Next-Generation, Gravitational-Wave Detectors

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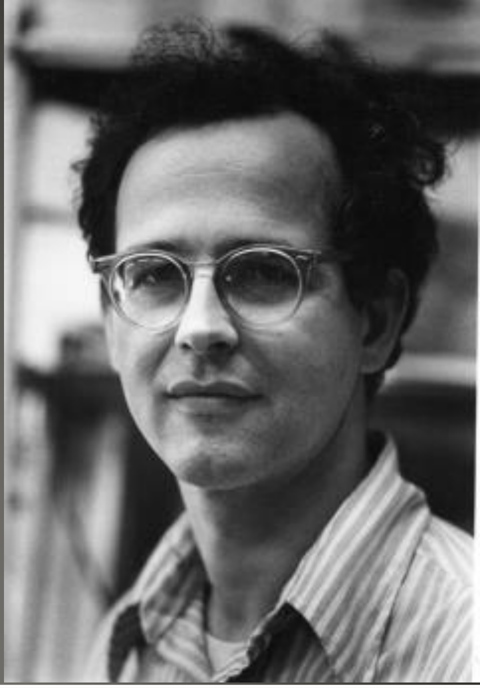
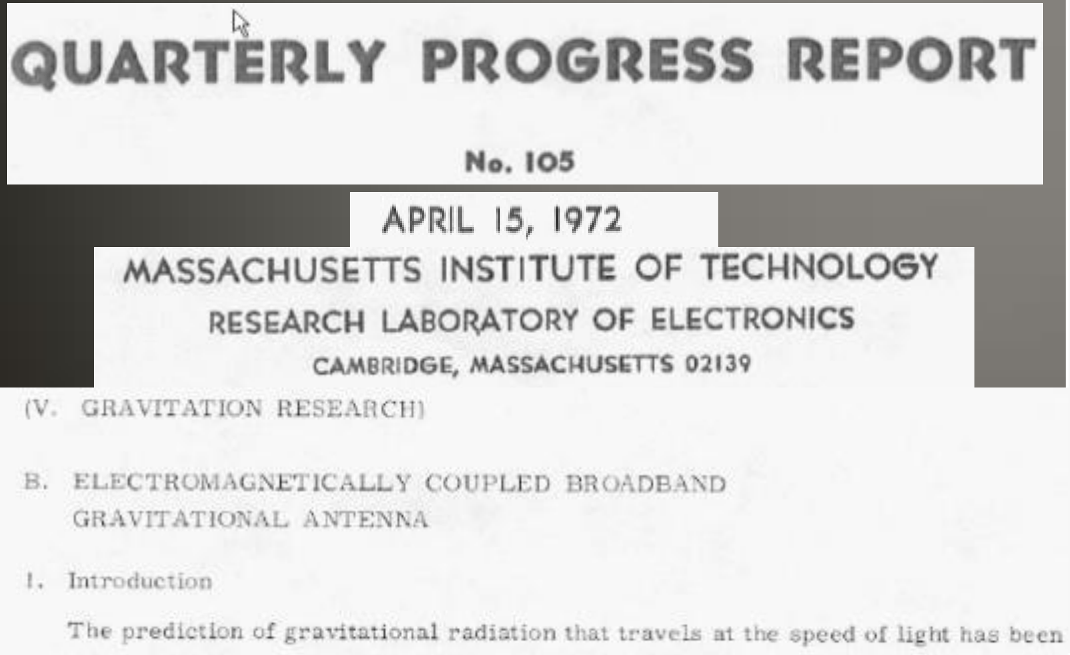
History



- Rai Weiss of MIT taught a course in GR at the end of the 60s, and searched for a problem to give to students
- How to detect GWs with laser interferometric detectors?
- Weiss wrote the first description of a detector



QUARTERLY PROGRESS REPORT

No. 105

APRIL 15, 1972

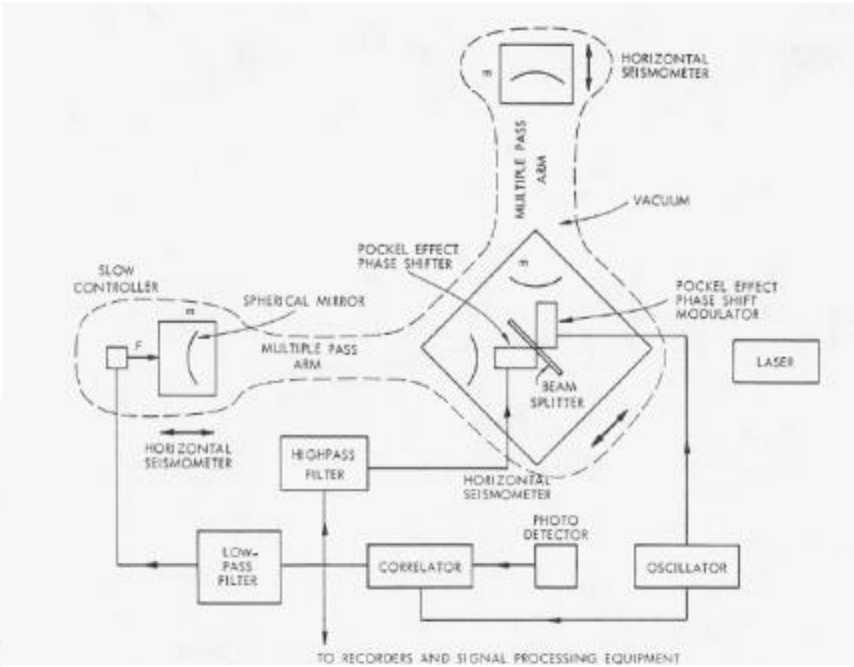
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
RESEARCH LABORATORY OF ELECTRONICS
CAMBRIDGE, MASSACHUSETTS 02139

(V. GRAVITATION RESEARCH)

B. ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

1. Introduction

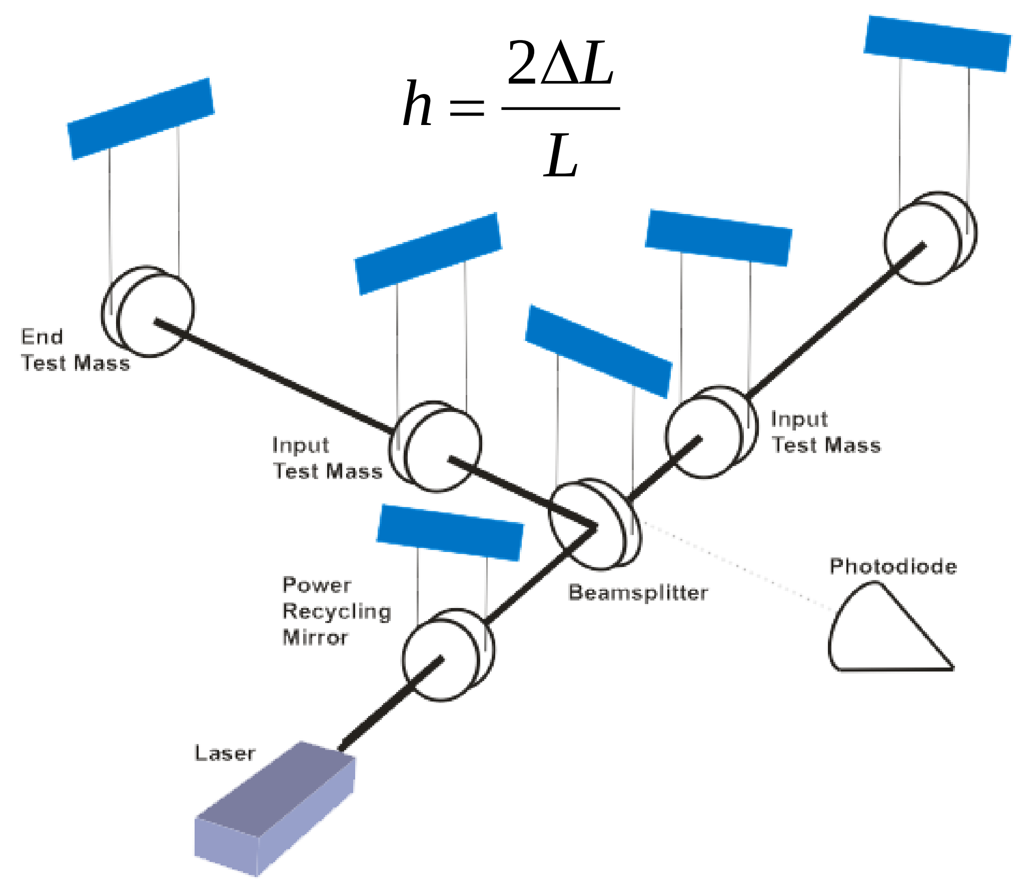
The prediction of gravitational radiation that travels at the speed of light has been



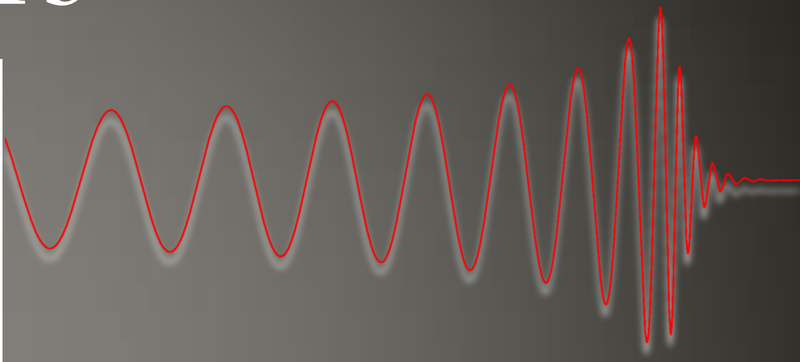
	Virgo	AdV	aLIGO	ET
1985	R&D White Paper, CDR (1989)			
1990	R&D Approval (1994)		R&D	
1995	Final Design, TDR (1995) Beginning Infrastructure (1996)	R&D	CDR (1999)	
2000	Completion installation Detector (2003)	First AdV sensitivity projection (2004)	R&D	
2005	Scientific data taking (2007)	AdV White Paper, CDR (2005) Approval (2009)	Funding (2006) Building (2008)	First Idea (2005) R&D
2010	Decommissioning (2011)	First orders (2010) TDR (2012)	Installing completion (2014)	CDR (2011)
2015		Completion Installation (2016) First data taking (2017)	Data taking (2015)	
2020				
2025				

Credits: H Lück

Basic Concept of LIGO/Virgo Detectors



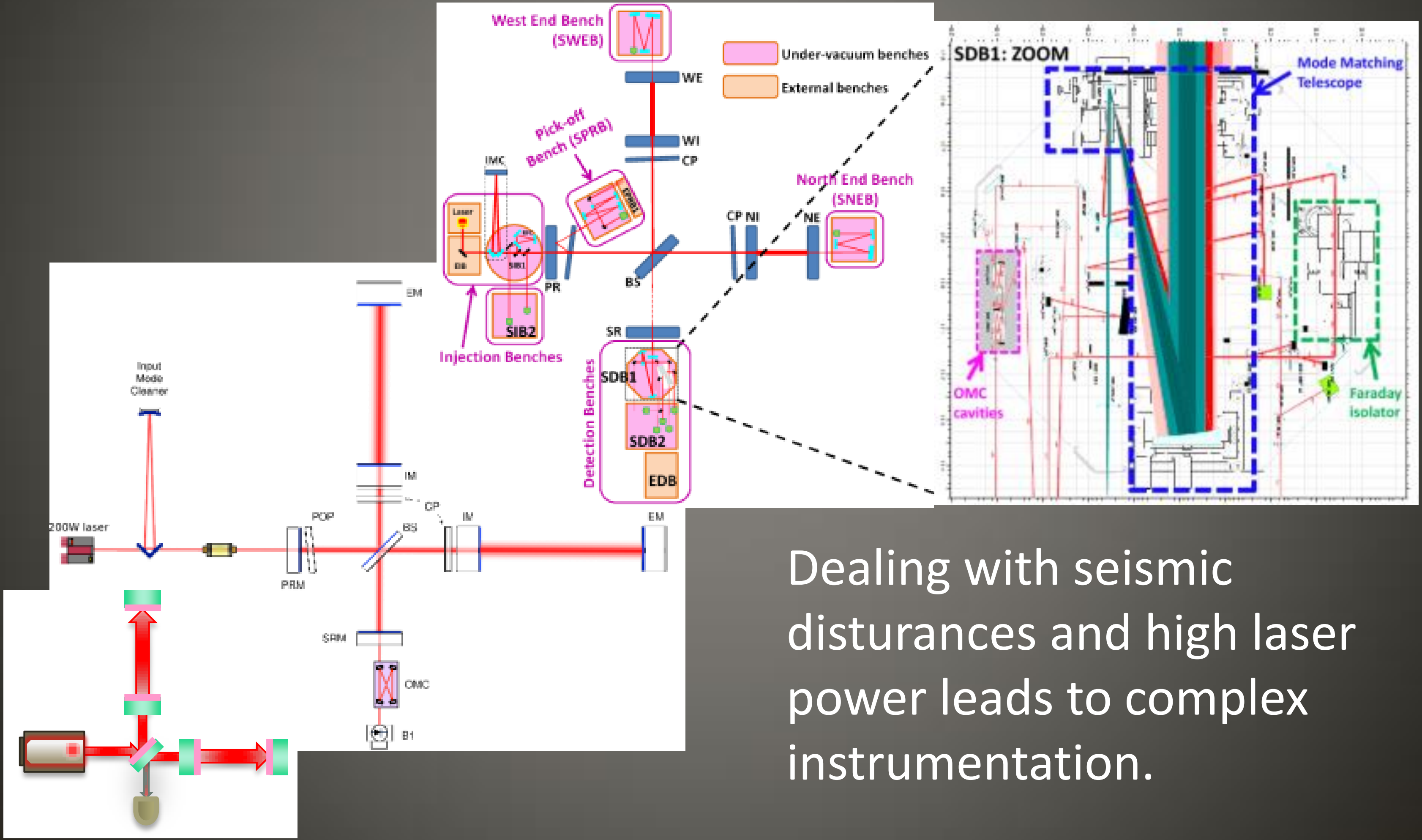
$$h = \frac{2\Delta L}{L}$$



Amplitude h on Earth:

