LIGO

The Promise of Future Gravitational-Wave Interferometers

Colliders and Beyond
June 26 2014
Trieste, Italy

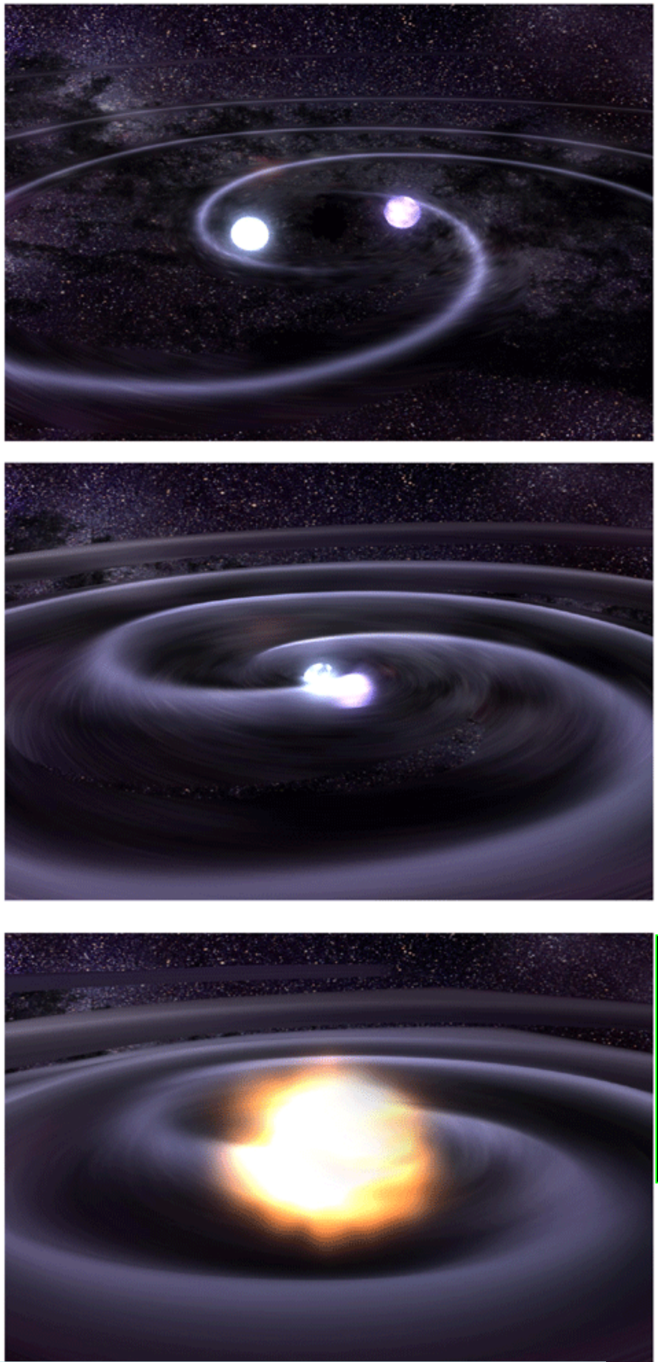
Stefan Ballmer
Syracuse University
for the LIGO collaboration

LIGO

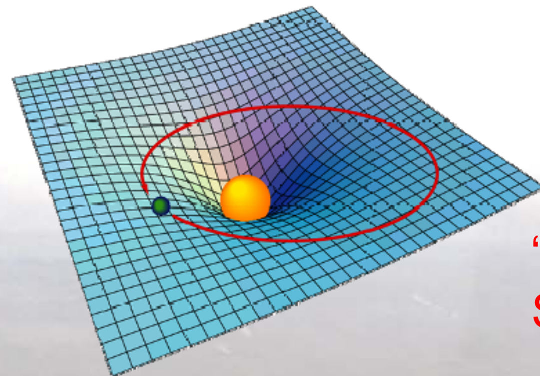
Outline

- Current status
  - LIGO (with detail), Timeline
  - Virgo, Kagra
- Limitations for sensitivity
- Other applications of GW interferometers

Gravitational Waves



NASA/Dana Berry, Sky Works Digital



$$G_{\mu\upsilon} = \frac{8\pi G}{c^4} T_{\mu\upsilon}$$

"Curvature of Space-Time"   "Matter"

Einstein's Equations:

When matter moves, or changes its configuration, its gravitational field changes. This change propagates outward as a *ripple in the curvature of space-time* : a gravitational wave.

GW Astronomy Science Goals

- Fundamental Physics
  - Is GR the correct theory of gravity?
  - Do black holes really have "no hair" ?
  - What is the neutron star equation of state?
- Astrophysics
  - What is the black hole mass distribution?
  - How did supermassive BHs grow?
  - What are the progenitors of GRBs?
- Cosmology
  - Can we directly see past the CMB?

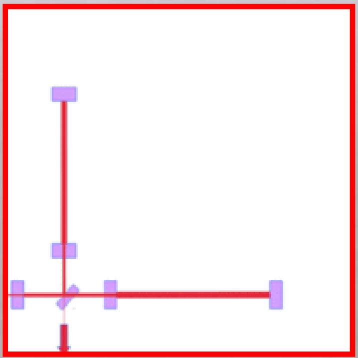
The wave’s field

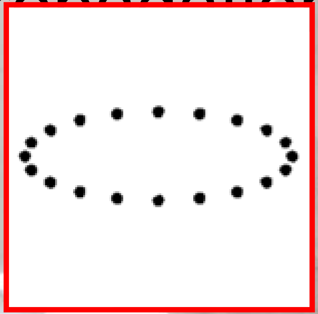
- “Ripples in Space-Time”
- Measureable effect:
  – Stretches/contracts distance between test masses perpendicular to propagation

Amplitude:

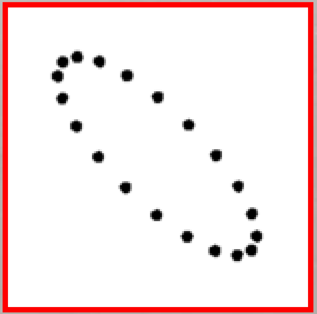
dL/L = h

Image credit: Google





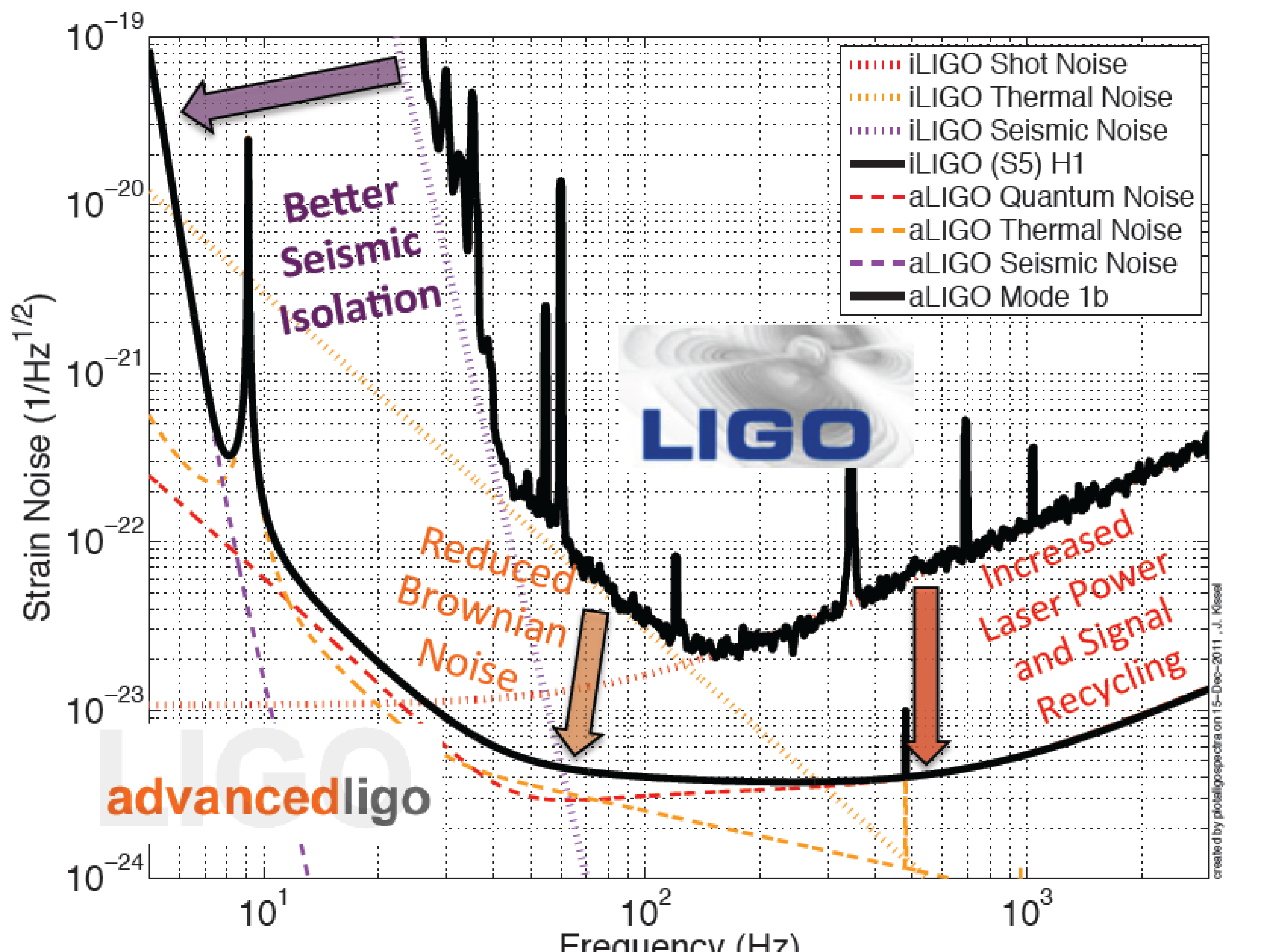
+ polarization



x polarization

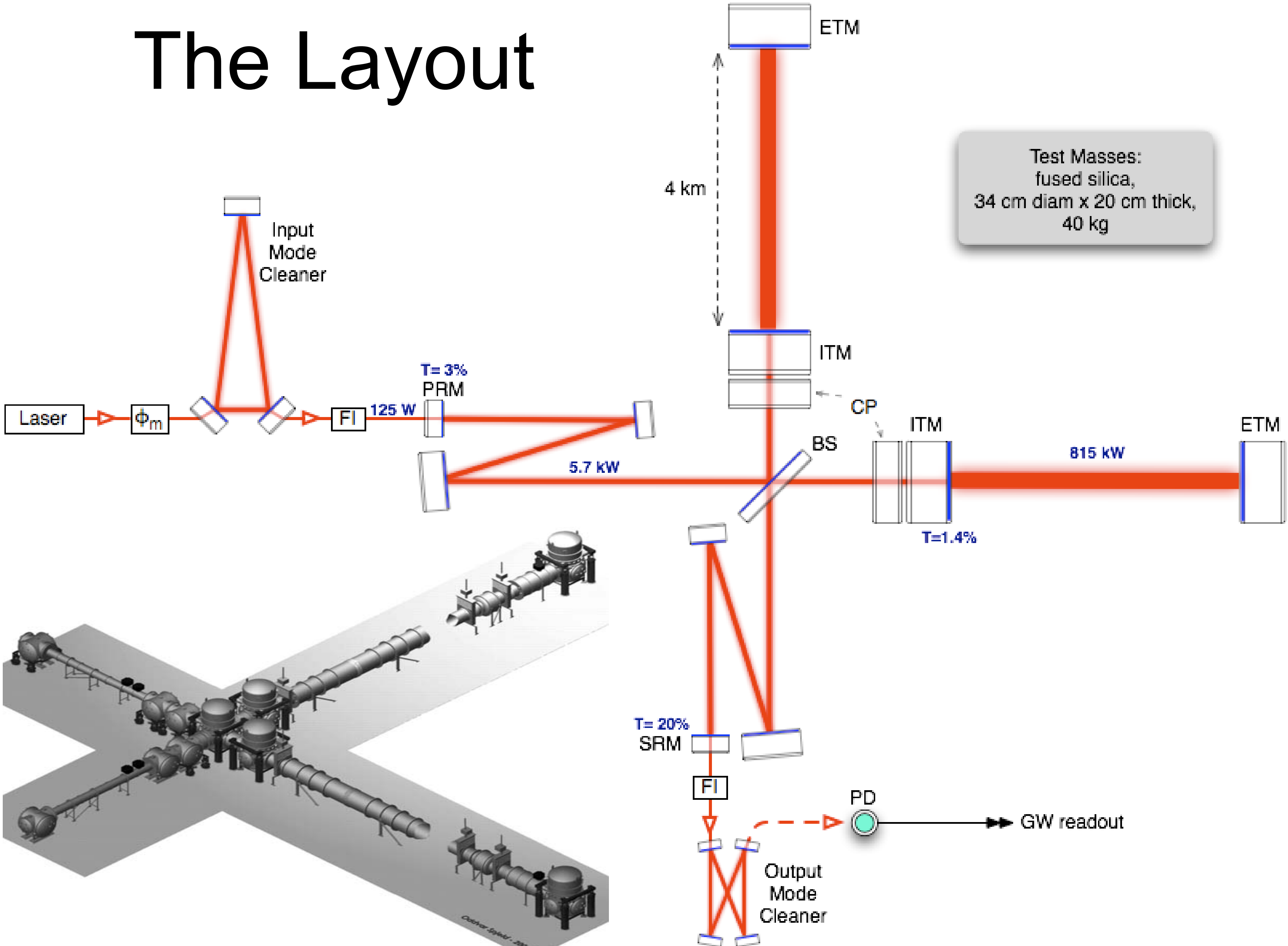
LIGO Livingston Observatory

LIGO Hanford Observatory



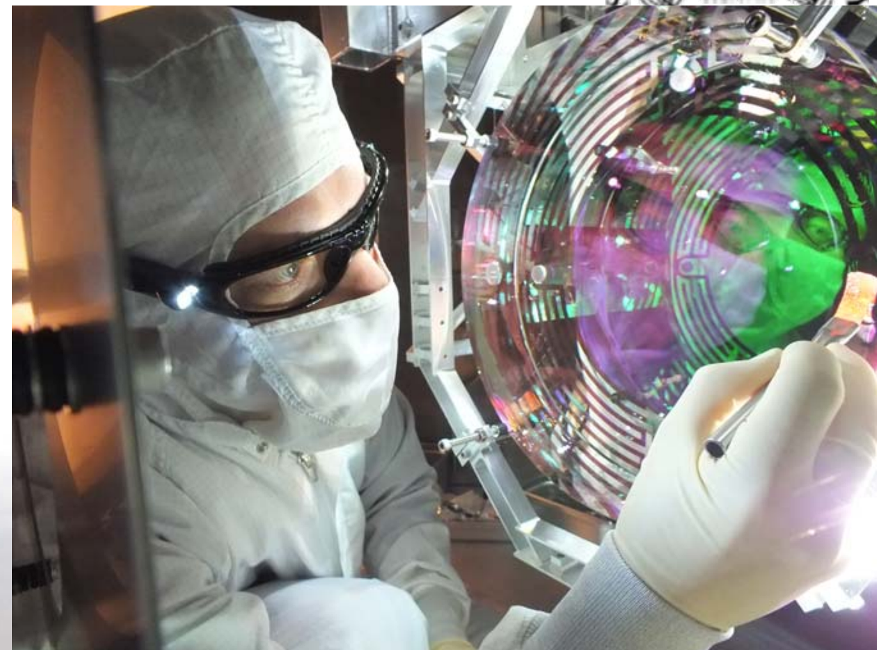
iLIGO Shot Noise
iLIGO Thermal Noise
iLIGO Seismic Noise
iLIGO (S5) H1
aLIGO Quantum Noise
aLIGO Thermal Noise
aLIGO Seismic Noise
aLIGO Mode 1b
Better Seismic Isolation
Reduced Brownian Noise
Increased Laser Power and Signal Recycling
LIGO
advancedligo
Strain Noise (1/Hz$^{1/2}$)
Frequency (Hz)
10^{-19}
10^{-20}
10^{-21}
10^{-22}
10^{-23}
10^{-24}
10^{1}
10^{2}
10^{3}
created by plotaligospectra on 15-Dec-2011 , J. Kissel

