Gravitational Waves: some (more) on the tech side and a look at the future

Prof. V. Fafone

University of Roma Tor Vergata and INFN

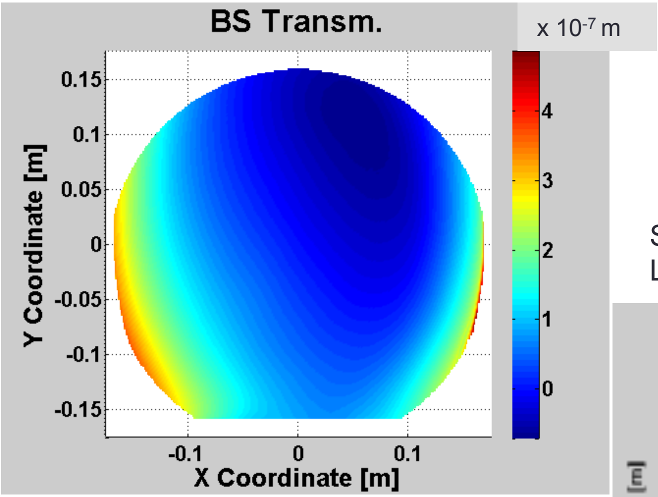
Disegno: I. Nardecchia

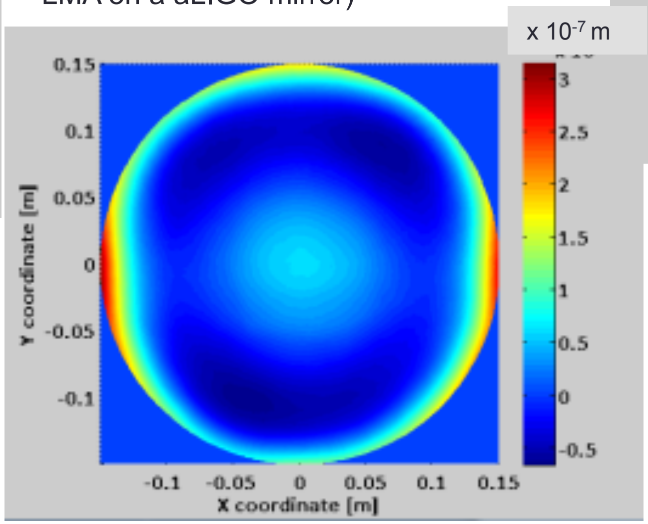
Outline

- ✓ The quest for “ideal” mirror test masses.
- ✓ How to further improve the sensitivity: toward generation 2.5 and 3.
- ✓ An overview on
  - the scientific case
  - some new technical challenges

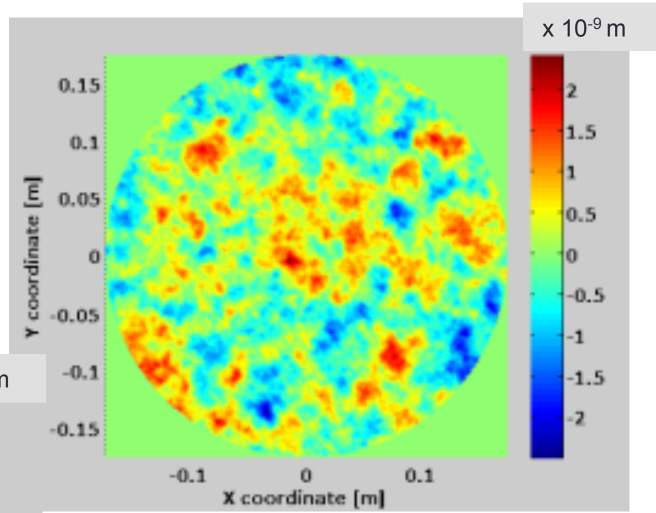
Test masses defects

- In an ITF there are several sources of optical defects, due to limitations in the mirrors fabrication process, the so called “cold” defects.
  - Non-uniformity of the substrate transmission map;
  - Mirror surface figure errors.

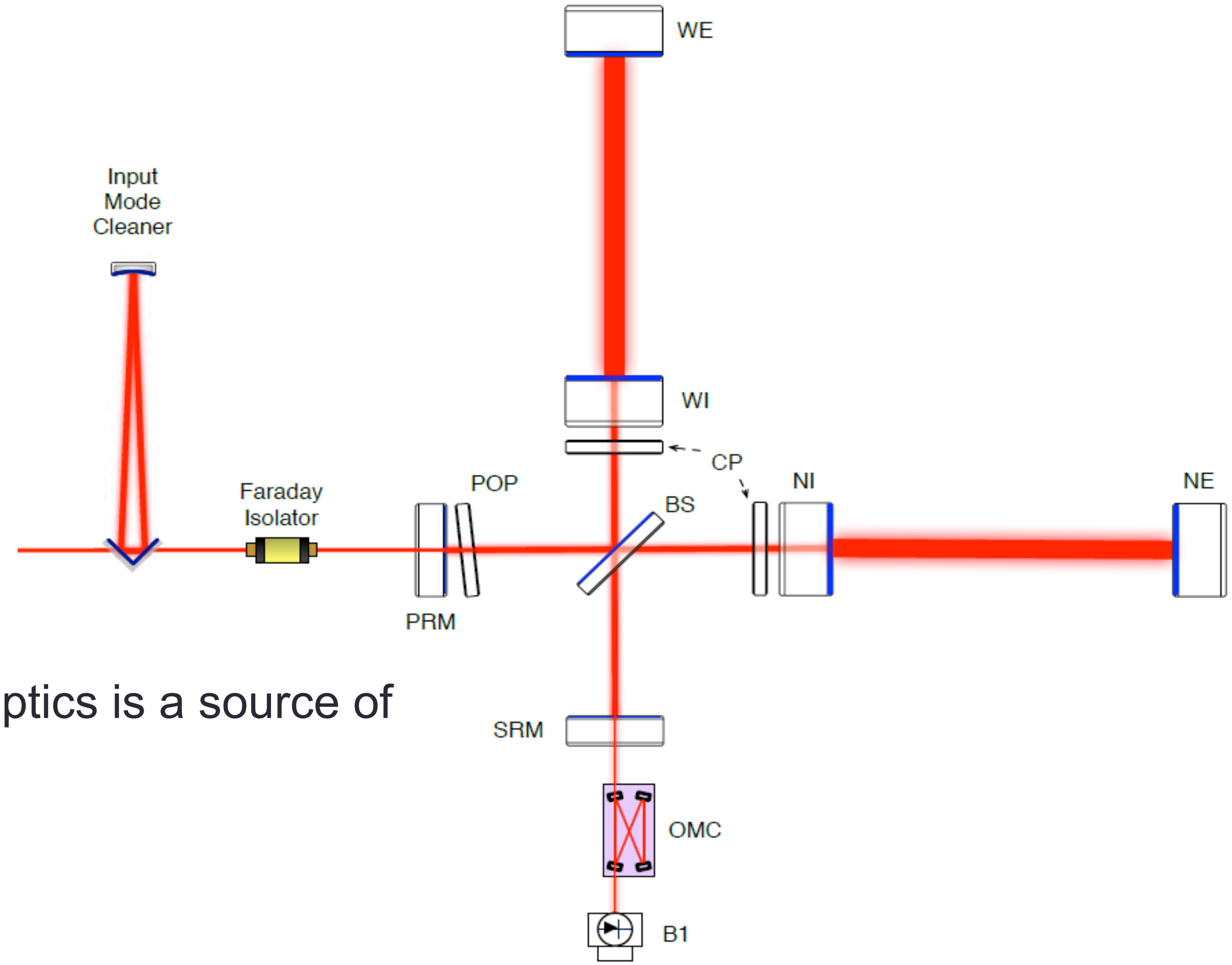




Substrate transmission map (measured at LMA on a aLIGO mirror)

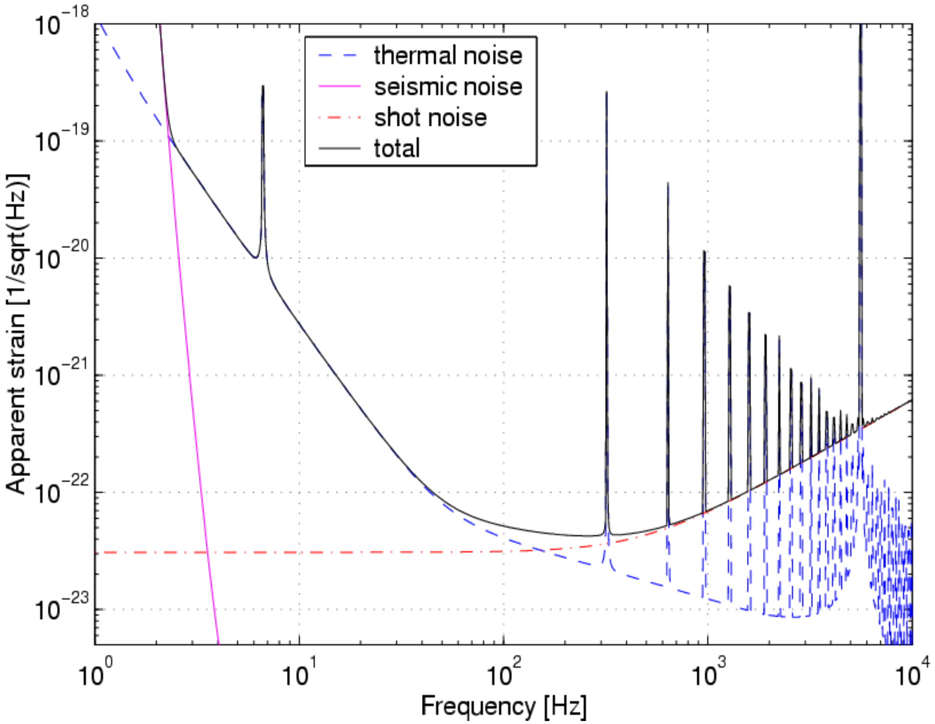


Surface roughness map (simulated)



Each of these optics is a source of aberrations

Sensitivity and shot noise…



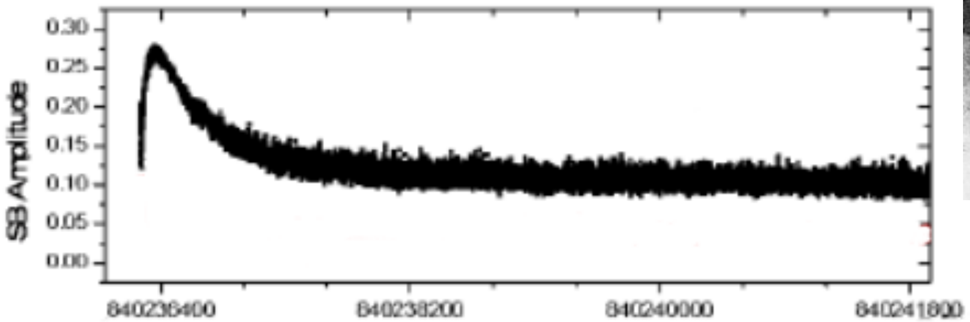
Shot noise becomes the limiting factor of our interferometer's sensitivity at frequencies above 200 Hz. To reduce the shot noise → increase the power circulating in the interferometer…

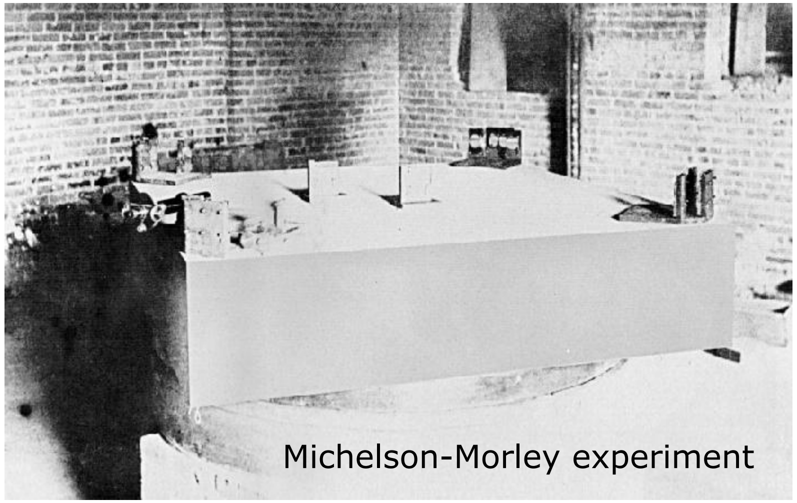
…and here is where a lot of problems start.

…and real life

So, you build the interferometer, develop your longitudinal and angular control loops, finally turn on the power!

But…



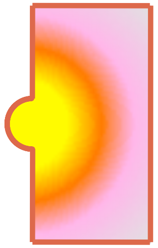


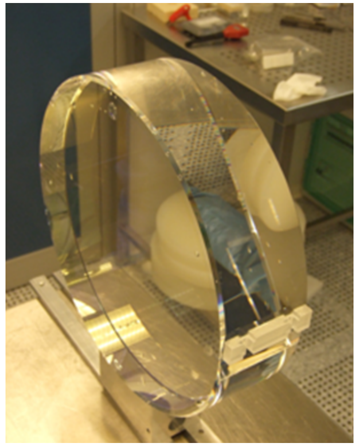
…the sidebands power starts to increase, it reaches a maximum and then starts to decrease.
No matter how you try to modify your control loops, it always happens and if you try to increase your input power, after few minutes the interferometer looses the lock (it un-locks)!
Only the sidebands are affected by this problem.

What is that? → THERMAL EFFECTS

Thermal effects: thermal lensing

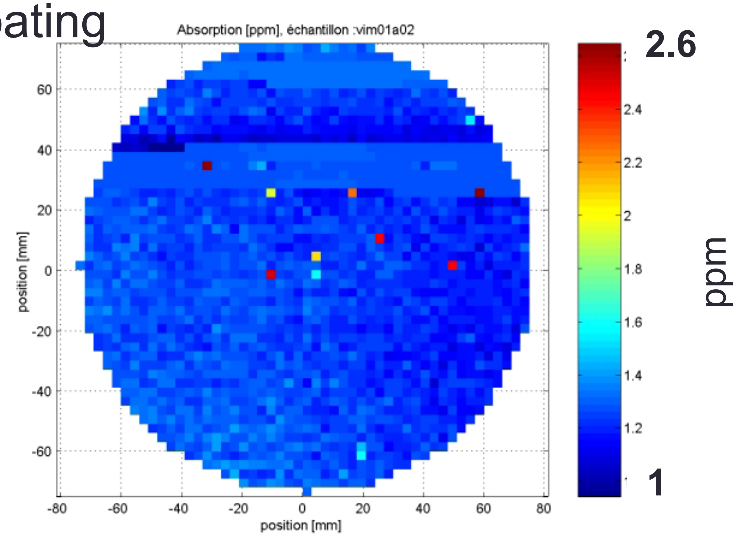
- Even if you purchased the most expensive mirrors, made of the purest materials, a tiny fraction of the power circulating in the interferometer is absorbed and converted into heat
- Mirror’s temperature increases
- Mirror deforms (thermo-elastic deformation)
- Refraction index depends on temperature
- So, you have thermal lensing



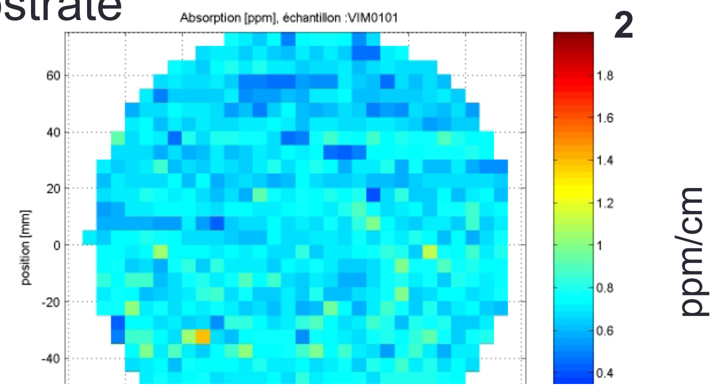


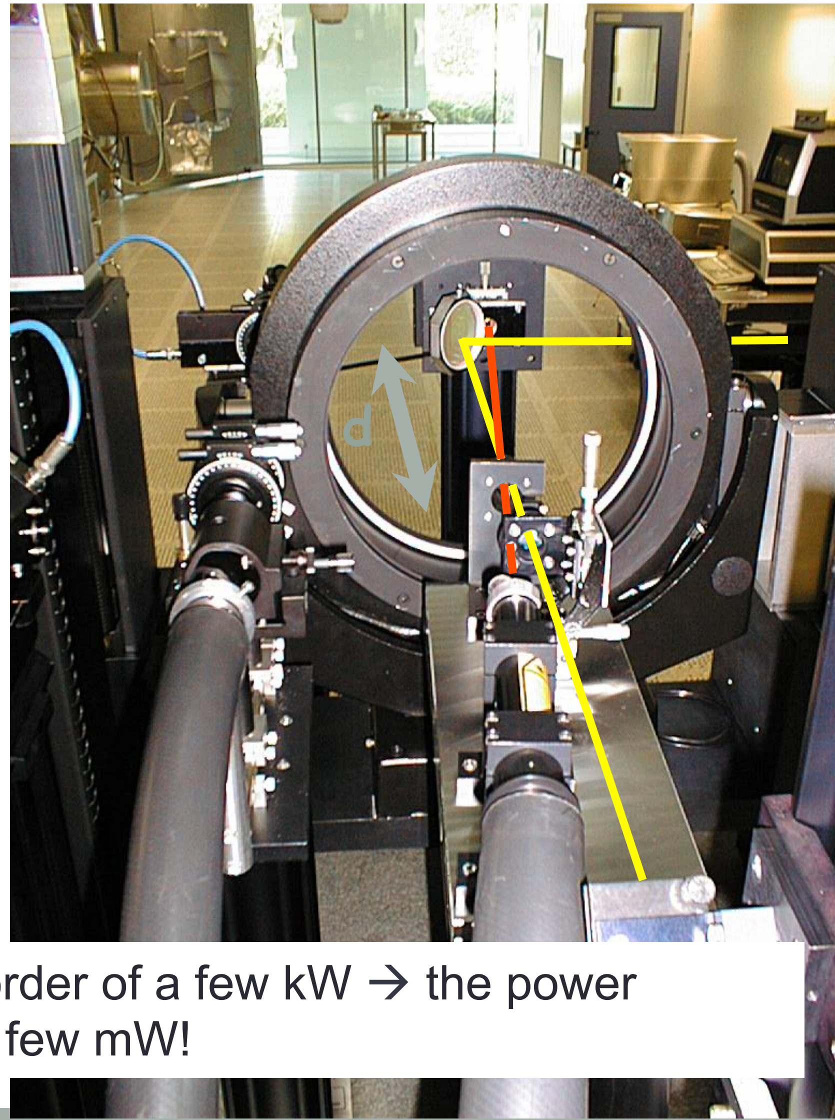
Mirrors' absorption maps

Coating



Substrate





So, if the power stored in the ITF is of the order of a few kW → the power absorbed by the mirrors is of the order of a few mW!

Thermal effects: thermal lensing

Consider a body at uniform temperature T_0, thickness l, refraction index n and $dn/dT \neq 0$. The *optical path length* through the body is:

$$OPL = n \cdot l$$

Now, we increase uniformly the temperature of the body by a quantity ΔT. Since the refraction index depends on the temperature (neglecting the thermal expansion), the new OPL through the body becomes:

$$OPL_1 = n_1 \cdot l$$

with

$$n_1 = n + \frac{dn}{dT}\Delta T$$

thus

$$OPL_1 = \left(n + \frac{dn}{dT}\Delta T\right) \cdot l = n \cdot l + \frac{dn}{dT}\Delta T \cdot l = OPL + \Delta OPL$$

So, we can define the *optical path length increase* as $\boxed{\Delta OPL = \frac{dn}{dT} \cdot \Delta T \cdot l}$

Thermal effects: thermal lensing

If we also take into account the effect of thermal expansion, the previous equation must be modified as:

$$\Delta OPL = \frac{dn}{dT}\cdot \Delta T \cdot l \quad \Rightarrow \quad \Delta OPL = \overbrace{\frac{dn}{dT}\cdot \Delta T \cdot l}^{\text{Thermo-optical}} + \overbrace{\alpha(1+\sigma)(n-1)\cdot \Delta T \cdot l}^{\text{Thermo-elastic}}$$

Where α is the thermal expansion coefficient and σ is the Poisson ratio.

In the most general case of a non-uniform heating, the general expression is:

$$\boxed{\Delta OPL(r,\theta) = \frac{dn}{dT}\cdot \int_0^l \Delta T(r,\theta,z)dz + \alpha(1+\sigma)(n-1)\cdot \int_0^l \Delta T(r,\theta,z)dz}$$

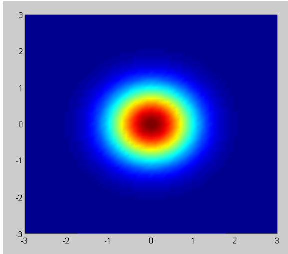
When the optical path length increase depends on the radial and angular coordinates, we are in presence of thermal lensing!

So we must determine the temperature increase inside the mirror

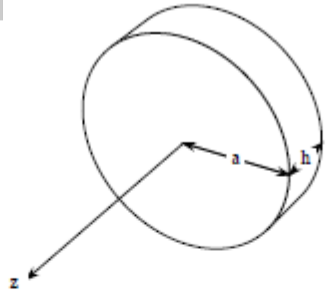
Thermal effects: thermal lensing

The laser beam in the interferometer crossing the mirrors has a Gaussian profile, the power density can be expressed as:

$$I(r) = \frac{2P}{\pi w^2} e^{-\frac{2r^2}{w^2}}$$



It does not depends on any angular coordinate nor on *z*. Our problem is thus axy-symmetric and we can use cylindrical coordinates (r, z, ϕ).



In this simple case it is possible to compute analytically the temperature distribution inside the mirror.

J.Y. Vinet, Living Rev. Relativity, **12**, 5 (2009)

Finite Element Models

When the problem does not have easy boundary conditions or it is not axy-symmetric, the analytical approach is replaced by Finite Element Modeling.

FEM: Method for numerical solution of field problems.

Description

- FEM cuts a structure into several elements (pieces of the structure).

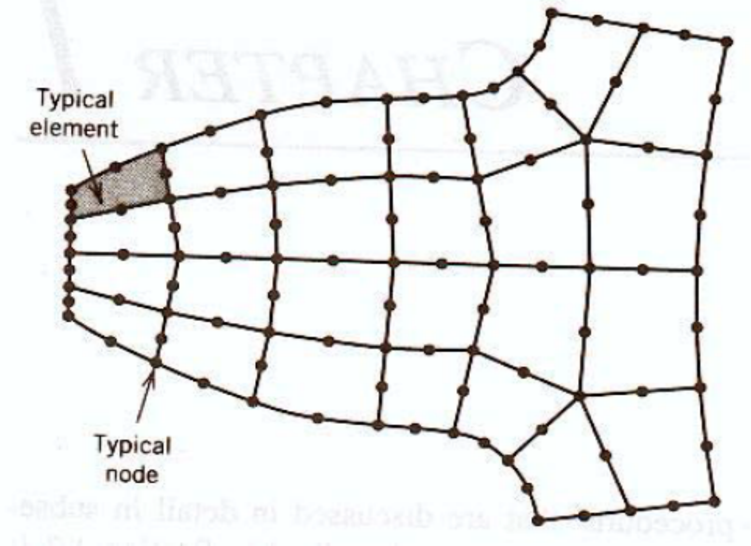
- Then reconnects elements at “nodes” as if nodes were pins or drops of glue that hold elements together.

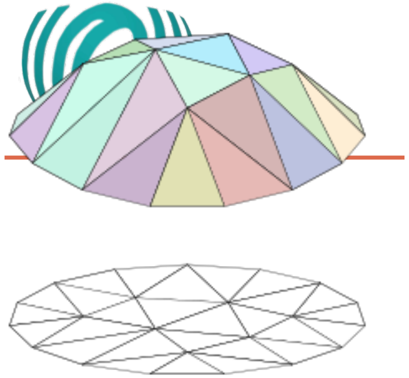
- This process results in a set of simultaneous algebraic equations.

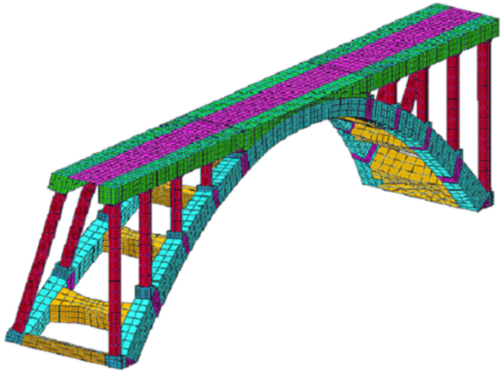
Number of degrees-of-freedom (DOF)

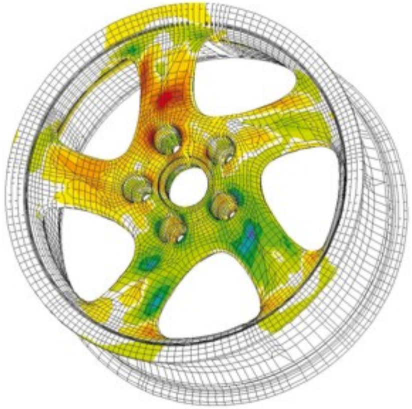
Continuum: Infinite

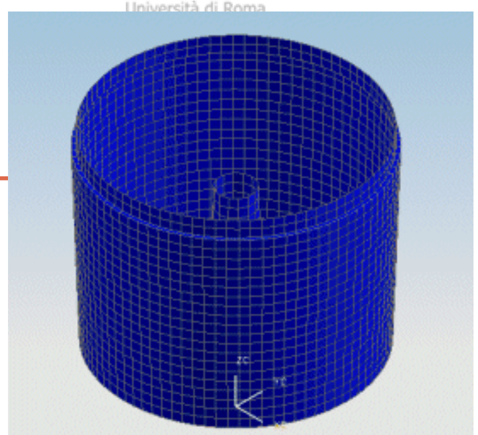
FEM: Finite
(This is the origin of the name, Finite Element Method)

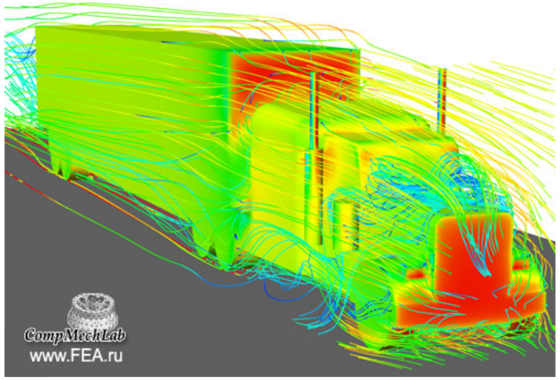








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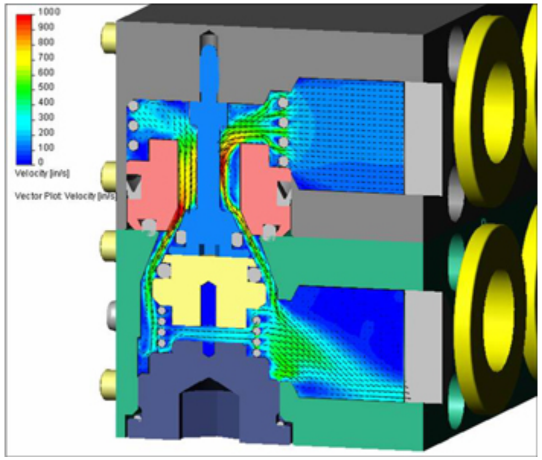
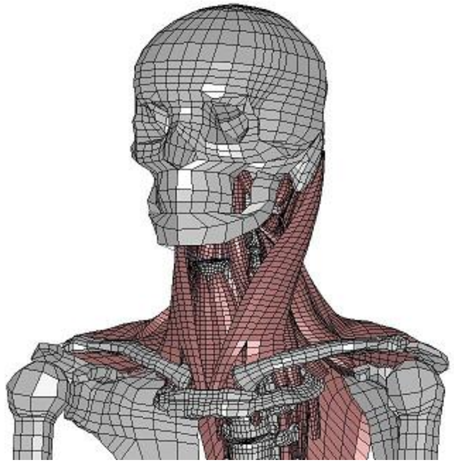
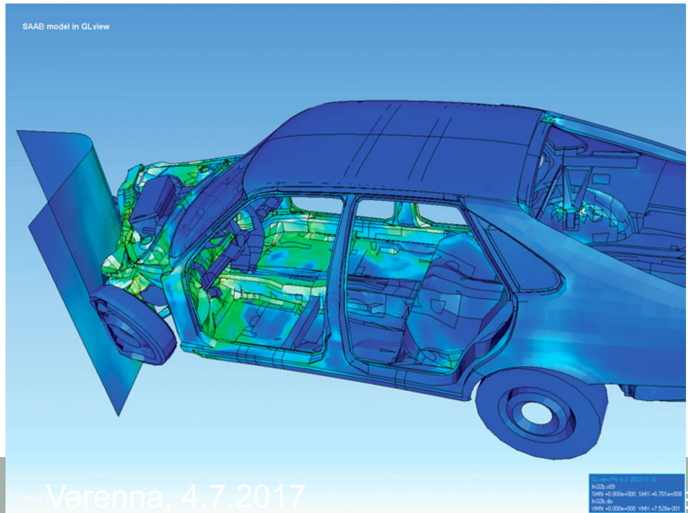
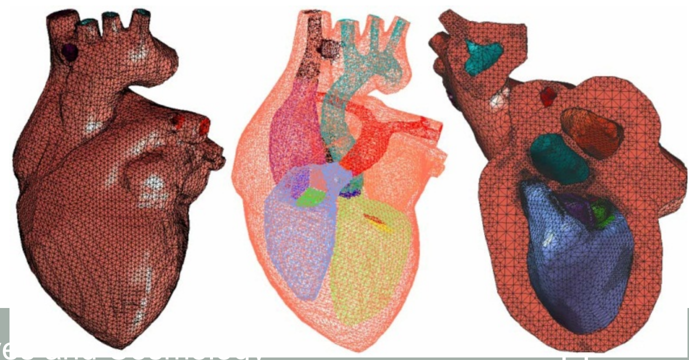

1000
900
800
700
600
500
400
300
200
100
0
Velocity [in/s]
Vector Plot: Velocity [in/s]




SAAB model in GLview



Temperature distribution

Virgo case:

Power impinging: 1W

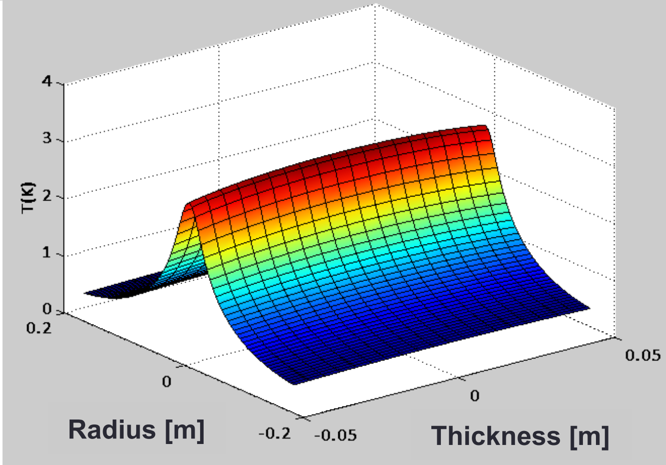
R=175mm

w=21.5mm,

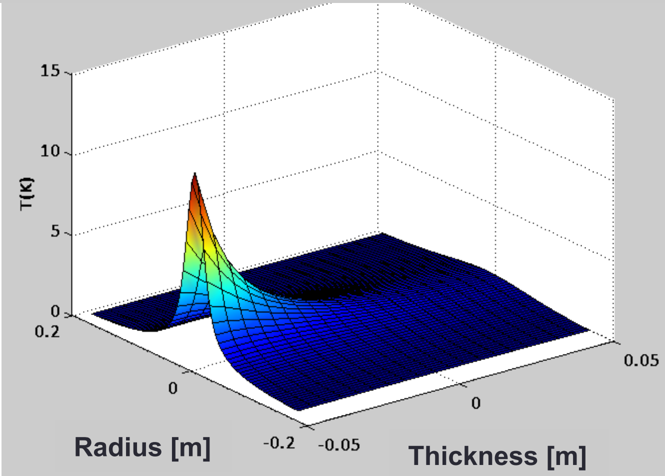
SiO_2 emissivity ~ 0.9

thermal conductivity =1.38W/(m·K)

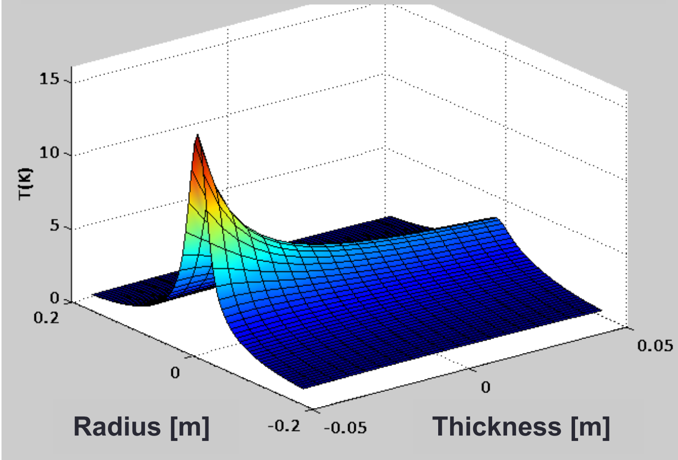
Temperature increase for 1 W absorbed in the substrate



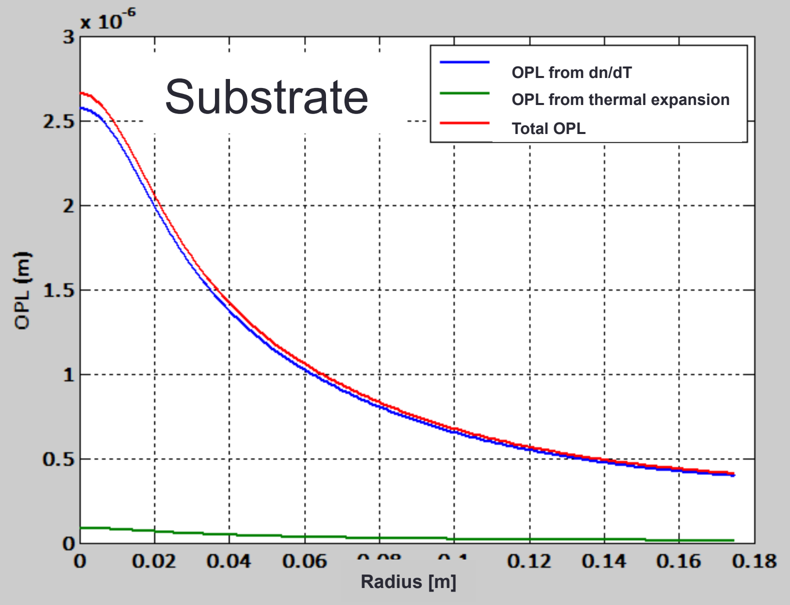
Temperature increase for 1 W absorbed in the coating

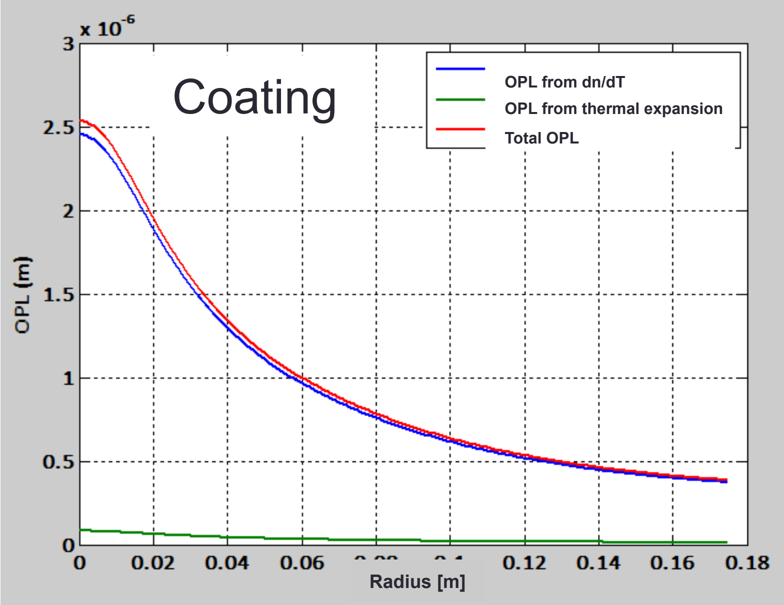


Temperature increase for 1 W absorbed C+S

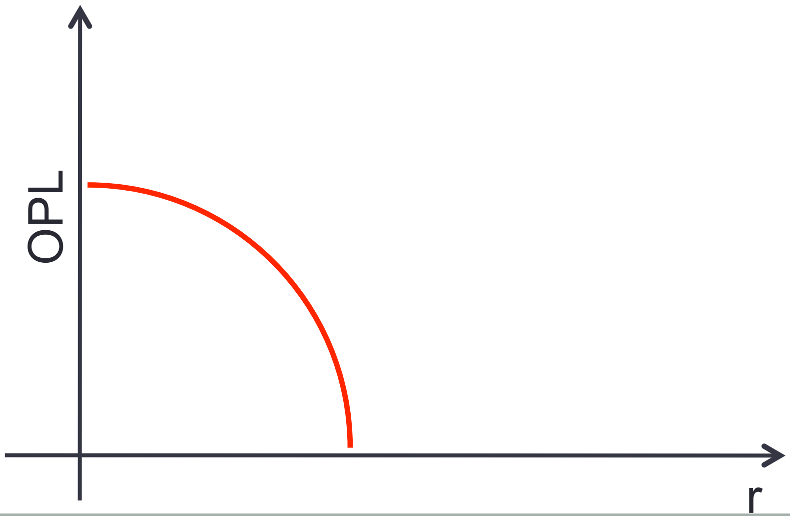


Thermal effects: thermal lensing





If the lens was spherical, we would have expected an optical path length increase of this kind…

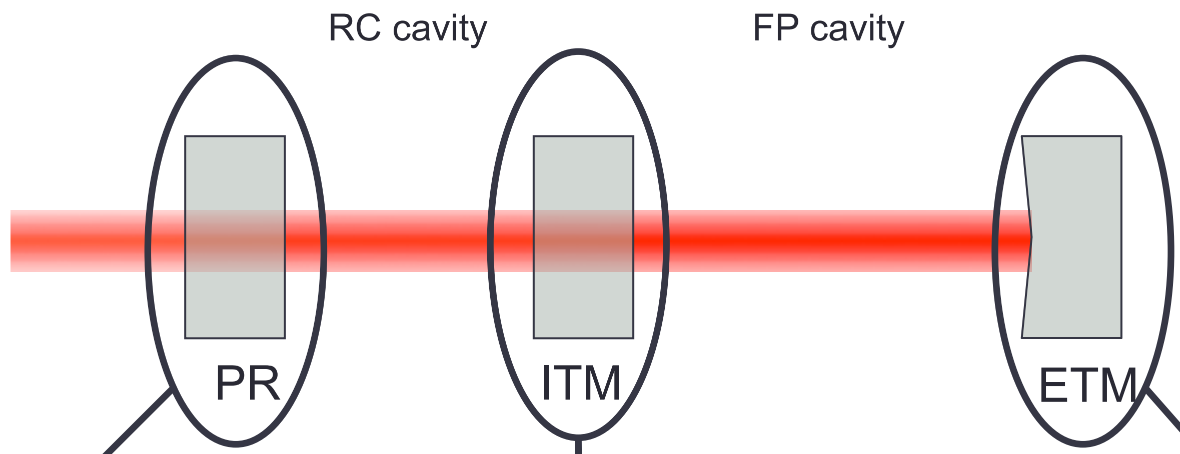


⇒ The lens is not spherical!

