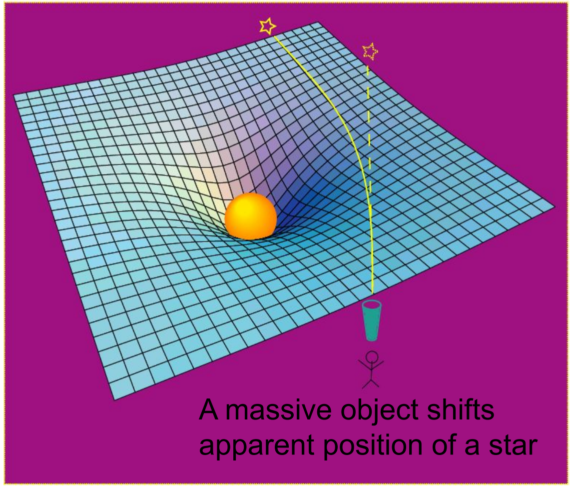
LVK detectors status and future plans

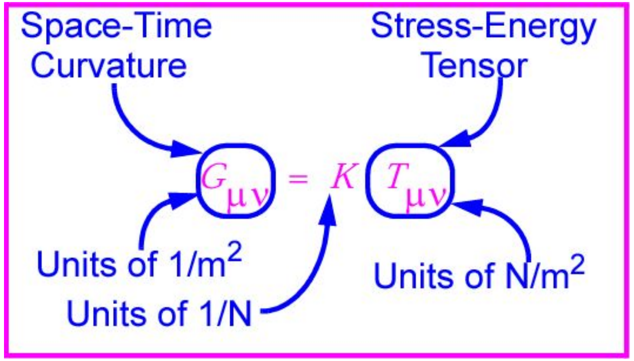
F. Sorrentino - INFN Genova
on behalf of the Virgo collaboration

GR & spacetime stiffness



A massive object shifts apparent position of a star

space stirred by two orbiting black holes



$$K \sim [G/c^4] \sim 10^{-44}\ \mathrm{N}^{-1}$$

- GW can carry large energy density with vanishingly small amplitude
- E.g. for a binary coalescence

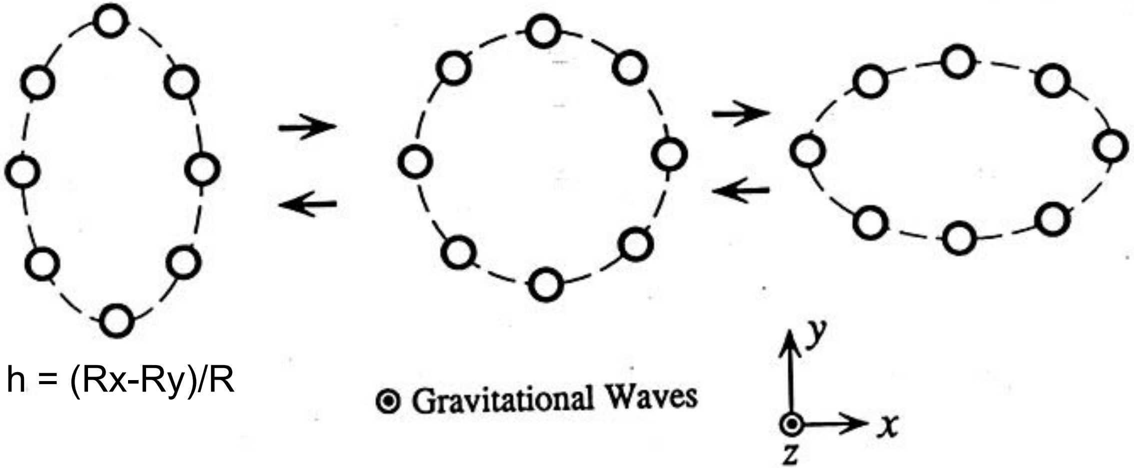
$$h \approx 32\pi^2 \cdot \frac{G}{c^4} \cdot \frac{1}{r} \cdot M \cdot R^2 \cdot f_{orb}^2$$

$M = 1.4\ M_{\odot}$, R = 20 km, f = 400 Hz,

$r = 10^{23}$ m (15 Mpc = 48,9 Mlyr)

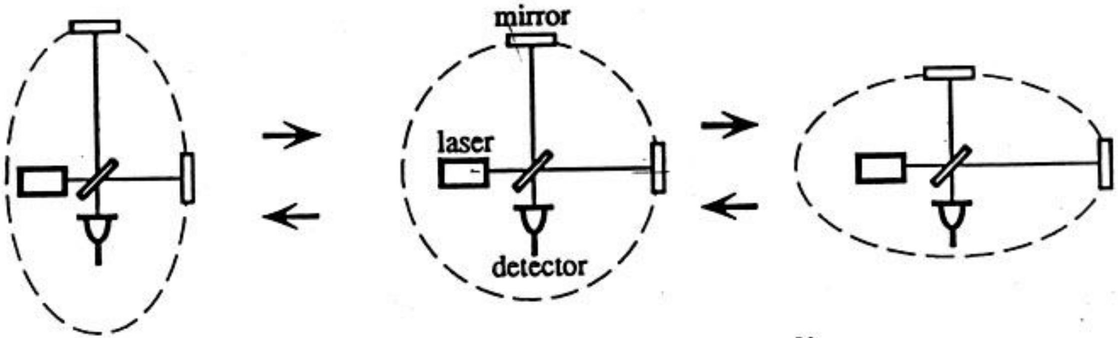
$h \sim 10^{-21}$

GW strain & Michelson interferometers



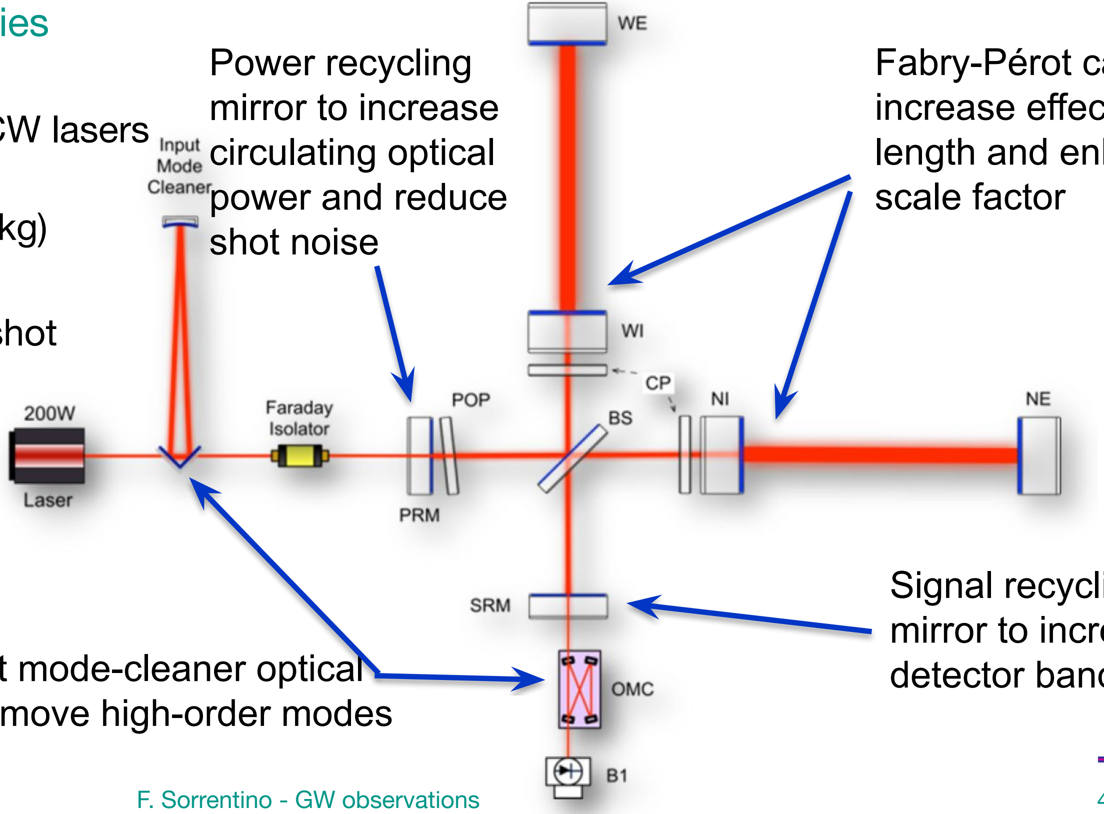
GW amplitude h = (Rx-Ry)/R

Spatial asymmetry induces relative phase shifts on light in arms



Optical configuration of GW detectors

- Doubly recycled Michelson interferometer with arm cavities
  - Km long arms
  - High power, ultrastable CW lasers (10÷100 W)
  - Suspended mirrors (~40 kg)
  - Under ultra-high vacuum
  - Quantum squeezing for shot noise mitigation



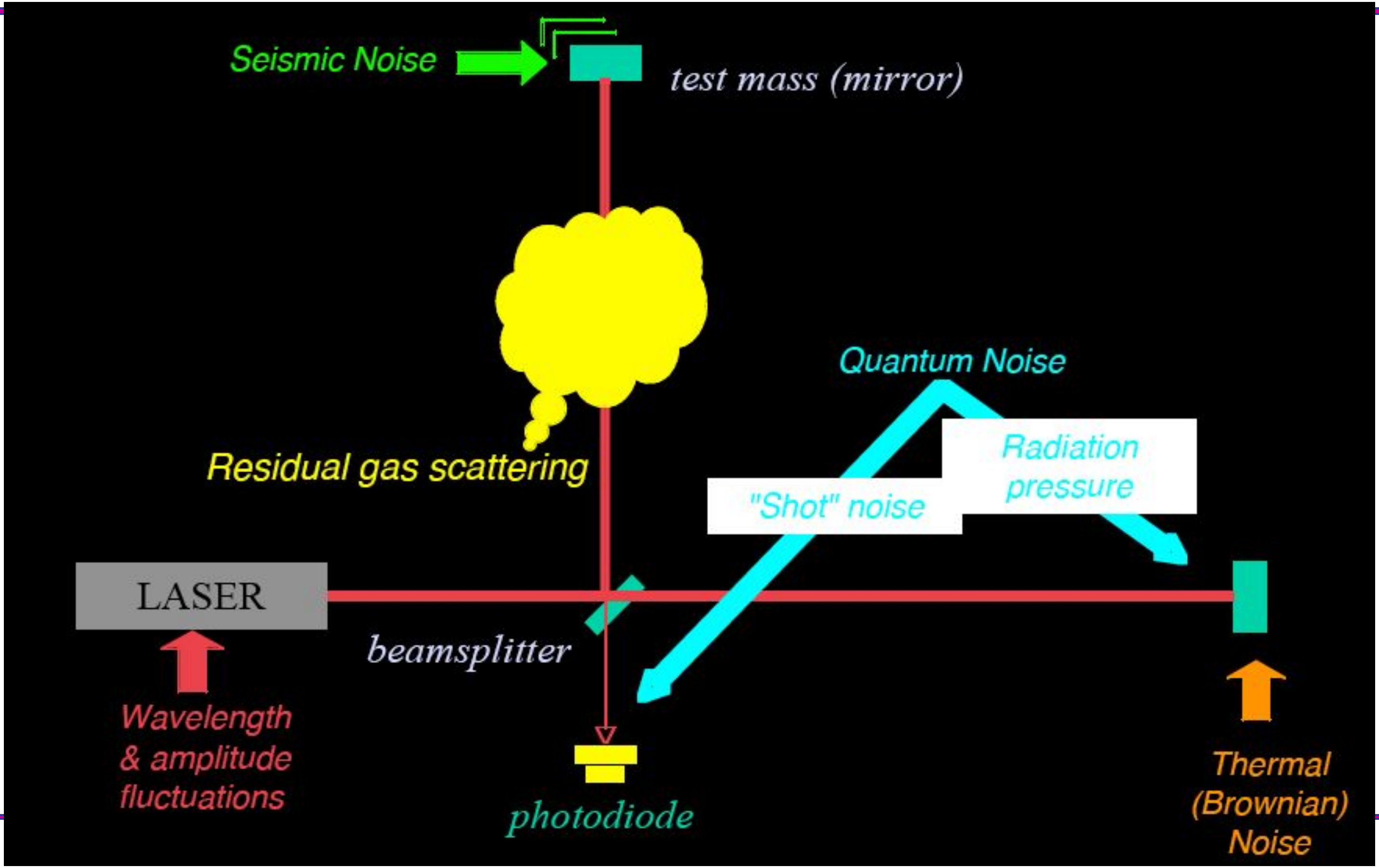
Power recycling mirror to increase circulating optical power and reduce shot noise

Fabry-Pérot cavities to increase effective arm length and enhance scale factor

Signal recycling mirror to increase detector bandwidth

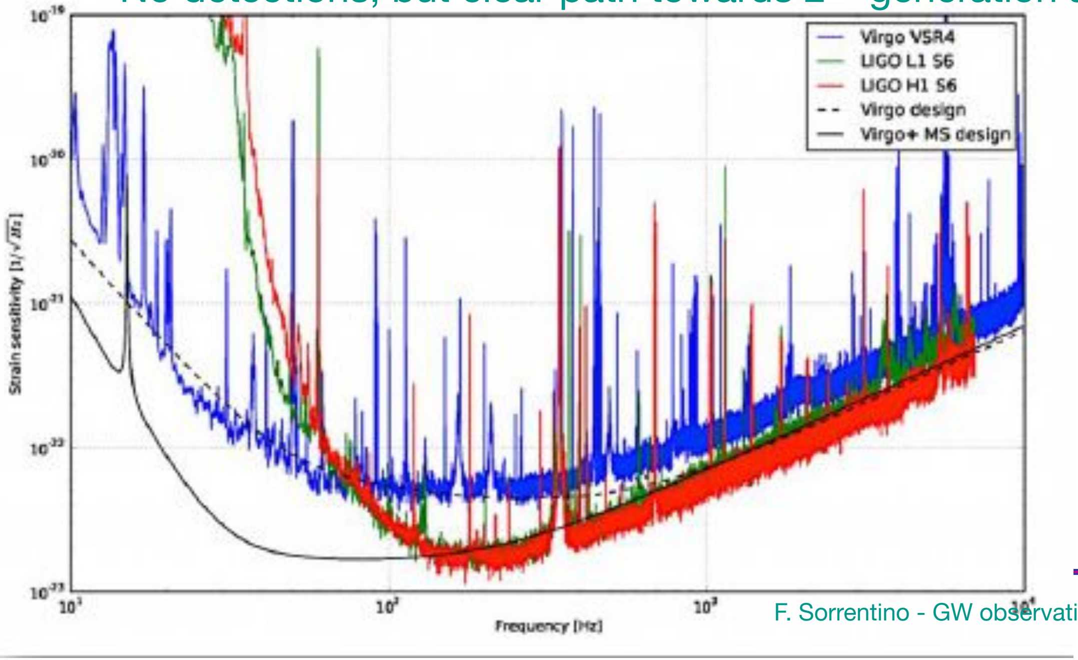
Input and output mode-cleaner optical resonators to remove high-order modes

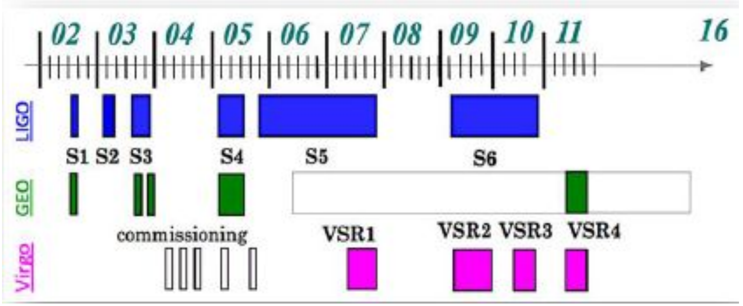
Noises limiting sensitivity of GW detectors



1st generation GW detectors

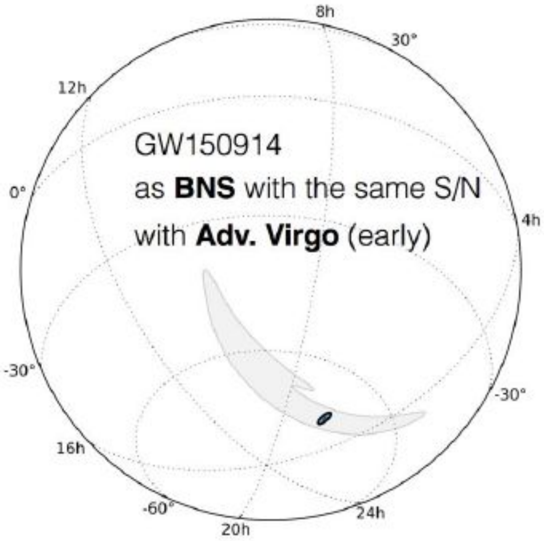
- LIGO, Virgo and GEO600 operated for about one decade, reaching design sensitivities
- Demonstrated a reliable technology
  - duty cycle up to 80%
  - good knowledge of limiting noise sources
- No detections, but clear path towards 2nd generation antennas



