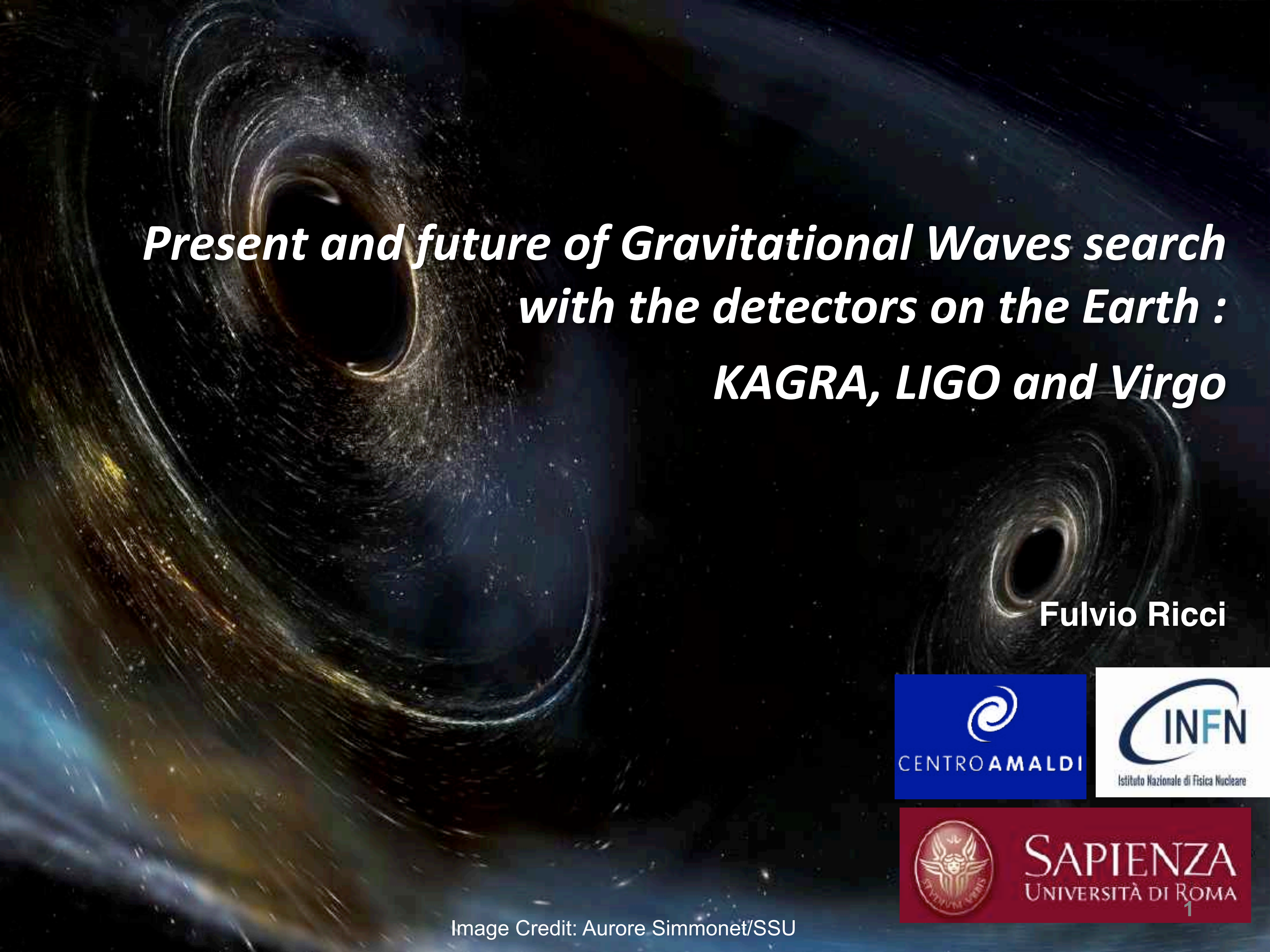


Present and future of Gravitational Waves search with the detectors on the Earth : KAGRA, LIGO and Virgo

Fulvio Ricci

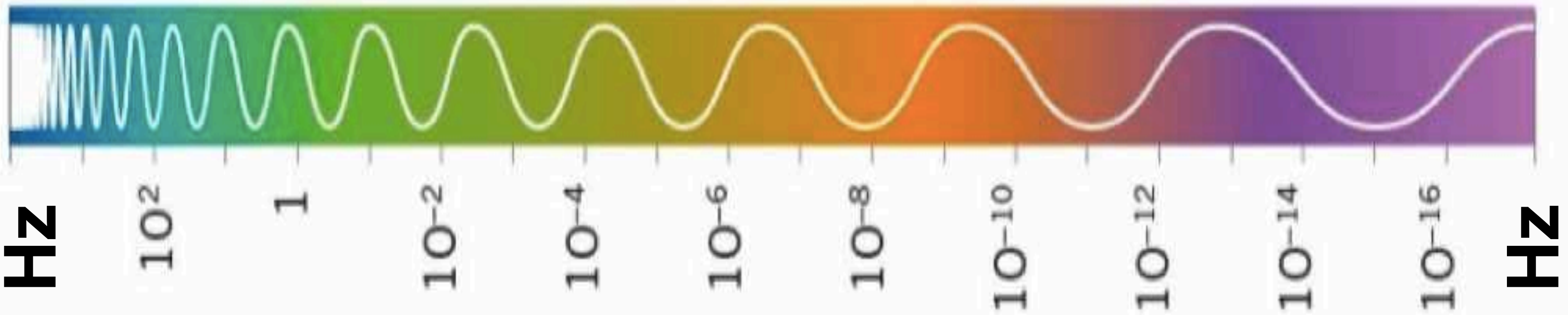
CENTRO AMALDI

INFN
Istituto Nazionale di Fisica Nucleare

SAPIENZA
Università di Roma

Image Credit: Aurore Simmonet/SSU

Exploring the Universe with the GW Detectors




Ground base Inteferometers

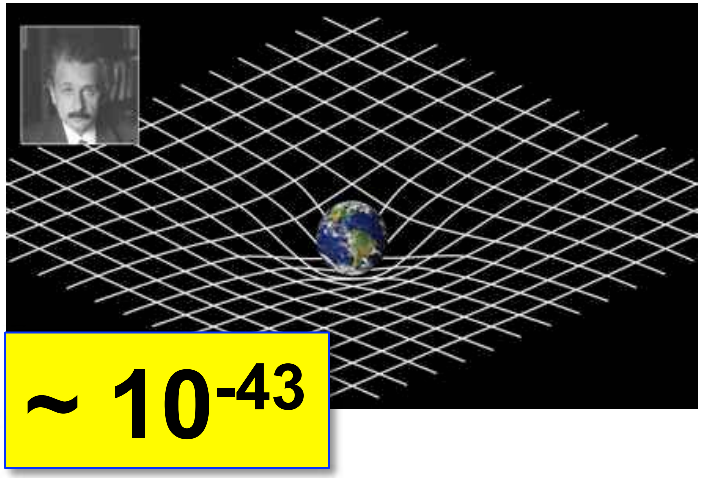

Space Inteferometers


Pulsar Timing


B-modes of the CMB

Gravitational Waves

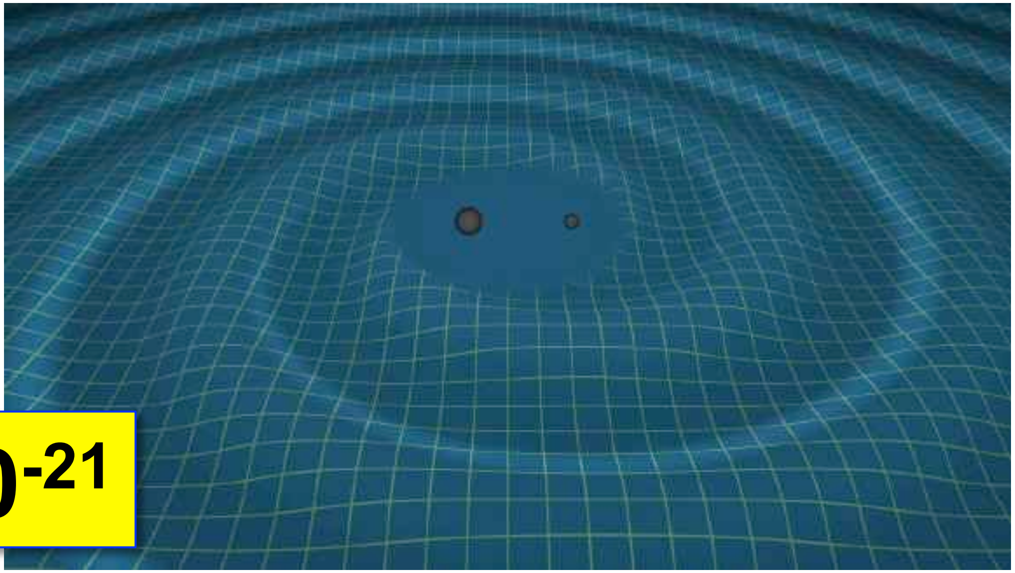
$$G_{\mu\nu} = \boxed{\frac{8\pi G}{c^4}} T_{\mu\nu}$$



~ 10^{-43}

$$\left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

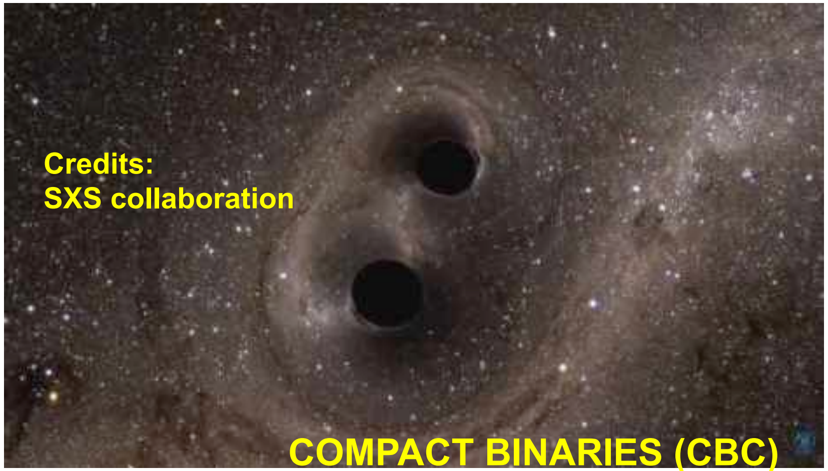
$$h_{\mu\nu} \approx \frac{1}{r}\frac{G}{c^4}\ddot{I}_{\mu\nu}$$



~ 10^{-21}

Gravitational Wave Signals

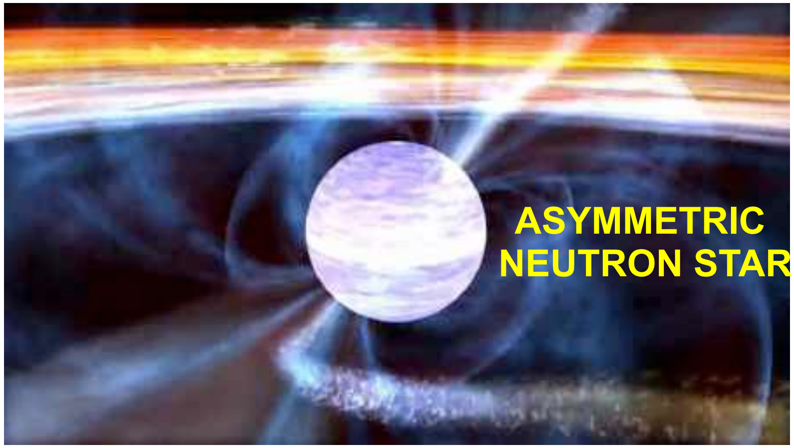
TRANSIENT



Credits:
SXS collaboration

COMPACT BINARIES (CBC)

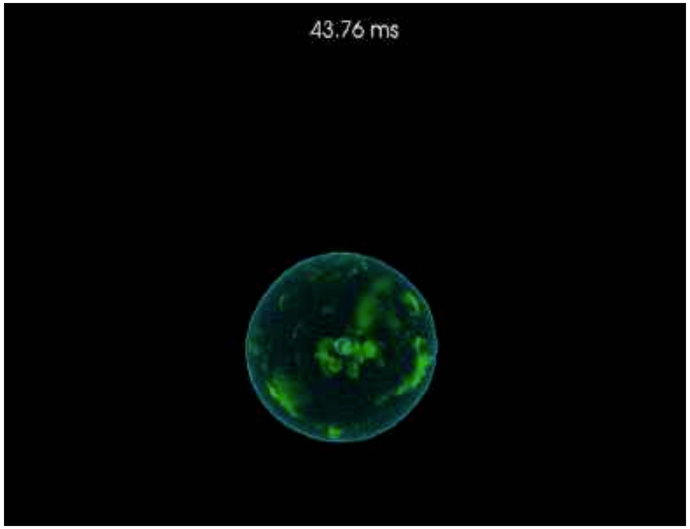
PERSISTENT



ASYMMETRIC
NEUTRON STAR

MATCHED FILTER

BURSTS
Core collapse Supernovae



STOCHASTIC BACKGROUND

UNMODELED

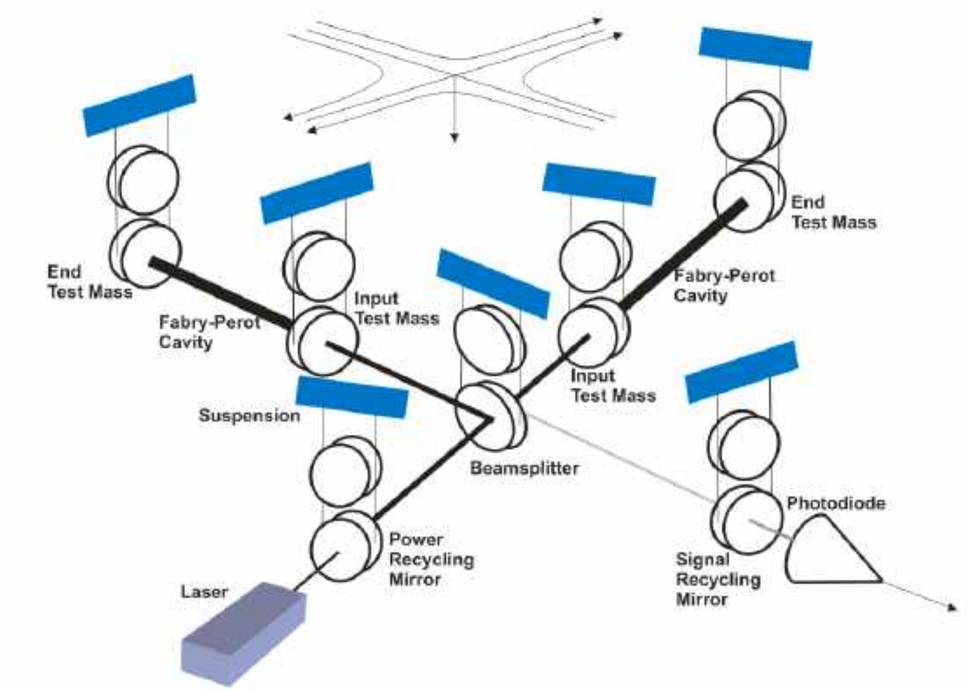
Talk Outline

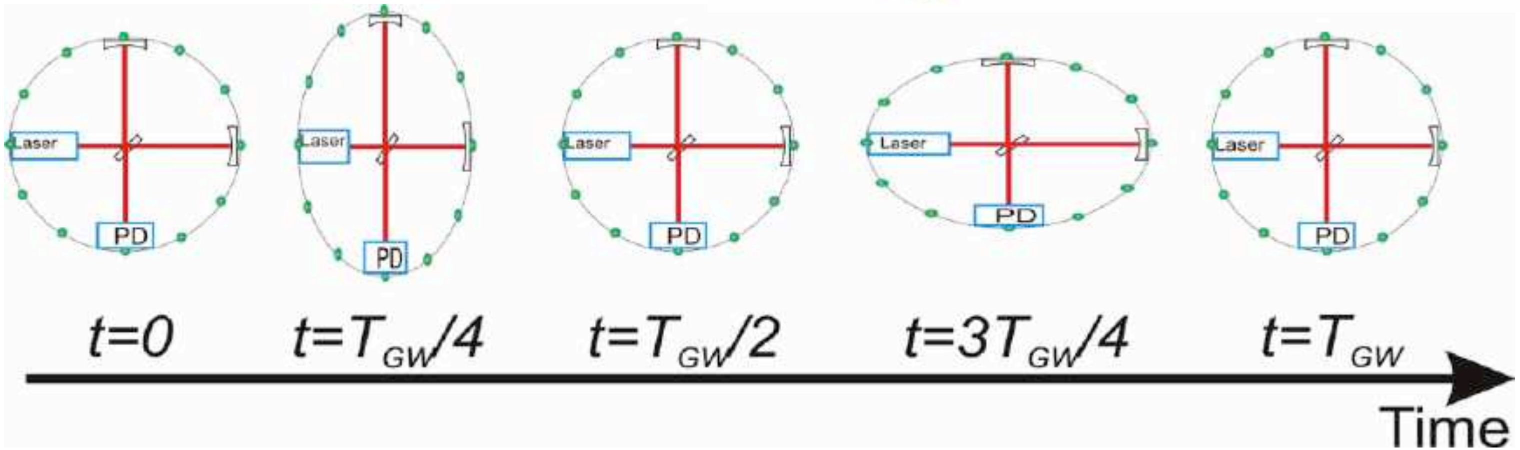
- *Gravitational Waves and GW Detectors on the Earth*
- *Recent Results*
    - *Binary Black Hole Mergers*
    - *Binary Neutron Star Merger GW170817*
- *Future Ground-based Gravitational-Wave Detectors*

Precision Gravitational-wave Interferometry

- LIGO uses enhanced Michelson interferometry
  - With suspended ('freely falling') mirrors
- Passing GWs stretch and compress the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - A coherent detector!

