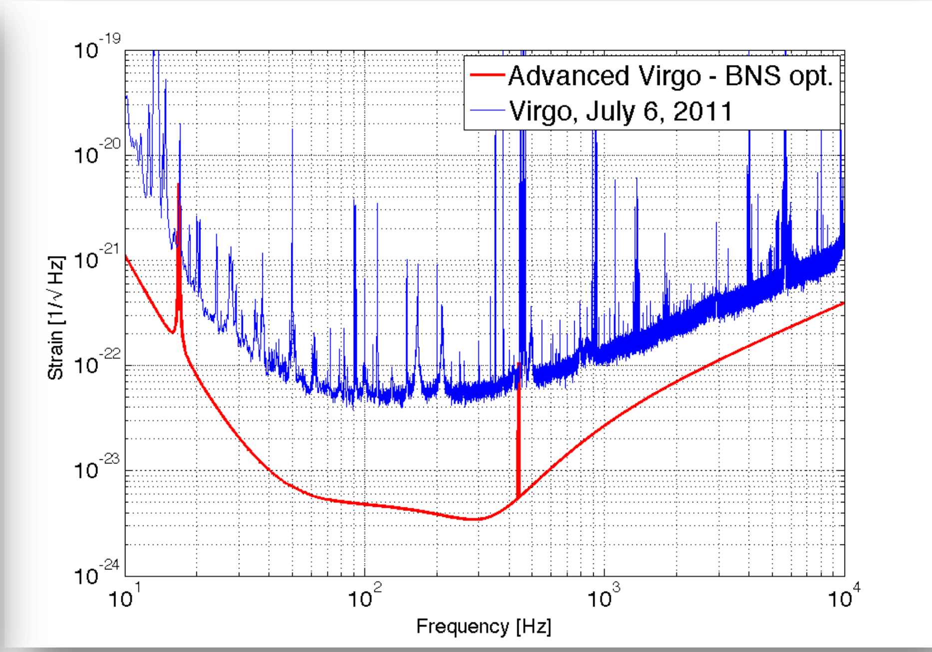
# Advanced detectors

- 2nd generation detectors
  - BNS inspiral range >10x better than Virgo
  - Detection rate: ~1000x better
  - 1 day of Adv data ≈ 3 yrs of data

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

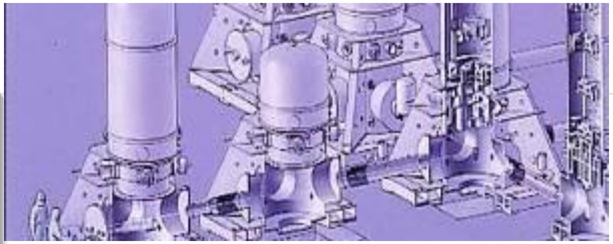



Measured spectrum courtesy of the Virgo Coll.



