





LIGO Scientific Collaboration





























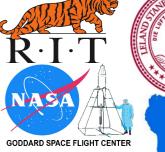




















MONTANA



MICHIGAN







OF ADELAIDE



UNIVERSITYOF

BIRMINGHAM





















Georgia Institute of Technology



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University of Southampton











Leibniz Universität









LIGO Scientific Collaboration





























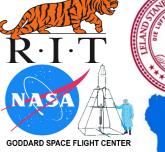




















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National Science Foundation + International partners

LIGO Scientific Collaboration





















UNIVERSITY OF THE WEST of SCOTLAND





UNIVERSITY.







for Gravitational Physics ALBERT EINSTEIN INSTITUTE













THE UNIVERSITY OF



CAMBRIDGE











































PRIFYSGOL *C*aerdyd









Georgia Institute of Technology of Southampton























Overview



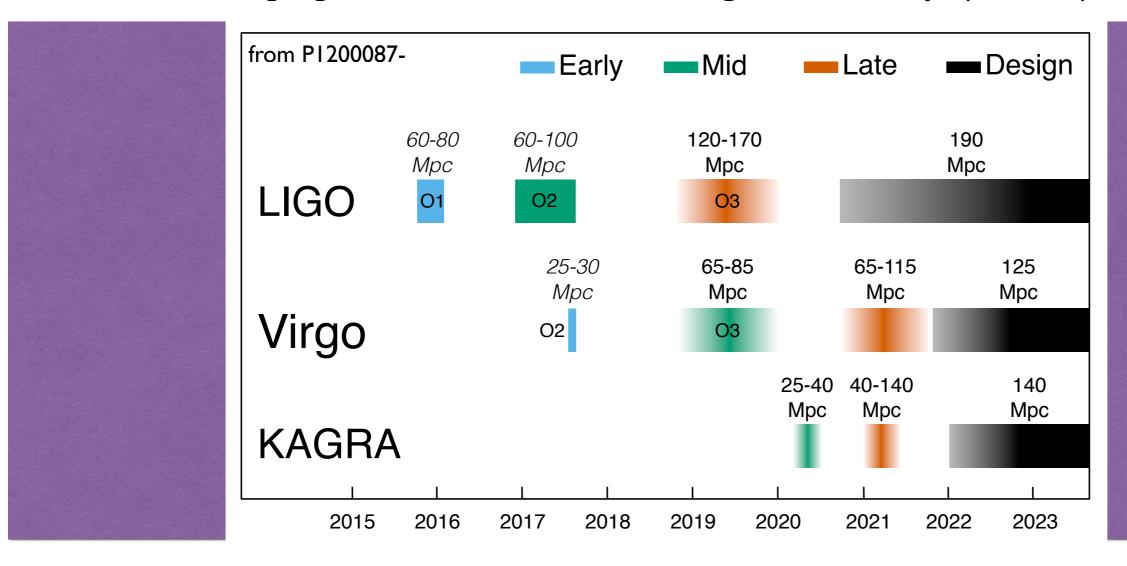
We've started to make detections

- the astrophysics is really cool - and many questions remain

Advanced LIGO and Advanced Virgo are the first instances of a new type of Observatory

So what comes next?

Start observing again in 2019, reach Design Sensitivity. (~2021)





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So what comes next?

Start observing again in 2019, reach Design Sensitivity. (~2021)

- here the speculation starts -

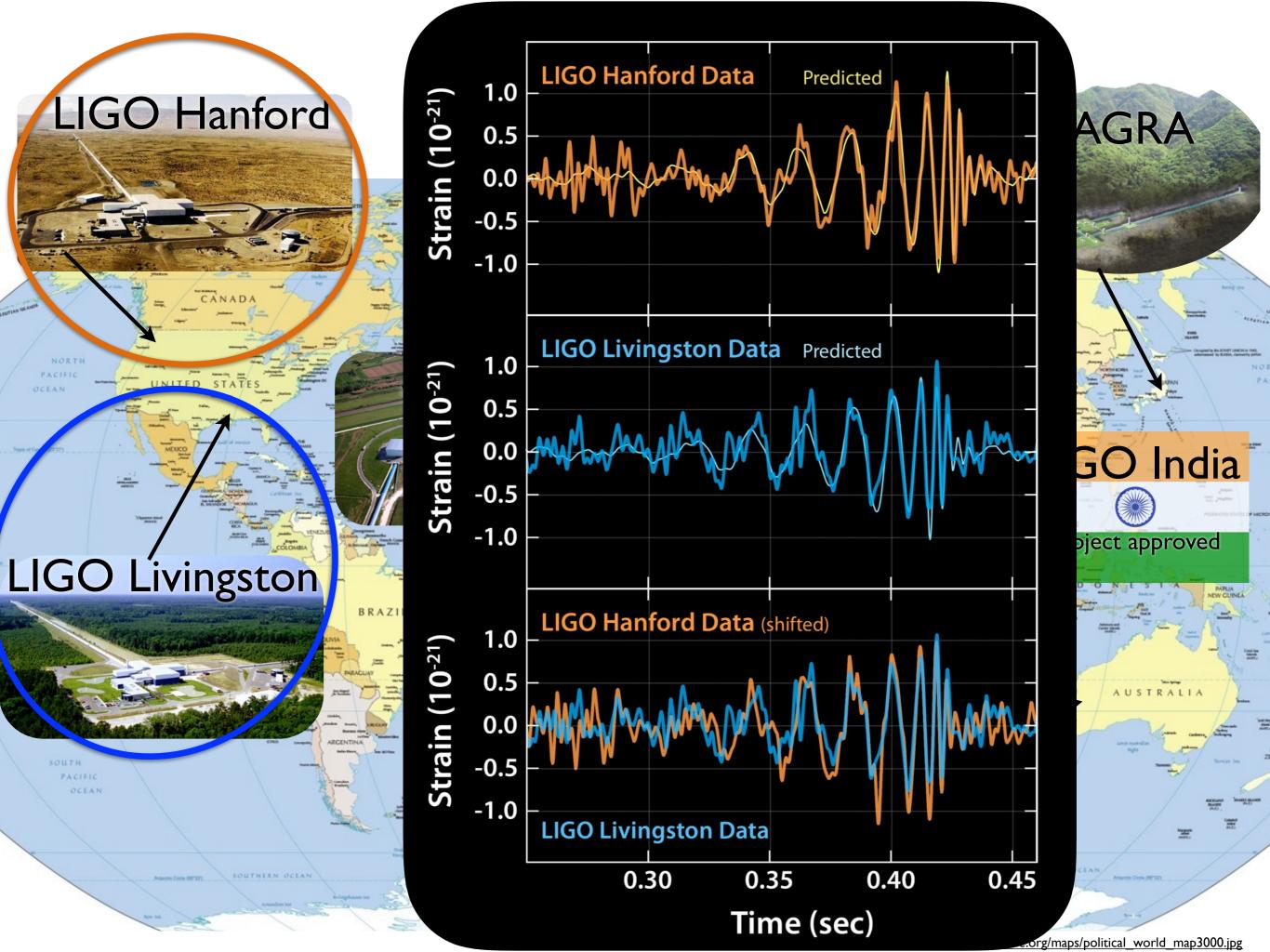
A+ Upgrade: better mirror coatings and better quantum noise. (~2024?)

LIGO Voyager: Low temperature operation in the existing facilities (~2030?)

New Facilities: Einstein Telescope/ Cosmic Explorer

International Network LIGO Hanford **GEO 600** KAGRA VIRGO LIGO India project approved LIGO Livingston **ACIGA**

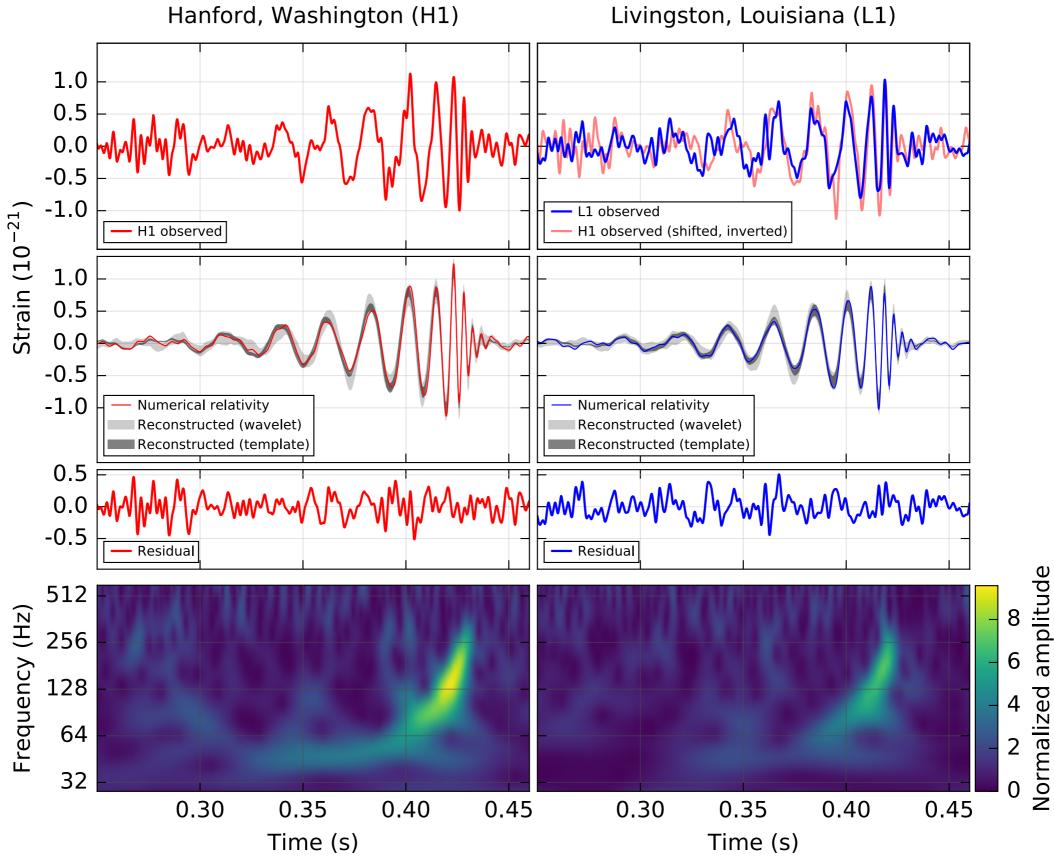






First signal - Sept 14, 2015











Initial Masses:

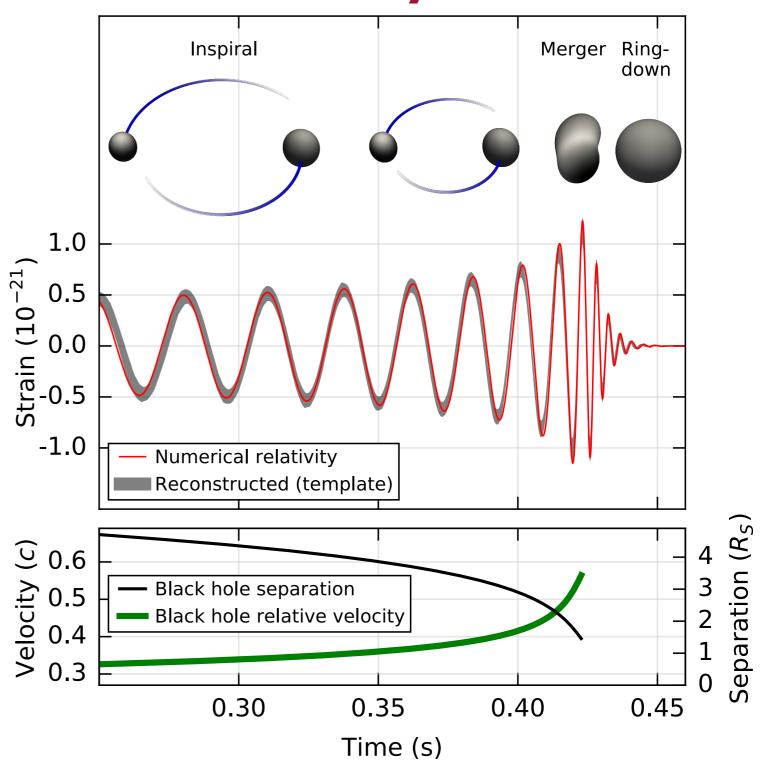
29 (+4/-4) & 36 (+5/-4) M_{sun}

Final Mass:

62 (+4/-4) M_{sun}

Distance

420 (+160/-180) MPc (1.3 Billion light years)









Initial Masses:

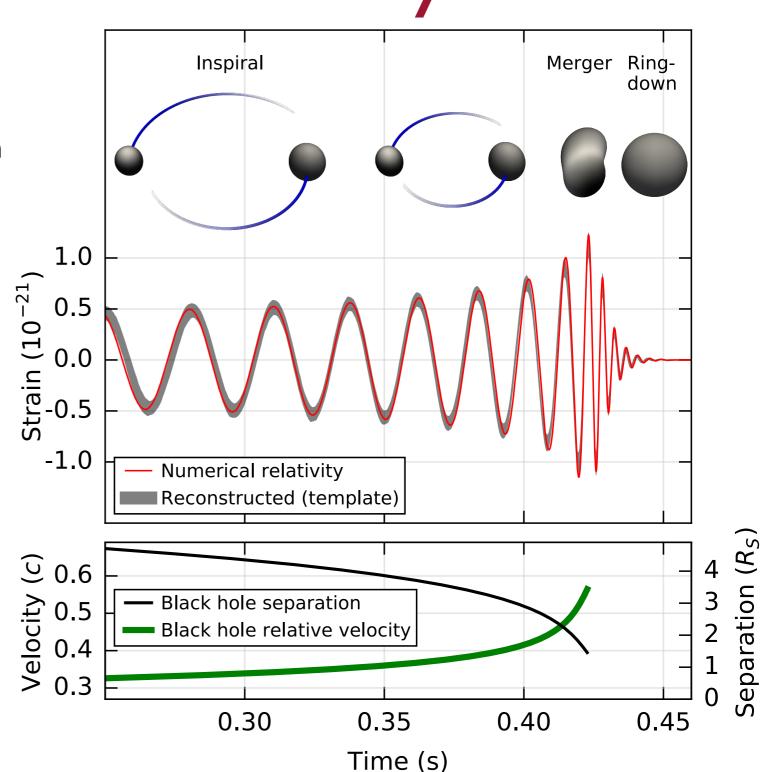
Final Mass:

Energy radiated

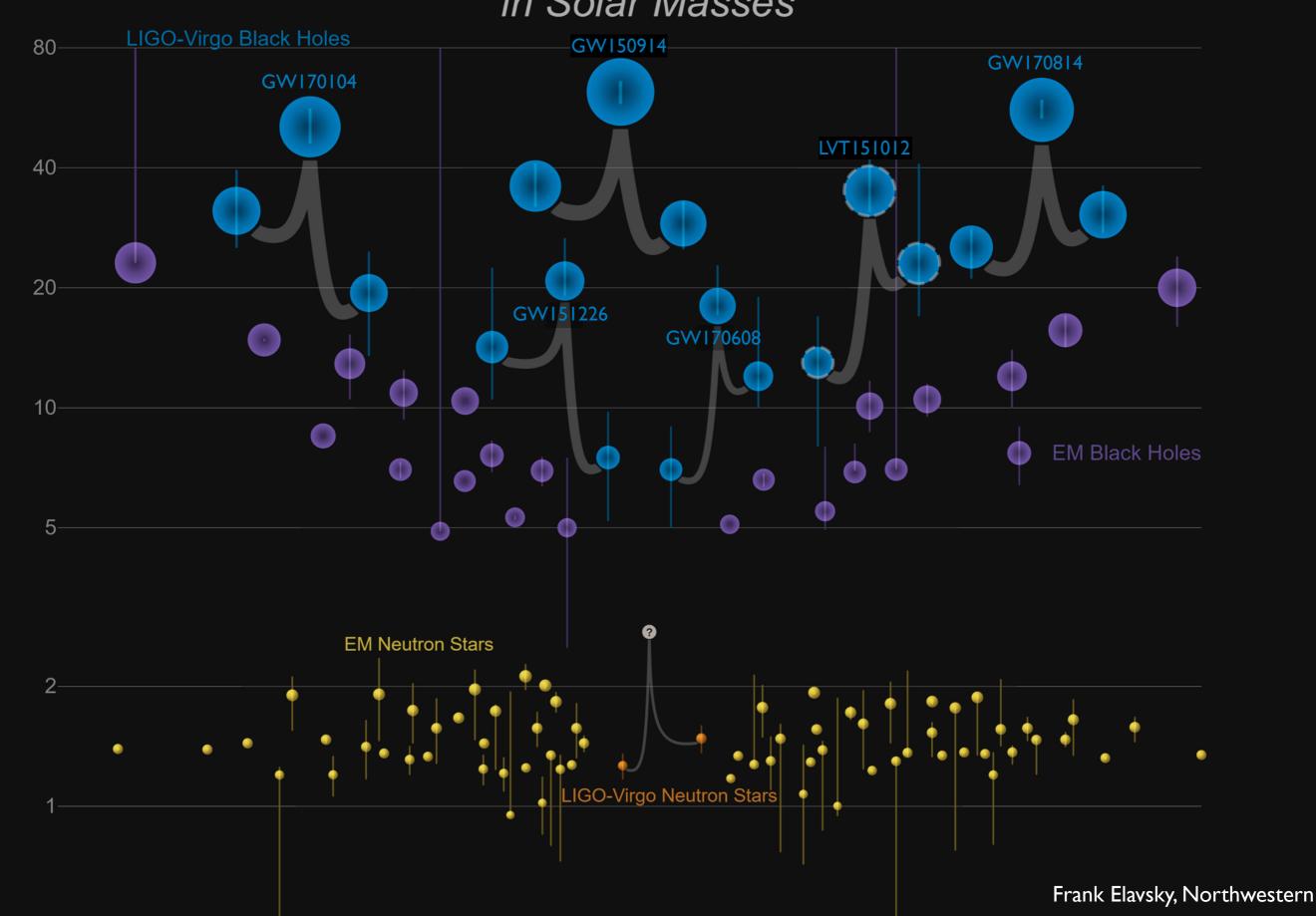
$$3 (+0.5/-0.5) M_{sun} c^2$$

Distance

(I.3 Billion light years)



Masses in the Stellar Graveyard in Solar Masses





Answers and Questions



Gravitational waves can be measured by LIGO.

Stellar mass Black Holes with mass > 25 M_{sun} exist.

Binary Black hole systems exist, and they merge (in less than 13 GYr.)

BBH merge at 12 - 213 events * GPc⁻³ * year⁻¹ (now).

The waveforms can be explained by strong field General Relativity.



Answers and Questions



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How many stellar mass Black Holes are there?

What is the distribution of Black Hole masses?

How did the binary systems form?

Are there Black Holes from the primordial universe?

How old was the universe when the Black Holes started merging?

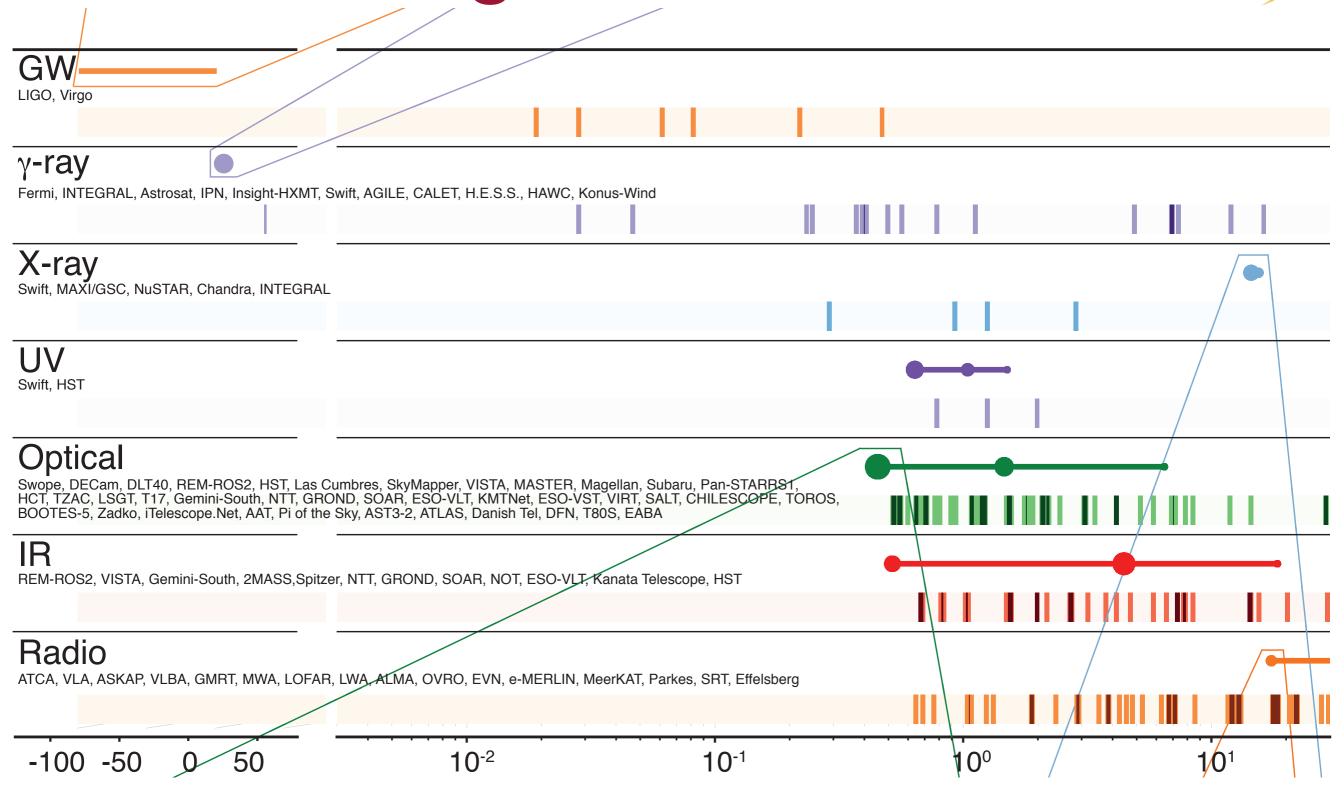
Can we find any deviations from General Relativity?

