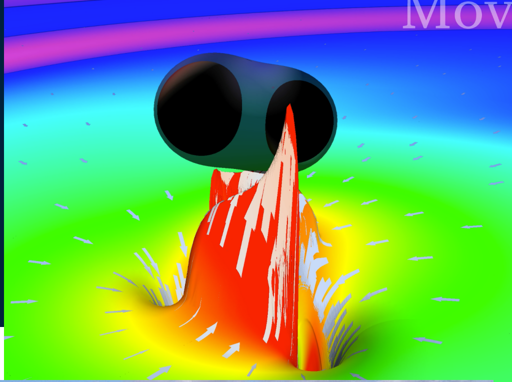
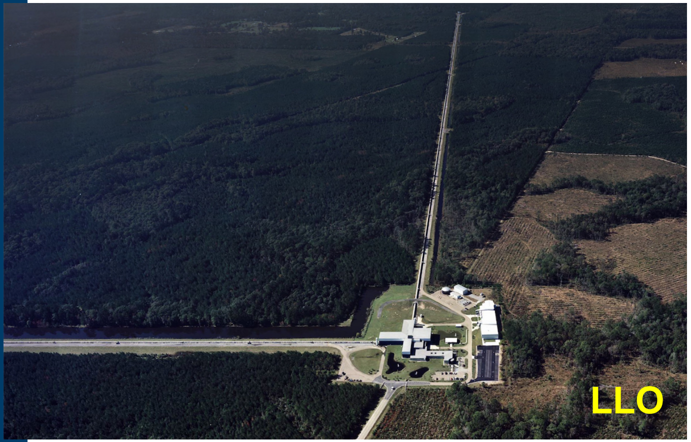
University of Glasgow

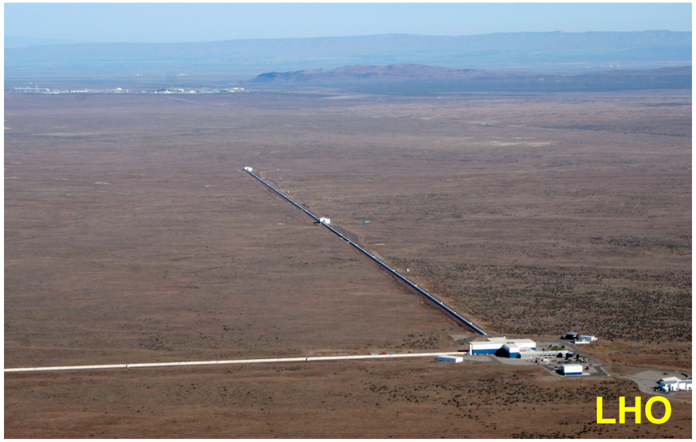
Science & Technology Facilities Council

LSC LIGO Scientific Collaboration

VIRGO



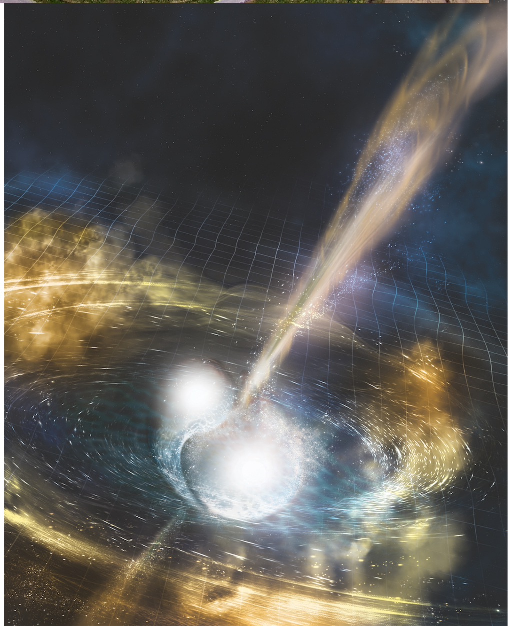




Gravitational waves

Results 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

https://www.zeemaps.com/map?group=245330

The LIGO Scientific collaboration (LSC) is made out of 1000+ scientist of more than 90 institutions in 16 countries. **www.ligo.org**

LSC - Institutions

Caltech
American University WASHINGTON, DC
Andrews University
Washington State University
California State University Fullerton
PennState
Southern University and Agricultural & Mechanical College
Massachusetts Institute of Technology

Leland Stanford Junior University 1891
The University Of Sheffield.
University of Maryland 1856
indigo
Texas Tech University
Hillsdale College
Montclair State University
清華大學 Tsinghua University

Université de Montréal
Monash University
UIB Universitat de les Illes Balears
International Institute of Physics
Cal State LA
Bellevue College
Montana State University
University of Cambridge
University of Southampton
Polytechnique Montréal
The University of Adelaide Australia

NCSA
University of Wisconsin UWMilwaukee
University of the West of Scotland UWS
University of Glasgow
Indian Institute of Technology Madras
W Bothell
Michigan
ACU
Trinity University
Australian National University
University of Strathclyde
Lomonosov Moscow State University
Syracuse University Founded AD 1870
OzGrav
Cardiff University Prifysgol Caerdydd

The University of Western Australia
R·I·T
Columbia University in the City of New York
Sonoma State University
University of Minnesota
Carleton College
RRCAT
Cornell University Founded A.D. 1865
NASA

The University of Chicago
IIT Hyderabad
University of Washington
東京大学 The University of Tokyo
Università degli Studi del Sannio
LSU Louisiana State University
Colorado State University
Charles Sturt University
Marshall Space Flight Center

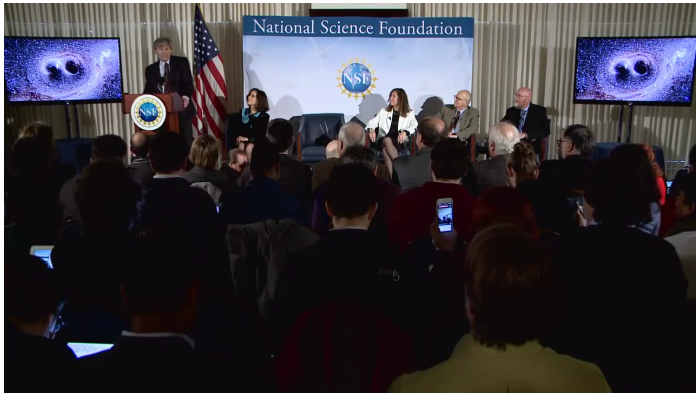
CMI Chennai Mathematical Institute
ICTS International Centre for Theoretical Sciences, Tata Institute of Fundamental Research
University of Birmingham
Georgia Institute of Technology
Korean Gravitational-Wave Group
ACIGA
UH Universität Hamburg Der Forschung | Der Lehre | Der Bildung

The University of Melbourne
Embry-Riddle Aeronautical University
Villanova University
UO
Whitman College
Northwestern
UF University of Florida

tifr
IUCAA
UTRGV
University and Institute of Advanced Research, The Puri Foundation for Education in India
Swinburne University of Technology
DISCE
The University of Mississippi
INPE
University of Southern California
Indian Institute of Technology Bombay

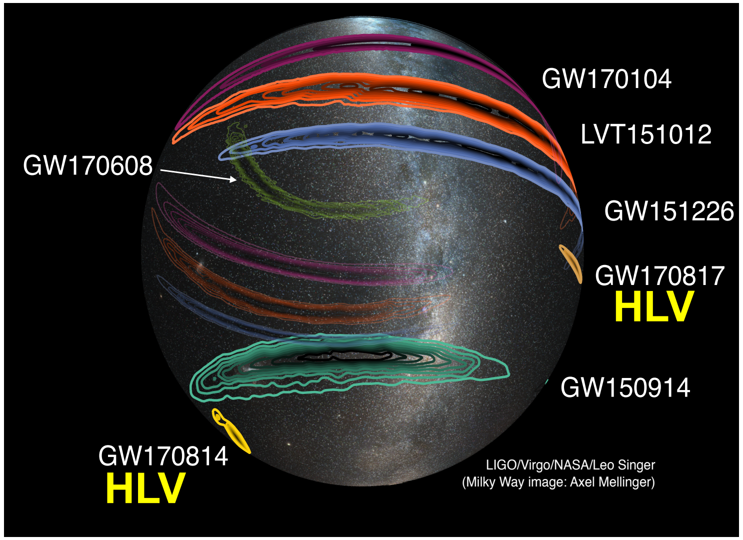
GEO 600
Max Planck Institute for Gravitational Physics Albert Einstein Institute
Leibniz Universität Hannover
University of Zurich UZH
IISER Thiruvananthapuram
CITA ICAT Canadian Institute for Theoretical Astrophysics, L'institut Canadien d'astrophysique théorique
King's College London
IISER Kolkata
NASA Goddard Space Flight Center

Overview of results

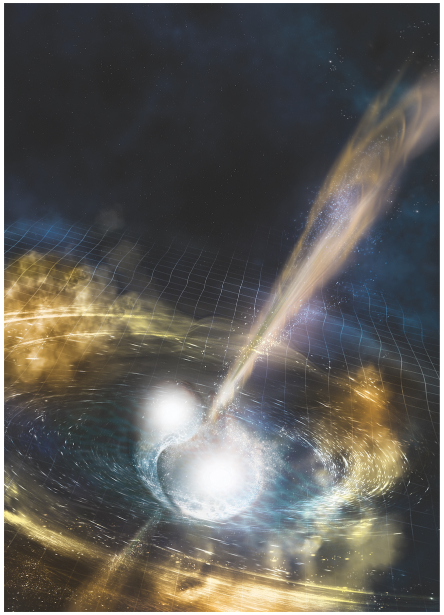


On **Feb 2016**, LIGO and Virgo collaborations announced **beginning of new era in astrophysics, based on GWs** (GW150914, first BBH signal).

- **5 BBH mergers observed to date** (latest a triple detection: LHO, LLO, Virgo) → No EM counterparts 🙁



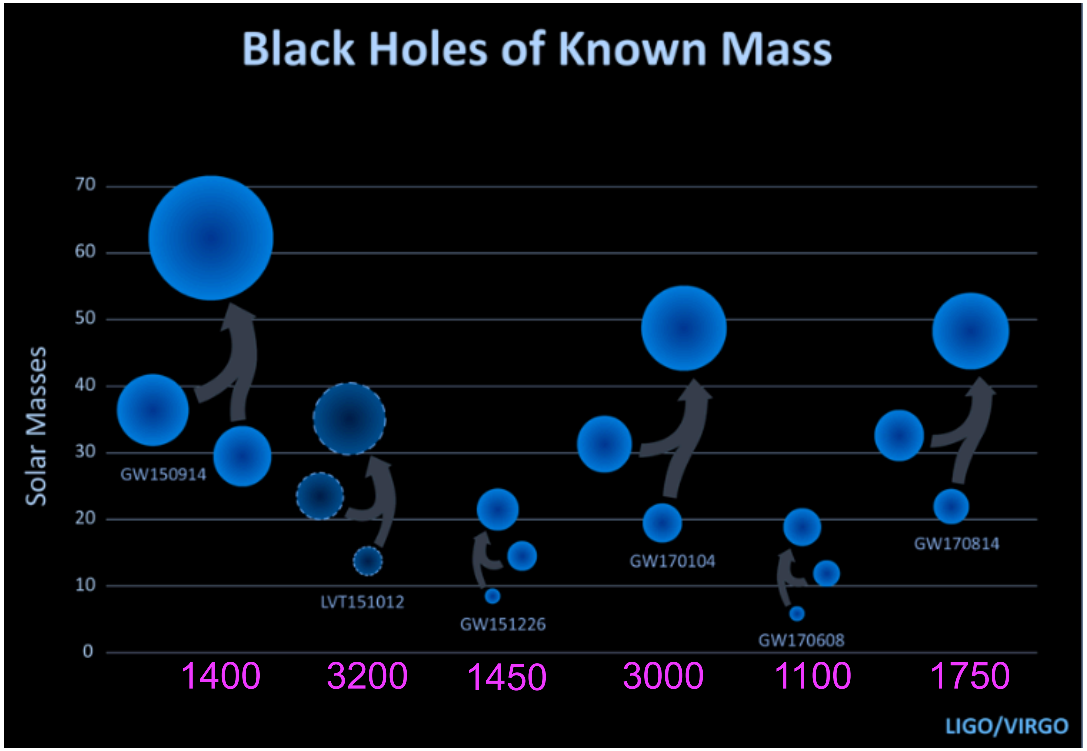
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)



- On **Oct 2017**, LIGO + Virgo + 70 EM observatories announced **the most complete observation of a BNS merger** (GW170817, first BNS signal) → Breakthrough for multi-messenger astronomy

Other BBH detections

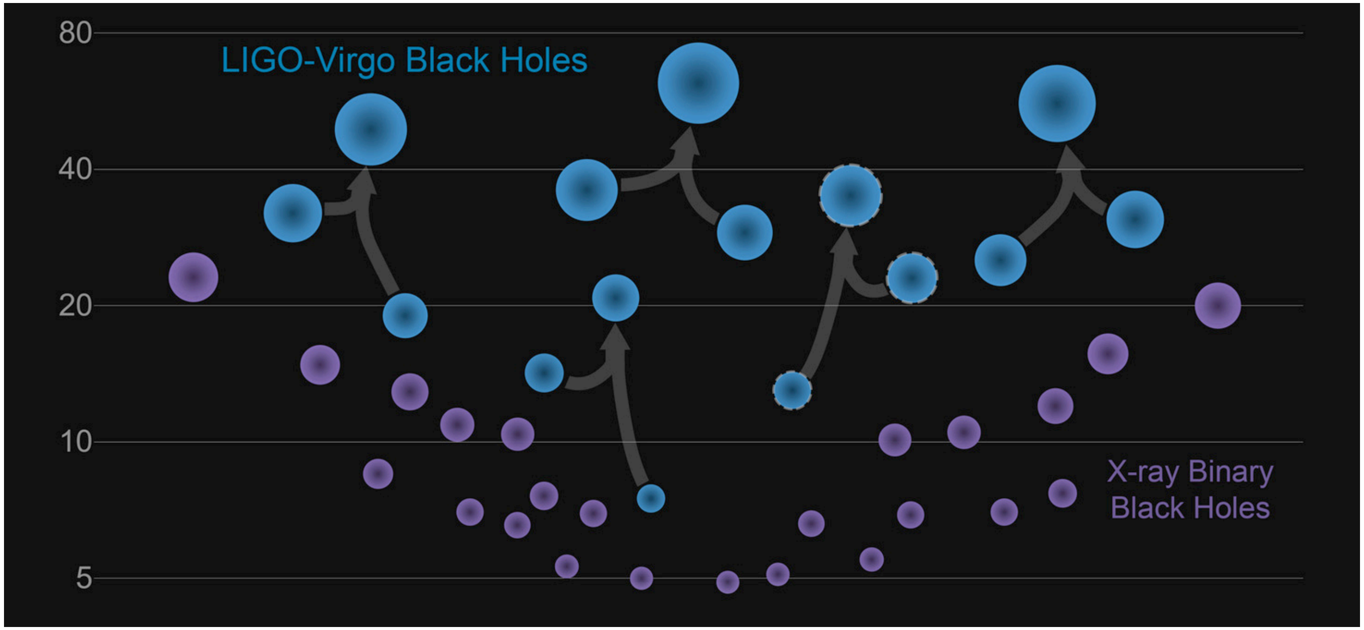
- During O1 (18 Sept 2015 – 12 Jan 2016): 2, GW150914 and GW151226.
- During O2 (30 Nov 2016 – 25 August 2017): 3 announced, GW170104, GW170608 and **GW170814**
- No EM → BHs dimension imply no accretion disc.



Distance to source in million light years

Other BBH detections

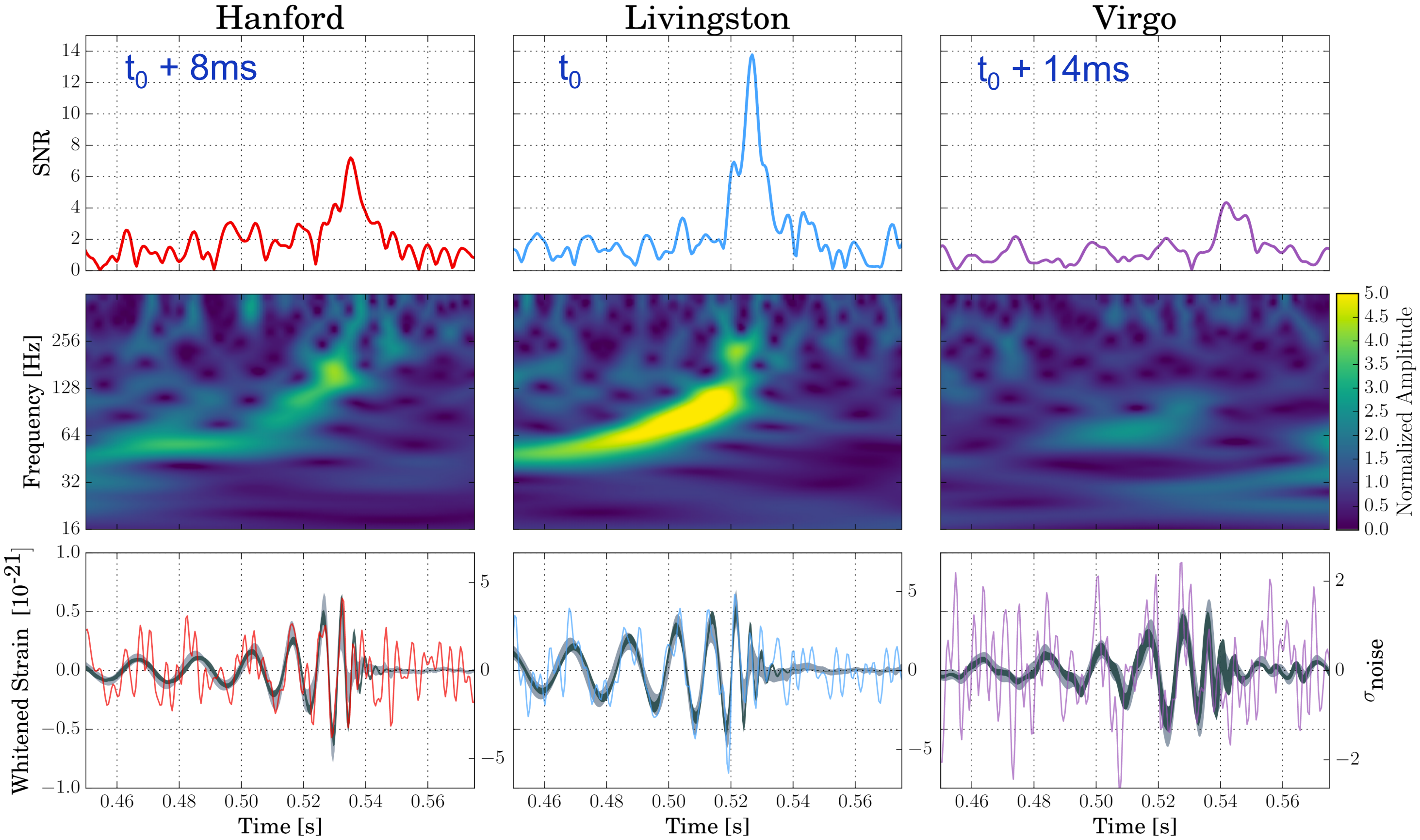
- During O1 (18 Sept 2015 – 12 Jan 2016): 2, GW150914 and GW151226.
- During O2 (30 Nov 2016 – 25 August 2017): 3 announced, GW170104, GW170608 and **GW170814**
- No EM → BHs dimension imply no accretion disc.