The Layout


ETM
4 km
ITM
Test Masses:
fused silica,
34 cm diam x 20 cm thick,
40 kg
Input
Mode
Cleaner
T= 3%
PRM
Laser
Φ_m
FI
125 W
5.7 kW
CP
ITM
ETM
BS
815 kW
T=1.4%
T= 20%
SRM
FI
PD
GW readout
Output
Mode
Cleaner

The Advanced LIGO Detectors
The Test Masses

LIGO

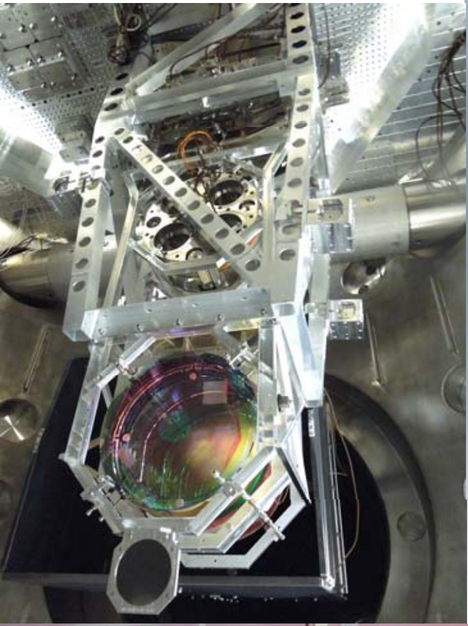


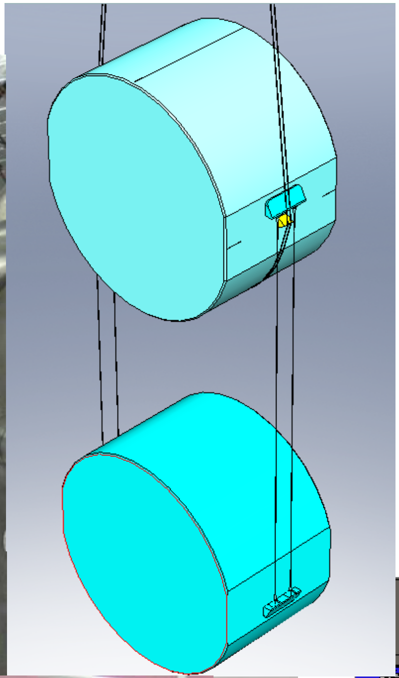
Reduce to photon pressure noise
- -large!

Reduce Brownian noise
- Lower Mechanical Loss
- Large surface area

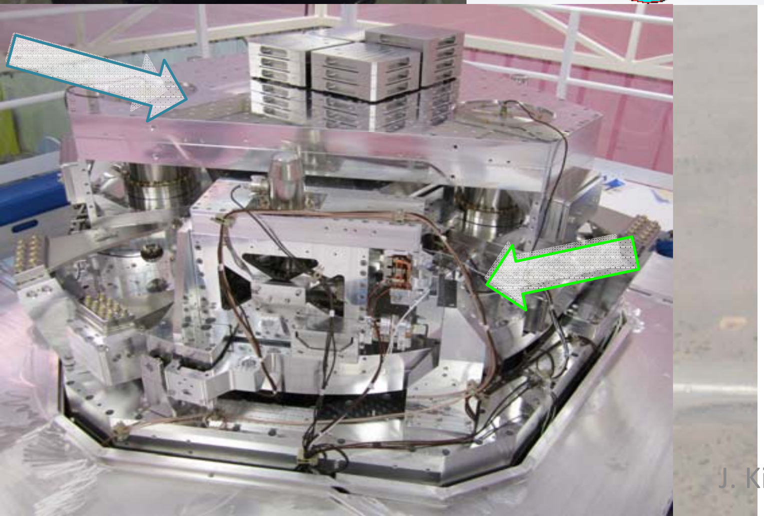
Diameter	**34 cm**
Thickness	**20 cm**
Mass	**40 kg**
1/e Beam Size	**6.2 cm**

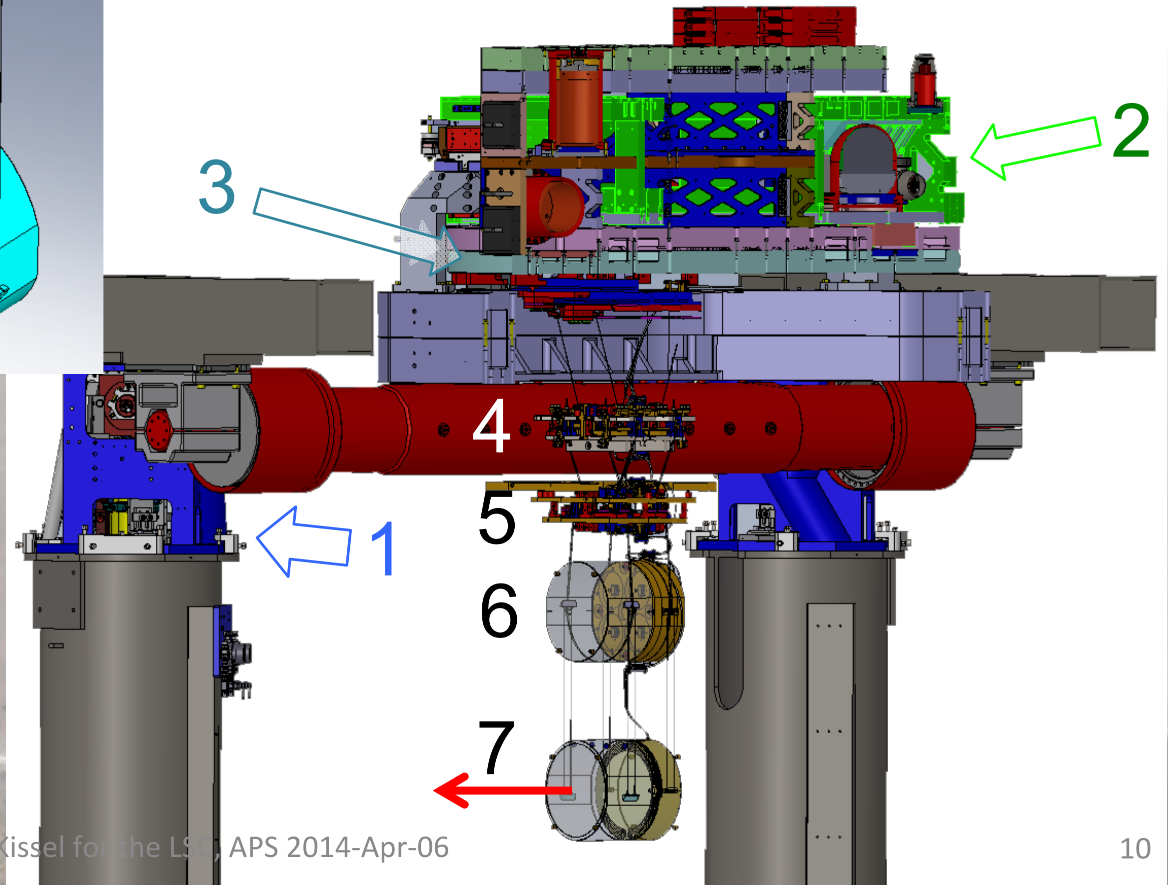
The Advanced LIGO Detectors
Seismic Isolation





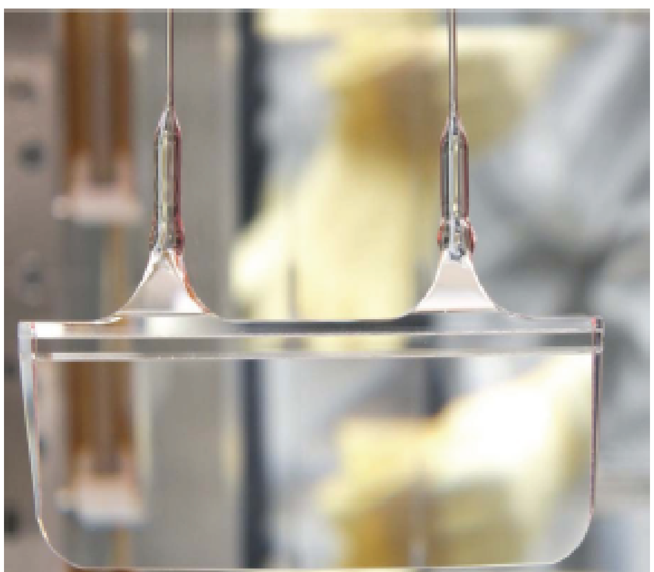
Last two stages are monolithic to improve Brownian noise

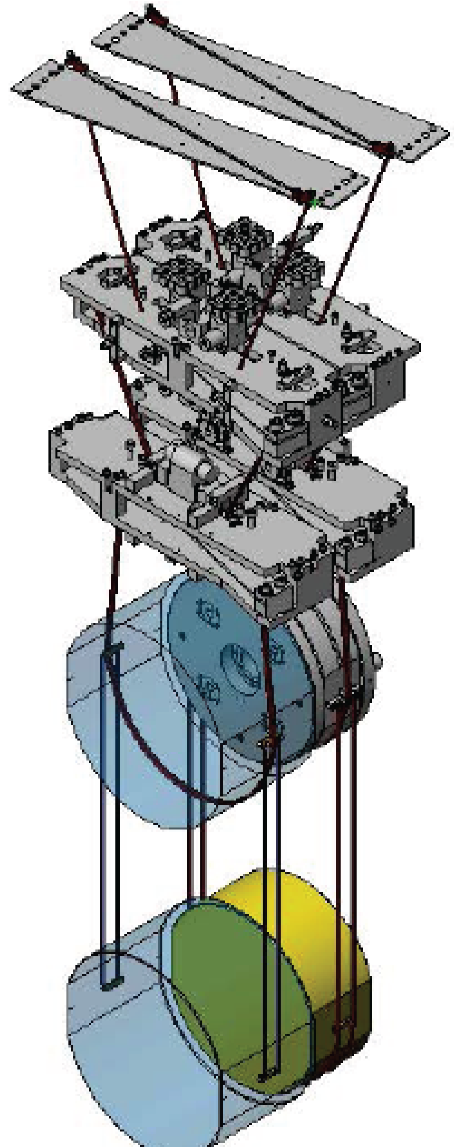




Test Mass Quadruple Pendulum Suspension

- Test masses are suspended with fused silica fibers (d=400 um) to minimize thermal noise
- Main chain recoils against the quiet reaction chain. Magnet-coil actuators on top stages, electro-static on the test mass.
- Laser welded
- Measured violin mode Q-factors ~10^9 (f_{violin}~500 Hz)

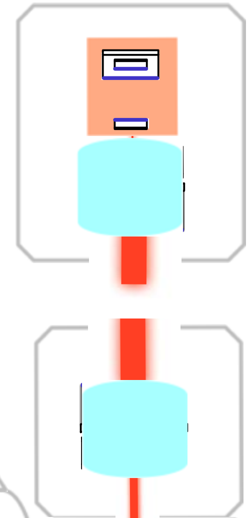


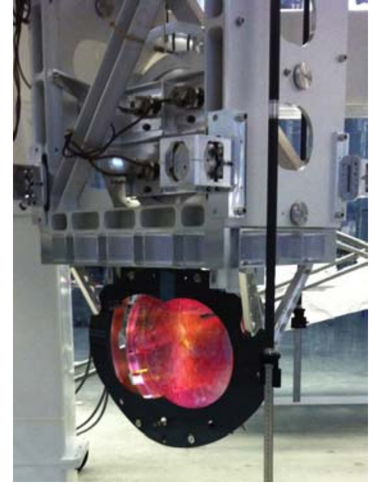


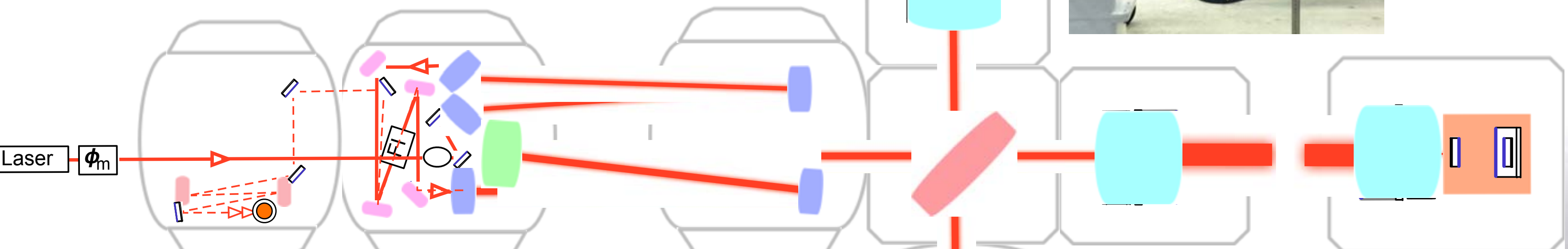
The Advanced LIGO Detectors
Seismic Isolation

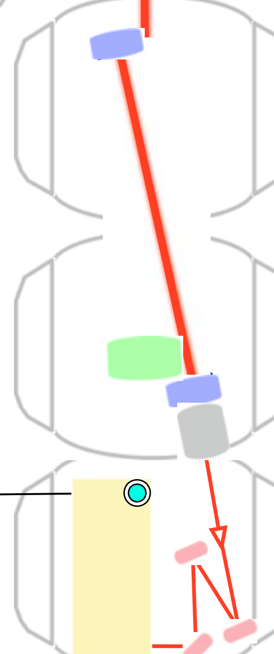
Test Masses are not the only thing that needs isolation…

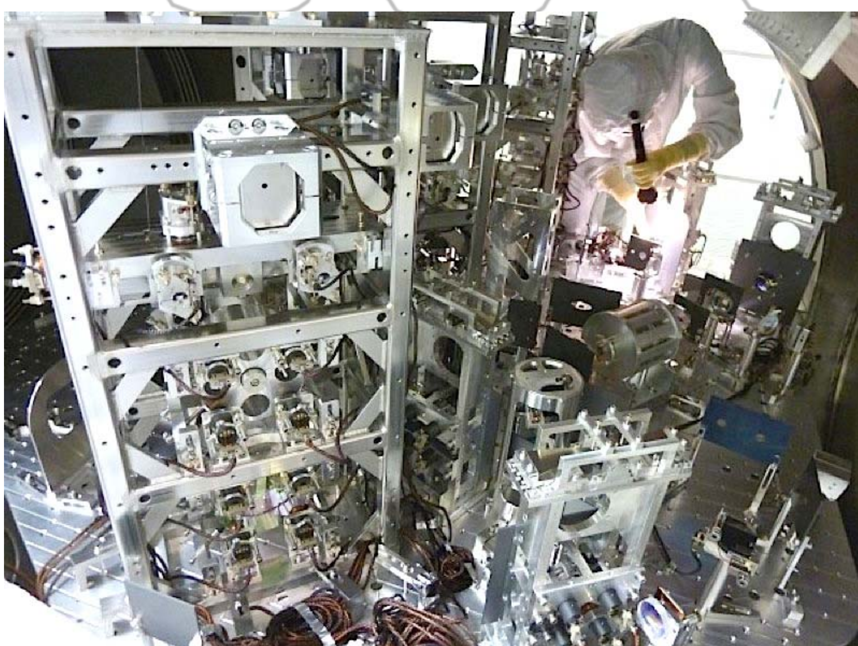
Interferometer is a zoo of seismic isolation!

