

Beyond Advanced LIGO

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LIGO-G1500810



Main focus: New Science!

It is no question that there is plenty of exciting science to be gained from making the aLIGO more sensitive.

Astrophysics

Cosmology

Fundamental Science

New Science! Some examples ...

What is the equation of state of dark energy?

Understanding supernovae

Cosmography

Merger dynamics of spinning black holes

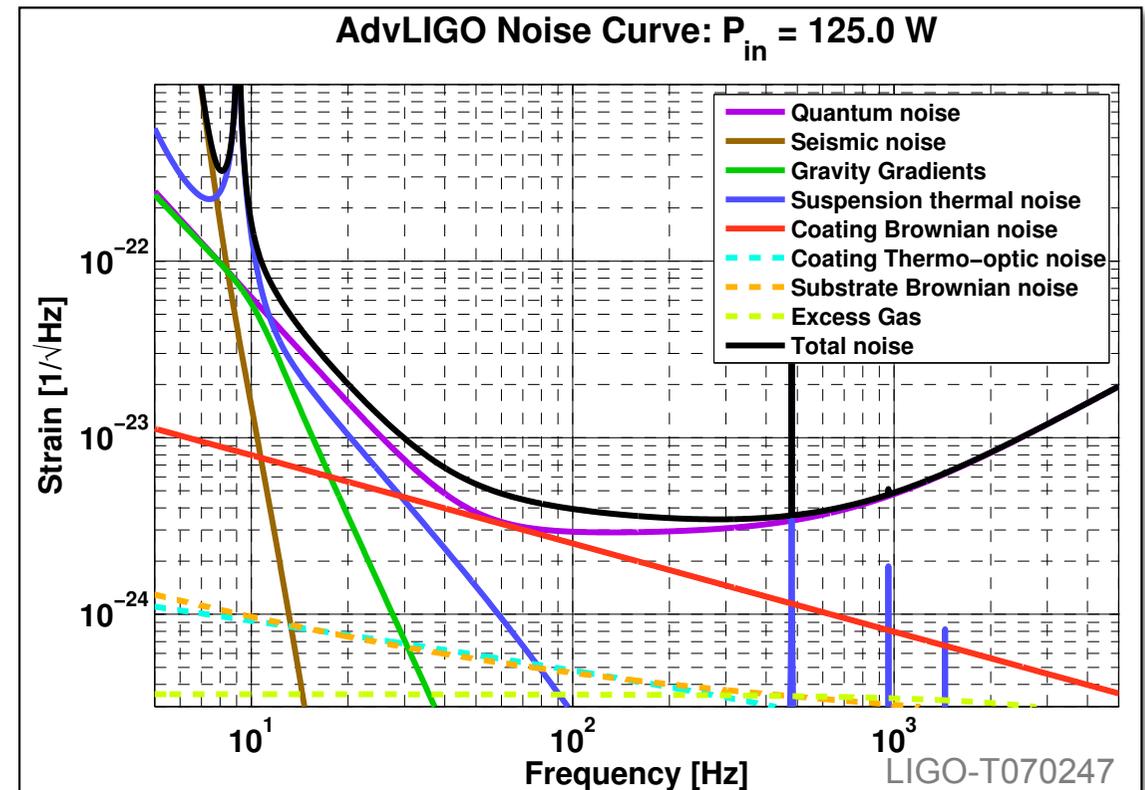
What are the progenitors of short gamma ray burts?

Intermediate mass black holes and black hole seeds

For more information refer to for instance:

- Sathyaprakash et al: "Scientific Objectives of Einstein Telescope", 2012 Class. Quantum Grav. 29 124013
- Adhikari et al: 'Astrophysical Motivations for the Third Generation LIGO Detectors', LIGO-T1200099–v2

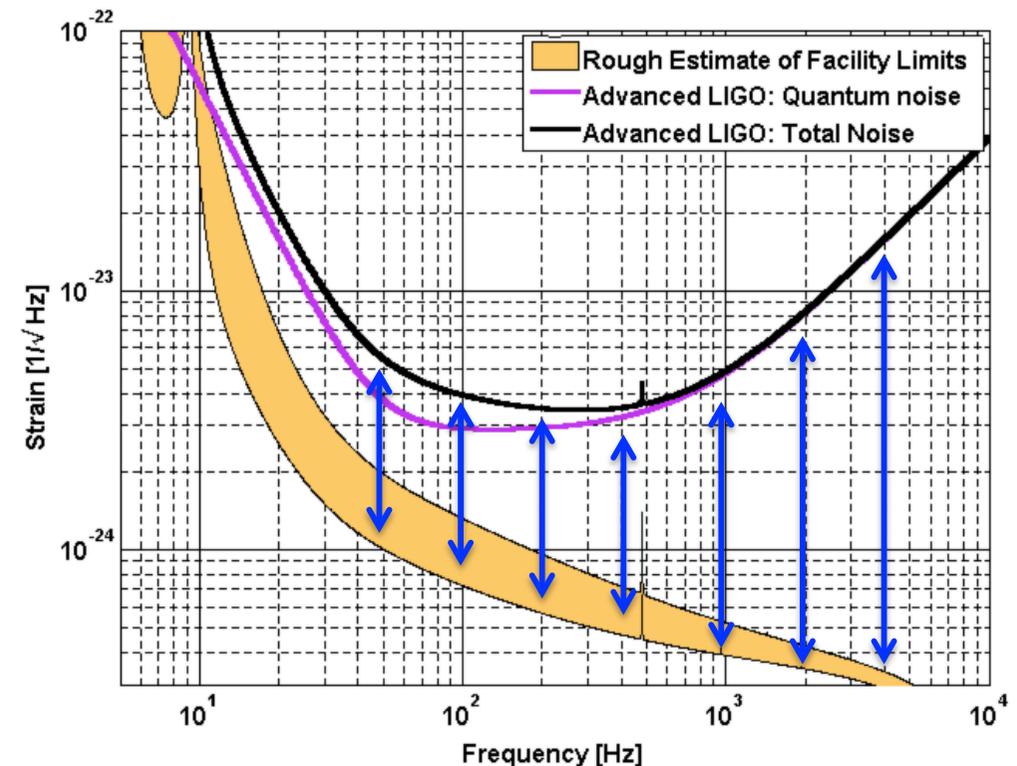
- ➔ In order to understand how we can potentially improve Advanced LIGO, we need to see what is limiting:
- **Quantum Noise** limits most of the frequency range.
 - **Coating Brownian** limits (or is close) in the range from 50 to 100Hz.
 - Below 50Hz we are limited by 'walls' made of **Suspension Thermal**, **Gravity Gradient** and **Seismic noise**.



Upgrades within the Advanced LIGO infrastructure

- ➔ The advanced LIGO baseline sensitivity is far away from the **infrastructure limits**.
- ➔ Infrastructure limit is usually defined as combination of residual gas noise and gravity gradient noise.
- ➔ **So there is plenty of room for advanced LIGO upgrades within the existing infrastructure!**

doi:10.1088/0264-9381/29/12/124006





Some aspects to keep an eye on



➔ New Technologies

- Potential improvement factor? Cost? Effort? Technical readiness? Can it work together with other technologies? Risks?



➔ Incremental or not?

- Incremental upgrade possible or does need to rip everything out again? Downtime (not available for observation)?



➔ Target spectrum

- Broad band or narrow band? Low frequency vs high frequency? (Might also change depending on what aLIGO will observe)



- ➔ Due to thermal fluctuations the position of the mirror sensed by the laser beam is not necessarily a good representation of the center of mass of the mirror.
- ➔ Various noise terms involved: Brownian, thermo-elastic and thermo-refractive noise of each substrate and coating (or coherent combinations of these, such as thermo-optic noise).
- ➔ For nearly all current and future designs coating Brownian is the dominating noise source:

$$S_x(f) = \frac{4k_B T}{\pi^2 f Y} \frac{d}{r_0^2} \left(\frac{Y'}{Y} \phi_{\parallel} + \frac{Y}{Y'} \phi_{\perp} \right)$$

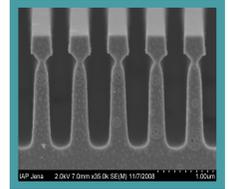
PSD of displacement
 Boltzmann constant
 Temperature
 Geometrical coating thickness
 Loss angle of coating
 Young's modulus of mirror substrate
 laser beam radius
 Young's modulus of coating

Harry et al, CQG 19, 897–917, 2002

How to reduce Mirror Thermal Noise?