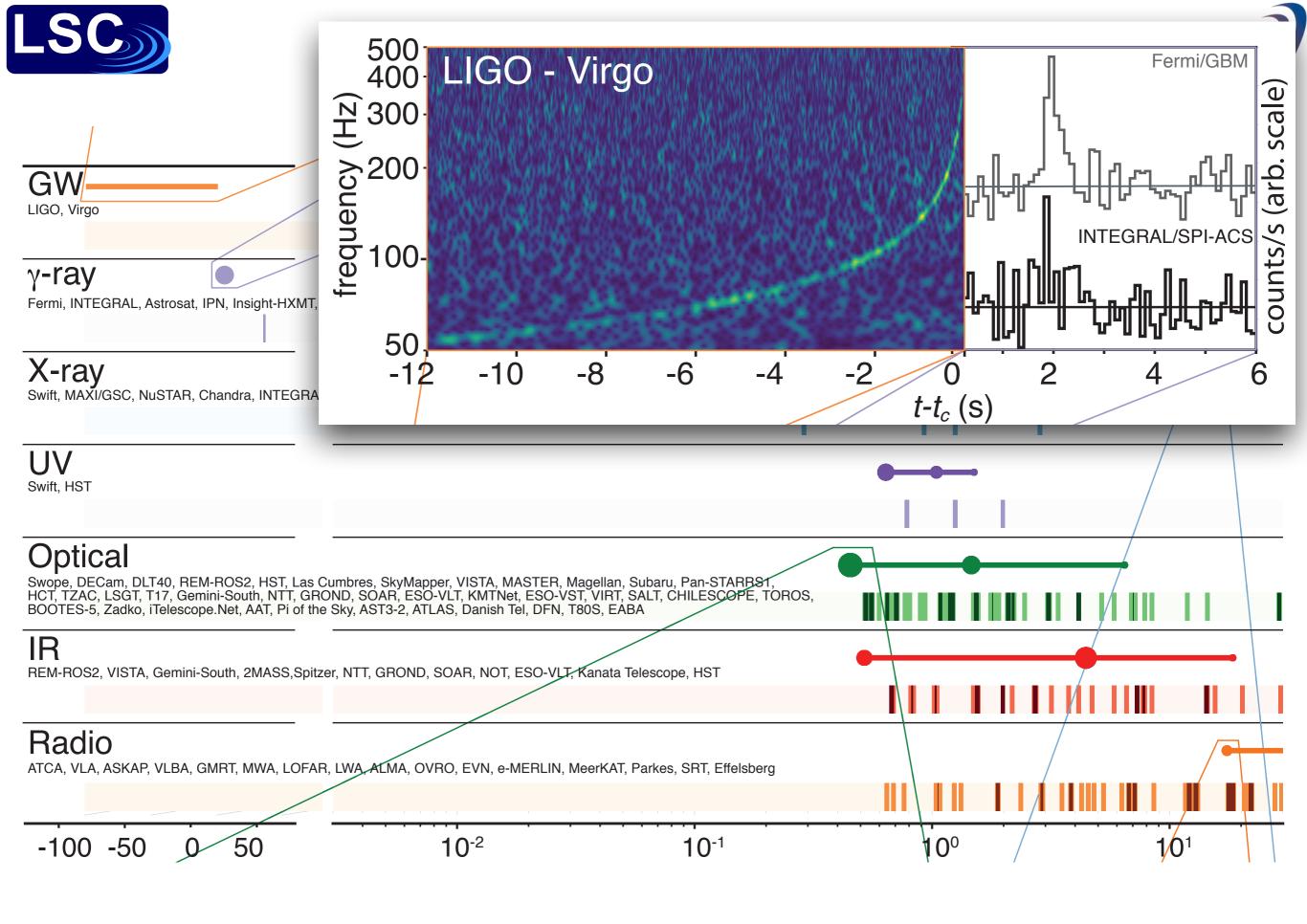


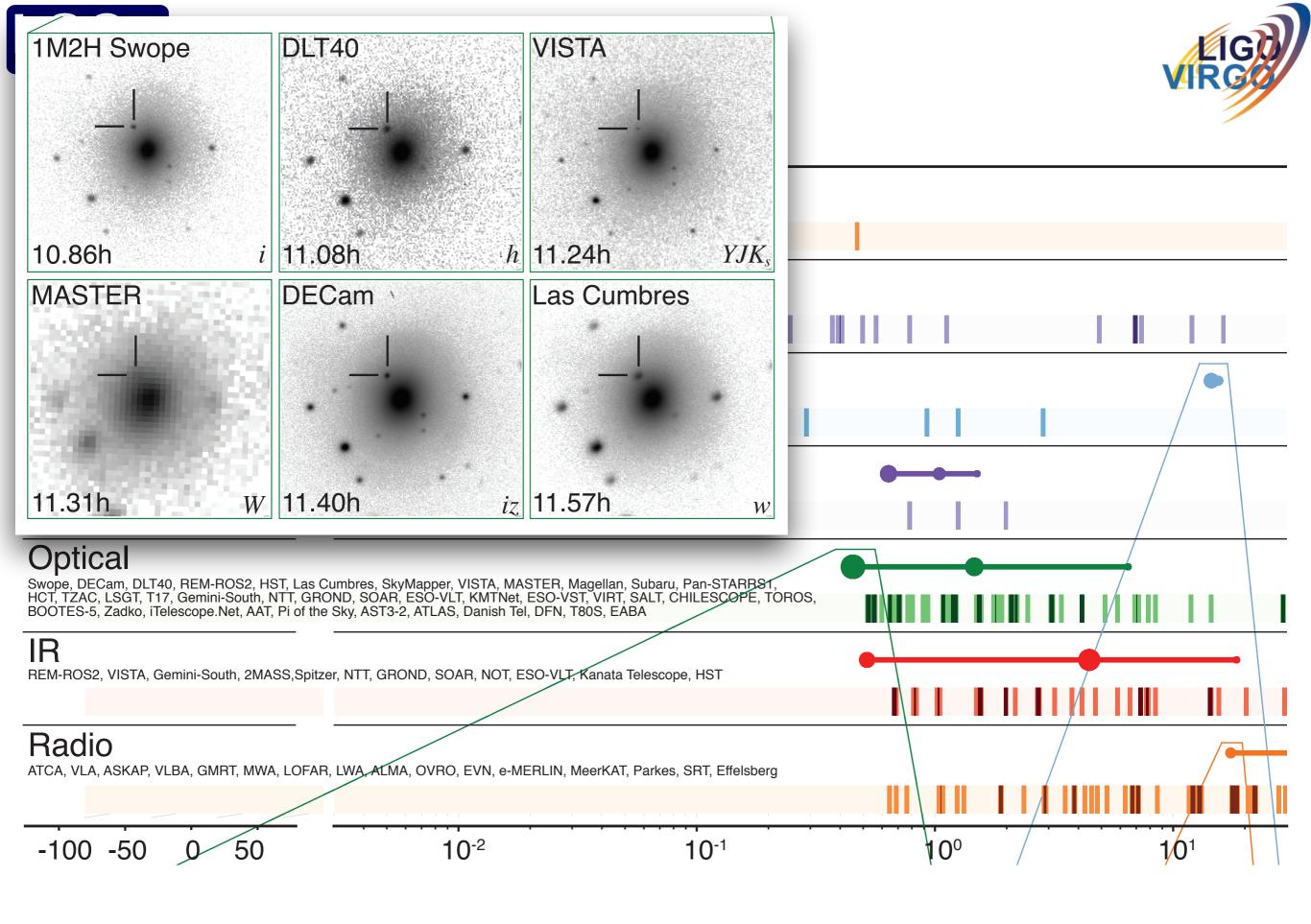


Amazing measurement set

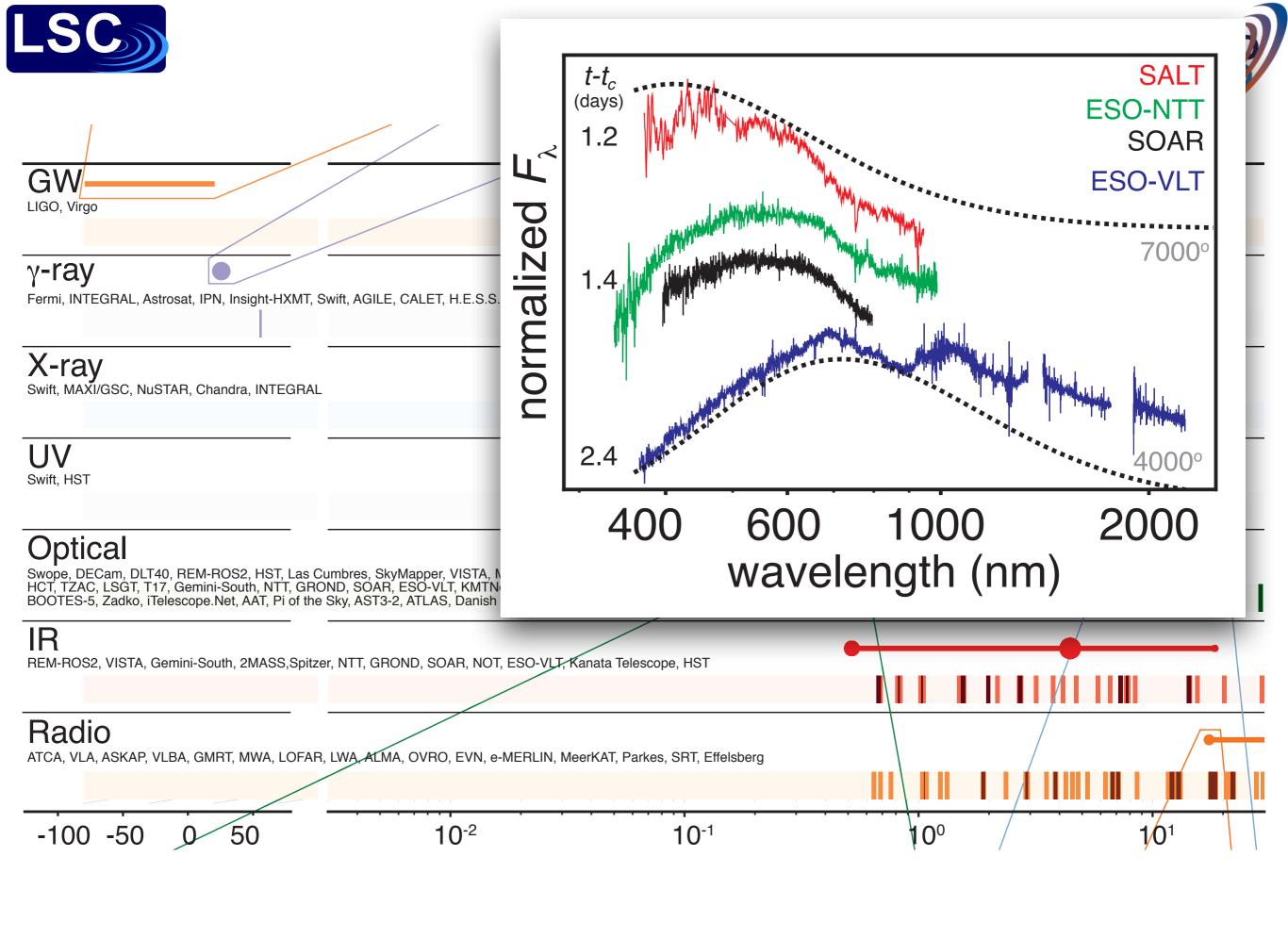






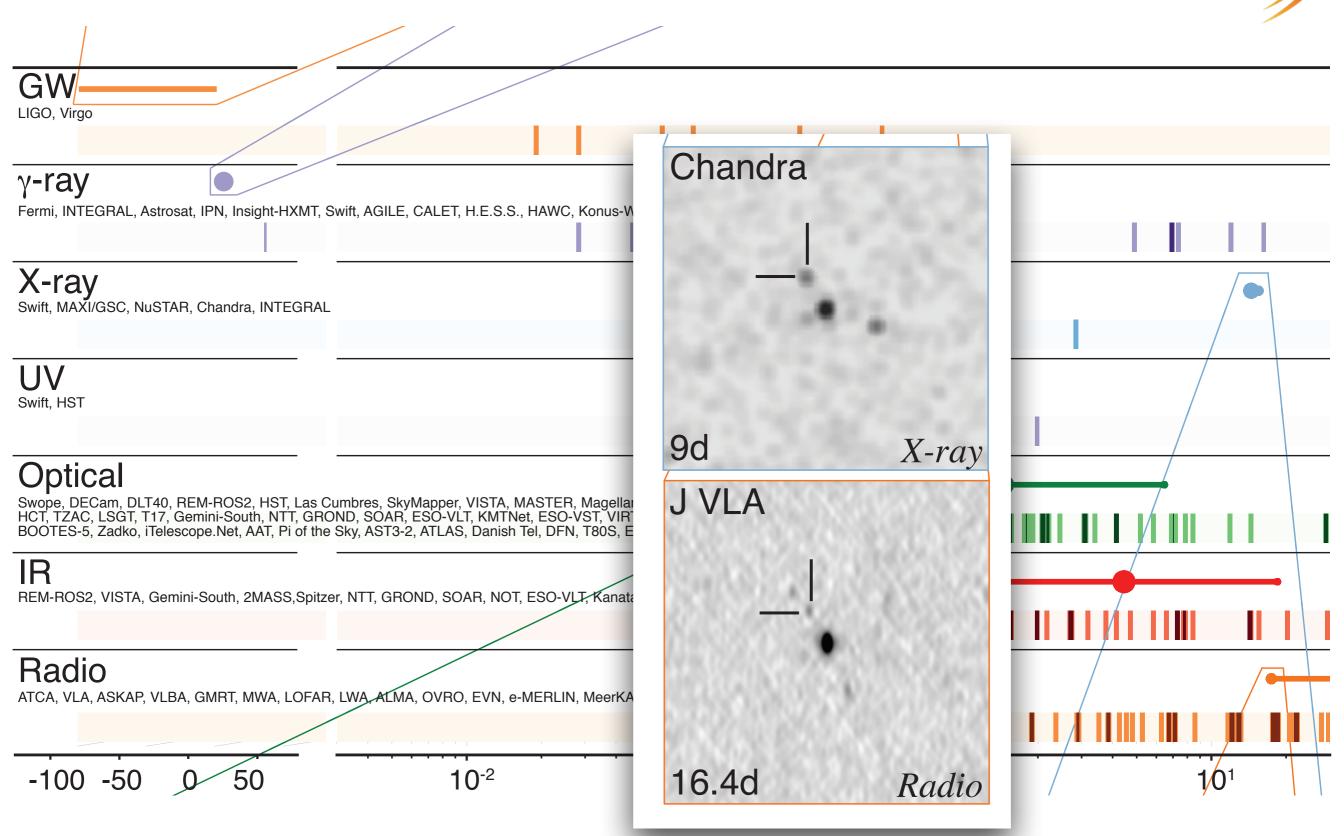


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Many things learned

- •These events do happen!
- •These events happen (330 4500) times / GPc³ Yr¹
- They follow an evolution similar to kilonova predictions
- They constrain the 'stiffness' or Equation of State of neutron stars
- You can get an estimate for the Hubble constant
- Many papers out now, many more expected
- Triumph of Multi-messenger astronomy distance, (H0/ angle), jet size, adiabatic glow vs. jet beam





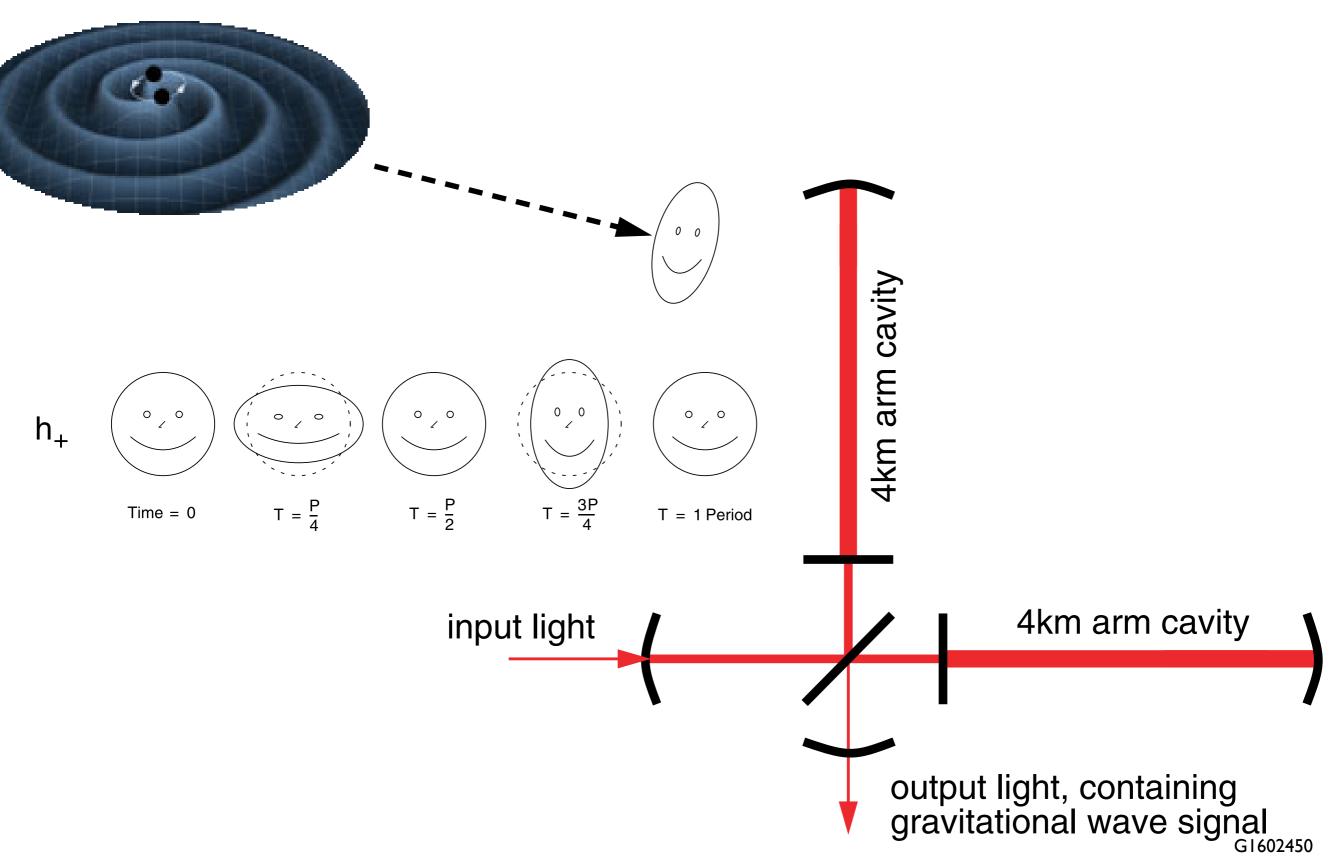
Many questions remain,

- •How common are kilonovas?
- Can they accurately predict the abundance of heavy elements?
- •This event was ~1000x less bright than other gamma-ray bursts with known distance observer effect?
- •What's going on with the jets?
- •Did it merge into a big neutron star or a small black hole?
- •Did it collapse to a BH later?
 Is that why the x-rays were late to the party?
- •What's the equation of state?
- •Can we learn more about the Hubble constant?





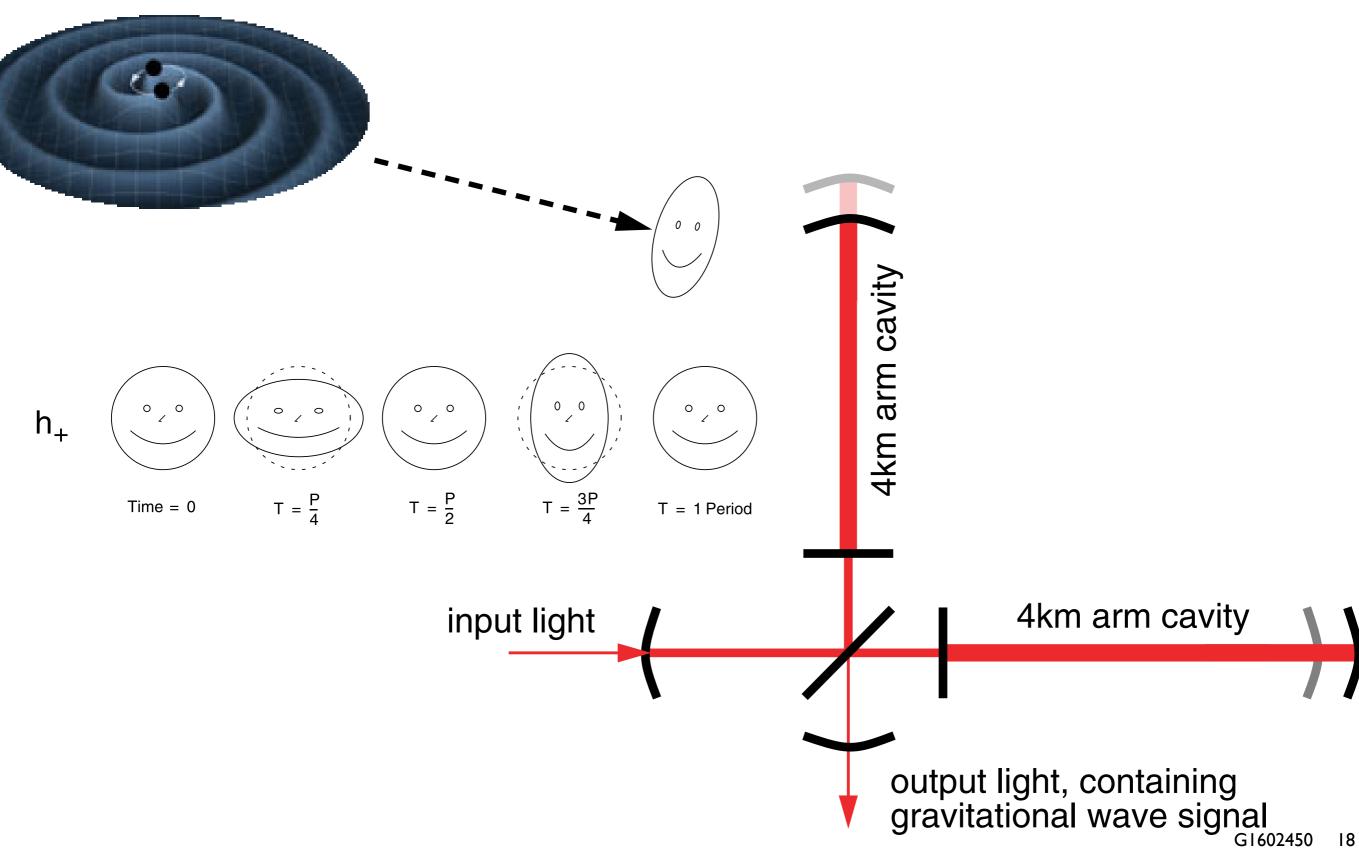
The LIGO concept







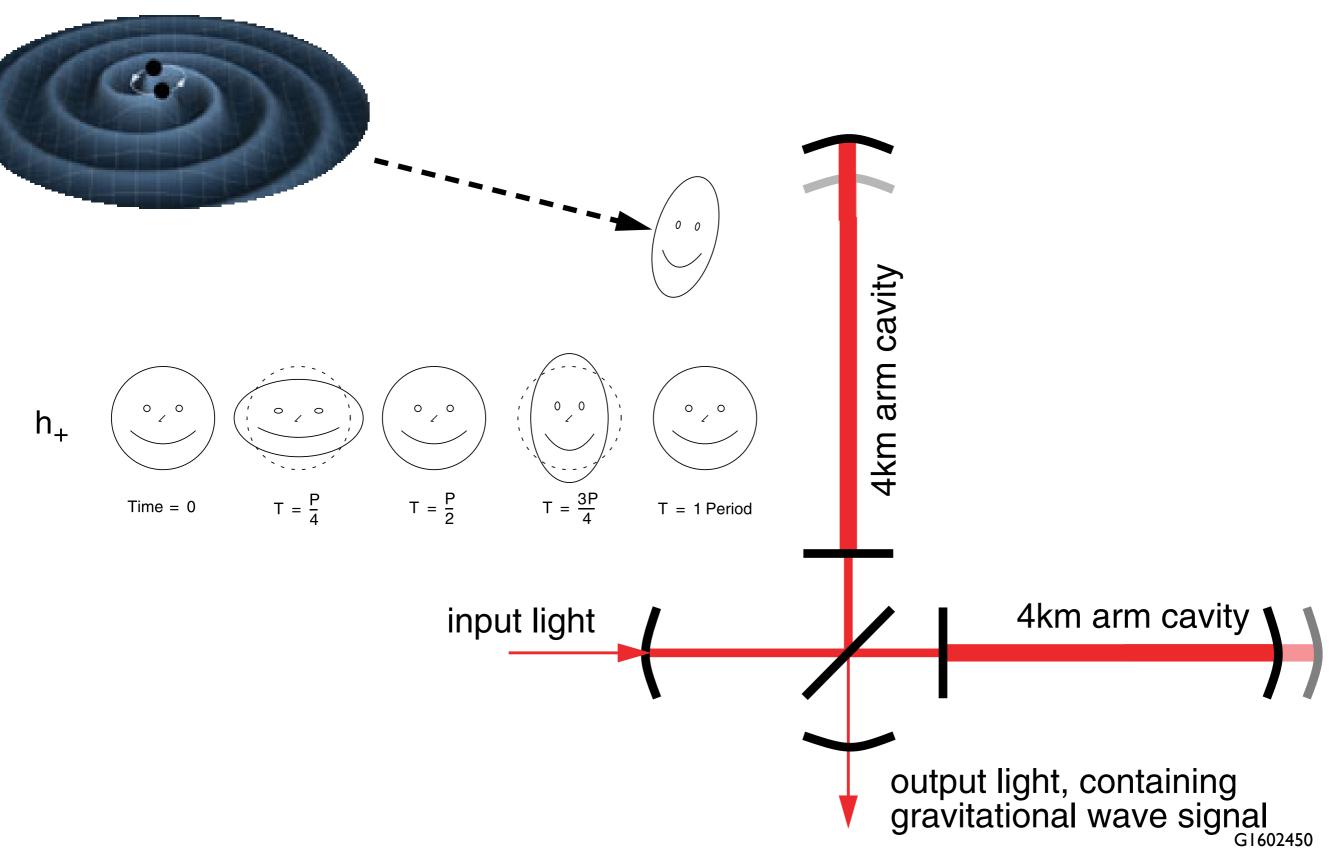








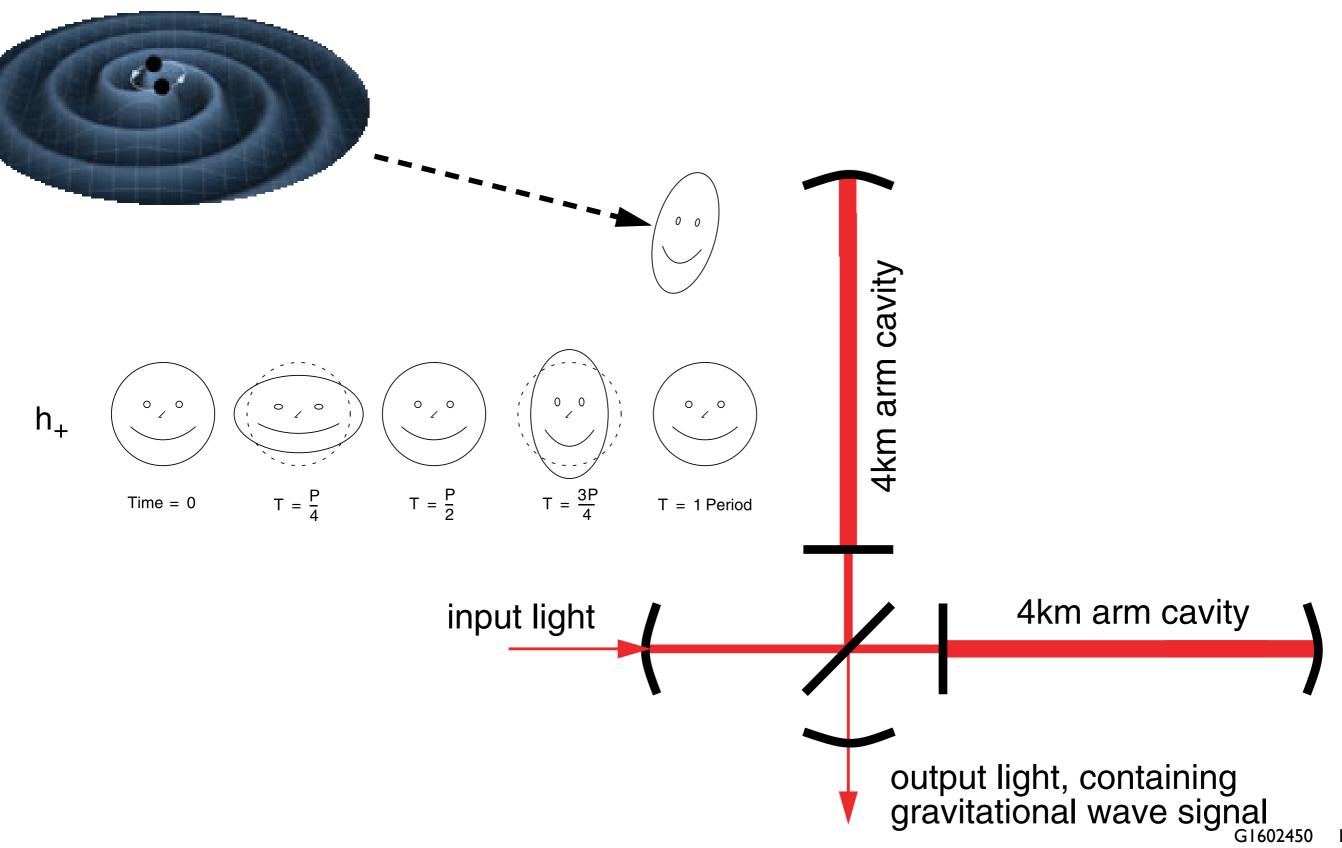
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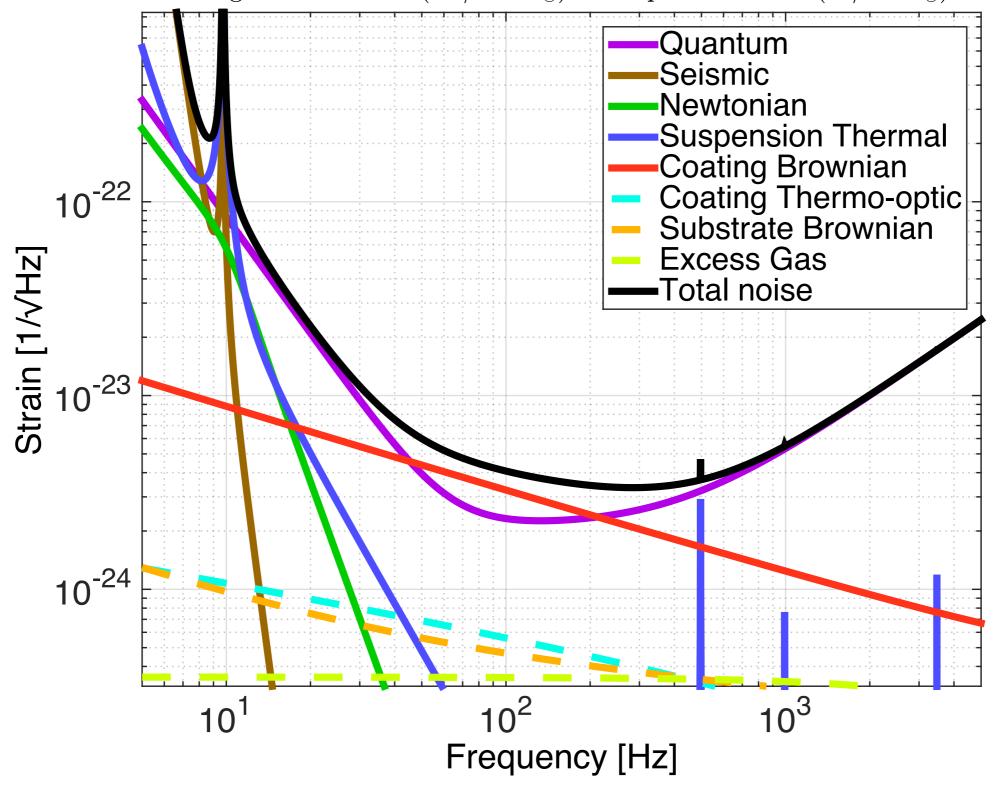


The LIGO Design Sensitivity



Barsotti et. al T1800044

aLIGO new design curve: NSNS $(1.4/1.4 M_{\odot})$ 173 Mpc and BHBH $(30/30 M_{\odot})$ 1606 Mpc



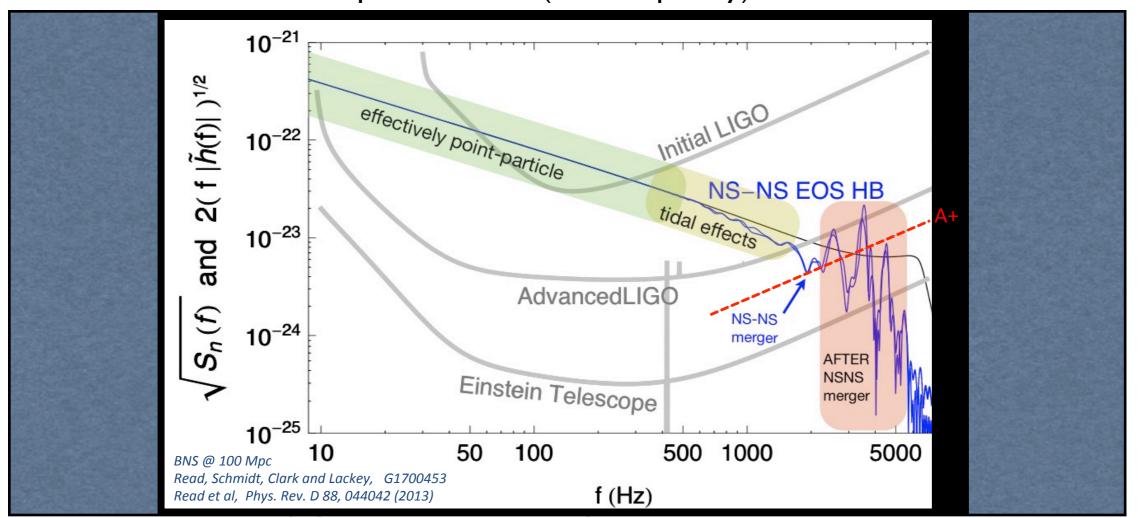


advancedligo

- How common are kilonovas?
 - Scales like the event rate. Mid-band for total signal
- What's going on with the jets?
- Can we learn more about the Hubble constant?
 - need to know inclination of source to us Polarization from network.
- What's the equation of state?
- Did it merge into a big neutron star or a small black hole?
 - dynamics at the merger better SNR at ~I-2 kHz
 - also evolution from 2 point masses (low frequency)
- How many stellar mass Black Holes are there?
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- Are there Black Holes from the primordial universe?
- How old was the universe when the Black Holes started merging?
 - Range. Midband.
- Can we find any deviations from General Relativity?
 - Statistics and very good SNR for nearby events.