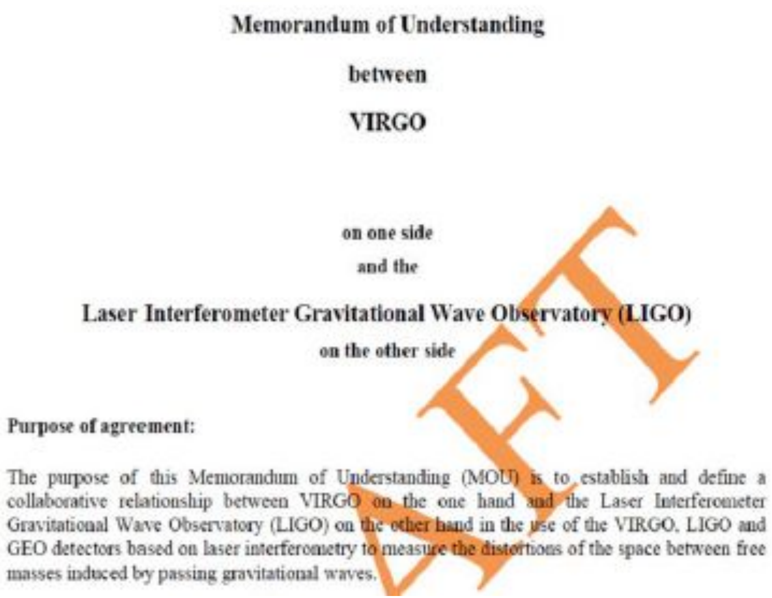


1° generation network of GW detectors

- GW antennas are poorly directional
- Source localization requires simultaneous distant detectors
- MoUs among LIGO, Virgo and GEO since 2007 for full exchange of data



from L SINGER, G1601468



Memorandum of Understanding

between

VIRGO

on one side

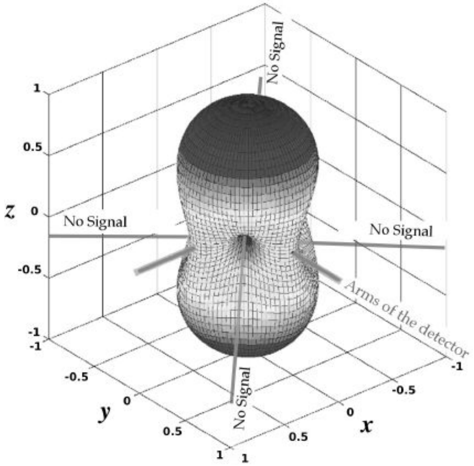
and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

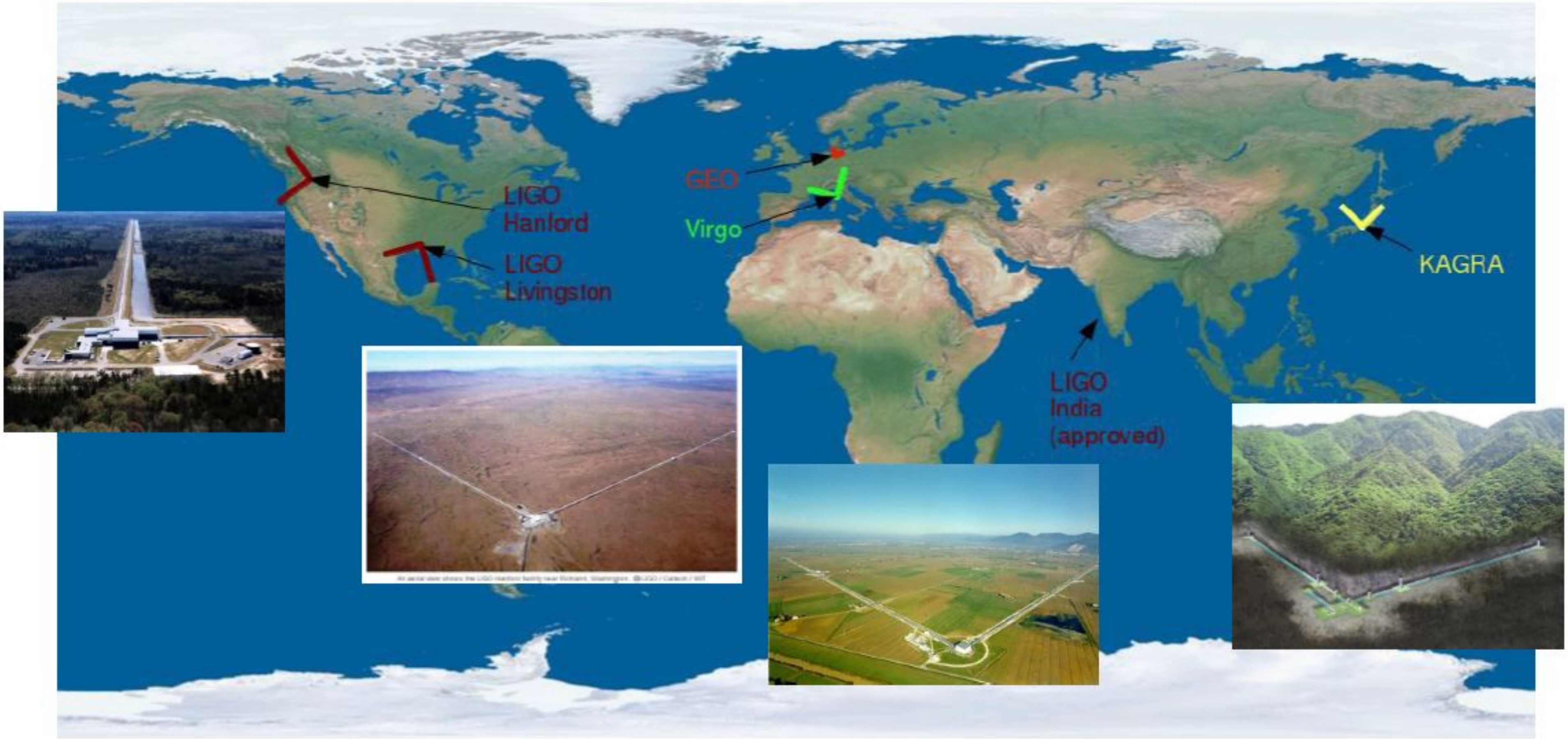
on the other side

Purpose of agreement:

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.

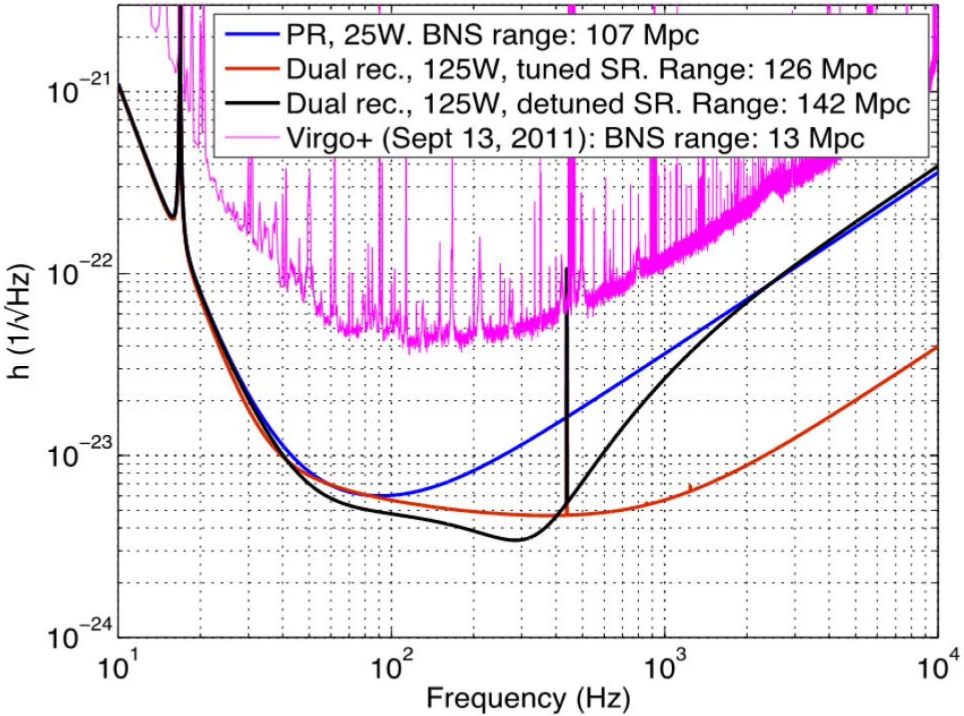


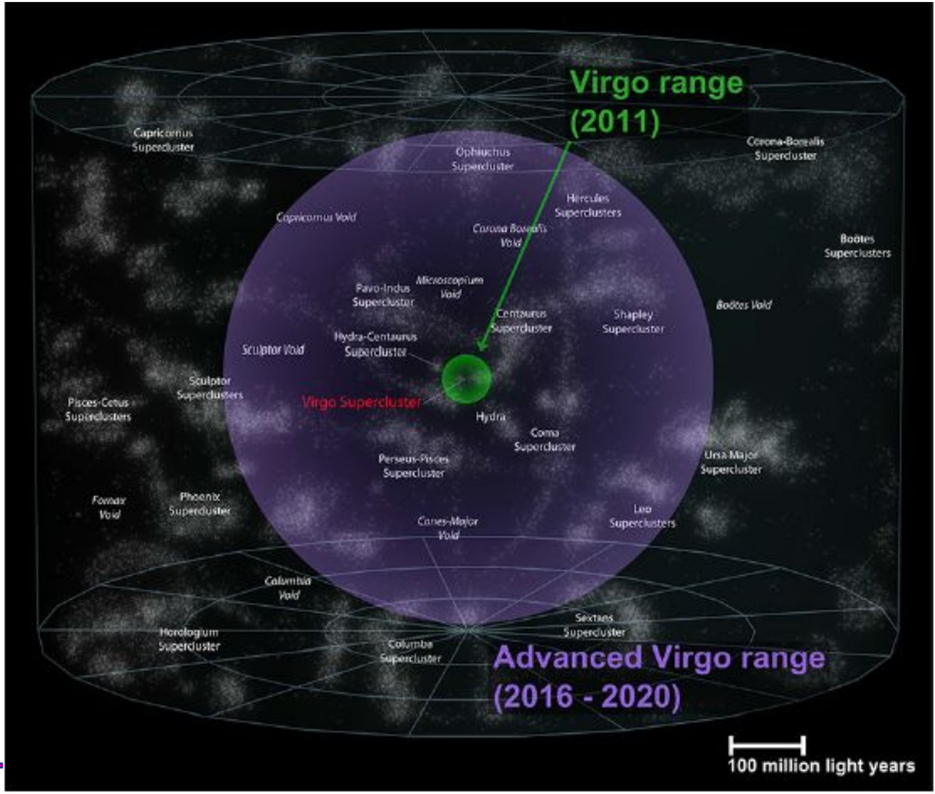
Network of GW detectors



Advanced detectors

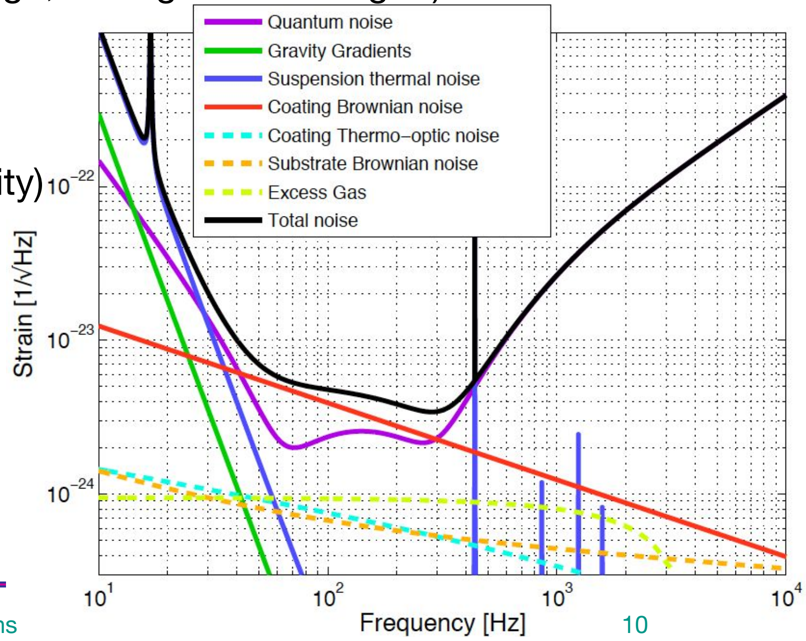
- 10 x sensitivity improvement over 1st generation detectors
- 1000 x increase of observation volume





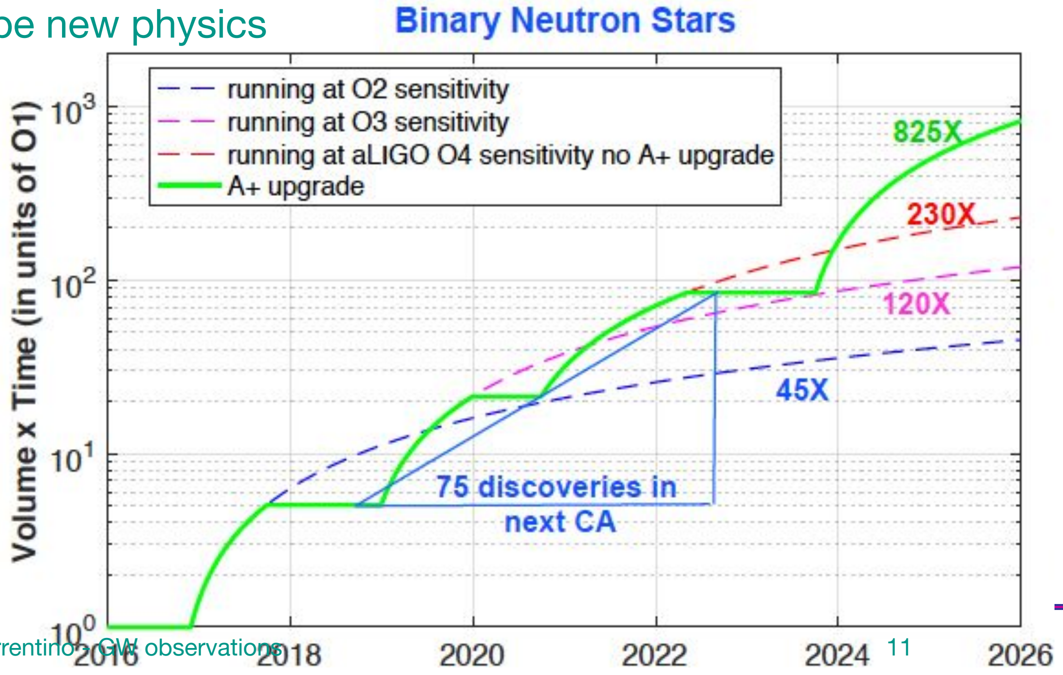
AdV challenges

- Reducing thermal noise:
  - increased beam size @ input TM (2.5 x higher)
  - improved mirrors' planarity (16 x better)
  - Improved coatings for lower losses (7 x better)
- Reducing quantum noise:
  - Increased finesse of arm cavities (9 x higher than iVirgo, 3 x higher than Virgo+)
  - High power laser (16 x more input power)
  - Heavier test masses (2 x heavier)
- Seismic isolation:
  - iVirgo superattenuators compatible with AdV specs
  - adapted for new payload (added mass and complexity)
  - new electronics
- Thermal compensation (100 x higher power on TM)
  - ring heaters
  - double axicon CO_2 actuators
  - CO_2 central heating
- Better vacuum (10^{-9} instead of 10^{-7})
- Stray light control
  - Suspended optical benches in vacuum
  - New set of baffles



Observing runs & detectors' upgrades

- GW science is driven by detectors' sensitivity
- Number of events ~ T*V
  - T= coincident observing time
  - V=volume probed ~ $(\text{Range})^3$
- Most sources require high SNR to probe new physics
  - BH ringdown
  - Tidal effects in BNS mergers
  - Stochastic background
  - Galactic supernovae
  - Isolated NS
  - Theories beyond GW