Improved coating materials (e.g. crystalline coatings like AlGaAs, GaPAs)
 Cole et al, APL 92, 261108, 2008

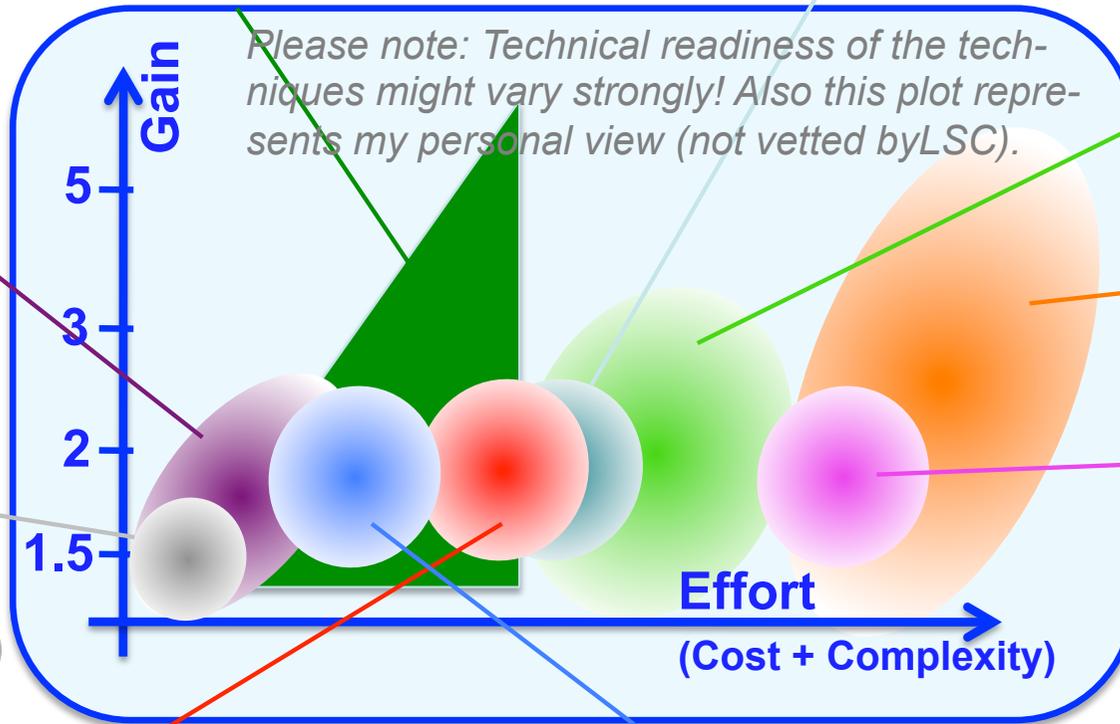
Waveguide mirrors
 Brueckner et al, Opt. Expr 17, 163, 2009
 PhD thesis of D.Friedrich



Larger beam size (needs larger mirrors)

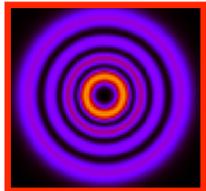
Harry et al, CQG 19, 897-917, 2002

Optimisation (annealing, layer thickness, doping)



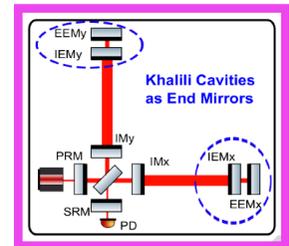
Cryogenic mirrors (120K)
Cryogenic mirrors (10-20K)
 Uchiyama et al, PRL 108, 141101 (2012)

Khalili cavities
 Khalili, PLA 334, 67, 2005
 Gurkovsky et al, PLA 375, 4147, 2011



Different beam shape
 Mours et al, CQG, 2006, 23, 5777
 Chelkowski et al, PRD, 2009, 79, 122002

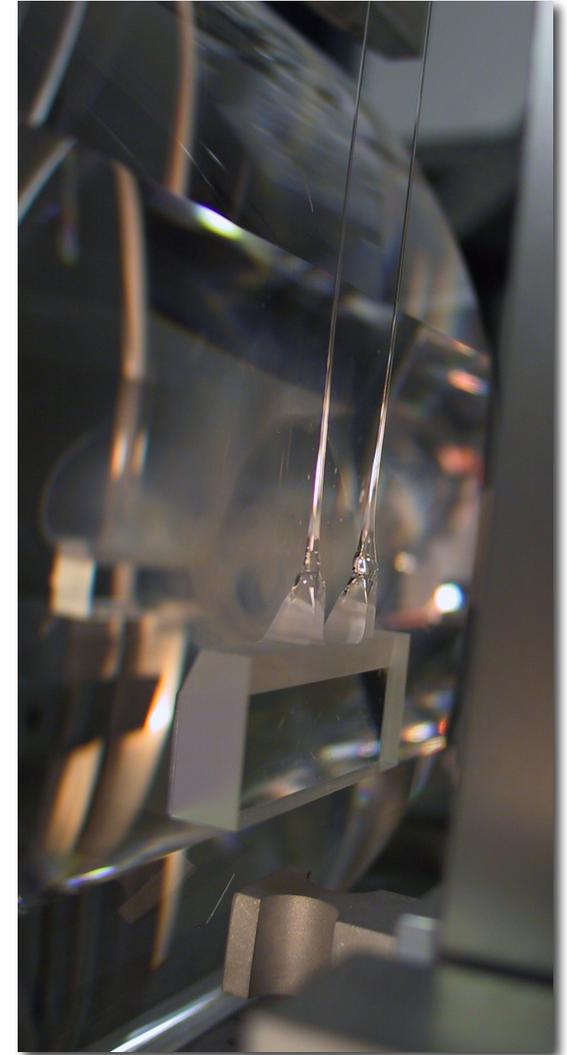
Amorphous Silicon coatings
 Liu et al, PRB 58, 9067, 1998



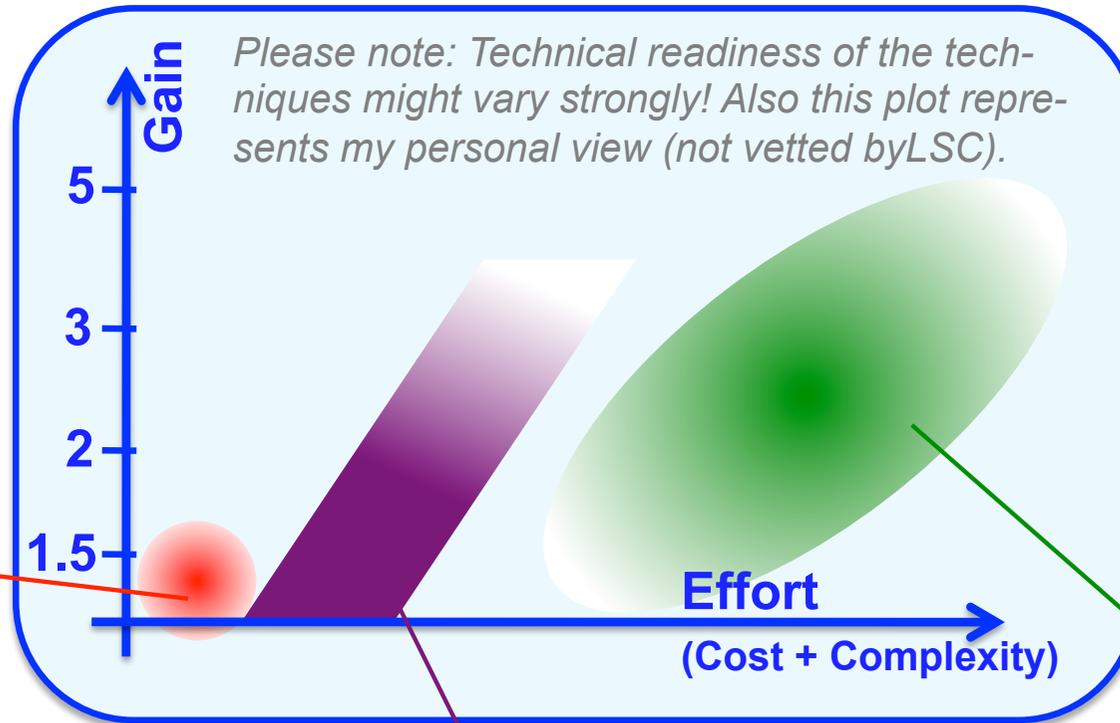
$$x^2(\omega) = \frac{4k_B T \omega_0^2 \phi(\omega)}{\omega m [(\omega_0^2 - \omega^2)^2 + \omega_0^4 \phi^2(\omega)]}$$