- $h \sim 10^{-21}$ (GW150914)
- $L = 3\text{km}$, $\Delta L \sim 10^{-18}$ m

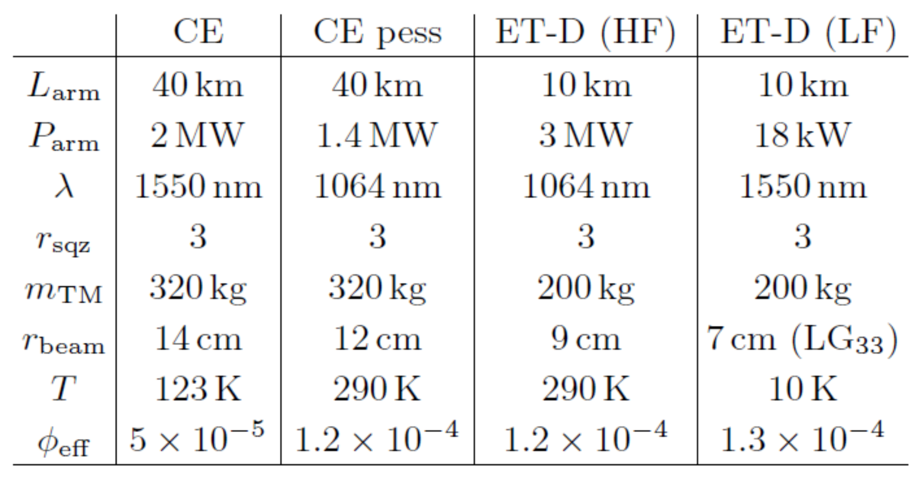
Ground-Based, Laser-Interferometric GW Detectors



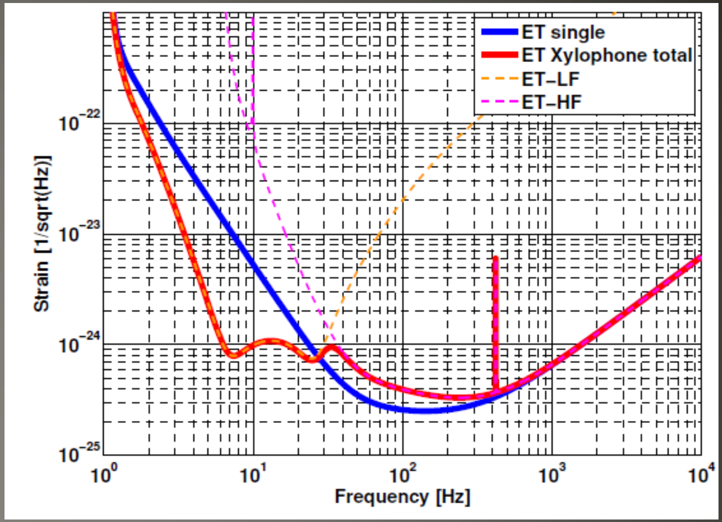
Dealing with seismic disturances and high laser power leads to complex instrumentation.

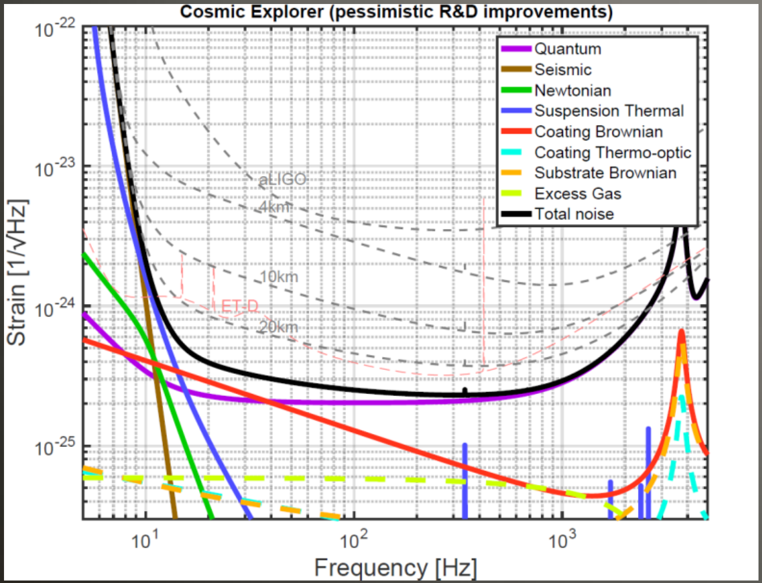
Technology for Third-Generation GW Detectors

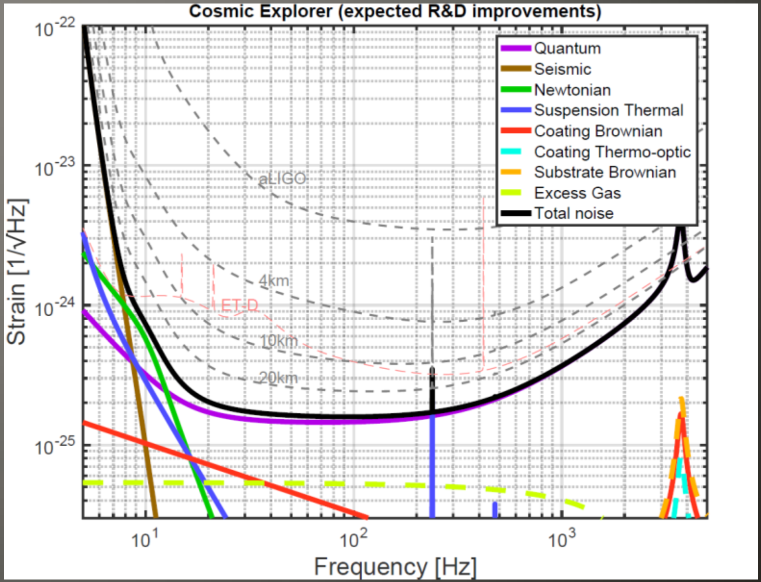
3G Concepts



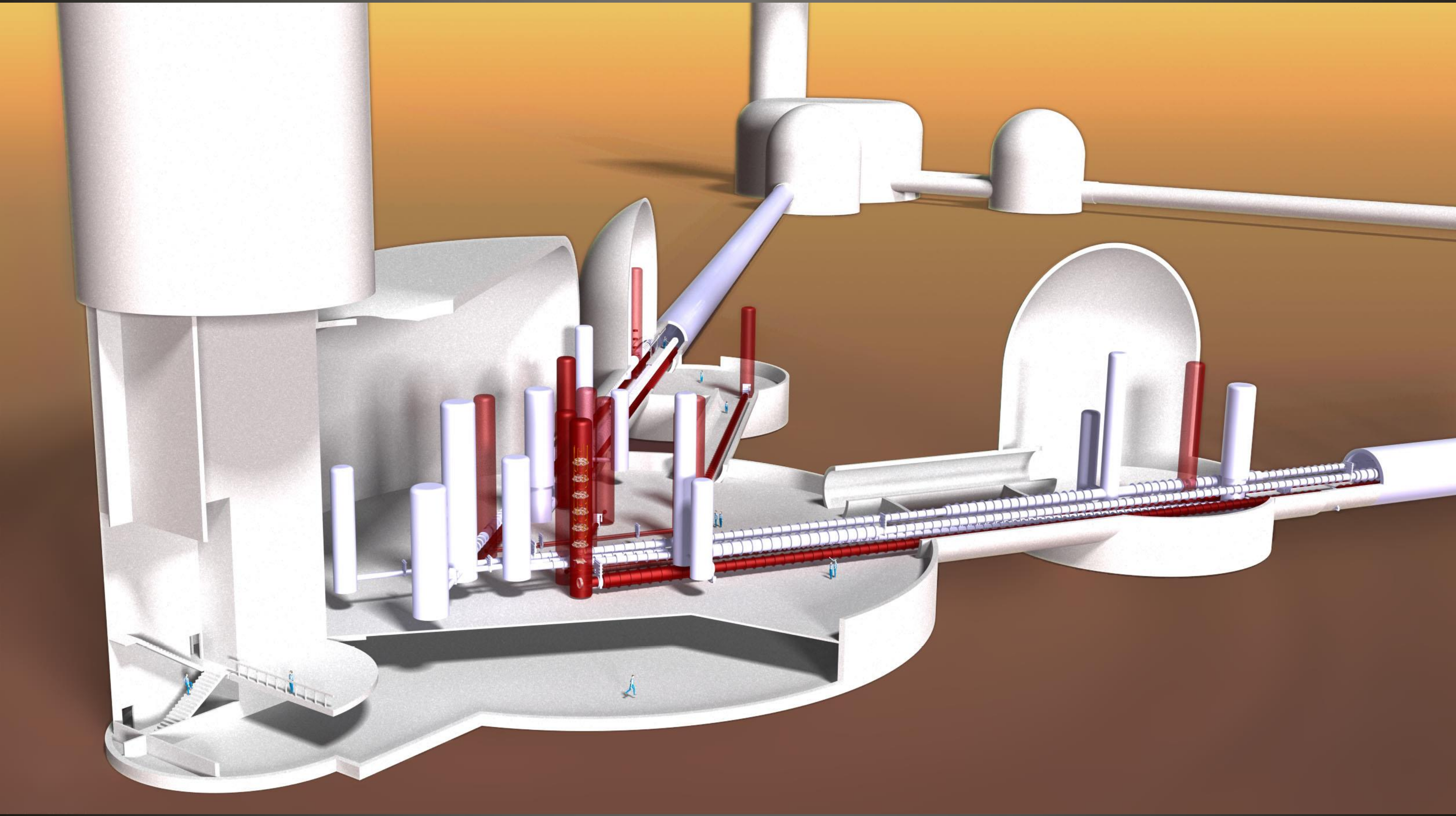
	CE	CE pess	ET-D (HF)	ET-D (LF)
L_{arm}	40 km	40 km	10 km	10 km
P_{arm}	2 MW	1.4 MW	3 MW	18 kW
λ	1550 nm	1064 nm	1064 nm	1550 nm
r_{sqz}	3	3	3	3
m_{TM}	320 kg	320 kg	200 kg	200 kg
r_{beam}	14 cm	12 cm	9 cm	7 cm (LG$_{33}$)
T	123 K	290 K	290 K	10 K
ϕ_{eff}	5×10^{-5}	1.2×10^{-4}	1.2×10^{-4}	1.3×10^{-4}