Advanced LIGO





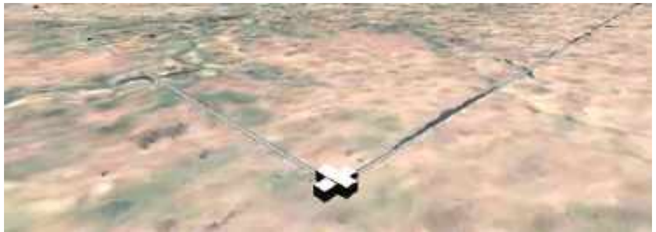
The Global GW Detector Network

LIGO
Louisiana,
USA
4 km arms

Virgo
Cascina
Italy
3 km arms

KAGRA
Kamioka Mountain, Japan
Underground, 3 km arms
Operational in 2020

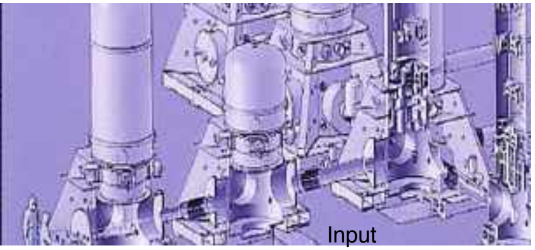
LIGO
Washington,
USA
4 km arms



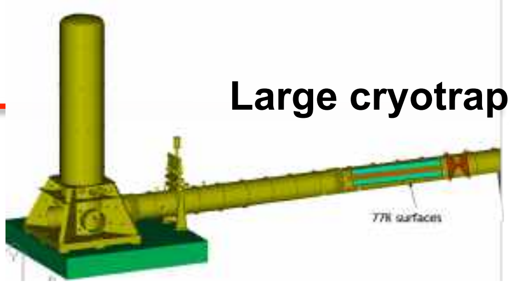
LIGO-India, Hingoli, India
4 km arms
Operational in ~ 2025

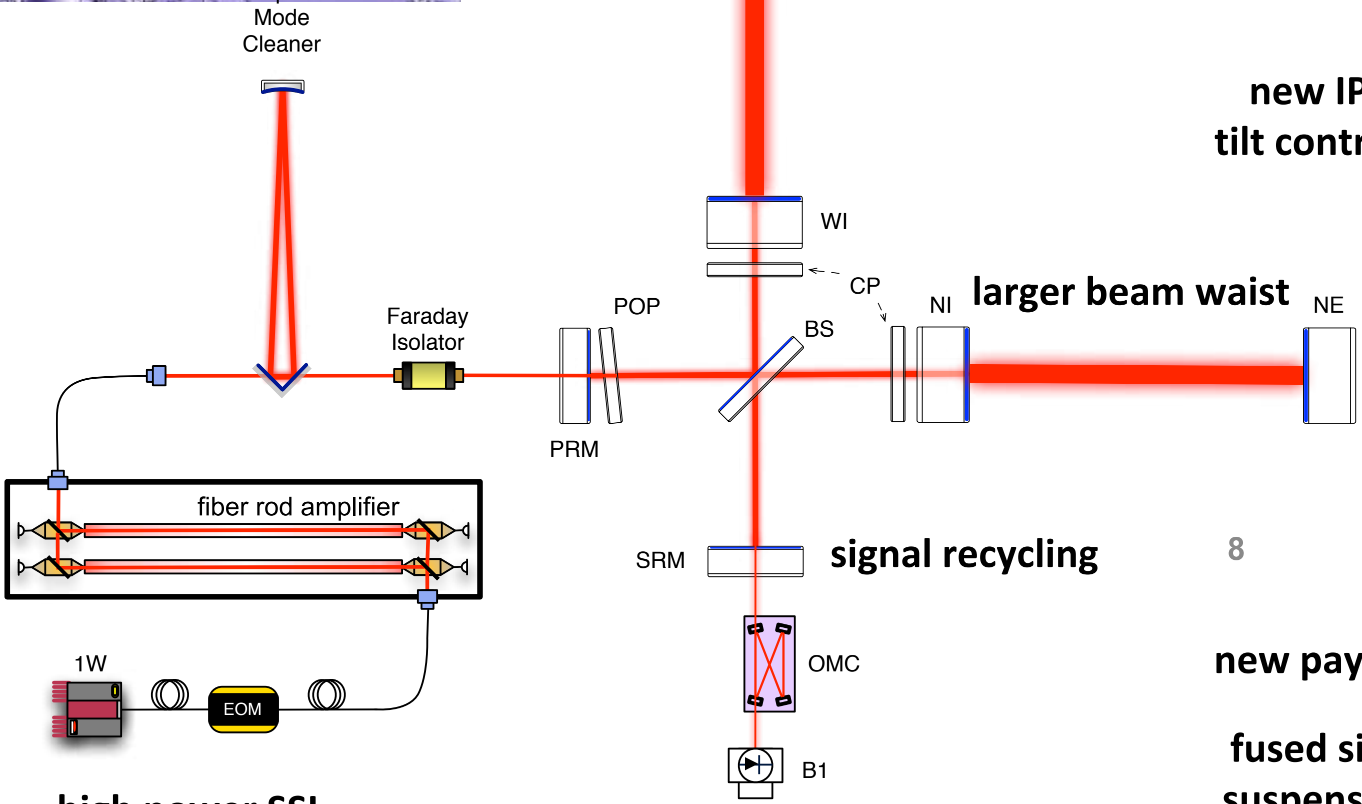
VIRGO Ad Virgo in a nutshell

Larger central vacuum links



Large cryotraps





heavier mirrors (42 kg)

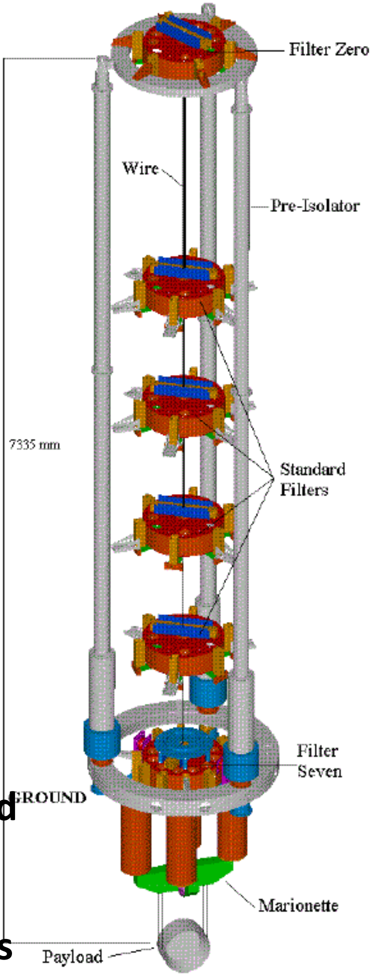
new IP tilt control

larger beam waist

signal recycling

new payload

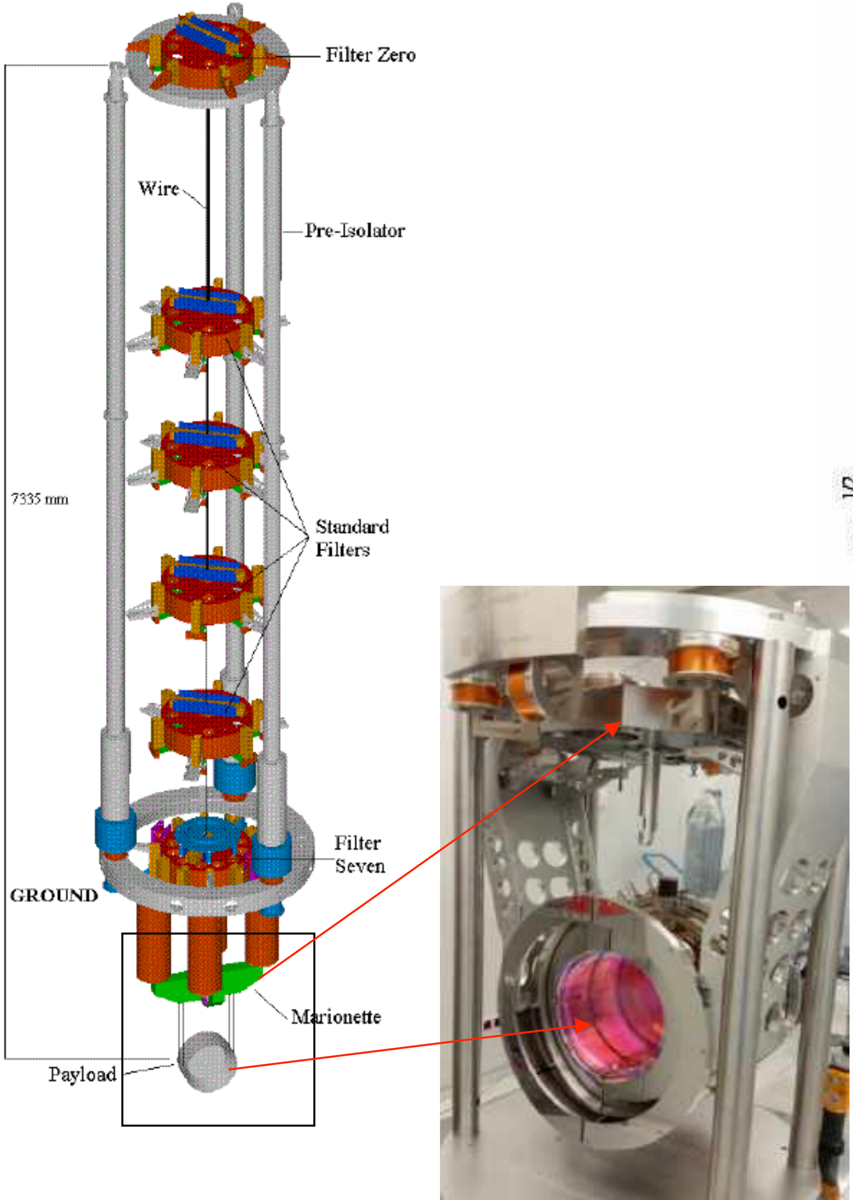
fused silica suspensions

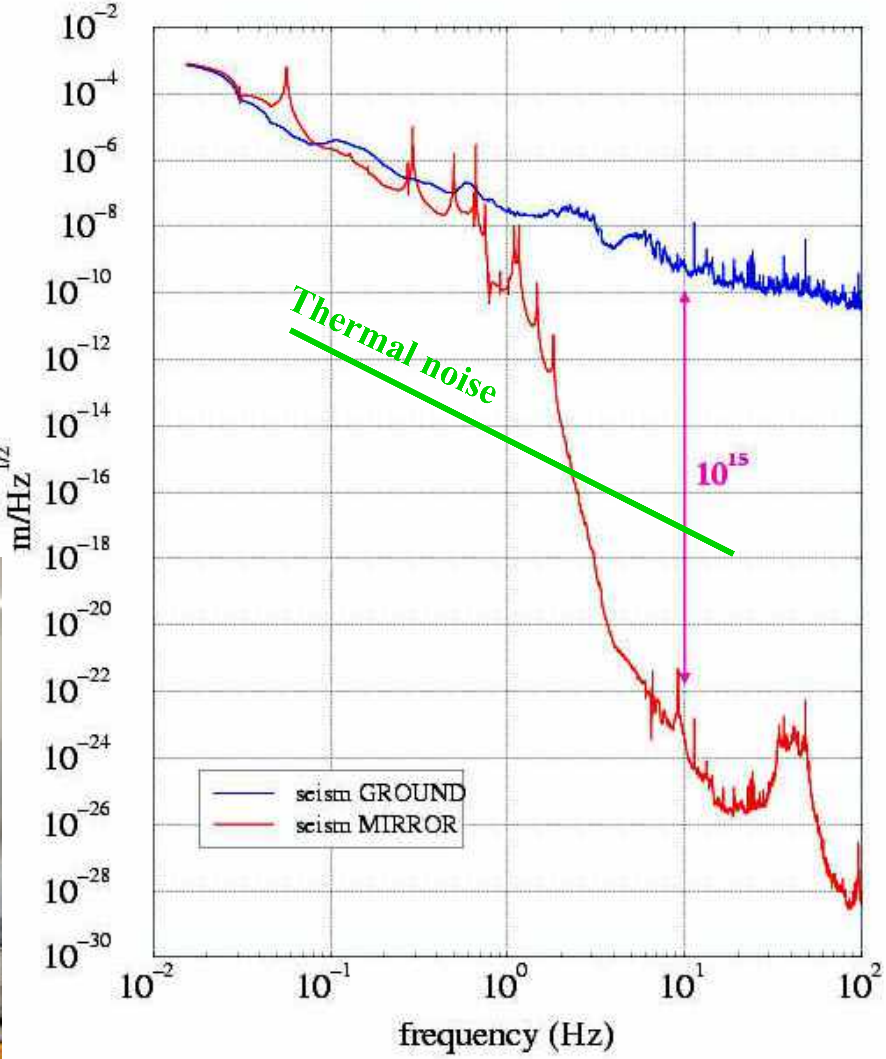


high power SSL

DC detection

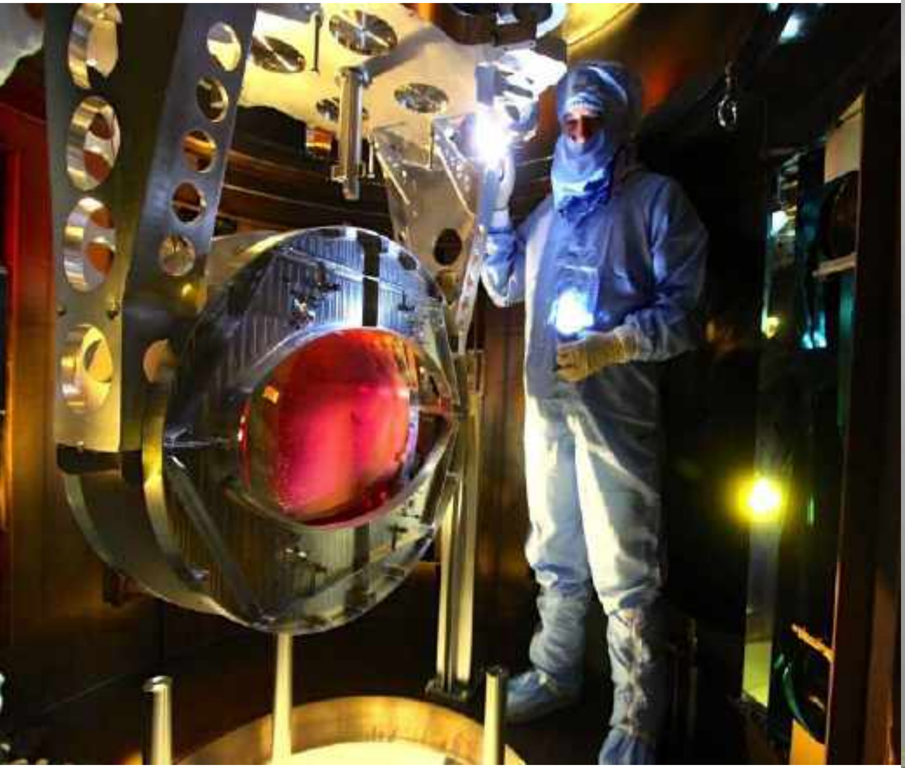
Free falling test masses: the virgo solution





Virgo Payloads

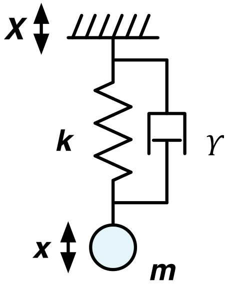
Beam Splitter integrated hooked to the super attenuator (now in vacuum)



Input mirror payloads of the FP cavities assembled and integrated in the super attenuator vacuum chamber

Advanced LIGO Suspensions

Concept: Harmonic Oscillator

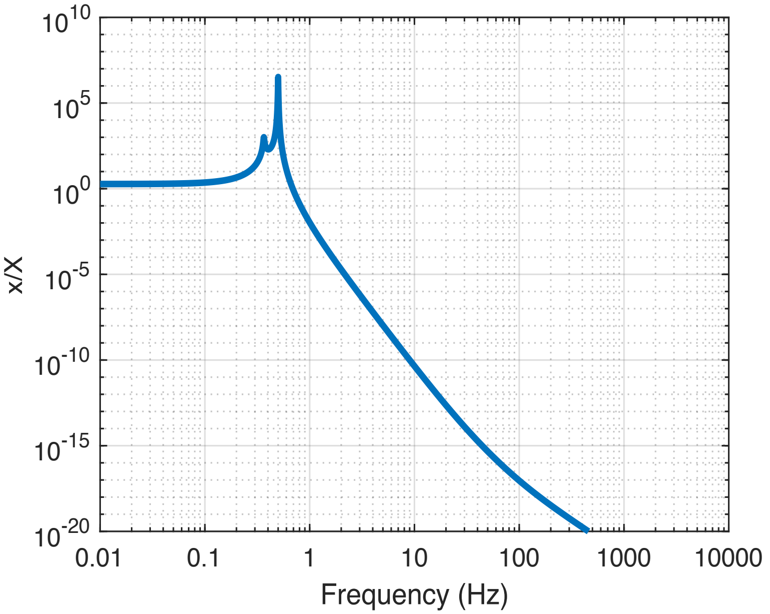


$$m\ddot{x} = -k(x-X) - \gamma(\dot{x}-\dot{X})$$

$$\left(\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2\right)\tilde{x} = \left(\omega_0^2 + i\frac{\gamma}{m}\omega\right)\tilde{X}$$

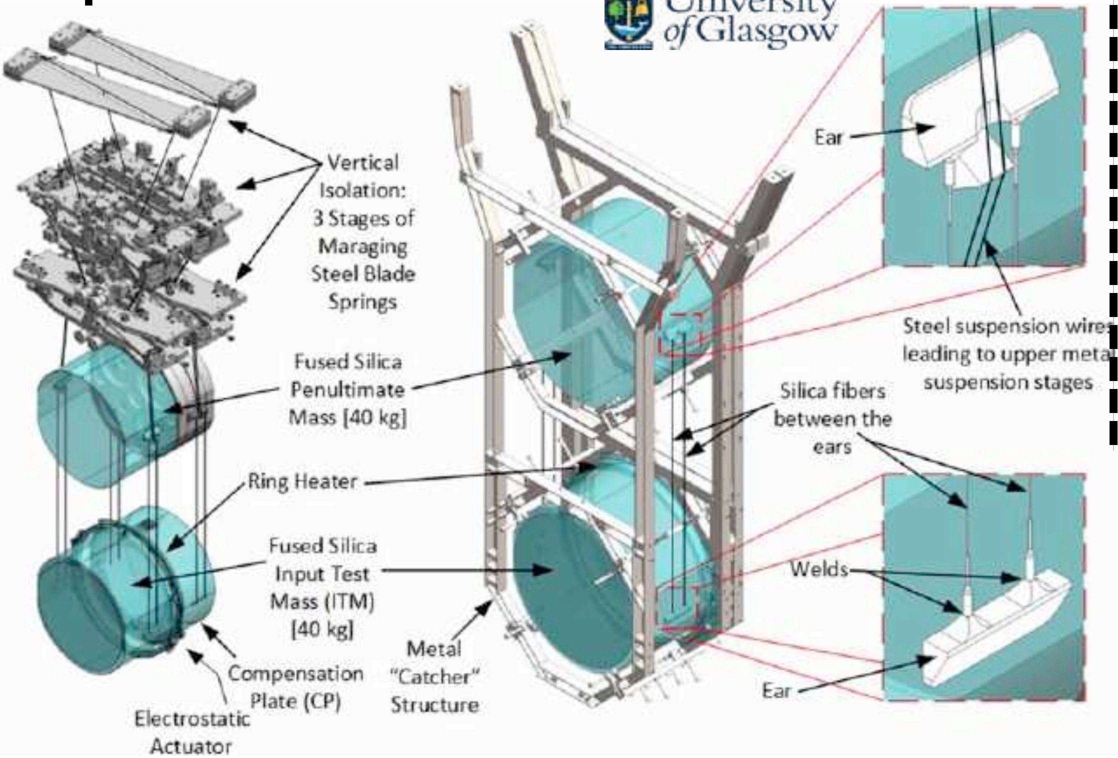
$$\frac{\tilde{x}}{\tilde{X}} = \frac{\omega_0^2 + i\frac{\gamma}{m}\omega}{\omega_0^2 + i\frac{\gamma}{m}\omega - \omega^2}$$

4 Stage Transfer Function:

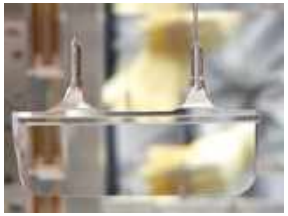


Implementation:

Collaboration w/ U. Glasgow

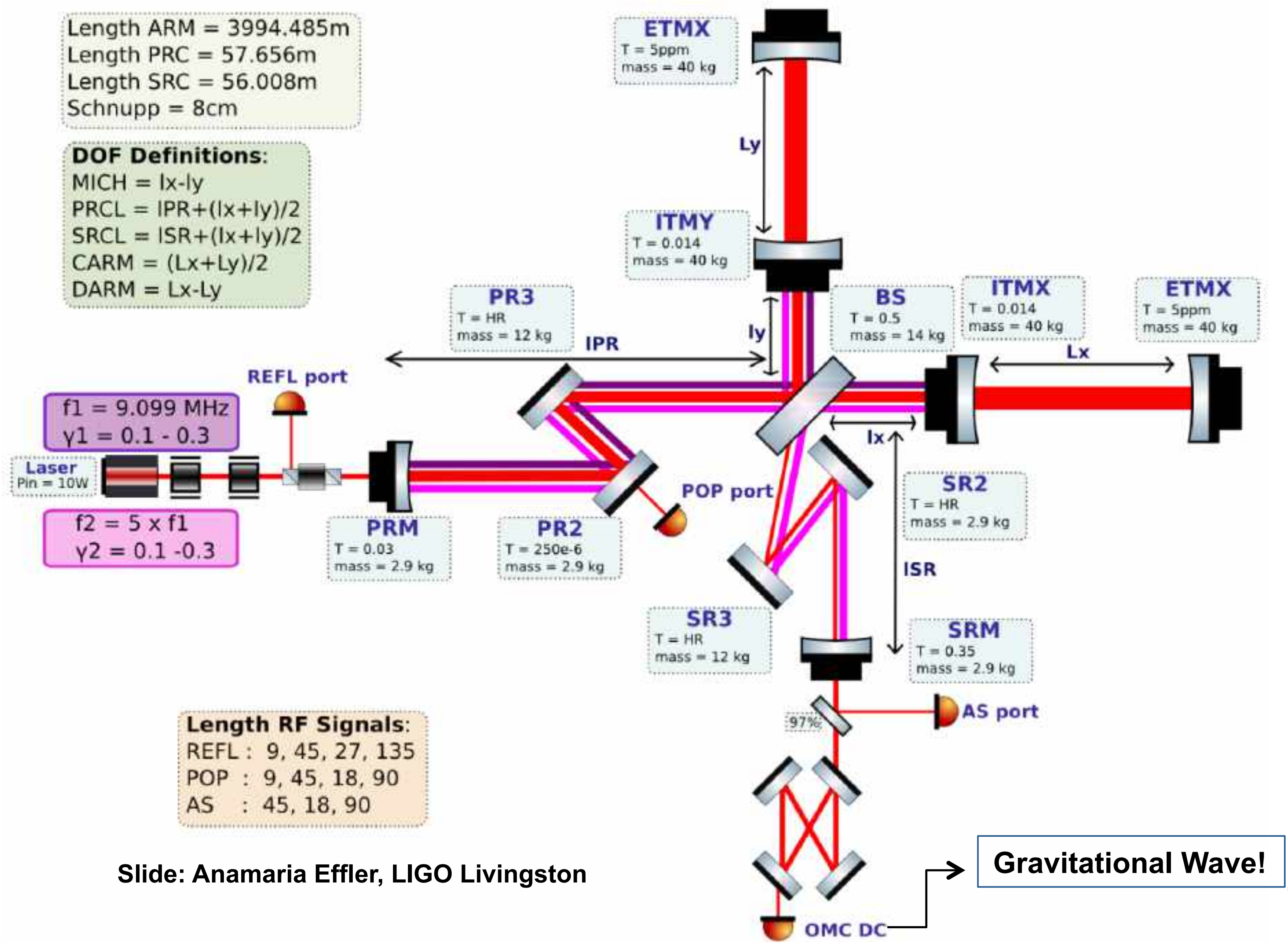


Upper 'ear'



Lower 'ear'

Advanced LIGO = Servo Control



Length ARM = 3994.485m
Length PRC = 57.656m
Length SRC = 56.008m
Schnupp = 8cm

DOF Definitions:
MICH = lx-ly
PRCL = lPR+(lx+ly)/2
SRCL = lSR+(lx+ly)/2
CARM = (Lx+Ly)/2
DARM = Lx-Ly

f1 = 9.099 MHz
γ1 = 0.1 - 0.3

f2 = 5 x f1
γ2 = 0.1 -0.3

Length RF Signals:
REFL : 9, 45, 27, 135
POP : 9, 45, 18, 90
AS : 45, 18, 90

Slide: Anamaria Effler, LIGO Livingston

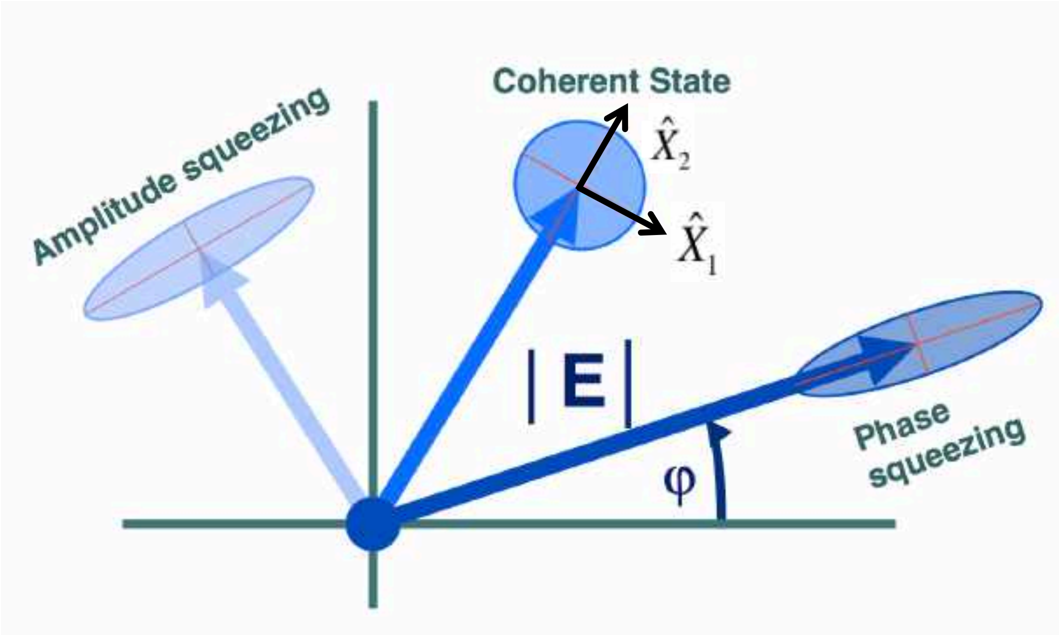
Quantum Engineering Light: Squeezed States

- **Electromagnetic fields are quantized:**

$$\hat{E} = \hat{X}_1 \cos\omega t + i\hat{X}_2 \sin\omega t$$

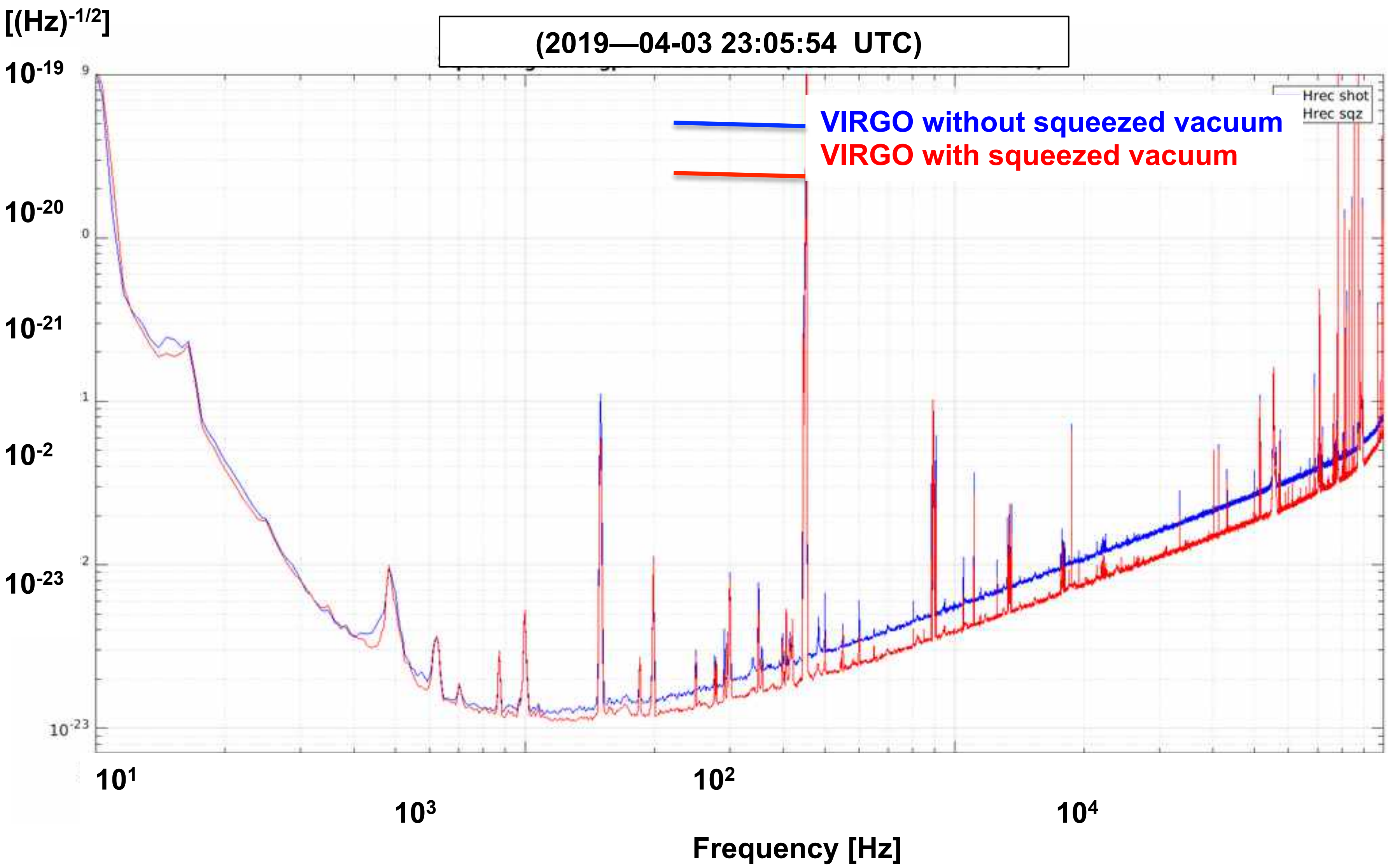
- **Quantum fluctuations exist in the vacuum state:**

$$\langle(\Delta\hat{X}_1)^2\rangle\langle(\Delta\hat{X}_2)^2\rangle \geq 1$$



H. P. Yuen, Phys. Rev. A**13**, 2226 (1976)
C. M. Caves, Phys. Rev. D**26**, 1817 (1982)
Wu, Kimble, Hall, Wu, PRL (1986)

Running a Quantum Optics Interferometer


(2019—04-03 23:05:54 UTC)

VIRGO without squeezed vacuum

VIRGO with squeezed vacuum

Precision Interferometry: Understanding Measurement Noises

Fundamental Noises:

I. Displacement Noises

→ $\Delta L(f)$

- Seismic noise
- Radiation Pressure
- Thermal noise
  - Suspensions
  - Optics

II. Sensing Noises

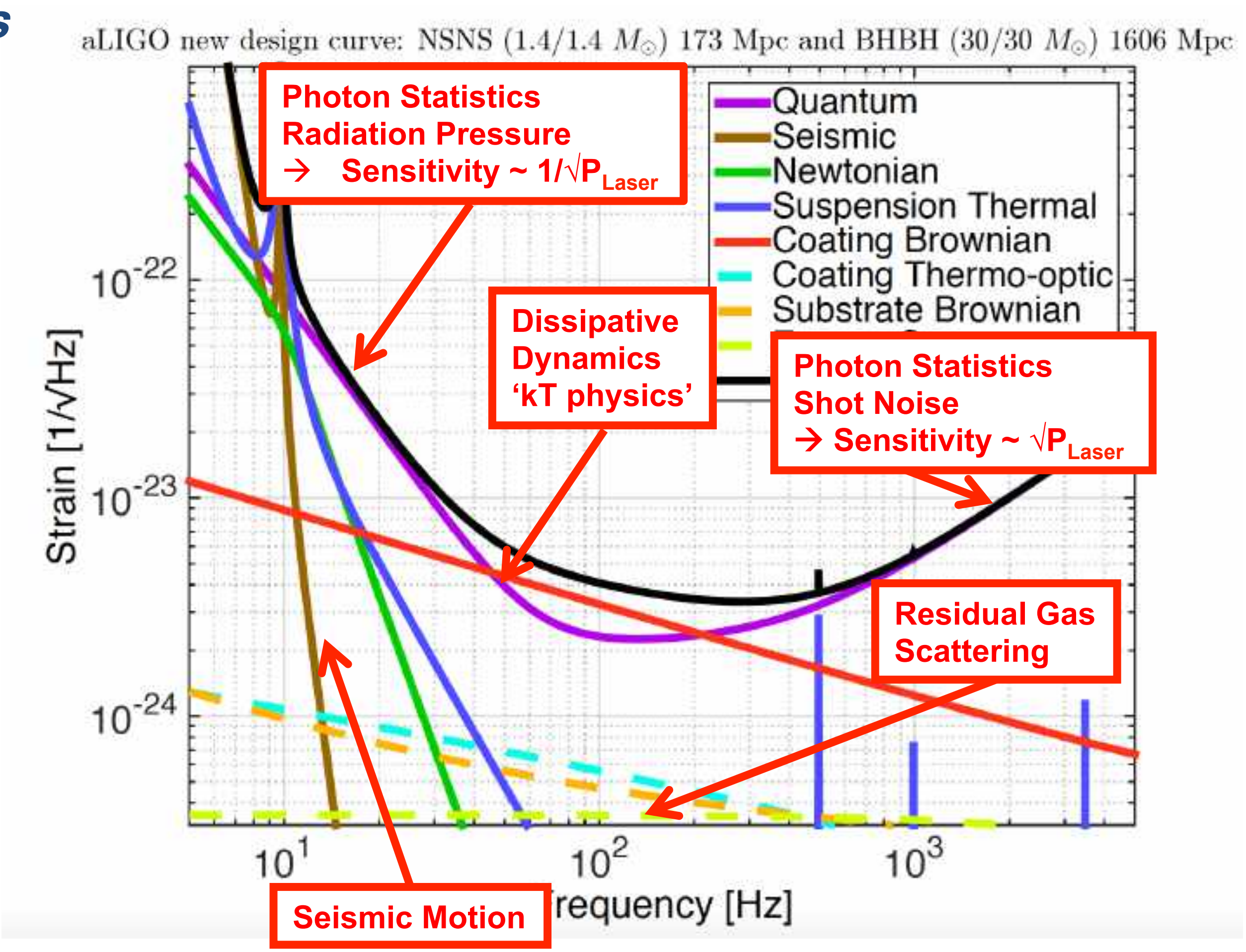
→ $\Delta t_{photon}(f)$

  - Shot Noise
  - Residual Gas

Technical Noises:

→ Hundreds of them…

Design Noise Budget



Photon Statistics
Radiation Pressure
→ Sensitivity ~ $1/\sqrt{P_{Laser}}$

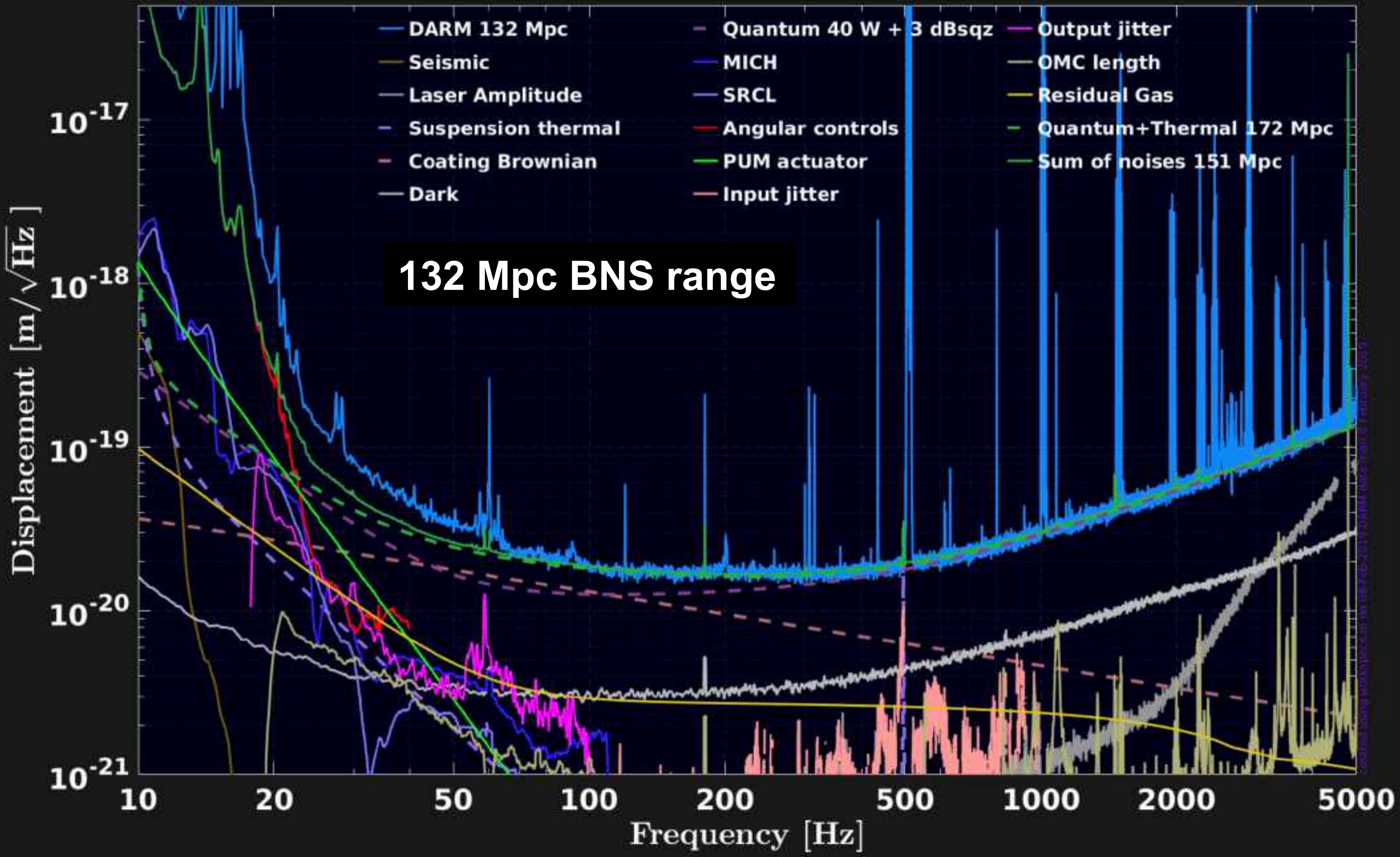
Dissipative Dynamics
'kT physics'

