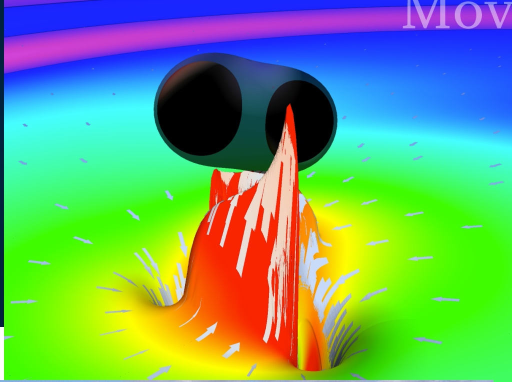
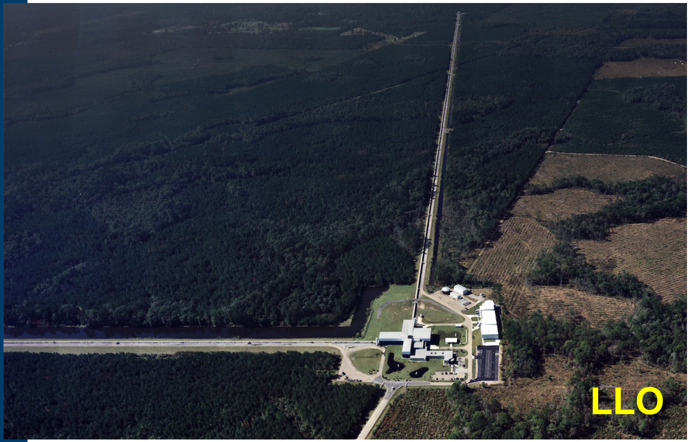
University of Glasgow

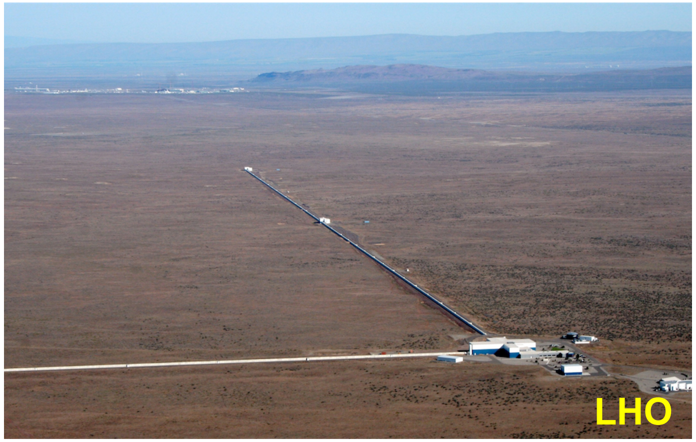
Science & Technology Facilities Council

LSC LIGO Scientific Collaboration

VIRGO



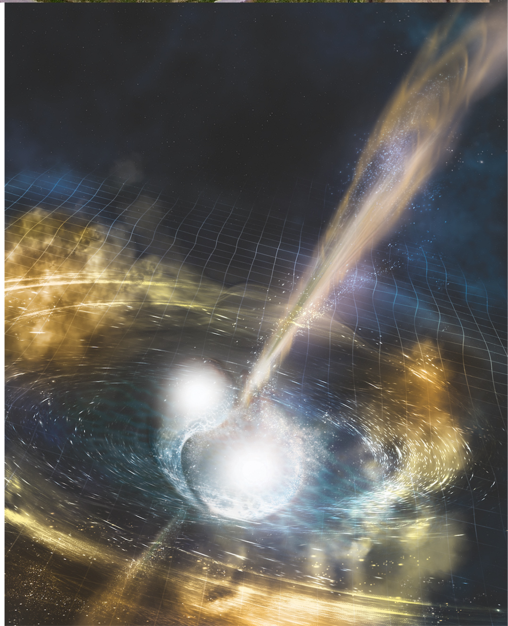




Gravitational waves

Detectors, detections and future prospects

Borja Sorazu
Institute for gravitational research, University of Glasgow
on behalf of the LIGO scientific collaboration and Virgo



LSC – a World town

The LIGO Scientific collaboration (LSC) is made out of 1300+ scientist from over 108 institutions and 18 countries worldwide. **www.ligo.org**

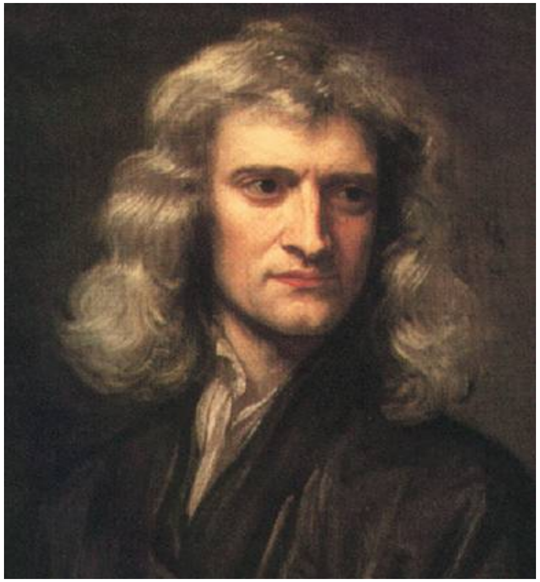
Introduction

- What are gravitational waves?
- Overview of GW detections
- GW170817 – the dawn of multi-messenger astronomy
- Gravitational wave detectors
- Fundamental noise sources
- Enhanced 2G detectors & Science case
- 3G detectors & Science case

What are gravitational waves?

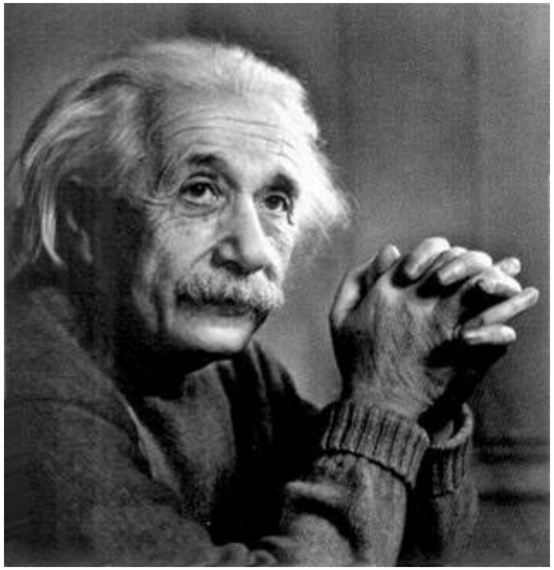
What is gravity?

First we need to understand what gravity is:



Classical interpretation by Newton:

It is an instantaneous action at a distance.



Einstein's theory of general relativity:

Gravity is the result of the distortion of the local space-time. This distortion, caused by the distribution of mass and energy, propagates at a finite speed.

What is space-time?

- Space and time independently are not objectively real → There is not universal agreement.
- Where do we find universal agreement? In causality!

$$\underbrace{(\Delta x)^2}_{\text{Distance between events}} - c^2 \underbrace{(\Delta t)^2}_{\text{Time between events}} \equiv \text{Spacetime separation between events (S.E)}$$

- S.E. informs if an event influences other event → Causality

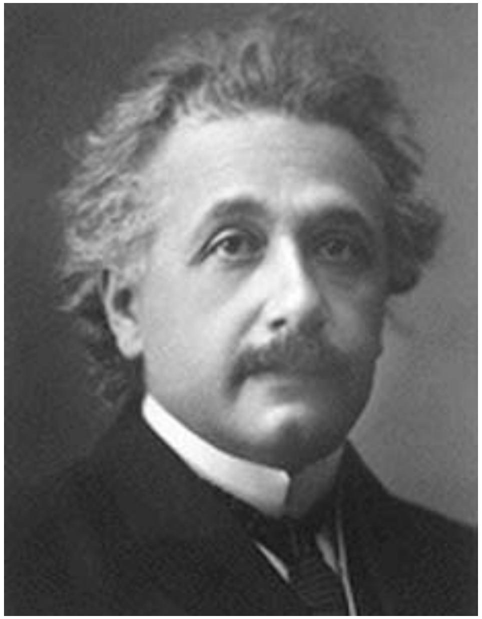
"Reality is not an space that evolves in time but rather it is a mathematical structure of 4D (unified space and time) without evolution." H. Minkowski

- Points in this 4D structure are events and S.E. is their "distance".

What is *c*? – velocity of causality

- It is the velocity of causality (Lorentz transformation).
- It is the maximum velocity at which an observer sees two parts of the universe communicate.
- Mass is the opposition to movement → Massless 'things' must propagate at maximum allowed speed → c.
- EM are massless → c.
- **Gravitational waves are massless → c!**

The Theory of General Relativity



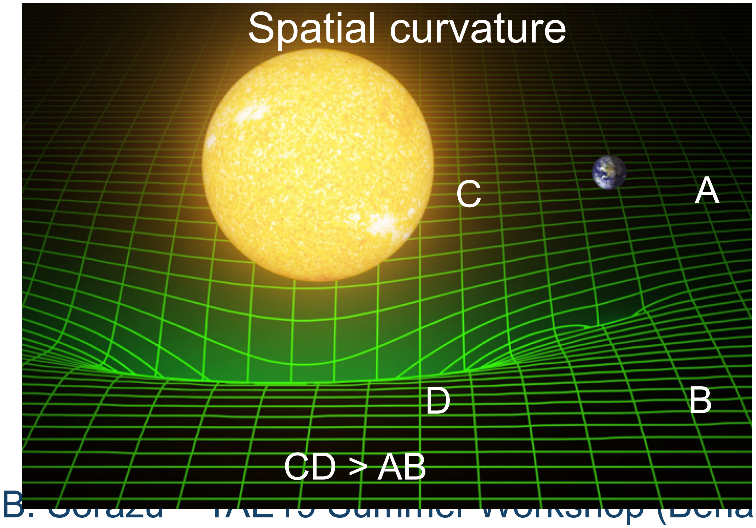
Informs matter how to move in a curved space-time →

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

← Informs matter how to curve space-time

"Mass tells space-time how to curve, and space-time tells mass how to move." John Wheeler

Gravity → movement of matter in this curved geometry.



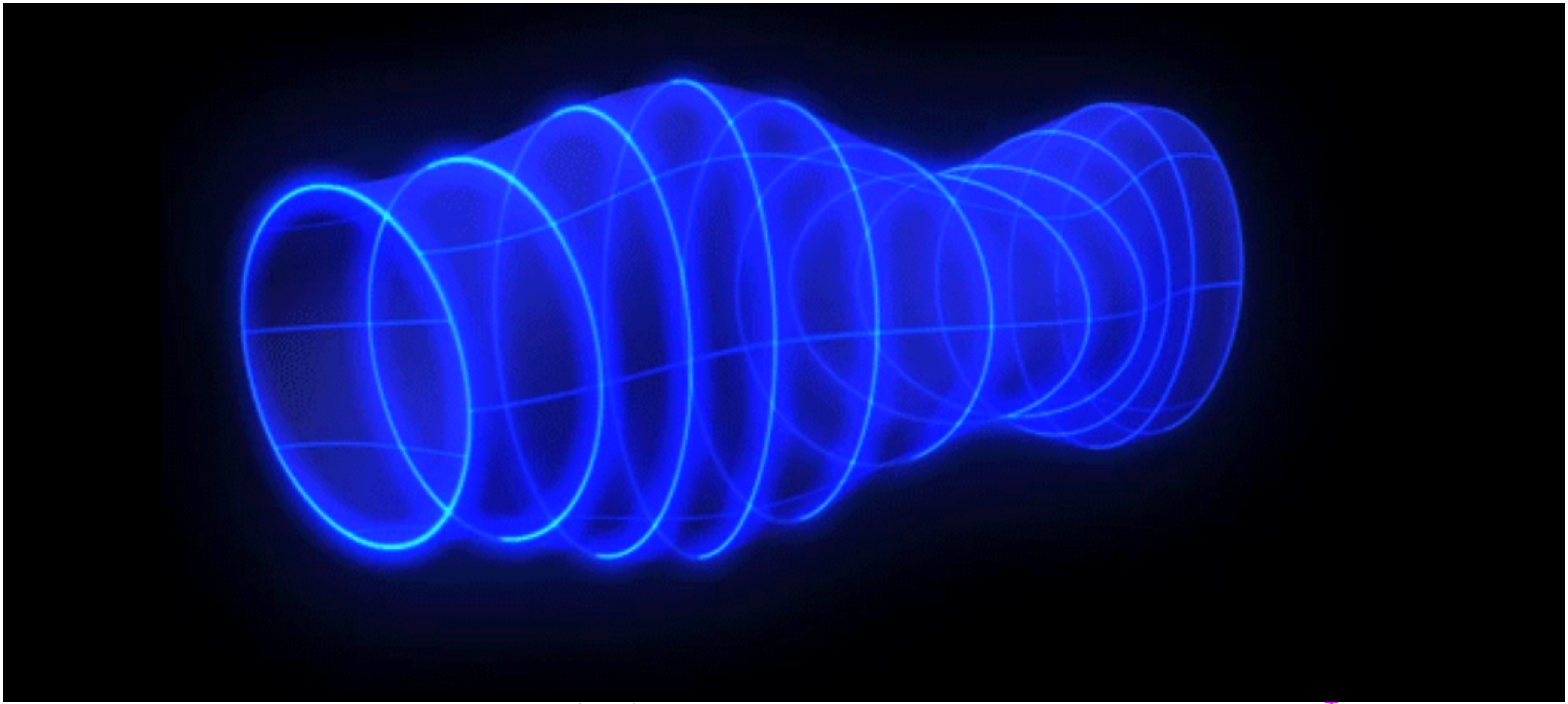
Spatial curvature

CD > AB

Time curvature

What are gravitational waves?

- Moving matter changes the curvature of the space-time in the form of waves.
- **Gravity** is the way in which matters perceives space-time distortion → **Waves of gravity**.



“Cross” polarisation ✕

“Plus” polarisation ✛

Gravitational waves are very faint

To detect a gravitational wave → measure the change it makes in the distance between two free particles.

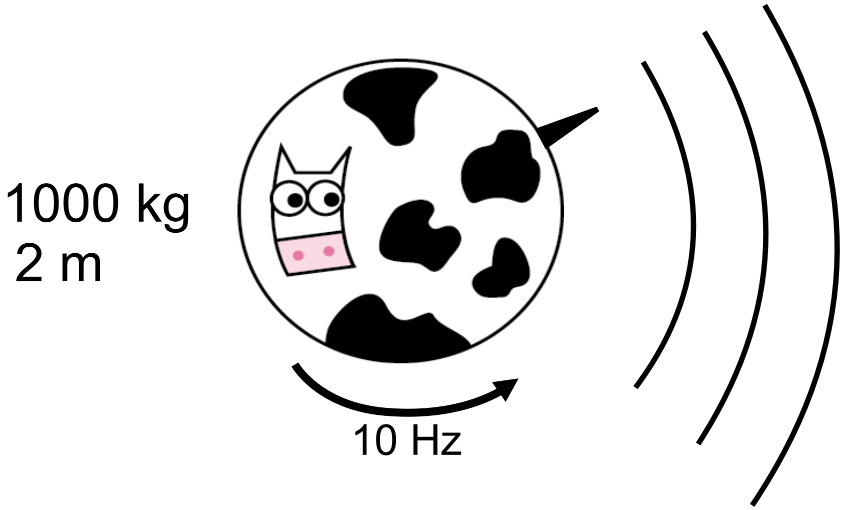
This change is very small because space-time is very stiff:

Stiffness of space-time

$$\boxed{T_{\mu\nu} = 5\cdot10^{42} G_{\mu\nu}}$$

Similar to Hooke's law:

$$(\vec{F} = k\vec{x})$$



$$h = \frac{\Delta l}{L} \approx 10^{-49}$$

Amplitude of GW (strain, deformation per unit length).

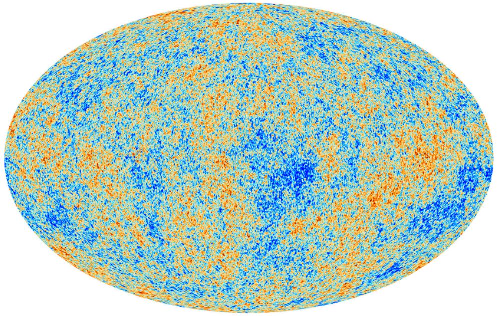
For a person 1.8m tall, it would stretch and shrink by: 0.000000000000000000000000000000000000000000000018 mm = 1.8 × 10^{-46} mm.
(proton radius= 0.85 × 10^{-12} mm)

What type of sources can we detect?

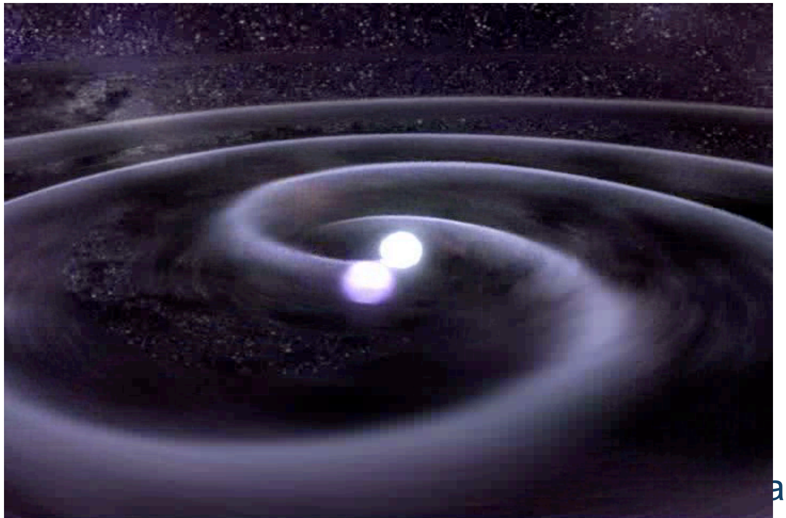
$$h \approx \frac{G}{c^2}\frac{M}{d}\left(\frac{v}{c}\right)^2$$

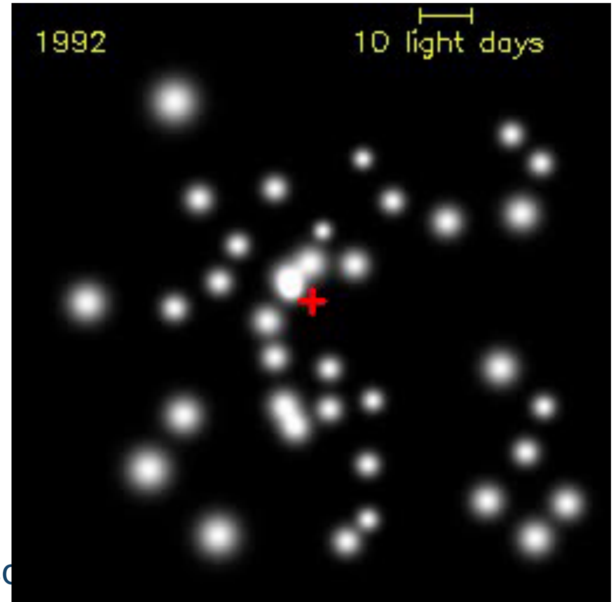
→ Sources of big mass, accelerated and moving at relativistic speeds:

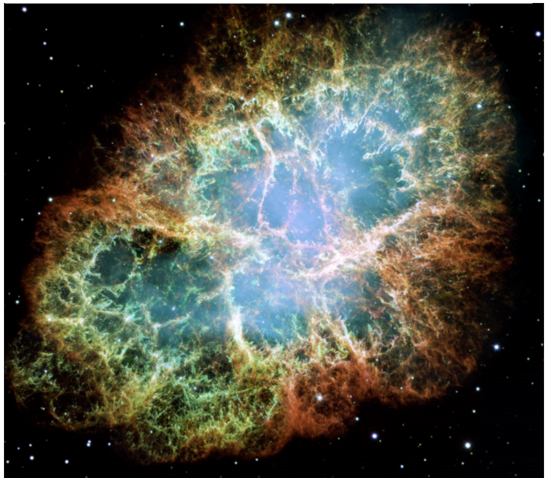
- Supermassive black holes at galaxy centres.
- Compact binary coalescent systems; NS-NS, NS-BH, BH-BH.
- Collapse of massive stars (supernovas).
- Inflation of the universe after the Big Bang.
- Pulsars y Gamma ray sources (asymmetric).



Credit: Planck Collaboration

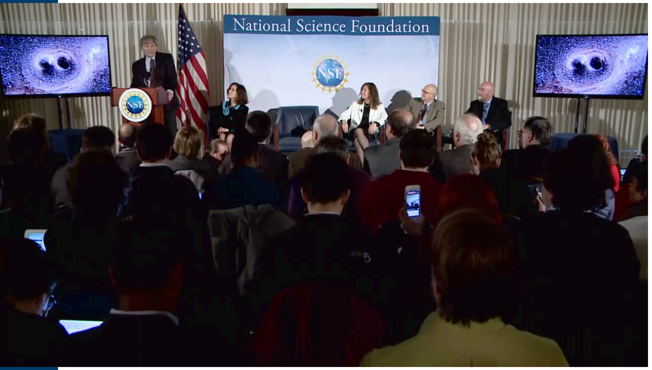






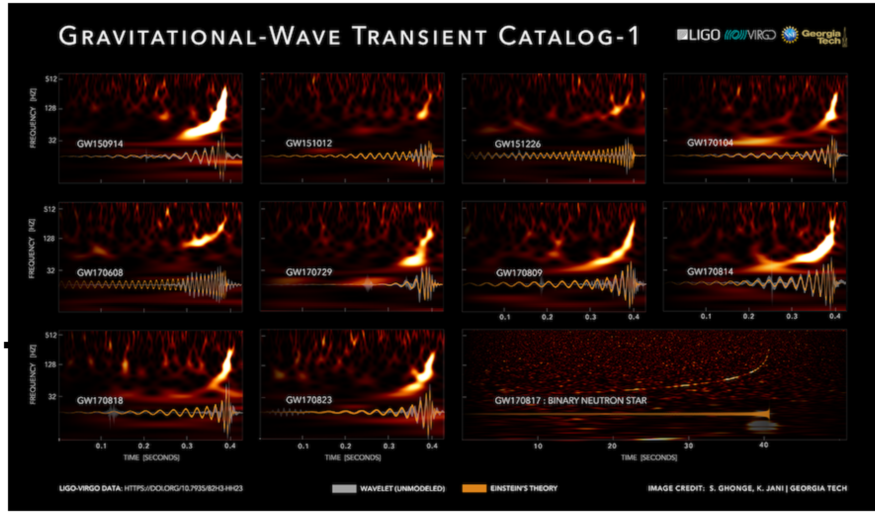
Overview of detections

Overview of results so far



Feb 2016, dawn of new era in astrophysics, based on GWs (GW150914, first BBH signal).

Pre O3: 10 BBH, including 1st triple detection.



1 BNS, First EM counterpart. Breakthrough in multi-messenger astron.

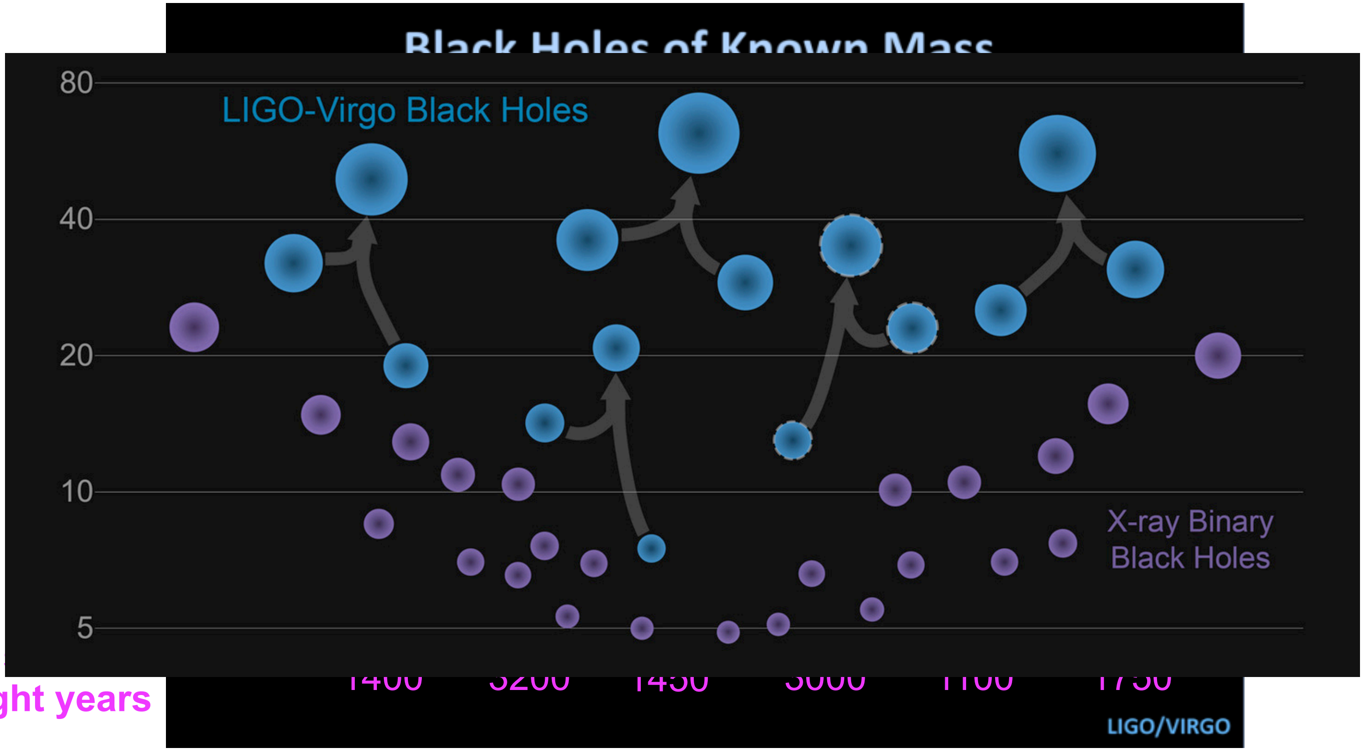
Key: 🟦 BBH 🟩 BNS 🟨 NSBH 🟪 MassGap 🟥 Terrestrial

GraceID	Distance (Mpc)	Instruments	FAR (One every ___)	Last Updated
S190915ak	1557 ± 381	H1,L1,V1	32.57 years	2019-09-17 19:20:45
S190910h	241 ± 89	L1	0.88 years	2019-09-18 10:01:31
S190910d	606 ± 197	H1,L1	8.53 years	2019-09-11 00:42:44
S190901ap	242 ± 81	L1,V1	4.51 years	2019-09-02 11:53:33
S190828l	1609 ± 426	H1,L1,V1	685.01 years	2019-08-28 07:40:08
S190828j	1803 ± 423	H1,L1,V1	37.42 Trillion years	2019-08-28 08:07:47
S190814bv	276 ± 56	H1,L1,V1	15.6 Septillion years	2019-08-15 10:19:10
S190728q	795 ± 197	H1,L1,V1	1.25 Quadrillion years	2019-07-28 20:29:12
S190727h	1104 ± 289	H1,L1,V1	230.08 years	2019-08-01 17:06:04
S190720a	1071 ± 323	H1,L1	8.34 years	2019-07-22 18:34:11
S190718y	227 ± 165	H1,L1,V1	0.87 years	2019-07-18 15:40:52

O3: Started on 1st April 2019, 1 year observation. Network of 3, 2G detectors. CBC detection rate ~1/week. So far: **~21 BBH, 4 BNS, 2 NSBH(?)** candidates. All shared with the public.