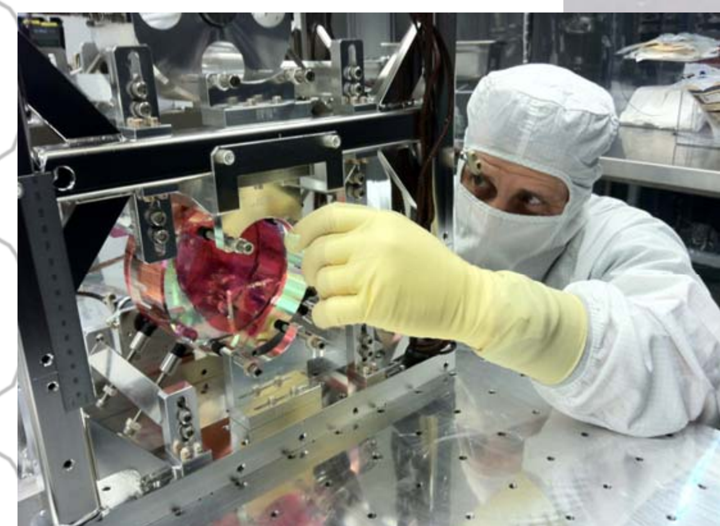




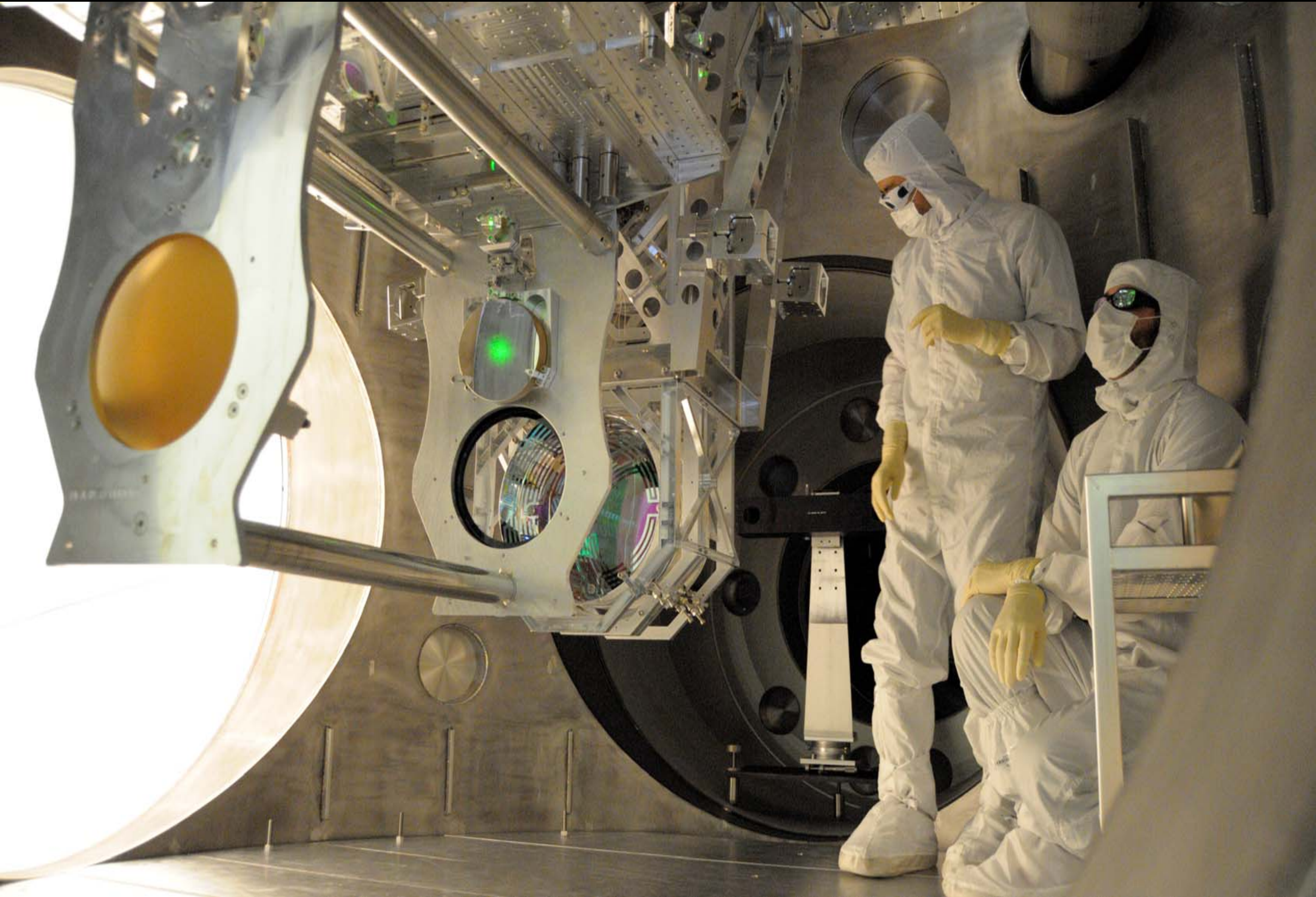






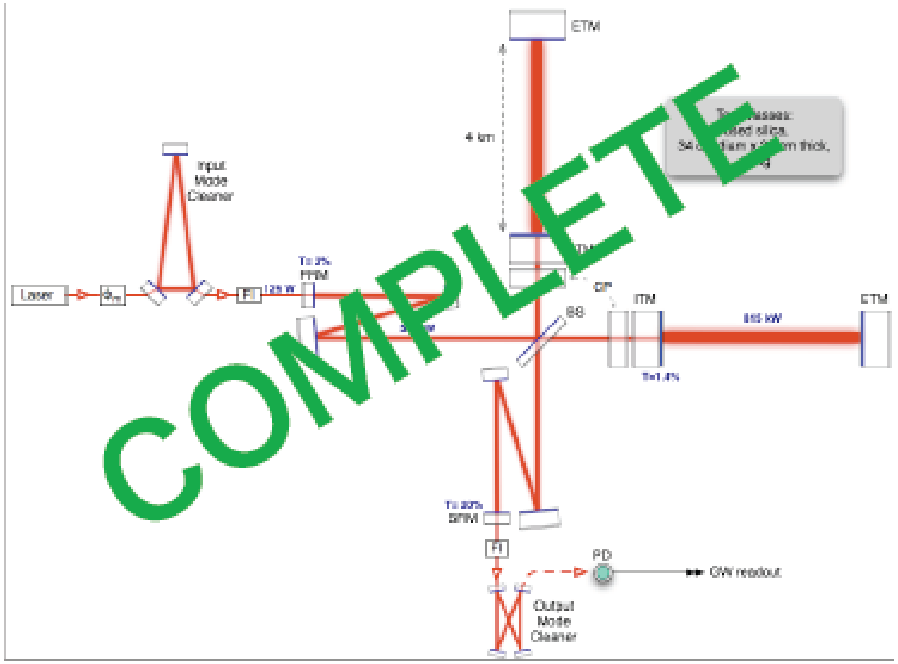


Advanced LIGO installation almost complete

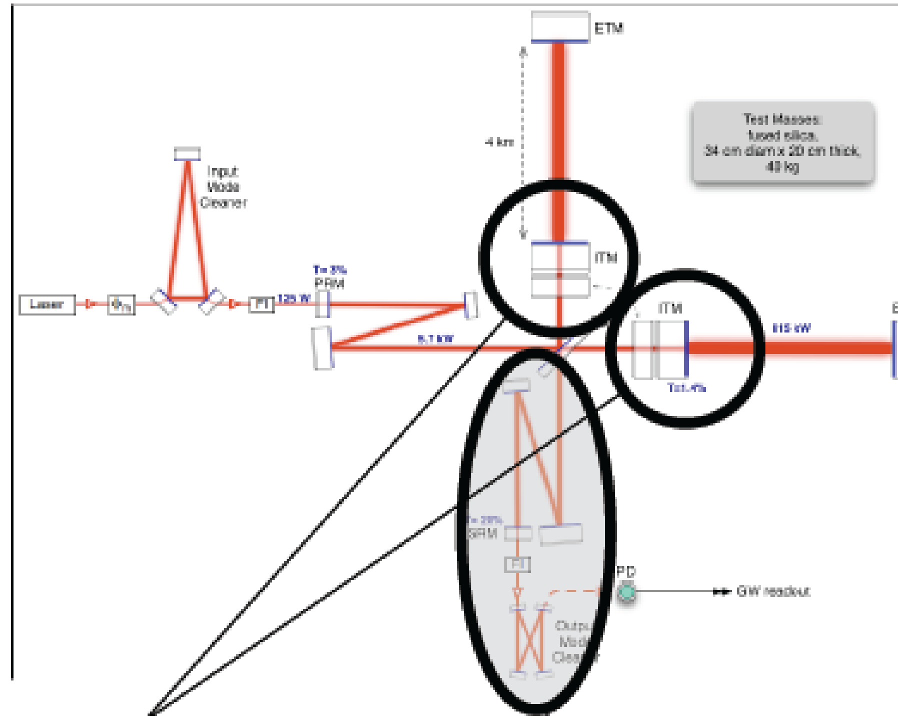


Installation Status

Linvingston

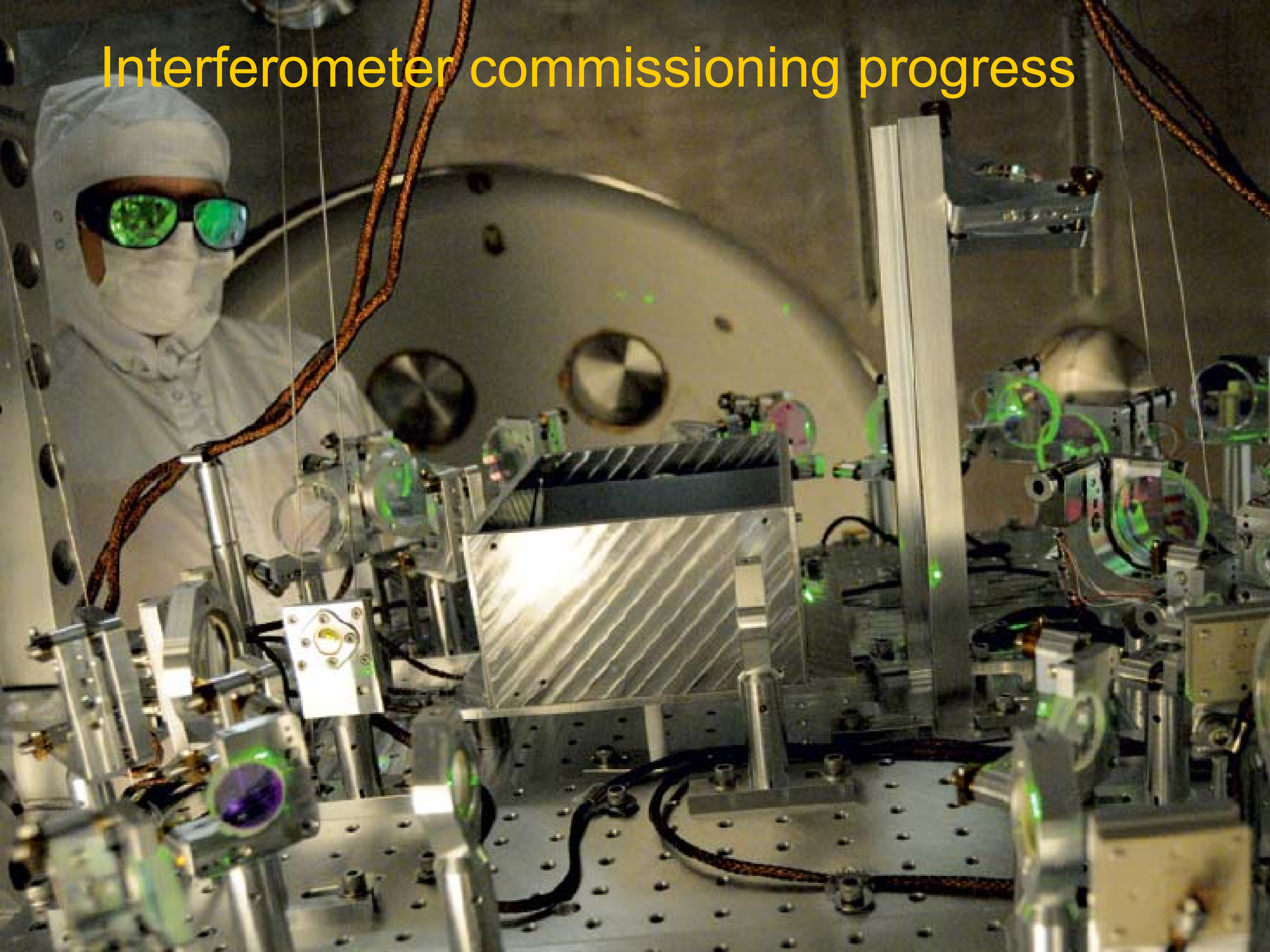


Hanford



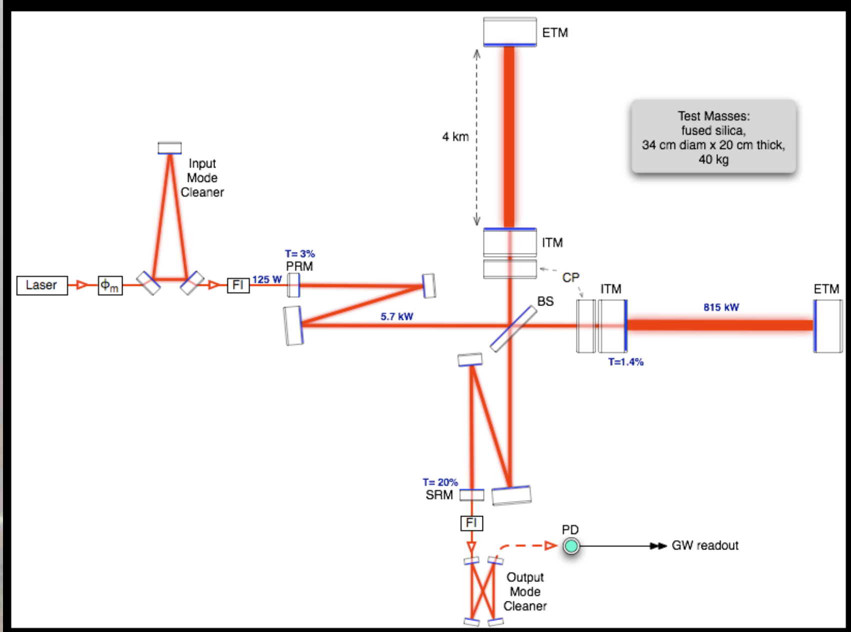
Currently installing
and aligning

Interferometer commissioning progress

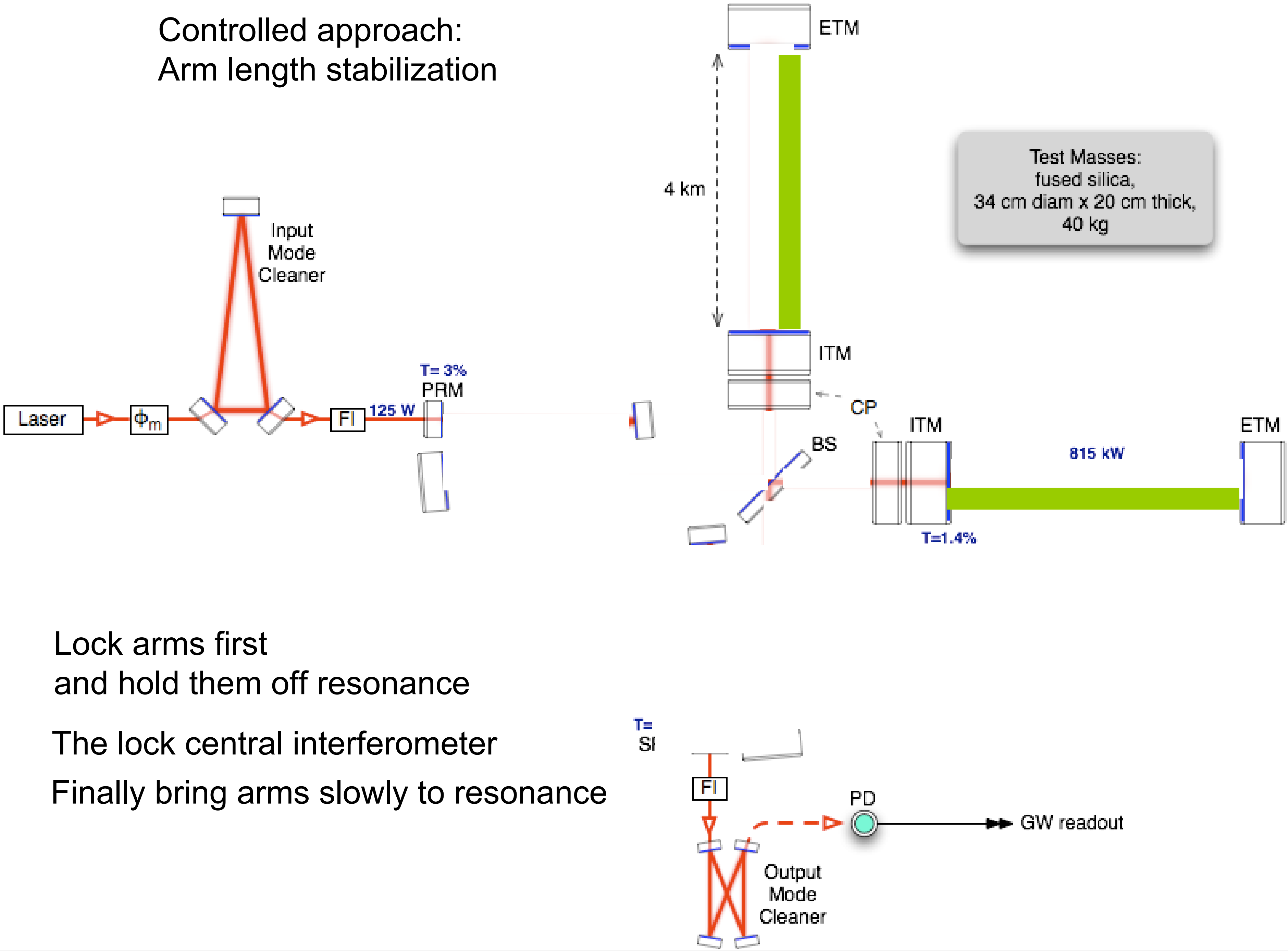


LIGO Lock Acquisition

- All 5 main cavities/path length need to be brought to resonance. ("Locking")
  - Too many degrees of freedom
  - Non-linear error signal, "false" locks
  - Too small actuation range on test masses



Controlled approach:
Arm length stabilization



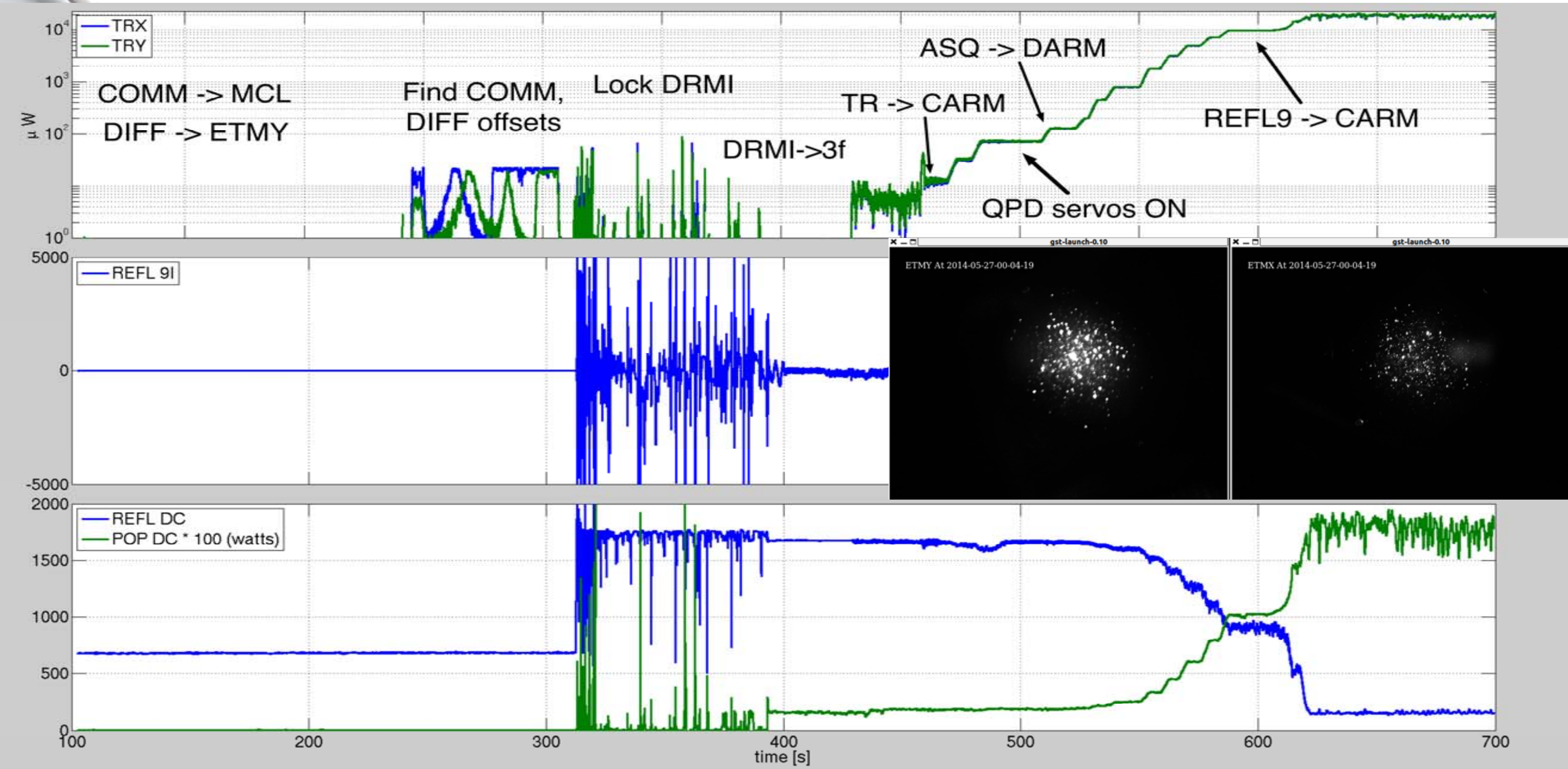
Lock arms first
and hold them off resonance

The lock central interferometer

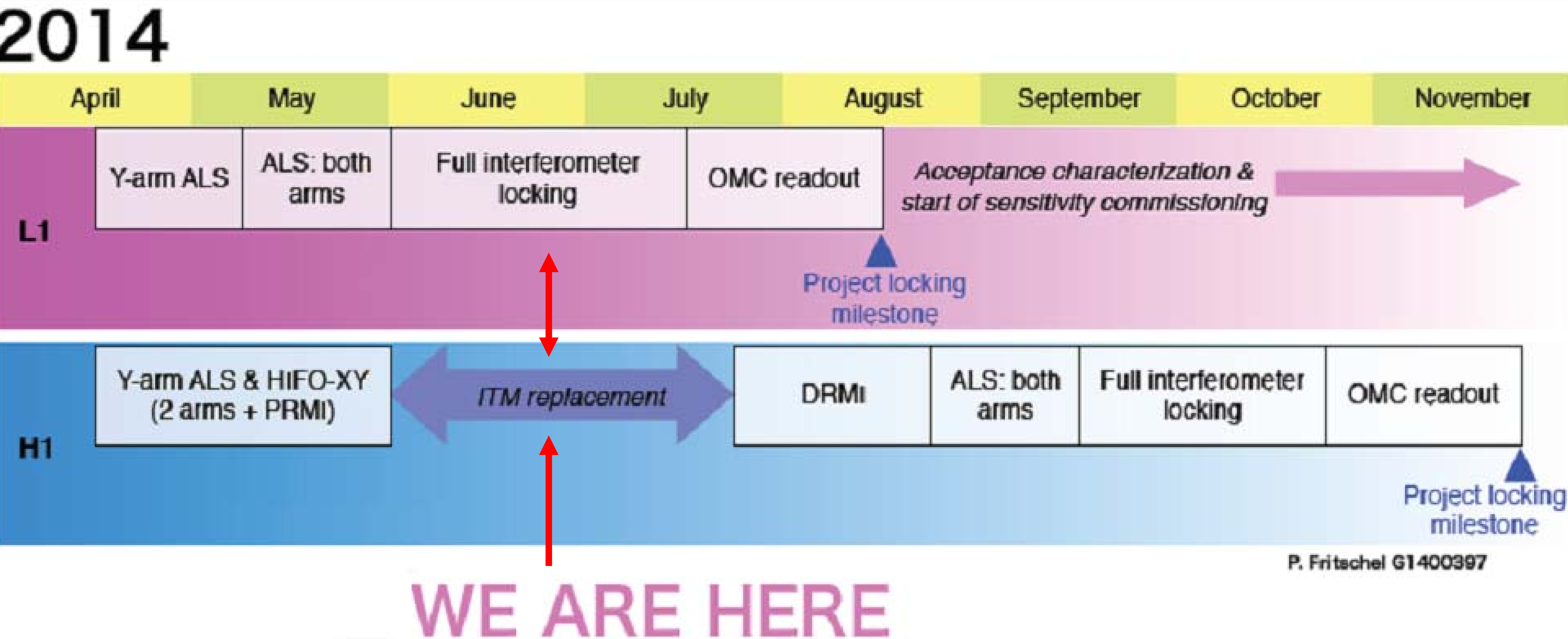
Finally bring arms slowly to resonance

1st Lock!

- May 27 2014 at Livingston Observatory