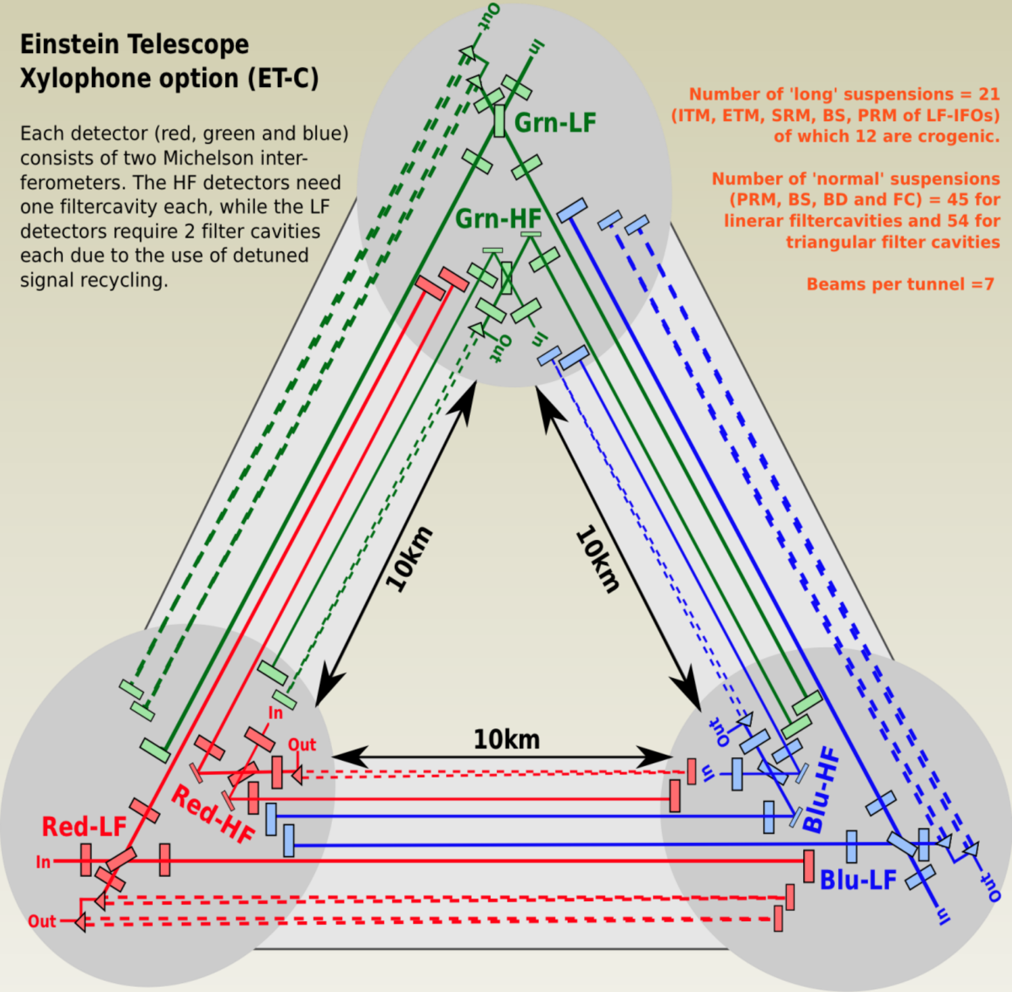

Cosmic Explorer (pessimistic R&D improvements)


Cosmic Explorer (expected R&D improvements)

Einstein Telescope: Infrastructure



ET: Xylophone Configuration



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.

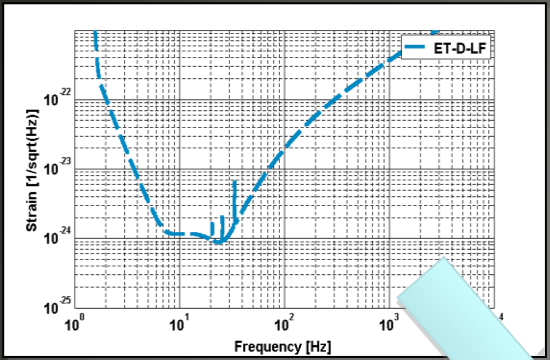
Number of 'long' suspensions = 21 (ITM, ETM, SRM, BS, PRM of LF-IFOs) of which 12 are crogenic.

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

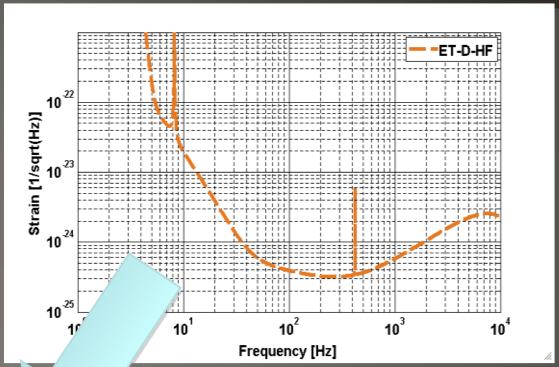
Beams per tunnel =7

- 3 interferometers to gain full profit from triangular detector shape
- Split each interferometer into two to optimize sensitivity and increase observation band