Confirmed BBH detections – preO3

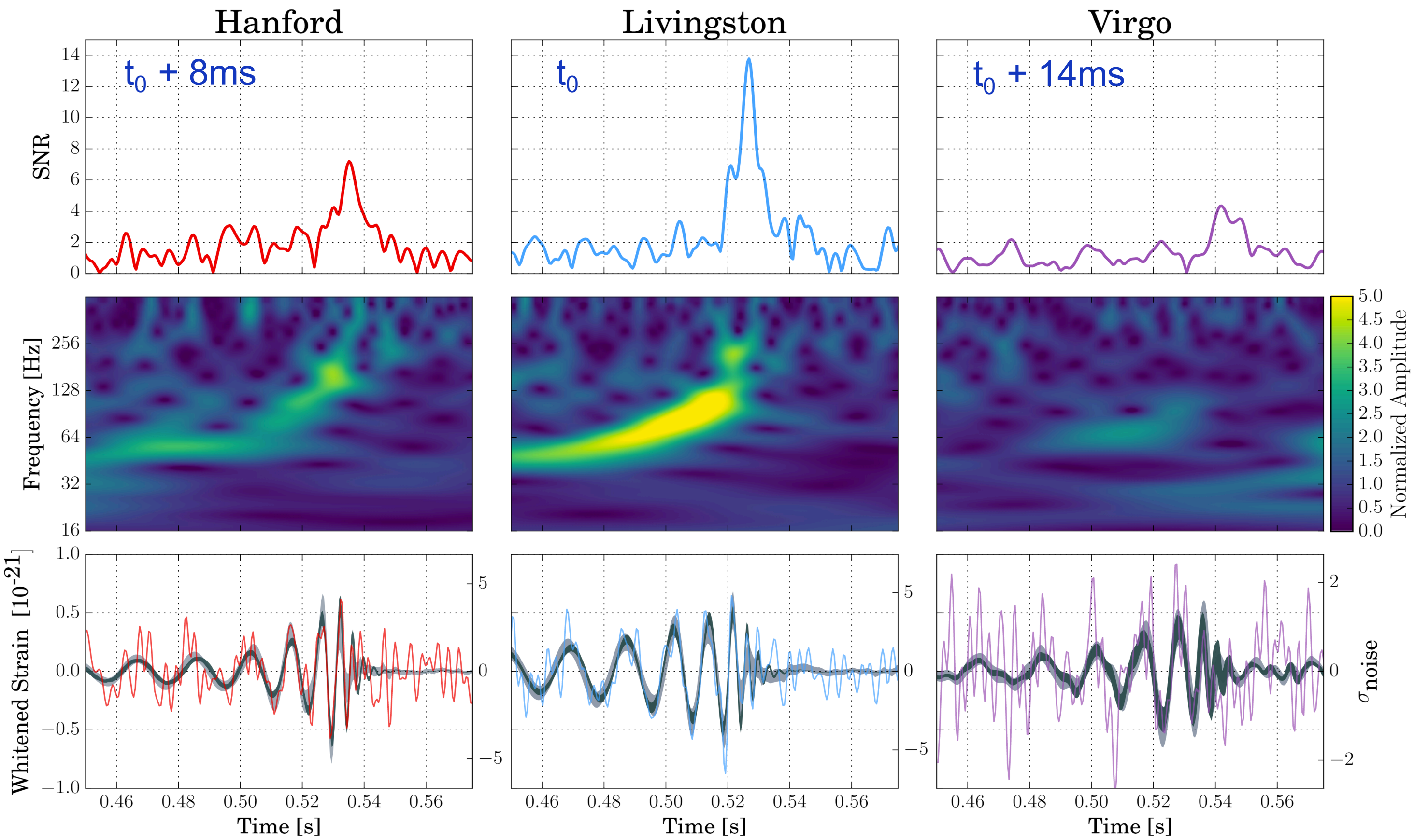
- During O1 (18 Sept 2015 – 12 Jan 2016): 2, GW150914 and GW151226.
- During O2 (30 Nov 2016 – 25 August 2017): 3 announced, GW170104, GW170608 and **GW170814**
- No EM → BHs dimension imply no accretion disc.



Distance to
in million light years

First triple detection GW170814: LIGO+Virgo

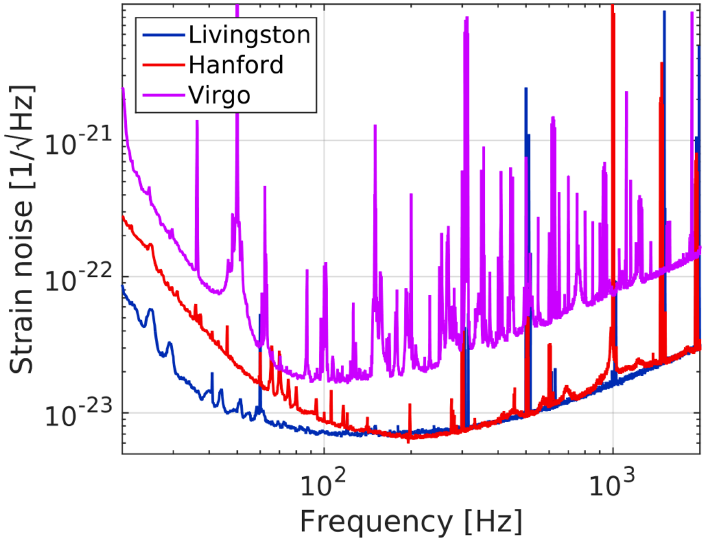
- **GW170814** first detection with 3 detectors (LLO, LHO and Virgo joining O2 on 1 August 2017).



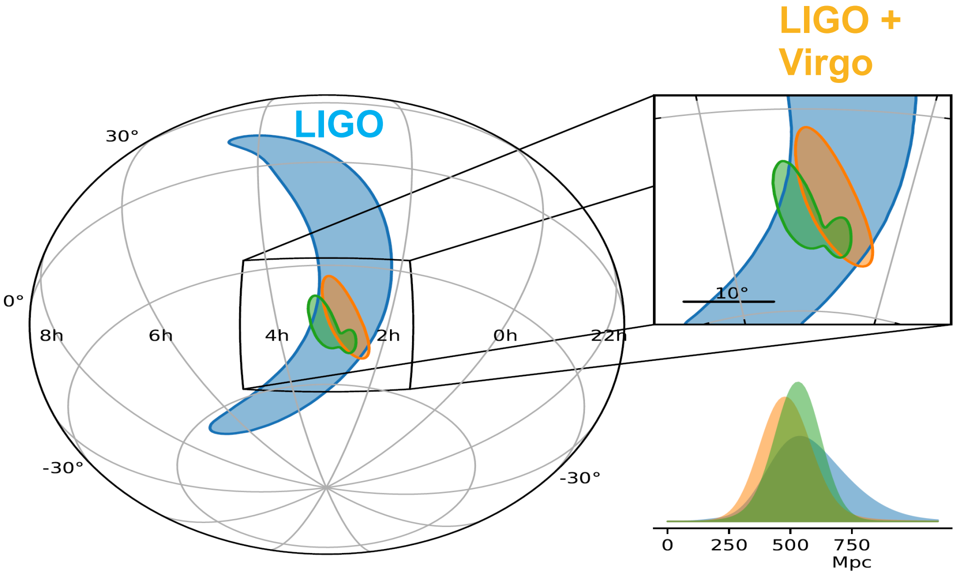
- Signal is observed at different times in the 3 detectors due to the finite propagation speed of GWs → source location.

First triple detection GW170814: LIGO+Virgo

- 3 detectors → Great localization improvement:
  - 90% credibility region: 1160 degrees^2 (LIGO), 60 degrees^2 (LIGO+Virgo).
  - Also improved luminosity distance uncertainty by 50%



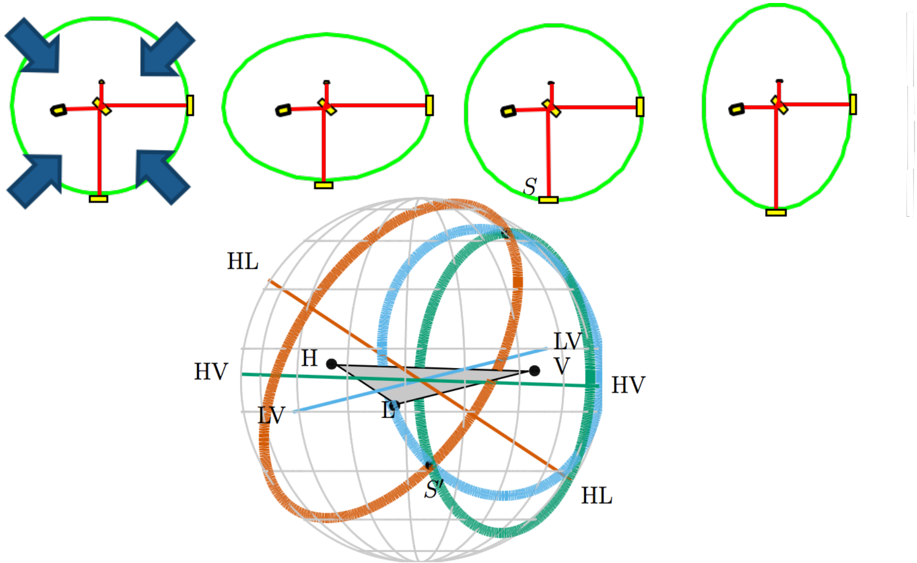
Sensitivity of the 3 detectors during GW170814

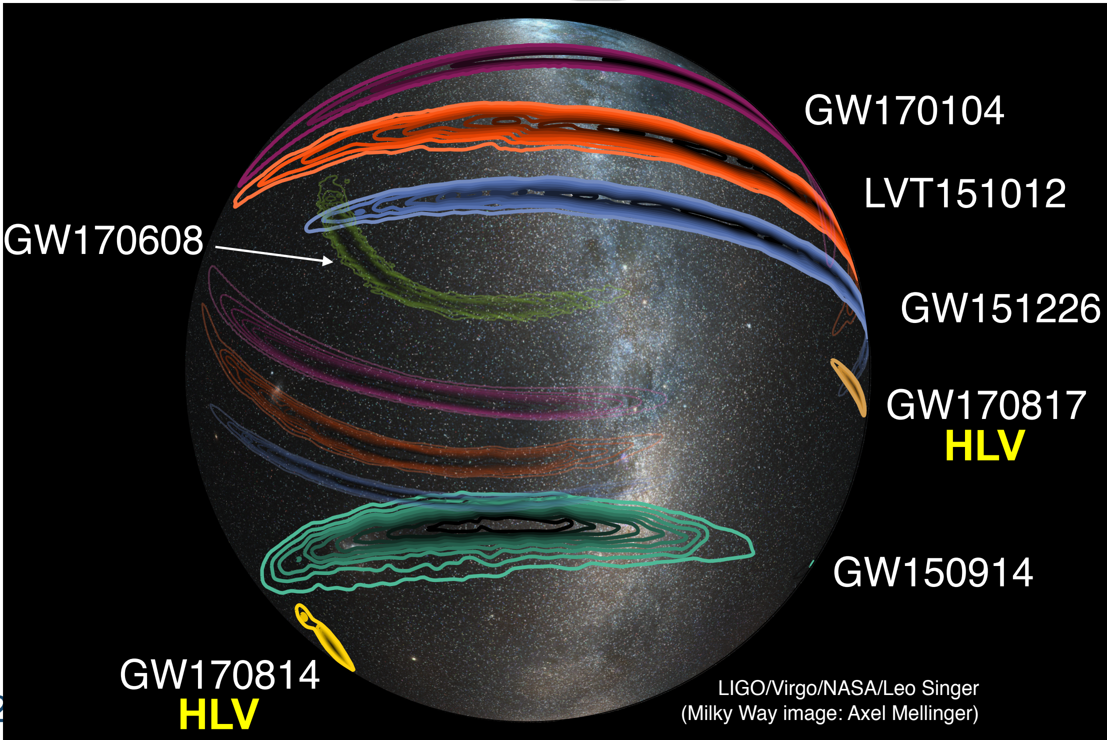


Source location of GW170814 inc. distance

Source location

- Detectors sensitive to all sky. Highest sensitivity vertical to detector plane.
- Triangulation by difference in arrival time to detectors…
- ... And consistency of signal’s amplitude and phase (affected by calibration uncertainty).
- <u>2 detectors</u>; localization in long bands (triangulation circle):
  - **hundreds degrees^2** (90% conf.)
  - Volume includes 10^9 Milky Ways
- <u>3 detectors</u>; better location (intersection of 3 circles):
  - **tens of degrees^2**



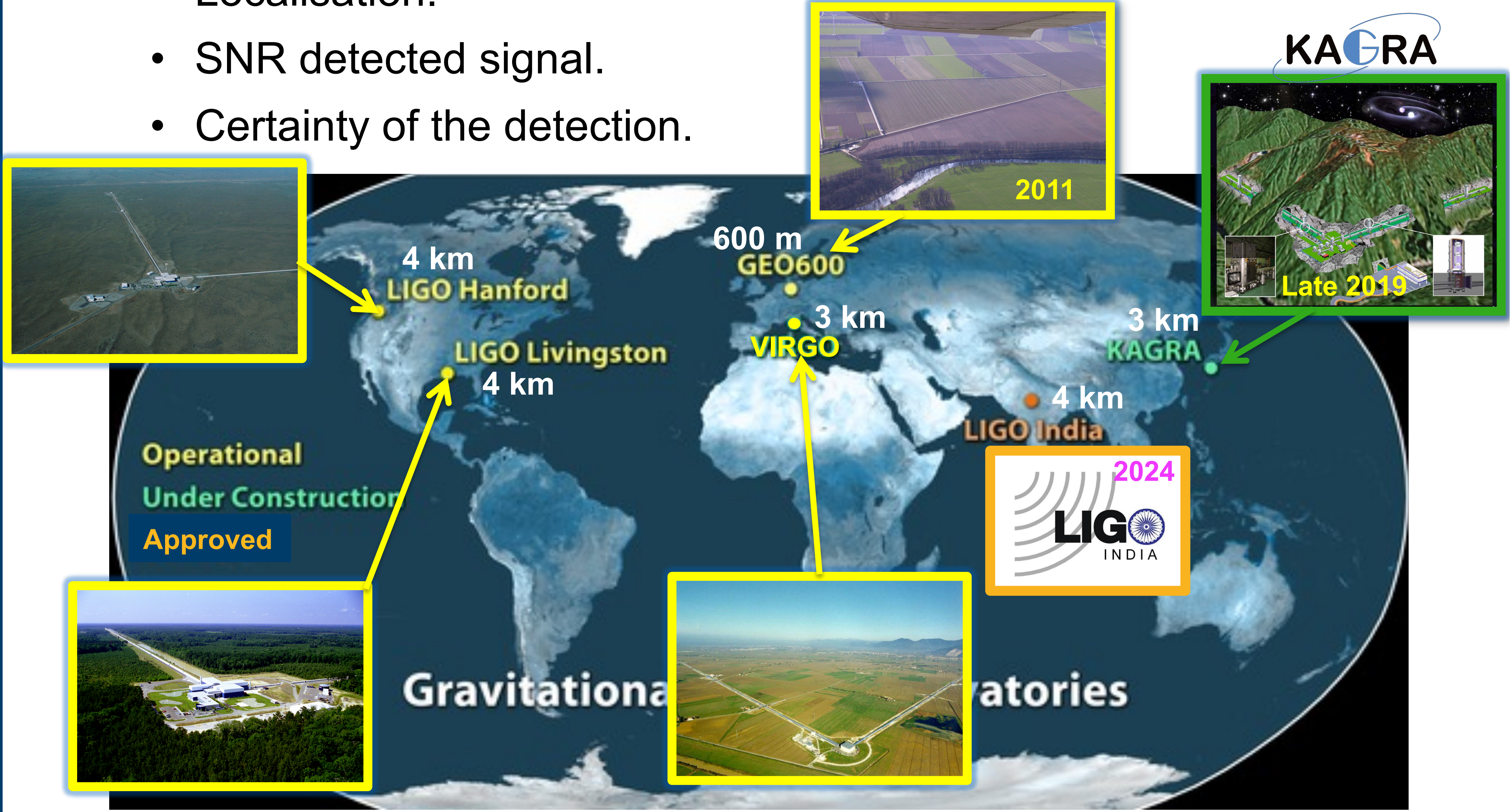


LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

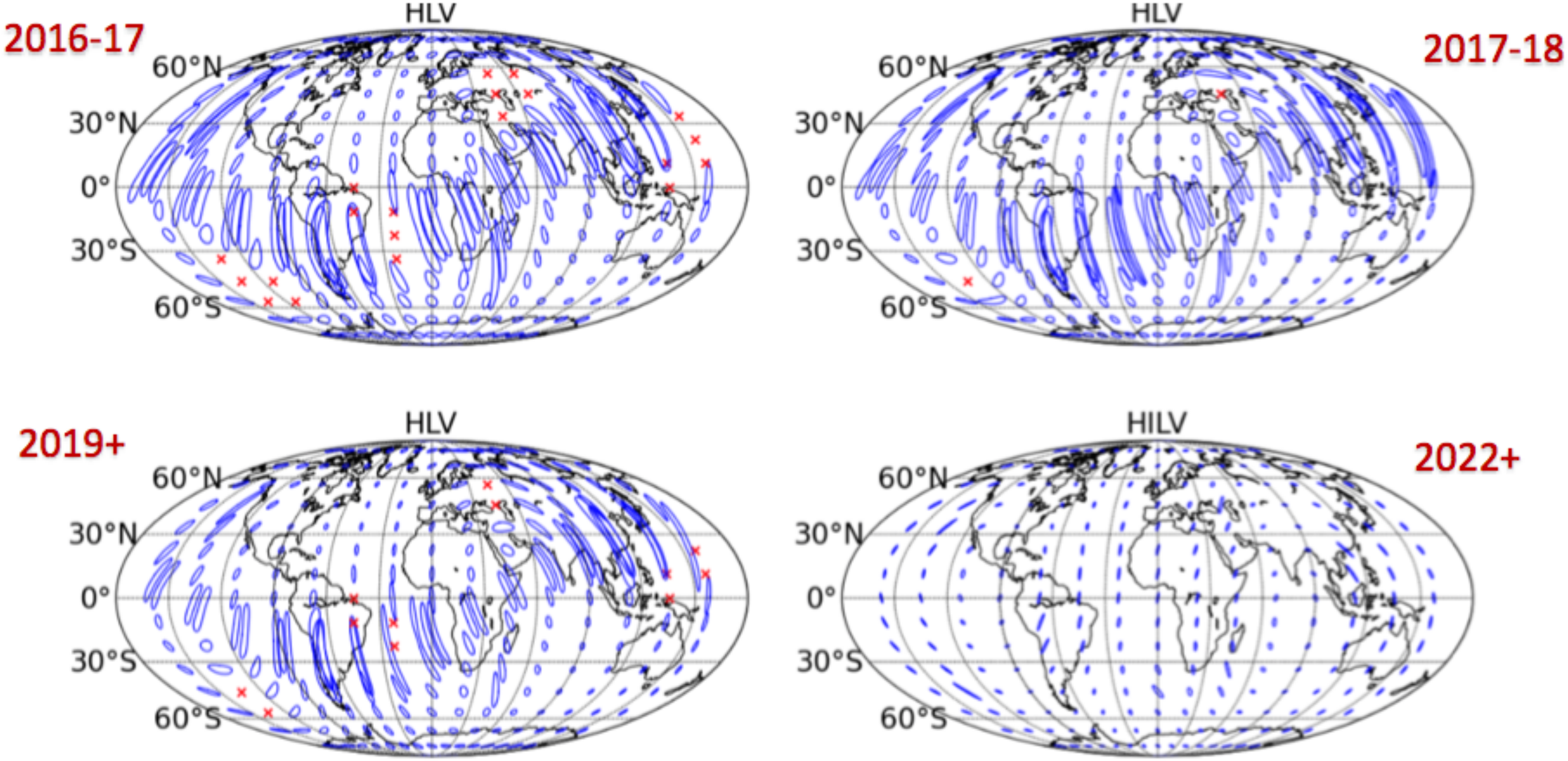
Global network of detectors

A global network of detectors improves:

- Localisation.
- SNR detected signal.
- Certainty of the detection.

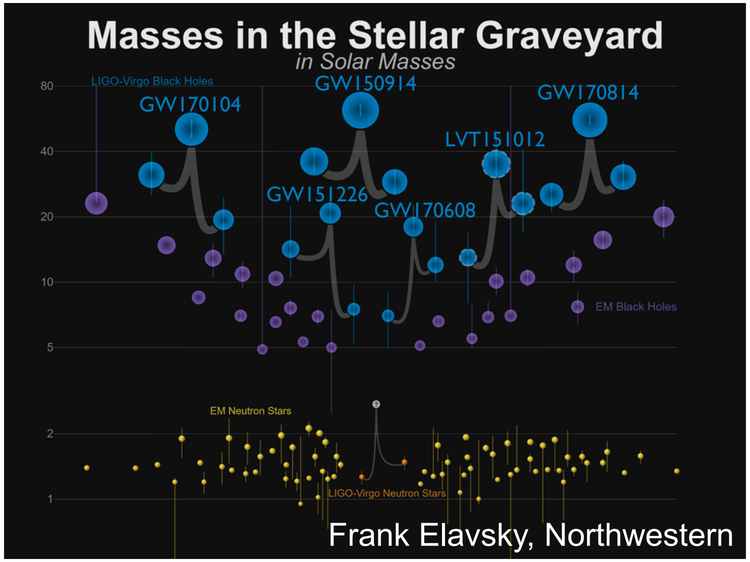


Global network of detectors- ‘Localization’



- Adding Virgo (August 2017) → breaks annular uncertainty. From hundreds to tens of degrees^2
- ↑ detectors’ sensitivity → ↓ source location error.
- With LIGO-India → great new improvement → few degrees^2

Scientific implications of BBH detections



Frank Elavsky, Northwestern

- First direct measurements of **BH properties** (mass, spin, distance, inclination)
- First observations of BBH systems (only possible through GWs) → they exist and merge (in less than 13G years).
- **BBH merge rate** (based in observations) ~ **10 - 200 events$\cdot$Gpc^{-3}yr^{-1}**
- First observations of **intermediate mass BHs** (25 < BH <10^6 solar masses)

- Most powerful events ever observed (few solar masses of energy radiated as GWs in less than 0.1s)
- First **tests of GR** in dynamic conditions of extreme gravity (so far no discrepancies observed)
- Test of GW polarizations (how spacetime can be deformed) → Confirming GR prediction (X and +)

GW170817

The dawn of multi-messenger astronomy

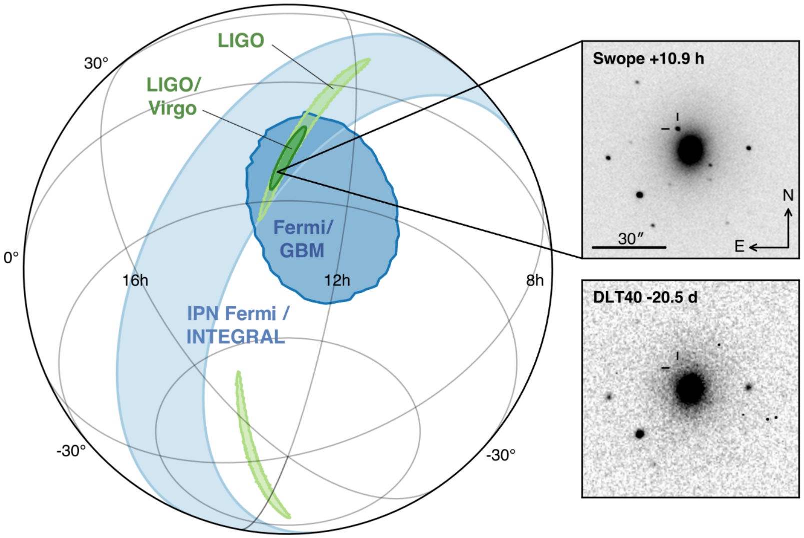
~4000 authors from about 1000 institutions.
Over 70 telescopes from all 7 continents + space involved.

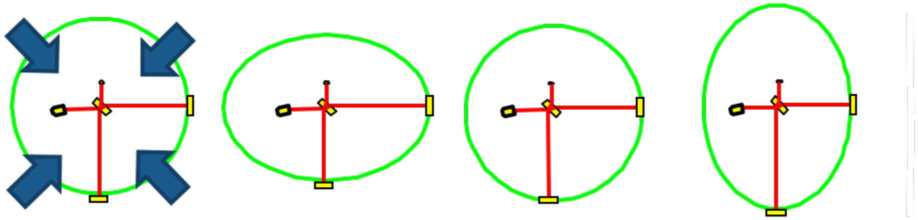
GW170817 – first GW signal of a BNS

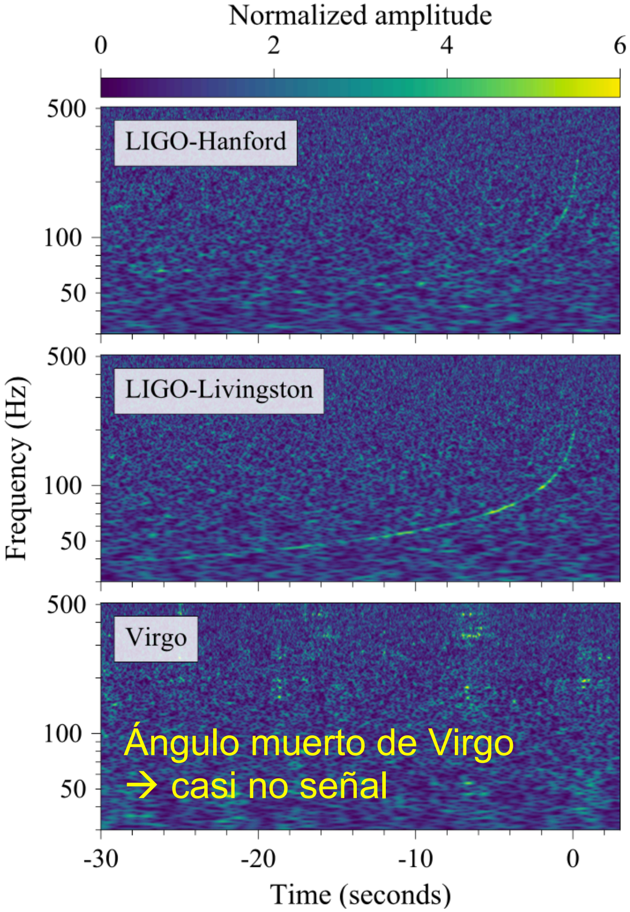
On 17 August 2017, the 2 aLIGO detectors and Virgo observed the GW signal emitted during 100 sec before the merger of two neutron stars. **This time there was an EM counterpart!!!**

Multi-messenger astronomy→The same event observed with GWs & EMs

GW170817 – dawn of multi-messenger astronomy







Ángulo muerto de Virgo
→ casi no señal

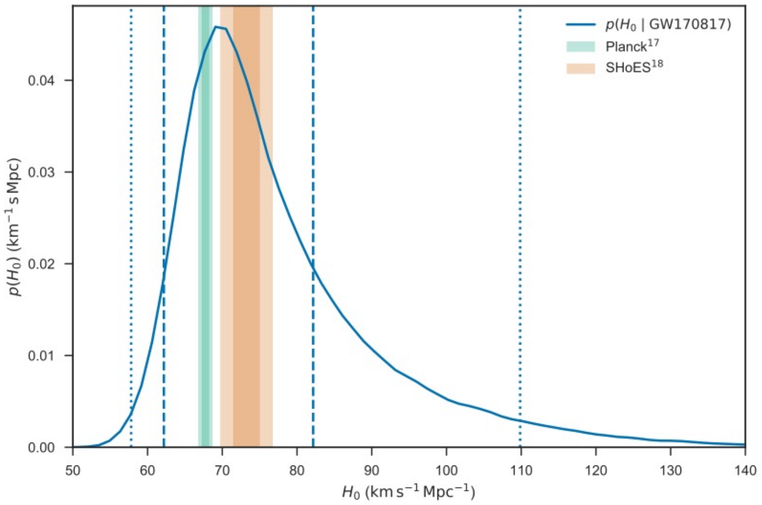
- GW detection provided high precision of sky localization and distance of the source → it allowed exhaustive follow up after the merger, through the whole EM spectrum → Confirm that **kilonova** are associated to BNS mergers.
- Closest source of GW detected, only 100 M light years. The highest SNR signal and of longest time duration.

