Les ondes gravitationnelles: principes de détection, résultats marquants et futurs projets

Journée SFP, Division Champs et Particules

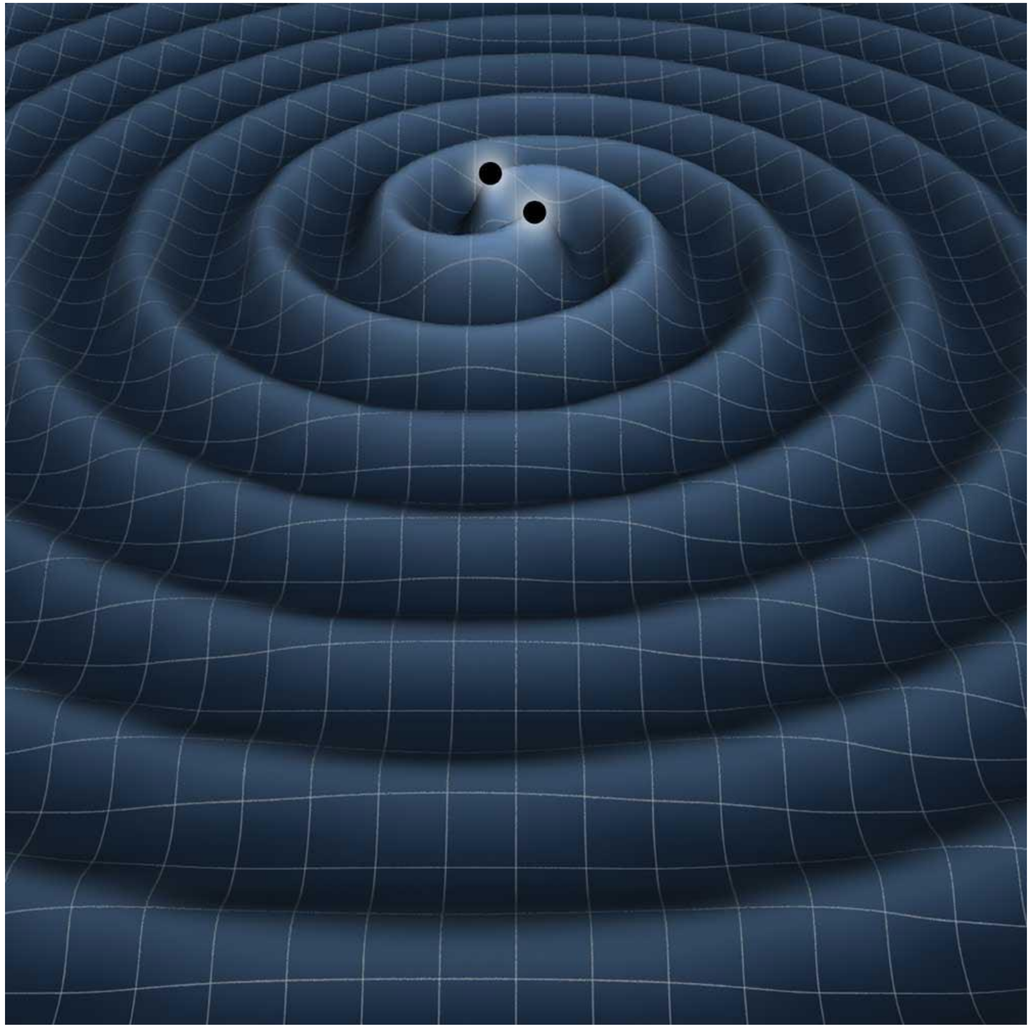
Edwige Tournefier

March 20th, 2025

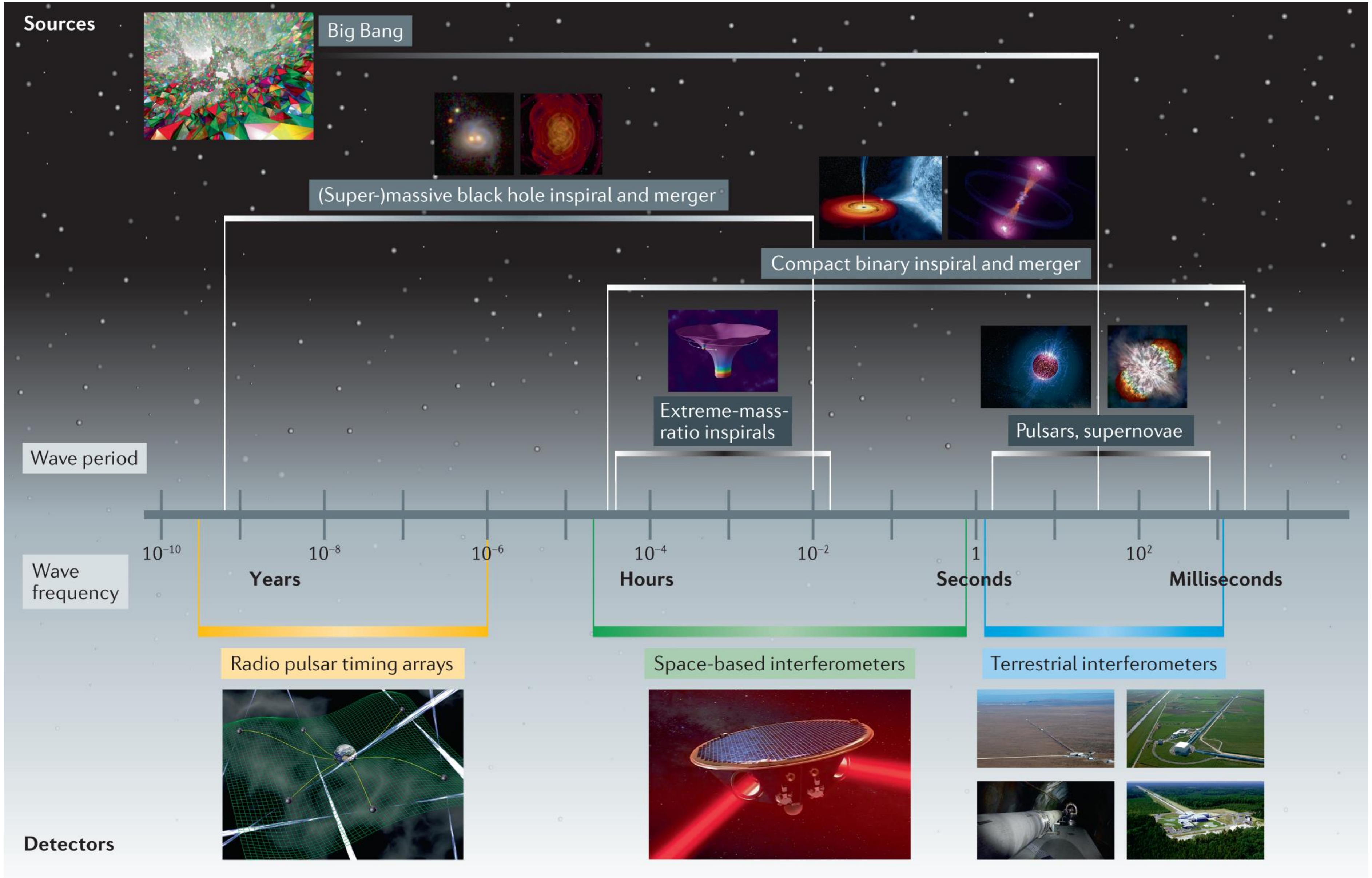
- GW = space time deformation predicted by General relativity

- GW produced by:
  - Binaries coalescence
  - Supernovae
  - Rotating neutron stars (pulsars)
  - Early universe

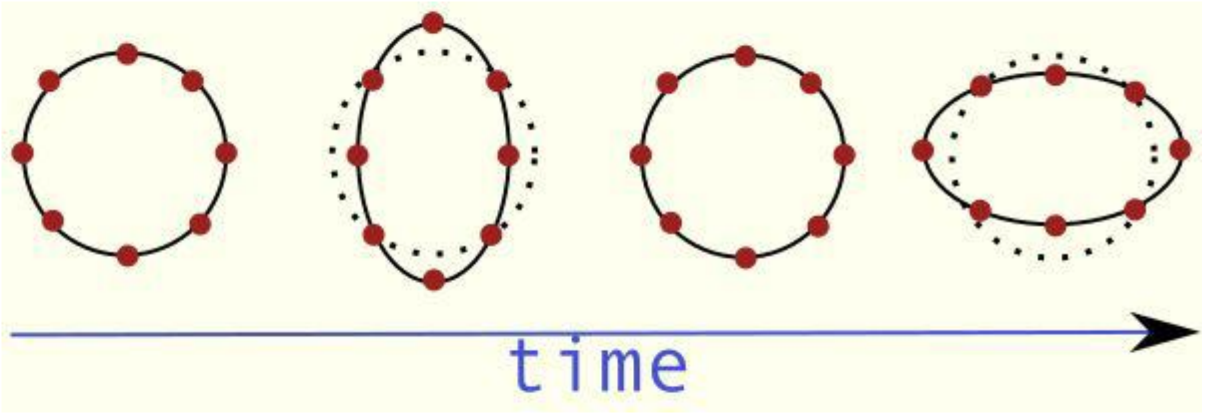
- Science:
  - Test of General relativity in several regimes
  - Cosmology
  - Equation of state of ultra dense matter (neutron stars)
  - Compact star population studies (formation and evolution)
  - Formation and evolution of galaxies
  - Dark matter

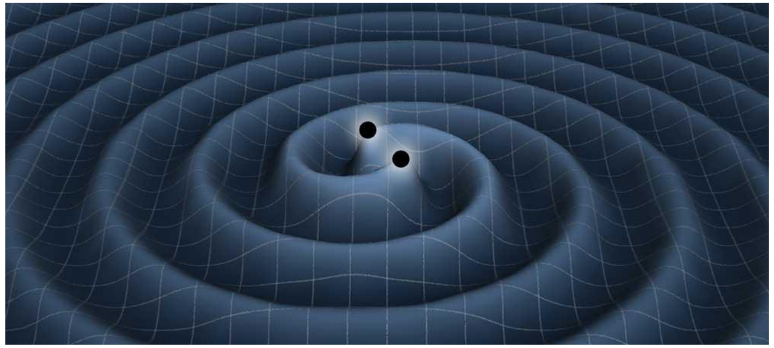


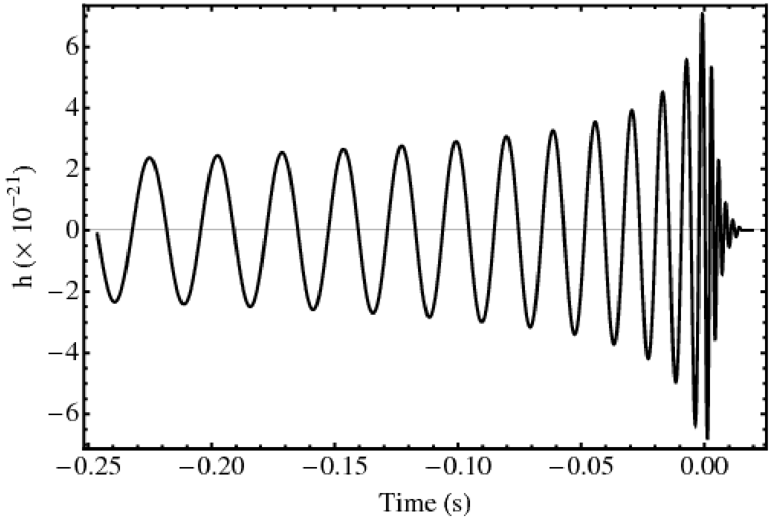
Gravitationnal waves: sources and detectors



- Effect of GW on free falling masses





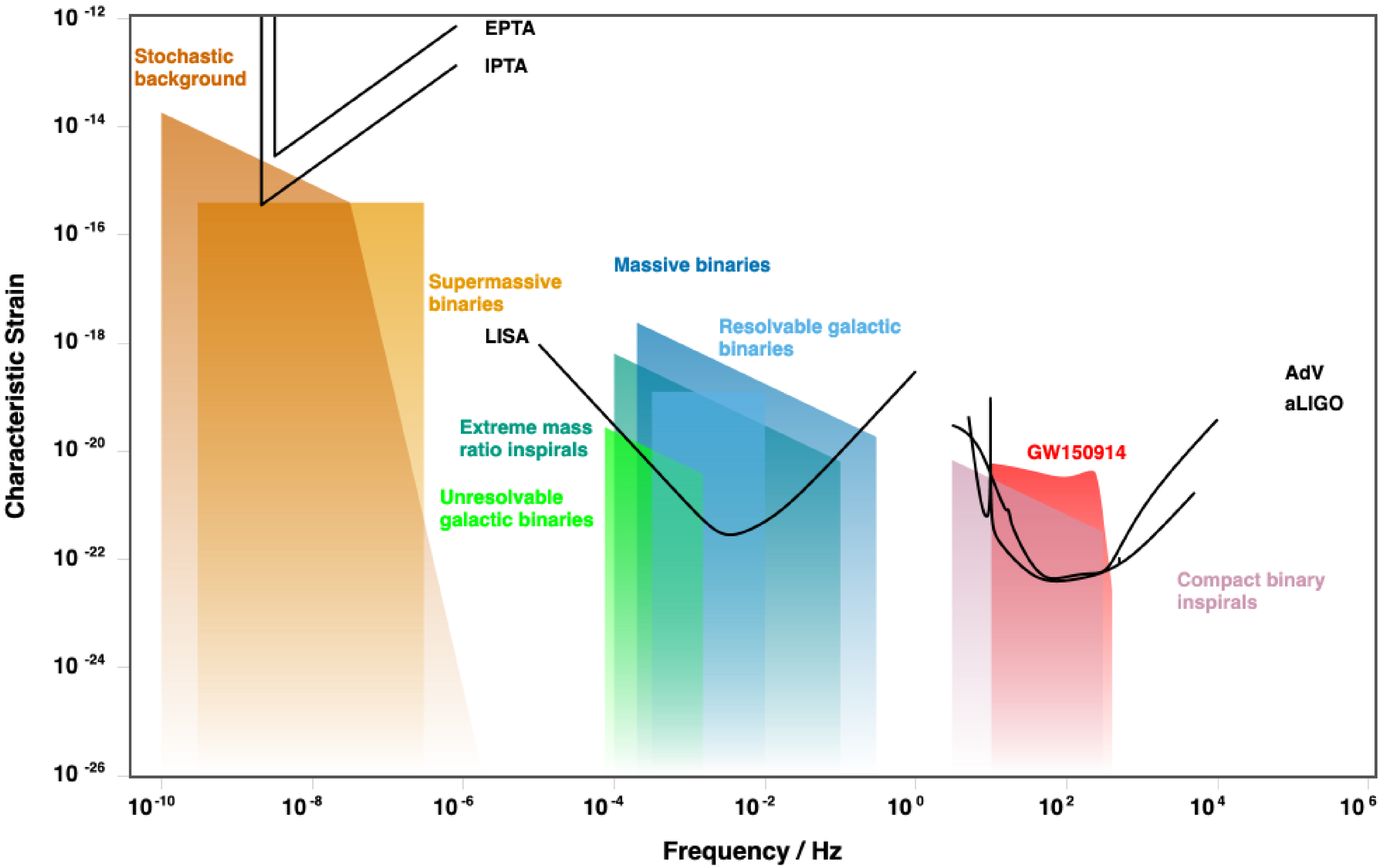


- GW amplitude: $h = \Delta L/L$

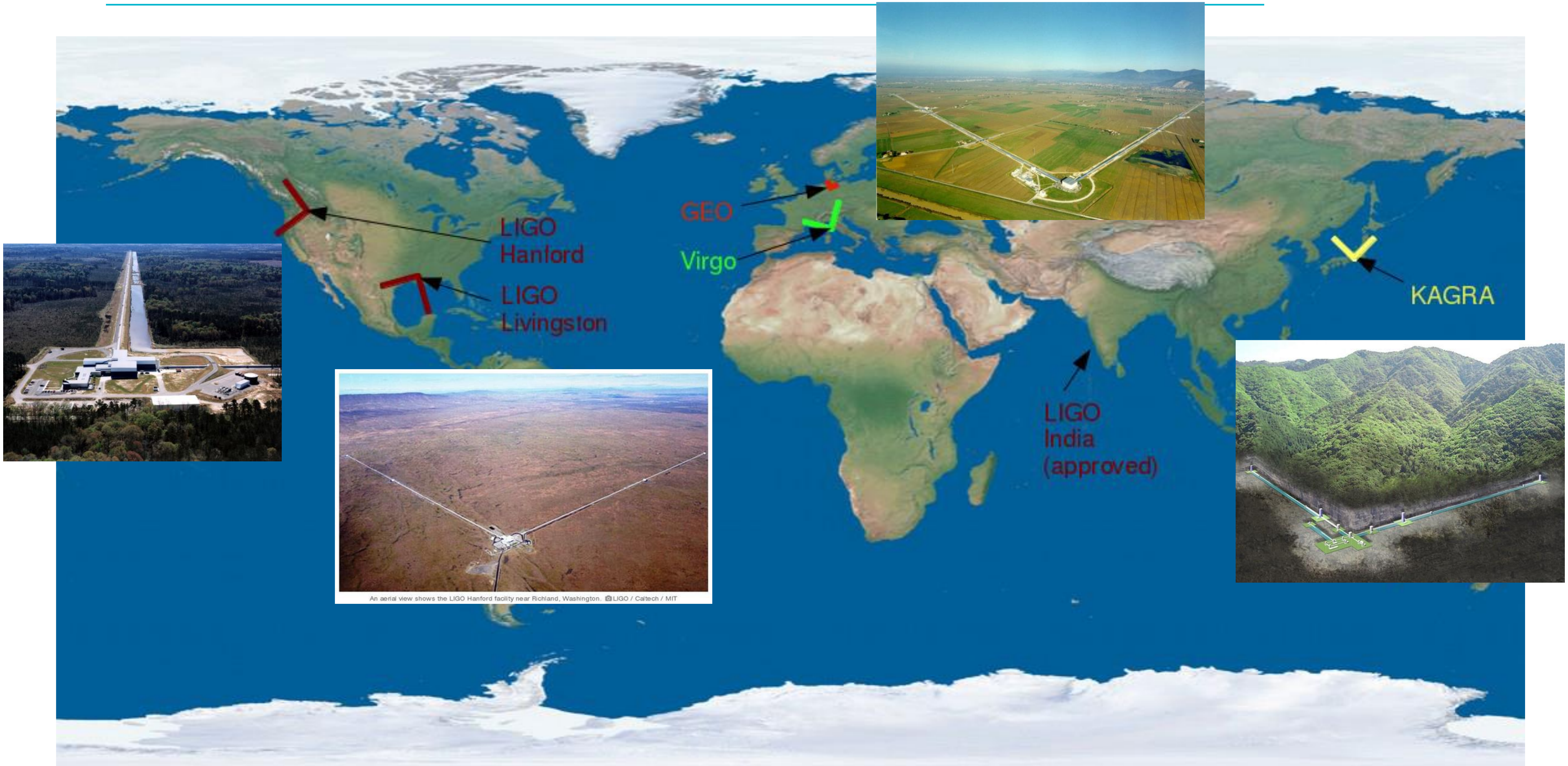
- Detection principle: measure relative length variation with time

- Typical amplitudes: $h = O(10^{-22})$

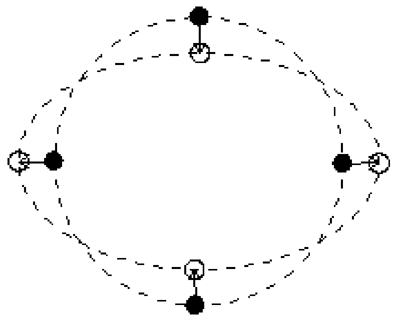
Detectors sensitivities and source amplitudes