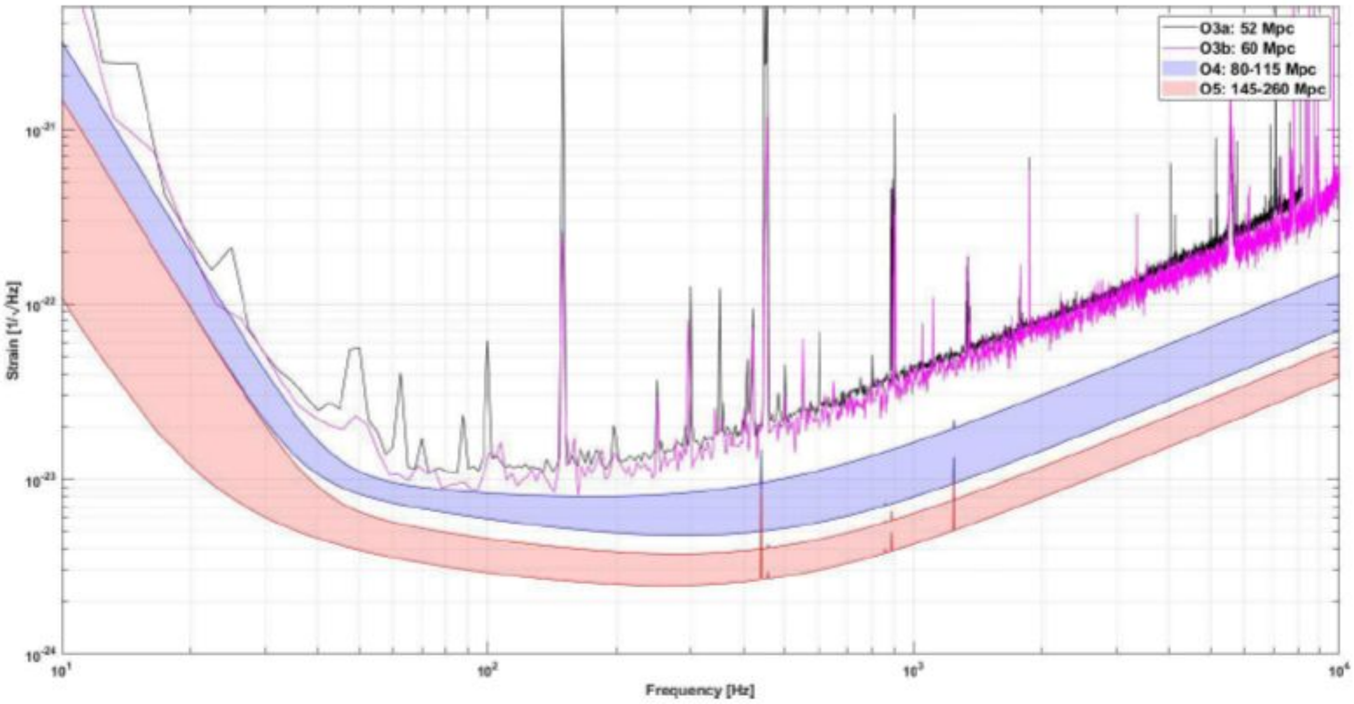
Upgrades for O4 & O5: AdV+

Phase I: reduce quantum noise, hit against coating thermal noise

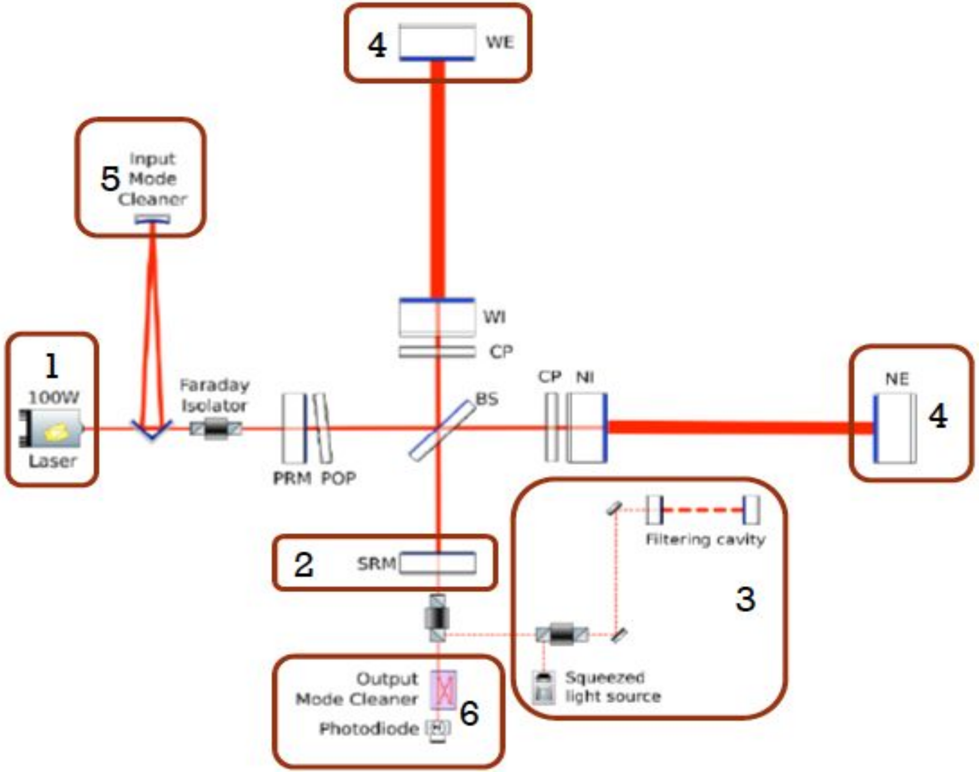
- BNS range ~ 100 Mpc

Phase II: lower thermal noise wall

- BNS range ~ 200 Mpc

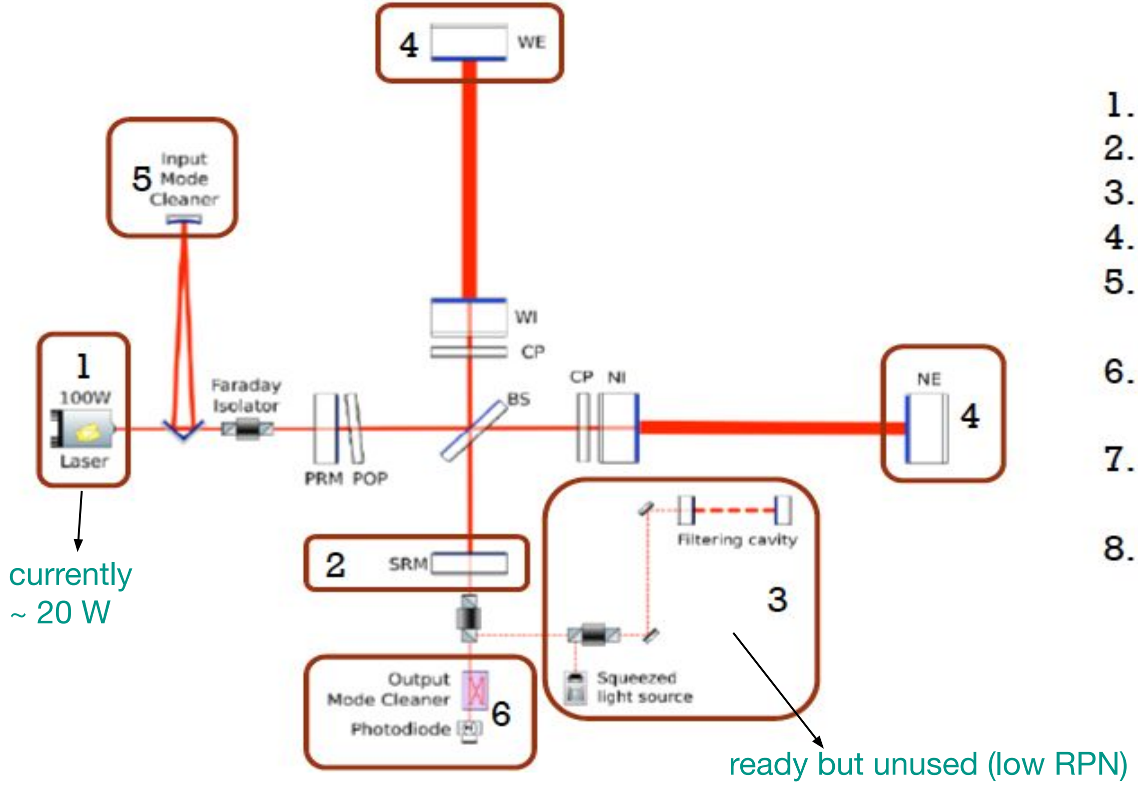


Upgrades for O4 & O5: AdV+



1. High-power fiber laser amplifier
2. Signal recycling mirror
3. Frequency dependent squeezing
4. Green light auxiliary laser system
5. New Input mode Cleaner payload with an instrumented baffle
6. New high finesse output mode cleaner and new read-out photodiodes.
7. HVAC upgrades and reduction of environmental noise.
8. Deployment of accelerometer arrays for Newtonian Noise characterization

Upgrades for O4 & O5: AdV+



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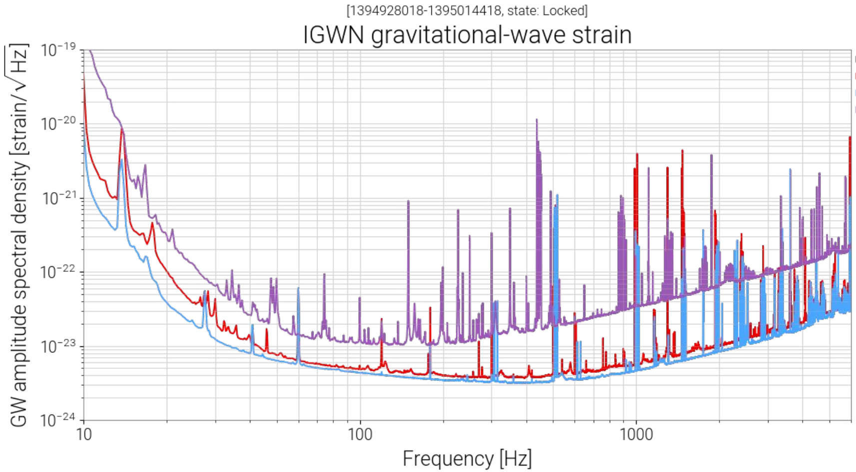
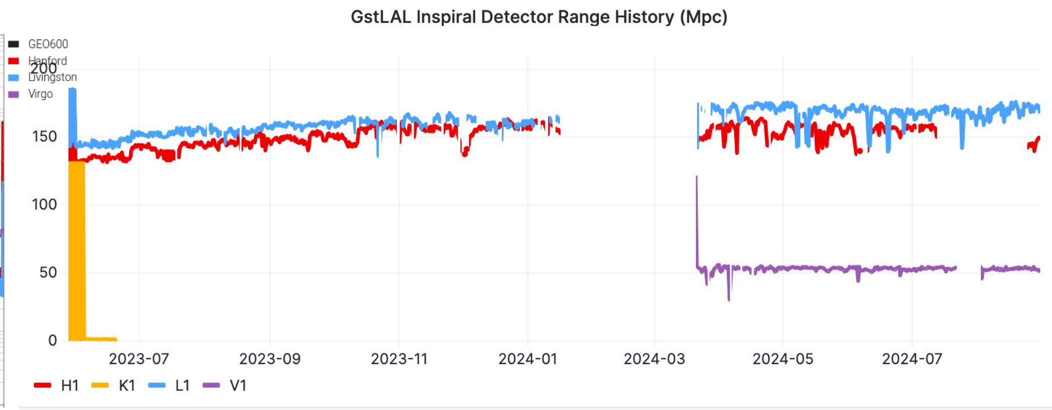
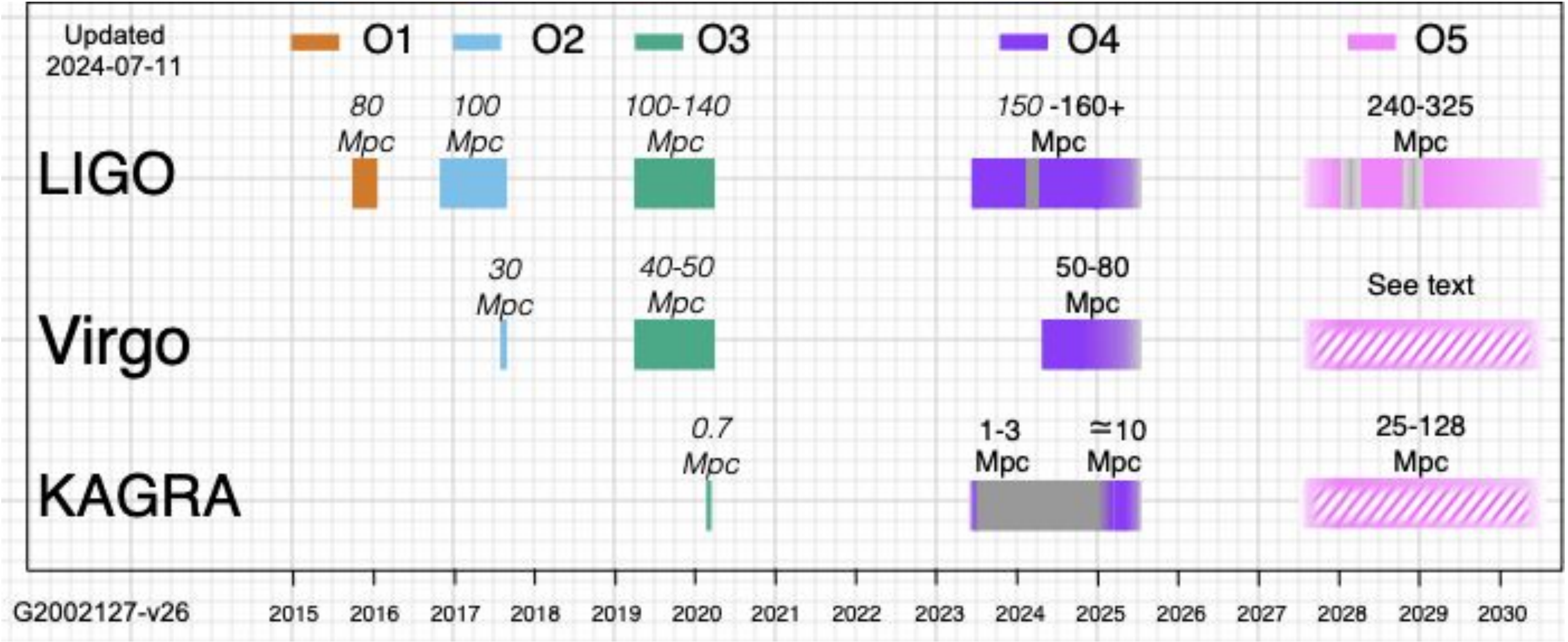
O4: current status

- O4a started on May 24, 2023 until January 16, 2024
  - data taking from LIGO detectors
- O4b started on April 3, 2024 and will end on June 2025
  - LIGO+Virgo
  - Kagra to join in 2025 to complete commissioning





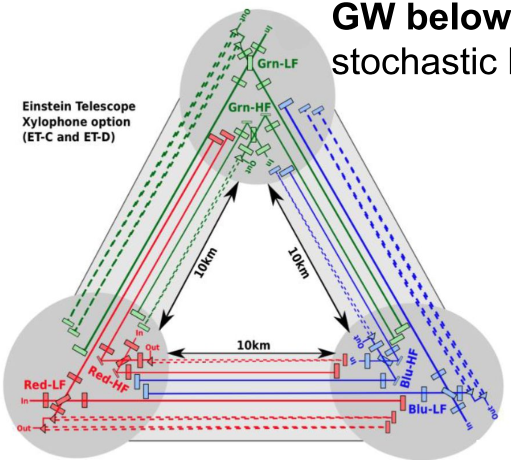
Observing scenario for terrestrial GW detectors

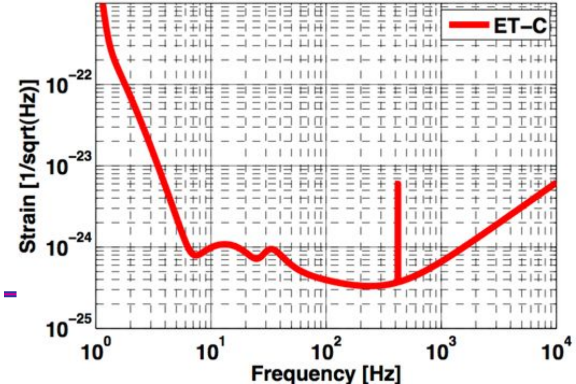


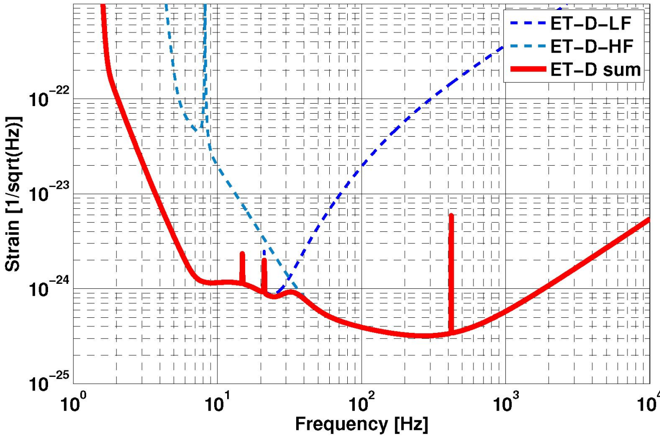
The future: 3^{rd} generation terrestrial detectors

- **Einstein Telescope (ET: EU) & Cosmics Explorere (CE: USA)**
  - **10 times more sensitive** than second-generation detectors;
- ET features
  - Three detector with shared arms;
  - Located underground ⟶ reduce seismic and Newtonian noise;
  - 10 km long arms, in an equilateral triangle configuration: resolve GW polarization and make self localization;
  - **Xylophone configuration**: three nested detectors, each composed of two interferometers, one optimized for operation below 30Hz and one optimized for operation at higher frequencies;

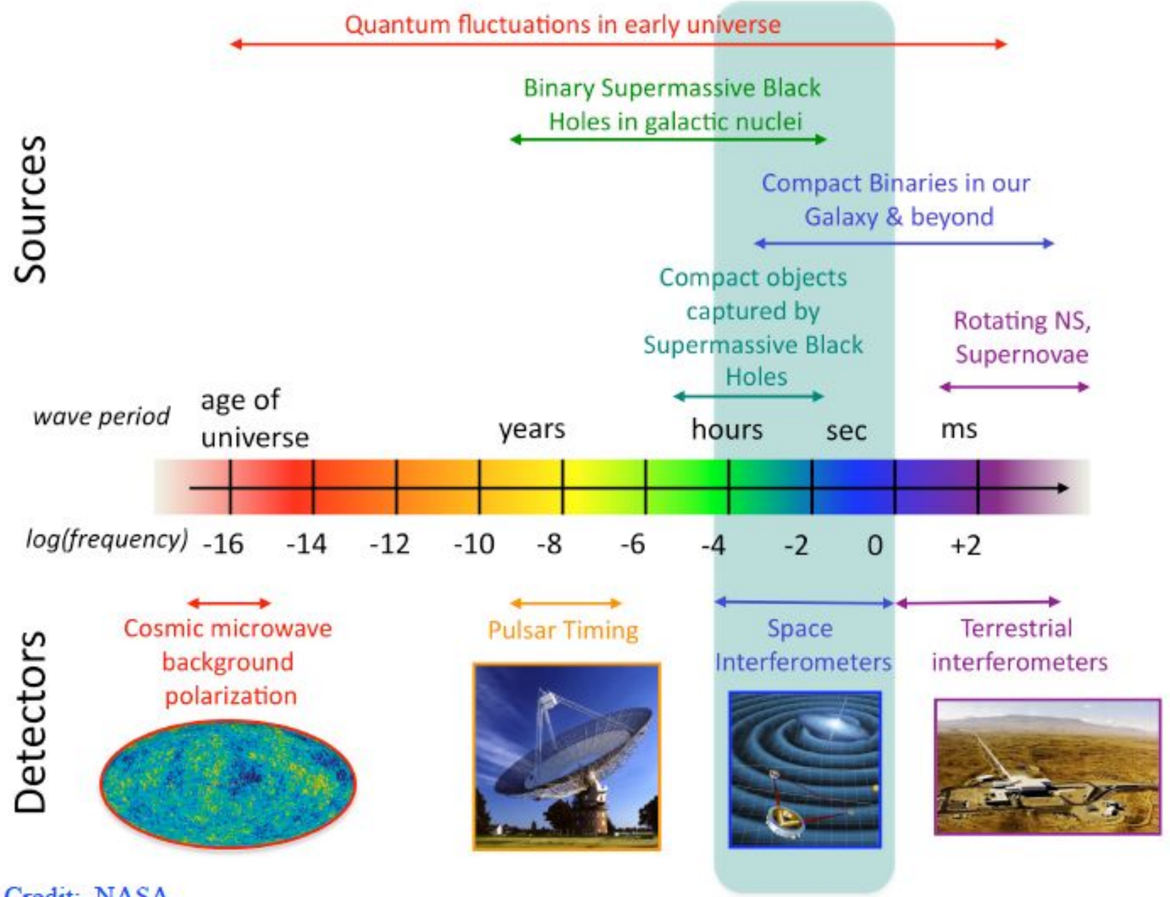
GW below 30 Hz: higher mass mergers, tidal effects on NSs, BHs close encounters, stochastic background.