# Advanced Virgo baseline design

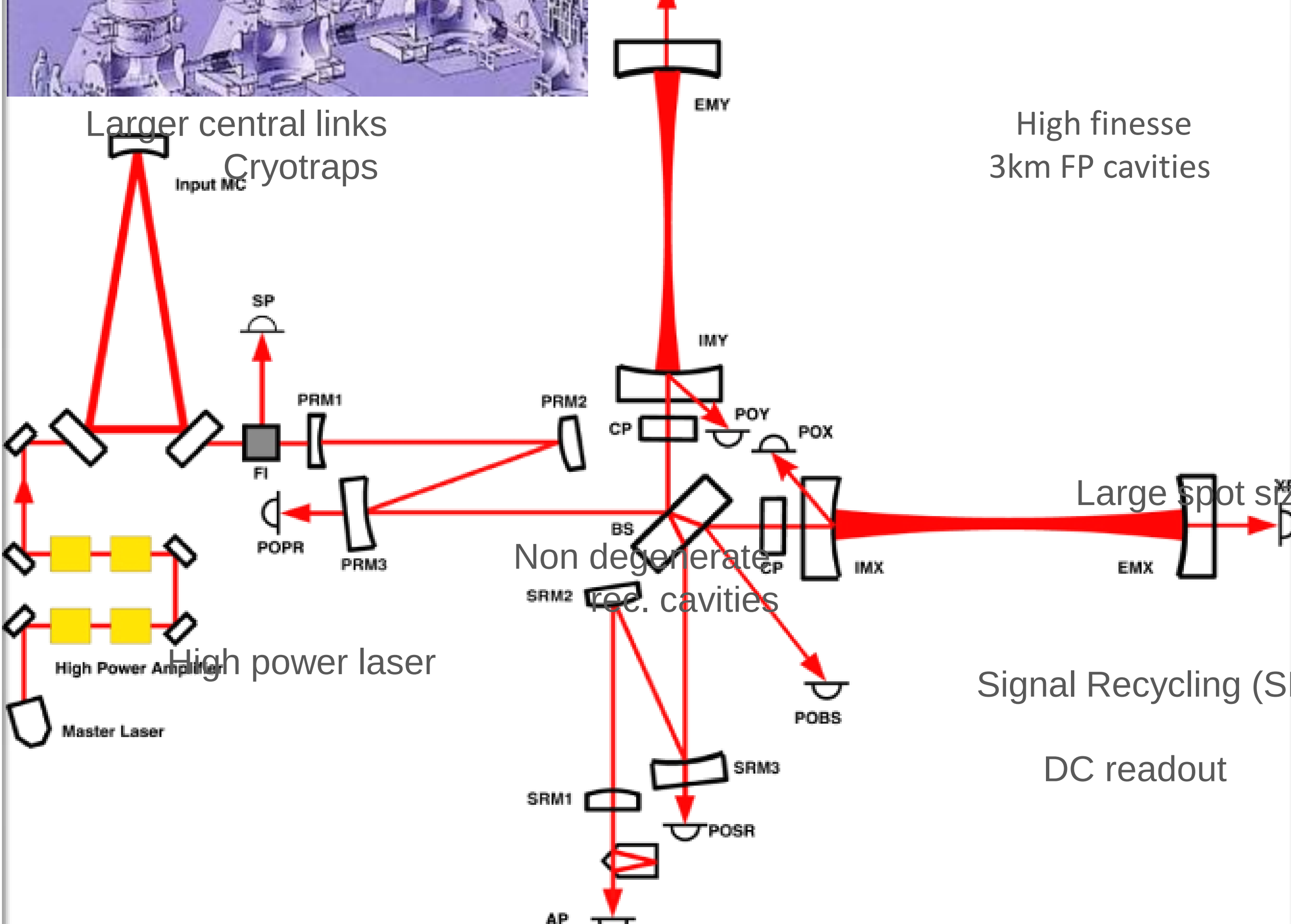
- Plan to be back in 2015 with LIGO



Heavier mirrors

Larger central links

Cryotraps




High finesse
3km FP cavities

Large spot size on TM

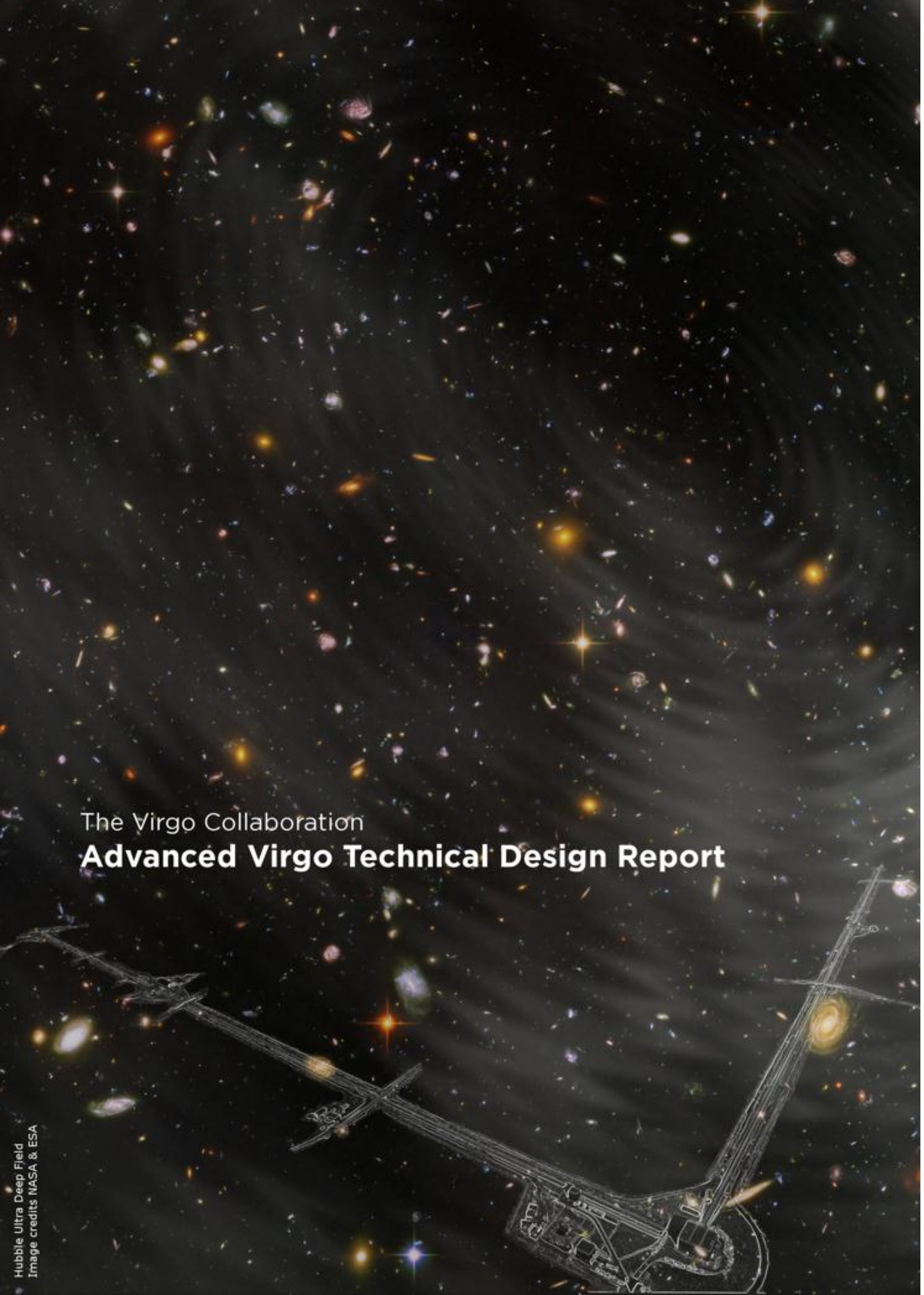
Non degenerate rec. cavities

High power laser

Signal Recycling (SR)