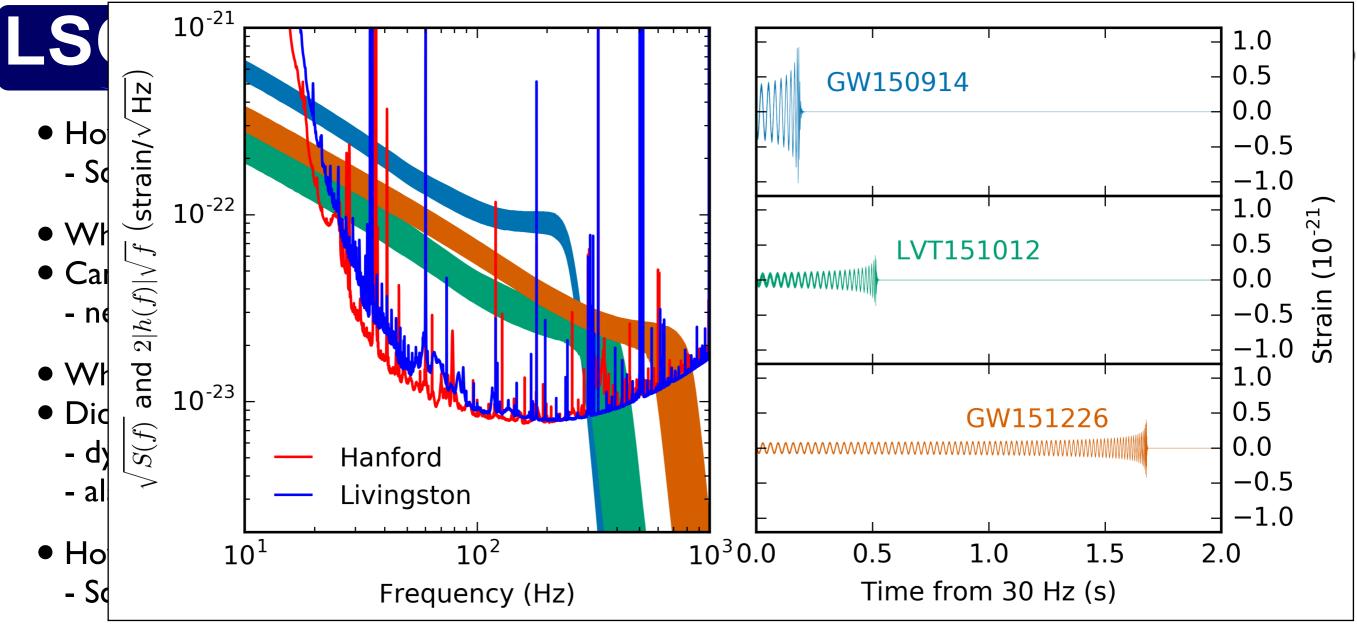
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advar

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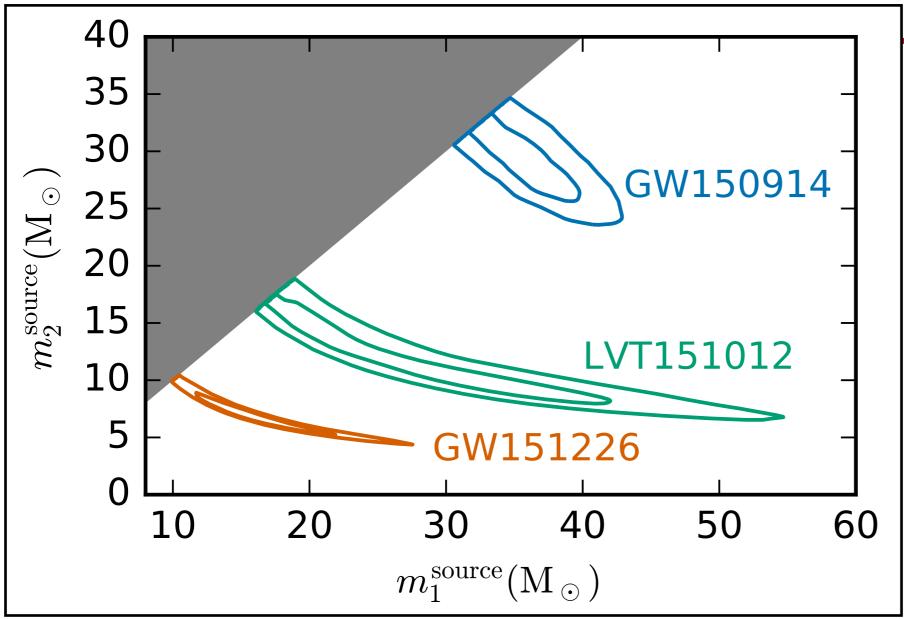
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nean science

network.

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advancedligo



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Better detectors mean better science

advancedligo

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- Can we learn
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- Did it merge
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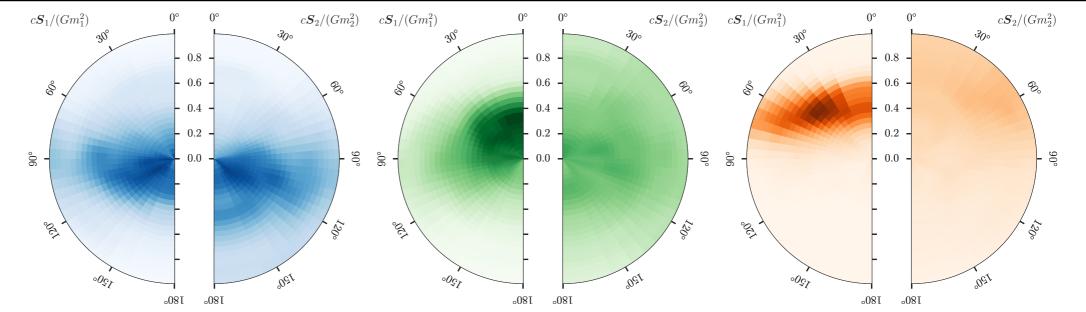


FIG. 5. Posterior probability distributions for for the dimensionless component spins $cS_1/(Gm_1^2)$ and $cS_2/(Gm_2^2)$ relative to the normal to the orbital plane L, marginalized over the azimuthal angles. The bins are constructed linearly in spin magnitude and the cosine of the tilt angles, and therefore have equal prior probability. The left plot shows the distribution for GW150914, the middle plot is for LVT151012 and the right plot is for GW151226.

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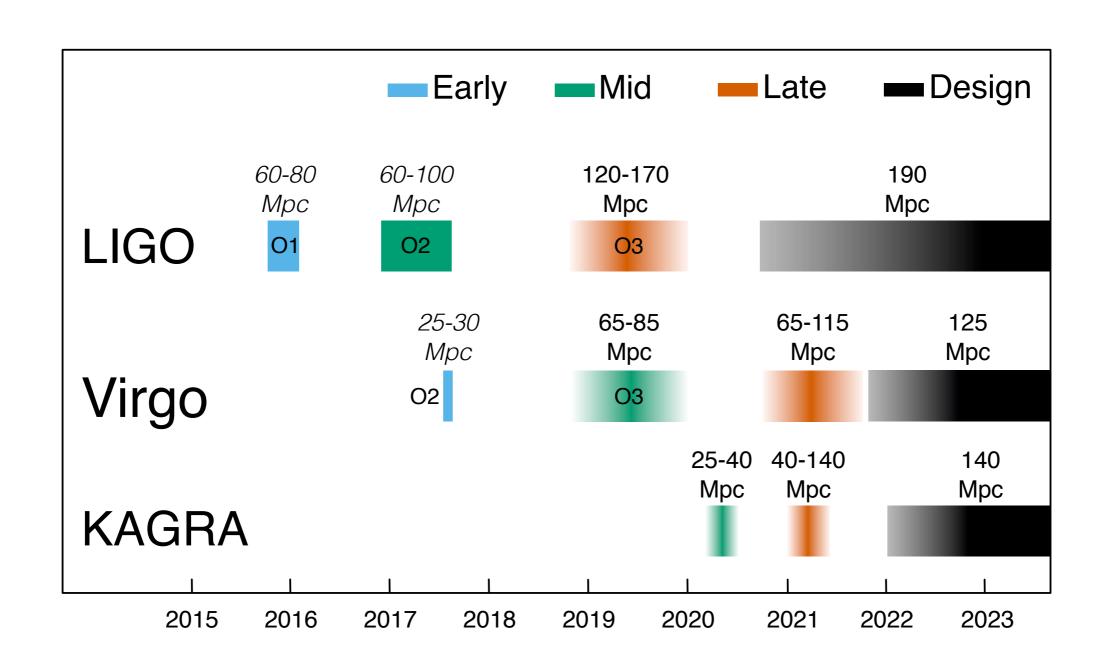


Getting better detectors



P1200087-v46

KAGRA Collaboration, LIGO Scientific Collaboration and Virgo Collaboration

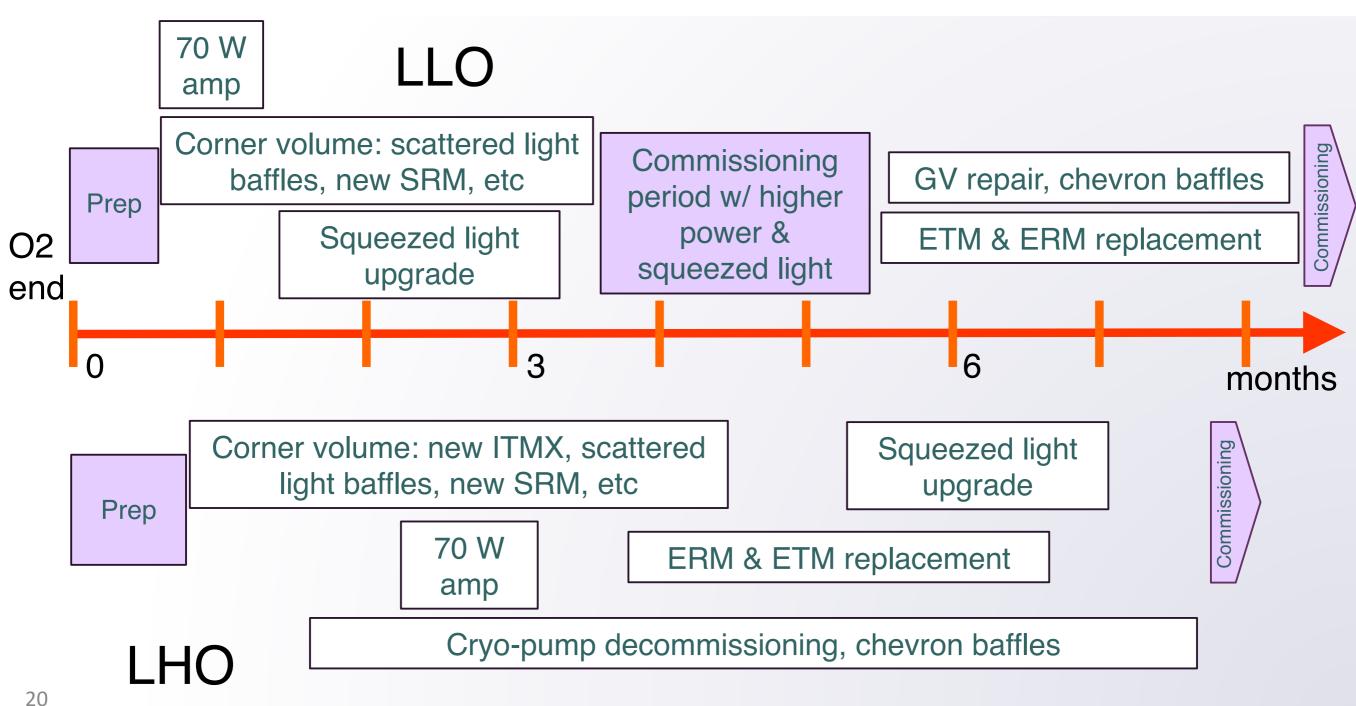




and we will be looking.



•LIGO is down for ~ I year making upgrades, preparing for O3.

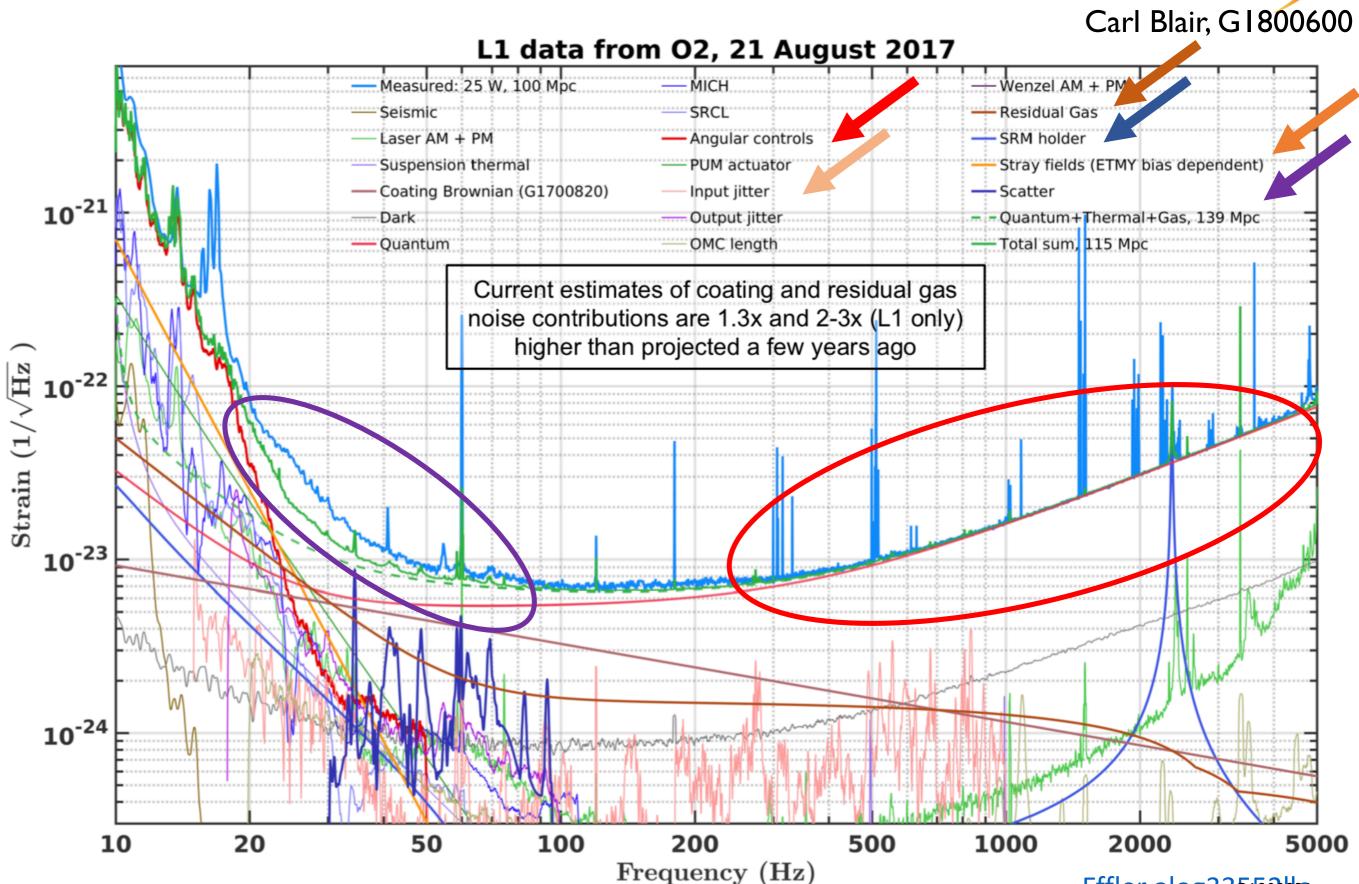




O2 Noise Budget



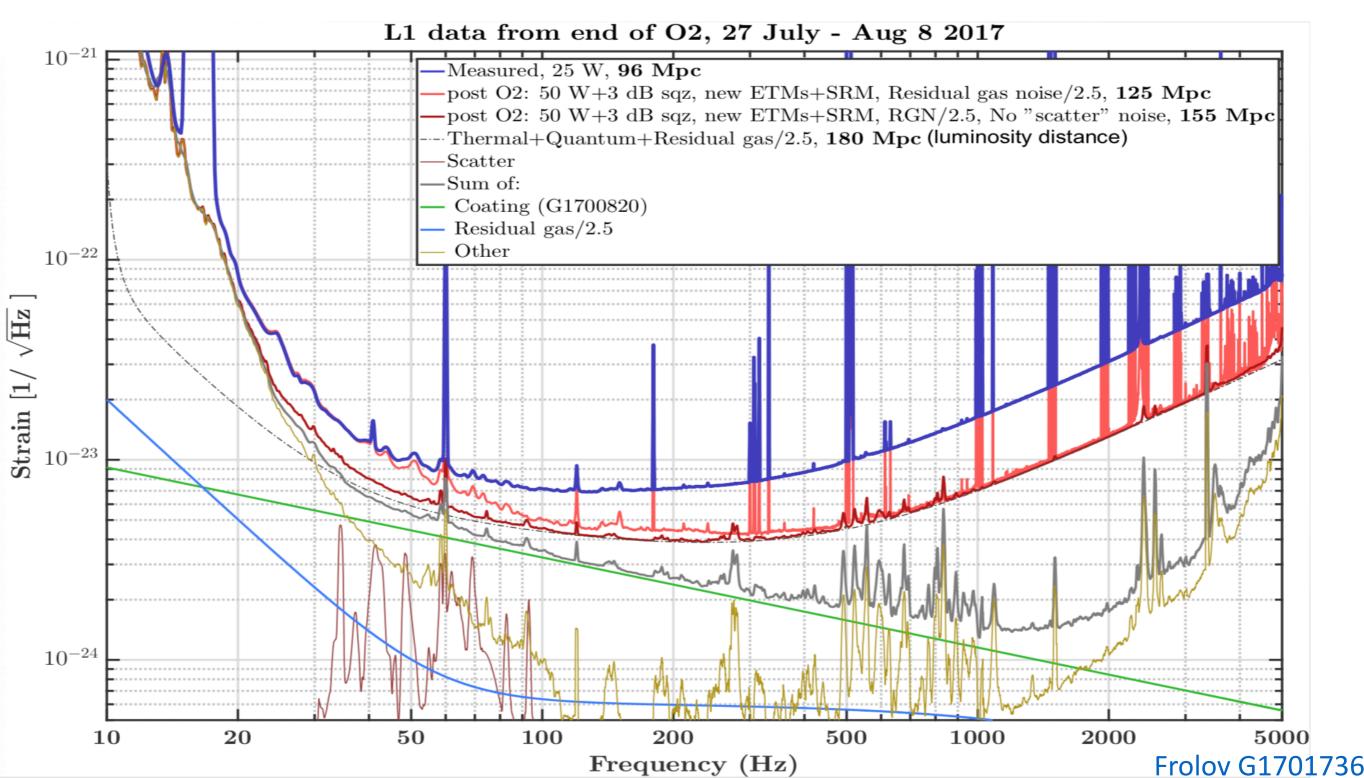
Effler alog3365080





O3 projection

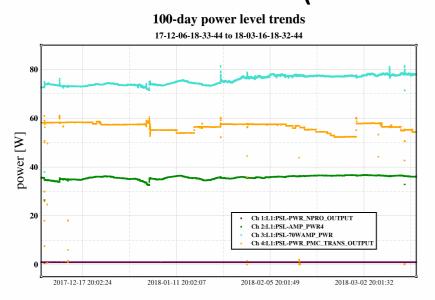






70 W amplifier update at LLO/LHO

- Replace 200W oscillator with 70W amplifier
- solid state laser amplifier
- 4 optically pumped crystals
- (fiber coupled pump diode lasers)
- small footprint, monolithic design
- Beckhoff controlled
- amplifies 35 W beam to >70 W
- Done at LLO (and stable)



70 W amplifier power stabilization illator (HPO) second loop input-modecleaner medium power amplifier pre-modenoise PD2 cleaner (PMC) eater EOM₁ FI 150W **NPRO PMC locking** ferometer injection locking EOM₂ **PSL** frequency frequency stabilization control

> reference cavity

LHO currently in process

Terra Hardwick, LVC meeting, LAWG, March 20, 2018



Optic replacements



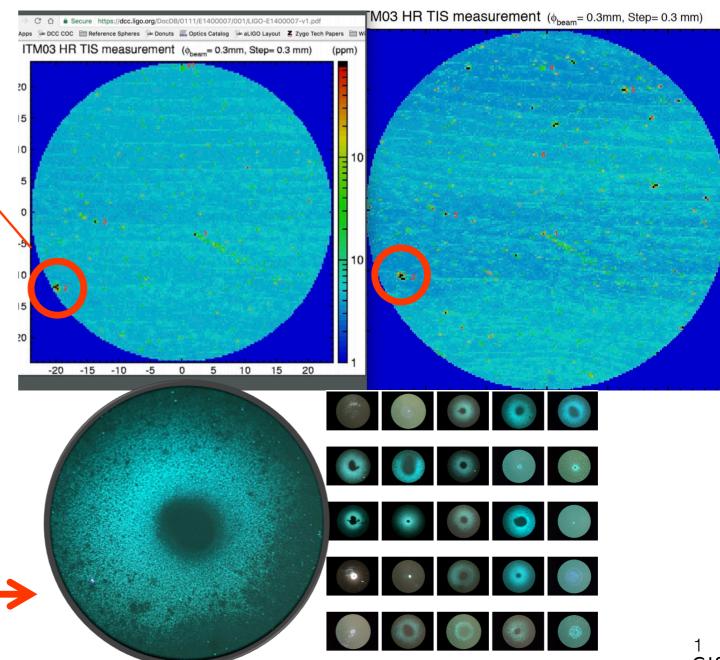
Absorber and more found on LHO ITMx (now replaced)

Billingsley, Brooks, Weaver, Zhang

Absorption > 1000
 ppm found where
 predicted by Hartman
 sensor

 Appears in pre and post installation scatter measurement

 Also found: "donuts" see G18000345 ~45 in beam. 1mm field

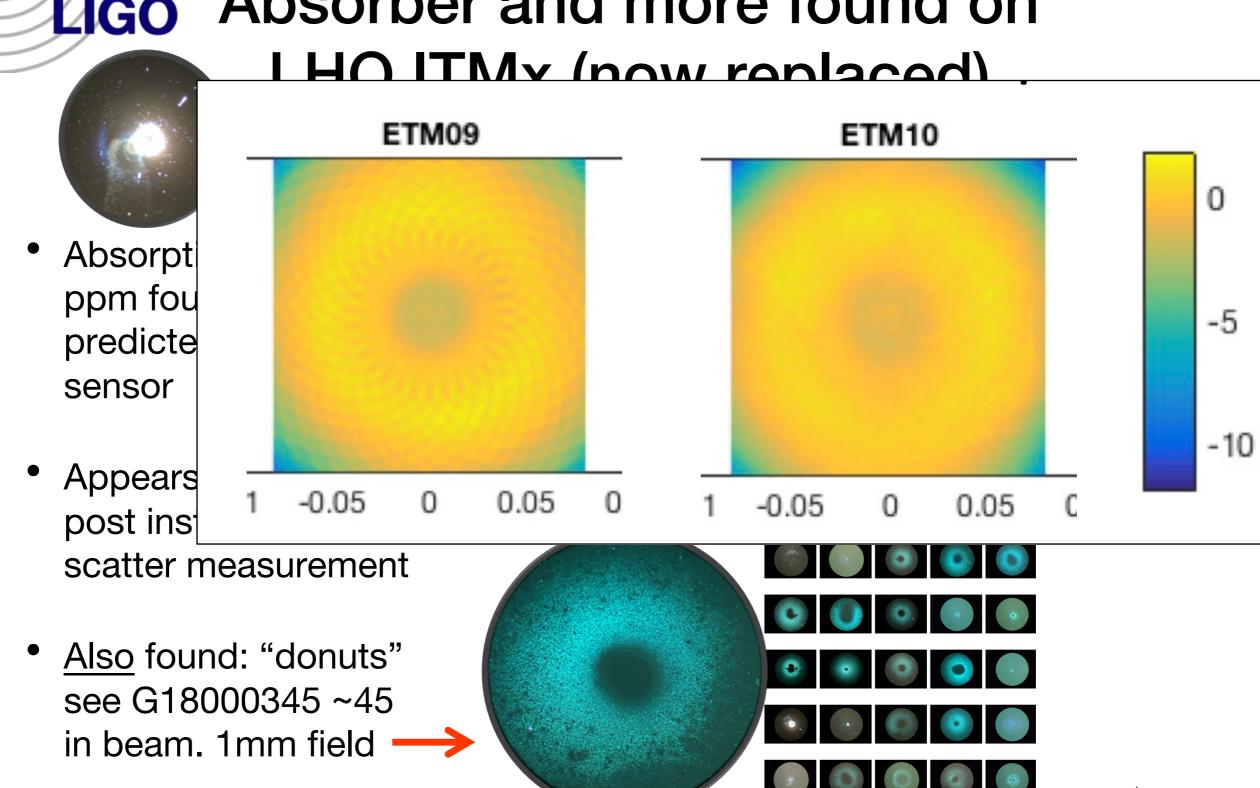




Optic replacements



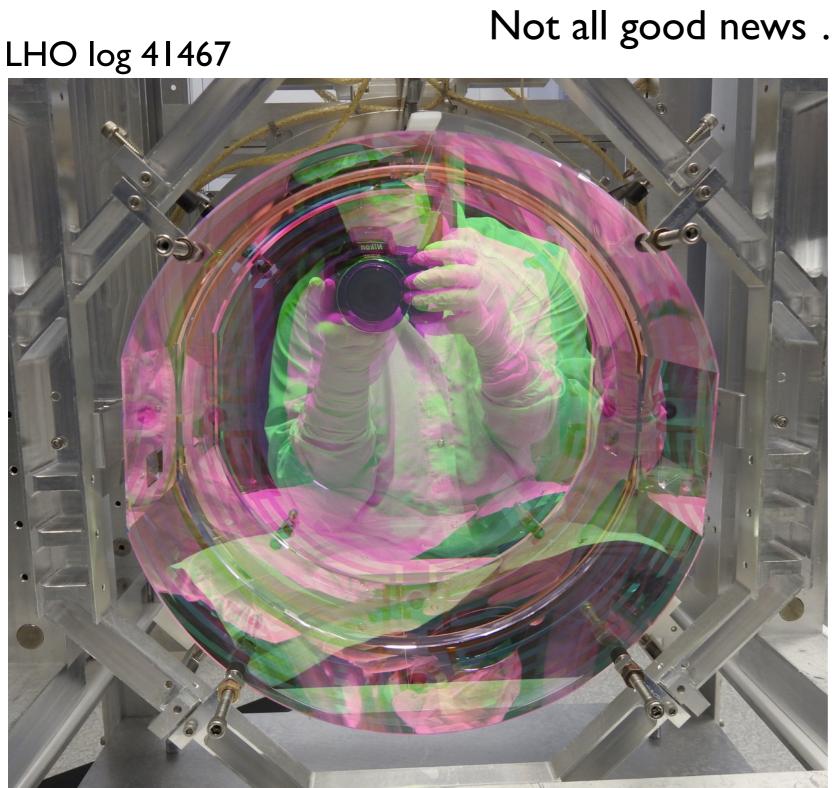


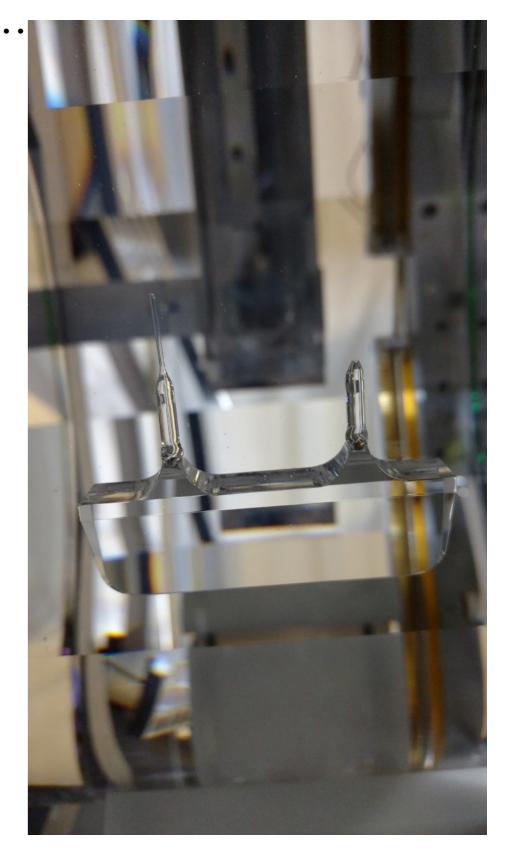




Optic replacements







O3 will probably start at the beginning of 2019

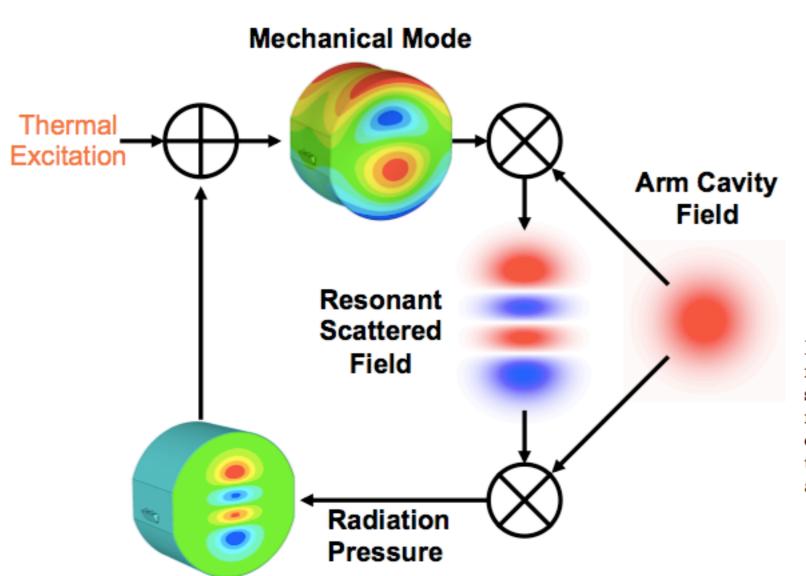




Parametric Instability

Low frequency noise & high power operation

Overlap of an mechanical mode of mirror and optical mode of cavity allow stored optical power to escape



Troublesome mode at 15.5 kHz:

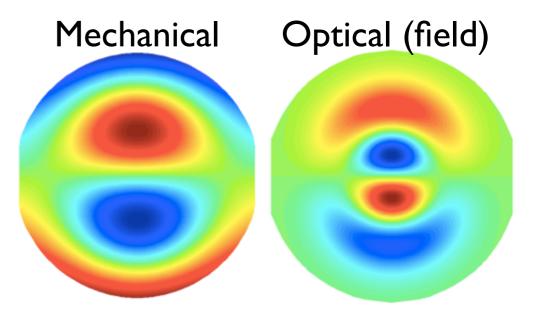
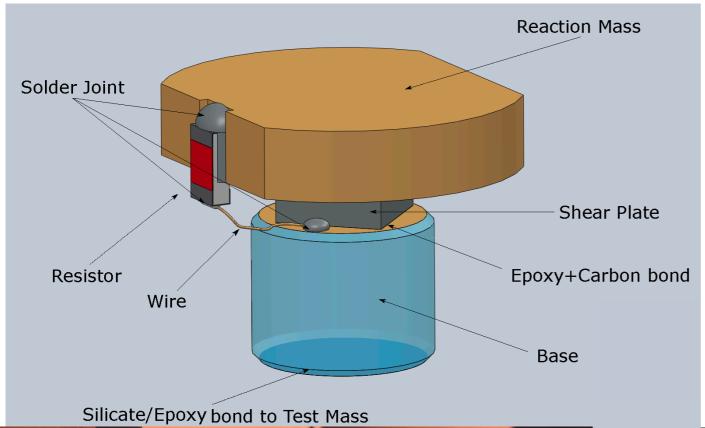


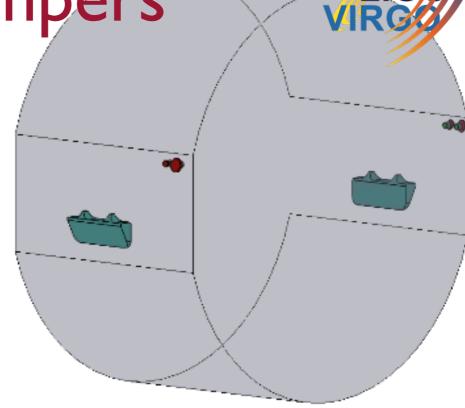
FIG. 3. The test mass mechanical mode and cavity optical mode responsible for the observed parametric instability are shown. The left panel is the test mass front surface displacement due to the mechanical mode, while the right panel is the optical mode field amplitude (red is positive and blue negative in both panels). Both of these modes occur at $15.5 \,\mathrm{kHz}$ and they have an overlap factor of $B_{m,n} = 0.1$.

