IJCLab
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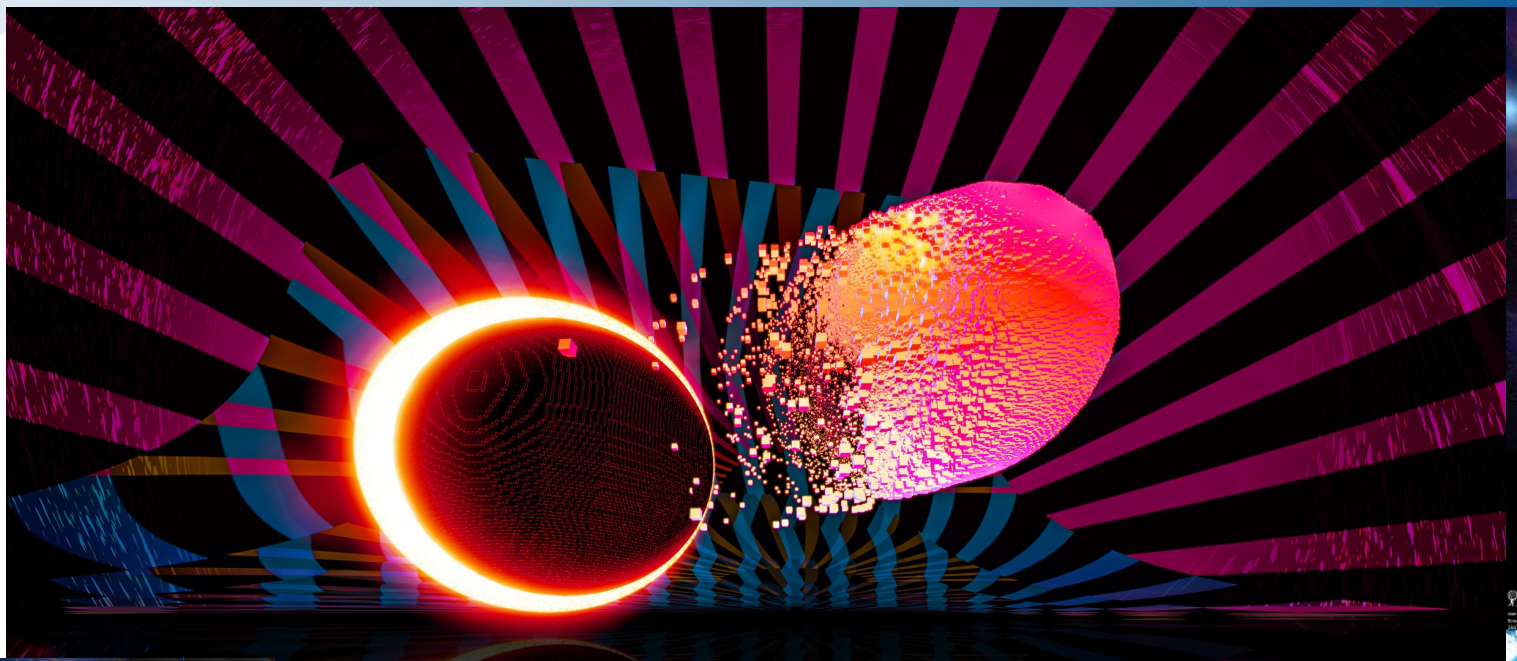
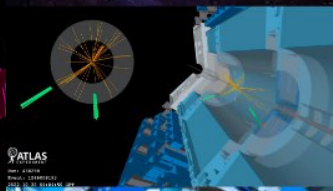
Laboratoire de Physique des 2 Infinis

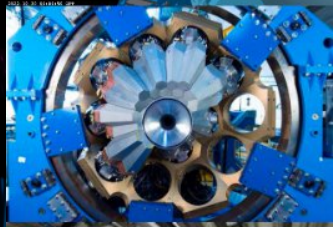
EINSTEIN TELESCOPE

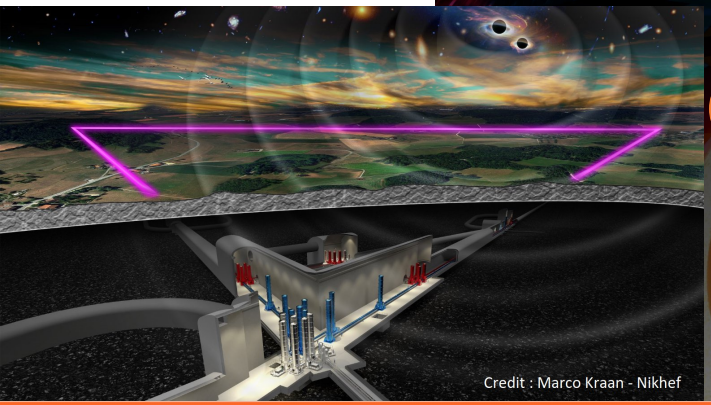
université PARIS-SACLAY
GRADUATE SCHOOL
Physique