The future: space detectors



Credit: NASA

Conclusions

- Exciting physics now accessible with GW observation
- Well established network of 2nd generation terrestrial GW detectors
- About 10^2 GW events from binary coalescences detected during the first 3 observing runs
  - Large science yield including GR tests, NS & BH physics, quantum gravity, etc.
- O4 ongoing (Virgo joined O4b since April 2024)
  - Rate of detections improved
- Prospect to further improve current network
- Currently studying 3rd generation detectors to further improve sensitivity by ~10
- More talks on GW science at this conference
  - L. D'Onofrio [110] 27/8 on observational science and results
  - V. Sequino [102] 3/9 on Quantum Noise Reduction

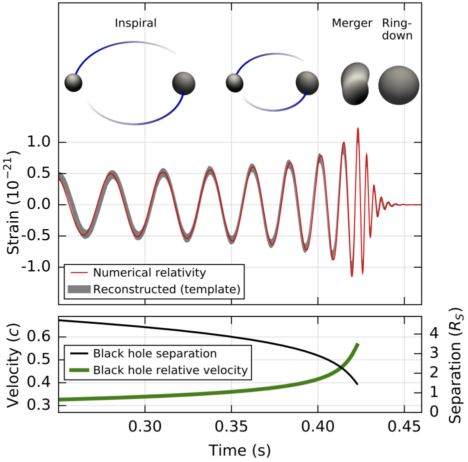
This material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation

Spare slides

Outline

- Gravitational waves physics
  - GW sources
  - Fundamental physics tests
  - Cosmology
- Gravitational waves detectors
  - Spacetime strain and Michelson interferometry
  - Optical configuration of interferometric detectors
  - Sensitivity limits
  - History of sensitivity evolution
  - Worldwide network of interferometric detectors
- GW observations
  - First detections
  - Observing runs and detectors' upgrades
  - Results from O3
- Present & future of GW detectors
  - Latest LIGO-Virgo upgrades & current status
  - Observing scenario for 2nd generation terrestrial detectors
  - 3rd generation terrestrial detectors
  - Space detectors

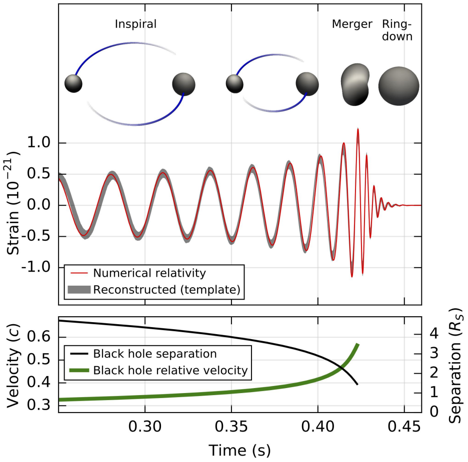
Gravitational waves sources

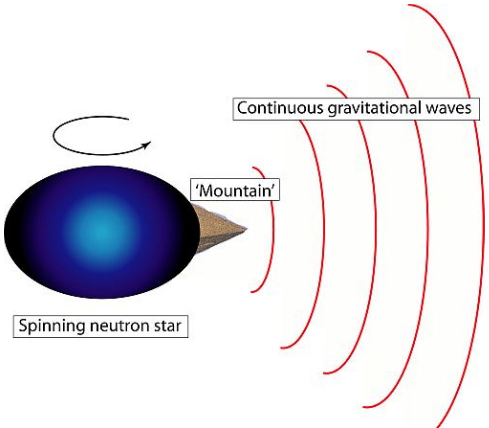


https://www.ligo.org/science/

- **Binary Compact Objects** (BH or NS): strong (transient) emitters, well modeled;

Gravitational waves sources





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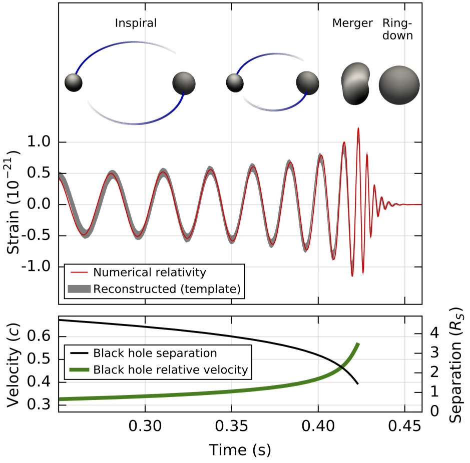
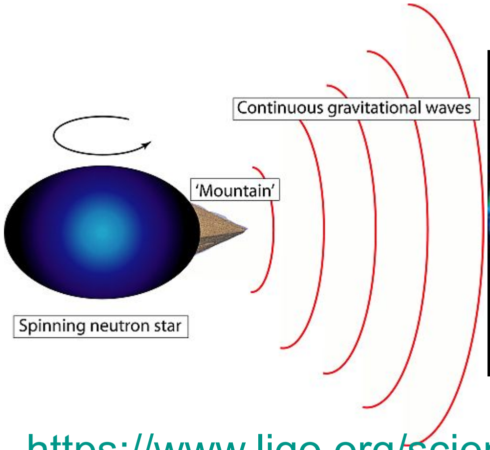
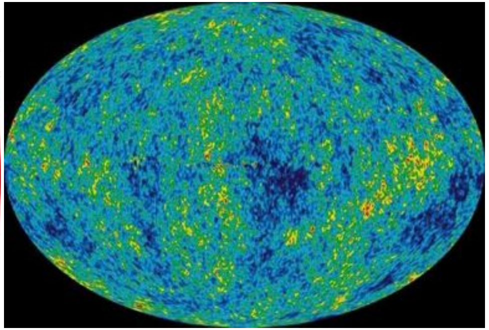
- **Binary Compact Objects** (BH or NS): strong (transient) emitters, well modeled;
- Non-spherical **spinning NSs:** narrow frequency band signal with well defined spectral components;

Gravitational waves sources







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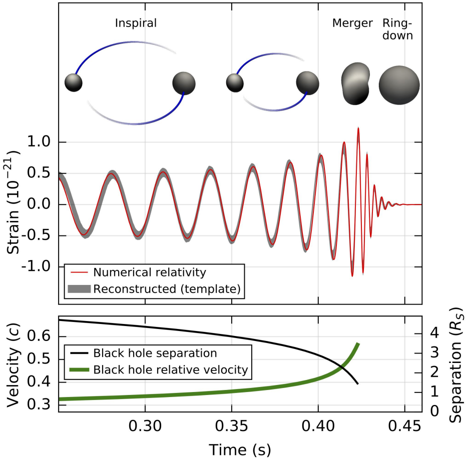
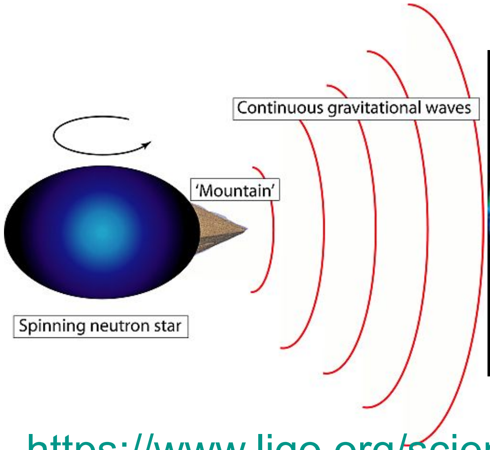
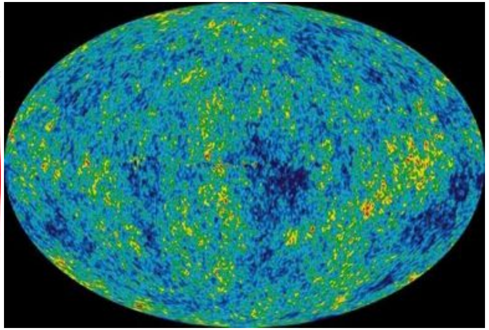
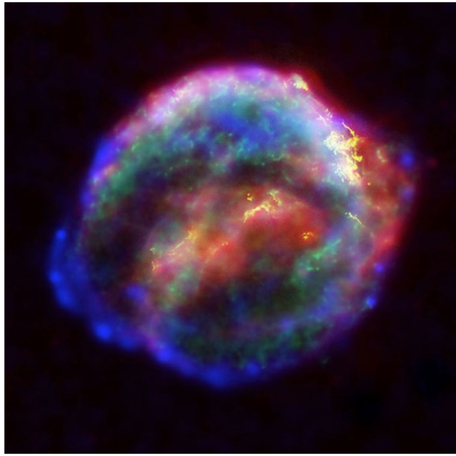
- **Binary Compact Objects** (BH or NS): strong (transient) emitters, well modeled;
- Non-spherical **spinning NSs:** narrow frequency band signal with well defined spectral components;
- GW **stochastic background,** cosmological origin or superposition of unresolved astrophysical sources: continuous GW with broad-band spectra;

Gravitational waves sources









https://www.ligo.org/science/

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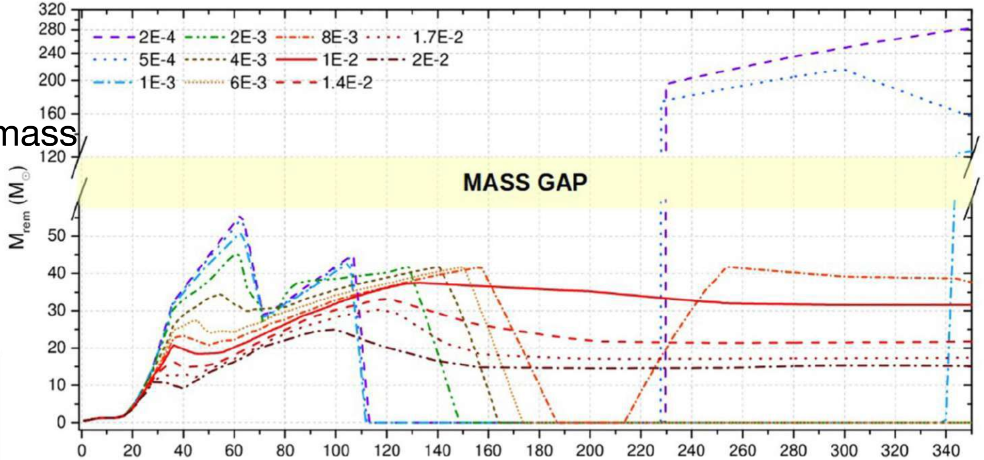
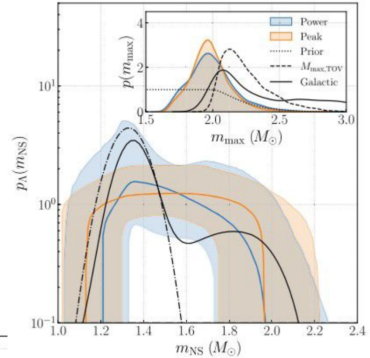
- Non-spherical **spinning NSs:** narrow frequency band signal with well defined spectral components;
- GW **stochastic background,** cosmological origin or superposition of unresolved astrophysical sources: continuous GW with broad-band spectra;
- Asymmetric core collapse **Supernovae**: GW burst, poorly modeled .

GW & astrophysics

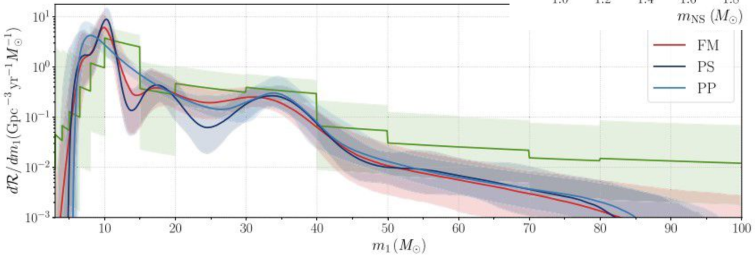
- BH & NS populations
- BH & BBH physics
  - Test of pair instability model from BH mass distribution
- BBH formation mechanism
  - isolated vs dynamical
- NS e.o.s.

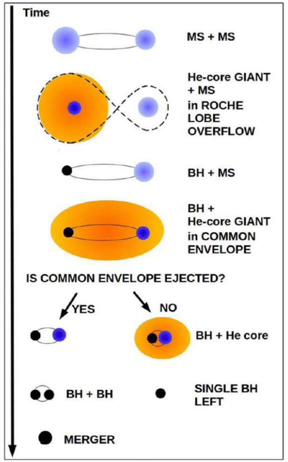


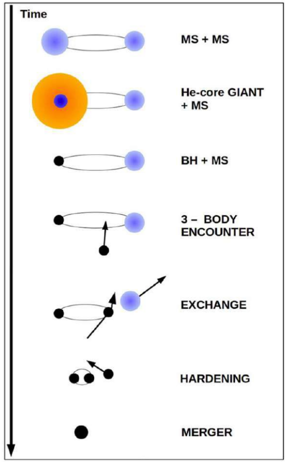
NS



BH

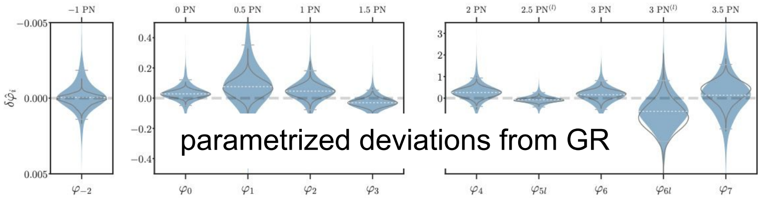




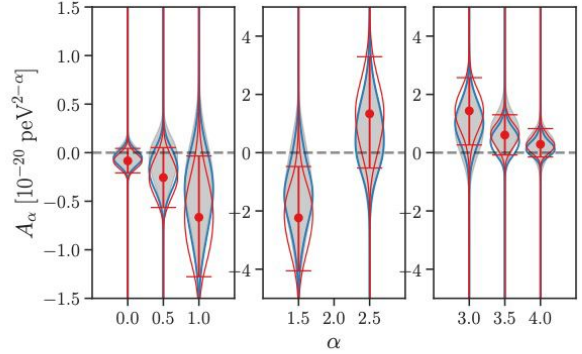


GW & fundamental physics

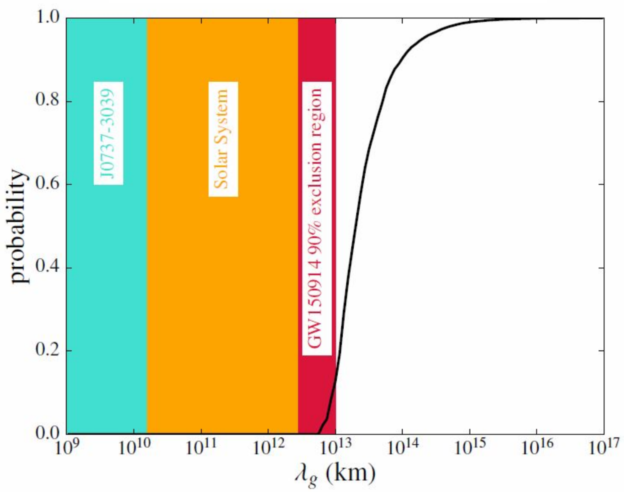
- Testing GR with GW:
  - dispersion of GW No non-GR modes of polarization
  - post-merger echoes
  - GW propagation
  - bound on graviton mass
  - Final mass and spin pre-merger and post-merger part consistency
- So far no evidence of physics beyond general relativity