Ground based interferometers: LIGO-Virgo-KAGRA network



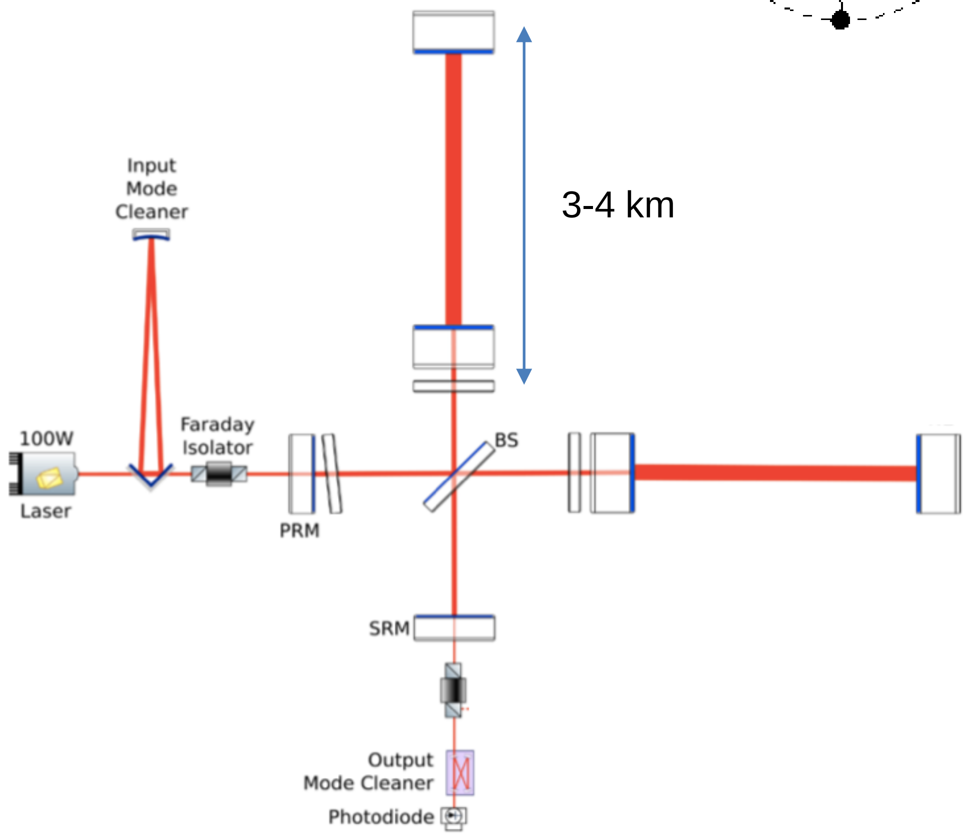
- Detection principle:
  - Michelson interferometer on dark fringe



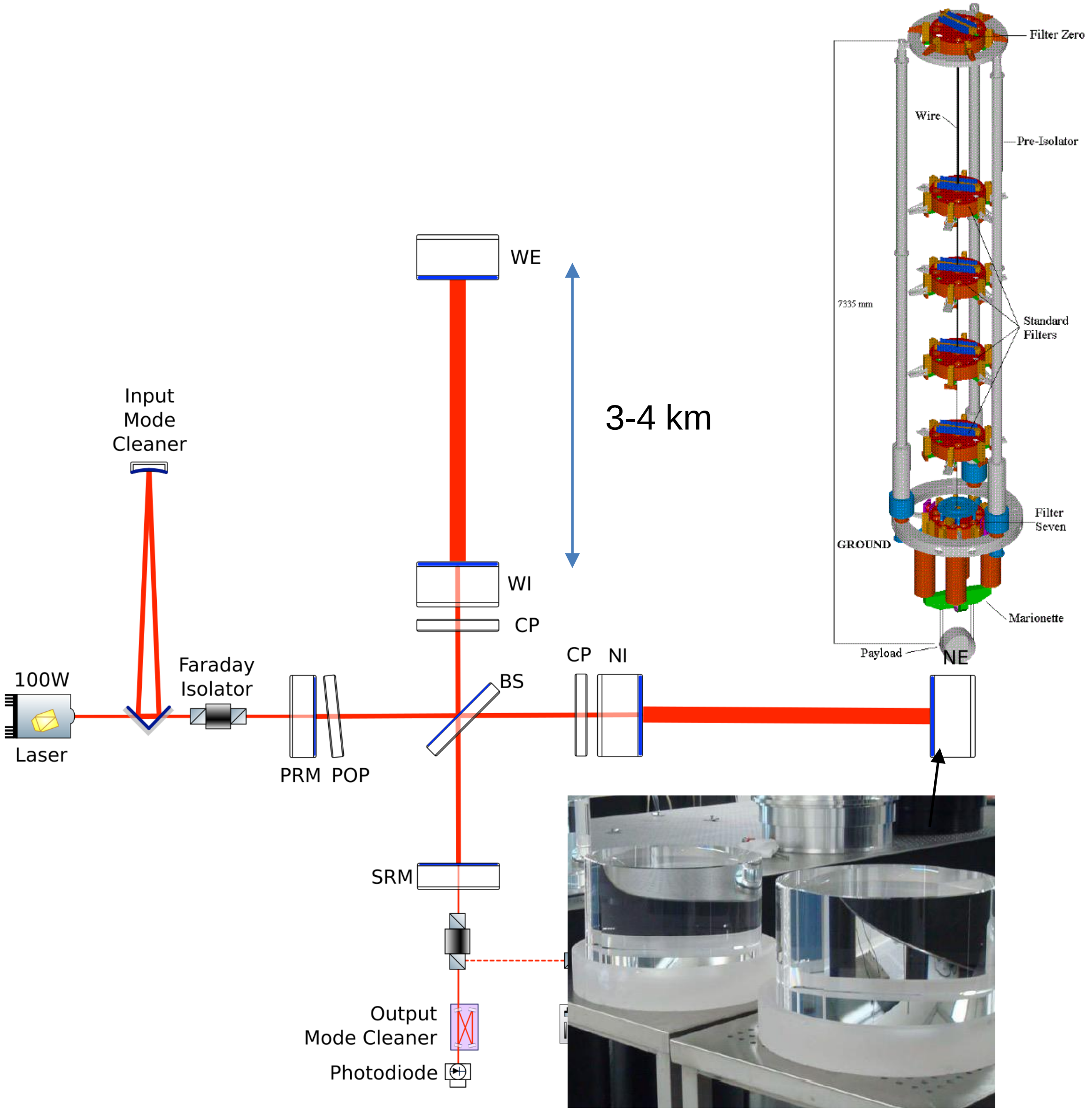
sensitivity: $\Rightarrow \tilde{h}_{\min} = \frac{\lambda}{4\pi}\frac{1}{L}\sqrt{\frac{h\nu}{2P_0}} \;/\sqrt{Hz}$

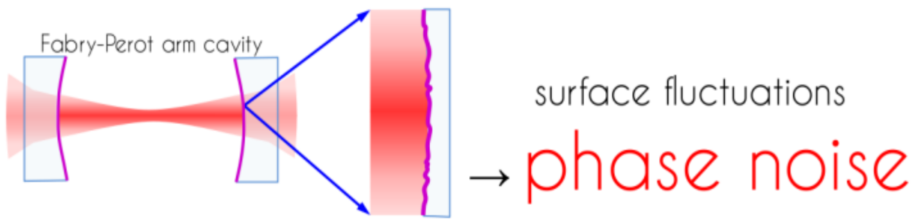
Sensitivity increased with:

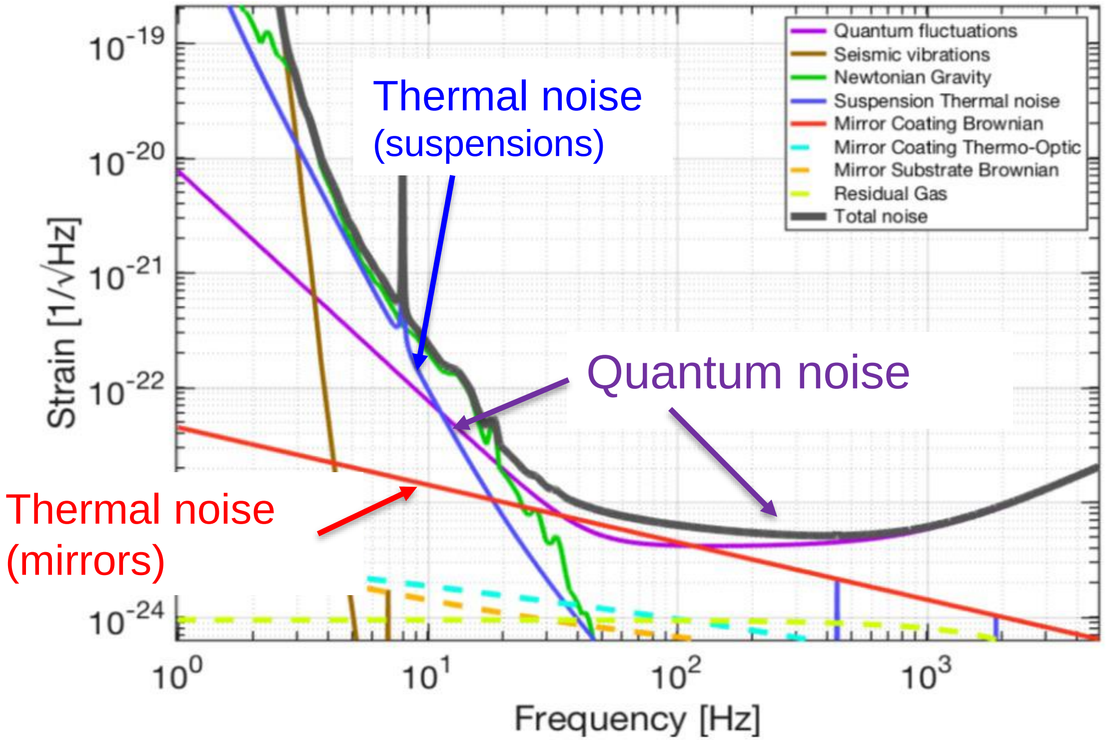
- Fabry-Perot cavities (increase effective L)
- Power recycling (increase effective P)
- Signal recycling



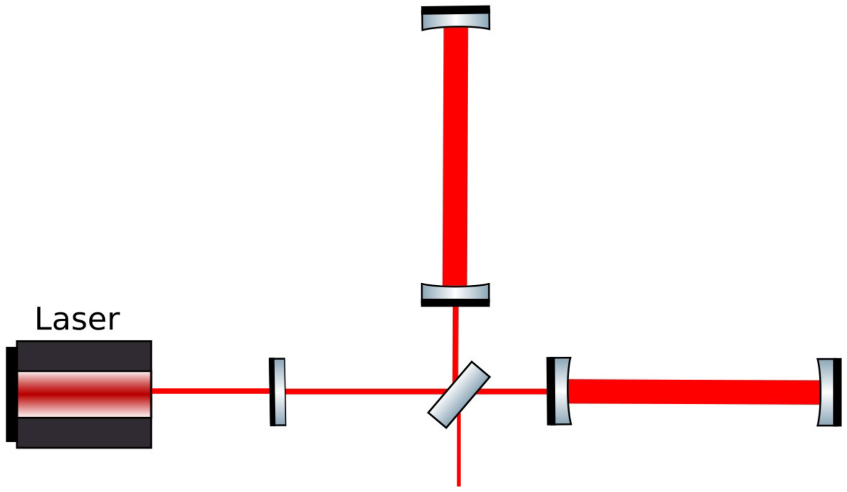
Fondamental noises

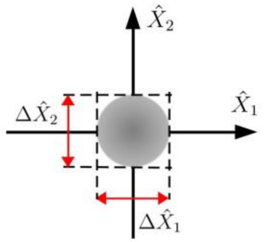




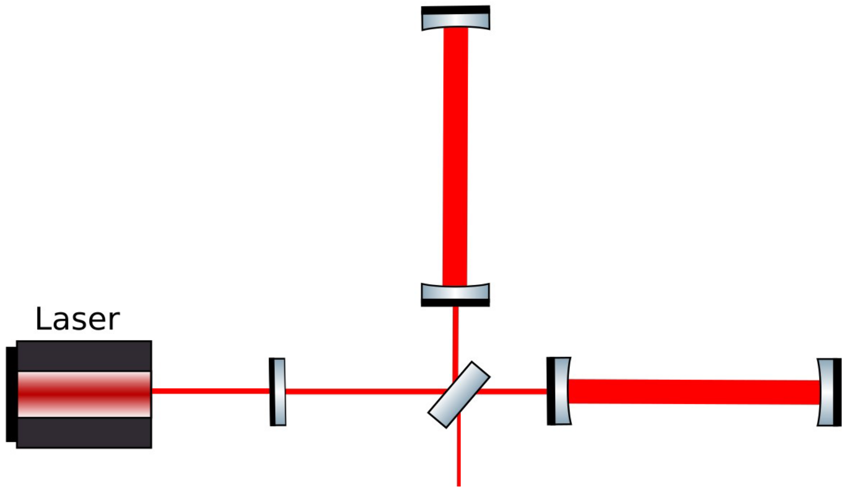


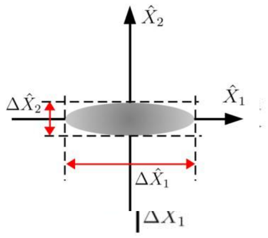
- Reduction of quantum noise:
  - Increased laser power
  - Quantum squeezing technique





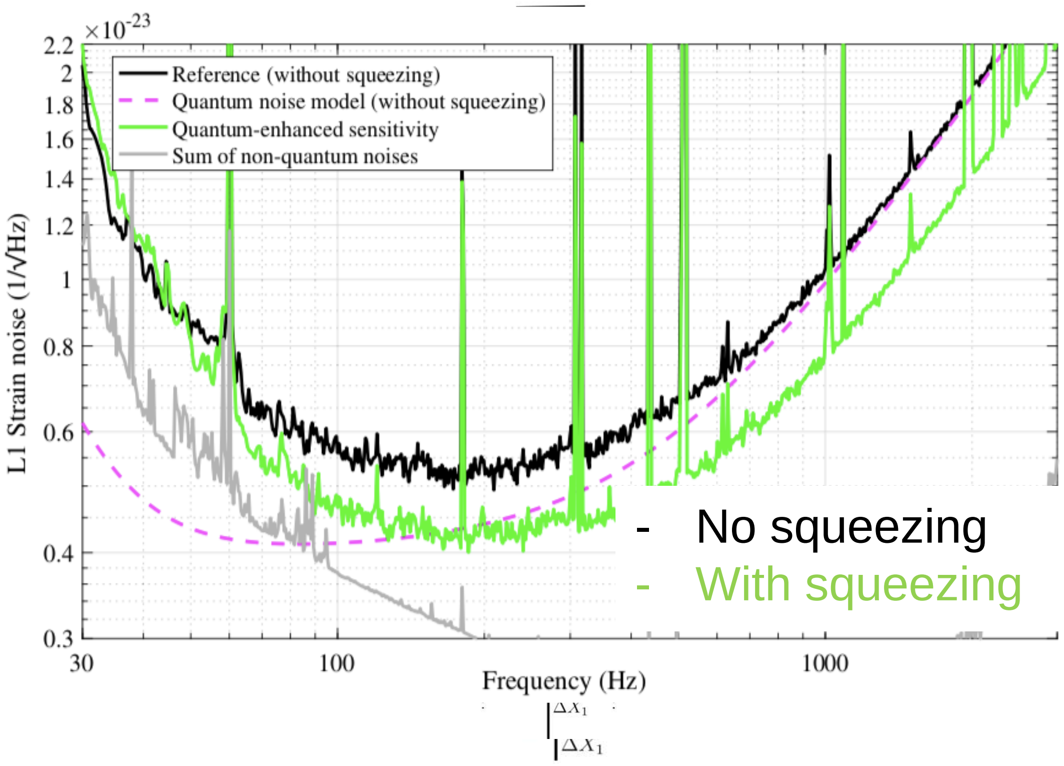
- Reduction of quantum noise:
  - Increased laser power
  - Quantum squeezing technique

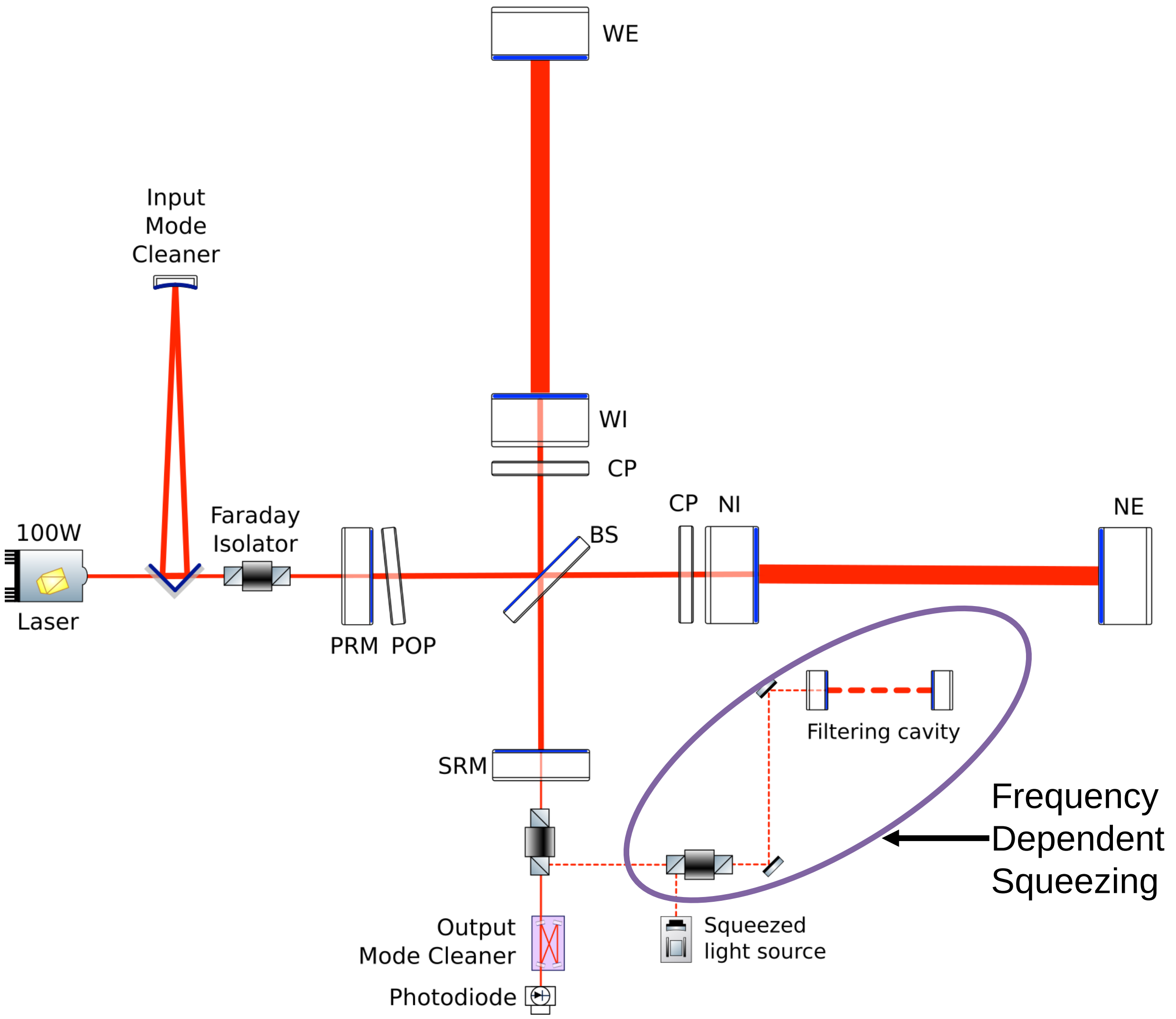




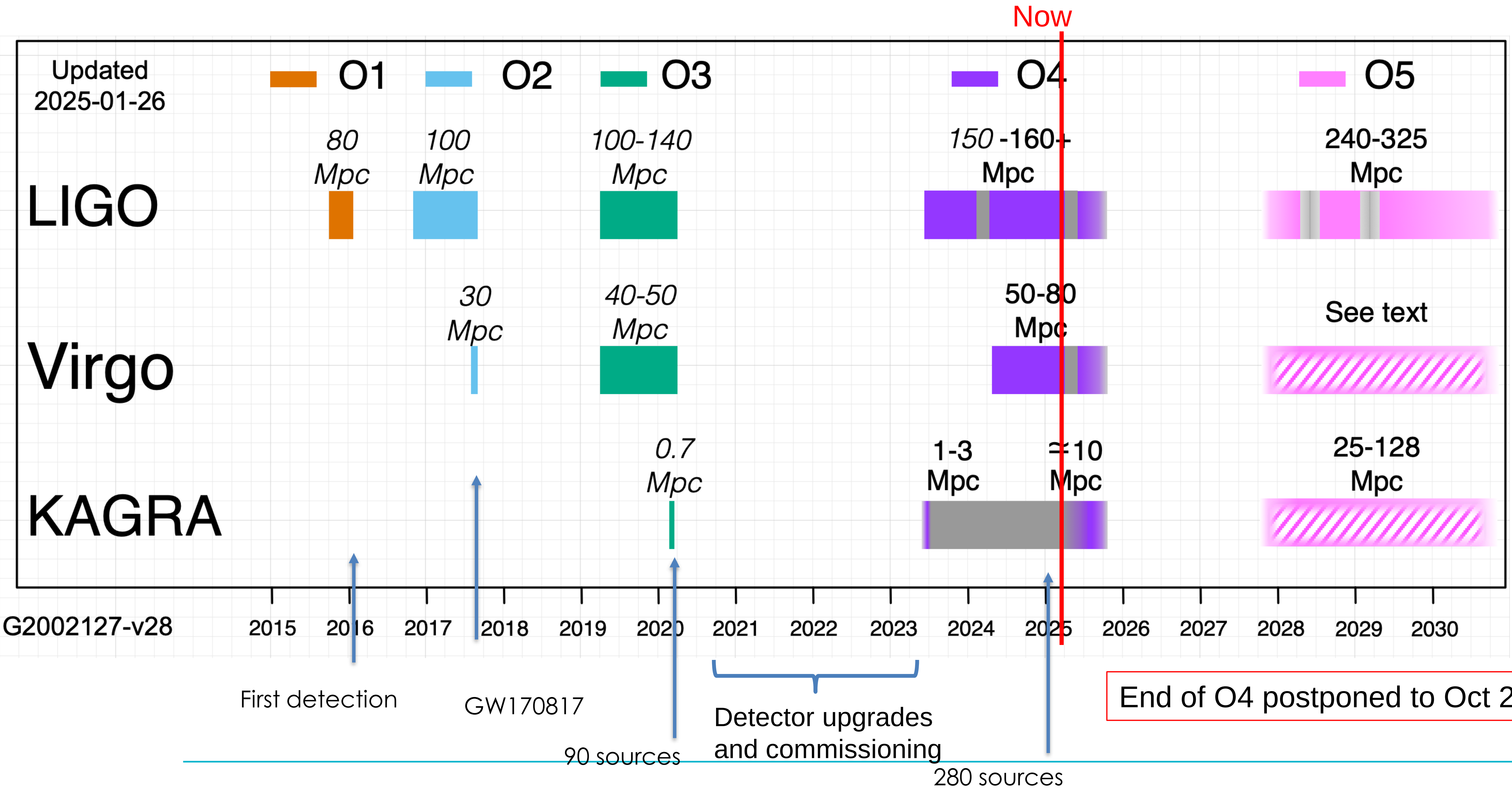
Fondamental noises: quantum noise reduction