DC readout

Monolithic suspensions




# Advanced Virgo Technical Design Report

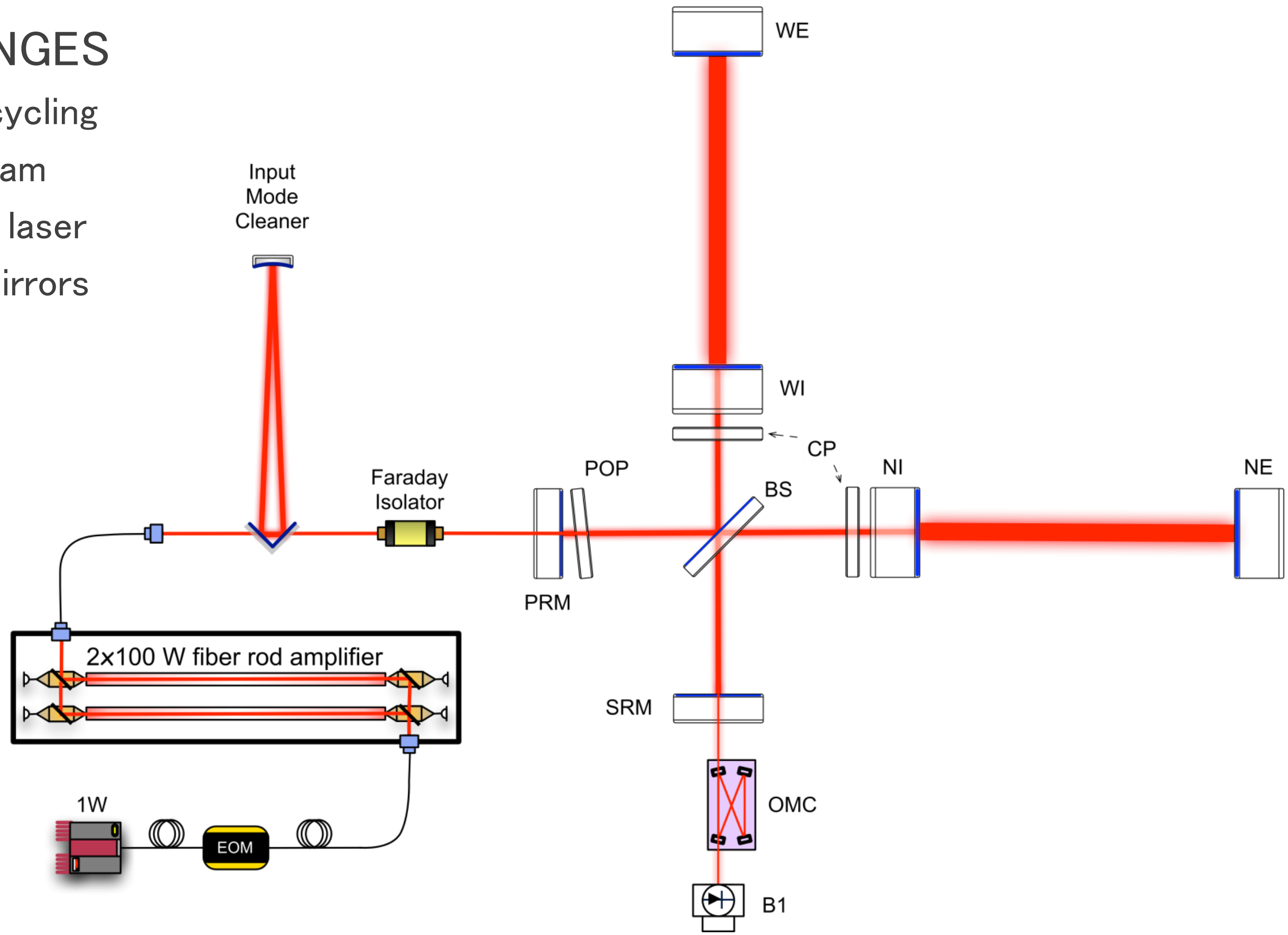
The Virgo Collaboration

VIR–0128A–12

April 13, 2012

# OPTICAL LAYOUT

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

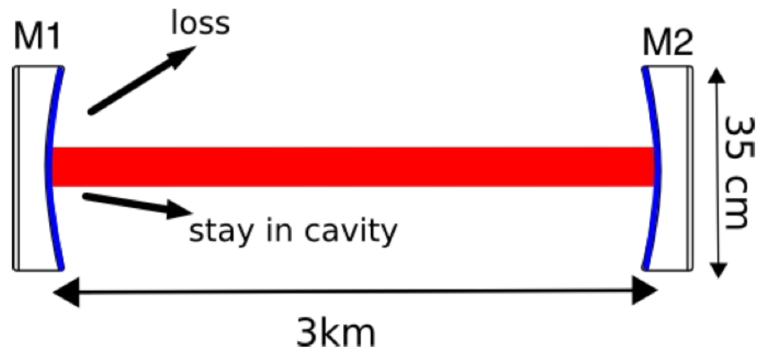


# MIRRORS – SUBSTRATES

- Large high quality mirrors: 35cm diameter, 20cm thick, 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…)

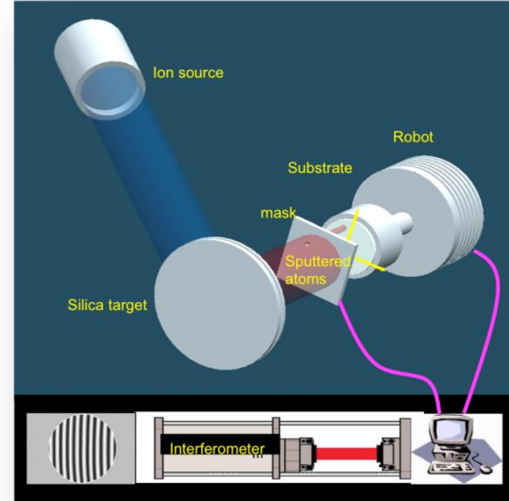



- AdV requirement: round-trip losses <50ppm →

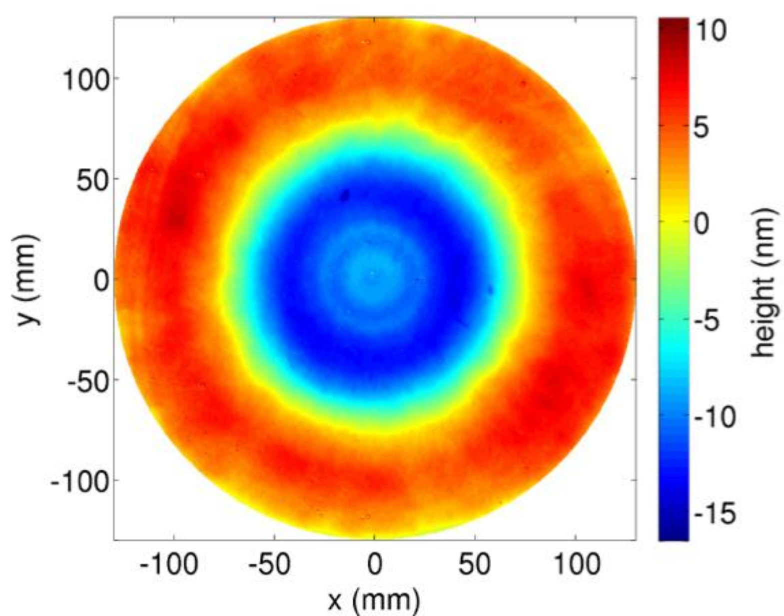
  → mirror flatness < 0.5 nm rms
- Standard polishing may achieve flatness ~2 nm rms
- To reach specifications we apply "corrective coating" to polished mirrors

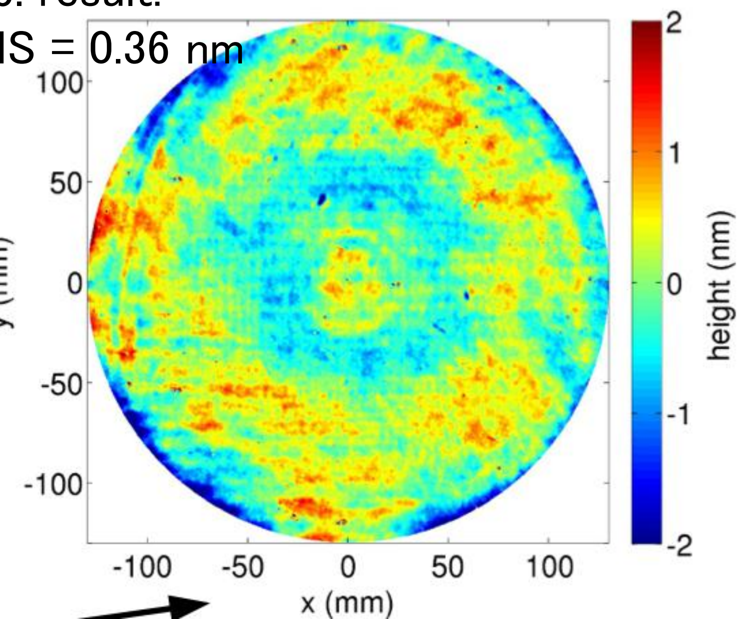
# CORRECTIVE COATING

- 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)