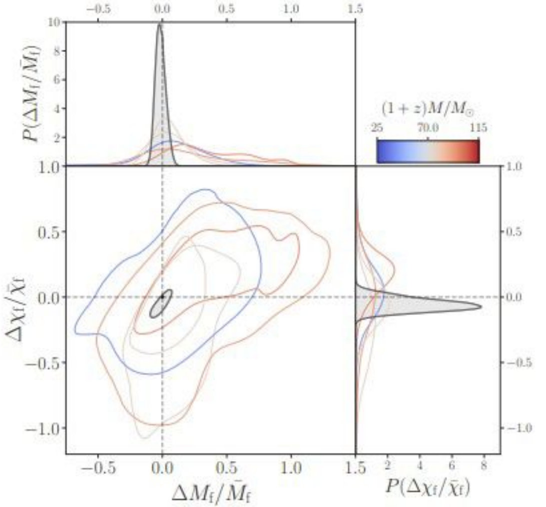


Dispersion during propagation



Graviton Compton wavelength

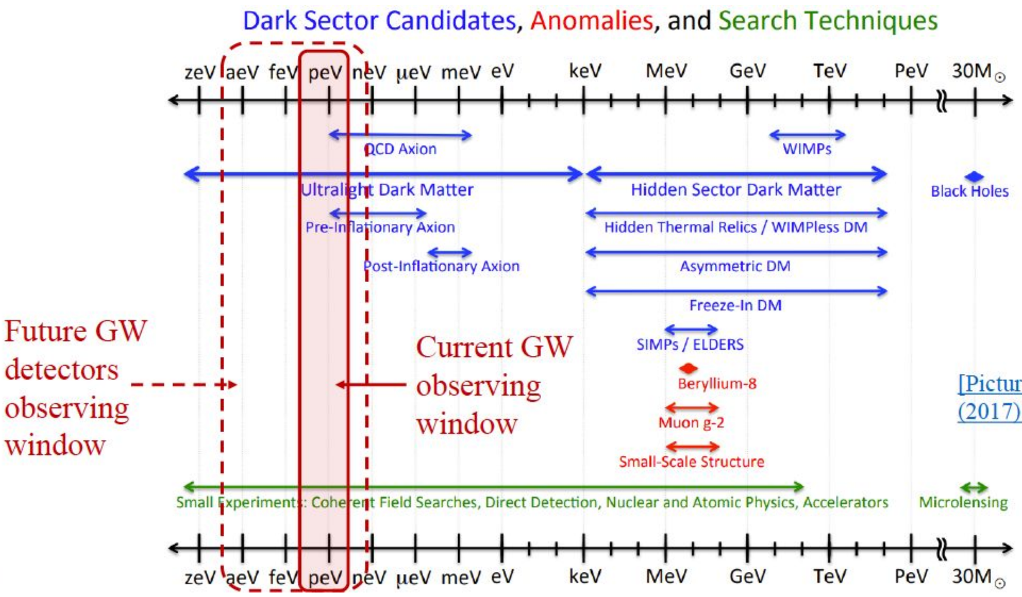




GW & fundamental physics

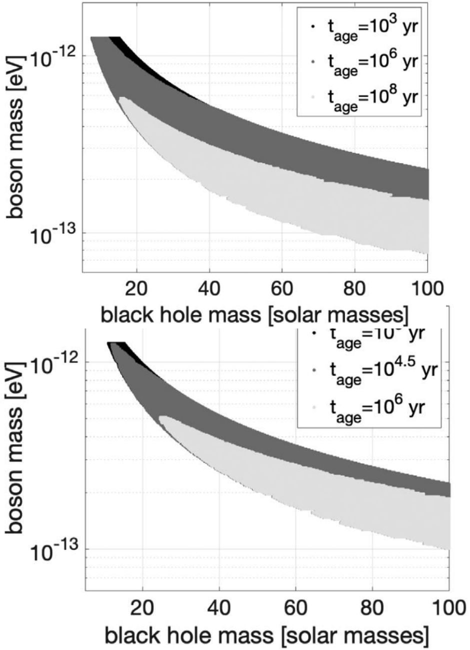
- Dark matter search
  - GW from ultra-light scalar boson clouds

$$h_0 \sim 6 \cdot 10^{-24} \left(\frac{M_{bh}}{10 M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^7 \left(\frac{1\,kpc}{r}\right) (\chi_i - \chi_c) \left(1 + \frac{t}{\tau_{age}}\right)^{-1}$$



[Picture: Battaglieri et al. (2017) arXiv:1707.04591]

Excluded regions from O3 data

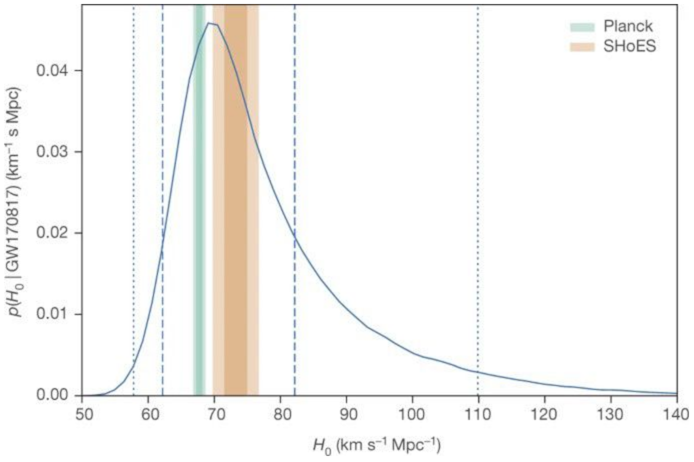


Abbott *et al*. (2022) **PRD 105**, 102001]

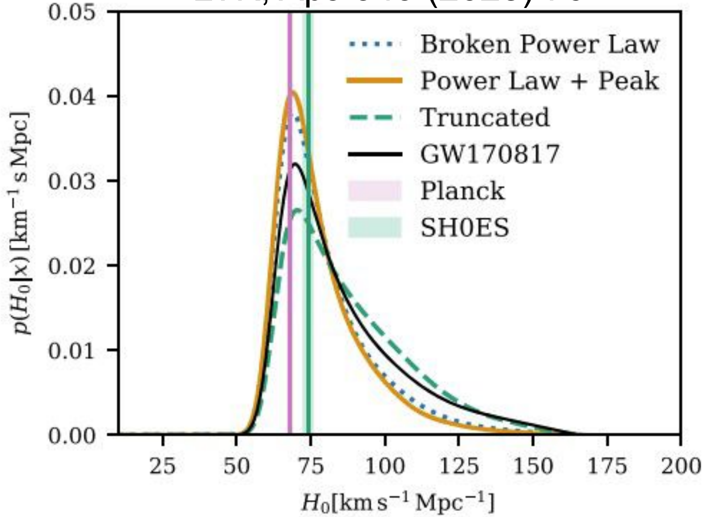
GW & cosmology: Hubble constant

- Two different methods
  - bright sirens (EM counterpart for redshift estimation)
  - dark sirens (no EM counterpart, galaxy catalogues for redshift estimation)

GW170817, bright siren
LVK Nat 551 (2017) 88



42 BBH w/wo GW170817
LVK, ApJ 949 (2023) 76



Quantum noise with suspended optics

While shot noise contribution decreases with optical power, radiation pressure level increases:

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

wavelength

optical power

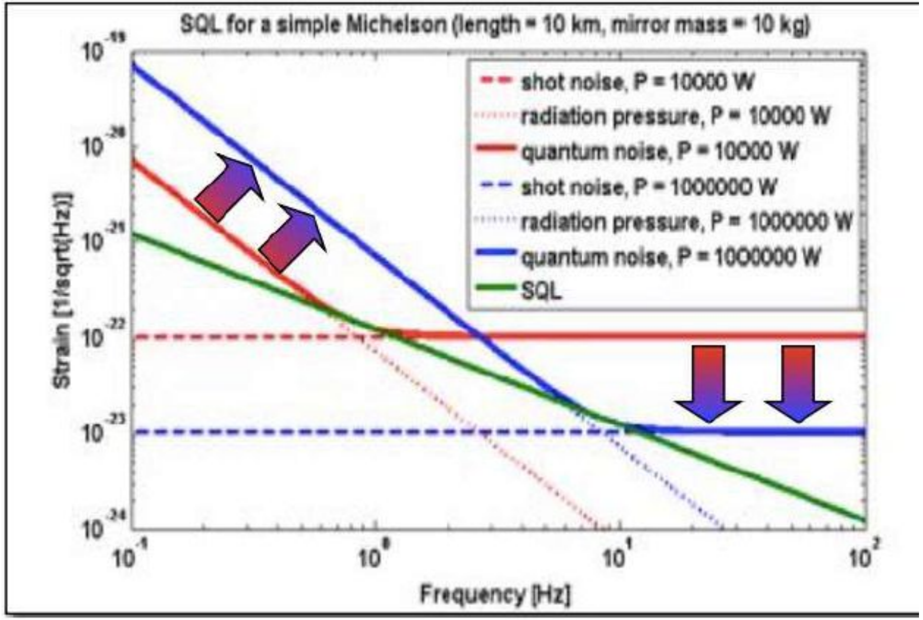
Arm length

Mirror mass

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

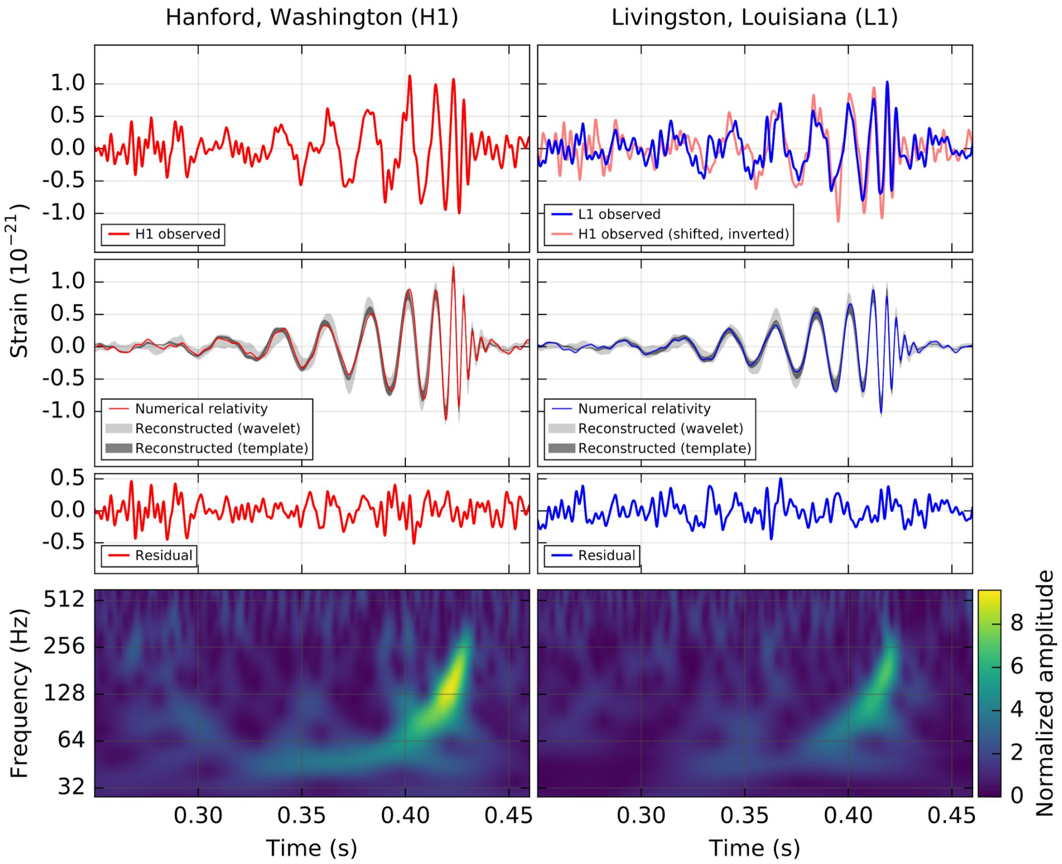
free mass response

- The SQL is the minimal sum of shot noise and radiation pressure noise
- Using a classical quantum measurement the SQL is the lowest achievable noise



V.B. Braginsky and F.Y. Khalili: Rev. Mod. Phys. 68 (1996)

The first detection: GW150914



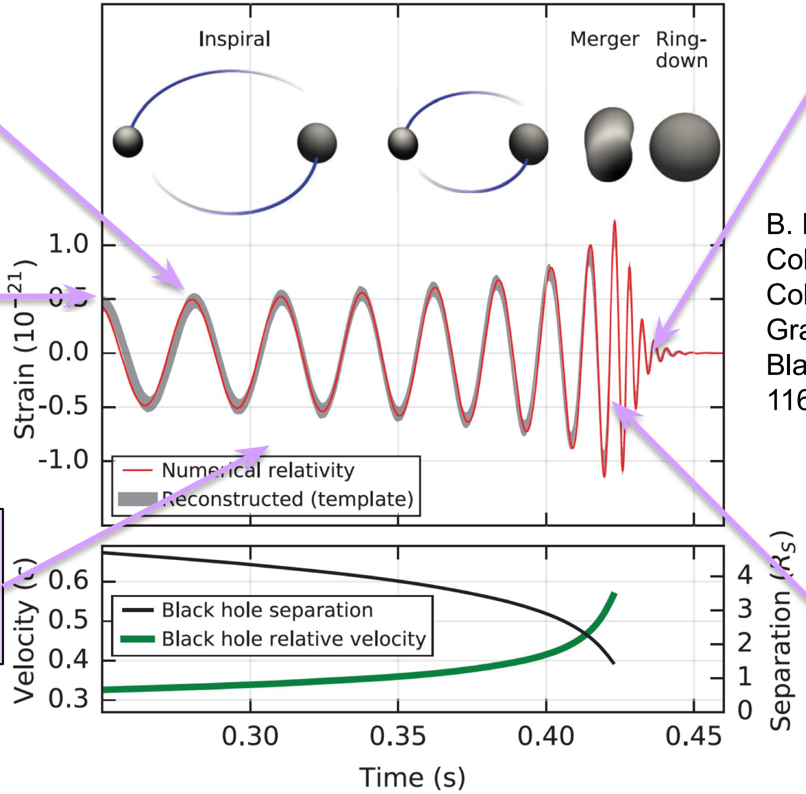
B. P. Abbott et al., Phys. Rev. Lett. 116, 061102

GW from a binary coalescence

Phase evolution gives chirp mass and aligned components of spin

Amplitude scale factor gives luminosity distance (standard siren)

Modulation of amplitude gives nonaligned spin components



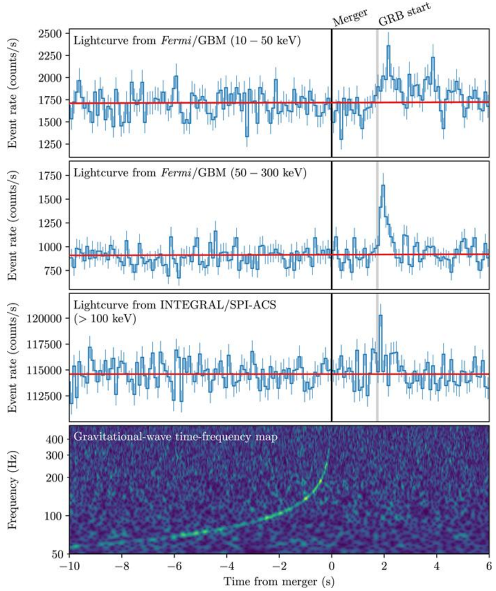
Ringdown frequency and Q give mass and spin of final black hole.

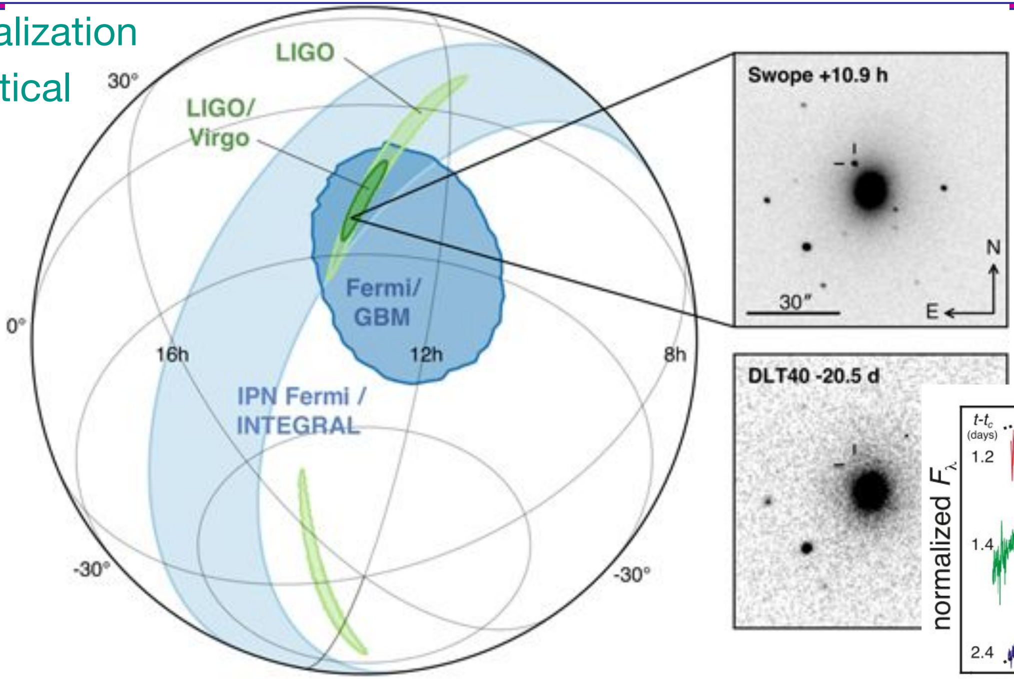
B. P. Abbott et al. (LIGO Scientific Collaboration and Virgo Collaboration), Observation of Gravitational Waves from a Binary Black Hole Merger, Phys. Rev. Lett. 116, 061102 (2016)

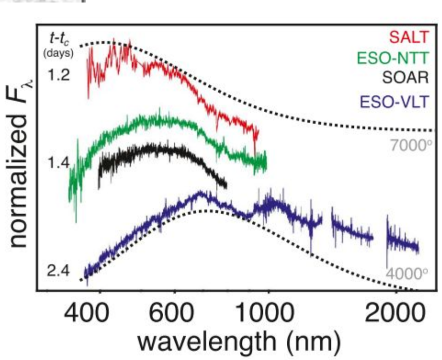
Highest frequency gives sizes of objects just before merger.