ET: Xylophone Sensitivity

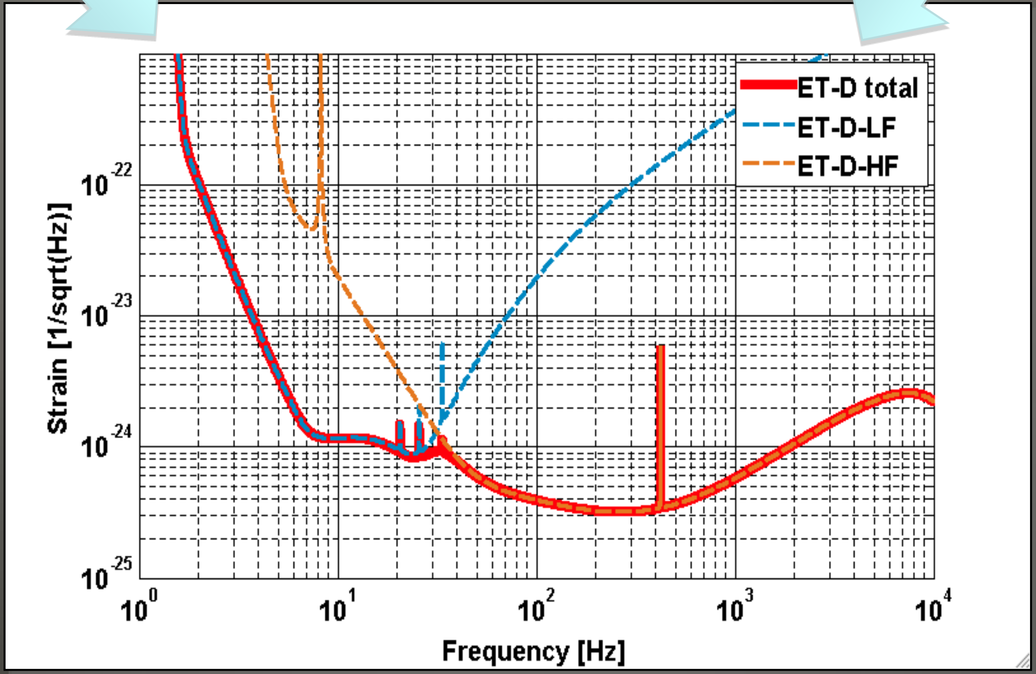


Combining the two interferometers

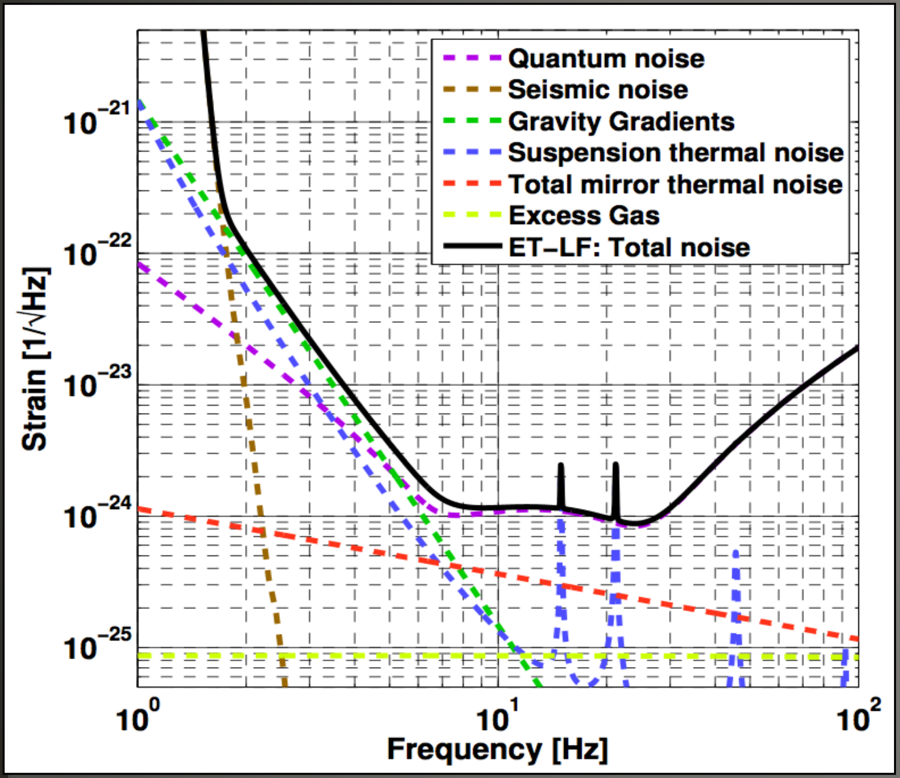


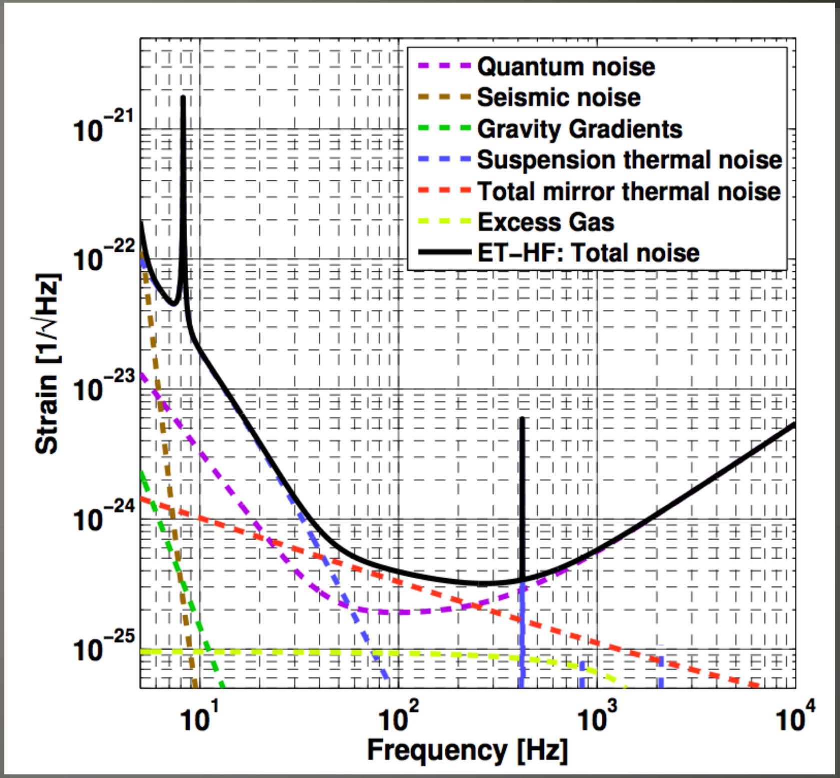
ET-D-LF

ET-D-HF



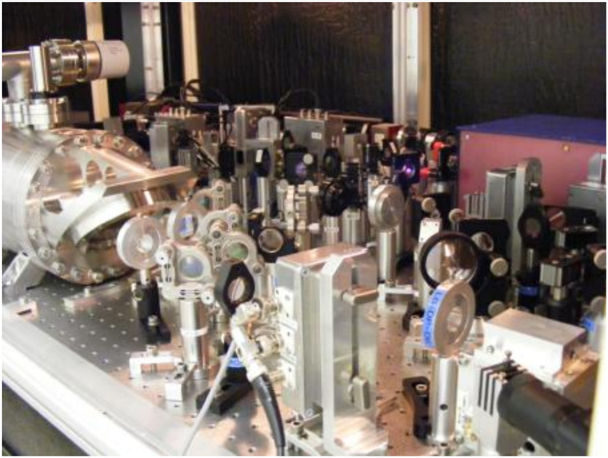
ET: Noise Budgets

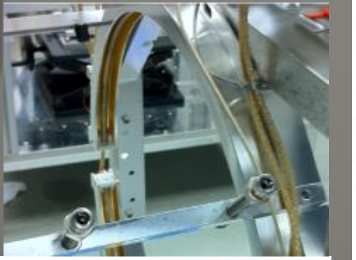




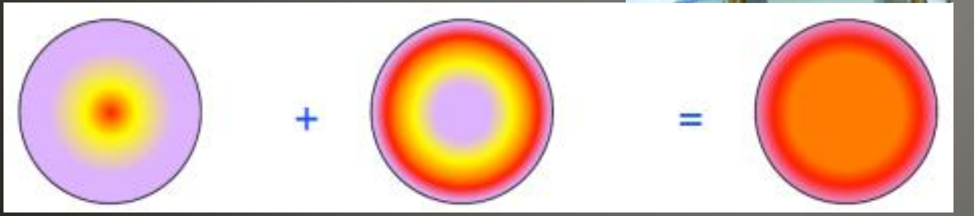
Key Technology: High Power

High-power laser





Thermal compensation

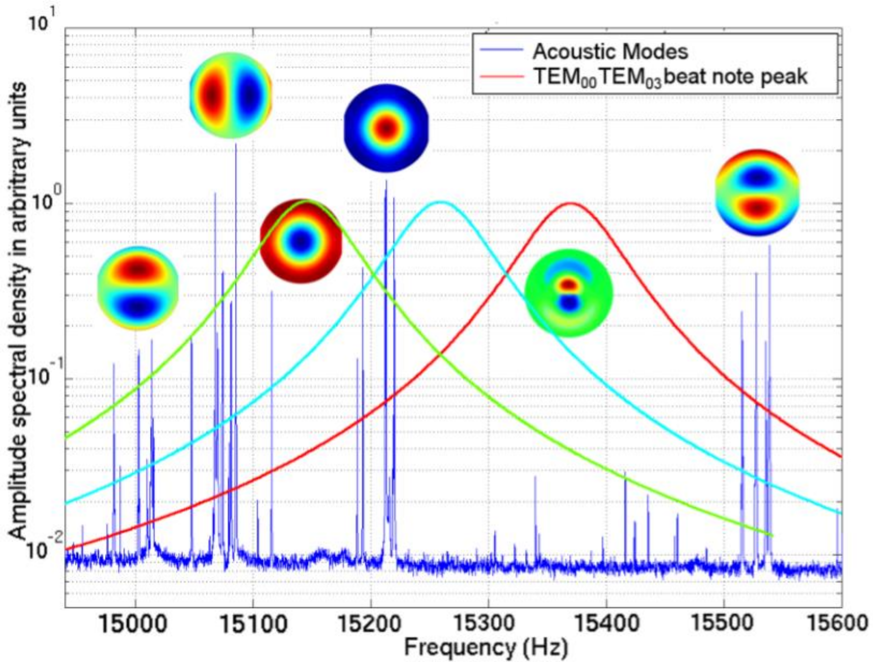


Laser

Ring heater

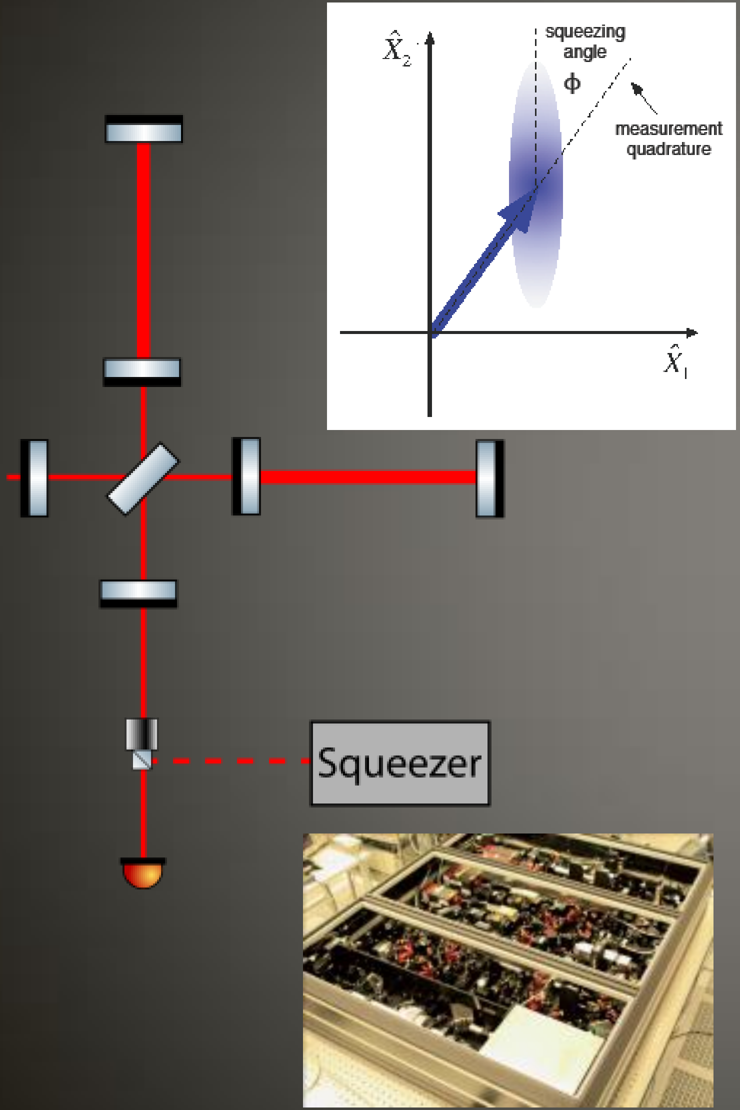
Reduced deformation

Damping of parametric instabilities

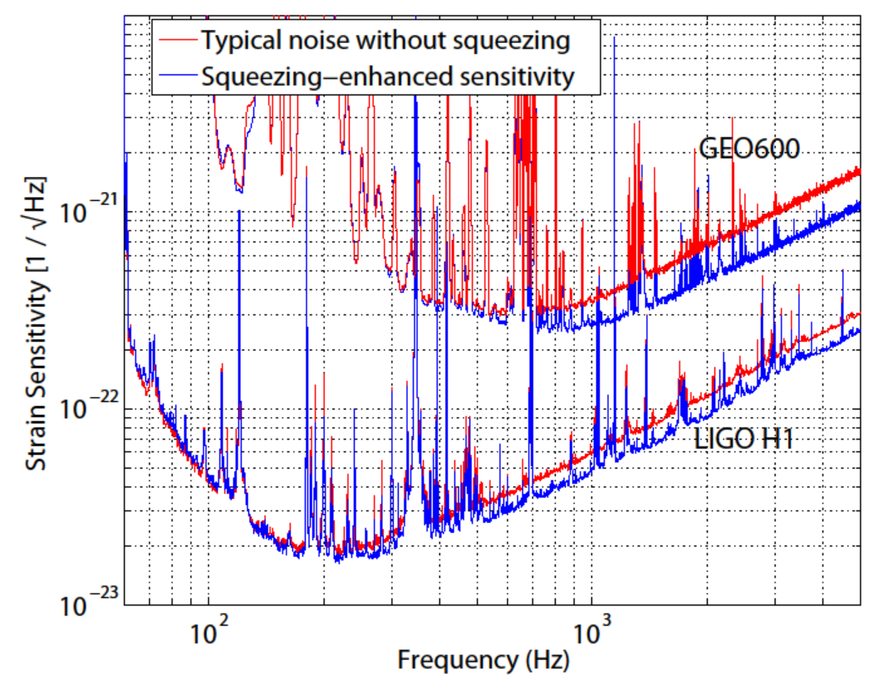


Blair&Jian, 2016

Key Technology: Squeezing

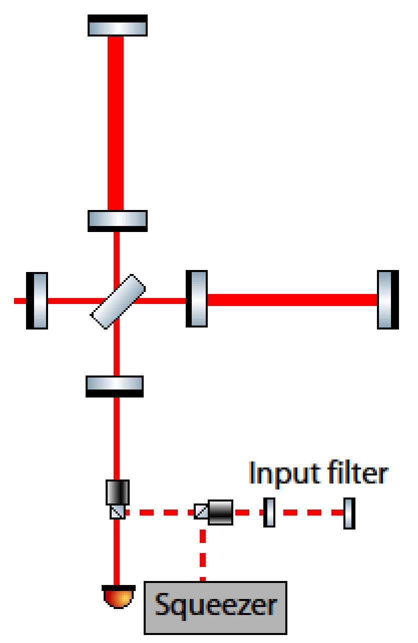


Squeezed light is produced by parametric down-conversion in non-linear crystals.

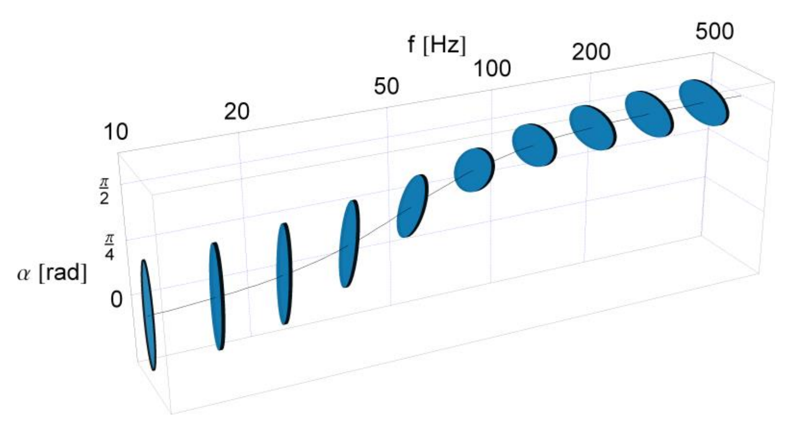


Key Technology: Filter Cavities

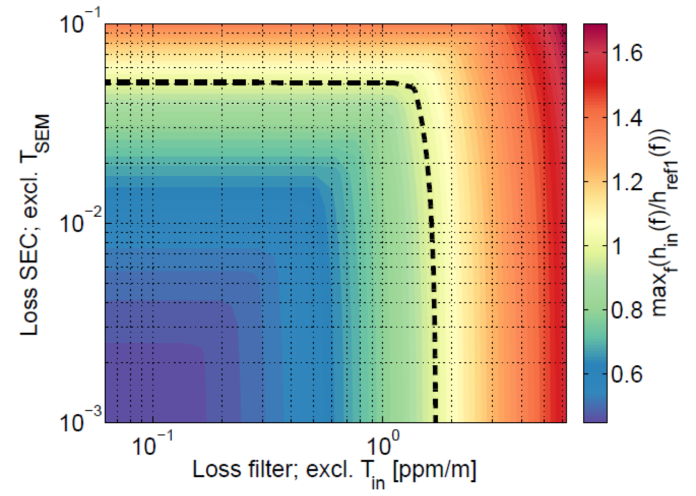
Reflect squeezed light from resonator before injecting it into the interferometer



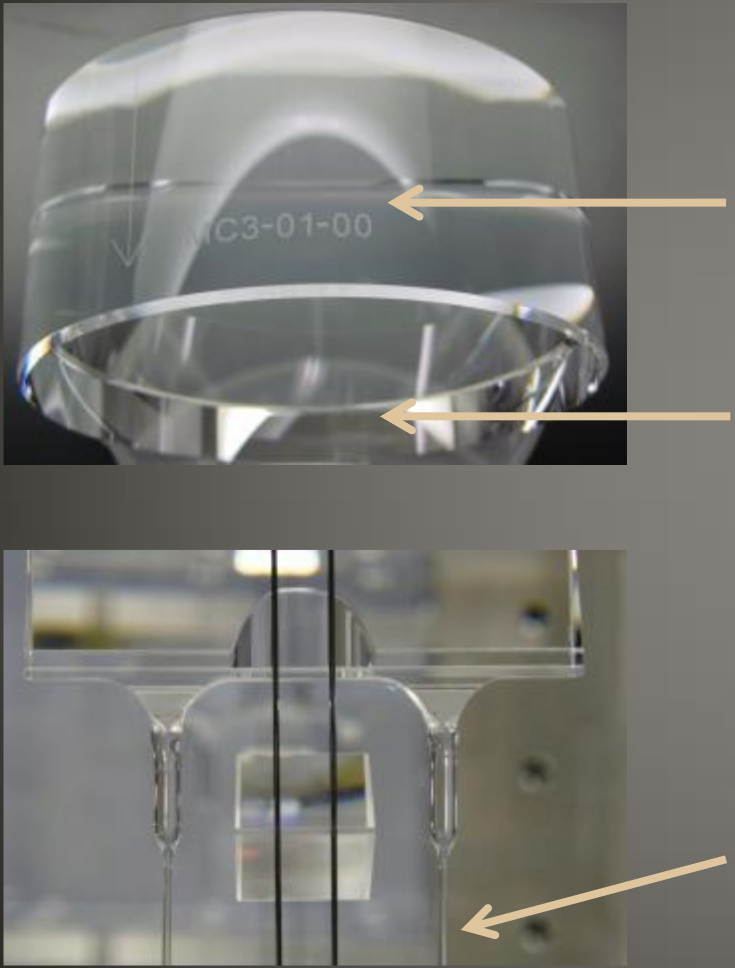
Squeezed-light rotation by filter cavity



Challenge: requires very low-loss cavities



Key Technology: High-Q Materials



Substrate thermal noise

- ***Thermo-elastic noise***
- Brownian noise

Coating thermal noise

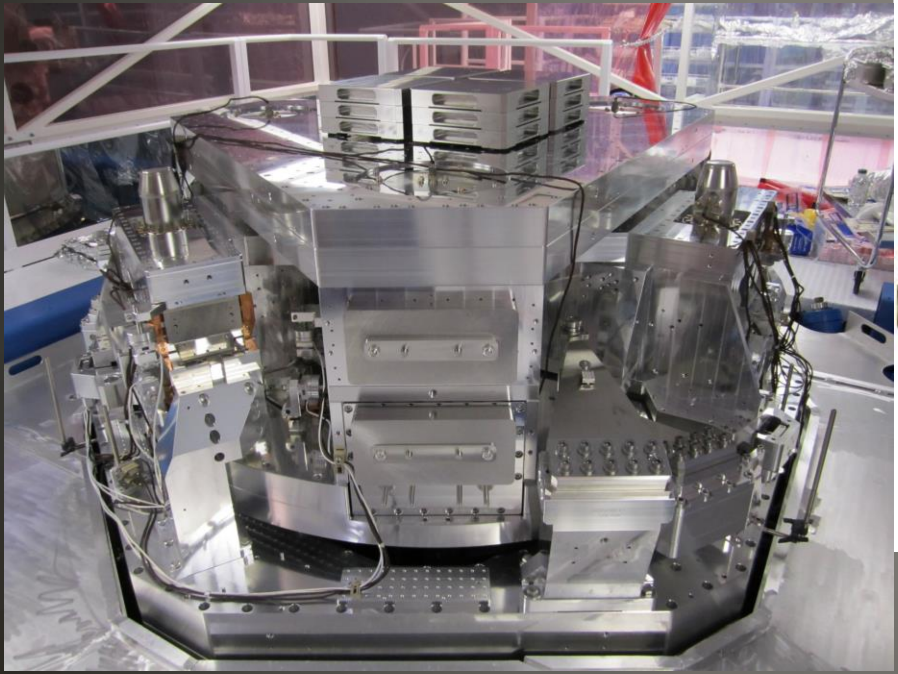
- ***Brownian noise***
- Thermo-refractive noise
- Thermo-elastic noise
- Photothermal noise