B. Sorazu – SUSY18 (Barcelona, 27 July 2018)

First triple detection GW170814: LIGO+Virgo

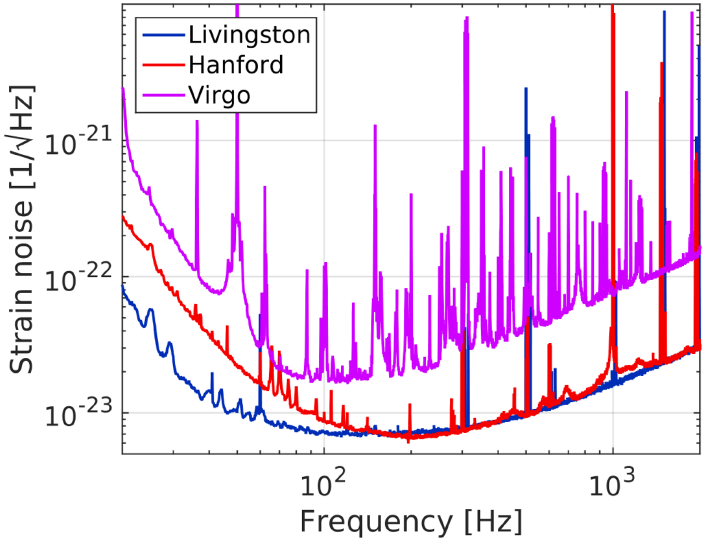
- **GW170814** first detection with 3 detectors (LLO, LHO and Virgo joining O2 on 1 August 2017).



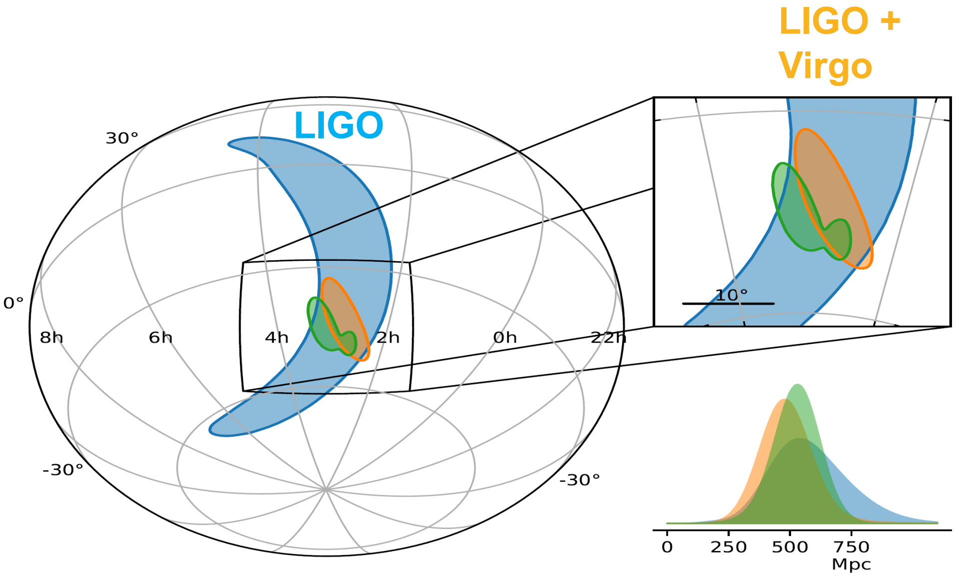
- Signal is observed at different times in the 3 detectors due to the finite propagation speed of GWs → source location.

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%



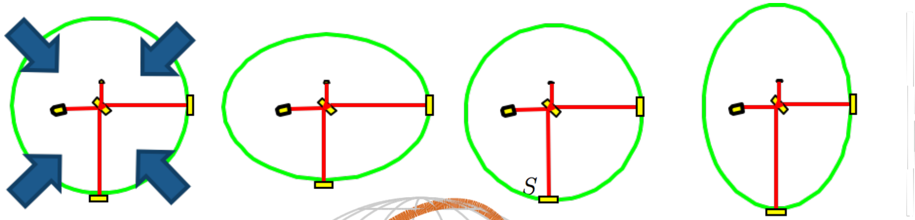
Sensitivity of the 3 detectors during GW170814

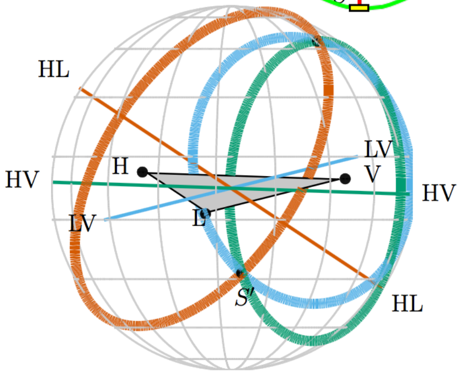


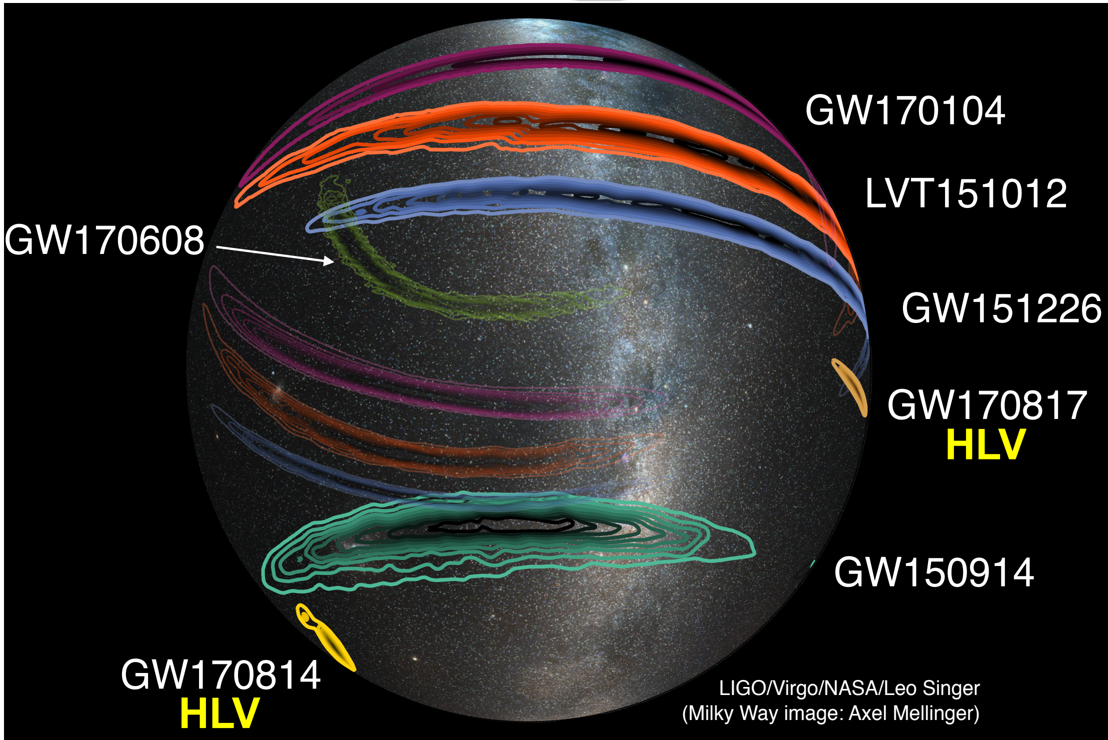
Source location of GW170814 inc. distance

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**





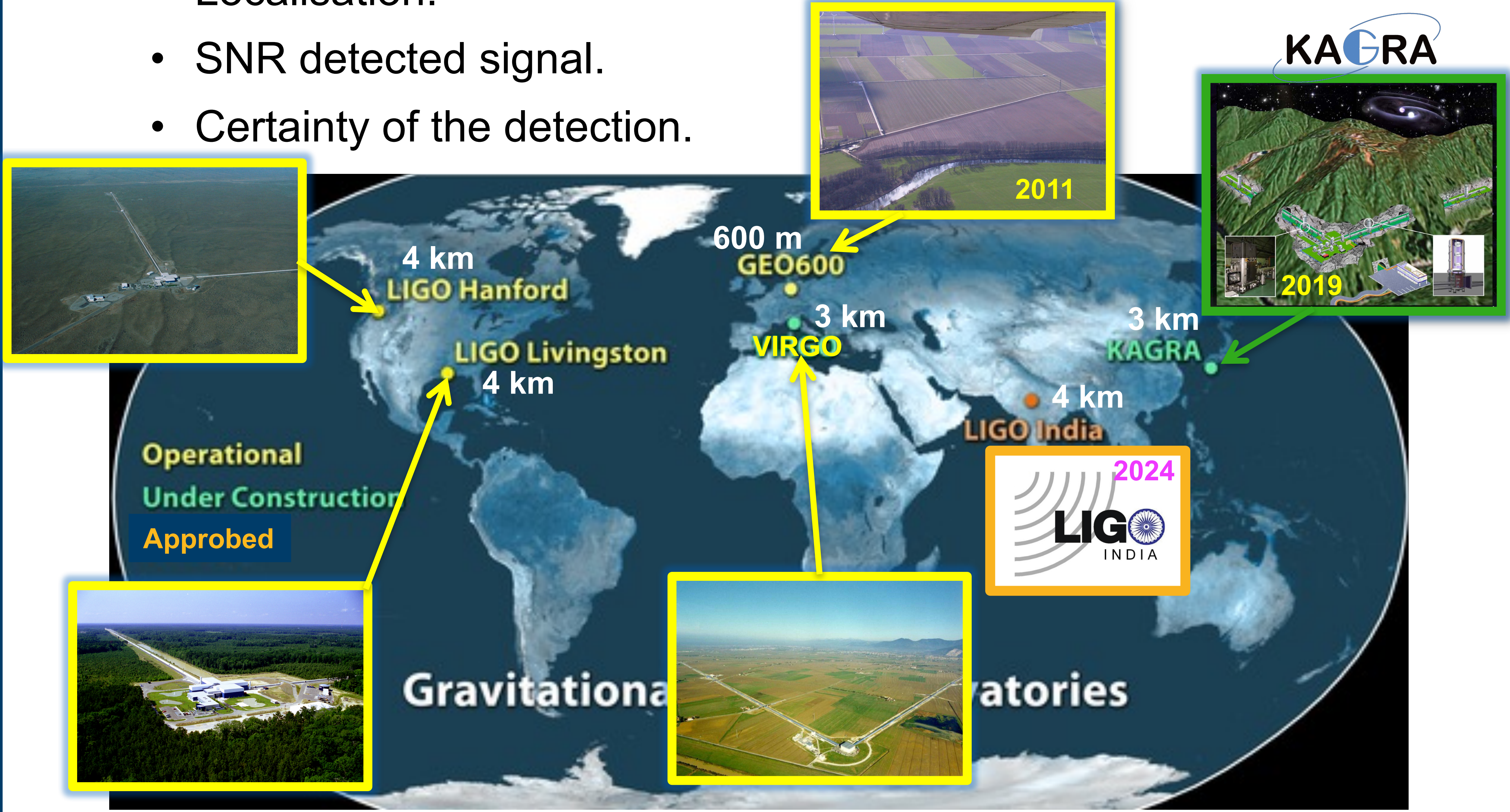


LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

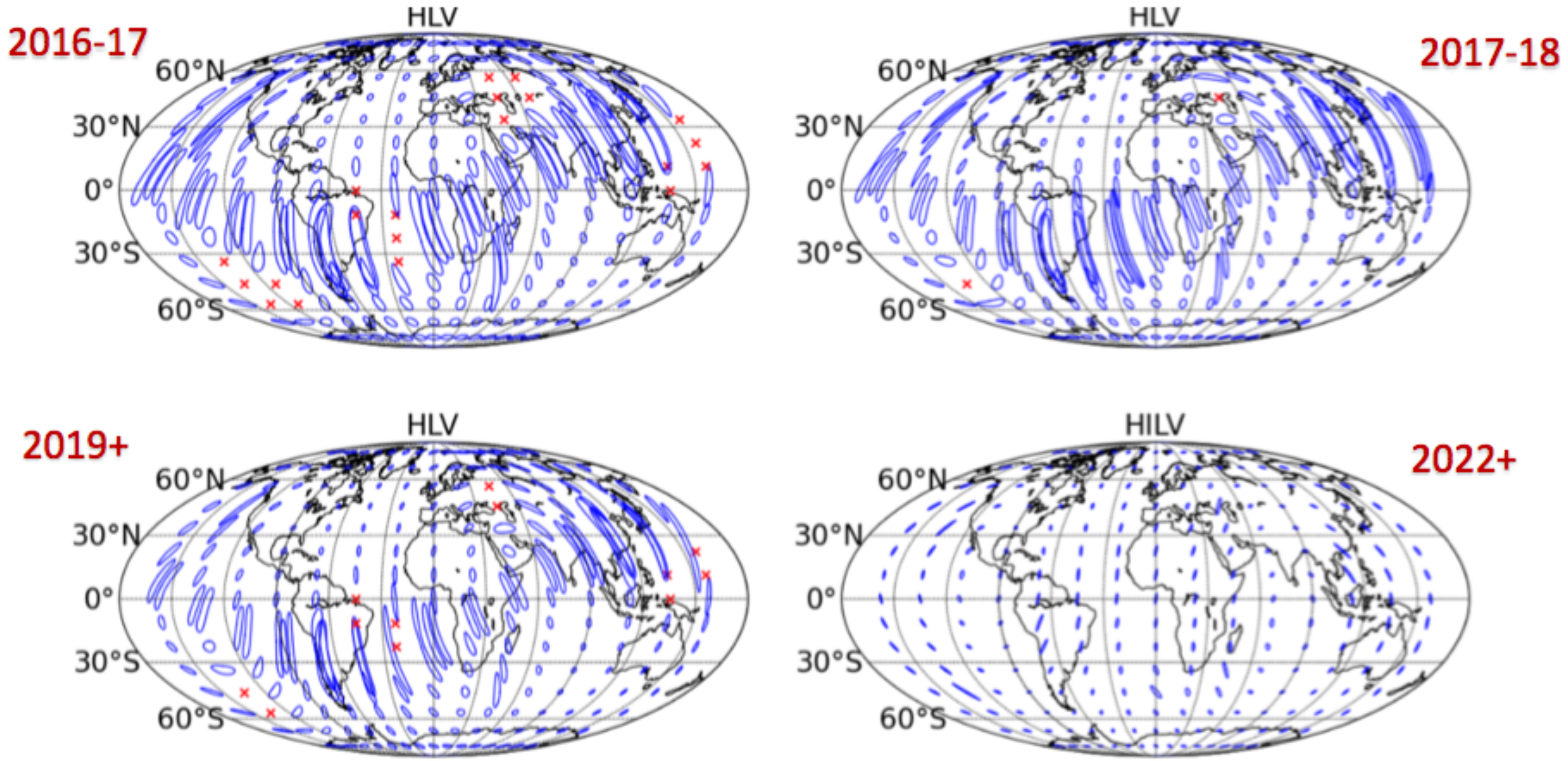
Global network of detectors

A global network of detectors improves:

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



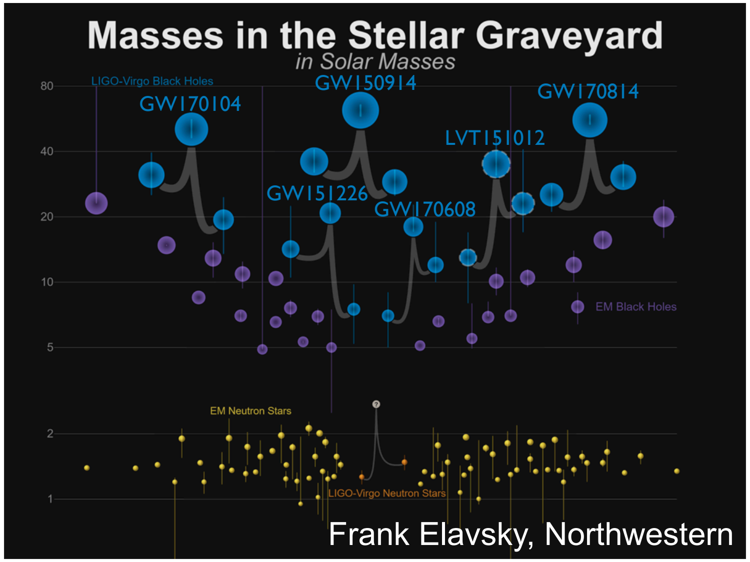
Global network of detectors- ‘Localization’



- 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

- 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·Gpc^{-3}yr^{-1}**



Masses in the Stellar Graveyard

in Solar Masses

Frank Elavsky, Northwestern

- 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

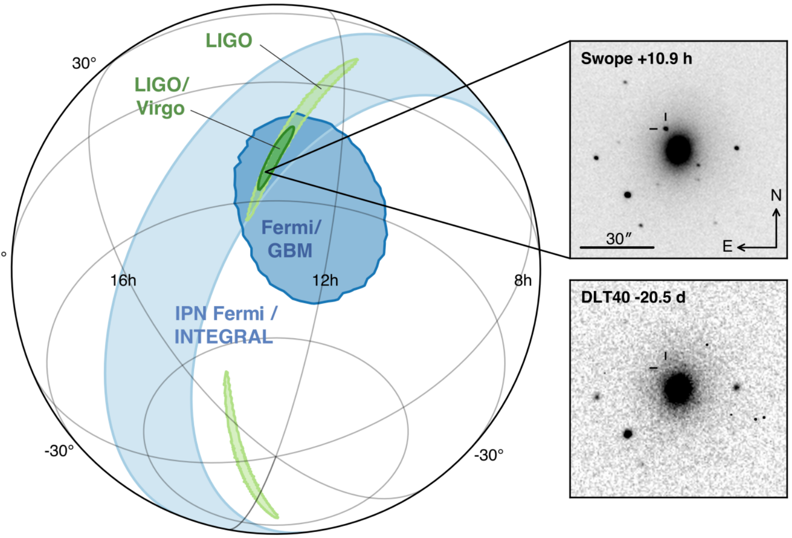
The dawn of multi-messenger astronomy

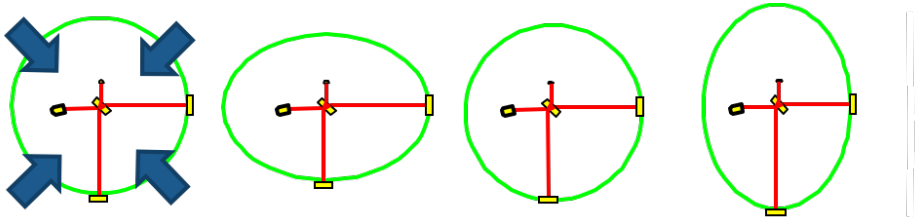
GW170817 – first GW signal of a BNS

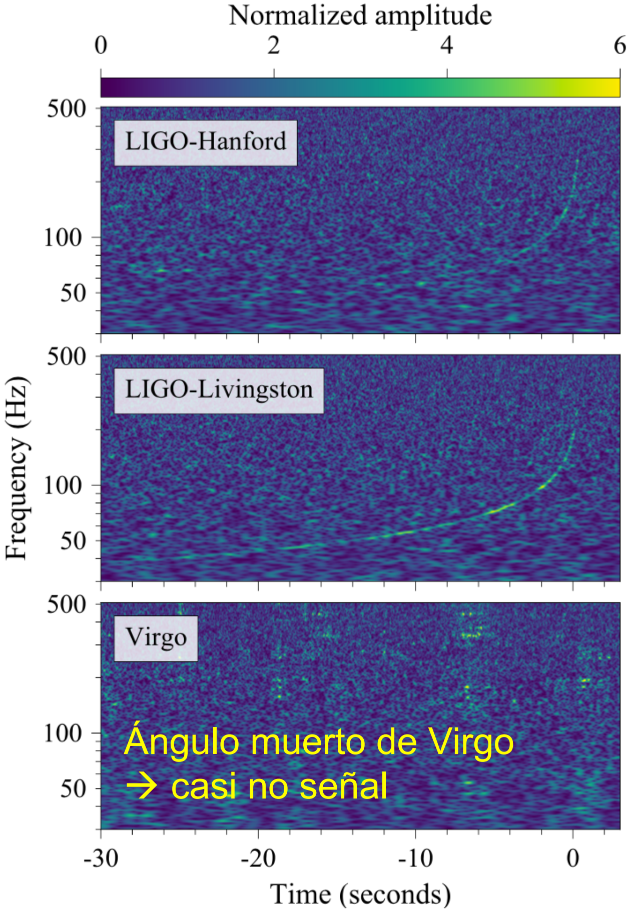
On 17 August 2017, the 2 aLIGO detectors and Virgo observed the GW signal emitted during 100 sec before the merger of two neutron stars. **This time there was an EM counterpart!!!**