⇒ Its effect in the ITF is not trivial

Thermal effects: thermal lensing

Where is thermal lensing occurring?



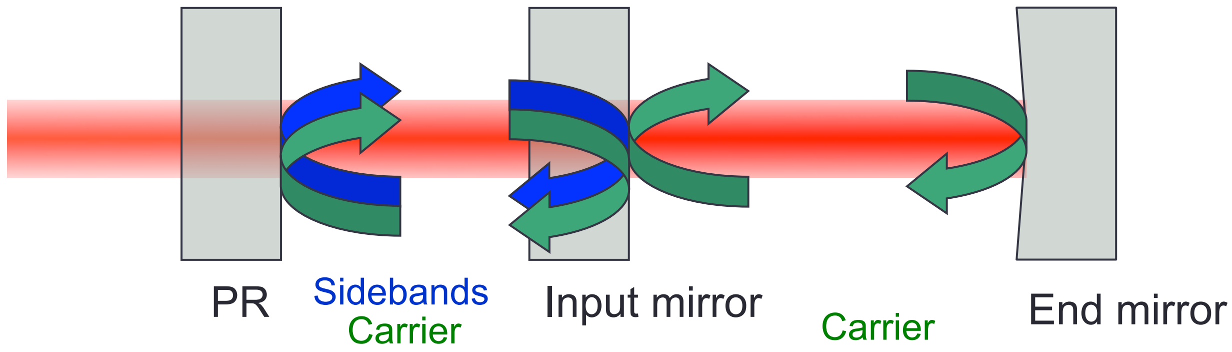
Some power is absorbed by the PR, but the PR substrate is “OUT” of the ITF!

Same as for the PR, the ETM substrate is “OUT” of the ITF!

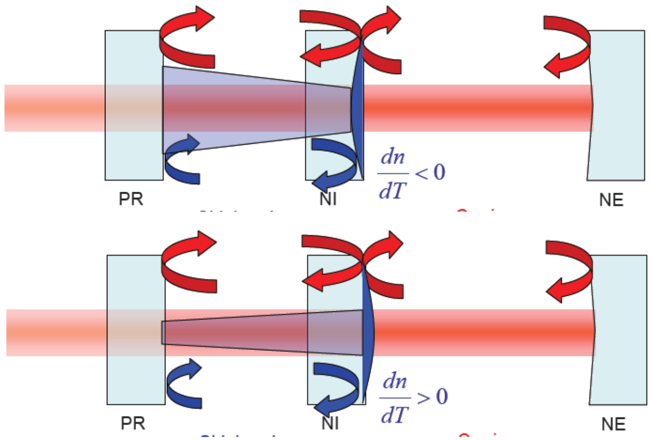
ITMs absorb some of the power stored in the RC cavity in their substrates, plus they absorb some of the FP cavity power in the HR coating.
ITM substrate is where the thermal lensing occurs, as it is inside the RC cavity

Thermal effects affect SBs

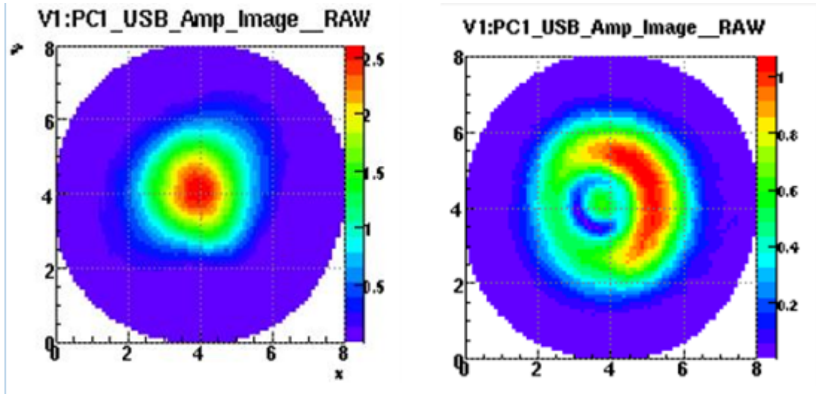
Thermal lensing ONLY affects sidebands



The carrier, resonating in the FP cavity, is «cleaned» by the finesse of the cavity.

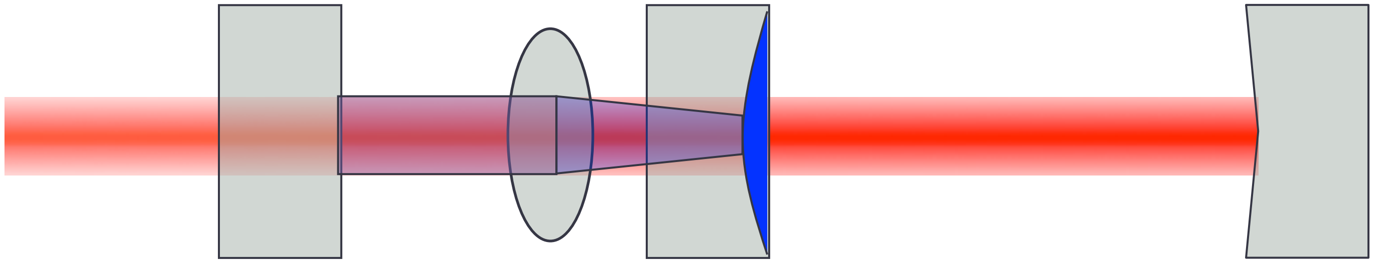


Since thermal effects give raise to a non-spherical lens, the sidebands fields in the recycling cavity are strongly **aberrated**. The cavity, seen by the sidebands, is “less” resonant and so the sidebands power decreases.



How to correct thermal effects?

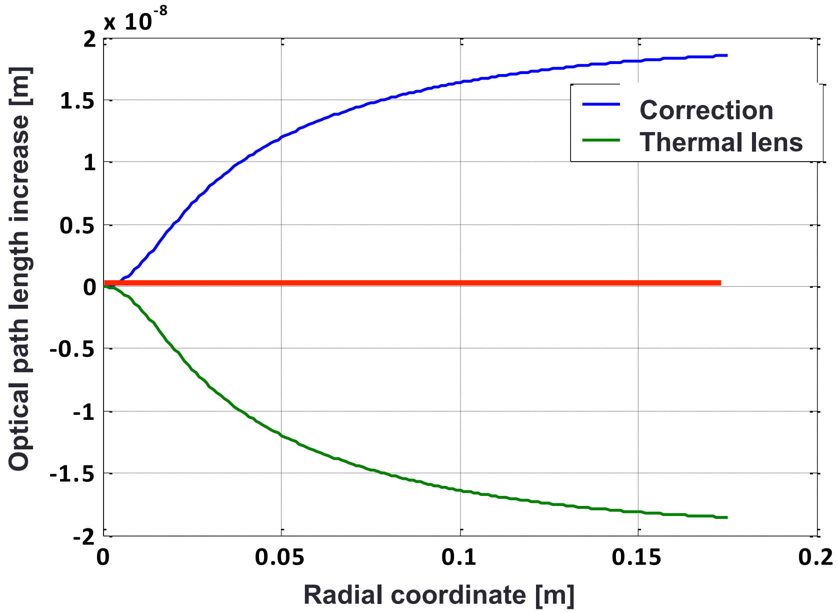
- One could think to introduce in the recycling cavity two spherical lenses, one for each ITM.



- Drawbacks:
  - We know that thermal lensing is NOT spherical;
  - The «strength» of the thermal lens changes according to the ITF input power…

General guidelines

- Somehow we must induce in the input mirrors a lens equal but opposite to the thermal one;



- The strength of the thermal lens will change with time: different ITF operating conditions, change in the absorption levels with time;
- We must use an **adaptive (flexible) system** in order to be able to change at will the strength and shape of the corrective lens;
- Do we have to flatten the OPL over the whole size of the mirror?

NO, only where there is the ITF beam!

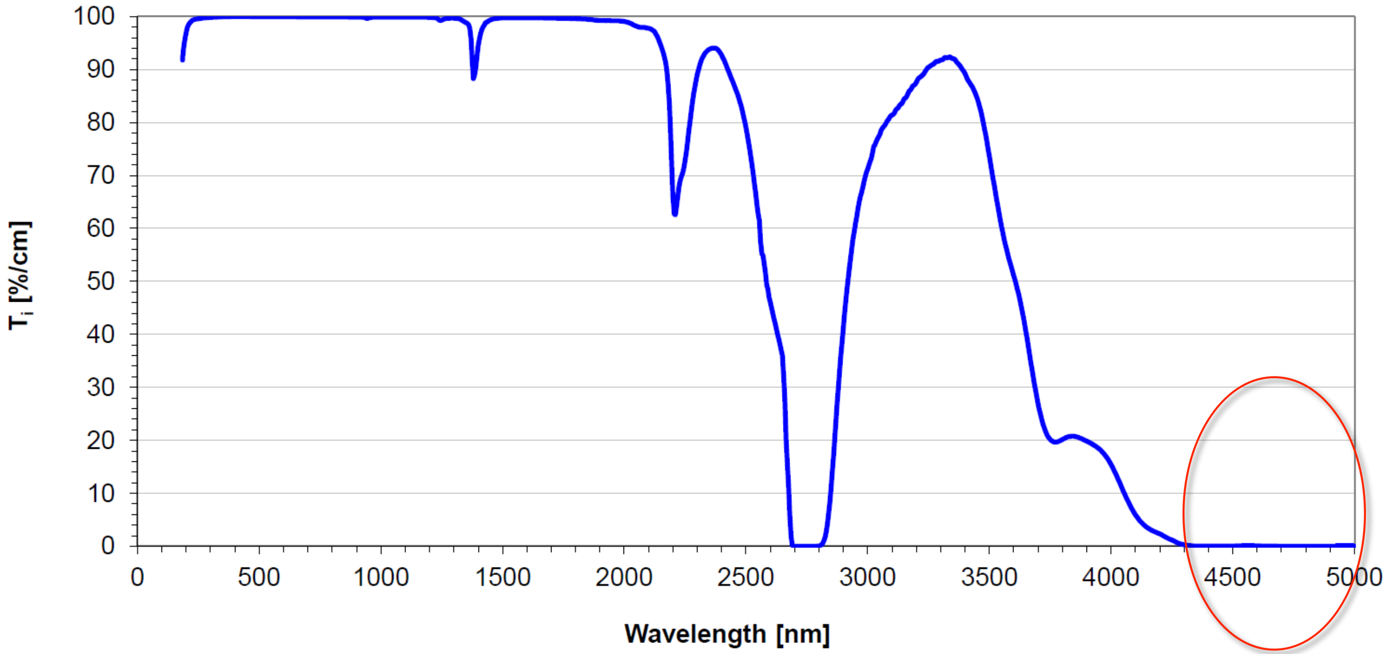
That is approximately 1.5 times the size of the beam on the ITMs.

General guidelines

We can think of heating the mirrors at specific locations, to induce a “corrective” thermal lens.

Since the mirrors are our free-fall test masses, we cannot think of gluing a heater on them.

The only “touchless” way to heat the mirror is by shining it with a radiation that is completely absorbed (>5μm for fused silica).

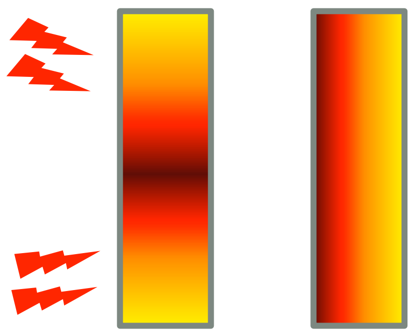


General guidelines

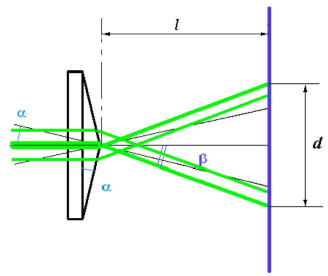
In the specific case of thermal lensing, which is <u>only</u> given by the radial component of the temperature gradient

$$\Delta OPL(r) = \frac{dn}{dT} \cdot \int_0^l \Delta T(r,z)dz + \alpha(1+\sigma)(n-1) \cdot \int_0^l \Delta T(r,z)dz$$

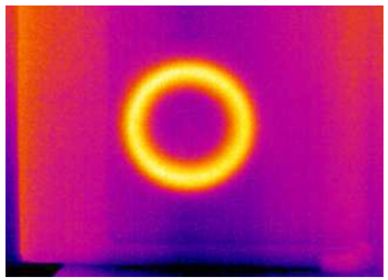
So, to null this component, we must heat the peripheral of the mirror:



This is done by the Thermal Compensation System (TCS)



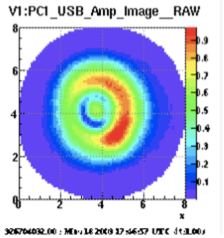
AXICON



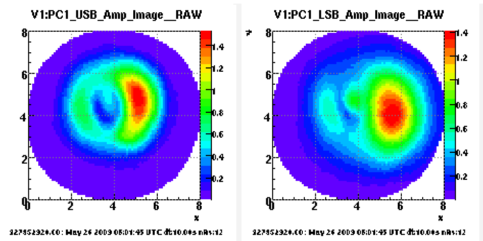
Virgo+ TCS performances

TCS was installed in Virgo+ with the main purpose of increasing the ITF input power. With no TCS, the maximum input power was 8-10W. Virgo+ TCS has been tested looking at the shape and position of the sidebands.

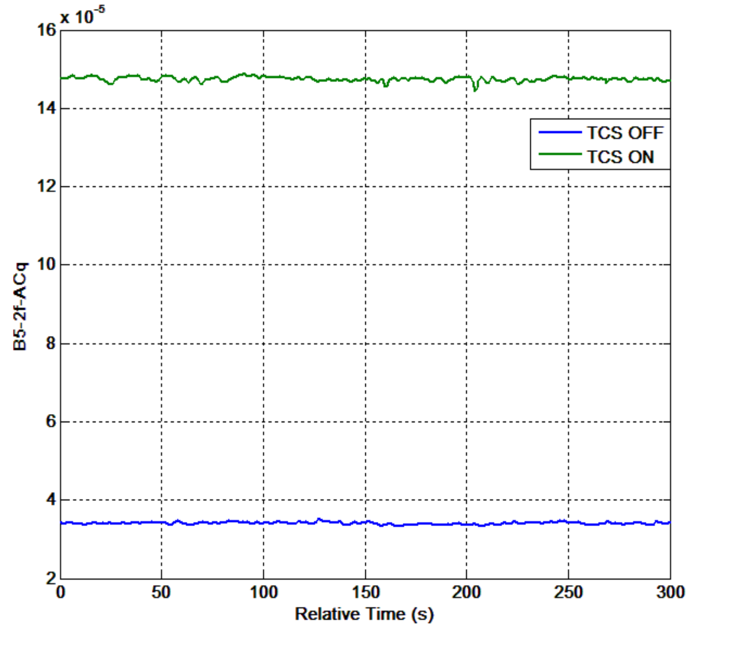
No TCS,
12W IFO



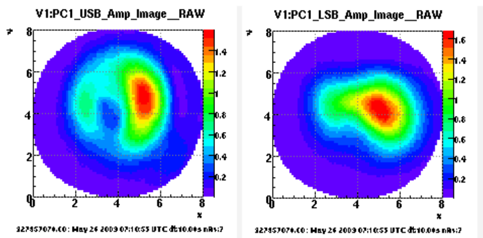
2.4W total TCS power



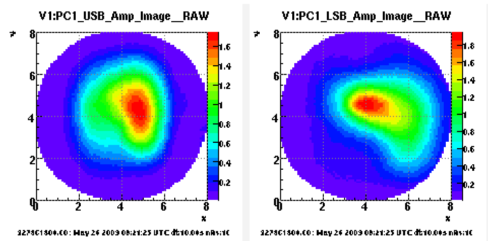
14.5W IFO



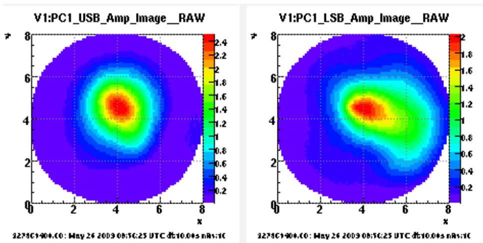
4W



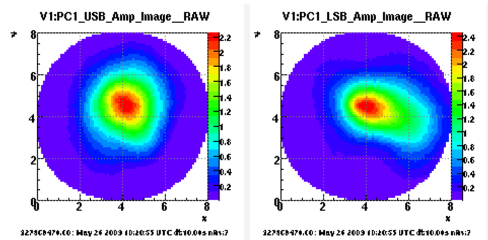
6W



6.5W

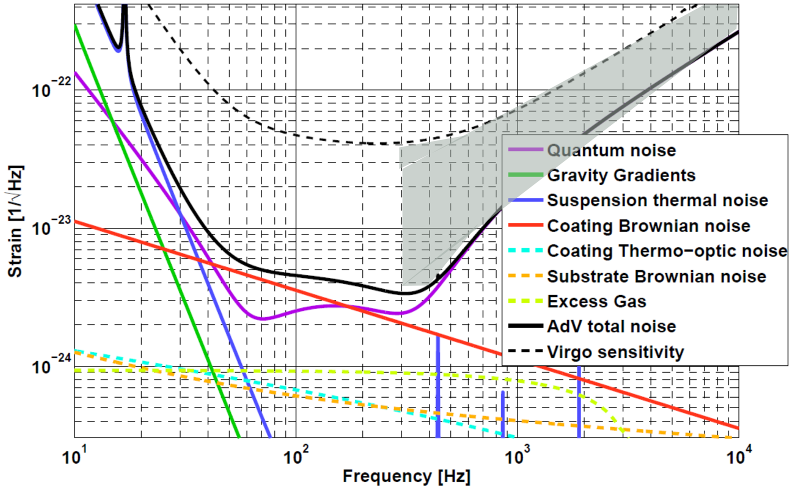


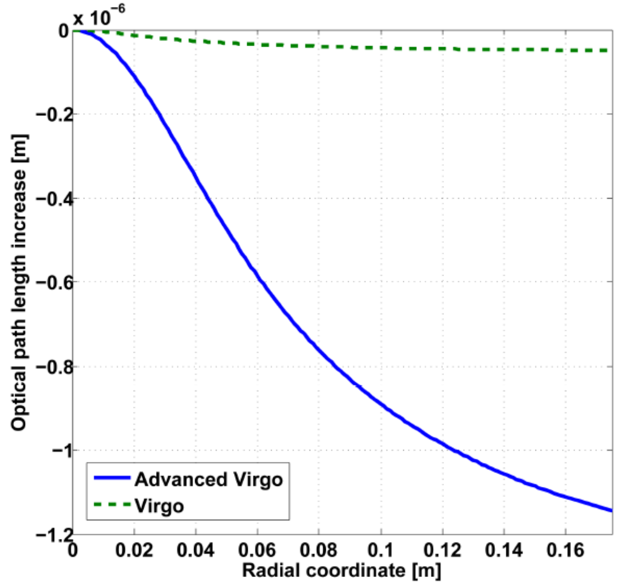
7W

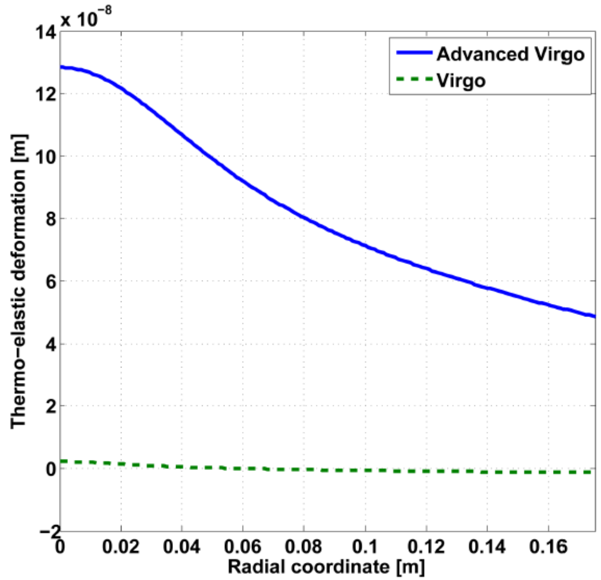


Thermal effects in advanced detectors

- Advanced detectors aim to improving the sensitivity by a factor of ten at all frequencies; also where the shot noise is limiting;
- Thus, there will be much more power circulating in the arm cavities (from 20 kW to 700 kW);
- Amplitude of the thermal lensing increases by more than one order of magnitude;
- One more effect becomes relevant: thermo-elastic deformation will change (increase) the RoC in both ITMs and ETMs, affects the FP cavity.







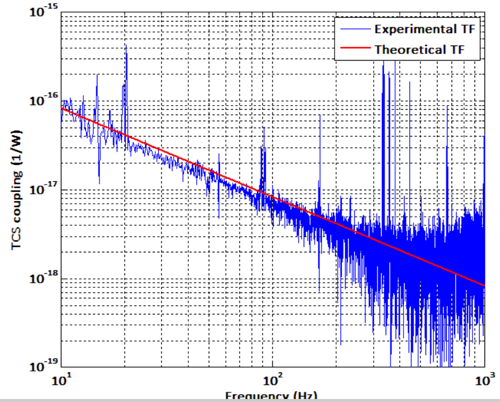
Noise from TCS

- TCS does not touch the mirrors BUT can inject displacement noise into the detector.

- Coupling mechanisms:
  - Thermo-elastic (TE) - fluctuations in locally deposited heat cause fluctuations in local thermal expansion
  - Thermo-refractive (TR) - fluctuations in locally deposited heat cause fluctuations in local refractive index
  - Flexure (F) - fluctuations in locally deposited heat cause fluctuations in *global* shape of optic
  - Radiation pressure (negligible)

$$\langle \Delta z_{TCS} \rangle = \frac{P}{2\pi f C \rho}\left(\Theta\left[(1+\eta)\alpha\left(1-\frac{\pi}{2F}(n-1)\right) - \frac{\pi}{2F}\frac{dn}{dT}\right] + \frac{6\alpha}{h^2}C_{num}\right) RIN$$

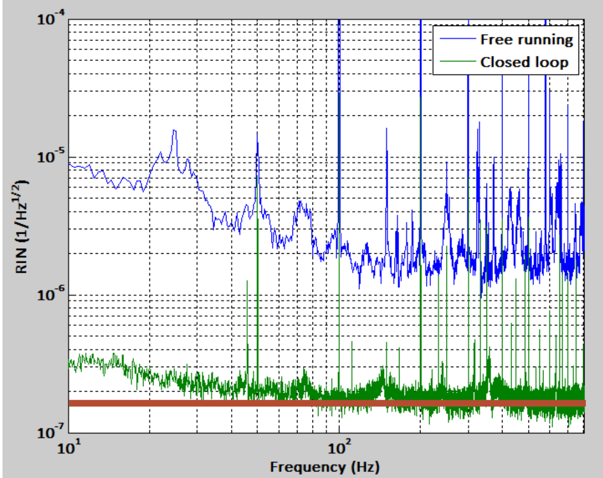
RIN = relative intensity noise TE TR F



Present detectors already require intensity stabilization of the CO_2 laser.

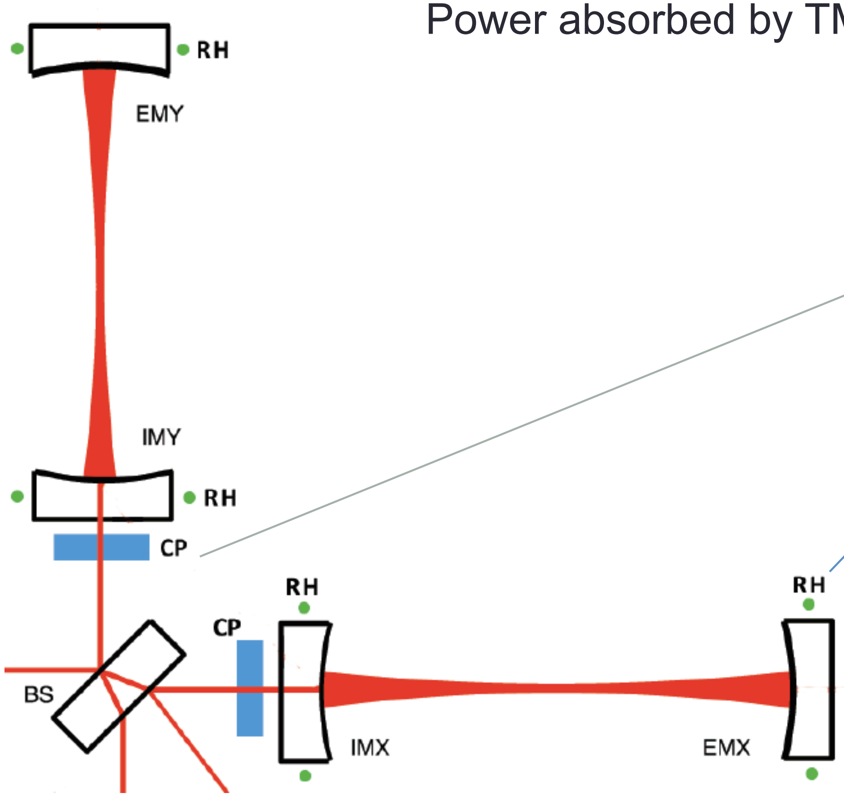
Achievable level of intensity stabilization ($10^{-7}/\sqrt{Hz}$) not enough to heat with CO_2 directly the TM in advanced detectors ($10^{-9}/\sqrt{Hz}$ needed) ⇒ compensation plates in the recycling cavity ⇒ noise coupling decreased by a factor of 2F/π.

PD dark noise limited



TCS in Advanced detectors

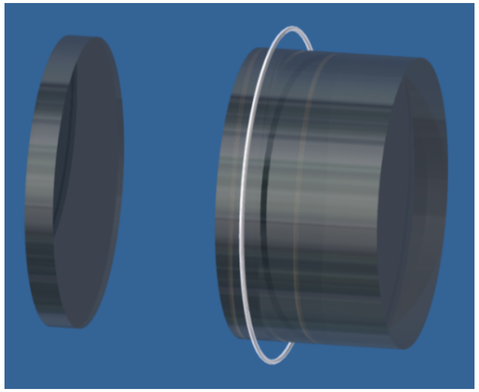
Power absorbed by TMs is about 0.5W, wrt ~20mW in initial detectors



Green dots: heating rings
Blue rectangles: CPs

Compensation plates shined with CO_2 laser will correct thermal effects in the RCs

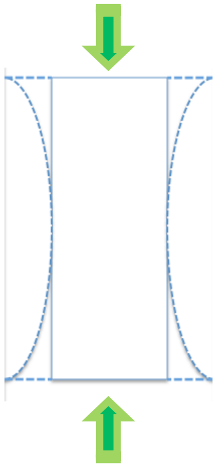
Ring heaters will compensate HR surface deformations



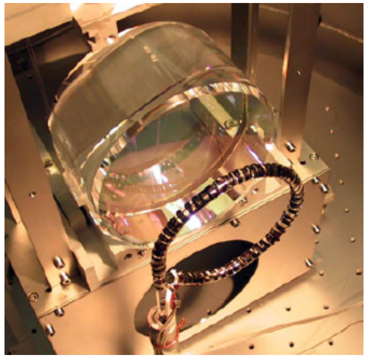
This set up allows to control independently the thermal lensing and the ROCs

TMs ROC tuning

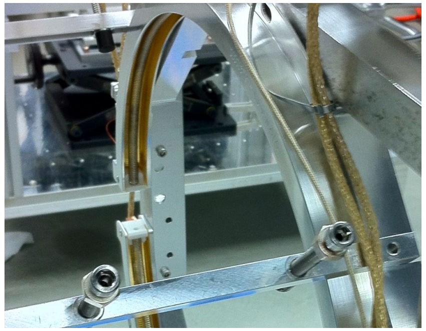
- Correction of the thermo-elastic deformation of the TMs is accomplished with RHs:
  - The RH bends the whole optic, in the opposite direction as the self-heating of the TM → ROC decreases;
  - Can apply correction if TM ROC does not meet the specifications and must be decreased;
  - On the ITMs, the RH also provides some correction of the thermal lensing.



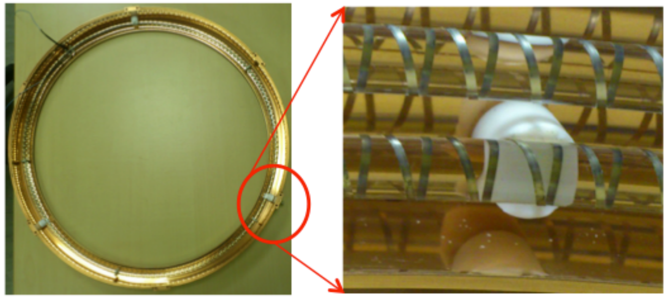
GEO



aLIGO

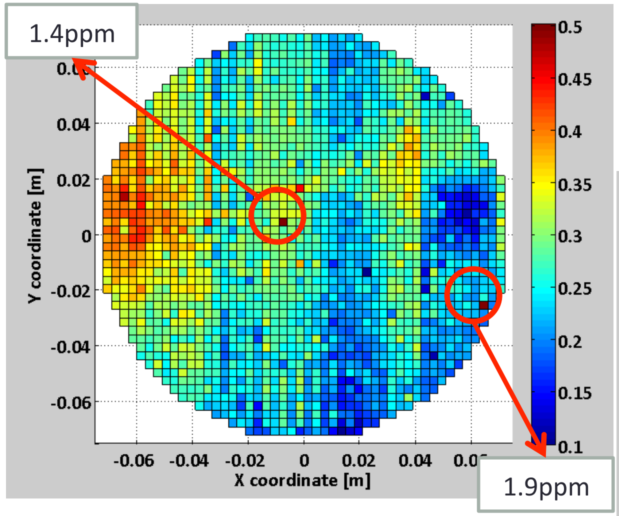


AdVirgo



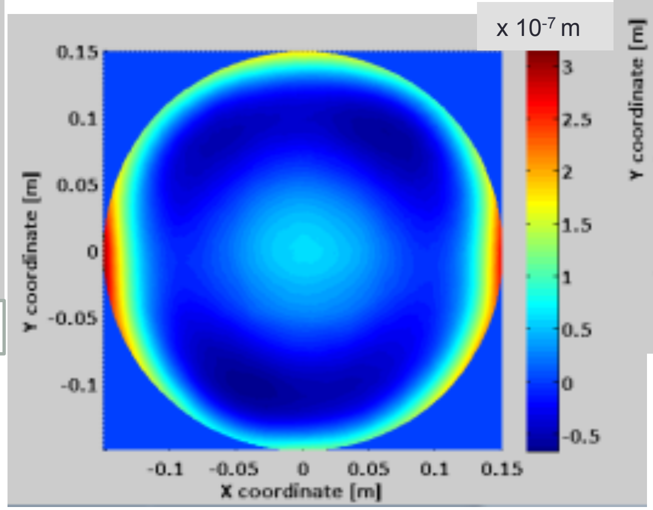
A new challenge: asymmetric defects

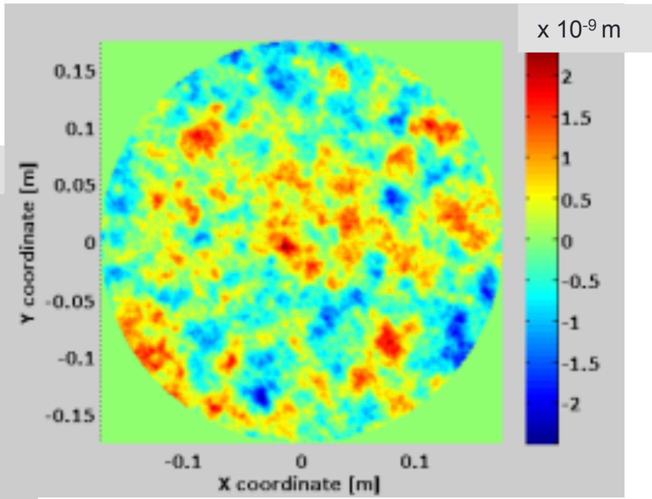
- The axicon system, due to its natural symmetry, can only correct axy-symmetric effects.
- However, in an ITF there are several sources of non-symmetric optical defects:
  - Inhomogeneity of the coating absorption;
  - Non-uniformity of the substrate transmission map;
  - Mirror surface figure errors.
- These defects lead to a strong aberration of the sideband fields, because of **marginally stable recycling cavities.**



Coating absorption map (measured at LMA on a aLIGO mirror)

Substrate transmission map (measured at LMA on a aLIGO mirror)



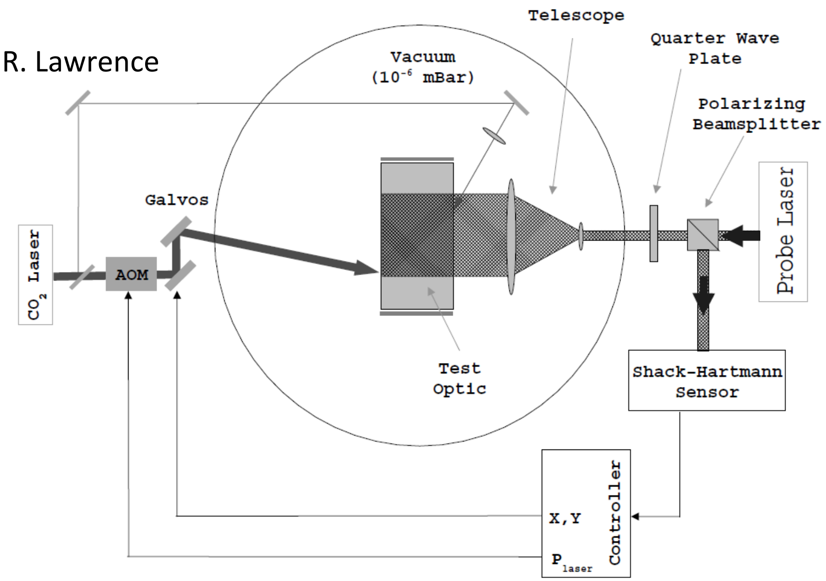


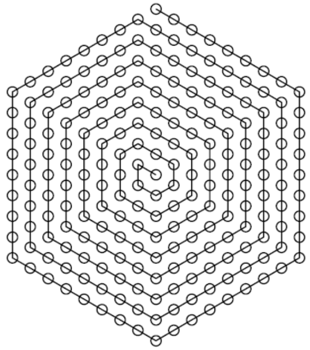
Surface roughness map (simulated)

Correction of asymmetric defects

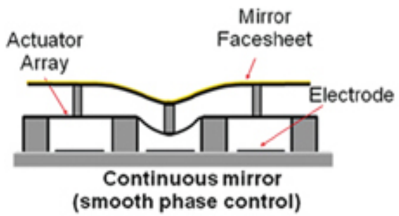
- In AdV, it is mandatory to develop a non-symmetric compensation system.
- CO_2 laser based techniques:
  - Scanning system – under construction;
  - MEMS deformable mirrors.

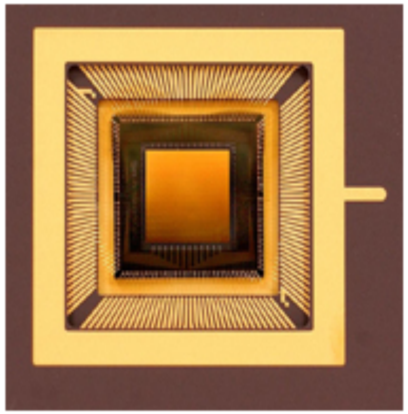
R. Lawrence





Hexagonal scanning pattern





Mirror Close-up

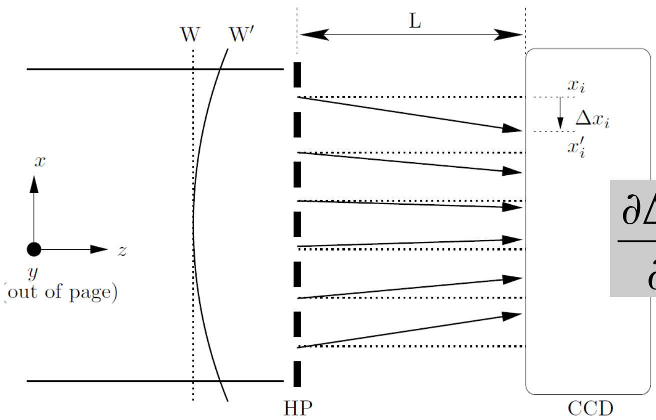
Check these videos if you want to see what a scanning system can do:

http://www.youtube.com/watch?feature=player_detailpage&v=Gm4BYcOJrMg

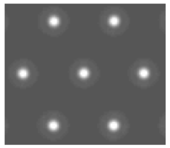
http://www.youtube.com/watch?feature=player_detailpage&v=1fCxO2G0h9A

How to measure the aberrations: the Hartmann sensor

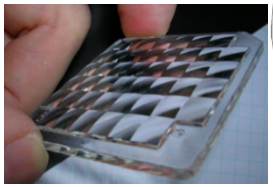
A Hartmann sensor consists of an opaque plate containing an array of apertures and an intensity recording medium. Originally, the recording medium was a photographic plate, but it is now almost exclusively a solid-state photo-sensitive array.

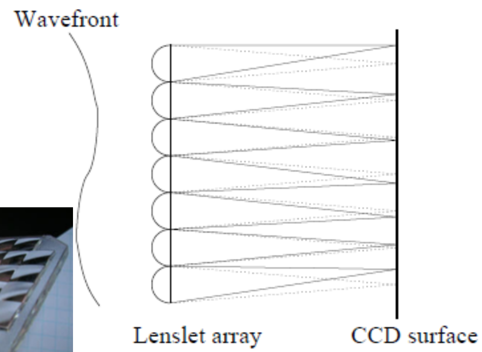


$$\frac{\partial \Delta W}{\partial x} = \frac{\Delta x}{L}$$



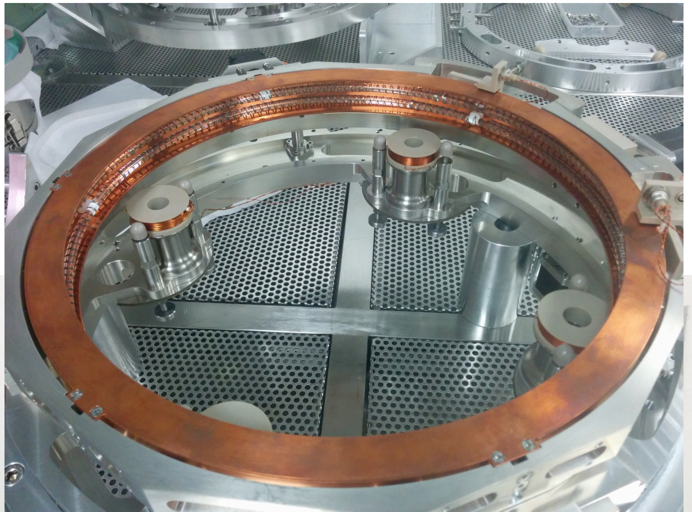
Shack-Hartmann sensor





An aberrated wave-front W′ is incident on a Hartmann plate (HP). The resulting rays propagate a distance L, normal to the wave-front, and are incident on a CCD. The spot position, x'_i, is determined by the centroid of that spot's intensity profile. The gradient of the wave-front at the i^{th} aperture is given by the displacement, Δx_i, from the reference position divided by L.