P2I
Physique des deux Infinis





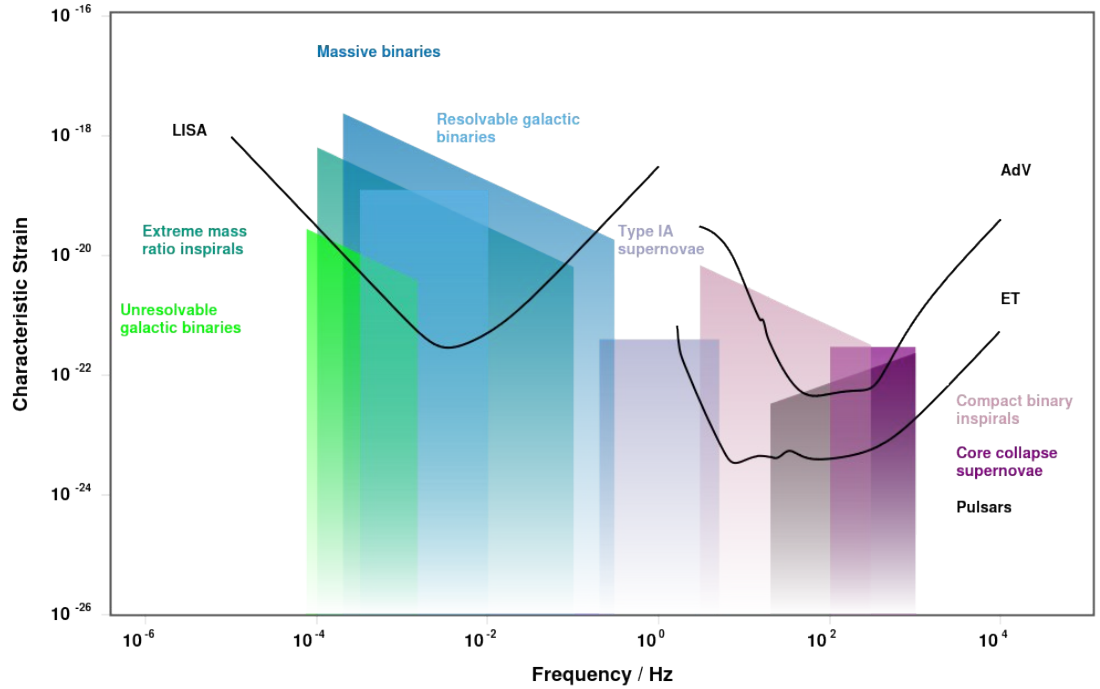



Credit : Marco Kraan - Nikhef

Gravitational waves and Einstein Telescope

What are gravitational waves?

- ripples in the spacetime curvature predicted by Albert Einstein in 1916
- emitted by accelerating masses: binary compact coalescence, supernovae, etc.
- propagate at the speed of light
- amplitude observable on Earth
  $h \sim 10^{-23}$-10^{-21} at frequencies $f \sim 1 - 10^4$ Hz



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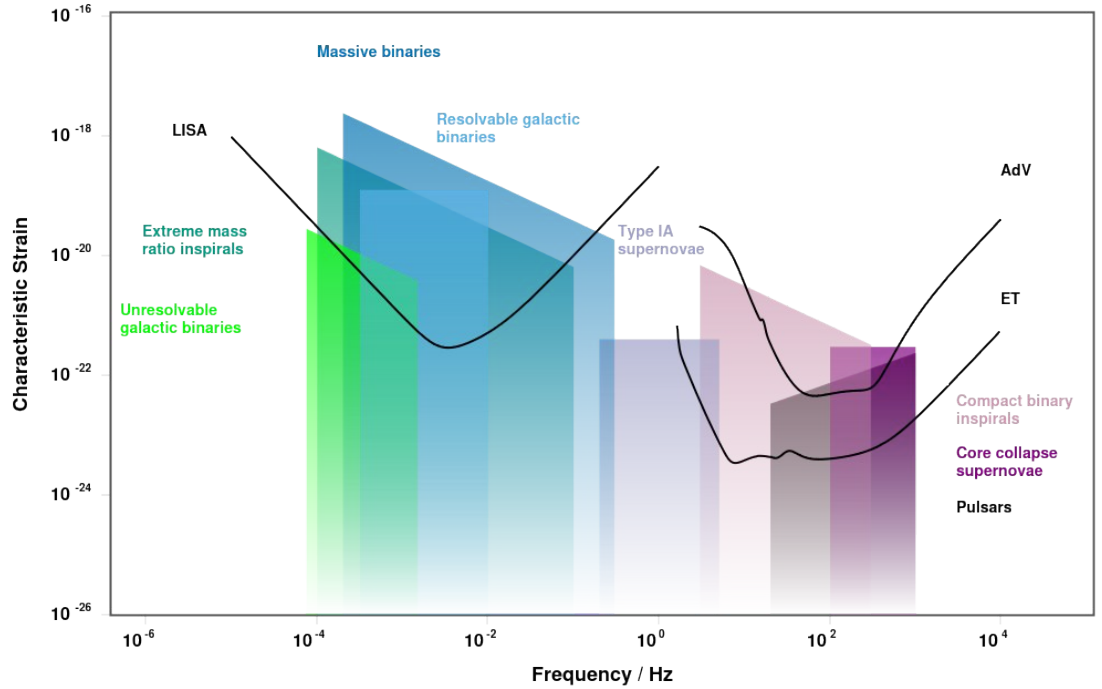
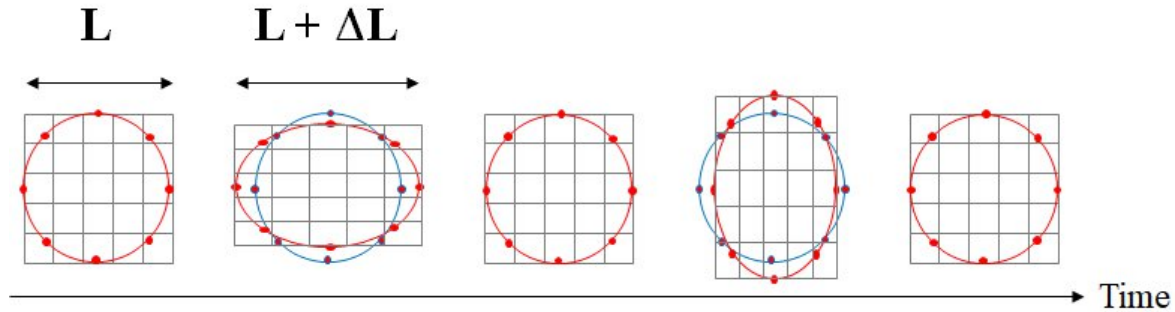
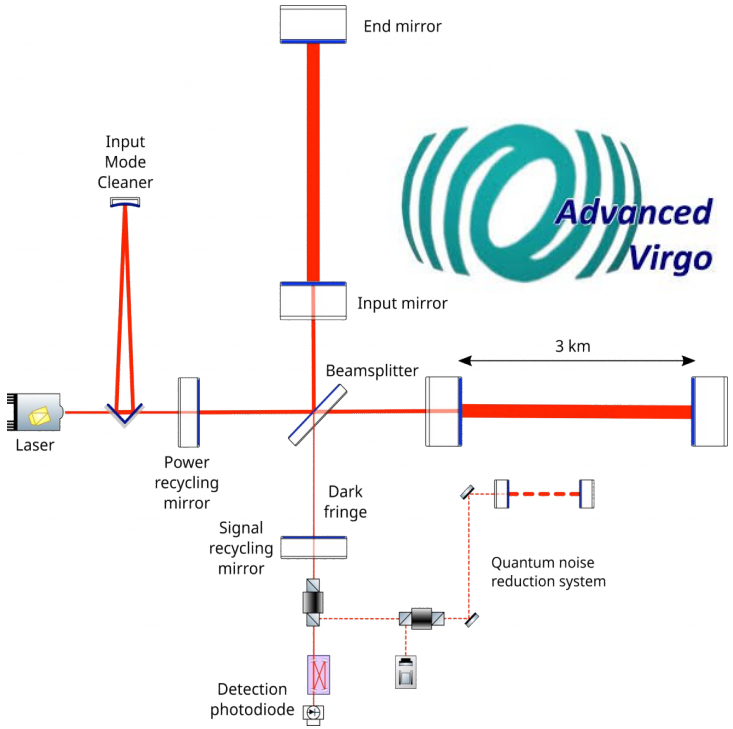