Scientific implications of BNS detection

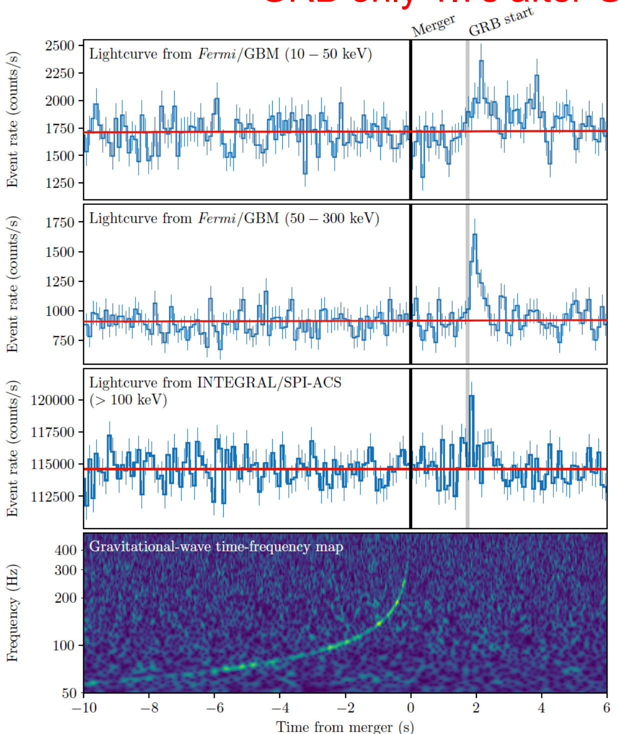
- First evidence that **short-GRB**s associated to **BNS mergers**
- **Kilonova** associated to **BNS mergers** → source of elements heavier than iron
- **‘Standard sirens’**→ measure **Hubble constant** independent from *cosmic distance ladder:*

$$H_0 = 70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

- Limits **equation of state** of neutron stars → probe properties of matter extreme conditions
- Constrain difference between speed of gravity and light → between -3×10^{-15} and $+7 \times 10^{-16}$
- Upper limit on **mass of graviton** $m_g <$ (few)10^{-23} eV/c^2 → ~0
- **BNS merge rate** ~ 330-4500 events·$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

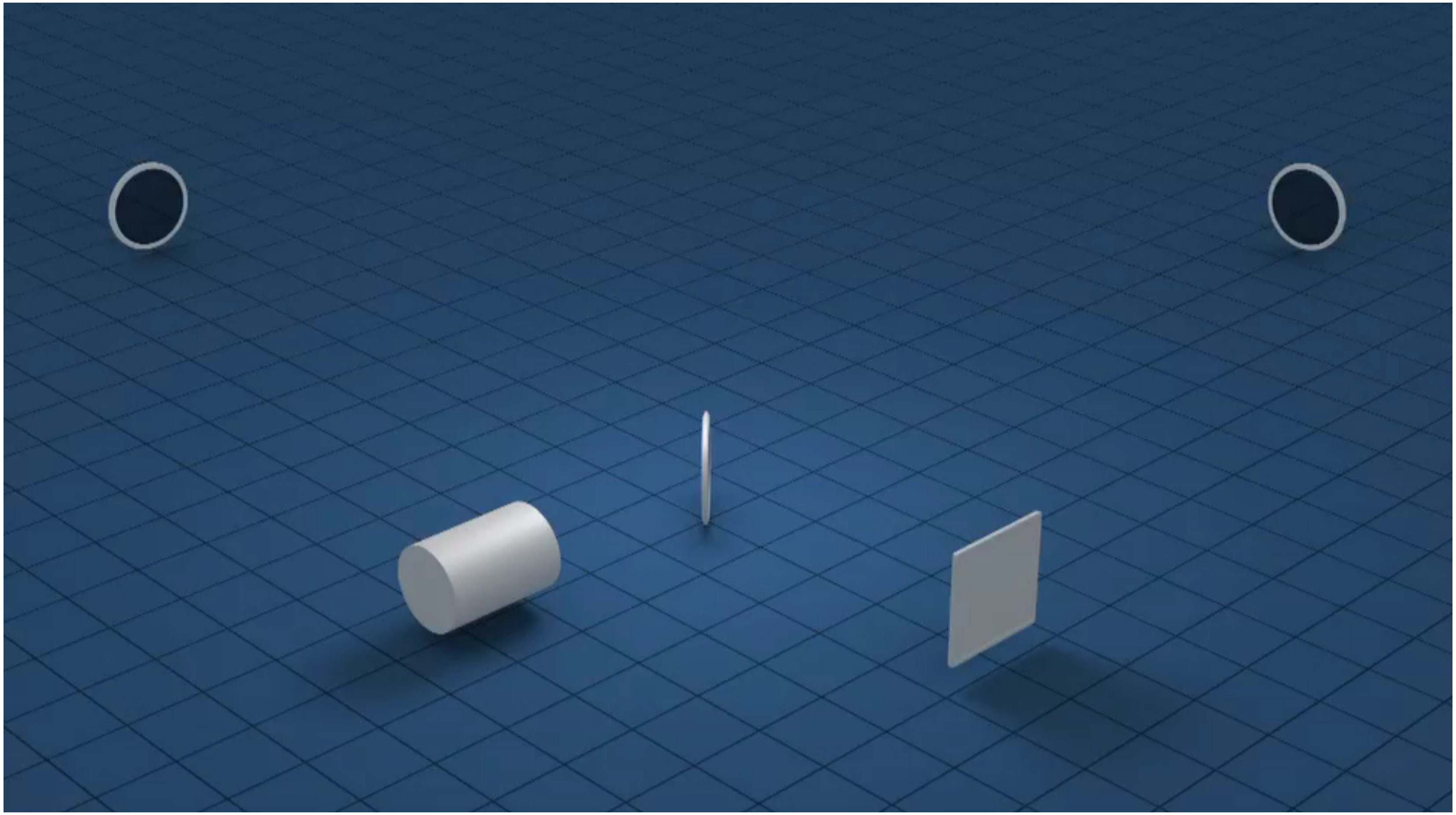


GRB only 1.7s after GW



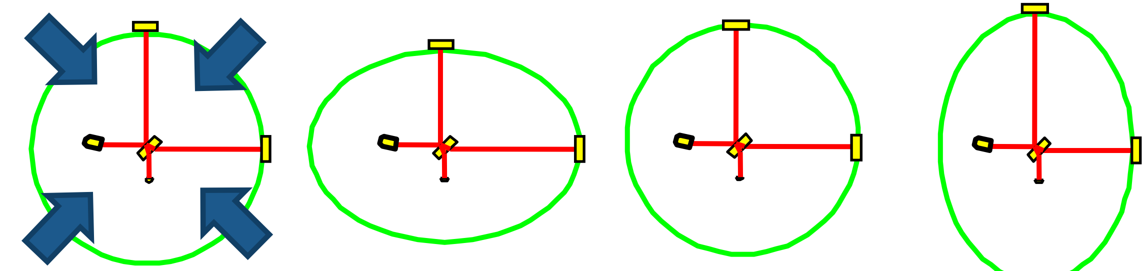
Gravitational wave detectors

Basics of a Michelson interferometer



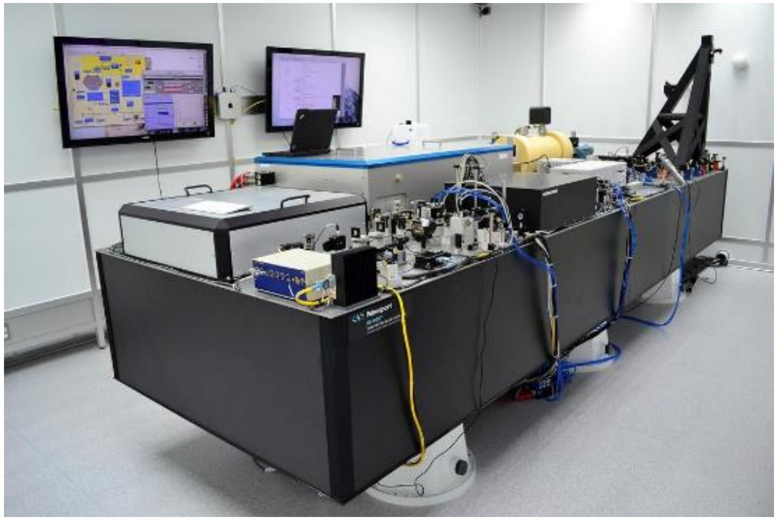
- Interferometry measures variations on the distance between mirrors.
- The laser beam behaves like a ruler, and its wavelength refer to the ticks on the ruler.

GW interferometric detectors



Blind angles

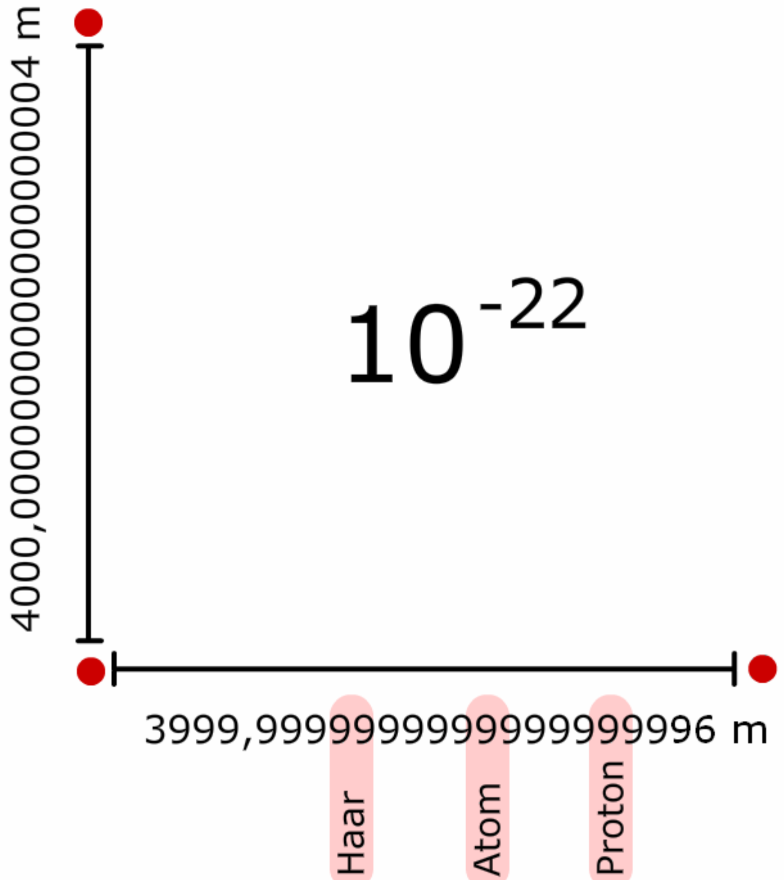
Maximum sensitivity to waves perpendicular to the detector's plane.



- GWs stretch and shrink each arm of the interferometer alternatively changing the distance between mirrors.
- **GWs also change light's wavelength!**
- Speed of light doesn't change → **chronometer.**

- **The longer the arms, the bigger the effect → Also reduces many fundamental noises**

GW detectors are the most sensitive instruments



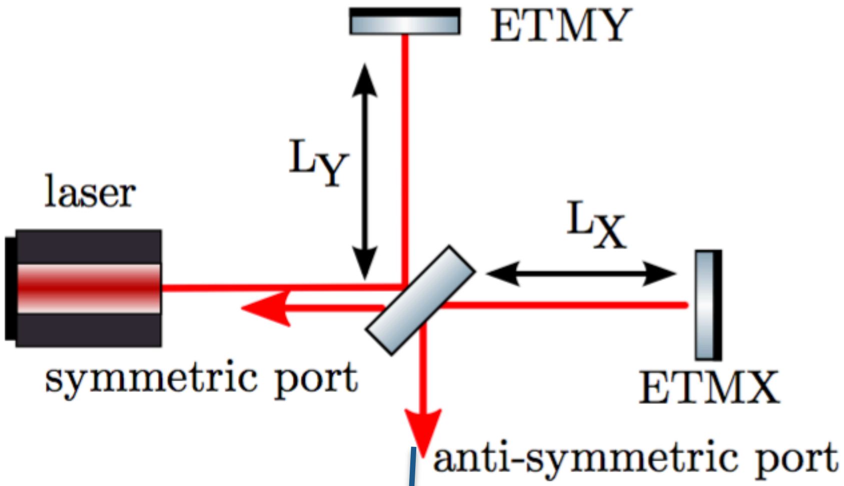
Maximum sensitivity of aLIGO:

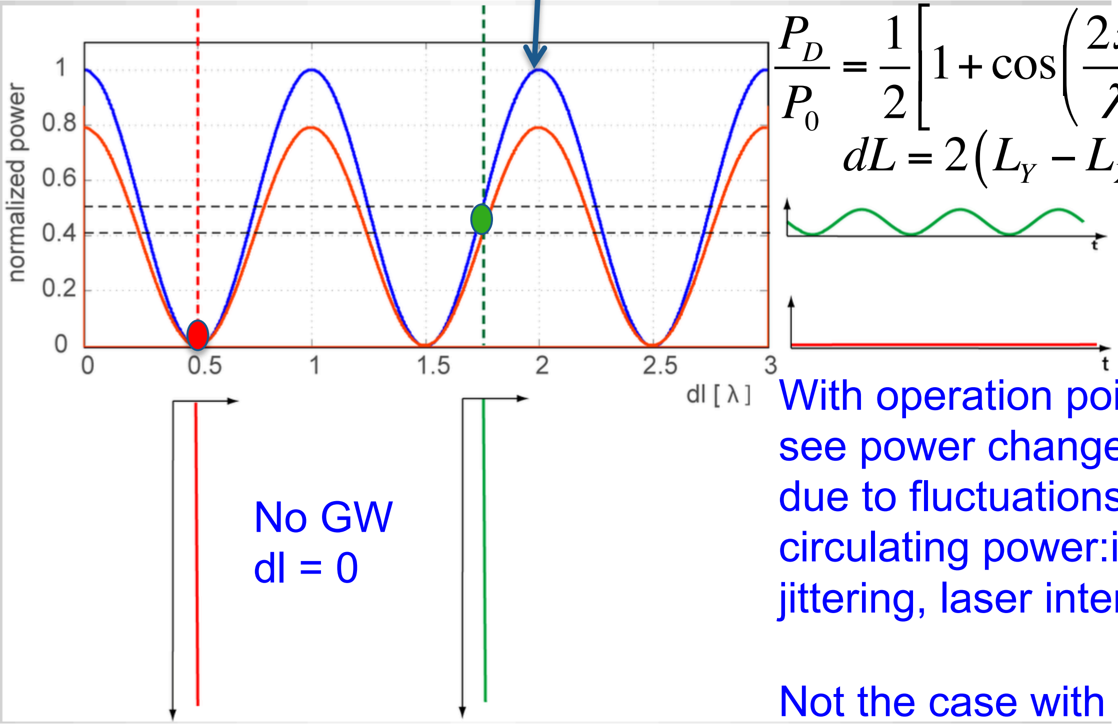
STRAIN: ~**10^{-22}** (bandwidth 1st detection) ⟷ **h < 10^{-21}** (amplitude 1st detection)

↕

DISTANCE: ~**10^{-19}** m (proton diameter/10000) ⟷ $\Delta l_{sismico} \simeq$ **0.1-1μm** (seismic noise)

Operation of a Michelson interferometer





$$\frac{P_D}{P_0} = \frac{1}{2}\left[1+\cos\left(\frac{2\pi}{\lambda}dL\right)\right]$$

$$dL = 2\left(L_Y - L_X\right)$$

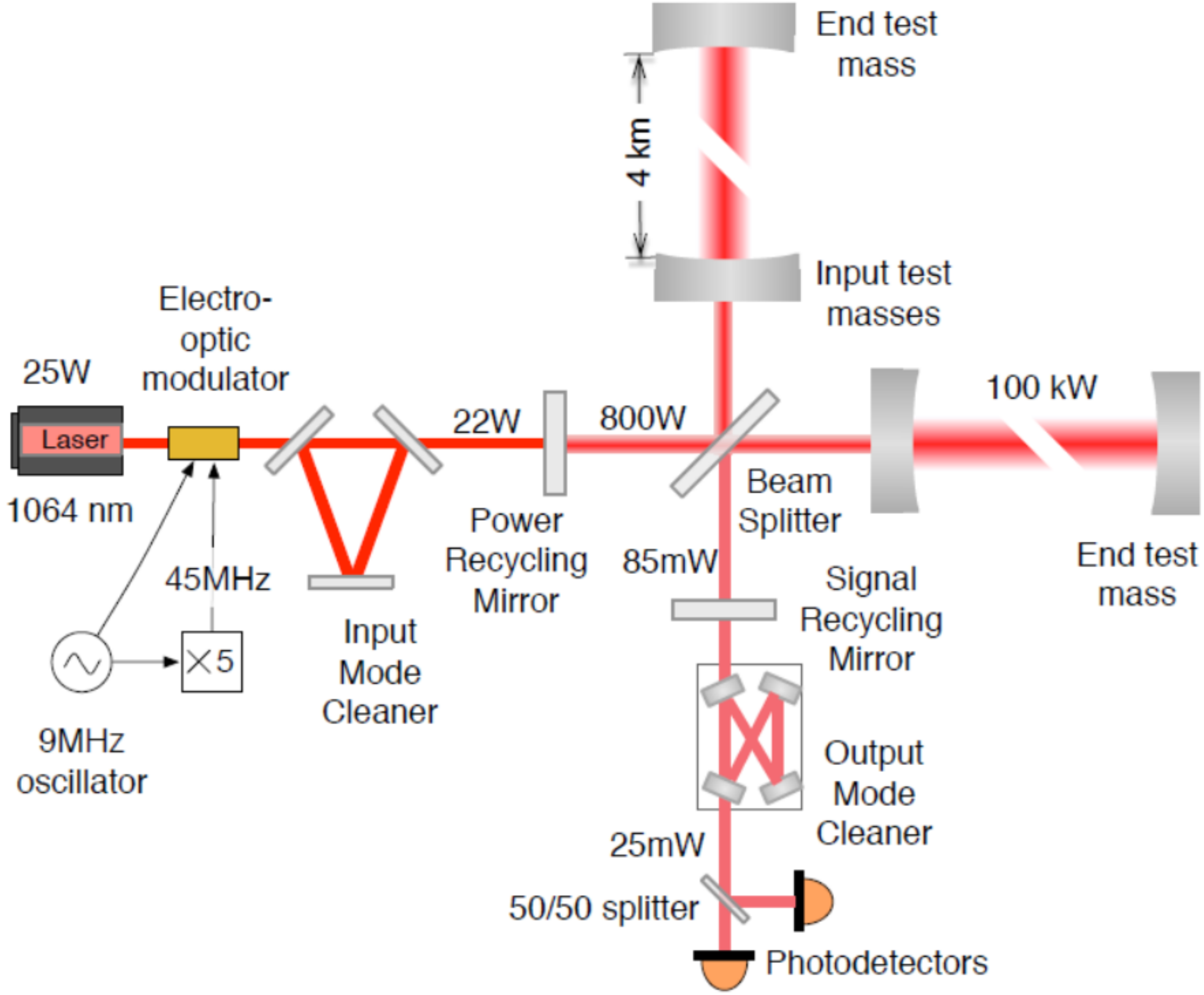
No GW
dl = 0

With operation point ●: We see power changes in output due to fluctuations of circulating power:input beam jittering, laser intensity noise.

Not the case with OP ●

- Signal on PD proportional to:
  - P_0 laser power
  - dl α h × L
  - 1/λ
- We want: longer arms, high circulating power and small λ.
- Operation point on dark fringe ● → light back to laser → can be recycled

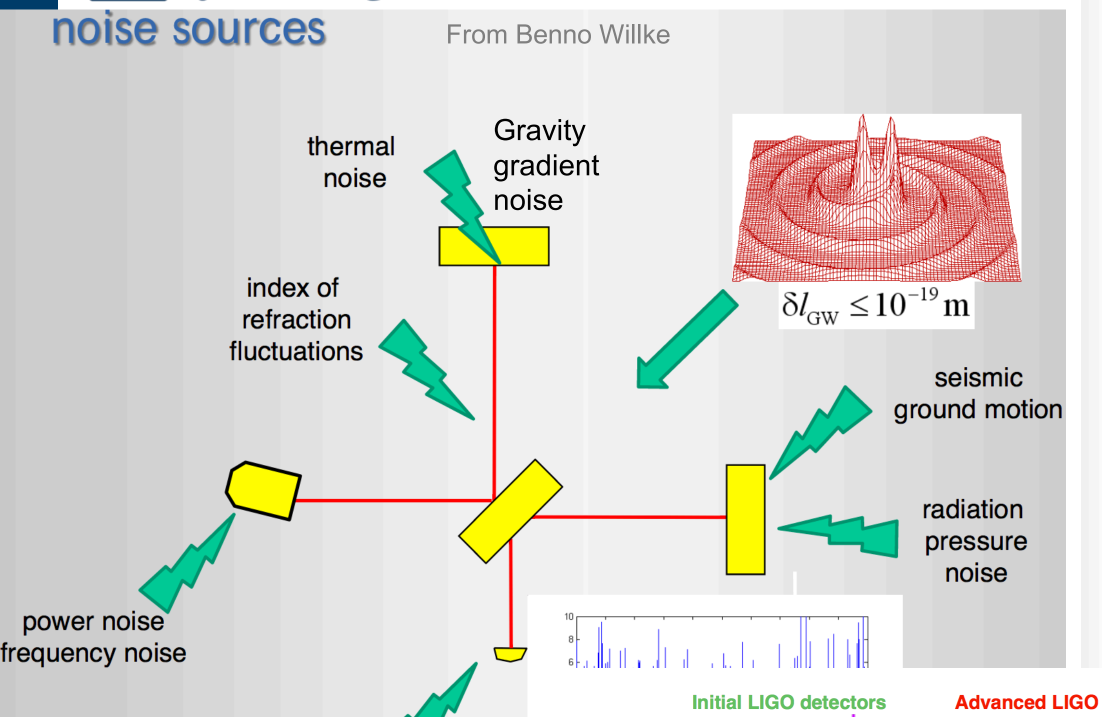
GW detectors are more complex

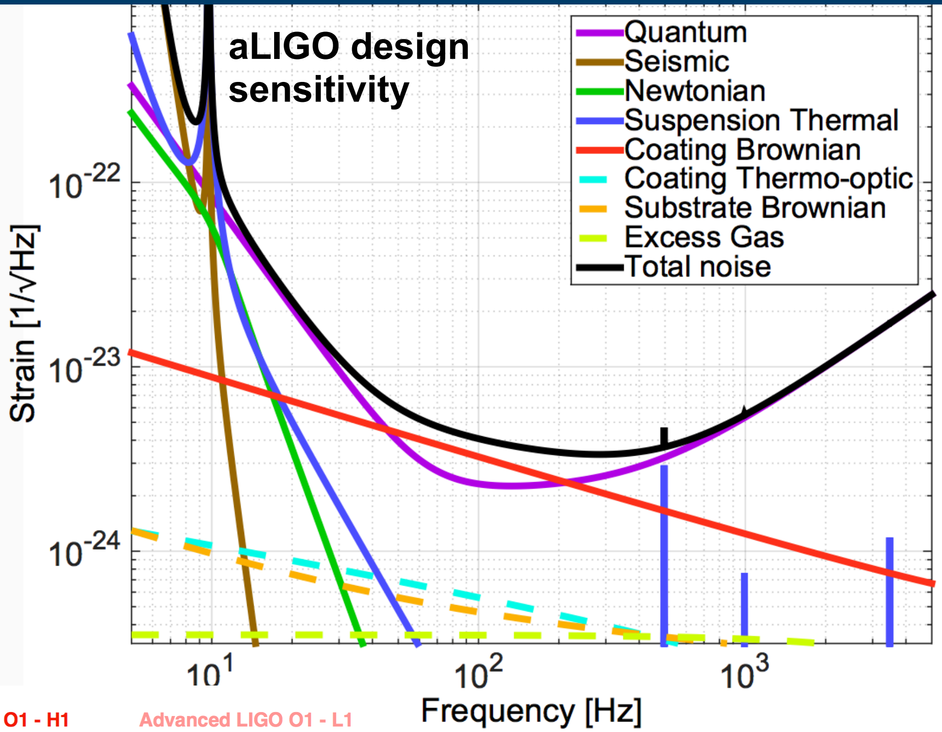


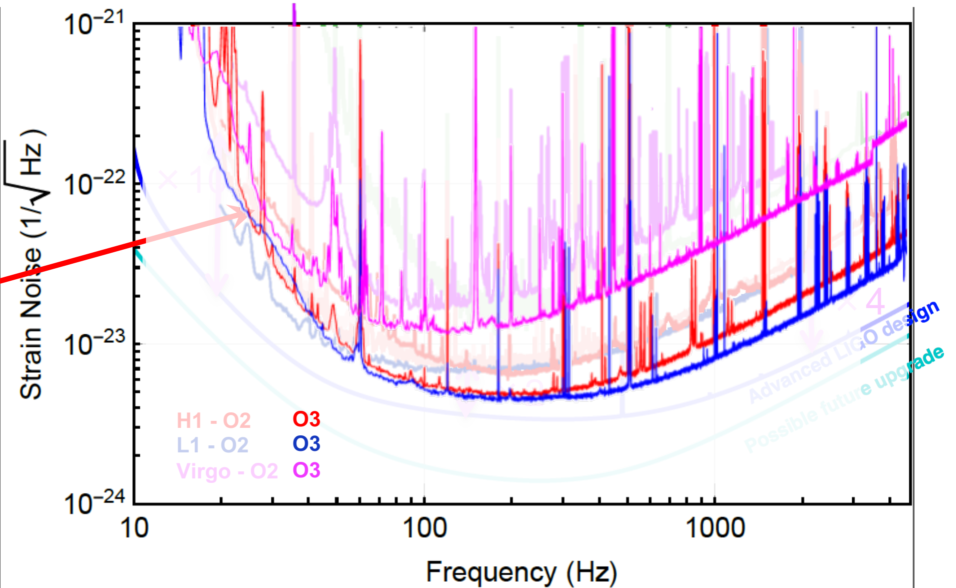
- Optical cavities on the arms to increase the circulating power and the effective arm length.
- PRM = Recycles the light coming back to laser (OP dark fringe)
- SRM = Recycles the GW signal back to the interferometer. It allows adjustment of the maximum sensitivity band.

