# 3G Global R&D

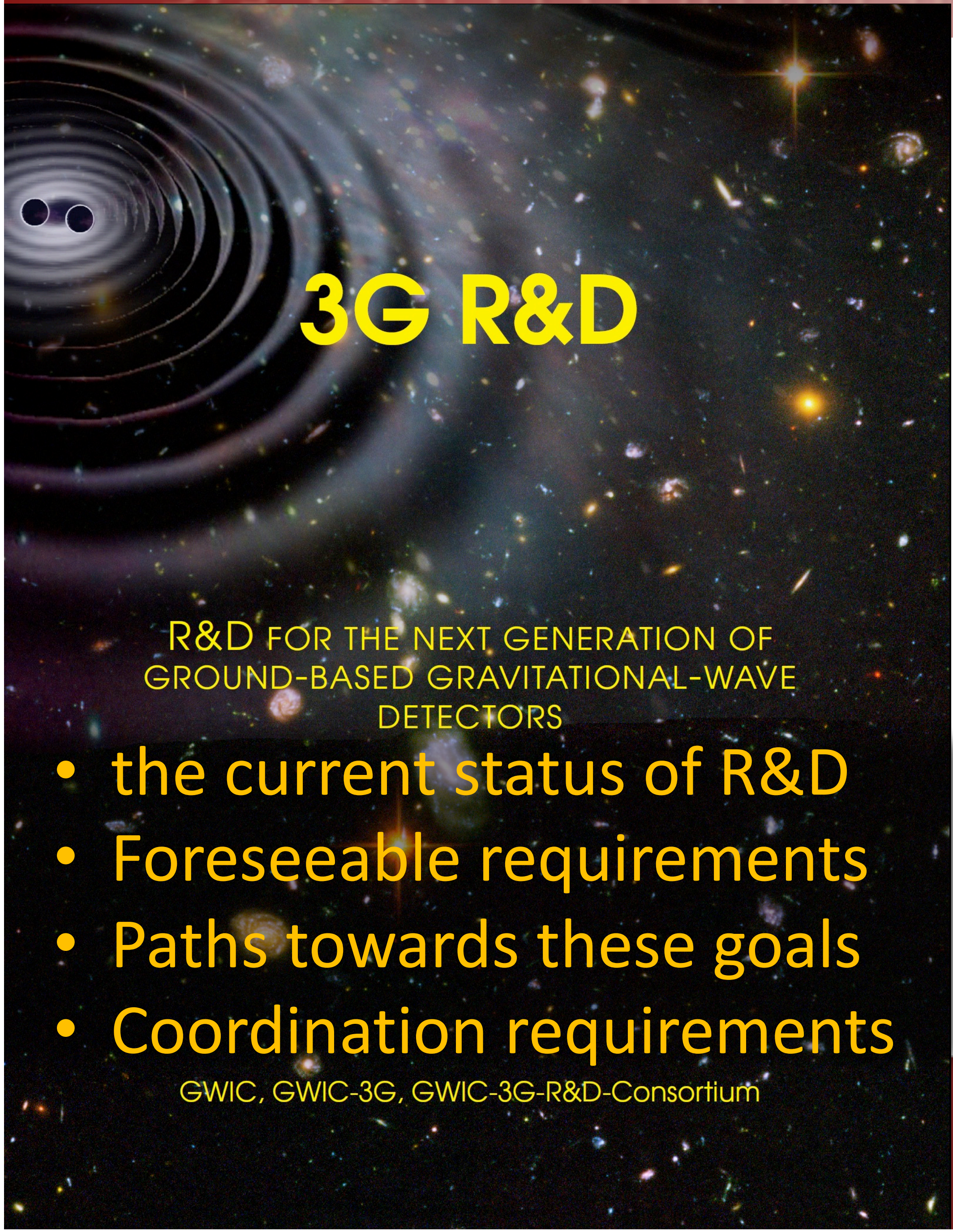
R&D needed to prepare for these detectors and the ideas about improving global coordination.

**GWIC3G R&D Subcommittee**

Chairs: David McClelland, ANU, Harald Lück, AEI

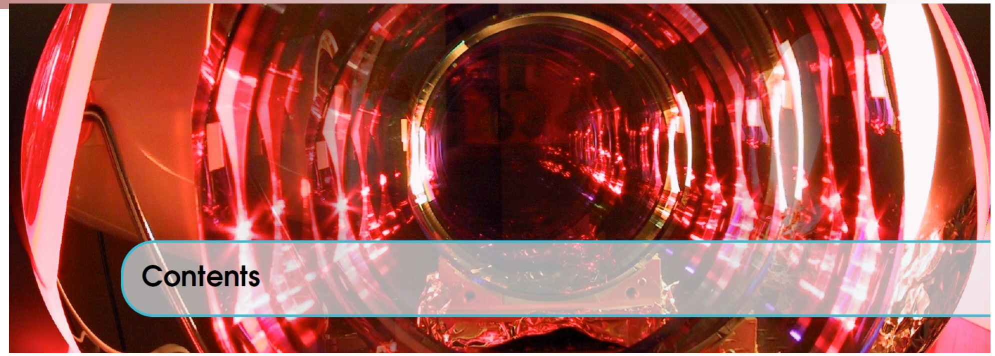
https://gwic.ligo.org/3Gsubcomm/charge.shtml

# 3G R&D coordination report




- the current status of R&D
- Foreseeable requirements
- Paths towards these goals
- Coordination requirements

GWIC, GWIC-3G, GWIC-3G-R&D-Consortium




- Facilities & Infrastructures
- Core Optics
- Coatings
- Cryogenics
- Newtonian Noise
- Light Sources
- Quantum Enhancements
- SAS & SUS
- Auxiliary Optics
- Simulation and Controls
- Calibration