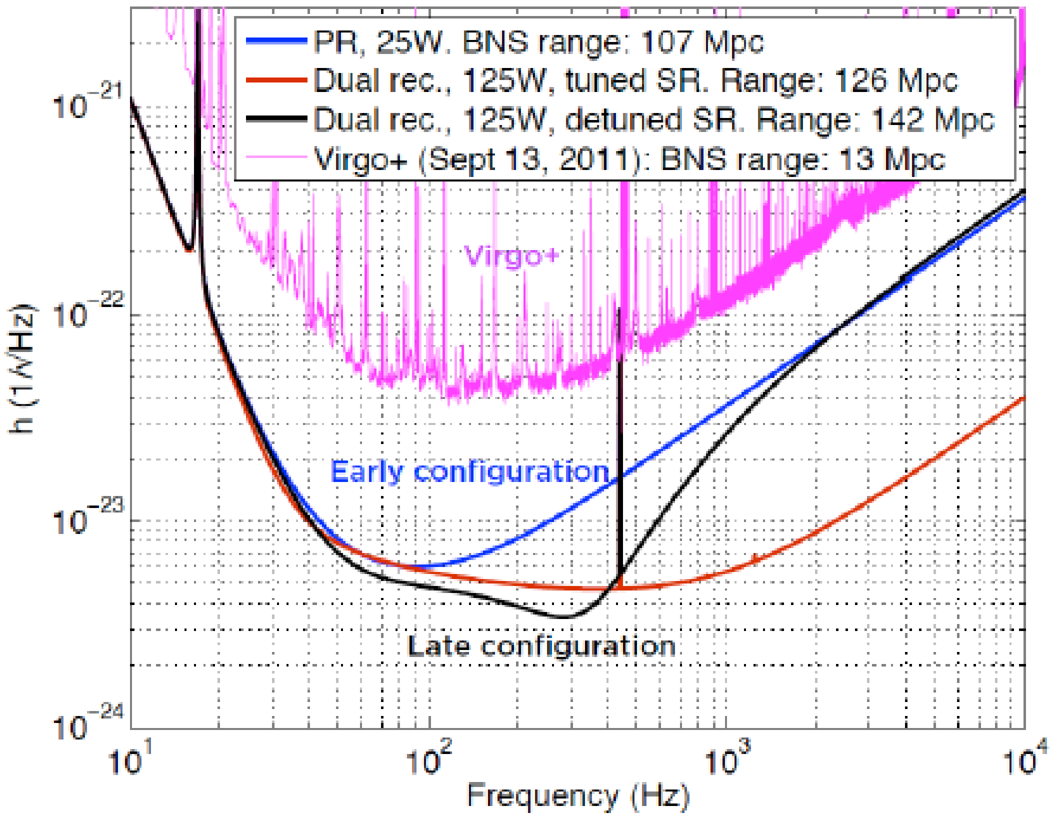
Time Line



Advanced LIGO project goals:

- Fully locked interferometer.
- Stable operation for 2 hours.

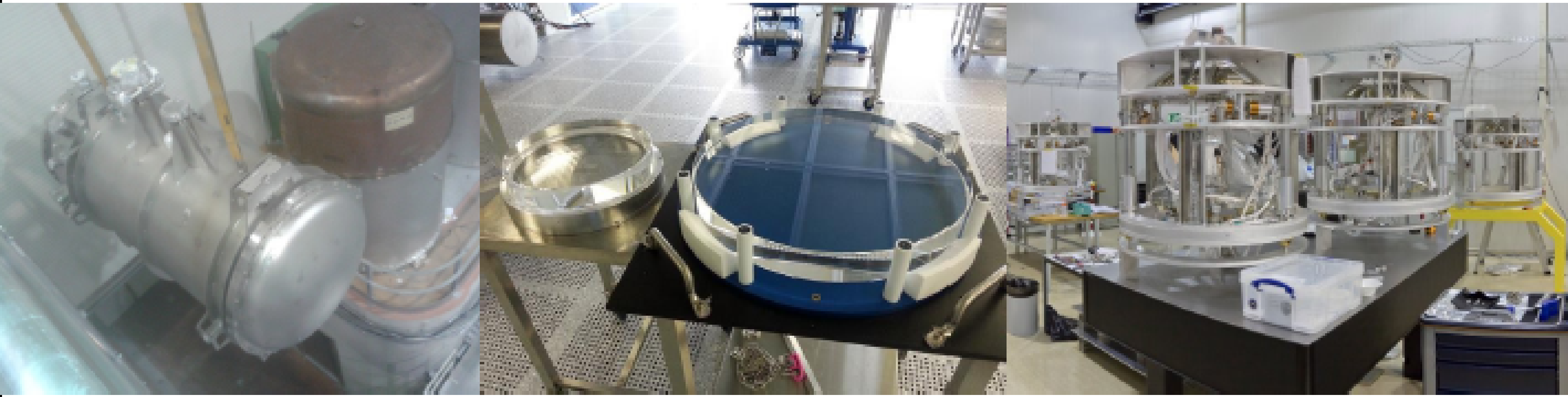
Advanced Virgo sensitivity



- Start at low power, no signal recycling mirror
- Add signal recycling mirror in tuned configuration
- Slowly increase input power
- Detuned signal recycling

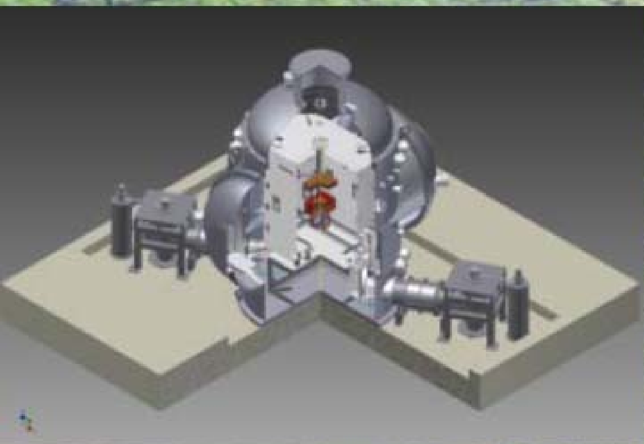
Advanced Virgo status

- Heavy infrastructure works mostly finished: building modifications, new cleanrooms, upgraded air-conditioning, …
- First large optics polished, good results so far (RMS < 1 nm)
- Most sub-systems near the end of construction
- First items already installed on site (MC, injection benches, cryotrap)
- Peak of installation starting in the next months, will last about 1 year



Key features of KAGRA

Cryogenic Mirror



Underground

Technologies crucial for the 3rd-generation detectors;
KAGRA can be regarded as a 2.5-generation detector.