DCC P1400254

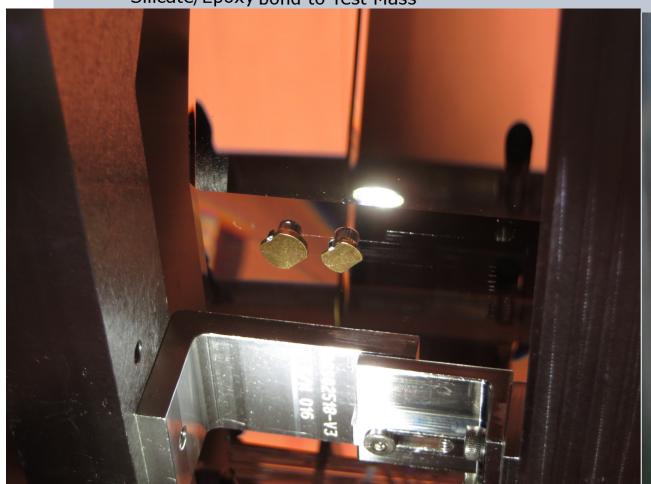


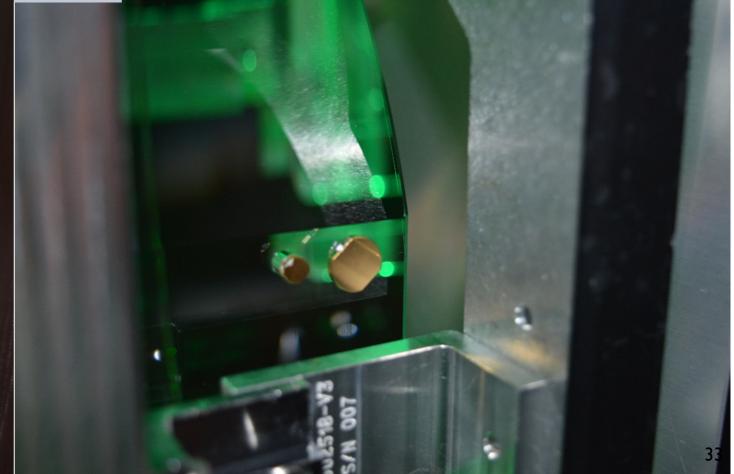
Acoustic Mode Dampers
Peter Fritschel - G1800454





Tested successfully at ETMX at LHO









Baffles
Install baffles throughout the system

- Very Black (DLC, Black Nickel)
- good coverage of the system
- careful control of vibrations
- improvements are not obvious

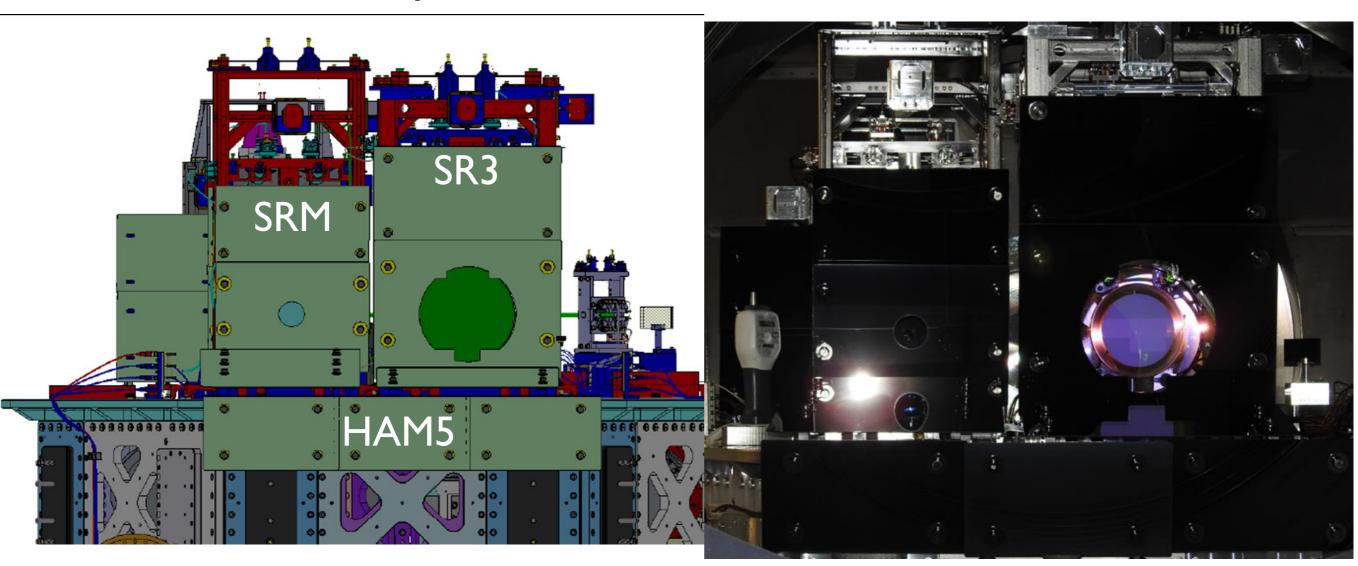
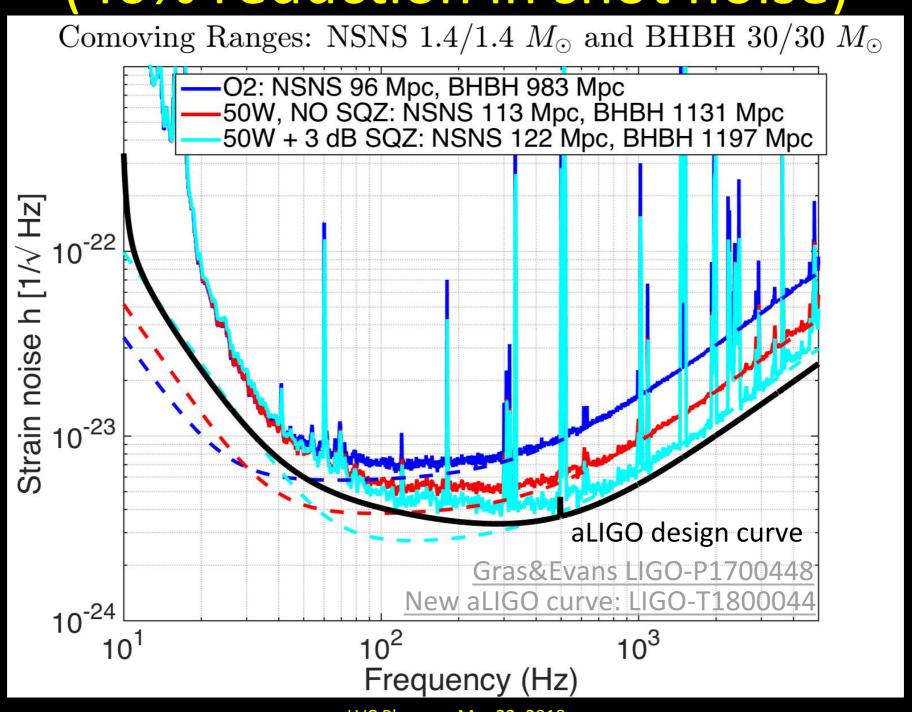


Photo taken by Alena Ananyeva and posted to the LLO logbook (#36113).

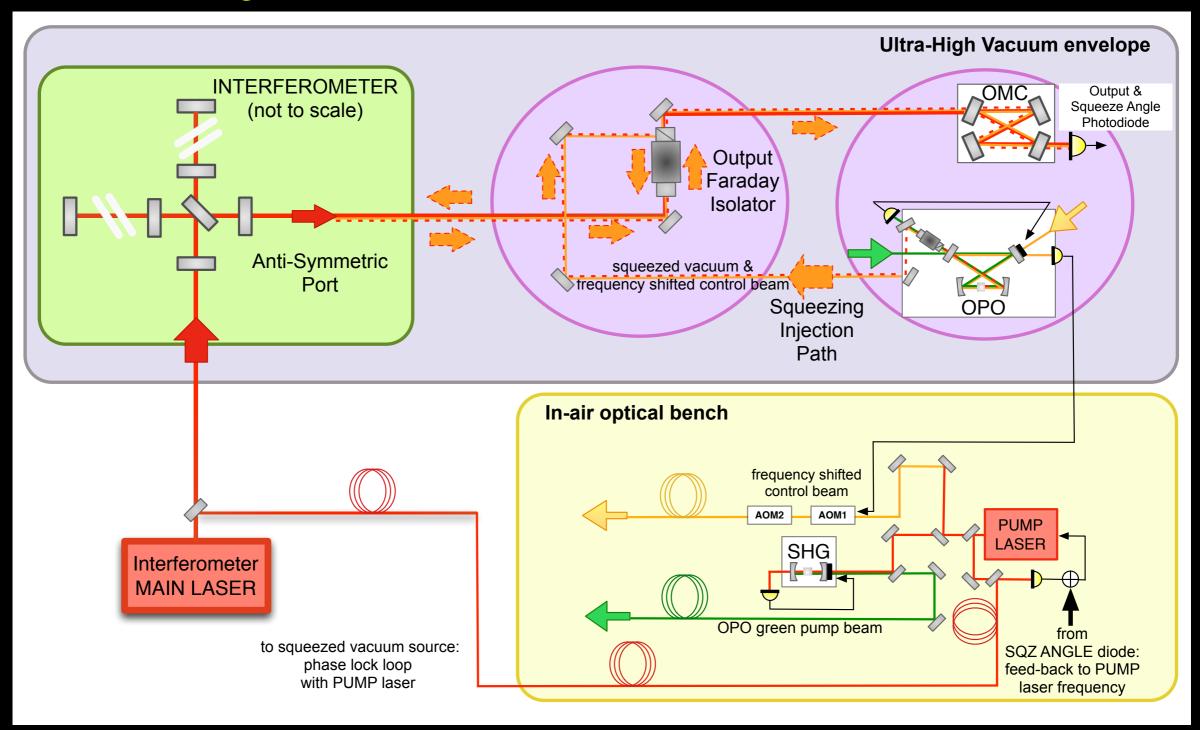
Squeezed light for O3

Lisa Barsotti - G1800598

Target: 3 dB of squeezing for O3 (40% reduction in shot noise)



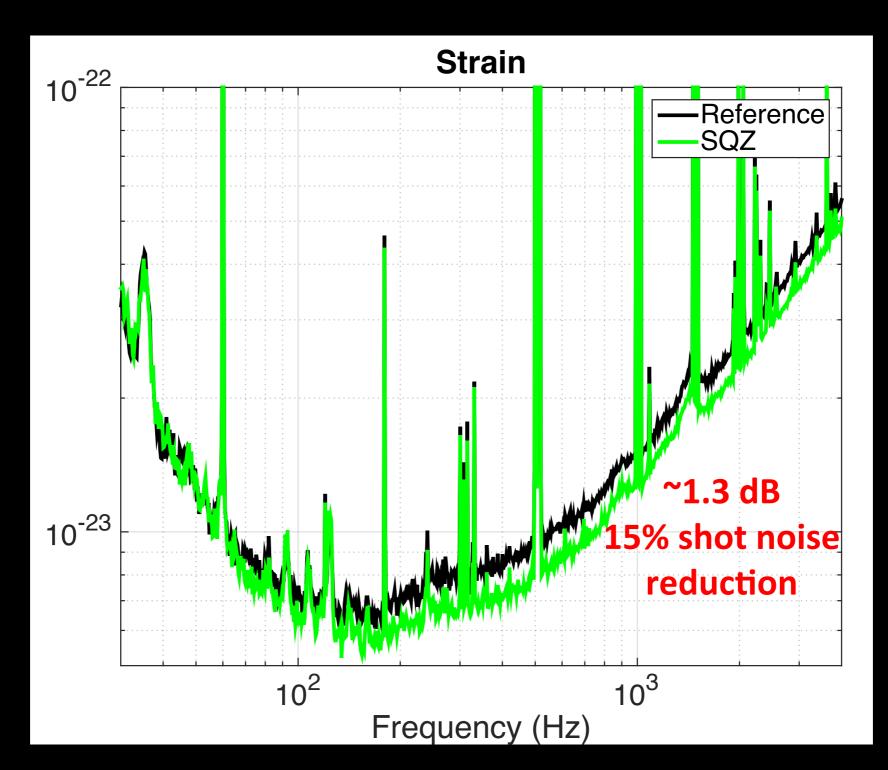
Conceptual layout of squeezing injection in Advanced LIGO



A suspended squeezed light source



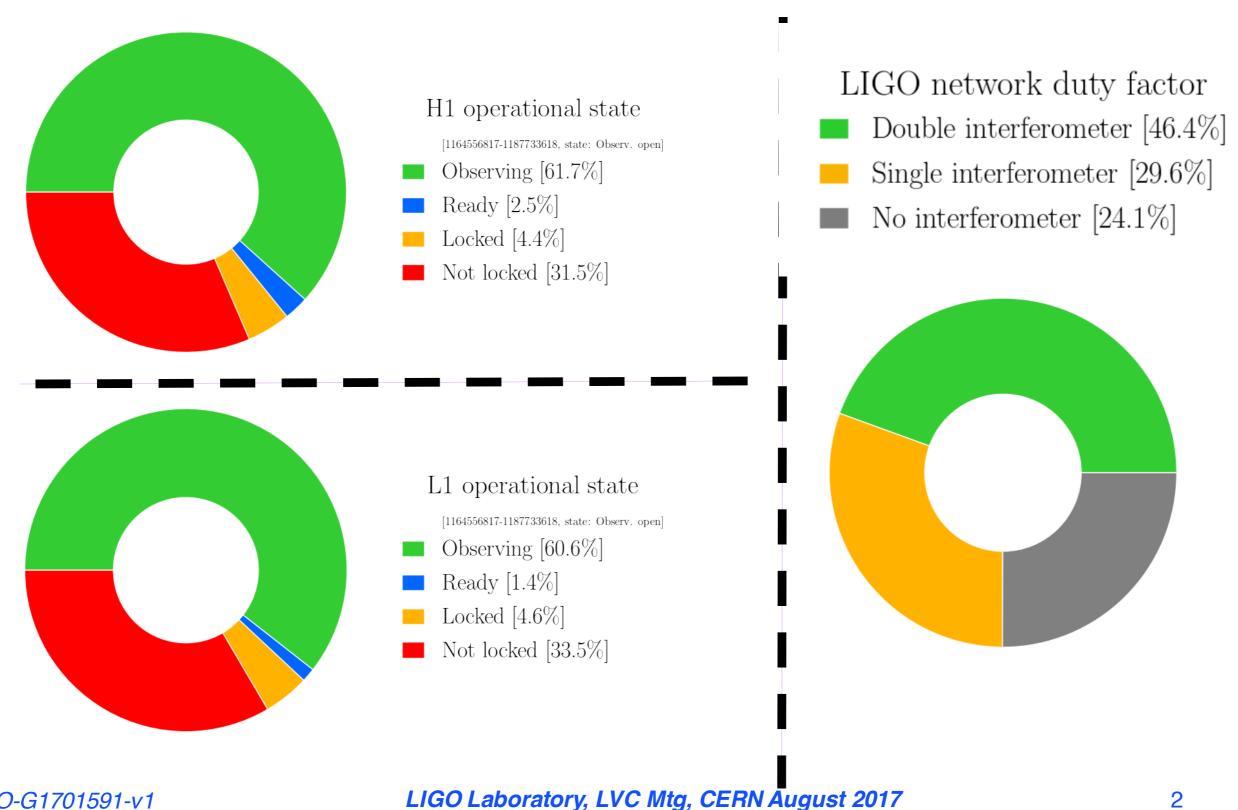
First squeezing injection into L1: it works!







O2 duty cycle not great

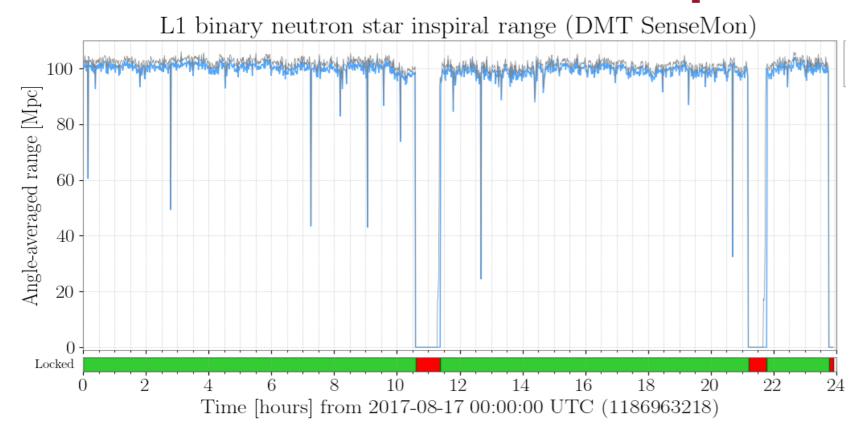


LIGO-G1701591-v1



Stable Operation

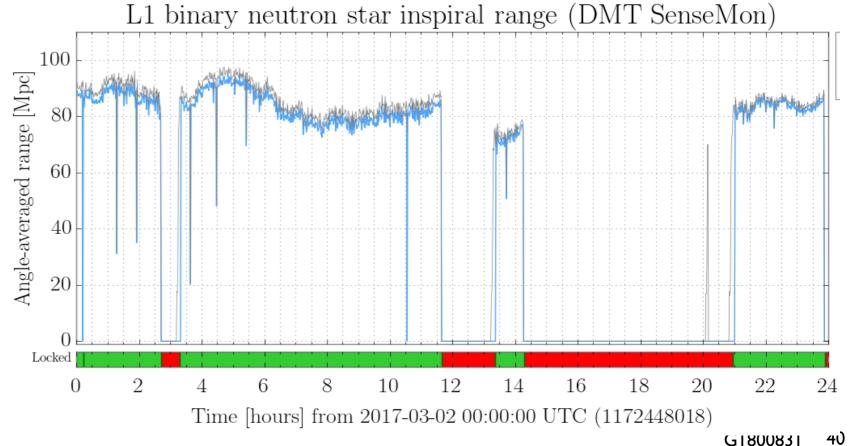




Good Days: Significant uptime, range is stable, **Observe BNS**

Frustrating Days: Poor uptime, range wanders, (noise not stationary)

- 2 earthquakes...
- I. Makes life hard.
- 2. Noise hunting difficult
- 3. Astrophysics difficult





Beam Rotation Sensor



Michael Ross - G1800439

Measures ground rotation (tilt) to allow operation during windy times.

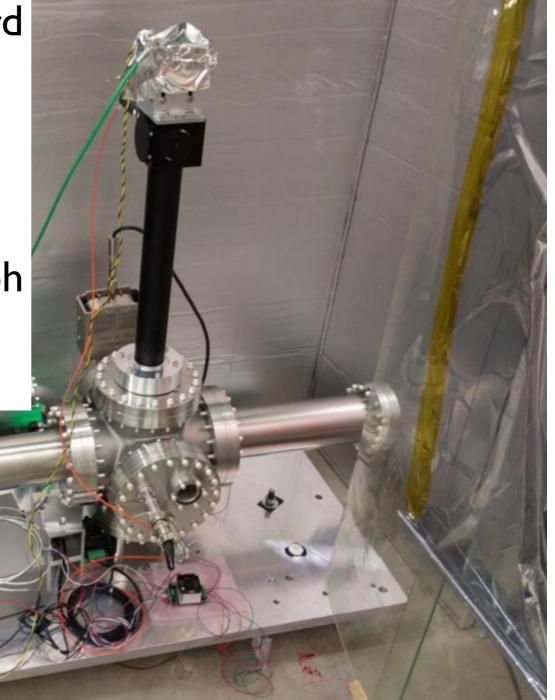
Two rotation sensors are installed at Hanford (only really necessary at the end stations)

Four more are being installed at Livingston (unable to find a quiet place in the corner.

pre-BRS: LHO hard to lock at wind > 20 mph

post-BRS: able to lock at up to 30 mph.

Jan 4 BBH detected in a 20 mph wind!

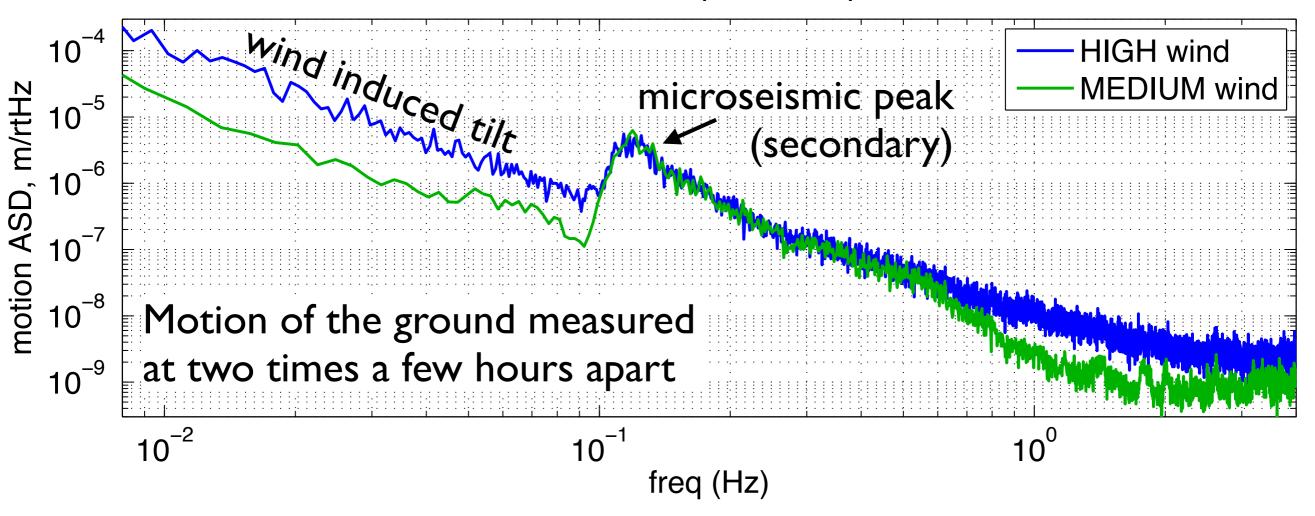




Recall - typical control condition



T240X as disp, loud v. quiet

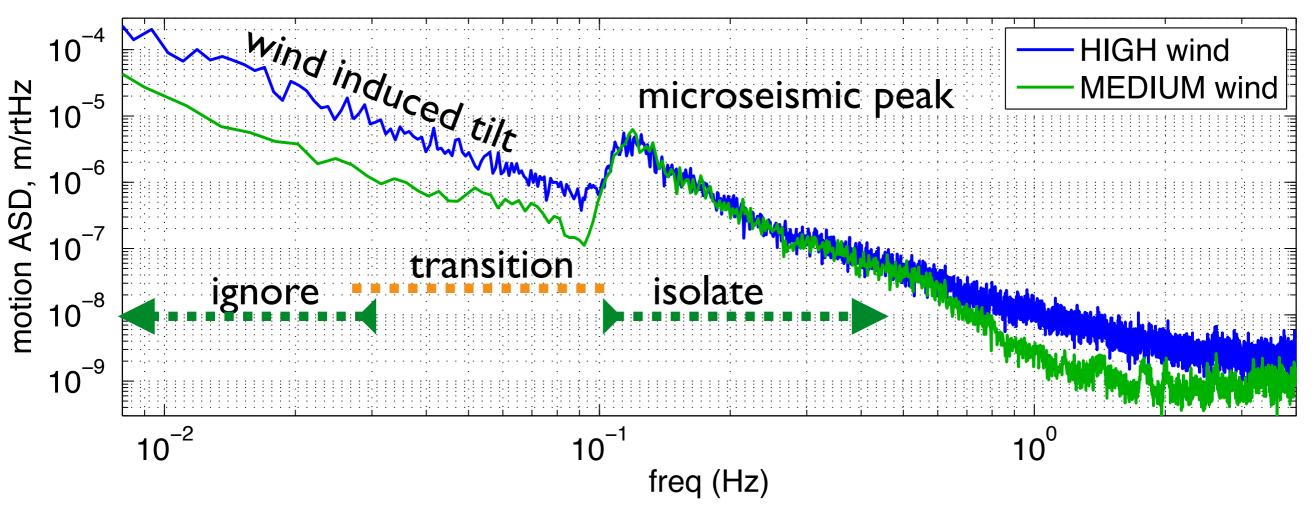




Recall - typical control condition



T240X as disp, loud v. quiet



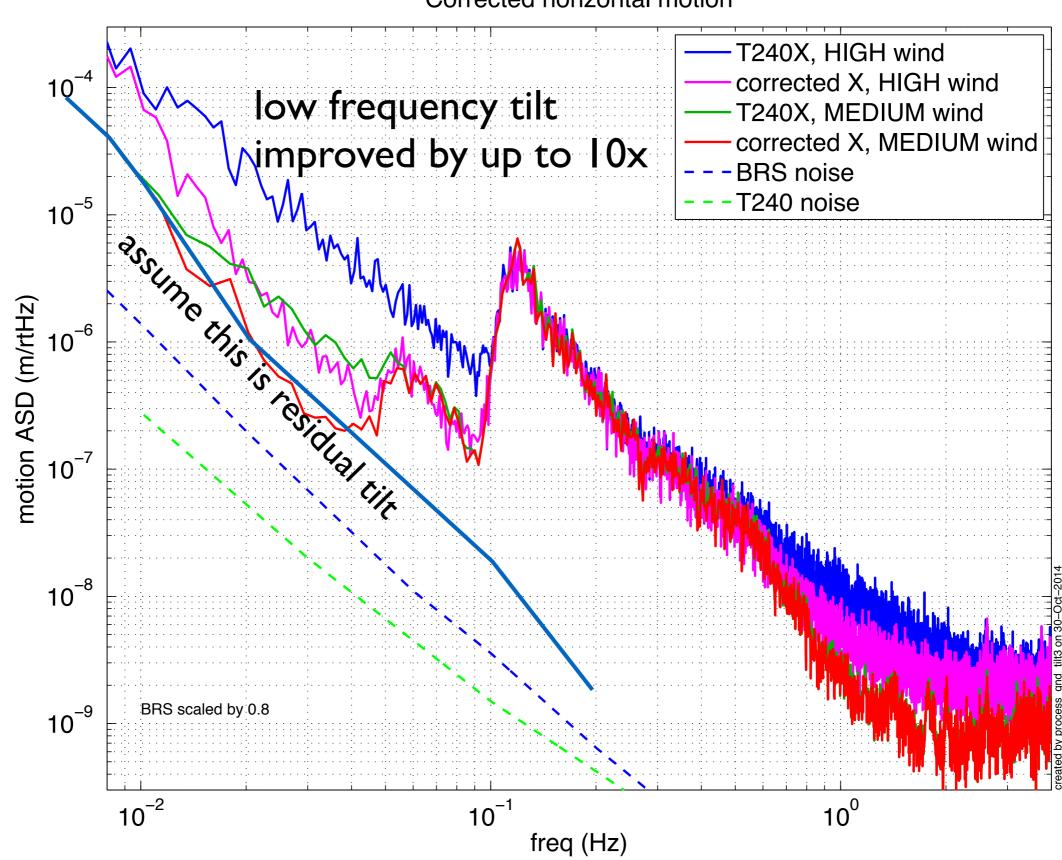
Use the ground motion signal for low freq. control (Sensor Correction)

- Use the signals above ~100 mHz to isolate against the microseism
- Filter out signals below ~30 mHz to not couple measured ground tilt.
- Transition band has amplification (waterbed effect). OK if band is quiet.