PSD of displacement $x^2(\omega)$
 Boltzmann constant k_B
 Temperature T
 Loss angle $\phi(\omega)$
 Mirror mass m
 Resonance frequency ω_0

- ➔ Mirrors need to be suspended in order to decouple them from seismic.
- ➔ Thermal noise in metal wires and glass fibres causes horizontal movement of mirror.
- ➔ Relevant loss terms originate from the bulk, surface and thermo-elastic loss of the fibres + bond and weld loss.
- ➔ Thermal noise in blade springs causes vertical movement which couples via imperfections of the suspension into horizontal noise.



How to reduce Suspension Thermal Noise?



Improve fibre geometry/profile

Bending points, energy stored via bending and neck profile can be potentially further optimised.

Increase length of final pendulum stage.

Allows the push suspension thermal noise out detection band.

Cooling of the suspension to cryogenic temperatures.
Usually also requires a change of materials.

Gravity Gradient Noise (also referred to as Newtonian)

- ➔ Seismic causes density changes in the ground and shaking of the mirror environment (walls, buildings, vacuum system).
- ➔ These fluctuations cause a change in the gravitational force acting on the mirror.
- ➔ Cannot shield the mirror from gravity. ☹️

Coupling constant (depends on type of seismic waves, soil properties, etc)

Gravitational constant

Density of ground

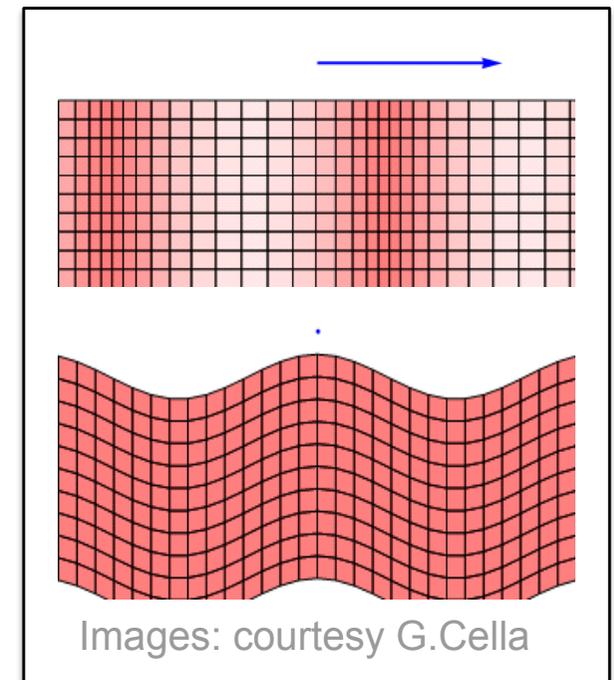
PSD of strain

$$N_{GG}(f)^2 = \frac{4 \cdot \beta^2 \cdot G^2 \cdot \rho_r^2}{L^2 \cdot f^4} \cdot X_{\text{seis}}^2$$

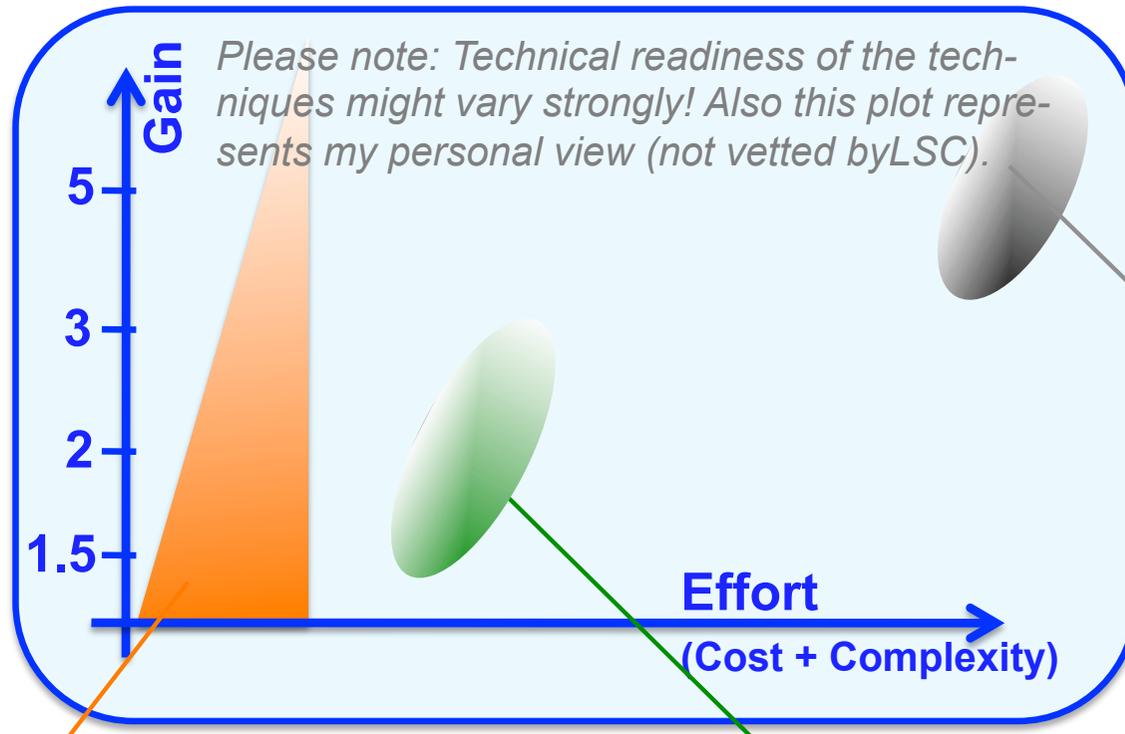
Arm length

frequency

PSD of seismic



How to reduce Gravity Gradient Noise?



Reduce seismic noise at site., i.e. select a quieter site, potentially underground.

Beker et al, Journal of Physics: Conference Series 363 (2012) 012004

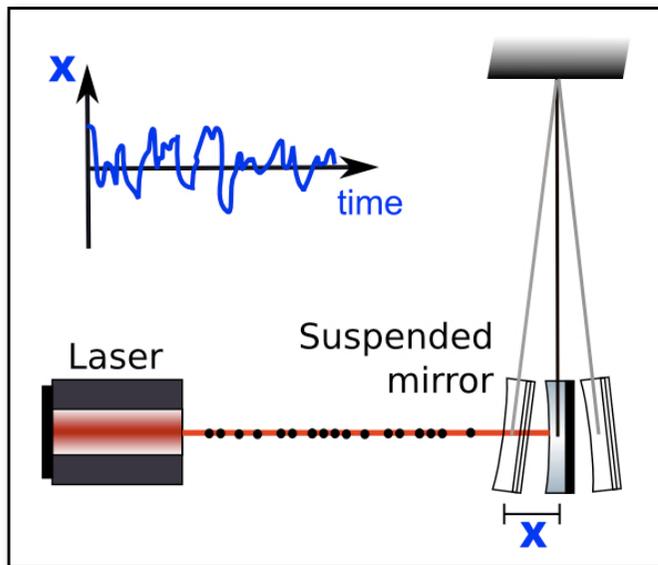
Subtraction of gravity gradient noise using an array of seismometers.