What is the observable?

- differential deformation of spacetime with $\frac{\Delta L}{L} \simeq \frac{h}{2}$



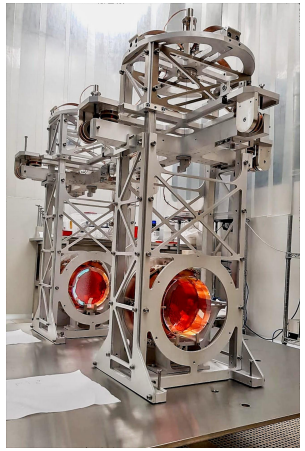
Advanced Virgo



Vacuum

~ 10 000 m³

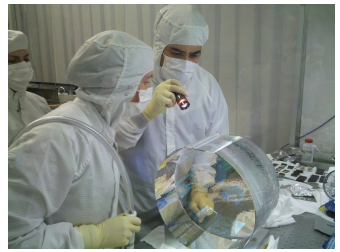
at a pressure of 10^{-9} mbar



Isolation

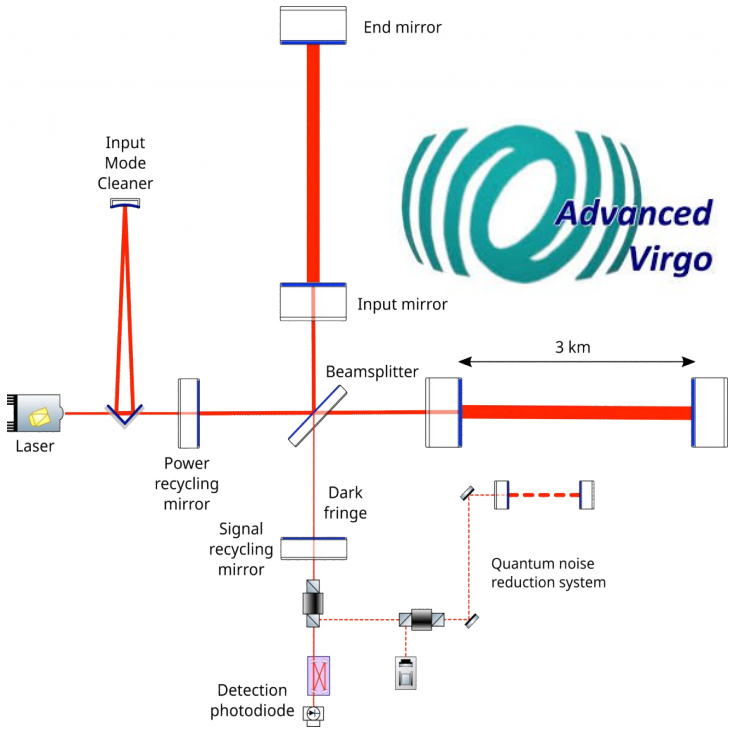
from ground motion with suspensions

Mirrors



Surface accurate to within 5 atoms and reflectivity at the technological limits

Advanced Virgo



An improved Michelson interferometer

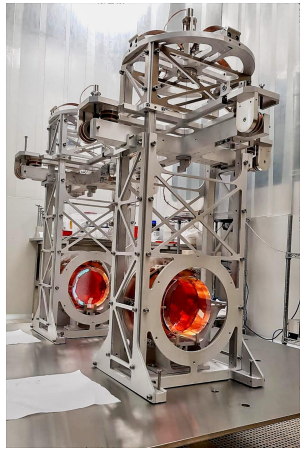
- Fabry-Perot cavities in the arms to increase the optical path
- Recycling of the power rejected by the interferometer
- Signal recycling to improve the signal-to-noise ratio
- Quantum noise reduction