BRS Improves measured motion Corrected horizontal motion

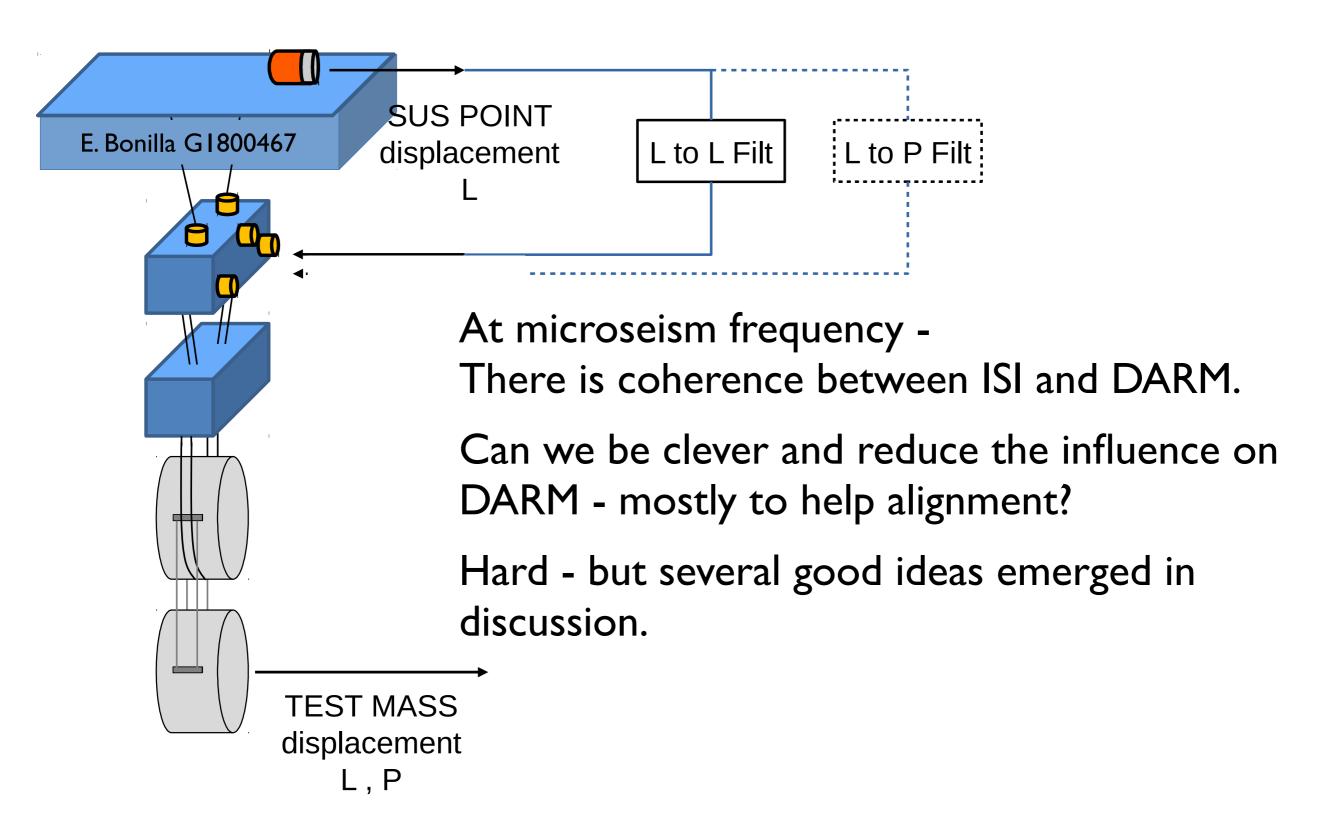






Improve DARM w/ Feedforward? VIRGO



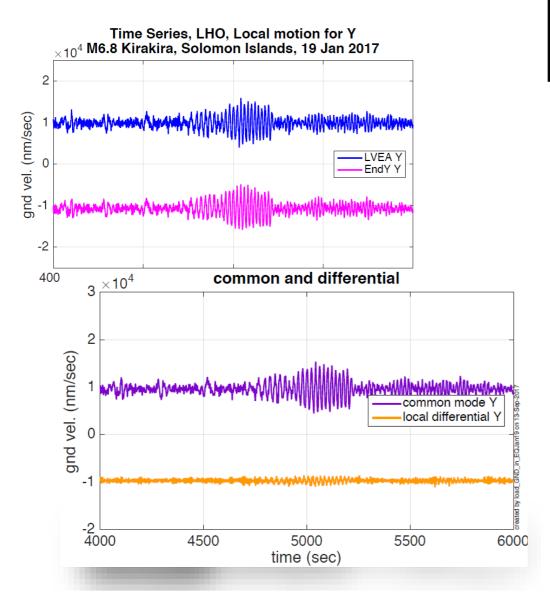


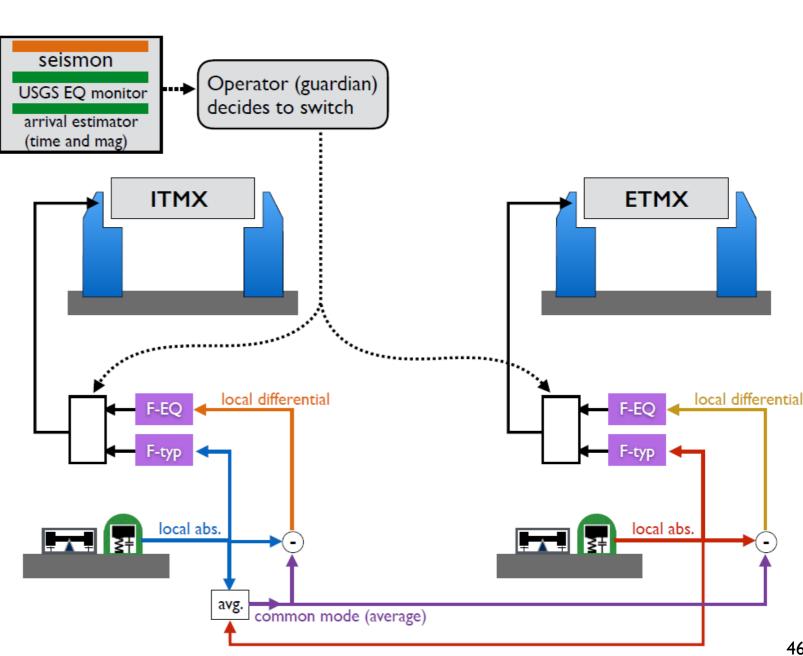


Seismic Control during Earthquakes: Brian Lantz, LIGO-G1800399



- New LIGO control scheme for use during teleseismic earthquakes
 - Do not isolate to minimize inertial motion; ride on common-mode motion & only isolate local differential
 - Similar to Virgo's GPIC
 - Installation very soon

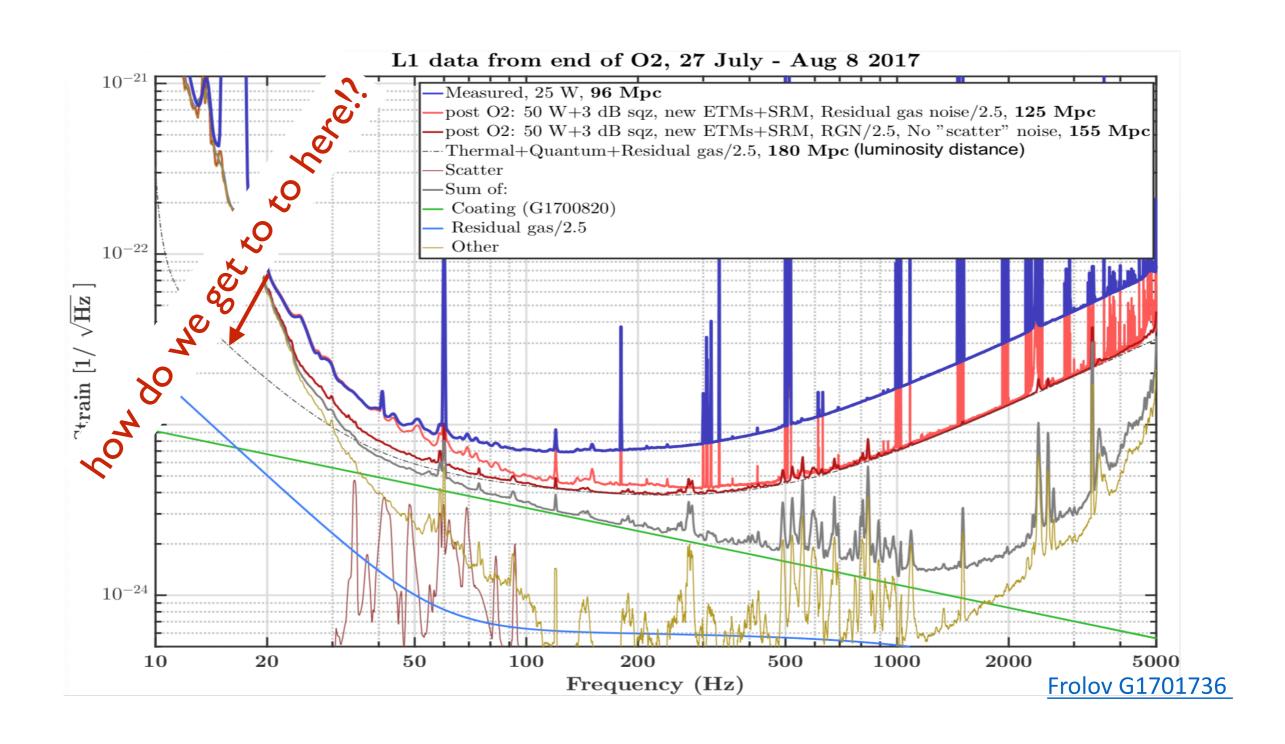






O4 - Design Sensitivity?







List of updates before O4.



D. Coyne G1800702

Likely?

- 08.06 Air Nozzle/Knife System
- 08.08 Reduced TM SUS response to B Fluctuation
- 08.69 PUM tuned mass dampers for violin modes
- 08.38 Imprv. vertical isolation for ISC Tip/Tilt SUS
- Stray Light improved Control (SLiC), parts B & C
- More new Real-time Control System I/O Chassis
- DAQ/DAQ Network software/hardware upgrade
- CDS Computer & Network 'refresh'
- **New High Power Laser**
- **Jitter Attenuation Cavity (JAC)**
- Wind Fence @LHO
- Improved alignment controls
- Added &/or Improved Alignment Sensors (QPDs?, Centroid Trackers?, ...)
- Global Seismic Control (non-inertial)
- Squeezer improvements

Possible?

- 08.27 Auto-centering of IMC WFS beams
- 08.28 Auto-centering of green ALS WFS
- 08.29 improve OptLev laser source
- 08.45 Acoustic abs. panels for PSL enclosures
- 08.47 RF centering to AS WFS
- Additional Electric Field Sensors (EFS)
- Compact BRS on ISI
- Quad thermal shielding
- Adaptive Wavefront Control (AWC) for the SRC
- 08.09 Incr. Vertical Isolation for SRC SUS: HSTS
- 08.10 Incr. Vertical Isolation for SRC SUS: HLTS
- Mode matching sensor
- Photon Actuator
- Machine Learning for Lock Acquisition
- Newtonian calibrator



Pre-O4 DI Jitter Attenuation Cavity (JAC)

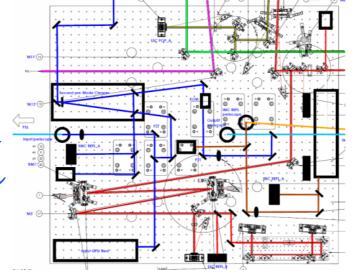


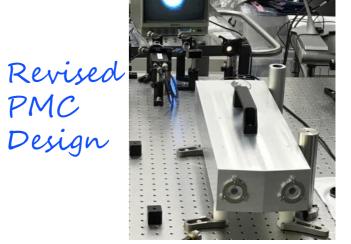
Requirements & conceptual design nearly completed

The optomechanical design of the Pre-Mode Cleaner

(PMC) will be adapted for the JAC

Sketch/concept for new JAC in HAM1

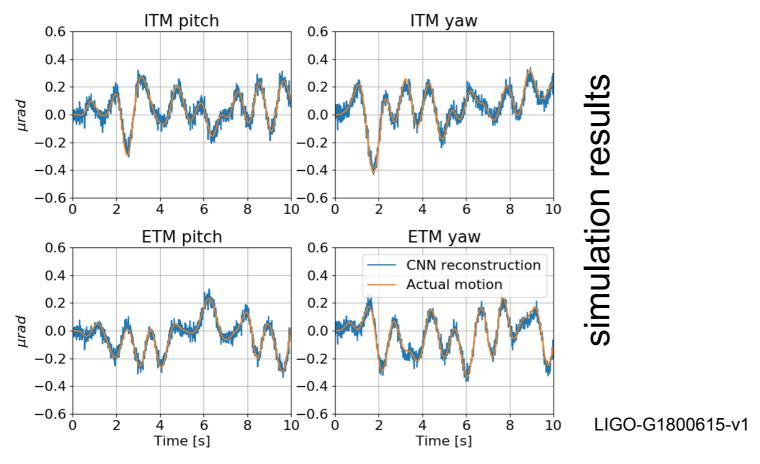


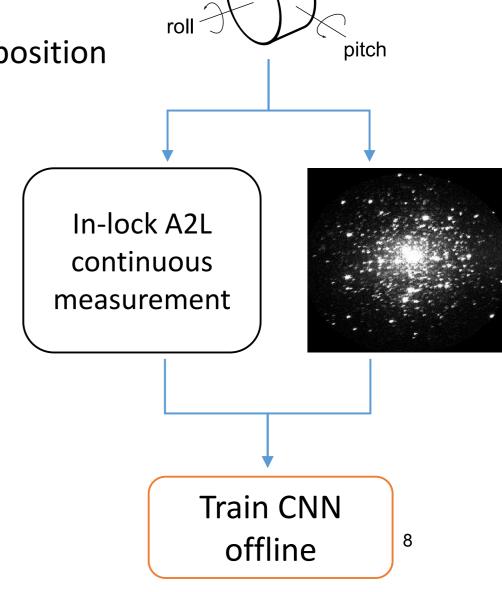


•	Task								2017				2018				2019				2020		Q3		2021		
U	Mode ▼	Task Name ▼	Duration 🔻	Start ▼	Finish 🔻	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2		Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
	*	CA start	0 days	Mon 10/1/18	Mon 10/1/18										4	10/1											
===	-5	O3	12 emons	Thu 11/1/18	Sun 10/27/19																						
		△ Dectector Improvements	1376 days	Mon 7/14/14	Mon 10/21/19															٦							
		Squeezed Light Upgrade (SLU, freq. independent)	750 days	Tue 9/15/15	Tue 7/31/18							1			7												
	-5	▷ Laser	955 days	Tue 2/23/16	Mon 10/21/19															٦							
		△ Jitter Attenuation Cavity (JAC)	645 days	Mon 12/19/16	Mon 6/10/19			Γ										$\overline{}$									
	*	Requirements & Conceptual Design	260 days	Mon 12/19/16	Fri 12/15/17																						
		Final Design (based on PMC)	6 mons	Mon 12/18/17	Fri 6/1/18							I															
		Fabrication, Procurement, Assy & Test	9 mons	Mon 10/1/18	Fri 6/7/19										1												
	*	JAC ready for install	0 days	Mon 6/10/19	Mon 6/10/19													*	6/10								
	-5	▶ Acoustic Mode Damper (AMD)	889 days	Fri 1/1/16	Thu 5/30/19																						
	-5	▶ Photon Actuation (Pact)	341 days	Wed 2/1/17	Wed 5/23/18							1		\neg													
	<u>_</u>	▶ Beam Rotation Sensor (BRS)	1010 days	Mon 7/14/14	Sat 5/26/18							1		\neg													
	*	▶ Installation	4.5 emons	Sun 10/27/19	Tue 3/10/20																						
	*	▷ Commissioning	6.5 emons	Tue 3/10/20	Mon 9/21/20																ì						
	*	04	36 emons	Mon 9/21/20	Wed 9/6/23																		ì				

Deep Learning for Controls Gabriele Vajente, LIGO-G1800359

- Beam spot position control
 - Beam decentering with angular noise couples to length!
 - Use fixed scatter points on test mass optics, convolved with the Gaussian beam, to determine beam centroid
 - Create training data set
 - Modulate pitch & yaw & demod to measure spot position (A2L procedure)
 - Train on images and measured beam spot
 - Apply to IFO to continuously reconstruct beam spot position
 - Plan to apply on LIGO IFO soon(ish)





yaw

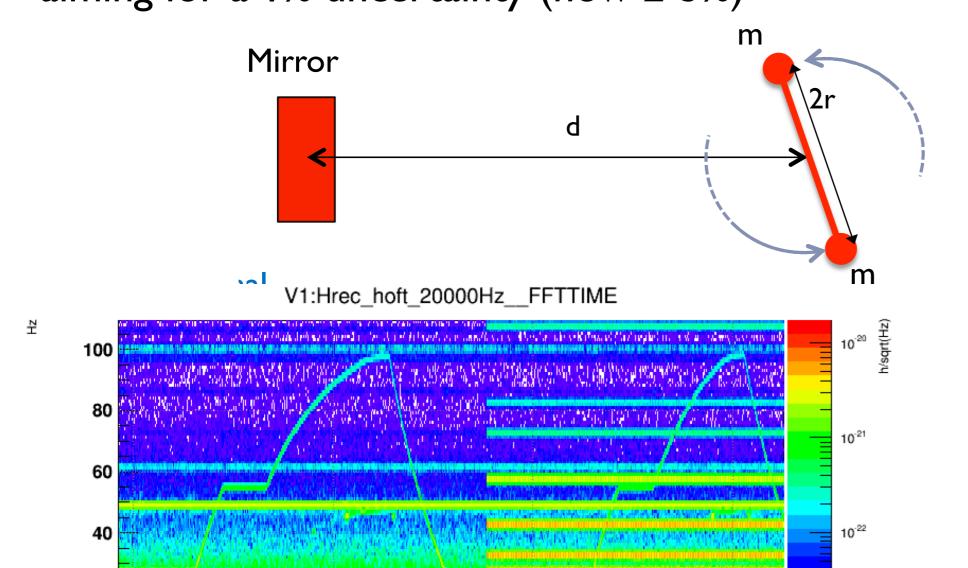


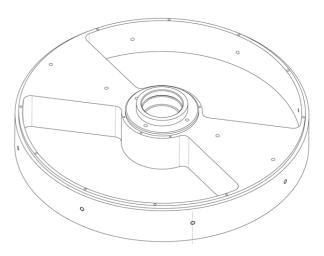
Newtonian Calibrator



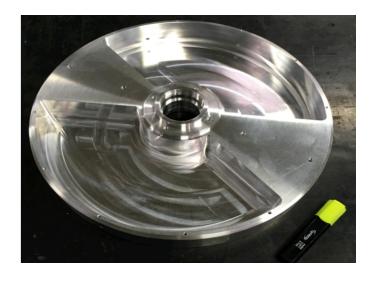
Benoit Mours - G1800442

Explore an additional calibration source - apply modulated force gravitationally (new apparatus to capitalize on an old idea) aiming for a 1% uncertainty (now 2-3%)





35 cm diameter



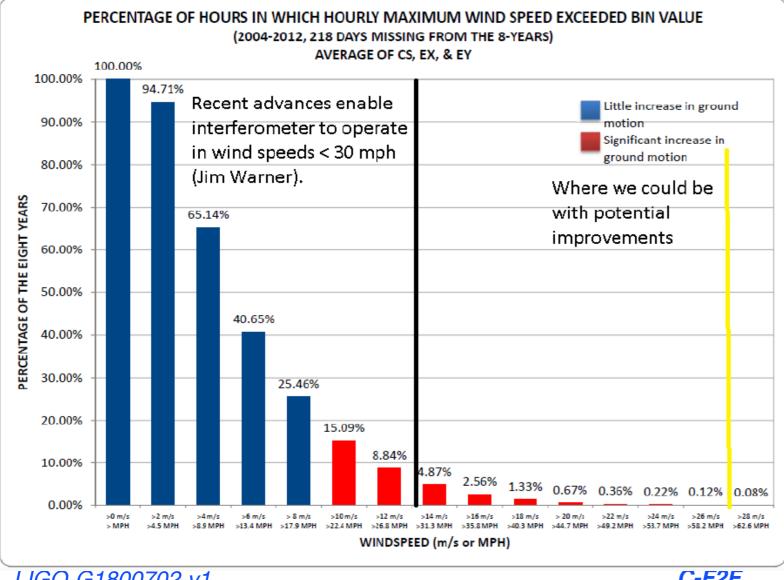
19h00

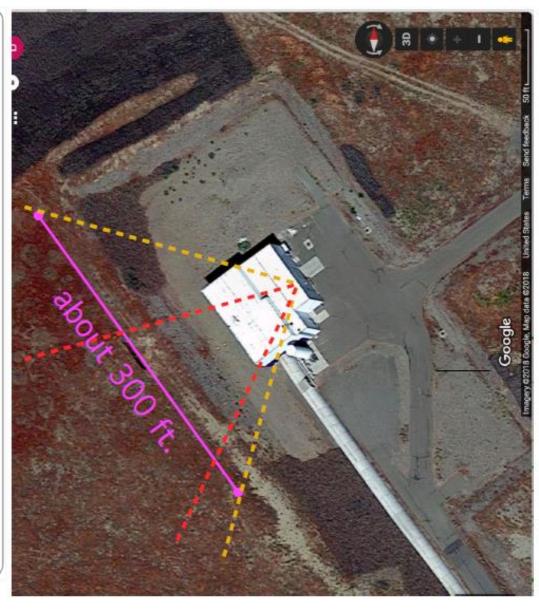
19h10



Pre-O4 DI Wind Fence @LHO

- Large/full scale fences for End-stations placed in direction of prevailing wind
- Pending ECR
- Candidate for pre-O3 install?
- Reference G1800148



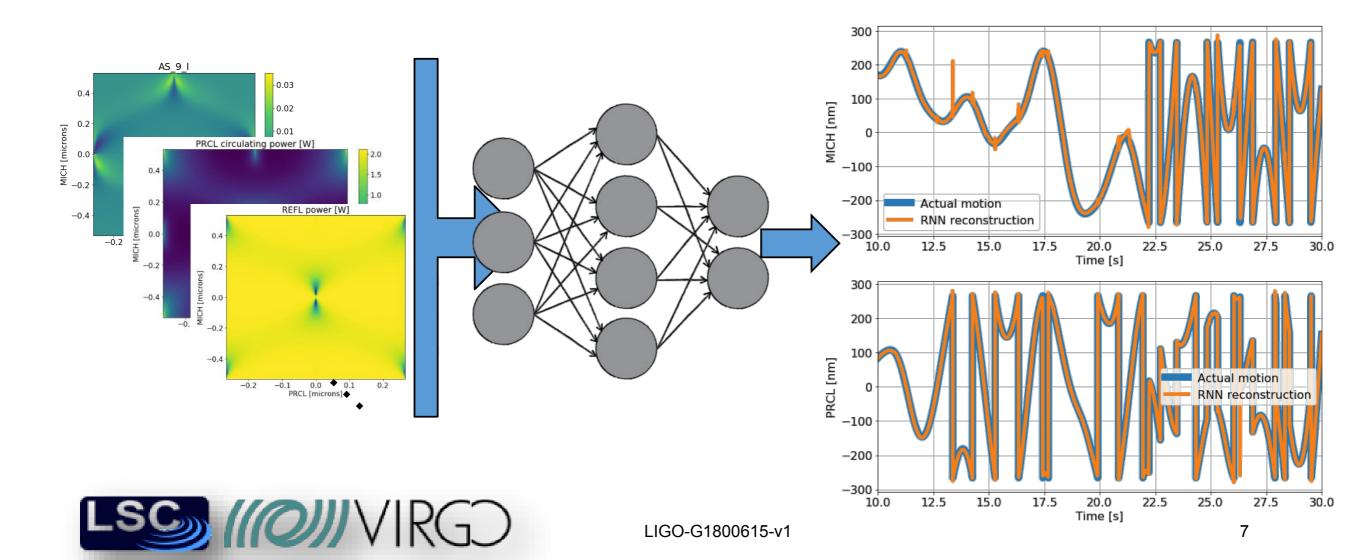


LIGO-G1800702-v1

C-F2F

Deep Learning for Controls Gabriele Vajente, LIGO-G1800359

- PRMI Lock Acquisition
 - Highly nonlinear problem; No signal except very close to resonance
 - Key insight use simulation to train RNN in "blind regions", then apply trained RNN to a real interferometer
 - Code being implemented for test on the 40m Lab @ Caltech



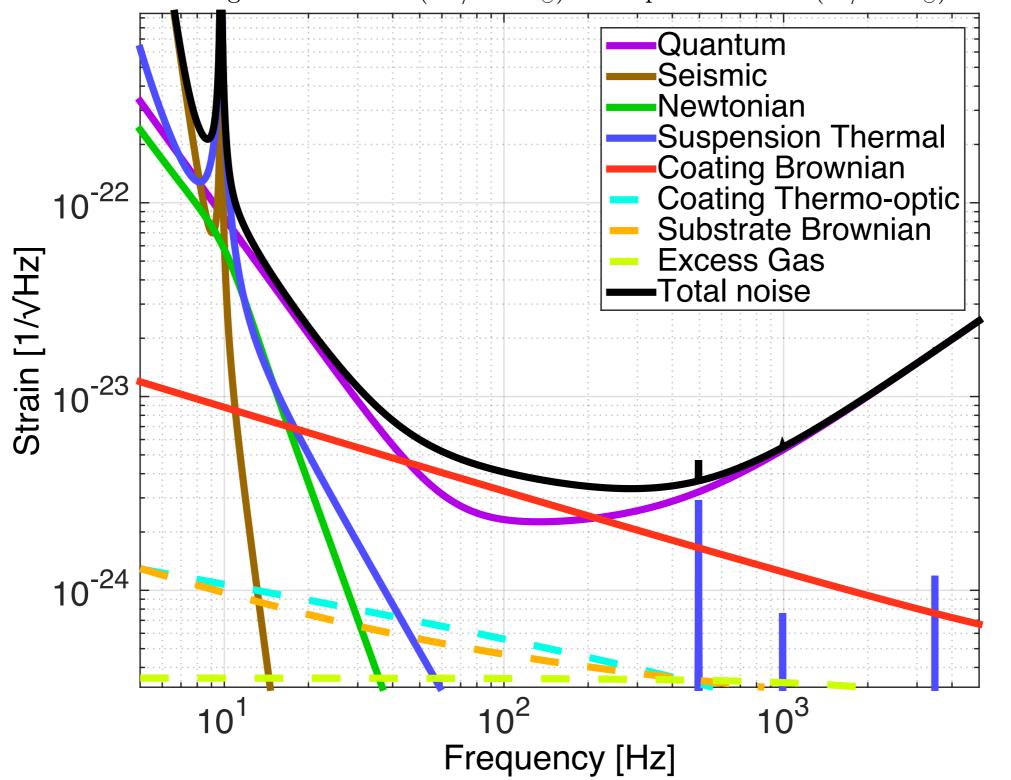


The LIGO Design Sensitivity



Barsotti et. al T1800044

aLIGO new design curve: NSNS $(1.4/1.4 M_{\odot})$ 173 Mpc and BHBH $(30/30 M_{\odot})$ 1606 Mpc





What is coming?