Photon Statistics
Shot Noise
→ Sensitivity ~ $\sqrt{P_{Laser}}$

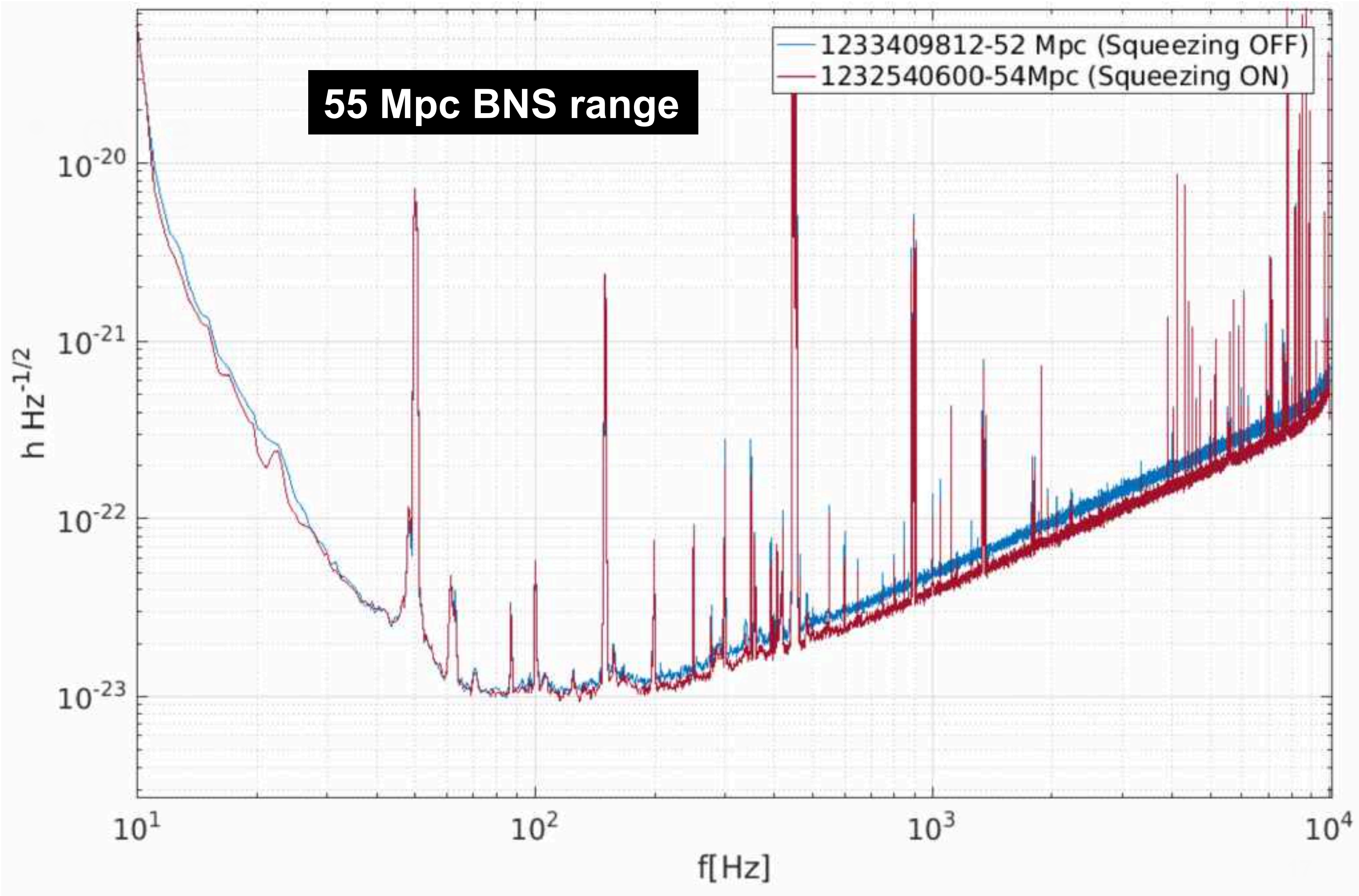
Residual Gas Scattering

Seismic Motion

Interferometer Sensitivity: LIGO Livingston



Interferometer Sensitivity: Virgo



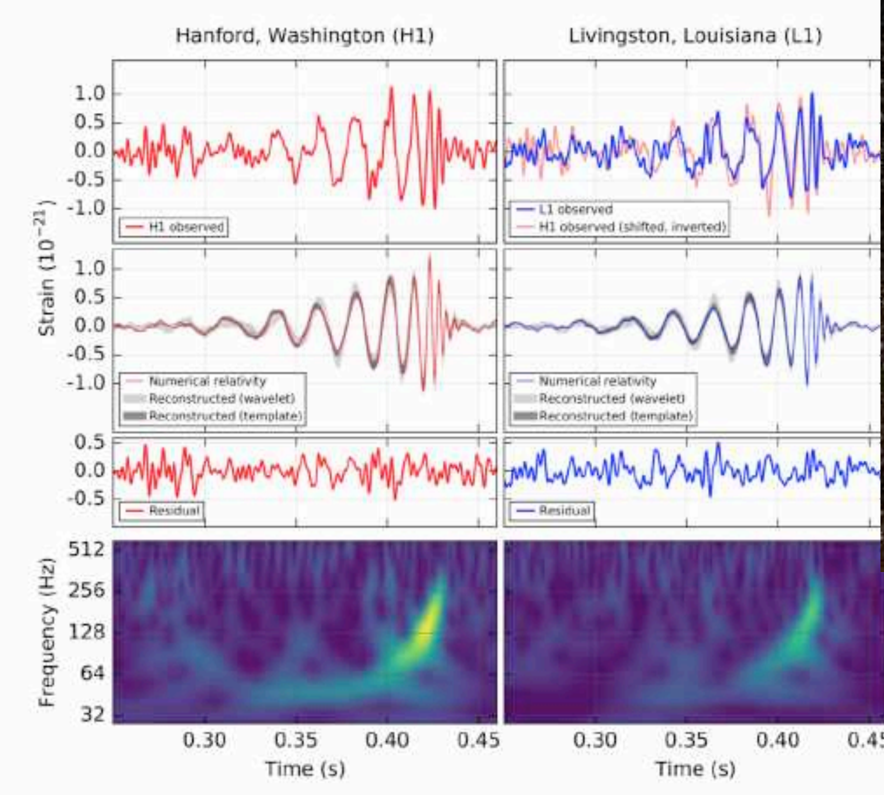
55 Mpc BNS range

Recent Results:

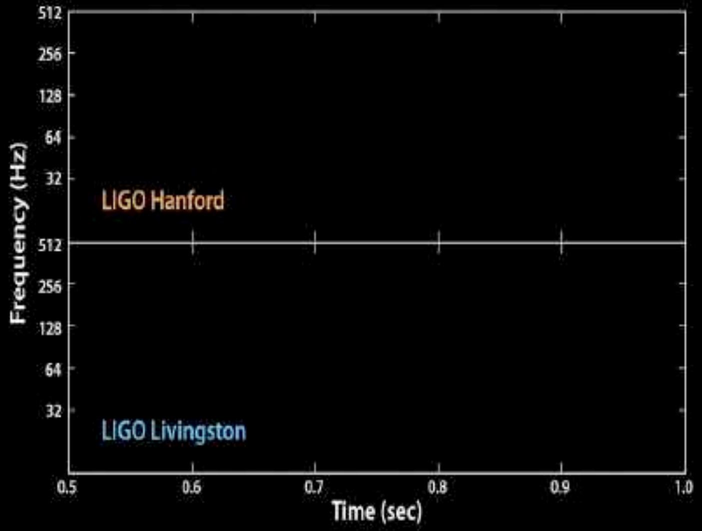
Binary Black Hole Mergers

Binary Neutron Star Merger GW170817

GW150914: The First Binary Black Hole Merger

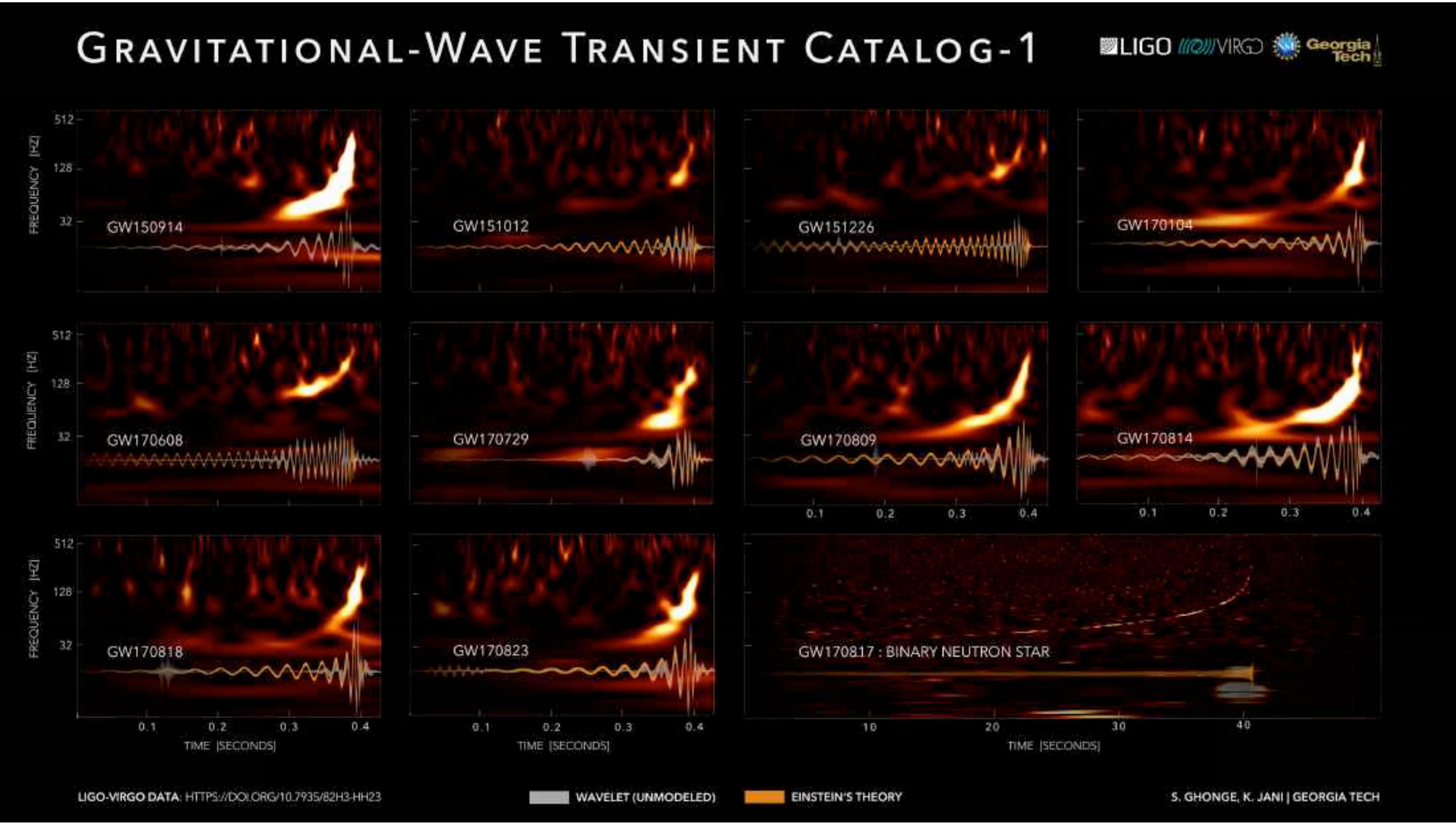


Andy Bohn, François Hébert, and William Throwe, SXS Collaboration

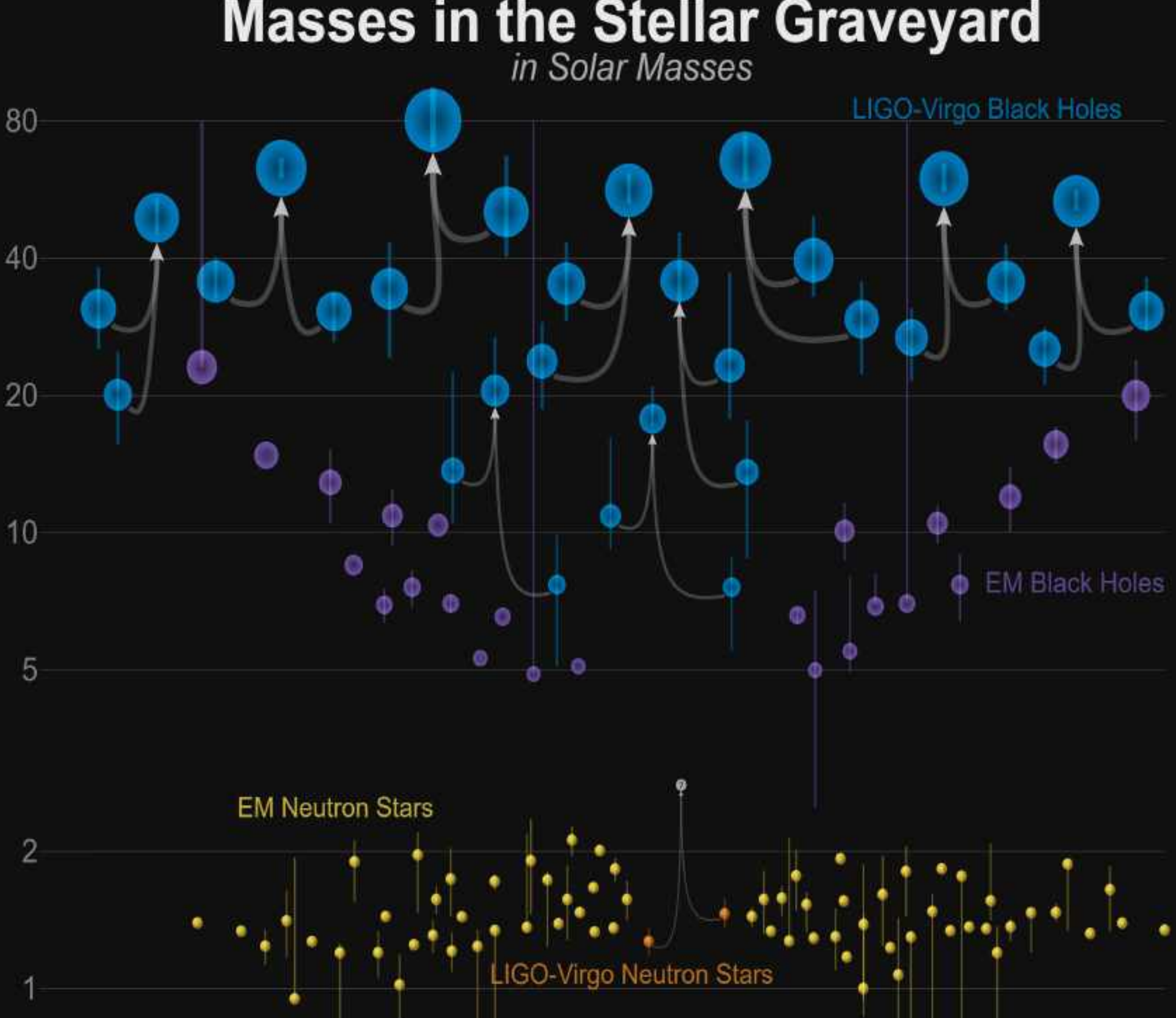


Abbott, et al. ‚LIGO Scientific Collaboration and Virgo Collaboration, "Observation of Gravitational Waves from a Binary Black Hole Merger" **Phys. Rev. Lett. 116, 061102 (2016)**

Just released: GWTC-1 GW Catalog



B. P. Abbott, et al., (LIGO Virgo Collaboration), “GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs” , https://arxiv.org/abs/1811.12907

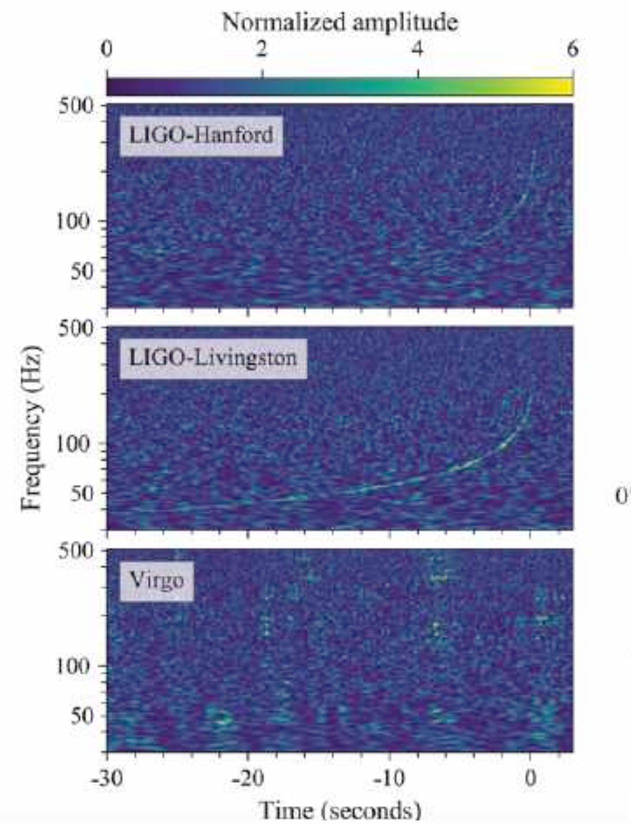


B. P. Abbott, et al., (LIGO Virgo Collaboration), “GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs” , https://arxiv.org/abs/1811.12907

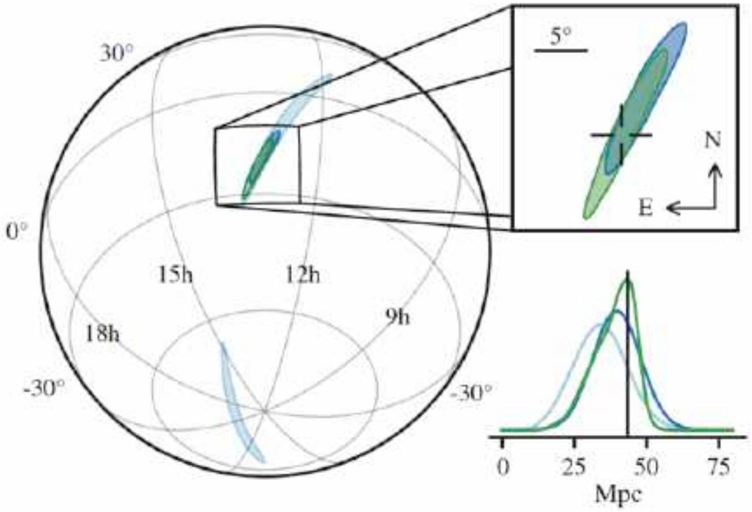
LIGO-Virgo | Frank Elavsky | Northwestern