- Beker et al: General Relativity and Gravitation Volume 43, Number 2 (2011), 623-656
- Driggers et al: arXiv:1207.0275v1 [gr-qc]

Shaping local topography

- Harms et al, CQG Volume 31, Number 18, 2014

- Quantum noise is a direct manifestation of the **Heisenberg Uncertainty Principle**.
- It is comprised of **photon shot noise (sensing noise)** at high frequencies and **photon radiation pressure noise (back-action noise)** at low frequencies.

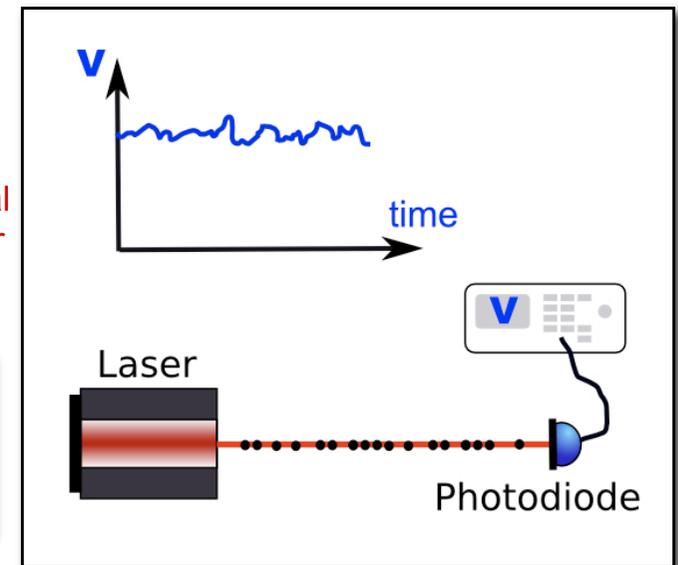


$$h_{\text{sn}}(f) = \frac{1}{L} \sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

wavelength (points to λ)
optical power (points to P)
Arm length (points to L)

$$h_{\text{rp}}(f) = \frac{1}{m f^2 L} \sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

Mirror mass (points to m)



photon radiation pressure noise

photon shot noise

Squeezing with frequency dependent squeezing angle

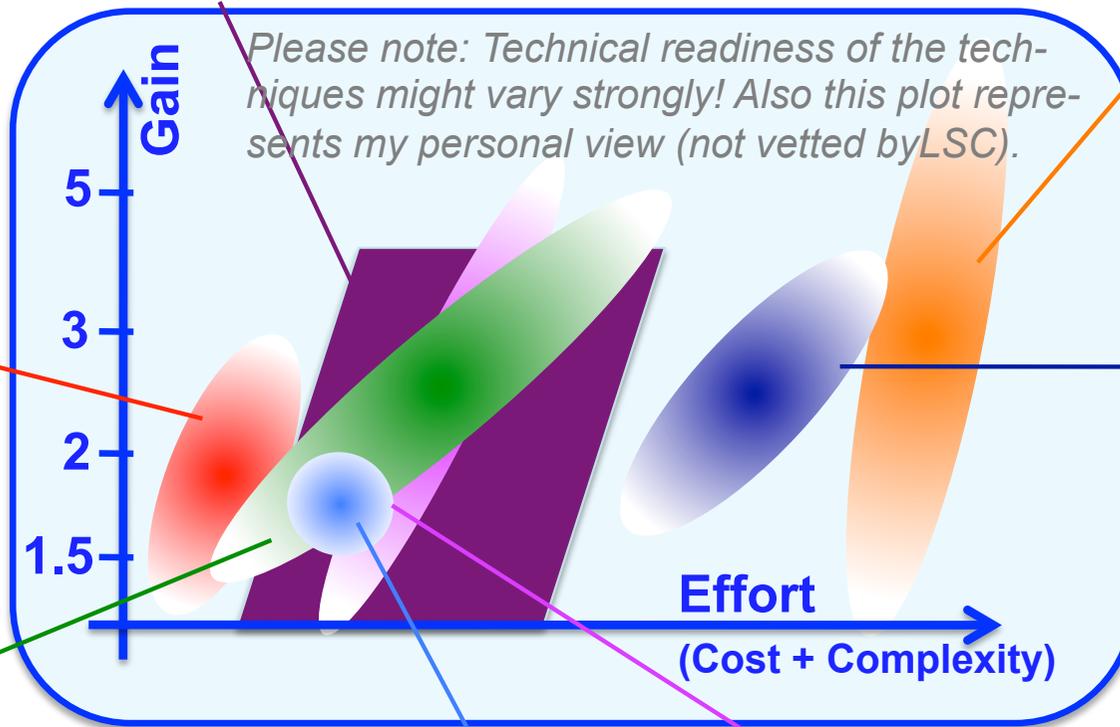
Kimble et al, PRD 65, 2002

Speedmeter

Measures momentum of test masses and is therefore not susceptible to Heisenberg Uncertainty Principle.
Chen, PRD 67, 122004, 2003

Squeezed Light

LIGO Scientific collaboration, Nature Phys. 7 962-65, 2011



Optical Bar + Optical Lever

Khalili, PLA 298, 308-14, 2002

Increased Laser Power

Need to deal with thermal problems and instabilities

Local readout

Rehbein et al, PRD 78, 062003, 2008

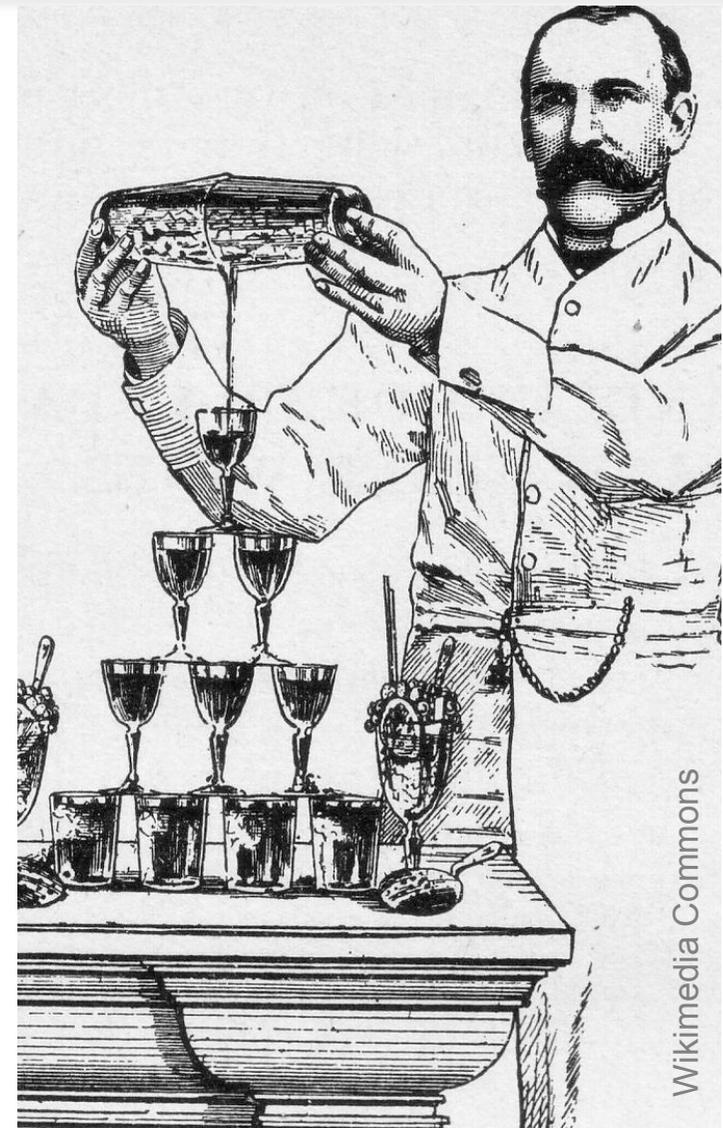
Increased Mirror Weight

Need to deal with thermal problems and instabilities

'Mix' your detector

Now everyone can take their favorite subset of noise reduction techniques, mix them together ...