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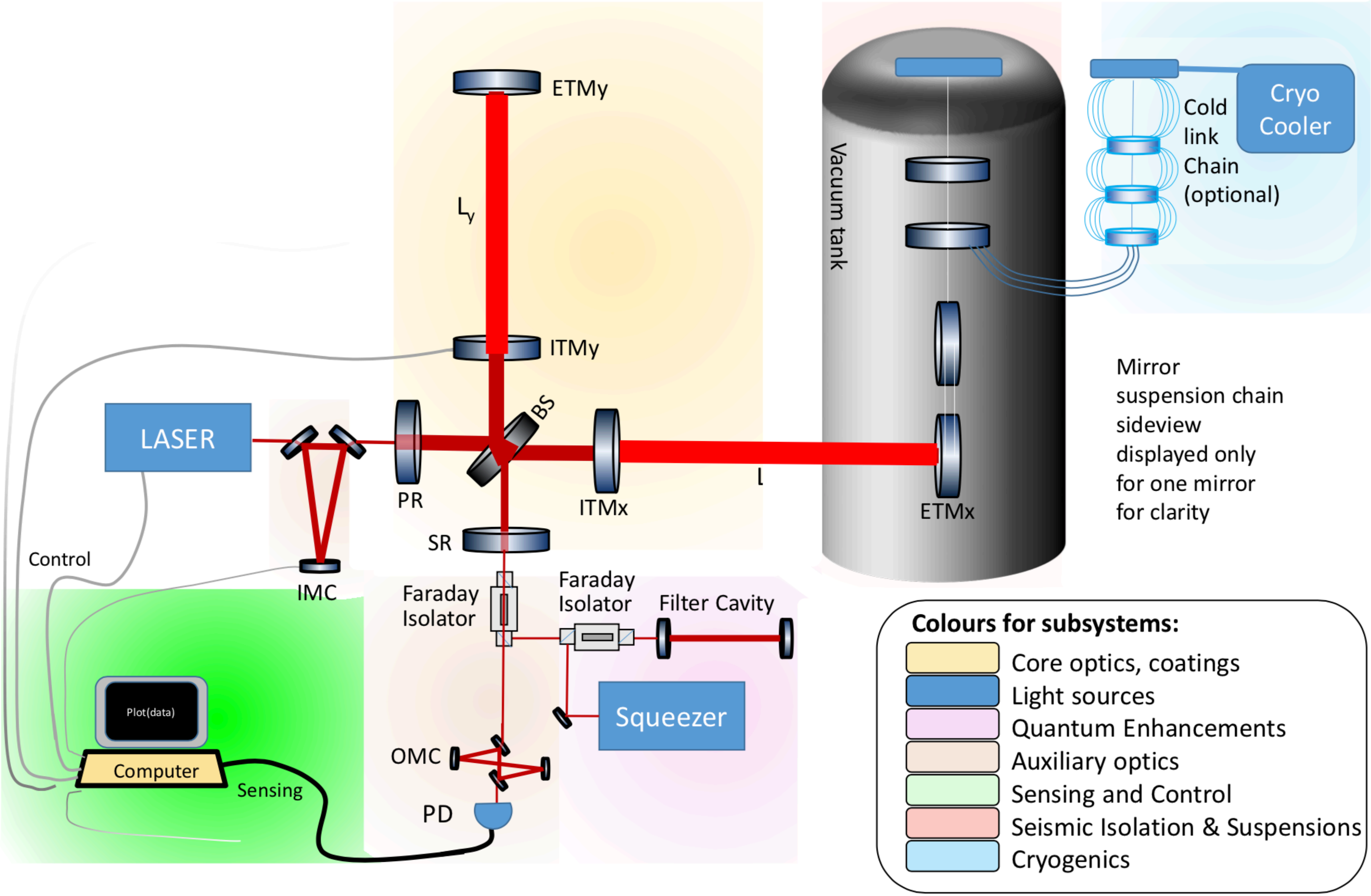
# Gravitational Wave Detection



# Fundamental noise sources

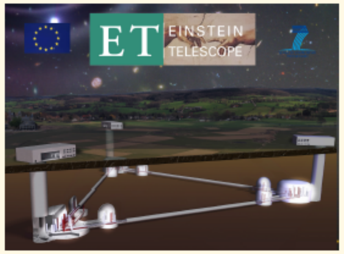
- Same fundamental noise sources -> same enabling technologies
- fundamental noise sources:
  - **Quantum noise – quantising laser (em) field**
    - modified by laser power, squeezing, low optical losses, massive mirrors and interferometer topology;
  - **Thermal (Brownian) noise – Fluctuation Dissipation Theorem**
    - in mirror substrates, coatings and suspensions is modified by temperature and material properties eg high Q (low mechanical loss), low alpha,..; and
  - **Newtonian noise - direct gravitational coupling**
    - gravitational forces of moving masses (such as air, the ground, and machinery) is modified by the location of the sites and subtraction schemes.

# GWIC 3G R&D report

- ET
  - Underground
  - Xylophone (RT+Cryo)
  - 1064nm + 1550 nm
- CE
  - 2 stages
    1. Up-scaled aLIGO technology
    2. Voyager technology
       - 123 K
       - 2 µm

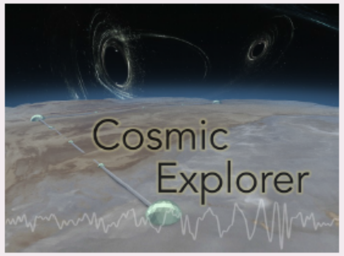
Infobox 1: **Future Gravitational Wave Observatories**

### The Einstein gravitational–wave Telescope (ET)




ET [4] is the European concept for a third generation gravitational-wave *observatory*. To reduce the effects of seismic motion, the ET concept calls for the site to be located at a depth of about 100 m to 200 m below ground. In its final configuration it shall be arranged as an equilateral triangle of three interlaced detectors, each consisting of two interferometers. The configuration of each detector dedicates one interferometer (ET-LF) to detecting the **L**ow **F**requency components of the gravitational-wave signal (2–40 Hz), while the other one (ET-HF) is dedicated to the **H**igh **F**requency components. Each interferometer will have a dual-recycled Michelson layout with Fabry-Perot arm cavities of about 10 km arm length. In ET-LF, which operates at cryogenic temperature, thermal, seismic, gravity gradient and radiation pressure noise sources are particularly suppressed; in ET-HF, sensitivity at high frequencies is improved by high laser light power circulating in the Fabry–Perot cavities and the use of frequency-dependent squeezed light technologies.