GW170817: birth of multimessenger astronomy

LIGO-Virgo network localization enables discovery of optical counterpart



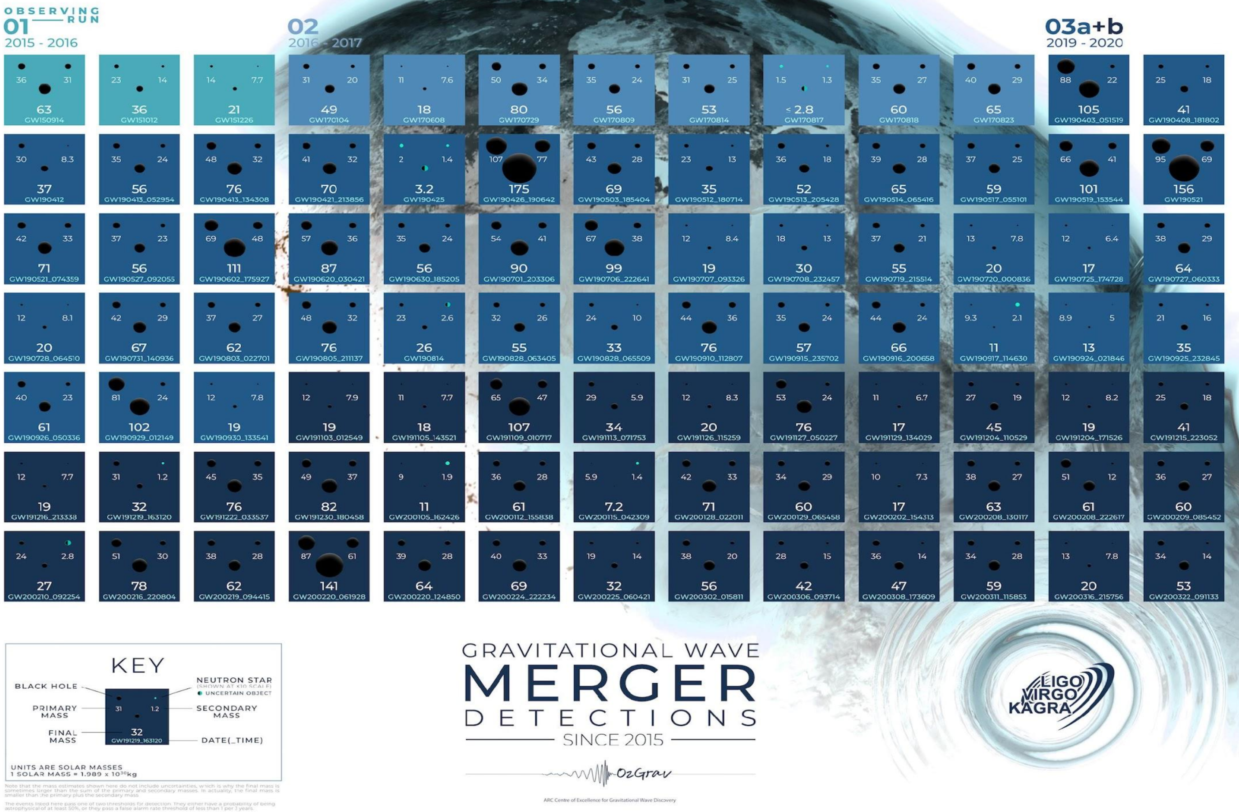




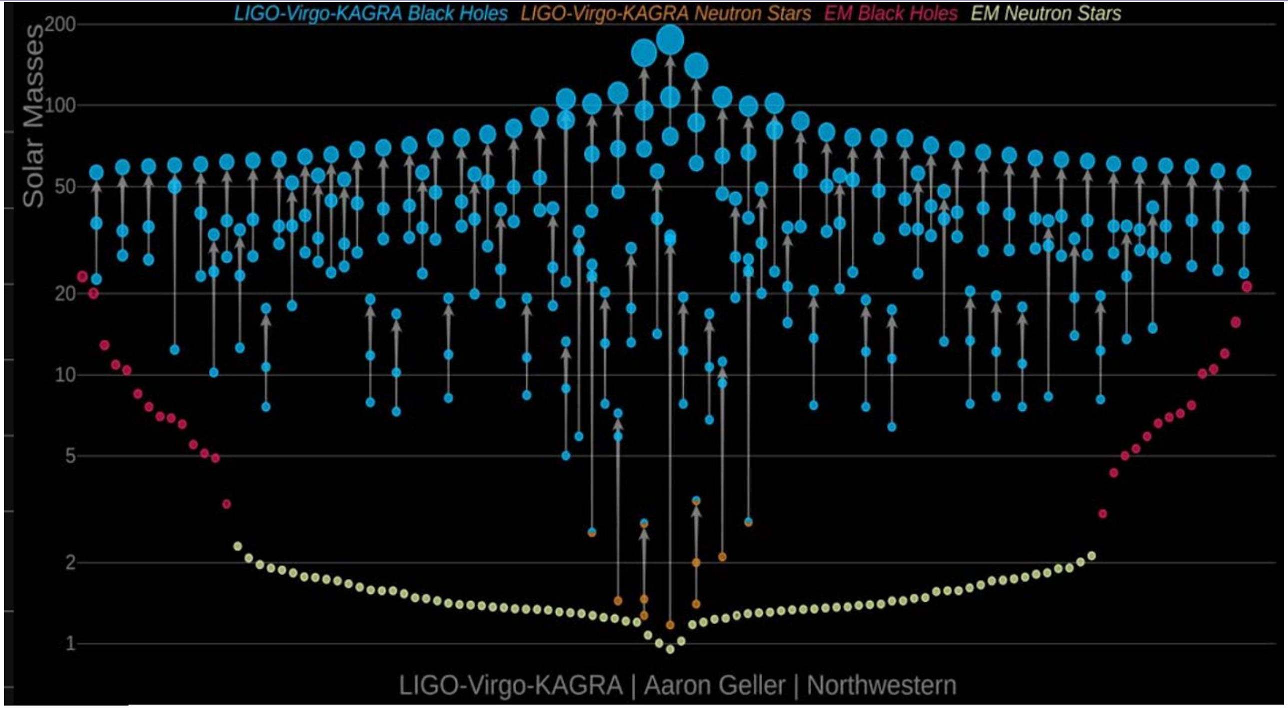
- Spectra of heavy metals in kilonova emission
- Highlight on nucleosynthesys problem

Figure 1 from *Multi-messenger Observations of a Binary Neutron Star Merger*
B. P. Abbott et al. 2017 ApJL 848 L12 doi:10.3847/2041-8213/aa91c9

GW catalog from O1 to O3



GW catalog from O1 to O3

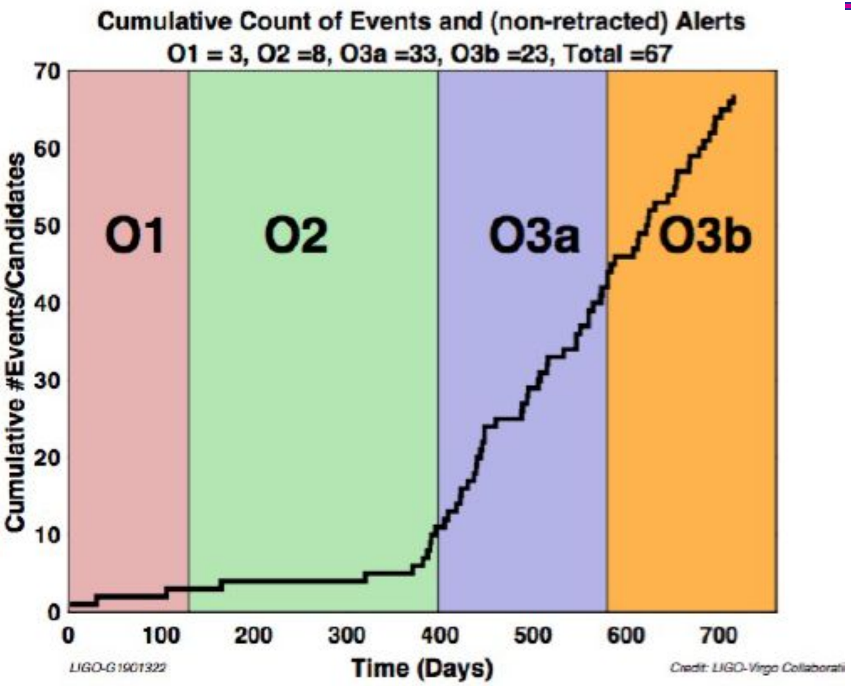


https://www.ligo.org/detections/O3bcatalog/files/gwmerger-poster-white-md.jpg

Highlights from O3

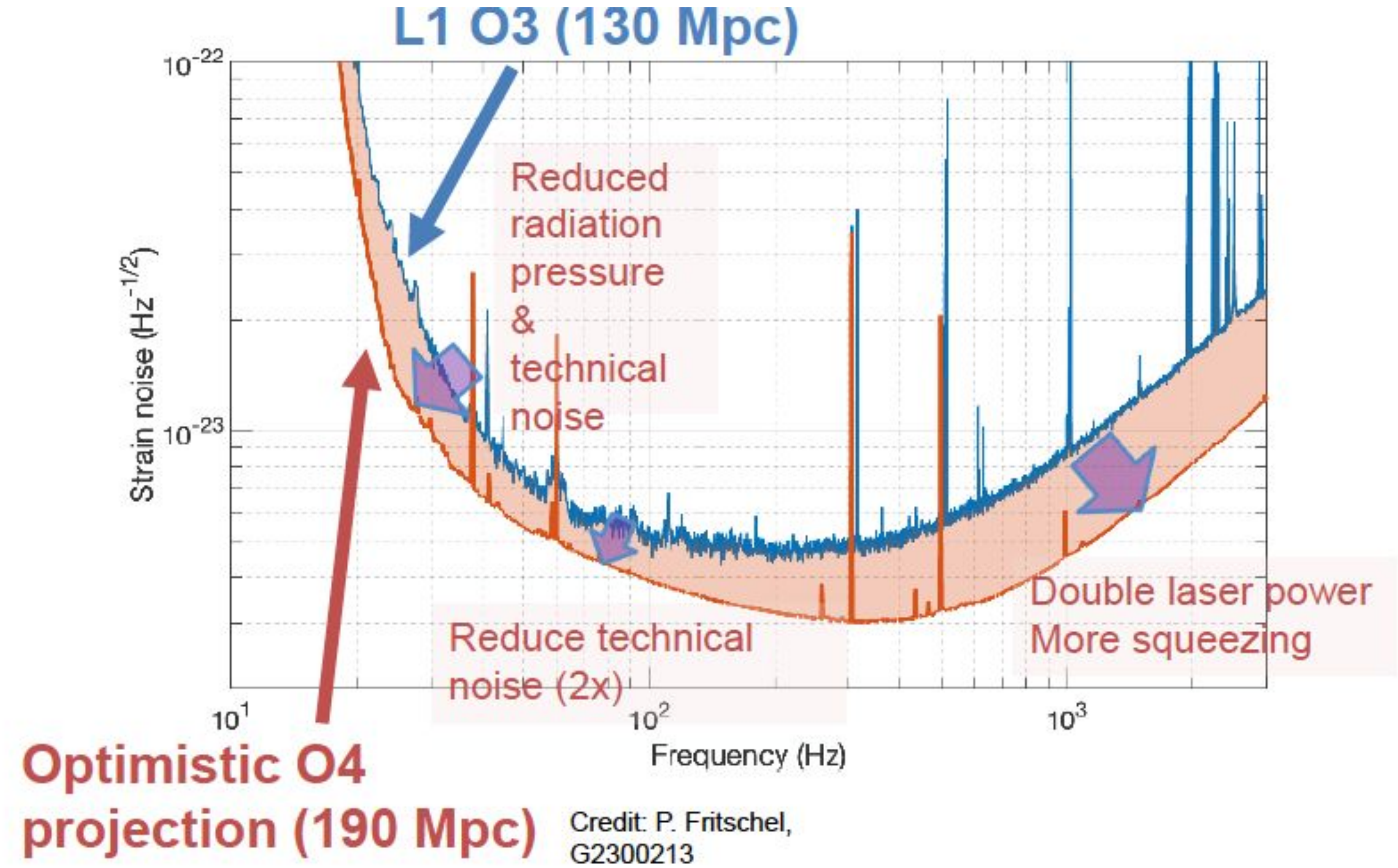
O3 ended on March 2020

- more than 1 GW event/week observed
- Mostly BH-BH coalescences
- Several exceptional events
  - **NS-BH coalescences**
  - **GW191219_163120** : extremely unequal mass components: 31 M⊙ + 1.2 M⊙, and the lightest NS ever observed
  - **GW200115_042309**: the brightest BH-NS coalescence detected up to now 6 M⊙ + 1.4 M⊙
  - **BH-BH coalescences with IMBH**
  - **GW190521_030229**: 85 M⊙ + 66 M⊙ -> 142 M⊙
  - **GW200220_061928**: 87 M⊙ + 61 M⊙ -> 148 M⊙
  - Coalescing BHs in the "pair instability mass gap" ~ 65 -- 120 M⊙



- GW191109_010717: 65 M⊙ + 47 M⊙ -> 107 M⊙
Negative effective spin of the binary system: spins of the two BHs opposite to the orbital angular momentum

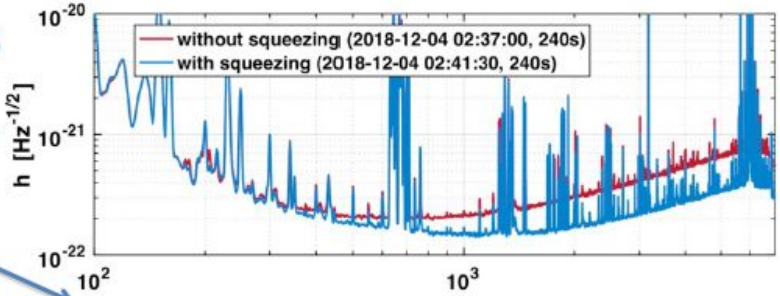
Upgrades for O4 & O5: ALIGO+

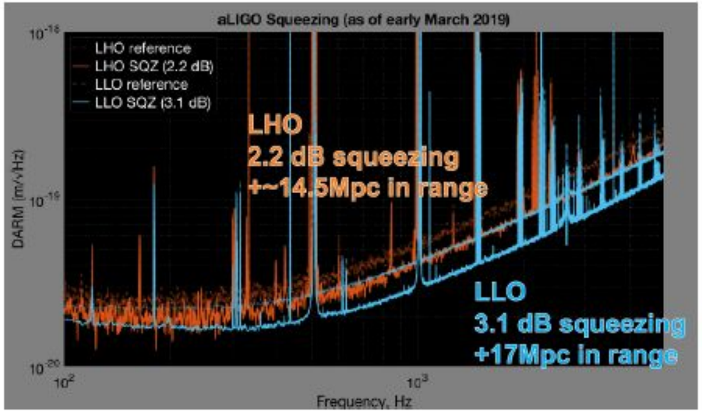


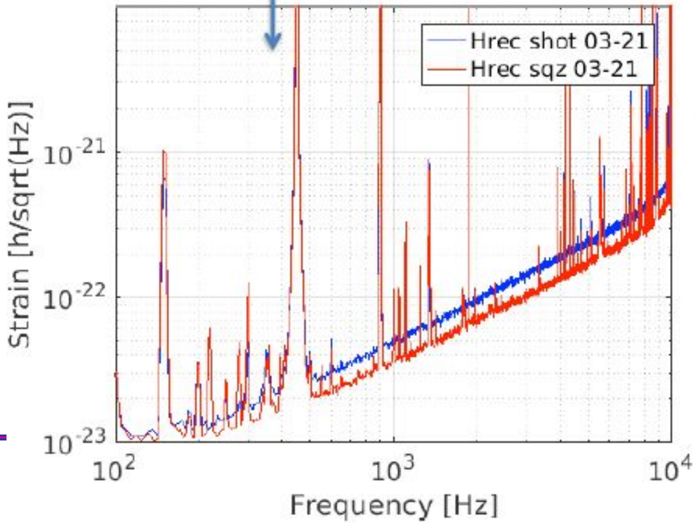
Quantum noise – frequency independent squeezing

Performances during O3

- GEO600: 6 dB
- A-LIGO: 3.1 dB
- AdV: 3.2 dB





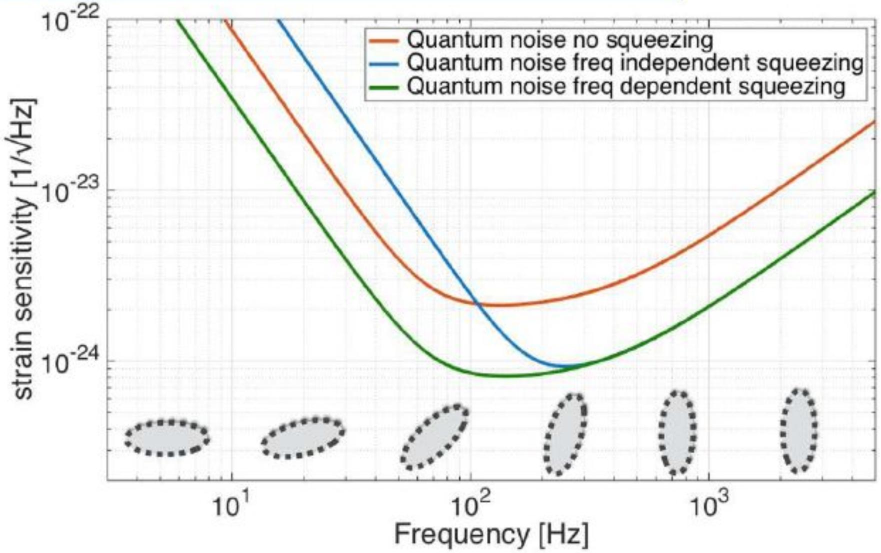


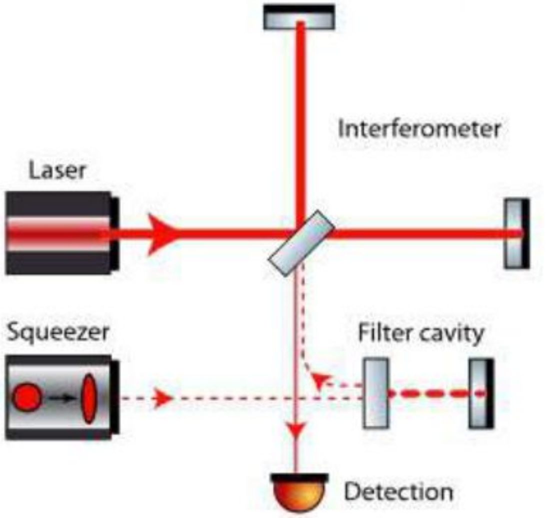
Frequency dependent squeezing

The driving idea
To simultaneously reduce shot noise at high frequencies and quantum radiation pressure noise at low frequencies requires a quantum noise filter cavity with low optical losses to rotate the squeezed quadrature as a function of frequency.