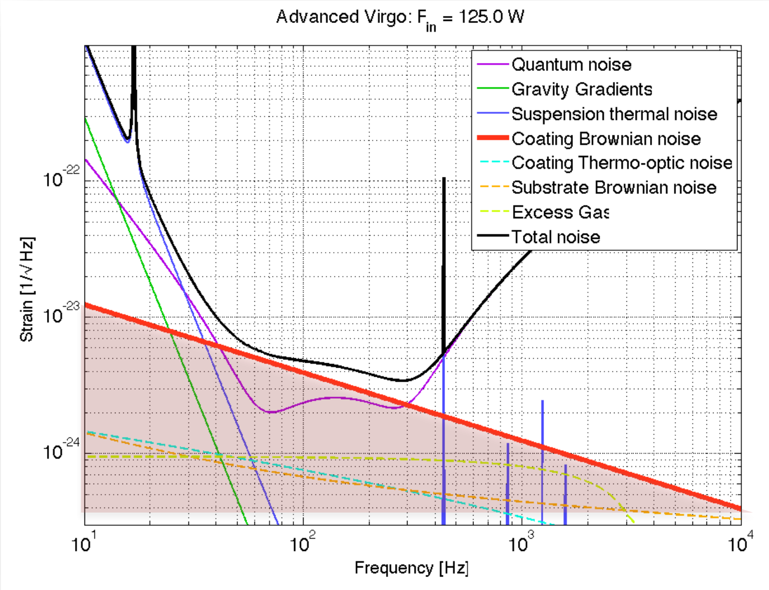

Exp. result:
RMS = 0.36 nm



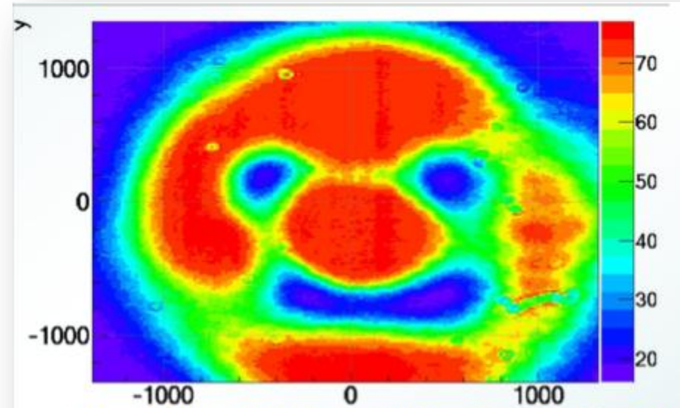
# COATINGS

- Coating thermal noise is THE noise limiting sensitivity in the mid-range (dissipation dominated by the high refractive index layer)
- Doping $Ta_2O_5$ with Ti has improved it, but losses are still $O(10^{-4})$
- Advanced LIGO/Virgo use large spot size (~5cm) on the test masses

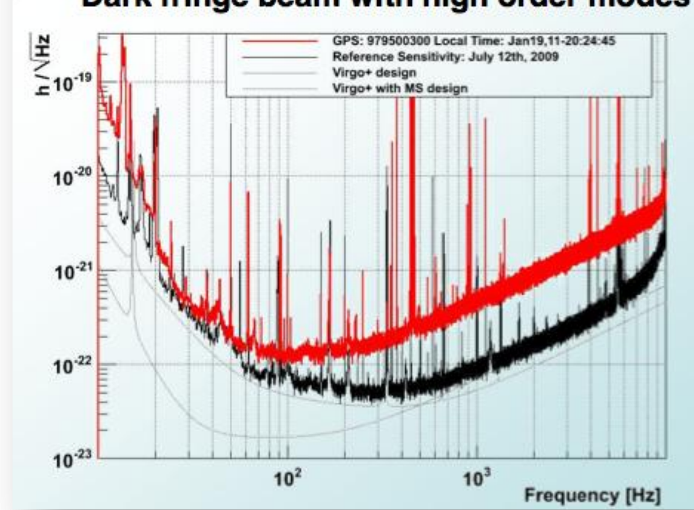


# THERMAL COMPENSATION

- 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

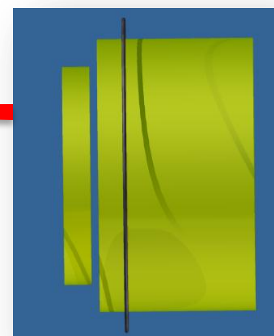



Dark fringe beam with high order modes




Effect of RoC asymmetry in Virgo+

$CO_2$ laser



$CO_2$ laser shined on the mirror: heat deposition where needed to compensate for aberrations

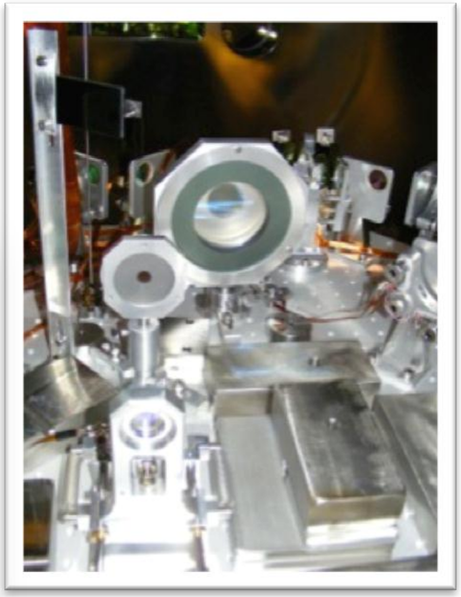
Heating rings around mirrors to tune RoC (accuracy: ~1m over 1500m)

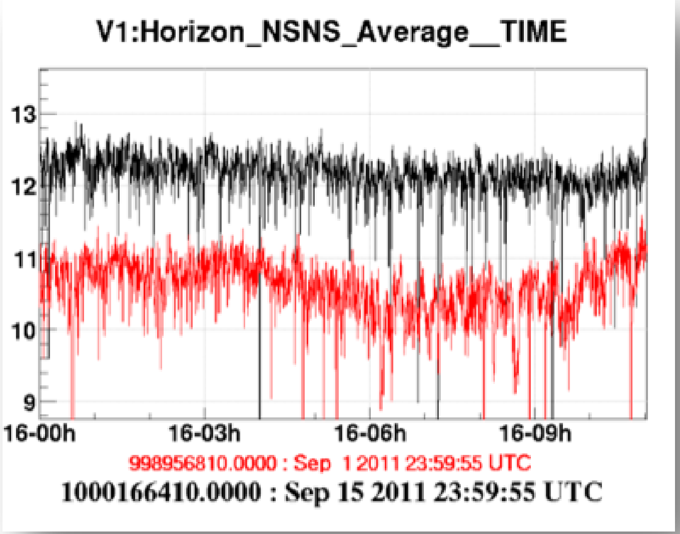
# STRAY LIGHT

- Scattered light has been one of the main issues of Virgo+
  - limiting the sensitivity in a wide frequency range
  - a lot of commissioning time used to mitigate it
- Thorough risk mitigation approach in AdV (large investment)

stray light on the output bench

SiC baffles added (+ other changes)