Vacuum

~ 10 000 m³ at a pressure of 10^{-9} mbar

Isolation

from ground motion with suspensions



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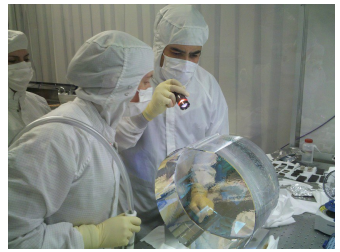
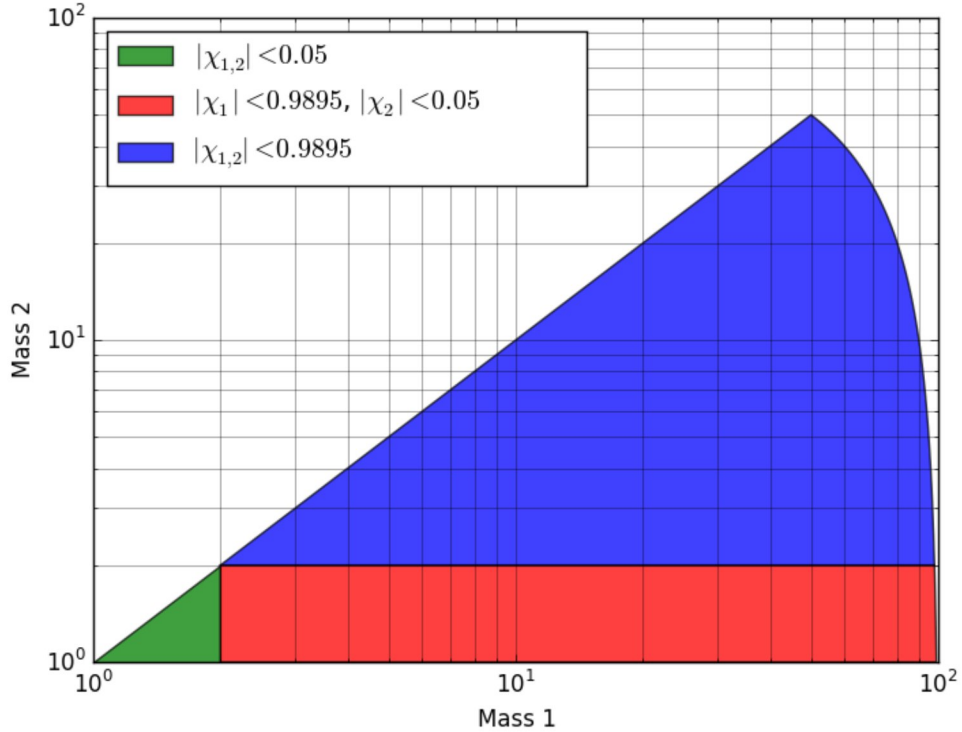


Surface accurate to within 5 atoms and reflectivity at the technological limits

Detection from the analysis point of view

- Taking into account the nature of the astrophysical objects we are looking for
- Different types of analysis depending on the type of signal (some using template banks of ~1 000 000 templates to do match-filtering analysis)
- Reconstructing the characteristics of the event