The AdV TCS



A look at the future

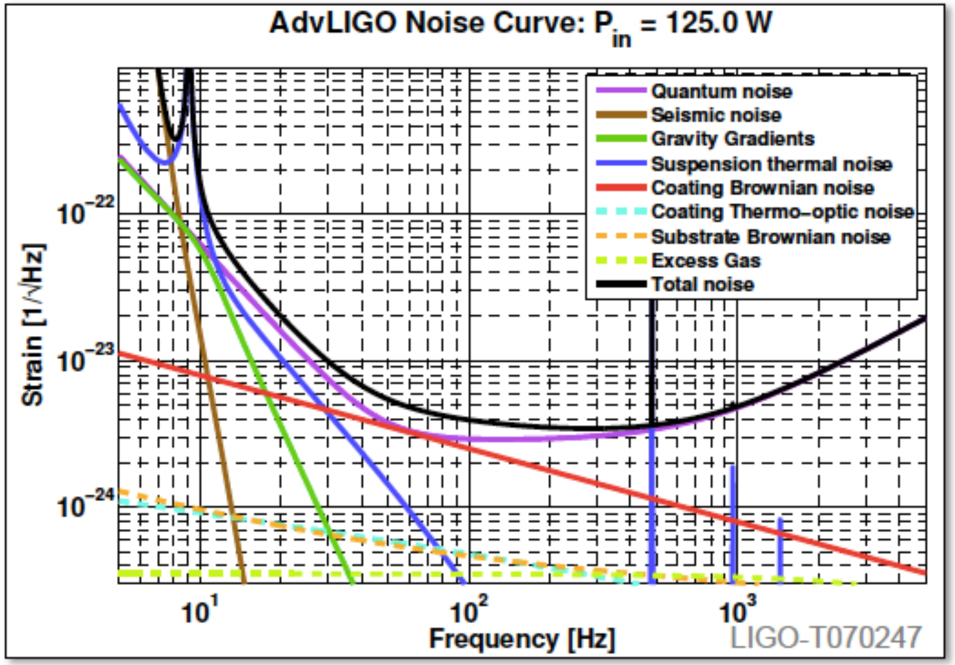
- How can we improve the sensitivity?
- Can we further exploit present infrastructures?
- And what next?
- What is scientific payoff?

Advanced detectors

The 2nd generation interferometers (LIGO, Virgo) all have similar noise limits

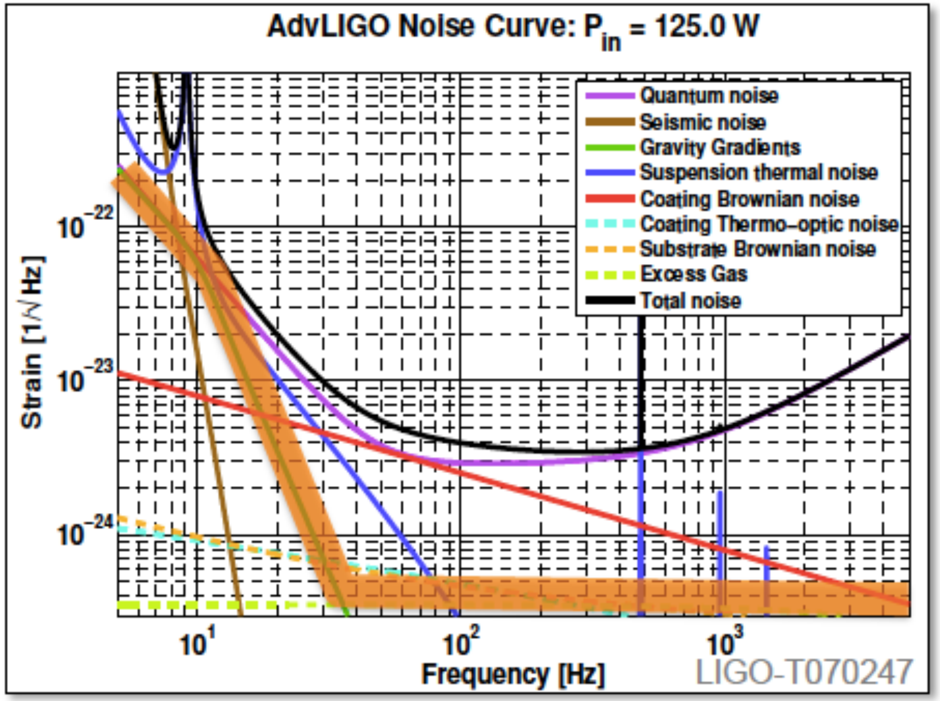
➲ In order to understand how we can potentially improve 2G detectors, we need to see what they are limited by:

- **Quantum Noise** limits most of the frequency range.
- **Coating Brownian** limits (or is close) in the range from 50 to 100Hz.
- Below 50Hz we are limited by 'walls' made of **Suspension Thermal**, **Gravity Gradient** and **Seismic noise**.



Advanced detectors

- The advanced detectors baseline sensitivity is far away from the infrastructure limits
- Infrastructure limit is usually defined as a combination of residual gas noise and gravity gradient noise
- So, there is plenty of room for upgrades within the existing infrastructures

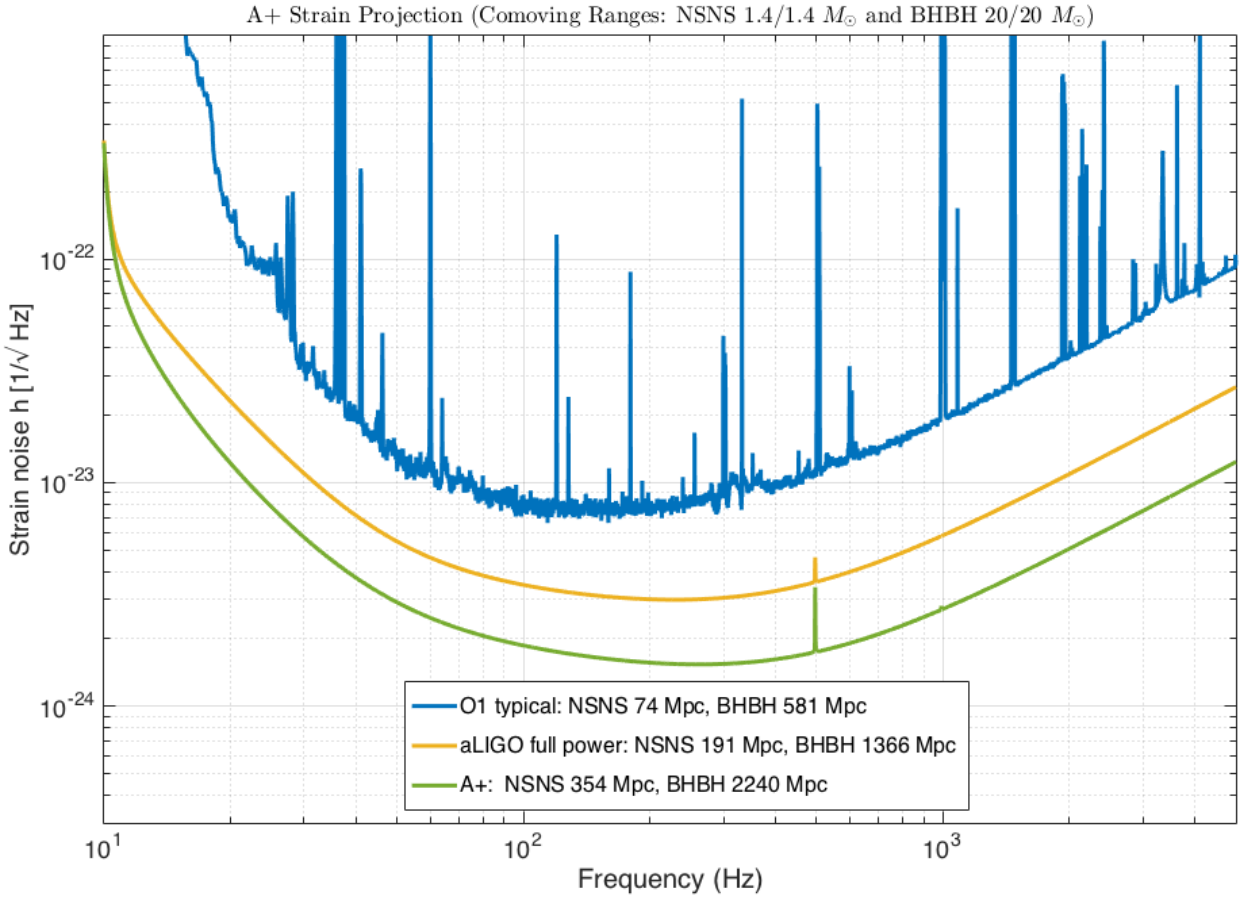


Beyond advanced detectors

- Advanced Virgo and Advanced LIGO are working to define a path toward the sensitivity improvement
- First step: Advanced Virgo+ (aka AdV+) and advanced LIGO+ (aka A+)
- An incremental upgrade that leverages existing technology and infrastructure, with moderate investment and risk
- Target: factor of 1.5-2 increase in range over advanced detectors
- About a factor of 3.5-8 greater CCB event rate
- Stepping stone to future 3G detector technologies!!
- Link to future GW astrophysics, cosmology, nuclear physics
- Could be observing within O(10) years (2020+)

Beyond advanced detectors

- A+ example



Coatings Thermal Noise reduction

- In the frequency band were advanced detectors are more sensitive, the dominant limiting noise is the thermal noise of coatings.
- Any reduction factor of coating thermal noise level will determine an increment of the same factor either of the maximum detection distance or of the signal-to-noise-ratio.
- Moreover, reducing the thermal noise will allow the interferometer to be quantum limited over most of its frequencies, enabling the fully benefit of using squeezed light.

Coatings Thermal Noise reduction

- Thermal noise spectral density

Substrate Poisson ratio

effective loss angle of the material

$$S_{xx}^{coat} = 2\,k_B T \cdot \frac{1-\sigma_s}{\sqrt{\pi^3}\,w\,Y_s} \cdot \frac{\phi_{eff}}{f} \cdot C_{FTM}^2$$

laser spot size on the mirror

Substrate Young's modulus

- Best material for the mirror substrate at room temperature: Suprasil® already used in present detectors
- → only possible reduction of coating thermal noise has to come from
  - **the increase of the beam radius w**
  - **the reduction of mechanical loss angle**

CTN reduction: increasing the beam radius

- Increasing the beam profile could be done in two complimentary ways:
  - **increasing the diameter of the mirror substrate** to keep the clipping losses at a negligible value.
  - Example: Advanced Virgo BS is 550 mm in diameter, 65 mm thick and weighting 40 kg (the same weight as the actual test masses). We already know that such piece could be handled, cleaned, coated and characterized at LMA. A suspension for such a large piece has already been developed and installed, albeit not a monolithic one. One can expect a possible increase of 60% of the size of the beam on the mirrors, compared to Advanced Virgo → a reduction of a factor 1.6 for the amplitude of the coating thermal noise. Additional positive side effect: a reduction of 2.6 for the magnitude of thermal lensing.

CTN reduction: increasing the beam radius

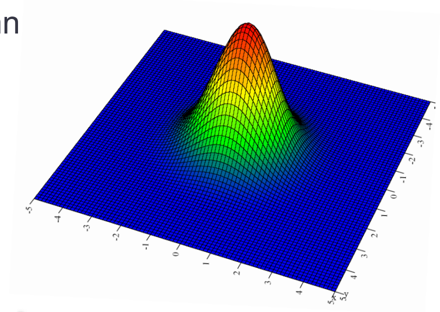
- Increasing the beam profile could be done in two complimentary ways:
  - **using higher-order modes**

Laser modes

The complete solution to the wave equation for a laser field is:

$$E_{mn}(x,y,z;t) = \underbrace{E_0 \frac{w_0}{w(z)} H_m\left(\frac{\sqrt{2}x}{w(z)}\right) H_n\left(\frac{\sqrt{2}y}{w(z)}\right) e^{\frac{-(x^2+y^2)}{w(z)^2}}}_{\text{Amplitude}} \underbrace{e^{\frac{ik(x^2+y^2)}{2R(z)}} e^{i\left[kz-(m+n+1)\tan^{-1}\left(\frac{\lambda z}{\pi w_0^2}\right)\right]} e^{-i\omega t}}_{\text{Phase}}$$

Where H_m and H_n are Hermite polynomials.
The solution depends on the choice of the coordinate system: if we chose the cylindrical coordinates, we would find another basis called Laguerre-Gauss modes (that uses Laguerre polynomials instead of the Hermite ones). These modes are also termed Transverse Electrical Modes (TEM$_{mn}$



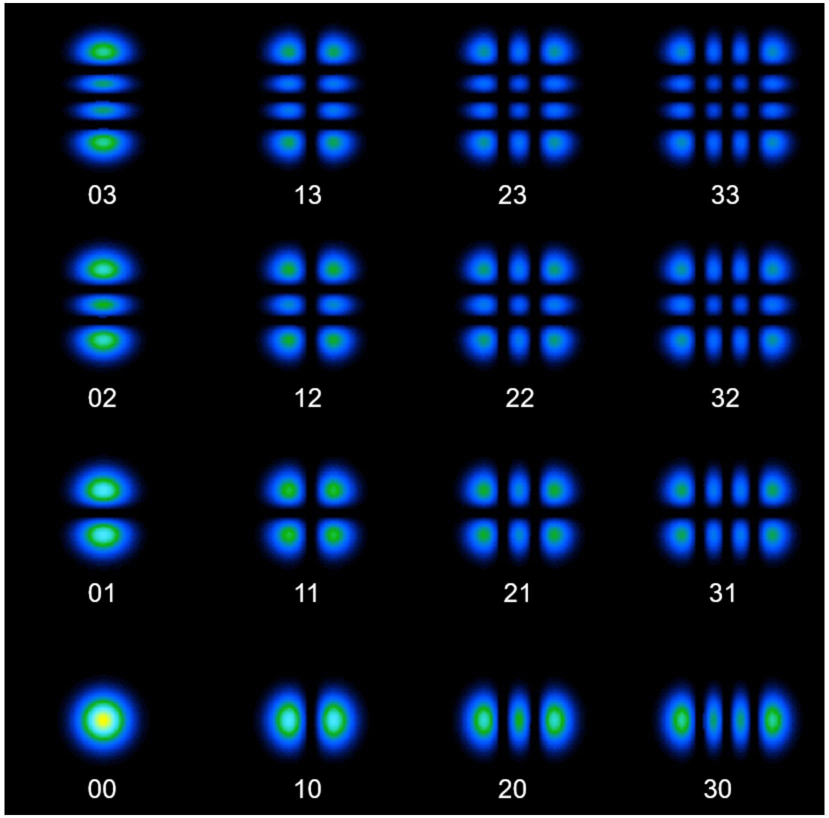
For $m=n=0$, the above equation reduces to equation (1), since $H_0=1$ and the corresponding mode is called TEM$_{00}$, or fundamental Gaussian mode.

$$E = E_0 e^{ik\frac{(x^2+y^2)}{2R}} e^{\frac{-(x^2+y^2)}{w^2}} e^{i(kz-\omega t)}$$

Laser modes

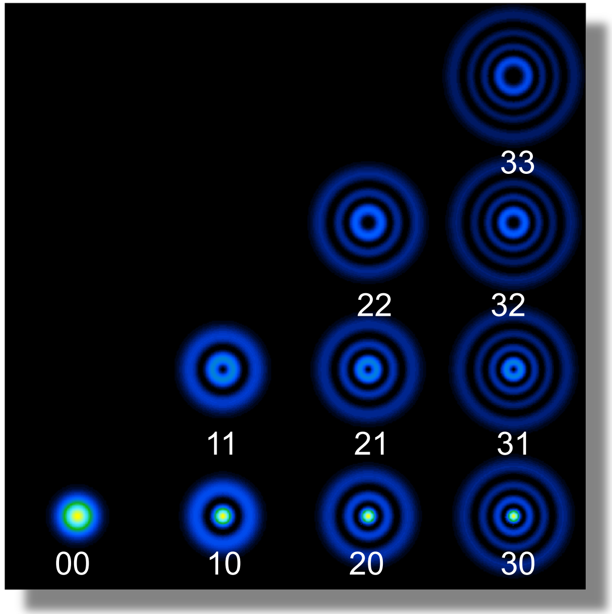
All cases where *m* or *n* or both differ from 0, are named higher order TEM modes.
The most fundamental light distribution emitted by a laser is the Gaussian beam, however, due to practical limits in the construction of the lasers, there is always a small pollution from higher order modes.

HG modes

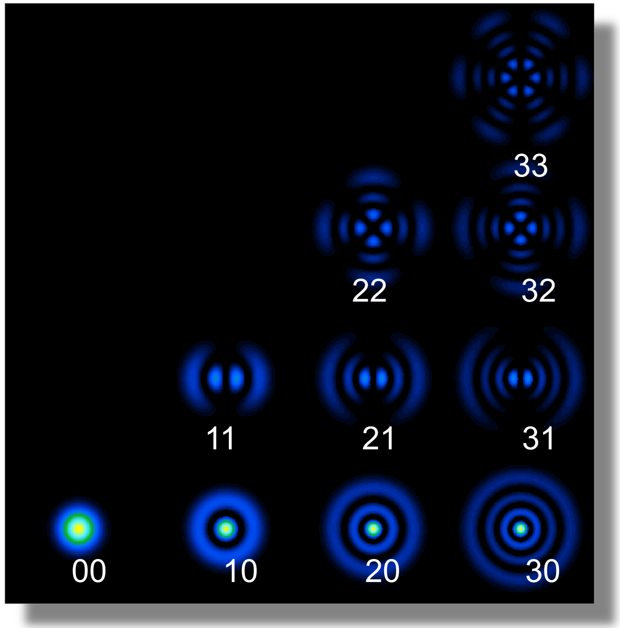


Laser modes

Helical LG modes



Sinusoidal LG modes



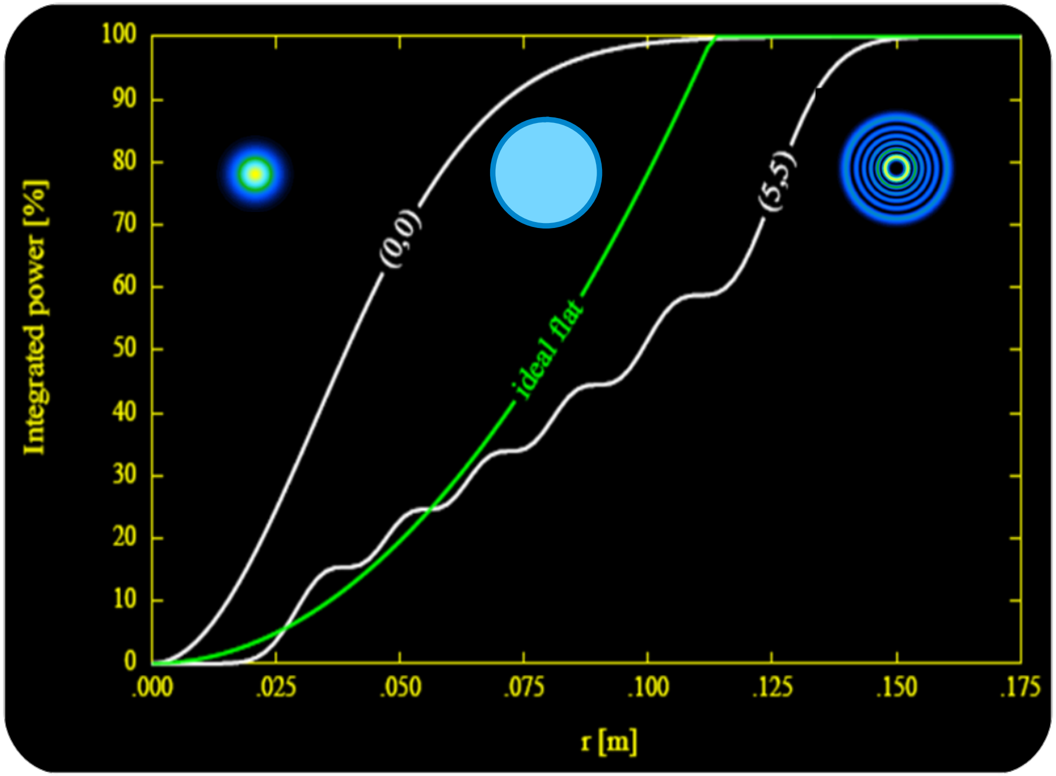
From Keiko Kokeyama, University of Birmingham
2nd ET Annual Workshop @ Erice, Italy (2009)

Laser modes

Power distribution of LG beams on the mirror surfaces

More uniform power distribution on a mirror surface than the fundamental mode.

Integrated beam power for modes with 1ppm loss on a mirror with d =35cm

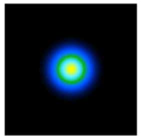


by M. Laval and J.Y. Vinet

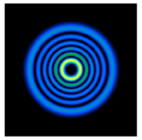
Any surface deformations are averaged out more smoothly and the temperature increase of the mirror is more uniform thereby reducing thermal deformation effects.

Laser modes and thermal noise

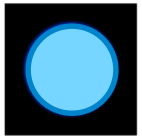
Thermal noise of LG and Flat beams



HG00 mode: $$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{1-\sigma^2}{2\sqrt{\pi}\,Y\,w}$$



LGnm modes: $$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{1-\sigma^2}{2\sqrt{\pi}\,Y\,w}\,\alpha_n^m$$



Flat beams: $$S_x(f) = \frac{4\,k_B\,T}{\pi\,f}\,\frac{1}{Q}\,\frac{8\left(1-\sigma^2\right)}{3\,\pi^2\,Y\,b}$$

J.Y. Vinet , *CQG* ***22*** *(2005) 1395*, Bondu et al. *Physics Letters A* ***246*** *(1998) 227*

formulas valid for infinite media

α_n^m

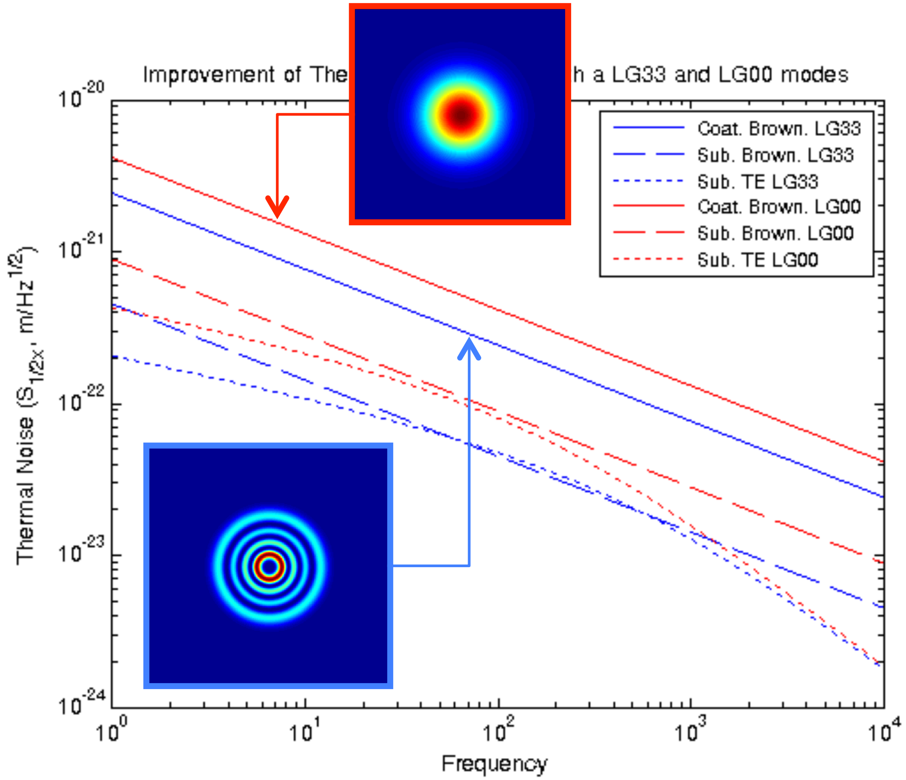
$\alpha_0^0 = 1$
$\alpha_1^1 = 0.5$
$\alpha_3^3 = 0.31$
$\alpha_5^5 = 0.25$

$$\mathrm{LG}_{33}\quad h_{33} = \frac{h_{00}}{1.8}$$

CTN reduction: increasing the beam radius

- Increasing the beam profile could be done in two complimentary ways:
  - **using higher-order modes**[1,2], in particular LG modes because the thermal noise of the mirrors can be reduced by a factor which depends on the spatial order

    $N = 2p+l$ of the LG^{l}_{p} mode resonant in the interferometer: higher N values → larger beams and lower thermal noise. Example: the thermal noise level could be decreased by nearly a factor of 2 by using an LG^{3}_{3} beam.

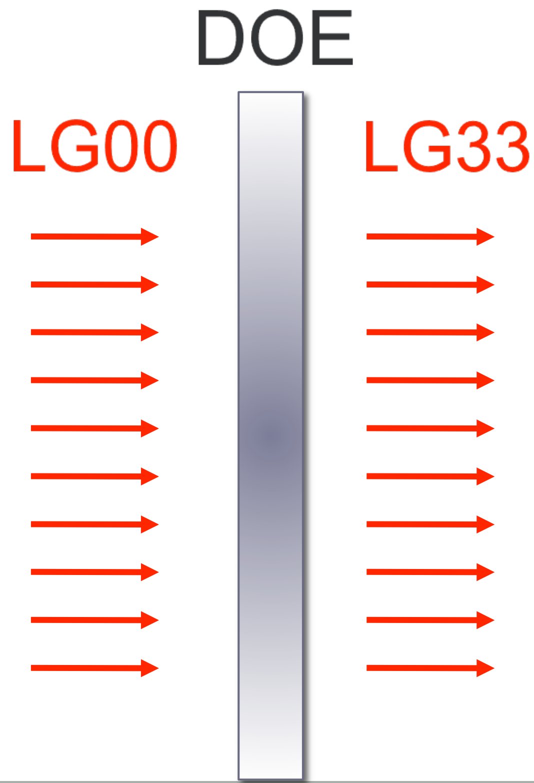


[1] Mours B. & al. , Class. Quant. Grav. 23 , 2006
[2] Vinet J. Y. , Living Rev. Relativity 12 , 2009

Generation of LG modes

- R&D studies for generation of high purity/high stability modes: Spiral phase plates, cylindrical mode converters, computer generated holograms, fibers, spatial light modulators,

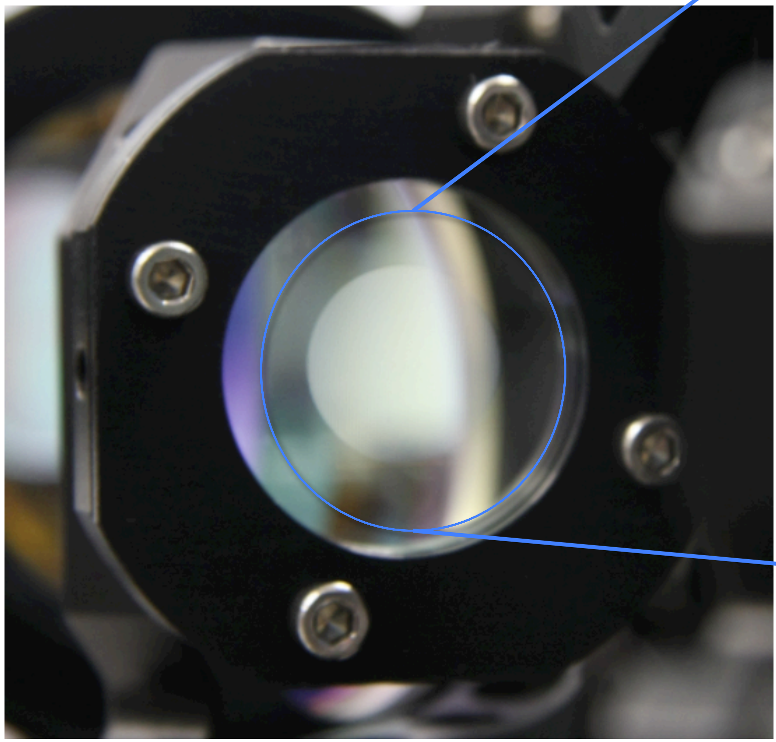
- **<u>Diffractive optical elements (DOEs) = etched plates of glass</u>**:
  - simple technique ✔
  - stable passive optics ✔
  - (in principle) can handle high power ✔

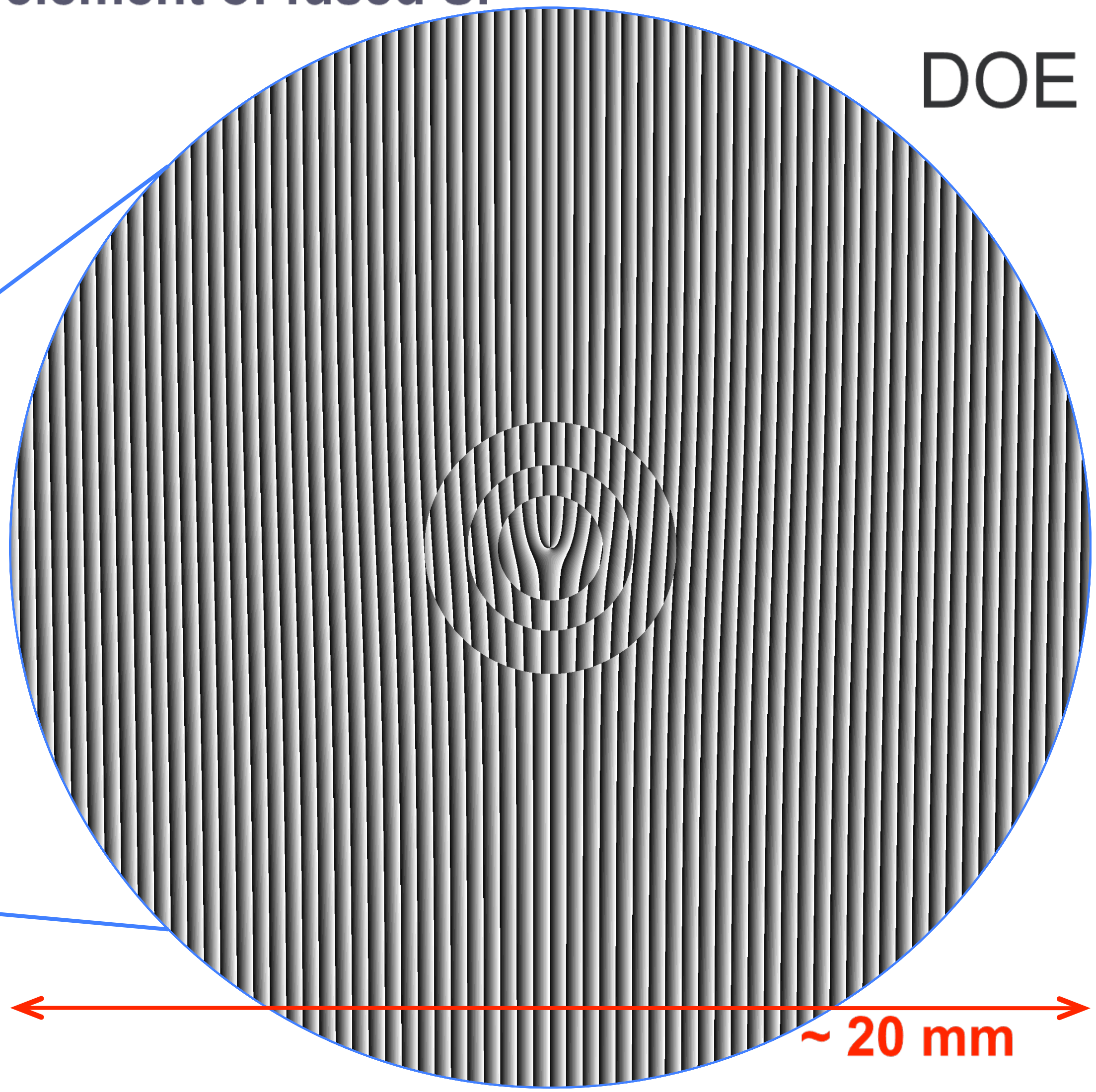


M. Granata et al. GWADW 2010

Generation of LG modes

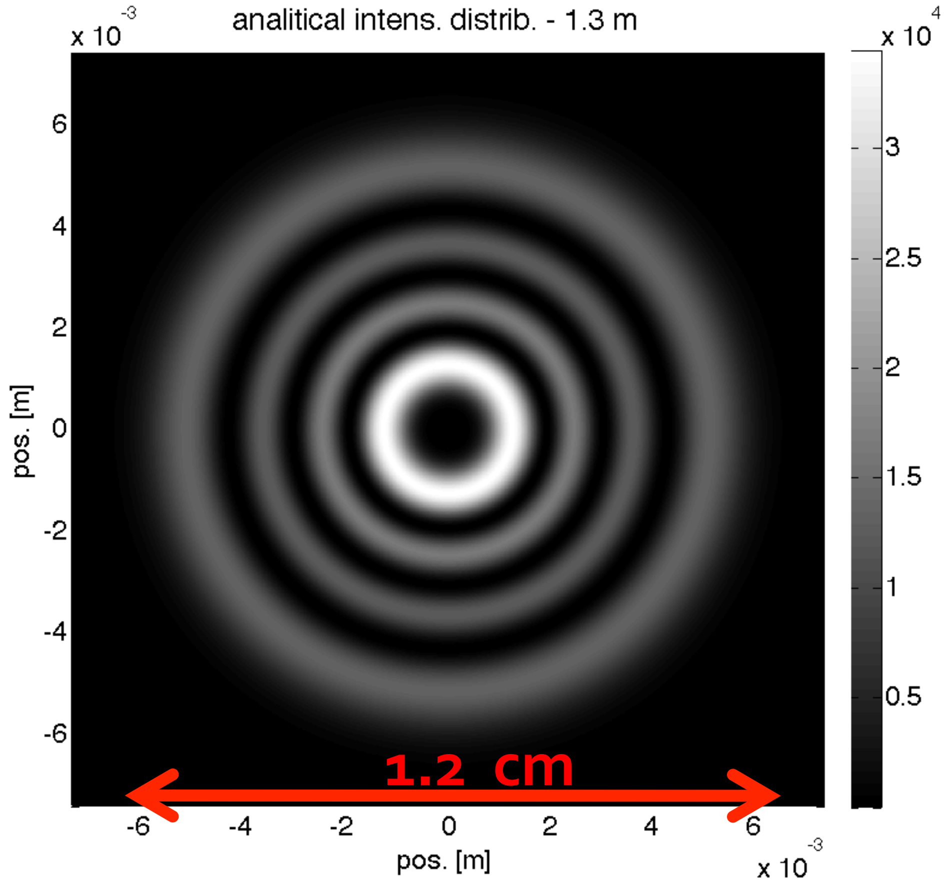
- **single transmission blazed element of fused Si**
  - 2400*2400 pixels
  - 1 pixel = 5.9 μm
  - 16 phase levels etched