LIGO-Virgo | Frank Elavsky | Northwestern

GW170817: The First Detected Binary Neutron Star Merger

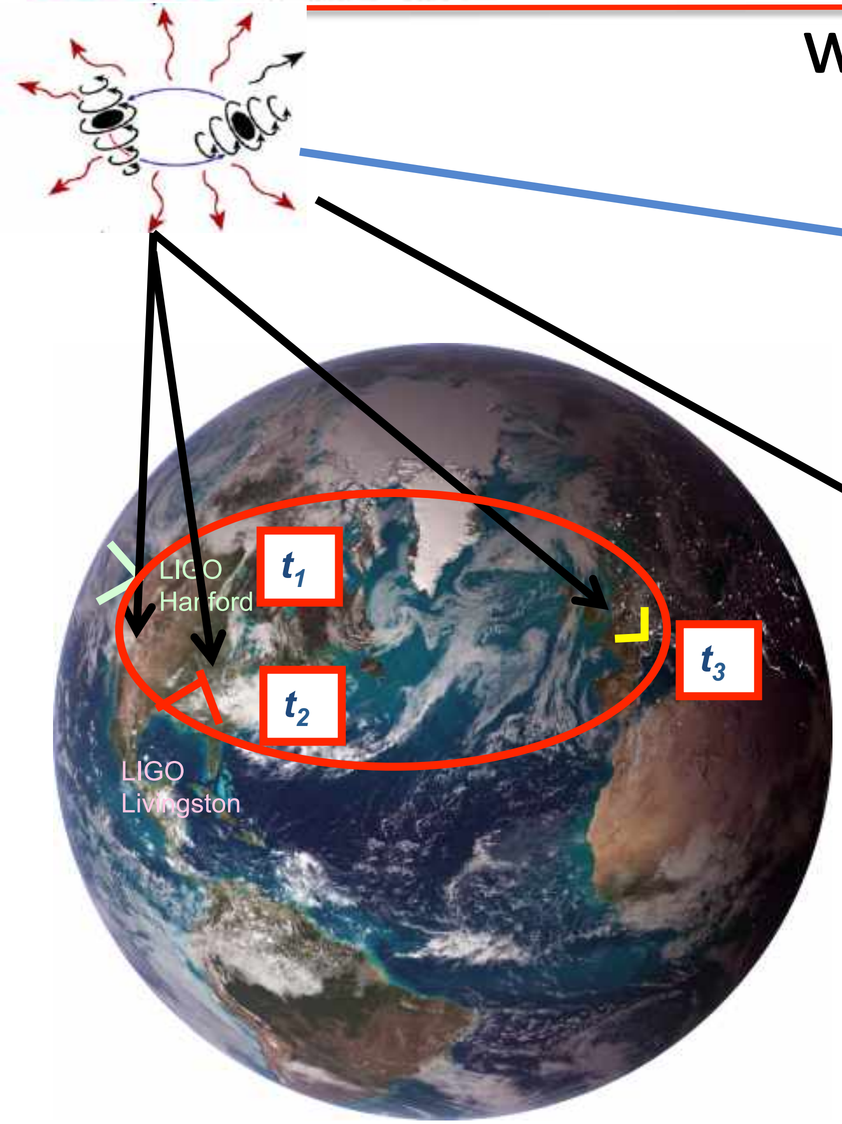


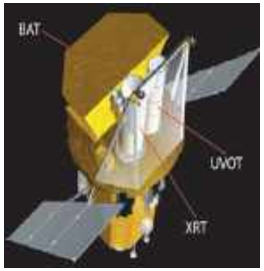
Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral” **Phys. Rev. Lett. 161101 (2017)**



	Low-spin priors ($|\chi| \leq 0.05$)	High-spin priors ($|\chi| \leq 0.89$)
Primary mass m_1	$1.36–1.60\ M_\odot$	$1.36–2.26\ M_\odot$
Secondary mass m_2	$1.17–1.36\ M_\odot$	$0.86–1.36\ M_\odot$
Chirp mass $\mathcal{M}$	$1.188^{+0.004}_{-0.002} M_\odot$	$1.188^{+0.004}_{-0.002} M_\odot$
Mass ratio m_2/m_1	$0.7–1.0$	$0.4–1.0$
Total mass $m_{\rm tot}$	$2.74^{+0.04}_{-0.01} M_\odot$	$2.82^{+0.47}_{-0.09} M_\odot$
Radiated energy $E_{\rm rad}$	$> 0.025 M_\odot c^2$	$> 0.025 M_\odot c^2$
Luminosity distance $D_{\rm L}$	40^{+8}_{-14} Mpc	40^{+8}_{-14} Mpc
Viewing angle Θ	$\lesssim 55°$	$\lesssim 56°$
Using NGC 4993 location	$\lesssim 28°$	$\lesssim 28°$
Combined dimensionless tidal deformability $\tilde{\Lambda}$	≤ 800	≤ 700
Dimensionless tidal deformability $\Lambda(1.4 M_\odot)$	≤ 800	≤ 1400

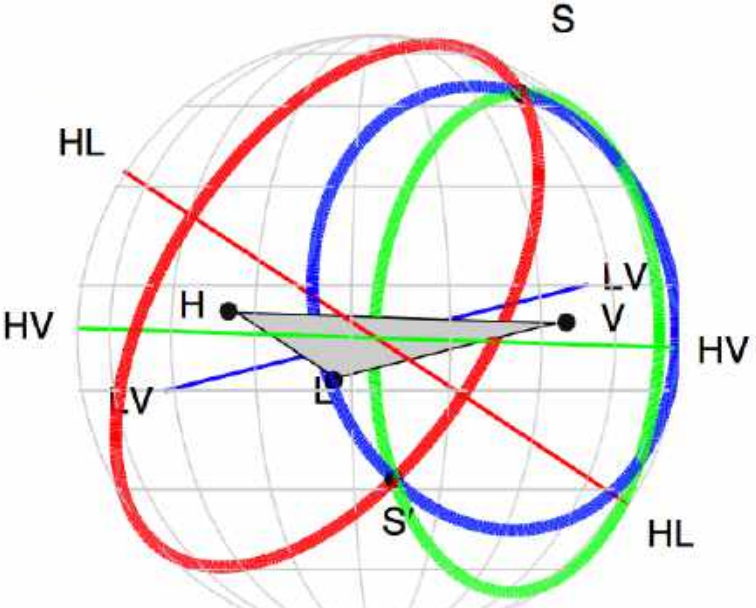
Enabling multi-messenger astronomy with gravitational waves





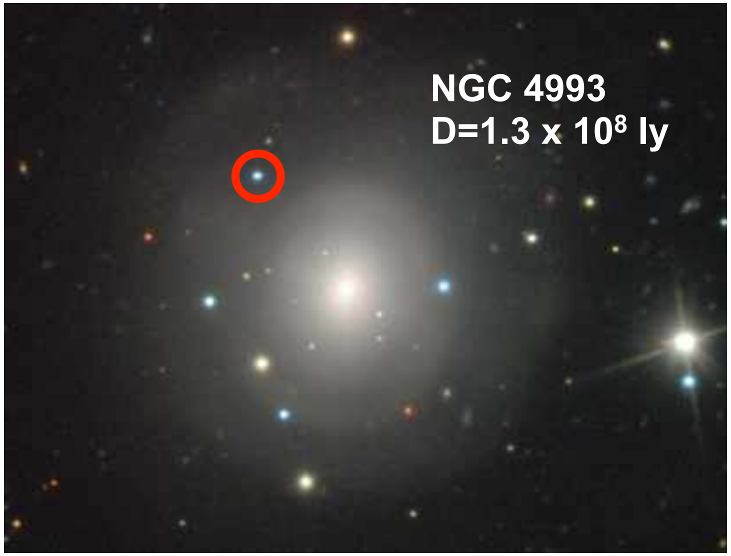
$$\theta_{GW} \sim \lambda_{GW} / d \sim \text{few degrees}$$

X-ray, γ-ray follow-up



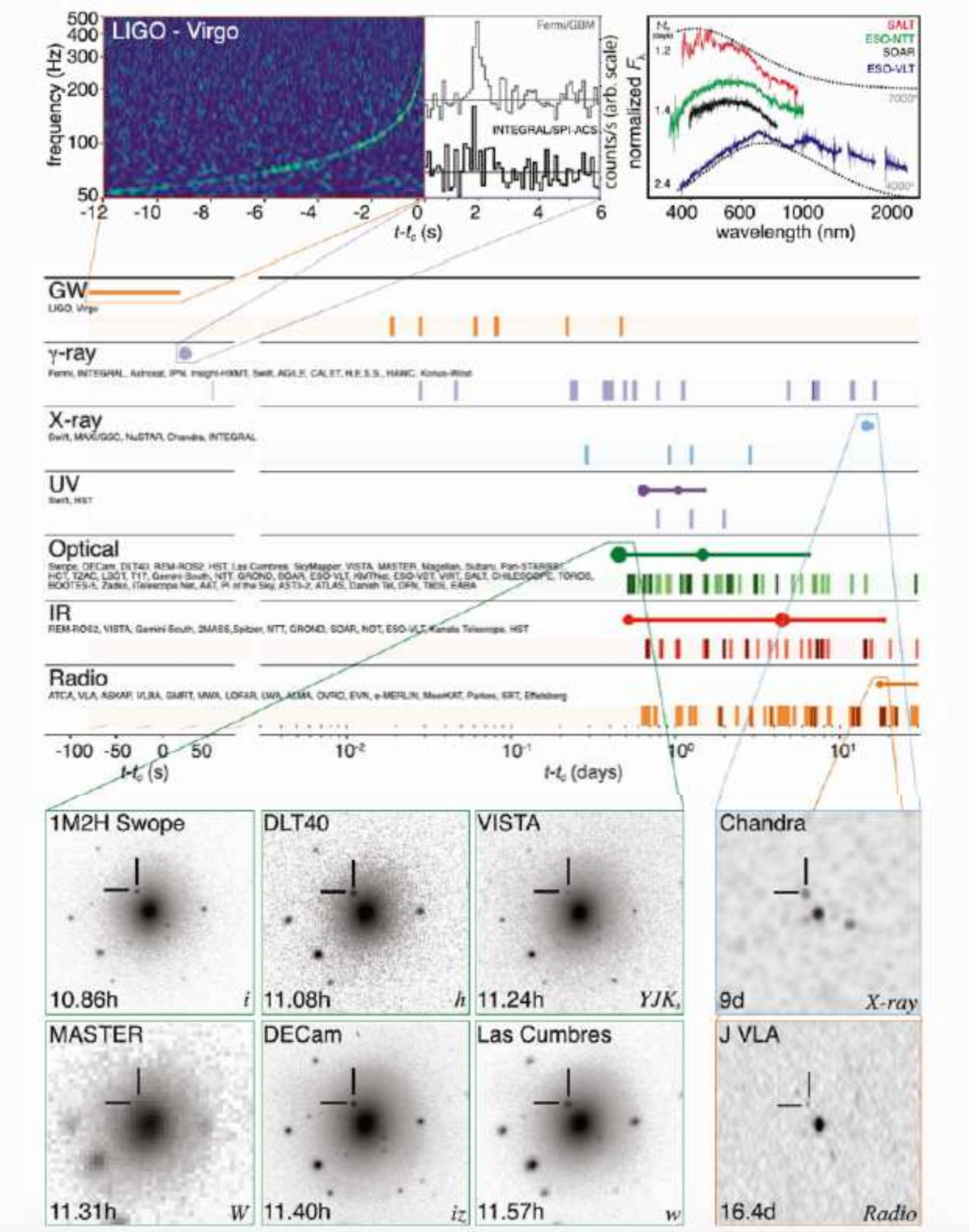
Abadie, et al, (LSC & Virgo Collaborations)
Astron. Astrophys. **541** (2012) A155.
Nissanke, Kalsiwal, Georgieva,
Astrophysical J. **767** (2013) 124.
Singer, Price, et al., Astrophysical J., 795 (2014) 105.

A Multi-messenger Astronomical Revolution!



Credit: European Southern Observatory Very Large Telescope

Abbott, et al. ,LIGO Scientific Collaboration and Virgo Collaboration, “Multi-messenger Observations of a Binary Neutron Star Merger” **Astrophys. J. Lett., 848:L12, (2017)**



Testing General Relativity
Are Gravitons Massless?

- GW170817 provides a stringent test of the speed of gravitational waves

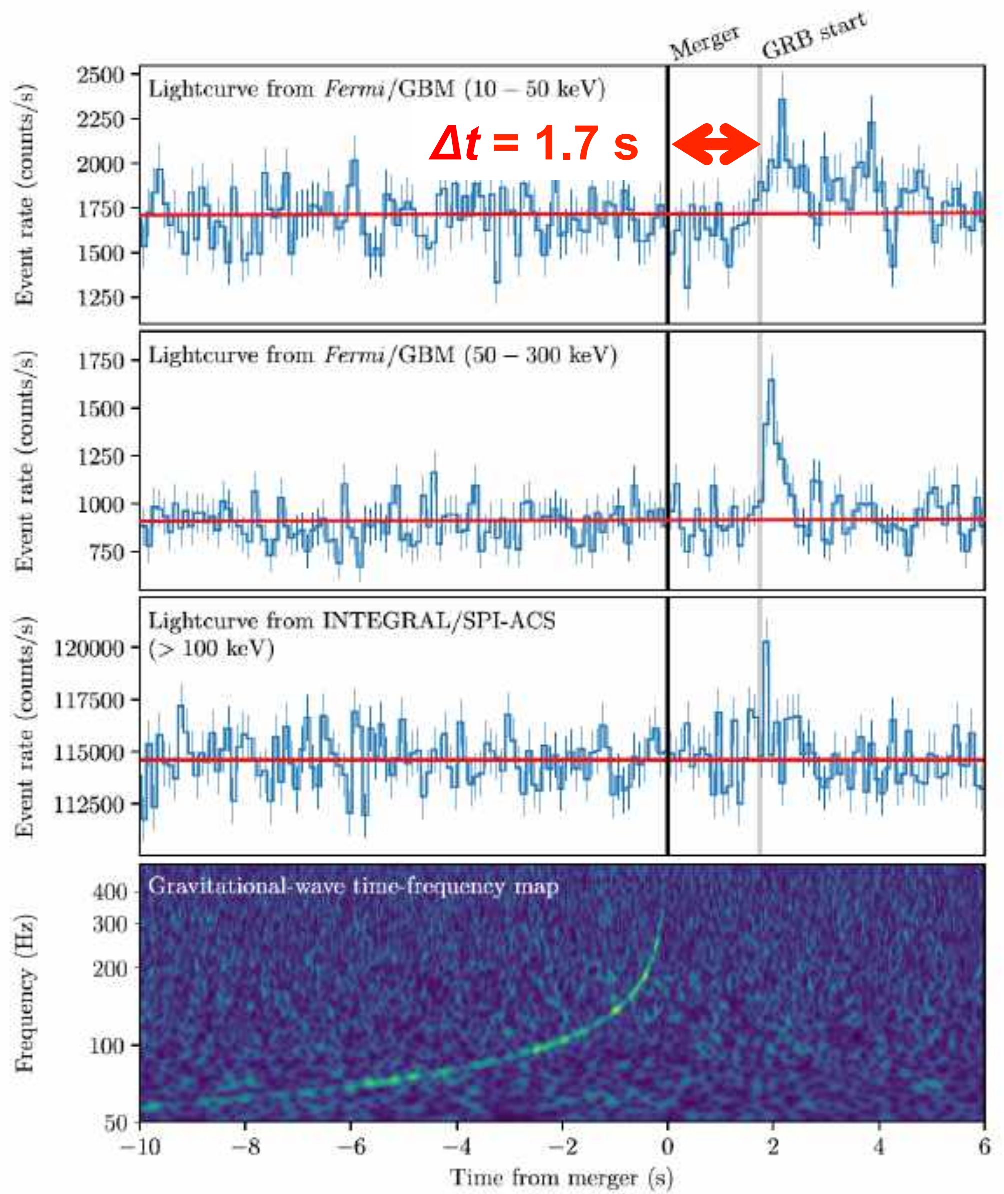
$$\frac{v_{GW}-c}{c}\approx\frac{c\Delta t}{D}$$

- Δt =1.
- $D \approx$ 26 Mpc
  - Conservative limit – use 90% confidence level lower limit on GW source from parameter estimation

$$\boxed{-3\times10^{-16}\leq\frac{v_{GW}-c}{c}\leq+7\times10^{-16}}$$

violations of Lorentz invariance and Equivalence Principle

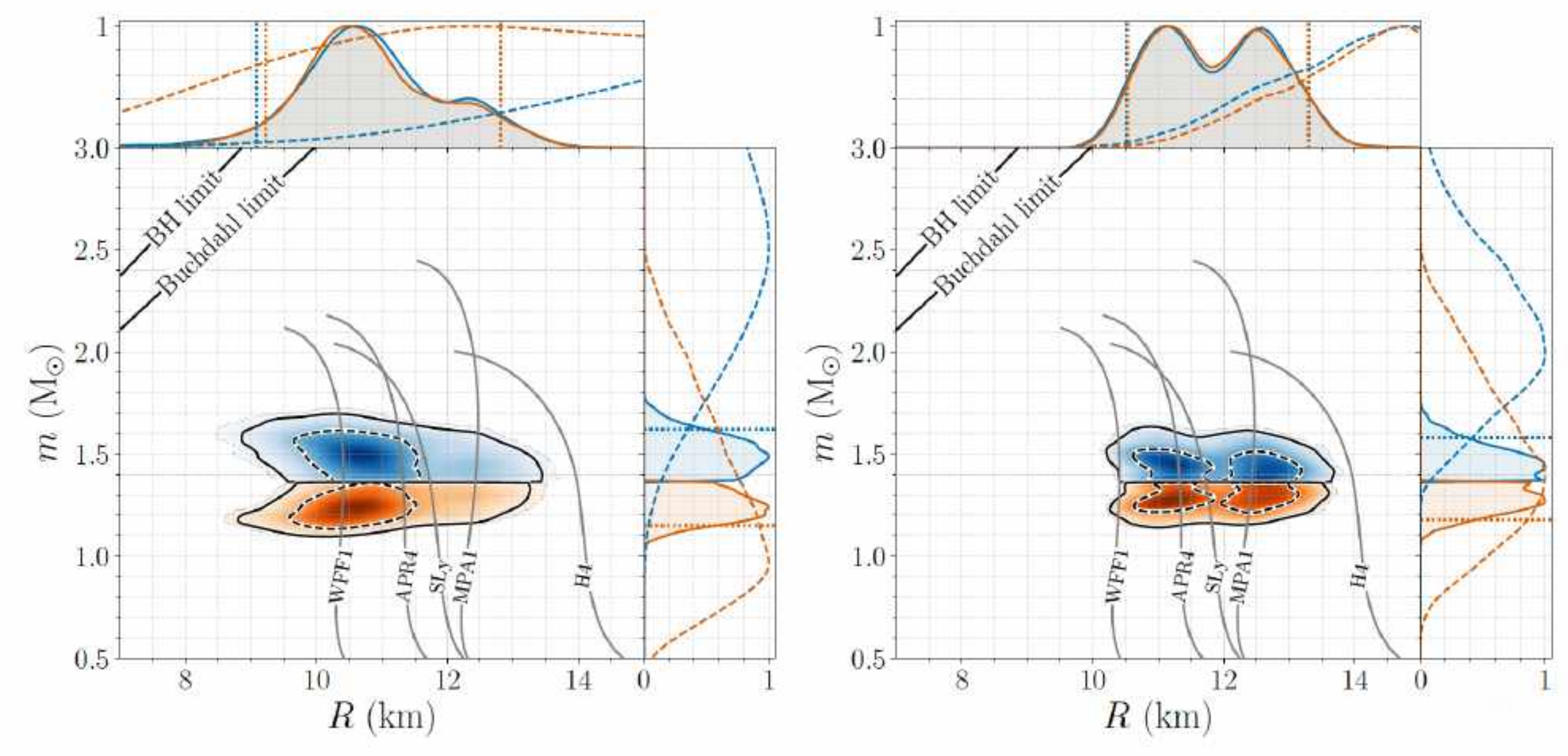
LIGO Scientific Collaboration and Virgo Collaboration, Gravitational Waves and Gamma-Rays from a Binary Neutron Star Merger: GW170817 and GRB 170817A" **Astrophys. J. Lett., 848:L13, (2017)**