- Reduction of quantum noise:
  - Increased laser power
  - Quantum squeezing technique



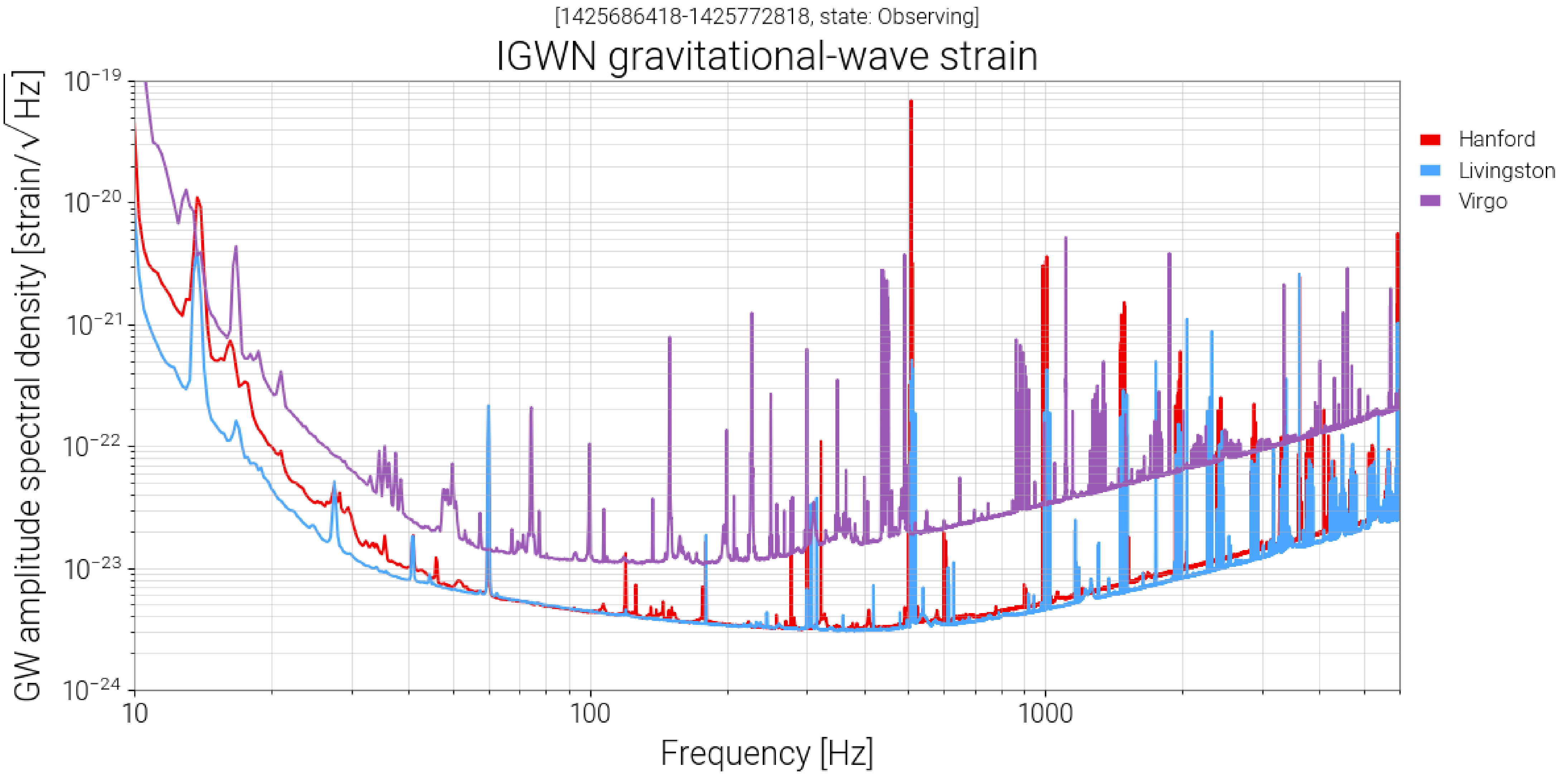


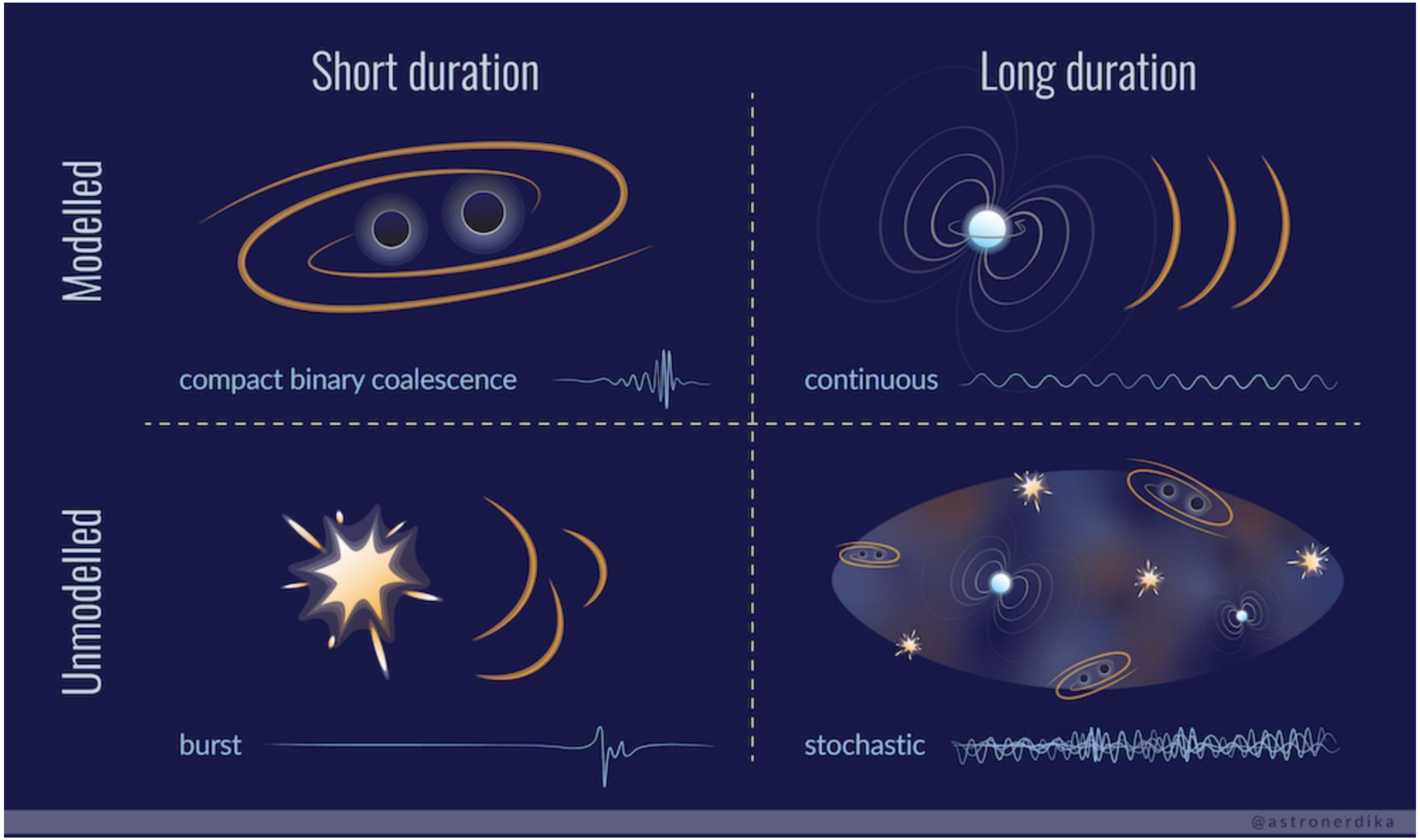
LIGO Virgo KAGRA (LVK) network timeline



End of O4 postponed to Oct 2025

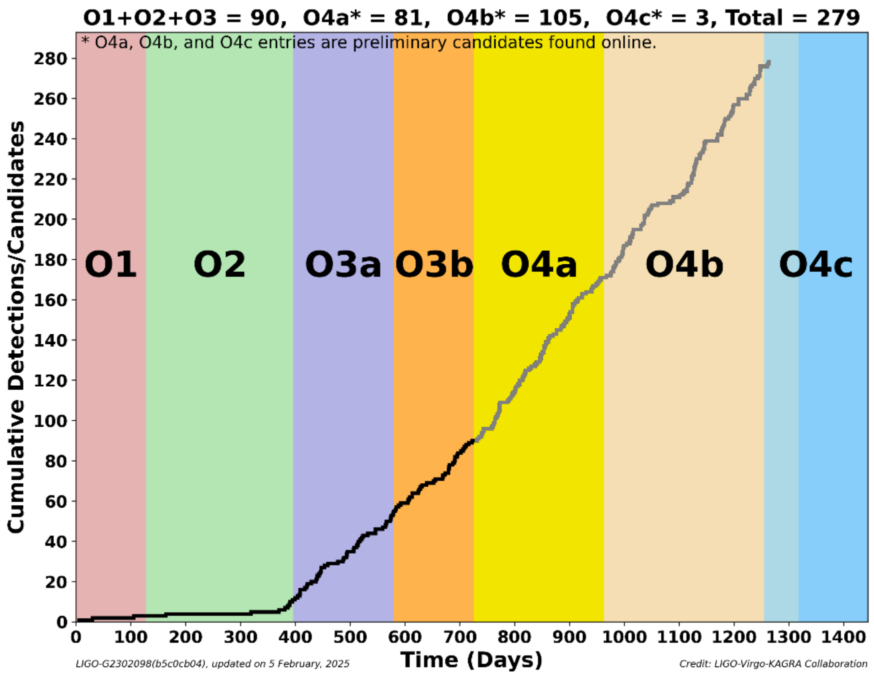
O4 detectors sensitivity

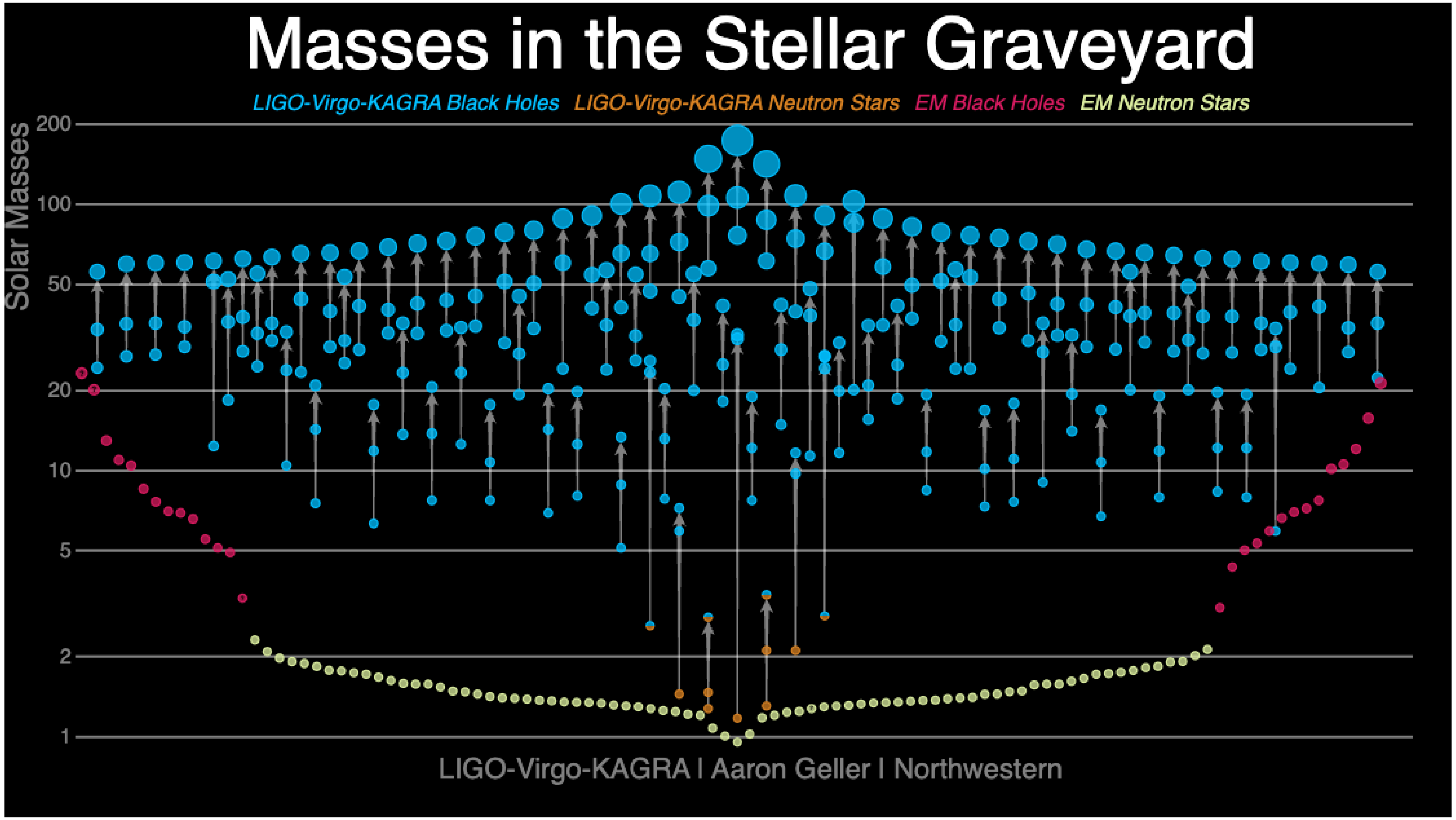



Short duration
Long duration
Modelled
Unmodelled
compact binary coalescence
continuous
burst
stochastic
@astronerdika

- Detection of binary coalescences by LVK
  - 2 NS-NS
  - 4 NS-BH
  - 273 BH-BH

NS = neutron stars
BH = black holes





End of O4c: Oct 2025

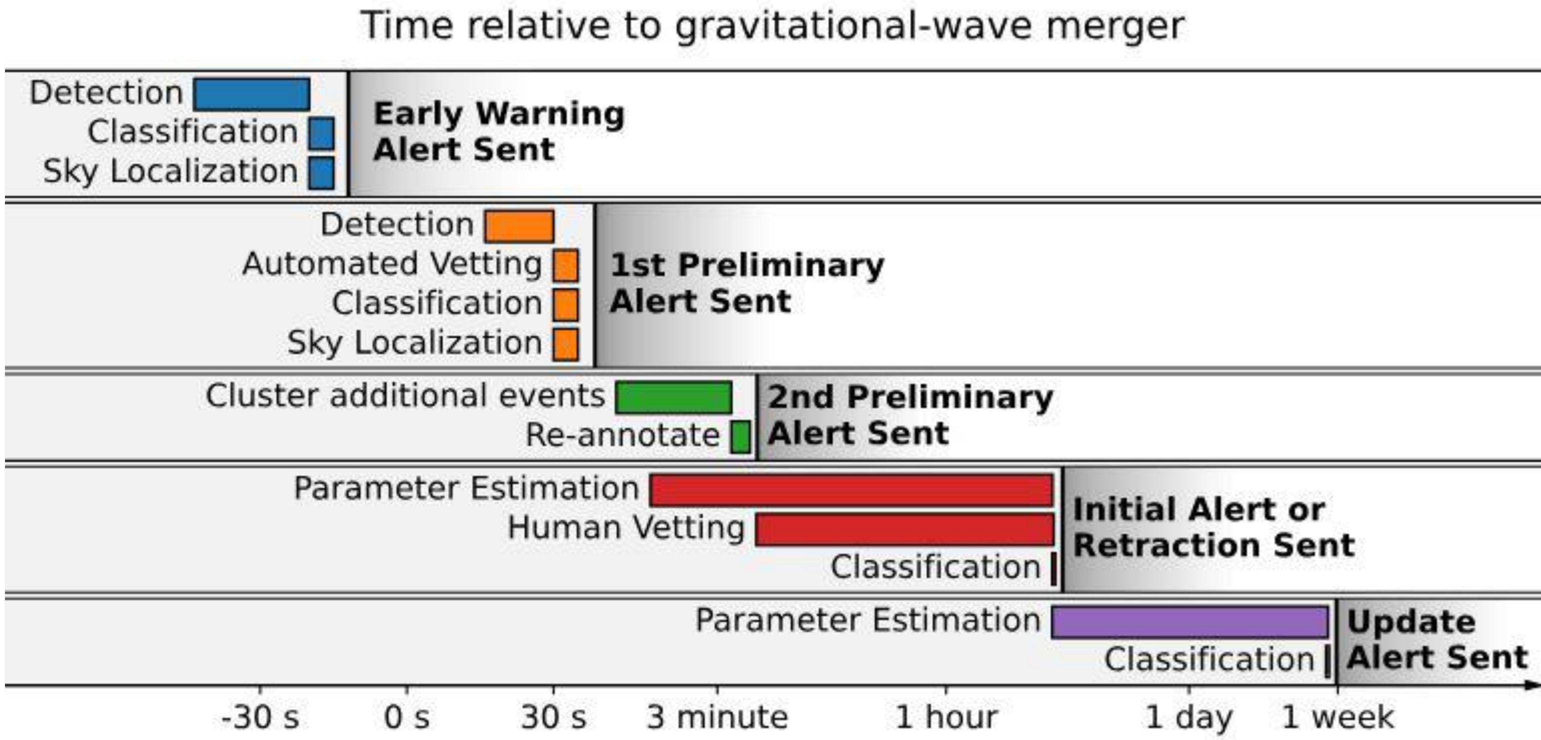
Multi-messenger: low latency analysis and public alerts

Optimize detection of multi-messenger events by

- Analyzing GW data in real time
- Sending alerts to enable follow-up

Alerts content:

- Sky localization
- Classification



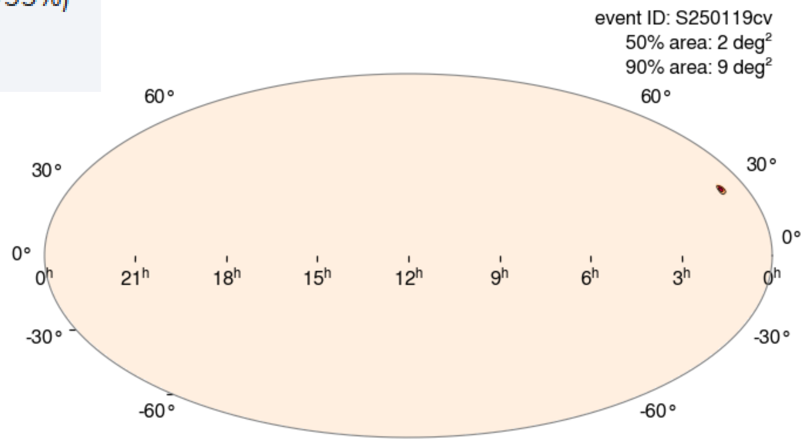
O1-O2: alerts sent to identified partners

O3: open public alerts

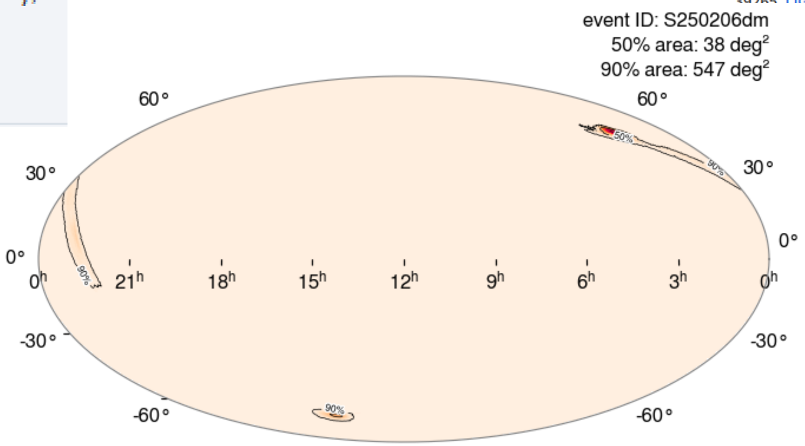
O4: reduced latency, include “early-warning” candidates, distributed via SCiMMA and GCN

Public alert examples

S250119cv BBH (>99%)



S250206dm NSBH (55%), BNS (37%), Terrestrial (8%)



GCN Circulars

GCN Circulars are rapid astronomical bulletins submitted by and distributed to community members worldwide. They are used to share discoveries, observations, quantitative near-term predictions, requests for follow-up observations, or future observing plans related to high-energy, multi-messenger, and variable or transient astrophysical events. See the documentation for help with subscribing to or submitting Circulars.