Table 1 Plausible target detector sensitivities. The different phases match those in Figure 1. We quote the range, the average distance to which a signal could be detected, for a $1.4M_{\odot}+1.4M_{\odot}$ binary neutron star (BNS) system and a $30M_{\odot}+30M_{\odot}$ binary black hole (BBH) system.

from PI200087

	LI	GO	Vi	rgo	KAGRA				
	BNS	BBH	BNS	BBH	BNS	BBH			
	range/Mpc	range/Mpc	range/Mpc	range/Mpc	range/Mpc	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			

Using our observation of GW170817, we calculate that the merger rate density has a 90% credible range of 320 - 4740 Gpc⁻³ yr⁻¹ (Geo. mean is 1200 Gpc⁻³ yr⁻¹)

From our observations of BBHs, we infer that their rate of mergers is in the range $\sim 1.2 \times 10^{-8} - 2.13 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$ (Geo. mean is 50 Gpc⁻³ yr⁻¹)

	BNS range	BNS vol	rate	BBH range	BBH Vol	BBH rate
O3	0.125	0.008	10	1.2	7.2	360
Design	0.173	0.022	26	1.6	17	860

A+ elevator pitch

- An incremental upgrade to aLIGO that leverages existing technology and infrastructure, with minimal new investment, and moderate risk
- Target: factor of 1.7* increase in range over aLIGO
 - → About a factor of 4-7 greater CBC event rate
- Bridge to future 3G GW astrophysics, cosmology, and nuclear physics
- Stepping stone to 3G detector technology
- Can be observing within 6 years (mid- 2024)
- "Scientific breakeven" within 1/2 year of operation

Zucker

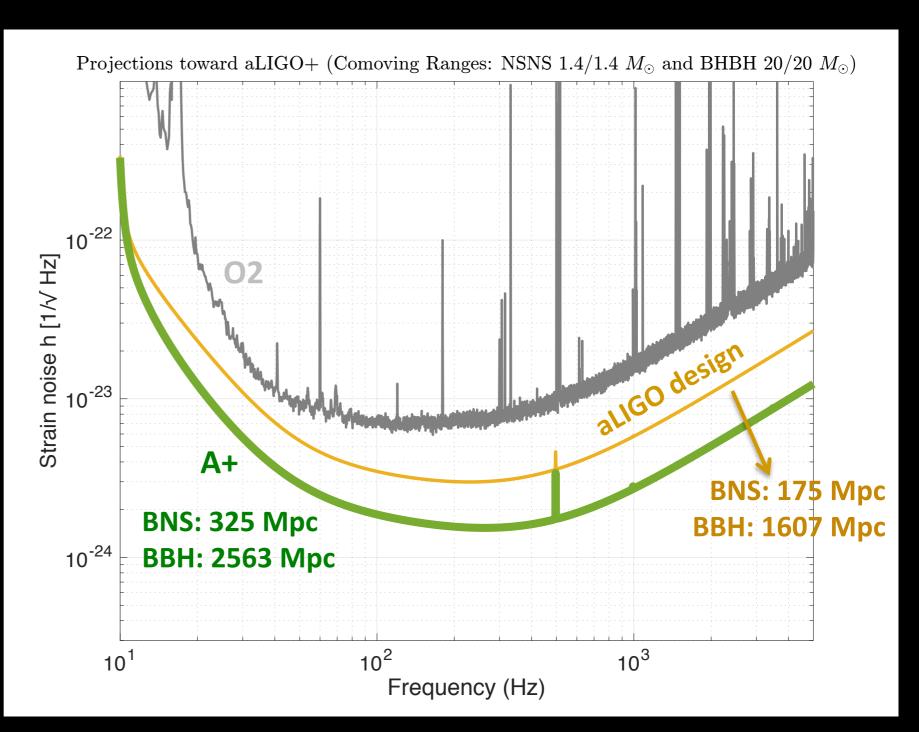
Incremental cost: a small increment on aLIGO

*BBH 30/30 M_{\odot} : 1.6x *BNS 1.4/1.4 M_{\odot} : 1.9x

A+: a mid-scale upgrade to Advanced LIGO

- Improved quantum & thermal noise
- Projected observation: mid-2024
- BNS rate 6.7x aLIGO
 1-13 BNS/month!*
- BBH rate 4.1x aLIGO
 17-300 BBH/month!*

A+ key parameters: 12dB injected squeezing 15% readout loss FDS, 300 m filter cavity 20 ppm RT FC loss CTN half of aLIGO

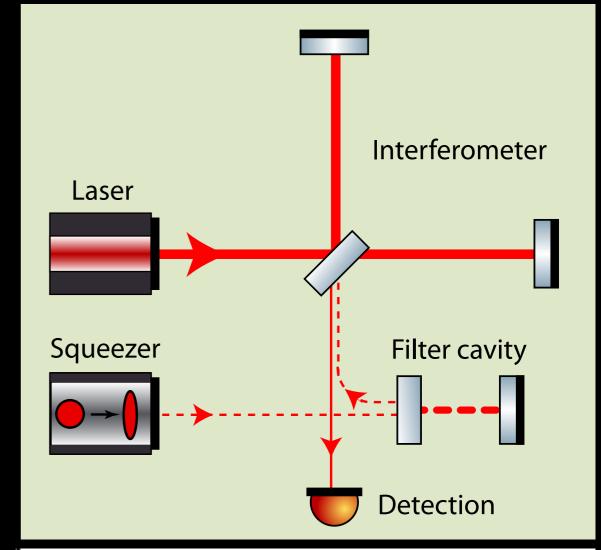


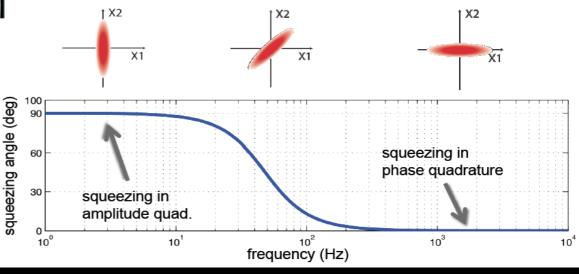
^{*}Based on P170608 and P170817 rate density estimates

Frequency-Dependent Squeezing

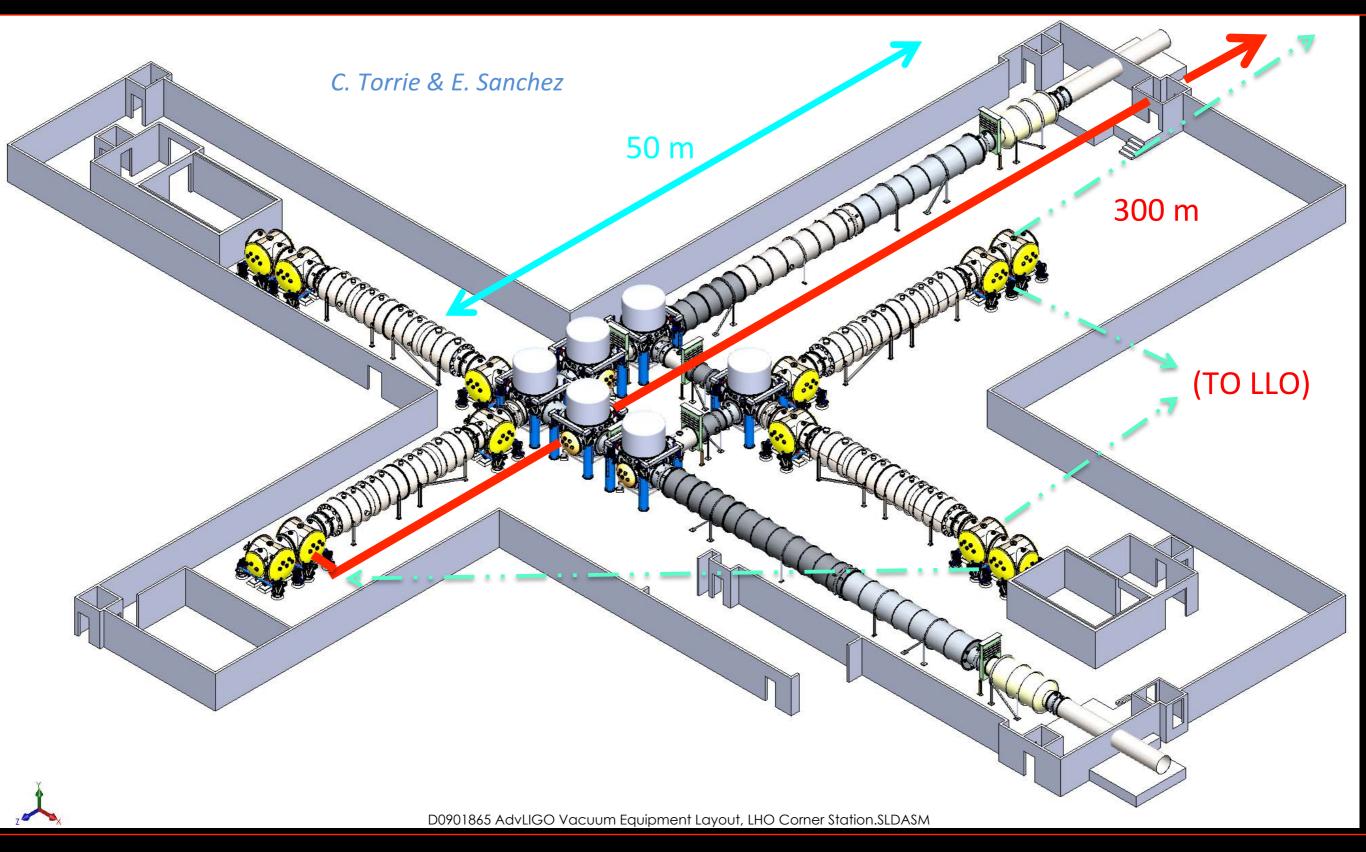
- Optical "filter cavity" (FC)
- Rotates squeezing phase to both improve radiation pressure at LF and phase noise at HF
- Low-loss, high finesse cavity with bandwidth ~100 Hz
- Sensitive to optical losses, scattering and mirror motion
- Requires seismic isolation and quiet mirror suspension
- Requires *high-quality FC mirrors*
- \rightarrow Requires $L_{FC} \sim 100 \text{ m}$

300 m!





Filter cavity vacuum system and facility mods

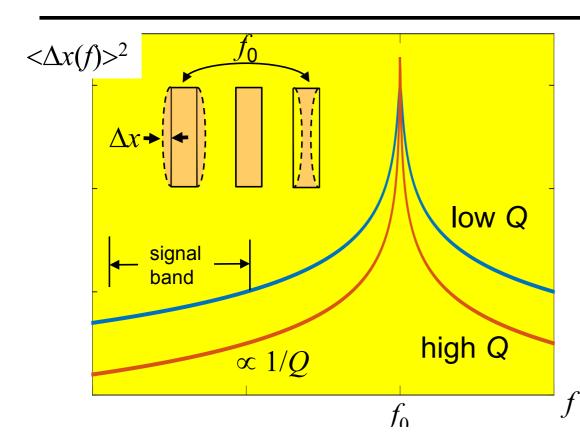




Improved Optical coatings



LSC Center for Coatings Research (CCR) is an ambitious program to address the challenging problem of reducing thermal noise from LIGO mirror coatings



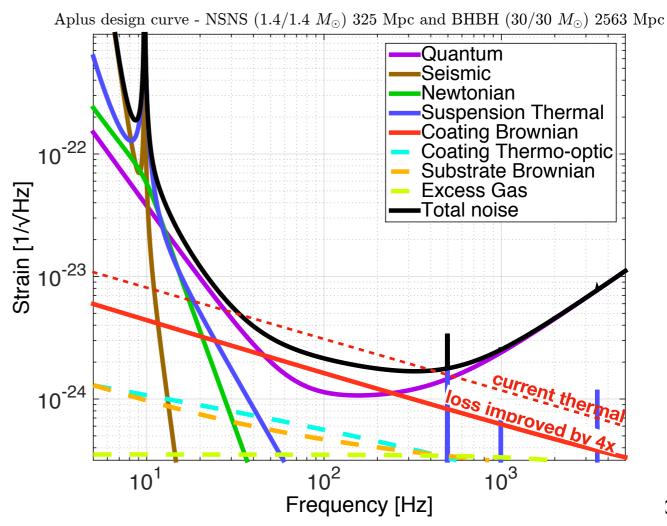
Coating-dominated loss structural damping:

temperature coating thickness
$$S_x(f,T) \approx \frac{2k_BT}{\pi^2f}\frac{d}{w^2Y}\phi\left(\frac{Y'}{Y} + \frac{Y}{Y'}\right)$$
 laser beam radius coating mechanical loss

Y Levin Phys. Rev. D 57

Oversimple: kT of energy per elastic mode uniform mass, viscous damping

moves front of mirror w.r.t. center of mass

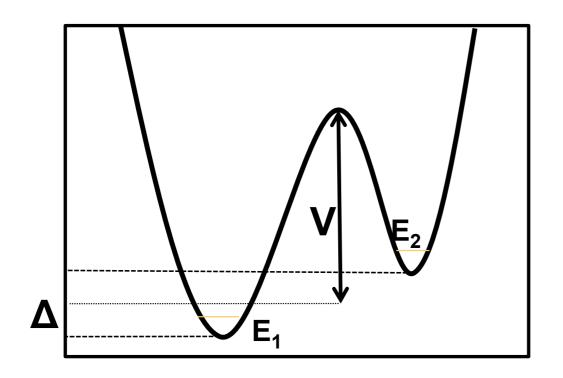


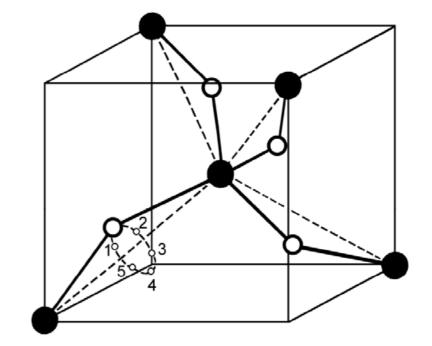




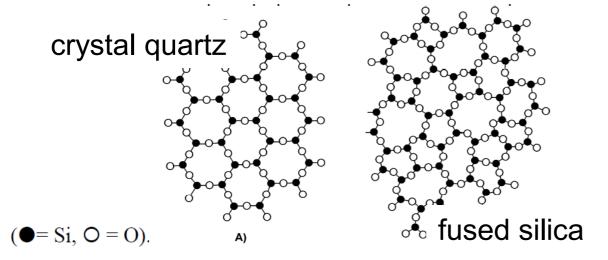
Low-frequency losses in amorphous dielectrics

- Conventionally associated with low energy excitations (LEEs)
 - conceptualized as two-level systems (TLS)





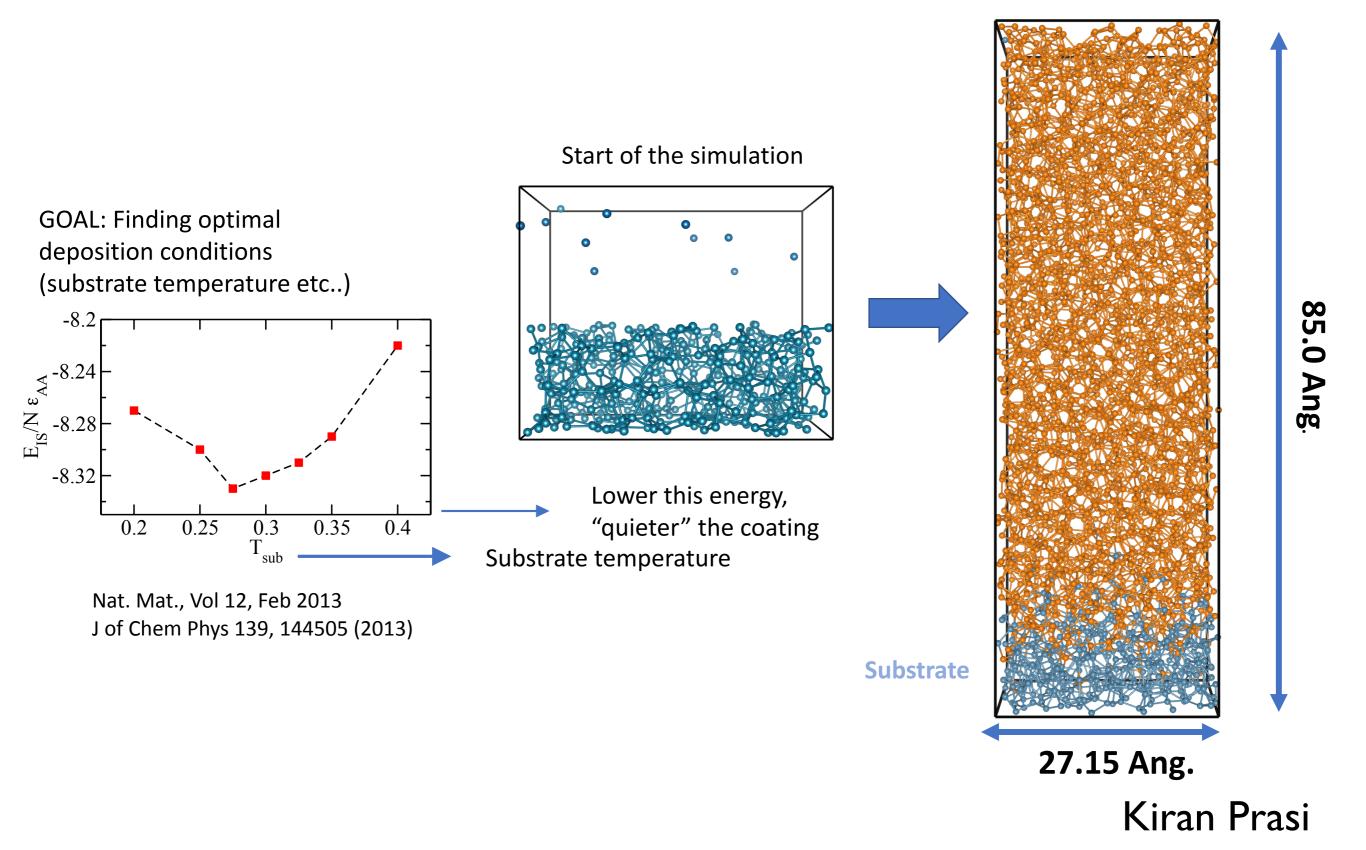
Oversimple picture: bond flopping



Distribution of TLS in silica due to disordered structure

figures from B.S. Lunin monograph

Vapor deposition simulations

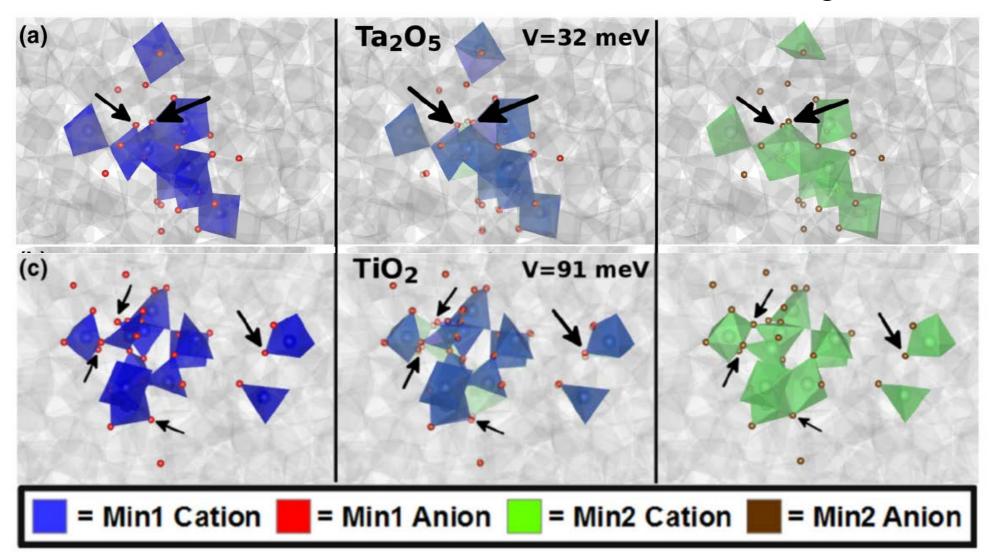




Theoretical Guidance: Molecular Dynamics



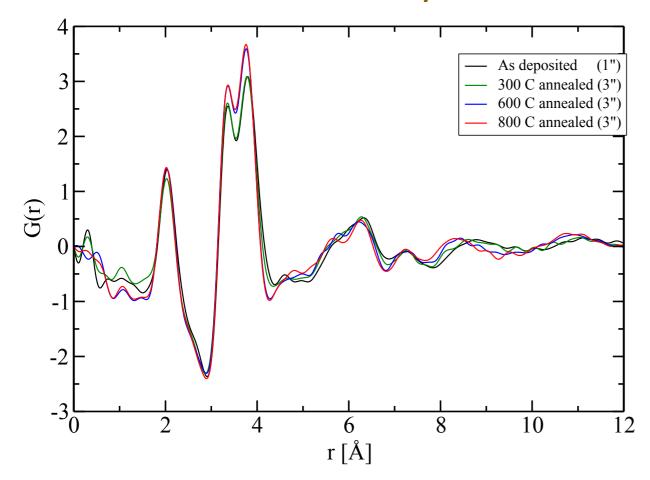
- Molecular dynamics calculations for amorphous materials
 - provide insight into dissipation mechanisms
 - can suggest promising material combinations
- Some observations: simple bond-flopping inadequate picture
 - TLS involves dozens of atoms in nm-scale configurations



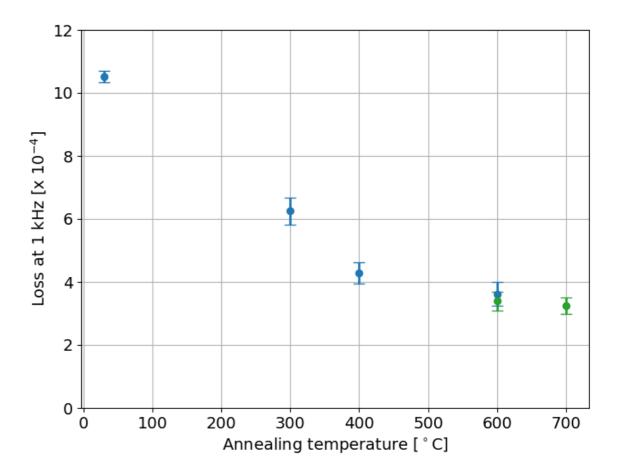
J. Trinastic, R. Hamdan, C. Billman, H. Cheng, Phys. Rev. **B93**, 014105 (2016)

Structure and mechanical loss characterization

Grazing Incidence Pair Distribution Function SLAC National Accelerator Laboratory



Data from SSRL, unpublished



Vajente et. al., Caltech, unpublished

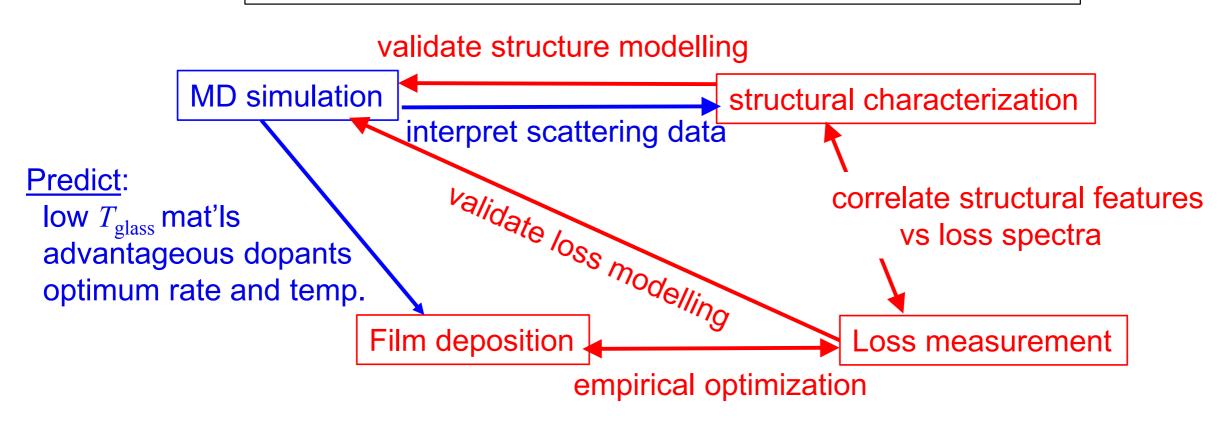


Three Research Themes



- Molecular dynamics simulation of atomic structure
 - simulate the deposition process
- Atomic structure determination: X-ray and electron microscopy
 - medium range order
- Macroscopic property measurements
 - elastic and optical properties

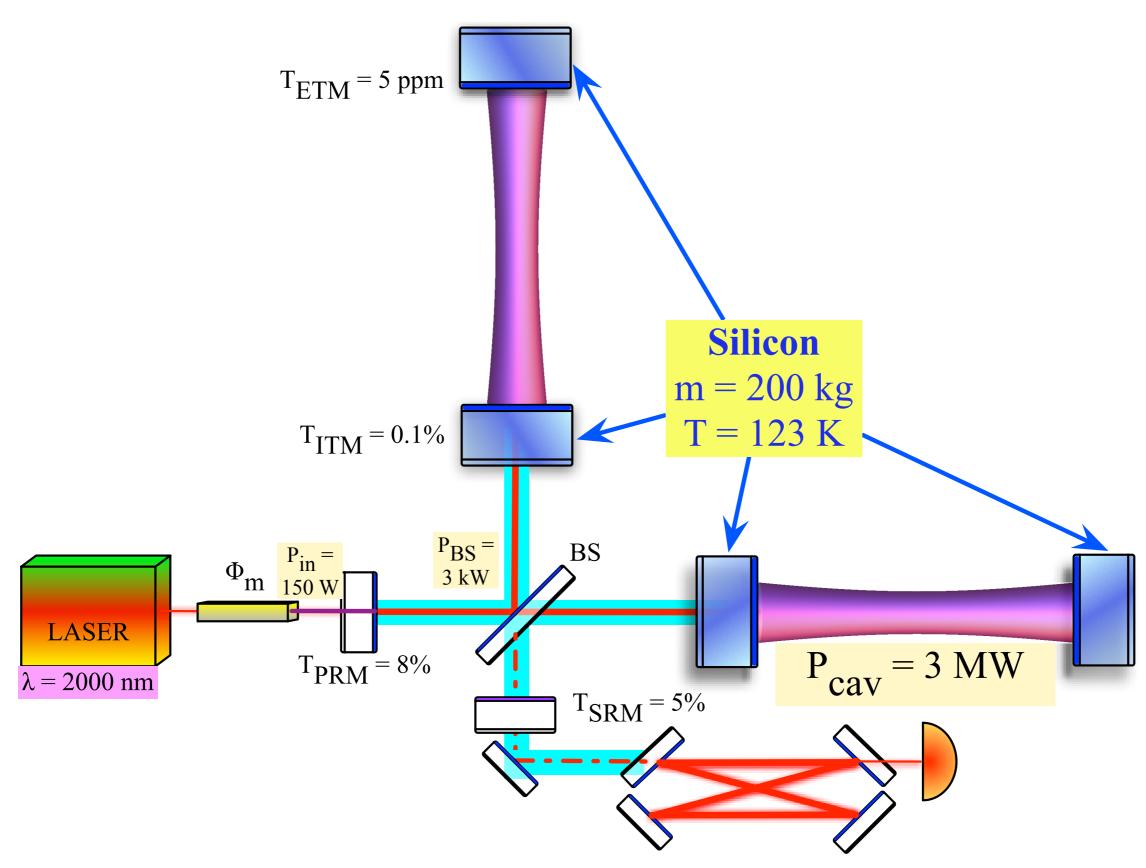
Experiment and theory reaching maturity to usefully interact





LIGO Voyager





Sub-Systems

A. Brooks, R. Adhikari G1800347

- Silicon Mirrors: 140-200 kg, mCZ (re-use all suspensions, except Quads)
- Coatings: a-Si/SiO₂ or others
- SEI: re-use of existing equipment (minimal modifications)
- Wavelength Choice: ~2 microns
- Cryogenics: 123 K (for zero CTE), radiative (non contact) cooling
- Lasers (~2 um): P_{PRM} ~ 140 W, P_{ARM} ~ 3 MW (re-use PSL infrastructure)
- Thermal Compensation: Silica compensation plates only (CO₂ lasers, no ring heaters; no heating of test mass)
- Photodiode Quantum Efficiency: 80 -> 99% for 2 um

Draft Whitepaper: https://dcc.ligo.org/LIGO-T1400226



Silicon mirrors at 123 K



A. Brooks, R. Adhikari G1800347



Magnetic Czochralski for 200 kg Si test masses





Normally all the ingots produced are processed into wafers

- We are procuring "slugs" to determine properties of interest to us
- 20 cm diameter by 1 cm





 Rana A & Eric G with 300 mm ingot at Shin-Etsu, WA





Instrument Science White Paper T1800133

- Measure low optical absorption and scattering, uniform optical index and birefringence across large pieces of bulk silicon.
- Procure, develop, and qualify large test masses.
- Initial cooldown of test masses and suspensions.
- Cool the mirrors in operation with low-vibration.
- Study additional vibrational noise due to and boiling cryogenic fluids.
- Stable control of the mirrors at low temperature.
- Improved controllability of suspensions without violating the load limits of the existing Seismic Isolation tables.
- Cryogenic Engineering of Test masses.
- Study bond loss for new suspensions: ears, ribbons, etc.
- Characterization of the thermo-mechanical properties of cryogenic materials (thermal expansion, thermal conductivity).
- Research on crackle noise in suspension elements and dissimilar materials joints for cryogenic operation.
- Development of inertial sensors which can operate at cryogenic temperatures.
- Development of passive damping materials which can operate at cryogenic temperatures.
- Development of cantilever springs fabricated from crystalline materials.





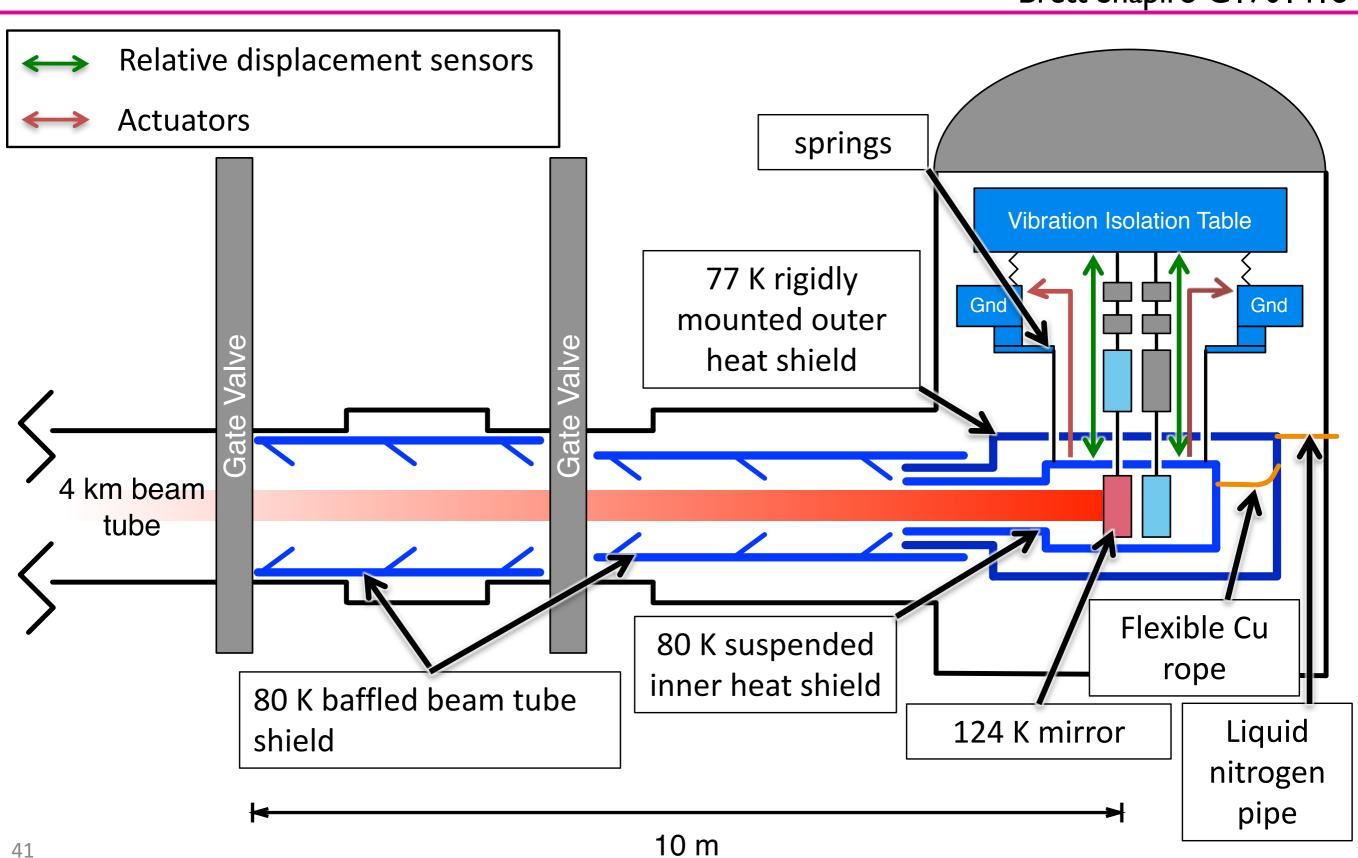
Instrument Science White Paper T1800133

- Development of crystalline suspension fibers (ribbons/fibers).
- Longer wavelength laser operating at 200 W.
- Longer wavelength squeezing.
- High power IO components (modulators, isolators) at new wavelengths.
- Low-noise, high quantum efficiency photodiodes for longer wavelength.
- Ion milling level metrology for chosen wavelength.
- Thermal compensation.
- Parametric instability avoidance and mitigation.
- High emissivity black coatings for mirror barrels (for radiative cooling).
- Low phase noise cryogenic interferometer prototype.
- Development of improved optical coatings (amorphous and crystalline) for longer wavelength, optimized for operating at cryogenic temperatures.
- Improved coating thickness uniformity and substrate surface figure error over the larger area of the larger test masses while managing the residual substrate fixed lens.
- Developing silicon substrate super-polishing, surface figuring, bulk scatter and refractive index uniformity.
- Arm length stabilization using a non-harmonically related laser wavelength.
- Contamination control of the low temperature mirror surface.