Measurements of the GW170817 BNS Radii and EoS

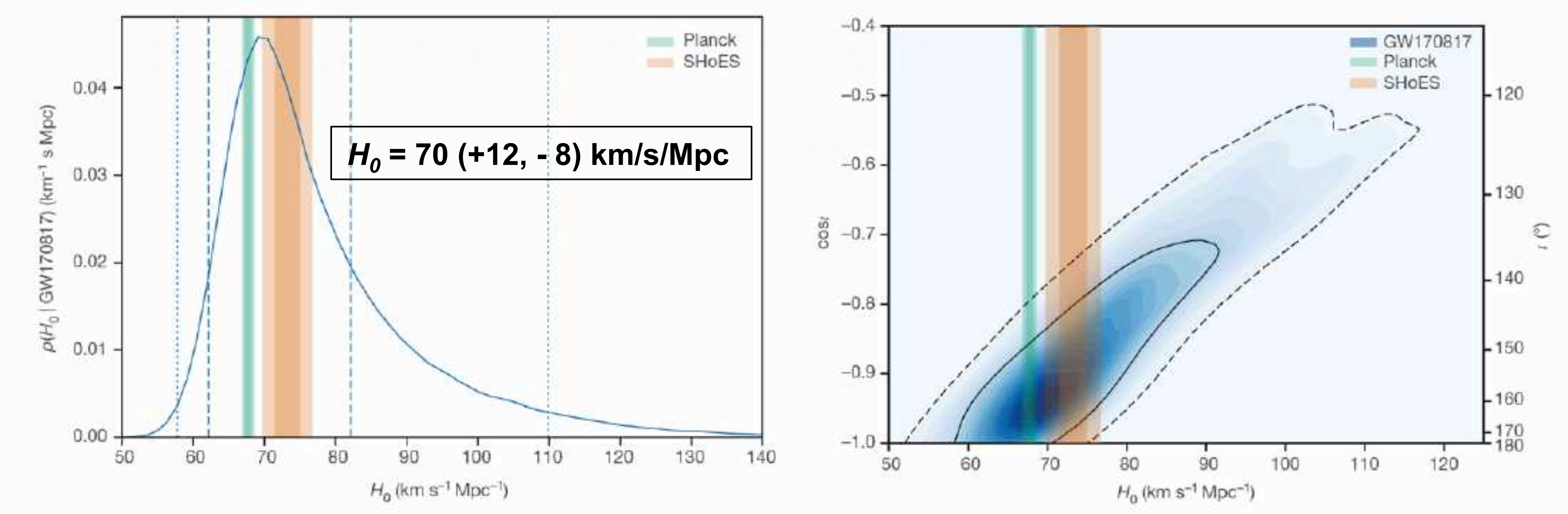
- Reanalysis of LIGO-Virgo data assuming components were NSs described by single EOS and consistent with EM observations
- → R_1 = 11.9 (+/- 1.4) km; R_2 = 11.9 (+/- 1.4) km
- Also constrain NS pressure-density relationship
  - → p @ 2X nuclear saturation density = 3.5×10^{34} dyn/cm^2

Abbott, et al., LIGO-Virgo Collaboration, “GW170817: Measurements of neutron star radii and equation of state” arXiv:1805.11581v1, PRL.



Cosmology: Measuring the Hubble Constant

- Gravitational waves are ‘standard sirens’, providing absolute measure of luminosity distance d_L
- GW detections can be used to determine H_0



H_0 = 70 (+12, - 8) km/s/Mpc

Abbott, et al., LIGO-Virgo Collaboration, 1M2H, DeCAM GW-EM & DES, DLT40, Las Cumbres Observatory, VINRO UGE, MASTER Collaborations, A gravitational-wave standard siren measurement of the Hubble constant”, *Nature* **551**, 85–88 (2017).

O3 summary I

-- O3 started on April 1 2019 with the three detectors H1, L1 and V in operation

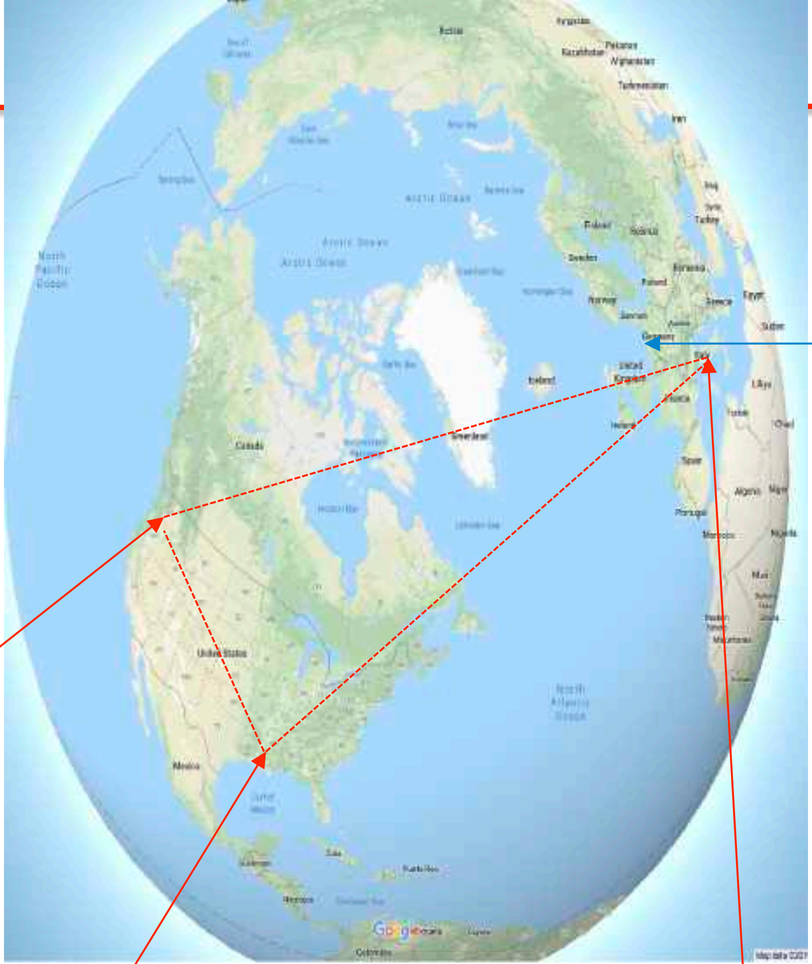
--the LIGO/Virgo collaboration took a short break from observing during the month of October 2019 to improve performance

-- Kamioka Gravitational Wave Detector (KRAGRA) in Japan became operational on 25 February 2020

-- the joint observation ended on March 27, 2020 due to health concerns from the COVID-19 pandemic

-- almost ~ 50 events clearly identified during the run

The Network in action nowdays



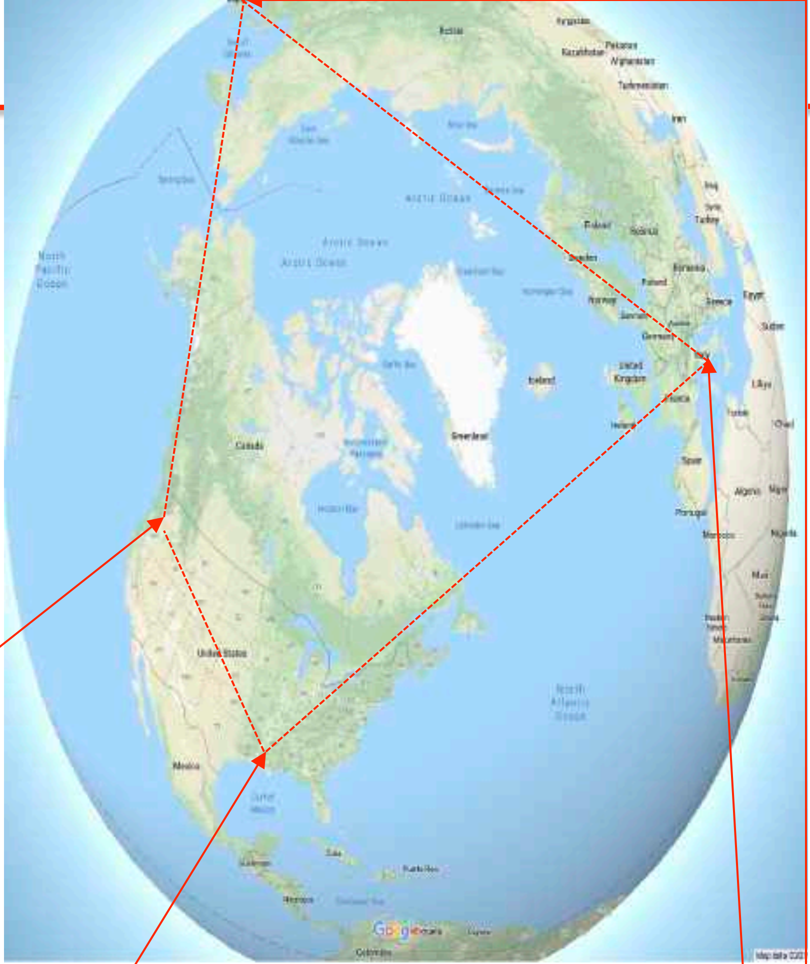
LIGO Hanford

LIGO Livingston

Virgo

GEO600

The network in the final part of O3



Effective time accuracy of a single detector

$$\sigma_t = (2\pi\rho\,\sigma_f)^{-1}$$

ρ → SNR

σ_f → effective bandwidth of the signal

LIGO Hanford

LIGO Livingston

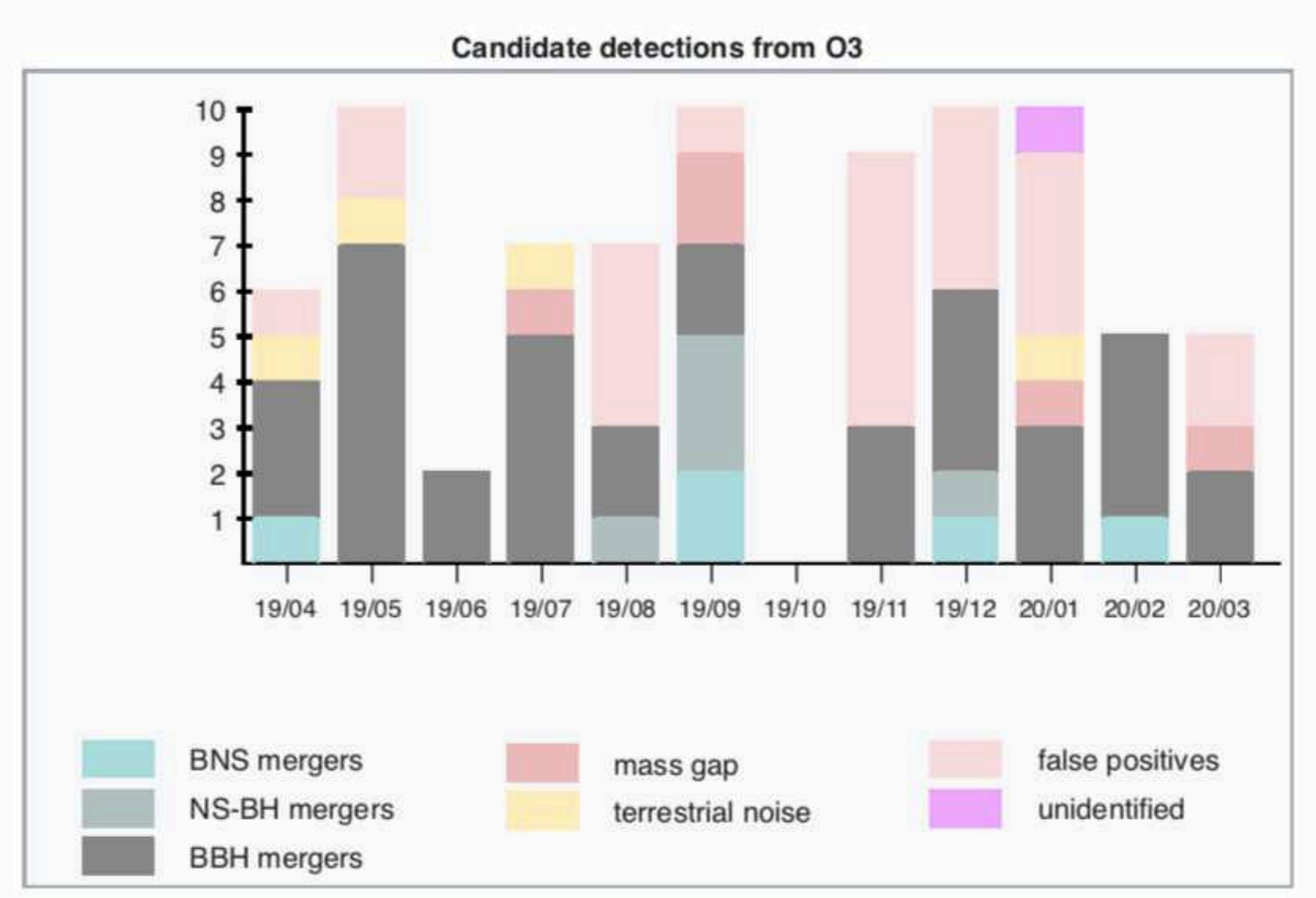
Virgo

KAGRA

O3 Summary II

-- A significant percentage of O3 candidate events detected by LIGO are accompanied by corresponding triggers at Virgo.

--False alarm rates (>1/20 years) are mixed with more than half of event:



Public Alert

-- O3 Observations published as Open Public Alerts https://gracedb.ligo.org/superevents/public/O3/ distributed through the public *Gamma-Ray Coordinates Network (GCN)* − *GCN and Circular*

-- Candidate event records can be directly accessed at the Gravitational Wave Candidate Event Database.

- --Circular will include instrument and data quality assessment, and *Retraction* if the event is rejected because the data are unsuitable. *Localization* estimate will be provided, if .

-- On 1 April 2019, the start of the third observation run was The first O3/2019 binary black hole detection alert was broadcast on 8 April 2019·

Event significance in GCN

Event names: example GWT 170817.529

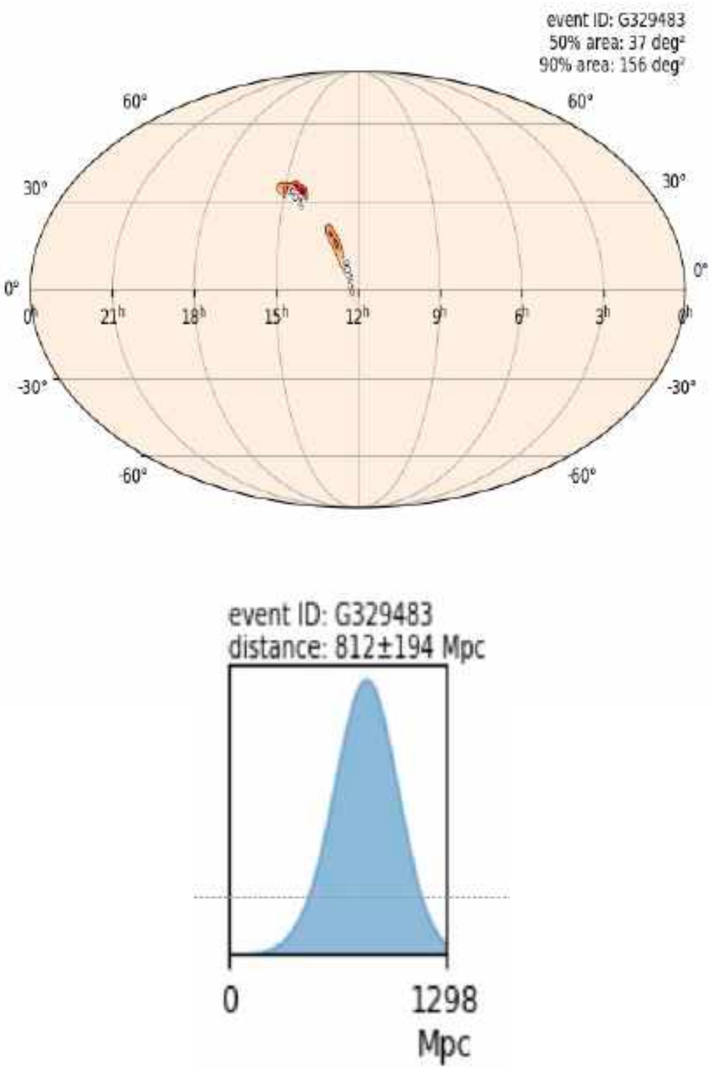
-- FAR ≥ 1/100 years: number will be stated in Circulars;
FAR ≤ 1/100 years: will be described simply as “highly significant”

-- FAR estimation is subject to large variation upon reanalysis or
analysis by different pipelines. Values much smaller (more significant) than 1/100 years are not very meaningful (who cares whether the false alarm rate was 1/100 years or 1/10000 years?)