From Steve Detweiler

Fundamental noises on GW detectors







‘Technical’ noise, worsen during pre O2 commissioning at LHO

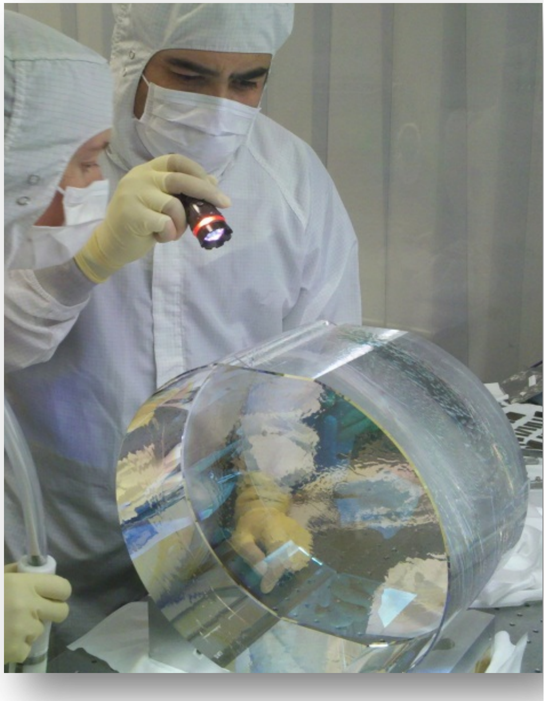
Coating thermal limits between 40 - 200Hz.

Quantum noise limits at all freqs.

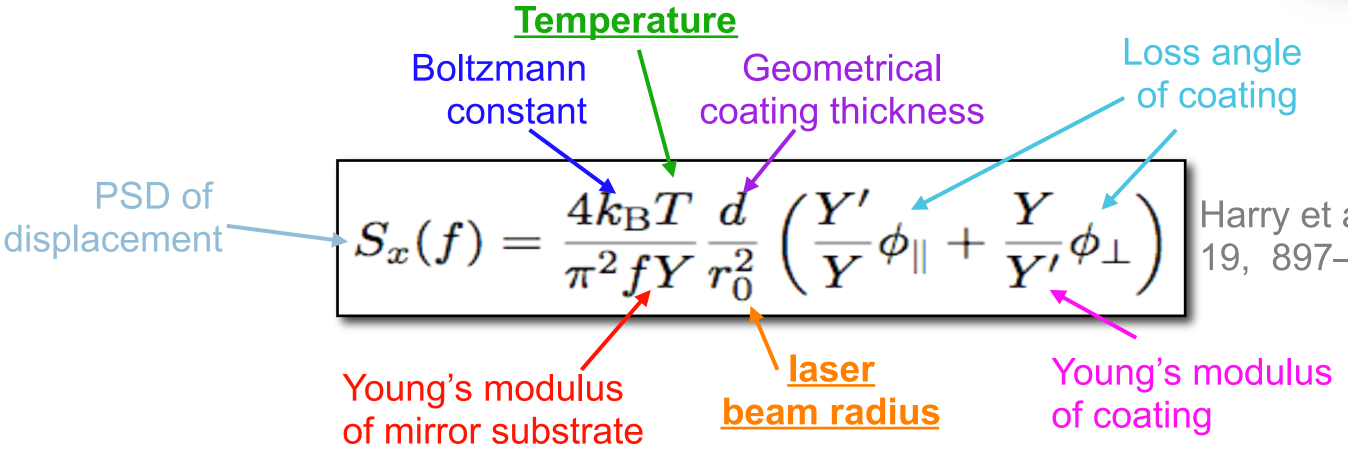
Below ~15Hz limited by ‘walls’ made of **Suspension thermal**, **Newtonian** and **Seismic** noises.

Reducing fundamental noises

What is **mirror thermal noise?**



- Due to **thermal fluctuations**, position of mirror sensed by laser beam doesn't represent CM.
- Various noise terms involved: **Brownian**, **thermo-elastic** and **thermo-refractive** noise of **substrate** and **coating** (or coherent combinations of these, such as thermo-optic noise).
- For nearly all current and future designs **coating Brownian is a dominant noise source**:



Temperature

Boltzmann constant

Geometrical coating thickness

Loss angle of coating

PSD of displacement

$$S_x(f) = \frac{4k_{\rm B}T}{\pi^2 fY}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{\|} + \frac{Y}{Y'}\phi_{\perp}\right)$$

Young's modulus of mirror substrate

laser beam radius

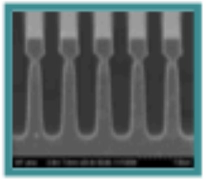
Young's modulus of coating

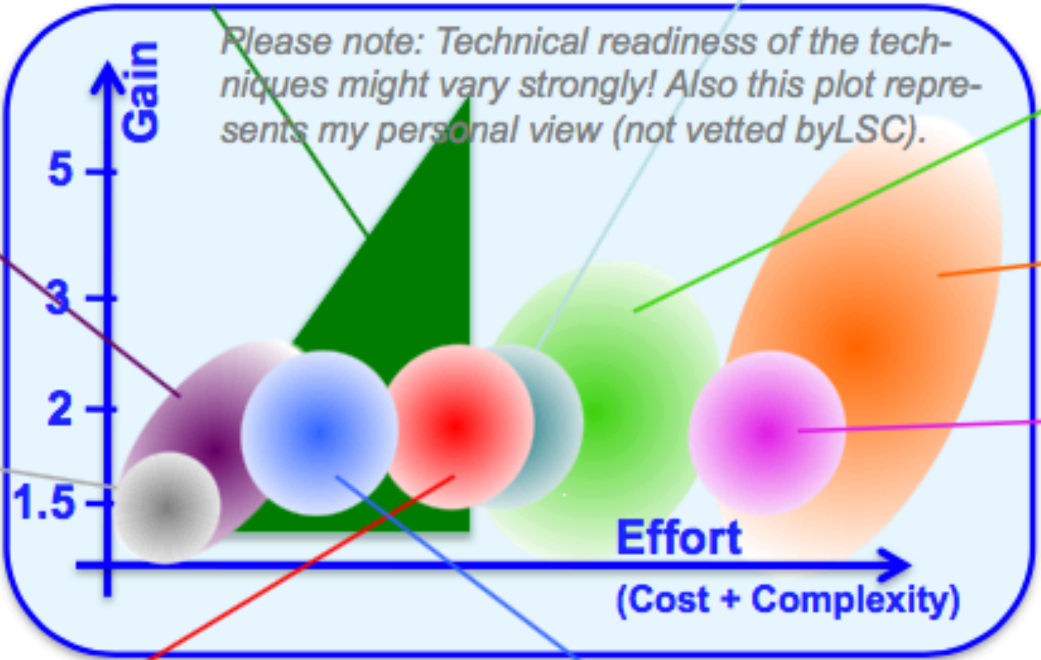
Harry et al, CQG 19, 897–917, 2002

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





Please note: Technical readiness of the techniques might vary strongly! Also this plot represents my personal view (not vetted byLSC).

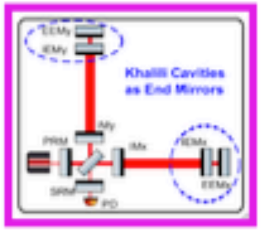
Larger beam size (needs larger mirrors)
Harry et al, CQG 19, 897–917, 2002

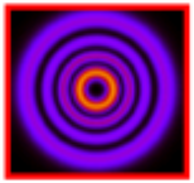
Optimisation (annealing, layer thickness, doping)

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

Thanks to S. Hild

What is **suspension thermal noise?**

- Mirrors are suspended to reduce seismic noise.
- Fluctuation-dissipation theorem: **Thermal noise in metal wires and silica 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**.

Boltzmann constant

Temperature

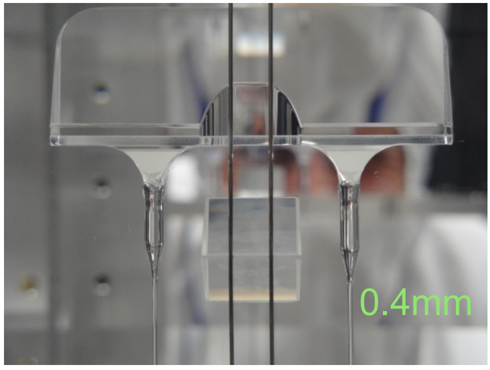
Loss angle

PSD of displacement

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

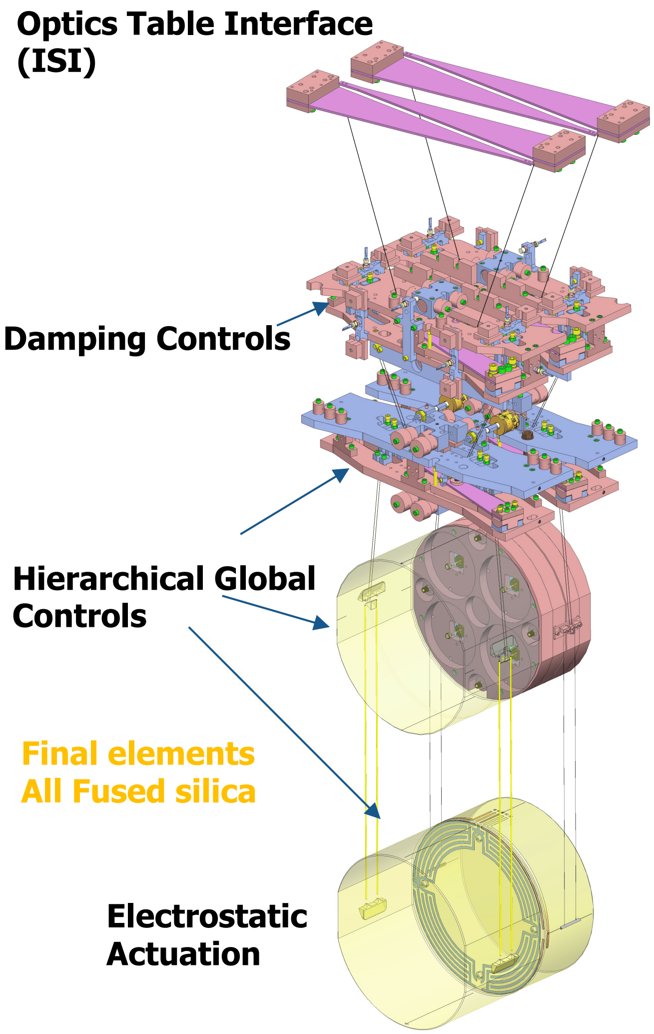
Mirror mass

Resonance frequency (function of fibre length)



Passive Seismic noise reduction

- Test masses suspended on a 4 stage pendulum:

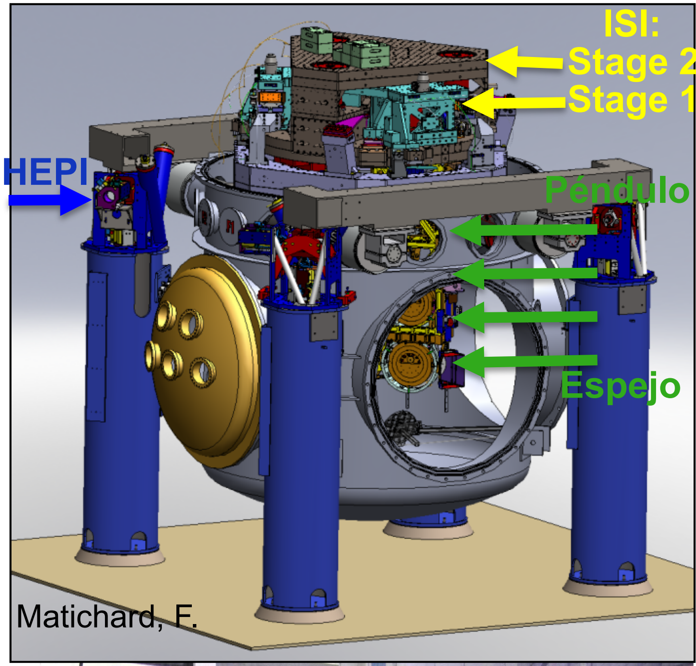


- Reduce $1/f^8$ residual motion of ISI.
- First three stages suspended via steel wire and blade-springs.
- Penultimate mass and test mass, both 40 kg fused silica, connected by fused silica fibres → ultra-high Q (low loss) structure.
- Each layer of the suspension is matched by an adjacent quadruple pendulum from which forces will be applied.
- The first 3stages contain electromagnetic coil drivers.
- Test mass controlled by electrostatic drive → further reduce control-induced noise.

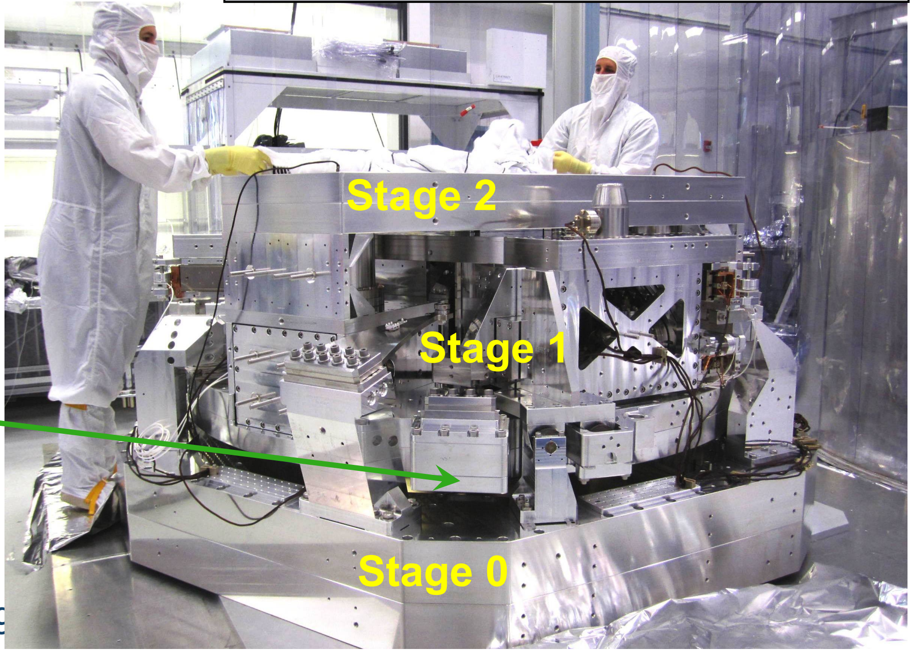
Active Seismic noise reduction

- 7 stages seismic isolation of test masses :
  - 3 active stages (HEPI y ISI)
  - 4 passive stages as a pendulum with the test masses on the bottom stage.
- 3 active stages with 6 degrees of freedom each:
  - Hydraulic external Pre-isolation (HEPI).
  - 2 internal stages (ISI).
- Active stages isolate the suspension pendulum through many sensors of position, acceleration and velocity on all degrees of freedom.

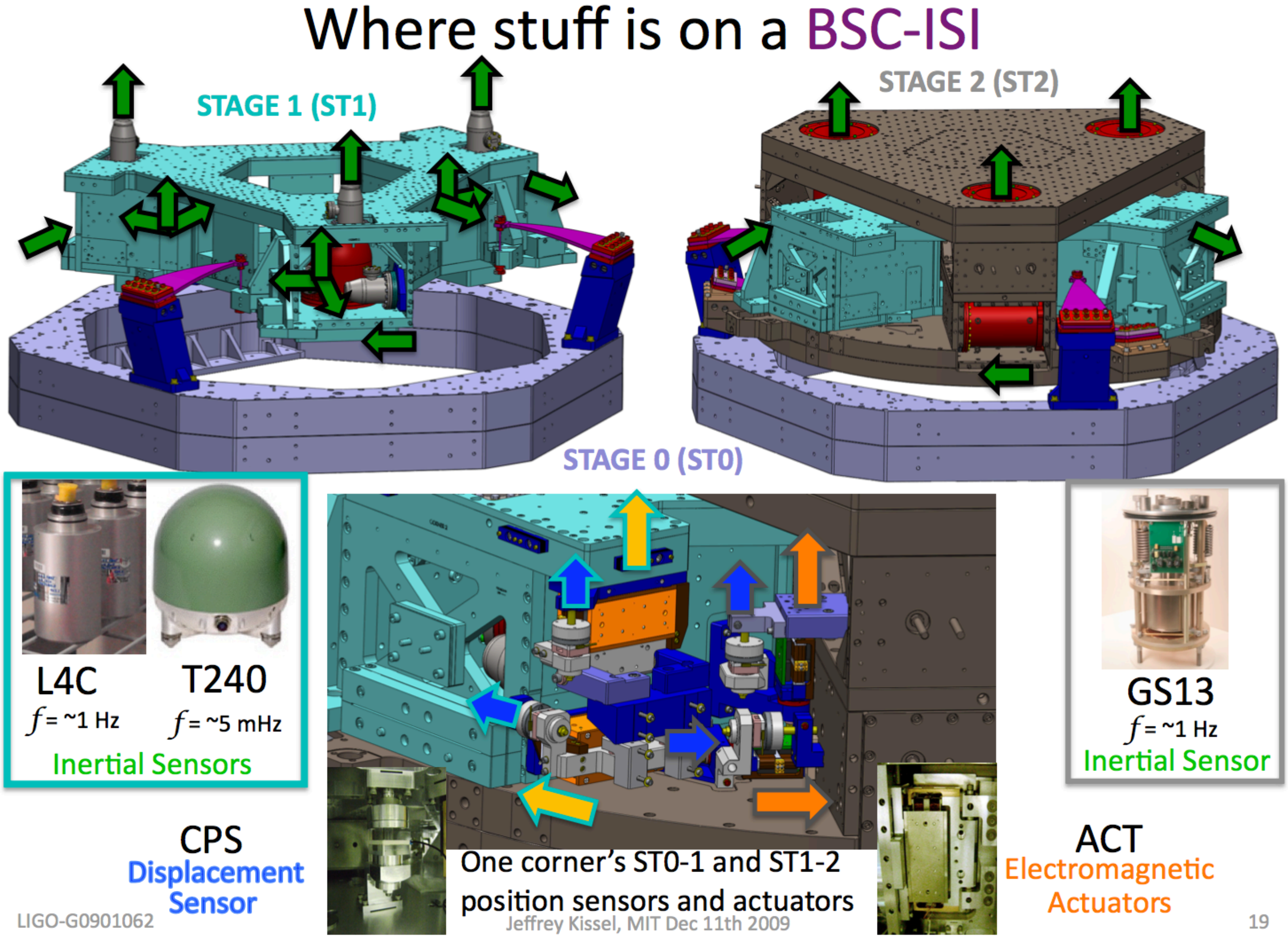
  The top stage of the pendulum is attached to the bottom plate of the ISI 2nd stage.



Matichard, F.



ISI stages



Where stuff is on a BSC-ISI

STAGE 1 (ST1)

STAGE 2 (ST2)

STAGE 0 (ST0)

L4C
f= ~1 Hz

T240
f= ~5 mHz

Inertial Sensors

GS13
f= ~1 Hz
Inertial Sensor

CPS
Displacement Sensor

One corner's ST0-1 and ST1-2 position sensors and actuators

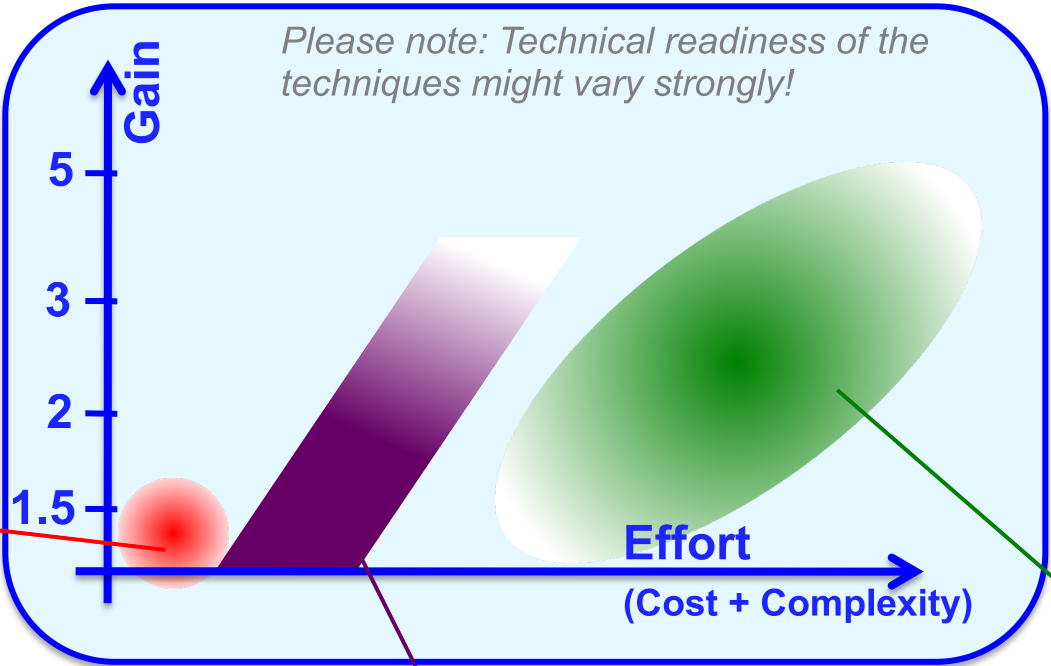
ACT
Electromagnetic Actuators

LIGO-G0901062

Jeffrey Kissel, MIT Dec 11th 2009

19

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 and thinner fibres.

Allows the push suspension thermal noise out detection band.

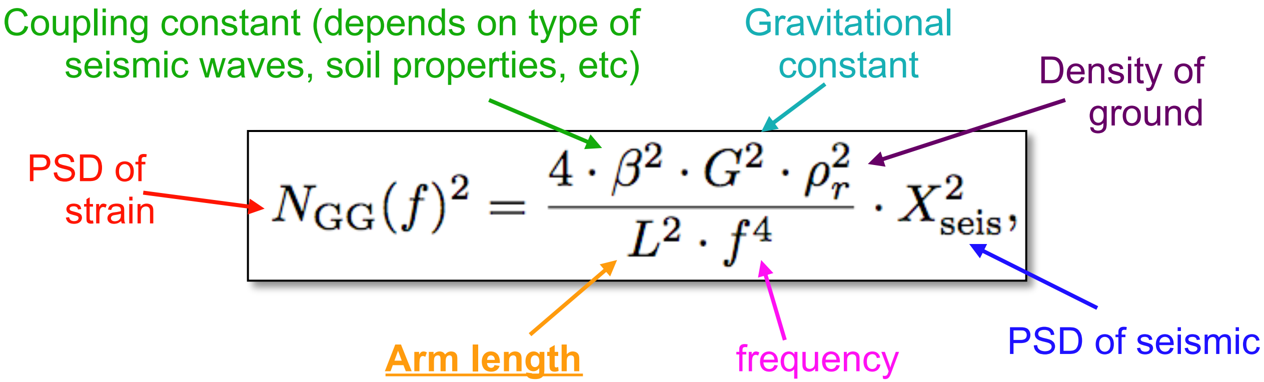
Cooling of the suspension to cryogenic temperatures.

Usually also requires a change of materials.

Thanks to S. Hild

What is **Newtonian noise?**

- **Seismic causes density changes in the ground and** shaking of the **mirror environment** (walls, buildings, vacuum system).
- This causes **fluctuations in the local Newtonian gravity field** 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

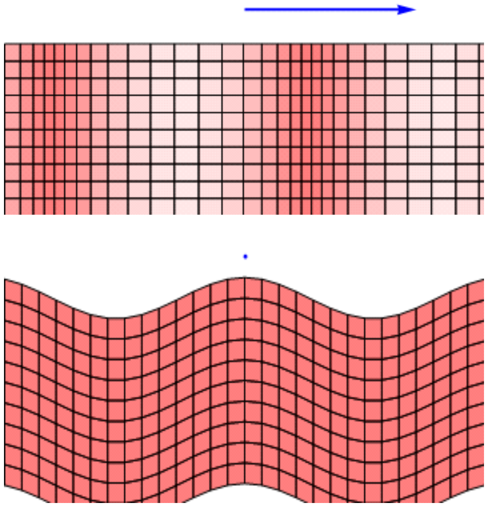
PSD of strain

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

Arm length

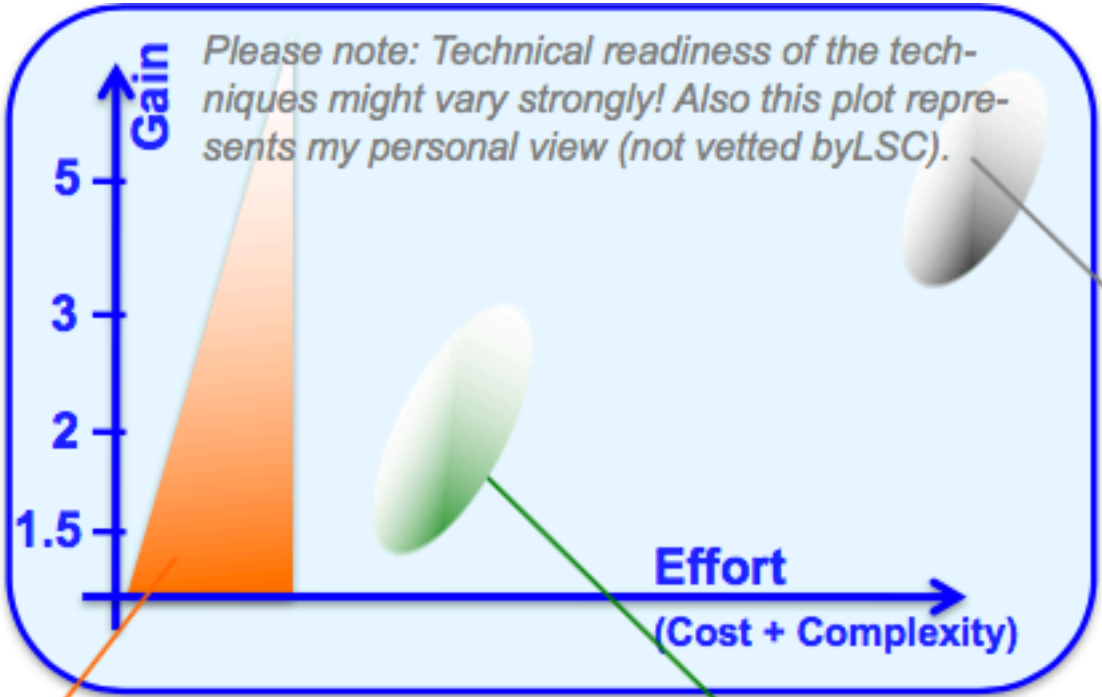
frequency

PSD of seismic



Images: courtesy G.Cella

How to reduce **Newtonian noise?**



Please note: Technical readiness of the techniques might vary strongly! Also this plot represents my personal view (not vetted byLSC).