S250206dm | New | Filter by date | Sort by Date

Search for Circulars by submitter, subject, or body text (e.g. 'Fermi GRB').
To navigate to a specific circular, enter the associated Circular ID (e.g. 'gcn123', 'Circular 123', or '123').

61 results found.

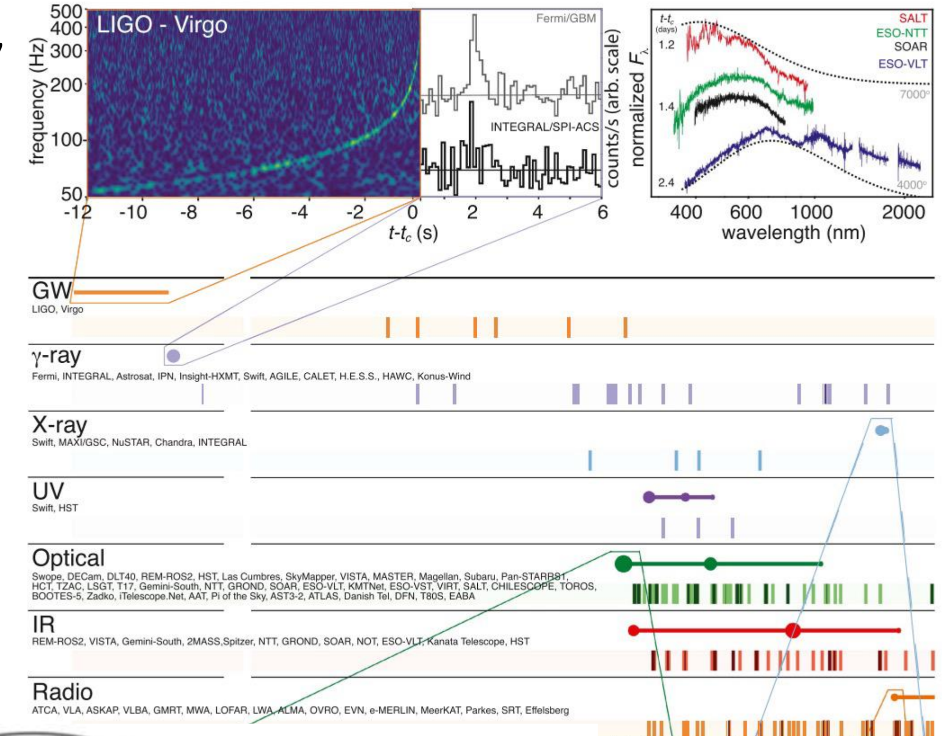
39715. LIGO/Virgo/KAGRA S250206dm & FRB 20250206A: Nondetection of Repeating Bursts from FRB 20250206A with FAST
39545. LIGO/Virgo/KAGRA S250206dm: early X-ray upper limits from Einstein Probe WXT and preliminary results of FXT observations
39510. LIGO/Virgo/KAGRA S250206dm: Upper limits from SVOM/GRM Observations
39428. LIGO/Virgo/KAGRA S250206dm: Upper limits from IceCube neutrino searches
39378. LIGO/Virgo/KAGRA S250206dm: Upper limits from MSU cubesats observations
39361. LIGO/Virgo/KAGRA S250206dm: AZT-33IK Target Optical Observations
39355. LIGO/Virgo/KAGRA S250206dm: observation in AbAO, optical transient near NED/GLADE+ galaxy WISEA J021210.14+514821.7
39338. LIGO/Virgo/KAGRA S250206dm: MASTER LC AT2025bbo
39318. LIGO/Virgo/KAGRA S250206dm: DECam GW-MMADS candidates
39311. LIGO/Virgo/KAGRA S250206dm: FTW observations of counterpart candidates AT2025bbo and AT2025bcx, and of NED galaxies
39303. LIGO/Virgo/KAGRA S250206dm: NEWFIRM NIR Follow-up of AT2025ber
39297. LIGO/Virgo/KAGRA S250206dm: GECKO Continued Observaiton with 7DT
39293. LIGO/Virgo/KAGRA S250206dm: AT 2025bbo observations with WFST
39286. LIGO/Virgo/KAGRA S250206dm: continued in SOAR galaxy targeted observations and identification of one possible transient
39285. LIGO/Virgo/KAGRA S250206dm: Kinder confirmation of a possible artefact in AT 2025bbo
39273. LIGO/VIRGO/KAGRA S250206dm: AT 2025bbo spectroscopic observations with NIRES on Keck II
39272. LIGO/Virgo/KAGRA S250206dm: Gemini-North spectroscopic observation of AT2025bbo and its host galaxy
39265. LIGO/Virgo/KAGRA S250206dm: MASTER detection AT2025bbo
rgo/KAGRA S250206dm: Upper limits from GECAM Observations
rgo/KAGRA S250206dm: Global MASTER-Net observations report
rgo/KAGRA S250206dm: COLIBRÍ/DDRAGO Observations of AT2025bbo and Galaxies in the Localization Volume
rgo/KAGRA S250206dm: Observations from WINTER
rgo/KAGRA S250206dm & FRB 20250206A: MASTER observations and possible mother galaxy
rgo/KAGRA S250206dm: Optical observations of candidate AT 2025bbo with Kinder
rgo/KAGRA S250206dm: WFST follow-up observations
rgo/KAGRA S250206dm: FRB 20250206A BOOTES-5 and 2.2m CAHA optical upper limits
rgo/KAGRA S250206dm: further Pan-STARRS observations and one candidate AT2025bbo
rgo/KAGRA S250206dm: GECKO Observation with 7DT and KMTNet
rgo/KAGRA S250206dm: (Update-7) NED Galaxies in the Localization Volume
rgo/KAGRA S250206dm: NEWFIRM NIR Observations
rgo/KAGRA S250206dm: Updated Sky localization and EM Bright Classification
rgo/KAGRA S250206dm: Spectroscopic Classification of AT2025bay and AT2025baz with Keck I/LRIS

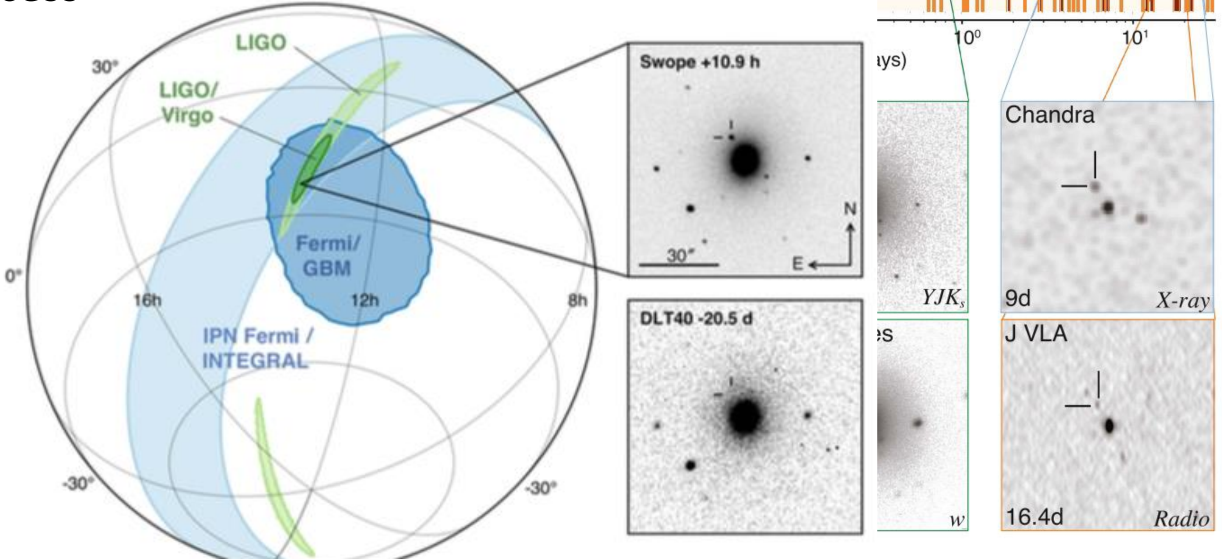
- **First binary neutron star merger (BNS) detection in 2017:** GW170817

- **Multi-messenger Astronomy with GW170817:**

event also observed across the EM spectrum:
  - short gamma-ray burst **GRB** 150101B
  - associated **kilonova:** bright electromagnetic radiation
  - MM publication: https://arxiv.org/pdf/1710.05833

- Many results:
  - confirms the production of heavy elements through r-process nucleosynthesis in BNS mergers
  - Link between BNS and GRBs
  - Hubble constant (see next slide)
  - Speed of GW (see next slide)
  - Constraint on EOS of NS
  - Tests of GR
  - ....



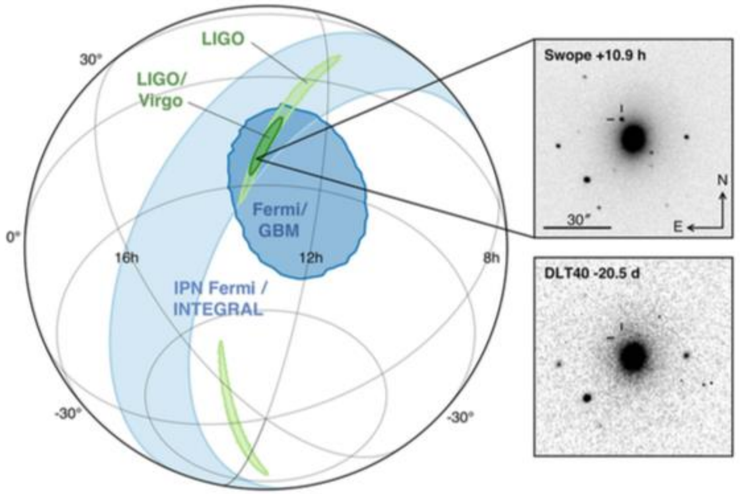


GW170817: the first and only bright standard siren

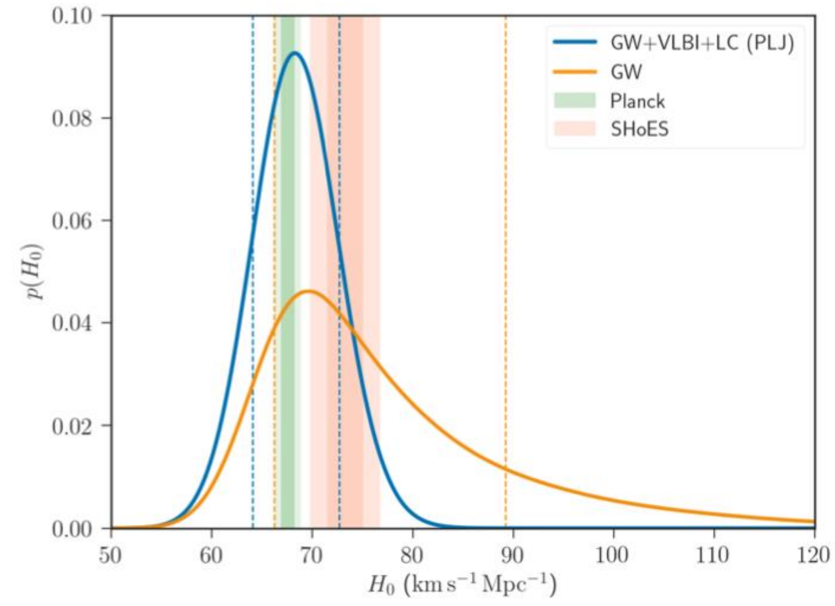
Hubble constant measurement:

The identification of an EM counterpart and host galaxy yielded the first cosmological measurements with GW standard sirens:

- GW signal => luminosity distance
- Host galaxy identified by EM observations => redshift measurement



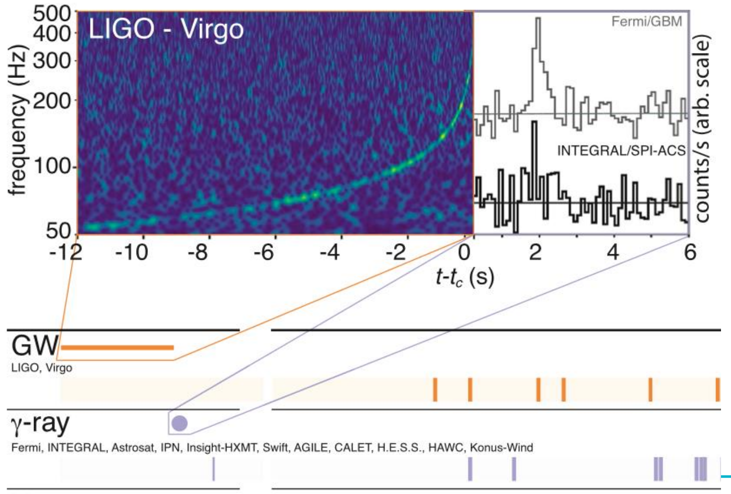
$$H_0 = 69^{+17}_{-8}\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$$



Speed of GW:

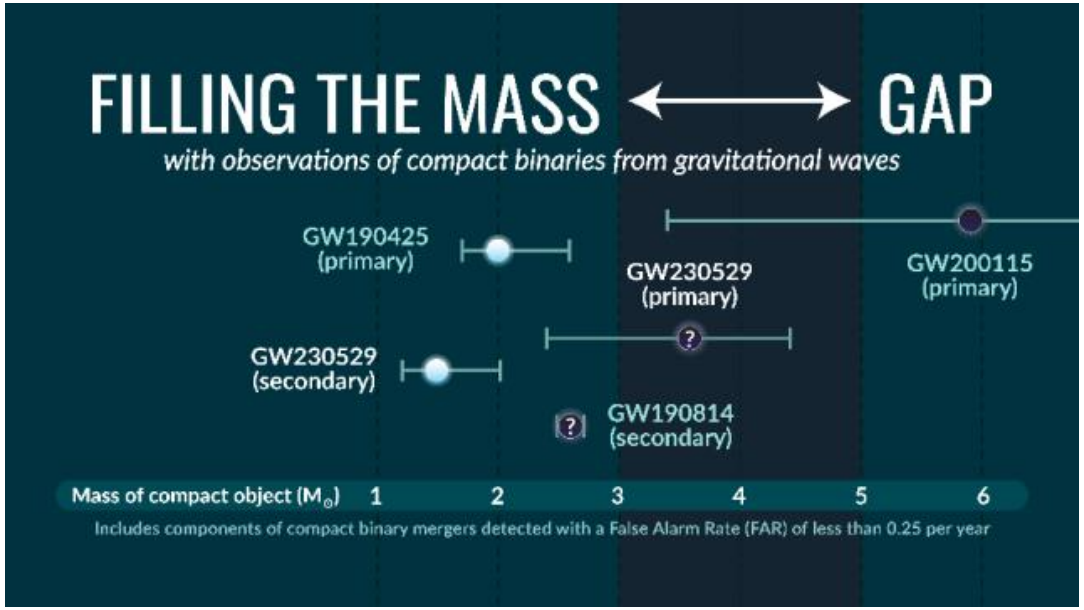
- Stringent constraints on the speed of GW:

$-3\times10^{-15} < c_g/c - 1 < 7\times10^{-16}$



=> rules out several modified gravity models

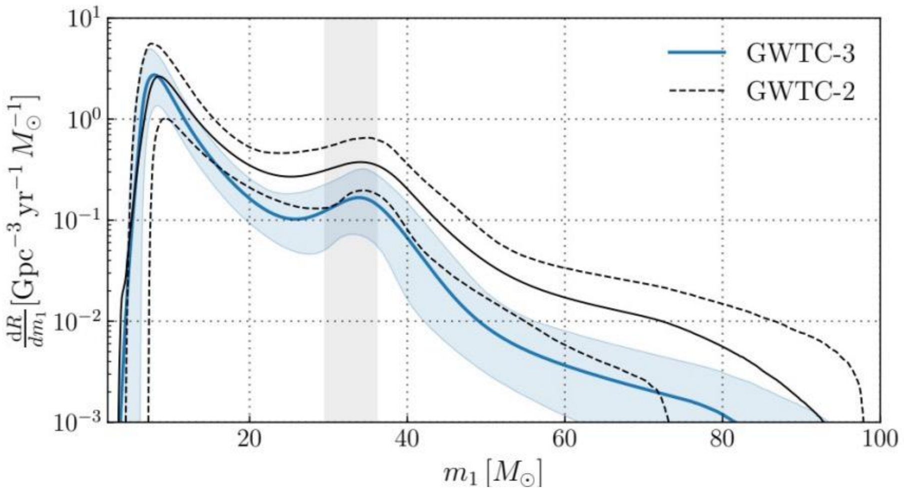
- GW230529: https://arxiv.org/abs/2404.04248
  - most probably a NS-BH coalescence
  - BH mass ~3 $M_{\odot}$: in the “mass gap” excluded by standard star evolution



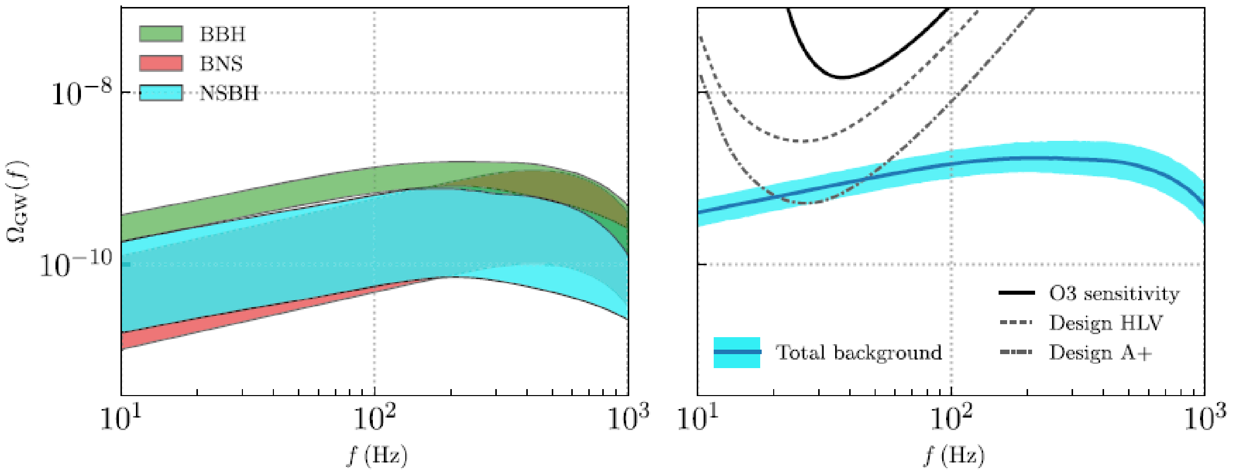
  - Formation hypothesis:
    - BH forms after supernovae by accretion of mass
    - BH formed by previous NS-NS coalescence (tripple system)
    - Primordial BH