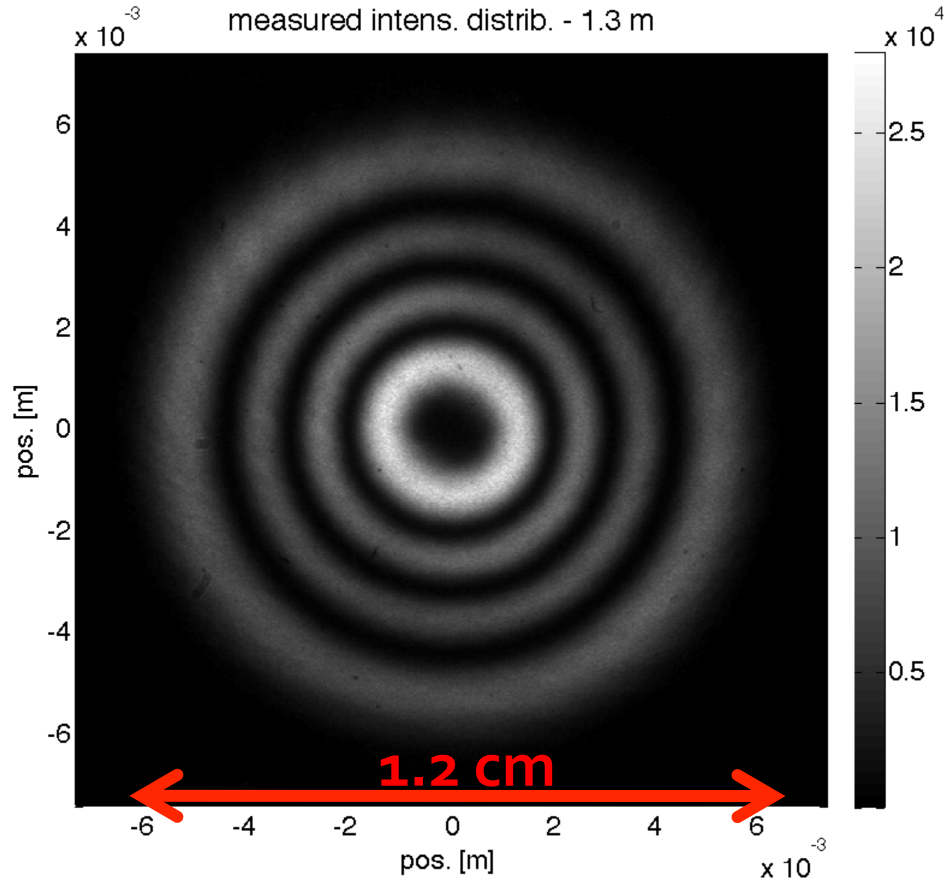


Generation of LG modes

LG33 - theory

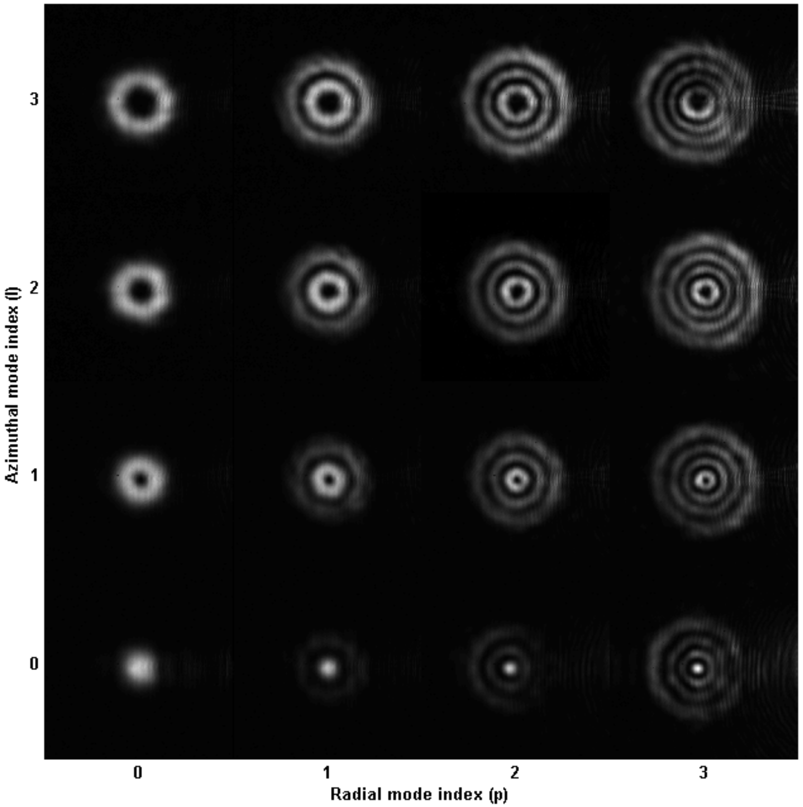


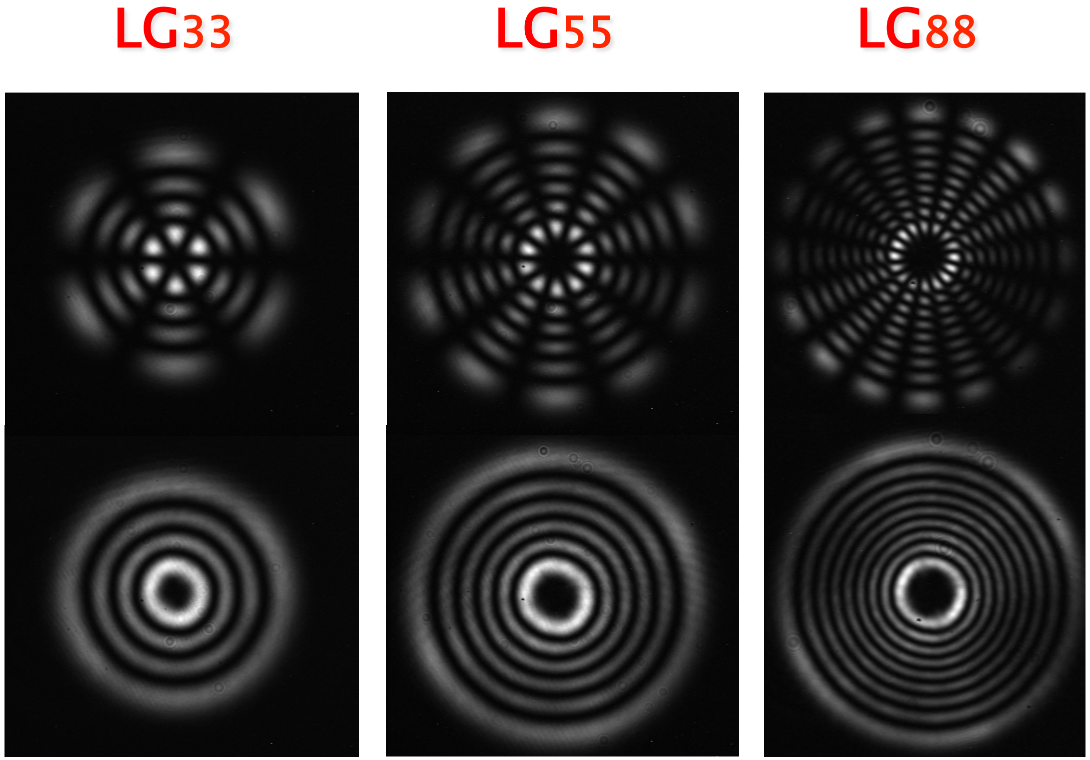
LG33 - measure



Transmitted beam (far field – 1.3 m)

More examples of generated LG beams





P. Fulda, A. Freise, Birmingham Univ.
GWADW, Kyoto, (2010)

CTN reduction: mechanical loss angle

- Existing coatings have excess mechanical dissipation, giving excess Brownian thermal noise
- New materials: Selection of new oxides and nitrides, optimization of the deposition parameters for optical and mechanical properties.
- Recent results suggest reduced dissipation via modified deposition and/or composition
  - high-temperature, ion assisted or low-rate deposition
  - Trinary (hybrid layer) designs
- If a factor of 4 lower dissipation can be achieved → a factor of 2 reduction in strain noise

Other technologies to improve sensitivity

- **Frequency dependent squeezing**
- **Newtonian Gravity Gradient Noise cancellation**

Gravity Gradient:
Seismic Isolation Shortcut

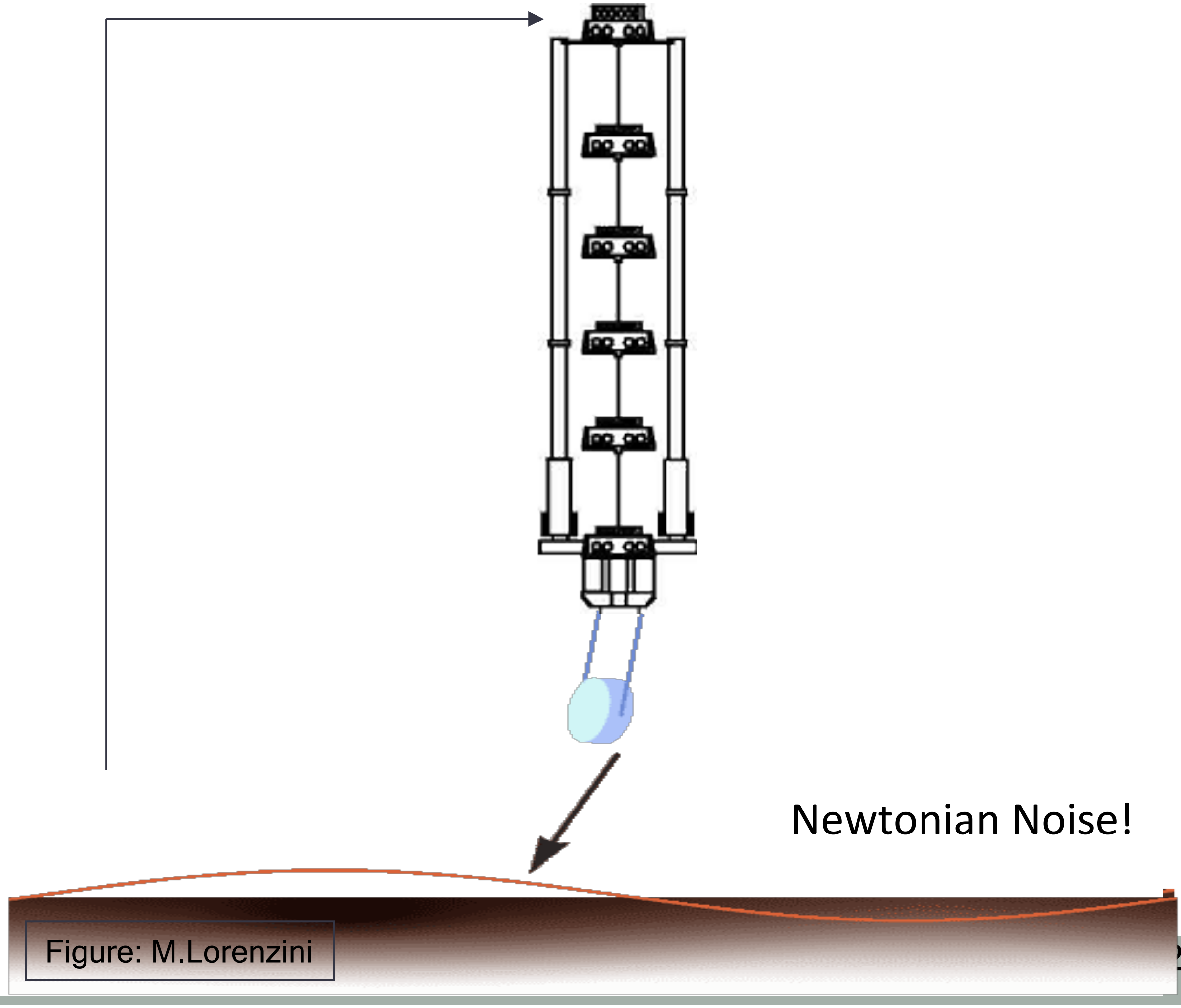
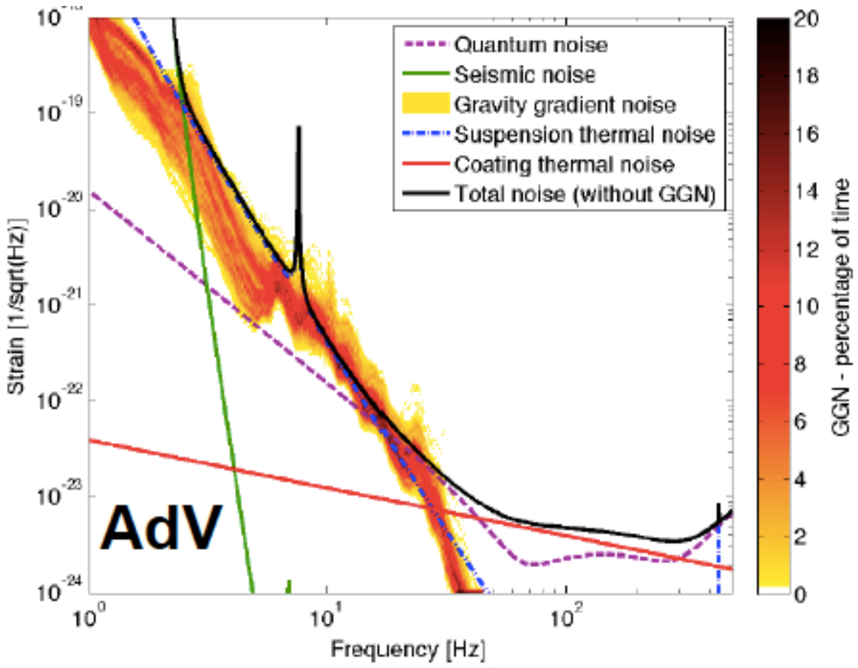


Figure: M.Lorenzini

Other technologies to improve sensitivity

- **Frequency dependent squeezing**
- **Newtonian Gravity Gradient Noise cancellation**

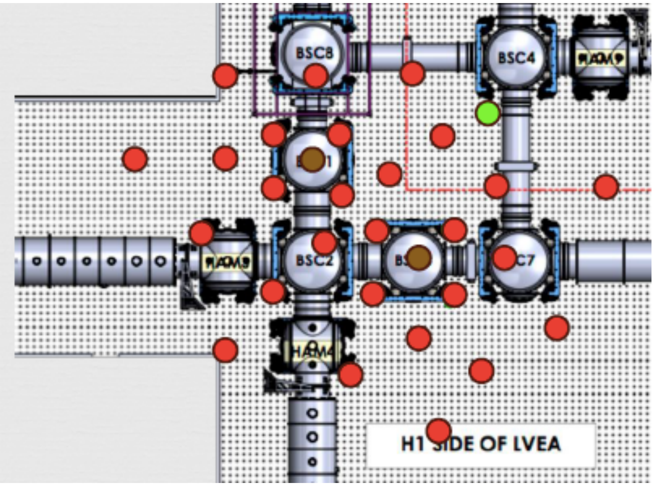
  - Advanced detectors
    - GGN starts to limit the sensitivity
    - Opportunity for measurement!



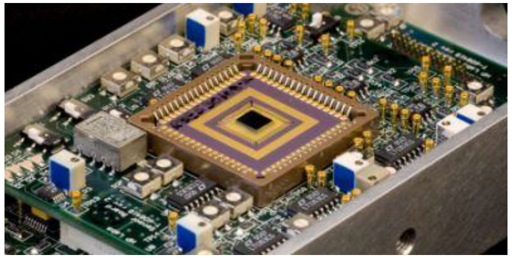
Other technologies to improve sensitivity

- **Frequency dependent squeezing**
- **Newtonian Gravity Gradient Noise cancellation**:
- Can be mitigated by modeling & subtracting local gravity fluctuations

  A detailed characterisation of the site to understand the seismic field in terms of its spectra and two-point spatial correlation, fundamental to the design of the seismic arrays for the purpose of noise cancellation.

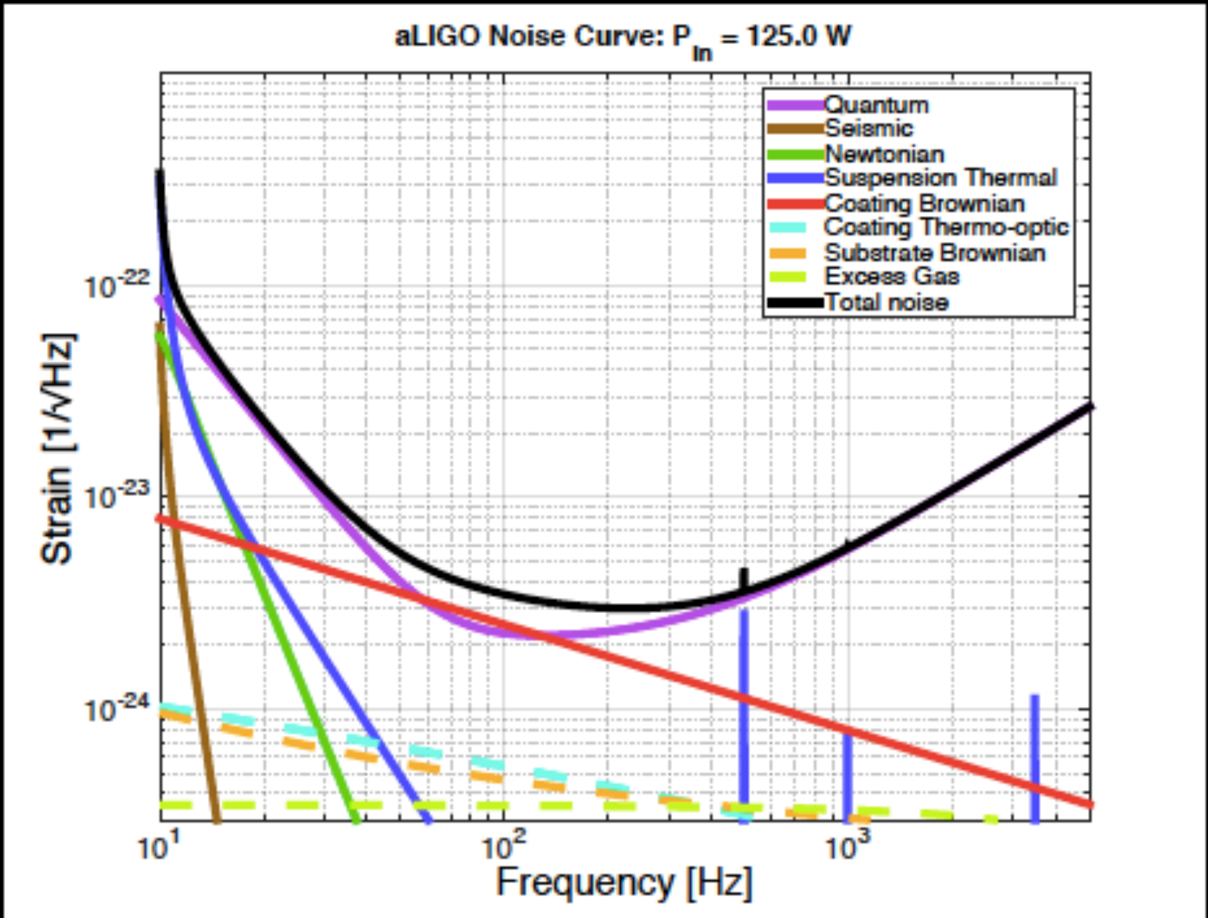


- Measurement of seismic noise with geophone sensors for NN cancellation
- Development of MEMS sensors and dedicated ASICs



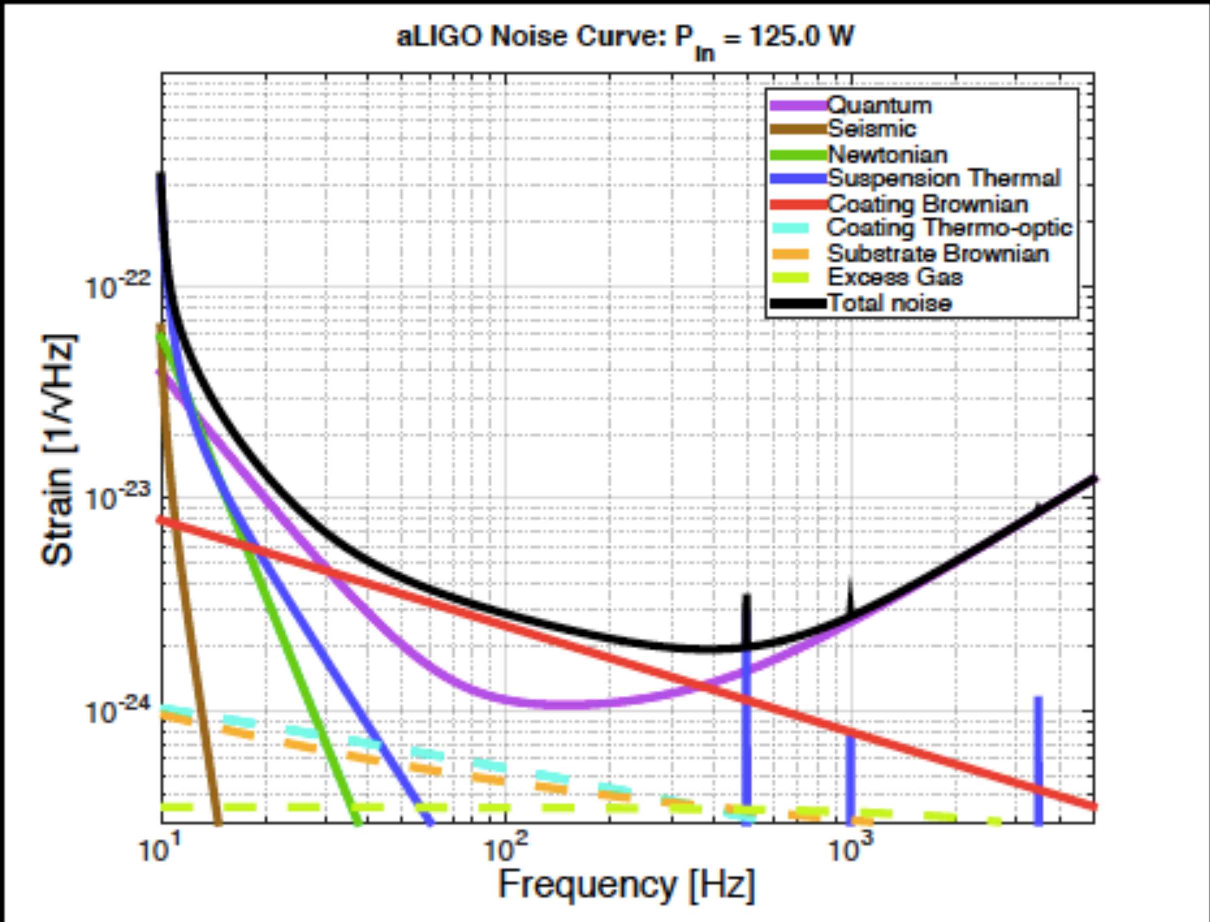
Example of sensitivity improvement

aLIGO operating at full power



Laser Power:	125.00 Watt
SRM Detuning:	0.00 degree
SRM transmission:	0.3500
ITM transmission:	0.0140
PRM transmission:	0.0300
Finesse:	446.41
Power Recycling Factor:	40.54
Arm power:	710.81 kW
Power on beam splitter:	5.07 kW
Thermal load on ITM:	0.385 W
Thermal load on BS:	0.051 W
BNS range:	191.04 Mpc (comoving)
BNS horizon:	436.32 Mpc (comoving)
BNS reach:	272.08 Mpc (comoving)
BBH range:	1.37 Gpc (comoving, z = 0.3)
BBH horizon:	3.24 Gpc (comoving, z = 0.9)
BBH reach:	2.12 Gpc (comoving, z = 0.5)
Stochastic Omega:	2.42e-09

..plus squeezing with ~100m scale filter cavity



Laser Power:	125.00 Watt
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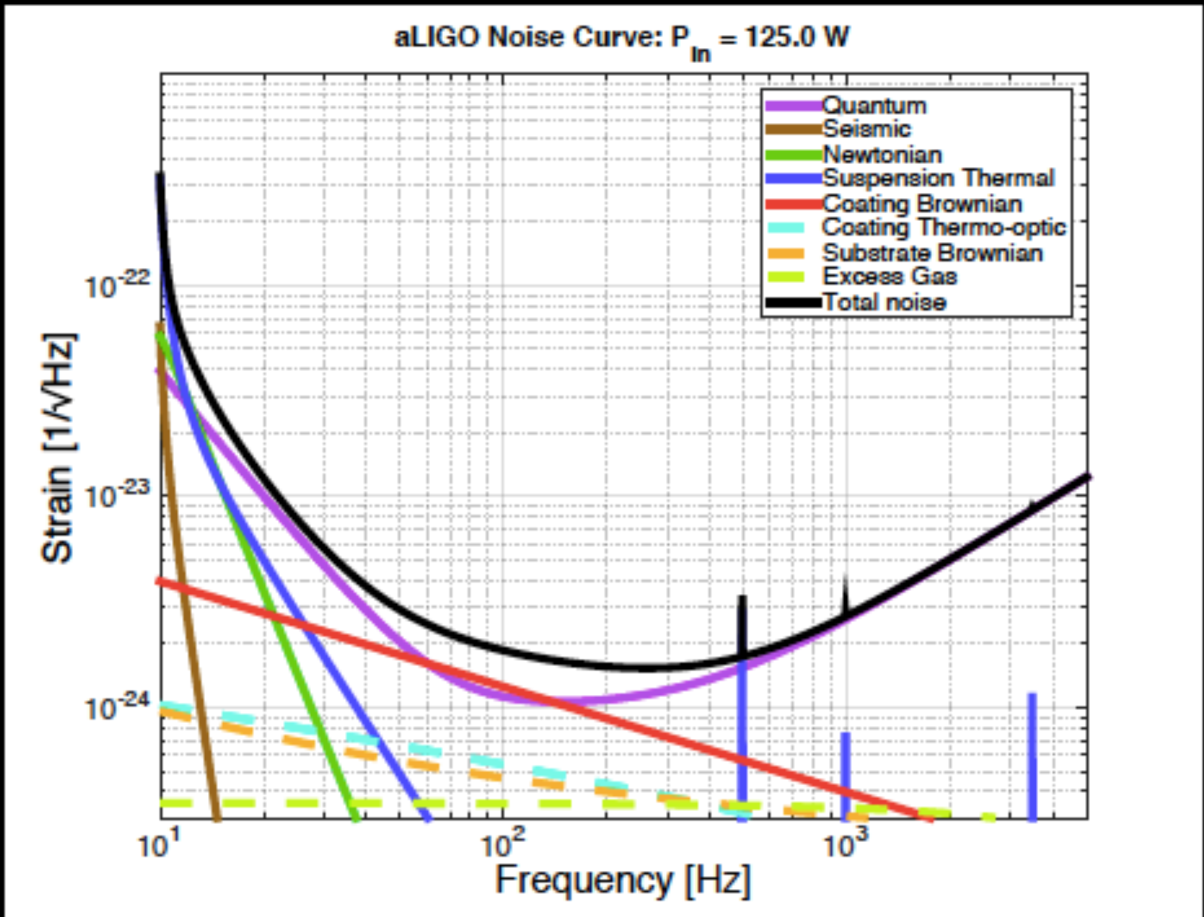
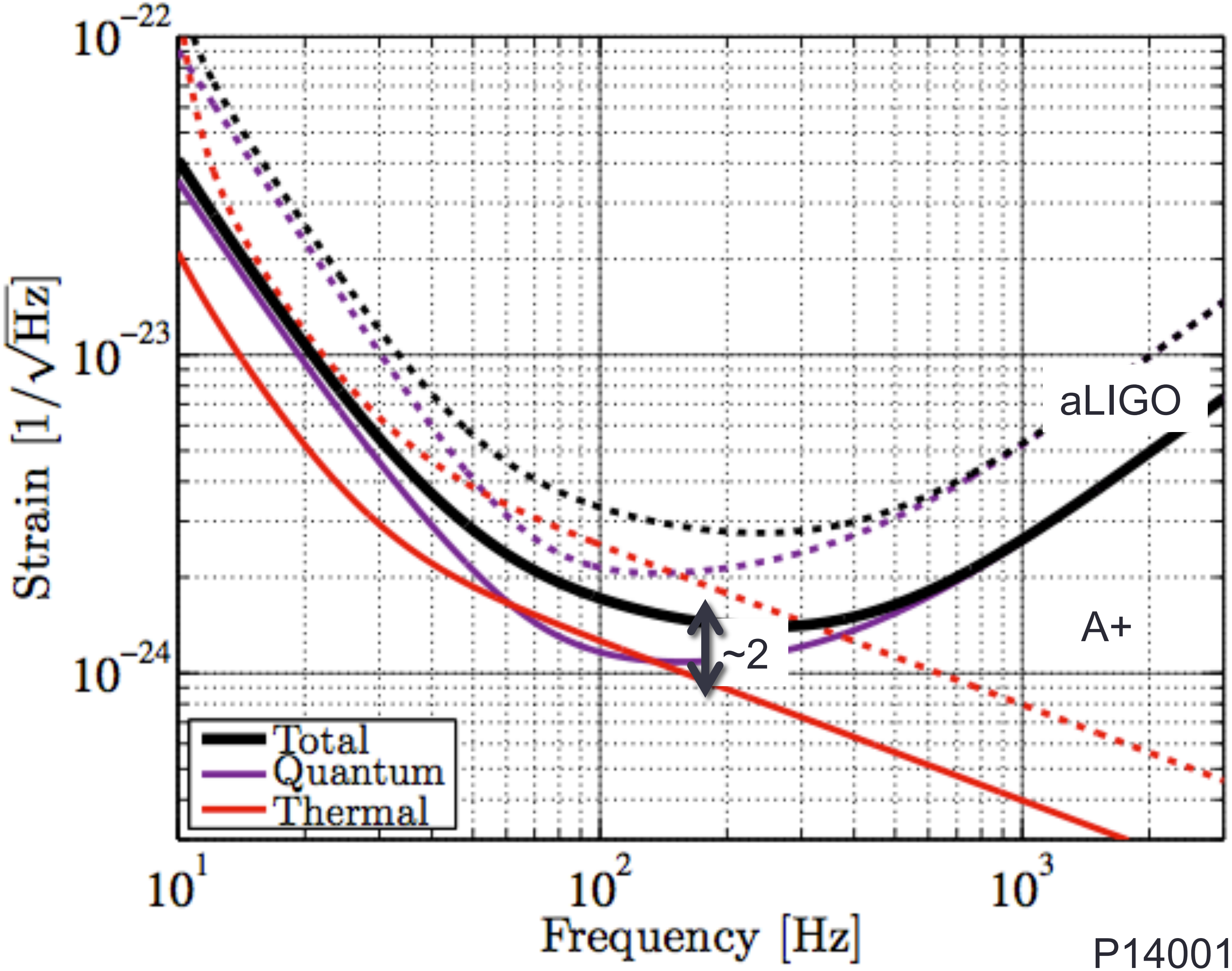
Power Recycling Factor:	40.54
Arm power:	710.81 kW
Power on beam splitter:	5.07 kW
Thermal load on ITM:	0.385 W
Thermal load on BS:	0.051 W
BNS range:	258.72 Mpc (comoving)
BNS horizon:	592.49 Mpc (comoving)
BNS reach:	370.29 Mpc (comoving)
BBH range:	1.74 Gpc (comoving, z = 0.4)
BBH horizon:	4.14 Gpc (comoving, z = 1.3)
BBH reach:	2.77 Gpc (comoving, z = 0.8)
Stochastic Omega:	9.32e-10

..plus coating thermal noise reduction



Laser Power:	125.00 Watt
SRM Detuning:	0.00 degree
SRM transmission:	0.3500
ITM transmission:	0.0140
PRM transmission:	0.0300
Finesse:	446.41
Power Recycling Factor:	40.54
Arm power:	710.81 kW
Power on beam splitter:	5.07 kW
Thermal load on ITM:	0.385 W
Thermal load on BS:	0.051 W
BNS range:	354.06 Mpc (comoving)
BNS horizon:	814.04 Mpc (comoving)
BNS reach:	510.28 Mpc (comoving)
BBH range:	2.24 Gpc (comoving, z = 0.6)
BBH horizon:	5395.58 Mpc (comoving, z = 2.1)
BBH reach:	3700.64 Mpc (comoving, z = 1.1)
Stochastic Omega:	6.78e-10

A+ Sensitivity



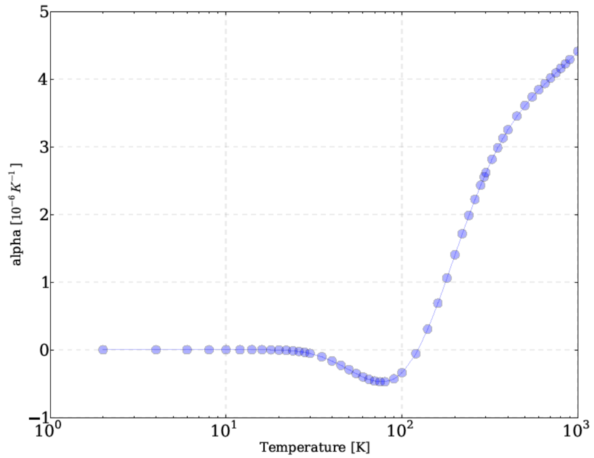
P1400164

Further exploiting existing infrastructures

- Example: Voyager
- This is a big step in a new direction (see LIGO T1400226)
  - "Low temperature" operation: 120K
  - new materials: Silicon
  - new wavelength: 1550nm
  - …
- Some large unknowns remain
- R&D here informs future detectors

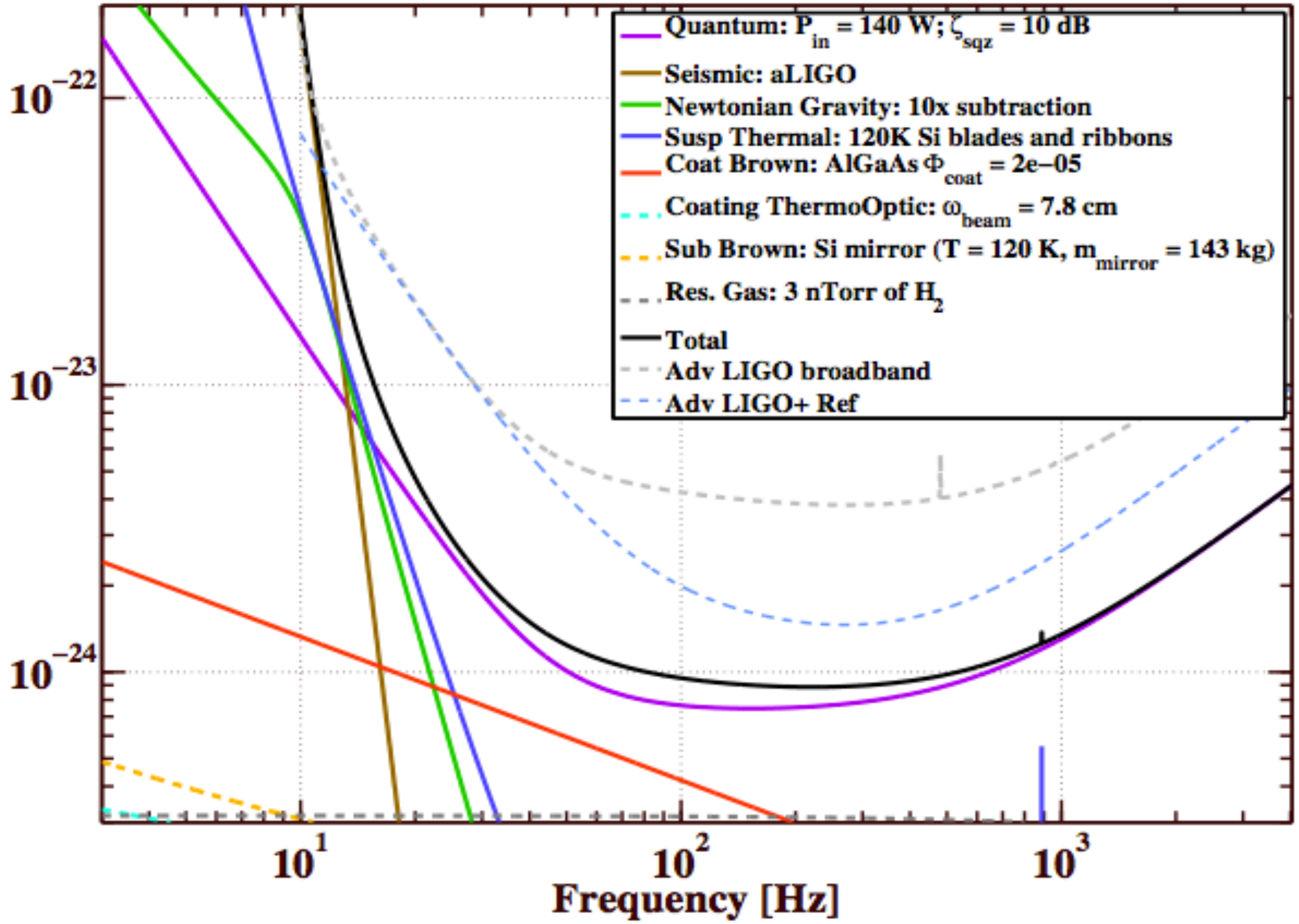
Why silicon? As with sapphire:
- No cryogenic loss peak
- High thermal conductivity
- Thermal expansion coeff $\alpha \rightarrow 0$ for T ~ 120 K
- Thermal deformation and thermoelastic noise both vanish
- Minimal thermal lensing +
- Minimal cryo @ 120 K

=> Opportunity for high power



Further exploiting existing infrastructures

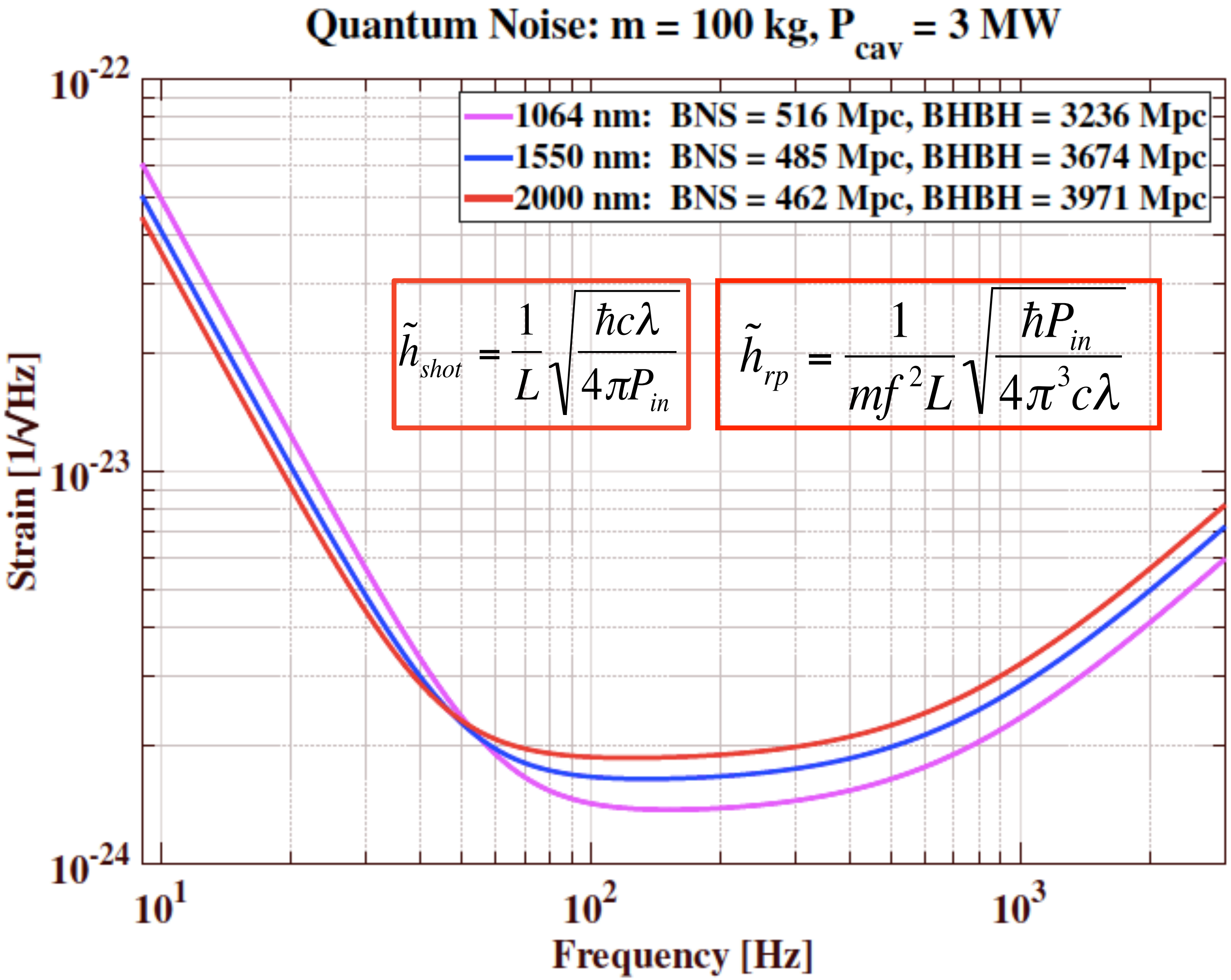
- Example: Voyager



More R&D needed

- Silicon Test Masses?
  - Bulk absorption, birefringence, uniformity of FZ Si
  - Bond loss for Si on Si: ears, ribbons, etc.
  - Procurement? (Can we buy these with 40cm diameter?)
- Coatings for 1550nm and 120K… crystalline coatings?
- 1550 nm Sources?
  - Lasers and input optics operating at 100 - 250 W
  - Audio band and frequency dependent squeezing