Adopted Method

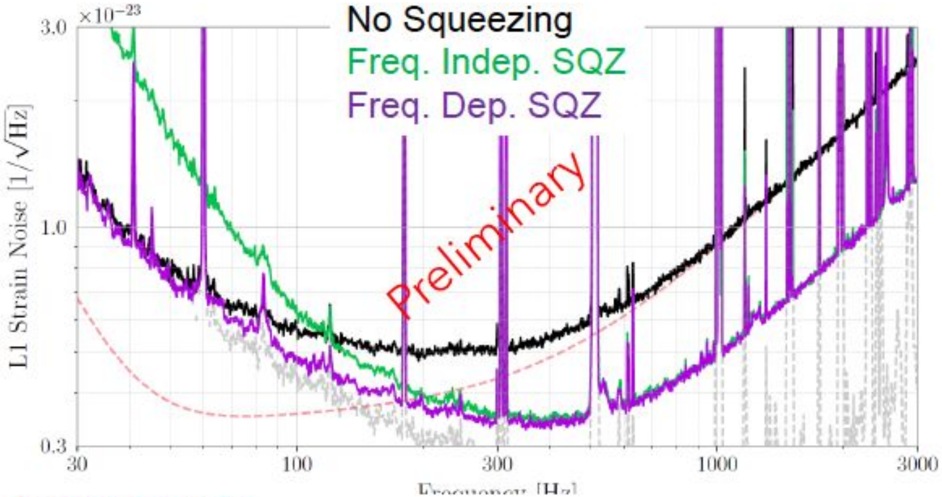
- Reflect frequency independent squeezing off a detuned Fabry-Perot cavity
- Rotation frequency depends on the cavity line-width





Frequency dependent squeezing - status

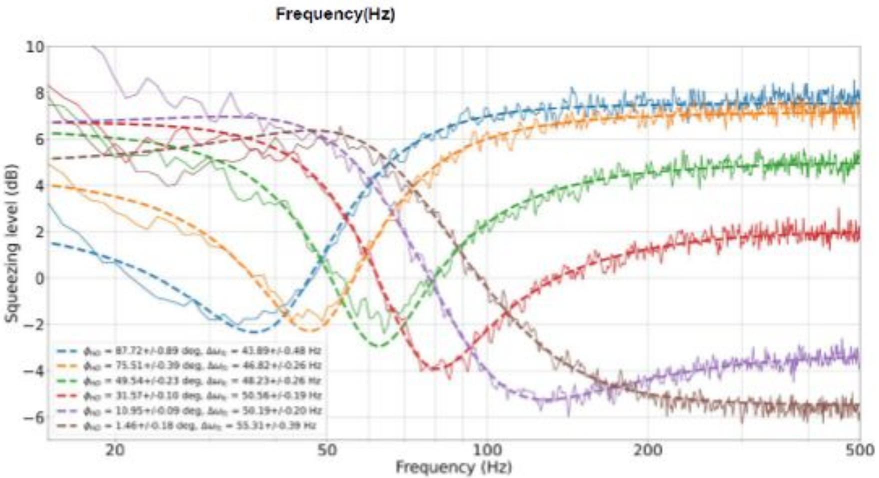
LIGO: FDS injected, 6dB reached(LLO)



In preparation

Broadband quantum enhancement of the LIGO detectors with frequency-dependent squeezing

Virgo: FDS demonstrated in stand alone



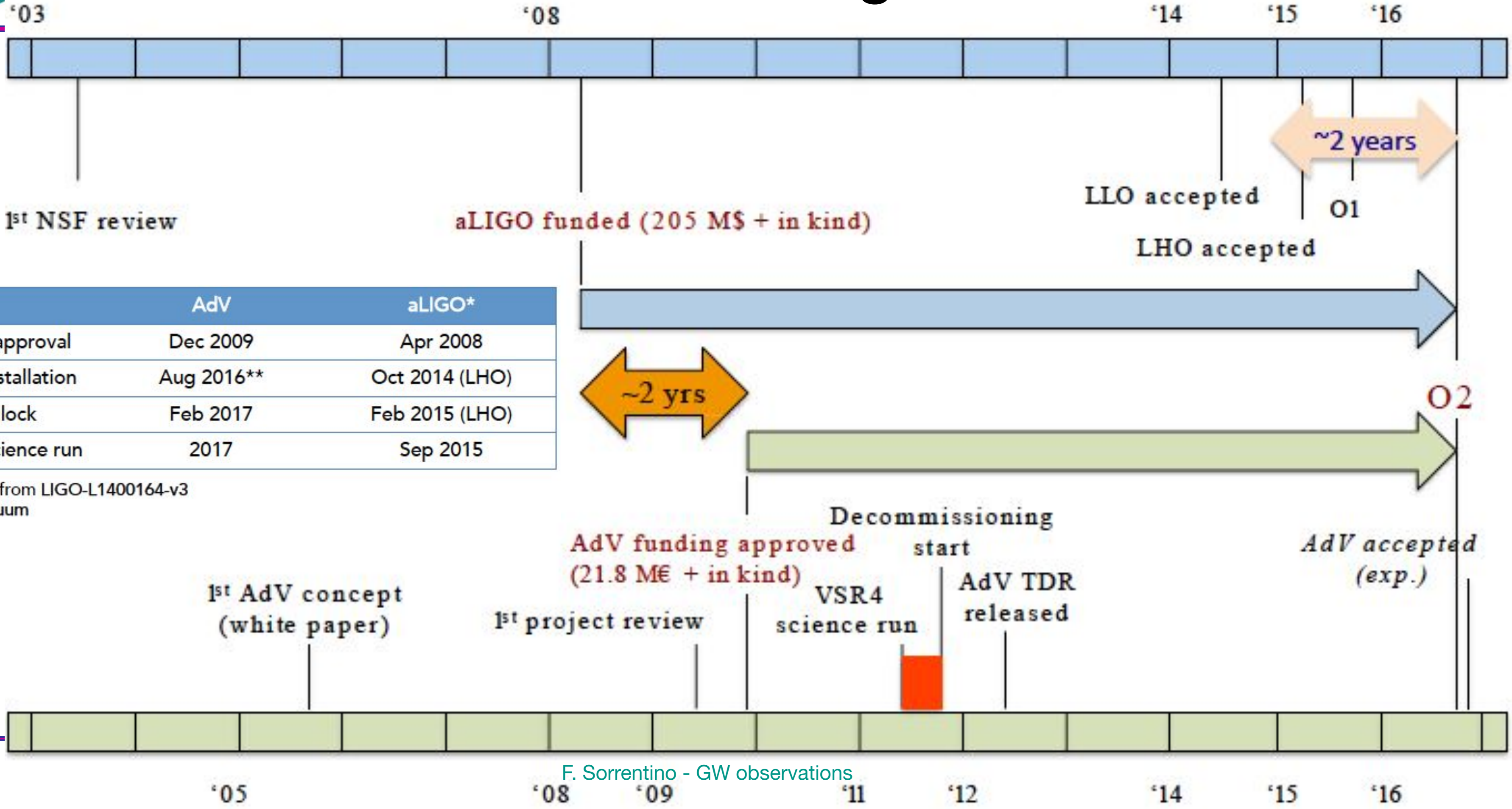
Frequency dependent squeezed vacuum source for the Advanced Virgo gravitational wave detector

F. Acernese *et al.* (the Virgo Collaboration),
H.Vahlbruch, M. Mehmet, H. Lück, and K. Danzmann
Institut für Gravitationsphysik, Leibniz Universität Hannover and Max-Planck-Institut für Gravitationsphysik (Albert-Einstein-Institut), Callinstr. 38, 30167 Hannover, Germany
(Dated: March 2, 2023)

Evolution of LIGO & Virgo detectors

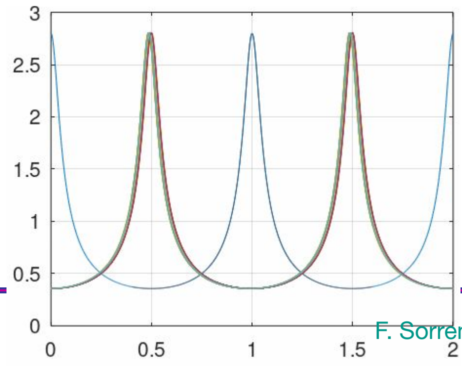
	AdV	aLIGO*
Date of approval	Dec 2009	Apr 2008
End of installation	Aug 2016**	Oct 2014 (LHO)
First lock	Feb 2017	Feb 2015 (LHO)
Start of science run	2017	Sep 2015

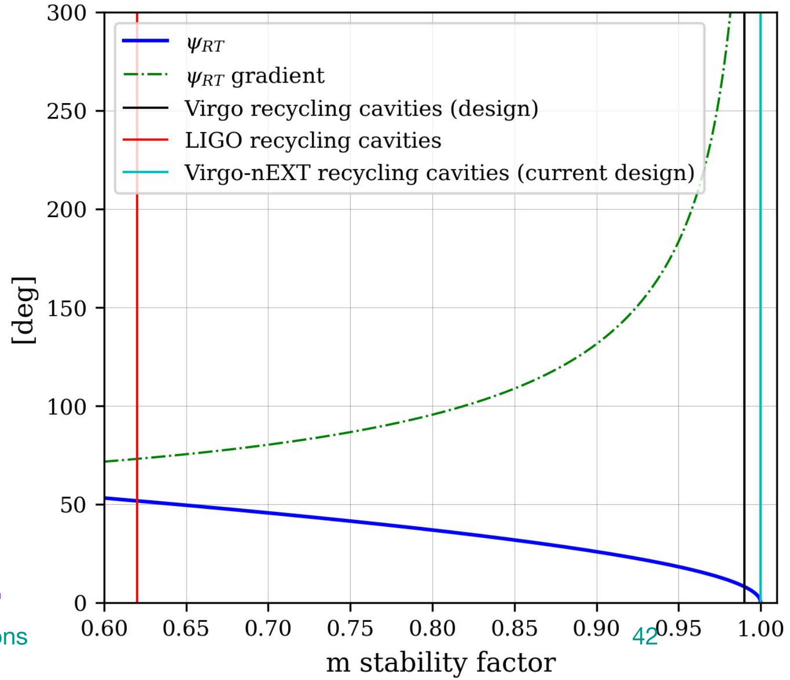
*LIGO data from LIGO-L1400164-v3
**ITF in vacuum



The challenge of degenerate recycling cavities

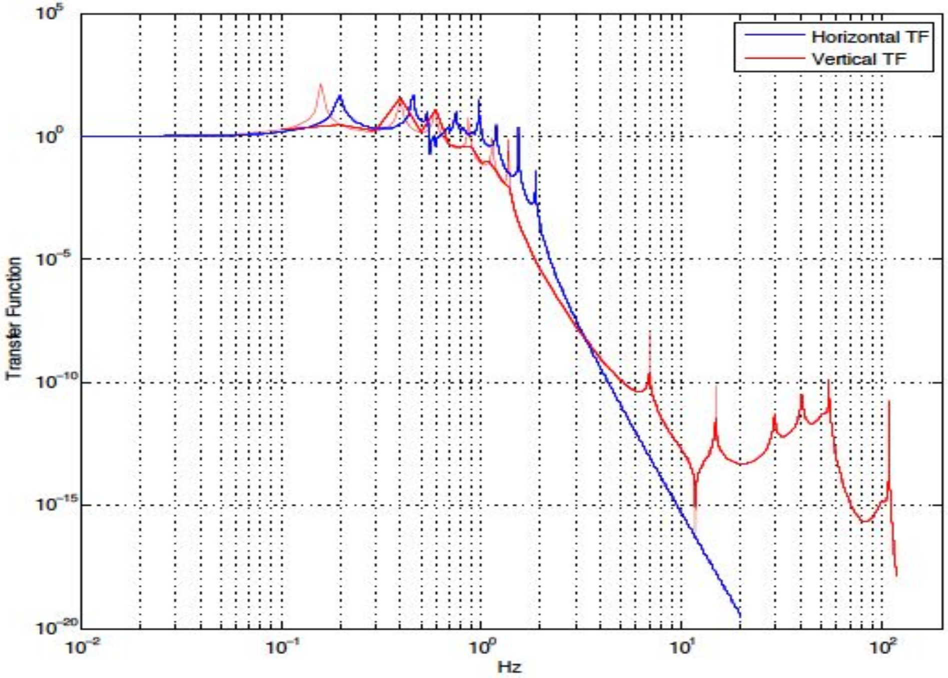
- In AdV design the optical cavities for power & signal recycling are close to the instability region
  - makes mode matching and alignment extremely critical
  - difficult to measure cavity mismatch, as most HOMs resonate simultaneously
  - large SQZ losses expected due to mismatch in central interferometer
- Signal recycling in LIGO
  - Increase detector bandwidth (double cavity pole)
  - Filter out high-order optical modes
- Signal recycling in Virgo
  - Increase detector bandwidth
  - Amplify (recycle) high-order optical modes

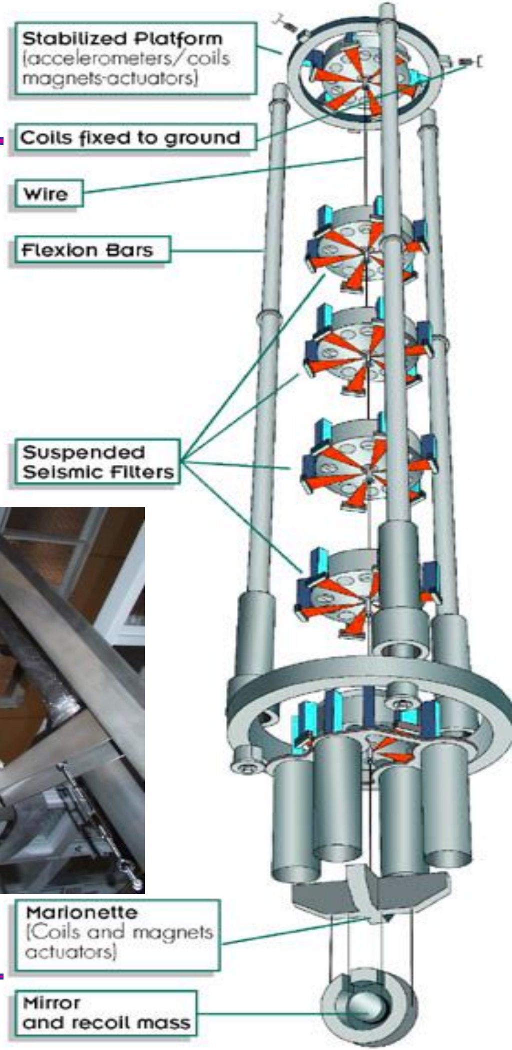




Seismic noise

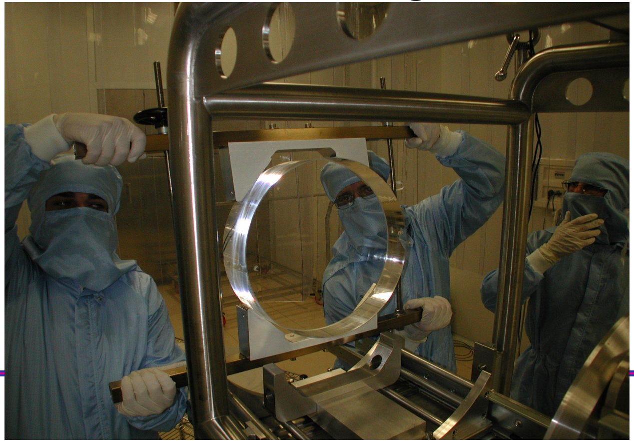
- *Typical RMS seismic noise in detection band (>10 Hz) is of the order of nm/√Hz*
  - *Need attenuation of about 10 orders of magnitude!*
- *Virgo superattenuator:*
  - *N cascaded mechanical filters: $(f_0^2/f^2)^N$*