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

GW170817 – dawn of multi-messenger astronomy







Ángulo muerto de Virgo
→ casi no señal

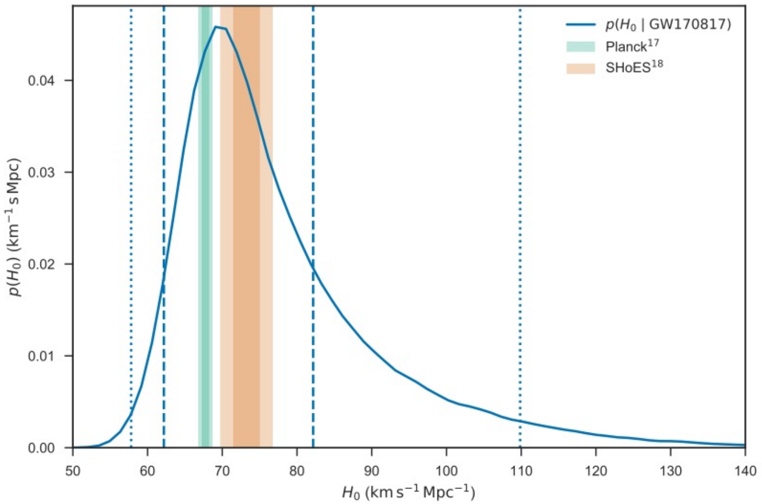
- GW detection provided high precision of sky localization and distance of the source → it allowed exhaustive follow up after the merger, through the whole EM spectrum → Confirm that **kilonova** are associated to BNS mergers.
- Closest source of GW detected, only 100 M light years. The highest SNR signal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

Scientific implications of BNS detection

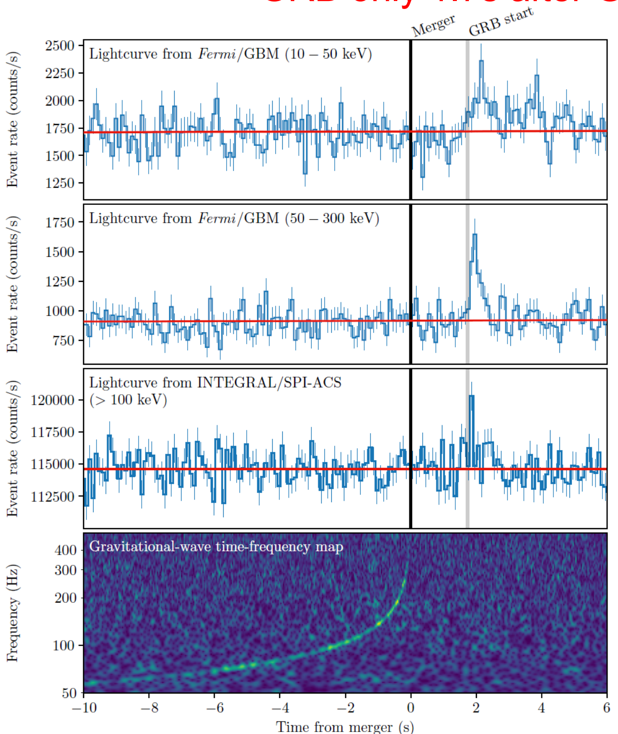
- First evidence that **short-GRB**s associated to **BNS mergers**
- **Kilonova** associated to **BNS mergers** → source of elements heavier than iron
- **'Standard sirens'**→ measure **Hubble constant** independent from *cosmic distance ladder:*

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

- 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** $m_g < (\text{few})10^{-23}$ eV/c^2 → ~0
- **BNS merge rate** ~ 330-4500 events·$\mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$



GRB only 1.7s after GW



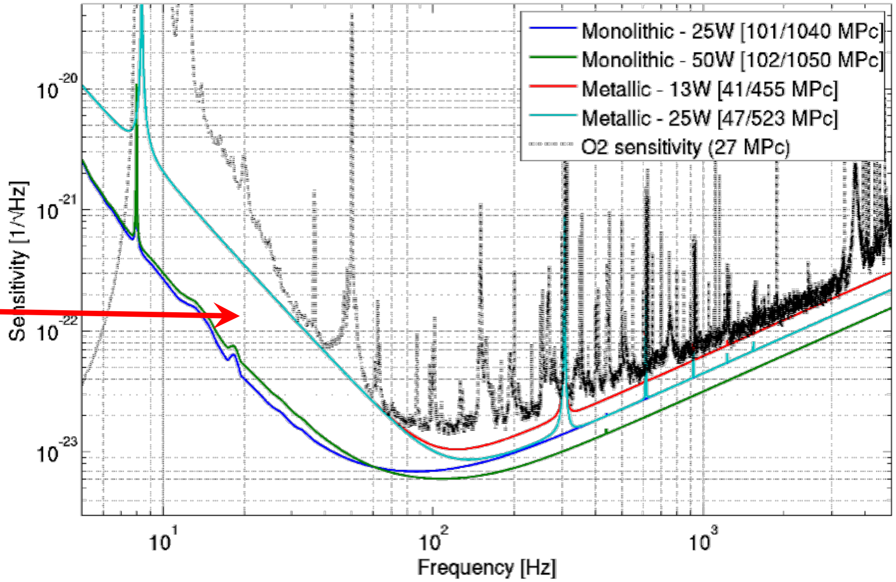
~12 months commissioning

Progress of detectors towards O3

Main Virgo upgrades

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

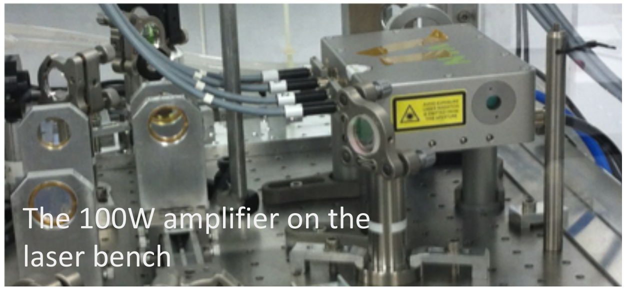
Will boost the low frequency sensitivity.



The AEI squeezer installed in the DET lab

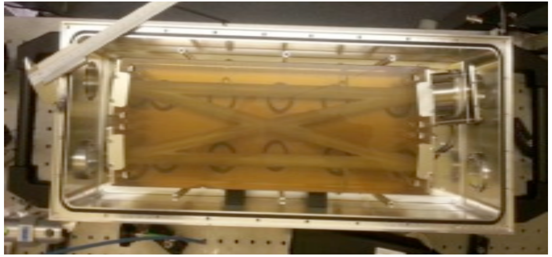
- Installation of GEO squeezer. On-site measured **squeezing**: around 10 dB;

Improves high frequency sensitivity.



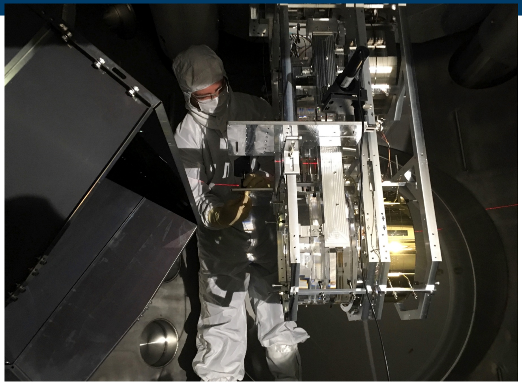
The 100W amplifier on the laser bench

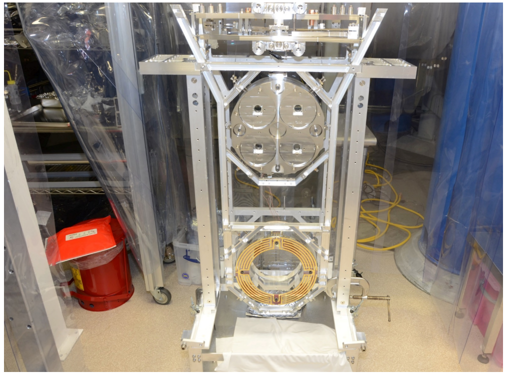
- New high power laser amplifier: delivers up to 60W to interferometer.
- New monolithic pre-mode-cleaner, for high power.



from Brian O'Reilly and Alessio Rocchi, G1800395

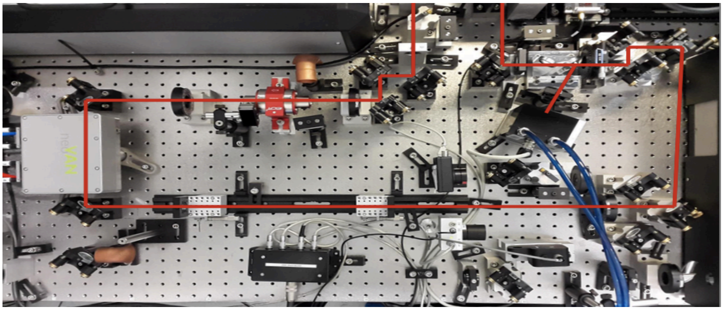
Main aLIGO upgrades





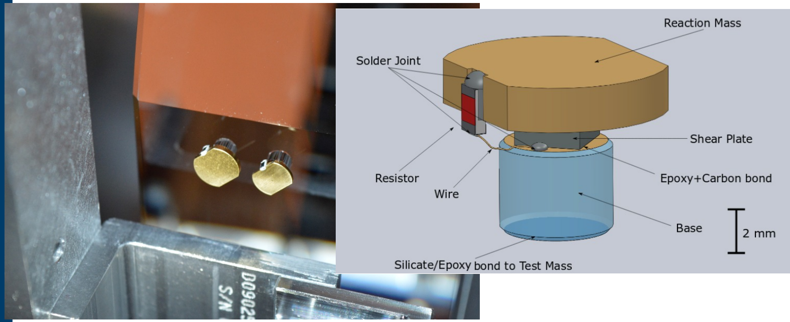
ITMX replacement (LHO), point absorber found on HR side
Affected ability of H1 to operate at higher power.

Also replace ETMs at both detectors.

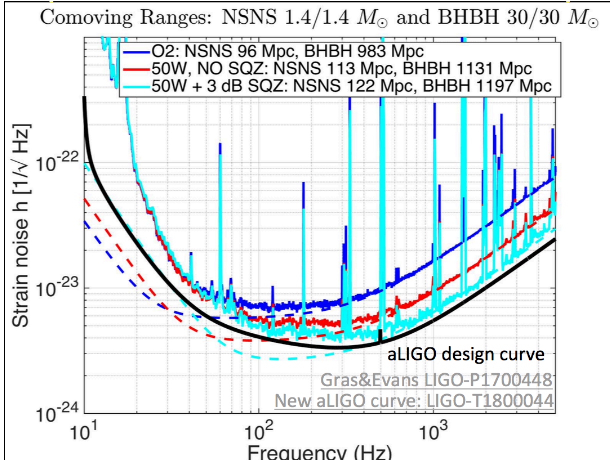


Installation of 70W laser amplifier at both detectors → delivering 50W to interferm.

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



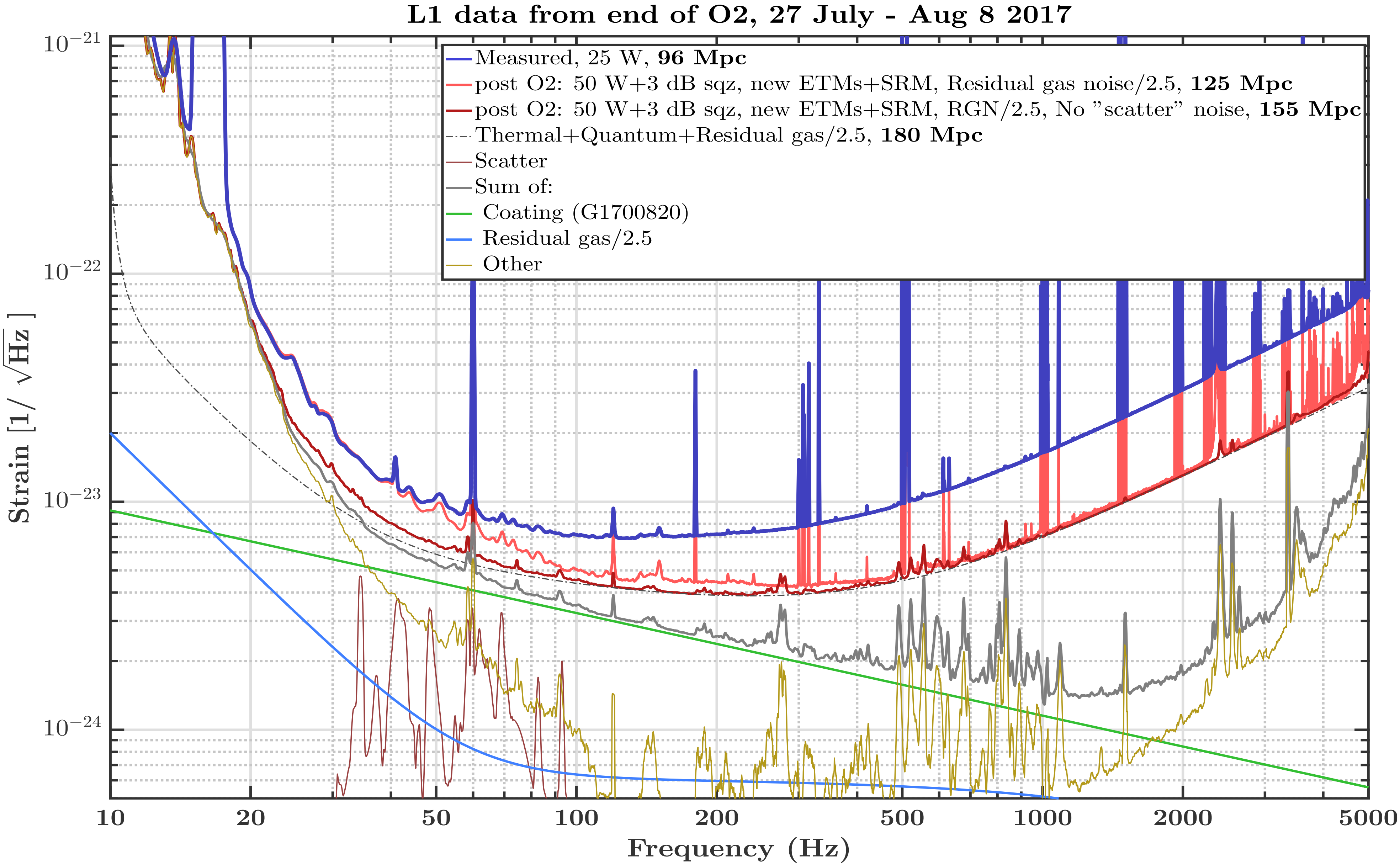
Installing acoustic mode dampers on test masses
Mitigate parametric instabilities at high power



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

Lots of new baffles installed to absorb scattered light

Possible aLIGO noise projection after upgrades



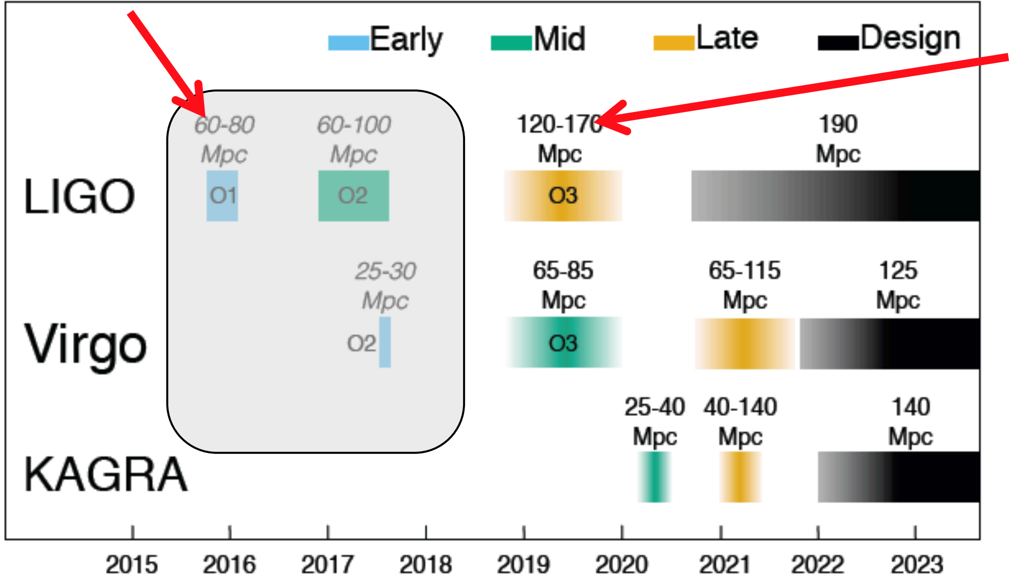
from Brian O'Reilly and Alessio Rocchi, G1800395

Sensitivity timeline and coalescent rates

Living Rev Relativ (2016) 19: 1

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

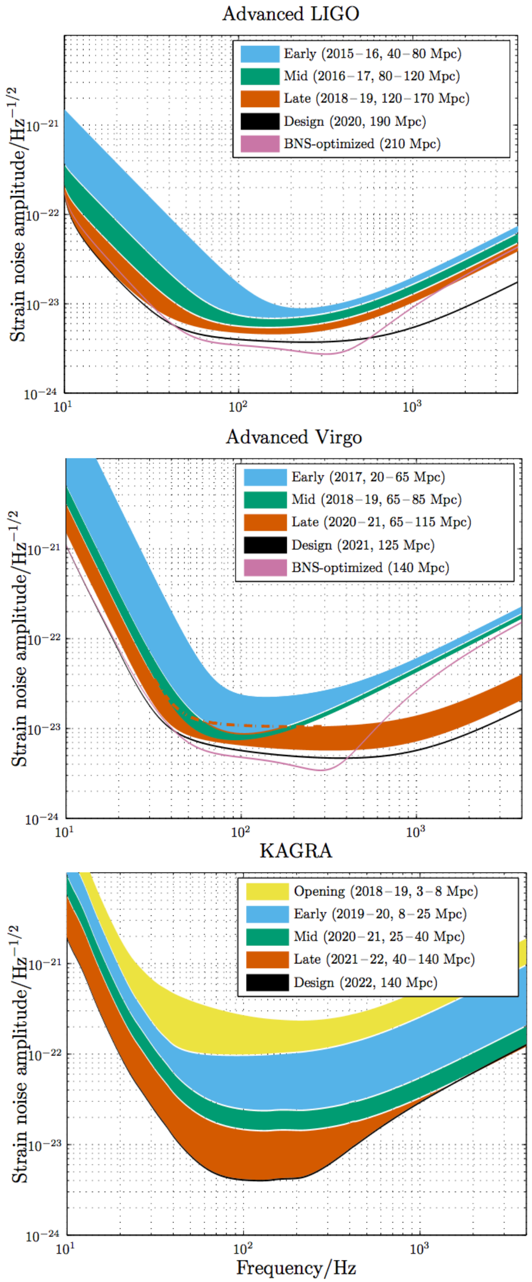
O1 data is public



O3: GW candidates with high confidence public to full astronomical community.