Suspension thermal noise

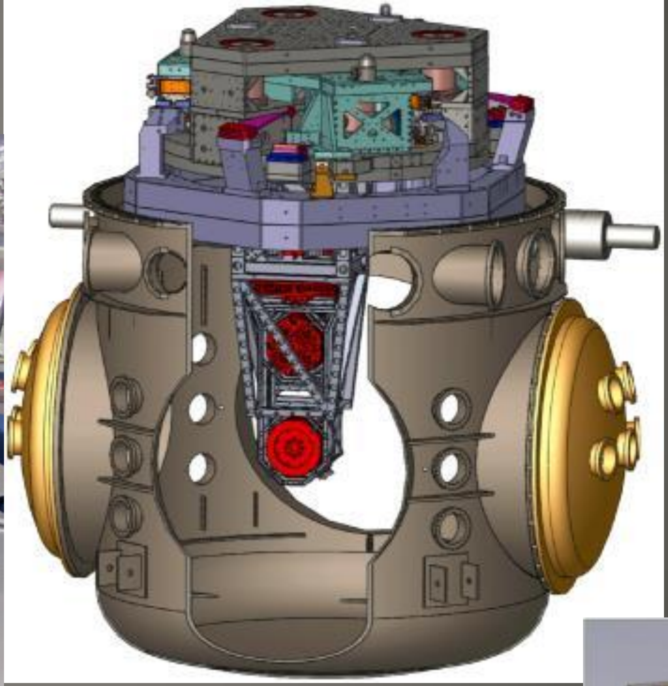
- Brownian noise
- ***Thermo-elastic noise***

Key Technology: Seismic Isolation LIGO Concept

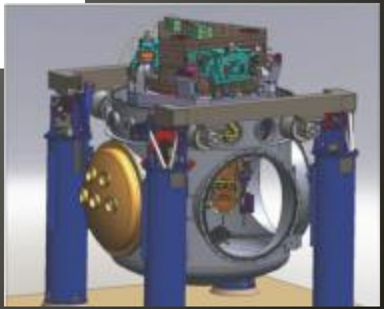
Seismic isolation platform under vacuum



Internal seismic isolation



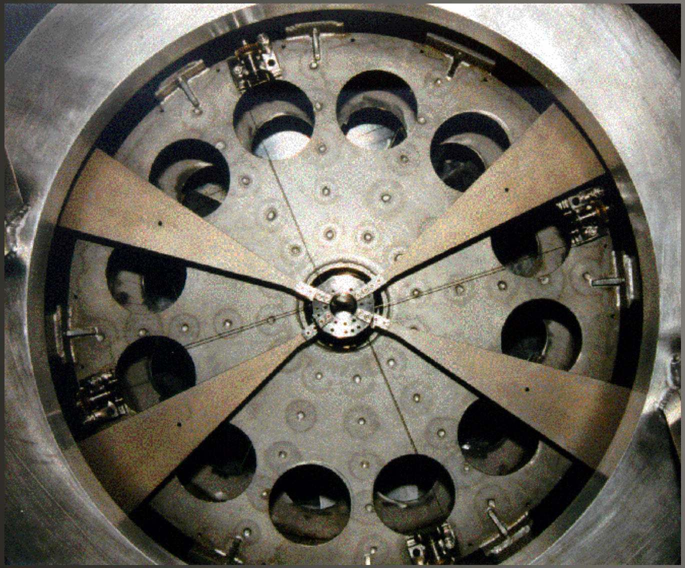
External (hydraulic)



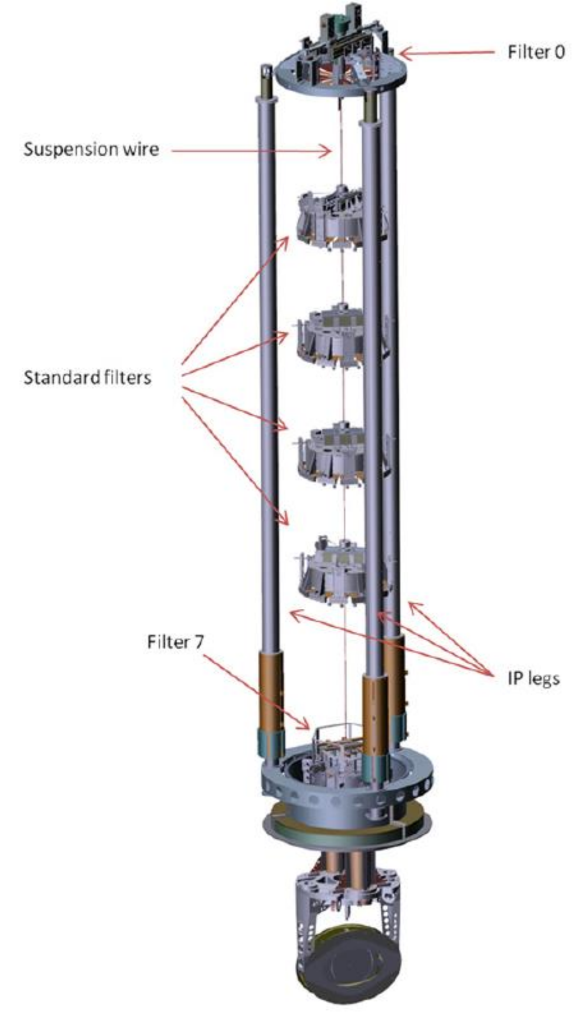
Active seismic isolation uses low-noise sensors and actuators to suppress seismic noise.

Key Technology: Seismic Isolation
Virgo Concept

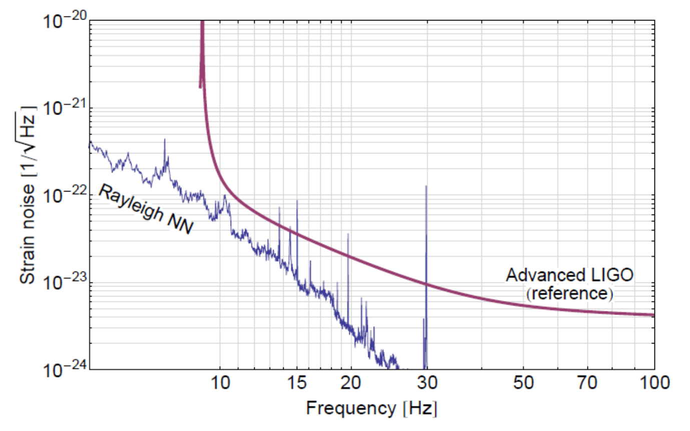
Mechanical filters

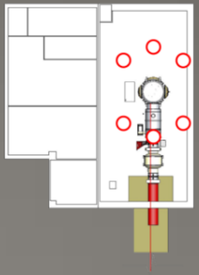


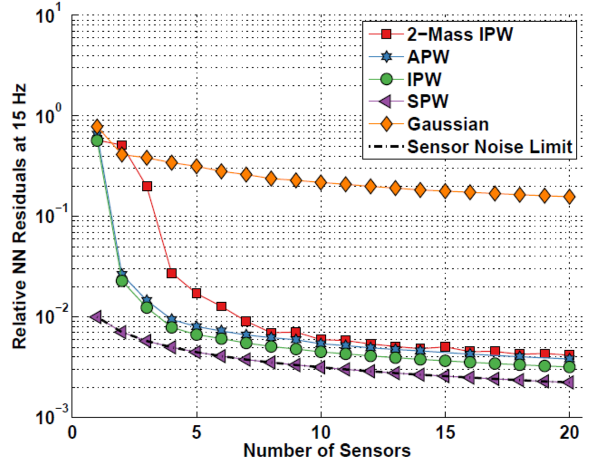
Superattenuator



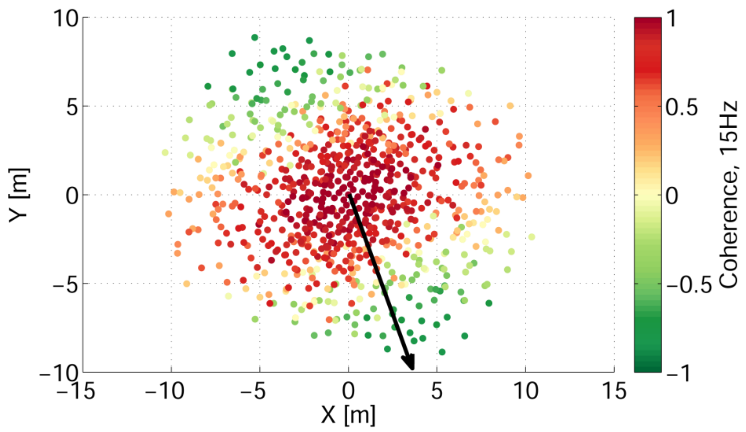
Key Technology: Gravity-Noise Cancellation

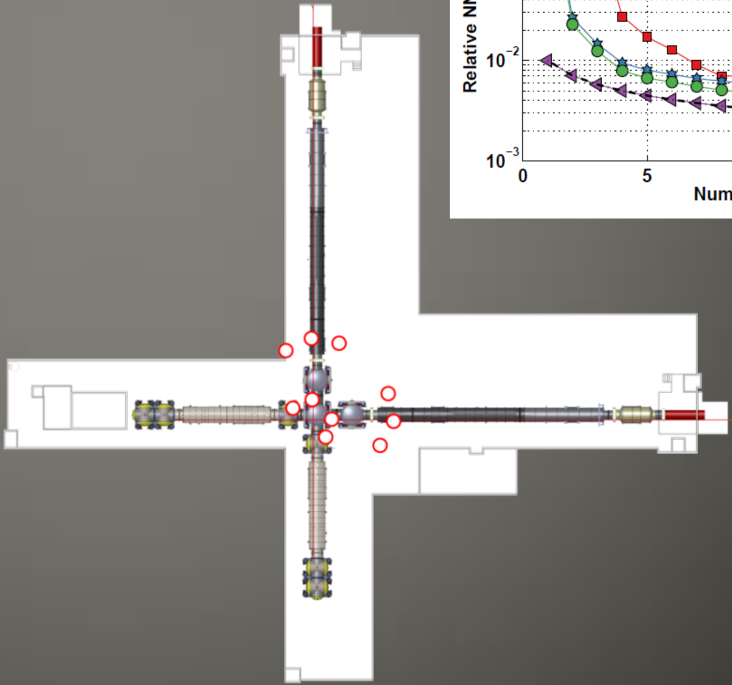


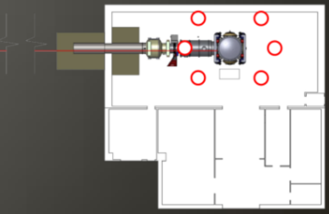




Observed seismic correlations







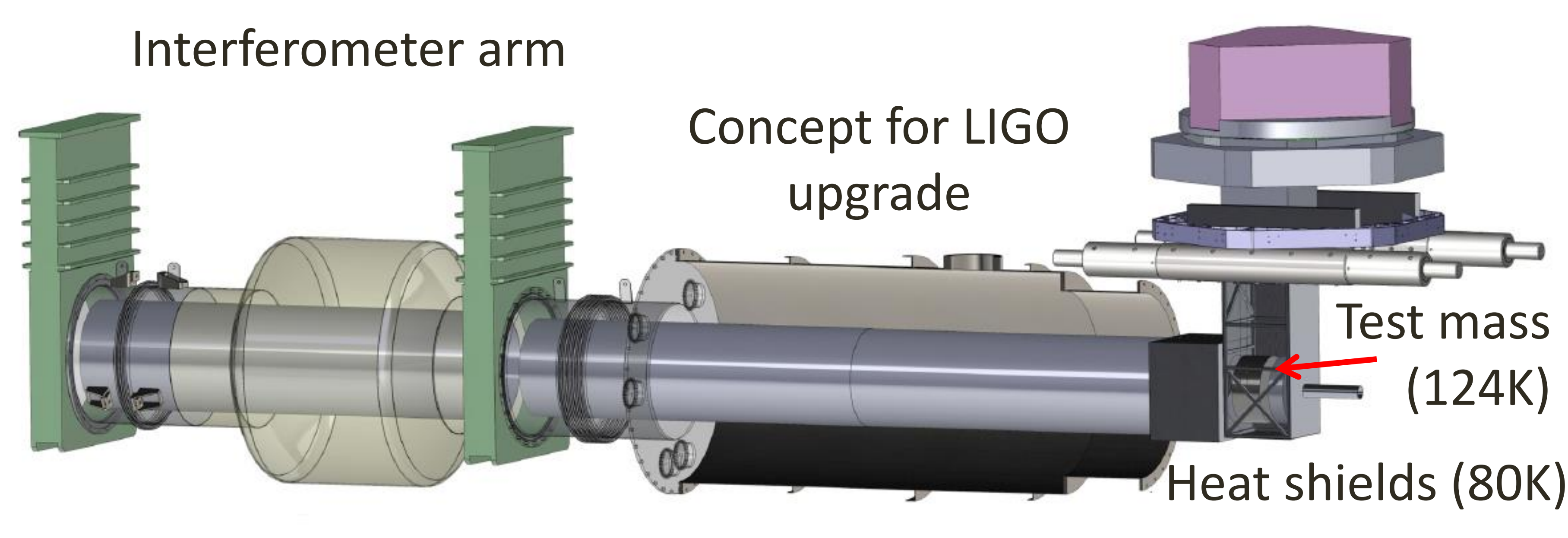
Key Technology: Cryogenics

Thermal noise reduction

1. Cool mirrors and suspensions
2. Noise scales with T or $T^{1/2}$

Challenges (some of them)