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

Thanks to S. Hild

What is **quantum noise?**

- Quantum fluctuations of laser light.
- It is comprised of:
  - **Photon shot noise**, statistical fluctuation in arrival time of photons at the interf. output (readout or sensing noise). High frequency noise.

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

wavelength

optical power

Arm length

  - **Photon radiation pressure noise**, fluctuation in number of photons impinging on test-mass (back-action noise). Low frequency noise.

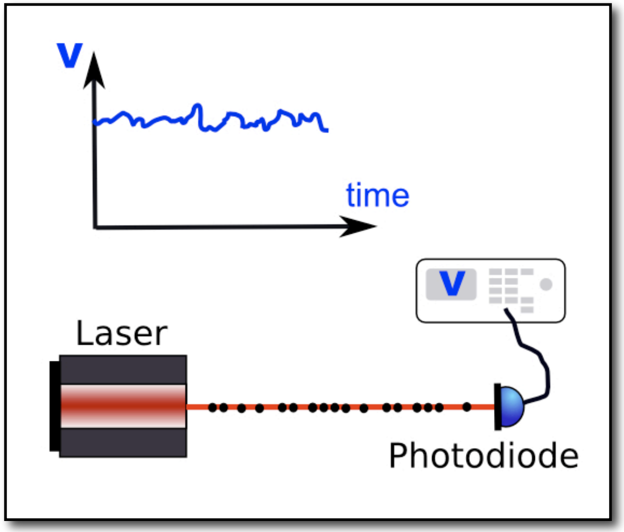
$$h_{\mathrm{rp}}(f) = \frac{1}{m f^2 L}\sqrt{\frac{\hbar P}{2\pi^3 c \lambda}}$$

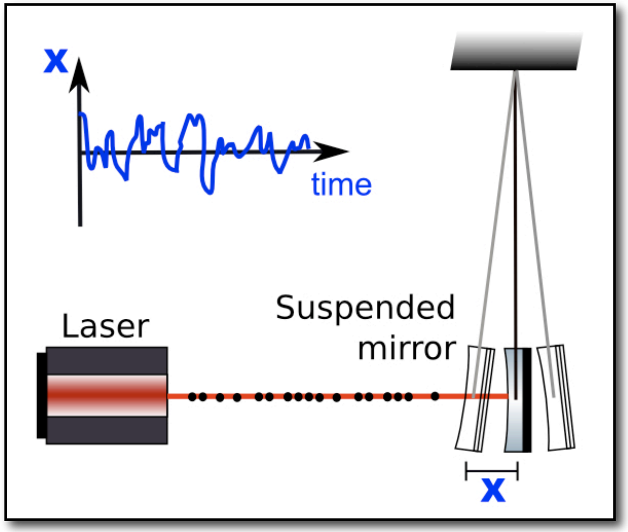
optical power

Mirror mass

Arm length

- It is a direct manifestation of the Heisenberg Uncertainty Principle.





What is **quantum noise?** – more detail

- Heisenberg uncertainty → Energy fluctuations of vacuum → $\Delta E \Delta t \geq \frac{\hbar}{2}$
- Distributed over amplitude and phase quadratures of EM field:

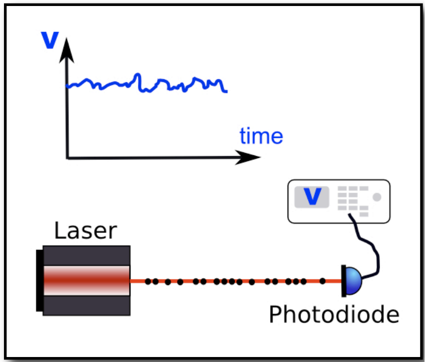
$$\Delta E = \Delta n \hbar \omega \qquad \Delta t = \Delta\phi/\omega \;\rightarrow\; \Delta n \Delta\phi = \frac{1}{2} \;\rightarrow\; \Delta n = \sqrt{N} \qquad \Delta\phi = \frac{1}{2\sqrt{N}}$$

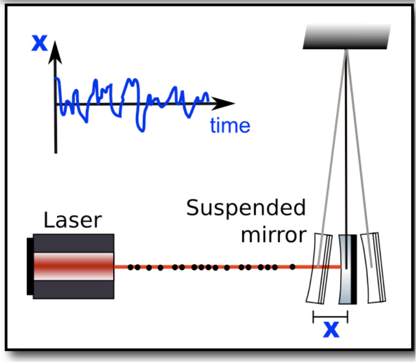
Photons follow Poisson stats

- Fluctuations enters interferometer's dark port, adds to arms' light and reach PD combining with GW signal field.

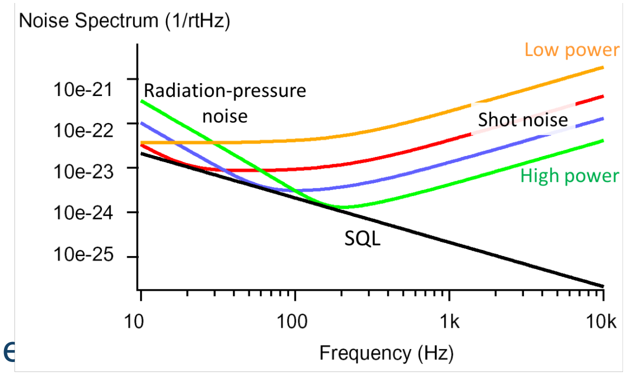
Quantum noise two forms:

- **shot noise**, intensity noise on PD current (photon count fluctuations)→limits precision arm displacement→**Δt**→**Δϕ** $\propto \frac{1}{\sqrt{P}}$
- **radiation pressure noise,** fluctuations of arms' light power→fluctuating radiation pressure moves mirrors → amplitude fluctuation **Δ**n coupled to phase quadrature. $\propto \frac{\sqrt{P}}{m}$

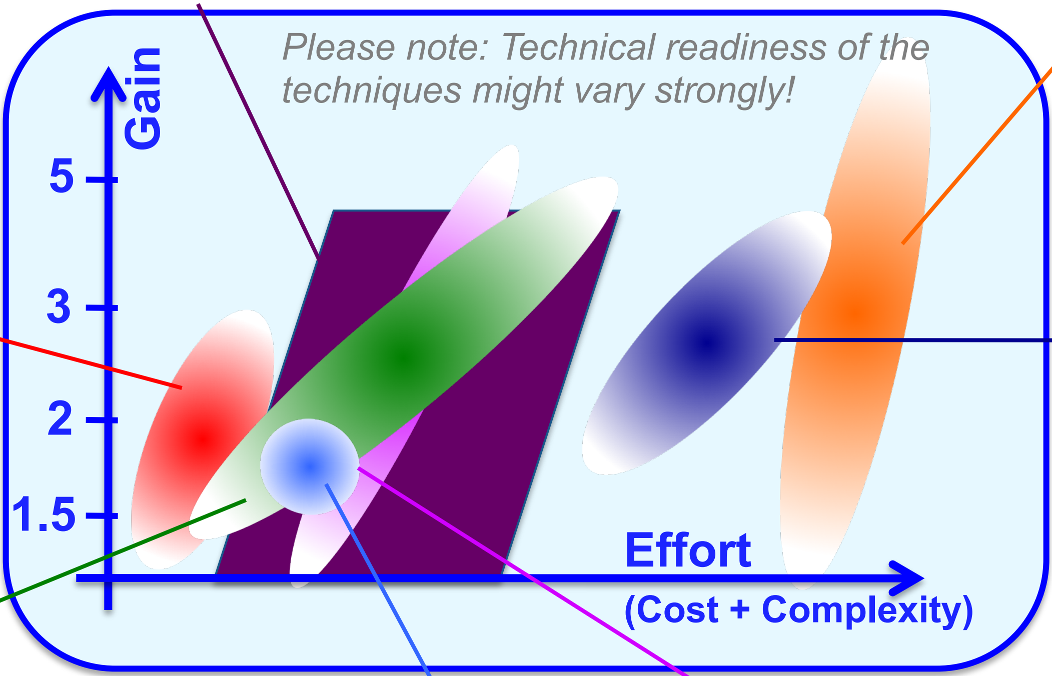




  - Trade-off is called SQL



How to reduce **quantum noise?**



Please note: Technical readiness of the techniques might vary strongly!

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 Uncertainity 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 parametric instabilities

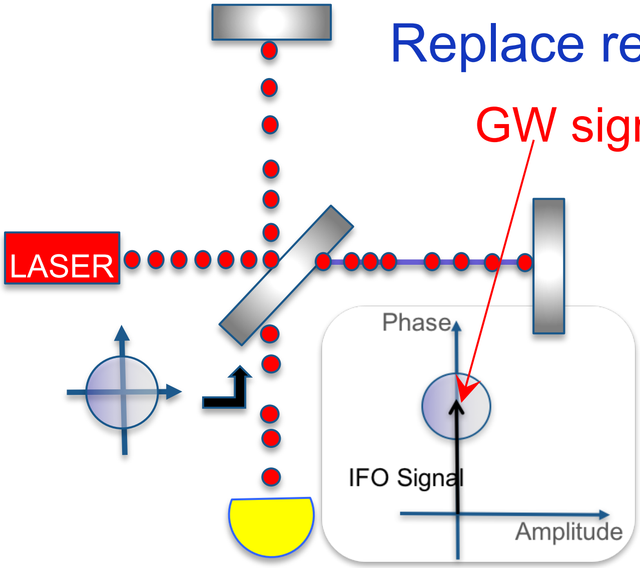
Local readout

Rehbein et al, PRD 78, 062003, 2008

Increased Mirror Weight

Need to deal with thermal problems and instabilities

Quantum noise reduction – Squeezed light

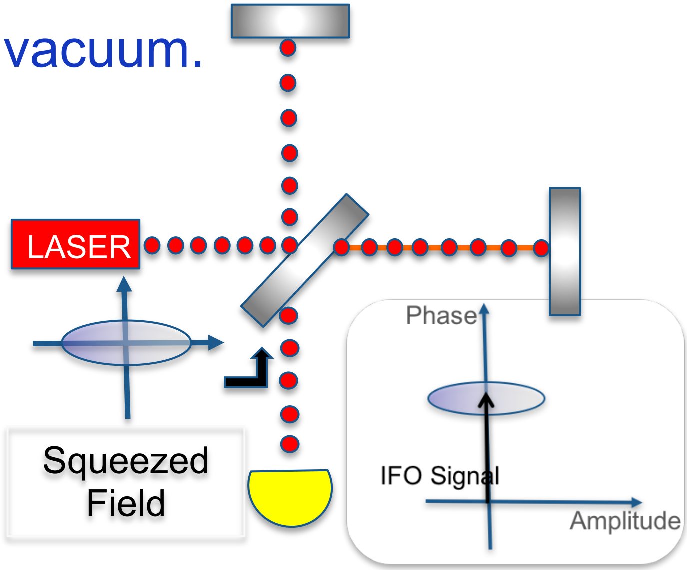


Replace regular vacuum with squeezed vacuum.

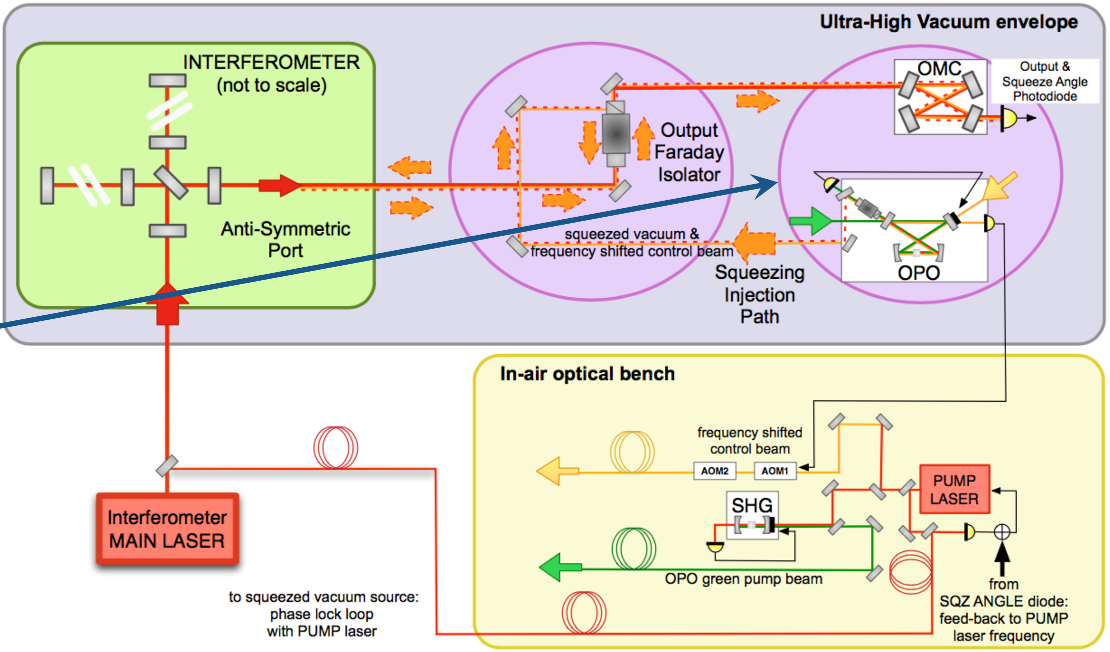
GW signal shows on Phase quadrature.

HUP → uncertainty area fixed →reducing uncertainty in one quadrature increases the other.

Squeezed phase quadrature reduces shot noise but increases rad. pressure noise due to increased amp. quadrat.



- Done using non-linear crystals acting as OPOs.



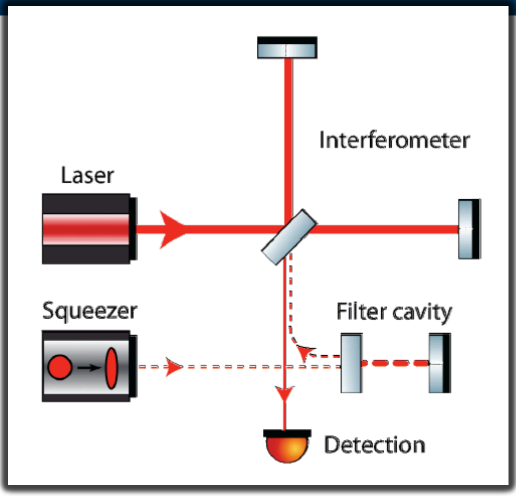
diagrams from Lisa Barsotti (G1800598 G1602253)

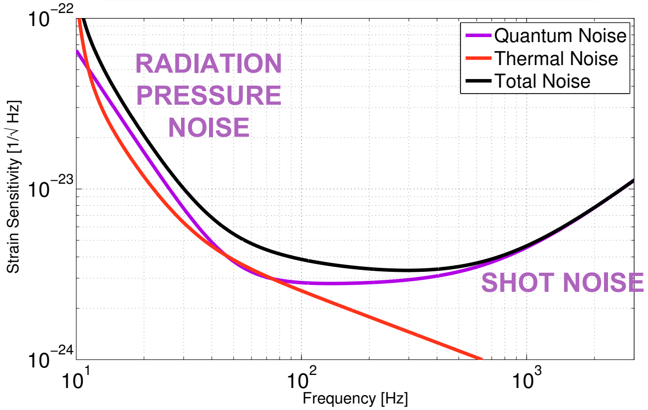
Enhanced 2G – Freq. dependent squeezing

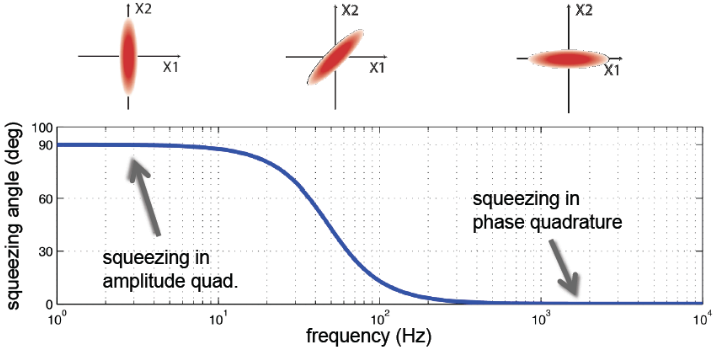
- Phase squeezed light ↓ shot noise (HF) but associated amplitude anti-squeezing ↑ radiation pressure (LF).
- **Freq. dependent squeezing:** Low loss, high finesse (thousands) detuned filter cavity which rotates squeezing angle as function of frequency.

Challenges: Very sensitive to optical losses, scattering and mirror motion

- Requires *seismic isolation and quiet mirror suspension*
- Requires *high-quality mirrors*
- Requires *active mode matching with squeezer*
- Requires *length* ~ 300 m (expensive civil and vacuum cost)







Kimble et al., Phys. Rev. D 65**(2) 022002** 2001

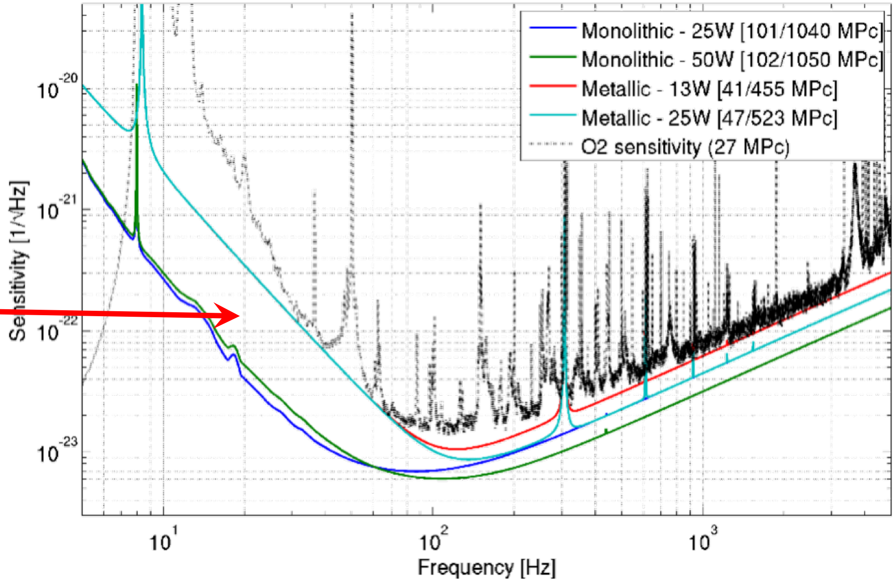
O3

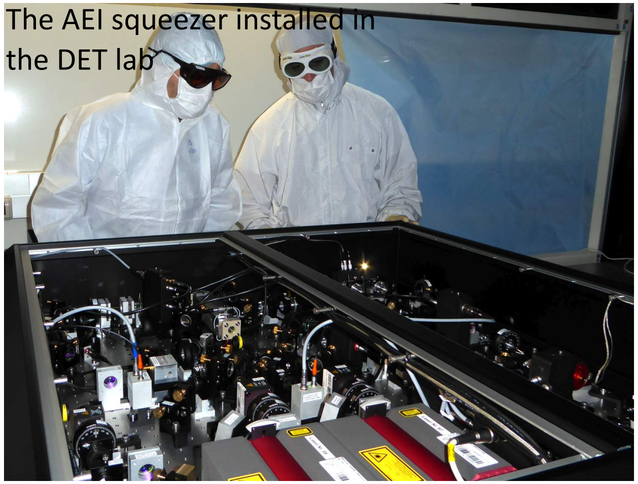
It took 1 year of commissioning

Main Virgo upgrades

- All test masses suspended with **fused silica fibers**

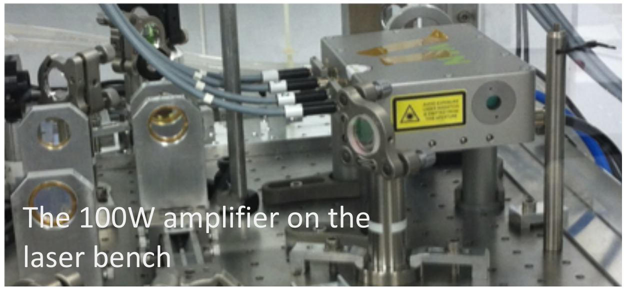
Will boost the low frequency sensitivity.



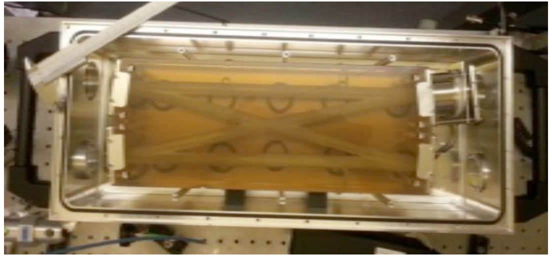

The AEI squeezer installed in the DET lab

- Installation of GEO squeezer. On-site measured **squeezing**: around 10 dB;

Improves high frequency sensitivity.


The 100W amplifier on the laser bench

- New high power laser amplifier: delivers up to 60W to interferometer.
- New monolithic pre-mode-cleaner, for high power.

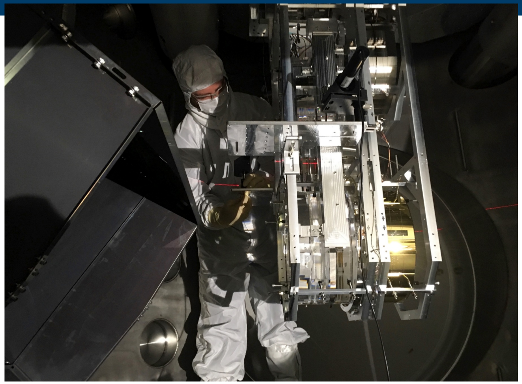


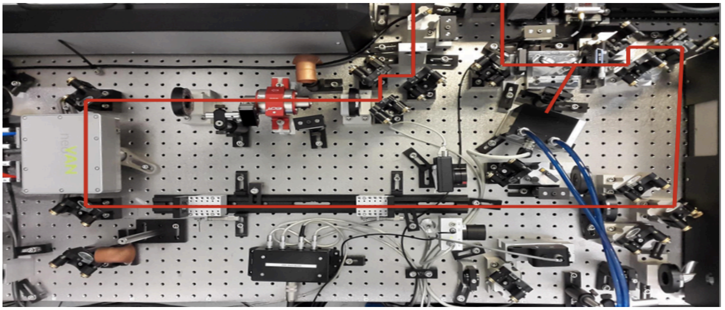
from Brian O'Reilly and Alessio Rocchi, G1800395

Main aLIGO upgrades

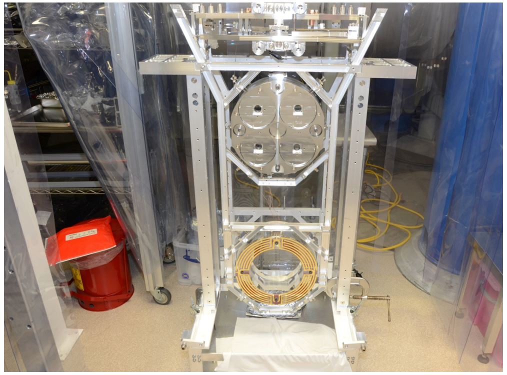
ITMX replacement (LHO), point absorber found on HR side
Affected ability of H1 to operate at higher power.

Also replace ETMs at both detectors.

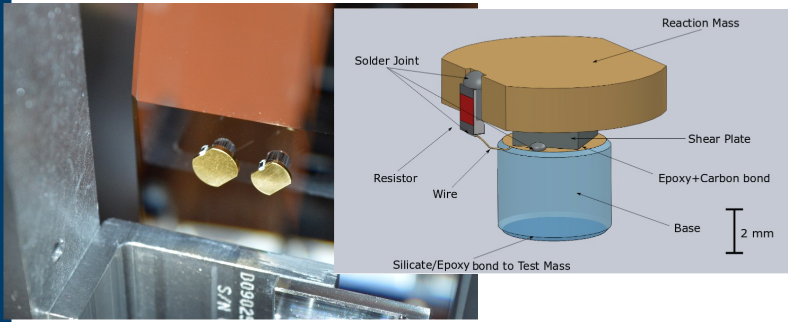




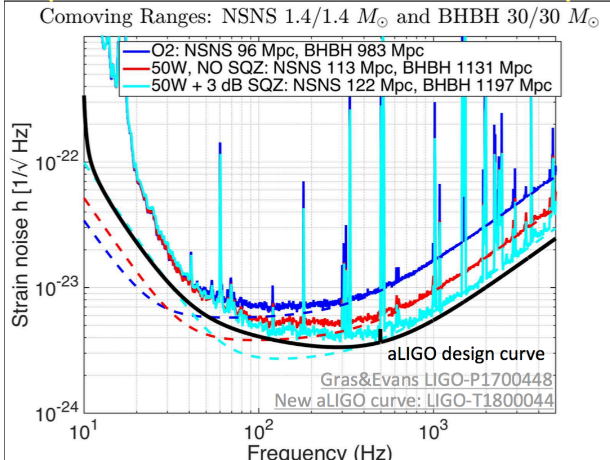
Installation of 70W laser amplifier at both detectors → delivering 50W to interferm.