Cryogenic mirror system

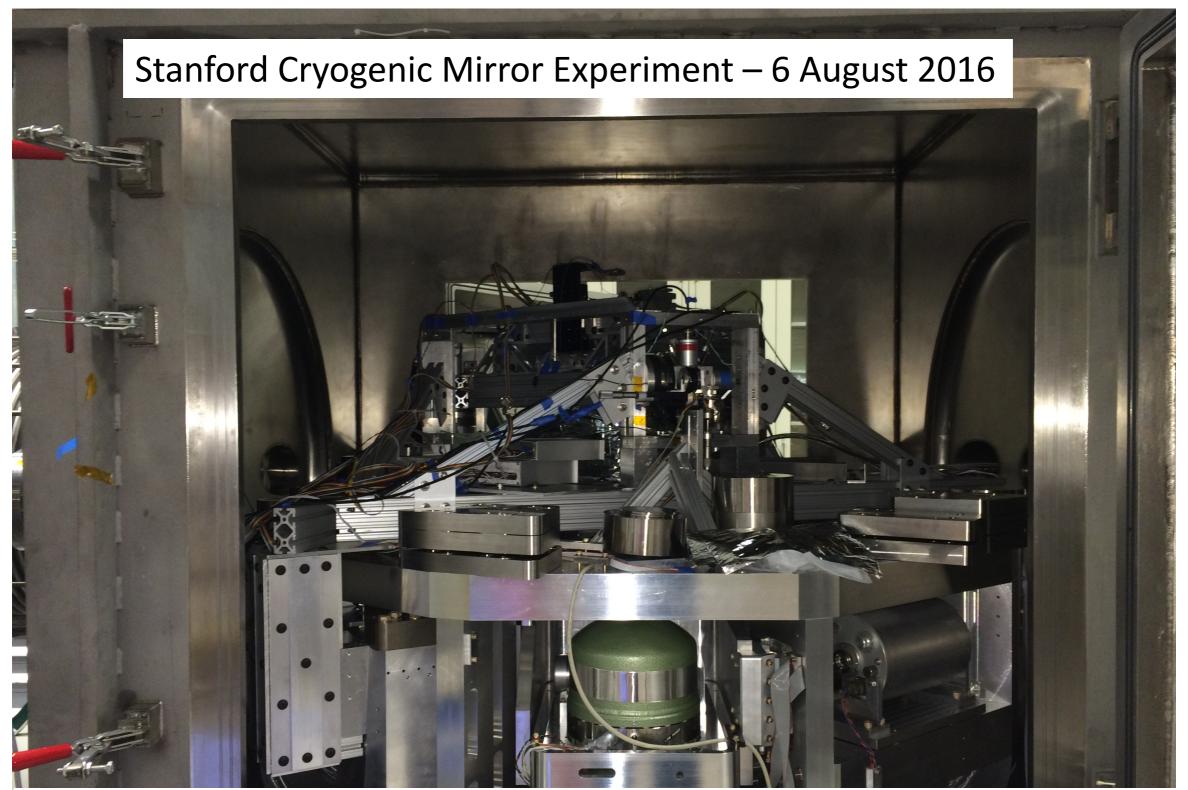
Brett Shapiro G1701418





Stanford Prototype





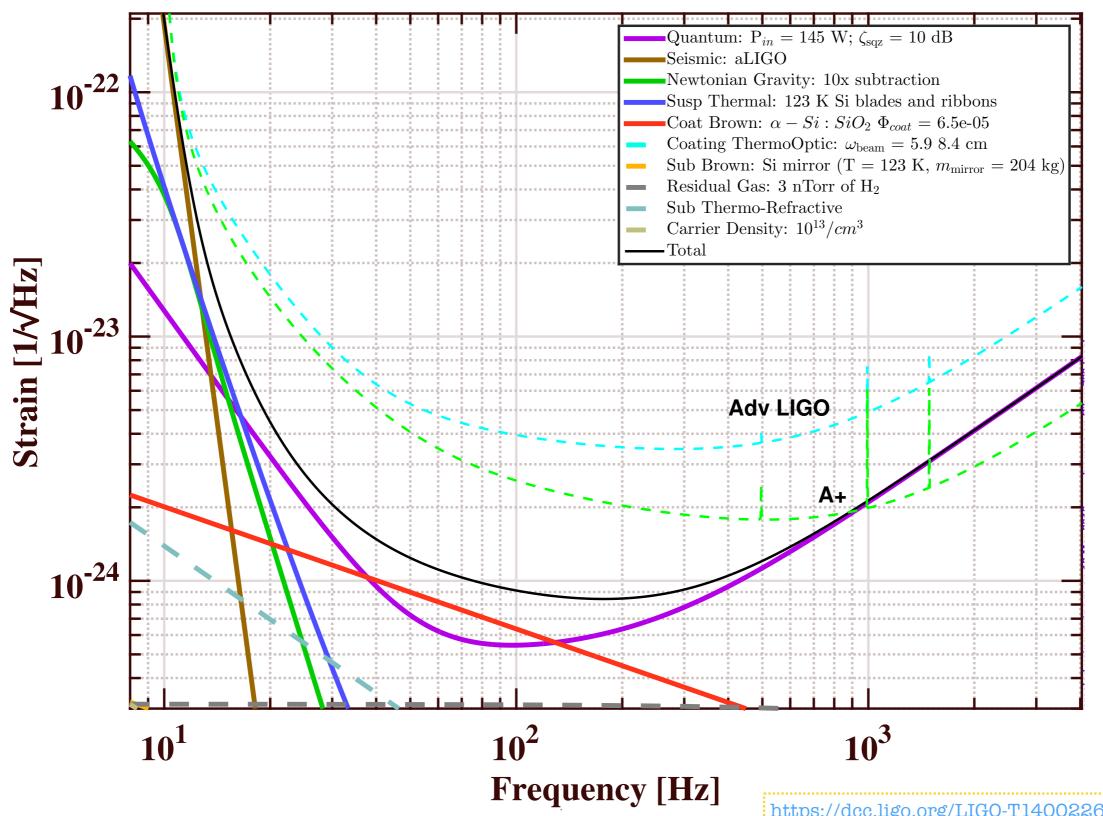
Reference: B. Shapiro, R. Adhikari, O. Aguiar, E. Bonilla, D. Fan, L. Gan, I. Gomez, S. Khandelwal, B. Lantz, T. MacDonald, and D. Madden-Fong. Cryogenically cooled ultra low vibration silicon mirrors for gravitational wave observatories. Cryogenics, 81:83 – 92, 2017

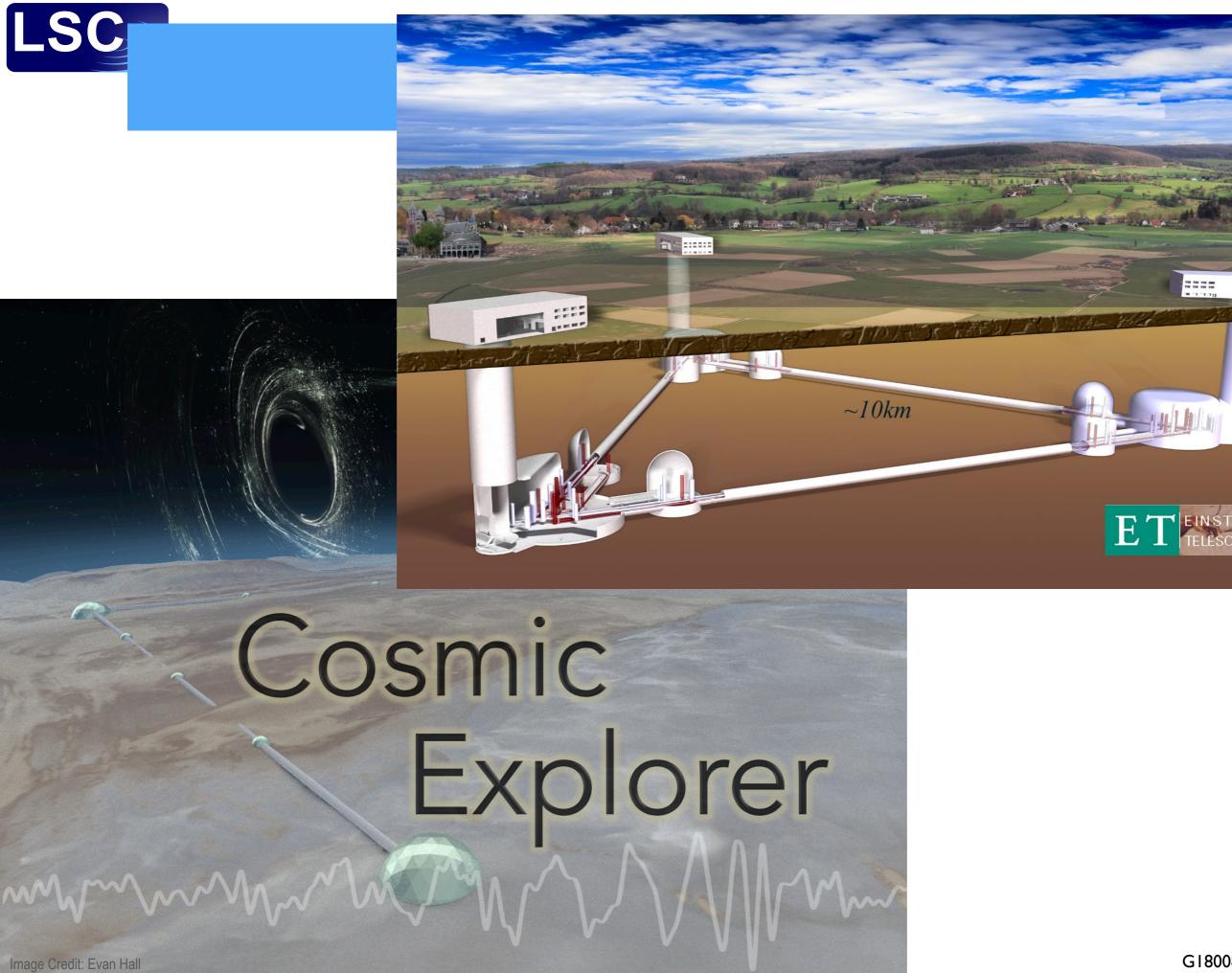


Voyager Noise floor



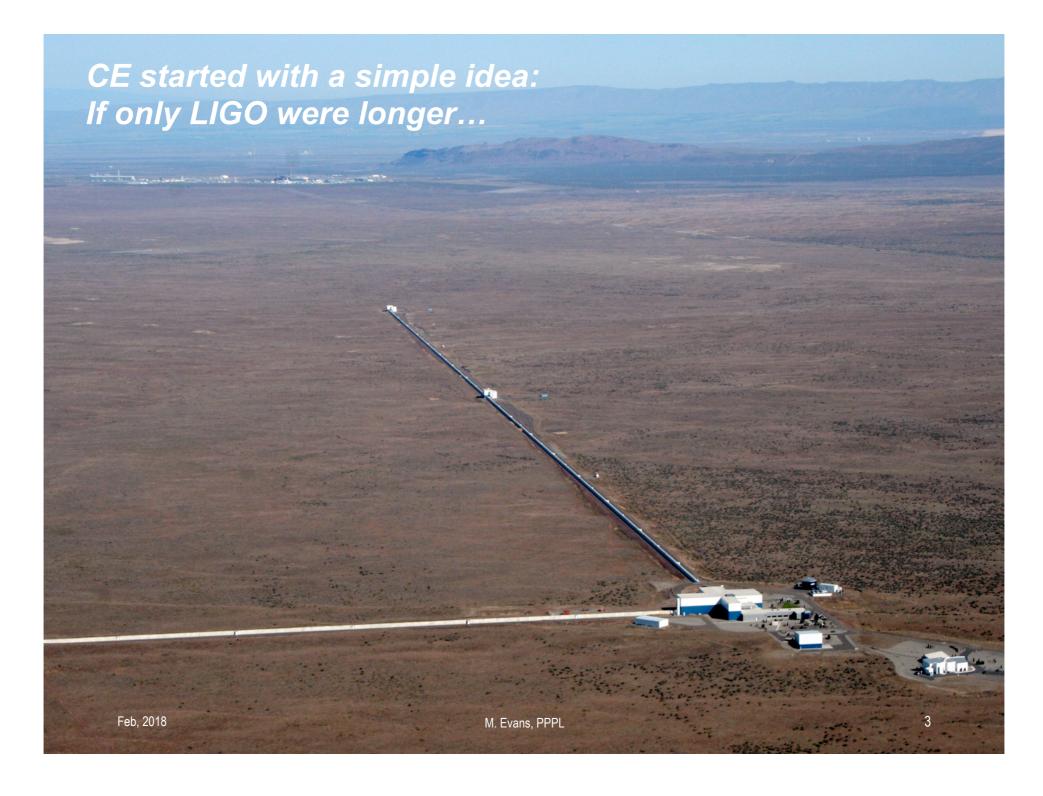
A. Brooks, R. Adhikari G1800347





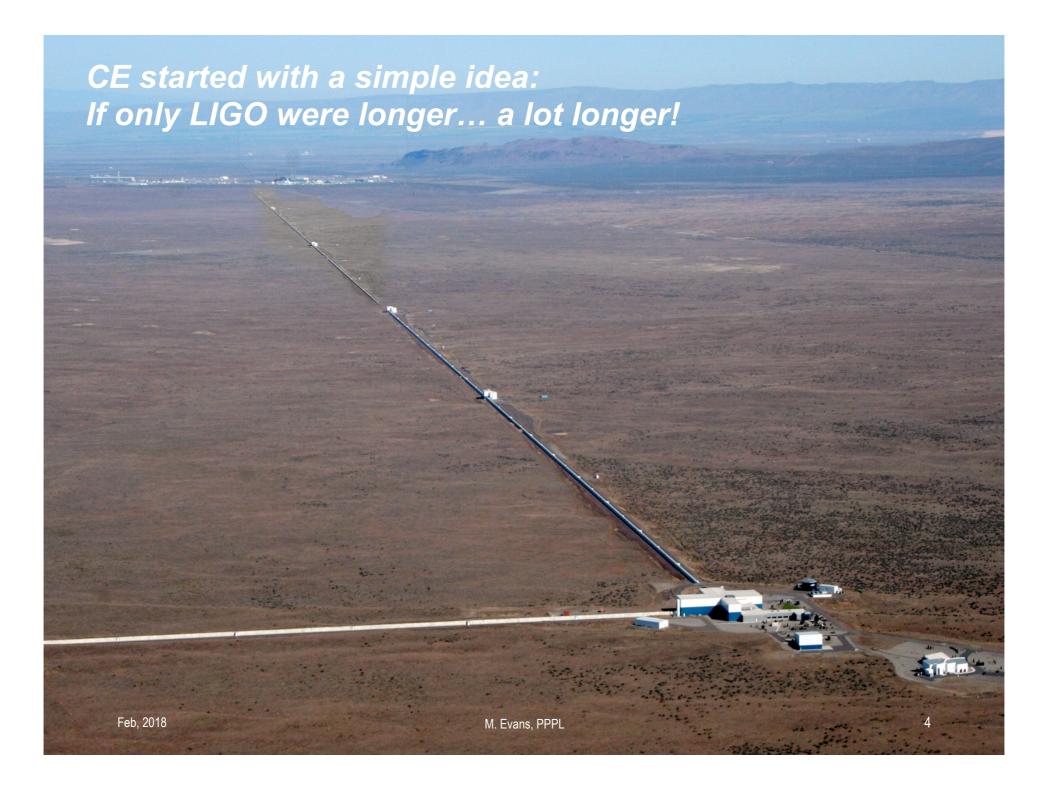












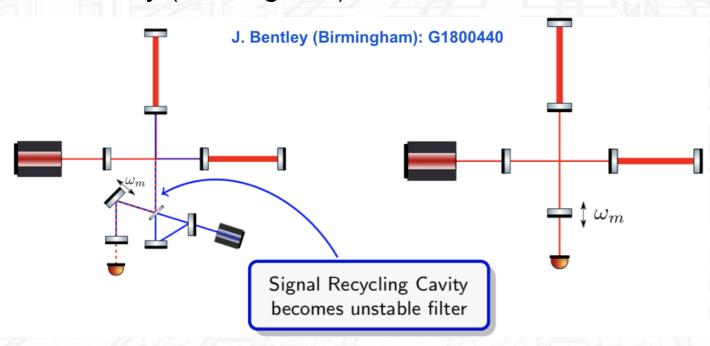


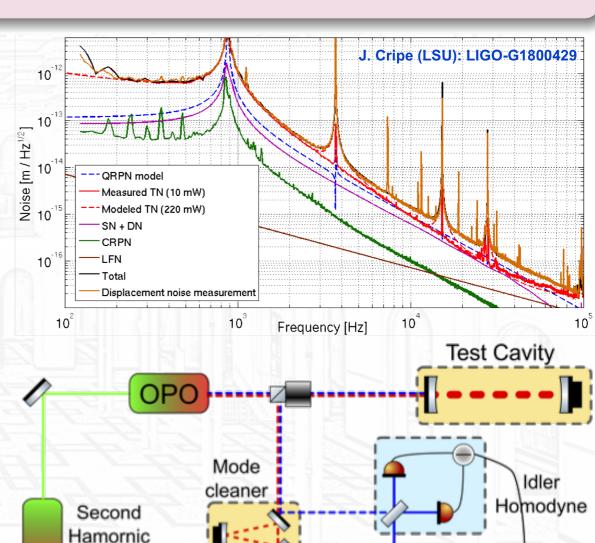
QNWG session highlights



We had a pleasing mix of reports of exciting experimental results and new theoretical proposals at the QNWG session.

- First observation of Quantum Radiation Pressure Noise in a broadband regime was reported by Jon Cripe (LSU): LIGO-G1800429
- Progress report of the EPR frequency dependent squeezing from ANU was given by Min Jet Yap: LIGO-G1800438
- New scheme of broadening CE bandwidth with unstable OM filter in the SR cavity reported by J. Bentley (Birmingham): LIGO-G1800440





Generator

Idler LO





The Message

- Next generation detectors will reach the entire Universe
 - BBH and BNS detection rate will be mostly determined by astrophysical population (>10 5 per year?), not detector sensitivity (peak near z ~ 3?)
 - high SNR signals will allow for detailed tests of GR, NS EOS,
- Plans for these detectors are taking form NOW
 - No, it is not too early... the lead-time on a new facility is 15-20 years
 - The designs are forward looking and R&D happening now will play an important role in these detectors (ask me how you can contribute!)
- You are encouraged to participate!
 - via the GWIC 3G subcommittee (contact Dave Reitze, Michele Punturo)
 - or the CE conceptual design study (contact me!)

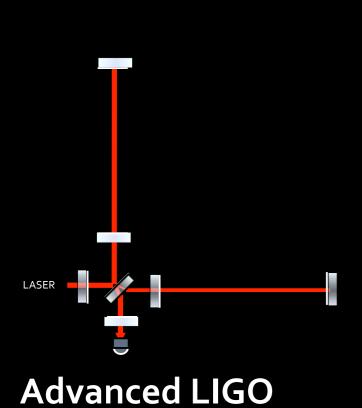
Feb, 2018 M. Evans, PPPL 22



The Size

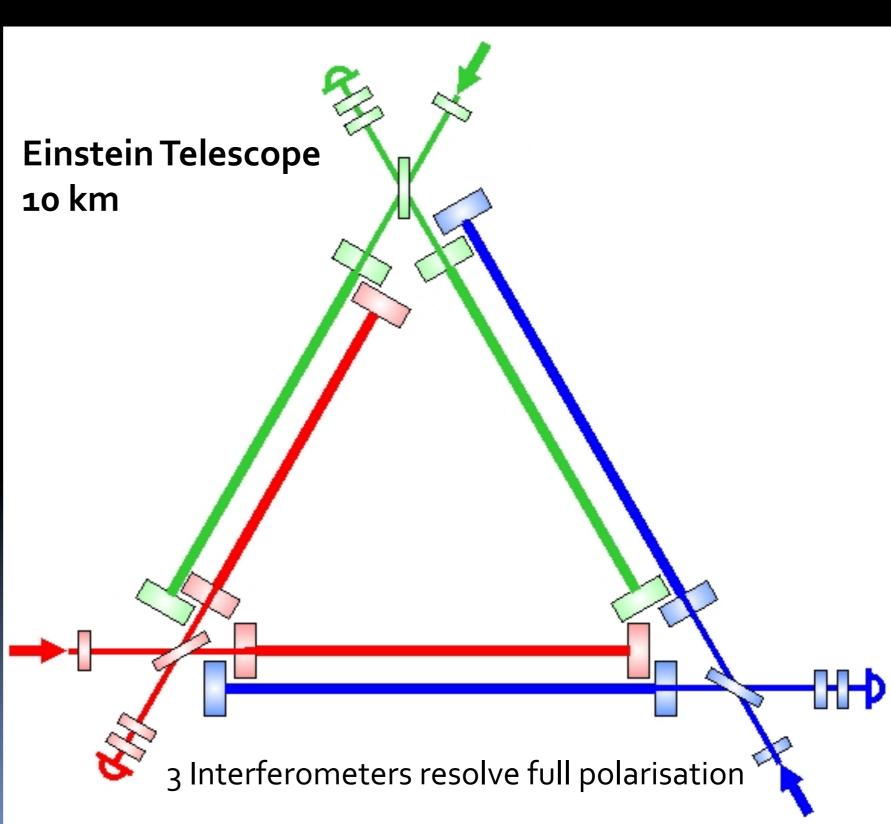


The Einstein Telescope will have 10 km arms → gain a factor >2.5 w.r.t. advanced LIGO



4 km







GO UNDERGROUND



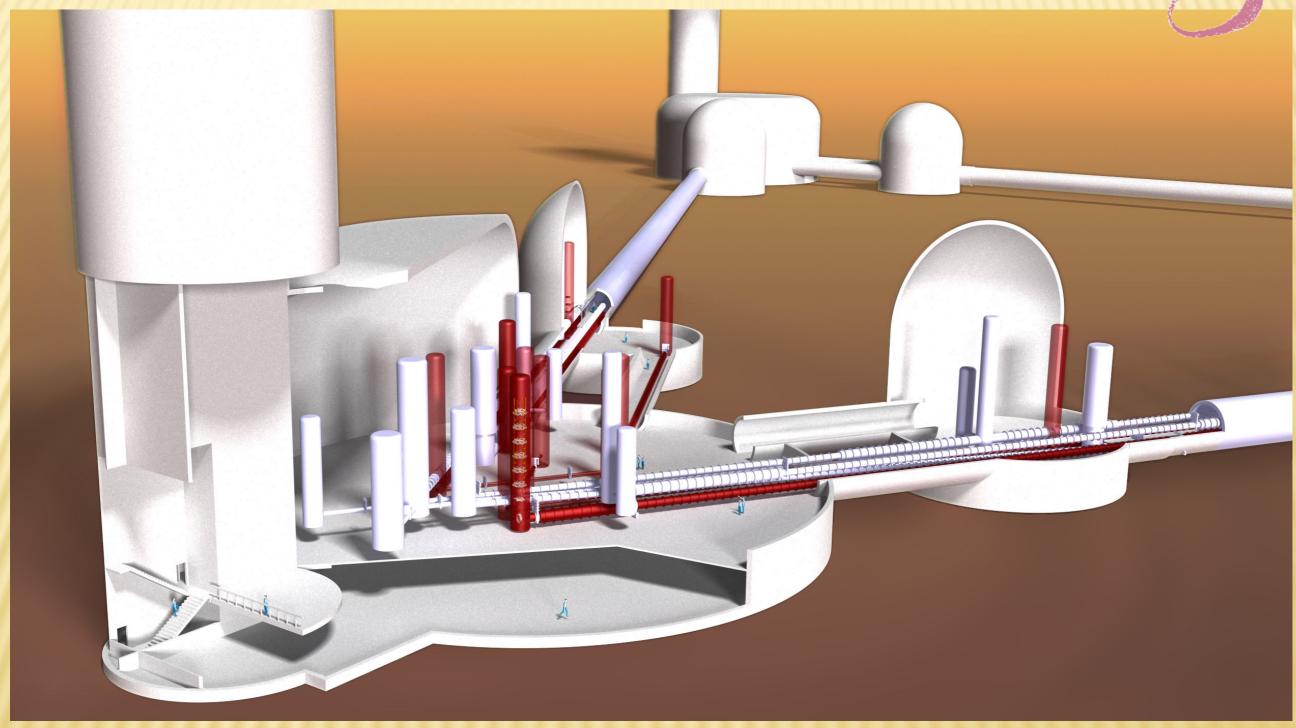


Image: Nikhef

ET Baseline: Build 200m underground;