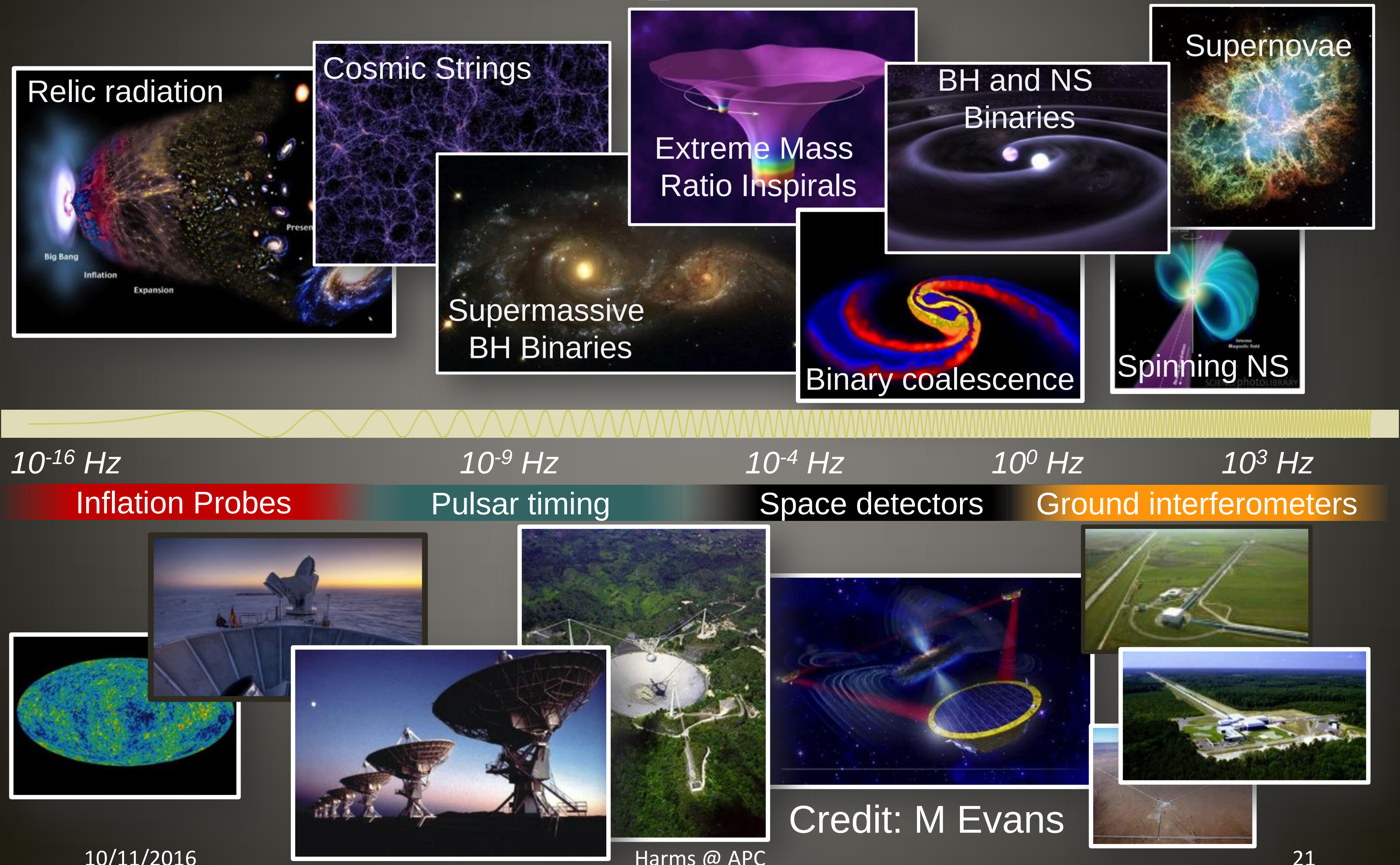
1. New materials
2. Seismic shortcuts from heat links and light scattered from heat shields



Shapiro et al, 2015

Science with Third-Generation GW Detectors

GW Spectrum



Relic radiation

Cosmic Strings

Supermassive BH Binaries

Extreme Mass Ratio Inspirals

BH and NS Binaries

Binary coalescence

Supernovae

Spinning NS

10^{-16} Hz

10^{-9} Hz

10^{-4} Hz

10^{0} Hz

10^{3} Hz

Inflation Probes

Pulsar timing

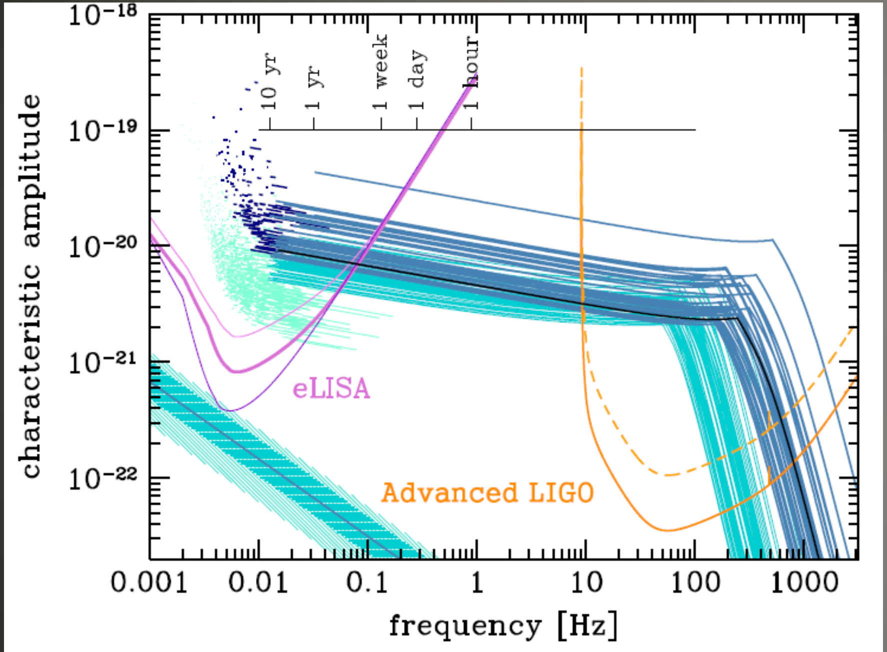
Space detectors

Ground interferometers

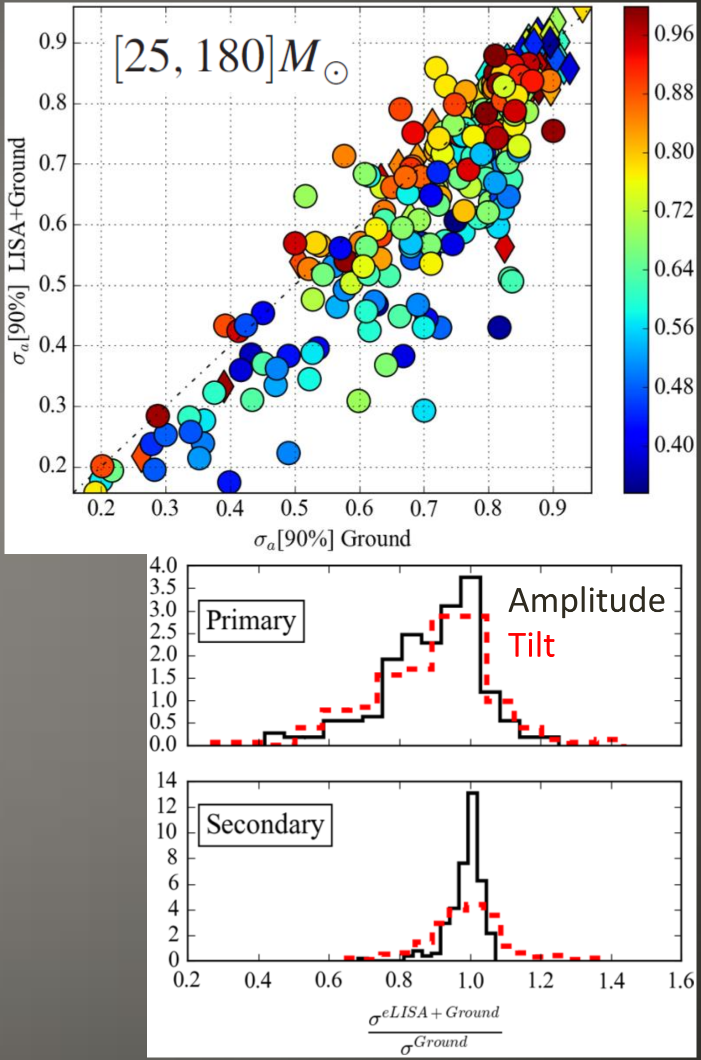
Credit: M Evans

Multiband Observations

Same BH mergers observable by aLIGO and eLISA



Sesana, 2016

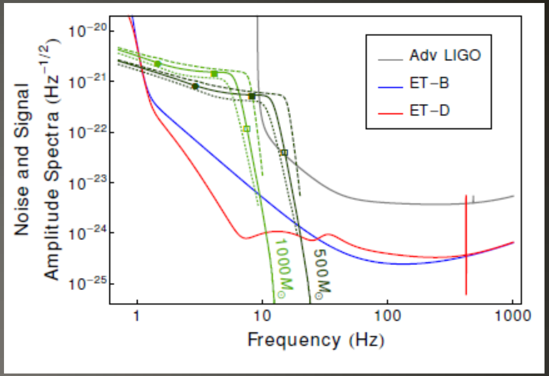


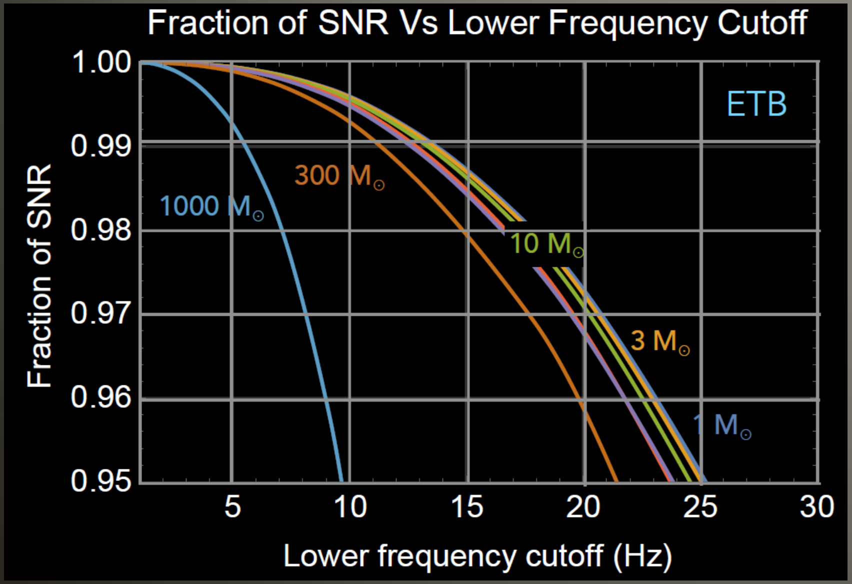
Mass ratio m_{sec}/m_{pri}

Vitale, 2016

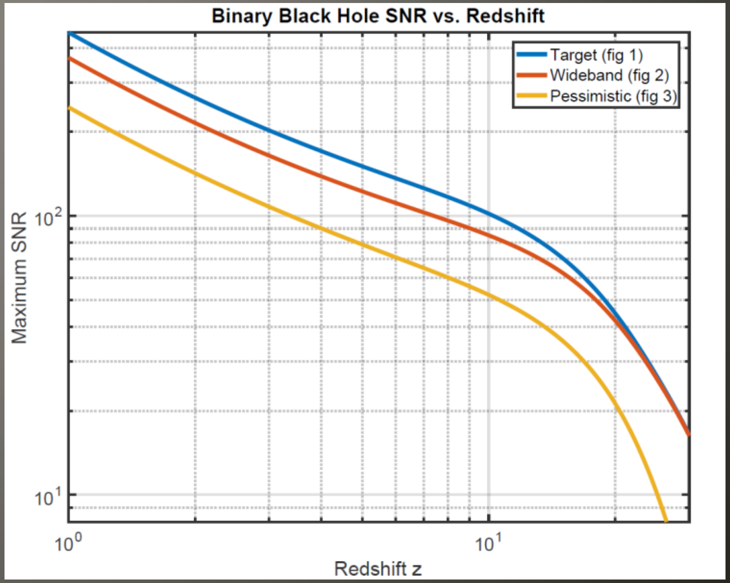
BH/BH Observations

- One can only observe redshifted masses (1+z)M
- For known detector concepts, there is a highest observable BH mass
- 3G detectors would take a BH census starting at an age of the Universe of about 650Myr