- Study based on GWTC3 catalog: 90 coalescences
  - Merger rates for BBH, BNS
  - Evolution of BBH rates with redshift
- Publication: https://arxiv.org/pdf/2111.03634

BBH differential merger rate



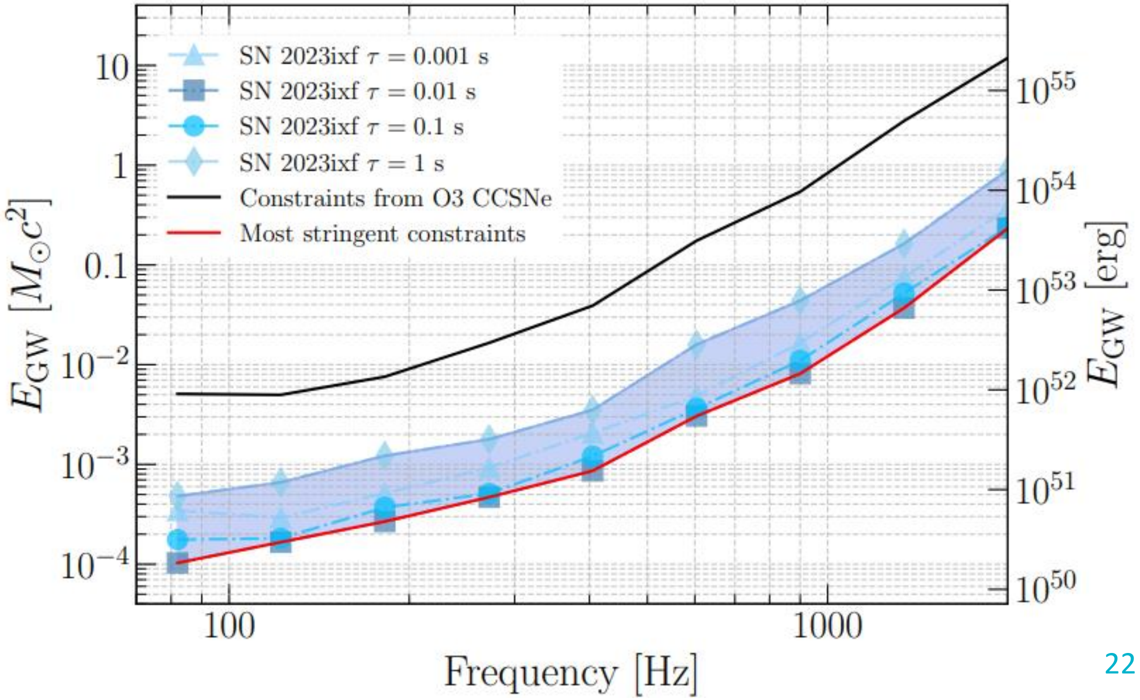
Forecast of astrophysical GW background

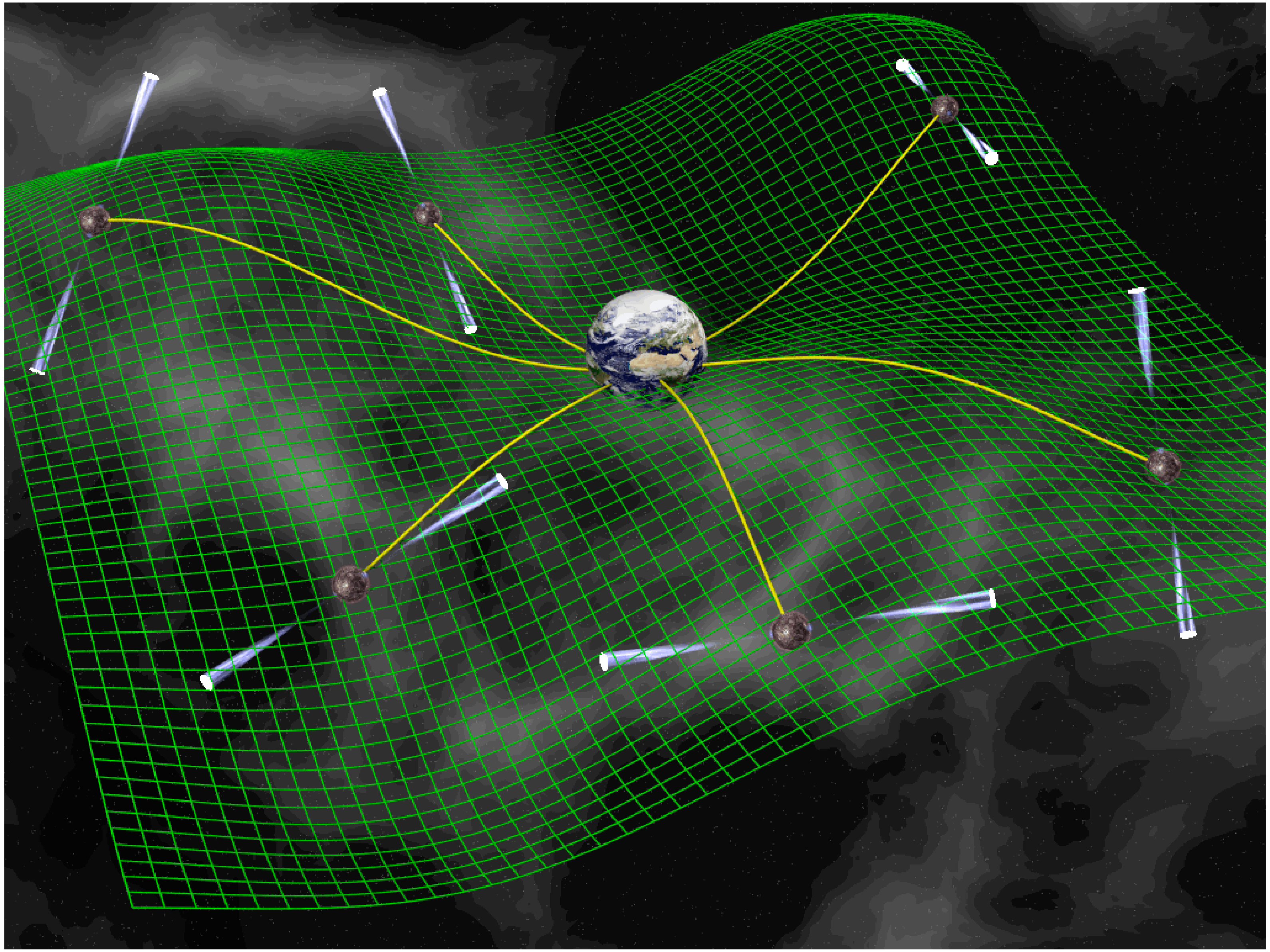


- Continous waves (pulsars): no detection, upper limits
- Burst (Supernovae, ...) : no detection, upper limits
- Stochastic background: upper limits

- Example of event follow up by LVK: the SN2023ixf event
  - Type II Supernovae in M101 galaxy (6.7Mpc) discovered by Itagaki

  => Improved upper limits on emitted GW energy
  - [Paper]

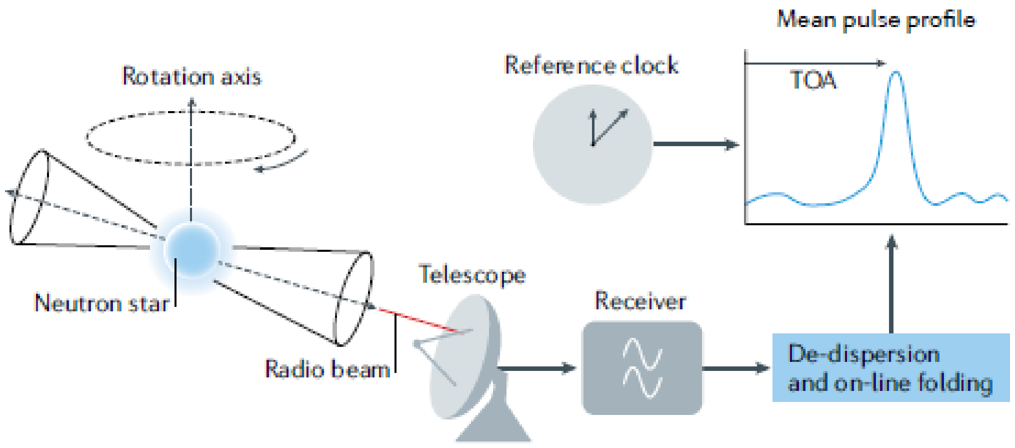


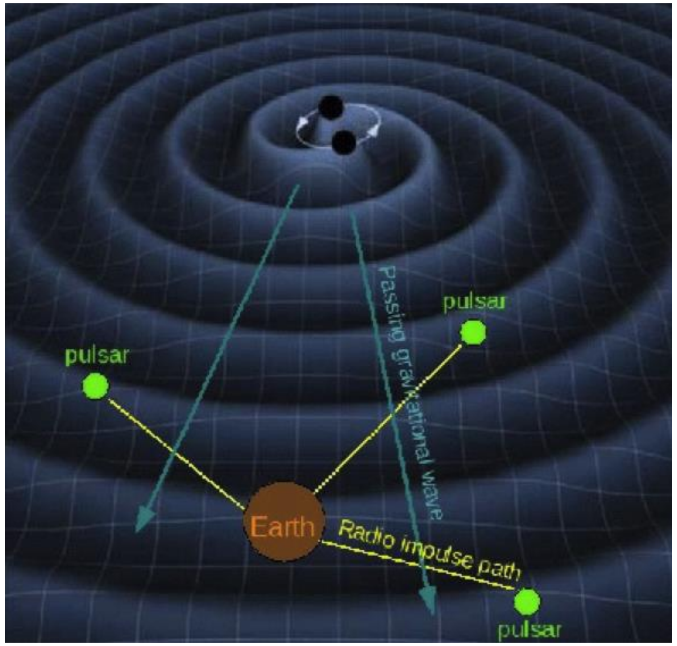


PTA detection principle:

- Monitor the distance between the earth and the pulsars using very stable pulsars
- Earth and pulsars = test masses
- Use correlation between pulsars

	PSR 1	PSR 2	PSR 3	PSR 4
PSR 1	WN RN GWB	GWB	GWB	GWB
PSR 2	GWB	WN RN GWB	GWB	GWB
PSR 3	GWB	GWB	WN RN GWB	GWB
PSR 4	GWB	GWB	GWB	WN RN GWB





Sensitivity:

- Observation times: T ~weeks to 10's of years
- Timing uncertainties : dt ~100ns

⇒ Sensitivity h=dt/T ~ 10^{-16}

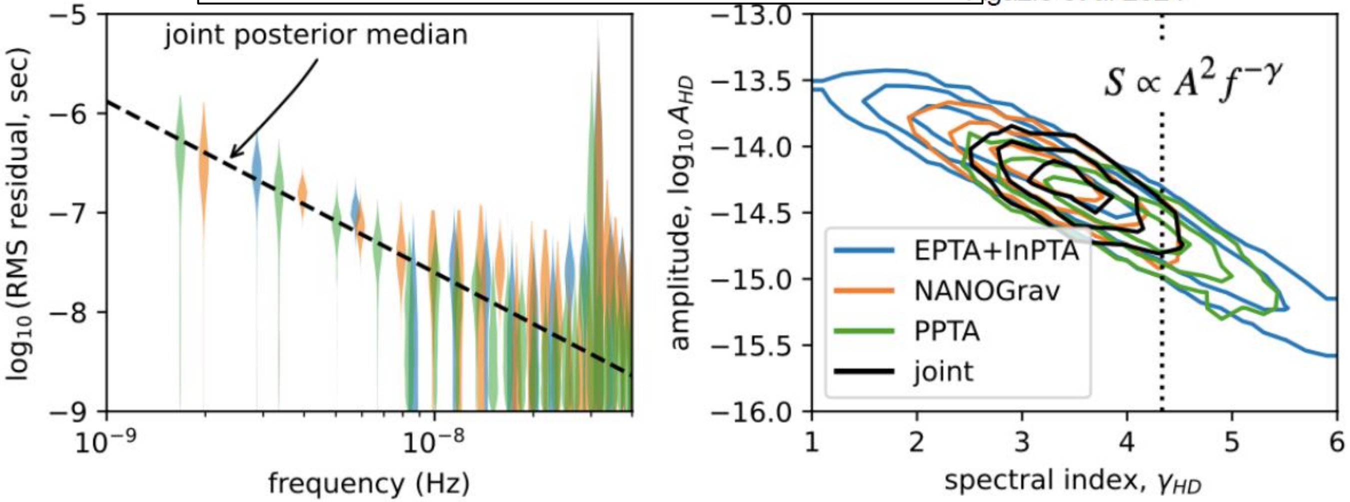
⇒ Frequency band ~ 1/T~ $[10^{-9} – 10^{-6}]$ Hz

- NanoGrav (US)
- EPTA (Europe)
- InPTA (India)
- PPTA (Australia)
- SAPTA (Africa)
- CPTA (China)

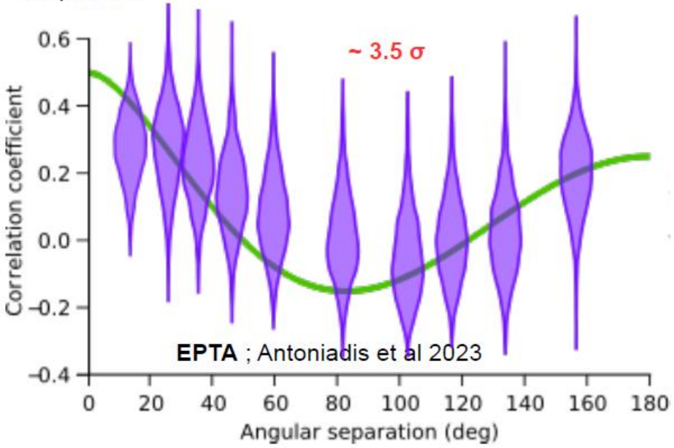
- Consistent results from EPTA, NANOGrav, PPTA (June 2023) – arXiv
  - recently confirmed by MeerKAT - arXiv

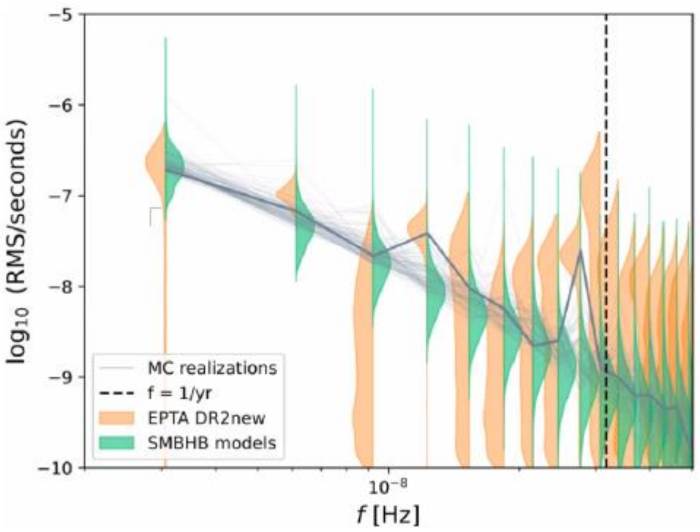
Measured spectrum and amplitude

Agazie et al 2024



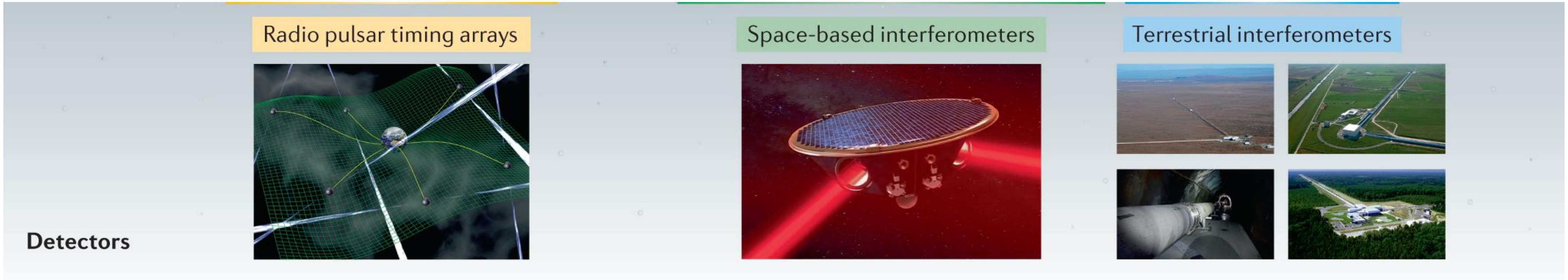
Spatial correlation of the signal





- Physical interpretation: arXiv:2306.16227
  - Comparison to Super massive Binary Black Holes population models
  - Constraint on the cosmology of primordial Universe
  - Constraint on Ultra Light Dark Matter density

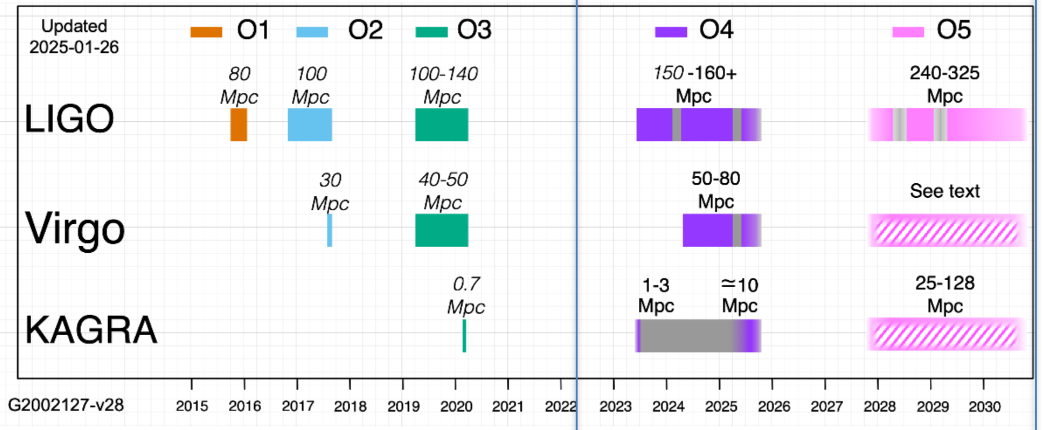
- Ground based laser interferometers
- Space interferometers
- Pulsar timing arrays
- Longer term: other space projects and atomic interferometers



- Upgrades of existing 2G detectors (LIGO, Virgo, KAGRA):
  - O5: increase range by a factor ~2
  - Virgo_nEXT and A# : push the infrastructures to their limits , increasing range by another factor 2
- Third generation detectors (3G):
  - Einstein Telescope and Comsic Explorer under preparation, to start in 2040's