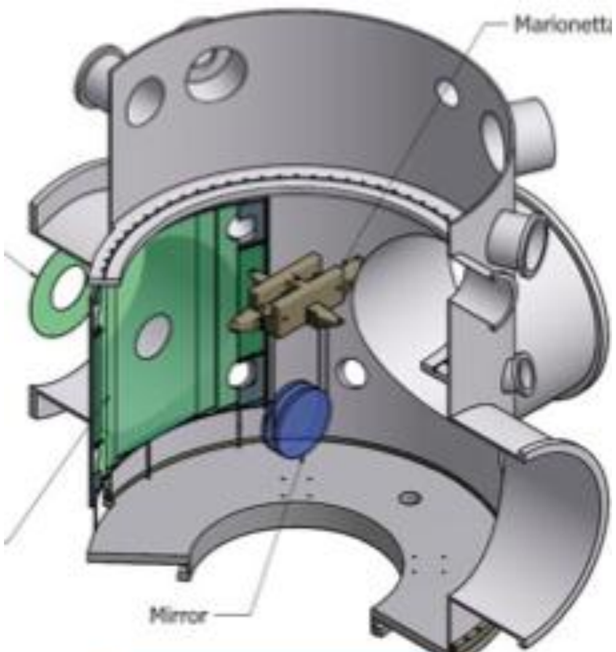




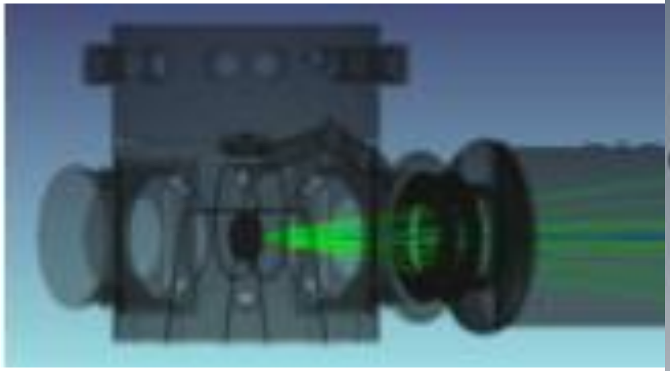

horizon more stable and higher

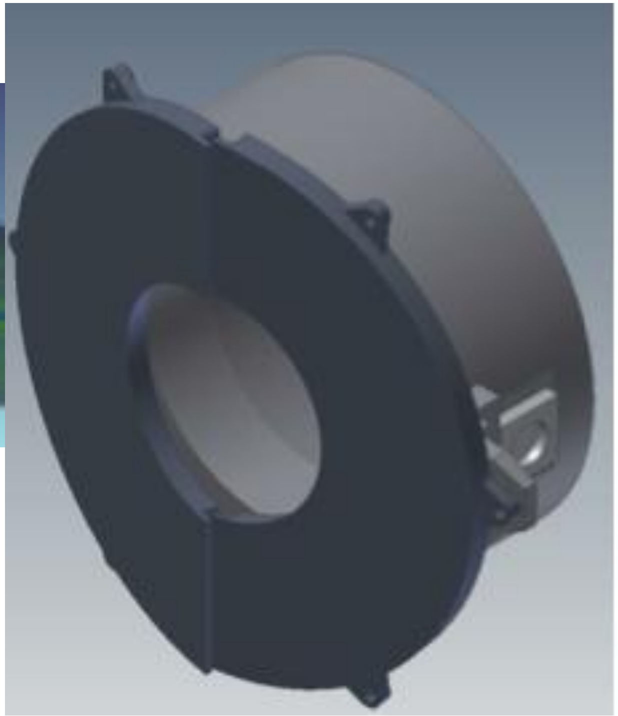
# STRAY LIGHT MITIGATION

- Baffles to shield mirrors, pipes, vacuum chambers exposed to scattered light

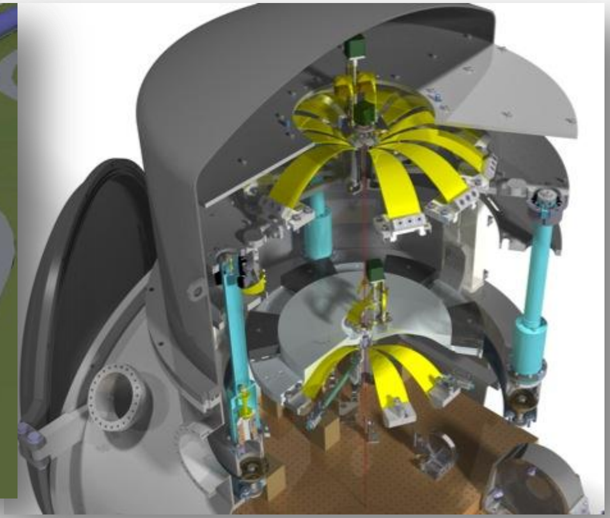


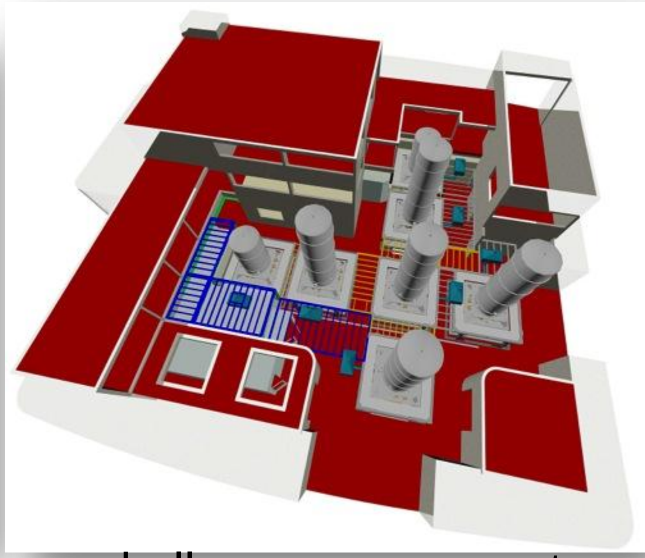

Virgo tower baffles (absorbing glass)