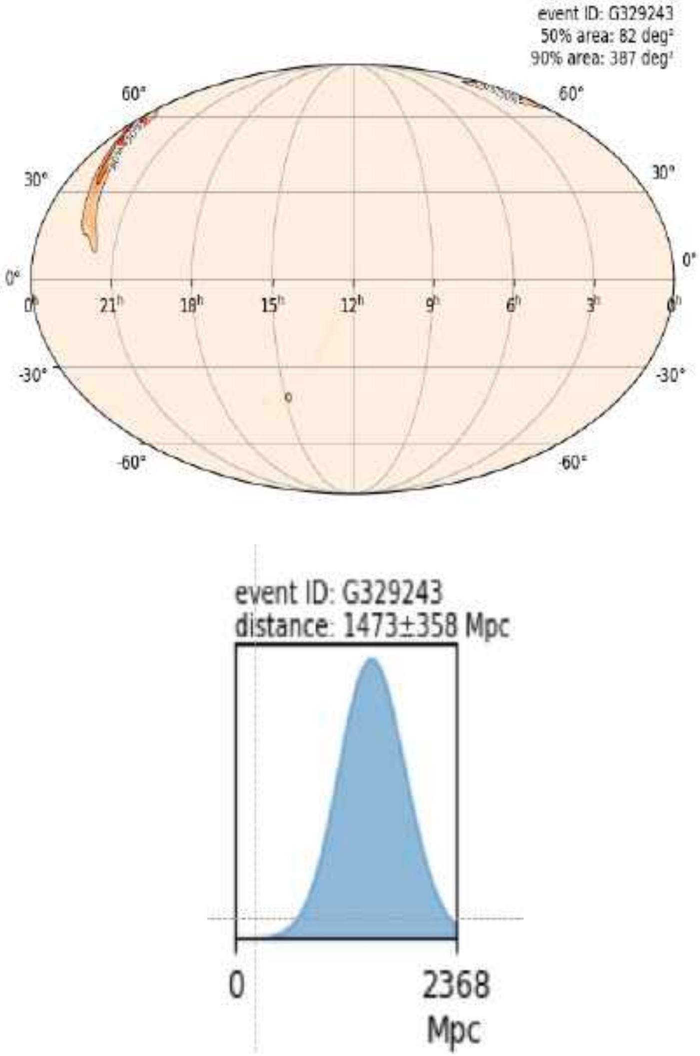
Source classification: BBH, NSBH , NSNSN

Example of a couple of SUPEVENTs: S190412m and S190408an

FAR= 1.683×10^{-27} Hz ➔ 1 per $1.883\times10^{+19}$ years



FAR= 2.81×10^{-18} Hz ➔ 1 per $1.1273\times10^{+10}$ years



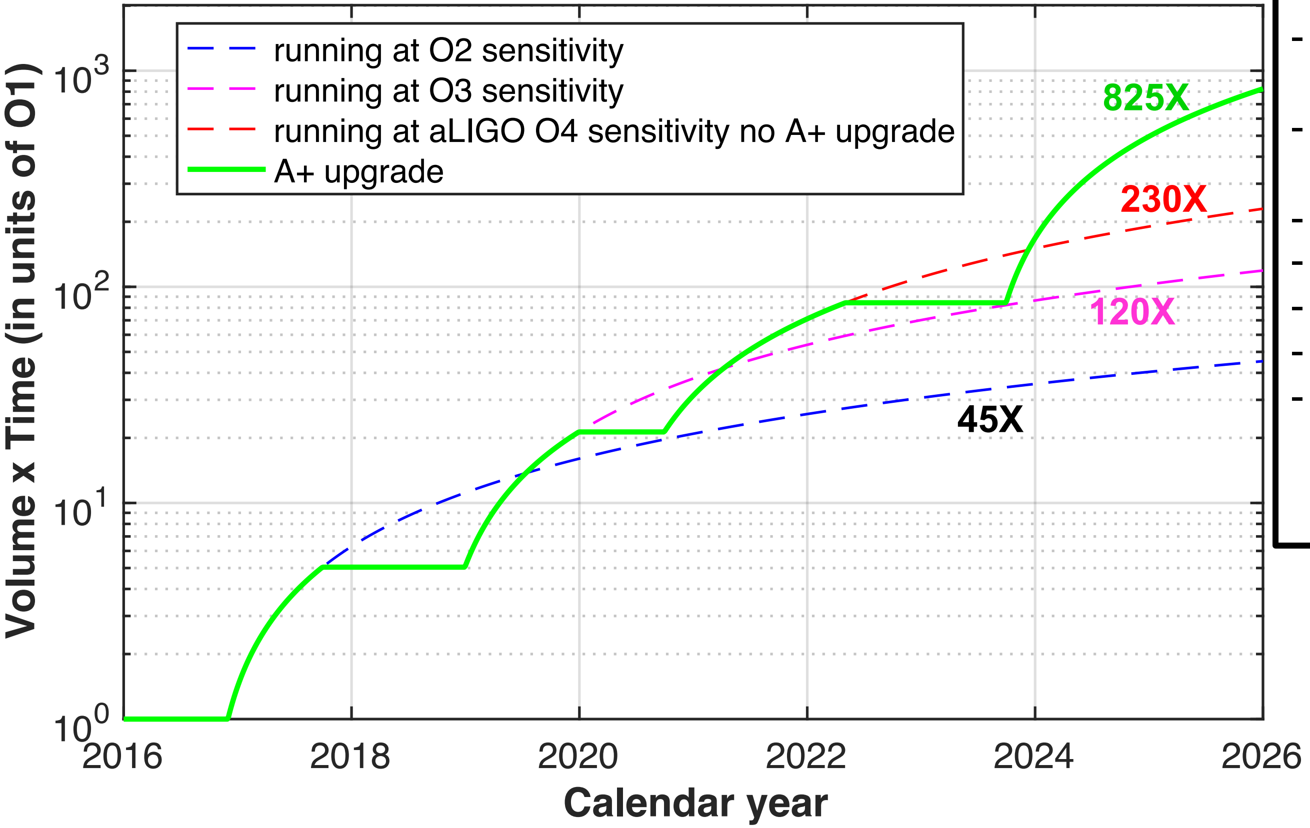
The Future of Ground-based Gravitational-wave Detectors

GW Science is Sensitivity Driven

1) **Rates:**

$$N_{events} = T_{observing} \int\int R(z)\, dz\, d\Omega$$

Binary Neutron Stars



2) *Many sources require higher SNR to uncover new astrophysics!!*

- **tidal disruption in BNS mergers**
- **tests of alternative theories of gravity**
- **Black hole ringdowns**
- **Stochastic background**
- **Isolated neutron stars**
- **Galactic supernova**
- **Surprises!**

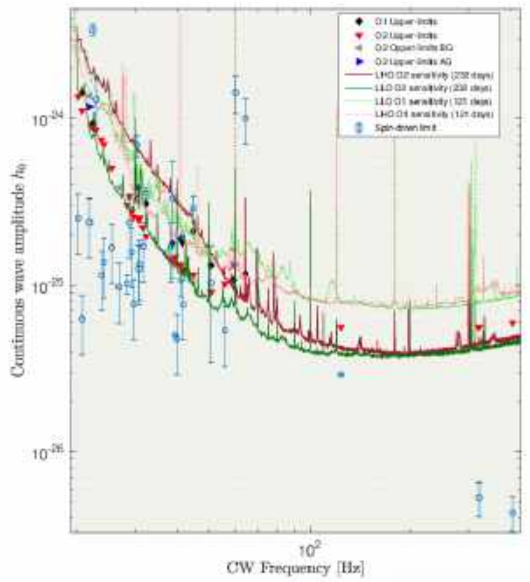
Signals still missing

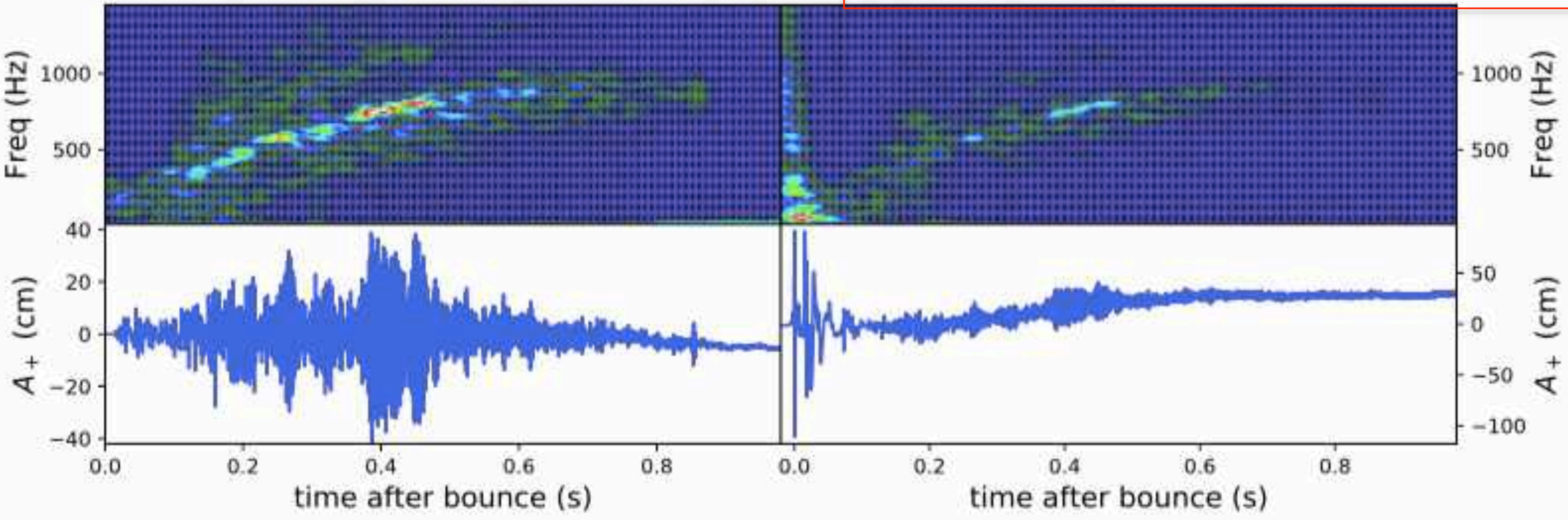
Supernovae explosions

GWs are created right at the central engine. the formation of a protomagnetar or a BH-torus system, or the fragmentation of the massive stellar core may be differentiated via GWs

It is believed that the origin of at least some long GRBs are the core collapses of massive stars. This could be confirmed if the GWs in coincidence with a long GRB progenitor were detected

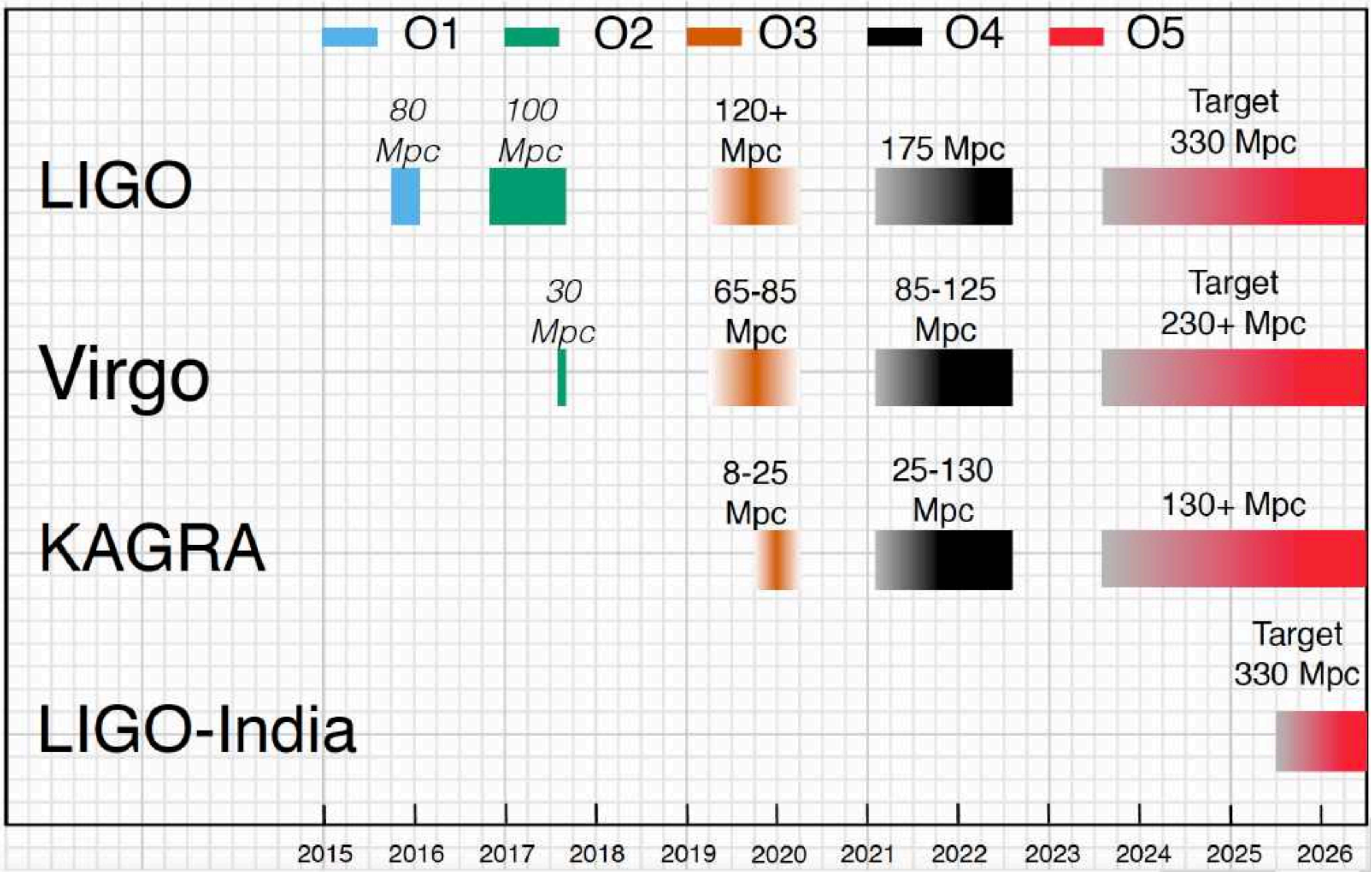
Continous GW
&
SGWB





Neutrino driven SNe explosion

Planned GW Observing Runs



Advanced Virgo: what next?

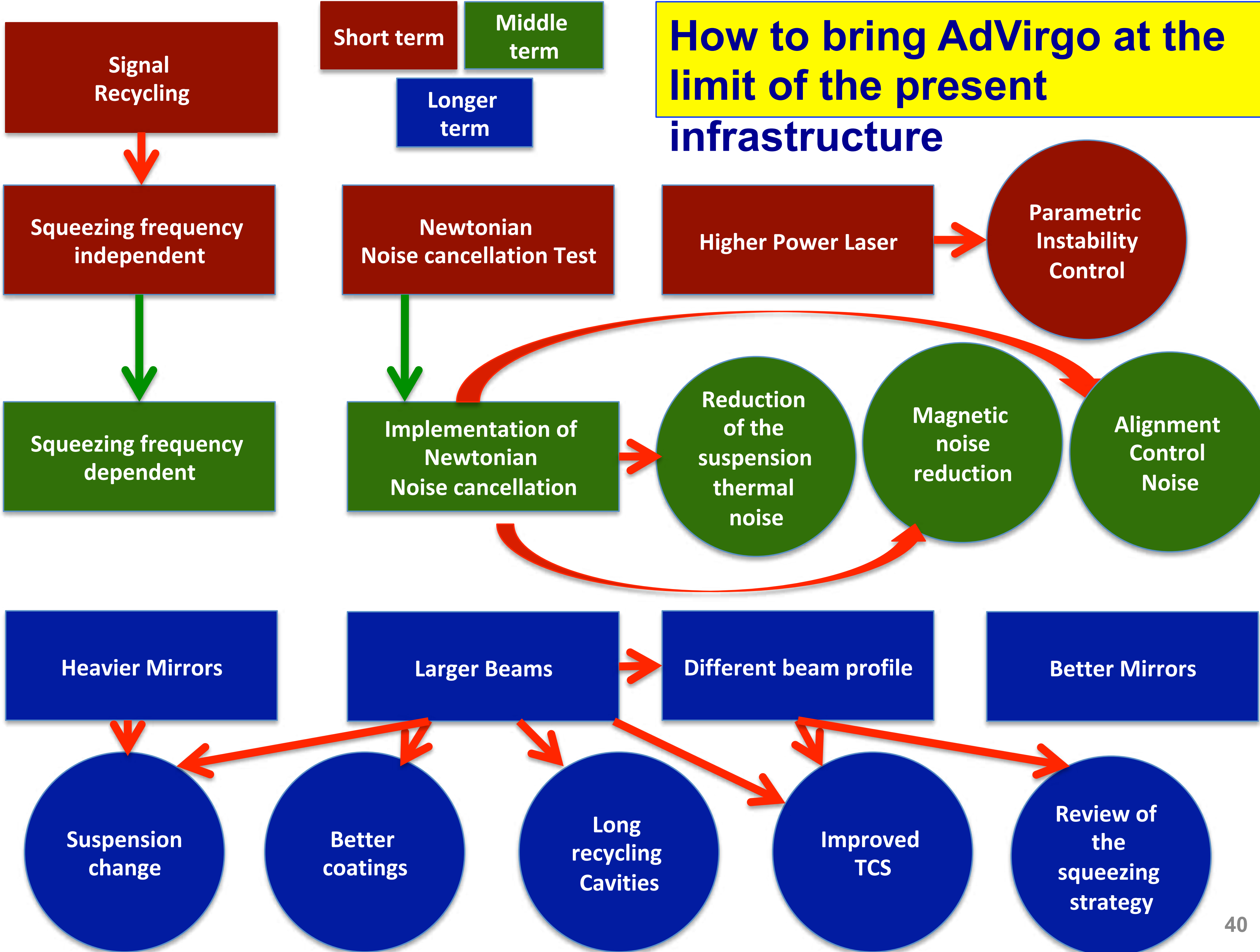
- Goal for the next decade: maximize the scientific output of AdV
  - Maximize data taking
  - Minimize downtime

- PHASE 1 (2017-2021):
  achieve the design sensitivity

- PHASE 2 (2021-2025):
  the best we can do in the current infrastructure

- PHASE 3 (>2025)
  rely on a new infrastructure

How to bring AdVirgo at the limit of the present infrastructure



Short term

Middle term

Longer term

Signal Recycling

Squeezing frequency independent

Squeezing frequency dependent

Newtonian Noise cancellation Test

Implementation of Newtonian Noise cancellation

Higher Power Laser

Parametric Instability Control

Reduction of the suspension thermal noise

Magnetic noise reduction

Alignment Control Noise

Heavier Mirrors

Larger Beams

Different beam profile

Better Mirrors

Suspension change

Better coatings

Long recycling Cavities

Improved TCS

Review of the squeezing strategy

Advanced Virgo+

- Phase I ➔ *budget secured and activity started even in theCOVID-19 epoch*
  - ✓ Signal recycling (not done in AdV yet)
  - ✓ Higher laser power (AdV run with 18 W so far)
  - ✓ Frequency dependent squeezing (frequency independent squeezing already done in AdV)
  - ✓ Newtonian noise cancellation

- Phase II
  - ✓ Further increase of laser power
  - ✓ Larger and heavier <u>end test masses</u> : beam radius~10 cm radius , m $\underline{\sim}$ 100 kg
  - ✓ Better coatings: lower mechanical losses, less point defects, better uniformity (gain will depend on coating R&D results at the end of Phase I)

POST O3 for aLIGO ➔ aLIGO+

- Modest-cost upgrade to Advanced LIGO
- Frequency-dependent squeezing
- Larger beam splitter
- Better mirror coatings / new test masses
- Balanced homodyne readout

Factor of 4 to 7 increase in observable volume

Funding from NSF and UKRI with support from Australia

Instrument Science White Paper LIGO T1600119-v4 public document

Motivations for New Detectors

- *Expand the exploration to the entire Universe*

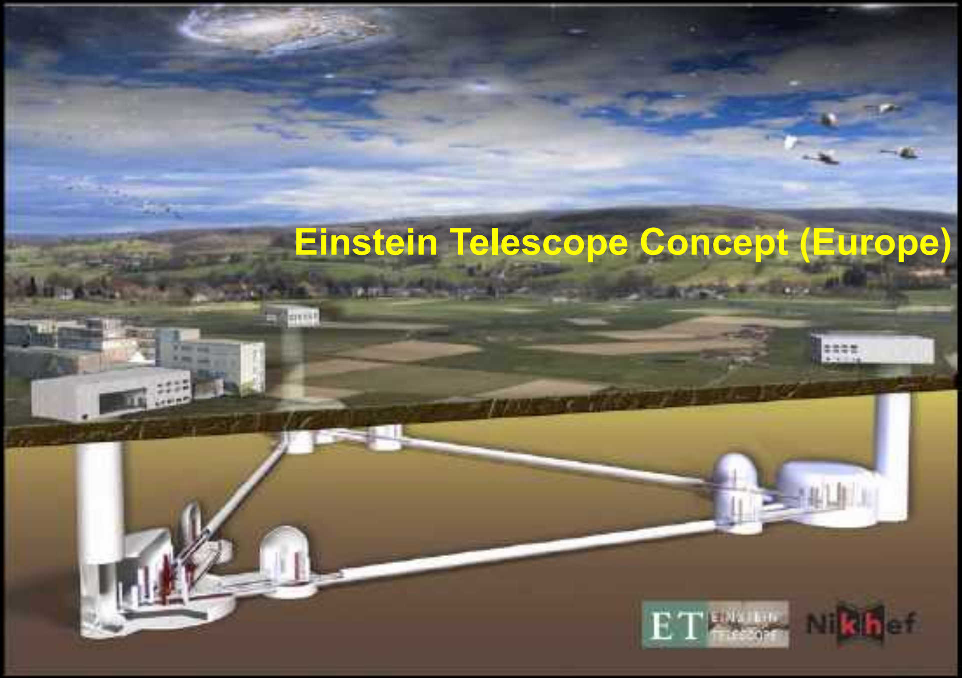
- Black holes through cosmic history
  - ✓ Formation, evolution and growth of black holes and their properties