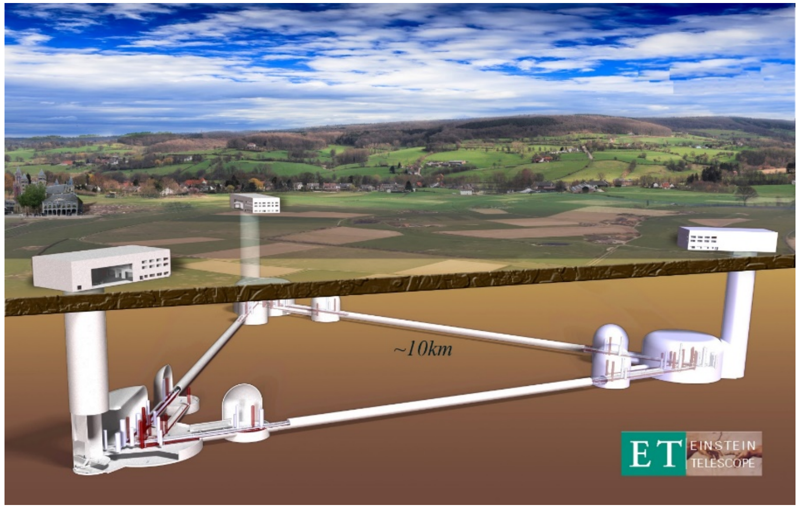
More R&D needed



1 MW @ 1064 nm ~ 2 MW @ 2128 nm

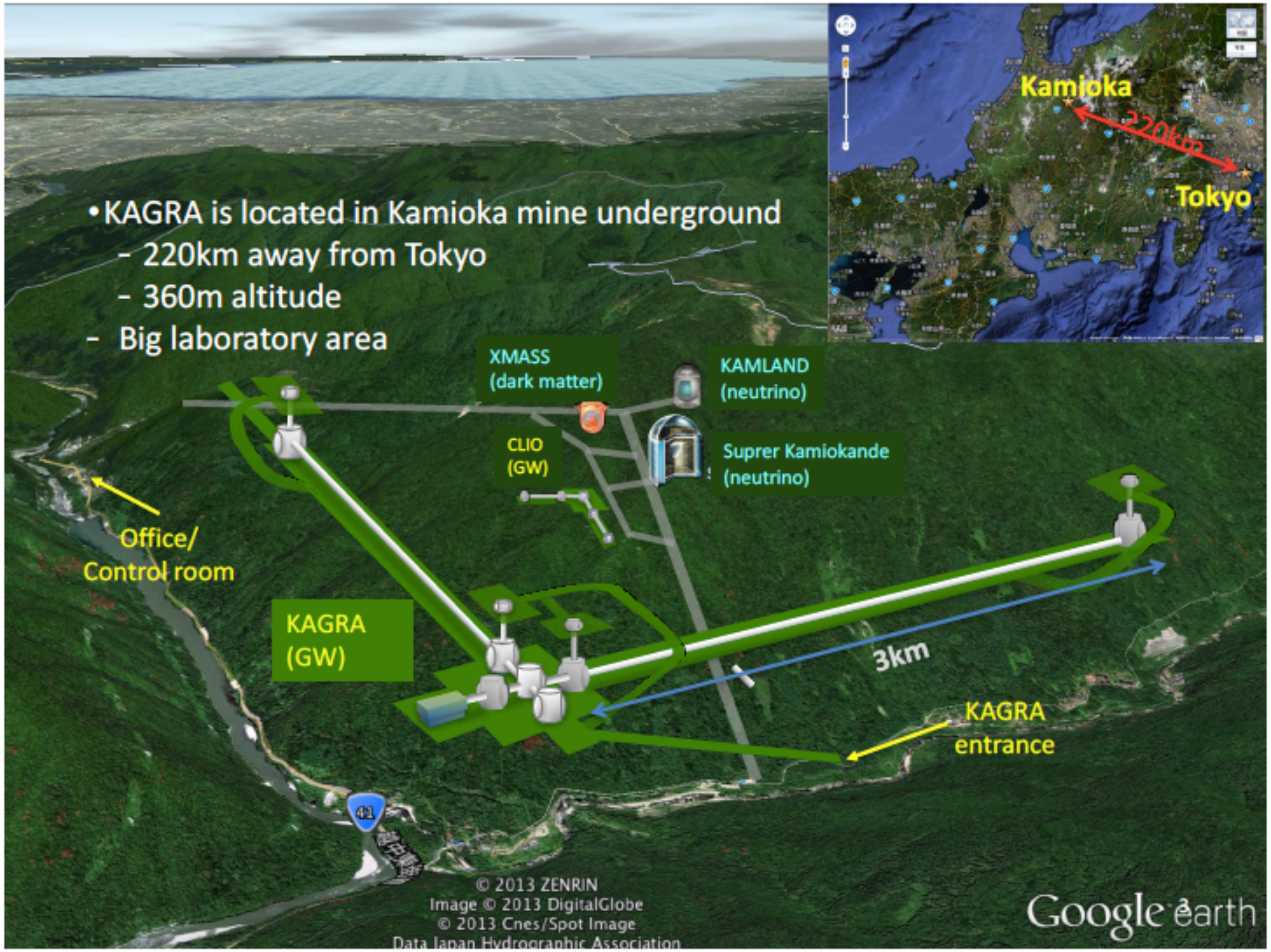
And what next?
3G: Einstein Telescope

- GW detectors will soon face the limits of their hosting infrastructures
- The idea of a 3G detector has been pioneered in the last decade with the Einstein Telescope European project
  - A 3G GW **observatory**:
    - Underground & Cryogenic
    - Multi-detector (capable to resolve the GW polarisations)
    - Multi-interferometer (Xylophone design)
    - x 10 gain in sensitivity with special focus on the «low» frequency band



Proposed to be operative in >2030

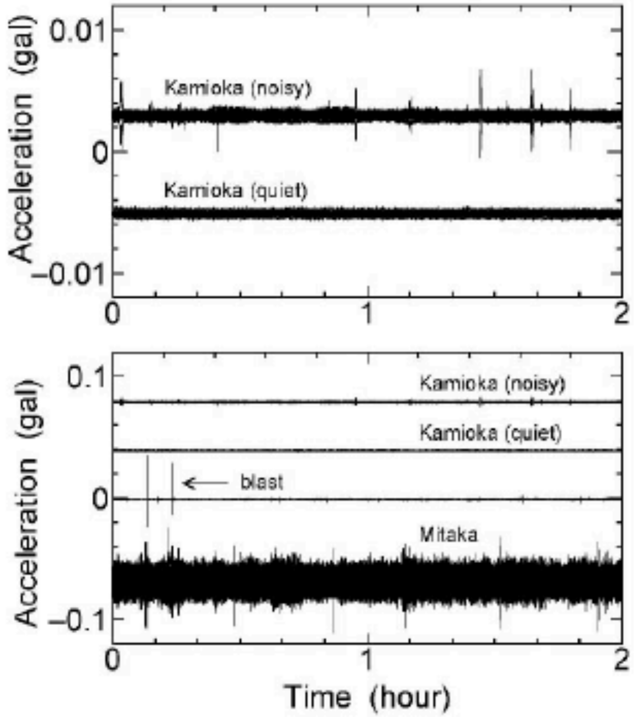
A precursor: KAGRA - 2.5 generation ITF

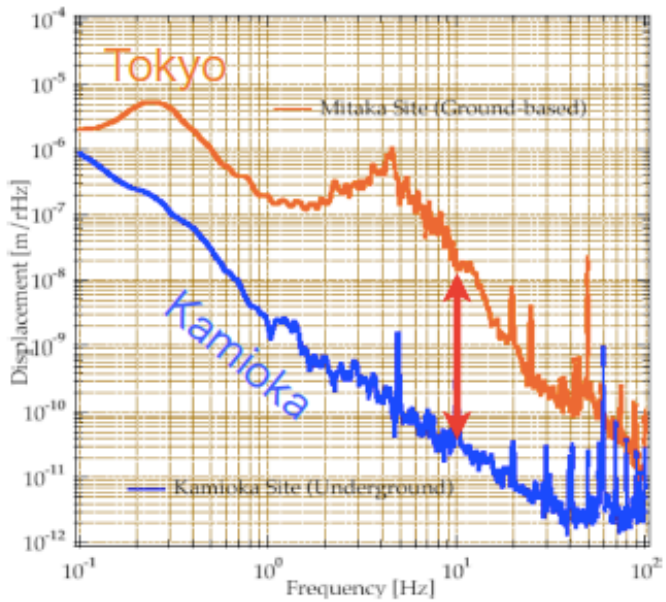


A precursor: KAGRA - 2.5 generation ITF

KAGRA

Quiet underground site



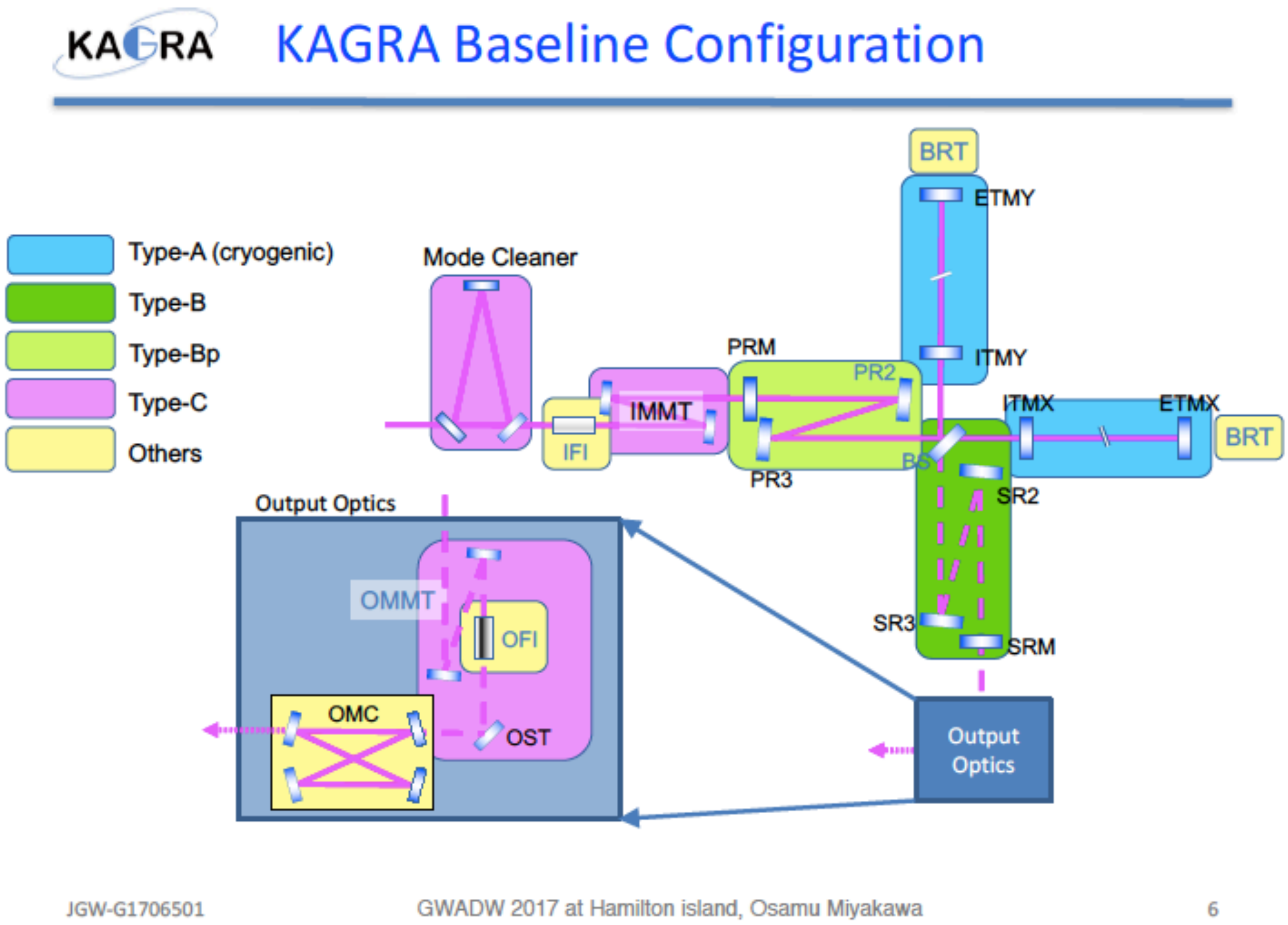


Amplitude of seismic motion

- Surrounded by hard rock (Hida-gneiss)
  - 5 km/sec sound speed

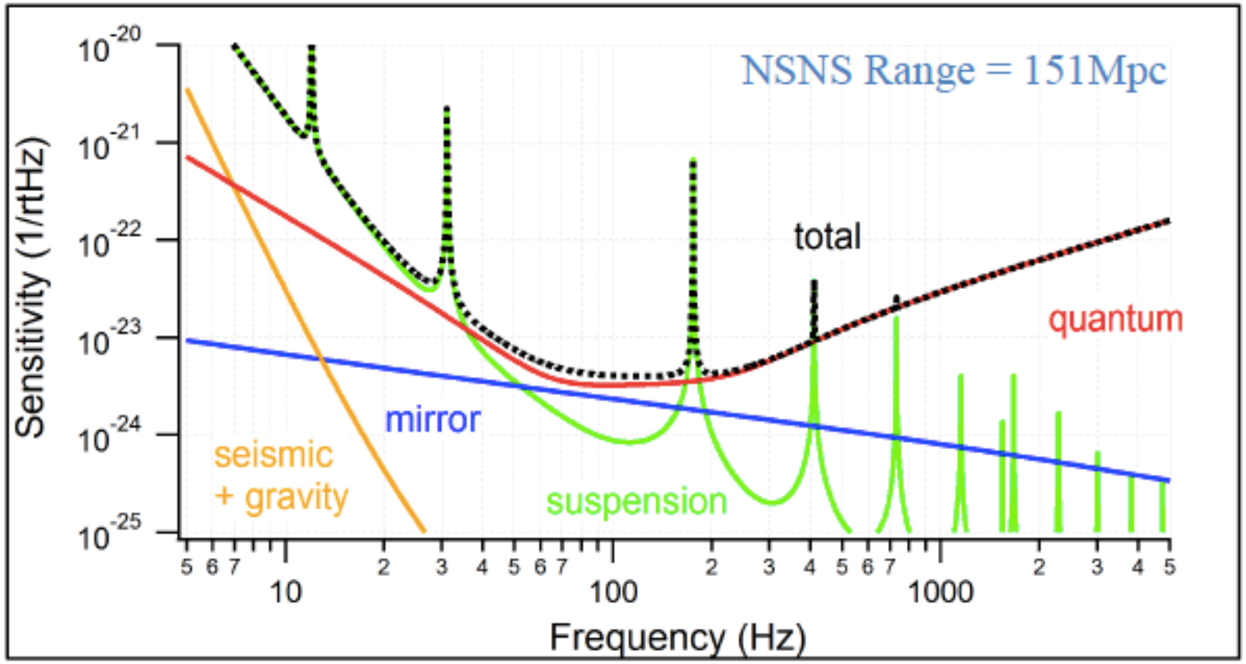
JGW-G1706501 GWADW 2017 at Hamilton island, Osamu Miyakawa 4

A precursor: KAGRA - 2.5 generation ITF



A precursor: KAGRA - 2.5 generation ITF

KAGRA Baseline Sensitivity



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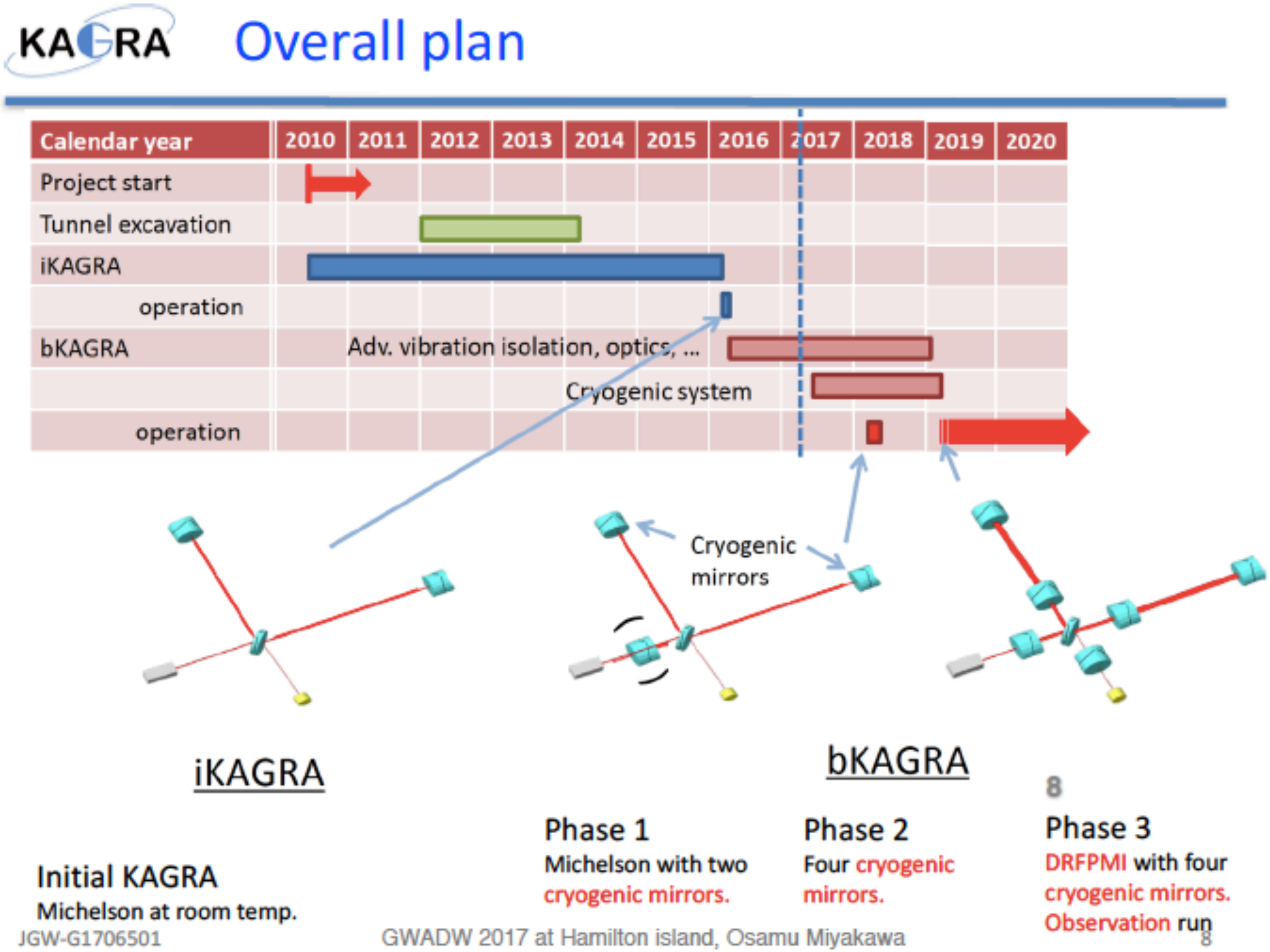
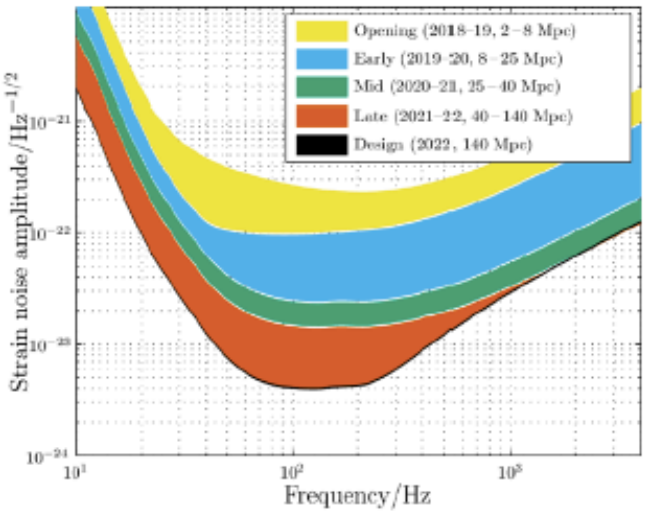
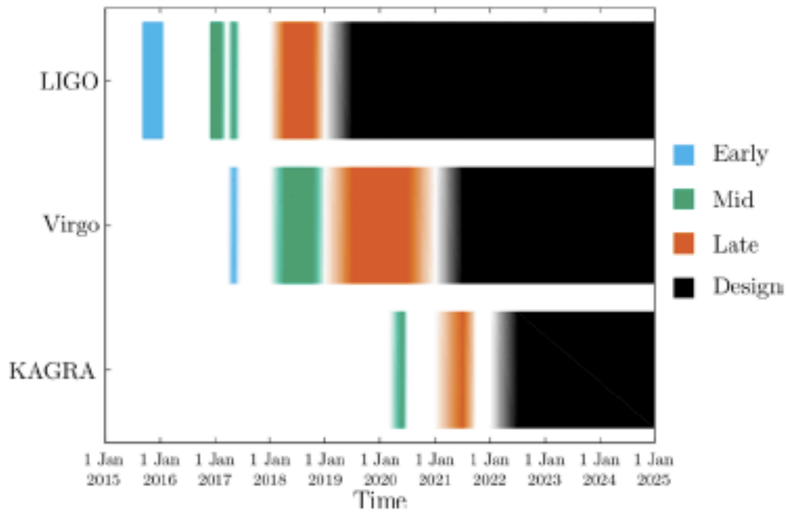
A precursor: KAGRA - 2.5 generation ITF



A precursor: KAGRA - 2.5 generation ITF

KAGRA Observation Scenario (Under discussion)





- Binary neutron-star range:
  With 25-40 Mpc in 2020, 40-140 Mpc in 2021

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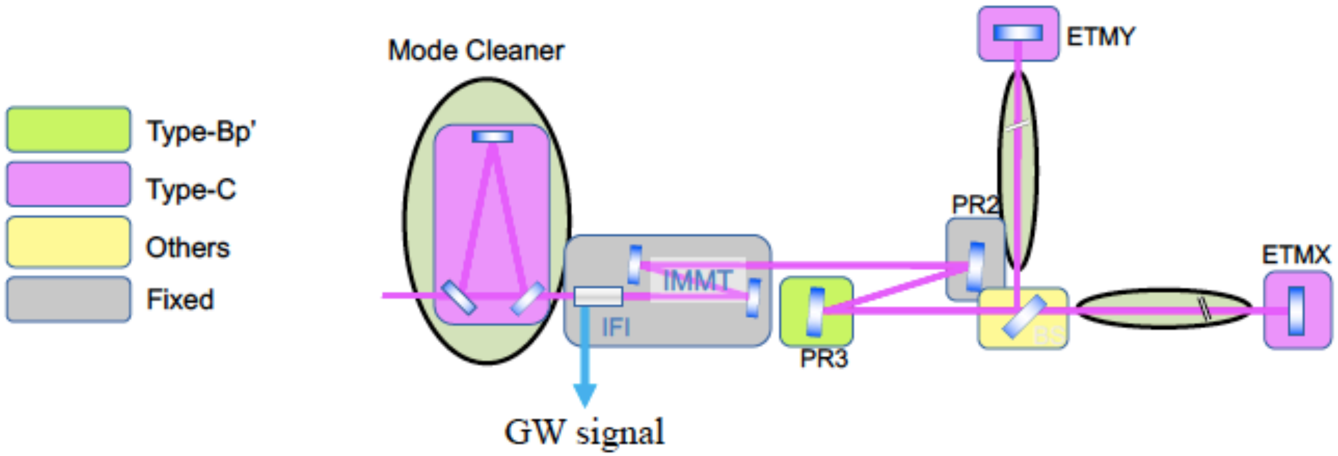
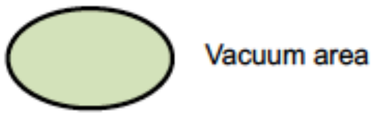
A precursor: KAGRA - 2.5 generation ITF

Initial KAGRA (iKAGRA)



- Michelson (mid-fringe lock -> RF readout)
- Room Temperature
- Temporary Suspensions
- Limited vacuum area
  - central part and both ends were at air
  - PR2-BS was not even connected



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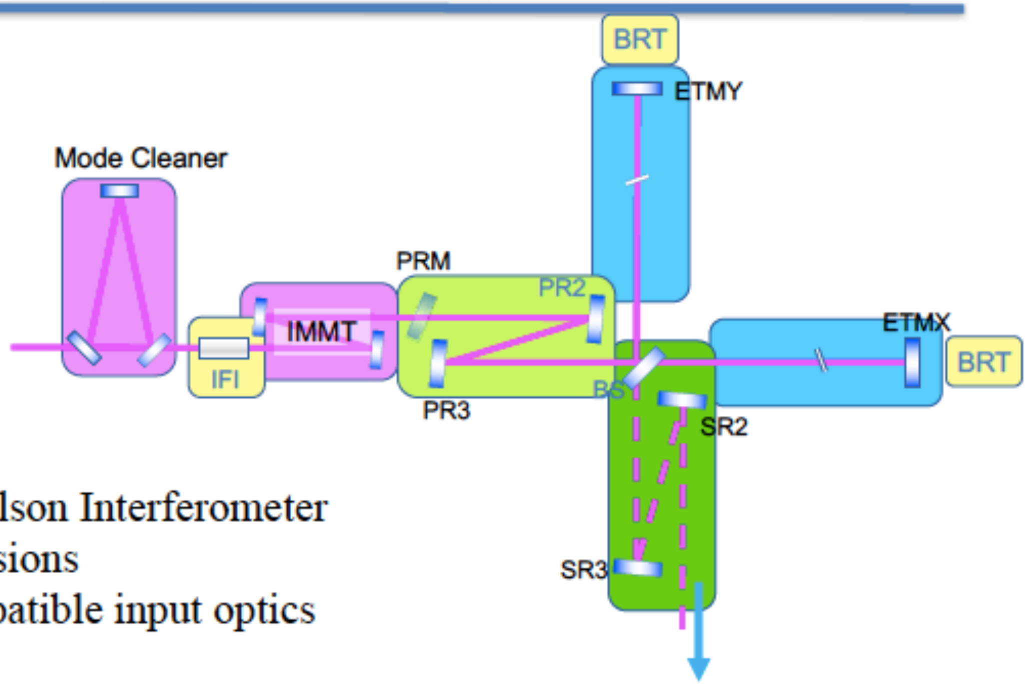
A precursor: KAGRA - 2.5 generation ITF

KAGRA bKAGRA phase 1



- Cryogenic Michelson Interferometer
- Full scale suspensions
- High power compatible input optics

Start operation by the end of March 2018

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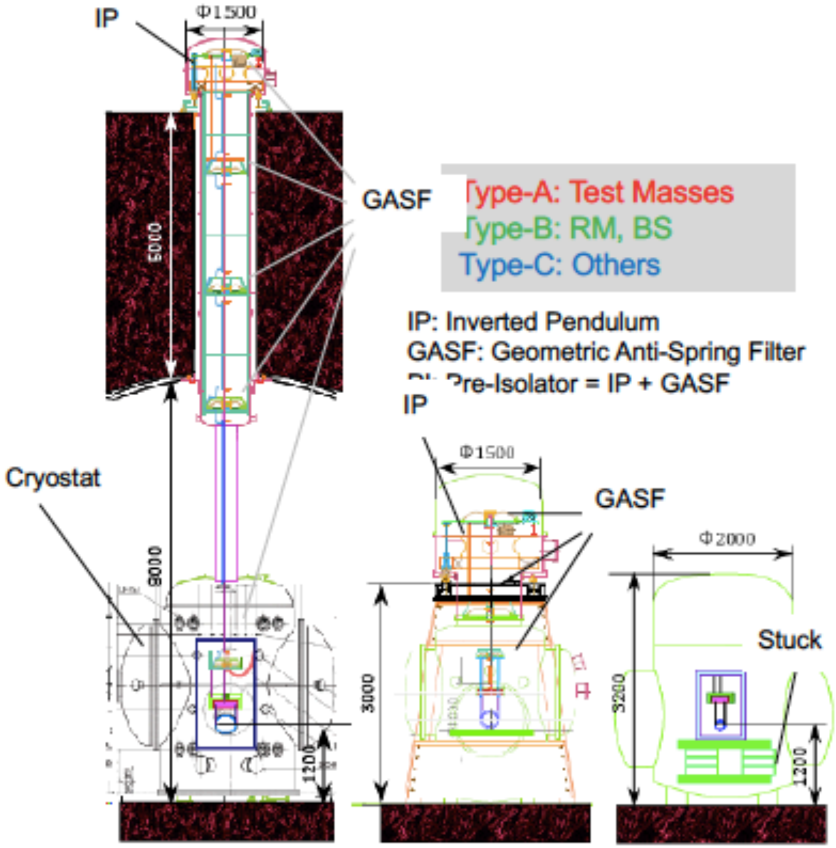
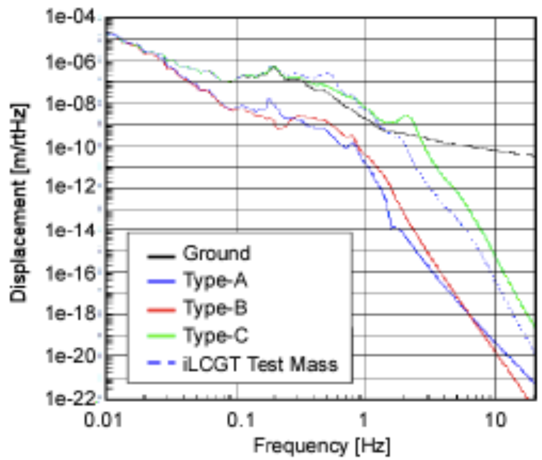
A precursor: KAGRA - 2.5 generation ITF

KAGRA Vibration Isolation System





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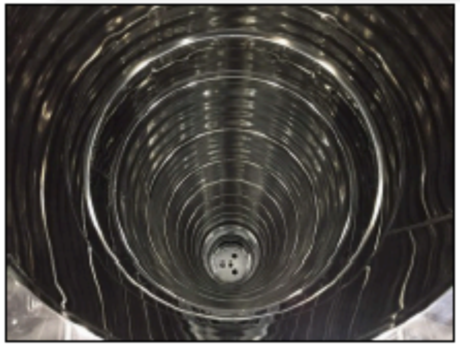
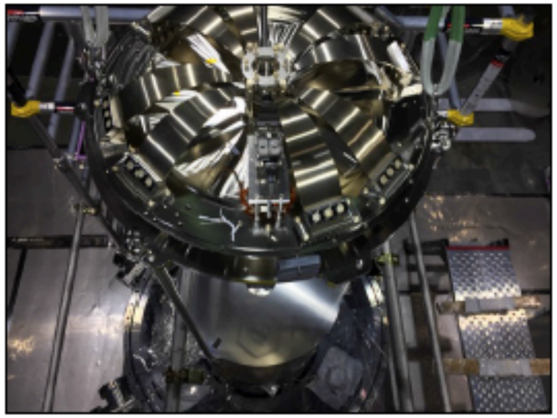
A precursor: KAGRA - 2.5 generation ITF

KAGRA Type-A Suspension Installation



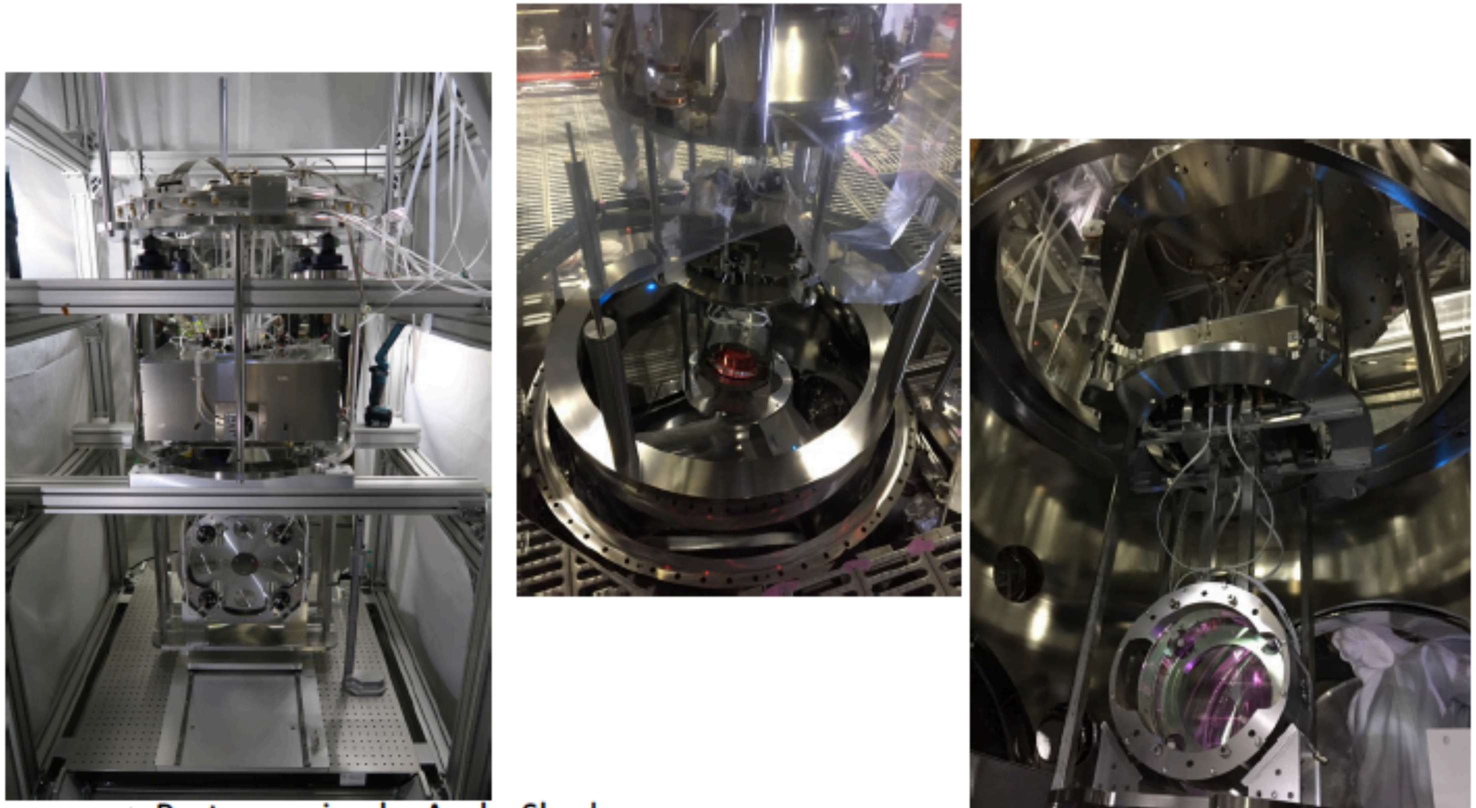


-> Koki Okutomi's talk on Thursday morning
"Controls of the KAGRA cryogenic vibration isolation system"

JGW-G1706501 GWADW 2017 at Hamilton island, Osamu Mi...

A precursor: KAGRA - 2.5 generation ITF

KAGRA **BS and PR Suspensions**



-> Poster session by Ayaka Shoda
"Controls of the KAGRA power recycling mirror suspensions"

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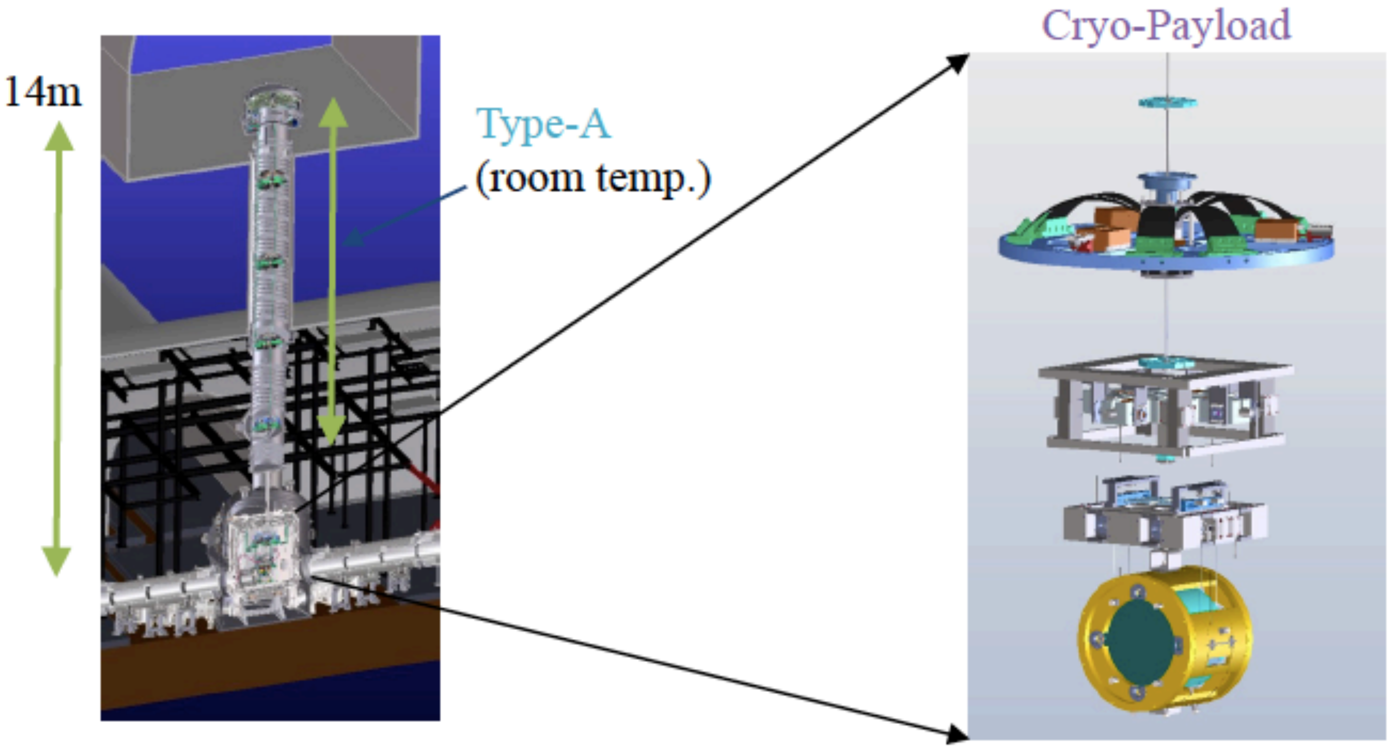
A precursor: KAGRA - 2.5 generation ITF

KAGRA Type-A + Cryogenic Suspension



-> Takafumi Ushiba's talk for cryo-payload on Wednesday morning.