# STRAY LIGHT MITIGATION

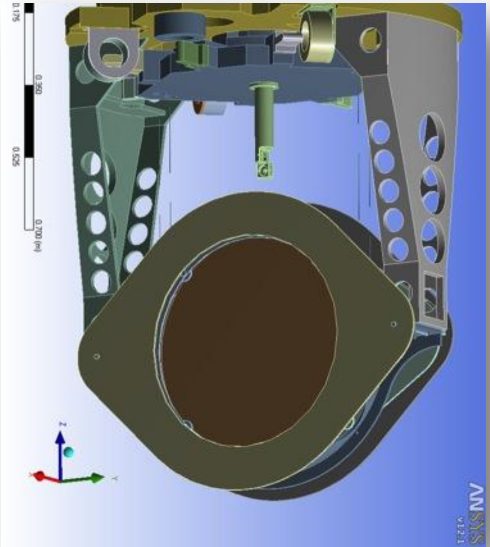




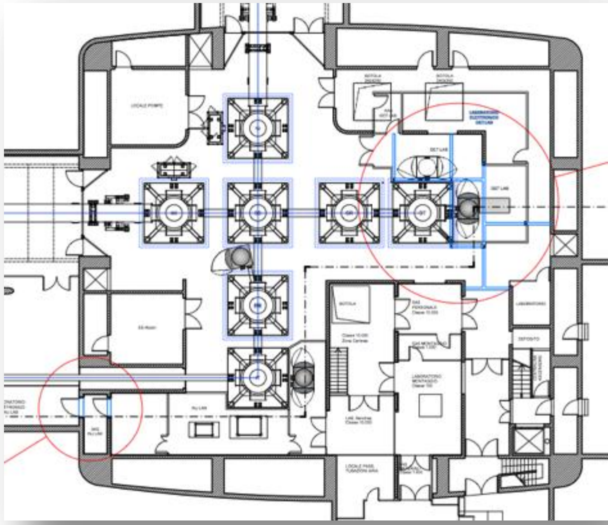
HVAC relocation
large suspended baffles

All photodiodes
seismically isolated
and In vacuum

halls re-arrangements
for hosting minitowers

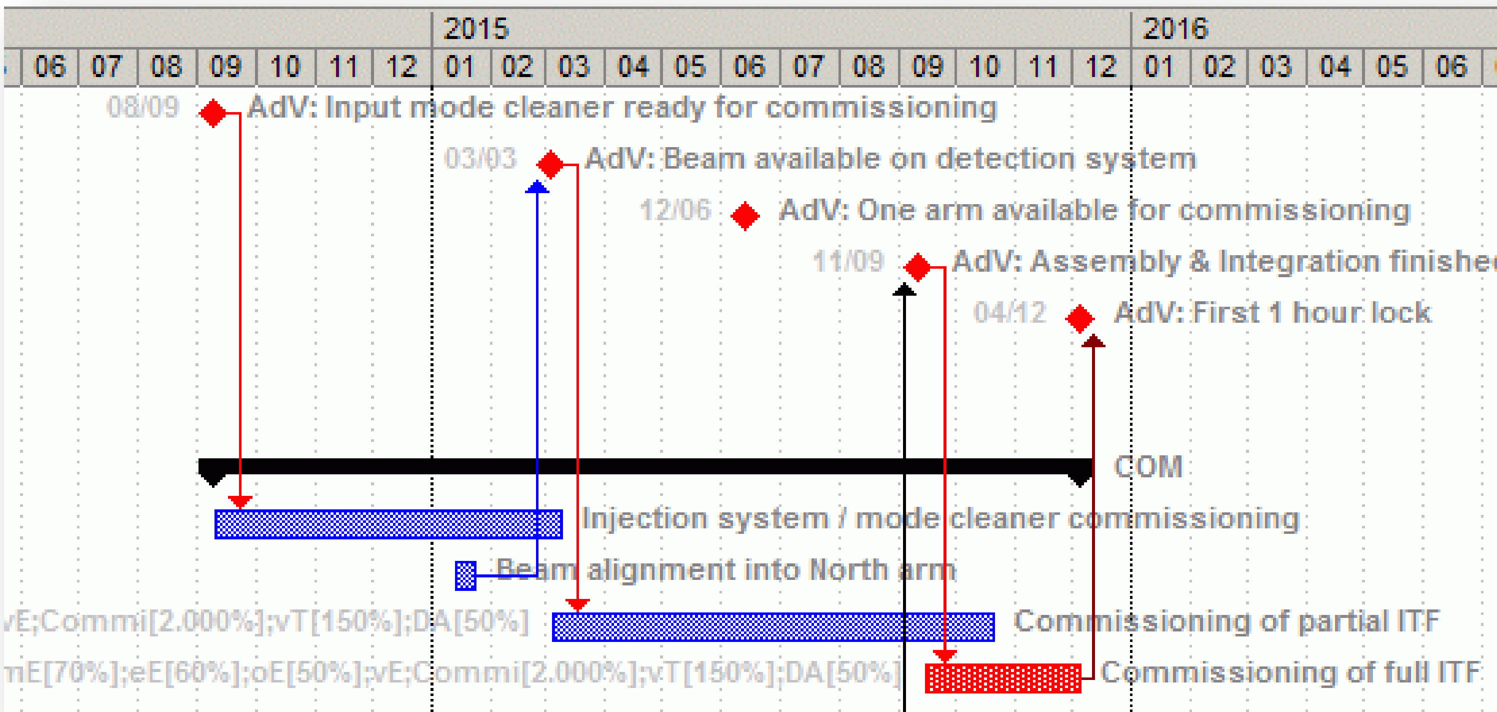


+
payloads/superattenuators/vacuum modifications
for the large baffles
suspension
+ superpolished optics on
suspended benches
+ …



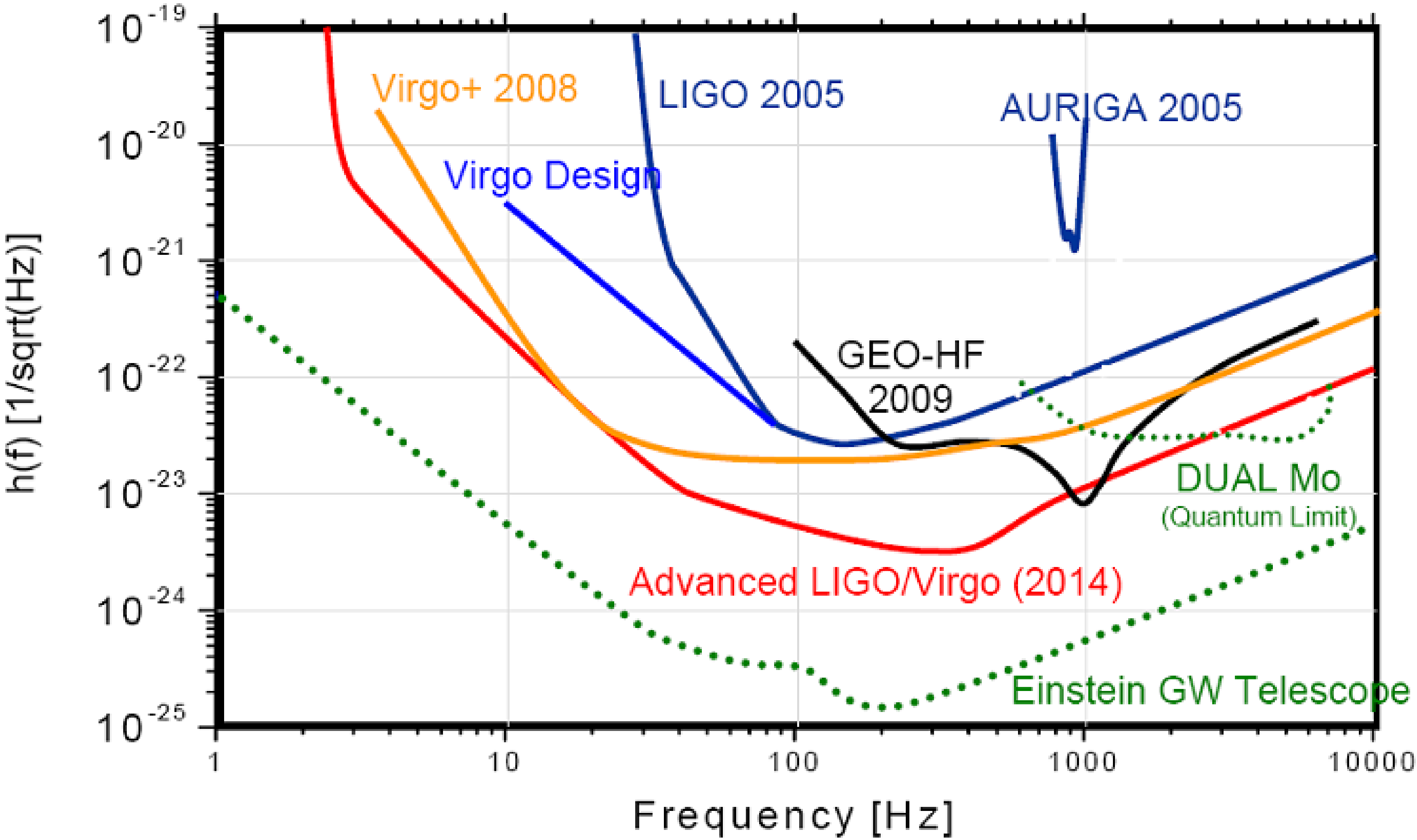
# CRUCIAL DATES

- About 1 year of commissioning on parts of the interferometer before the end of installation
  - Allows speeding up the time needed for the first full lock
  - Requires early organization of the commissioning activities