The KAGRA Tunnel in the Kamioka mine

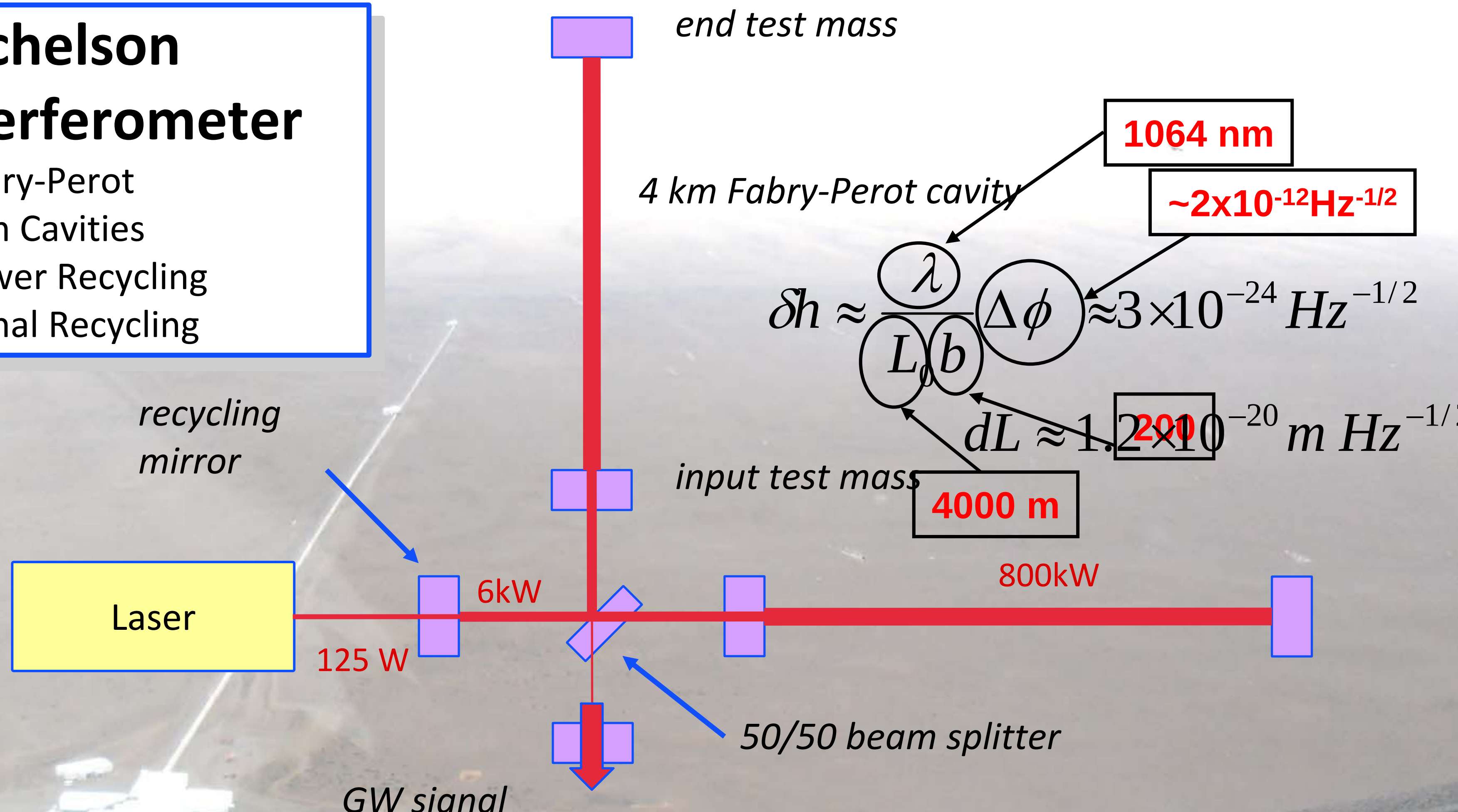
Outline

- Current status
  - LIGO (with detail), Timeline
  - Virgo, Kagra
- Limitations for sensitivity
- Other applications of GW interferometers

Interferometer Sensitivity: Quantum noise

Michelson Interferometer

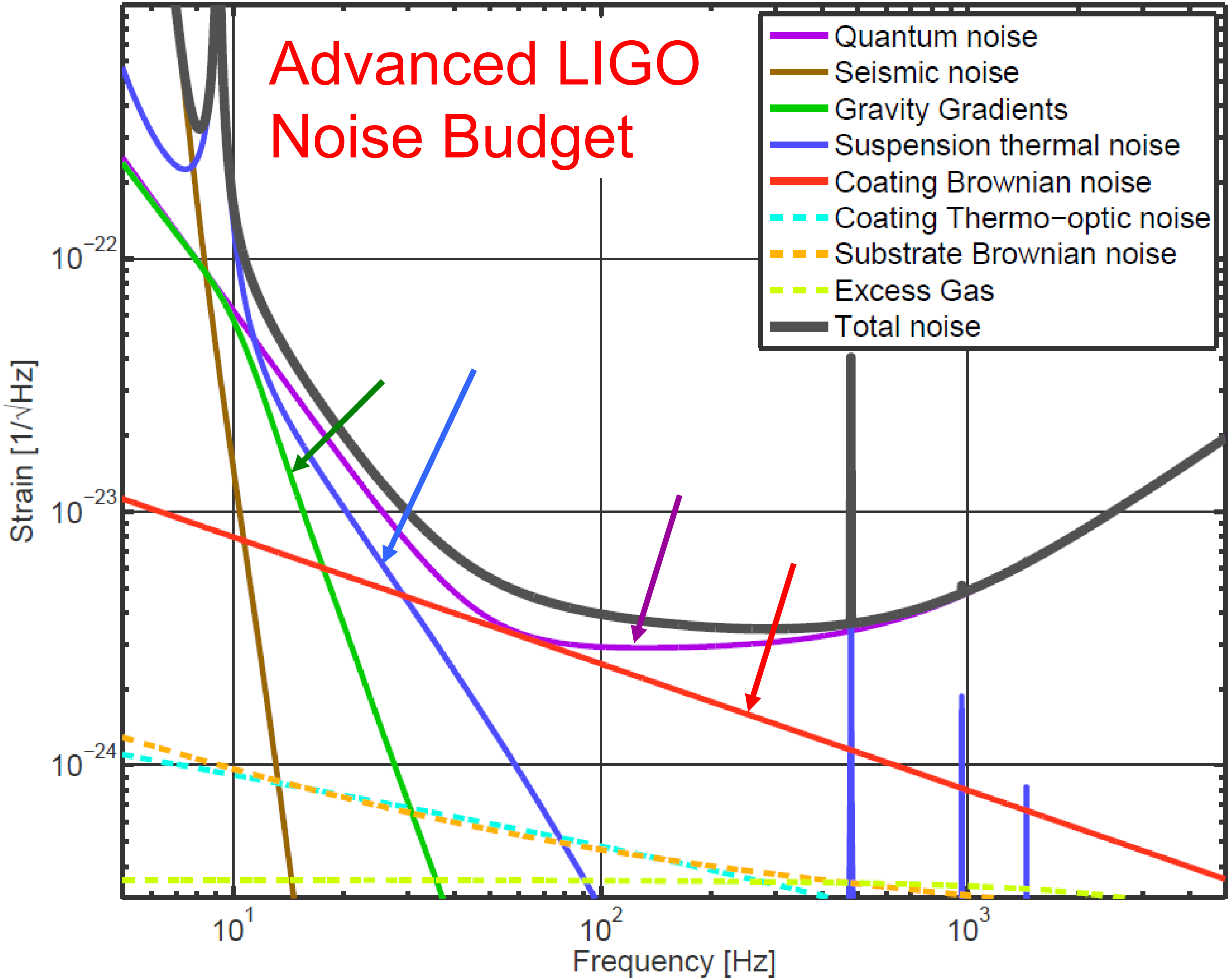
+ Fabry-Perot Arm Cavities
+ Power Recycling
+ Signal Recycling



$$\delta h \approx \frac{\lambda}{L_0 b} \Delta\phi \approx 3\times 10^{-24}\ Hz^{-1/2}$$

$$dL \approx 1.2\times 10^{-20}\ m\ Hz^{-1/2}$$

(Numbers for aLIGO design)



Advanced LIGO
Noise Budget
Quantum noise
Seismic noise
Gravity Gradients
Suspension thermal noise
Coating Brownian noise
Coating Thermo−optic noise
Substrate Brownian noise
Excess Gas
Total noise
Strain [1/√Hz]
10^−22
10^−23
10^−24
10^1
10^2
10^3
Frequency [Hz]

Key technological hurdles

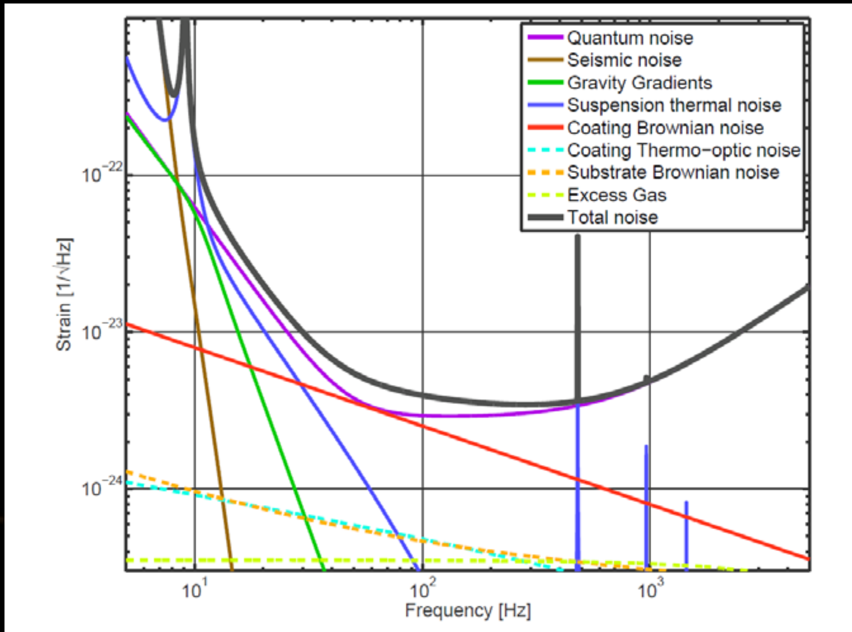
- Quantum noise (radiation pressure/shot)
  - Quantum mechanical measurement limitations
- Thermal noise (coating)
  - Thermal motion of the mirror surface
- Newtonian (Gravity Gradient) noise
  - Newtonian gravity short-circuits suspensions (not this talk)

Quantum Noise

- Go heavy…

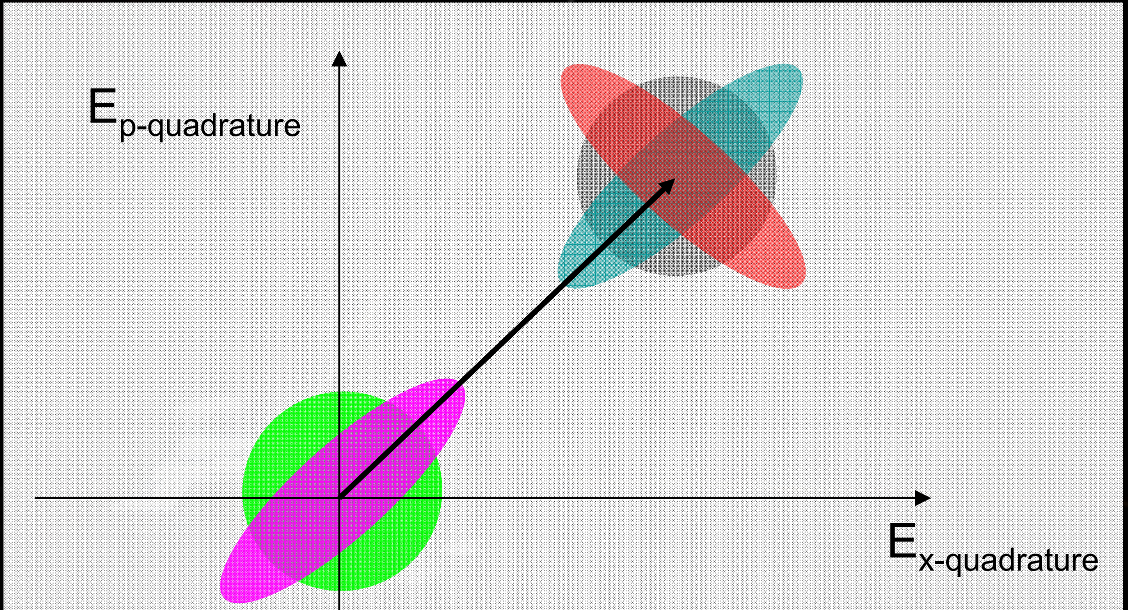
$$x_{\mathrm{SQL}} = \sqrt{\frac{2\hbar}{m\pi^2 f^2}}$$

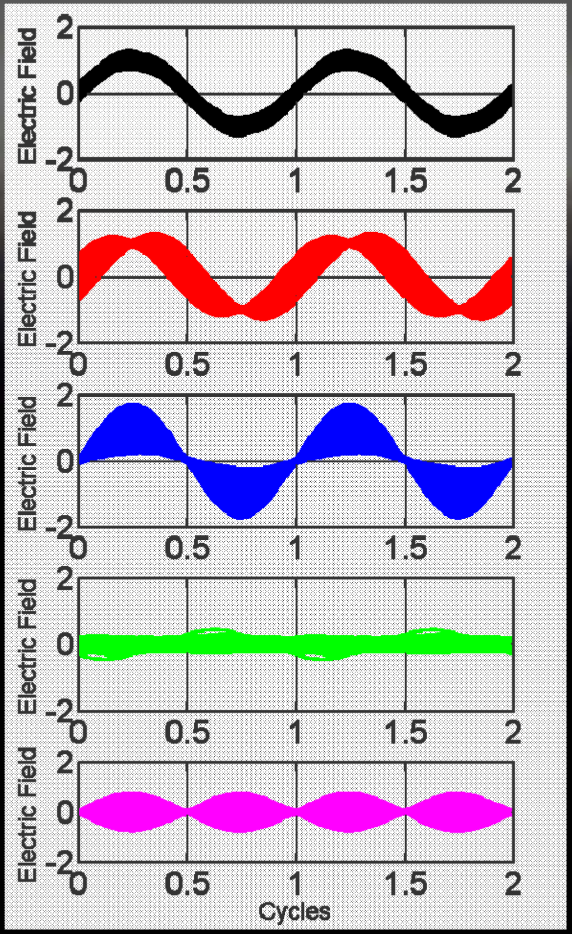
- Squeezing
  - External squeezed light injection
  - Filter cavities