### Cosmic Explorer (CE)

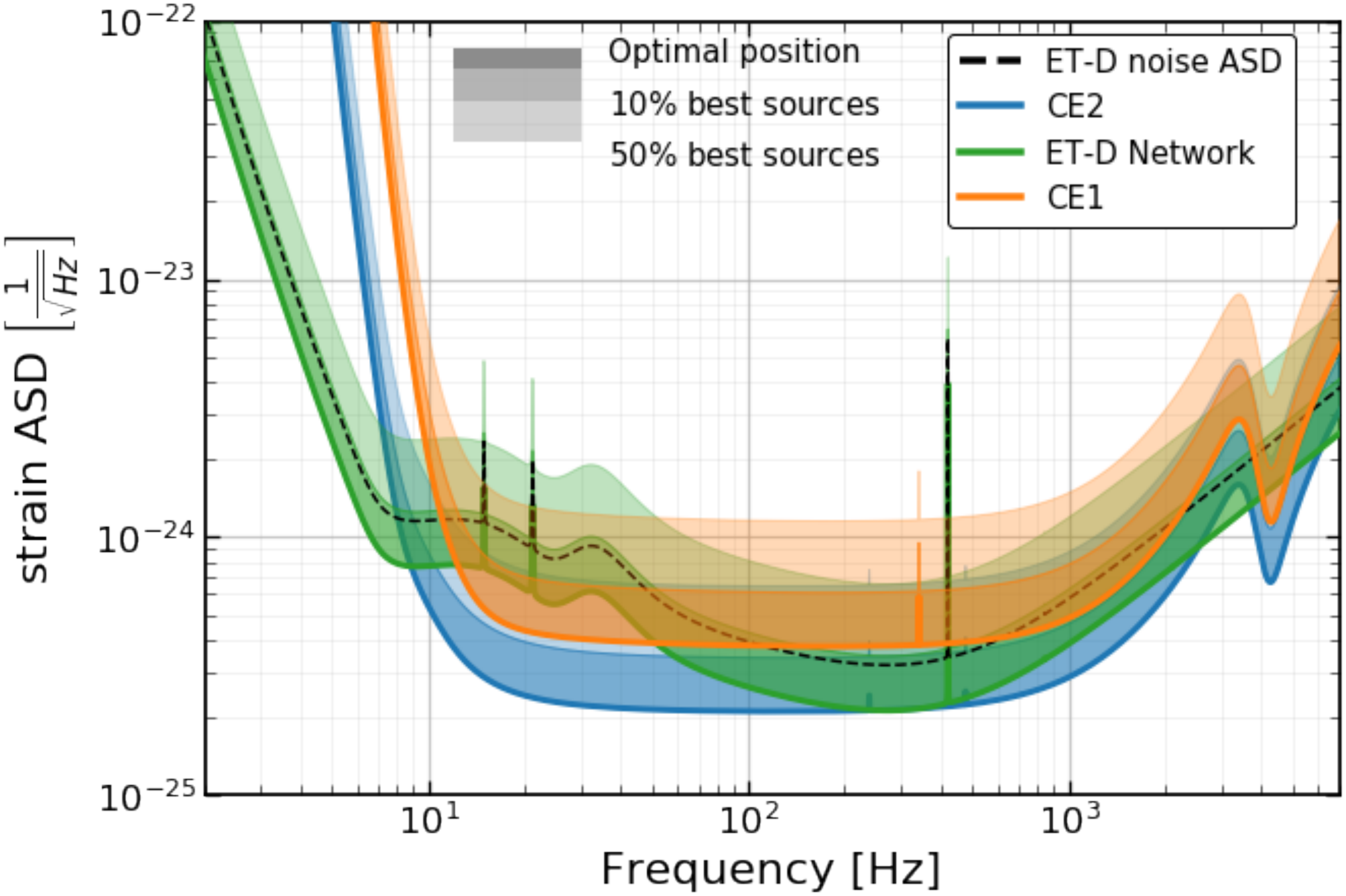



CE [5] is a US concept envisioning an L-shaped above-ground observatory with 40 km arm-length, operating a dual recycled Michelson interferometer with Fabry–Perot arm cavities. Its initial phase, called CE1, will employ scaled-up *Advanced LIGO technology* including 320 kg fused silica test masses, 1.4 MW of optical power, and frequency-dependent squeezing. A major upgrade, CE2, will exploit the full potential of the new facility by using *Voyager technology* such as silicon test masses and amorphous silicon coatings operating at 123 K, with 1.5 or 2 $\mu m$ laser light and 3 MW of optical power in its arm cavities.