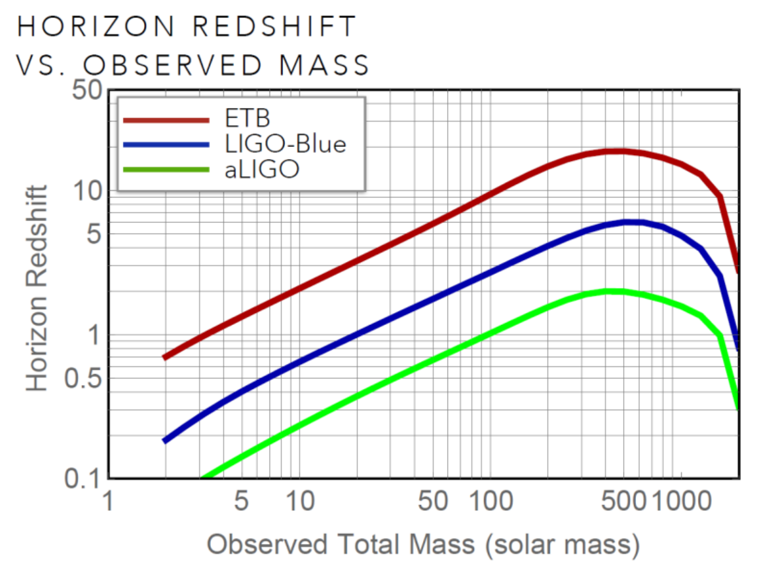


$30M_{sol}+30M_{sol}$ (intrinsic masses)

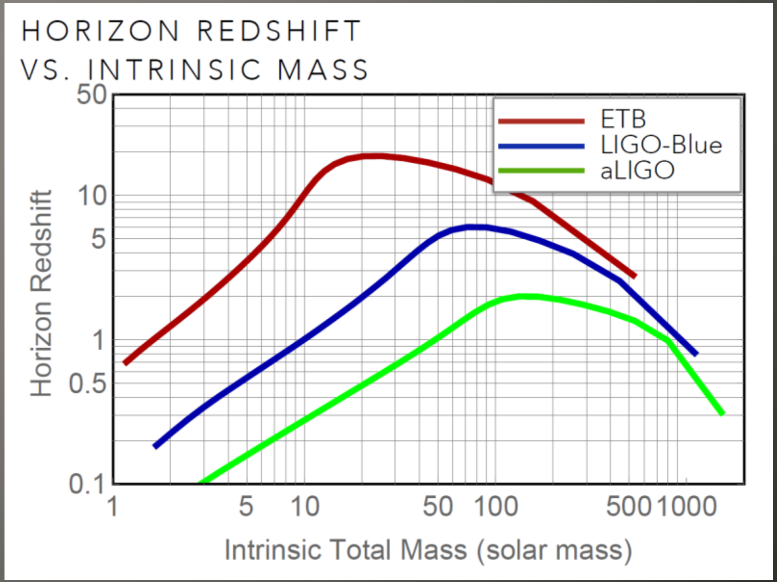


BH/BH Horizon

- Redshift effect causes detection horizons to peak at relatively low BH/BH masses.
- Horizons for observed masses peak at similar values
- Redshift effect is stronger for 3G detectors so that 3G horizons peak at lower intrinsic masses



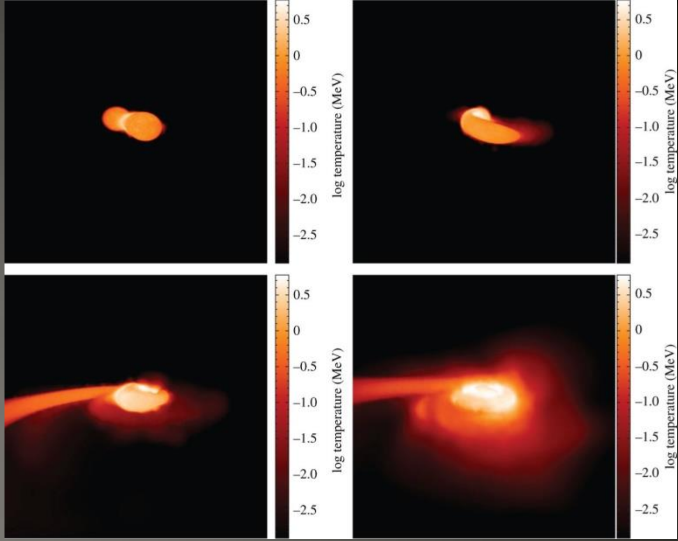
Sathya, 2015



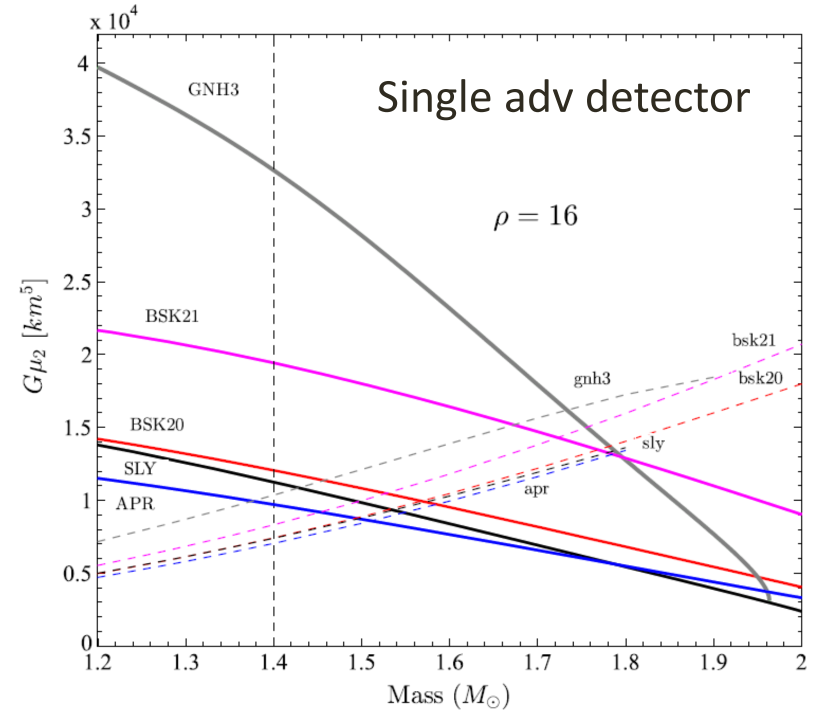
Sathya, 2015

NS Equation of State

Tidal deformation parameterized by NS polarizability μ_2, which is proportional to Love number k_2.

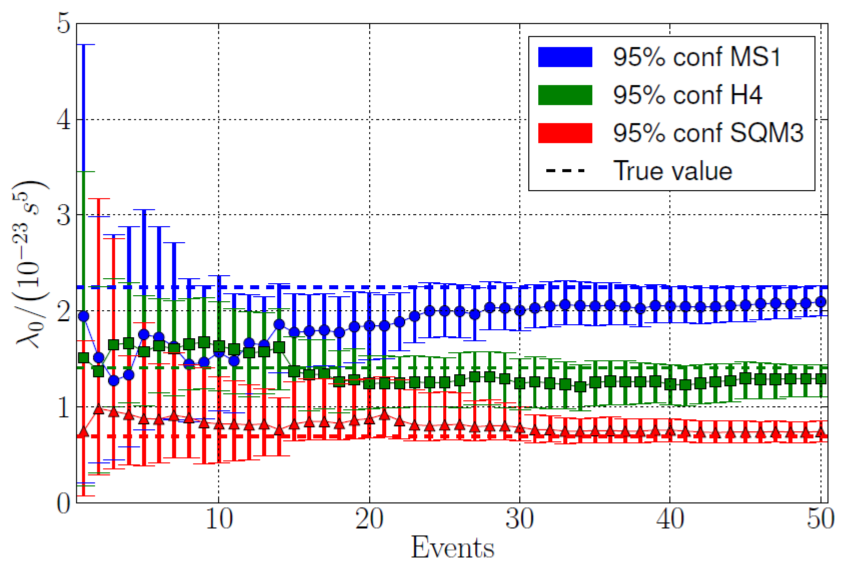


Rosswog, 2012



Damour et al, 2012

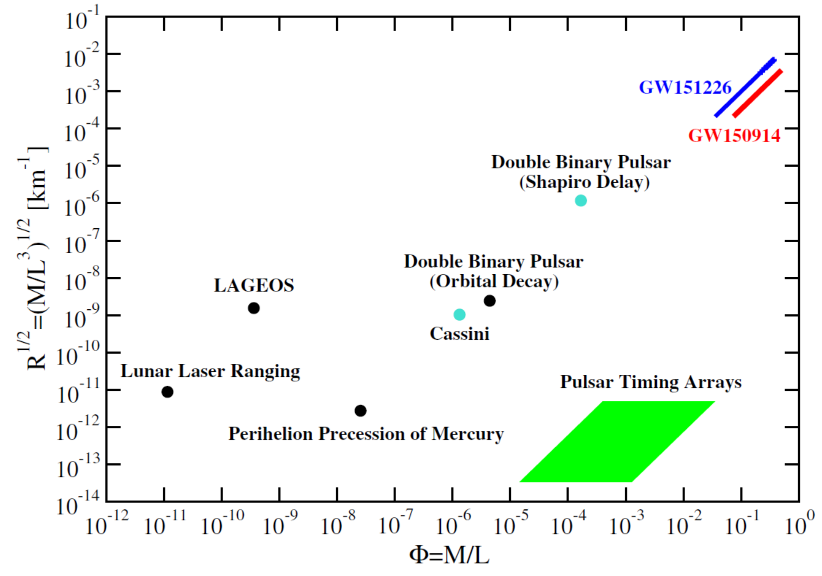
NS equation of state (assuming Adv LIGO/Virgo network)



Del Pozzo et al, 2013

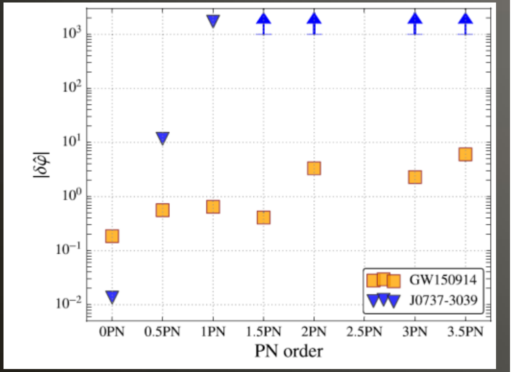
Testing GR

Yunes et al, 2016

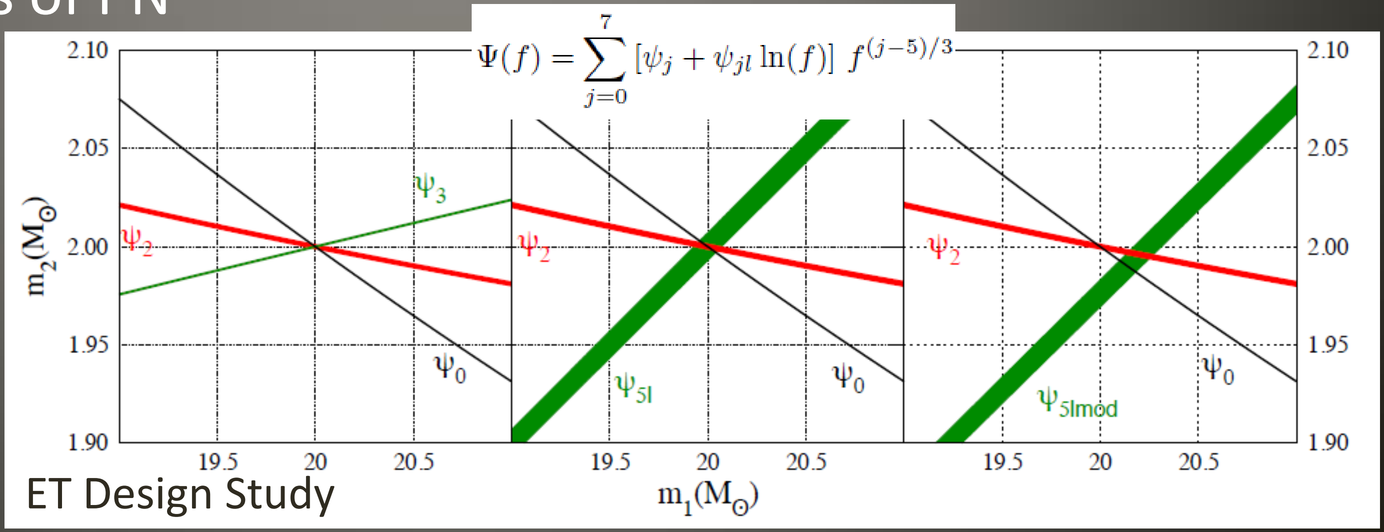


Observing BH mergers, we access a completely new regime of gravity (strong field).