Replace End Reaction Masses by annular version
Hope to reduce residual gas damping noise by 2.5 (issue < 60Hz)



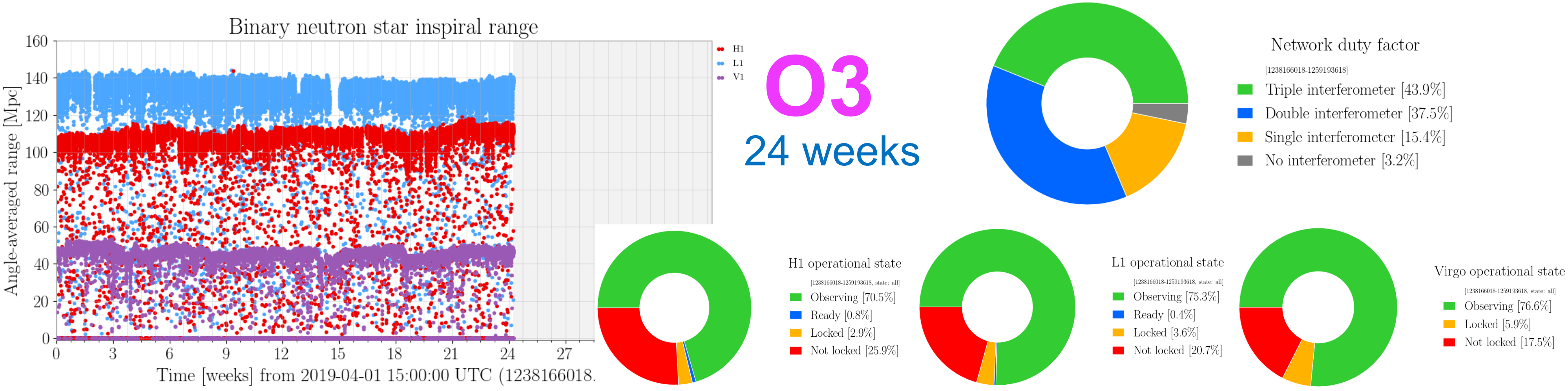
Installing acoustic mode dampers on test masses
Mitigate parametric instabilities at high power



Targeting 3dB squeezing for O3 (40% shot-noise reduction) → **Equivalent to doubling the laser power!**

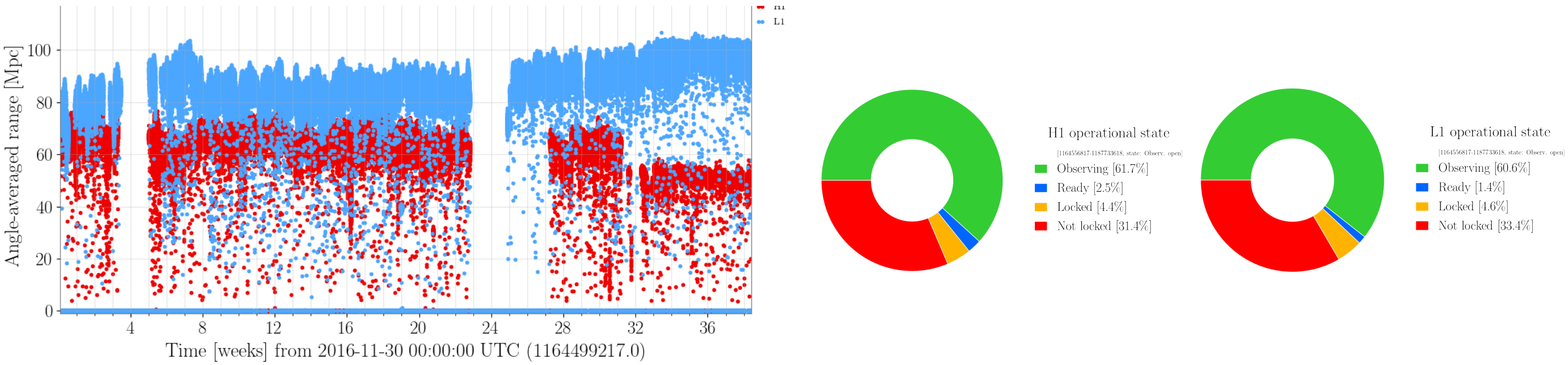
Lots of new baffles installed to absorb scattered light

Status summary of network of detectors



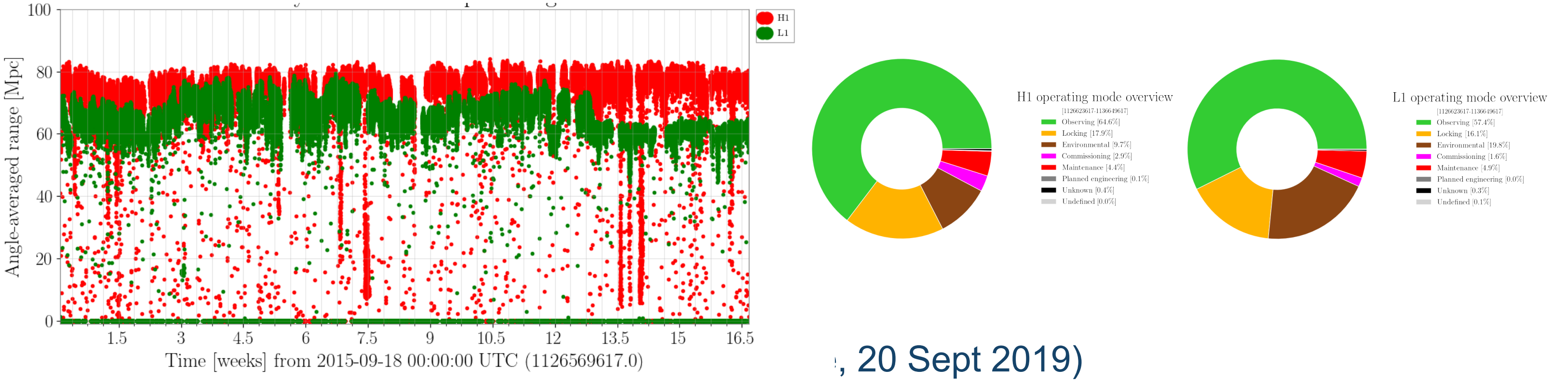
O3

24 weeks



O2

38 weeks



O1

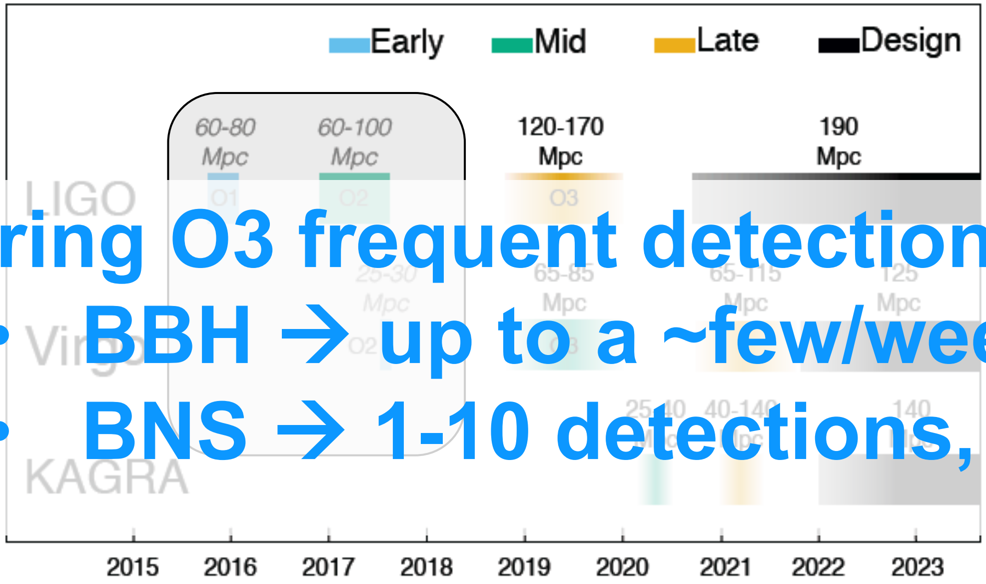
16.5 weeks

, 20 Sept 2019)

2G Sensitivity timeline and coalescent rates

Living Rev Relativ (2016) 19: 1

Prospects for Observing and Localizing GW Transients with aLIGO, AdV and KAGRA 7



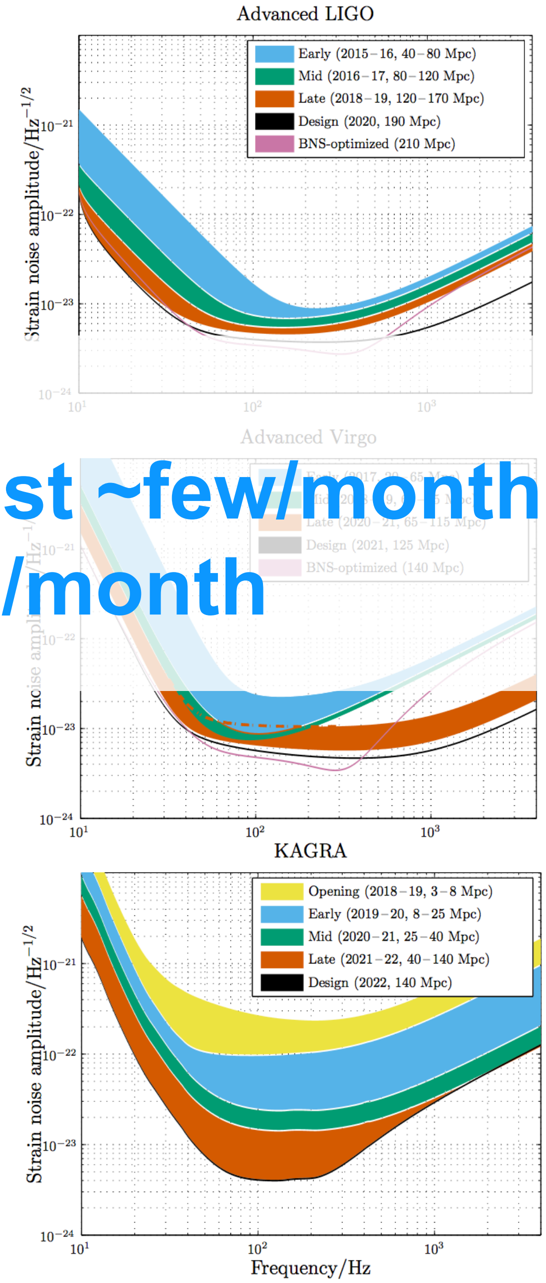
During O3 frequent detections:

- BBH → up to a ~few/week, at least ~few/month
- BNS → 1-10 detections, up to ~1/month

Numbers are BNS range sensitivity

	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40 – 80	415 – 775	20 – 65	220 – 615	8 – 25	80 – 250
Mid	80 – 120	775 – 1110	65 – 85	615 – 790	25 – 40	250 – 405
Late	120 – 170	1110 – 1490	65 – 115	610 – 1030	40 – 140	405 – 1270
Design	190	1640	125	1130	140	1270

- ~35% increased sensitivity from O3 to O4 to reach design sensitivity (O4 in 2021).



Enhanced 2G

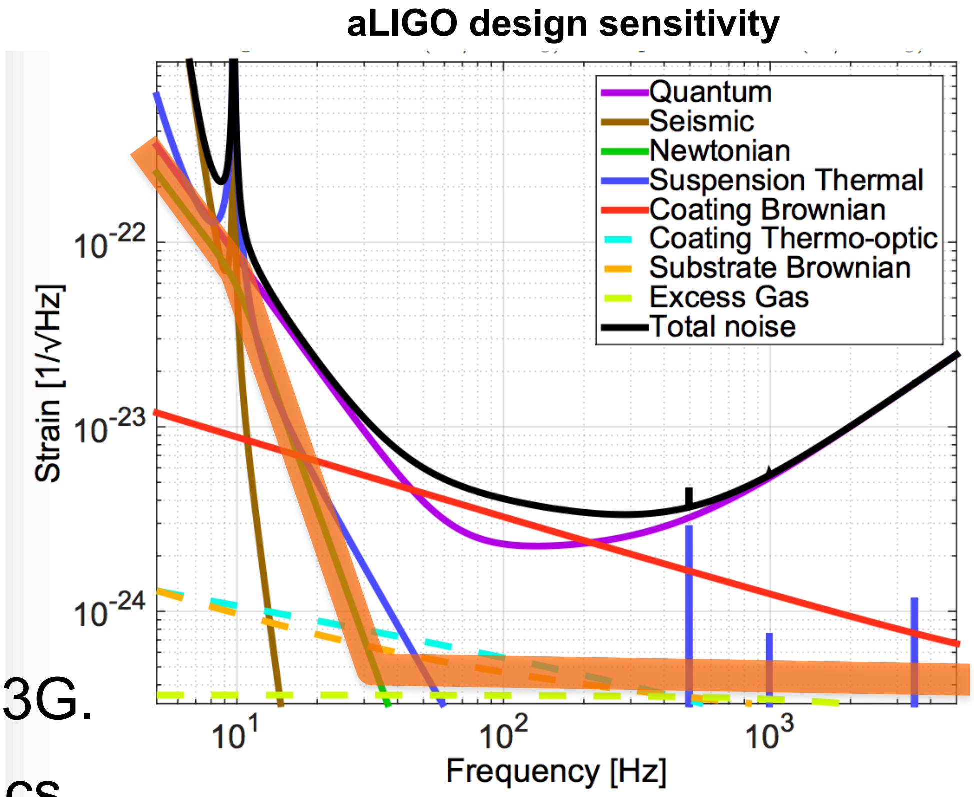
AdV+ A+

Motivation for upgrades to 2nd gen. detectors

- 2G sensitivity far from infrastructure limits (residual gas + Newtonian noise).

- Feasible to increase sensitivity by 2 (event rate by factor of 8) → Minor to medium upgrades within existing infrastructure.

- Explore technologies essential for 3G.
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics



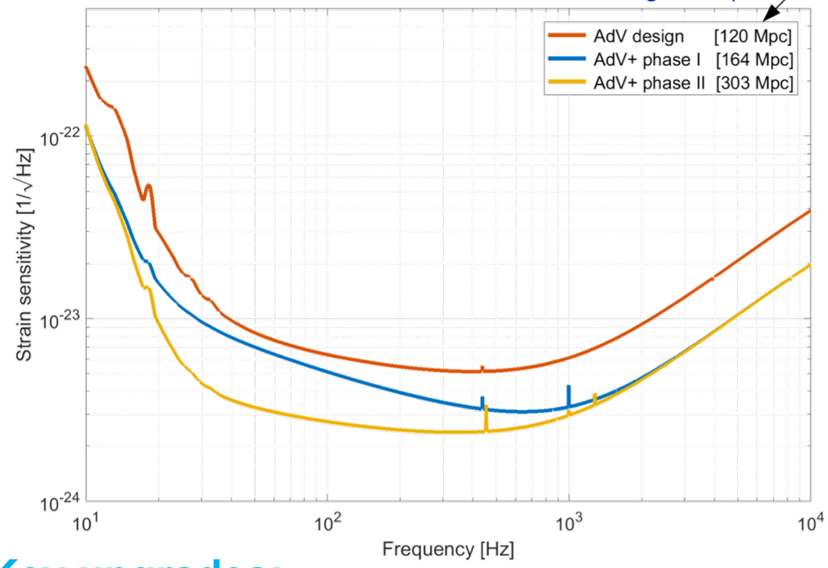
- Enhanced 2G approved (A+) → sensitivity increase ~1.6/1.9 BBH/BNS → 20-300/1-13 BBH/BNS events/month. Run starts 2024.

Enhanced 2G sensitivity increase

- Upgrades mainly target quantum and coating thermal noise.

AdV+ Upgrade in 2 phases: Starts 2020 → observing 2024 (1st phase). Cost ~€30M

from J. Degallaix (G1800999)



Key upgrades:

P1
QN
€10M

Add signal recycling & ↑ laser power (200W): 120 Mpc
Freq. dependent squeezing (8dB, 300m FC): 150 Mpc
Newtonian noise cancellation (seismic sensors network): 160 Mpc

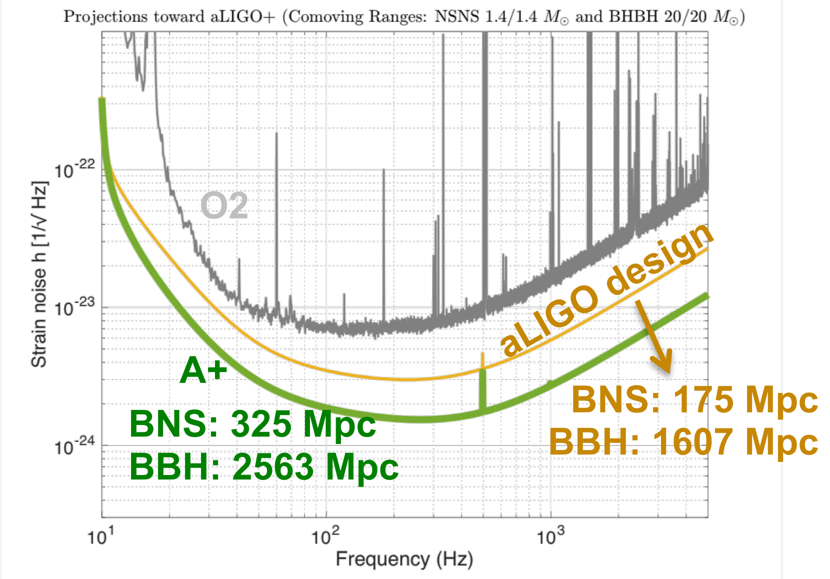
P2
TN
€10-20M

Larger mirrors (105 kg): 200-230 Mpc
Improved coatings (↓ coating TN by 3): 260-300 Mpc

AdV+ bridges to 3G detectors (new facilities).

A+ project starts mid-2020 → observing 2024
Cost ~$20M

from M. Zucker (G1800514)



detection rate increase by 4 (for BBH) – 7 (for BNS)

Key technology elements:

Frequency-dependent squeezing → ↓ QN
  6dB freq-dependent squeezing → 300m filter cavity (high finesse) & 20ppm roundtrip loss

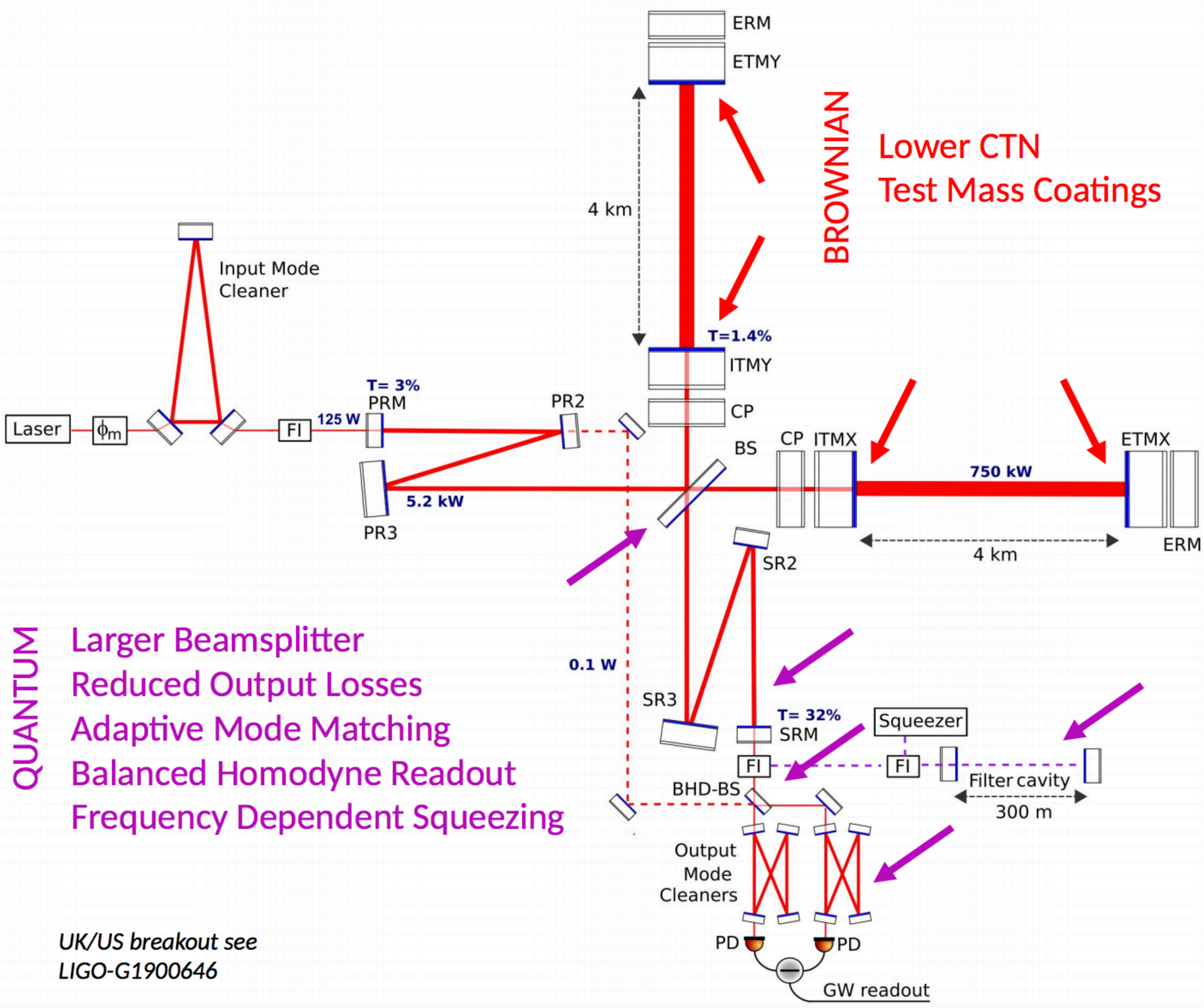
Improved mirror coatings → ↓ coating TN by 2

Improved suspension fibres.

Between 3G and A+ → **Voyager (?)**: cryogenic upgrade (same facilities)

A+ – Core optics layout

P. Fritschel, S. Hild



BROWNIAN

Lower CTN
Test Mass Coatings

QUANTUM

- Larger Beamsplitter
- Reduced Output Losses
- Adaptive Mode Matching
- Balanced Homodyne Readout
- Frequency Dependent Squeezing

UK/US breakout see
LIGO-G1900646

Science case

Enhanced 2G – Science case

- A+ will survey 5 times more volume that aLIGO → Deliver in few years the equivalent of 2 decades of aLIGO Science.

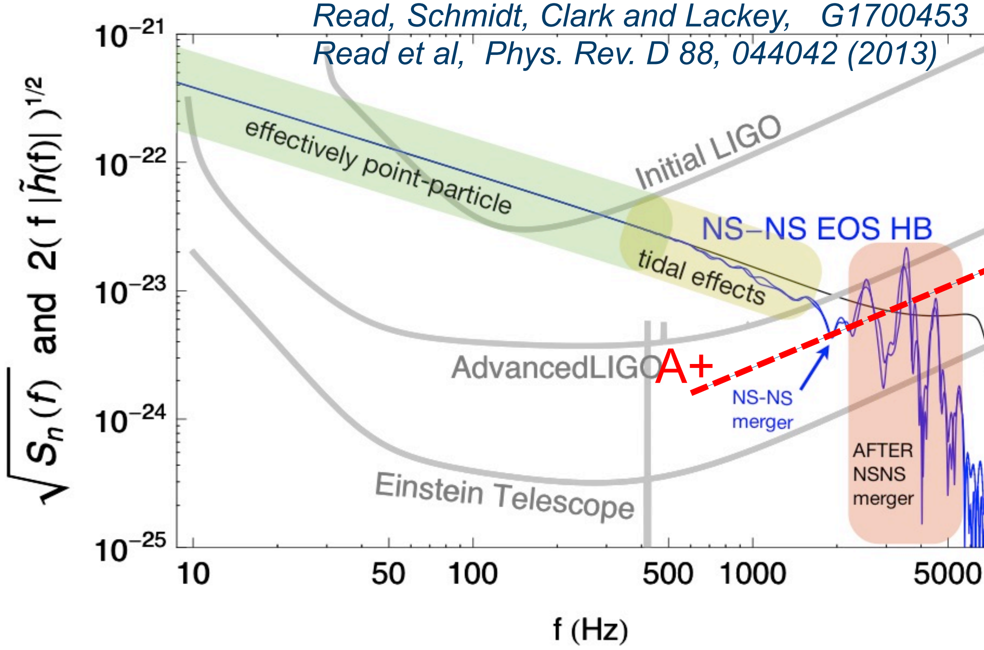
BNS

Numerous 'sGRBs + GWs' observations (↑ by 6 rate of coincident observations) → Probe physics of sGRB central engine, and opening angle of jets, …

Properties of matter at extreme density:

- Deviations from tidal disruption before merger.
- **Observe 'ringing' of post-merger remnant →** constrain EoS.

Kilonova investigations: LSST (2023) optical/IR observations of kilonova up tp 300Mpc → ↑ multimessenger observations (improve host identif. and redshift) → improve Hubble const.


Read, Schmidt, Clark and Lackey, G1700453
Read et al, Phys. Rev. D 88, 044042 (2013)

BBH

Understand BBH progenitor population and origins:

- A+ allow precision measurements of BH spins.
- A+ SNR reduces '***face-on***' orbits selection bias of aLIGO. '***Edge-on***' waveforms have less degeneracy, uniquely encoding component spins and putative "non-GR" anomalies.