... and there is your future GW detector.



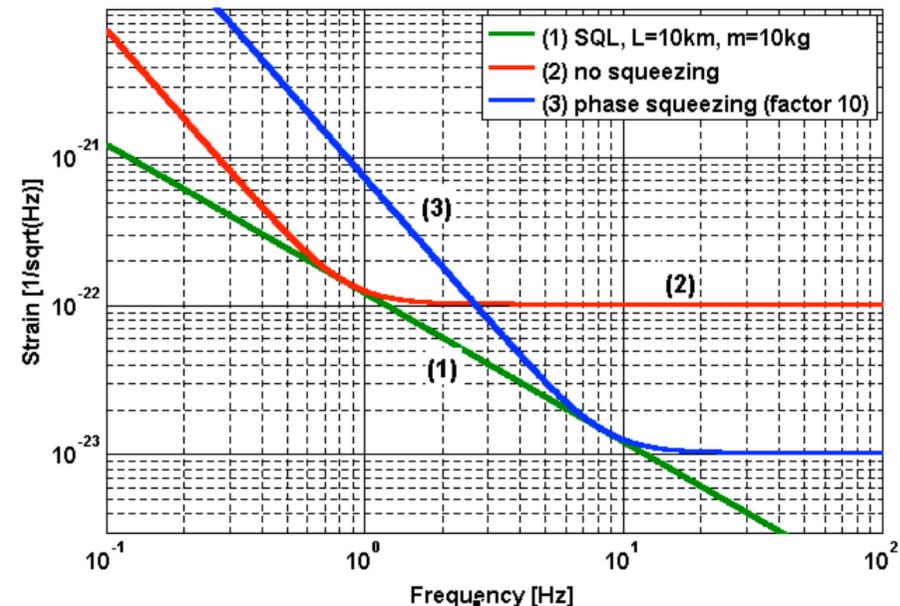
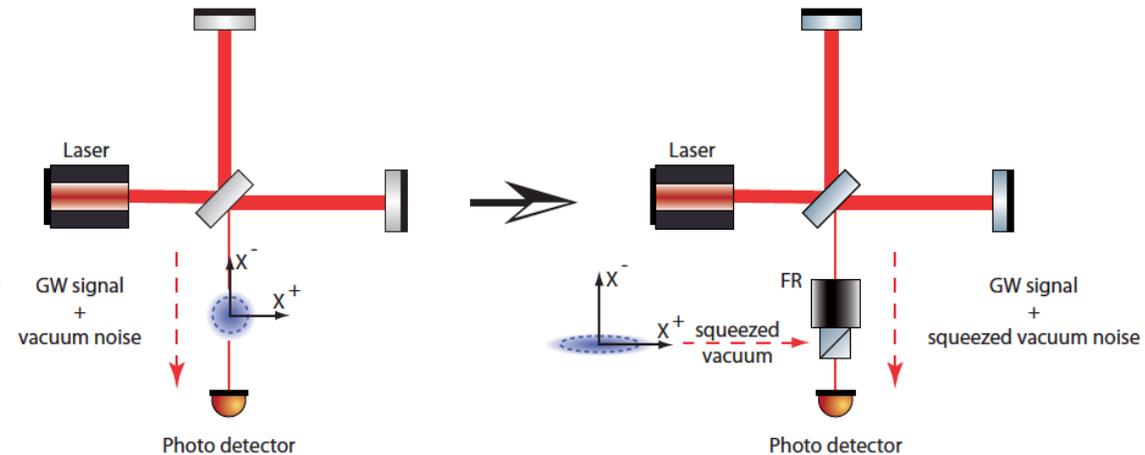
So what do we think will happen?

Or better what are the plans discussed within the LIGO scientific collaboration?

(Note: sensitivity plots I show are taken from LSC instrument white paper)

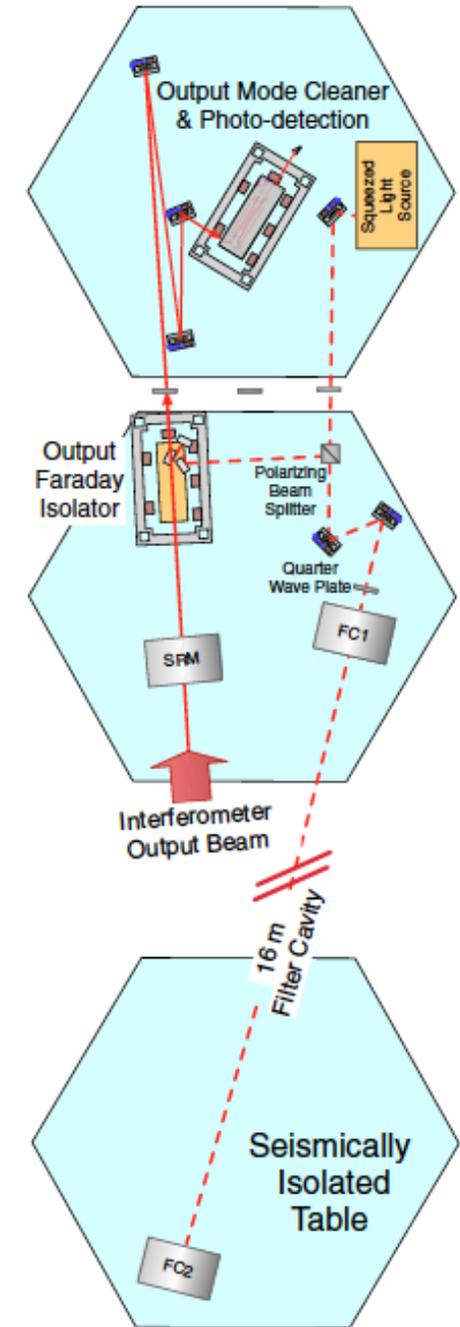
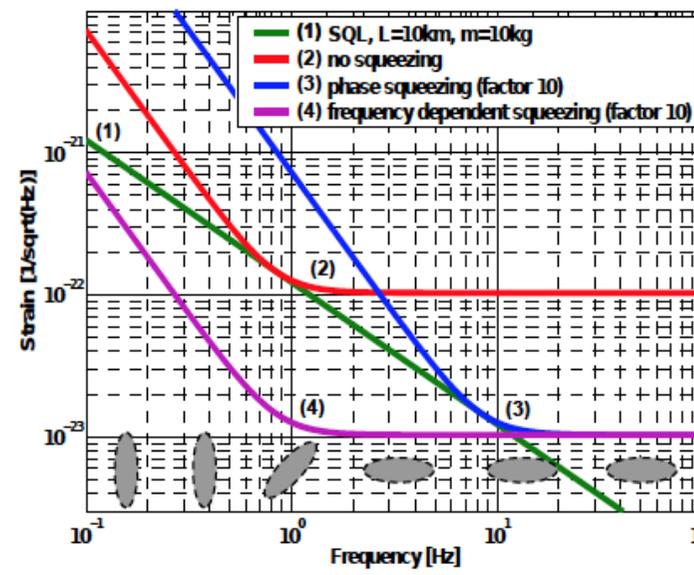
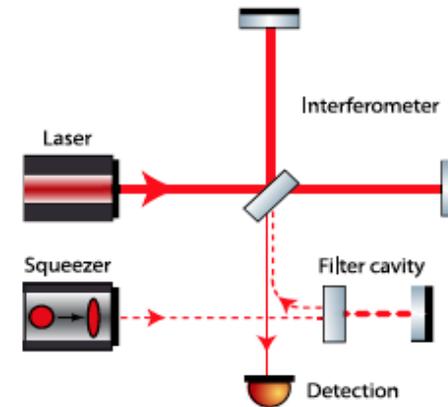
LIGO-T1500290-v1

- ➔ No doubt, 1st upgrade will be speezed light injection
 - Established technology
 - Low risk (can always block beam)
 - Incremental, low downtime.
 - Low cost
- ➔ Can also be used for risk reduction (high power and Parametric Instability).
- ➔ However, at design sensitivity (full power, good low frequency sensitivity), phase squeezing spoils sensitivity at low frequency.



aLIGO+

- ➔ 2nd upgrade: 16m filter cavity to provide frequency dependent squeezing
 - Low risk (can always block beam)
 - Incremental, low downtime.
 - Low-moderate cost
 - Prototyping underway at MIT
- ➔ Aim: obtain squeezing at high frequency without spoiling low frequency due to anti-squeezing. Short cavity sufficient.