Squeezed light source

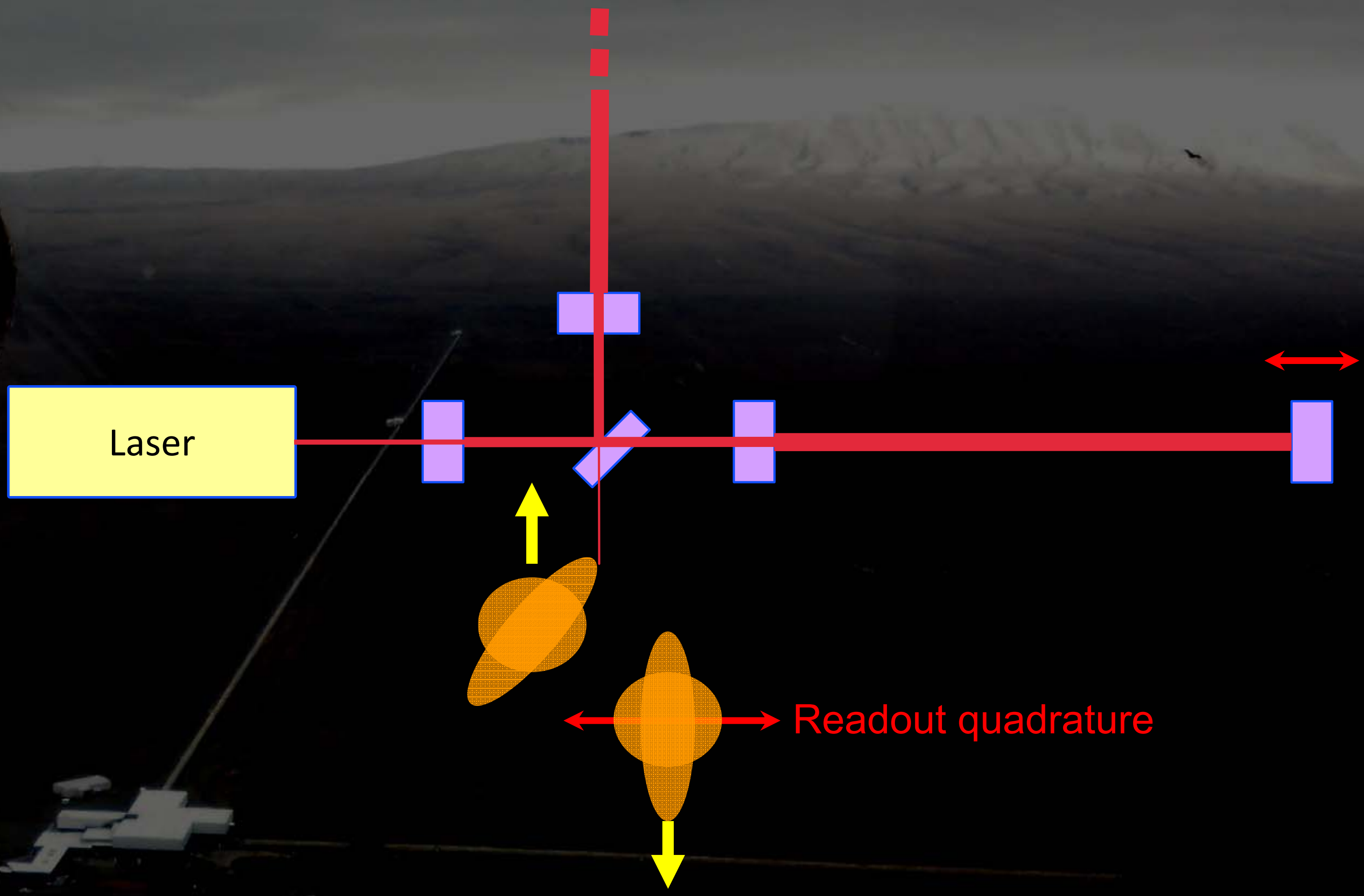
- Quantum trade-off between phase and amplitude noise
- Strain sensing is only sensitive to one of them





Schematic representation of Electric field, various states

Why does squeezing work?



Filter cavities

- Concept:
  - A cavity operated in reflection:
    → frequency dependent phase shift
      - No delay above cavity pole
  - Used on squeezed light: frequency dependent rotation on squeezing ellipse

- Keep squeezing ellipse in correct orientation
- Draw-back: very sensitive to optical losses

Thermal Noise - basics

- Fluctuation-dissipation theorem: It's the loss!
  - Equipartition theorem.:

$$\frac{1}{2}m\langle \dot{x}^2 \rangle = \frac{k_B T}{2}$$

vs.

$$Z\dot{x} = m\ddot{x} + kx + \gamma\,\dot{x} = F_{\text{noise}}$$

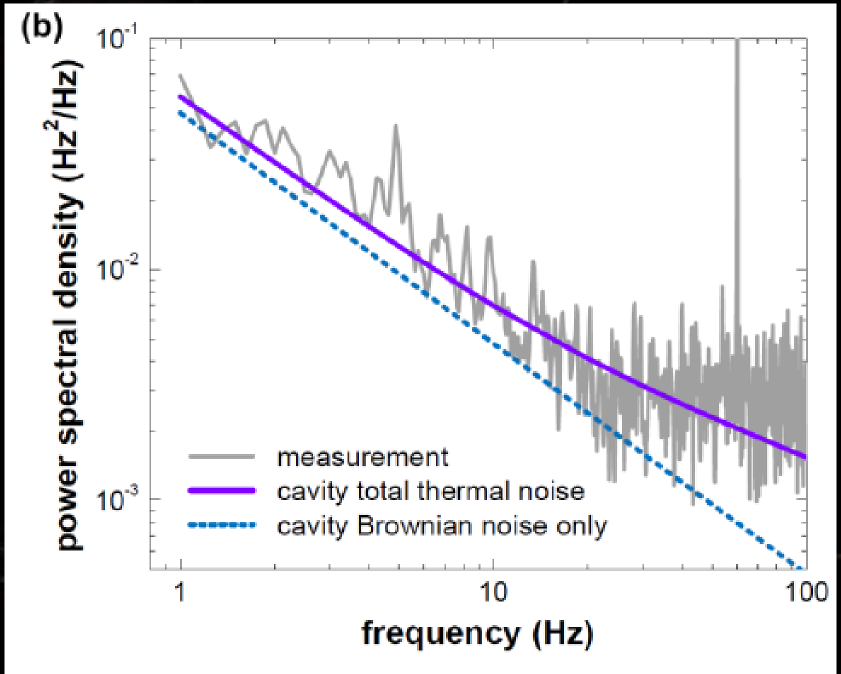
- Fluctuation-dissipation theorem

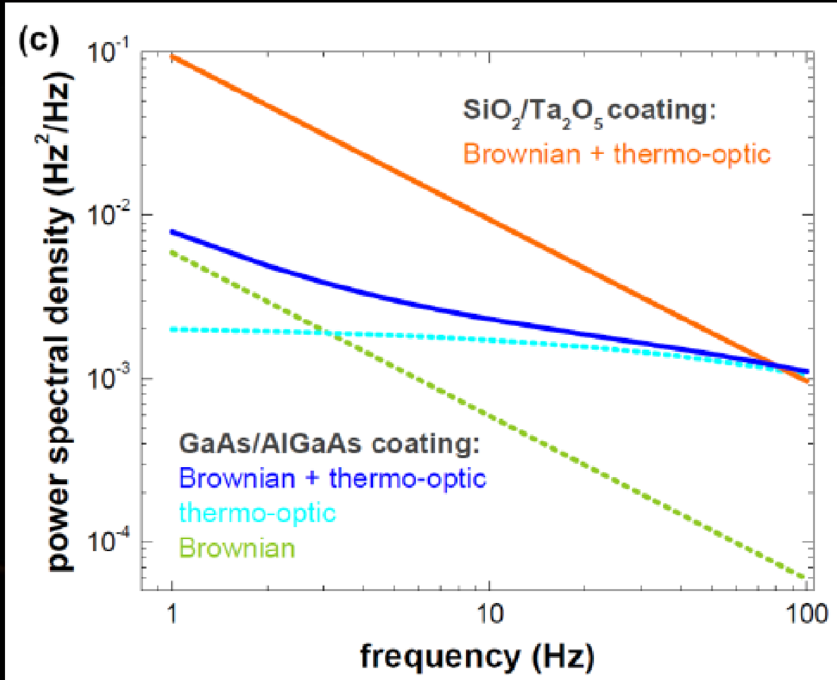
$$S_{vv}(f) = 4k_B T\,\frac{P_{\text{diss}}(f)}{\langle \mathrm{F}^2 \rangle}$$

  - The energy loss per cycle (normalized by the driving force squared) is proportional to the velocity power spectrum

Crystal coatings - AlGaAs

- Recent result:
  - Tenfold reduction of Brownian noise in optical interferometry (G. Cole et. al.,arXiv:1302.6489)
  - Loss angle < 4e-5



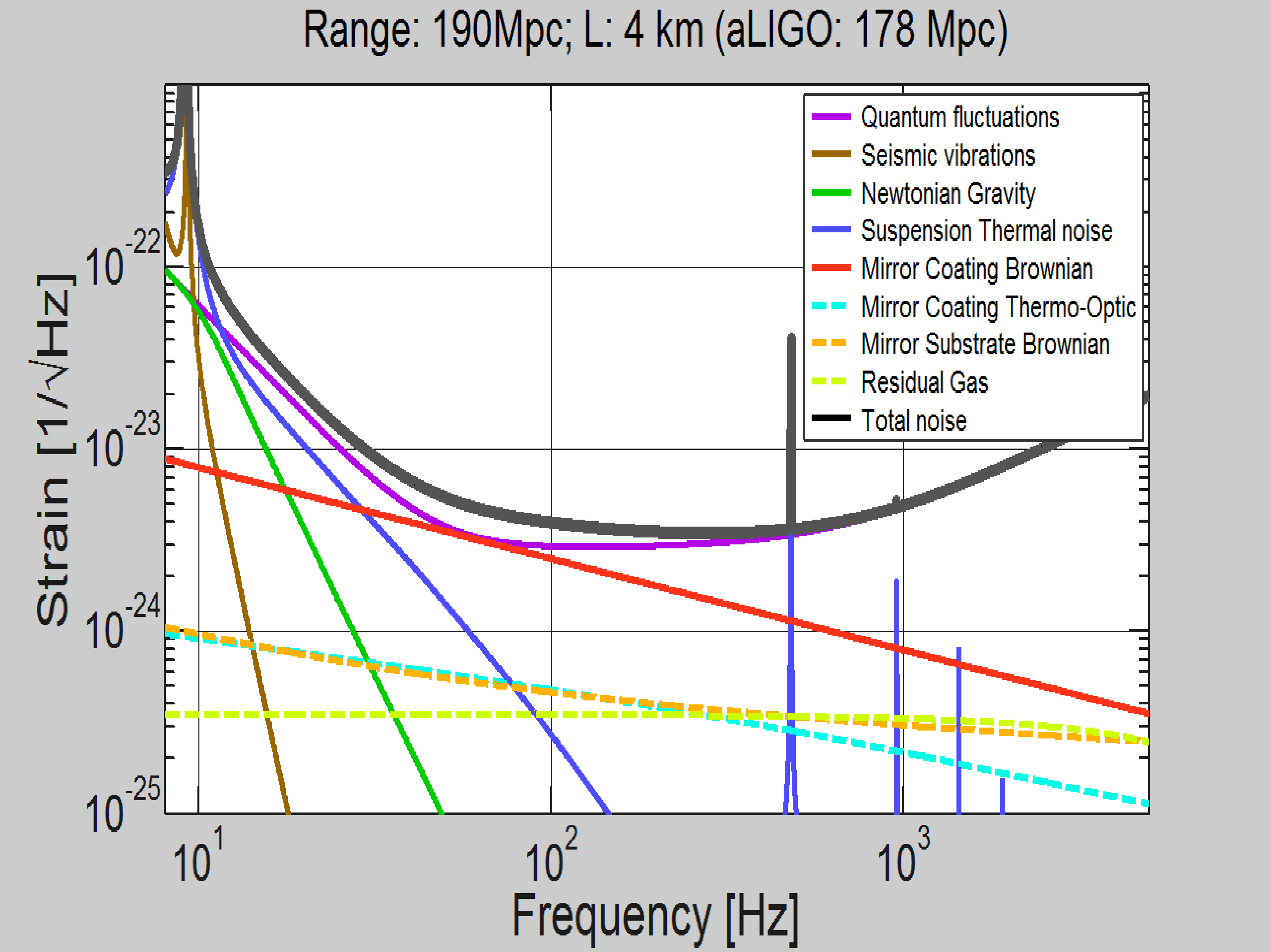


Cryogenic operation

- Thermal Noise? Cool!
  - Young's modulus, mech. loss, therm conductivity and capacity need to be well-behaved at low T.
  - New substrate material e.g. crystalline Si (aLIGO uses SiO_2
- Implications:
  - Need to change laser wavelength to 1.6u (band edge)
  - Affects coating choice
  - Technical integration challenge
    - Vibrations, cooling beam pipes, etc.

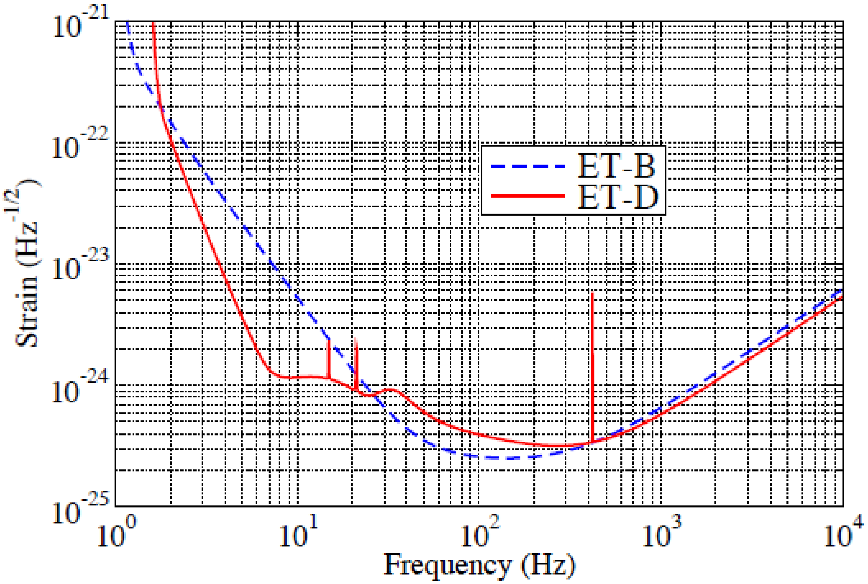
Long is good!