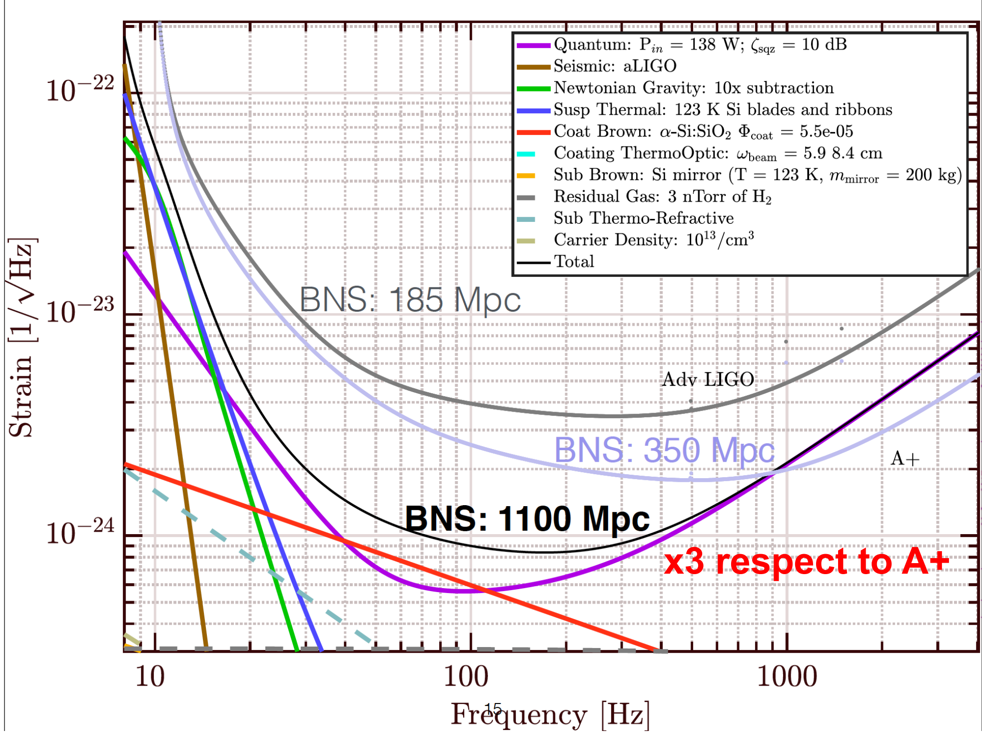
Stringent test of GR: enabled by A+ very high SNR BBH signals (GW150914 SNR > 100 in A+) → Speed & mass of graviton, tensor nature of GW radiation, Lorentz covariance, …

LIGO Voyager

Pre-3G

LIGO Voyager – Ultimate sensitivity LIGO sites can deliver

- New detector on existing facilities → Technology demonstrator for 3G
- Medium cost upgrade ($50M to $100M), proposal ~2025(?) commissioning ~ 2030(?).
- It mitigates A+ limiting noise by:
  - Cryogenic operation: 123K (radiative, non-contact cooling)
  - Silicon test masses: 200kg, 45cm dia., mCZ
  - Coatings: a-Si/SiO_2 (a-Si =amorphous Silicon ~lossless)
  - Laser wavelength: 2µm
  - Newtonian noise reduction factor 10



Required R&D:

- Bulk absorption measurements in float zone Silicon
- Mirror Surface Roughness
- Bulk Index/Birefringence Non-uniformity
- Procure / develop / qualify large Silicon test masses
- Initial Cooldown of Test Masses
- Cryogenic Engineering of Test masses
- low opt/mech loss coatings at 120 K
- Bond loss for Si on Si: ears, ribbons, etc.
- 2µm PSL operating at 180W
- 2µm squeezing
- High power IO components (modulators, isolators) at 2µm
- Low noise PD quantum efficiency from 80% to 99% at 2µm
- Black Coatings for Mirror Barrels
- Develop crystalline suspension fibres.
- Low Phase Noise cryogenic Silicon interferometer prototype

Characterise themo-mechan. properties of cryo materials

Develop; inertial sensors and passive damping that operates at cryo temp.

Instrument Science whitepaper – T1800133

3G

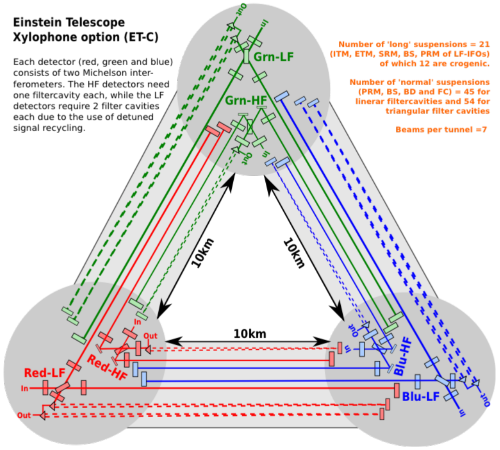
Europe → ET

USA → Cosmic Explorer

The future of experimental GW physics

- **3G detectors** in new facilities. x10 2G sensitivity >100Hz, x100 at 20Hz, low freq. wall from 10→few Hz. **2 designs**:

Europe (ET): underground, triangle 3 detectors, each made of 2 IFOs.



Einstein Telescope Xylophone option (ET-C)

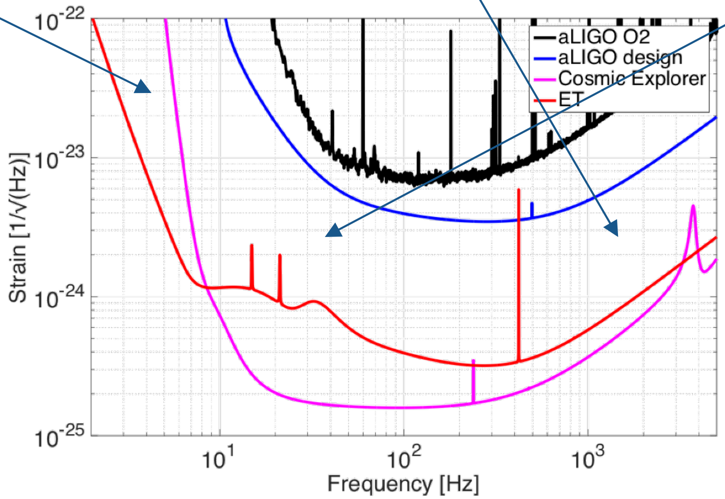
Each detector (red, green and blue) consists of two Michelson interferometers. The HF detectors need one filtercavity each, while the LF detectors require 2 filter cavities each due to the use of detuned signal recycling.

Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

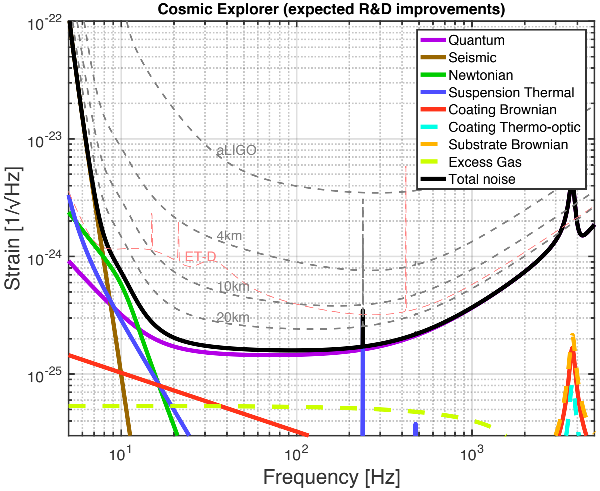
Number of 'normal' suspensions (PRM, BS, BD and FC) = 45 for linerar filtercavities and 54 for triangular filter cavities

Beams per tunnel =7

Operating 2030



US (CE): L-shape IFO 40km arms.



CE Operating 2030+

Same **enabling technologies**:

Cryogenics: **Si** masses 100s kg, new suspensions, new coatings, new lasers (1.5,2μm) & new detectors.

Higher power + freq. dep squeezing → parametric instabilities, scattered light.

Vacuum systems, technical noise sources, control, Newtonian noise.

ET – European 3G detector proposal

- Vision for a European 3G observatory → **50+ years lifespan → Multiple generations of detectors.**
- ET conceptual design study 2008–2011
- ET Collaboration formed 2018-2019

- ET timeline:

2018: Transform ET community into ET collaboration

2019: Submitted ET proposal to ESFRI roadmap (reduced list of site candidates)

2021-2022: Decision on site location

2023: Full technical design

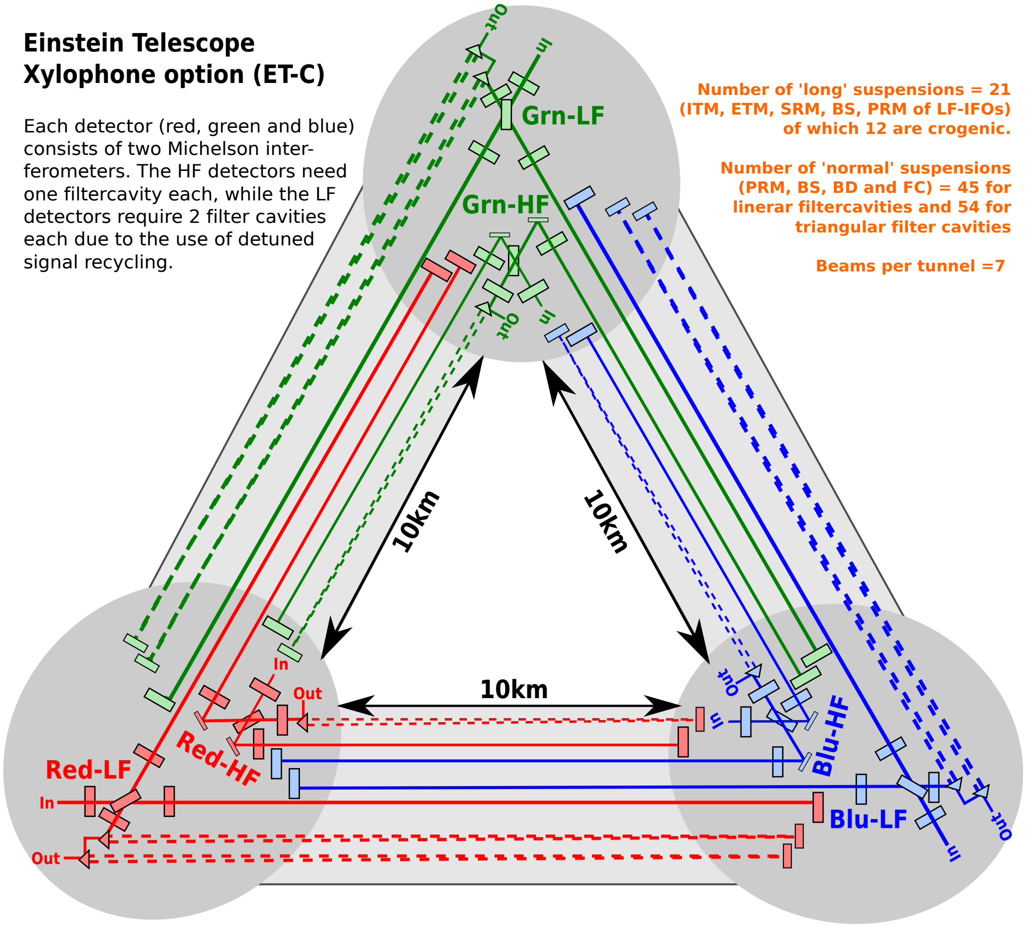
2025: Beginning of construction work

2032+: Installation/Commissioning/Operation

ET – European 3G detector proposal

- Underground (depth 100-200m).
- Equilateral triangle of 3 detectors, each of 2 IFOs (arms 10Km).
- Start with a single xylophone det.
- Add second Xylophone detector to fully resolve polarisation.
- Add third Xylophone detector for redundancy and null-streams.

•Infrastructure Estimated cost ~1B€ (for one Xylophone detector).



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Beams per tunnel =7

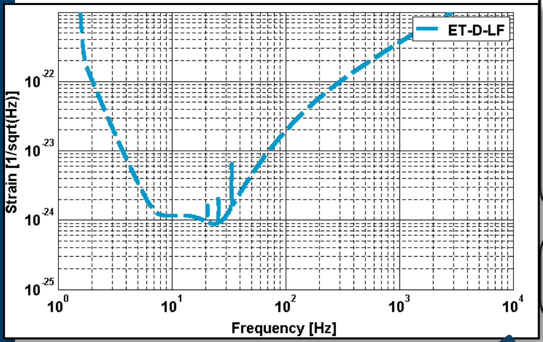
ET – Xylophone approach

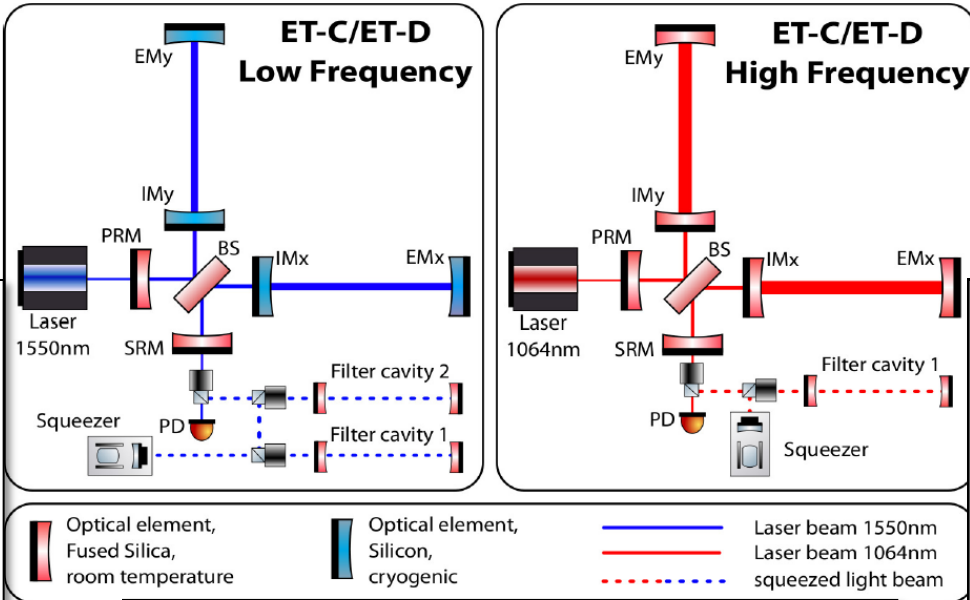
- Split detector into two interferometers optimised at low & high freq. bands:

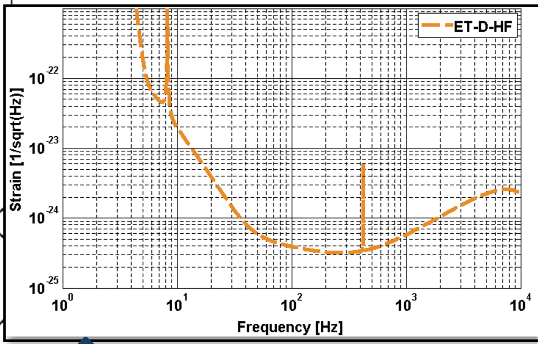
Low Frequencies = Low power & cryogenics
10K, 18kW, 1550nm

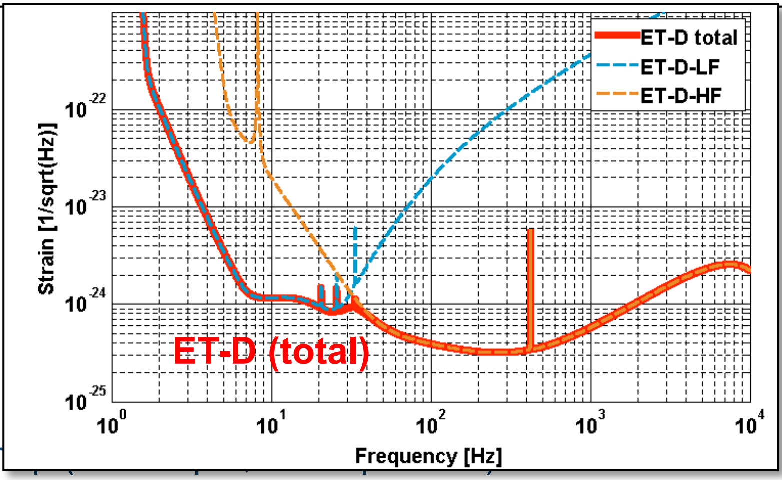
High Frequencies = High power & room temp.
300K, 3MW, 1064nm

2-40 Hz









Cosmic Explorer – US 3G detector proposal

Target sensitivity: 10 times better than A+.

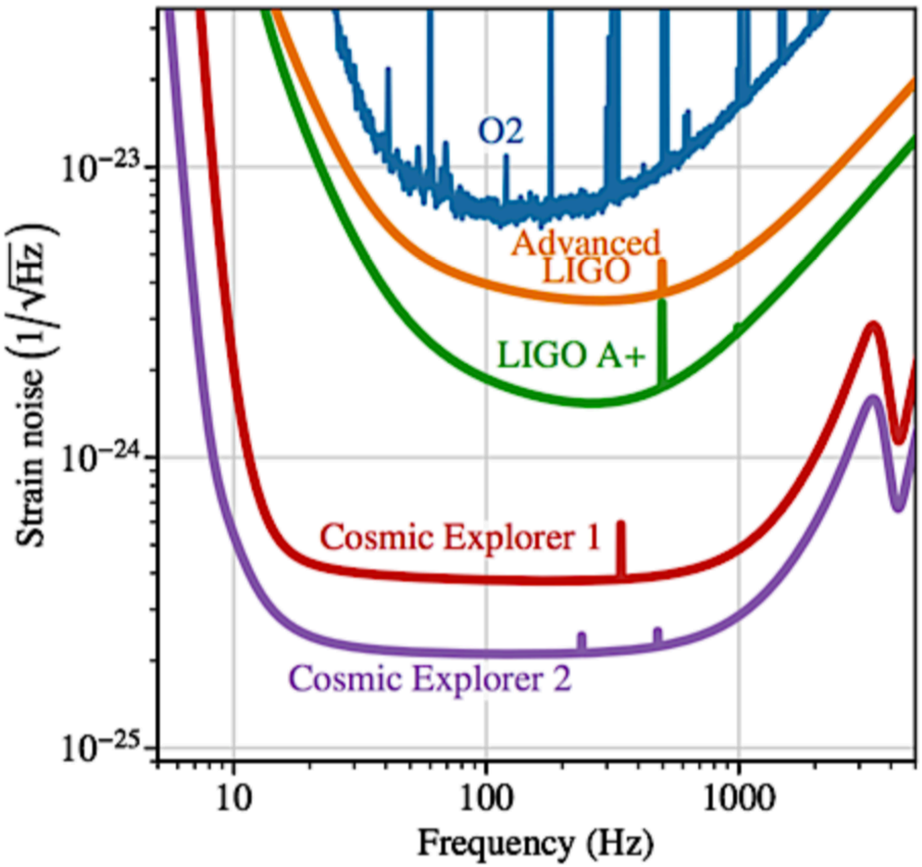
The target design is essentially a 40km Voyager (L-shaped, above ground).

Staged approach:

- CE1, operating in late 2030s (room T, A+ tech.).
- CE2, operating in mid-2040s (cryogenic, major tech. upgrades).

Still R&D needed

- more massive mirrors (factor ~10)
- Flatter mirrors → impacts contrast & alignment.
- Arm tubes expensive→limited diameter→scattering
- 4kHz FSR → frequency servo implications



CE design study funded by NSF. Submission to Astro2020 Decadal survey.

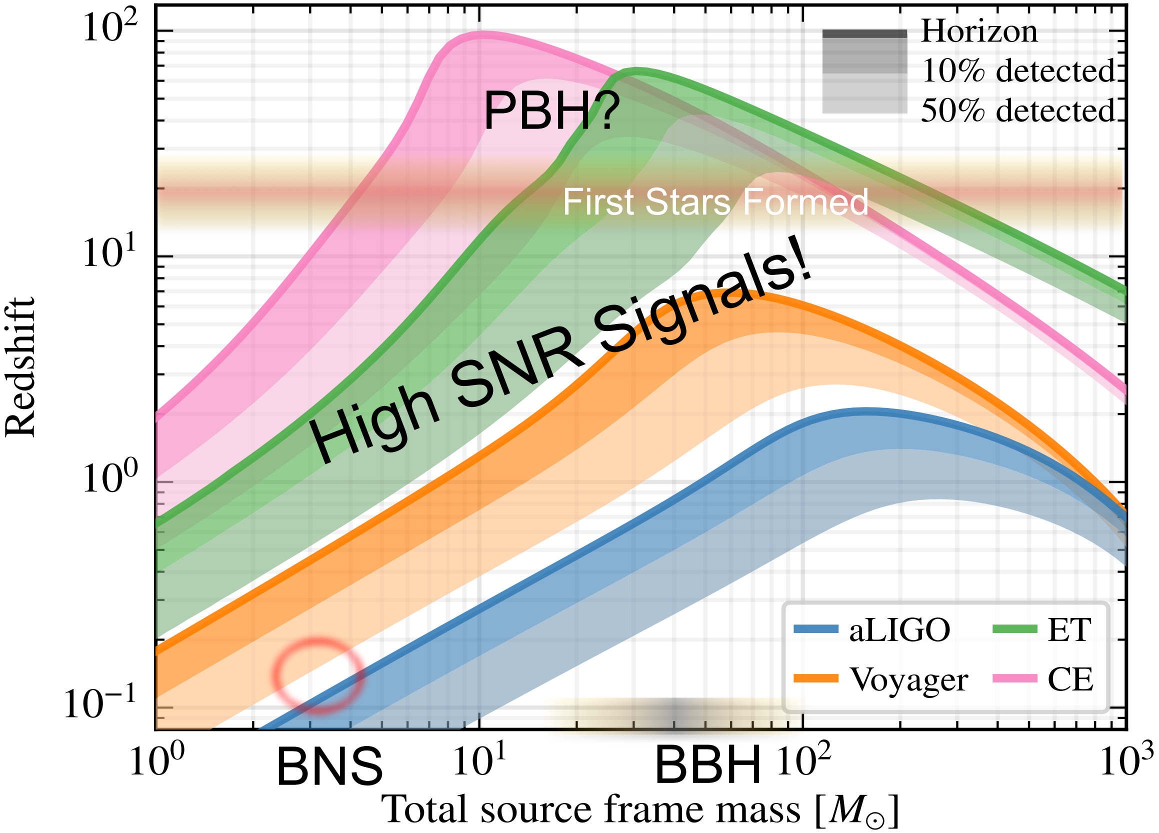
ET (2030) → stand alone underground facility, with full sky coverage & polarization recovery.
CE (2030+) → complement ET, optimized to increase network reach & SNR.

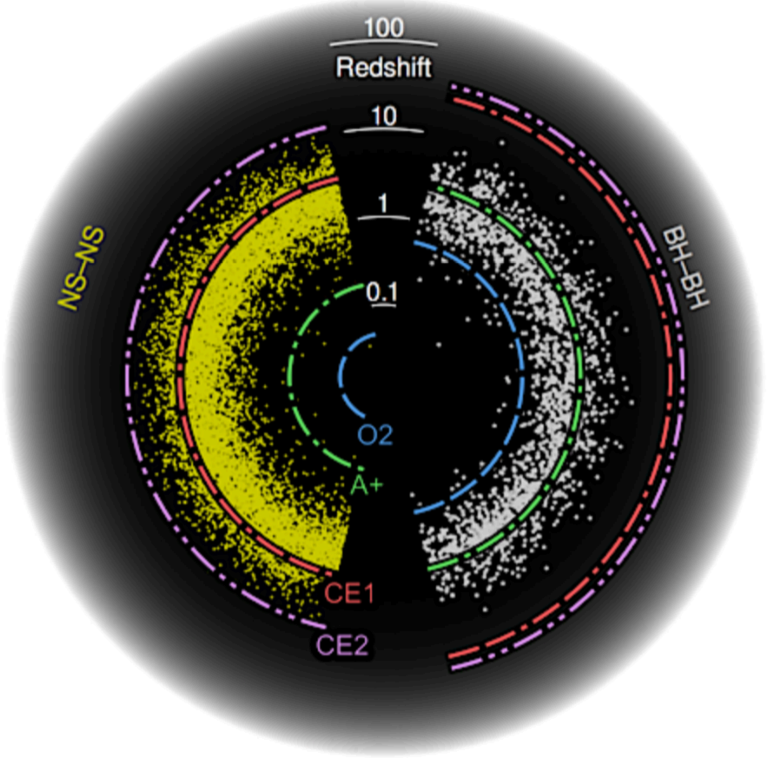
from M. Evans– GWADW 2018

Science case

3G – Science case

- **3G Science will transform our understanding of the Universe.**
- We will observe BNS and BBH from **the entire Universe**!
- Measure mergers of **BBH from 1st starts** (Pop III) as a function of redshift.
- CBC **mass and spin** distribution **through cosmic time**.
- Map **demographics of BH seeds** and their growth through the Universe
- Formation and cosmological evolution of BBH and BNS and their population.





Hall / Vitale arXiv:1903.04615

3G – Science case

Multi-messenger observations:

- What is the contribution of NS-NS and/or NS-BH mergers to r-process production?
- How does this vary with redshift?
- Where in the galaxies do these mergers occur and what the location tell us?

Neutron stars / Nuclear physics:

- Decipher the equation of state and structure of dense NS cores.

Supernovae:

- Can we distinguish the various phases of supernovae explosion?
- Shed light on the mechanism of gravitational collapse and core bounce.

Extreme Gravity:

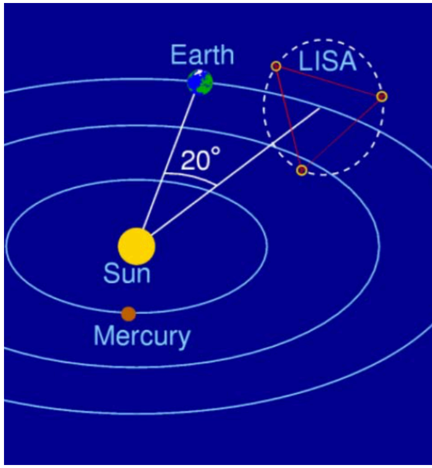
- Horizon dynamics during BBH mergers.
- Can we observe multiple ringdown modes? → verify no-hair theorem
- Do exotic compact objects (e.g. boson stars) exist?
- Test alternative theories of gravity (new polarizations, graviton mass, Lorentz violation)

Cosmology:

- Measure Hubble constant and dark energy equation of state with standard sirens.

Space
Broadening the detection frequency band

Broadening frequency band – Space → LISA



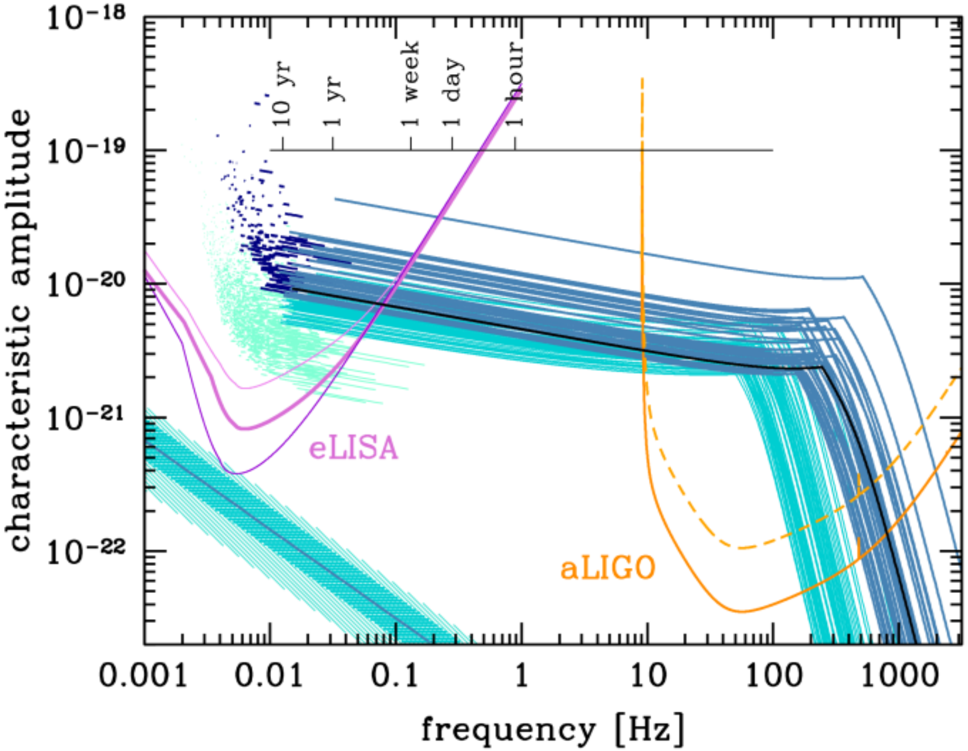
3 satellites separated 2.5 Mkm on triangular formation.