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



Coalescent rates based on observations:

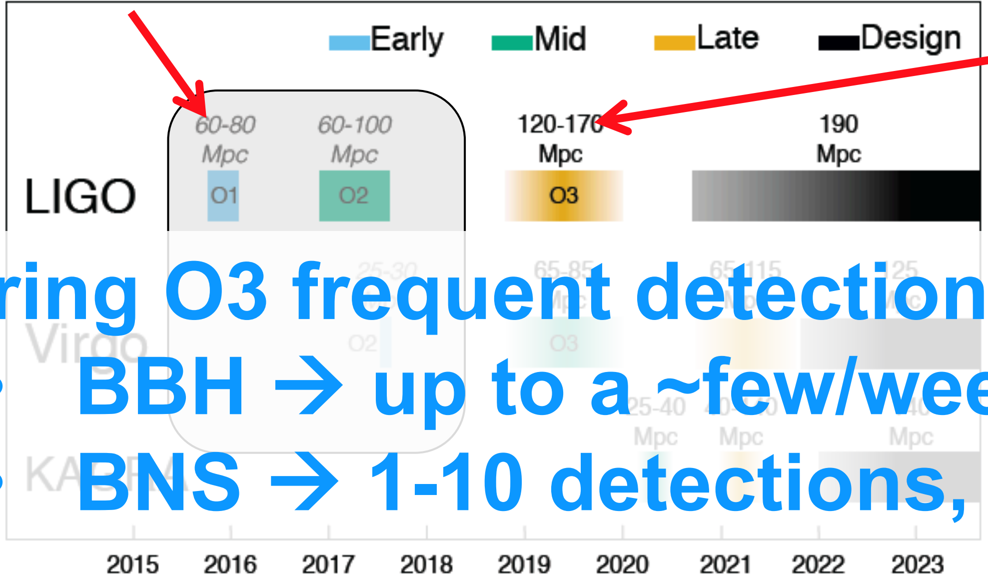
- BNS: post-GW170817 (O1 as prior): R_{BNS}=0.3 – 4.5 Mpc^{-3}Myr^{-1}
- BBH: post-GW170104: R_{BBH}=0.01-0.2 Mpc^{-3}Myr^{-1}

Sensitivity timeline and coalescent rates

Living Rev Relativ (2016) 19: 1

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

O1 data is public



O3: GW candidates with high confidence public to full astronomical community.

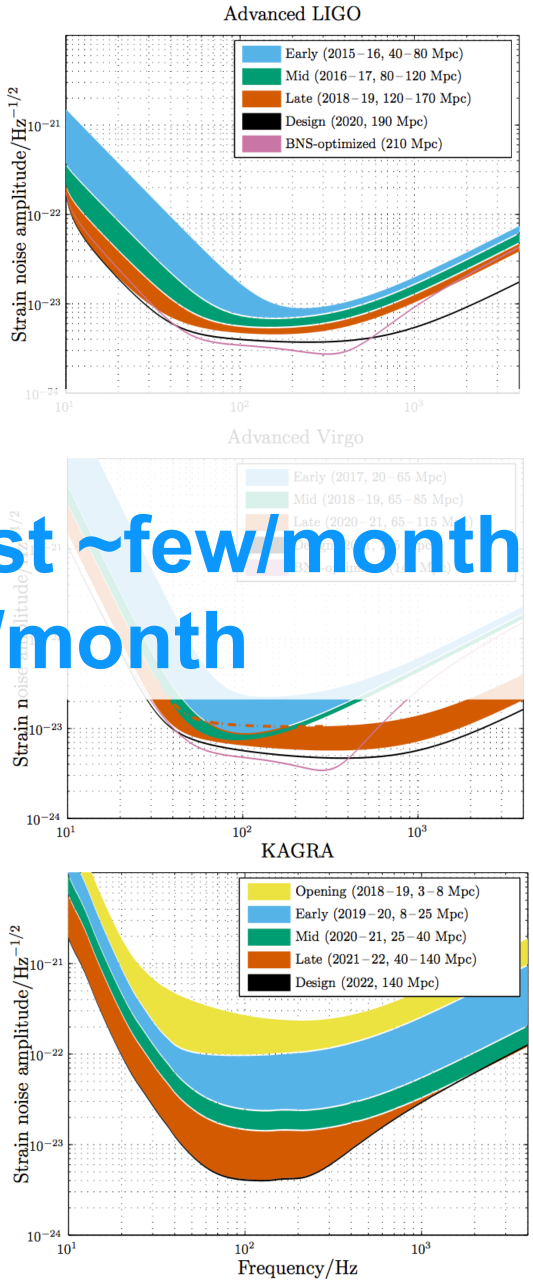
During O3 frequent detections:

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

	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

Coalescent rates based on observations:

- BNS: post-GW170817 (O1 as prior): R_{BNS}=0.3 – 4.5 Mpc^{-3}Myr^{-1}
- BBH: post-GW170104: R_{BBH}=0.01-0.2 Mpc^{-3}Myr^{-1}



Enhanced 2G

Motivation for upgrades to 2nd gen. detectors

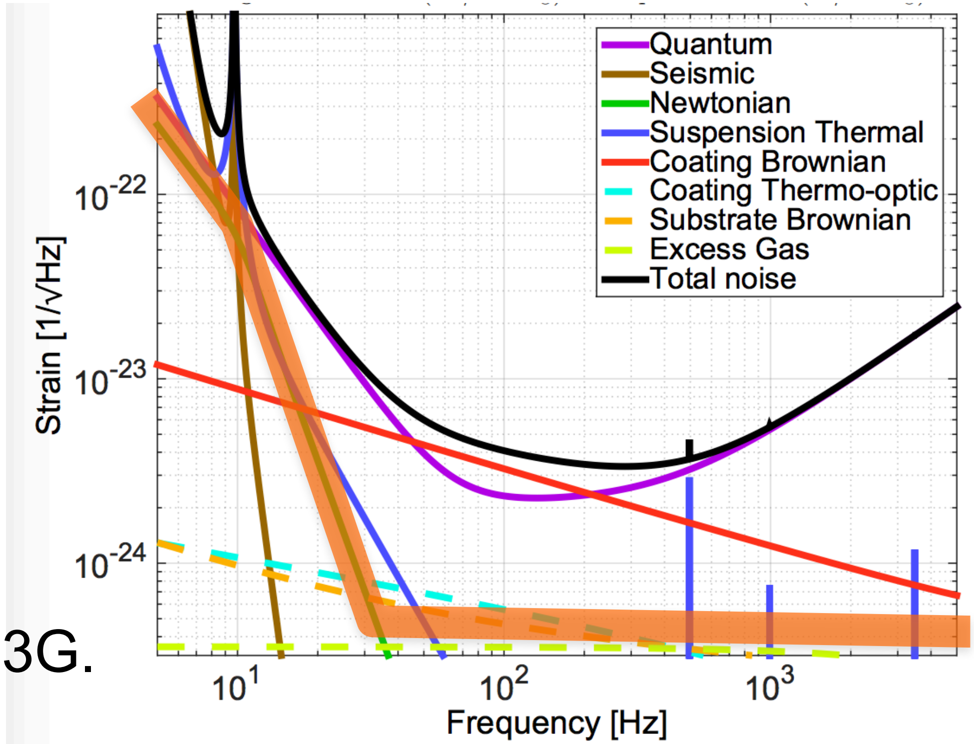
- Increasing sensitivity improves detection SNR, detection rate, range, localization, and likelihood of witnessing rare sources.

- 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.

aLIGO design sensitivity

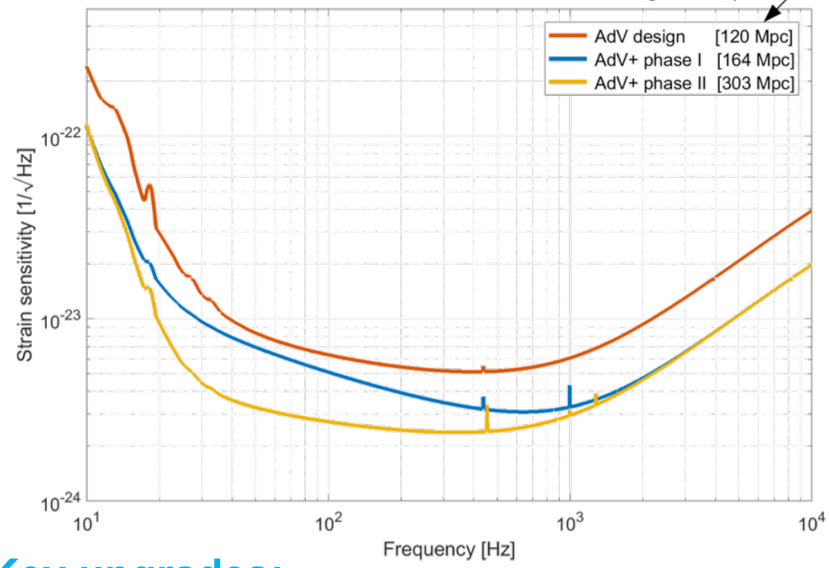


Enhanced 2G sensitivity increase

- Upgrades mainly target quantum and coating thermal noise.

AdV+ Upgrade in 2 phases: Starts 2020 → observing 2024. Cost ~€30M

from J. Degallaix (G1800999)



Key upgrades:

Add signal recycling & ↑ laser power (200W): 120 Mpc

P1 Freq. dependent squeezing (8dB, 300m FC): 150 Mpc

QN Newtonian noise cancellation (seismic sensors network): 160 Mpc

P2 Larger mirrors (105 kg): 200-230 Mpc

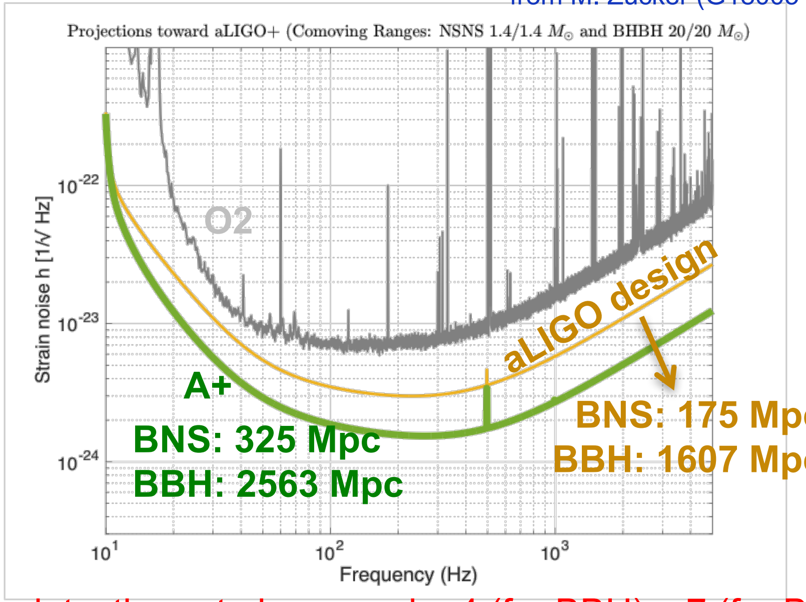
TN Improved coatings (↓ coating TN by 3): 260-300 Mpc

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

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

Science case

Enhanced 2G – Science case

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

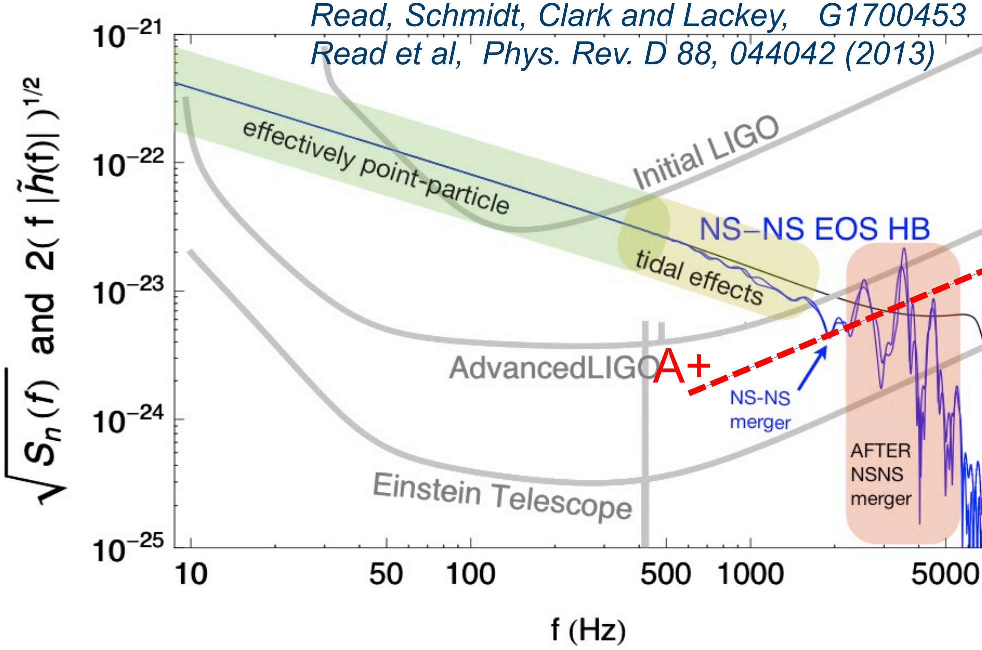
BNS

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 to 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

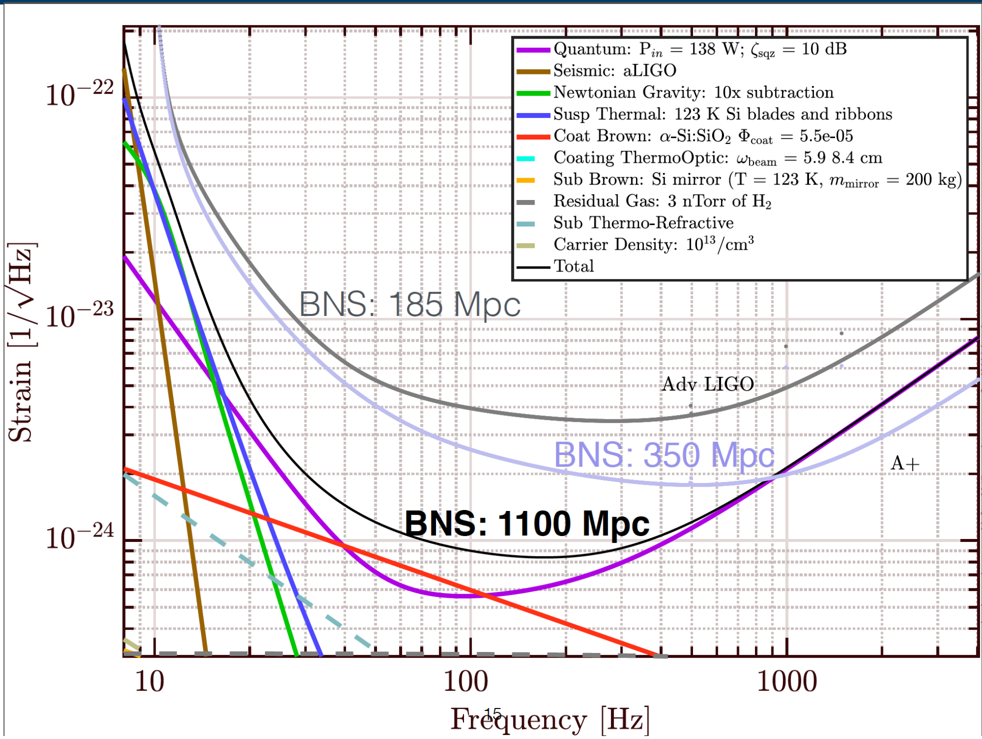
Understand BBH progenitor population and origins:

- 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 – Ultimate sensitivity LIGO sites can deliver

- New detector on existing facilities → Pre 3G
- Medium cost upgrade ($50M to $100M), proposal ~2025(?) commissioning ~ 2030(?).
- It mitigates A+ limiting noise by:
  - Cryogenic operation: 123K (radiative, non-contact cooling)
  - Silicon test masses: 200kg, 45cm dia., mCZ process
  - Coatings: a-Si/SiO$_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.

B. Sorazu – SUSY18 (Barcelona, 27 July 2018)

Instrument Science whitepaper – T1800133

3G

ET & Cosmic Explorer

3G: Where does the community want the field to be in the next one to two decades?

- **Case for proposing a 3G detector never as good as next few years**
- **Gravitational Wave International Committee (GWIC) has launched an effort to develop a science case for 3G**
- Has established a dialog with global agencies counterpart – Gravitational Wave Agencies Correspondents (GWAC)
- **Science case is the 1st priority for a 3G detector case …**

  What is the compelling science beyond the 2nd generation instruments?

  What capabilities are required beyond the 2nd generation instruments?

  What will the network of detectors look like?
- **Conditioned by the other realities …**

  What will the network cost?

  How many detectors? Where?

  How will the overall construction & operation be organized for success?
- **International planning & coordination**

  In US, NSF indicated that doesn't want to undertake enterprise independently.
- **Support & advocacy from broader scientific community**

  GW science adds to their science (astronomers, nuclear physicists,…)

Excerpted from D. Reitze Amaldi 12 Town Hall meeting

ET – European 3G detector proposal

- ET conceptual design study May 2008 – 2011 (originally France, Germany, Italy, Netherlands and UK, later joined Hungary, Poland and Spain)
- ET Collaboration now forming (letter of intent released: http://www.et-gw.eu/index.php/letter-of-intent)

- APPEC strongly supports ET.
- ET timeline:

2018: Transform ET community into ET collaboration

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

2021-2022: Decision on site location

2025: Beginning of construction work

2029: Operating

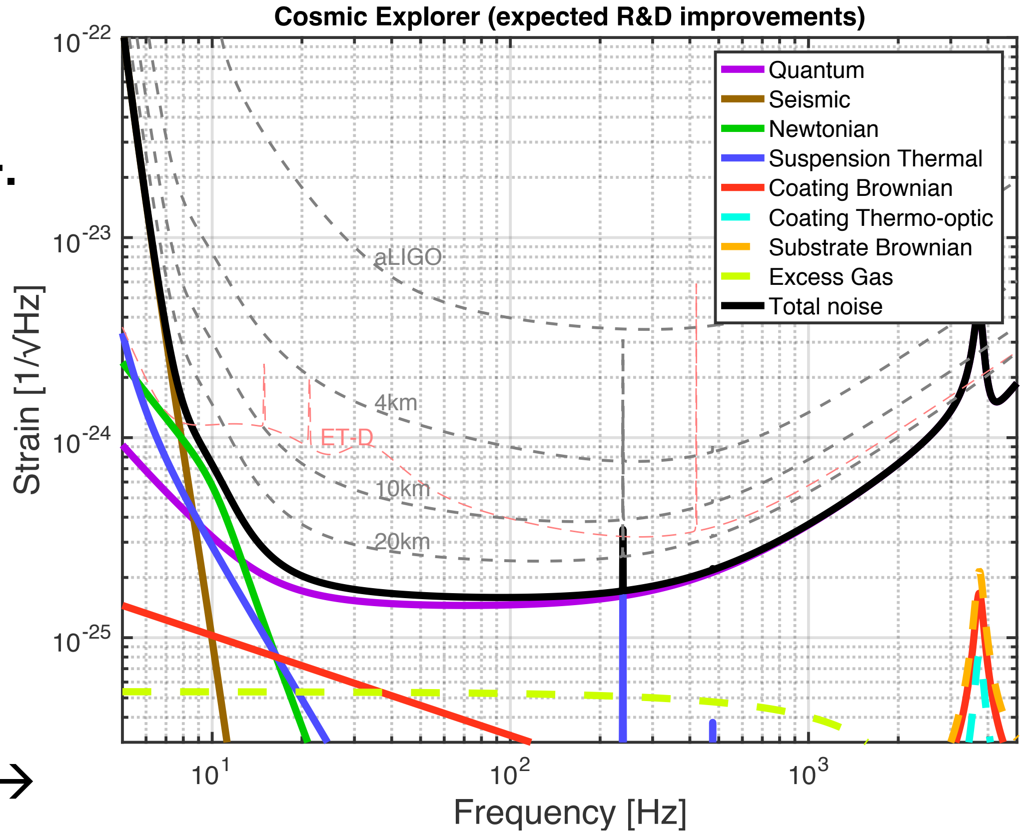
Cosmic Explorer – US 3G detector proposal

Target sensitivity: 10 times better than A+.