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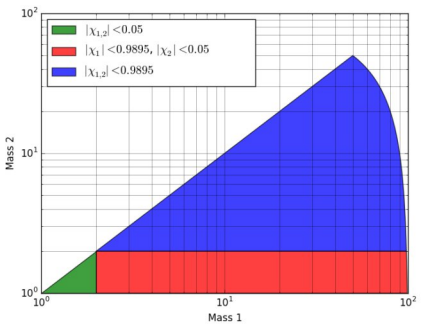
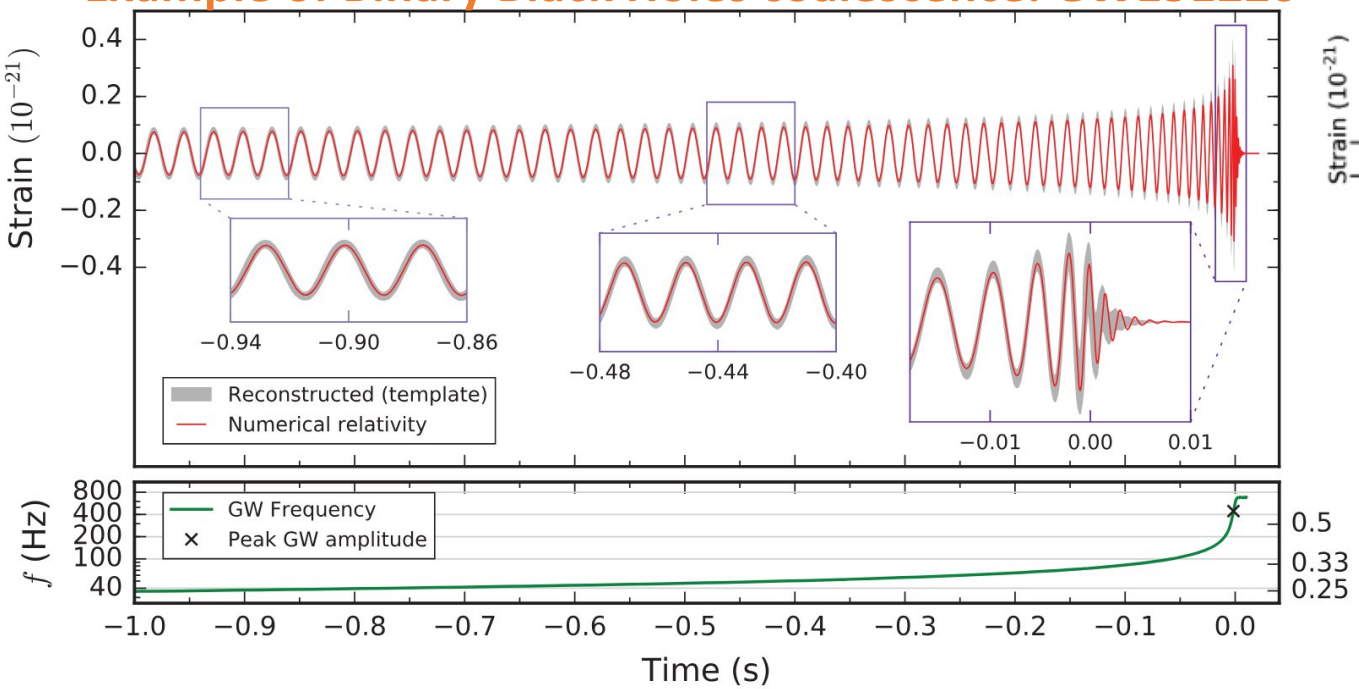
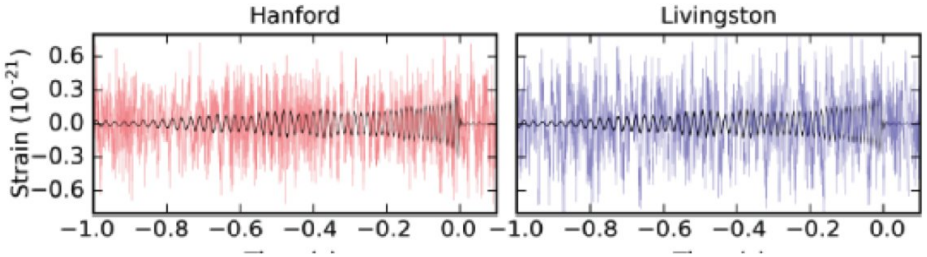
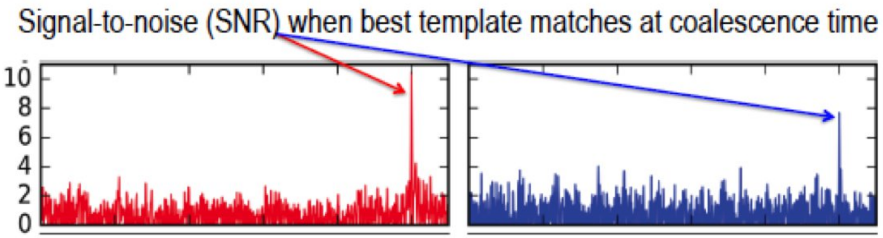