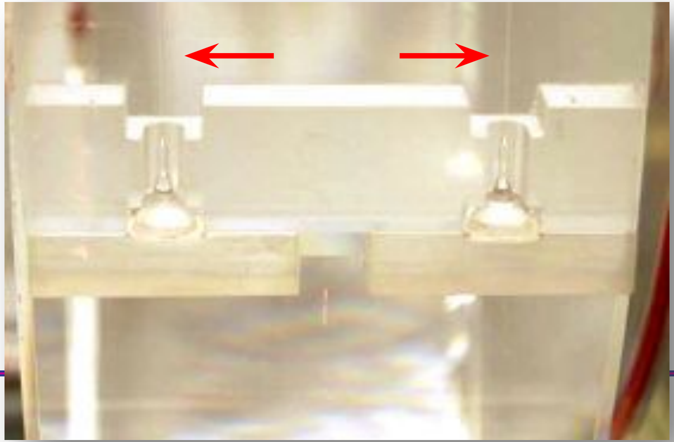


Thermal noise

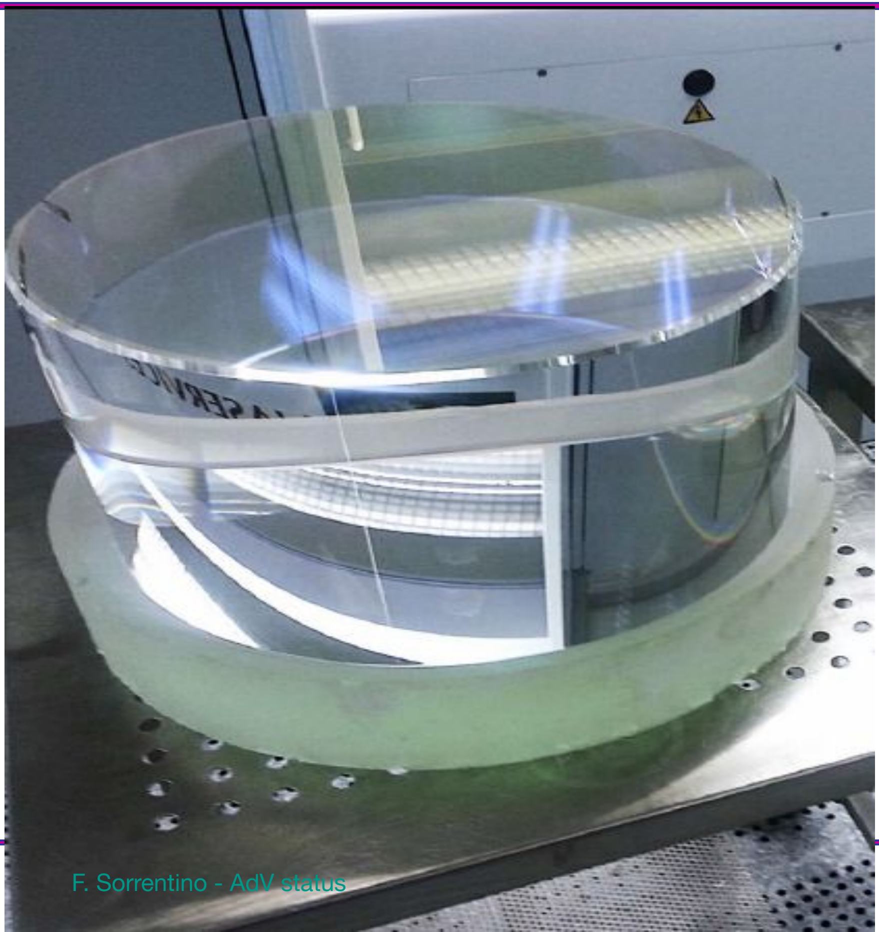
- On mirrors
  - **Brownian motion**
  - Thermo-elastic fluctuations in bulk and coating
  - Thermo-refractive fluctuations
- Improved by
  - larger beam size to sample larger mirror surface
  - low loss coatings



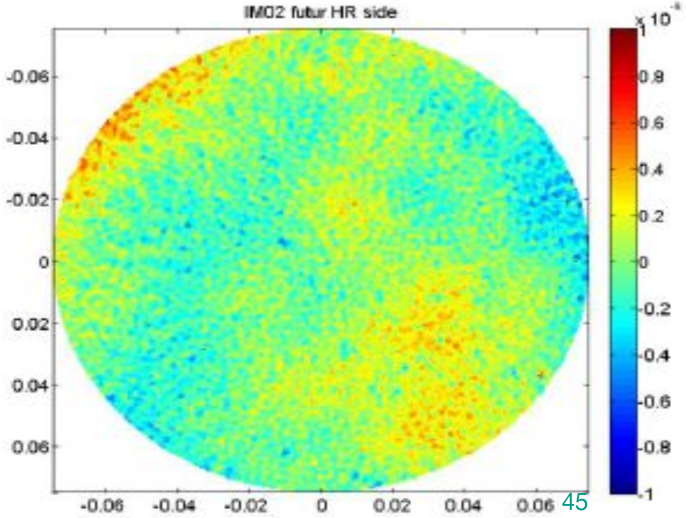
- On suspensions
  - Pendulum thermal fluctuations
  - Vertical thermal fluctuations
  - **Violin modes**
- Improved by monolithic suspensions
  - Only after O2 science run



Mirrors

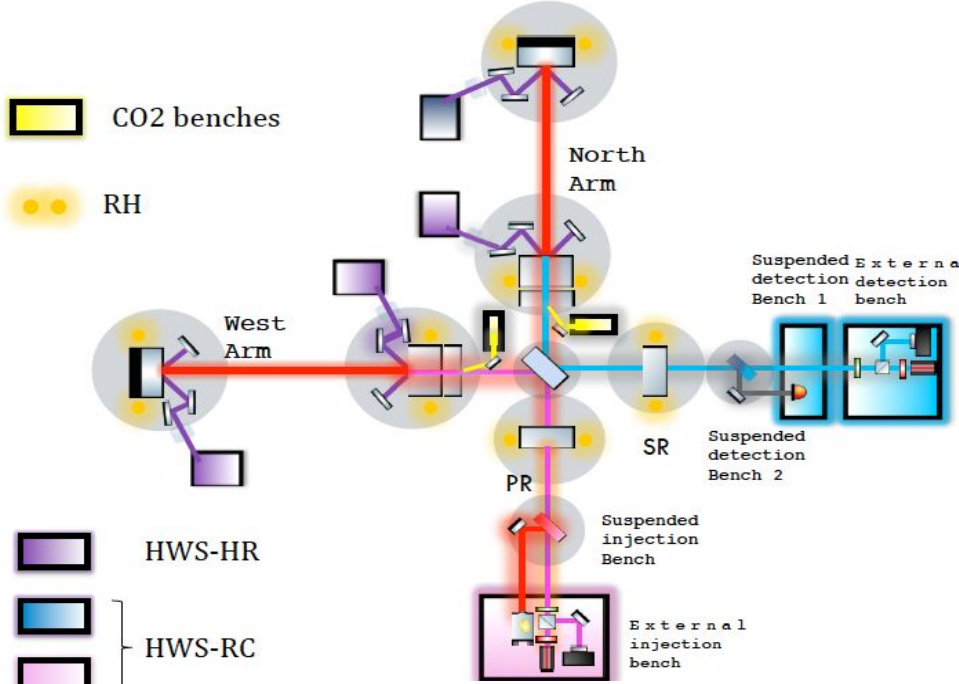


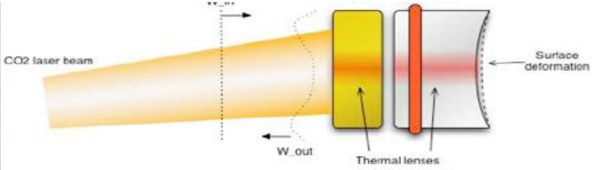
- Low mechanical losses
- Low optical absorption
- Low scattering
- 42 kg, 35 cm diam., 20 cm thick
- Flatness < 0.5 nm rms
- Roughness < 0.1 nm rms
- Absorption < 0.5 ppm

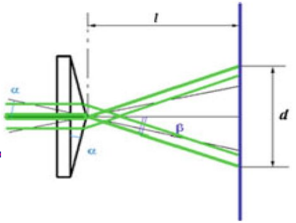


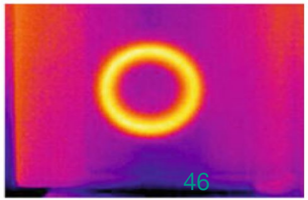
Thermal compensation

- Some AdV upgrades:
  - Higher laser power (lower shot noise)
  - Higher F-P cavity finesse (scale factor)
- But higher power increases thermal aberrations, and higher finesse makes ITF more sensitive to aberrations
- Thermal aberrations were already relevant in 1st generation detectors
  - Thermal Compensation System (TCS)
- AdV TCS sensing:
  - Hartmann sensors
  - phase cameras
- AdV TCS actuators:
  - CO2 laser projector to correct thermal lensing
    - Double axicon for better thermal lens correction
    - Compensation plates to reduce CO_2 laser noise coupling
  - Ring heater to tune mirror RoCs by thermoelastic deformation of the HR surface



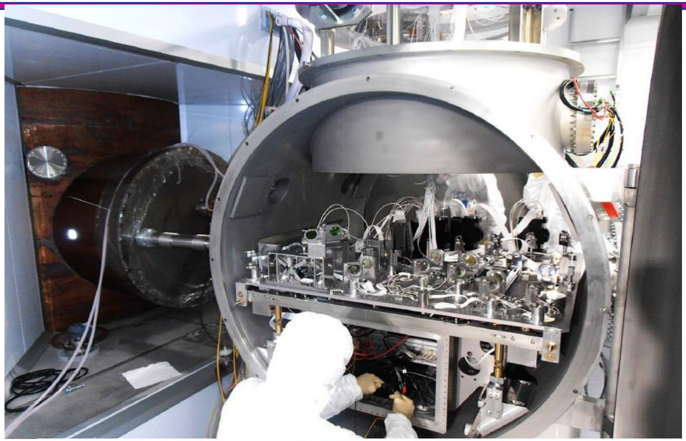


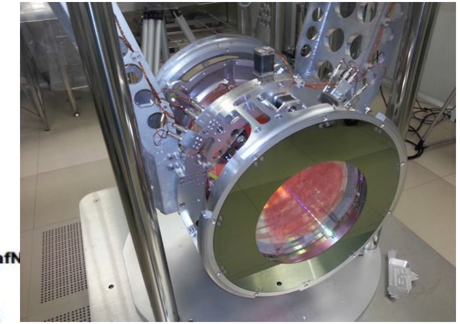


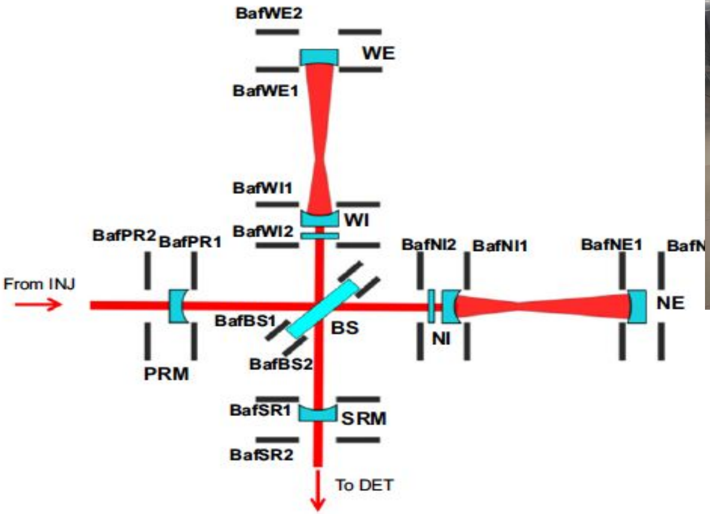


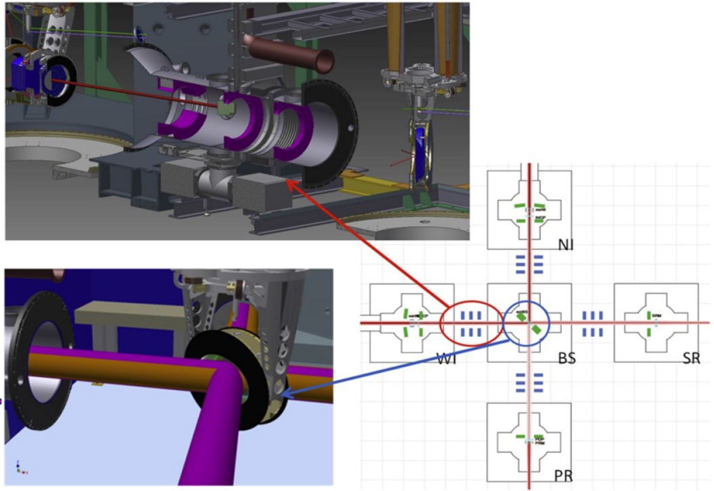
Stray light control

- Reducing amount of scattered light
  - 320 baffles welded to pipes
- Reduce relative motion between scattering surfaces and detection photodiodes
  - Baffles integrated on each suspended payload
  - Photodiodes hosted on suspended benches in vacuum



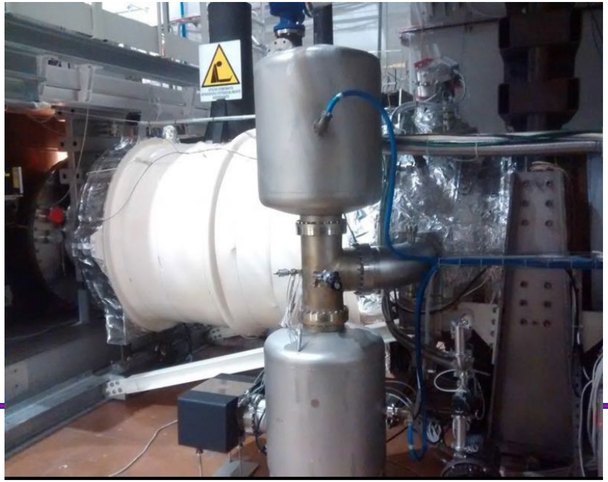




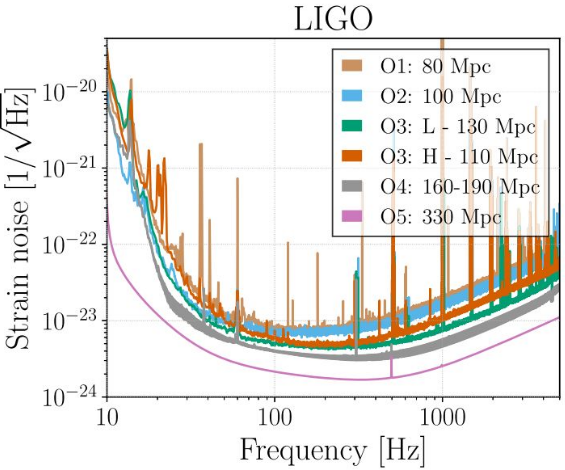


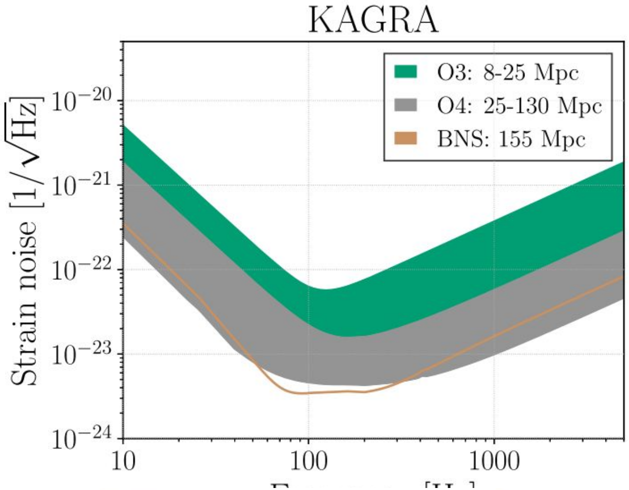
Vacuum

- With iVirgo vacuum level (10^{-7} mbar, dominated by H_2O) phase noise from background gas would limit AdV sensitivity
- Need to reduce phase noise by a factor 10 => improve vacuum by a factor 100 (scaling with √P)
- Backing arm tubes already tested to 10^{-9} mbar (dominated by hydrogen)
- Backing TM towers not opportune
- Large cryo-traps close to towers

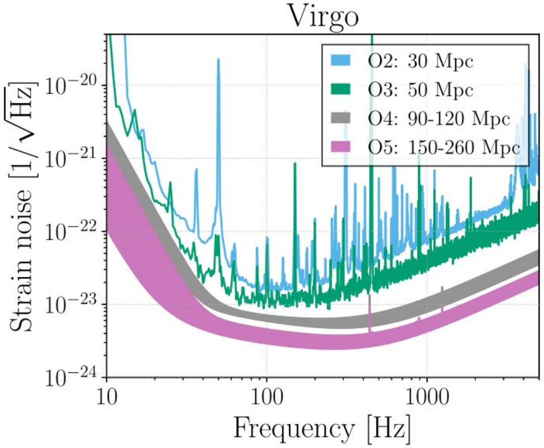


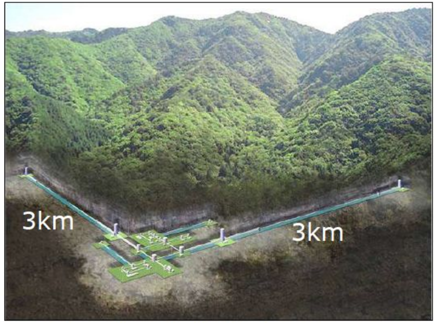
Network of GW detectors





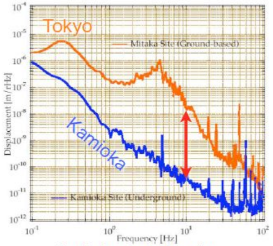
World's first
2.5th generation GW detector





Fabry-Perot Michelson type
Laser interferometer

Cryogenic to reduce
thermal noises
(T=20K @mirrors)
Underground to reduce
seismic noises



Amplitude of seismic motion

The future: space detectors