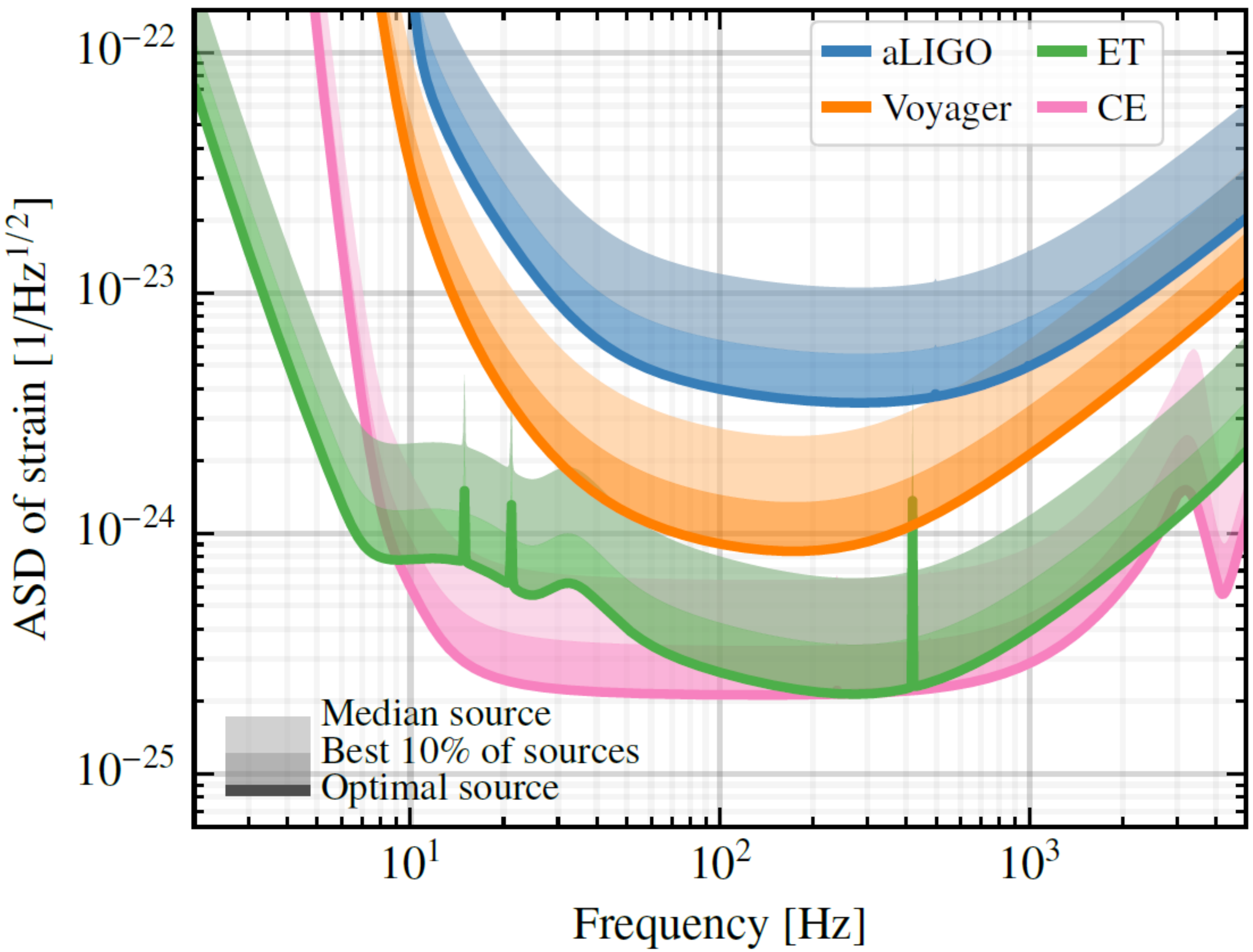
### LIGO Voyager


LIGO Voyager [6, 7] is the tentative concept for a new detector in the current LIGO observatory facilities designed to maximize the observational reach of the LIGO infrastructure and demonstrate the key technologies to be used for 3G observatories in new infrastructures. Voyager would use heavy (ca. 200 kg) cryogenic mirrors with improved coatings and upgraded suspensions made of ultra-pure silicon at a temperature of 123 K in the existing LIGO vacuum envelope and a laser wavelength of $\sim 1.5 - 2\,\mu m$. A further factor of 3 increase in BNS range (to 1100 Mpc) is envisioned along with a reduction of the low frequency cutoff down to 10 Hz. In the context of this report we use the term *Voyager Technology* for this type of technology irrespective of plans to implement it in any existing or future infrastructure.

# The goal ←→ technology



# The goal



aLIGO
ET
Voyager
CE
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^{-25}$
ASD of strain [1/Hz$^{1/2}$]
Median source
Best 10% of sources
Optimal source
$10^{1}$
$10^{2}$
$10^{3}$
Frequency [Hz]