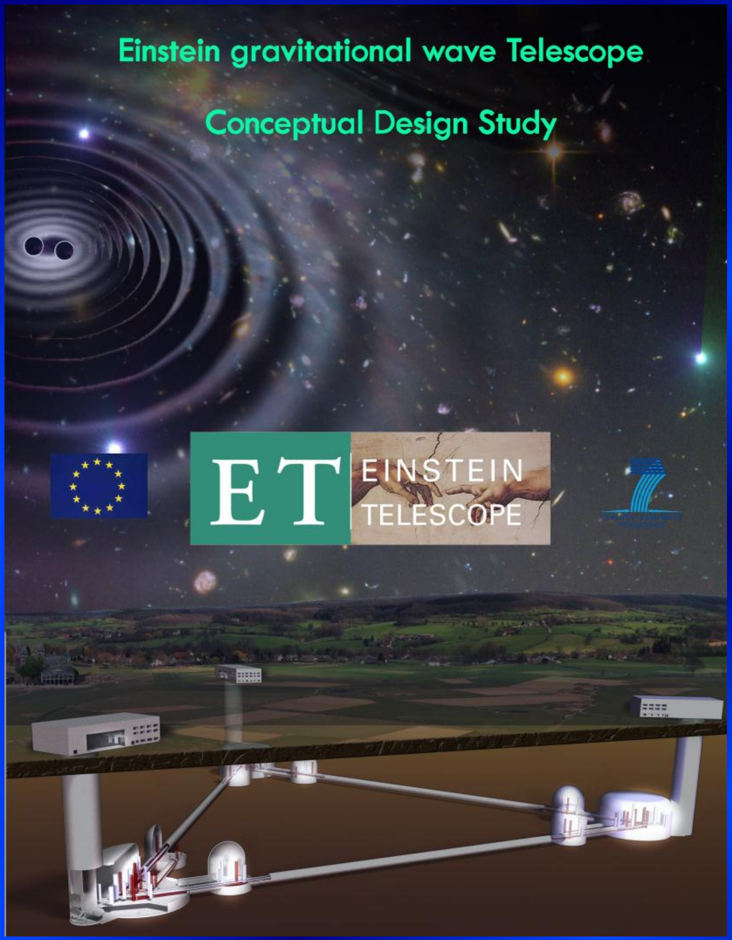
# Perspective

# Sensitivity future evolution

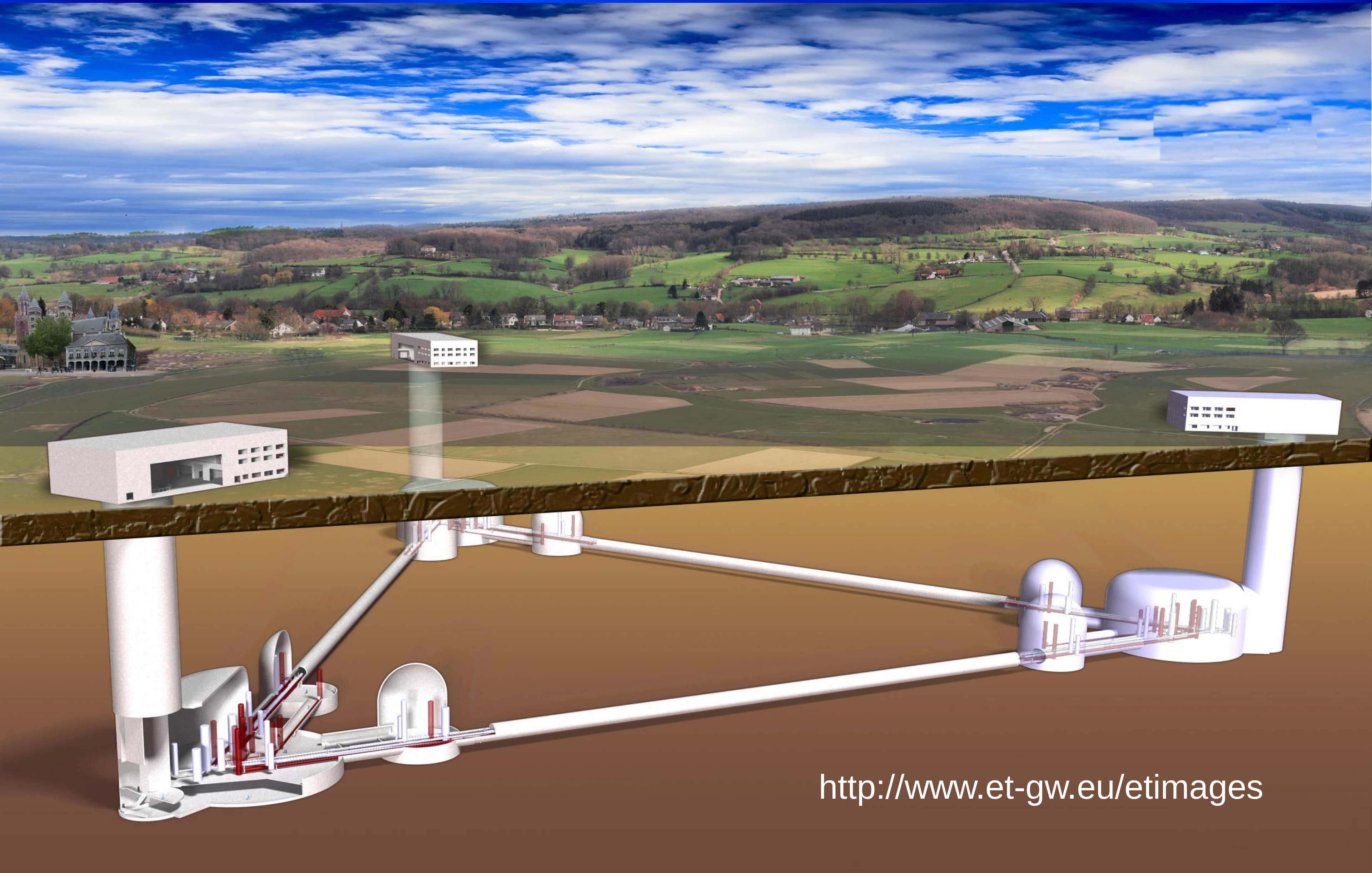


# Conceptual Design Document

- ET conceptual design document released:
  - https://tds.ego-gw.it/ql/?c=7954
- ~400 pages describing the main characteristics of the observatory
- To be sent to the European Commission at the end of September
- To be published on CQG