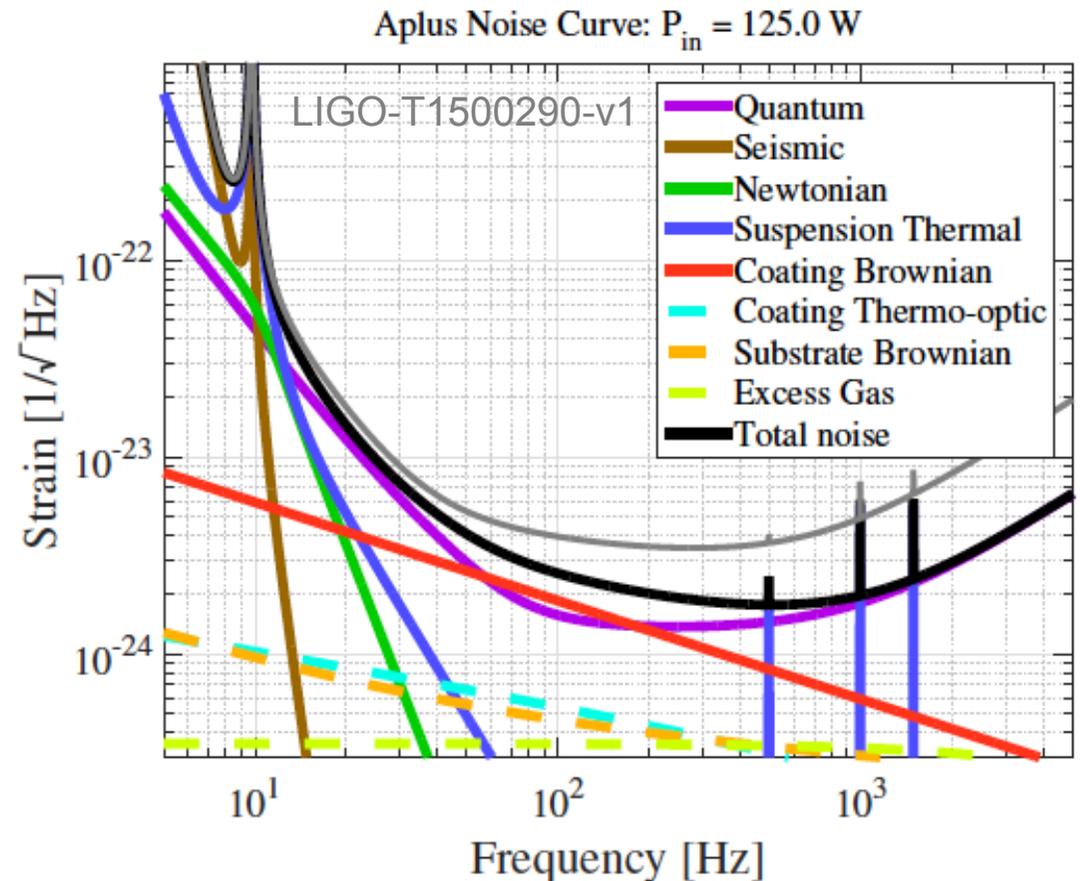


⇒ If better coatings become available then this would be the 3rd step:

- Threshold for this to become useful somewhere between $\sqrt{2}$ and 2 improvement in h .
- If replacing mirrors for better coatings, probably also minor suspension fibre changes.

⇒ Plot shows aLIGO+ (6dB squeezing, 16m FC, factor 2 better coating noise), yielding BNS of 320Mpc.

- Factor 4 increase in detection rate



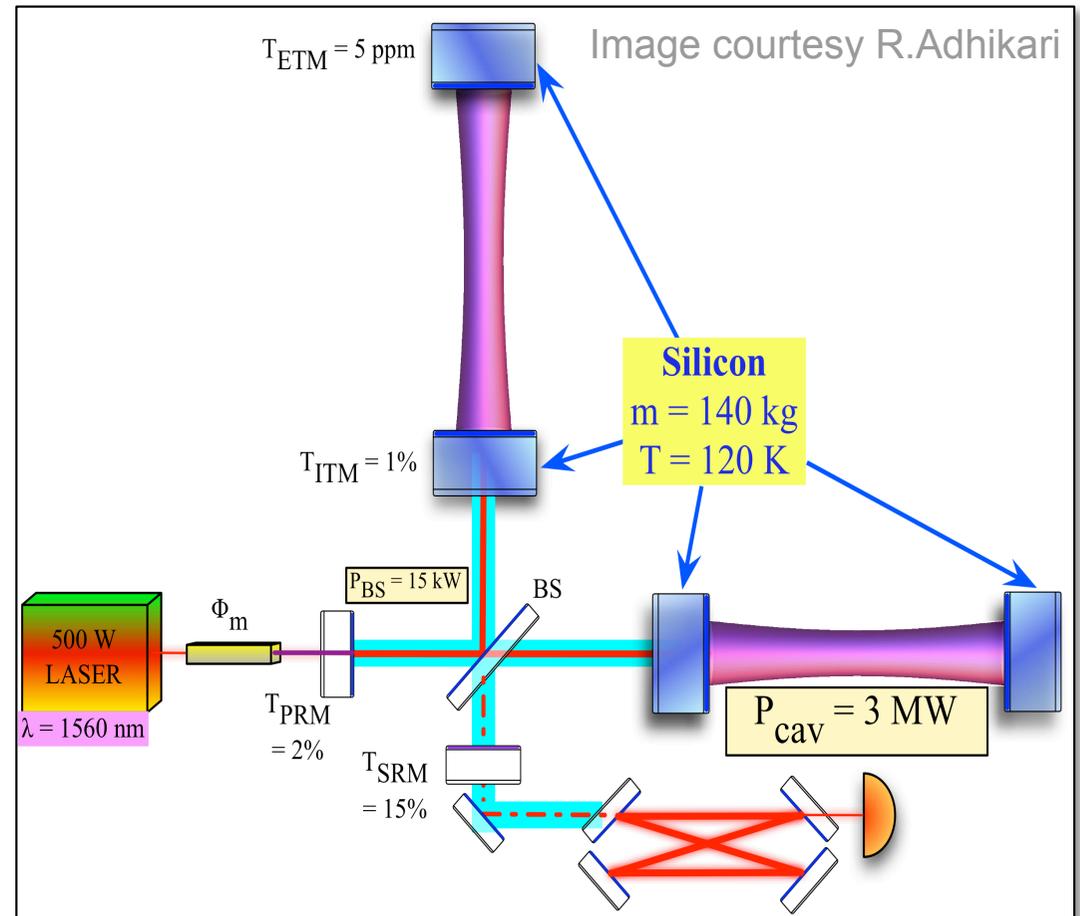


What could one achieve in the LIGO infrastructure with more dramatic changes, i.e. re-installation?