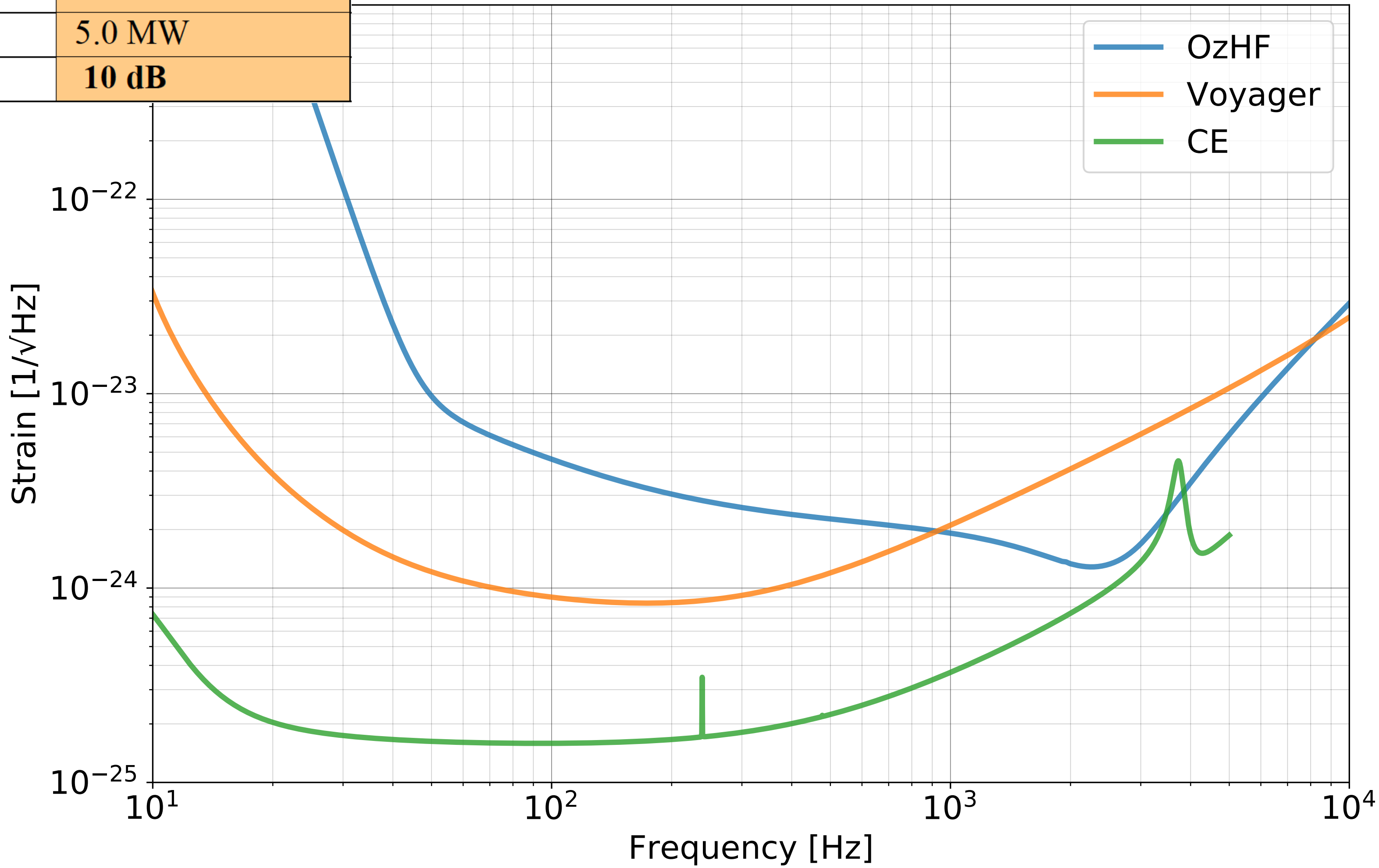
# Parameter of future GWDs

| | aLIGO / AdV | A+/V+ | KAGRA | CE 1 | CE 2 | ET-LF | ET-HF |
|---|---|---|---|---|---|---|---|
| Arm Length [km] | 4 / 3 | 4 | 3 | 40 | 40 | 10 | 10 |
| Mirror Mass [kg] | 40 / 42 | 40 | 23 | 320 | 320 | 211 | 200 |
| Mirror Material | silica | silica | sapphire | silica | silicon | silicon | silica |
| Mirror Temp [K] | 295 | 295 | 20 | 295 | 123 | 10 | 290 |
| Suspension Fiber | 0.6m/0.7m SiO2 | 0.6m SiO2 | 0.35m Al2O3 | 1.2m SiO2 | 1.2m Si | 2m Si | 0.6m SiO2 |
| Fiber Type | Fiber | Fiber | Fiber | Fiber | Ribbon | Fiber | Fiber |
| Input Power [W] | 125 | 125 | 70 | 150 | 220 | 3 | 500 |
| Arm Power [kW] | 710 / 700 | 750 | 350 | 1400 | 2000 | 18 | 3000 |
| Wavelength [nm] | 1064 | 1064 | 1064 | 1064 | 2000 | 1550 | 1064 |
| NN Suppression | 1 | 1 | 1 | 10 | 10 | 1 | 1 |
| Beam Size [cm] | (5.5/6.2) / 6 | 5.5/6.2 | 3.5/3.5 | 12/12 | 14/14 | 9/9 | 12/12 |
| SQZ Factor [dB] | 0 | 6 | foreseen | 10 | 10 | 10 | 10 |
| F. C. Length [m] | none | 300 | unknown | 4000 | 4000 | 10000 | 500 |

# High Frequency (HF) Detector

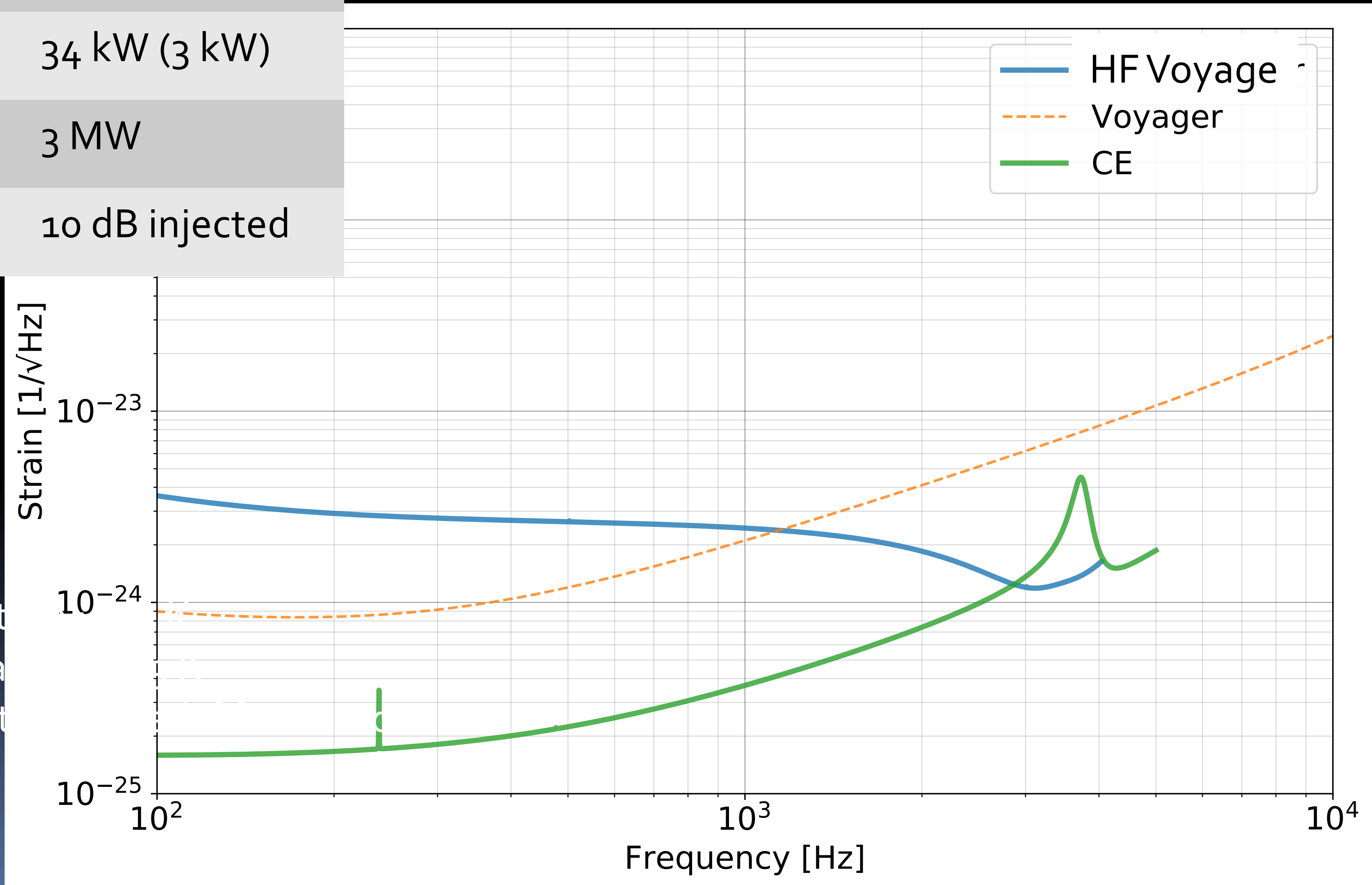
Credit: V. Adya and the OzGravHF team

| Parameter | OZHF (long SRC) |
| --- | --- |
| Wavelength | **2000 nm** |
| Mirror Mass | 94.4 kg |
| Arm length | **2 km** |
| Power recycling gain | 54 |
| Signal recycling transmissivity | 0.048 |
| Signal recycling length | **500 m** |
| Arm cavity bandwidth | 66 Hz |
| Input power | 500 W |
| Power on beamsplitter | 27 kW |
| Arm cavity power | 5.0 MW |
| Squeezing level | **10 dB** |