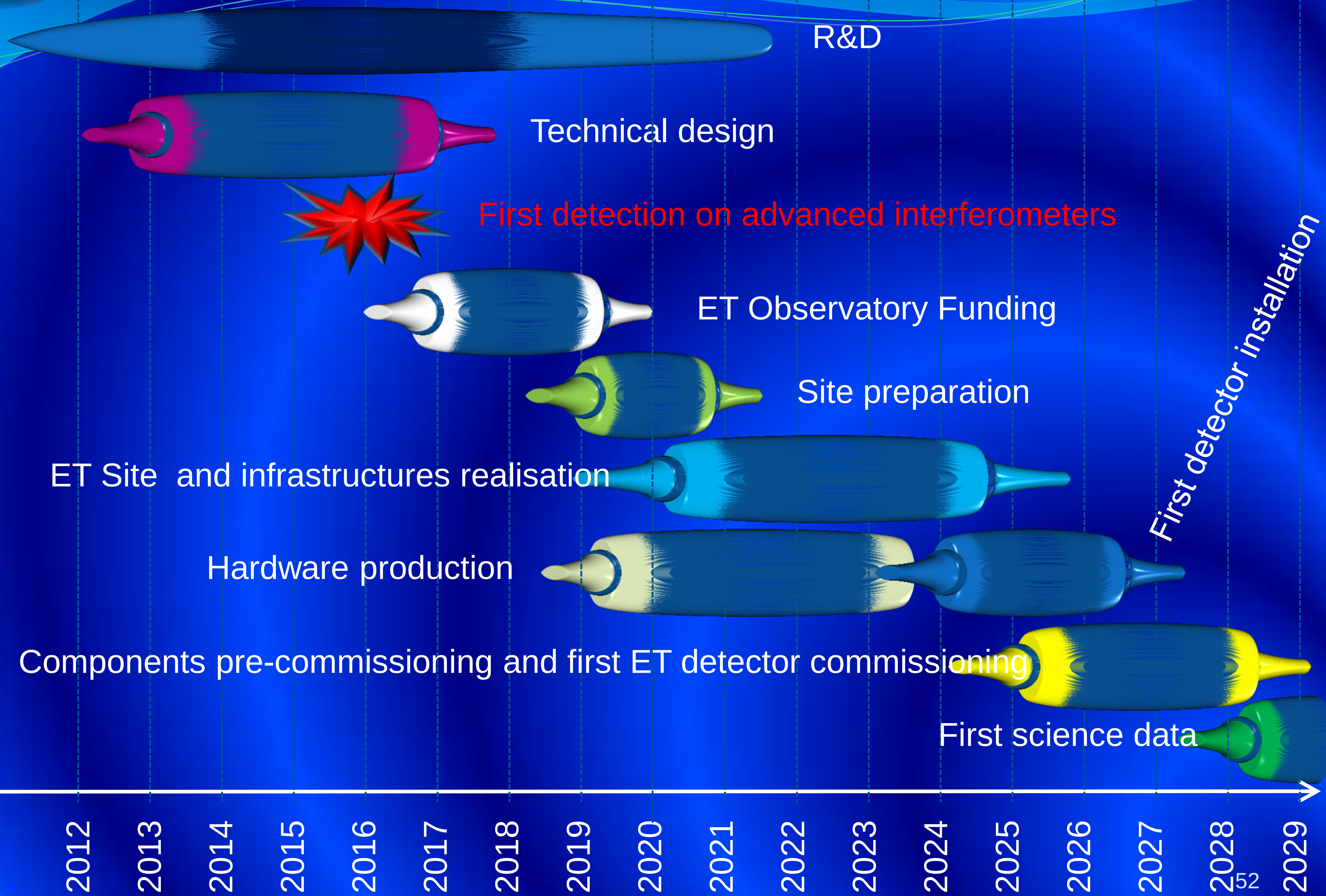


# Artistic/Schematic views



http://www.et-gw.eu/etimages

# ET Conceptual design



# The ET Science

- Summary by B. Sathyaprakash, chair of ET WG 4 Astrophysics issues

# Fundamental Physics

- Properties of gravitational waves
  - Testing GR beyond the quadrupole formula
    - Binary pulsars consistent with quadrupole formula; they don't measure properties of GW
  - How many polarizations are there?
    - In Einstein's theory only two polarizations; a scalar-tensor theory could have six
  - Do gravitational waves travel at the speed of light?
    - There are strong motivations from string theory to consider massive gravitons
    - Binary pulsars constrain the speed to few parts in a thousand
    - GW observations can constrain to 1 part in $10^{18}$
- EoS of dark energy
  - Black hole binaries are standard candles/sirens
- EoS of supra-nuclear matter
  - Signature of EoS in GW emitted when neutron stars merge
- Black hole no-hair theorem and cosmic censorship
  - Are BH (candidates) of nature BH of general relativity?
- An independent constraint/measurement of neutrino mass
  - Delay in the arrival times of neutrinos and gravitational waves

# Cosmology

- Cosmography
  - Build the cosmic distance ladder, strengthen existing calibrations at high $z$
  - Measure the Hubble parameter, dark matter and dark energy densities, dark energy EoS $w$, variation of $w$ with $z$
- Black hole seeds
  - Black hole seeds could be intermediate mass black holes
  - Might explore hierarchical growth of central engines of black holes
- Dipole anisotropy in the Hubble parameter
  - The Hubble parameter will be "slightly" different in different directions due to the local flow of our galaxy
- Anisotropic cosmologies
  - In an anisotropic Universe the distribution of $H$ on the sky should show residual quadrupole and higher-order anisotropies
- Primordial gravitational waves
  - Quantum fluctuations in the early Universe could produce a stochastic b/g
- Production of GW during early Universe phase transitions
  - Phase transitions, pre-heating, re-heating, etc., could produce detectable stochastic GW

# Astrophysics

- Unveiling progenitors of short-hard GRBs
  - Understand the demographics and different classes of short-hard GRBs
- Understanding Supernovae
  - Astrophysics of gravitational collapse and accompanying supernova?
- Evolutionary paths of compact binaries
  - Evolution of compact binaries involves complex astrophysics
    - Initial mass function, stellar winds, kicks from supernova, common envelope phase
- Finding why pulsars glitch and magnetars flare
  - What causes sudden excursions in pulsar spin frequencies and what is behind ultra high-energy transients of EM radiation in magnetars
    - Could reveal the composition and structure of neutron star cores
- Ellipticity of neutron stars as small as 1 part in a billion (10μm)
  - Mountains of what size can be supported on neutron stars?
- NS spin frequencies in LMXBs
  - Why are spin frequencies of neutron stars in low-mass X-ray binaries bounded?
- Onset/evolution of relativistic instabilities
  - CFS instability and r-modes

# Summary of Science with ET

- Fundamental Physics
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Is Einstein theory the correct theory of gravity?
  - Are black holes in nature black holes of GR?
  - Are there naked singularities?
- Astrophysics
  - What is the nature of gravitational collapse?
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - How did massive black holes at galactic nuclei form and evolve?
  - What is dark energy?
  - What phase transitions took place in the early Universe?
  - What were the physical conditions at the big bang?

# Conclusions

- We are at the edge of starting a new, fascinating field of science
- After “first words”, there is room for a large expansion in observations
- Room for unexpected
- In spite of the size, the instrument can be run by a single (clever) person
- New developments will be first by table top experiments
- High interdisciplinary views required
- Will reward junior and senior scientists

Thank you !