Example of Binary Black Holes coalescence: GW151226



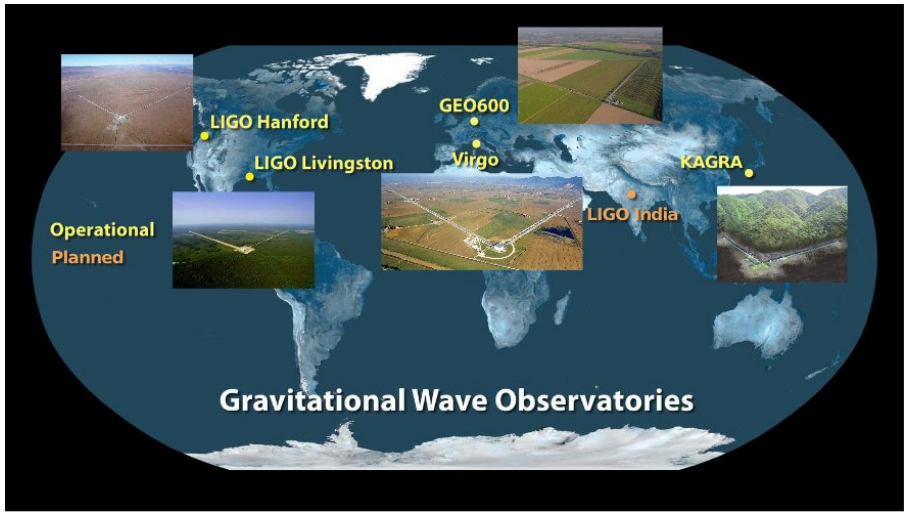


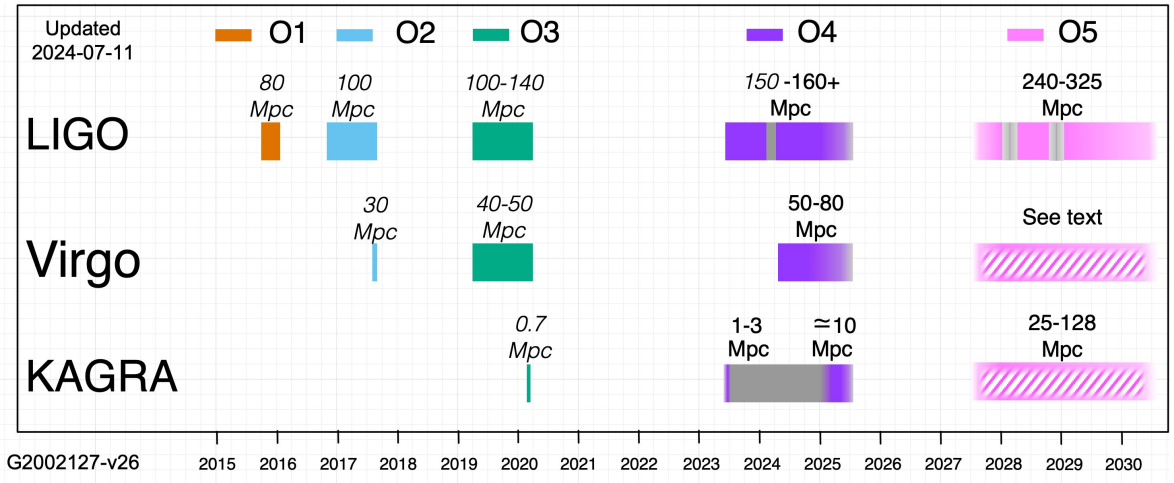


14.2$M_\odot$+7.5$M_\odot$->20.8$M_\odot$ @440 Mpc

RevLett.116.241103

Gravitational Wave astronomy today





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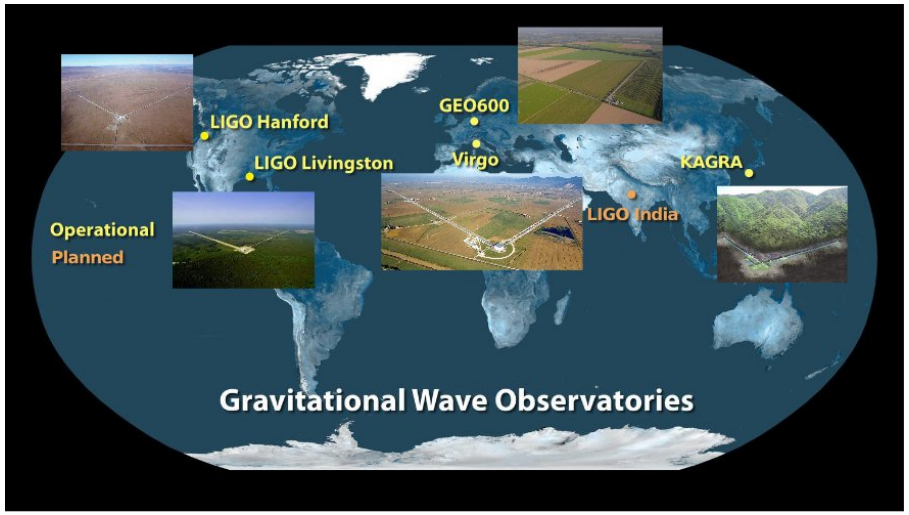
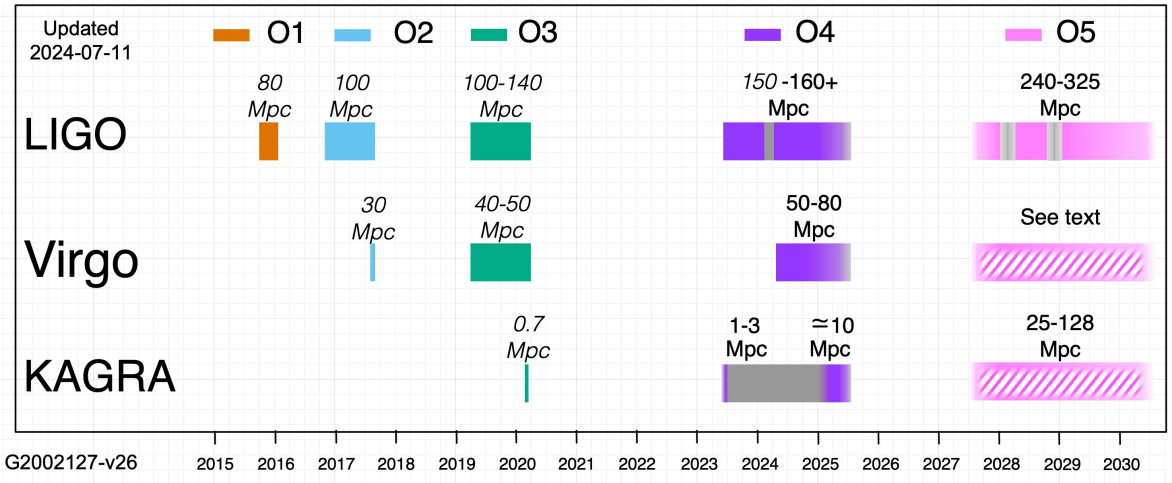
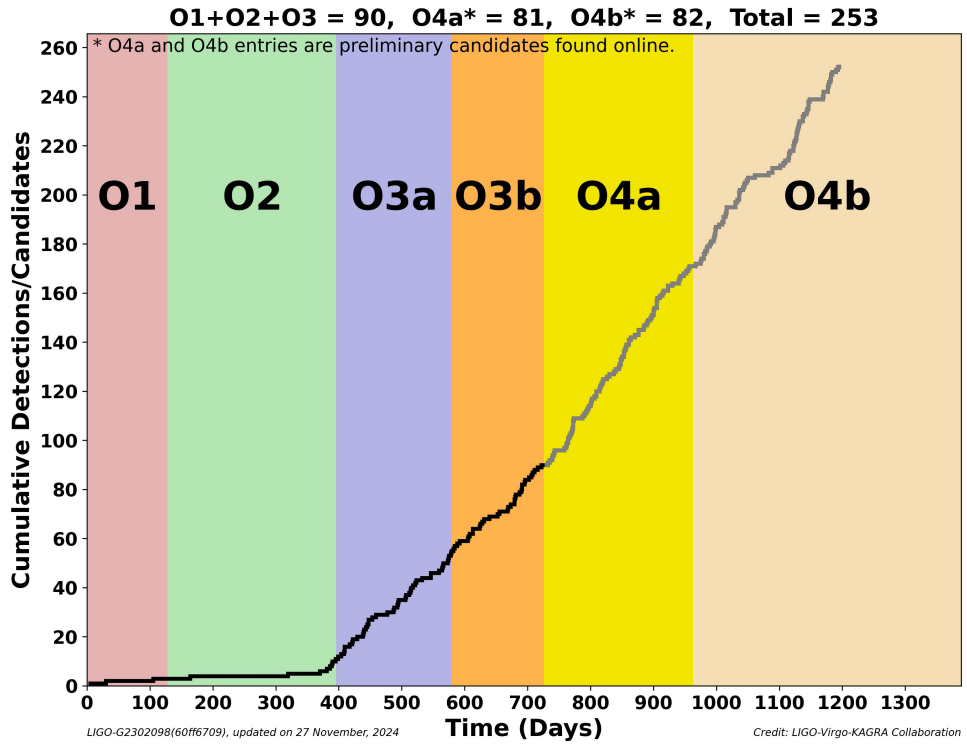