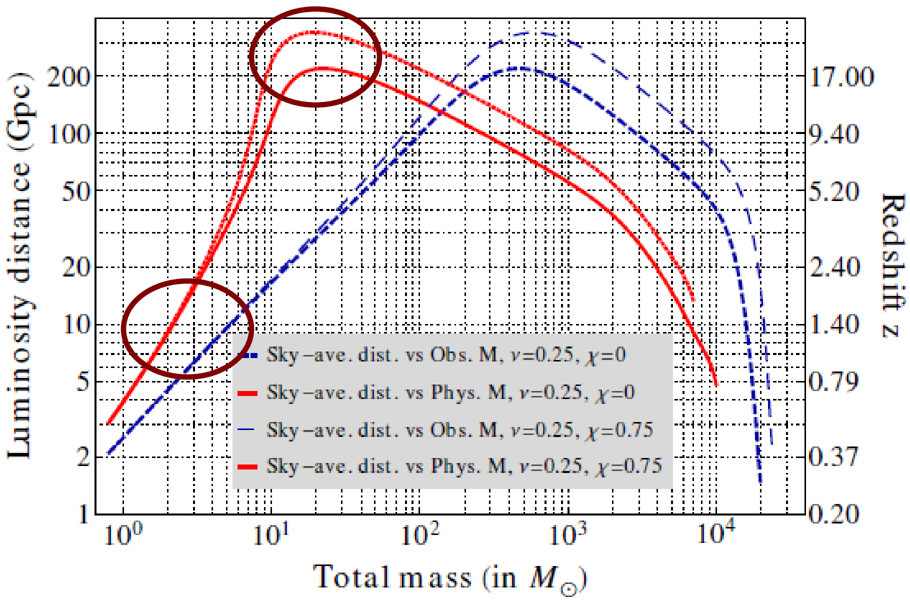
- Coating thermal noise
  - Gain: $L^{1.5}$
  - Cryogenic/Crystal: no need
- Displacement noise
  - Gain: L
  - Newtonian N. irrelevant
- Radiation pressure
  - Becomes irrelevant
- Shot noise
  - Gain: ~sqrt(L)
  - Freq. indep. Squeezing
- Vertical susp. Thermal
  - Gain: constant

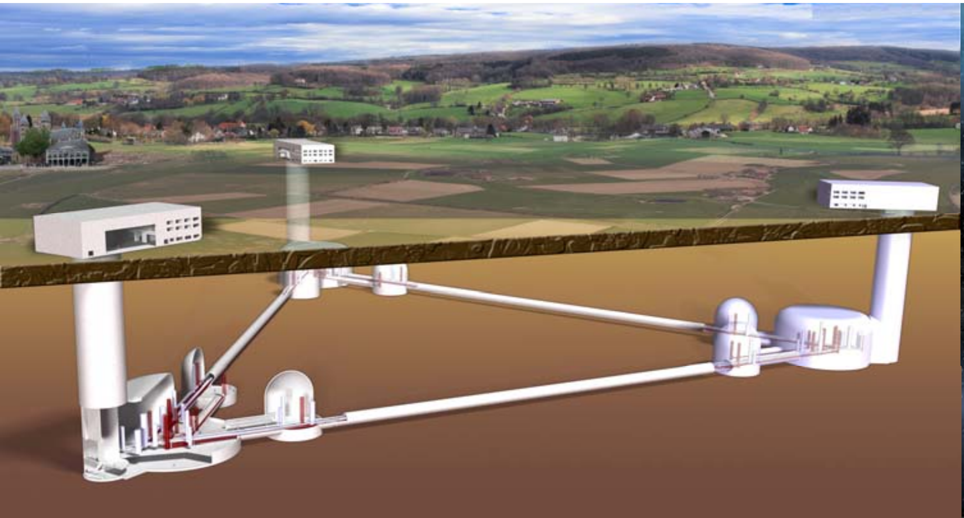


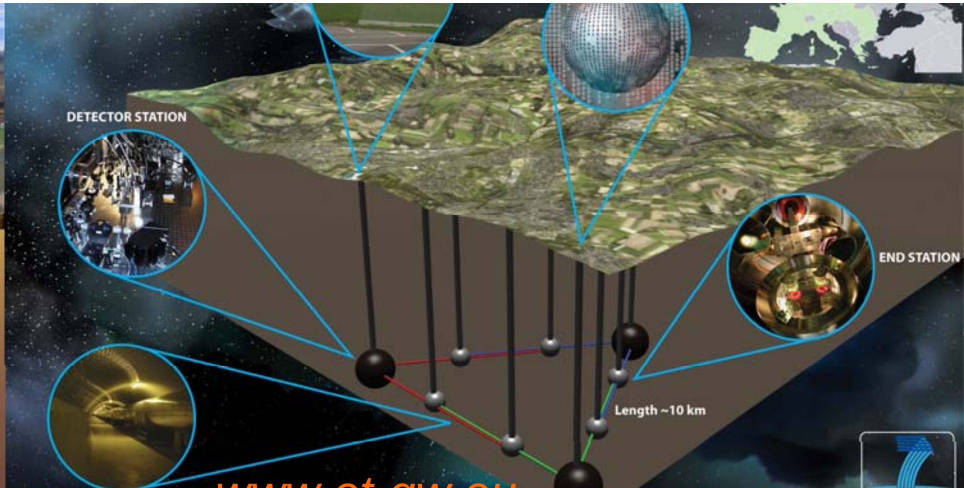
Range: 190Mpc; L: 4 km (aLIGO: 178 Mpc)
Quantum fluctuations
Seismic vibrations
Newtonian Gravity
Suspension Thermal noise
Mirror Coating Brownian
Mirror Coating Thermo-Optic
Mirror Substrate Brownian
Residual Gas
Total noise
Strain [1/√Hz]
10-22
10-23
10-24
10-25
10 1
10 2
10 3
Frequency [Hz]

Einstein Telescope Design Study









www.et-gw.eu

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What else can interferometers be good for?

- Dark matter: What if no WIMPS?

R. Adhikari (CIT), A. Derevianko (UNR), V. Frolo (LLO), M. Giesler (CIT), E. Hall (CIT), J. Hunacek (CIT), H. Muller (UCB), M. Pospelov (PI/UVIC)

- Earthquake early warning

M. Barsuglia (APC-CNRS) J-.P Ampuero (Caltech), E. Chassande-Mottin (APC-CNRS), J. Harms (INFN Firenze/Urbino), J.-P. Montagner (IPGP), S. N. Somala (Caltech), B. F. Whiting (U. Florida)

LIGO Alternative to WIMPS?

- DM clumps?
  - E.g. conglomerates of DM particles (dust), bound my gravity or other force
  - Bound on size from Micro-lensing: $<\sim M_{Earth}$
  - Encounter at galactic orbital velocity (230m/s) produces characteristic acceleration signal

Encounters with DM Clumps

Signal is due to Newtonian force - no GW involved

Choose clump mass M as a parameter
Number density can be obtained:

$$\rho_{DM} = nM$$

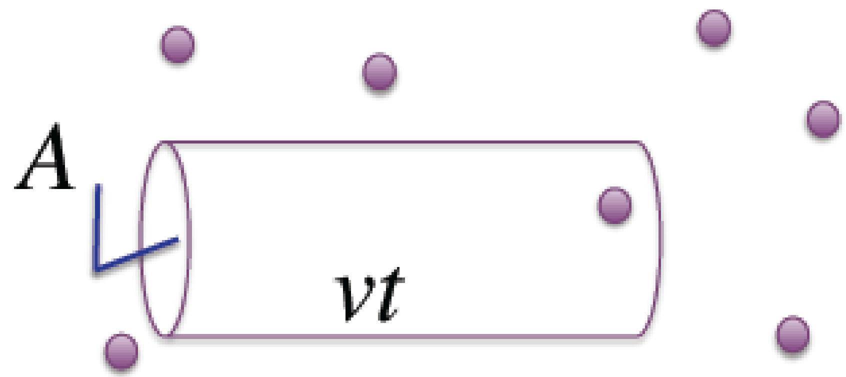
t - time between encounters
A - cross section
v = 230 km/s velocity w.r.t galactic rest frame

$$vt = \frac{1}{An}$$

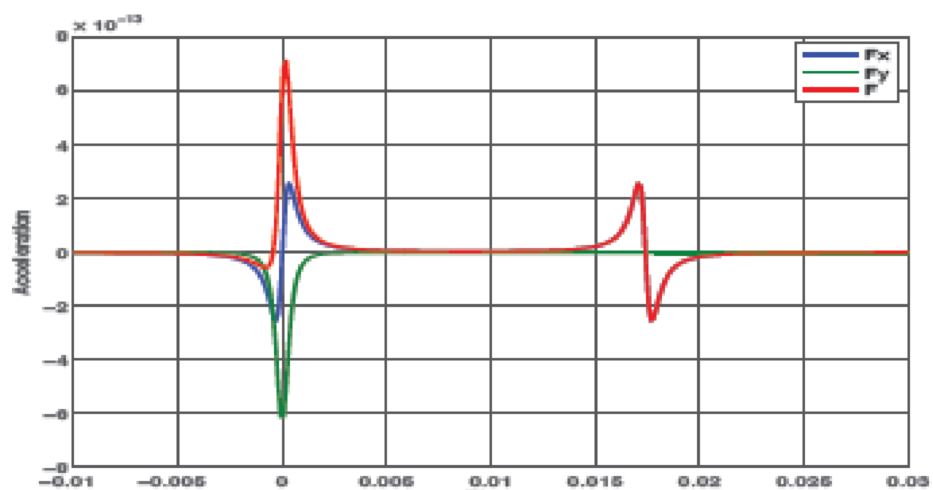
Characteristic area(distance):

$$A = \frac{M}{\rho_{DM} vt}$$

Clump size < d, L_{arm}



Signal from a clump moving along X arm



V. Frolov, GWADW 2014

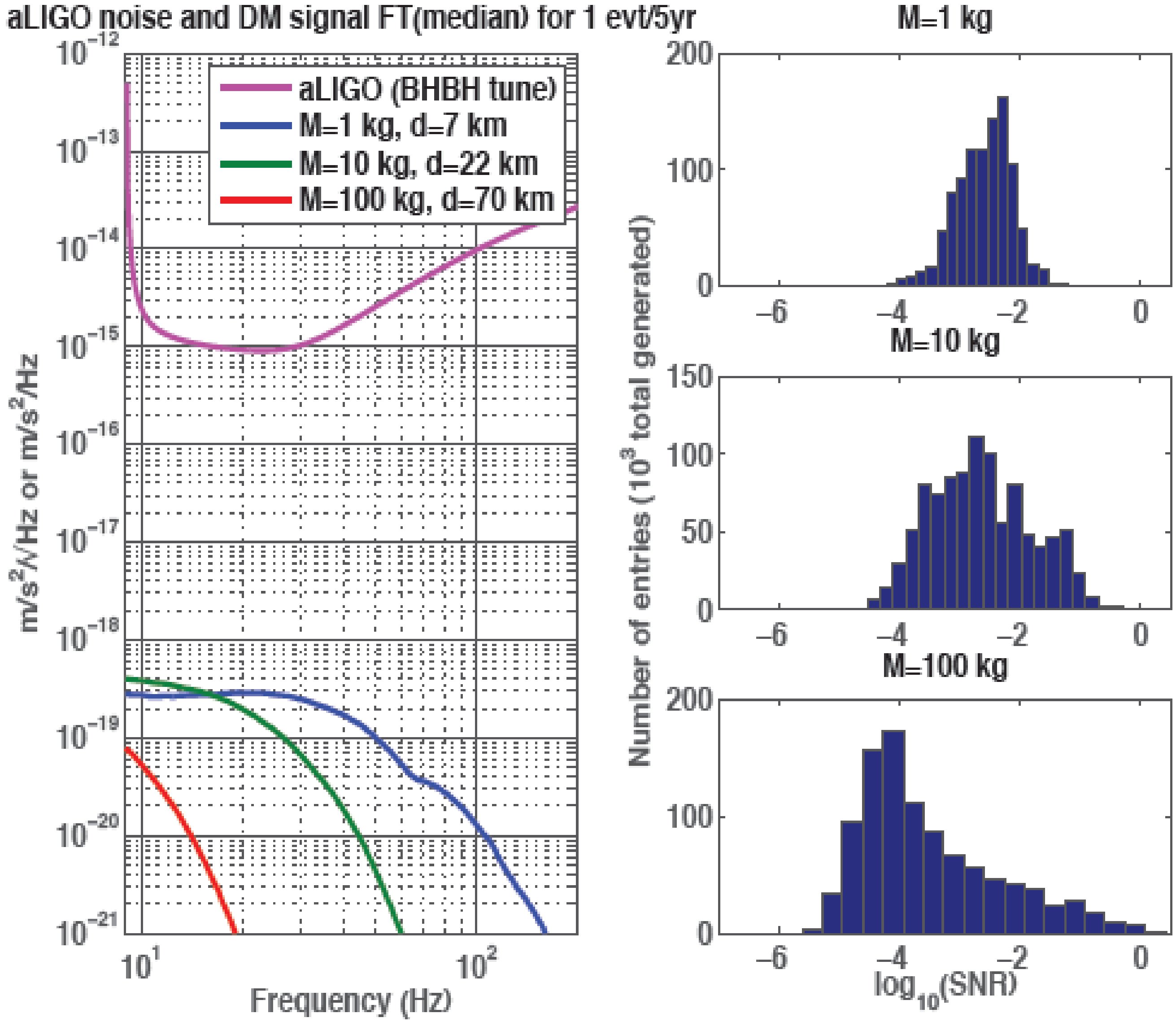
Signal in aLIGO

Random angle and position

Signal from gravitational interaction is small but DM may have long range non-minimal interaction - lot of room for model building and testing

SNR was obtained by integration. Searches should be done using templates.