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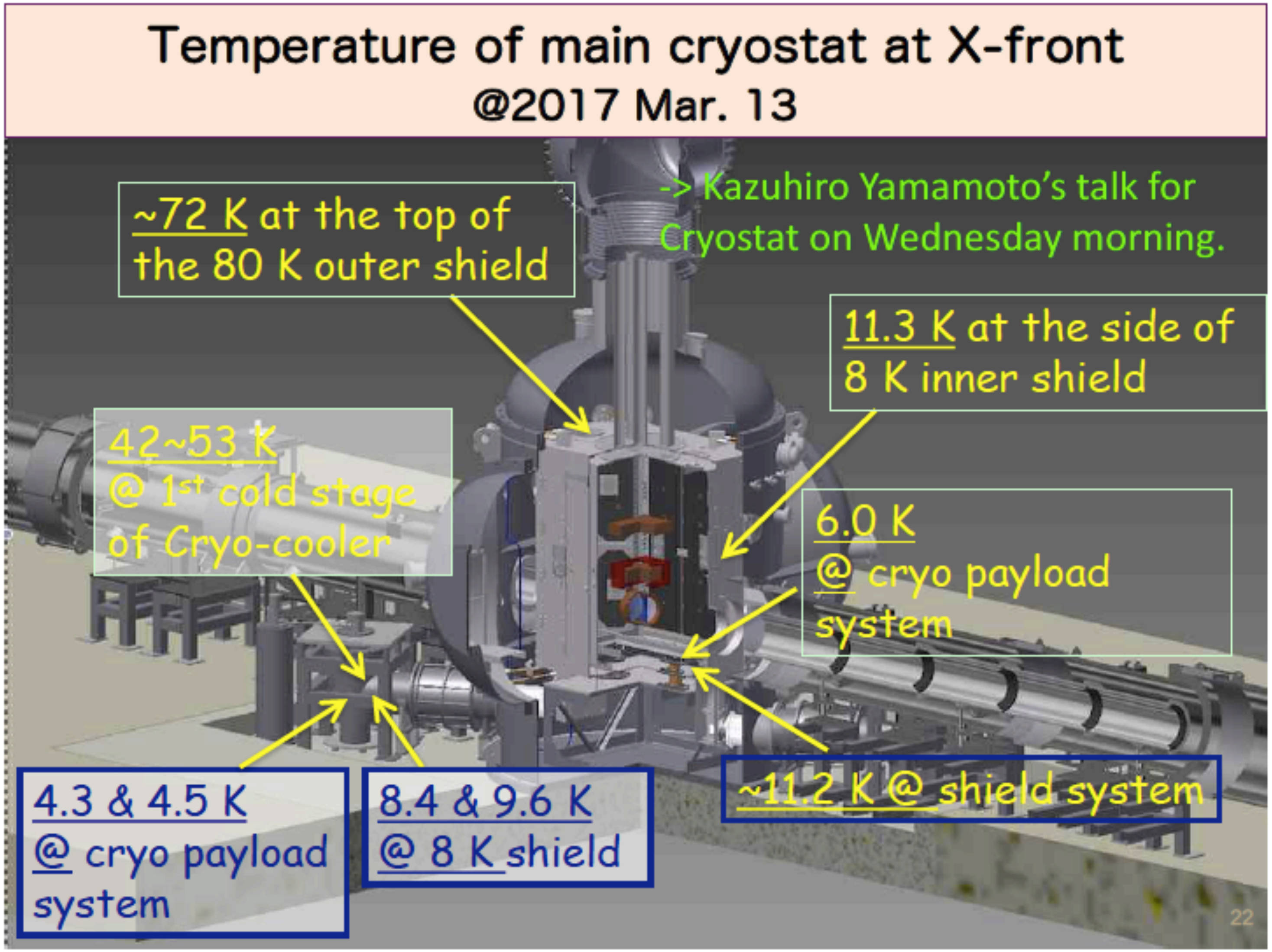
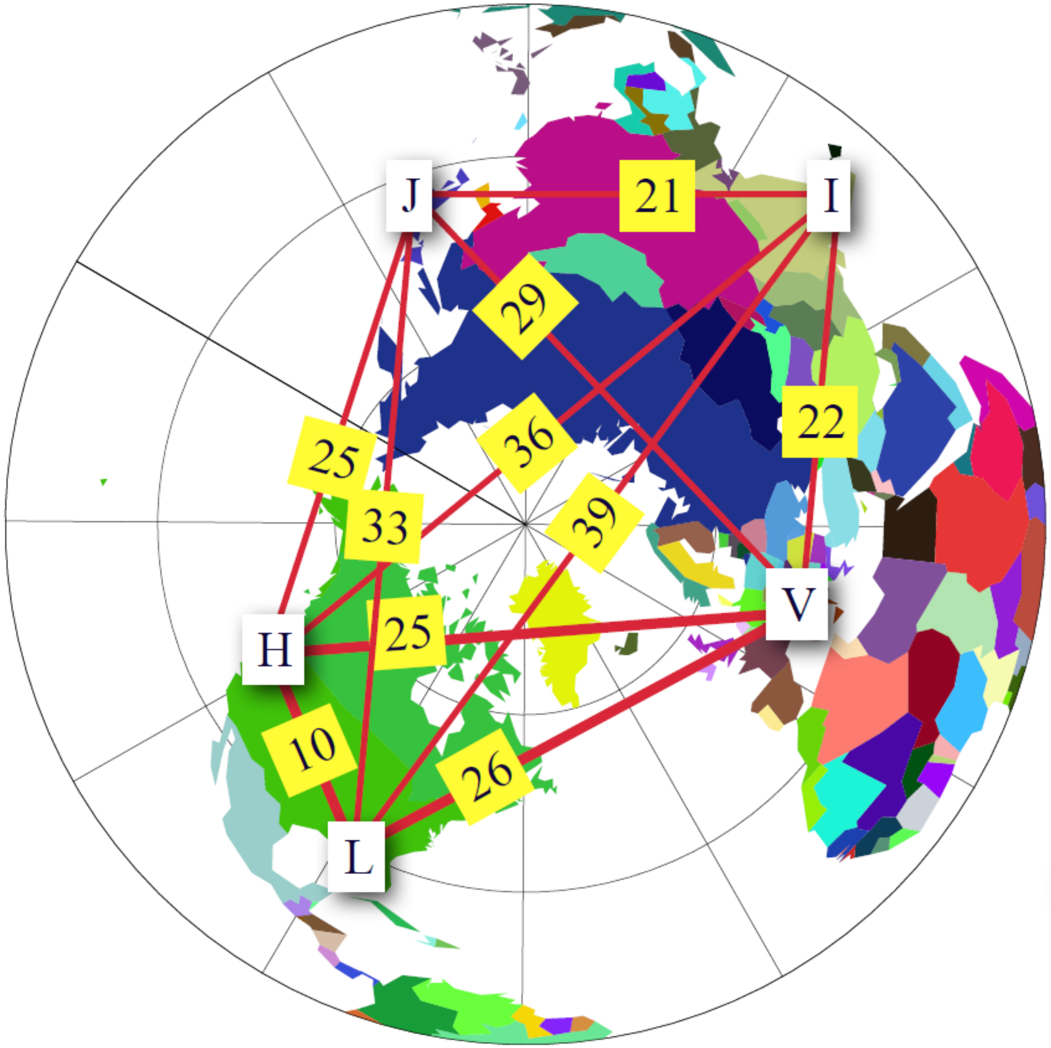
A precursor: KAGRA - 2.5 generation ITF



Ground-based Detectors

Advanced detectors 2016-2025 (…)

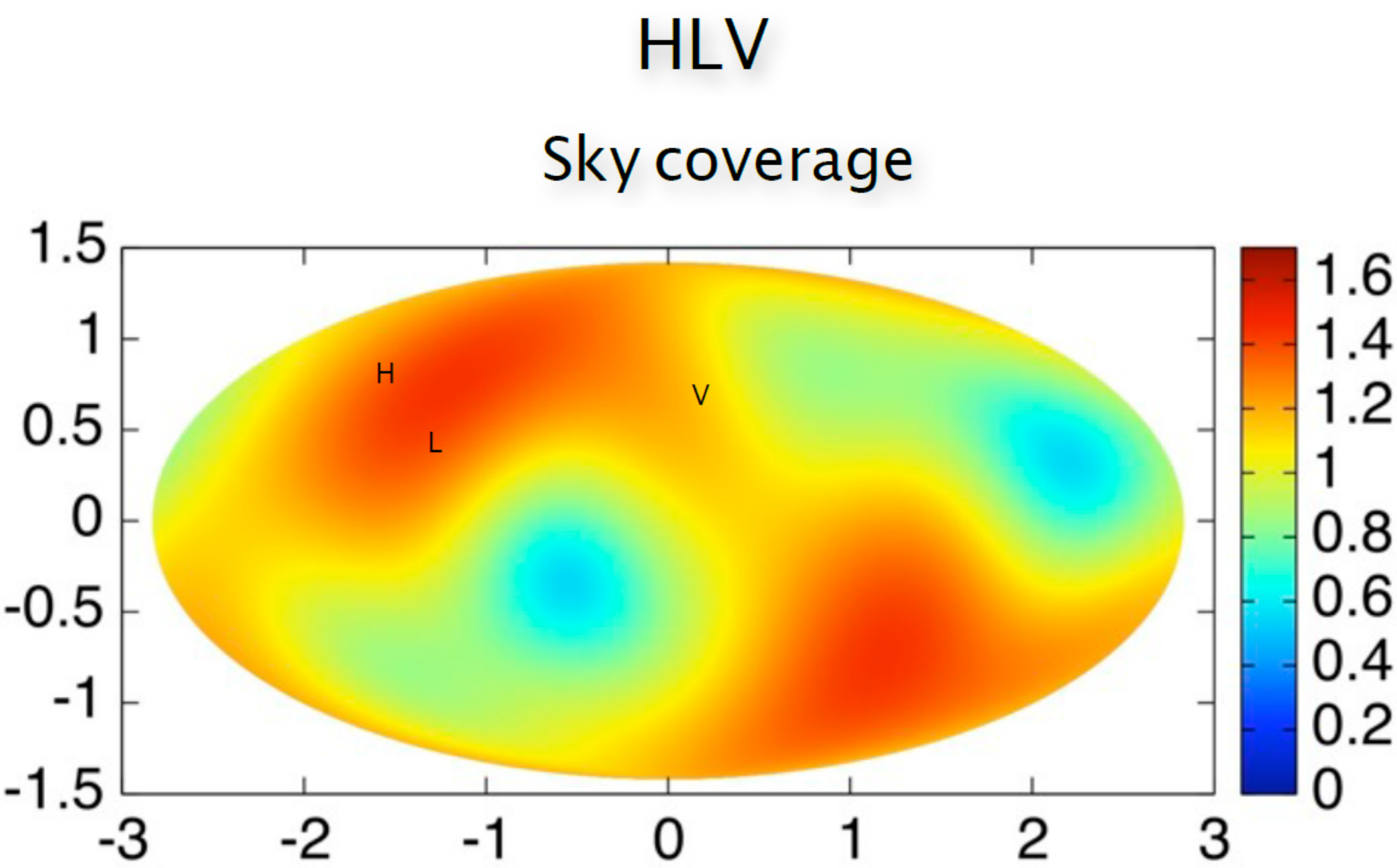
Network of advanced detectors



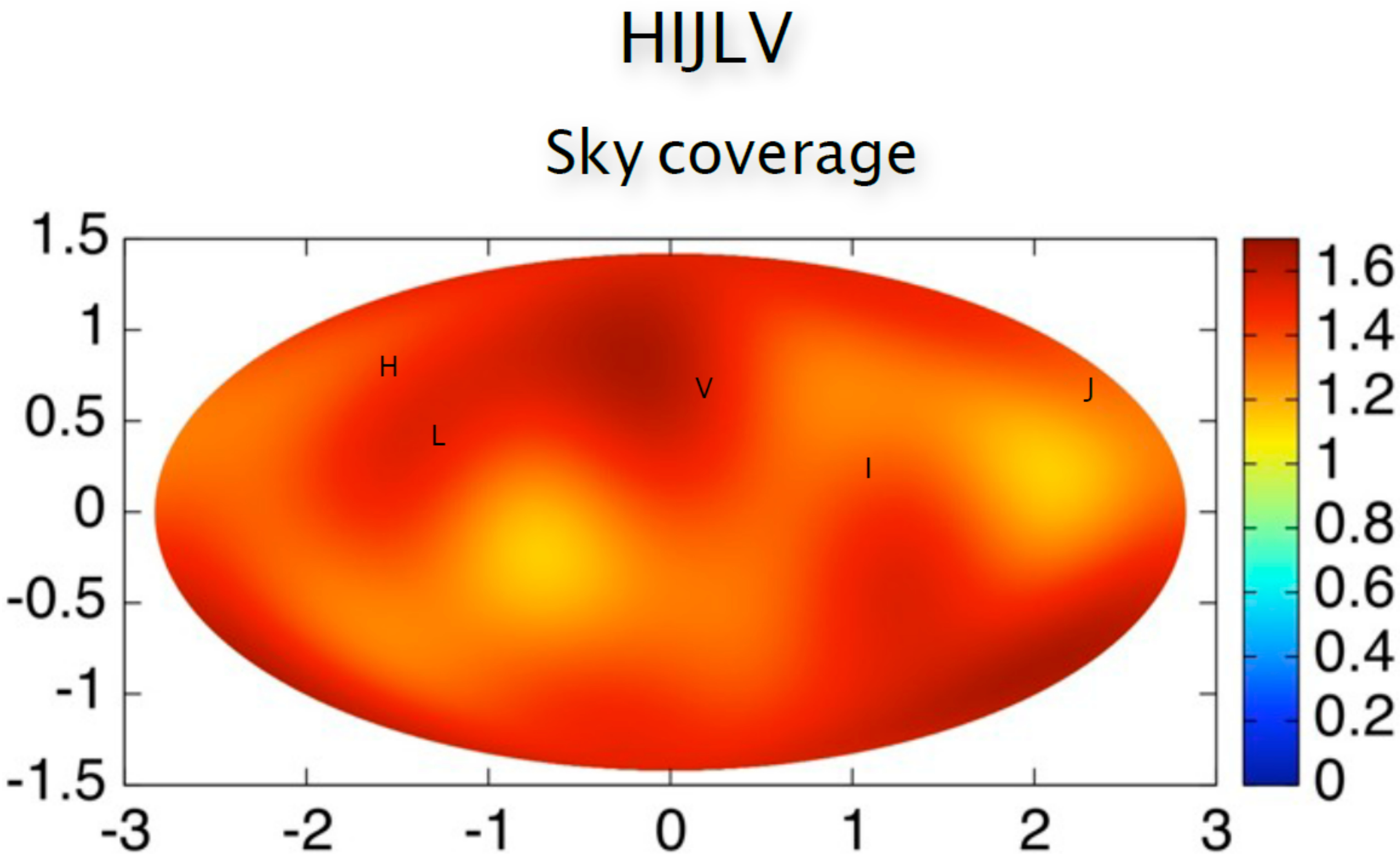
Detector Networks 2015-2025

Baselines in light travel time (ms)

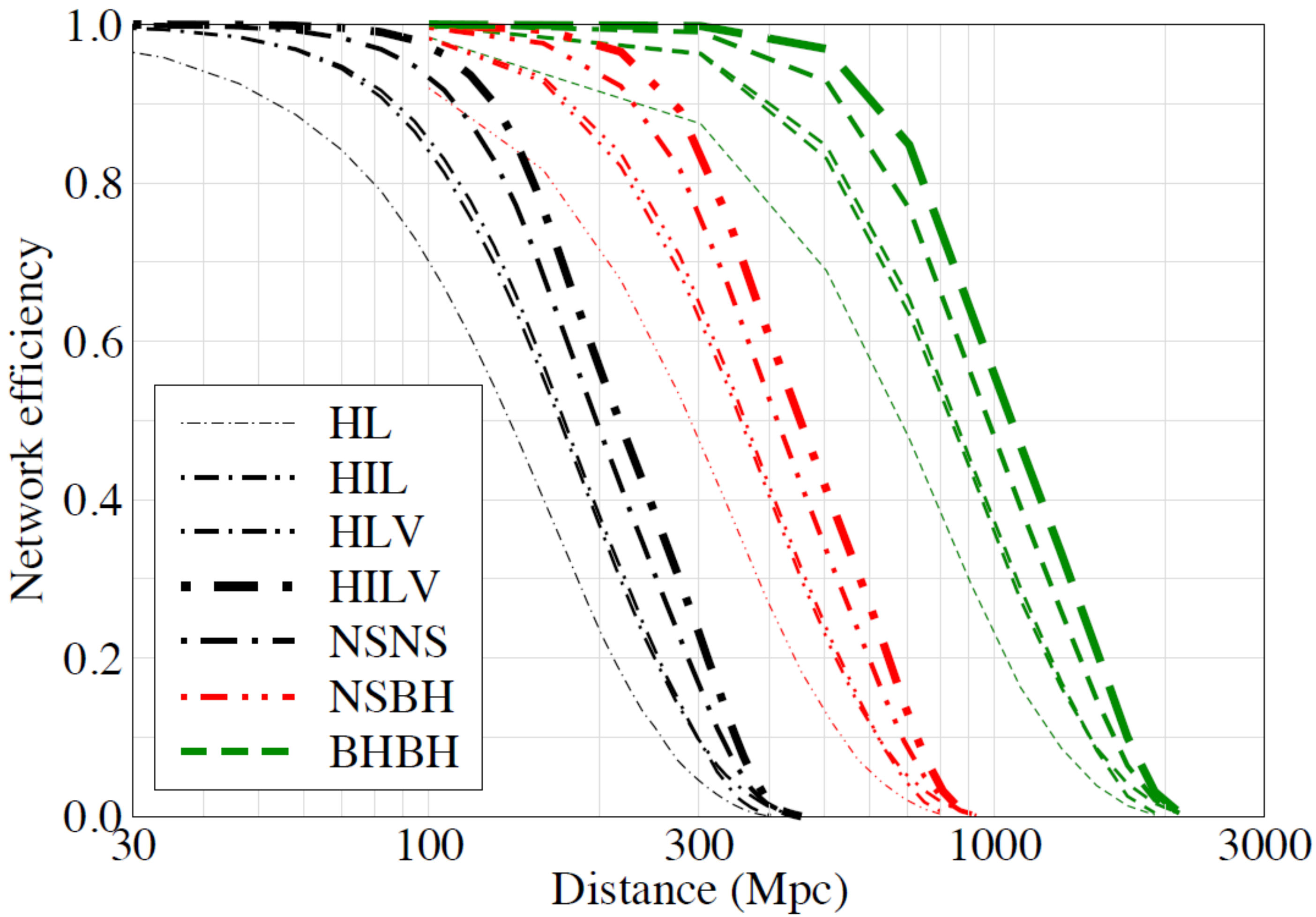
Sky coverage



Sky coverage



Network Efficiency

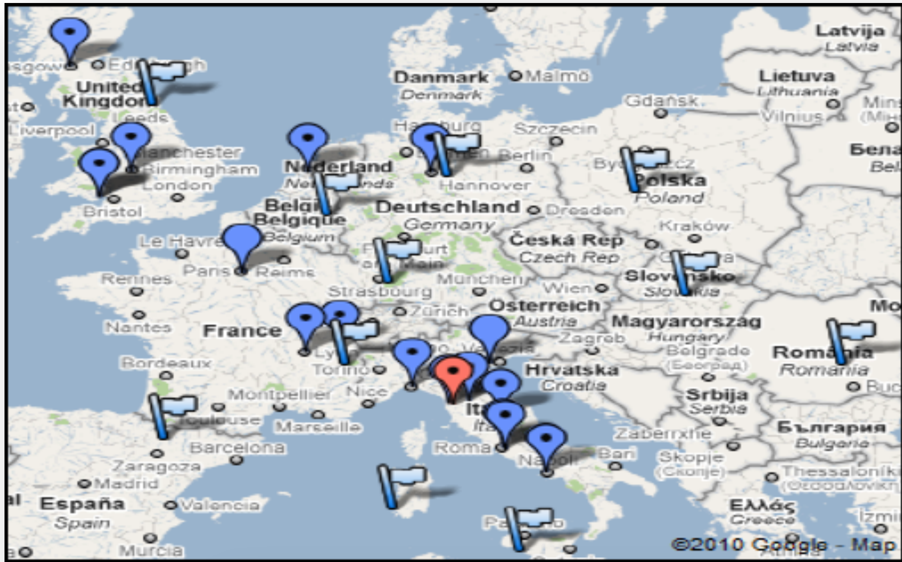


3Gs need new facilities

- Gains the in current facility are becoming increasingly challenging, and the current facilities are aging
- A new facility is a very long lead-time item… ~15 years!
- We need an effective design which uses mature technologies to define the facility infrastructure

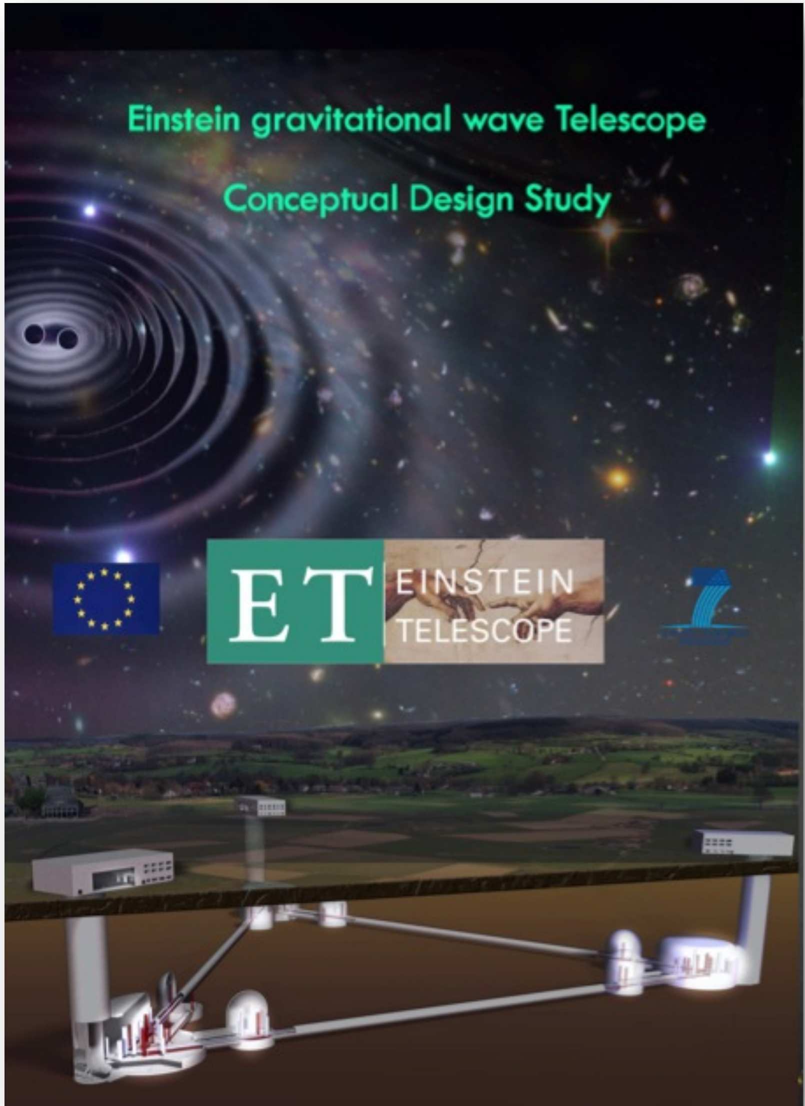
ET Design Study

- The Einstein Telescope project conceptual design study was supported by the European Community FP7 with about 3M€ from May 2008 to July 2011.
- The target of this design phase was to understand the feasibility of a new generation of GW observatory that will permit to gain one order of magnitude in sensitivity at all frequencies.
- The main deliverable, at the end of these 3 years, has been a **conceptual design of such an infrastructure.**



Participant	Country
EGO	Italy/France
INFN	Italy
MPG	Germany
CNRS	France
University of Birmingham	UK
University of Glasgow	UK
Nikhef	NL
Cardiff University	UK

ET Design Study Document



Author list: **ET Science Team**

M Abernathy[1], F Acernese[2,3], P Ajith[30], B Allen[4], P Amaro-Seoane[54,32], N Andersson[5], S Aoudia[54], P Astone[6,7], B Krishnan[4], L Barack[5], F Barone[2,3], B Barr[1], M Barsuglia[8], M Bassan[9,10], R Bassiri[1], M Beker[11], N Beveridge[1], M Bizouard[12], C Bond[13], S Bose[14], L Bosi[15], S Braccini[16], C Bradaschia[16,17], M Britzger[4], F Brueckner[18], T Bulik[19], H J Bulten[20], O Burmeister[4], E Calloni[2,21], P Campsie[1], L Carbone[13], G Cella[16], E Chalkley[13], E Chassande-Mottin[8], S Chelkowski[13], A Chincarini[22], A Di Cintio[6], J Clark[26], E Coccia[9,10], C N Colacino[16], J Colas[17], A Colla[6,7], A Corsi[30], A Cumming[1], L Cunningham[1], E Cuoco[17], S Danilishin[23], K Danzmann[4], E Daw[28], R De Salvo[25], W Del Pozzo[11], T Dent[26], R De Rosa[2,21], L Di Fiore[2], M Di Paolo Emilio[9], A Di Virgilio[16], A Dietz[27], M Doets[11], J Dueck[4], M Edwards[26], V Fafone[9,10] S Fairhurst[26], P Falferi[29,56], M Favata[30], V Ferrari[6,7], F Ferrini[17], F Fidecaro[17,51], R Flaminio[31], J Franc[31], F Frasconi[16], A Freise[13], D Friedrich[4], P Fulda[13], J Gair[57], M Galimberti[31], G Gemme[22], E Genin[17], A Gennai[16], A Giazotto[16,17], K Glampedakis[40], R Gouaty[27], C Graef[4], W Graham[1], M Granata[8], H Grote[4], G Guidi[33,34], J Hallam[13], G Hammond[1], M Hannam[26], J Harms[30], K Haughian[1], I Hawke[5], D Heinert[18], M Hendry[1], I Heng[1], E Hennes[11], S Hild[1], J Hough[1], D Huet[17], S Husa[55], S Huttner[1], B Iyer[38], I Jones[5], G Jones[1], I Kamaretsos[26], C Kant Mishra[38], F Kawazoe[4], F Khalili[39], B Kley[18], K Kokeyama[13], K Kokkotas[40], S Kroker[18], R Kumar[1], K Kuroda[41], B Lagrange[31], N Lastzka[4], T G F Li[11], M Lorenzini[33], G Losurdo[33,17], H Lück[4], E Majorana[6], V Malvezzi[9,10], I Mandel[42,13], V Mandic[36], S Marka[50], F Marin[33], F Marion[27], J Marque[17], I Martin[1], D Mc Leod[26], D Mckechan[26], M Mehmet[4], C Michel[31], Y Minenkov[9], N Morgado[31], A Morgia[9], S Mosca[2,21] L Moscatelli[6], B Mours[27], H Müller-Ebhardt[4], P Murray[1], L Naticchioni[6,7], R Nawrodt[18], J Nelson[1], R O' Shaughnessy[43], C D Ott[30], C Palomba[6], A Paoli[17], G Parguez[17], A Pasqualetti[17], R Passaquieti[16], D Passuello[16], M Perciballi[6], F Piergiovanni[33,34], L Pinard[31], M Pitkin[1], W Plastino[44], M Plissi[1], R Poggiani[16], P Popolizio[17], E Porter[8], M Prato[22], G Prodi[45,56], M Punturo[15,17], P Puppo[6], D Rabeling[20], I Racz[46], P Rapagnani[6,7], V Re[9], J Read[37], T Regimbau[47], H Rehbein[4], S Reid[1], L Rezzolla[54], F Ricci[6,7], F Richard[17], A Rocchi[9], R Romano[2], S Rowan[1], A Rüdiger[4], A Samblowski[4], L Santamaría[30], B Sassolas[31], B Sathyaprakash[26], R Schilling[4], P Schmidt[26], R Schnabel[4], B Schutz[26,54], C Schwarz[18], J Scott[1], P Seidel[18], A M Sintes[55], K Somiya[48], C F Sopuerta[49], B Sorazu[1], F Speirits[1], L Storchi[15], K Strain[1], S Strigin[23], P Sutton[26], S Tarabrin[4], B Taylor[4], A Thürin[4], K Tokmakov[1], M Tonelli[16,51], H Tournefier[27], R Vaccarone[17], H Vahlbruch[4], J F J van den Brand[11,20], C Van Den Broeck[11], S van der Putten[11], M van Veggel[1], A Vecchio[13], J Veitch[26], F Vetrano[33,34], A Vicere[33,34], S Vyatchanin[23], P Weßels[52], B Willke[4], W Winkler[4], G Woan[1], K Wojcik[26], A Woodcraft[53], K Yamamoto[35]

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

ET target sensitivity

- Target sensitivity of the new, 3rd generation “observatory” (the Einstein Telescope, ET) is the result of the trade off between several requirements

1. Science targets
2. Available technologies (detector realization)
3. Infrastructure & site costs

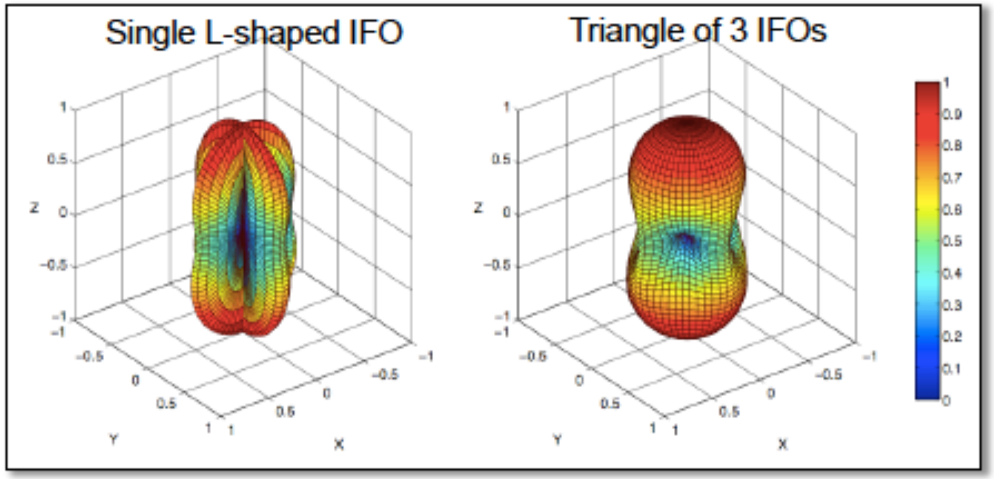
As starting point of our studies we defined two rough requirements:

Improvement by a factor 10 of the advanced sensitivities

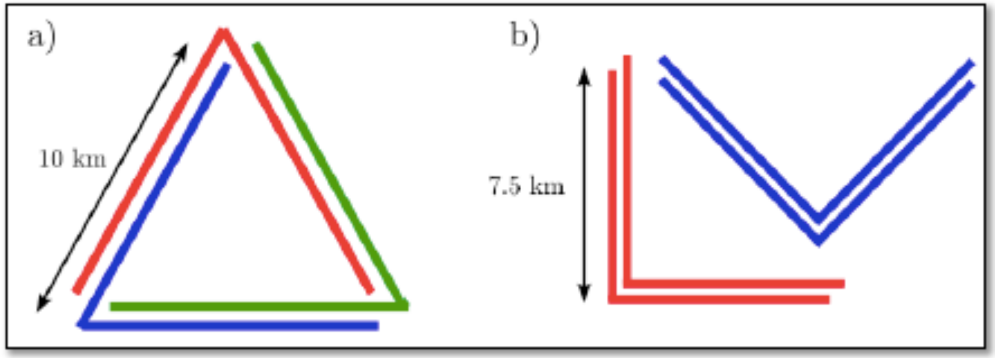
Access, as much as possible, to the 1-10Hz frequency range

The ET footprint

- As ET is a new infra-structure, we can start from scratch.
- Want to see the full sky.
- Want to resolve both polarisations.
- Want to have redundancy.
- 1 Triangle vs 4 Ls:
  - Both have 30km integrated tunnel length
  - Both resolve both polarisations and offer redundancy.
  - Both give equivalent sensitivity.
  - Triangle reduces the number of end stations.
- ET will be a triangle.



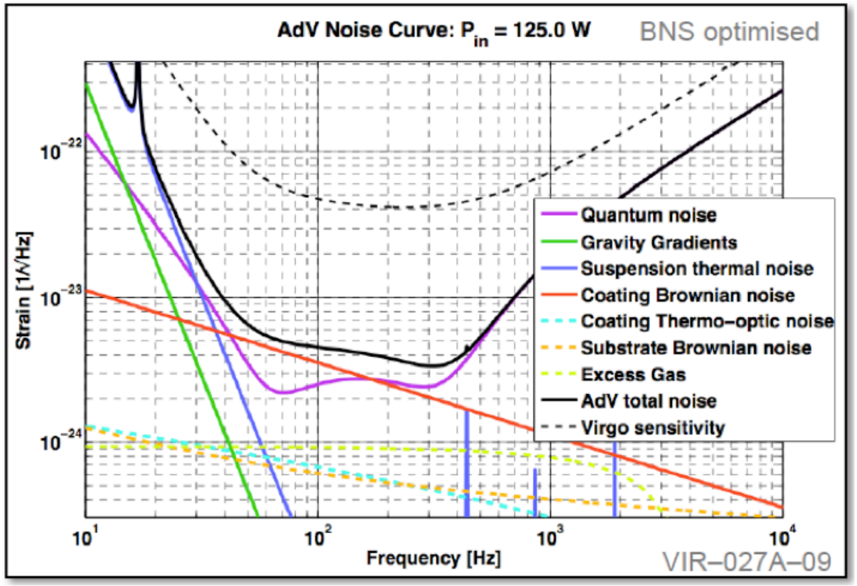
Freise, A.; Chelkowski, S.; Hild, S.; Pozzo, W. D.; Perreca, A. & Vecchio, A. *CQG*, 2009, *26*, 085012 (14pp)



Triangle first proposed:1985, MPQ-101. W.Winkler, K.Maischberger, A.Rüdiger, R.Schilling, L.Schnupp, D.Shoemaker,: Plans for a Large Gravitational Wave Antenna in Germany

Recap of noise sources

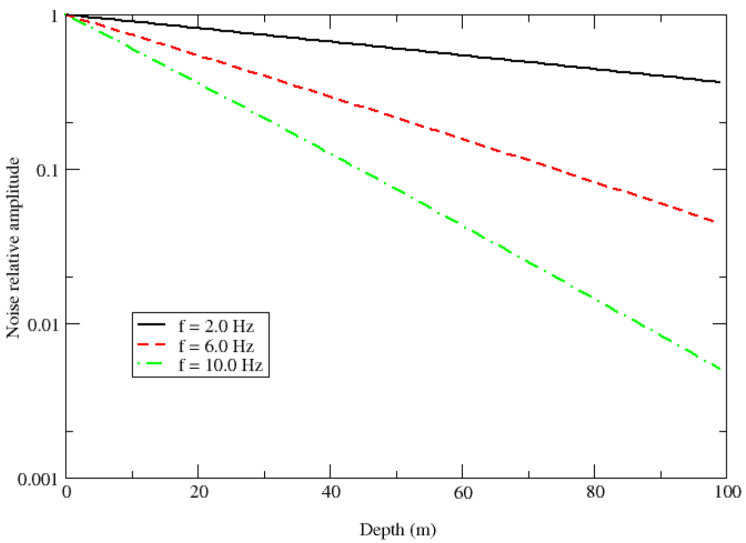
- Quantum Noise limits most of the frequency range.
- Coating Brownian limits (or is close) in the range from 50 to 100Hz.



- Below 50Hz we are limited by 'walls' made of Suspension Thermal, Gravity Gradient and Seismic noise.

Seismic noise reduction

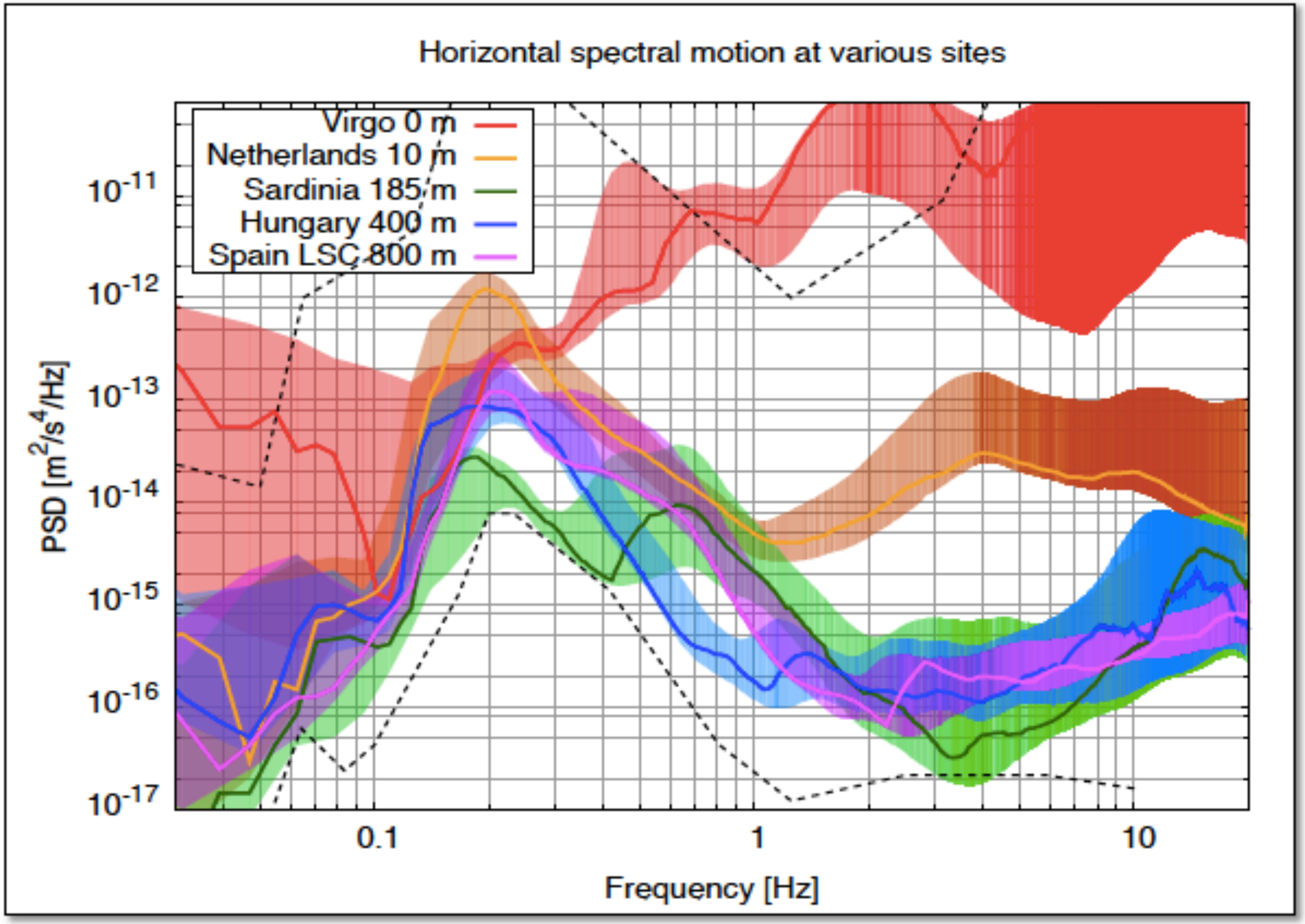
- Virgo and advanced Virgo seismic filtering is already close to the top of the possible performances;
- Gravity gradient noise bypasses the seismic filtering;
- In order to improve the performances in the 1-10Hz range, i.e. appealing for IMBH, is to select a site with very low seismic noise



Surface waves die exponentially with depth

→ GO UNDERGROUND!