Current infrastructures

New infrastructures



Advanced Virgo+
Advanced LIGO+

LIGO upgrade A#

Virgo_nEXT

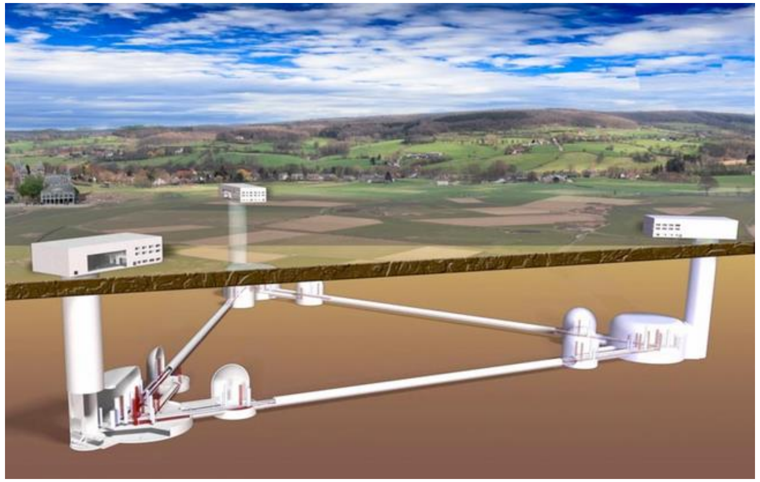
KAGRA upgrade

2030's

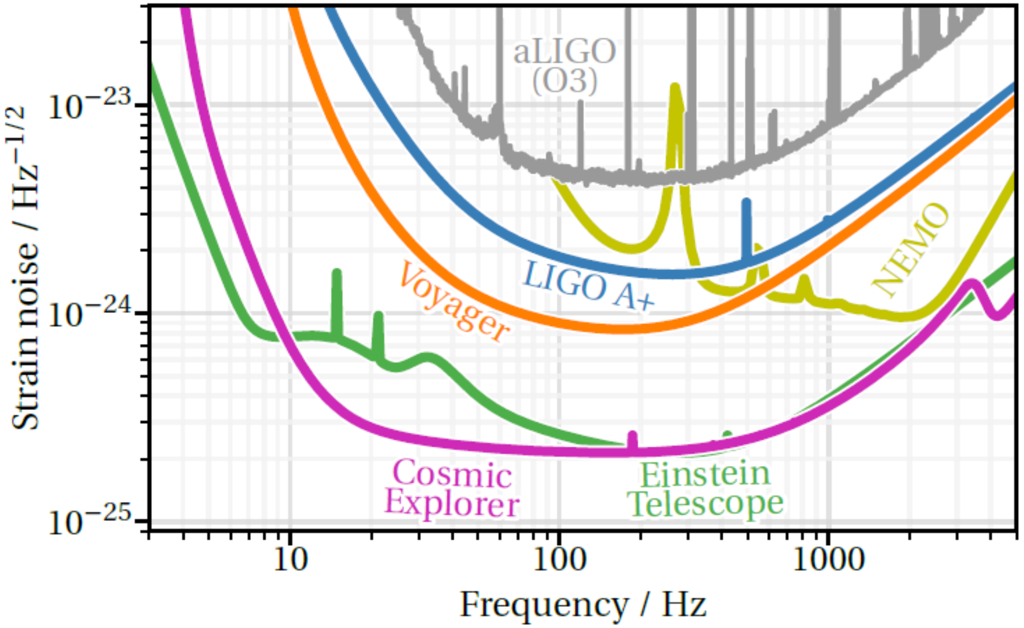
Cosmic Explorer

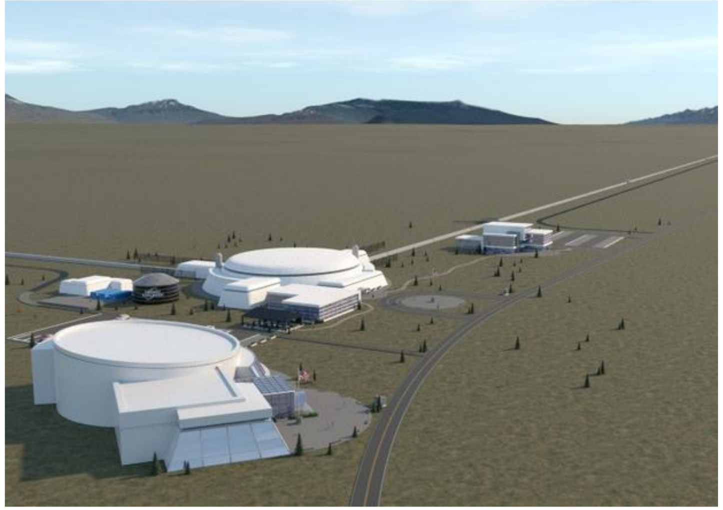
Einstein Telescope

- Einstein Telescope:
  - Xylophone principle: 2 different detectors (low frequency / high frequency)
  - New technologies for low frequency detector (cryogeny, different wavelength)
  - 10km arms



- Cosmic Explorer:
  - 40km and 20km long arms
  - Same technology as 2G, with further improvements
  - Foresee upgrades with new technologies





2G detectors (LVK)

- Expect hundreds of CBC signals well localized (area smaller than the field of view of the Vera Rubin Observatory)

→ high chances of multi-messenger observations

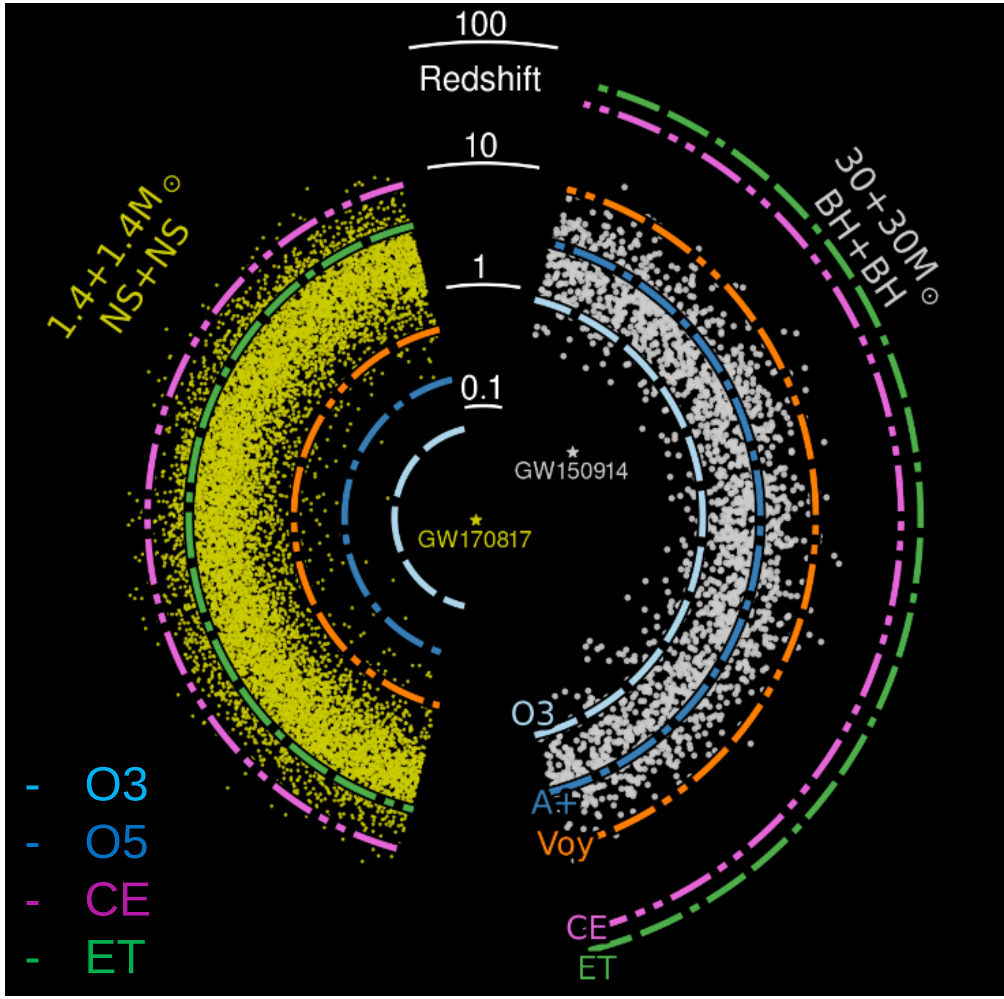
- Hubble constant within a few percent

3G detectors

At their ultimate sensitivities, ET and CE will be able to observe all stellar mass BBH and most of BNS mergers in the Universe

- high precision, high statistics era (10^6 BBH / 10^5 BNS / year)

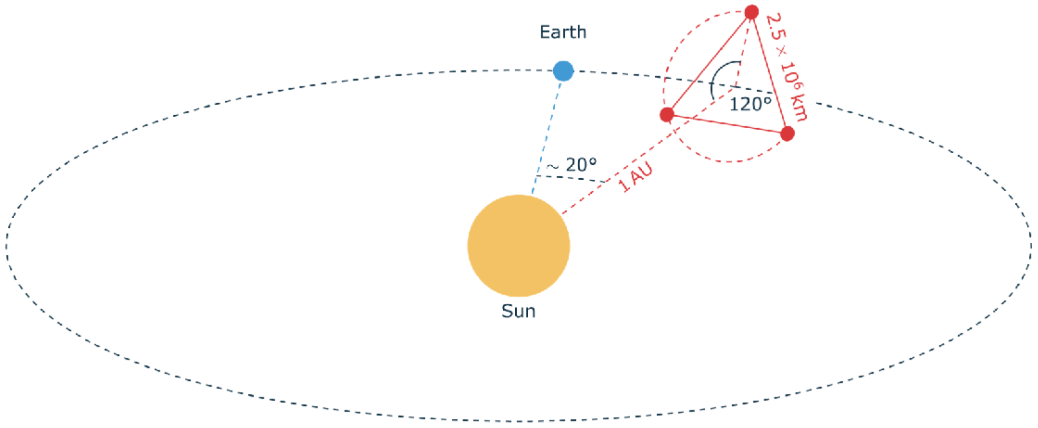
- Multi-messenger astronomy : expect 10-100 detections per year with EM counterpart

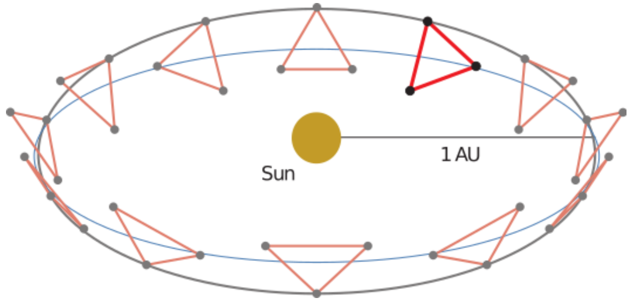


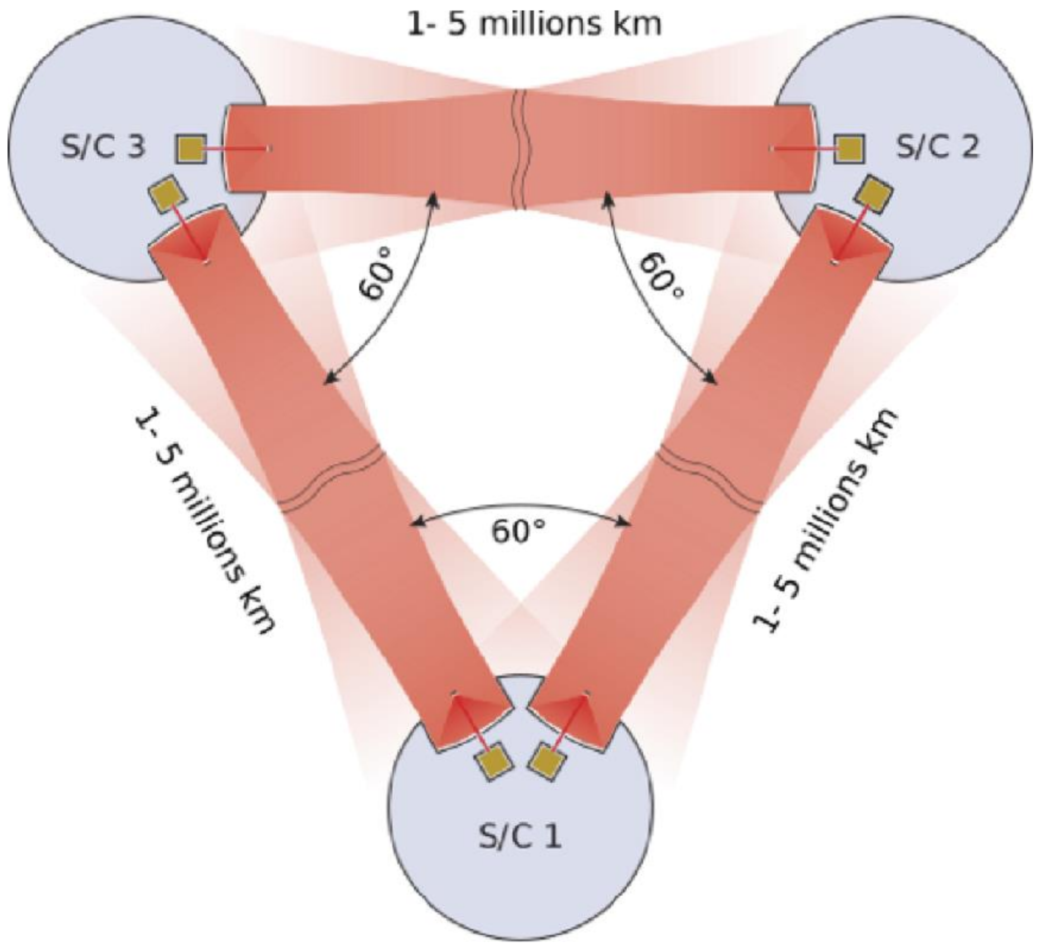
Laser Interferometer Space Antenna (LISA)

- 3 space craft separated by 2.5 million km
- Goal: monitor the arm length at picometer level

=> $h \sim 10^{-21}$

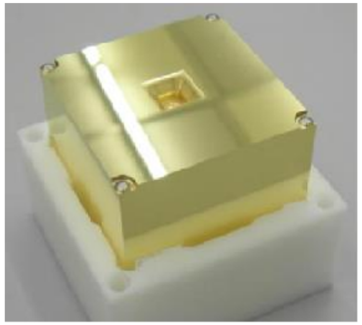






LISA's detection principle

- Test masses (TM) are protected from external forces by spacecraft
- Spacecraft position adjustement with respect to TM : capacitive sensing
- Interferometric sensing



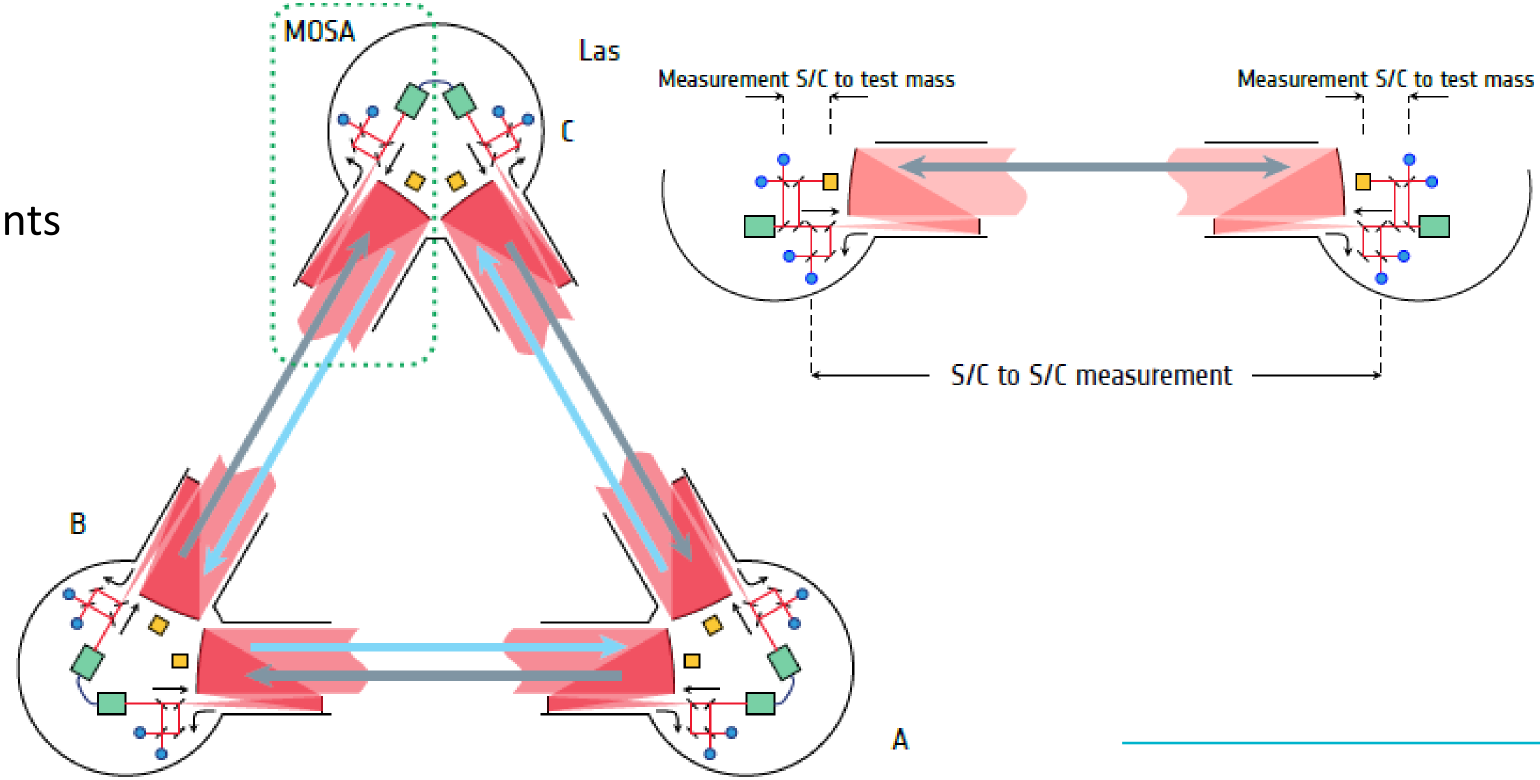
Test mass

- Time delay interferometry:
  - 6 channels

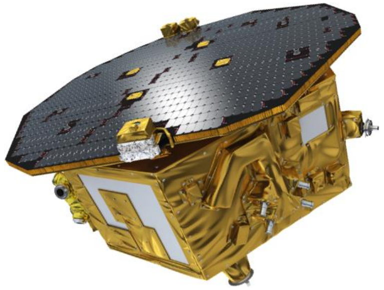
  => build 2 ~independent measurements

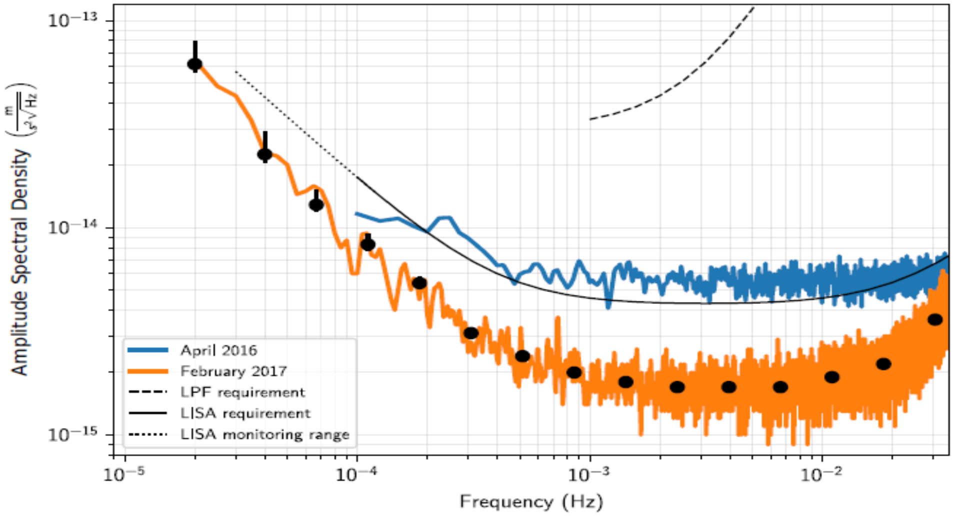
  ⇒ cancelation of laser noise

  ⇒ Extraction of GW signal



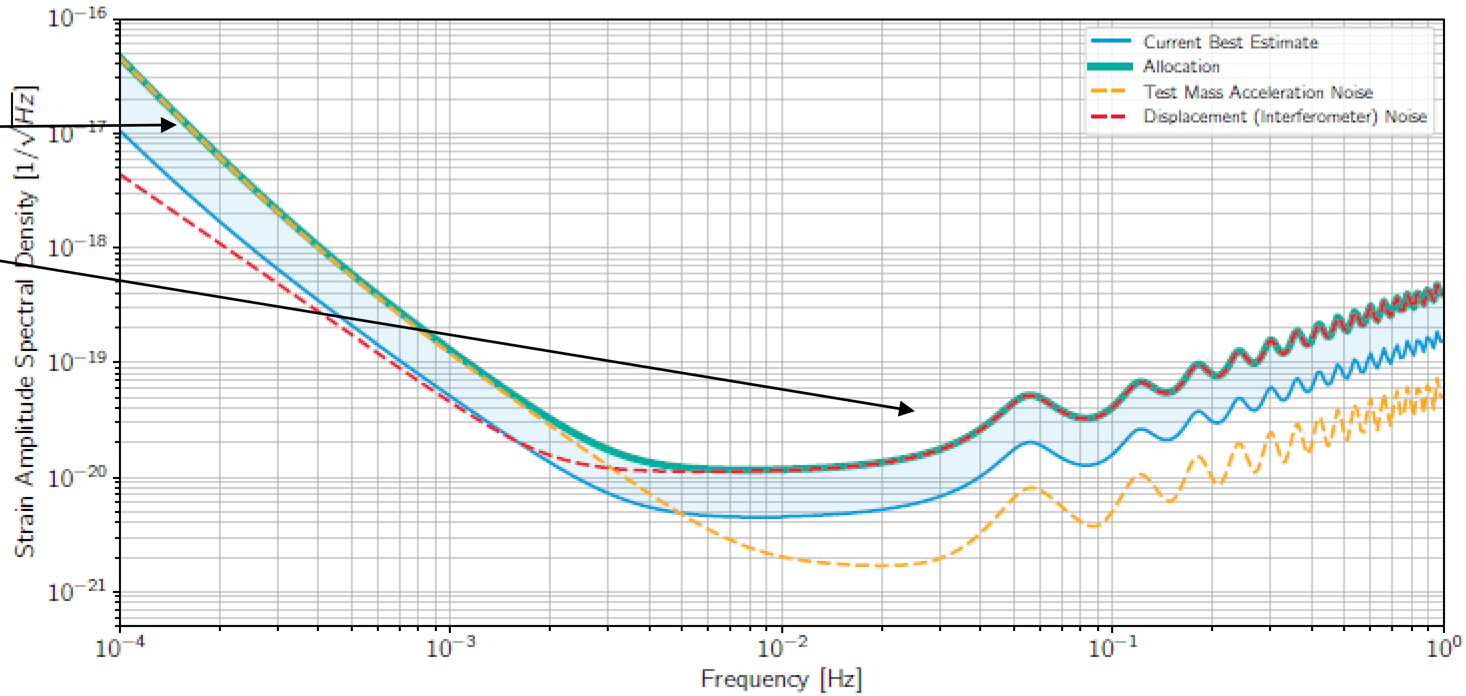
- Test mass shielding performances validated by the LISA Pathfinder mission