- Understanding extremes of physics
  - ✓ Structure and dynamics of neutron stars
  - ✓ Physics of extreme gravity

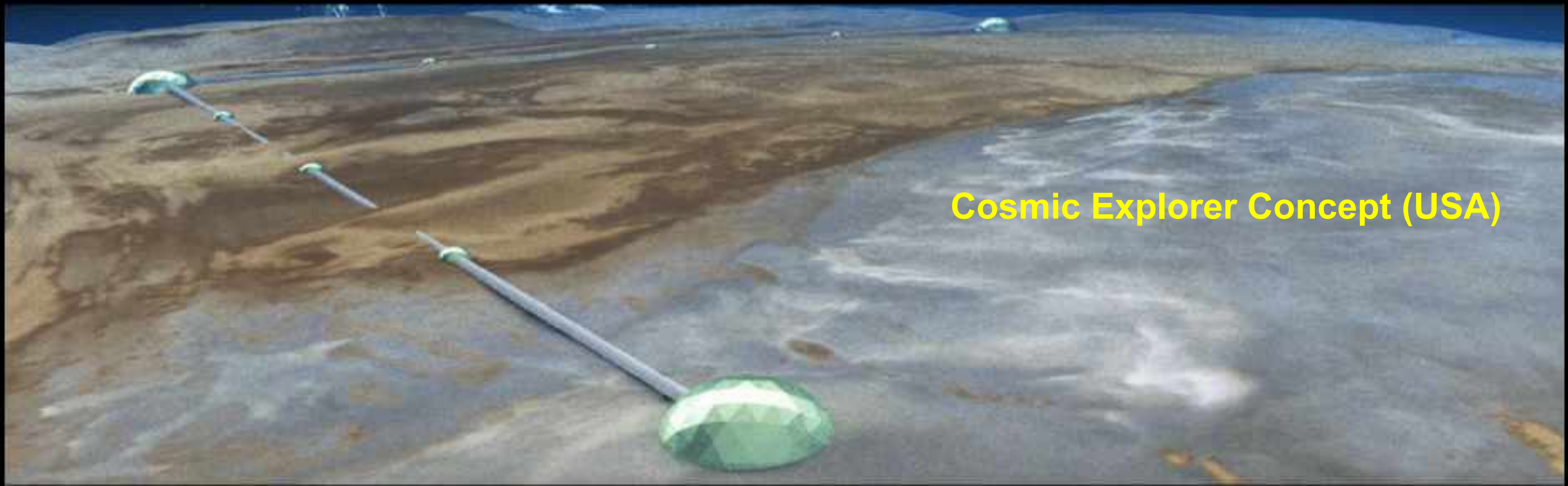
- Probing the transient Universe
  - ✓ Gamma ray bursts, gravitational collapse and Supernovae

- Beyond GR looking for new Physics: gravstars, wormholes, new particles and fields

‘Third Gen’ Ground-based Observatories: Einstein Telescope and Cosmic Explorer in the 2030s

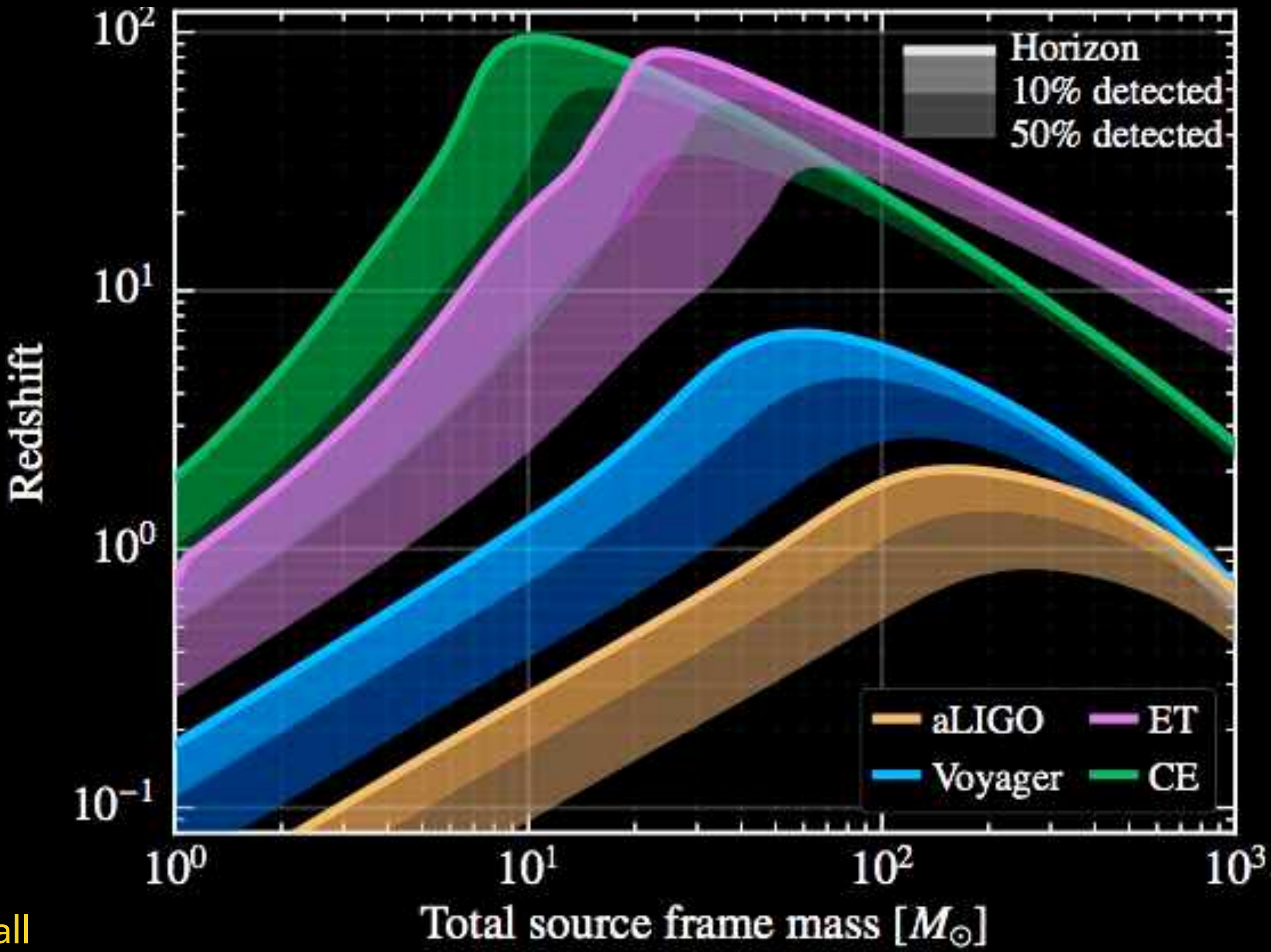


Einstein Telescope Concept (Europe)



Cosmic Explorer Concept (USA)

OBSERVING EARLIEST MOMENTS OF FORMATION OF STARS AND STRUCTURE



Evan Hall

Why a new infrastructure

- Increase the arm length to gain in sensitivity
- Implementation of new technological plants requiring more space (cryogenics system)
- Reduce the seismic impact of the sensitivity (Underground detector)
- Permit longer data taking runs of the 2G detectors by relaxing the needs to implement new technologies on 2G
- Prepare the transition from obsolete to new infrastructures

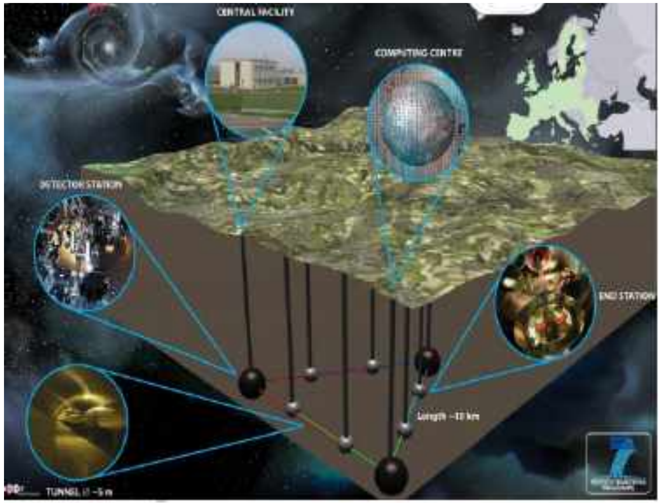
The target should be to realize a 3G-infrastructure in the next decay choosing sites that must have specific features that can enhance the planned investments.

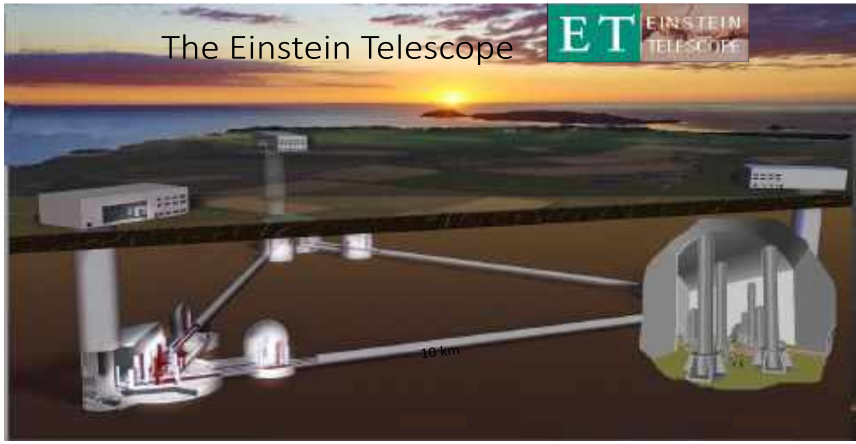
The 3rd GENERATION: site basic requirements

- lower seismic motion, meteorologically generated seismic noise, anthropogenic activity anthropogenic activity (local infrastructure, population density, etc.);

- lower Newtonian noise originates from fluctuations in the surround geologic and atmospheric density, causing a variation in the Newtonian gravitational field.

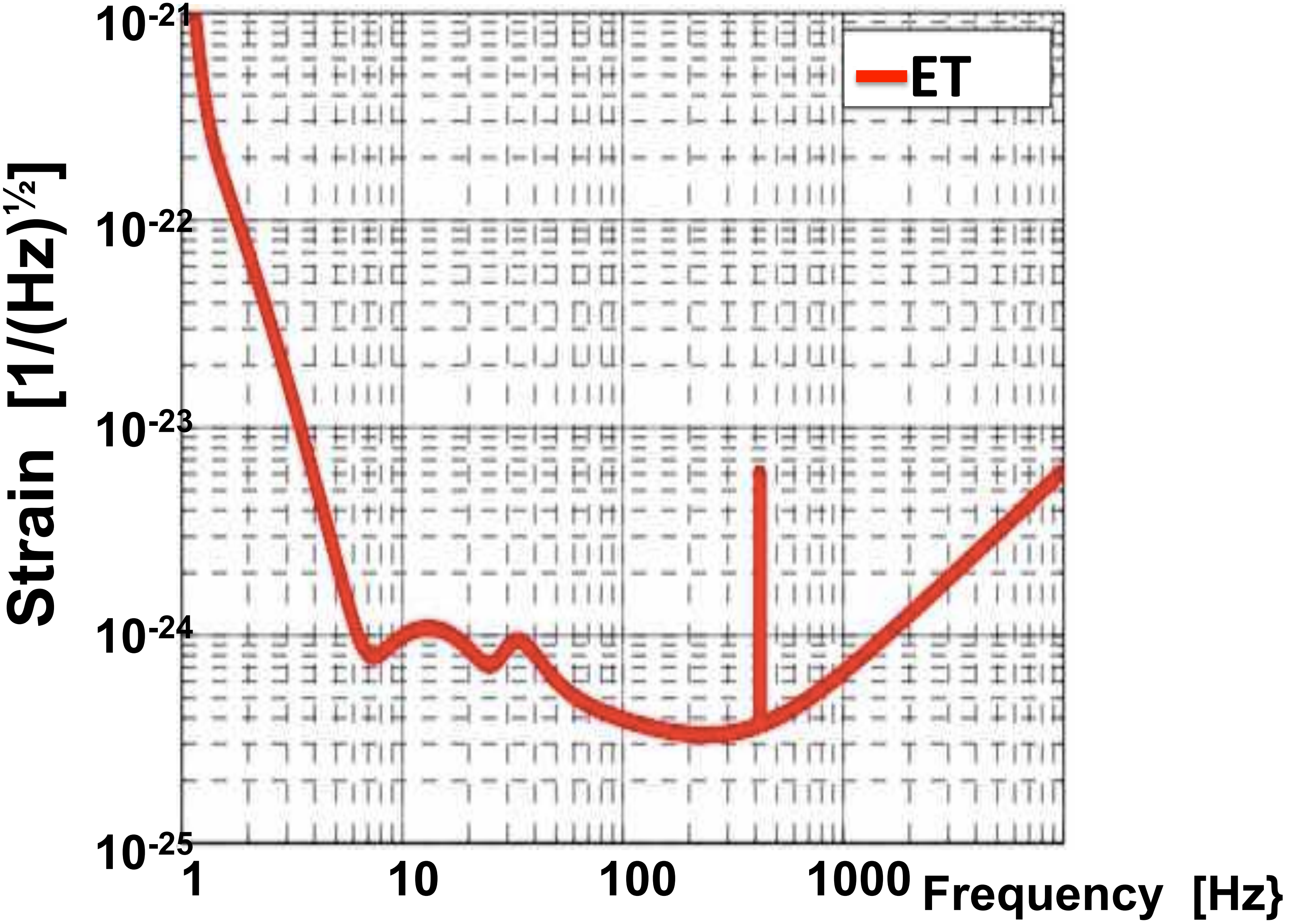
The Einstein Telescope (ET) case





The Einstein Telescope will be located underground at a depth of about 100 m to 200 m and, in the complete configuration, will consist of three nested detectors each in turn composed of two interferometers

ET Sensitivity Curve



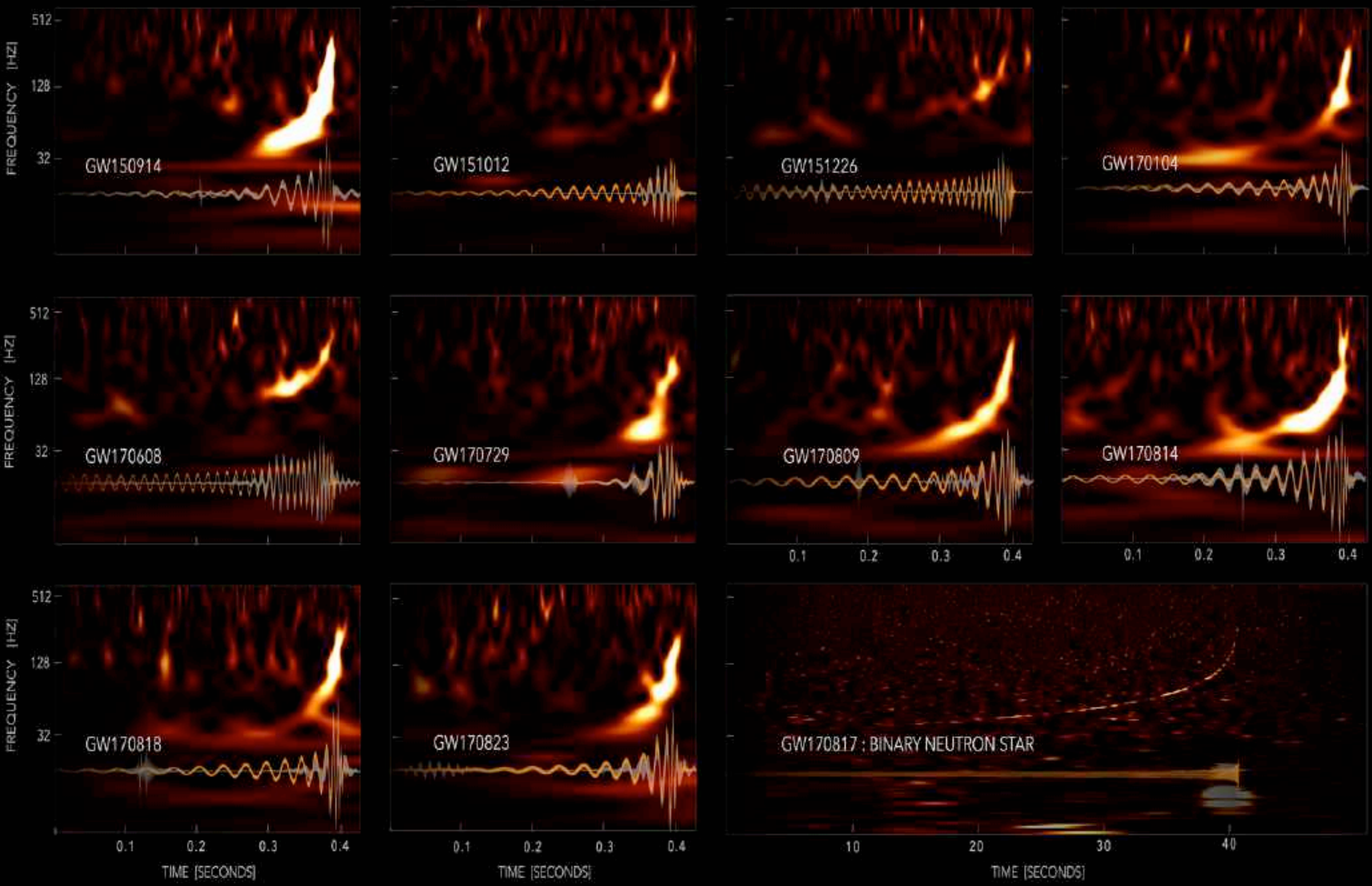
Conclusions

- Ground-based gravitational wave detectors are capable of measuring dynamical strains in space-time to a better then 10^{-22} rms in their most sensitive frequency bands.

- In the past three years, LIGO and Virgo have made detections of binary black hole mergers and one binary neutron star merger. These detections have:
  - Opened a new window on the universe
  - Have begun to answer many fundamental questions on the nature of gravity, black holes, neutron stars, the expansion of the universe

- Future ground-based gravitational-wave detectors will be able to see
  - Serious planning efforts have begun for a new generation of GW observatories to being operations in the 2030s

GRAVITATIONAL-WAVE TRANSIENT CATALOG-1



LIGO-VIRGO DATA: HTTPS://DOI.ORG/10.7935/82H3-HH23

▨ WAVELET (UNMODELED)

▨ EINSTEIN'S THEORY

S. GHONGE, K. JANI | GEORGIA TECH