ET will "go underground"



ET design study document

Xylophone Concept

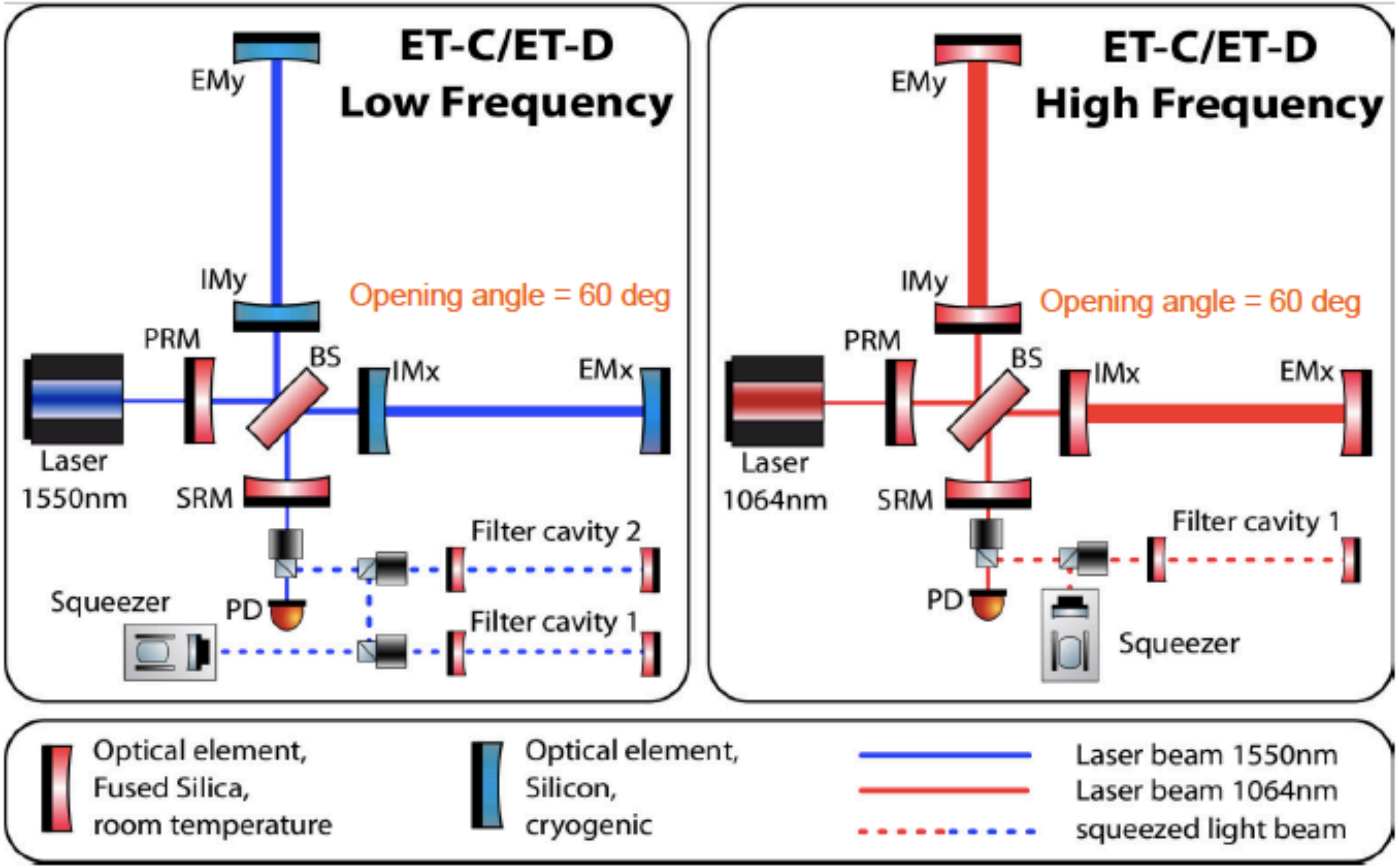
- As our detectors become more and more complex and at the same time aim increase even further the observation bandwidth the xylophone concept becomes more and more attractive.
- The xylophone concept was originally suggested for advanced LIGO:

  R.DeSalvo, CQG 21 (2004) S1145-S1154
  G.Conforto and R.DeSalvo, Nuc. Instruments 518 (2004) 228 - 232
  D.Shoemaker, presentation at Aspen meeting (2001), http://www.ligo.caltech.edu/docs/G/G010026-00.pdf

- Allows to overcome 'contradicting' requirements in the technical detector design:
  - To reduce shot noise you have to increase the light power, which in turn will reduce the sensitivity at low frequencies due to higher radiation pressure noise.
  - Need cryogenic mirrors for low frequency sensitivity. However, due to residual absorption it is hard to combine cryogenic mirrors with high power interferometers.
- For ET we choose the conservative approach (designing an infrastructure) and went for a 2-band xylophone: low-power, cryogenic low-frequency detector and a high-power, room-temperature high-frequency detector.

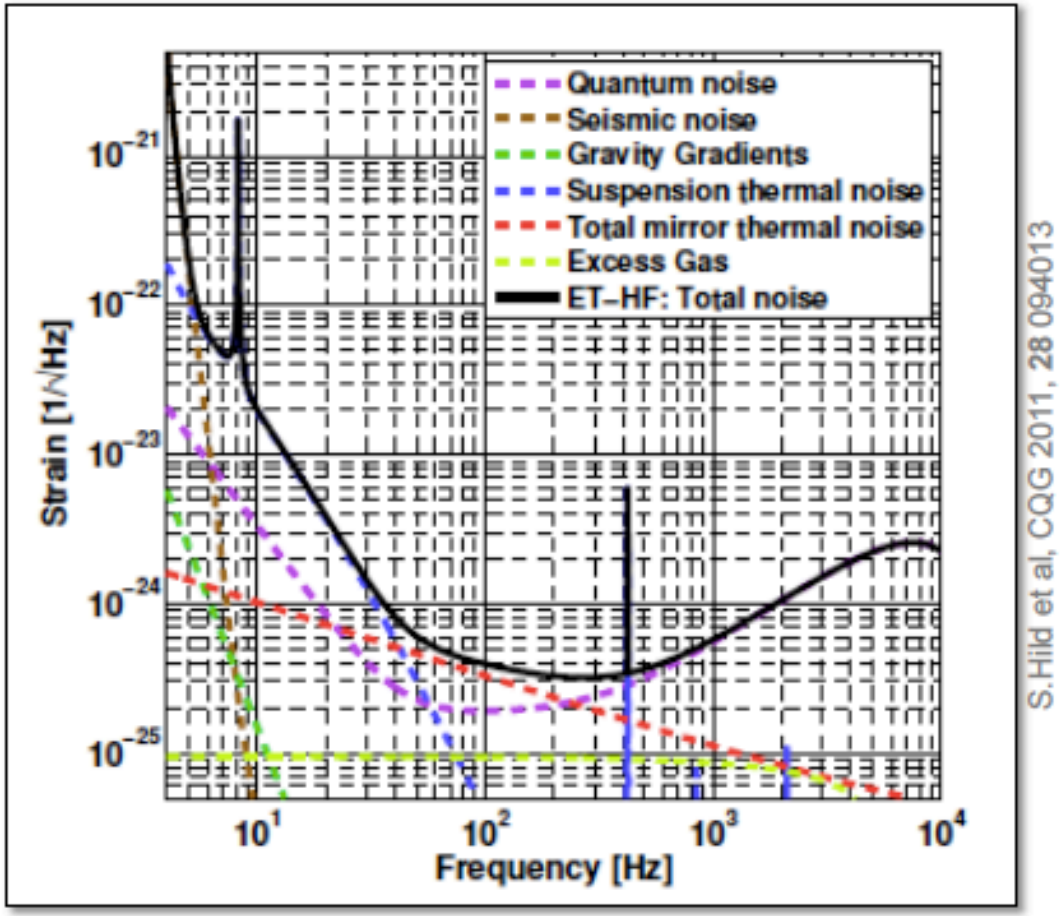
S. Hild, E. Amaldi Conference 2011

The ET core interferometer



The High-Frequency Detector

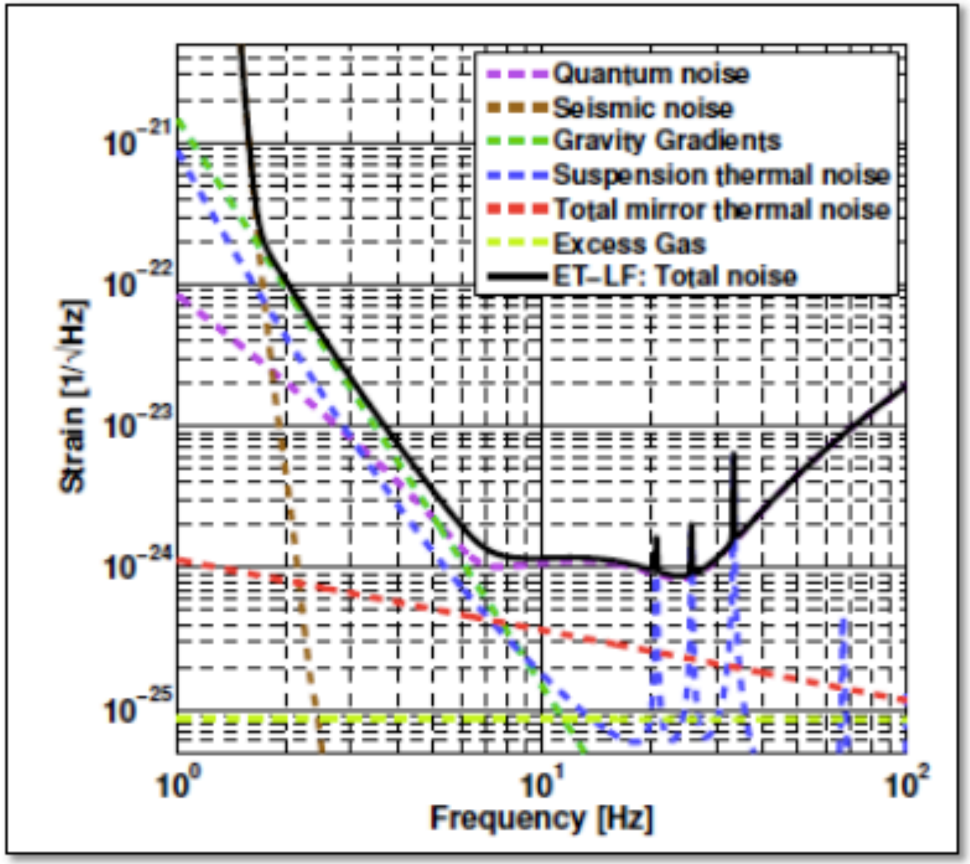
- **Quantum noise:** 3MW, tuned Signal-Recyling, 10dB Squeezing, 200kg mirrors.
- **Suspension Thermal and Seismic:** Superattenuator
- **Gravity gradient:** No Subtraction
- **Thermal noise:** 290K, 12cm beam radius, fused Silica, LG33 (reduction factor of 1.6 compared to TEM00).



Coating Brownian reduction factors (compared to 2G): 3.3 (arm length), 2 (beam size) and 1.6 (LG33) = 10.5

The Low-Frequency Detector

- **Quantum noise:** 18kW, detuned Signal-Recycling, 10dB frequency dependent squeezing, 211kg mirrors, 1550nm.
- **Seismic:** 17m Superattenuator
- **Gravity gradient:** Underground, Black forest location
- **Thermal noise:** 10K, Silicon, 9cm beam radius, TEM00.
- **Suspension Thermal:** 3mm Silicon fibres. Penultimate mass at 2K.

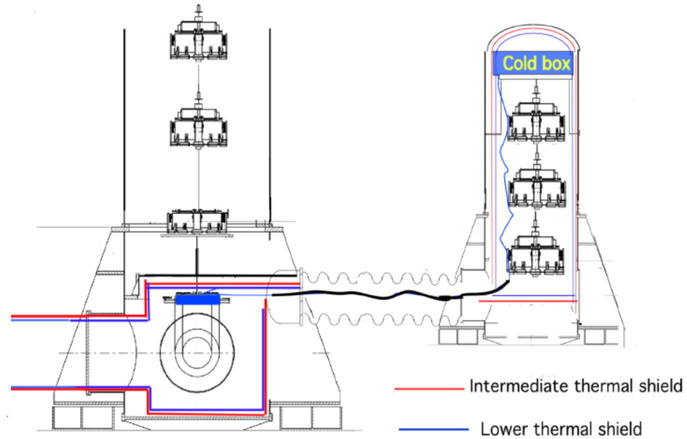


S.Hild et al, CQG 2011, 28 094013

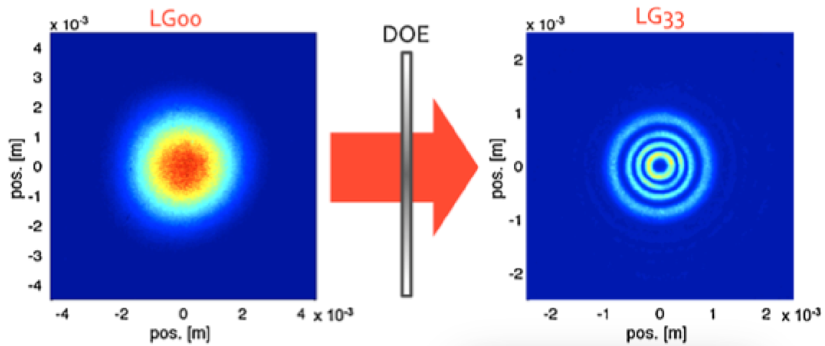
As mirror TN is no longer limiting, one can relax the assumptions on the material parameters and the beam size…

Thermal Noise reduction

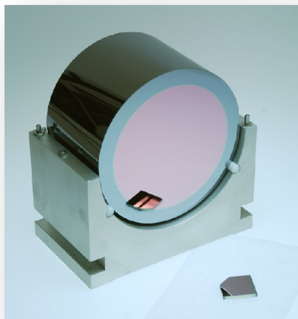
- The Einstein Telescope will be cryogenic: suspensions and mirrors cooled to 20 K;



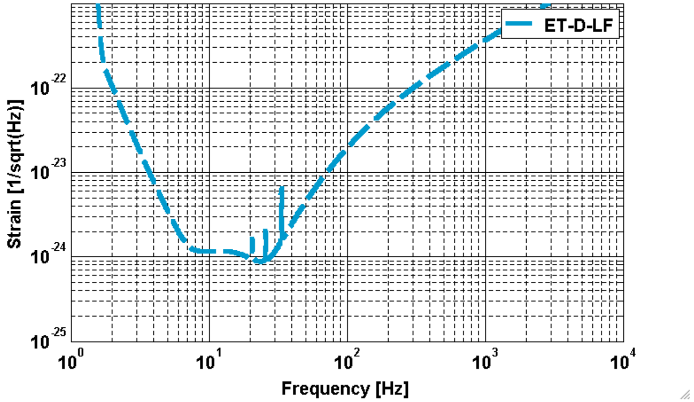
- ET will use higher LG modes:
  - improve coating Brownian noise by distributing the power more homogeneously over the mirror surface and therefore better averaging over the local thermal fluctuations;

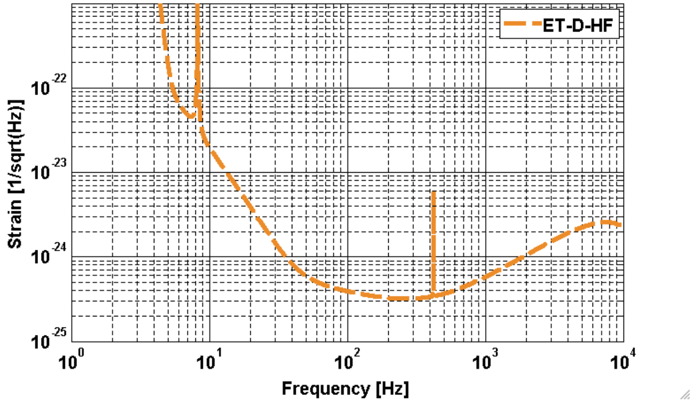


- Mirror substrates made of Silicon rather than Fused Silica: lower mechanical losses → laser wavelength from 1064 nm to 1550 nm.



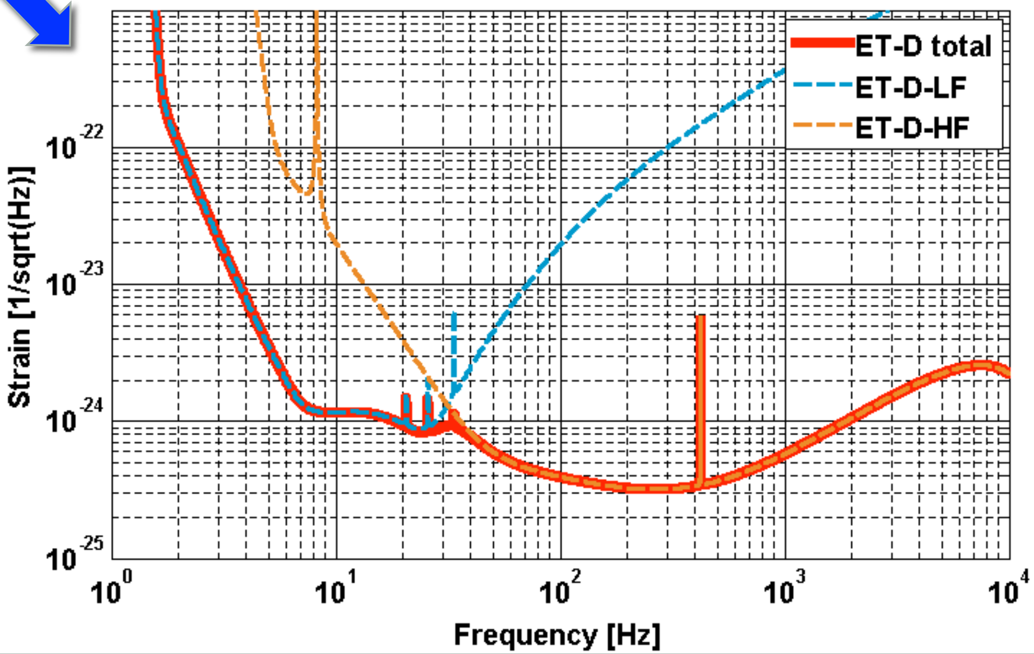
Combining 2 ITFs





ET-LF

ET-HF

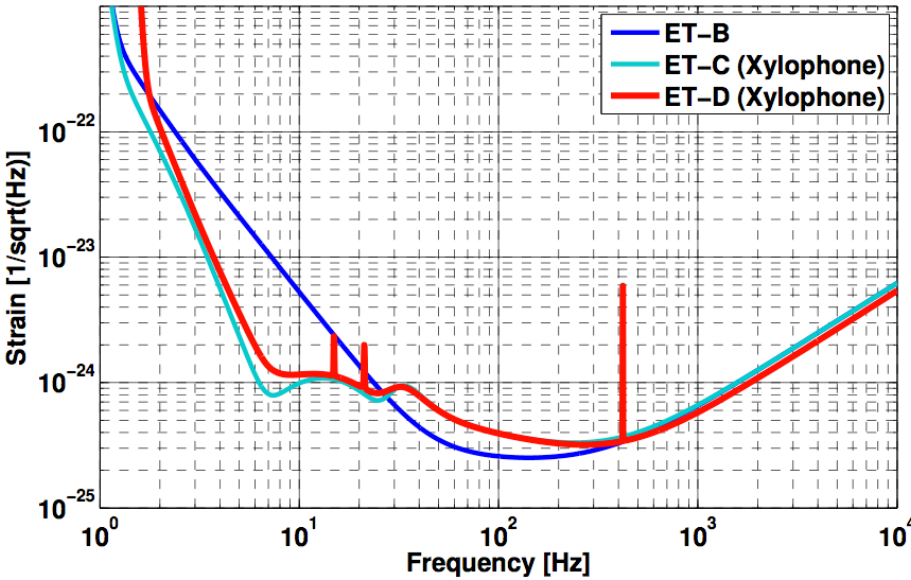


ET parameters

Parameter	ET-D-HF	ET-D-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10 K
Mirror material	Fused silica	Silicon
Mirror diameter / thickness	62 cm / 30 cm	min 45 cm/ TBD
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1 × 10 km	2 × 10 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	LG_{33}	TEM_{00}
Beam radius	7.25 cm	9 cm
Scatter loss per surface	37.5 ppm	37.5 ppm
Partial pressurefor H_2O, H_2, N_2	10^{-8}, $5 \cdot 10^{-8}$, 10^{-9} Pa	10^{-8}, $5 \cdot 10^{-8}$, 10^{-9} Pa
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$	$5 \cdot 10^{-10}\,\mathrm{m}/f^2$
Gravity gradient subtraction	none	none

- Data from ET-LF and ET-HF can be coherently or incoherently be added, depending on the requirements of the analysis.
- Sensitivity data available for download at: http://www.et-gw.eu/etsensitivities

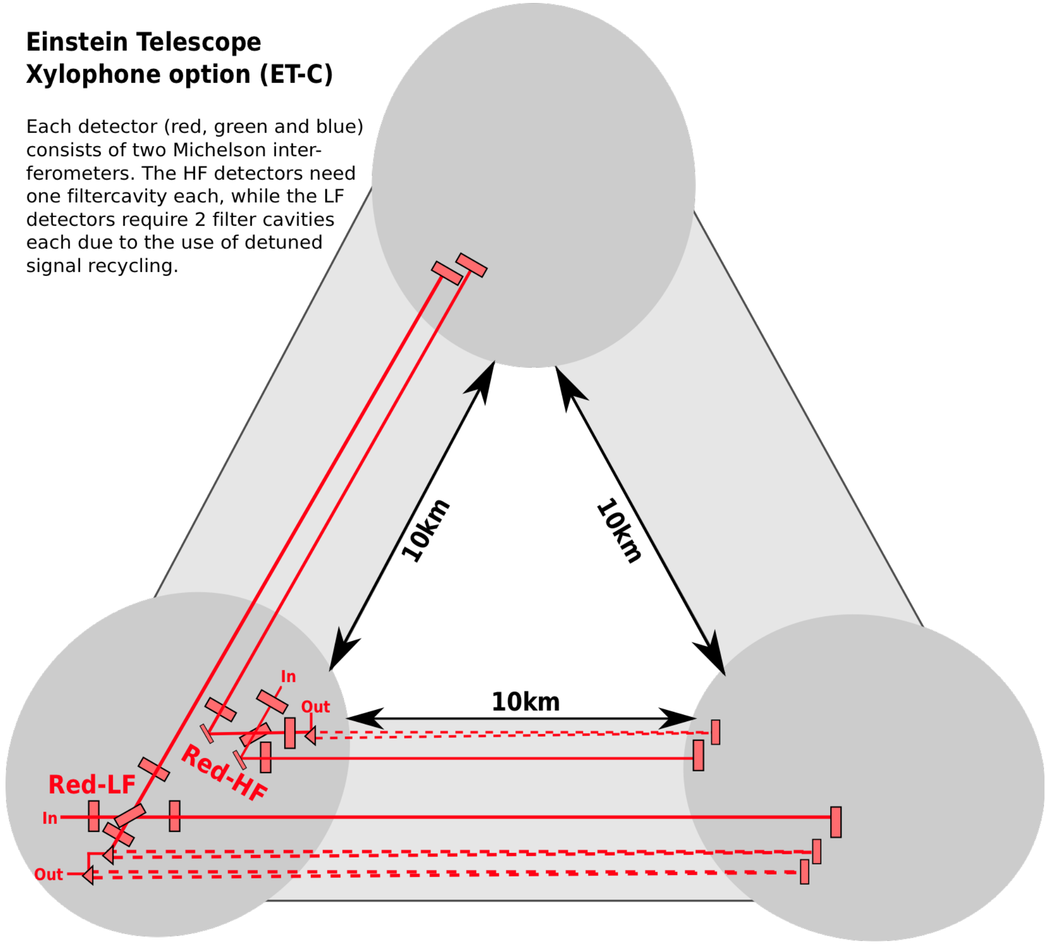
S.Hild et al: 'A Xylophone Configuration for a third Generation Gravitational Wave Detector', CQG 2010, 27, 015003
S.Hild et al: 'Sensitivity Studies for Third-Generation Gravitational Wave Observatories', CQG 2011, 28 094013.



S. Hild Amaldi Conference 2011

How to build the Observatory

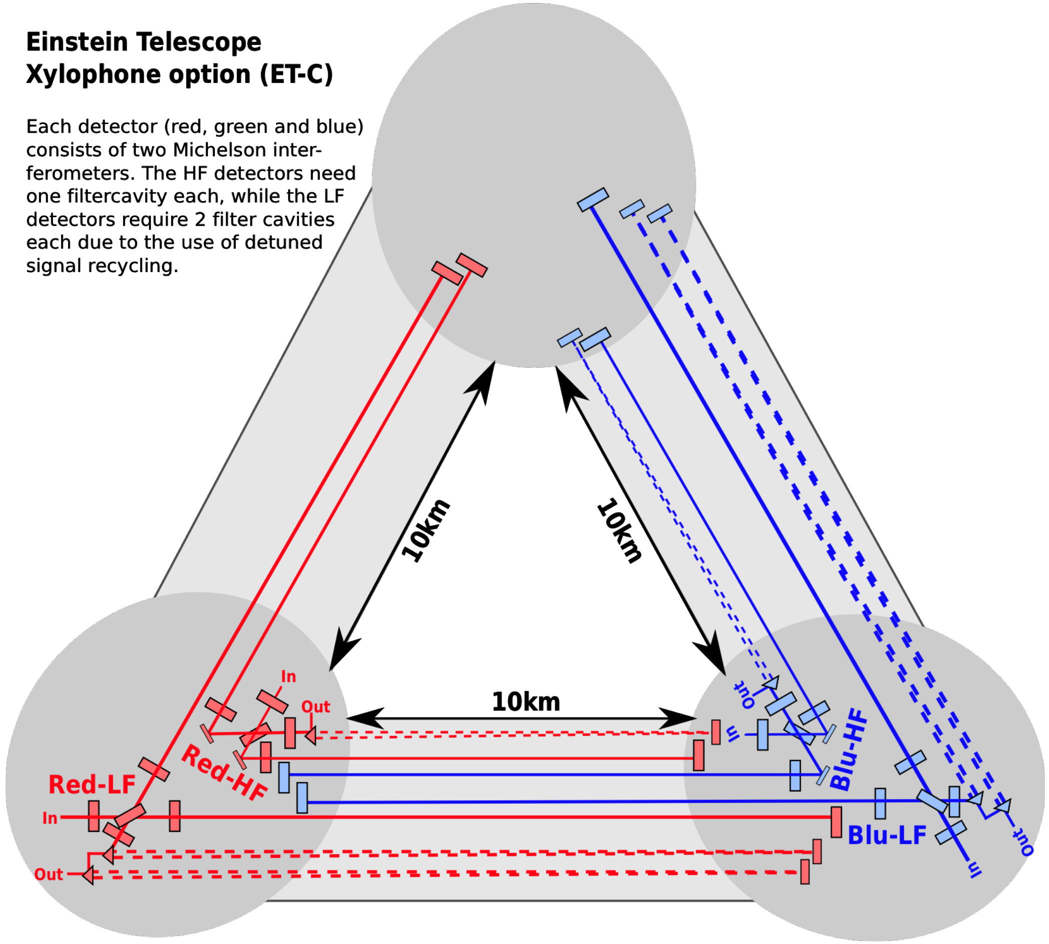
- For efficiency reasons build a triangle.
- Start with a single xylophone detector.



S. Hild Amaldi
Conference 2011

How to build the Observatory

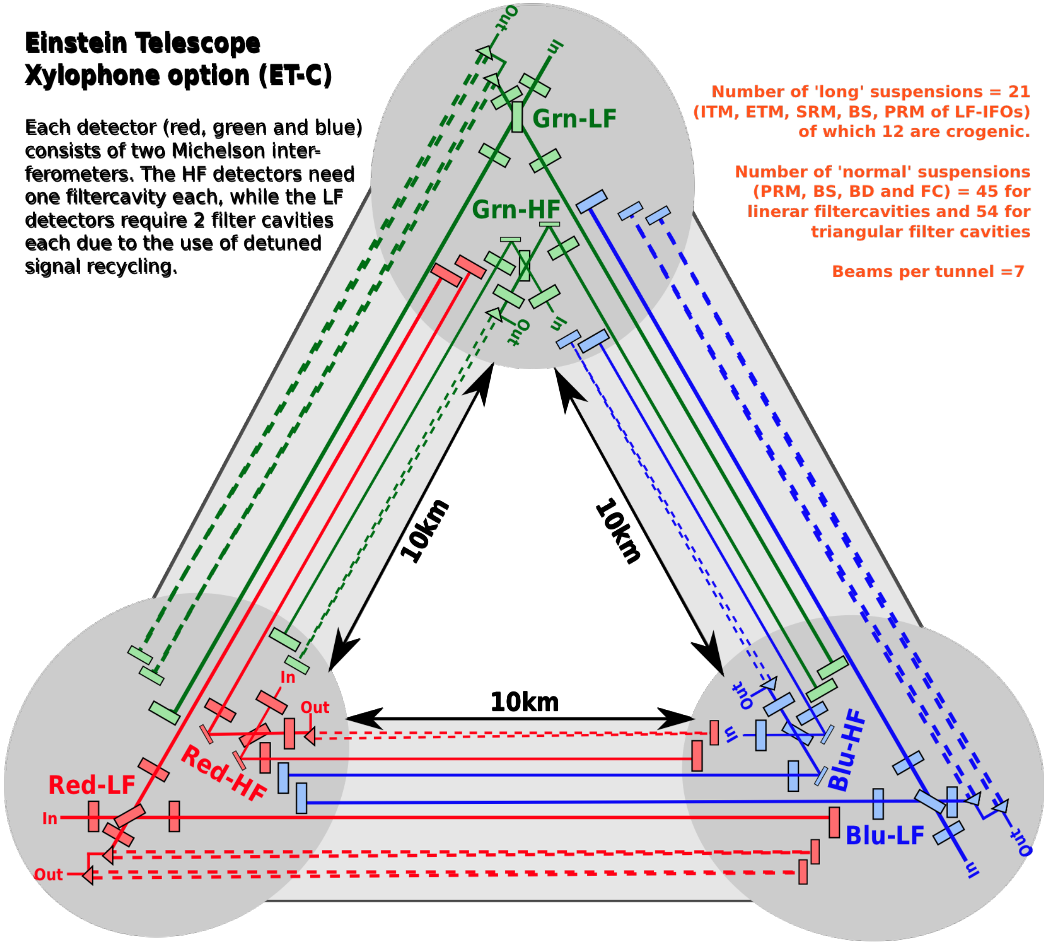
- For efficiency reasons build a triangle.
- Start with a single xylophone detector.
- Add second Xylophone detector to fully resolve polarisation.



S. Hild Amaldi Conference 2011

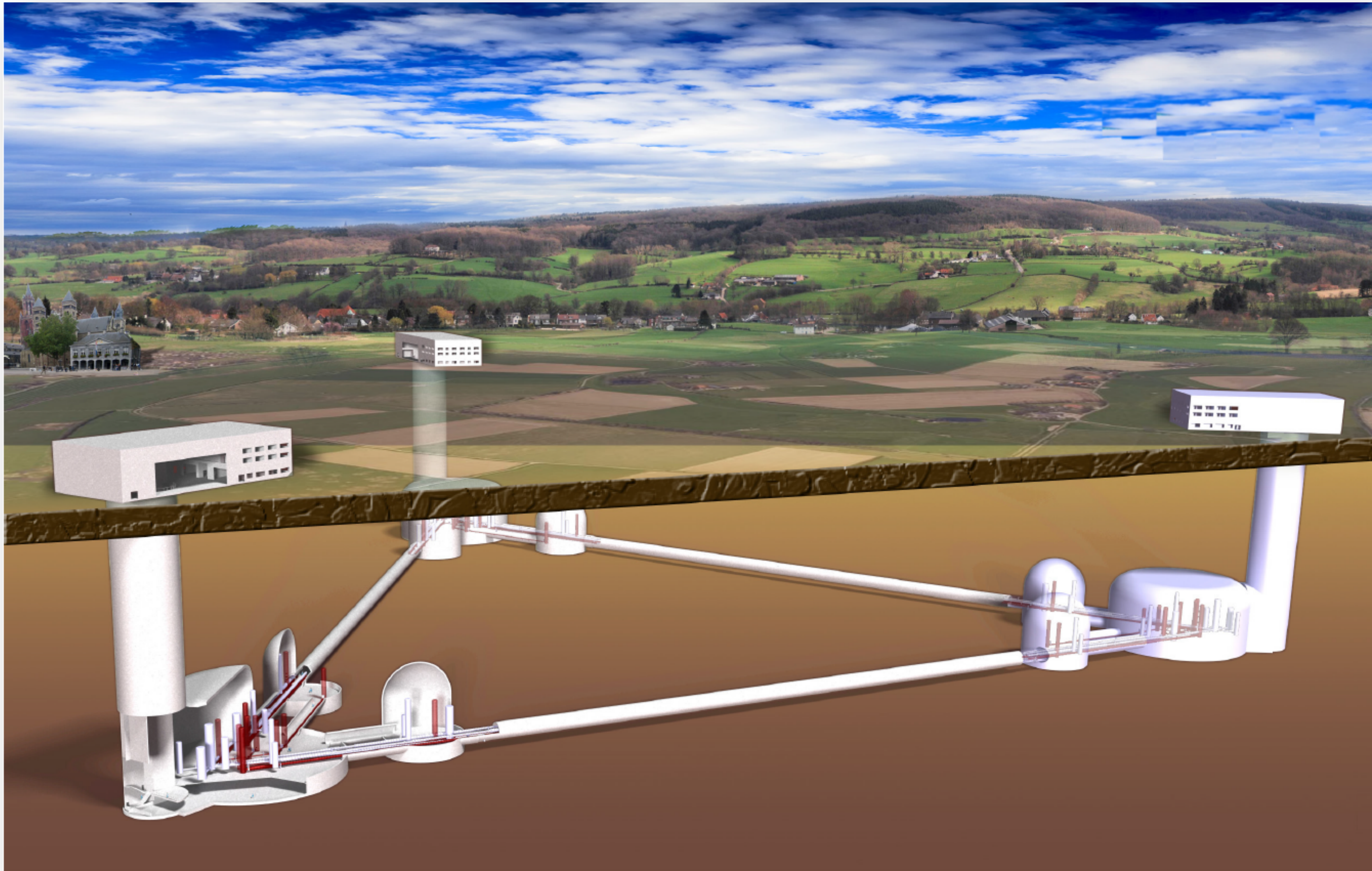
How to build the Observatory

- For efficiency reasons build a triangle.
- Start with a single xylophone detector.
- Add second Xylophone detector to fully resolve polarisation.
- Add third Xylophone detector for redundancy and null-streams.