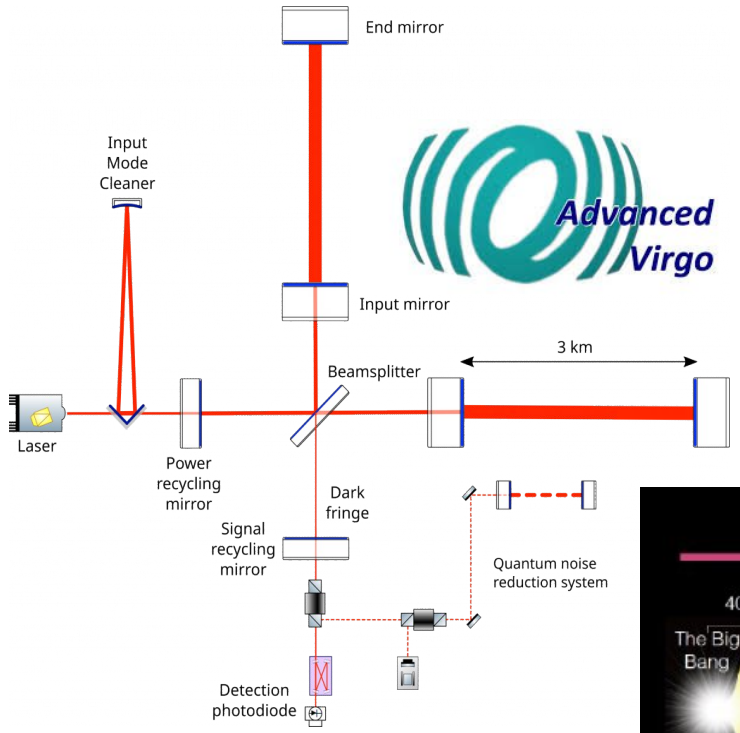


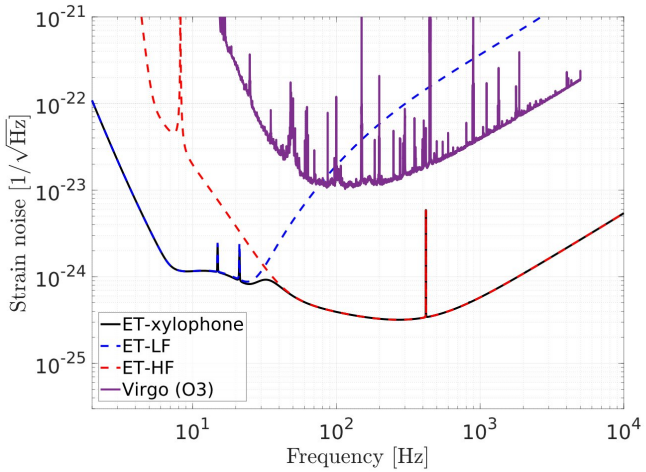
2024: ~250 detections (90 published from O1+O2+O3 and ~160 public alerts in O4).

➔ All consistent with Compact Binary Coalescences

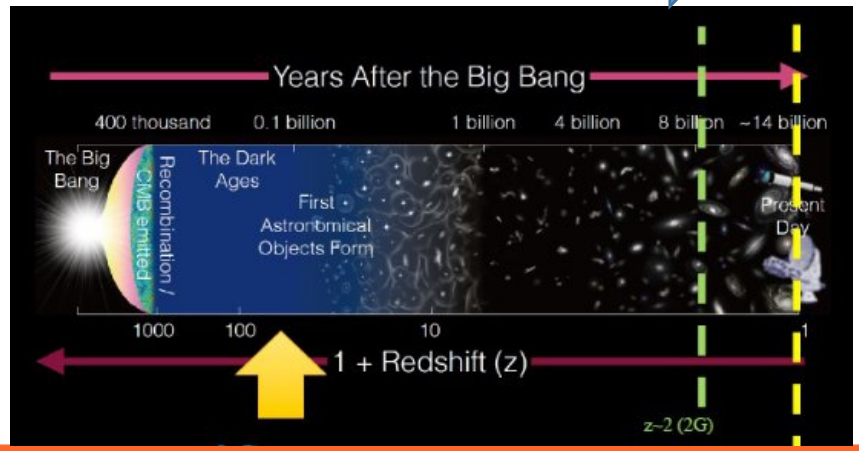
Towards next generation: everything bigger = more expensive