Observe deviations of PN parameters



LVC, 2016



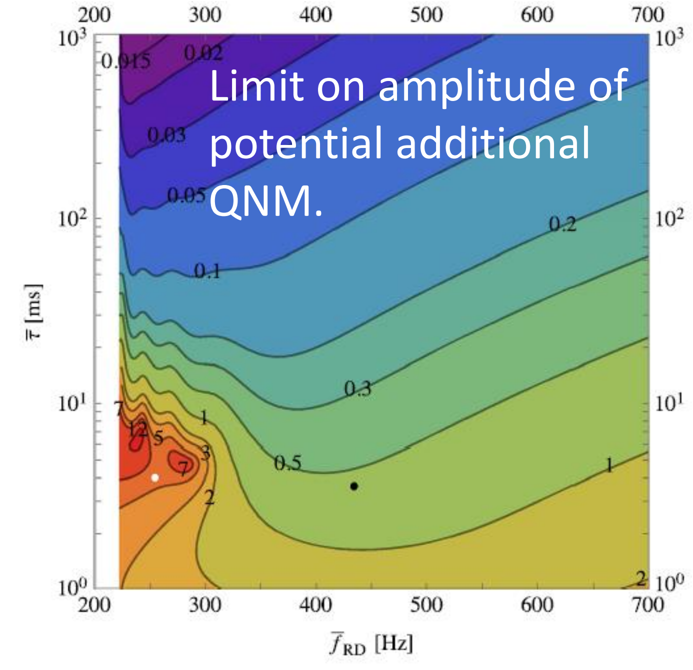
$$\Psi(f) = \sum_{j=0}^{7} [\psi_j + \psi_{jl} \ln(f)]\ f^{(j-5)/3}$$

ET Design Study

Black-Hole Spectroscopy

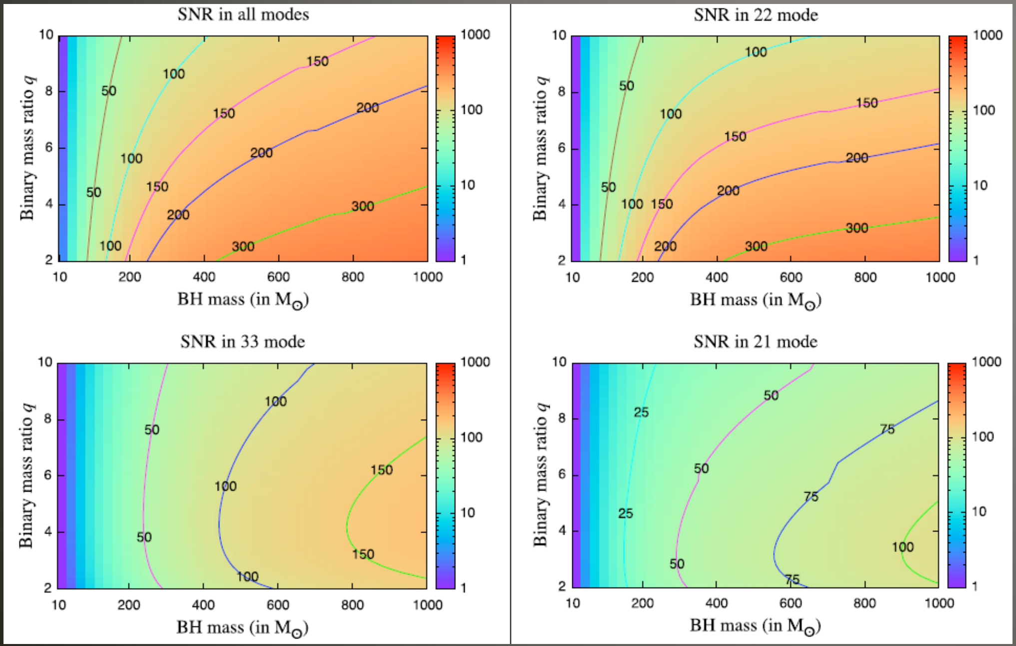
Observe quasi-normal modes at ringdown. SNR dominated by mode l,m=22, then 33 and 21. Energy has different distribution for other objects.

	GW150914	BH	Boson star	NS (n)	NS (B)
Shear $\bar{\eta}$	$\mathbf{4 \times 10^{28}}$	1×10^{30}	7×10^{26}	2×10^{14}	1×10^{27}
Bulk $\lvert\bar{\zeta}\rvert$	$\mathbf{3 \times 10^{30}}$	1×10^{30}	5×10^{28}	6×10^{28}	$\cdots$



Limit on amplitude of potential additional QNM.

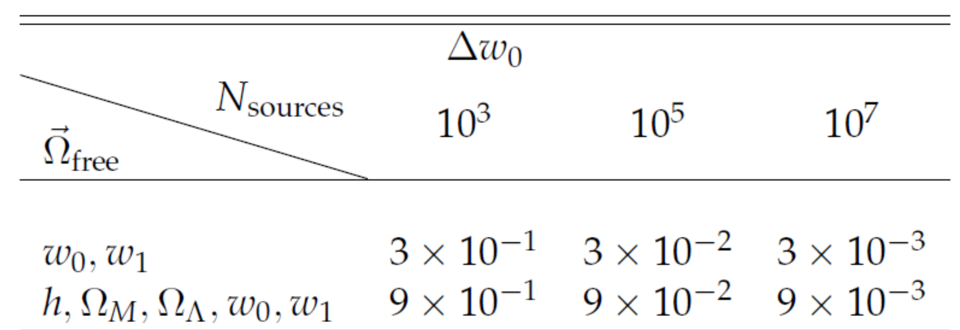
Yunes et al, 2016



ET Design Study

Cosmology/Cosmography

Dark energy EOS



	Δw_0		
N_{sources} / $\vec{\Omega}_{\text{free}}$	10^3	10^5	10^7
w_0, w_1	3×10^{-1}	3×10^{-2}	3×10^{-3}
$h, \Omega_M, \Omega_\Lambda, w_0, w_1$	9×10^{-1}	9×10^{-2}	9×10^{-3}

Li, 2014

1. Measure tidal effects in BNS mergers
2. Estimate intrinsic mass of NS (knowing NS EOS)
3. Infer redshift of source (if exists, use EM counterpart instead)

Cosmological stochastic GW background

1. Detection unlikely
2. Interesting physics: inflaton decay

Black-hole survey

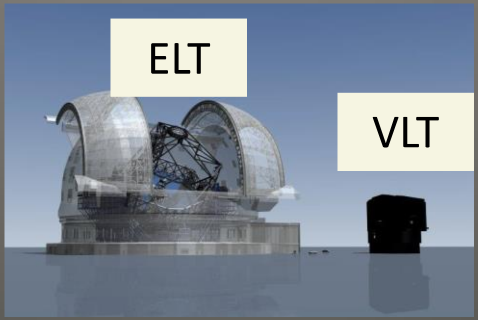
1. Black hole evolution
2. Intermediate-mass black holes
3. Stellar environment as function of redshift
4. Possible primordial BH detection

Electromagnetic Follow-Up

Wide-field telescope
FOV >1 sq.degree

"Fast" and "smart" software to select a sample of candidate counterparts

Larger telescope to **characterize** the candidate nature



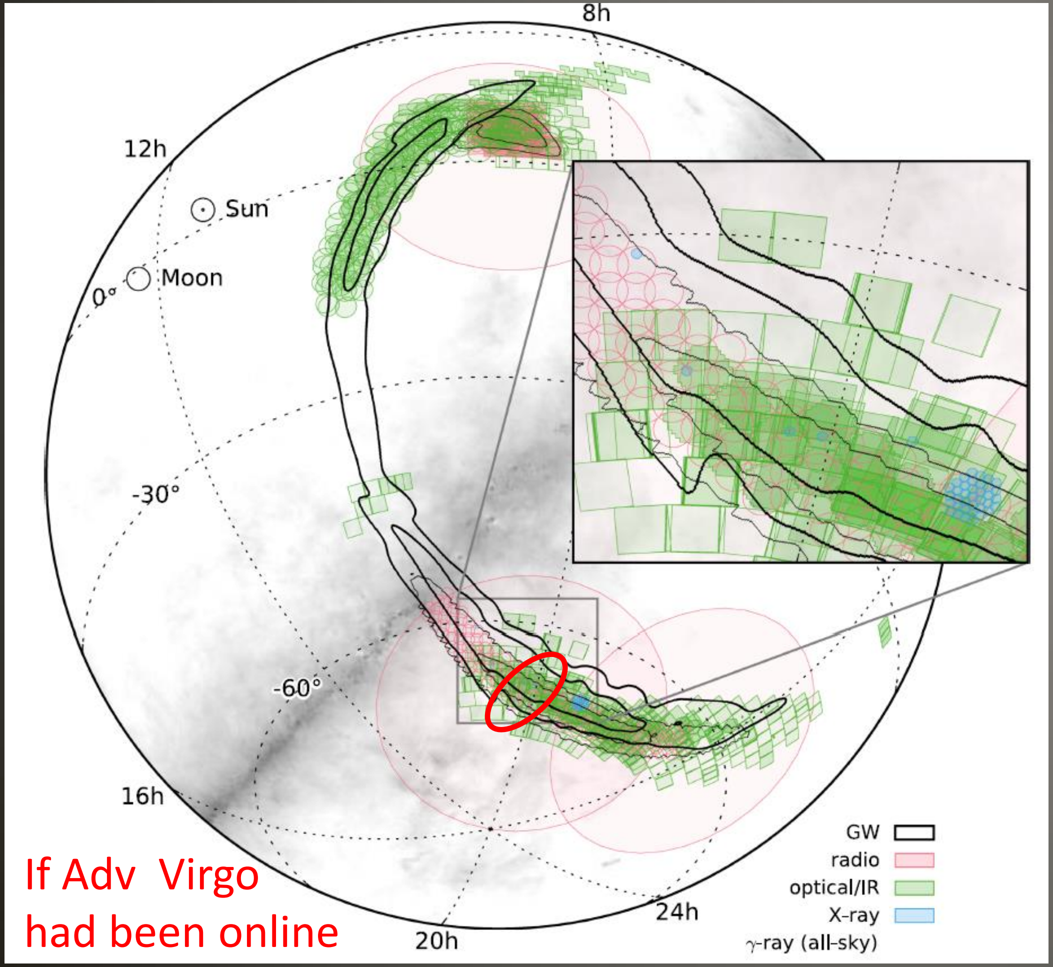
The EM Counterpart!

Credit: J Harms

Credit: M Branchesi

Source Localization

EM follow-up of GW150914



If Adv Virgo had been online

Not easy to cover hundreds of deg^2 of sky with FOV of 1-10 deg^2!

Localization Near Detection Range

(1.38+1.42)BNS	SNR	SKY ΔΩ DEG^2	INC. ΔI DEG	DIST ΔD/D	CHIRP MASS (PPM)	EPOCH ΔT (MS)
3XBB (800 MPC)	12	**43**	23	75%	50	0.47
3XETB (3 GPC)	12.85	**55**	23	78%	60	0.52
3XALIGO (200 MPC)	10	56	27	62%	30	0.52

BB = Adv LIGO/Virgo upgrade

Sathya, 2015

Localization Depending on Detector

(1.38+1.42)BNS at 800Mpc	SNR	SKY $\Delta\Omega$ DEG^2	INC. ΔI DEG	DIST $\Delta D/D$	CHIRP MASS (PPM)	EPOCH ΔT (MS)
2 X BB + ETB	37	41	22	71%	5.6	0.41
3 X ETB	39	5.7	7.6	25%	5.2	0.16
3 X BB	12	43	23	75%	52	0.47

Sathya, 2015