Building a 10 km Δ -shaped facility above ground in Europe = impossible



ET XYLOPHONE STRATEGY



Split detector into two interferometers optimised for

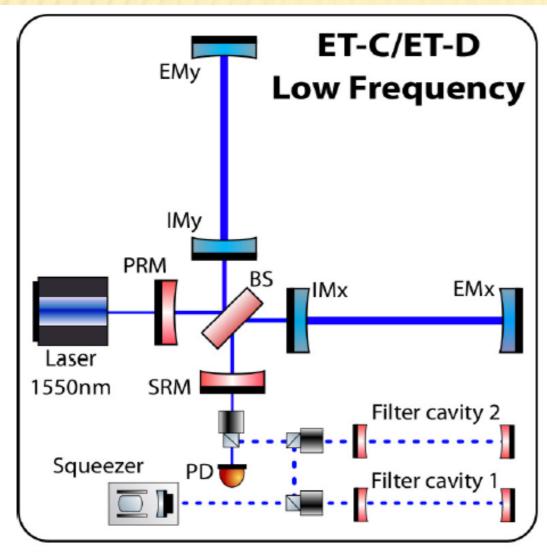
Low Frequencies

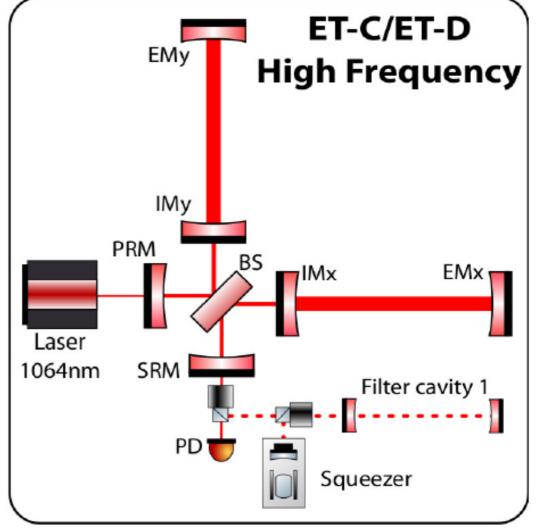
and

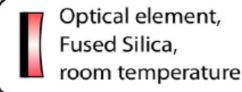
High Frequencies

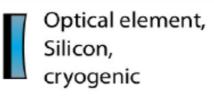
10K, 18kW, 1550nm

300K, 3MW, 1064nm







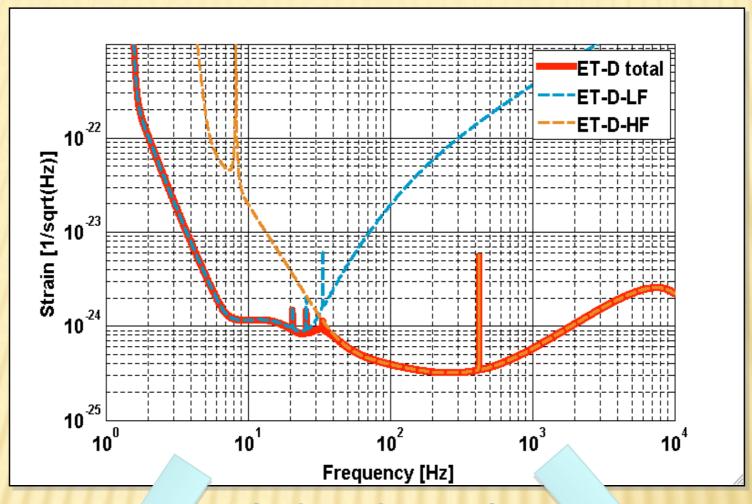


Laser beam 1550nm
Laser beam 1064nm
squeezed light beam

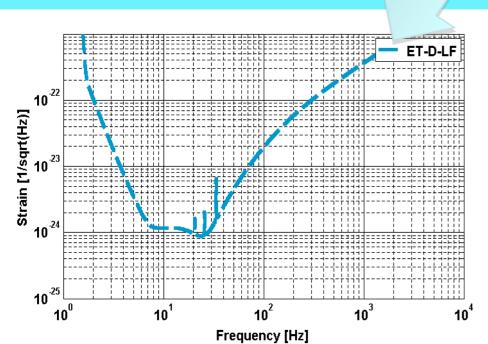


ET-D XYLOPHONE SENSITIVITY





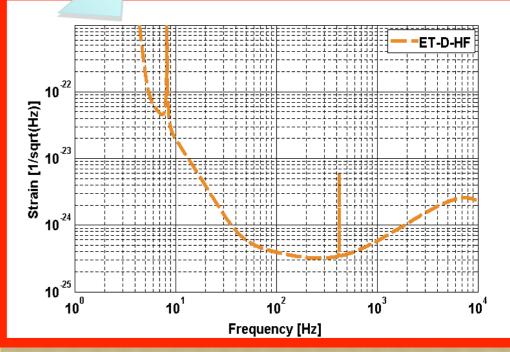




Subdividing the



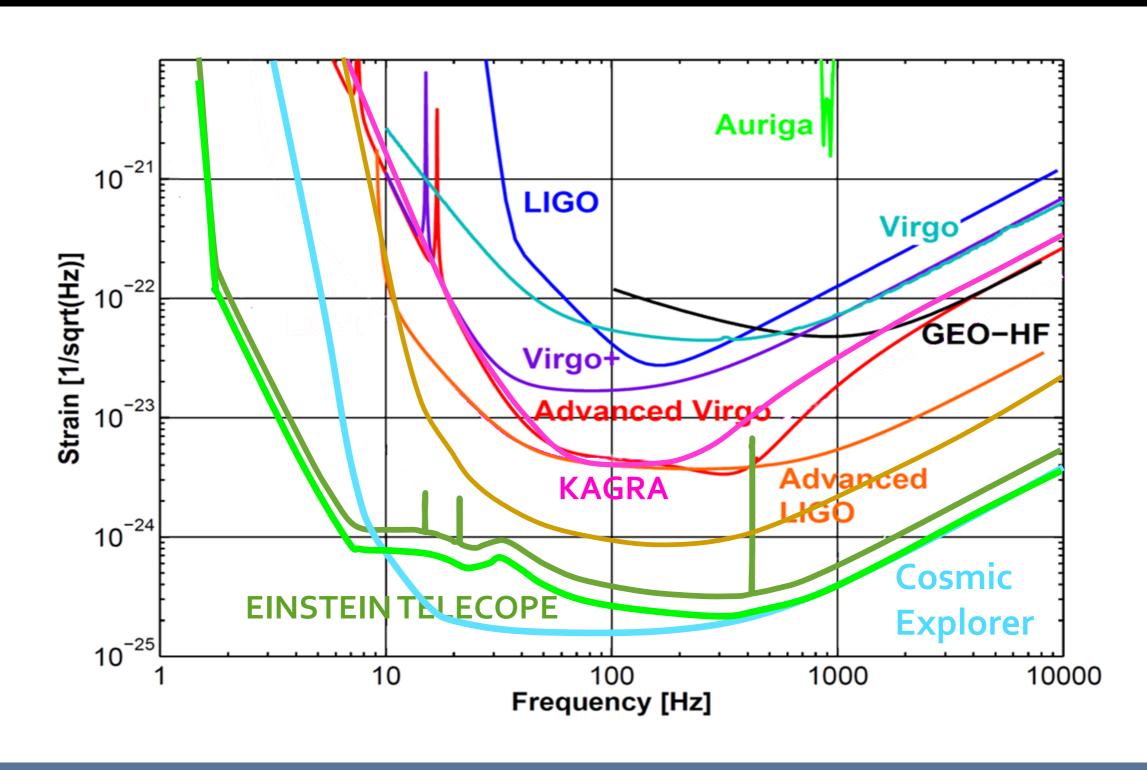
ET-D-HF



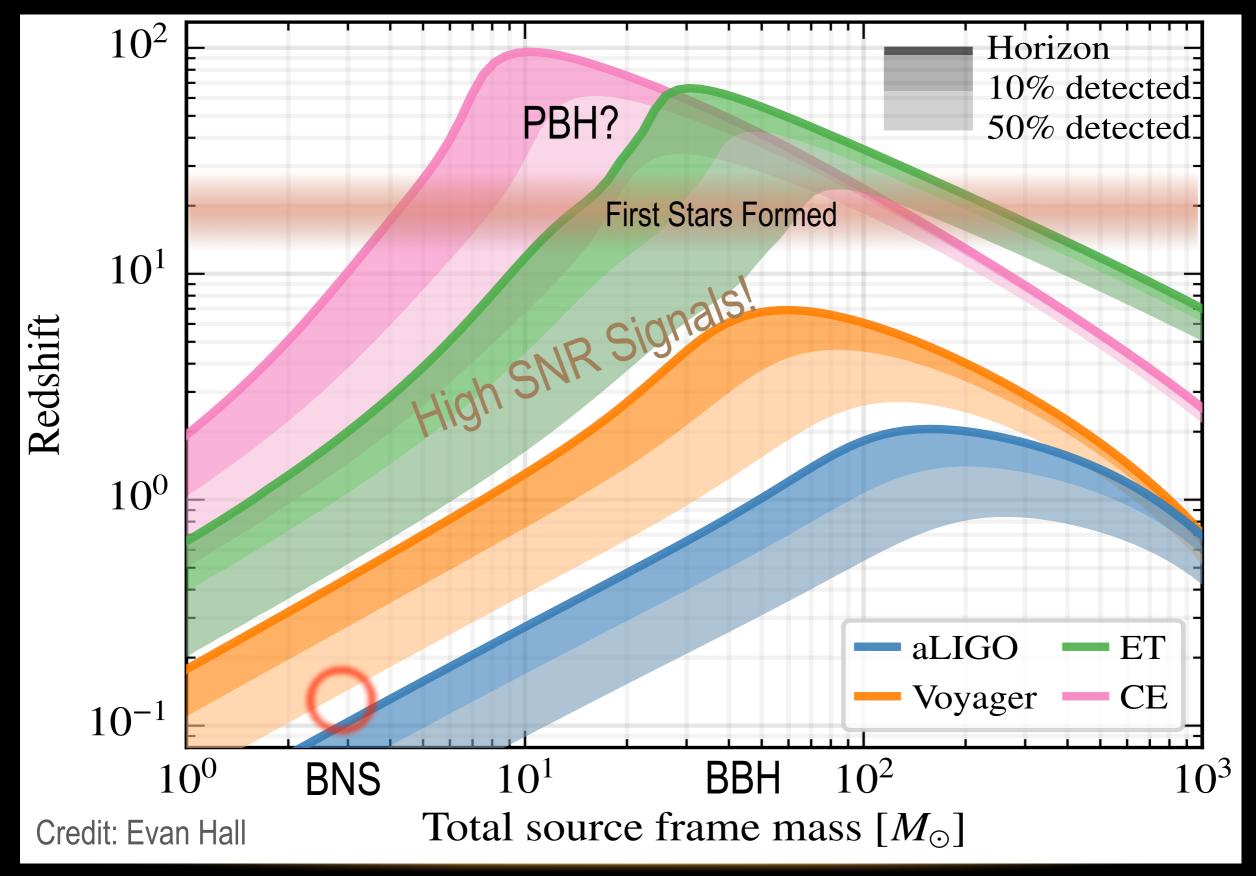
Sensitivity evolution

Comparison ET vs CE tricky : Δ vs L

Taking into account polarisation resolution



BBH and BNS from the entire Universe!

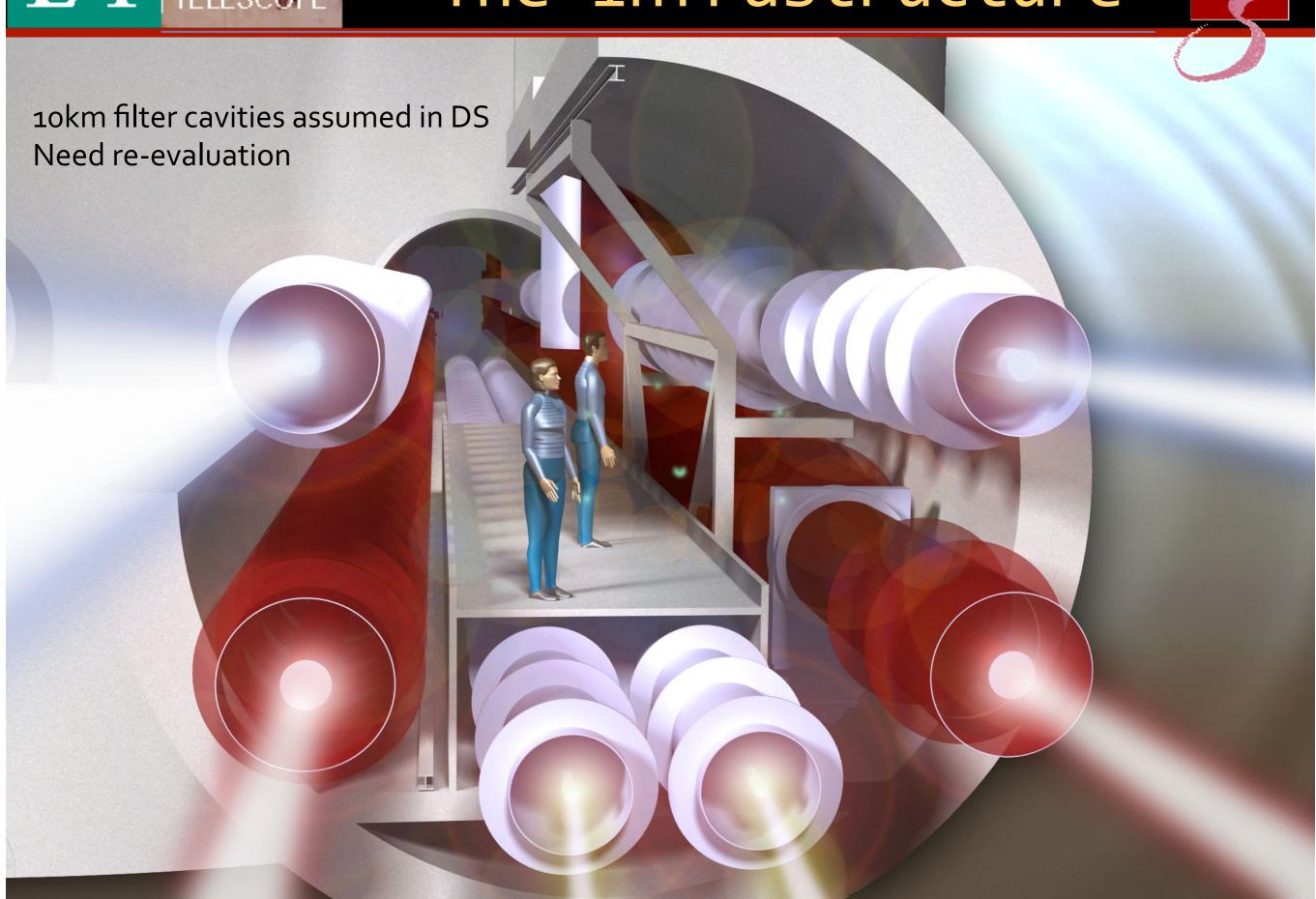








ET TELESCOPE The infrastructure











extra slides







PI200087-v46

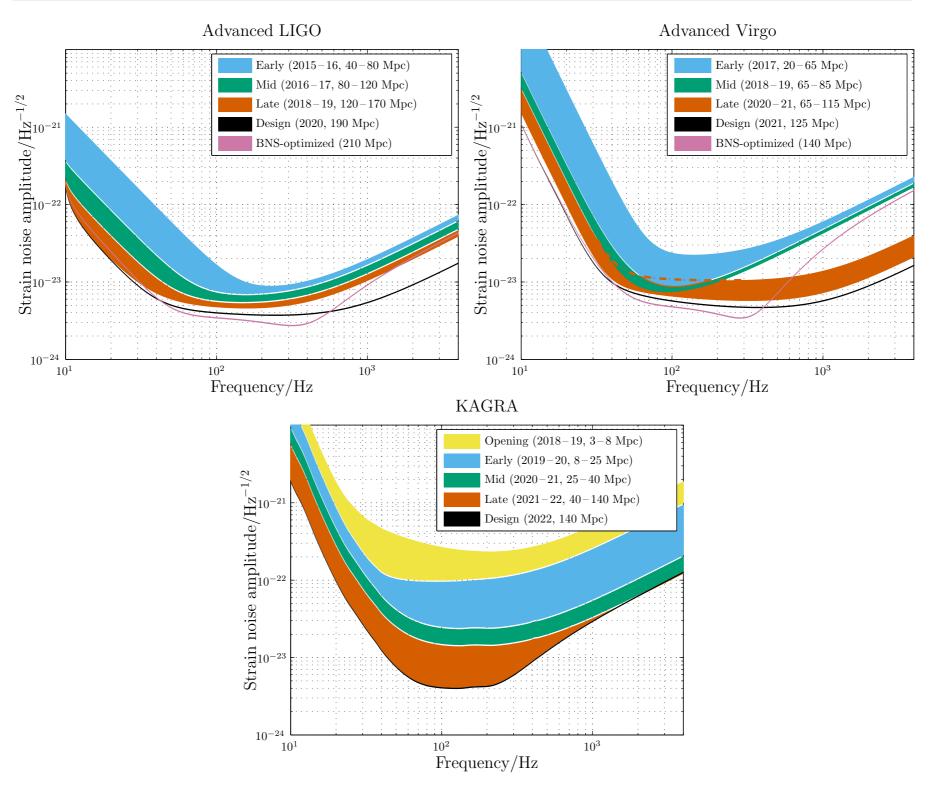
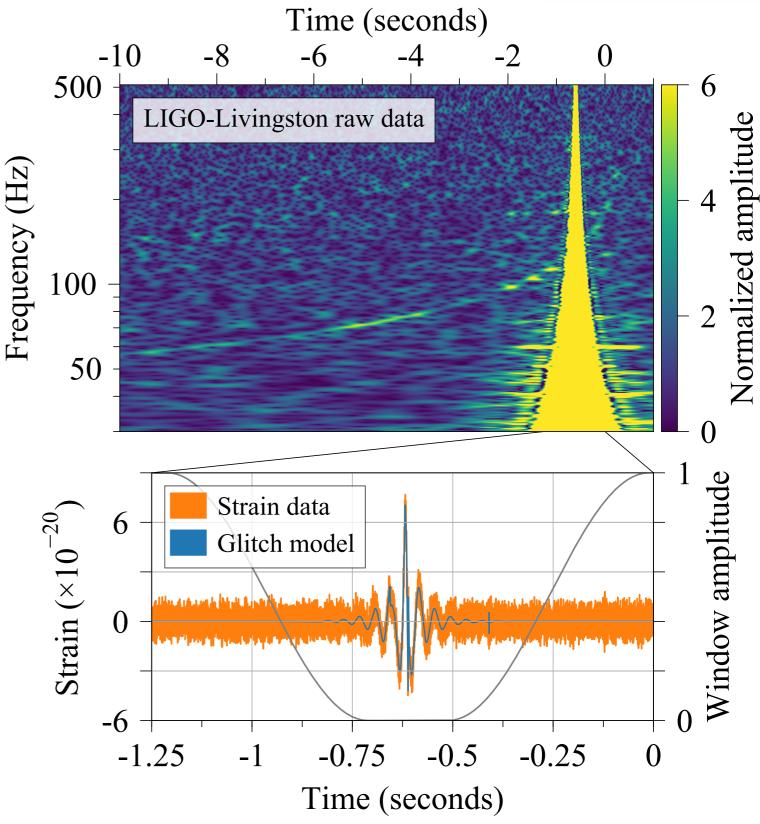


Fig. 1 Regions of aLIGO (*top left*), AdV (*top right*) and KAGRA (*bottom*) target strain sensitivities as a function of frequency. The binary neutron star (BNS) range, the average distance to which these signals could be detected, is given in megaparsec. Current notions of the progression of sensitivity are given for early, mid and late commissioning phases, as well as the design sensitivity target and the BNS-optimized sensitivity. While both dates and sensitivity curves are subject to change, the overall progression represents our best current estimates.



Mitigation of the glitch in LIGO-Livingston data. Times are shown relative to August 17, 2017 12:41:04 UTC. Top panel: A time-frequency representation [57] of the raw LIGO-Livingston data used in the initial identification of GW170817 [62]. The coalescence time reported by the search is at time 0.4s in this figure and the glitch occurs 1.1s before this time. The time-frequency track of GW170817 is clearly visible despite the presence of the glitch. Bottom panel: The raw LIGO-Livingston strain data (orange curve) showing the glitch in the time domain. To mitigate the glitch in the rapid re-analysis that produced the sky-map shown in Figure 3 [63], the raw detector data was multiplied by an inverse Tukey window (grey curve, right axis) that zeroed out the data around the glitch [64]. To mitigate the glitch in the measurement of the source's properties, a model of the glitch based on a wavelet reconstruction [65] (blue curve) was subtracted from the data. The time-series data visualized in this figure have been band-passed between 30 Hz and 2 kHz so that the the detector's sensitive band is emphasized. The gravitational-wave strain amplitude of GW170817 is of the order of 10^{-22} and so is not visible in the bottom panel.







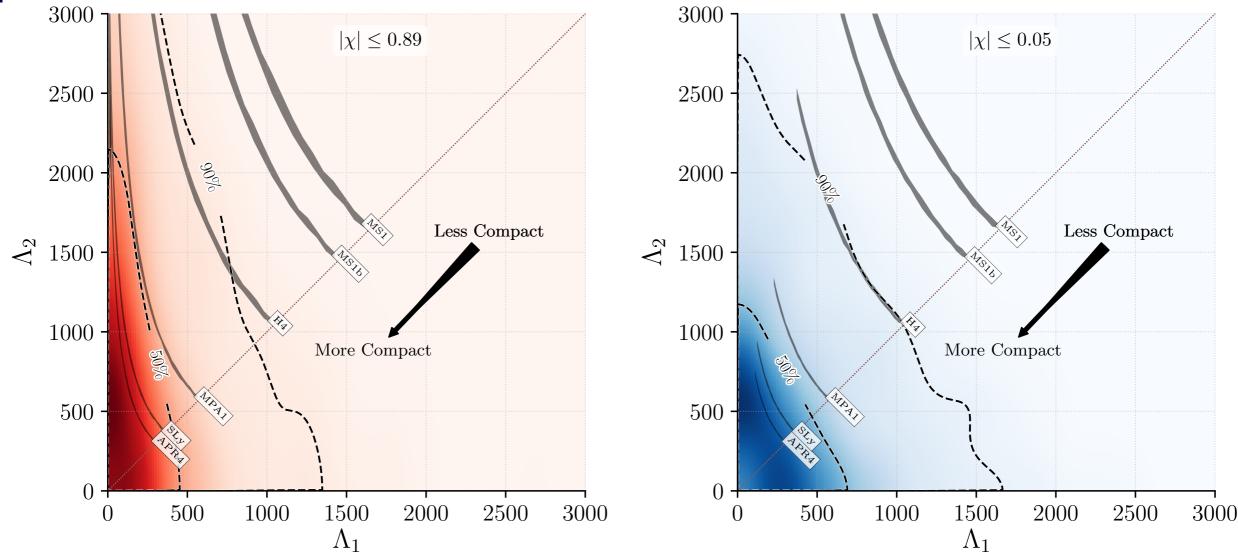


FIG. 5. Probability density for the tidal deformability parameters of the high and low mass components inferred from the detected signals using the post-Newtonian model. Contours enclosing 90% and 50% of the probability density are overlaid (dashed lines). The diagonal dashed line indicates the $\Lambda_1=\Lambda_2$ boundary. The Λ_1 and Λ_2 parameters characterize the size of the tidally-induced mass deformations of each star and are proportional to $k_2(R/m)^5$. Constraints are shown for the high-spin scenario, $|\chi| \leq 0.89$, (left panel) and for the low-spin, $|\chi| \leq 0.05$, (right panel). As a comparison, we plot predictions for tidal deformability given by a set of representative equations of state [148–152] (shaded filled regions), with labels following [153], all of which support stars of $2.01\,M_\odot$. Under the assumption that both components are neutron stars, we apply the function $\Lambda(m)$ prescribed by that equation of state to the 90% most probable region of the component mass posterior distributions shown in Figure 4. EOS that produce less compact stars, such as MS1 and MS1b, predict Λ values ouside our 90% contour.





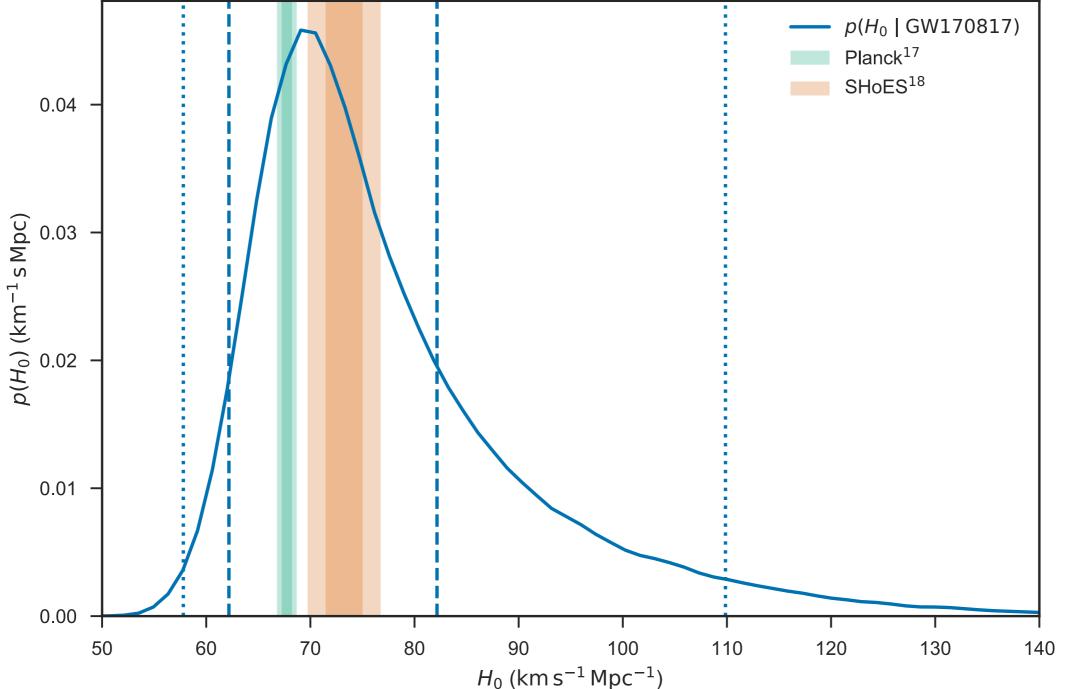


Figure 1 GW170817 measurement of H_0 . Marginalized posterior density for H_0 (blue curve). Constraints at 1-and 2 σ from Planck and SHoES are shown in green and orange. The maximum a posteriori value and minimal 68.3% credible interval from this PDF is $H = 70.0^{+12.0, -8.0}$ km s⁻¹ Mpc⁻¹. The 68.3% (1 σ) and 95.4% (2 σ) minimal credible intervals are indicated by dashed and dotted lines.

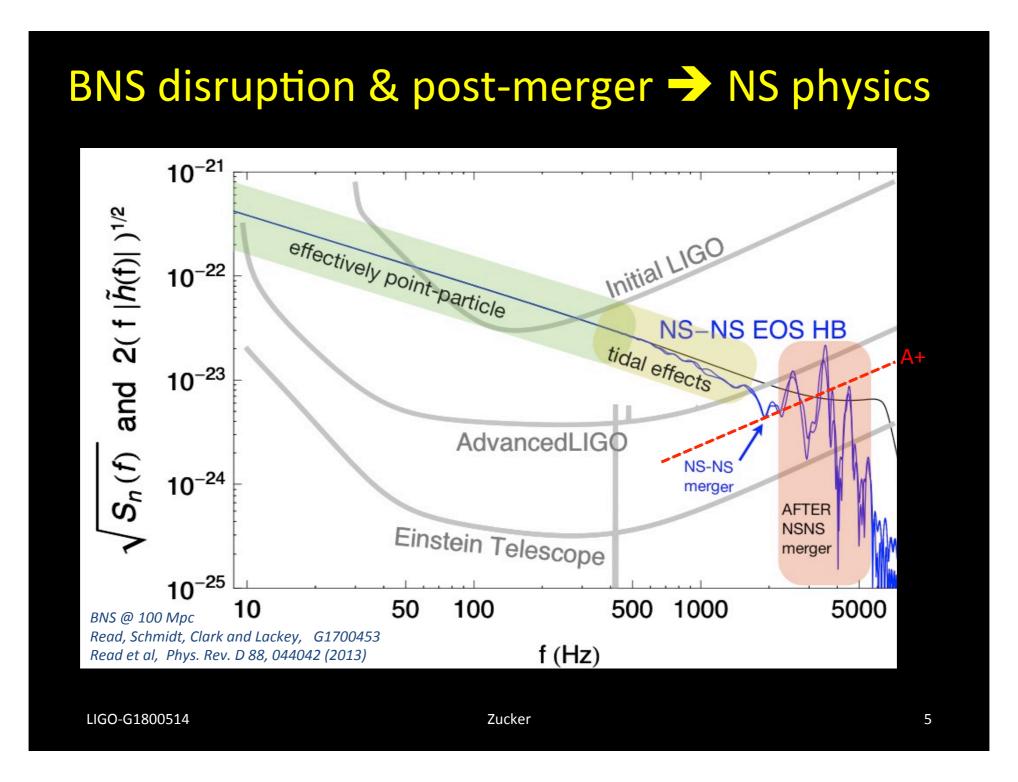
A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTEI Collaboration

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We suspect that ~1/2 of all heavy elements are created in kilonovas.

Energetic explosion in a neutron rich environment -> nuclei in ejecta

GW170817: The Merger of Two Neutron Stars





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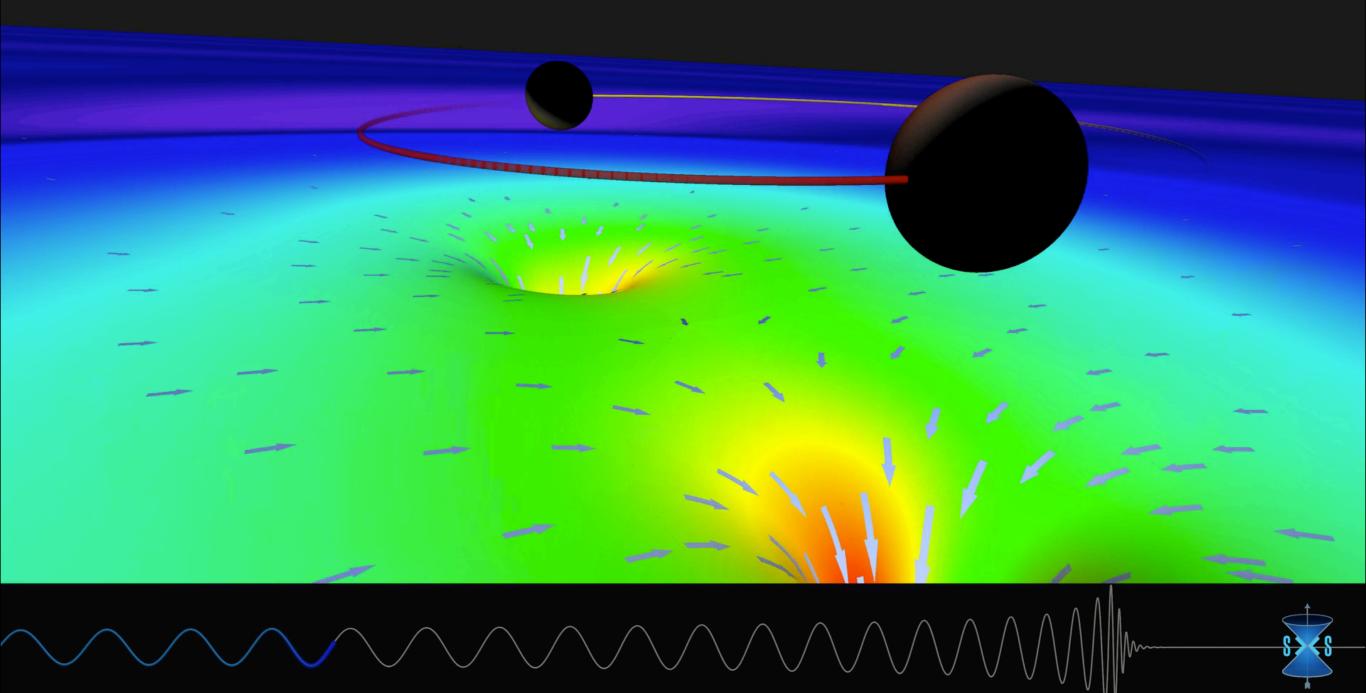
GW170817: The Merger of Two Neutron Stars





Simulation of the event

-0.42s



Simulation of the event

-0.42s