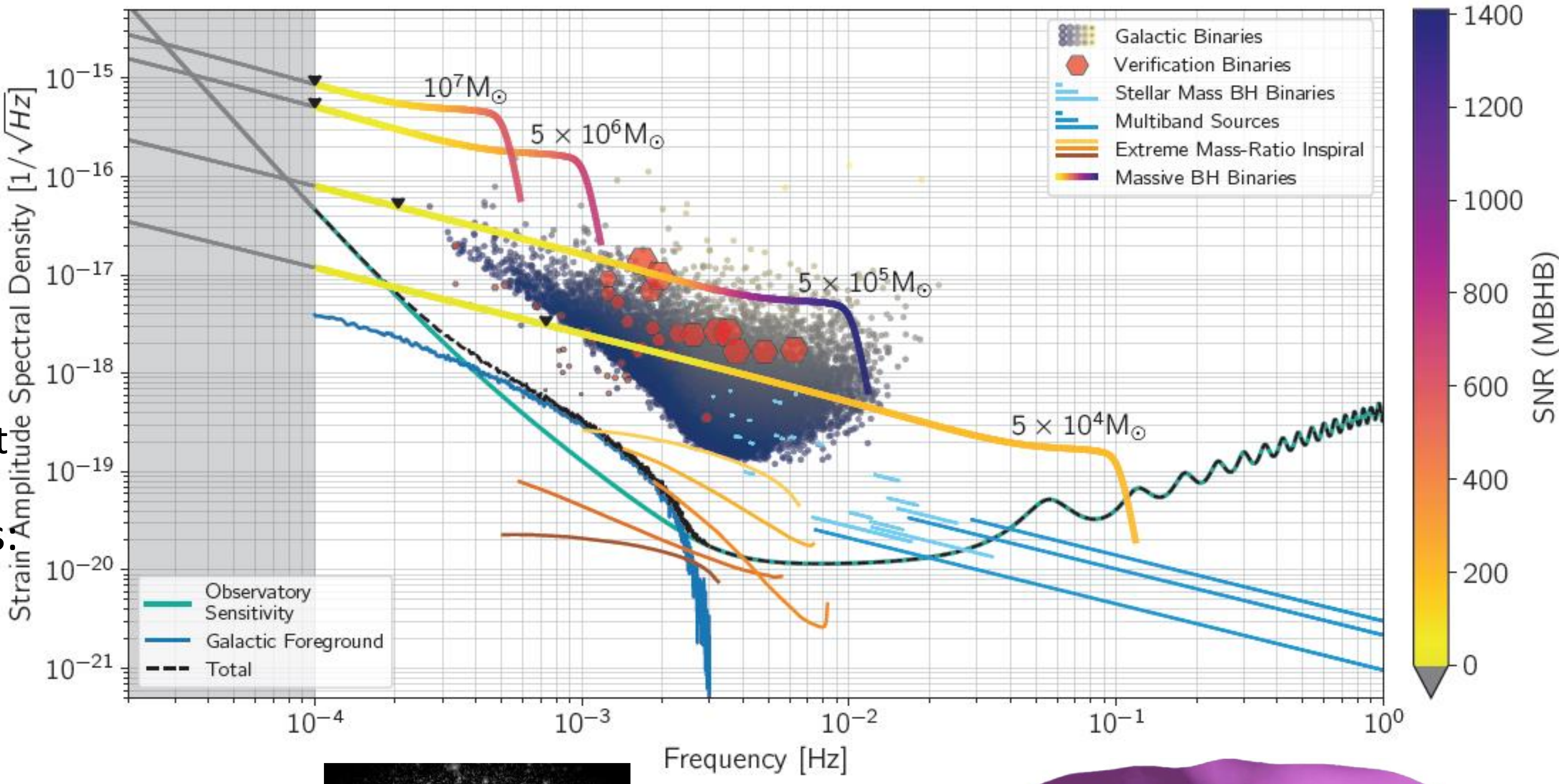


- LISA sensitivity limitations:
  - Test mass acceleration
  - Interferometer noise (shot noise, …)

- LISA red book (arXiv)



- Galactic white dwarf binaries:
  - multi- messenger studies
- Stellar mass BH binaries :
  - multi-wavelength observations
  - multi-messenger?
- Extreme mass ratio inspirals
  - properties of MBH environment
- (Super)Massive BH coalescences:
  - possibility of EM signals
  - typical sky localisation ~deg^2

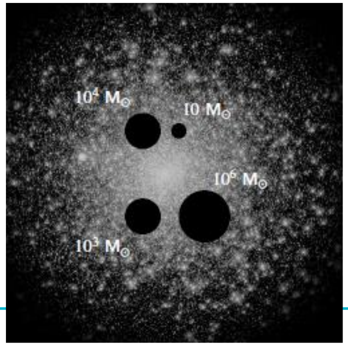


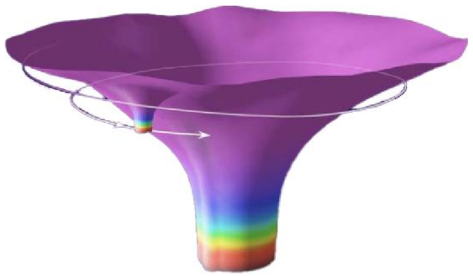
$\Rightarrow$ GR tests in different regimes

$\Rightarrow$ H_0 measurement to few percent

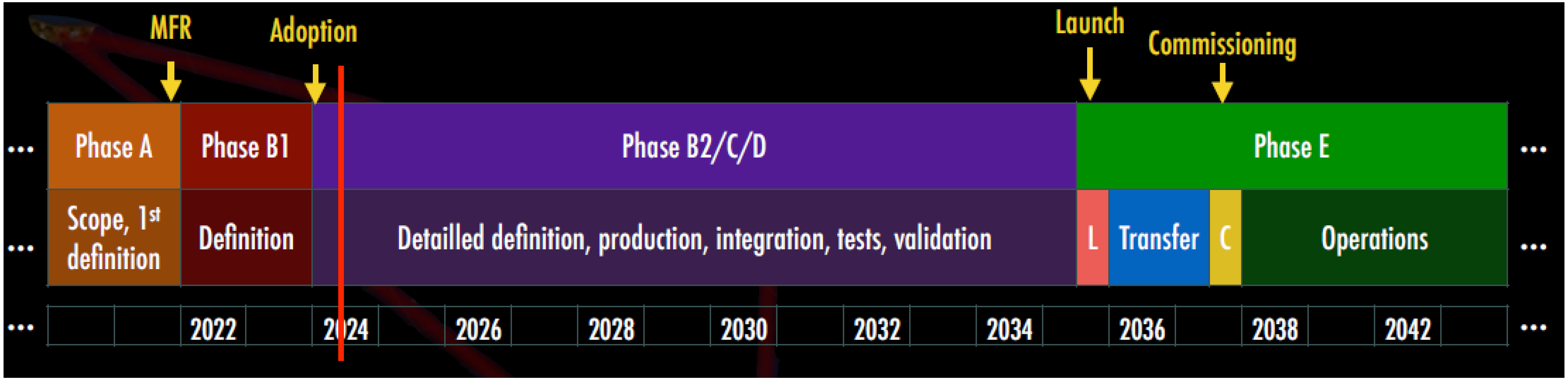
$\Rightarrow$ structure formation

$\Rightarrow$ ...





LISA’s timeline



- Design validated
- Ressources allocated to build the instrument
- Launch: 2035
- Time for transfer: 1.5 years
- Operation: 4.5 years nominal + 6.5 years of extension

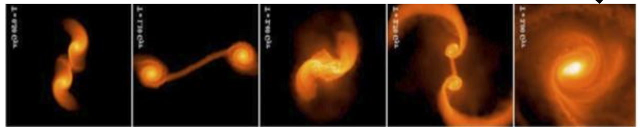
Pulsar timing arrays

Future

- Combine and jointly analyze data under the IPTA umbrella
- More sensitive detectors coming up:
  - MeerKAT, FAST already taking data
  - SKA > 2029
- Soon reach 5σ level?
- Threat: crowded radio spectrum from human activities

Sources

- Super-massive BH (SMBBH)
- Stochastic background



Science

- Multi-messenger observations of SMBBHs
- Formation of large structures
- Rate of galaxy mergers
- GR tests & cosmology of primordial Universe

DECIGO

- Concept:
  - laser interferometer in space
  - Intermediate between LISA and ground based (0.1-1Hz band)

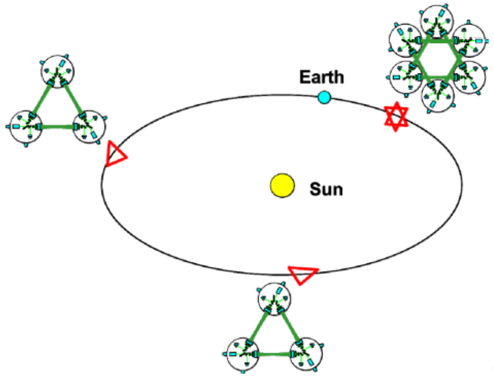


Fig. 1. Orbit of DECIGO. Four clusters of DECIGO are put in the heliocentric orbit: two at the same position and the other two at different positions.

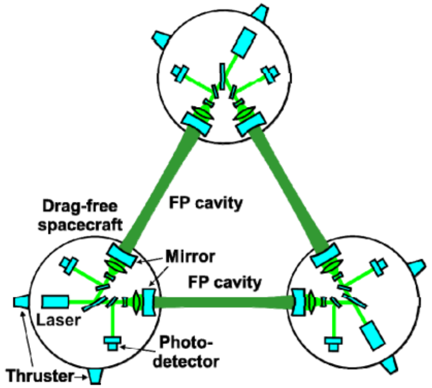
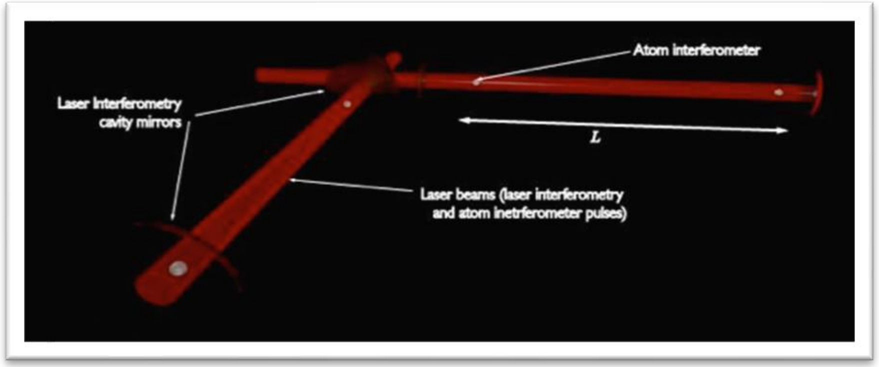


Fig. 2. Conceptual design of DECIGO. One cluster of DECIGO consists of three drag-free spacecraft. FP cavities are used to measure a change in the arm length.

Atomic interferometers

- In the development/proof of concept phase
- First prototypes ~10m scale being prototyped

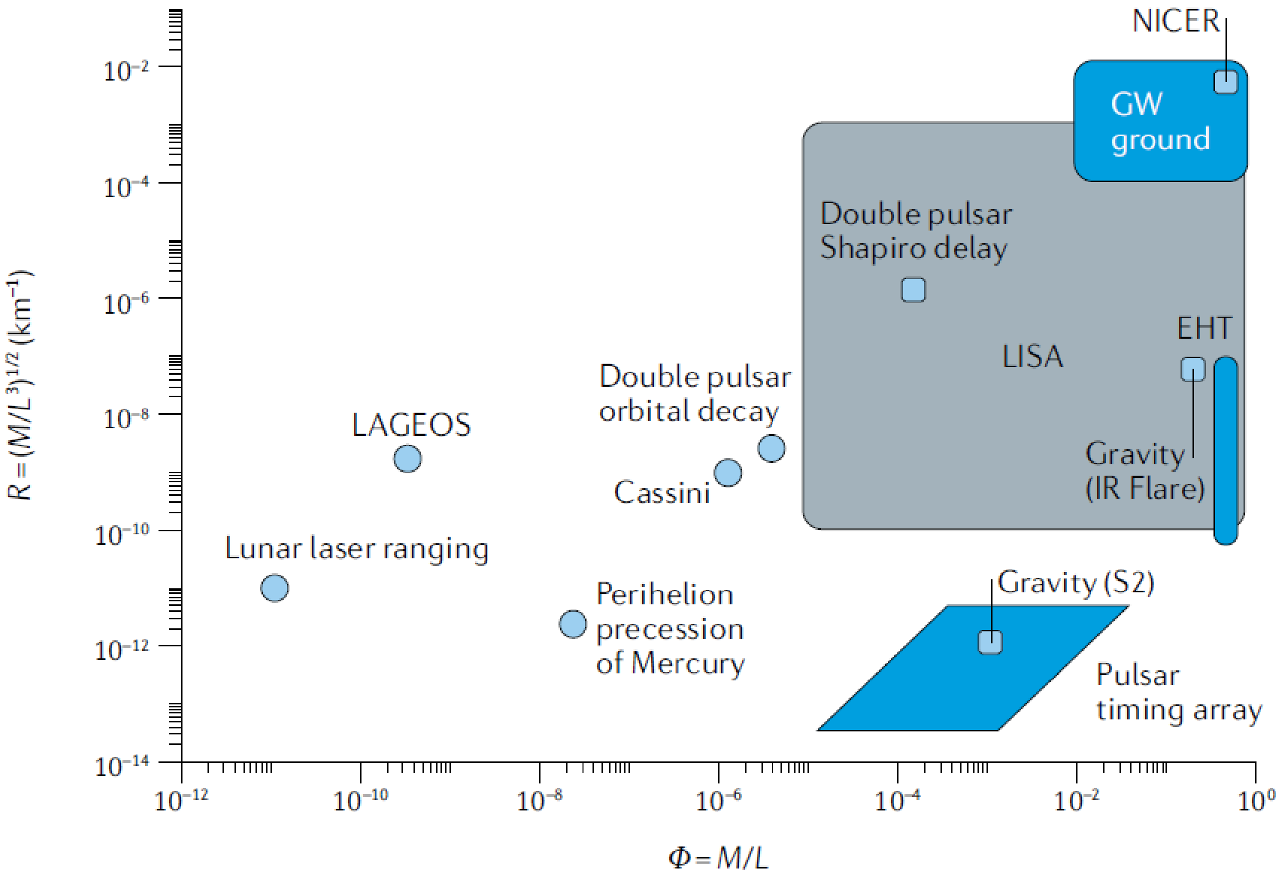


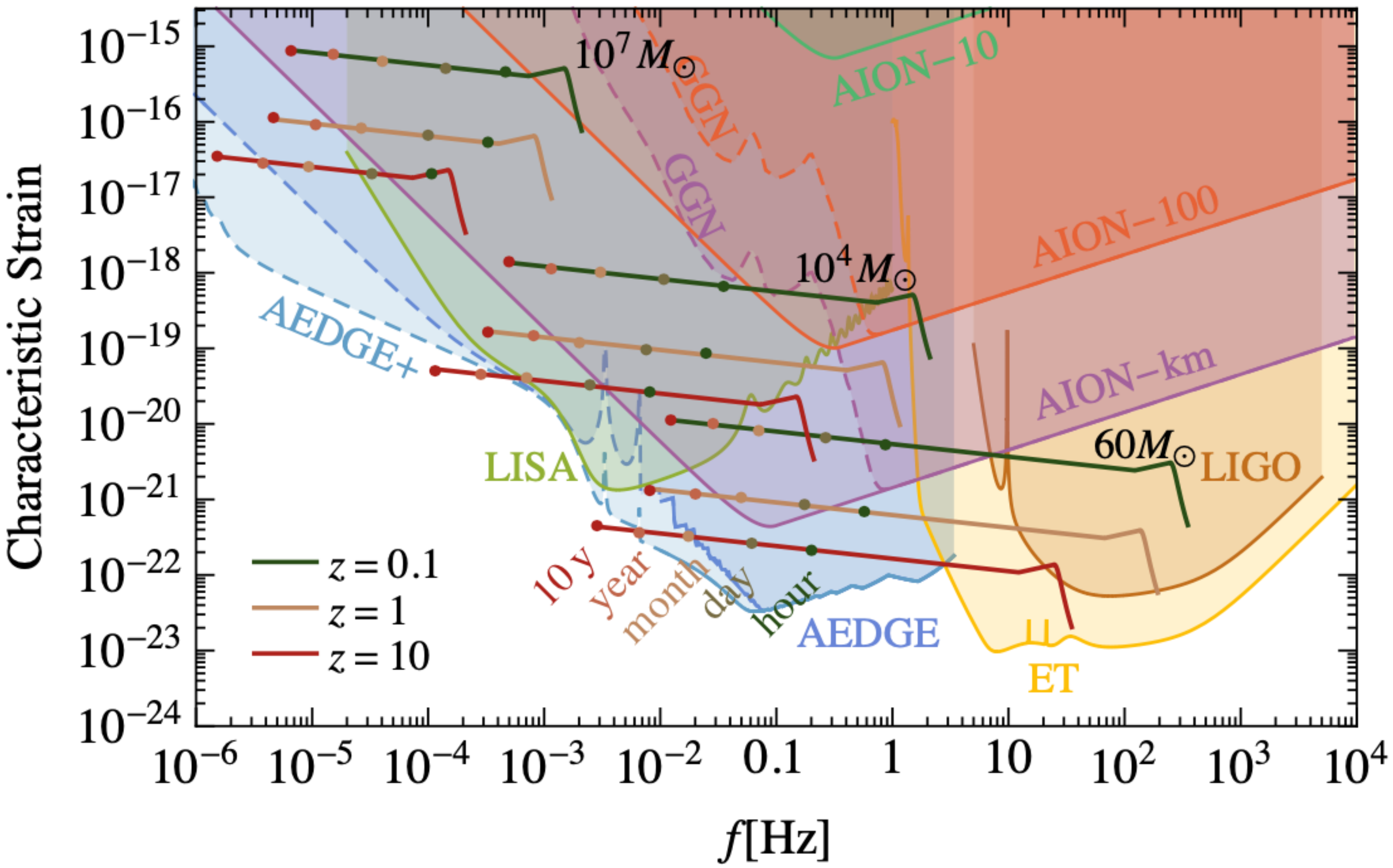
- Regular GW detections by 2G detectors
  - Now ~280 mergers (mostly BBH)
  - O4 run will continue until Oct 2025
  - Alert system including early alerts
  - Only one “bright siren” observed (GW170817): results show the potential of multi-messenger observations
  - Next: long break to allow consequent upgrade of detectors for O5 run
  - High statistics expected after upgrades (2030’s)