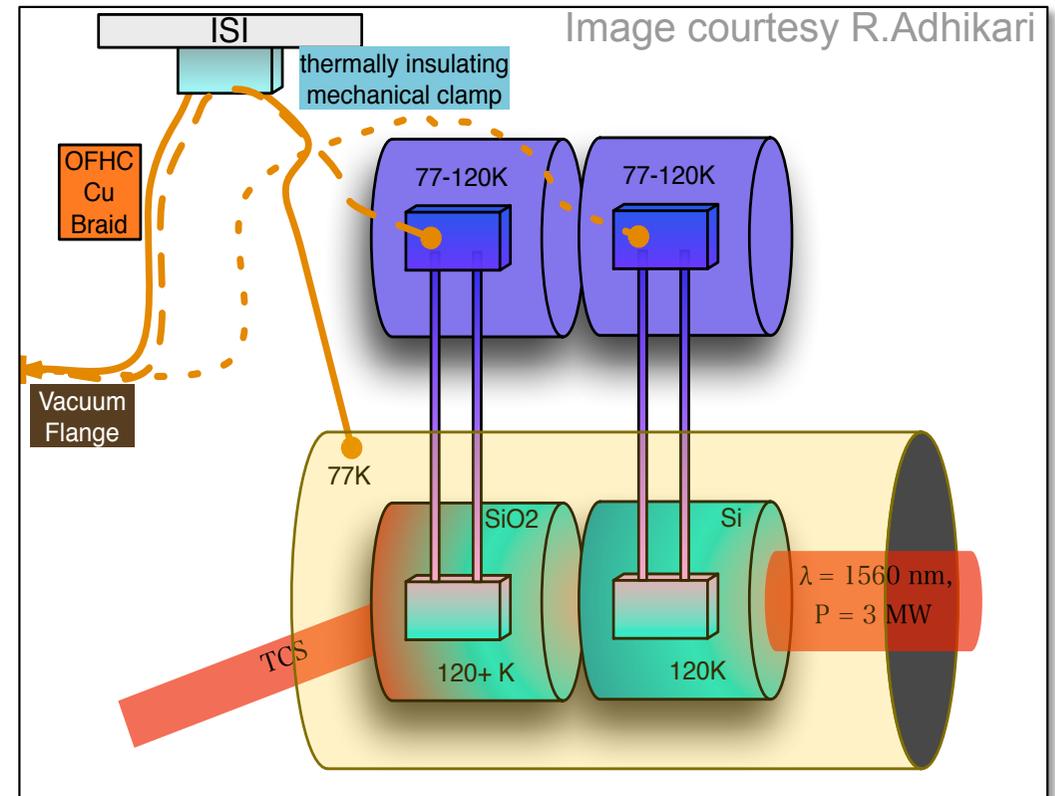
Note: The following slides reflect our current thinking, but will no doubt evolve and change once we detect gravitational waves and learn more about the needed technologies.

- ➔ Based on **cryogenic (120K) silicon test masses** and suspensions to reduce thermal noise.
- ➔ Good properties of silicon:
 - Thermal expansion has a zero-crossing at 120K.
 - High thermal conductivity => smaller thermal gradients.

Winkler et al, Phys. Rev. A 44, 7022–7036 (1991)
- ➔ Plan to use 4 times higher optical power than aLIGO.
- ➔ Lots of R&D underway within the LSC ...



- ➔ In contrast to the Einstein Telescope and KAGRA (both operating at 10-40K range) the **cooling in Voyager design will mainly be done via radiation** (and not via conduction through the fibres).
- ➔ As a result the **cryogenic implementation is simpler** and **higher optical powers** can be possible.
- ➔ **Not incremental**
- ➔ Also strongly coupled design choices. (see next slide)

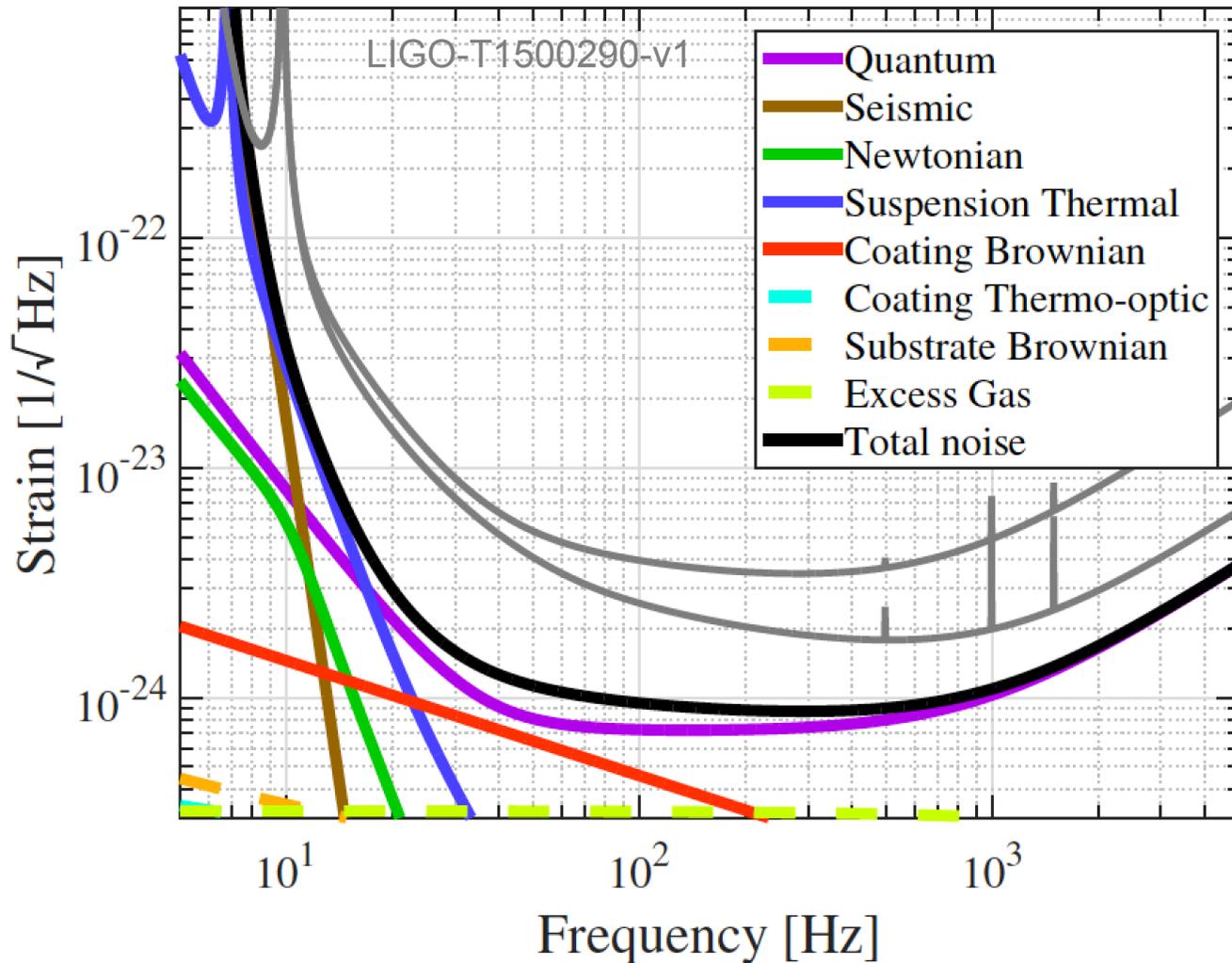


- ➔ While for ALIGO many of the design choices could have been made to first order independently:
 - signal recycling **yes** vs **no**,
 - DC-readout vs **heterodyne**,
 - seismic isolation **active** vs **passive**,
 - test mass material **silica** vs **sapphire**,
 - suspensions **fibres** vs **ribbons**,
 - non-degenerate recycling cavity design vs **marginally stable**,

- ➔ For Voyager this will be different: Mirror temperature is a new parameter and it has strong dependencies on mirror material (silica => silicon), laser wavelength (1064nm => about 1.5microns) etc...

Voyager sensitivity

Voyager Noise Curve: $P_{in} = 300.0 \text{ W}$



aLIGO baseline

aLIGO+

- Increased power, heavier mirrors, better squeezing, long filter cavity.
- 120K, crystalline coatings, larger beam size
- Length of final suspension stage increased
- Newtonian noise subtraction



What could be done with a new facility?
How should such a facility look like?

- ➔ LIGO = 4km, ET = 10km. Why not go longer?
- ➔ Signal increases proportional to length. So, if the other parameters kept identical then coating, seismic, newtonian, radiation pressure and suspension noise reduce by $1/L$. Shot noise and residual gas also decrease but only with $\sqrt{1/L}$.
- ➔ Suggestion put forward for a 40km interferometer (Dwyer et al)
- ➔ Trade-off between underground/shorter arm length vs longer arms on the surface.
- ➔ Key question: How important is sensitivity in the 2-10Hz band?