The target design is essentially a 40km Voyager

Still R&D needed

- Making the interferometer longer means bigger beams (by at least x2)
- more massive mirrors (factor ~10)
- their curvatures are larger (flatter), which impacts contrast and alignment.
- Arm tubes expensive → limited diameter → scattering
- 4kHz FSR → frequency servo implications

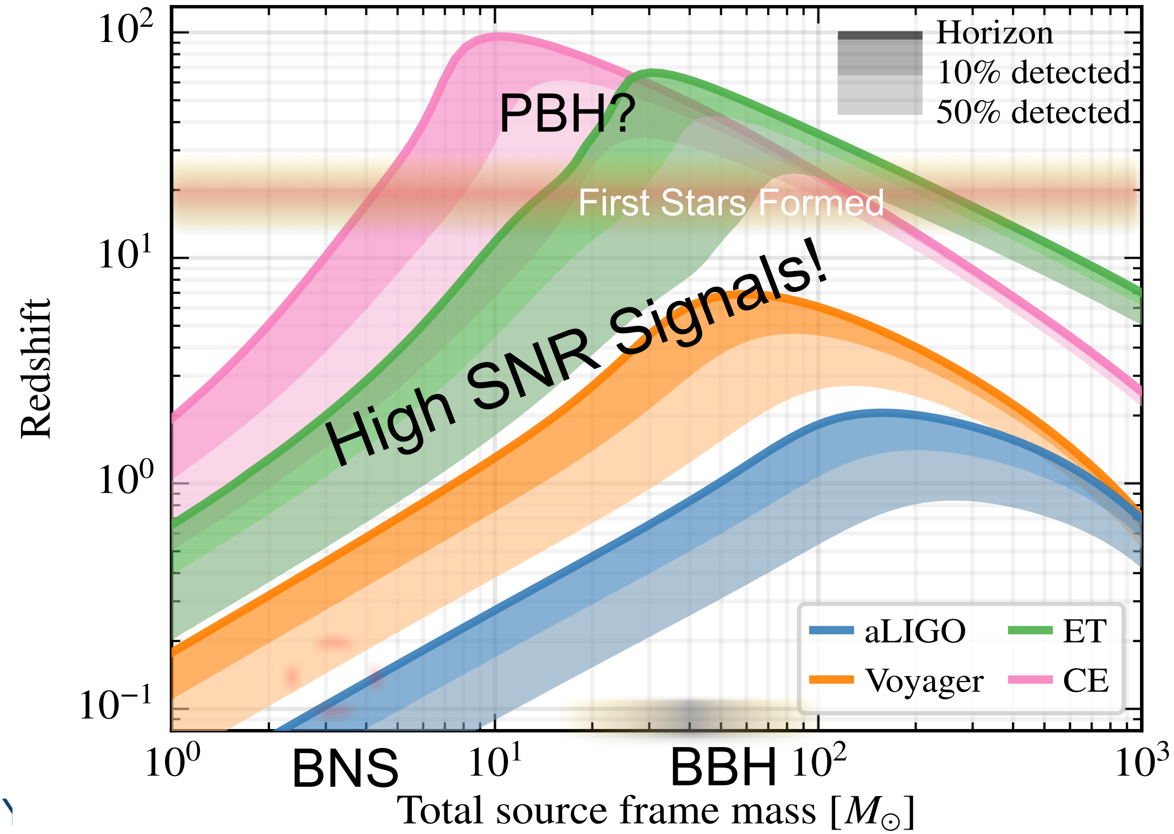


Exploring the sensitivity of next generation gravitational wave detectors (2017) CQG 34, 044001

from M. Evans– GWADW 2018

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.



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)

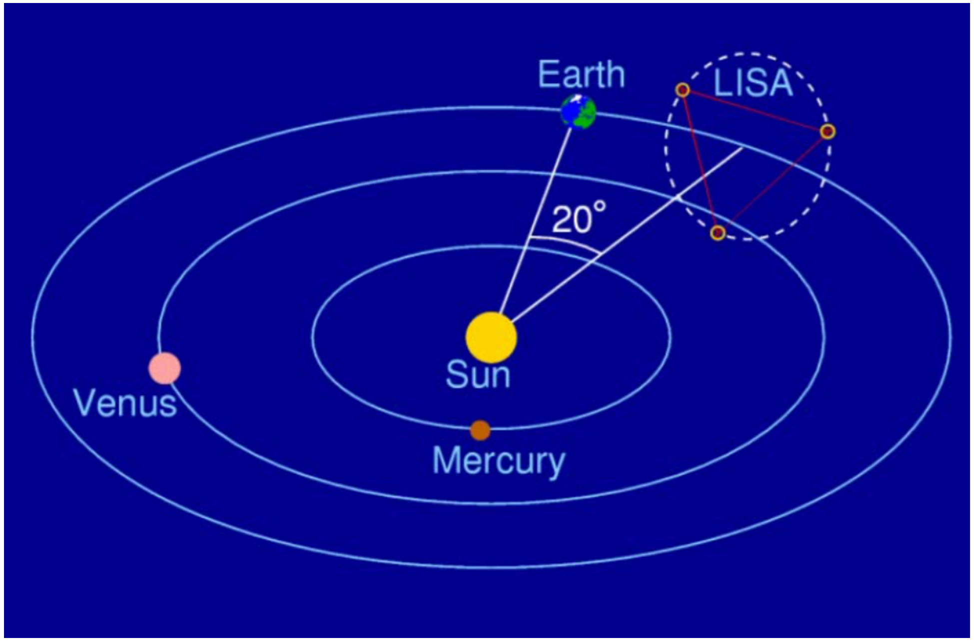
Cosmology:

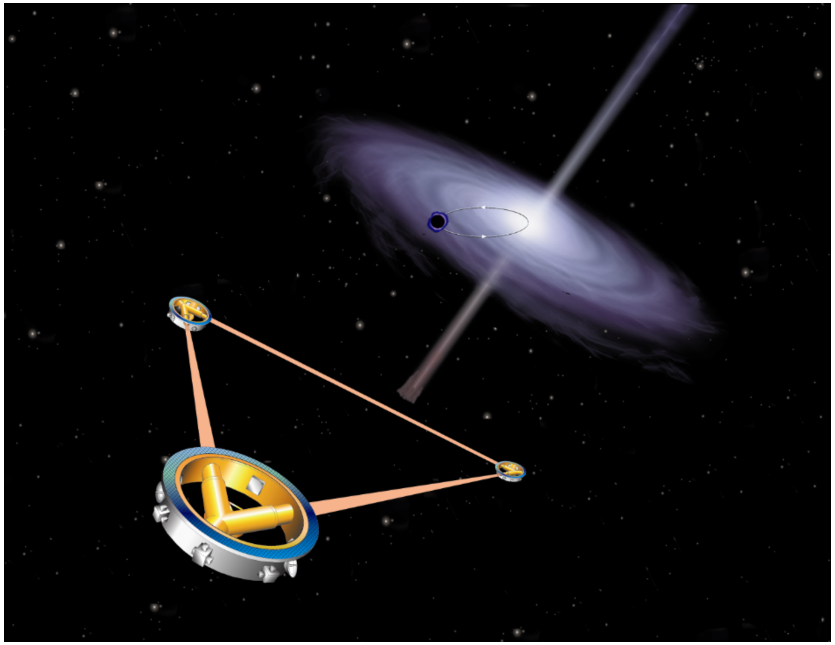
- Measure Hubble constant and dark energy equation of state with standard sirens.

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 expected 2034.

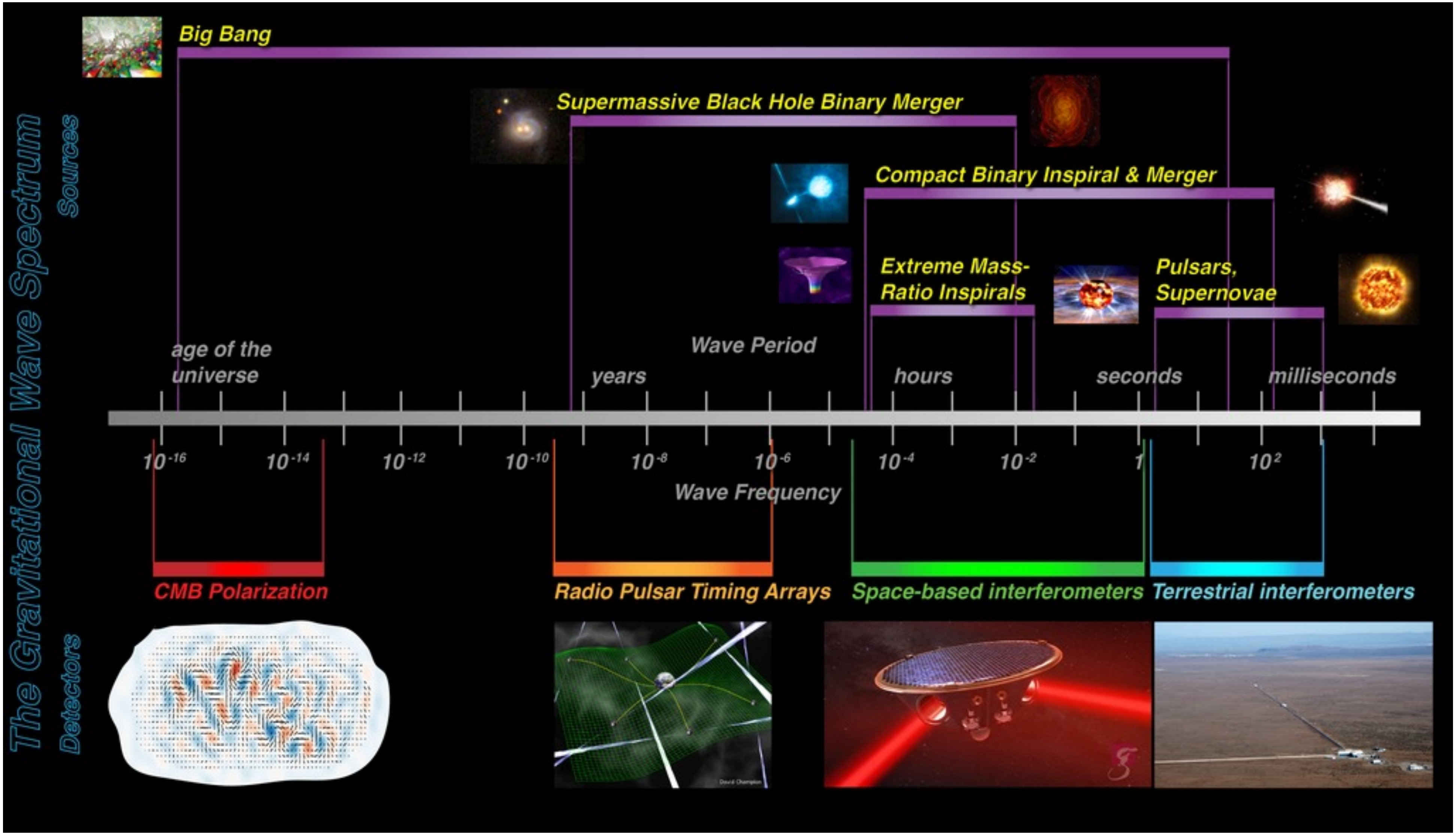
www.elisascience.org





From Steve Detweiler

GWs frequency spectrum

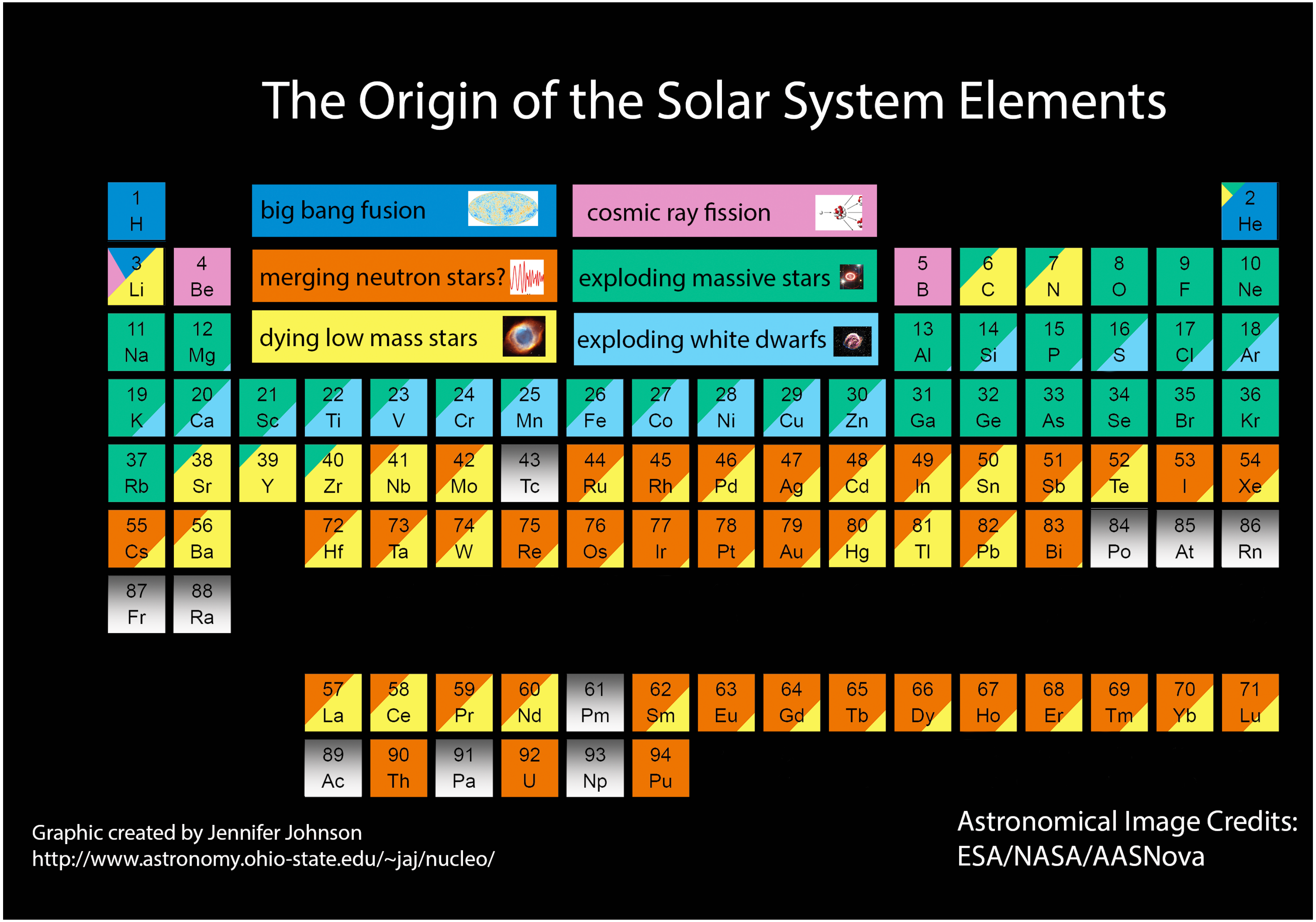


Thank you for your attention

Questions?

Other slides

GW170817 – Kilonova



The Origin of the Solar System Elements

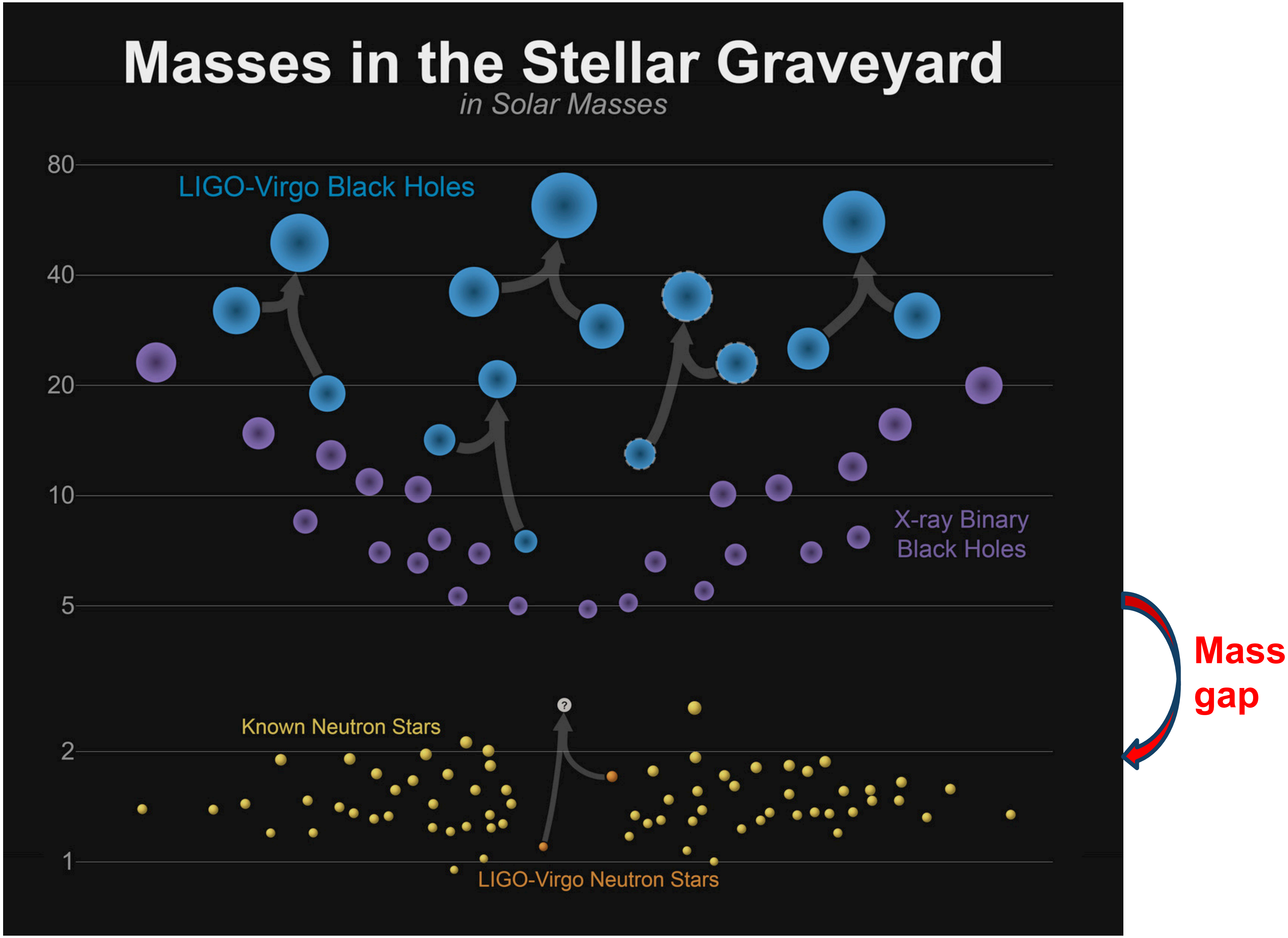
big bang fusion
cosmic ray fission
merging neutron stars?
exploding massive stars
dying low mass stars
exploding white dwarfs