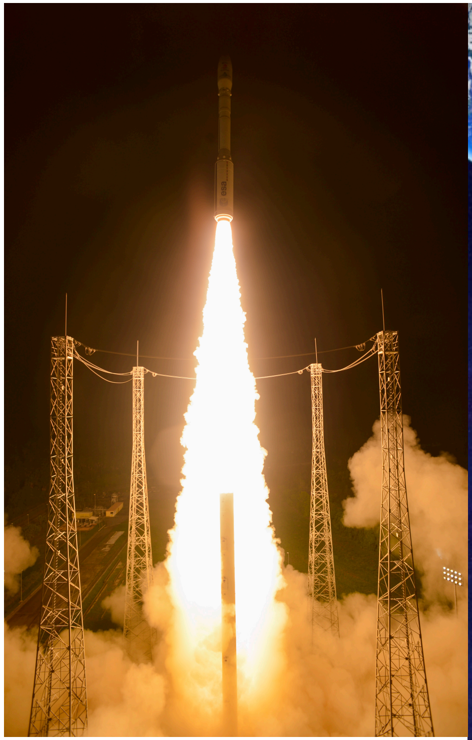
Following Earth on its orbit round the Sun.

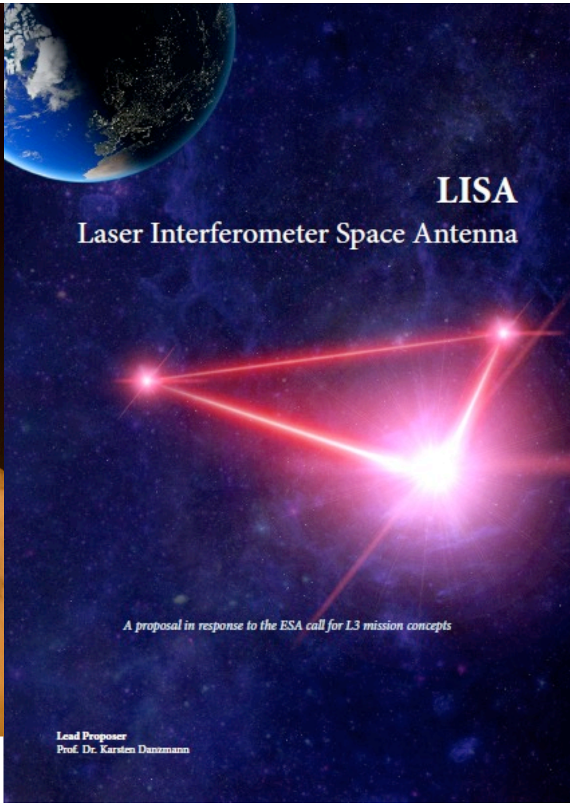
Laser interferometry to measure their relative distances.

ESA approved mission June 2017→Launch 2034.

www.elisascience.org







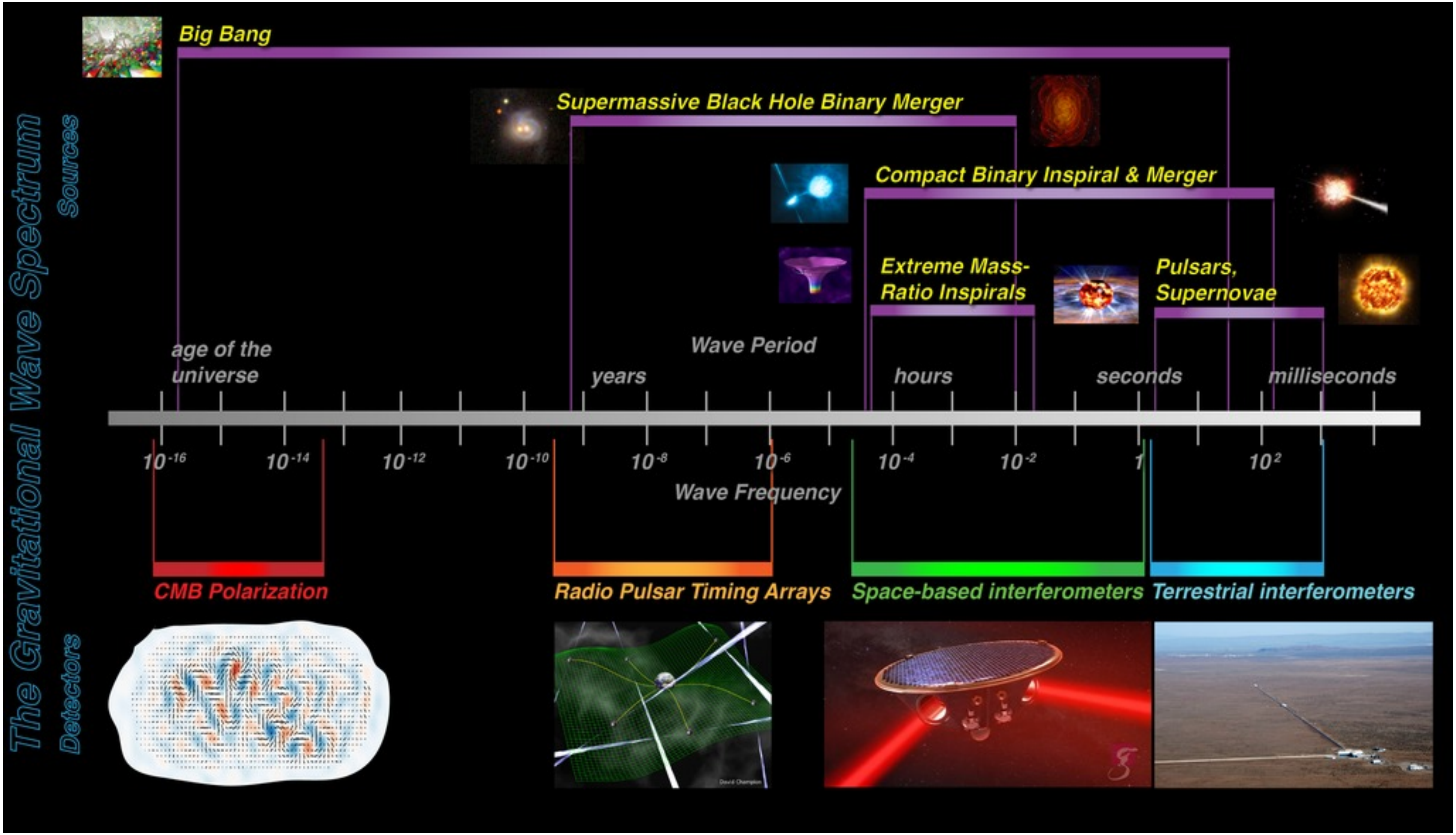
LISA

Laser Interferometer Space Antenna

A proposal in response to the ESA call for L3 mission concepts

Lead Proposer
Prof. Dr. Karsten Danzmann

GWs frequency spectrum

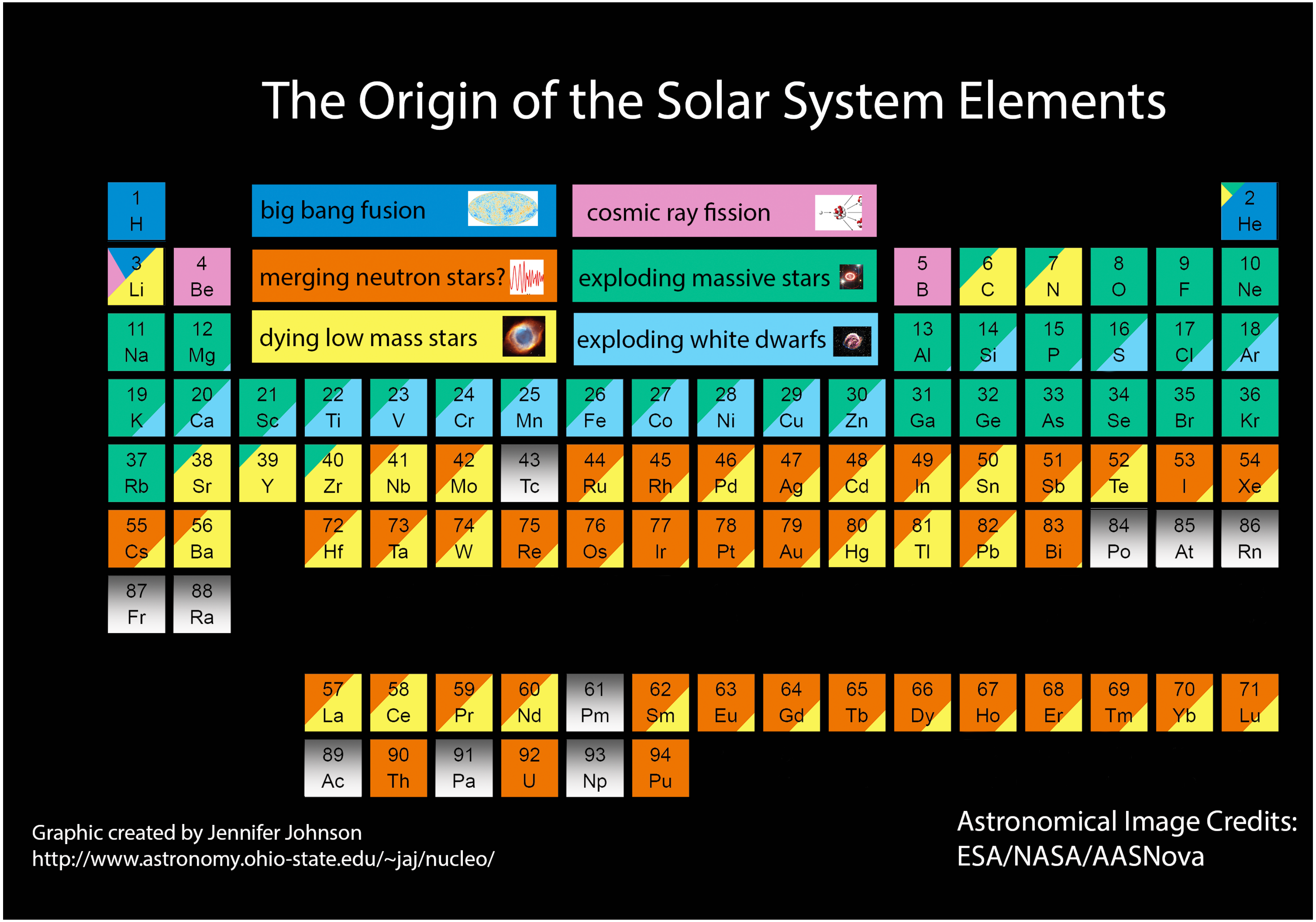


Thank you for your attention

Questions?

Other slides

GW170817 – Kilonova



The Origin of the Solar System Elements

big bang fusion

cosmic ray fission

merging neutron stars?

exploding massive stars

dying low mass stars

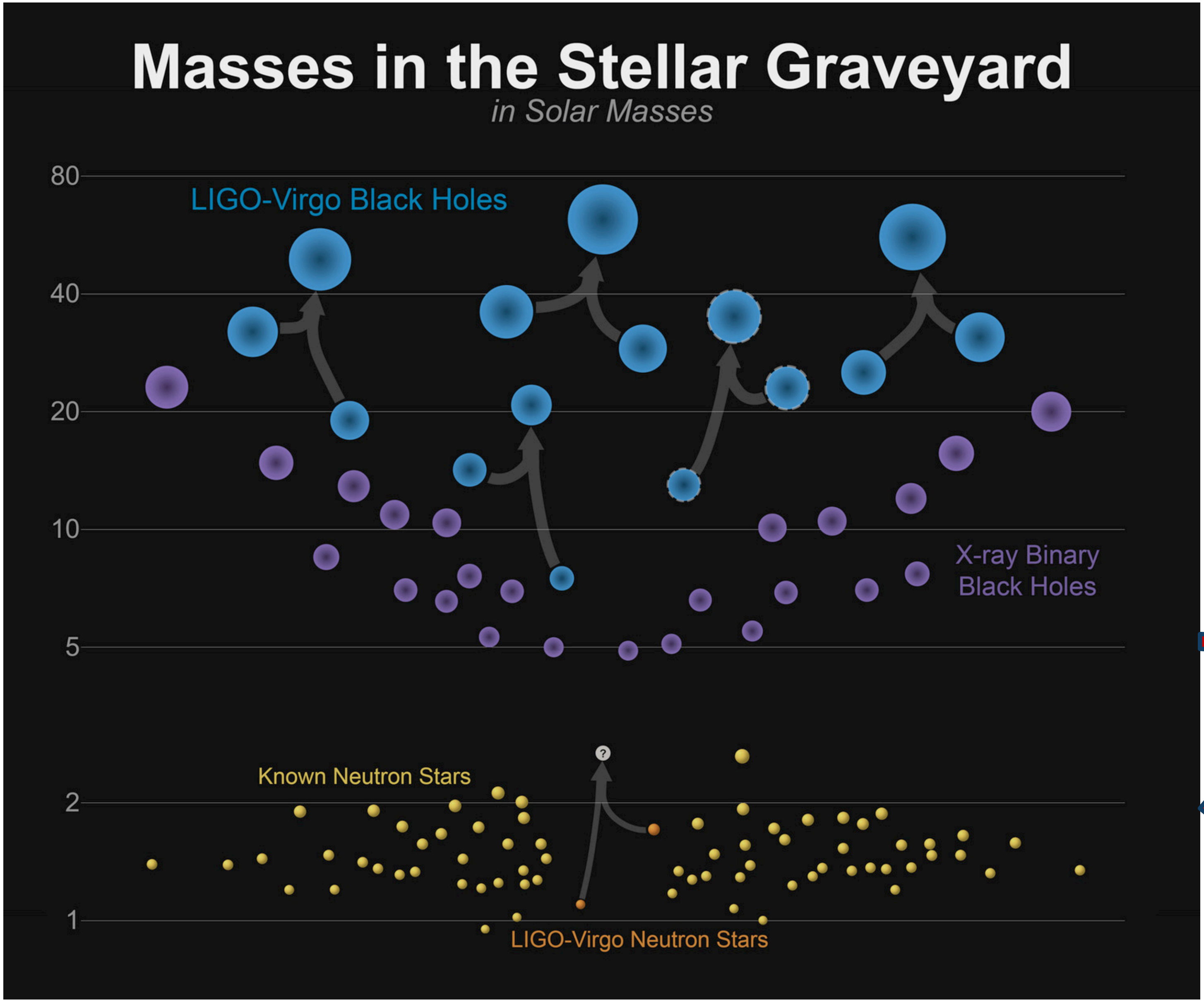
exploding white dwarfs

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba		72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra																
			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu									

Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

Mass gap between known NS and BH



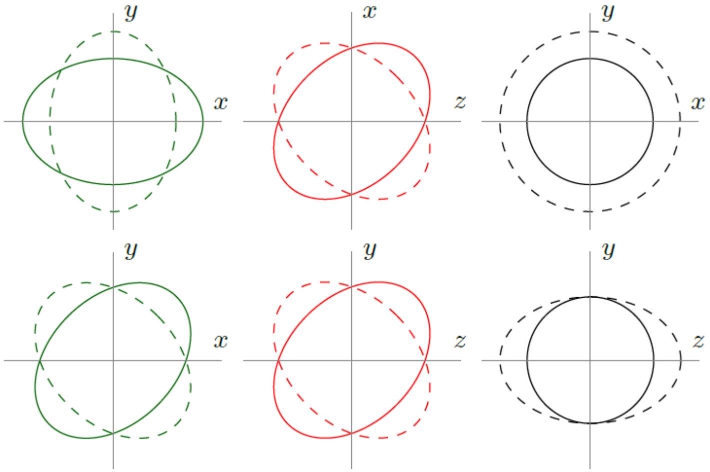
Mass gap

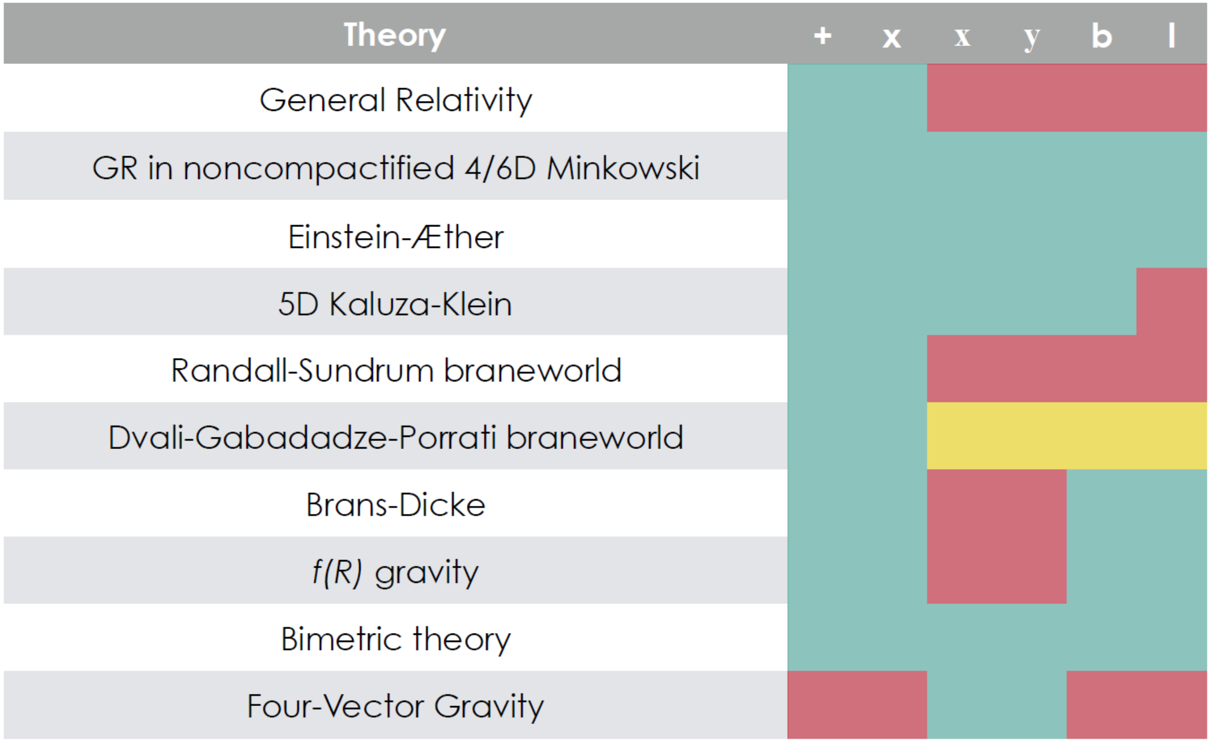
Polarization of gravitational waves

- **Polarization, fundamental property of space-time →** how space-time can be deformed.
- General metric theories allow six polarizations. General Relativity allows two (tensor) polarizations.

GR only allows (T) polarizations (cross and plus)

General metric theories also know vector (V) and scalar (S) polarizations





Theory	+	x	x	y	b	l
General Relativity	🟩	🟩	🟥	🟥	🟥	🟥
GR in noncompactified 4/6D Minkowski	🟩	🟩	🟩	🟩	🟩	🟩
Einstein-Æther	🟩	🟩	🟩	🟩	🟩	🟩
5D Kaluza-Klein	🟩	🟩	🟩	🟩	🟩	🟥
Randall-Sundrum braneworld	🟩	🟩	🟥	🟥	🟥	🟥
Dvali-Gabadadze-Porrati braneworld	🟩	🟩	🟨	🟨	🟨	🟨
Brans-Dicke	🟩	🟩	🟥	🟥	🟩	🟩
f(*R*) gravity	🟩	🟩	🟥	🟥	🟩	🟩
Bimetric theory	🟩	🟩	🟩	🟩	🟩	🟩
Four-Vector Gravity	🟥	🟥	🟩	🟩	🟥	🟥

Nishizawa et al., Phys. Rev. D 79, 082002 (2009) [except G4v & Einstein-Æther].

allowed / depends / forbidden

from Jo van den Brand

ET – HF detector

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

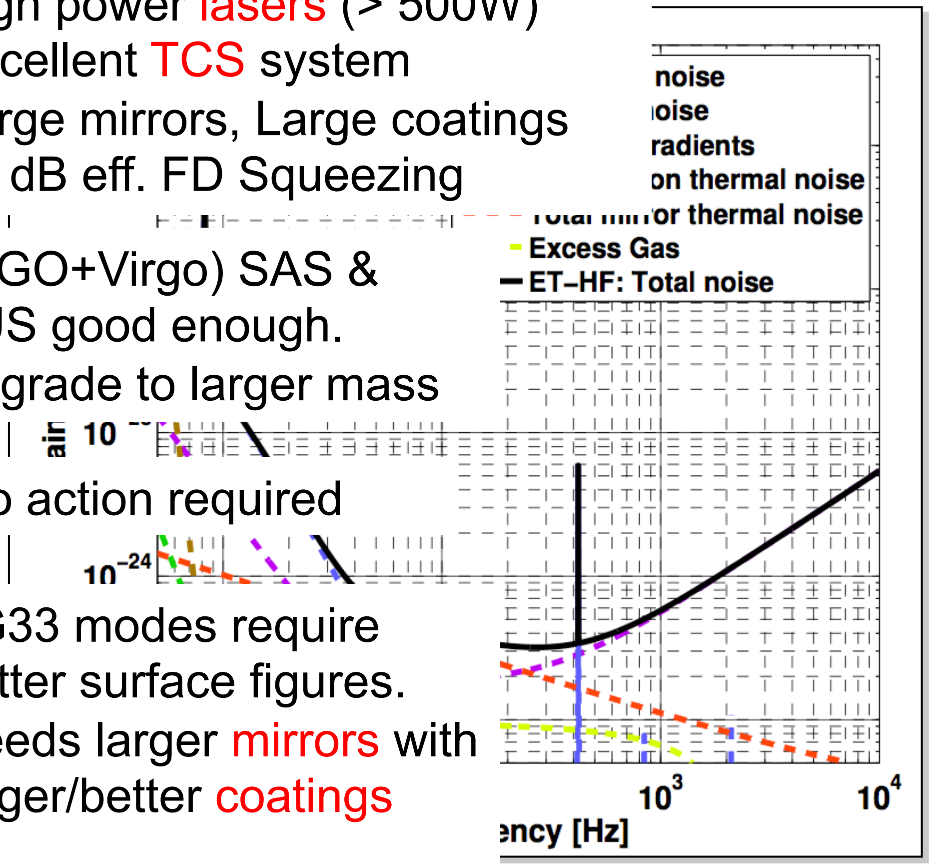
Challenges:

High power lasers (> 500W)
Excellent TCS system
Large mirrors, Large coatings
10 dB eff. FD Squeezing

(LIGO+Virgo) SAS & SUS good enough.
Upgrade to larger mass

No action required

LG33 modes require better surface figures.
Needs larger mirrors with larger/better coatings



Most requirements = extension from Advanced techniques

Coating Brownian reduction factors (compared to 2G):
3.3 (arm length), 2 (beam size) and 1.6 (LG33) = **10.5**
Shot Noise reduction factors (compared to 2G):
1.6 (arm length), 1.9 (power), 3.2 (squeezing (10dB)) = **9.7**

from H. Luck – GWADW 2018

ET – LF detector

- **Quantum noise:** 18kW, detuned Signal-Recyling, 10dB freq. dep. squeezing, 211kg mirrors, 1550nm
- **Seismic:** extended Superattenuator, 17m tall
- **Gravity gradient:** underground
- **Mirror thermal :** 10K, Silicon, 9cm beam radius, TEM00.
- **Suspension Thermal:** penultimate mass at 2K, 3mm silicon fibres, 2m long; limiting noise contribution from 1Hz-10Hz

Challenges:

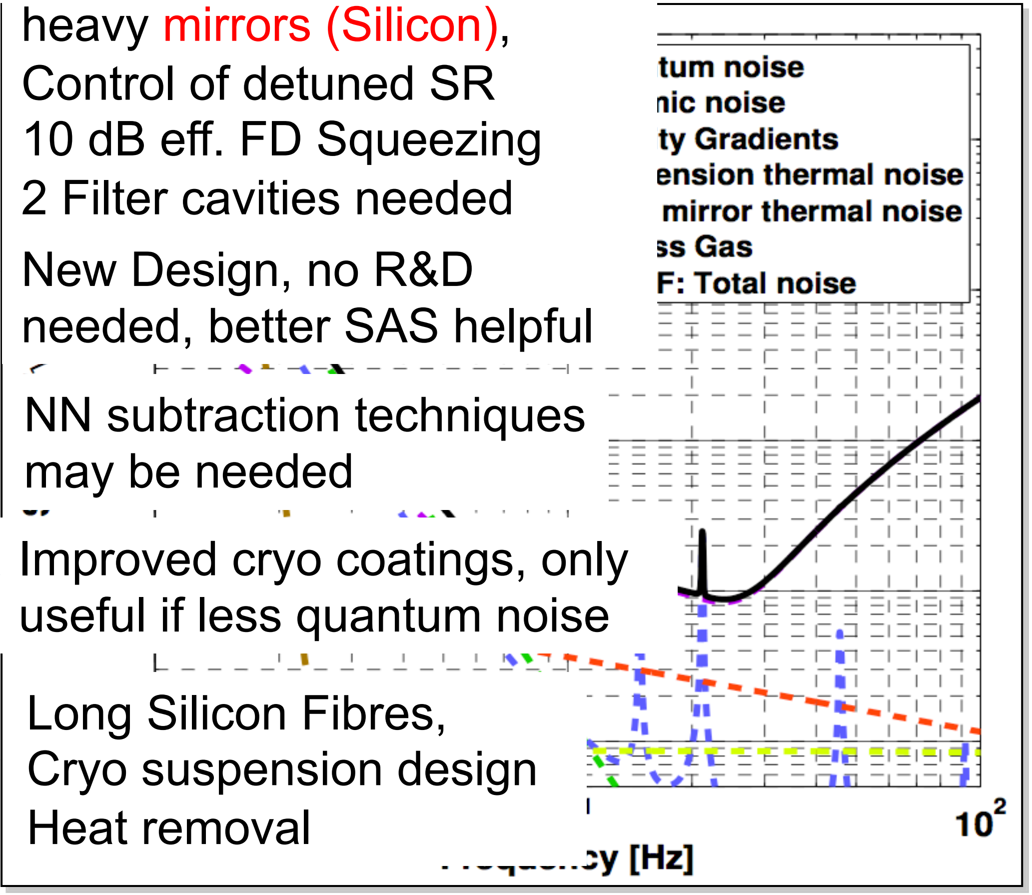
Max. power = f(coating abs.)
heavy mirrors (Silicon),
Control of detuned SR
10 dB eff. FD Squeezing
2 Filter cavities needed

New Design, no R&D needed, better SAS helpful

NN subtraction techniques may be needed

Improved cryo coatings, only useful if less quantum noise

Long Silicon Fibres,
Cryo suspension design
Heat removal



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

from H. Luck – GWADW 2018