| Parameter | Value |
|---|---|
| SRC length | 303 m (53 m) |
| T_ITM | 0.02 (0.002) |
| P_in | 400 W (125 W) |
| P_BS | 34 kW (3 kW) |
| P_Arm | 3 MW |
| Squeezing | 10 dB injected |

# HF Voyager




ITM temperat
ETM tempera
No Filter cavit
HF only

# Executive Summary

- **New 3G infrastructure** will enable successive generations of detectors to be installed as new technologies and techniques mature.
- **Enabling technologies**: substrates, coatings, cryogenics, suspensions, Newtonian noise cancellation, lasers and quantum enhancement are **similar** at the research level. Timely progress in the development of these enabling technologies will require global collaboration and coordination.

# Executive Summary ctd.

- In order to accomplish the scientific program of the 3G network, a **broad coherent detector R&D program is needed now**, addressing key technological challenges over the next 5-7 years.
- Four areas in particular are of such a scale that global coordination will need to be accompanied by global R&D funding:
  1. facility and vacuum infrastructure;
  2. substrates;
  3. coatings;
  4. large scale prototyping for demonstration of technology readiness

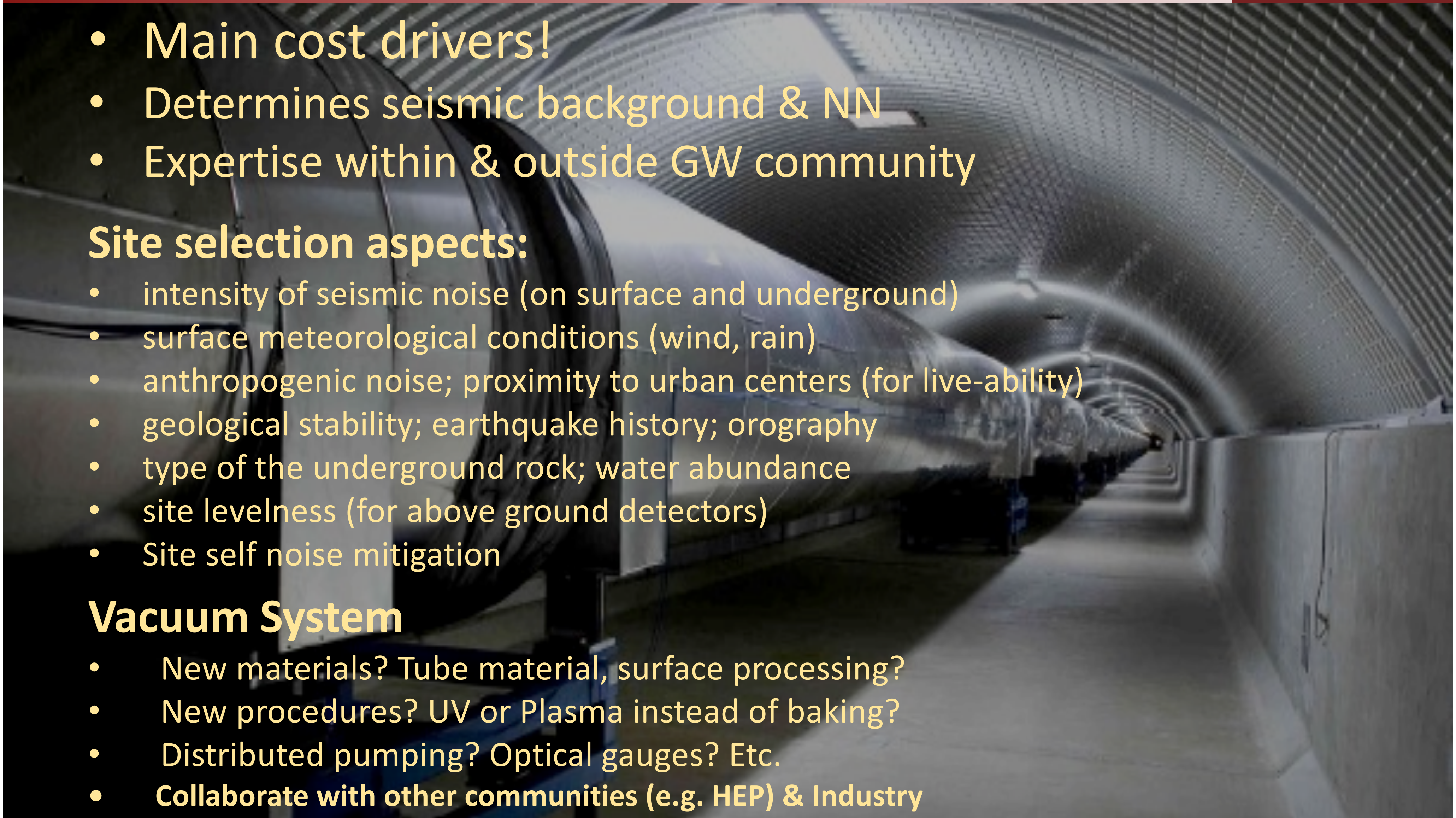
# Executive Summary ctd.