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

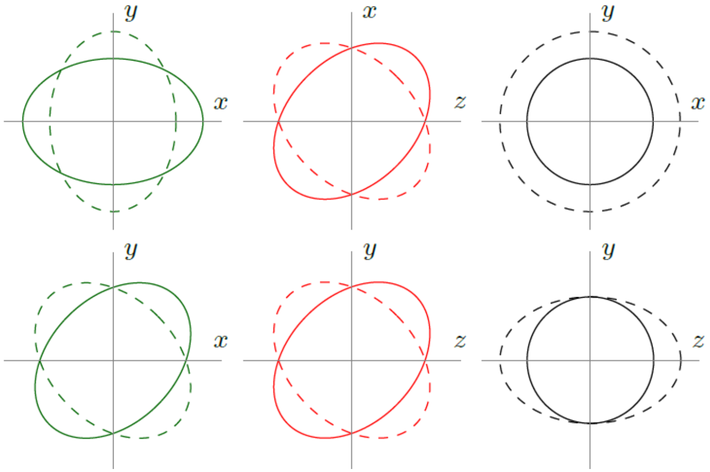


Polarization of gravitational waves

- **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



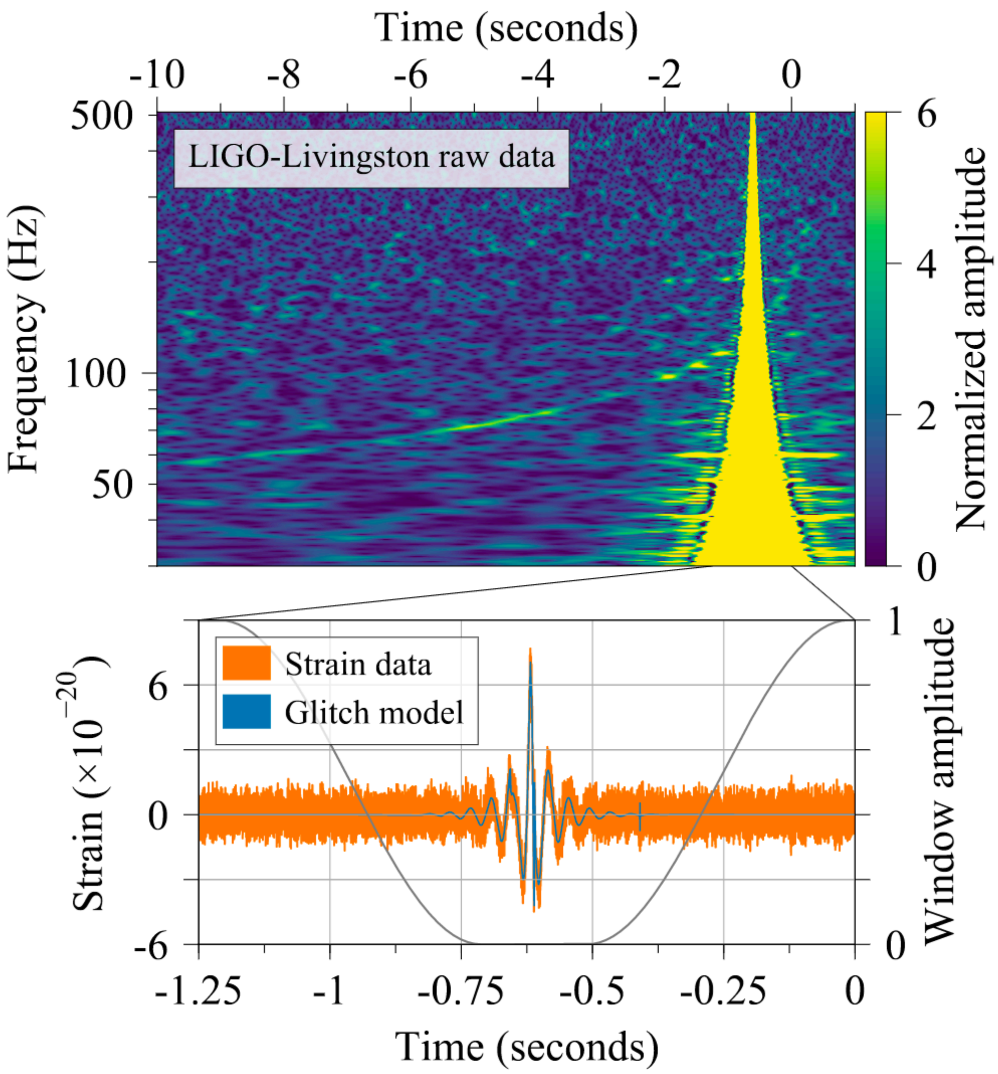
Theory	+	x	x	y	b	l
General Relativity	🟩	🟩	🟥	🟥	🟥	🟥
GR in noncompactified 4/6D Minkowski	🟩	🟩	🟩	🟩	🟩	🟩
Einstein-Æther	🟩	🟩	🟩	🟩	🟩	🟩
5D Kaluza-Klein	🟩	🟩	🟩	🟩	🟩	🟥
Randall-Sundrum braneworld	🟩	🟩	🟥	🟥	🟥	🟥
Dvali-Gabadadze-Porrati braneworld	🟩	🟩	🟨	🟨	🟨	🟨
Brans-Dicke	🟩	🟩	🟥	🟥	🟩	🟩
f(*R*) gravity	🟩	🟩	🟥	🟥	🟩	🟩
Bimetric theory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

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

🟩 allowed / 🟨 depends / 🟥 forbidden

from Jo van den Brand

GW170817 – Glitch in LLO



- Instrumental Glitch, due to breve (5ms) saturations of DAC that provides control signal to the position of the test masses.
- Easy to remove after identifying and characterising type of glitch:
  - Fast analysis, detection: remove the time interval of the glitch (Tukey window).
  - Full analysis, paramater estimation: Glitch model and subtraction.

GW151226 – Match filtering in action

LVC , Physical Review Letters 116, 241103 (2016)

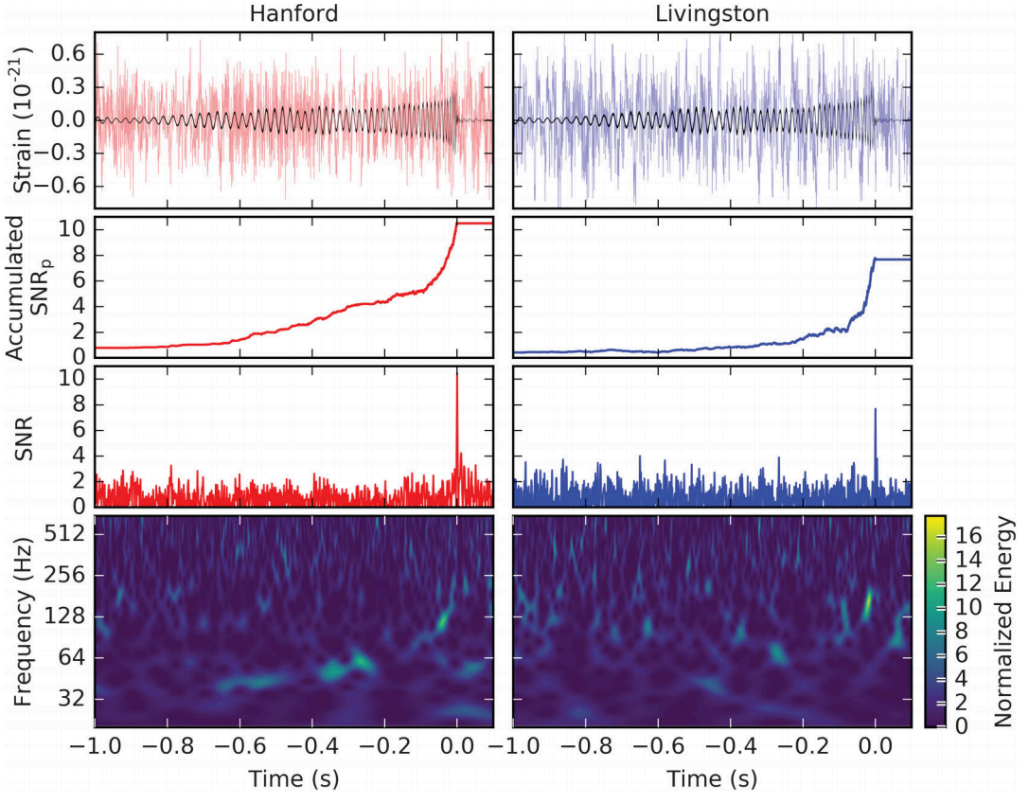


FIG. 1. GW151226 observed by the LIGO Hanford (left column) and Livingston (right column) detectors, where times are relative to December 26, 2015 at 03:38:53.648 UTC. *First row:* Strain data from the two detectors, where the data are filtered with a 30–600-Hz bandpass filter to suppress large fluctuations outside this range and band-reject filters to remove strong instrumental spectral lines [46]. Also shown (black) is the best-match template from a nonprecessing spin waveform model reconstructed using a Bayesian analysis [21] with the same filtering applied. As a result, modulations in the waveform are present due to this conditioning and not due to precession effects. The thickness of the line indicates the 90% credible region. See Fig. 5 for a reconstruction of the best-match template with no filtering applied. *Second row:* The accumulated peak signal-to-noise ratio (SNR$_p$) as a function of time when integrating from the start of the best-match template, corresponding to a gravitational-wave frequency of 30 Hz, up to its merger time. The total accumulated SNR$_p$ corresponds to the peak in the next row. *Third row:* Signal-to-noise ratio (SNR) time series produced by time shifting the best-match template waveform and computing the integrated SNR at each point in time. The peak of the SNR time series gives the merger time of the best-match template for which the highest overlap with the data is achieved. The single-detector SNRs in LIGO Hanford and Livingston are 10.5 and 7.9, respectively, primarily because of the detectors' differing sensitivities. *Fourth row:* Time-frequency representation [47] of the strain data around the time of GW151226. In contrast to GW150914 [4], the signal is not easily visible.

GW151226:
at 03:38:53 UTC

$14M_\odot + 8M_\odot = 21\ M_\odot$

SNR = 13, > 5 sigmas

$E_{\text{radiated}} = 1M_\odot c^2$
in 1 second

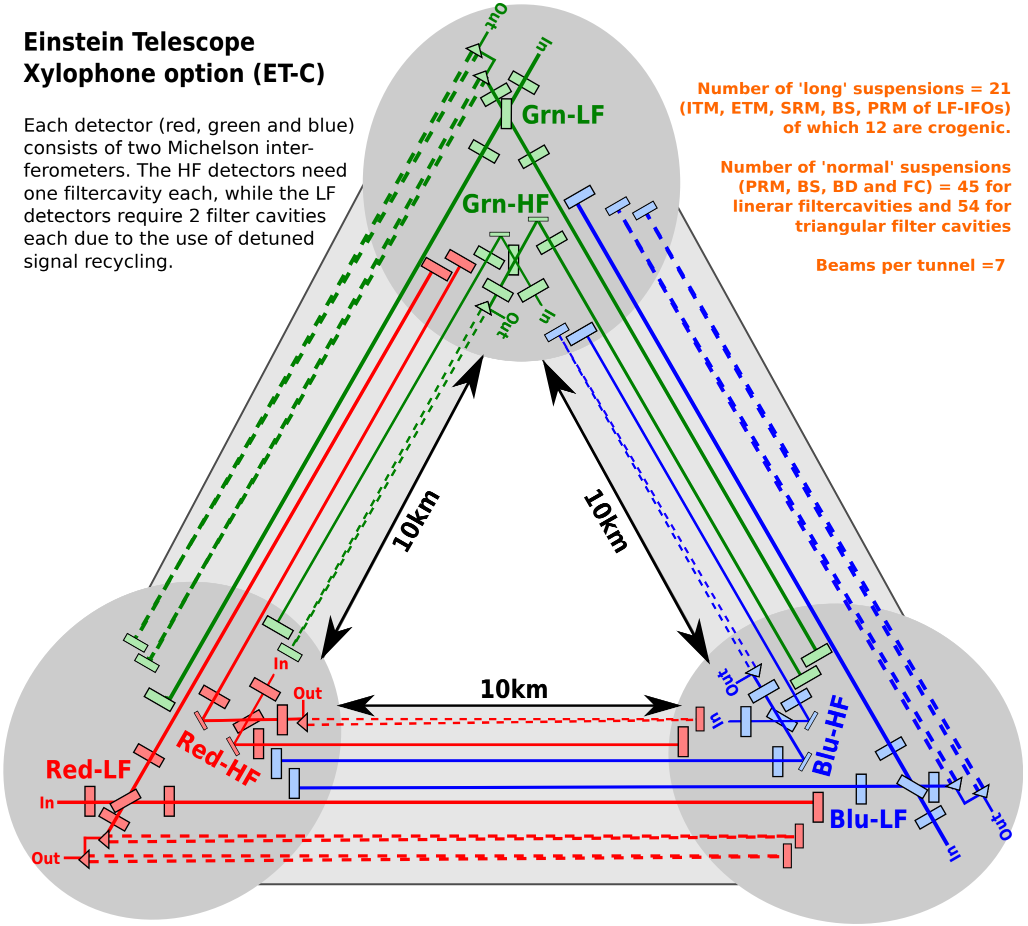
440 Mpc, z=0.09

~1.4 billion light years

ET – European 3G detector proposal

- Start with a single xylophone detector.
- 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).



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

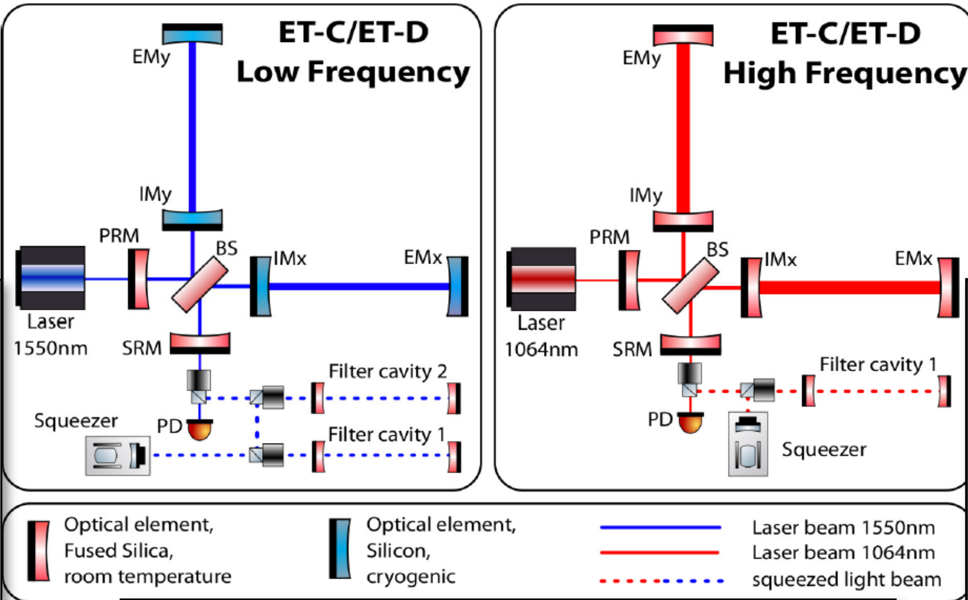
Beams per tunnel =7

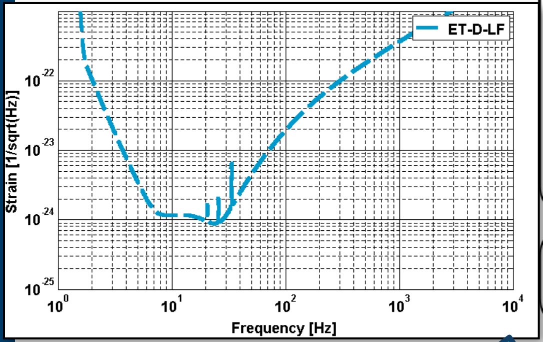
ET – Xylophone approach

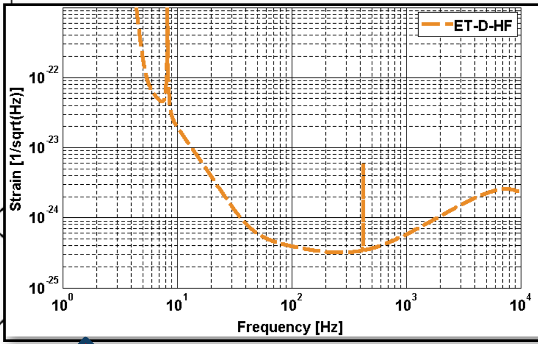
- Split detector into two interferometers optimised at low & high freq. bands:

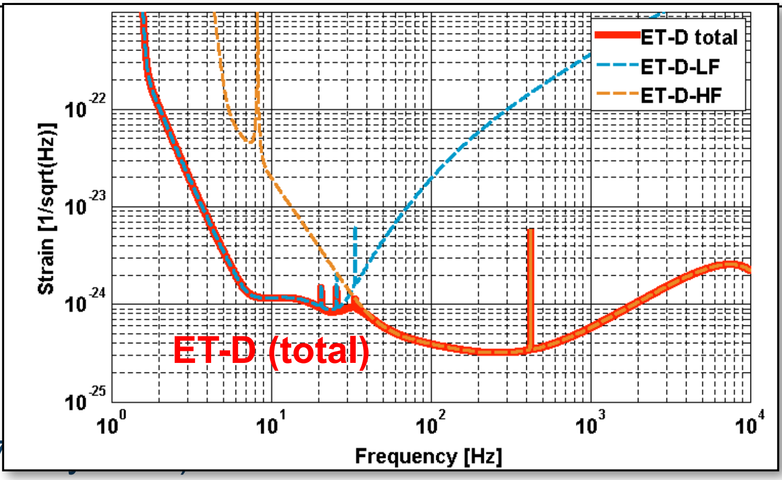
Low Frequencies = Low power & cryogenics
10K, 18kW, 1550nm