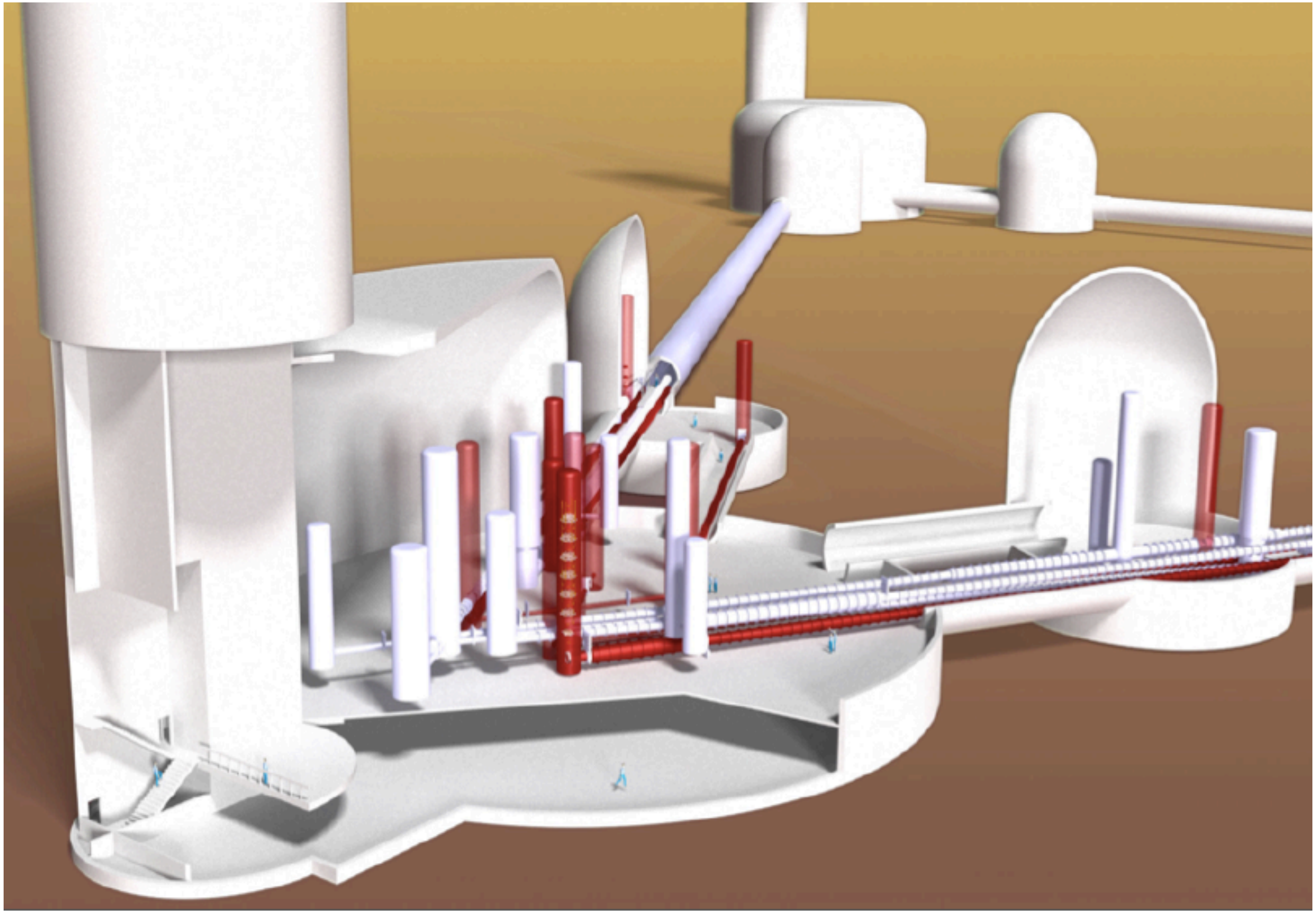


S. Hild
Amaldi Conference 2011

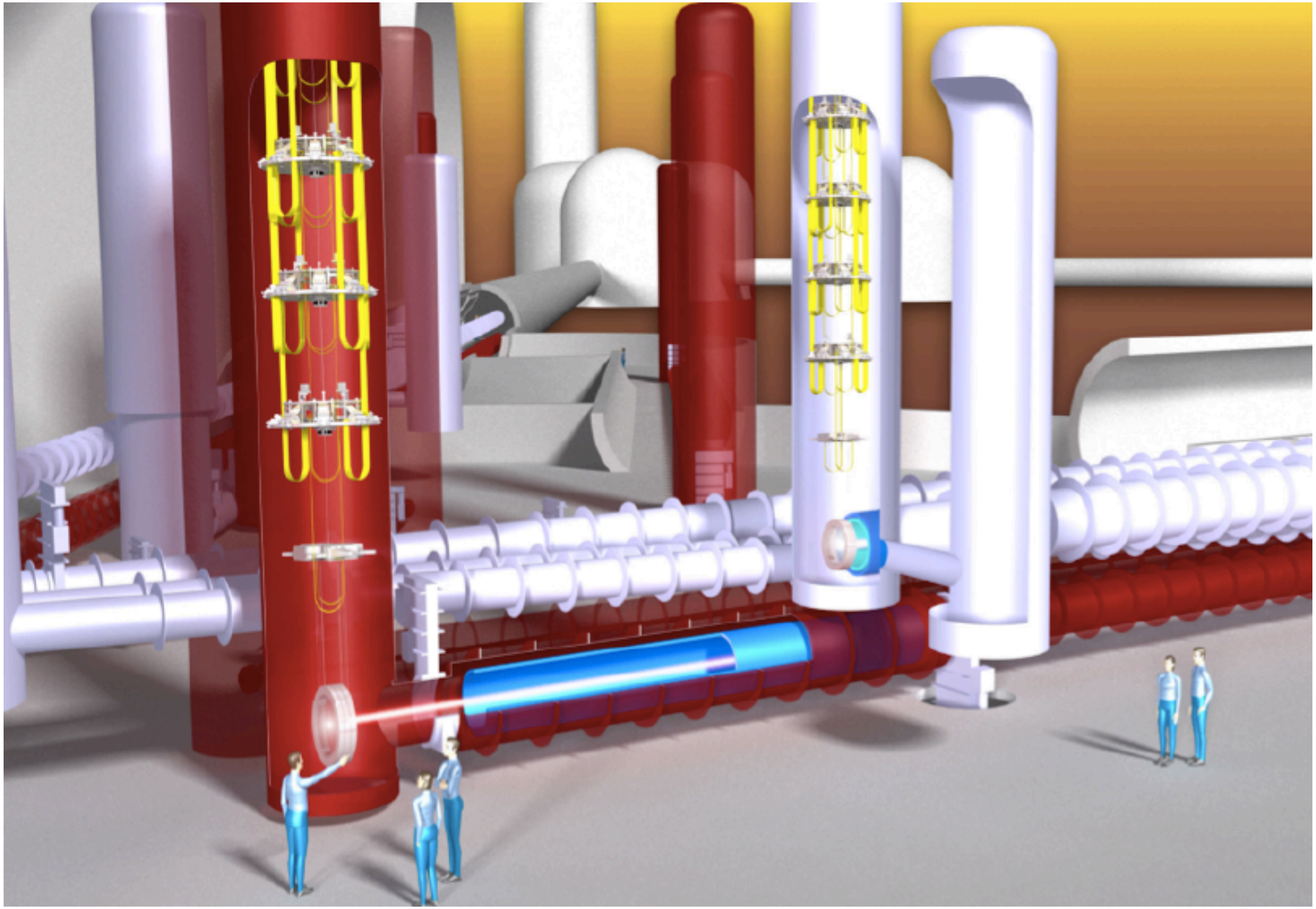
Artist's views



Artist's views

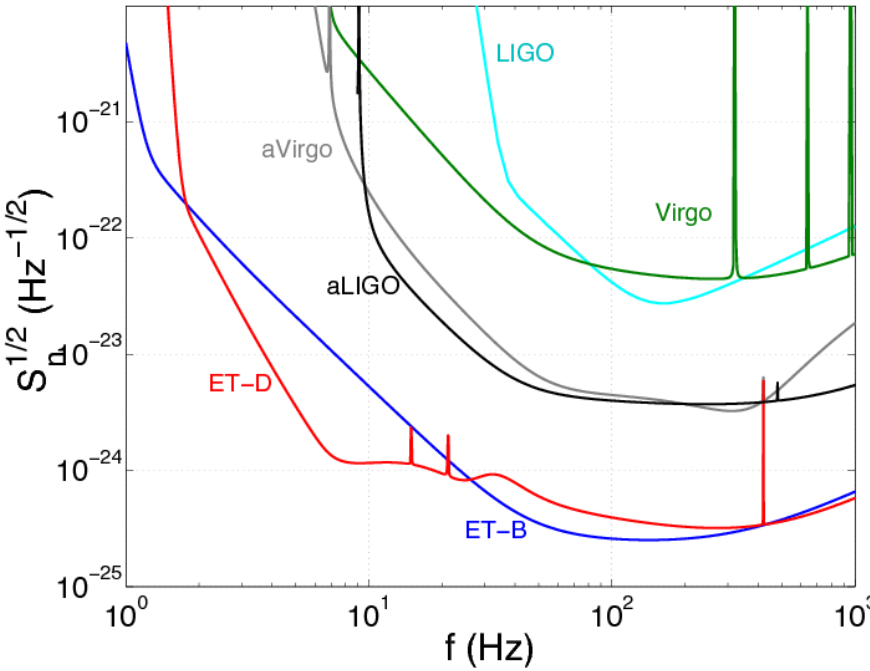


Artist's views

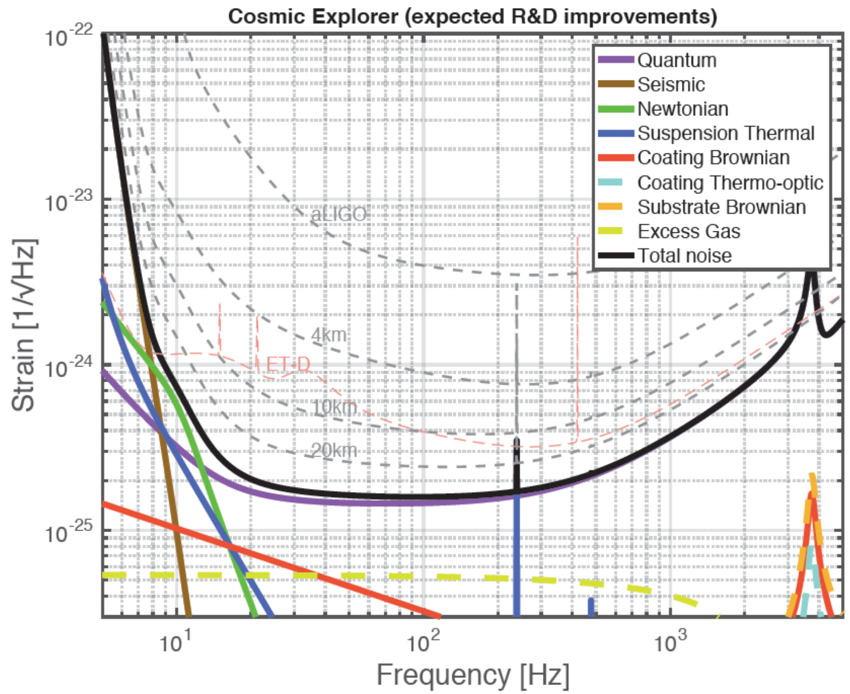


3G projects

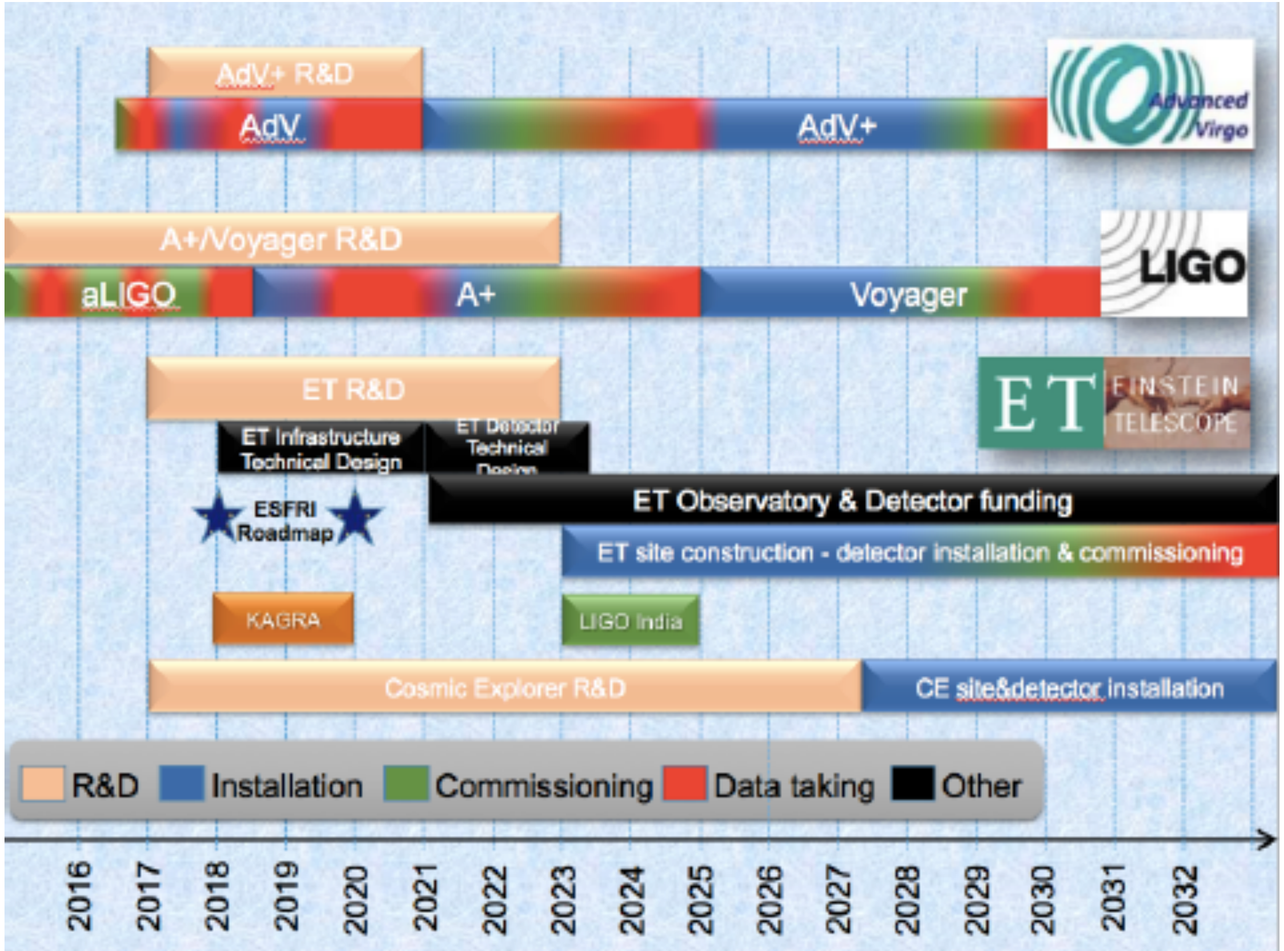
Einstein Telescope
– 10 Km long arms
– Triangular shape
– Underground
– Sensitivity down to few Hz



Cosmic Explorer (AKA LUNGO)
– 40 Km long arms
– L shaped
– Over ground
– Sensitivity down to ~8Hz



The roadmap



AdV+ R&D
AdV
AdV+
A+/Voyager R&D
aLIGO
A+
Voyager
LIGO
ET R&D
ET Infrastructure Technical Design
ET Detector Technical Design
ET EINSTEIN TELESCOPE
ESFRI Roadmap
ET Observatory & Detector funding
ET site construction - detector installation & commissioning
KAGRA
LIGO India
Cosmic Explorer R&D
CE site&detector installation
R&D
Installation
Commissioning
Data taking
Other
2016
2017
2018
2019
2020
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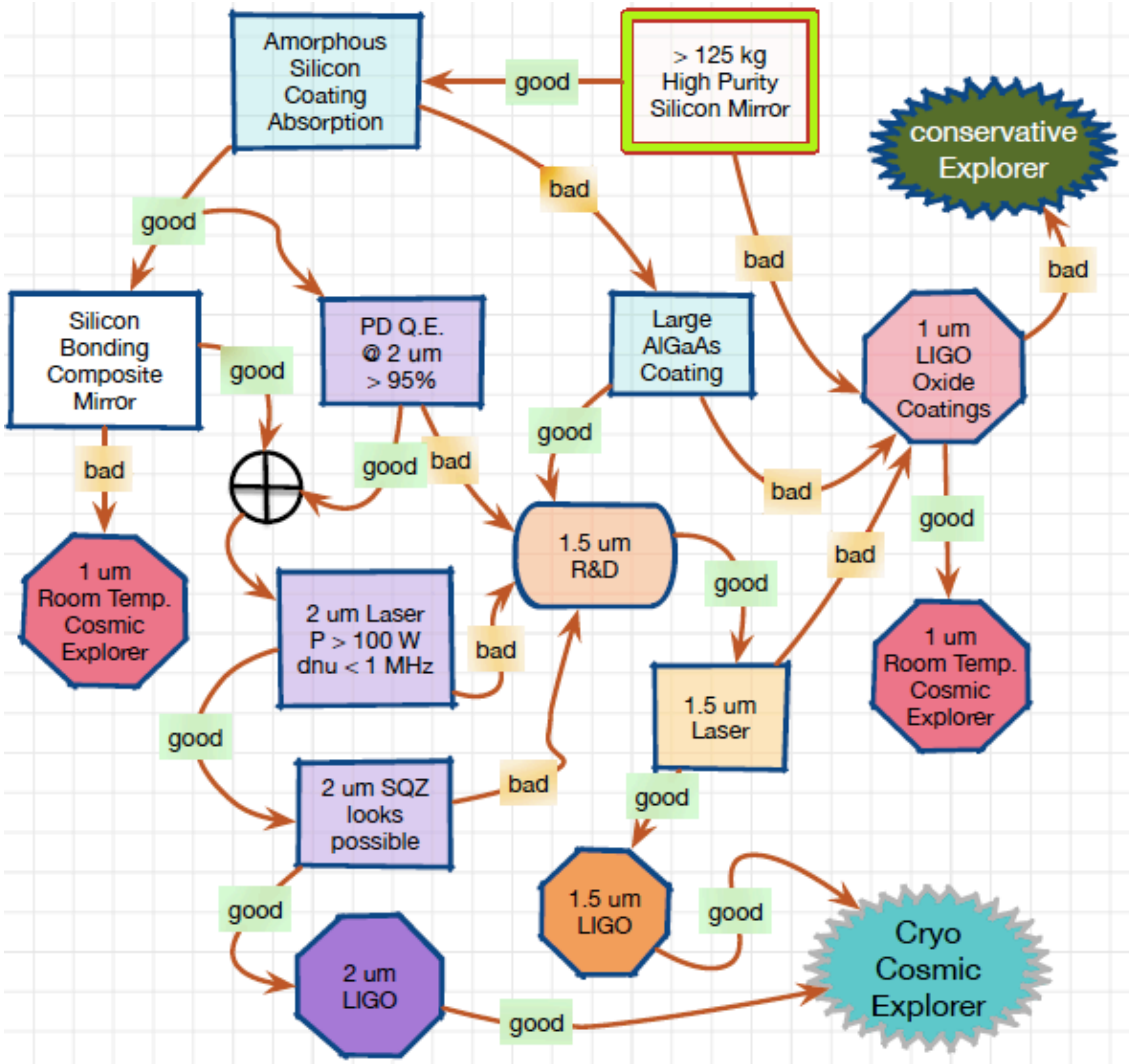
2032

Decisional path is complex…



LIGO-T1400226-v7
LIGO Voyager Upgrade
Conceptual Design

… ideally driven by Science

IMPORTANT QUESTIONS TO BE ADDRESSED BY FUTURE DETECTORS

Astrophysics
- NSNS, NSBH and BHBH merger rates as a function of redshift
- masses and spins of neutron stars and black holes
- astrophysical models of the formation and evolution of compact object binaries,
- progenitors of GRBs
- Supernovae, magnetars, non-axisymmetric neutron stars

Fundamental physics
- equation of state of neutron stars
- post-Newtonian theory and strong field tests of general relativity
- black hole no-hair theorem (black holes, naked singularity or exotica)

Cosmology and Cosmography
- measure both luminosity distance and redshift from GW observations
- Hubble parameter
- dark energy equation of state
- dark matter
- primordial or astrophysical background
- anisotropic cosmology

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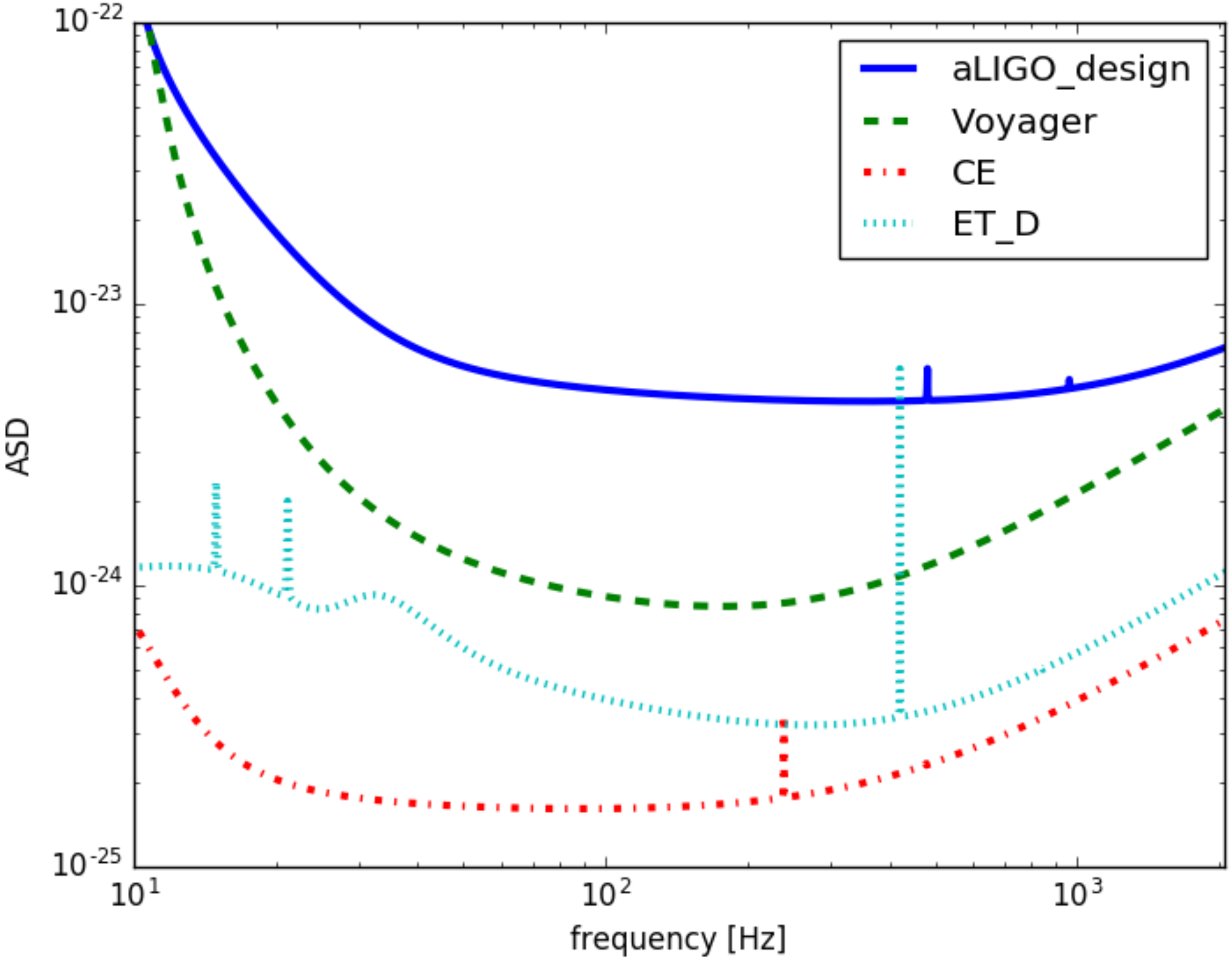
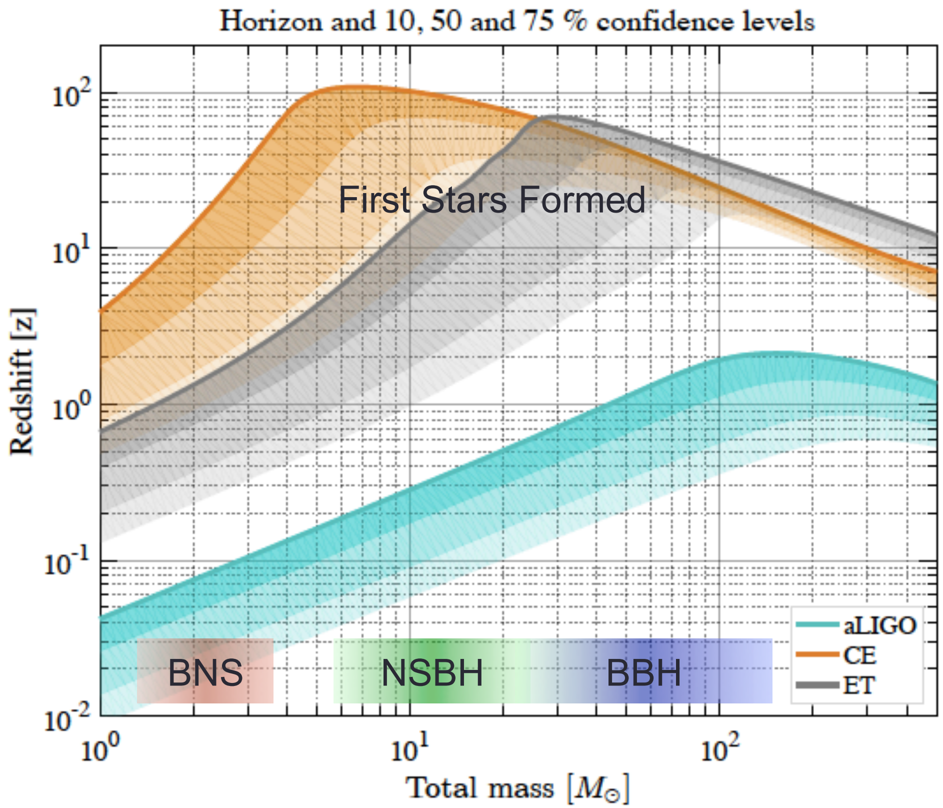
Possible scenario



Observable distance for CBC

- Horizon distance = maximum distance up to which a detector observe sources
- A binary system at the horizon distance, located in a direction normal to the plane of a detector and face-on produces a signal-to-noise ratio of 8

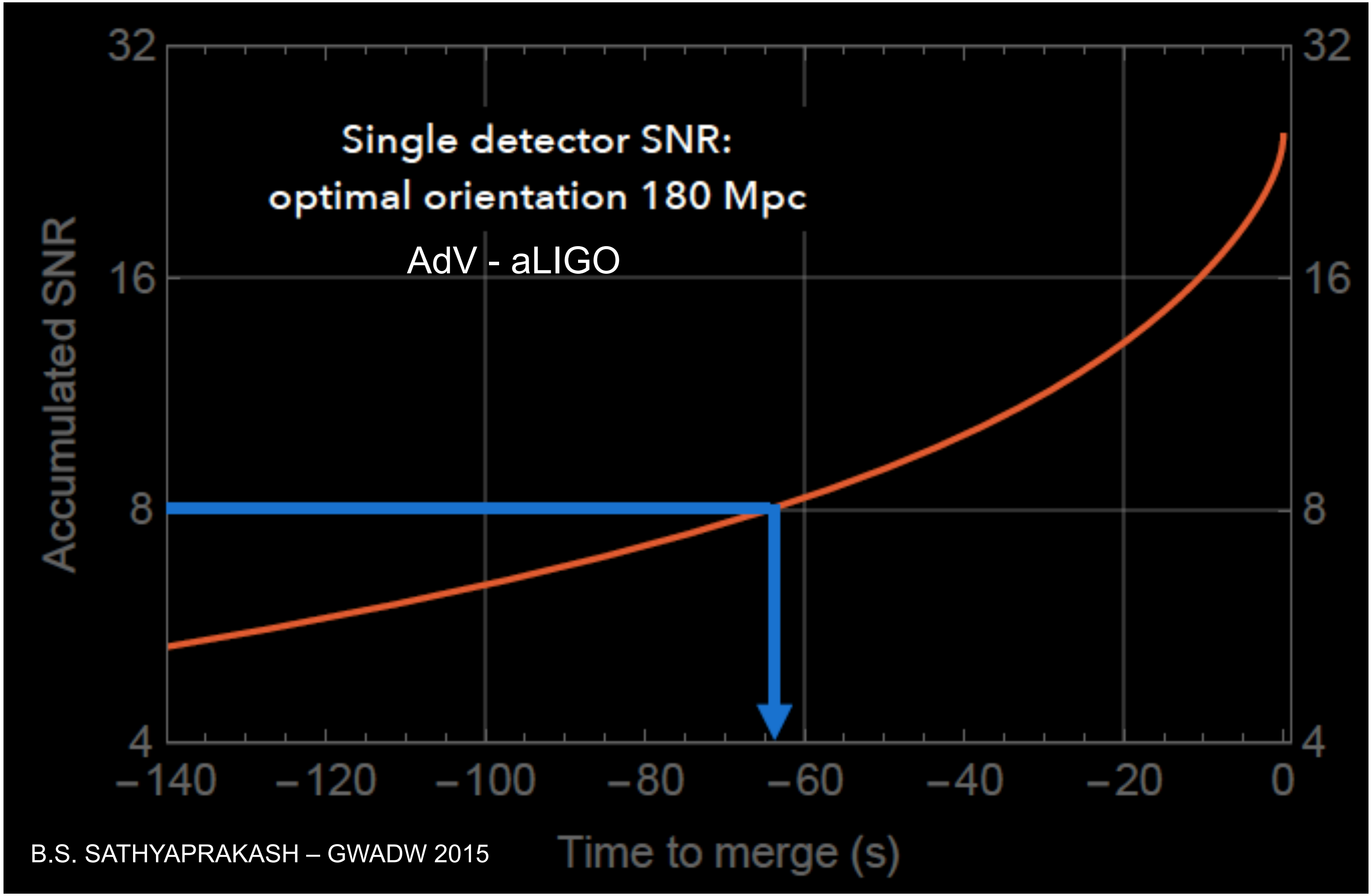
LIGO-T1600119 -Instrument Science White Paper



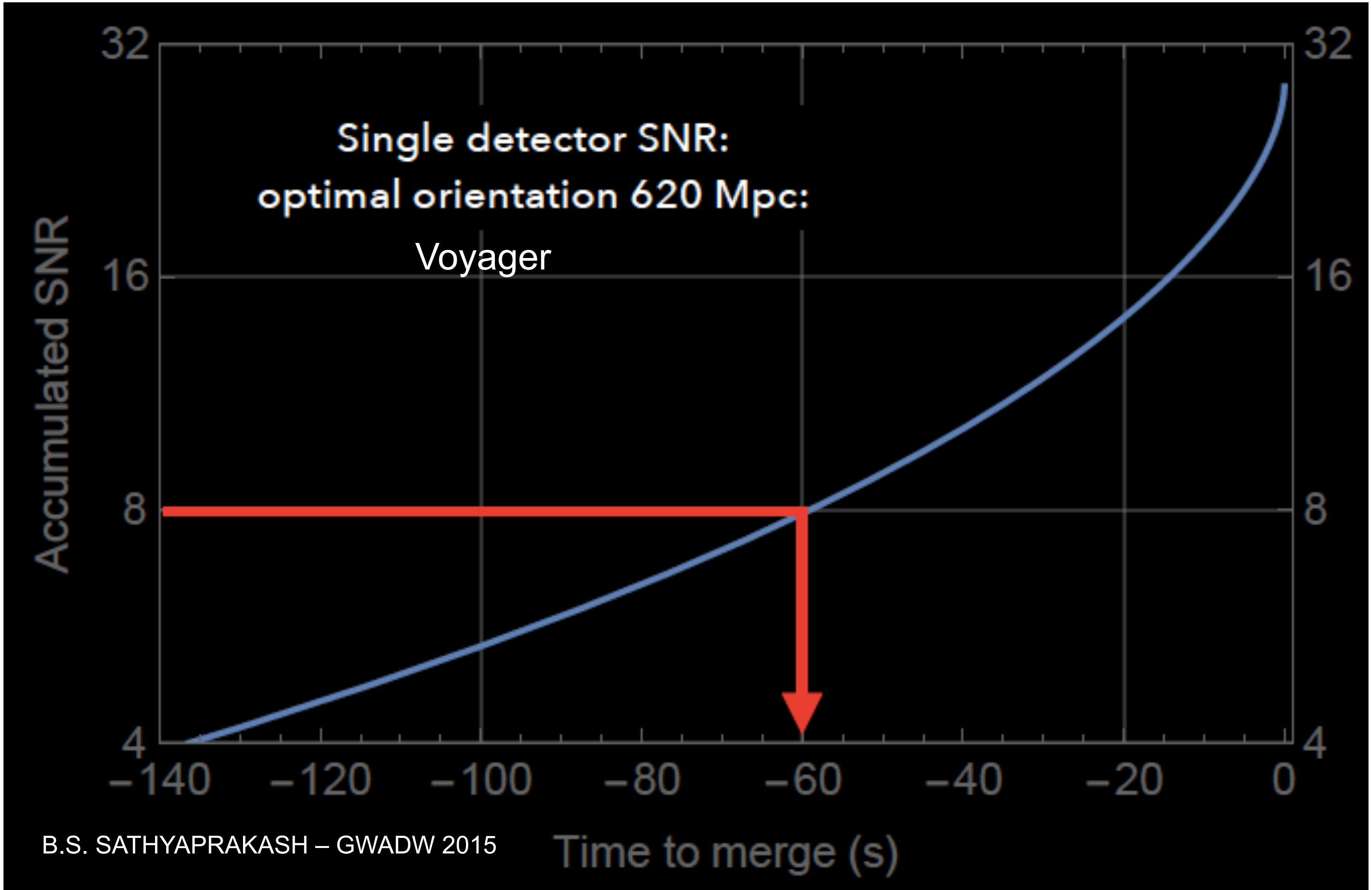
$$m^s = \frac{m^{det}}{1+z}$$

Maximum observable distance vs total intrinsic mass of the system. Baring a large number of primordial BHs, at z ≥ 10 there will be few sources. Thus, a horizon of z > 20 for a given mass should be taken to indicate that essentially *all* CBC in the universe will be observable by a network of similar detectors, many with a high SNR. A Hubble constant of 67.9 km/s/Mpc and a LCDM model of expansion is assumed

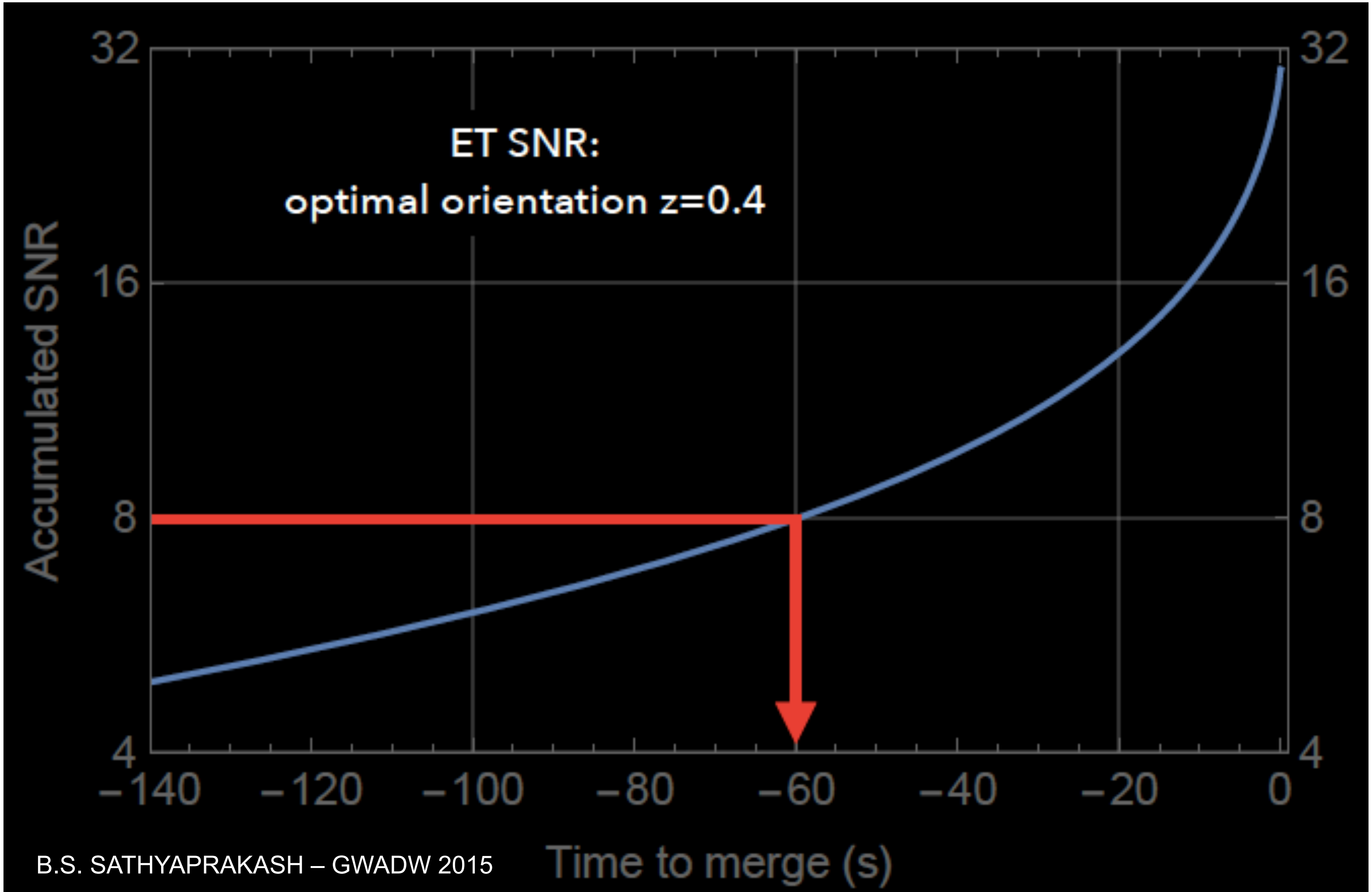
SNR build-up for BNS



SNR build-up for BNS



SNR build-up for BNS



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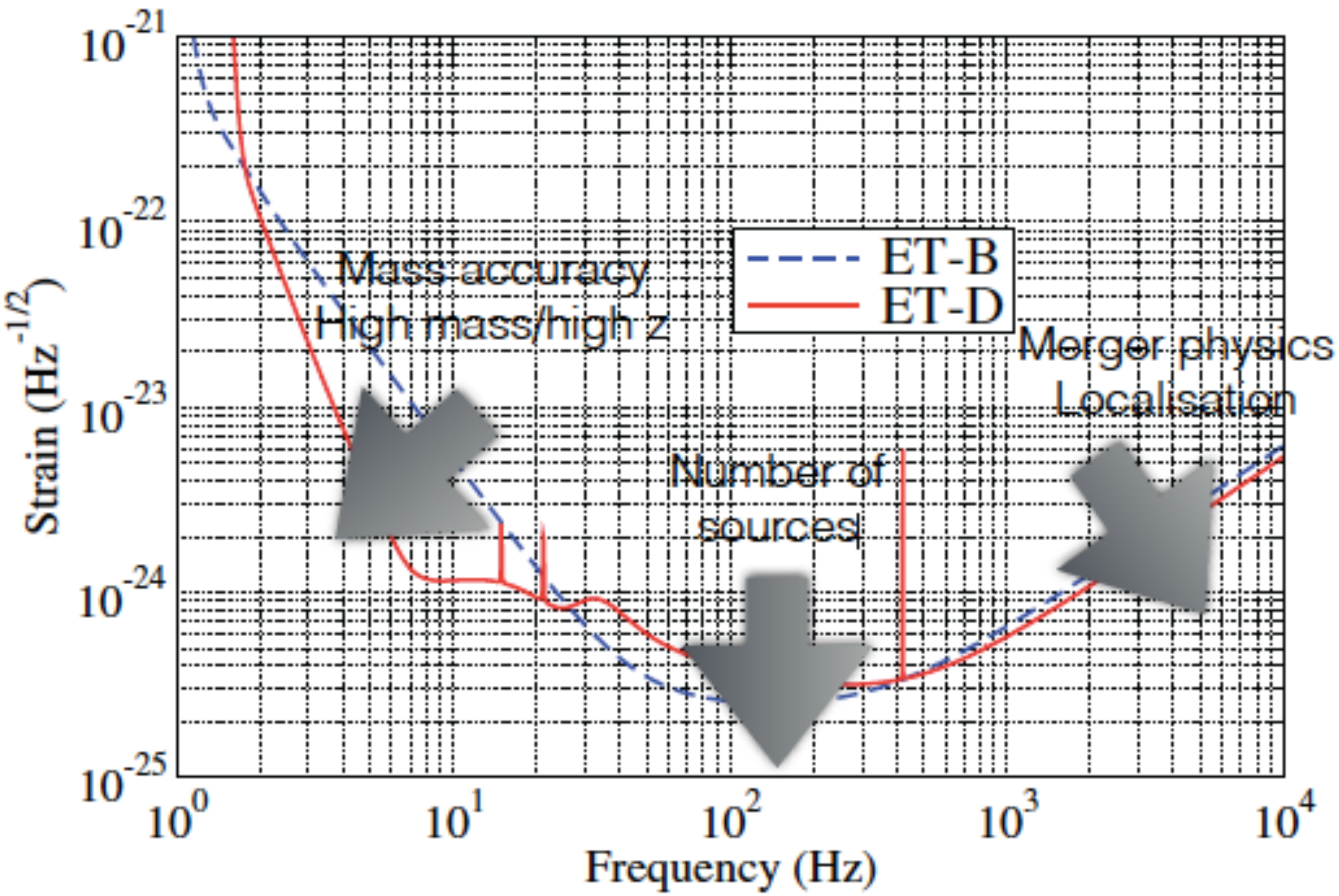
CBC vs sensitivity curve



Relevance of low and high f

FUNDAMENTAL PHYSICS	LOW FREQ	HIGH FREQ	EITHER
NS EOS	X	X	
DARK ENERGY	X		X
PN COEFF.	X	X	
STRONG FIELD TESTS		XX	
BH NO-HAIR THEOREM		XX	
PRIMORDIAL B/G	X		

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Relevance of low and high f

COSMOLOGY	LOW FREQ	HIGH FREQ	EITHER
HUBBLE CONST.	X		X
DARK MATTER	X		X
STAR FORMATION			X
ANISOTROPIC UNI.		X	
Z-MEASURE REDSHIFT		XX	
ASTROPHYSICAL B/G	XX		

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Relevance of low and high f

ASTROPHYSICS	LOW FREQ	HIGH FREQ	EITHER
RATES			X
LOCALIZATION		X	
GRB PROGENITORS	X	X	
SN, MAGNETRAS, NS		X	
MASSES AND SPINS	X		
BINARY EVEVOLUTION	X	X	
MASS GAP	X		

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Relevance of low and high f

- There are no obvious choices
  - questions addressed by low- and high- frequency improvements are both interesting
  - low frequencies improve measurement but high frequency contains strong field dynamics
- High SNR events are important:
  - for testing general relativity or measuring equation of state; but large number of events can also be used
- Large number of events are important for:
  - measuring cosmological parameters, testing astrophysical models, etc., few SNR events are not of much use
- Rare events might tell us some important physics
  - Supernovae, precessing binaries, magnetar glitches, long GRBs, …

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Questions still open in 10 years time

Astrophysics

- we would have measured the rate, confirmed also the existence of NSBH, confirmed GRB progenitors, but probably not much else
- astrophysical models would require a large (~10^3) population of sources
- it is unlikely that advanced or A+ detectors would detect SNe or magnetars
- NS ellipticities might be really low: might need to go beyond A+

Fundamental physics

- equation of state of neutron stars would require 20-30 events (or one within 50 Mpc) - possible within advanced detector era or Voyager
- ET/CE would constrain the radius to within 500 m
- dark energy equation of state - would require thousands of BNS or even 10^5 sources, will only be possible with ET/CE
- testing gravity would require 100's or even 1000's of events, again in the ET/CE era
- black hole no-hair theorem requires 10's of sources in ET

Cosmology and Cosmography

- might have measured H_0 but probably not much else
- numbers are important but no breakthrough is expected until we reach ET/CE

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Future is reach of physics

Food for brain for future generations ...