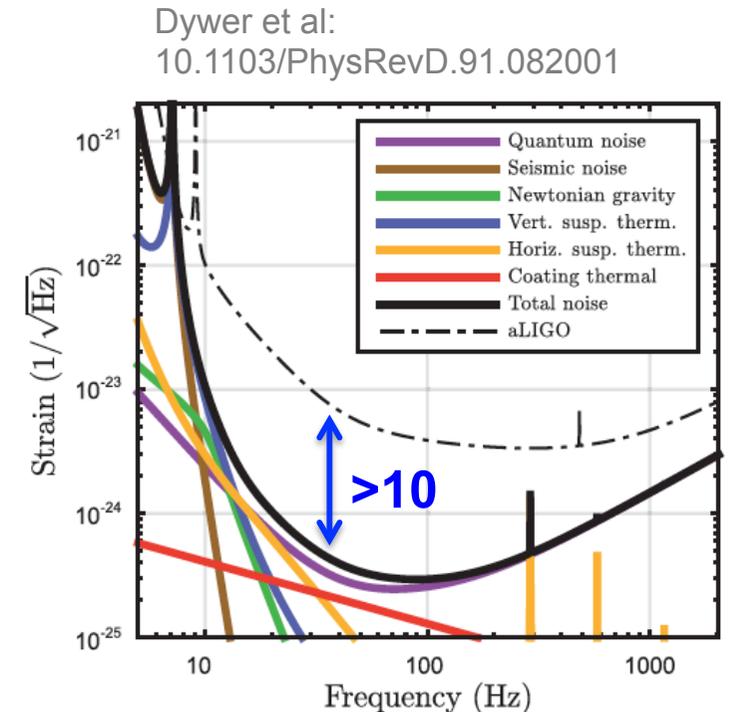
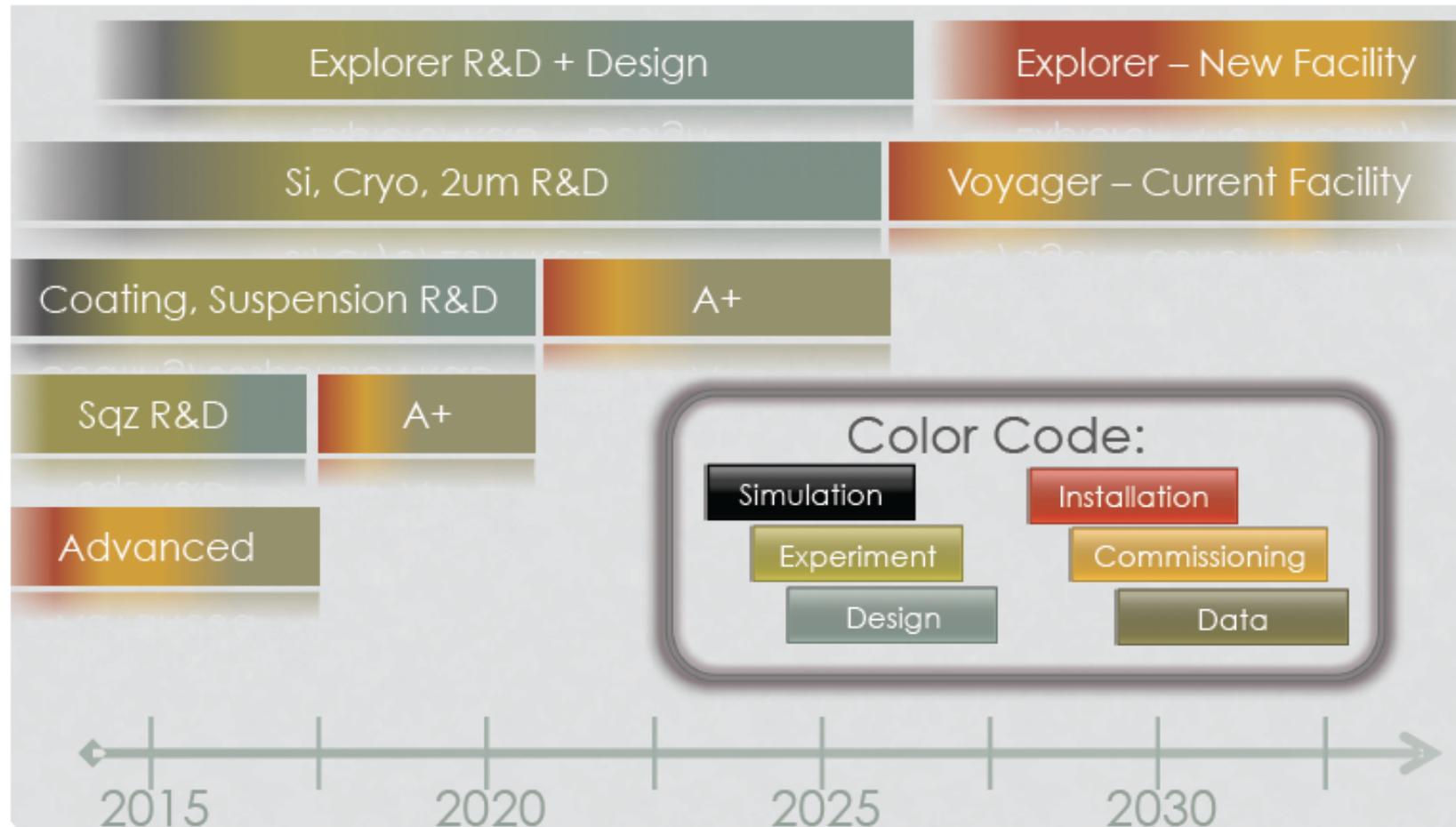


FIG. 1 (color). Projected sensitivity of a 40 km long interferometer based on Advanced LIGO. The only major added technology with respect to the existing interferometers is the use of a squeezed light source for reducing quantum noise.



Timeline from LSC Whitepaper



Originally from Matt Evans

Figure 2: Timeline for A+, LIGO Voyager and LIGO Cosmic Explorer.

- ➔ Upgrade path with 3 major steps has been identified:
 1. aLIGO+ (before 2020): Squeezing + better coatings if available
 2. Voyager (2025-2030): Completely new detector; cryogenic (120K) high power.
 3. New facility (2030+): Very long surface detector under consideration
- ➔ Relevant R&D is underway
- ➔ Upgrade time-line and technology choices might also depend on what is observed by aLIGO and the event rate. Various trade-offs and stakeholders involved ...
- ➔ **Loads of new science on the horizon!**



**Thanks very much for your
attention.**



Can we learn from ALIGO ?



- ➔ In principle Yes!
- ➔ Interesting to remind ourselves of the aLIGO timeline:
 - 1999 aLIGO White Paper
 - 2005 Proposal to NSF
 - 2008 Project start (was made conditional on reaching the initial LIGO sensitivity curve and completing one year observation)
 - 2015 Project complete
- ➔ In contrast eLIGO was much faster.
- ➔ Depending on how drastic the chosen LIGO-3 design is, one might hope to be somewhere between the scale of aLIGO and eLIGO.
- ➔ LIGO-3 investigations started in 2011 ...



How we deal with upgrades might depend on what aLIGO will see



- ➔ Let's do a quick Gedanken-experiment for aLIGO at design sensitivity
 - Scenario 1: Less than 1 detection in the first 2 years
 - Scenario 2: About one detection per year
 - Scenario 3: many detections per year

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

From Asai et al: <http://arxiv.org/abs/1304.0670>



How we deal with upgrades might depend on what aLIGO will see



- ➔ Let's do a quick Gedanken-experiment for aLIGO at design sensitivity
 - **Scenario 1:** Less than 1 detection in the first 2 years
 - **Scenario 2:** About one detection per year
 - **Scenario 3:** many detections per year
- ➔ **Scenario 1:** Will there be any money for going beyond aLIGO?
- ➔ **Scenario 2:** improving the sensitivity by a factor 3-5 might actually make a huge difference.
- ➔ **Scenario 3:** Will there be pressure from astro-community and funding agencies to stay online and take more data before upgrading? Might there be a tendency to aim for more like a factor 10 and go for a new facility?