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



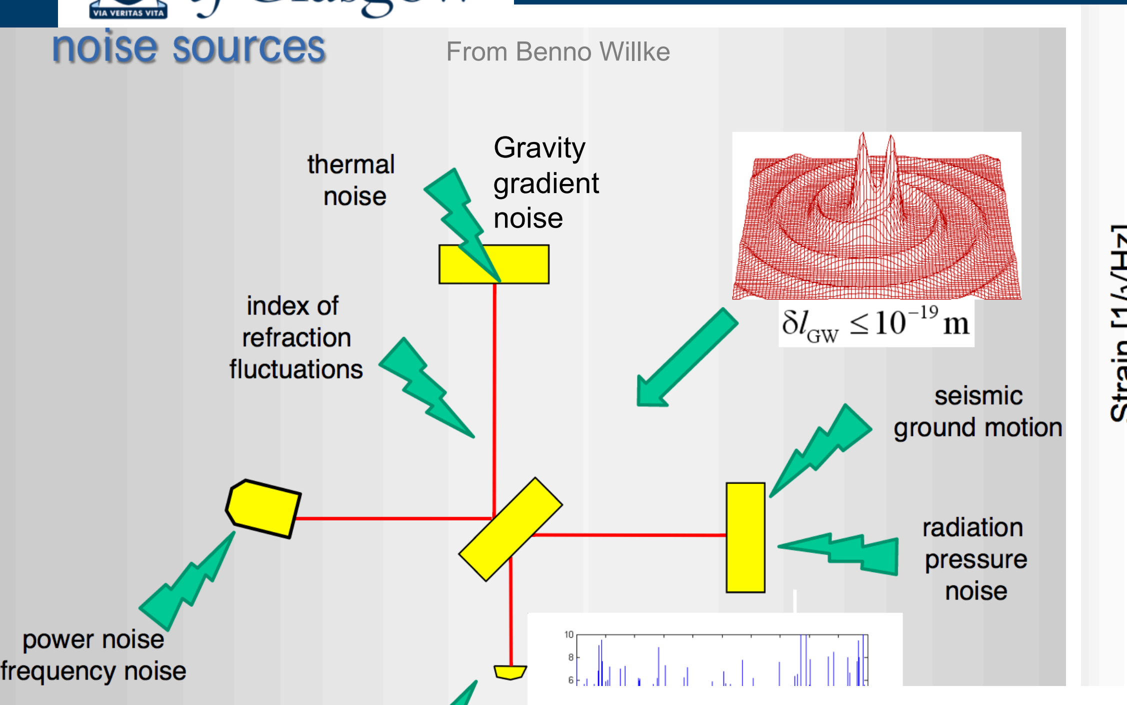






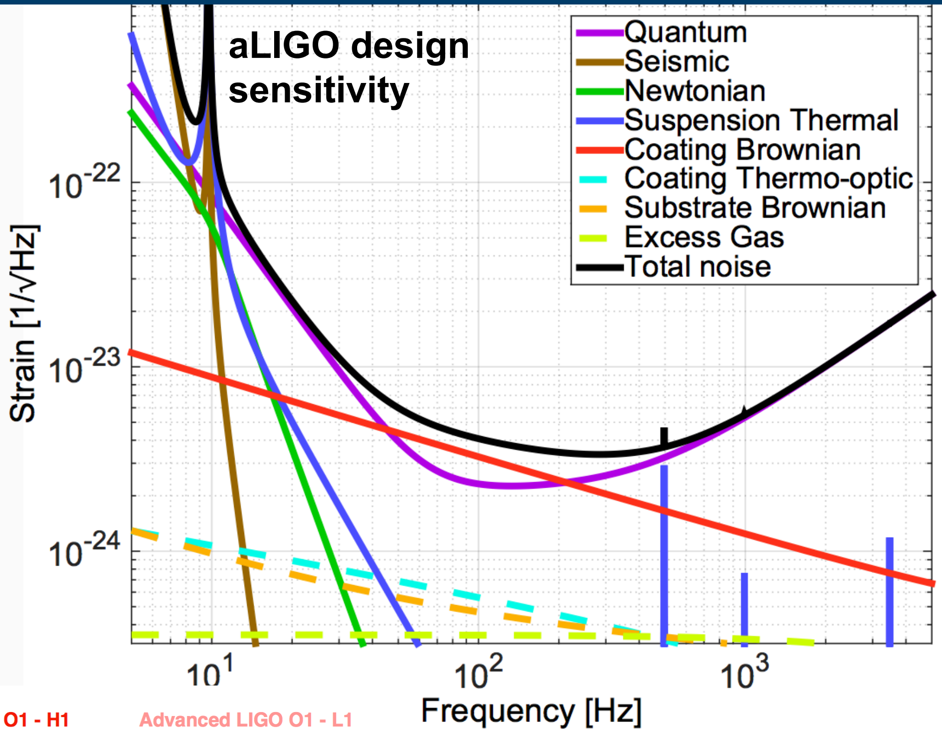
Reducing fundamental noises

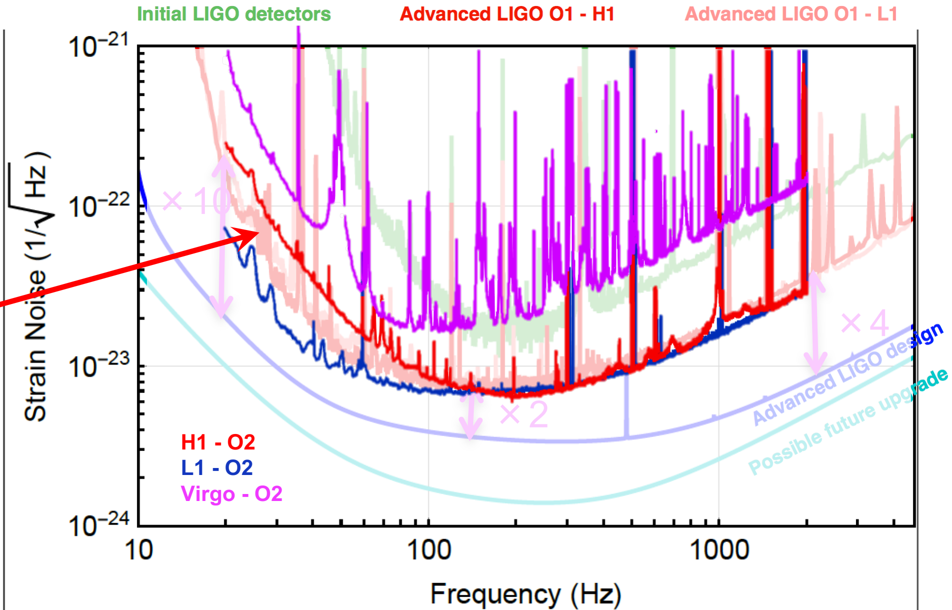
Fundamental noises on GW detectors



noise sources

From Benno Willke





'Technical' noise, worsen during pre O2 commissioning at LHO

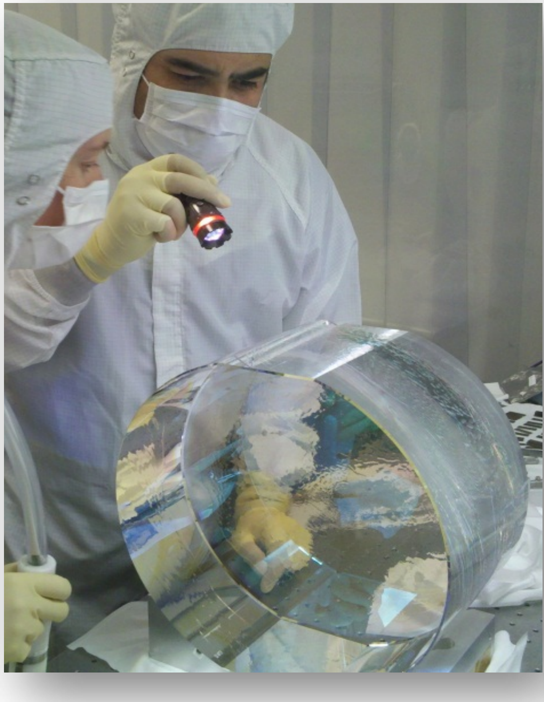
Coating thermal limits between 40 - 200Hz.

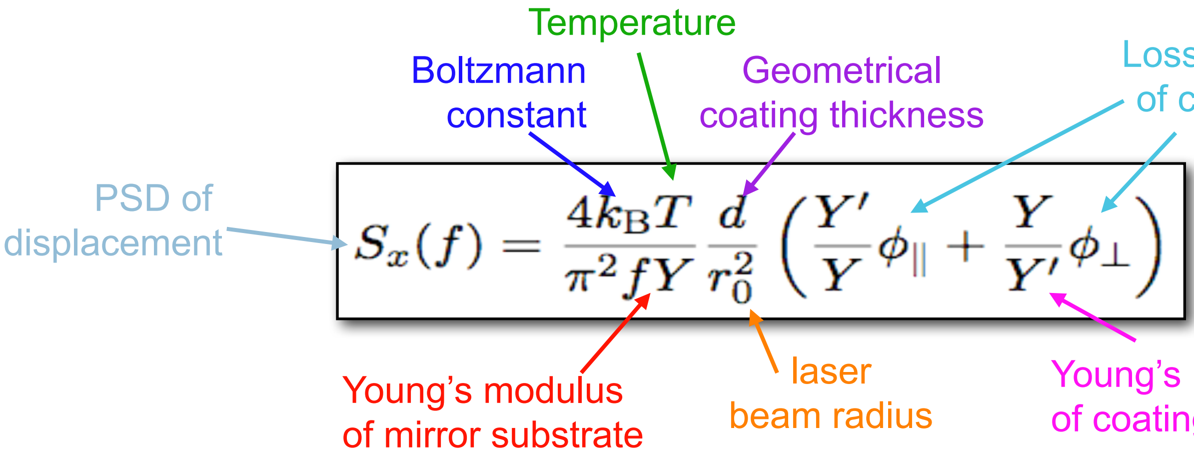
Quantum noise limits at all freqs.

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

What is **mirror thermal noise?**

- Due to **thermal fluctuations,** position of the mirror sensed by the laser beam not good representation of 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 the dominating noise source**:





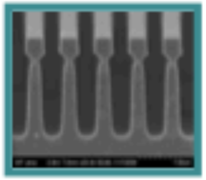
$$S_x(f) = \frac{4k_{\rm B}T}{\pi^2 fY}\frac{d}{r_0^2}\left(\frac{Y'}{Y}\phi_{\parallel} + \frac{Y}{Y'}\phi_{\perp}\right)$$

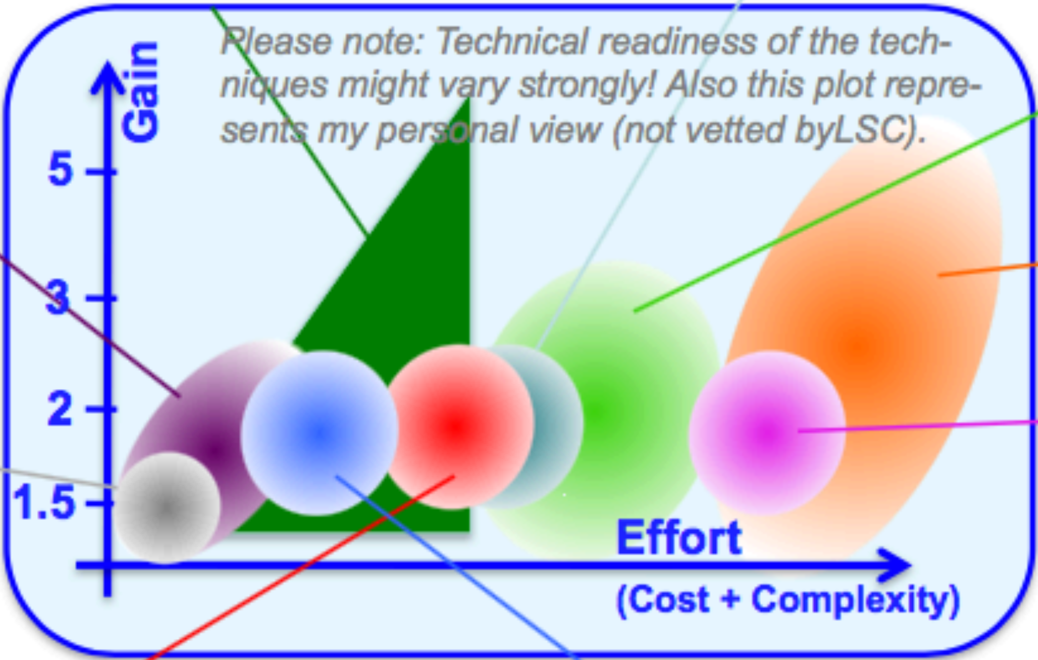
Harry et al, CQG 19, 897–917, 2002

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).

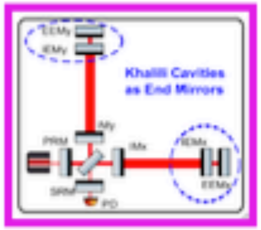
Larger beam size (needs larger mirrors)
Harry et al, CQG 19, 897–917, 2002

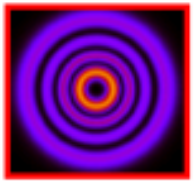
Optimisation (annealing, layer thickness, doping)

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





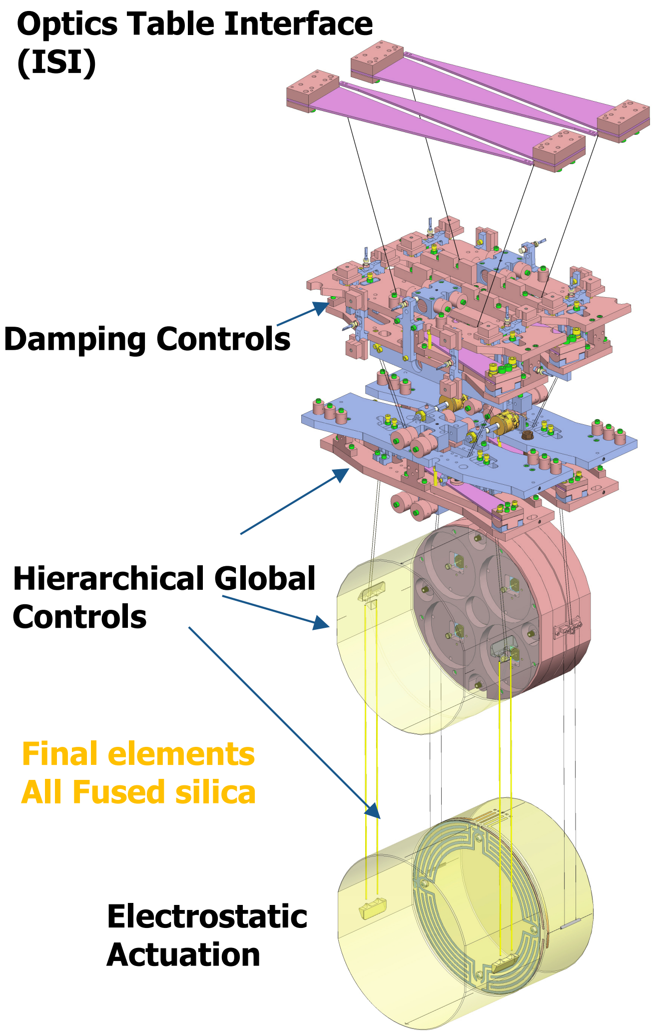
Different beam shape
Mours et al, CQG, 2006, 23, 5777
Chelkowski et al, PRD, 2009, 79, 122002

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

Thanks to S. Hild

Passive Seismic noise reduction

- Test masses suspended on a 4 stage pendulum:

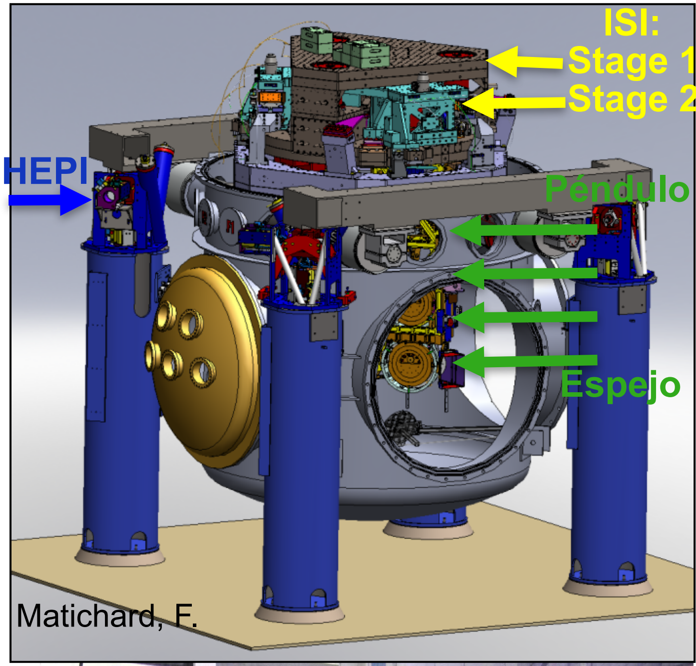


- Reduce 1/f^8 residual motion of ISI.
- First three stages suspended via steel wire and blade-springs.
- Penultimate mass and test mass, both 40 kg fused silica, connected by fused silica fibres → ultra-high Q (low loss) structure.
- Each layer of the suspension is matched by an adjacent quadruple pendulum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

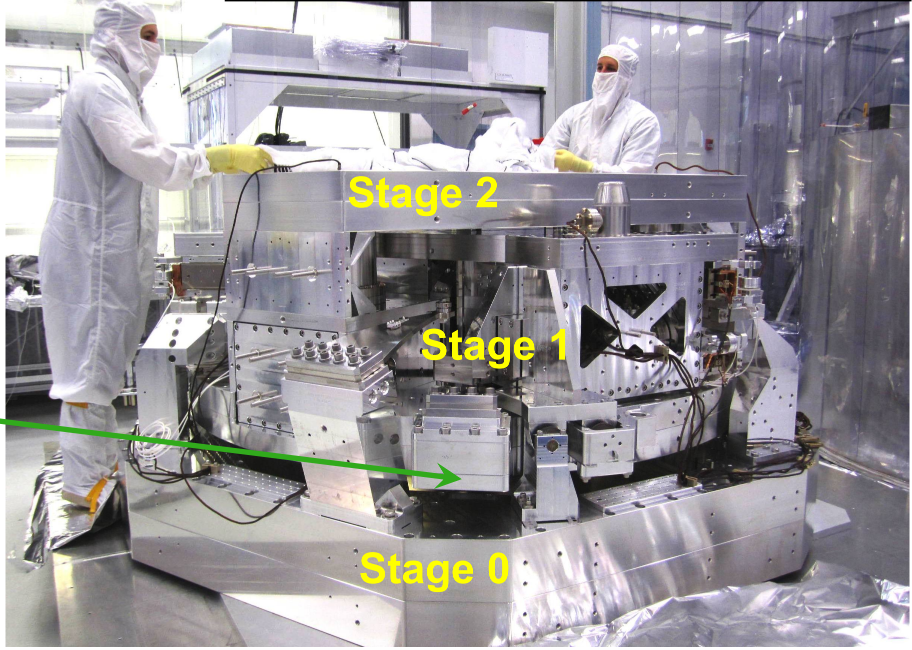
Active Seismic noise reduction

- 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.



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

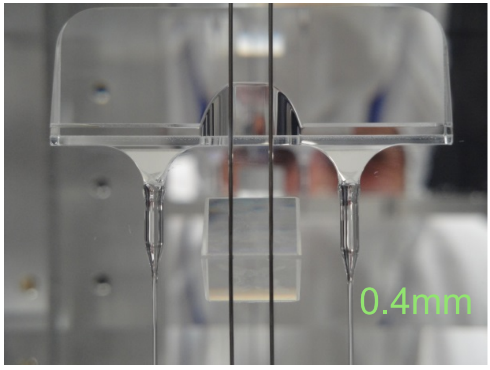
Loss angle

PSD of displacement

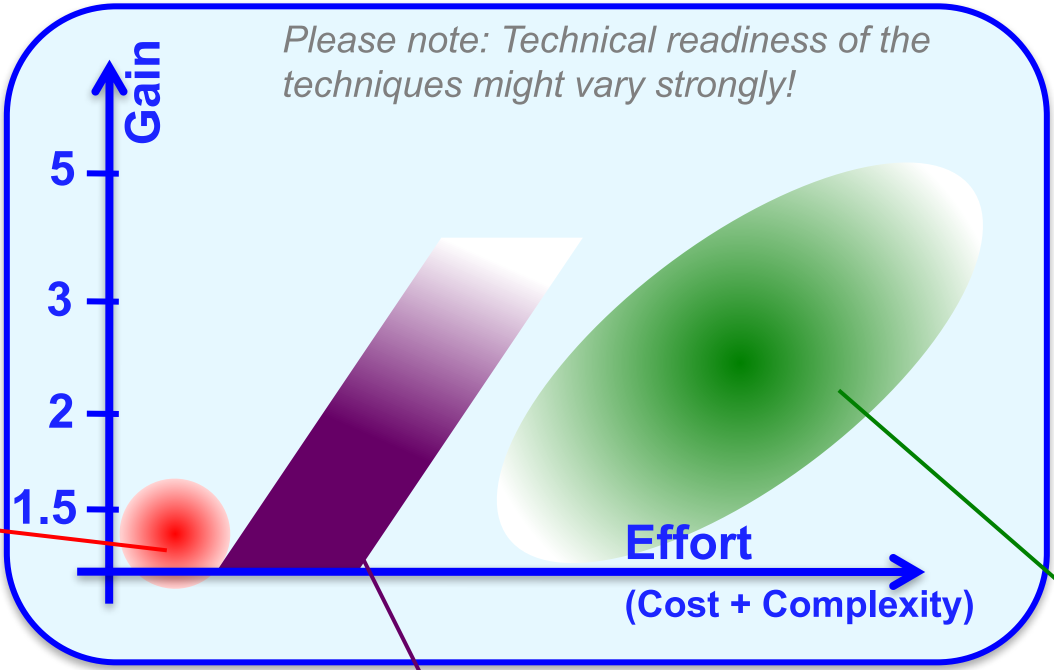
$$\boxed{x^2(\omega) = \frac{4k_\mathrm{B}T\omega_0^2\phi(\omega)}{\omega m[(\omega_0^2-\omega^2)^2+\omega_0^4\phi^2(\omega)]}}$$

Mirror mass

Resonance frequency (function of fibre length)



How to reduce **suspension thermal noise?**



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

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.