1. facility and vacuum infrastructure;
2. substrates;
3. coatings;
4. large scale prototyping for demonstration of technology readiness

- Progress in **areas 1, 2 and 3** will require significant involvement with industry, with some areas potentially requiring the field to build its own plants. *Area 1 is likely to have the greatest impact on cost.*
- **Area 4** has seen recent growth in Europe but more prototyping facilities are likely to be required.
- 3G techniques may be tested and employed to improve the sensitivity of 2G detectors.

# Site & Infrastructure

3G



- Main cost drivers!
- Determines seismic background & NN
- Expertise within & outside GW community

## Site selection aspects:

- intensity of seismic noise (on surface and underground)
- surface meteorological conditions (wind, rain)
- anthropogenic noise; proximity to urban centers (for live-ability)
- geological stability; earthquake history; orography
- type of the underground rock; water abundance
- site levelness (for above ground detectors)
- Site self noise mitigation

## Vacuum System

- New materials? Tube material, surface processing?
- New procedures? UV or Plasma instead of baking?
- Distributed pumping? Optical gauges? Etc.
- **Collaborate with other communities (e.g. HEP) & Industry**

# Core Optics

3G

- **Room temperature**:
  - **Fused Silica**, available in large size with 2D homogeneity. 3D homogeneity only for 40 kg
- **Cryogenic Temperatures**
  - **Sapphire**:
    - high absorption & scatter; Inhomogeneities
    - large size in good quality still to be developed
    - fibres ok
  - **Silicon**
    - requires λ>=1500nm, α=0@18k,124K
    - possible to reach absorption of few ppm/cm @ 124K and ca. 15ppm/cm @ 20K with MCZ grown X-tals
    - Silicon fibres needed
    - scaling

# Coatings

3G

- Multiparameter challenge
  - λ = 1064nm, 1550 nm, 2 μm
  - T= 293K, 124 K, 10K
  - Material, technology
    - amorphous dielectric (IBS)
    - amorphous semiconductor (aSi, SiN) LPCVD
    - X-tal (Al_GaAs, Al_GaP) (MBE)
    - Multimaterial combinations

best path not yet known

# Coatings



**Theoretical µ-scopic understanding improving**
**Multi-Institutional challenge;**
**Follow mutliple approaches**
**and define decision points**

**Need more characterisation facilities**

- **optical (absorption, scatter, homogeneity)**
- **thermal noise (indirect via mechanical losses and direct)**

- **Single large coating supplier risk**

# Cryogenics

3G

**Operating temperatures: 10-20K, 124K, (293K)**

| Cryogenic interferometers | | | |
|---|---|---|---|
| Interferometer | Mirror Temperature [K] | Mirror Material | Suspension |
| CLIO | 20 K | Glass | Steel wires |
| KAGRA | 20 K | sapphire | sapphire fit |
| ET | 20 or 123 K | silicon | silicon |
| CE | 123 K | silicon | silicon ribb |
| Voyager | 123 K | silicon | silicon ribb |

**Cryo challenges:**

- **quietness**
- **underground operation**
- **heat removal through suspensions @ cryo temps**
- testing and improving the best candidate cooling technologies in terms of cooling power, vibration level, safety and ready these technologies for implementation

**Coordination/Collaboration:**

**internally (KAGRA, Voyager) and externally HEP**

**Cryo Prototypes needed for testing various aspects**

# Newtonian Noise

3G

**Character of NN and the choice of the 3G sites are strongly interdependent.**

- **NN criteria be incorporated into any site evaluation,**
- **Infrastructure and facilities be designed to mitigate and minimise NN**

**Needs:**

- **Atmospheric density field monitors (surface det.) Sound fields (underground det.)**
- **Accoustic and seismic self-noise mitigation Improved models of seismic and atmospheric NN coupling**
- **NN subtraction schemes (above/below ground)**

# Light Sources

3G

**Lasers:** Define power requirements for each wavelength

- ET:
  - ET-HF: 500 W 1064 nm
  - ET-LF: 3W, 1550 nm, TEM00
- CE: 200-500W, ~2µm, TEM00

Stability requirements: TBD

**Squeezers:**

Squeezed vacuum source with > 15 dB squeezing level for λ = 1064nm, 1550nm, 2µm

# Quantum Enhancements

3G

FD Squeezing as baseline for all 2G+ and 3G observatories

Requirements:

- High QE PDs needed **for all wavelengths**
- Extremely low optical losses of all components
- Demonstrate 10 dB of effective squeezing
- Low noise control schemes for filter cavities
- Prototypes for testing other QND schemes
- Development of unified classification scheme of QND techniques and a common approach to analysing and comparing their performances

# Suspension and Isolation Systems

3G

**Room Temperature**:

- Fused Silica suspension systems well established (GEO600, AdV, aLIGO),
  well developed solutions for 2.5G
- SAS scalable; will benefit from improved sensors (TBD)
- Combine best of aLIGO and AdV SAS

**Cryogenic Temperatures:**

Sapphire fibres @ 20K in KAGRA

# Suspension and Isolation Systems

3G

- KAGRA is a ground-breaking pioneer

Need

- Robust techniques for handling thinner fibres and heavier masses
- X-tal fibre production
- Frequency tuning for thick heat removal fibres/ribbons
- Low mechanical loss coatings for radiative cooling @ 124K,
- Investigation of 'Out of thermal equilibrium effects'
- Develop suitable sensors and actuators for cryogenic use
- Reducing cooling time
- Prototypes needed soon (10-15y timescale to develop SAS/SUS to implementation readiness)