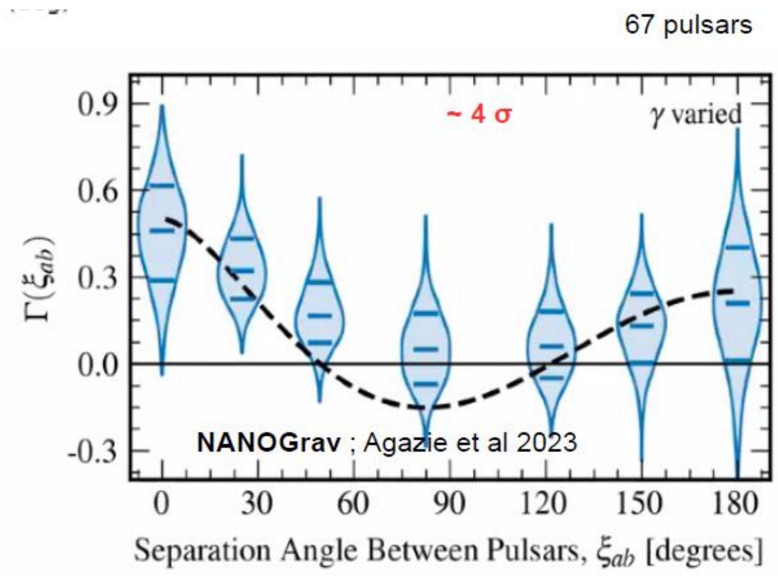
- GW evidence by PTAs
  - First constraints from nHz GW observation
  - Multi-messenger observations expected for the future

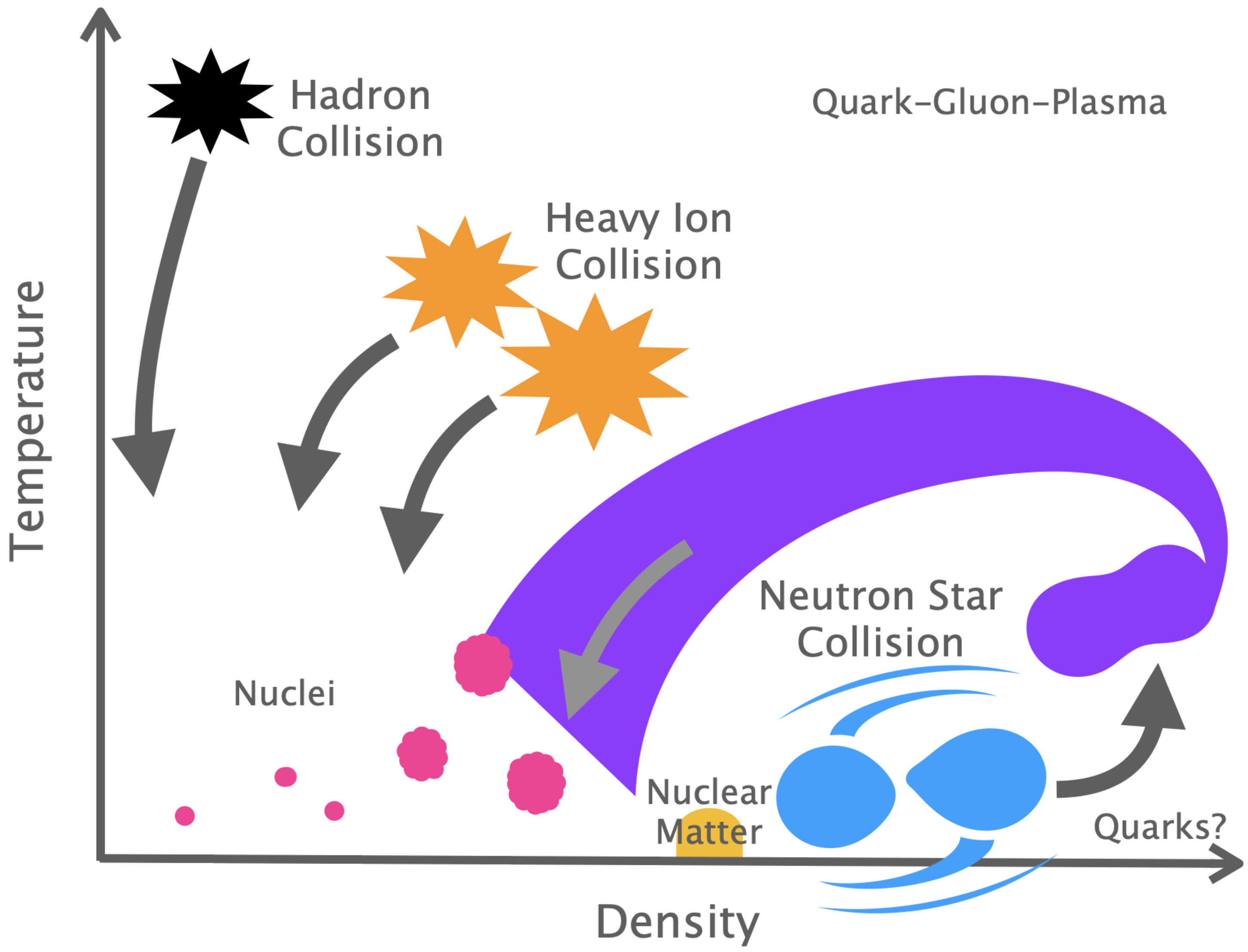
- LISA space mission entered the construction phase, 3G detectors in the design phase : operation in 2040’s
  - ⇒ Many different sources
  - ⇒ High statistics, high precision era
  - ⇒ Many potential multi-messenger, multi-wavelength observations

SPARE SLIDES


NICER
GW ground
Double pulsar Shapiro delay
LISA
EHT
Gravity (IR Flare)
Double pulsar orbital decay
LAGEOS
Cassini
Lunar laser ranging
Perihelion precession of Mercury
Gravity (S2)
Pulsar timing array
$R = (M/L^3)^{1/2}$ (km^{-1})
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{-12}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^{0}
$\Phi = M/L$

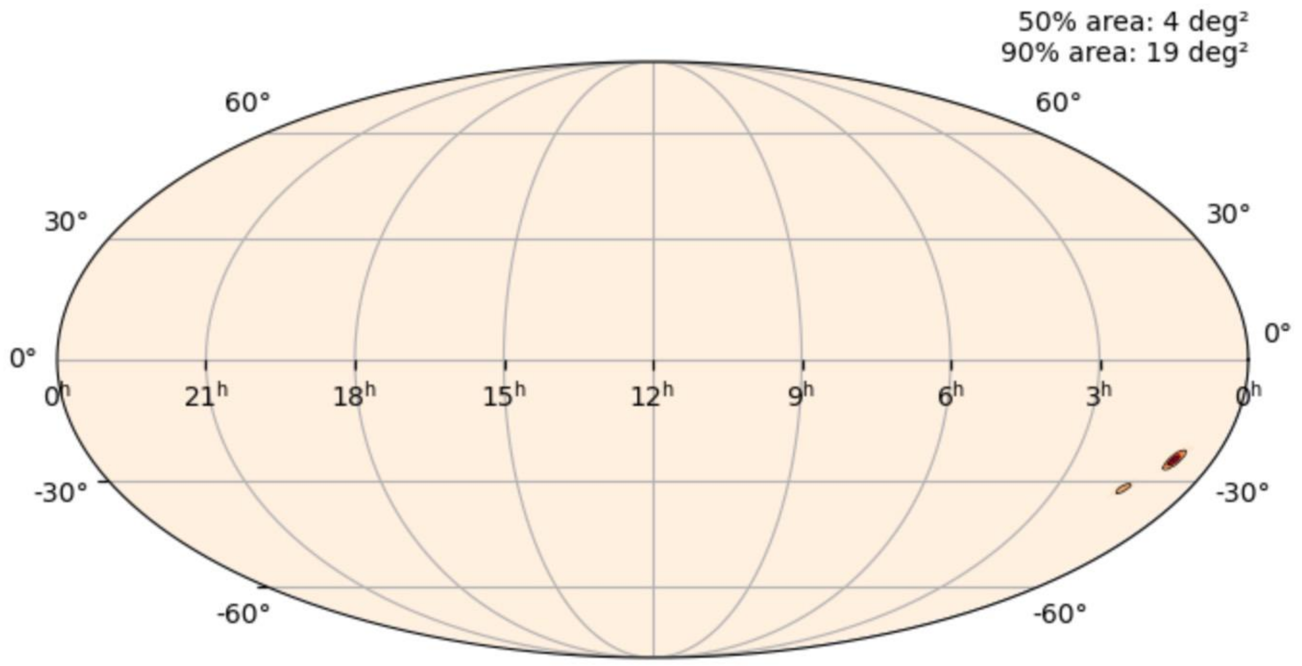

Characteristic Strain
f[Hz]
AEDGE+
AEDGE
LISA
AION−10
AION−100
AION−km
GGN
LIGO
ET
10 y
year
month
day
hour
$z = 0.1$
$z = 1$
$z = 10$
$10^7 M_\odot$
$10^4 M_\odot$
$60 M_\odot$

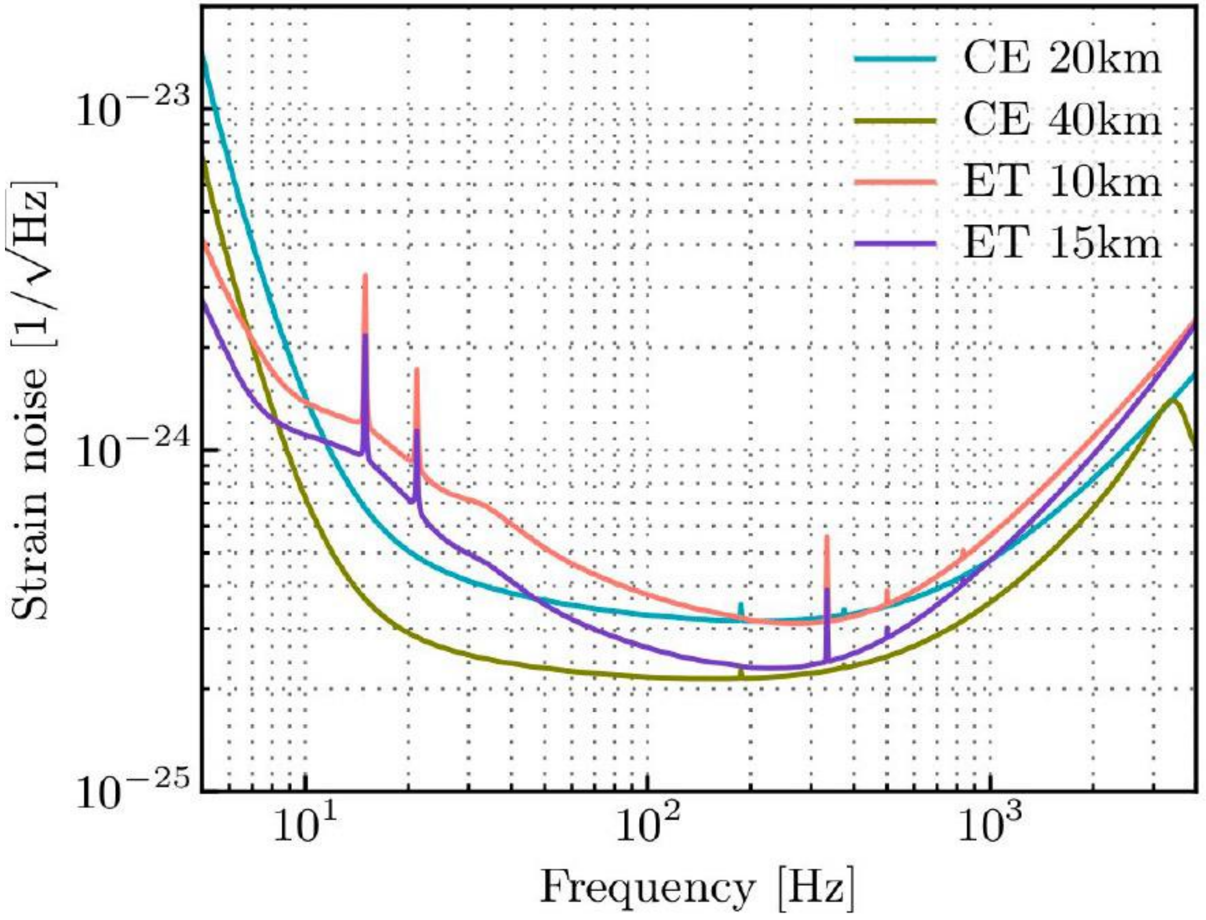

67 pulsars
~ 4 σ
γ varied
NANOGrav ; Agazie et al 2023
$\Gamma(\xi_{ab})$
Separation Angle Between Pulsars, ξ_{ab} [degrees]


Hadron Collision
Quark–Gluon–Plasma
Heavy Ion Collision
Temperature
Neutron Star Collision
Nuclei
Nuclear Matter
Quarks?
Density

GW190814

- A merger involving a 23 solar mass black hole and a 2.6 solar mass
- 2nd object is potentially the lightest black hole or the heaviest neutron star ever observed.
- Publication: https://arxiv.org/abs/2006.12611

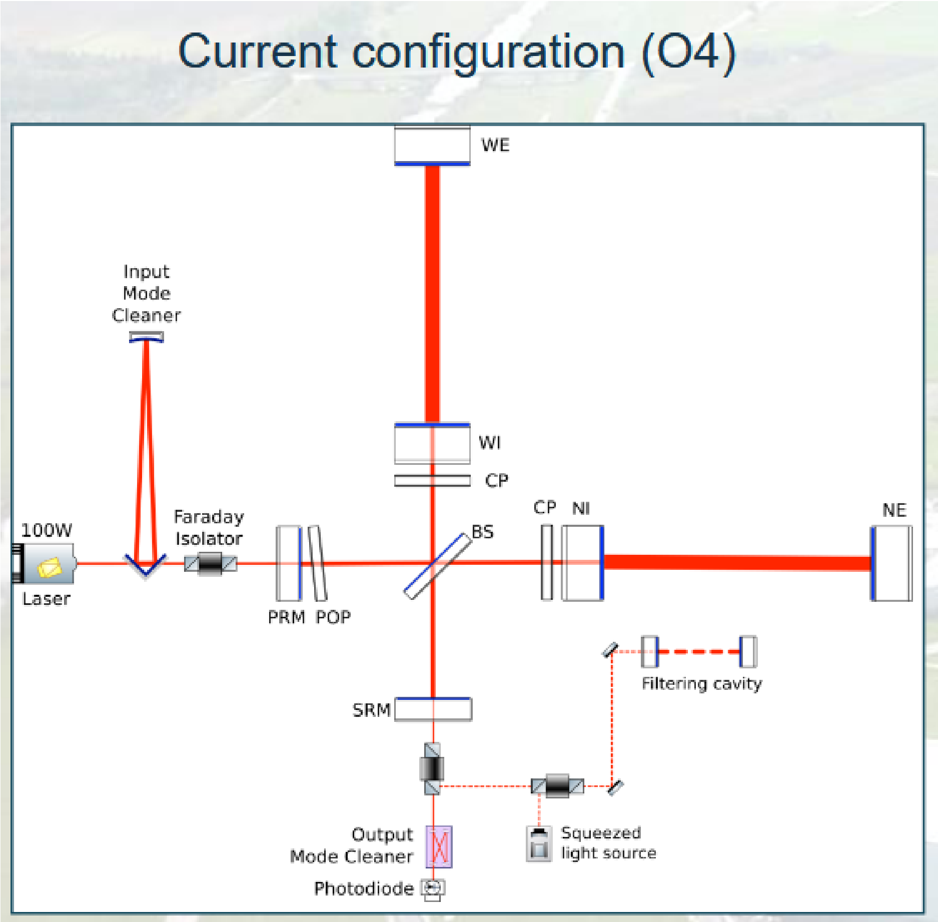


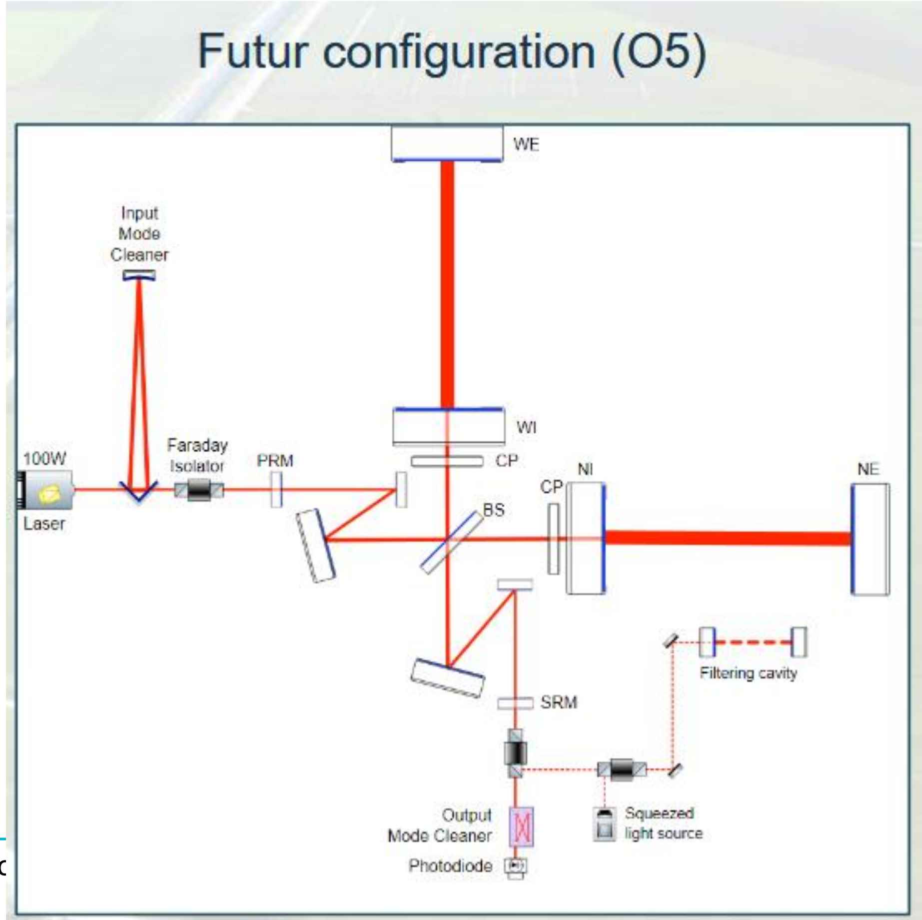


CE 20km
CE 40km
ET 10km
ET 15km
10^{-23}
10^{-24}
10^{-25}
Strain noise [$1/\sqrt{\text{Hz}}$]
10^1
10^2
10^3
Frequency [Hz]

Stable recycling cavities

- Current recycling cavities recycle all beam modes (including noise carried by high-order modes)
  - ➢ create problems to **control**/understand the interferometer
  - ➢ limit maximum input power and squeezing performance → **poor sensitivity** of the detector
- Implementation of stable recycling cavities + increased effort on optical simulations
  - ➢ Need longer cavities, fitting in the existing building → **folded cavities**





Parameter	O4 high	O4 low	O5 high	O5 low	post-O5low
Power injected	25 W	40 W	60 W	80 W	277 W
Arm power	120 kW	190 kW	290 kW	390 kW	1.5 MW
PR gain	34	34	35	35	39
Finesse	446	446	446	446	446
Signal recycling	Yes	Yes	Yes	Yes	Yes
Squeezing type	FIS	FDS	FDS	FDS	FDS
Squeezing detected level	3 dB	4.5 dB	4.5 dB	6 dB	10.5
Payload type	AdV	AdV	AdV	AdV	Triple pendulum
ITM mass	42 kg	42kg	42 kg	42 kg	105 kg
ETM mass	42 kg	42kg	105 kg	105 kg	105 kg
ITM beam radius	49 mm	49 mm	49 mm	49 mm	49 mm
ETM beam radius	58 mm	58 mm	91 mm	91 mm	91 mm
Coating losses ETM	2.37e-4	2.37e-4	2.37e-4	0.79e-4	6.2e-6
Coating losses ITM	1.63e-4	1.63e-4	1.63e-4	0.54e-4	6.2e-6
Newtonian noise reduction	None	1/3	1/3	1/5	1/5
Technical noise	"Late high"	"Late low"	"Late low"	None	None
BNS range	90 Mpc	115 Mpc	145 Mpc	260 Mpc	500 Mpc