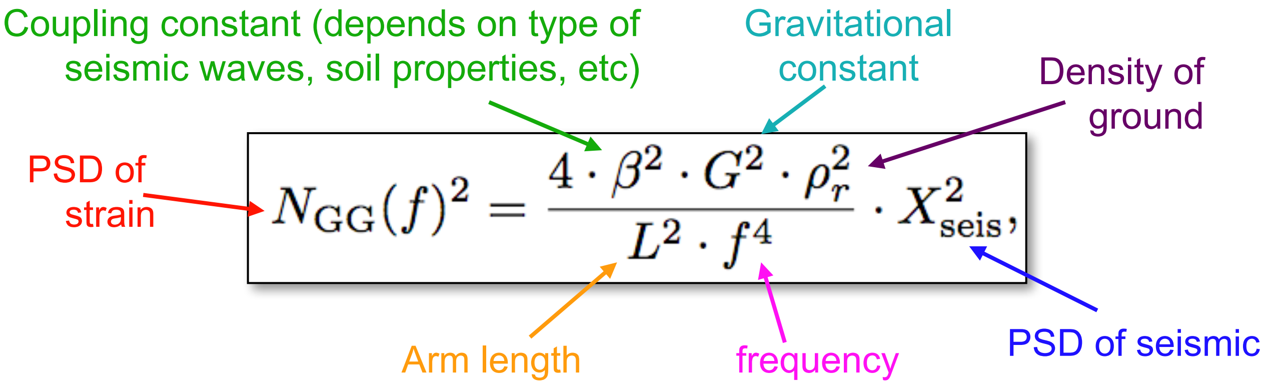
Cooling of the suspension to cryogenic temperatures.

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.



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

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

Gravitational constant

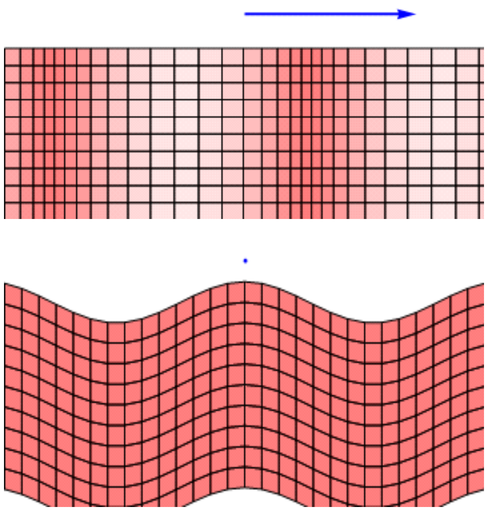
Density of ground

PSD of strain

Arm length

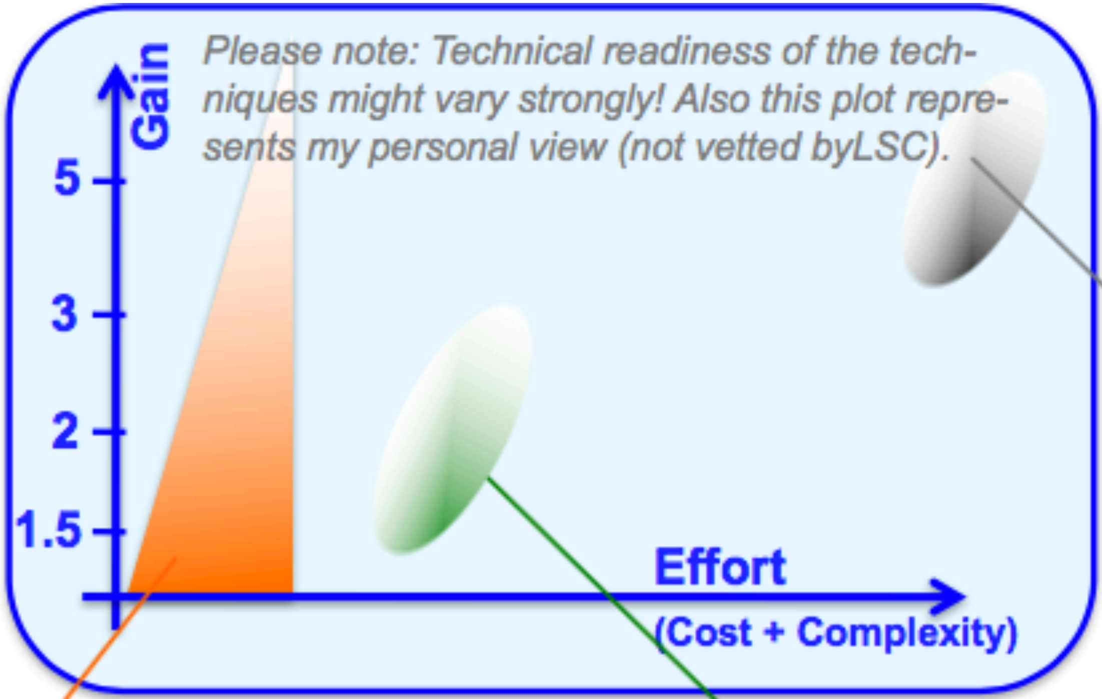
frequency

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

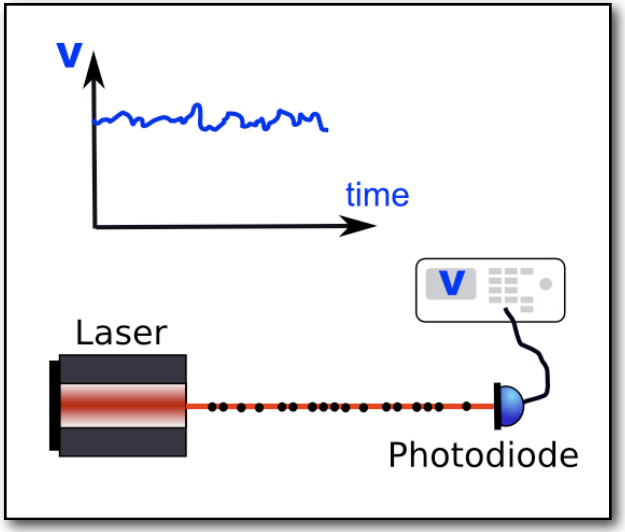
  - **Photon radiation pressure noise**, fluctuation in number of photons impinging on test-mass (back-action noise). Low frequency noise.

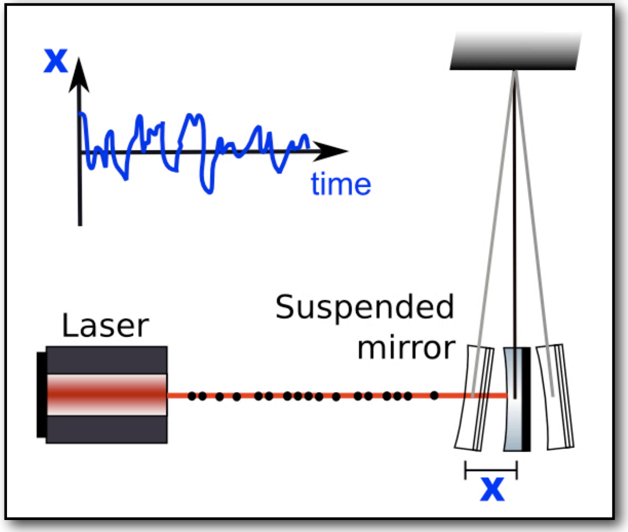
$$h_{\mathrm{rp}}(f) = \frac{1}{m f^{2} L}\sqrt{\frac{\hbar P}{2\pi^{3} c\lambda}}$$

optical power

Mirror mass

- 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:

$$\Delta E = \Delta n \hbar \omega$$

$$\Delta t = \frac{\phi}{\omega}$$

$$\Rightarrow \quad \Delta n \Delta \phi = \frac{1}{2} \quad \Rightarrow$$

Photons follow Poisson stats

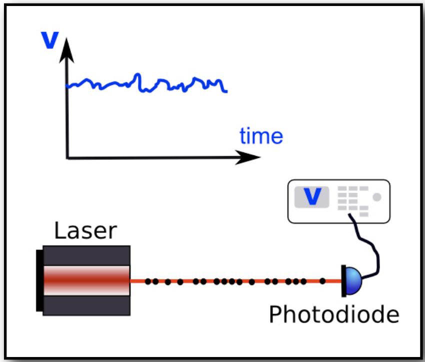
$$\Delta n = \sqrt{N}$$

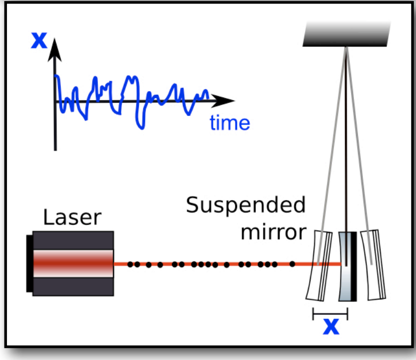
$$\Delta \phi = \frac{1}{2\sqrt{N}}$$

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

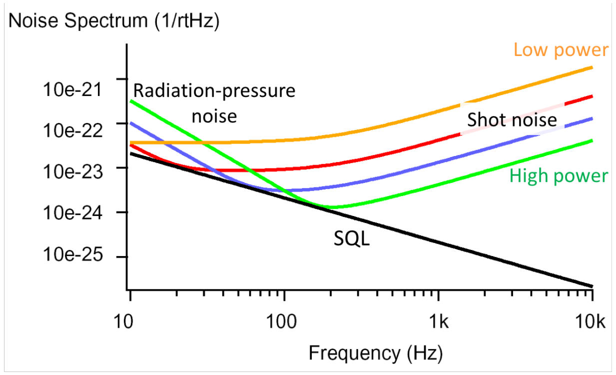
Quantum noise two forms:

- **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. $\propto \frac{\sqrt{P}}{m}$

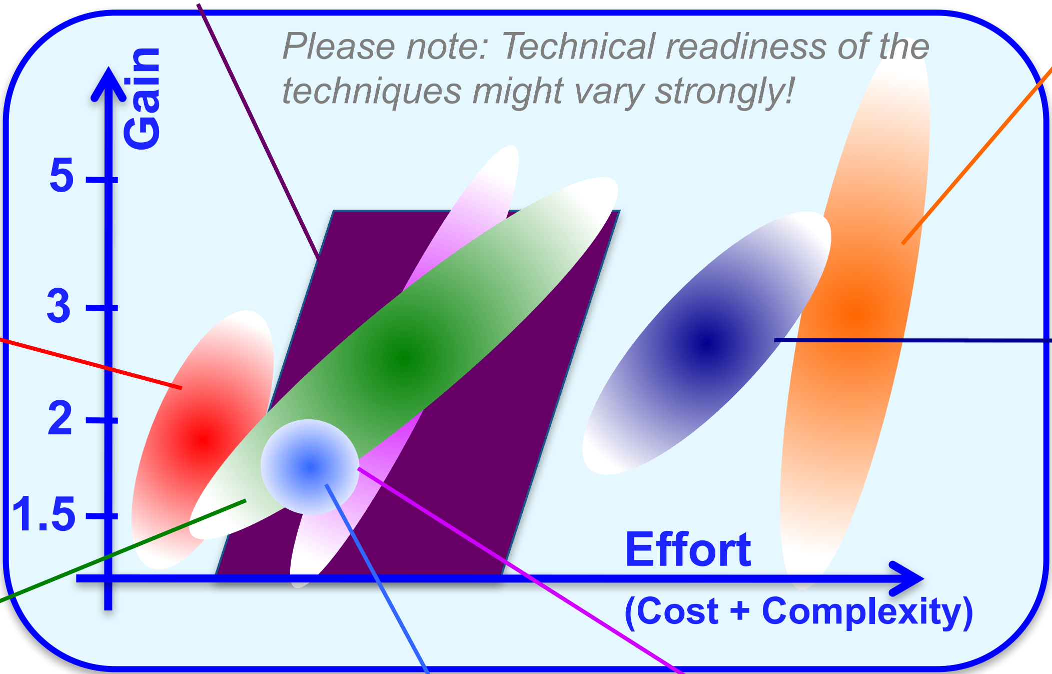




- Trade-off is called SQL



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

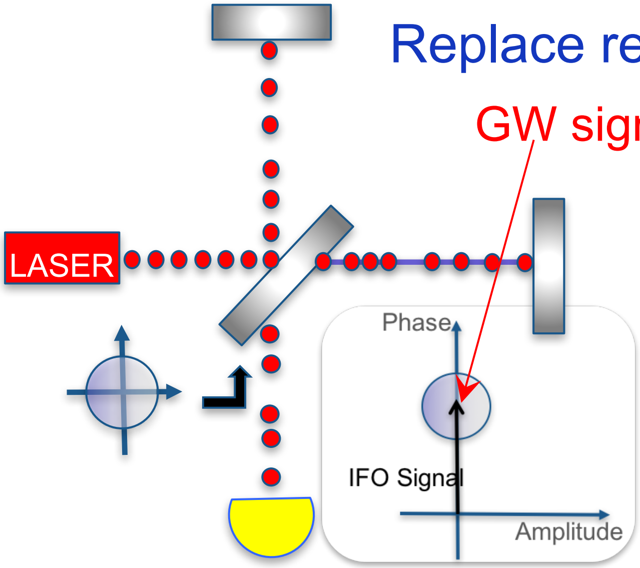
Optical Bar + Optical Lever
Khalili, PLA 298, 308-14, 2002

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

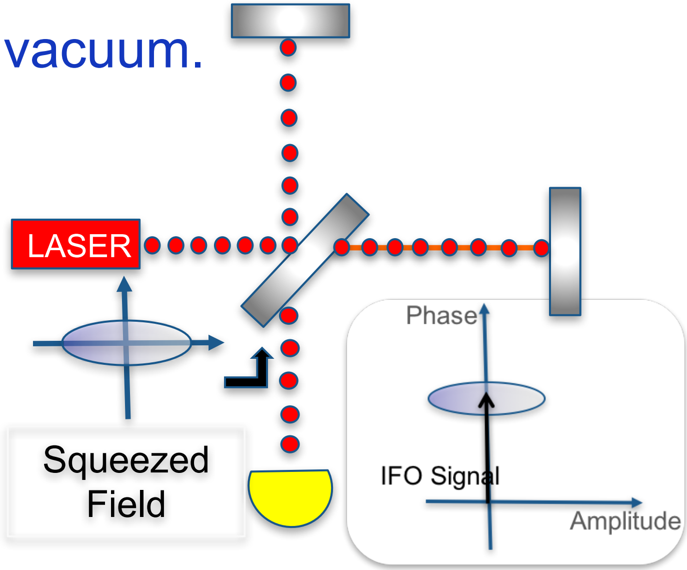


Replace regular vacuum with squeezed vacuum.

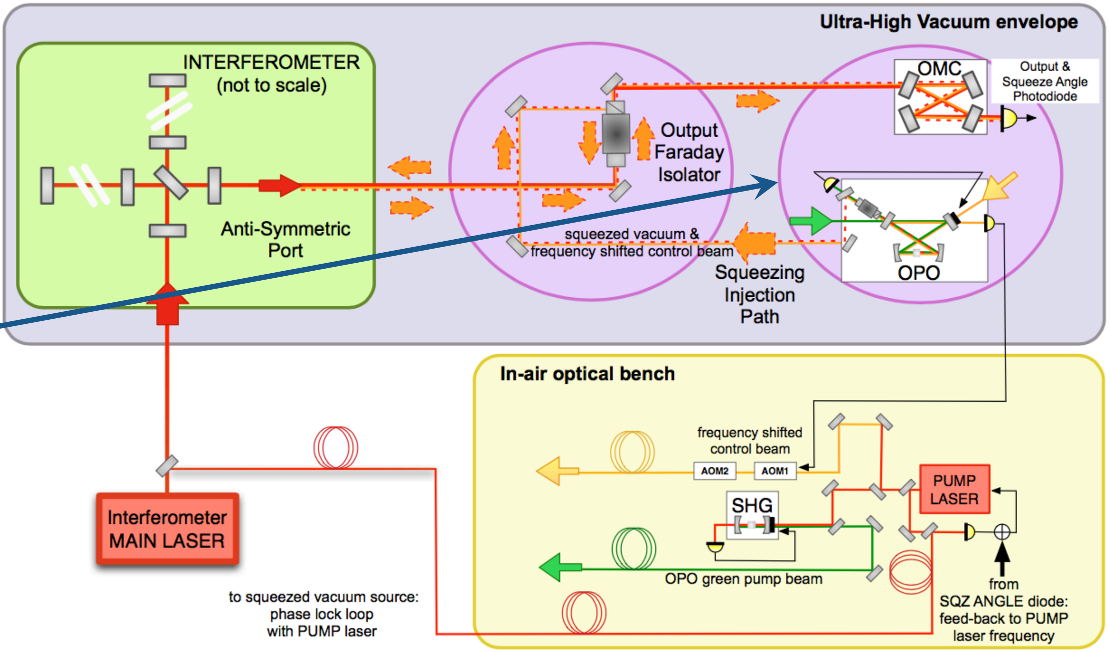
GW signal shows on Phase quadrature.

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.



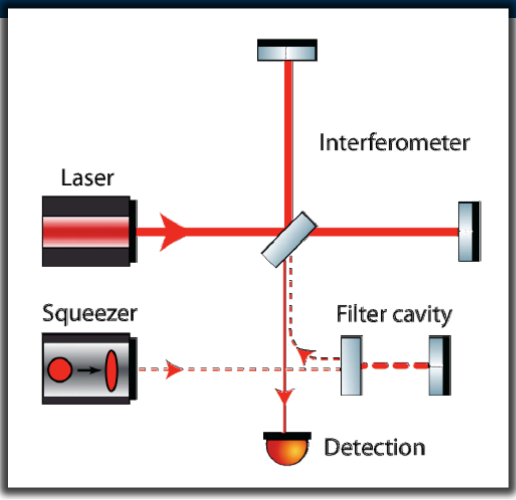
diagrams from Lisa Barsotti (G1800598 G1602253)

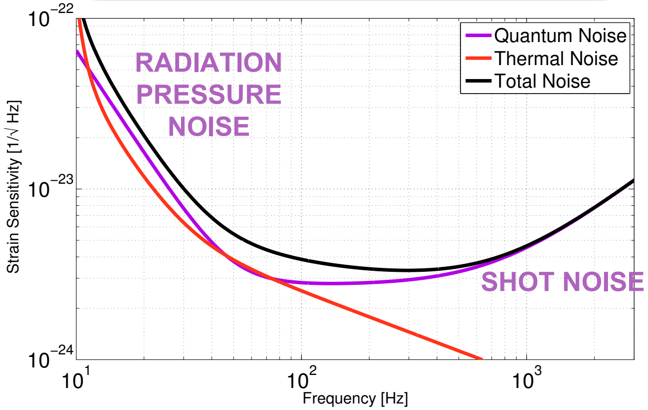
Enhanced 2G – Freq. dependent squeezing

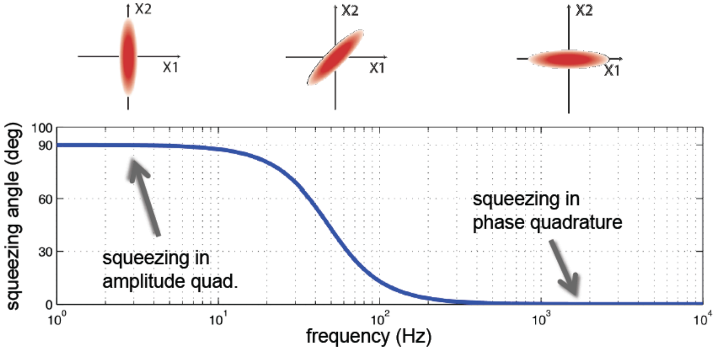
- Phase squeezed light ↓ shot noise (HF) but associated amplitude anti-squeezing ↑ radiation pressure (LF).
- **Freq. dependent squeezing:** Low loss, high finesse (thousands) detuned filter cavity which rotates squeezing angle as function of frequency.

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