# Auxiliary Optics

3G

**Input Optics**
- Input Telescope
- EOMs
- FI
- AOMs

**Active Wavefront Control**
- Bulls-Eye
- Hartmann
- Phase Camera
- Actuators

**Aux Optics R&D Needs**
- Lower losses for OO
- Mostly fine for 1064nm and 1550nm
- Little known for 2µm

**Output Optics**
- Output Telescope
- OMC
- High QE-PD
- OFI
- FC
- BHD

**Stray Light Control**
- Baffles
- Path length control/stabilisation

**Size of subsystem underestimated! “Only Aux. Optics“**

**Others**
- Aux Length Sens. System
- Optical levers
- SPI

# Simulation & Control

3G

**Interferometer Noise Calculators**

- GWINC

SimPlant

Ray Tracing

- IfoCAD
- OptoCAD

**Frequency Domain**

- FFT propagation
  - SIS
  - OSCAR
  
    DarkF
- Modal Analyses
  - Optickle
  - FINESSE
  - MIST

**Time Domain**

- Siesta
- E2E

**Modelling support needed for**:

- High-power operation at low optical loss.
- Squeezed light in higher-order modes
- Improved thermal compensation systems
- Improved mode matching techniques
- Scattered light control
- Modelling of backscatter of detection optics and interferometer scatter.
- Include noise injection with specific coherence into interferometer modelling tools
- Non-sequential ray-tracing. Monte-Carlo methods.
- Control design: Make better models of control by developing more effective tools for analyzing in-loop cross coupling of a mixed mechanical, optical and electronic system, and for the analysis of modern control strategies.
- Advanced quantum noise schemes, development of a robust 'fundamental' quantum limit.
- Modelling of quantum correlations through complex MIMO systems.
- Add polarization to ifo models
- NN
- Comprehensive mechanical simulation tool for various SAS &SUS designs including thermal noise for any configuration

# Control

3G

**Low Noise operation**
Huge dynamic range esp. @ LF

**Non-linear lock acquisition**
Transition from highly non-linear behaviour to linear „locked“ regime. Need fast & reliable procedures

**Noise cancellation**
- linear stationary noise cancellation techniques are already implemented
- the residual noise couplings are bound to be either non-linear or non-stationary.
- control strategies for Non-LTI systems needed → Machine Learning methods promising

**Optimisation**
- Systematic methods to explore parameter spaces of control systems; robust automated filter design
- Optimal MIMO sensing, control, and system identification methods
- Needs a combination of offline DA and simulations

Control schemes should be developed and tested early as an integral part of detector designs.

**Robustness**
System must withstand varying external disturbances
→ Multi state configuration („ride out earthquakes“)

# Calibration

3G

3G observatories will produce signals with SNR ~1000

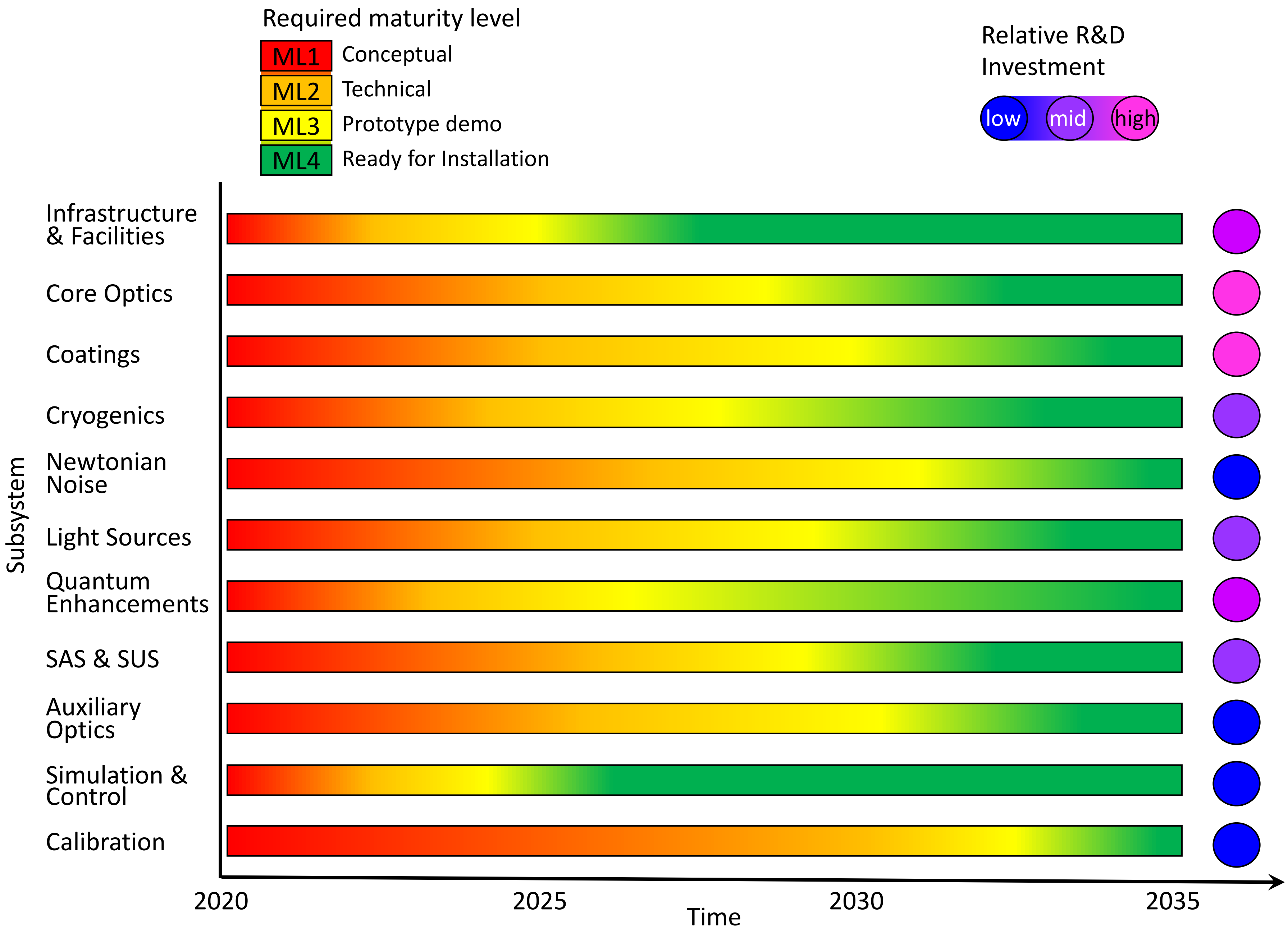
To extract optimal science **calibration errors of < 0.5%** will be required

Currently used:

- Estimates of sensing and actuation systems
- Photon pressure calibrator (E=0.8%)
- Newtonian calibrator (E< 0.2% [with PCAL,KAGRA])
- Astrophysical sources (e.g. BNS, ca. 10%)

# Timelines for subsystems

3G



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Very valuable comments.
Thank you!
Some still
to be incorporated

# The Global Network c. 2030+