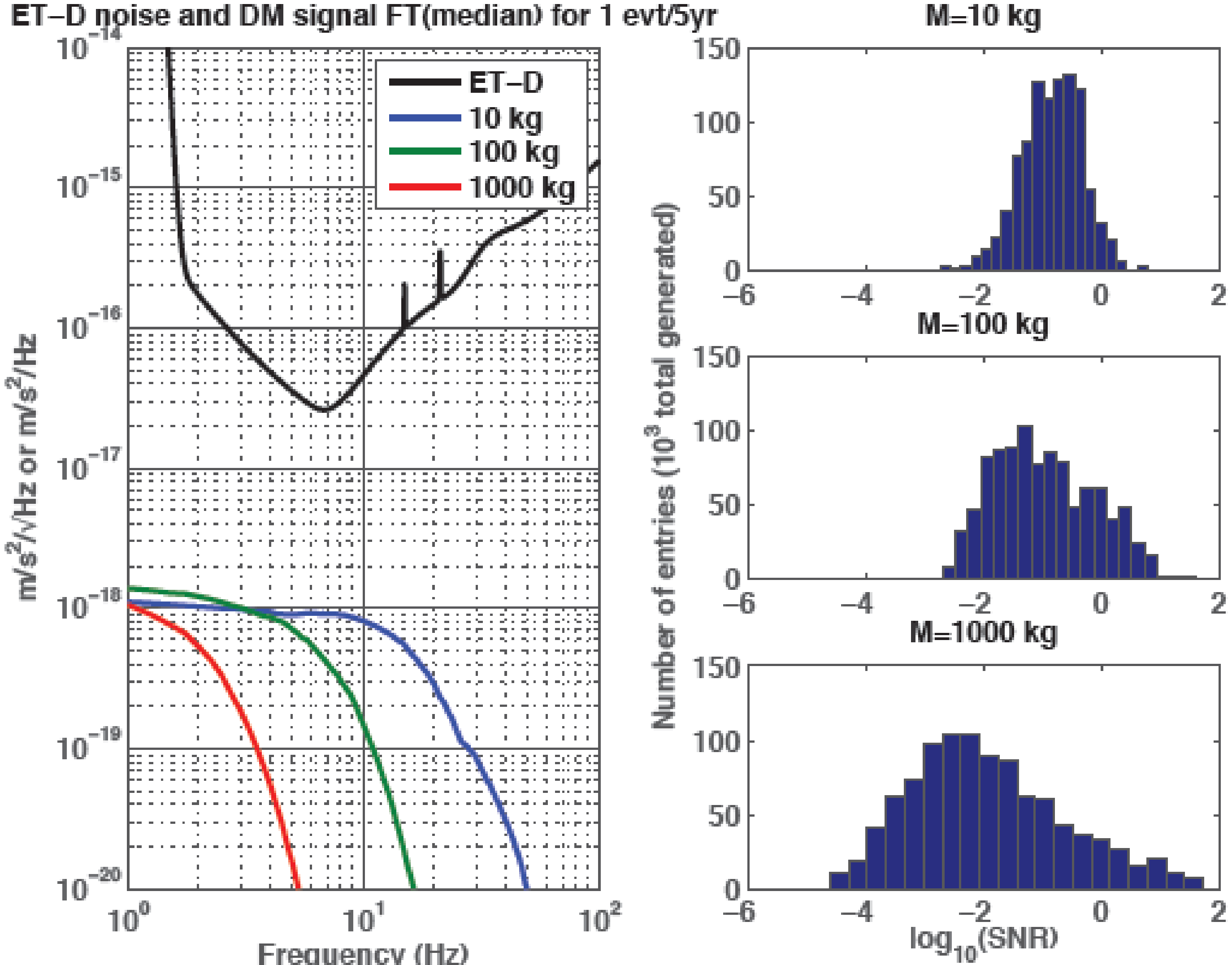
No coincidences between non-colocated interferometers due to solid angle



V. Frolov, GWADW 2014

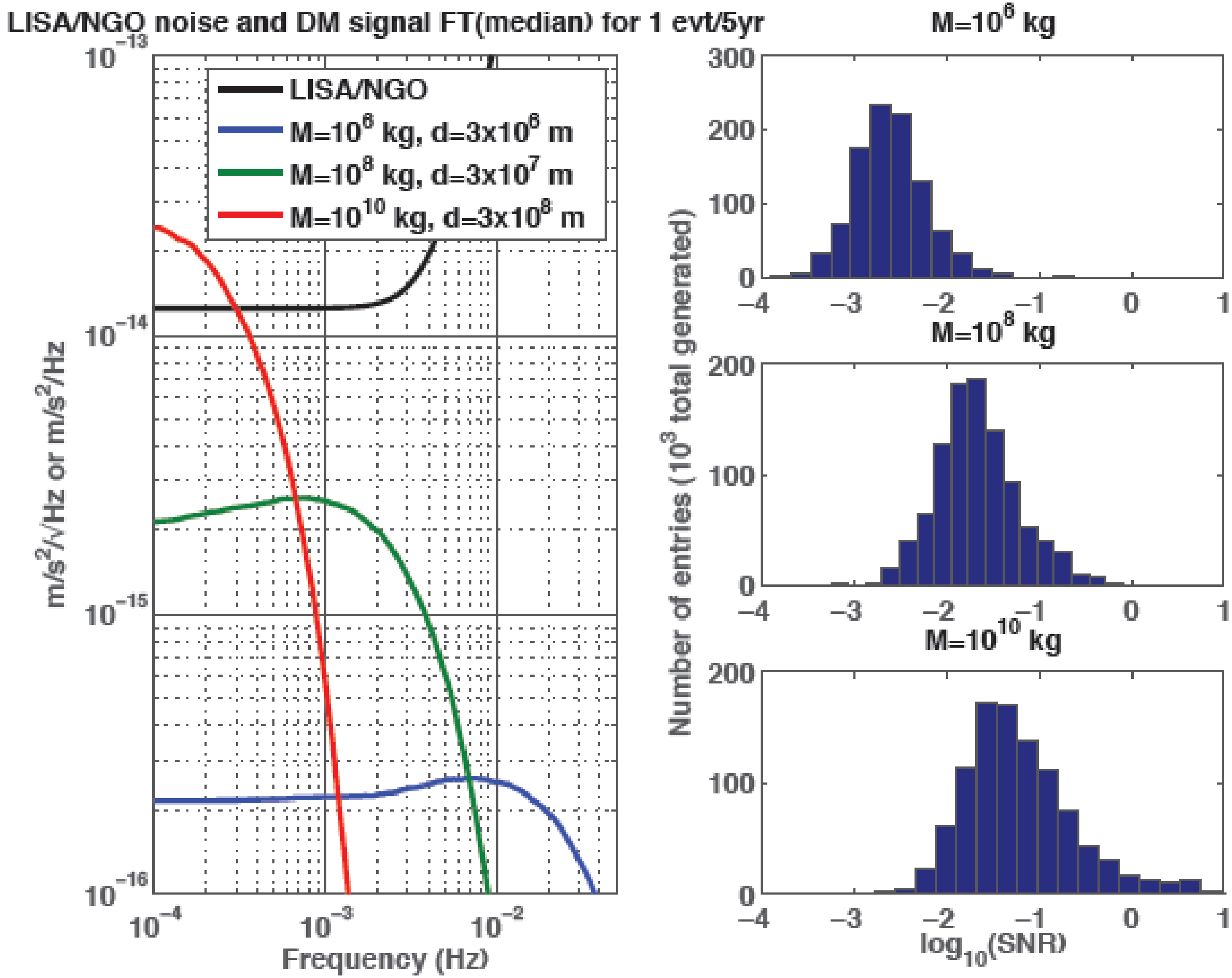
Signal in ET

Three interferometers are co-located. Coincidence and wave form analysis allows background rejection.



V. Frolov, GWADW 2014

Signal in LISA



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Earthquake early warning

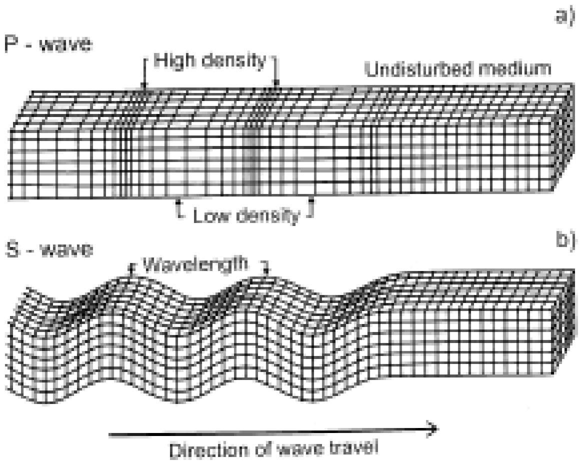
- Gravimeters already see local gravity changes due to mass dislocations in earth quakes

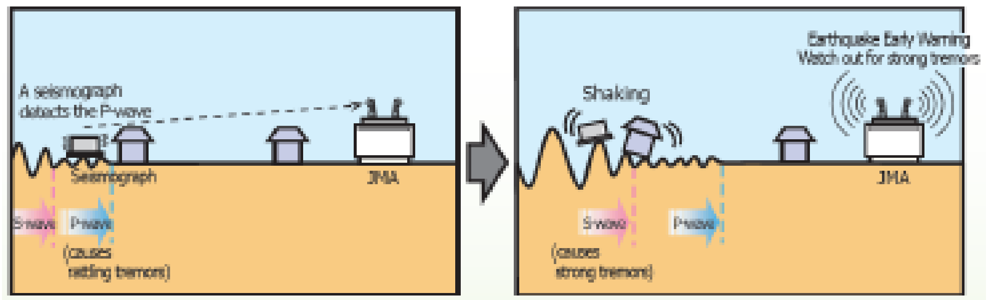
- Can this change be seen promptly, providing an early warning system?

- Early warning time increased by ~ p-wave propagation time

Earthquake early warning

Main motivations: Earthquake early-warning systems





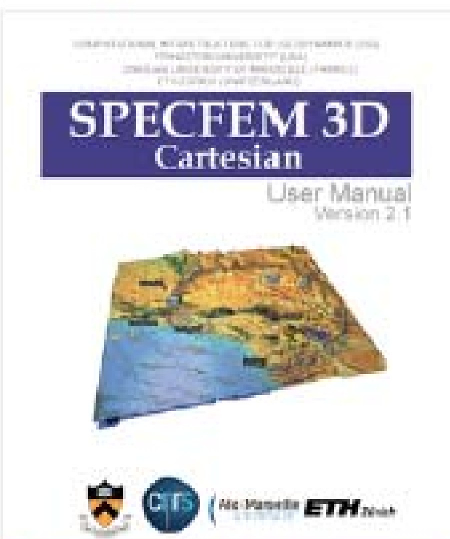
Source: Japan meterological agency

For example, for some densities: P-waves ~ 5 km/s S-waves~ 2.5 km/s

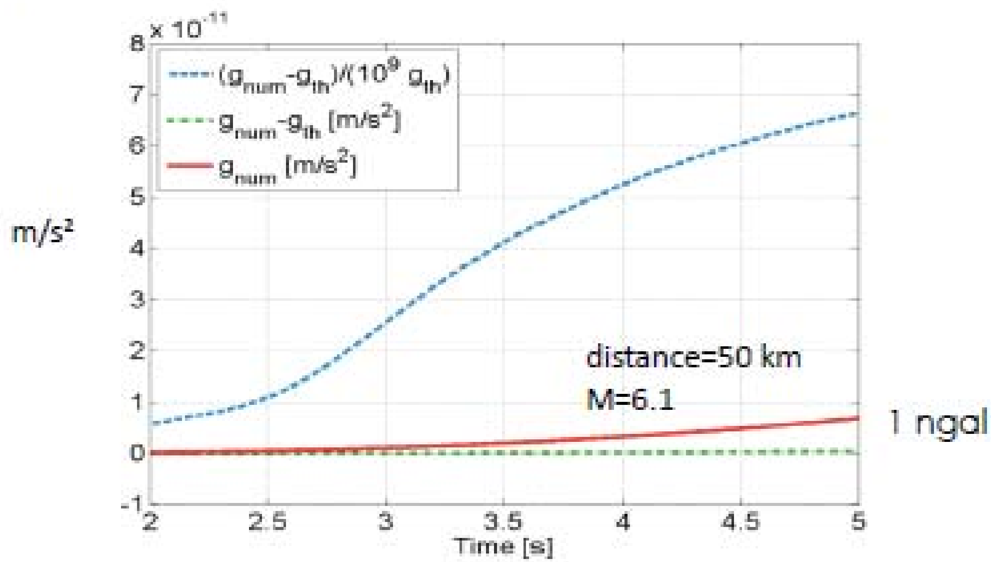
LIGO Low frequencies!

Gravity signals: simulation vs calculation

computation of gravity field implemented in the program SPECFEM3D

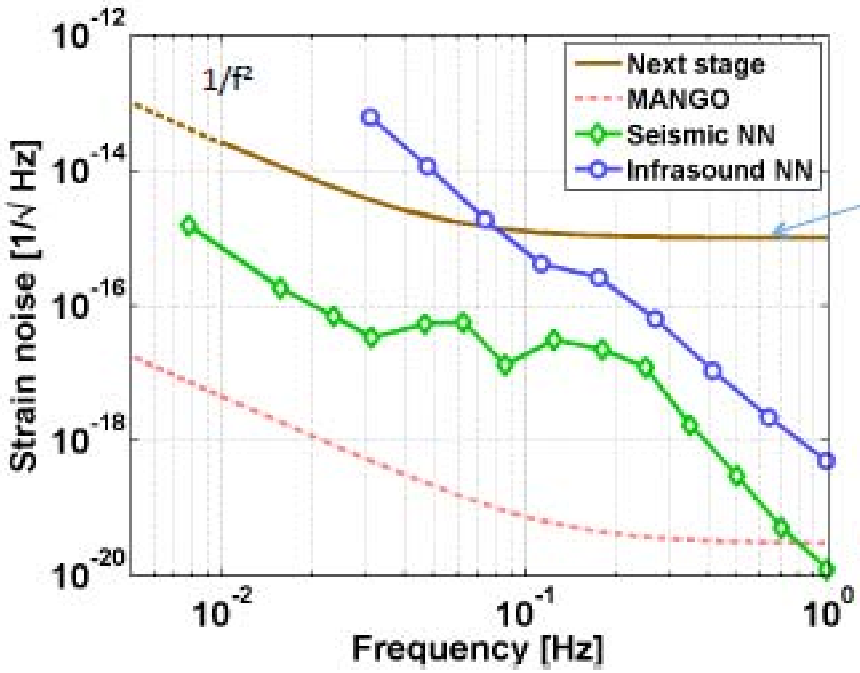


http://geodynamics.org/cig/software/specfem3d/



Example with torsion bar

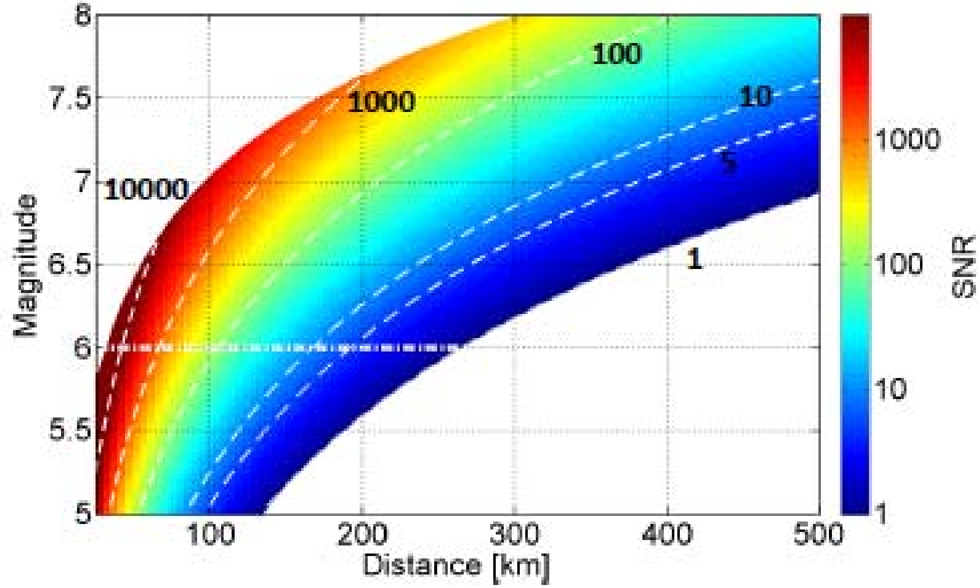
Possible sensitivity curve



Low-Frequency Terrestrial Gravitational-Wave Detectors, Jan Harms, Bram J. J. Slagmolen, Rana X. Adhikari, M. Coleman Miller, Matthew Evans, Yanbei Chen, Holger Muller and Masaki Ando, Phys. Rev. D 88, 122003 (2013)

Signal to noise ratio

$$\mathrm{SNR}^2 = \int \mathrm{d}f\, \frac{|H(\vec{r}_0, f)|^2}{S(f)}$$



$$\langle h_+(r_0, t)\rangle = \langle h_\times(r_0, t)\rangle = \frac{6\sqrt{14/5}\,G}{r_0^5} I_4[M_0](t)$$

$$M(f) = \frac{1}{2\pi f}\frac{M_0}{1+(f/f_c)^2}$$

Brune, J. N. (1970), *Tectonic stress and the spectra of seismic shear waves from earthquakes*, Journal of geophysical research, 75(26), 4997–5009

Madariaga, R. (1976), *Dynamics of an expanding circular fault*, Bulletin of the Seismological Society of America, 66(3), 639– 666

Conclusion

- Advanced LIGO was locked. Sensitivity commissioning started. Observing soon (within 2 years).
- Further significant sensitivity improvements (z=1 for NS/NS) seems possible, but requires research.
- Unexpected applications of GW interferometers do also exist.


Thank you!