Advanced Virgo





Increase astrophysical reach



- 1 interferometer

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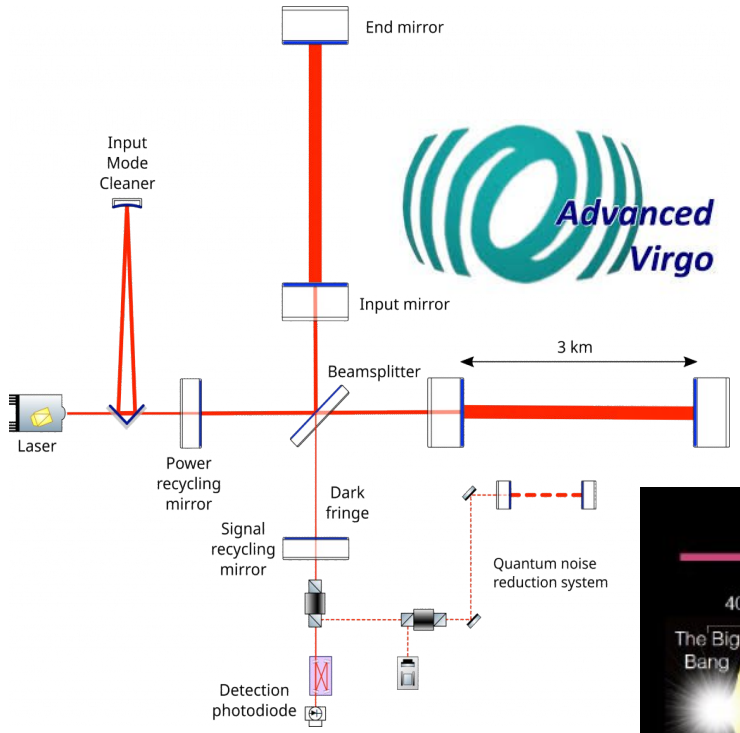

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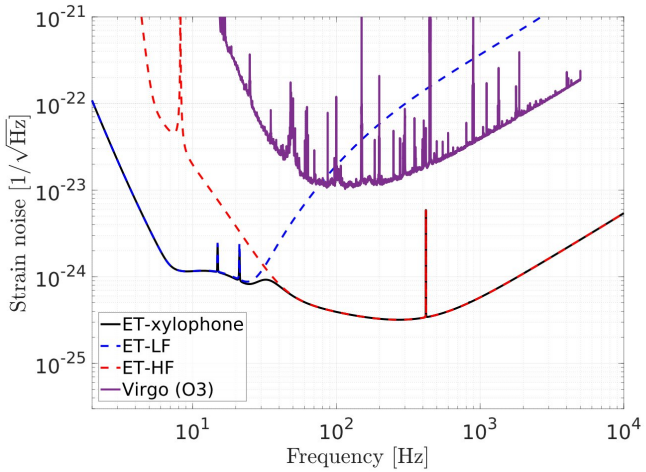

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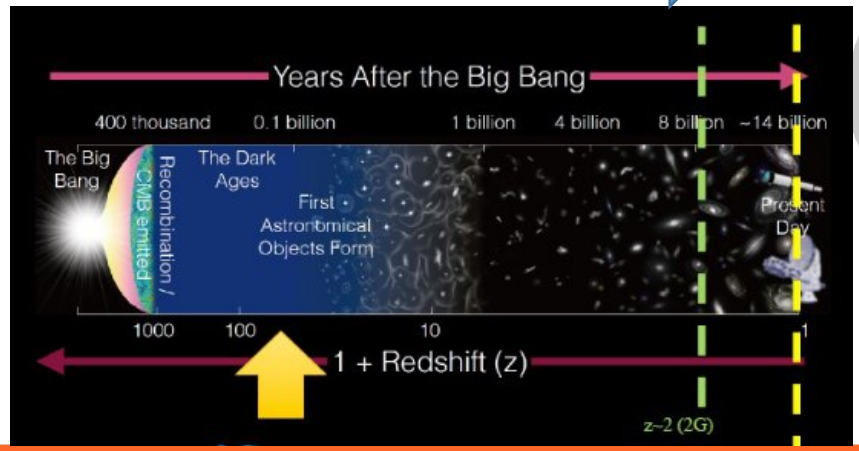
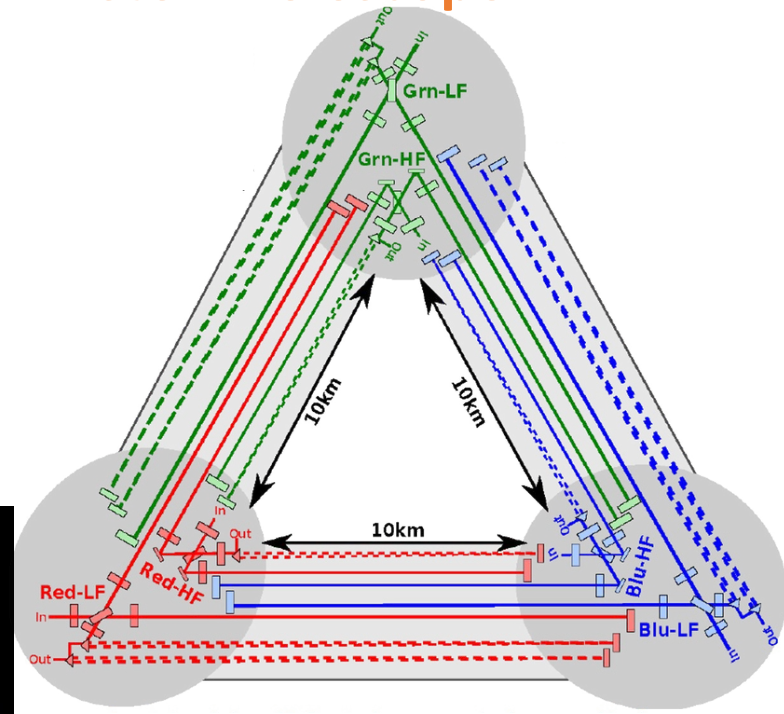


Einstein Telescope



- 3 "xylophone" interferometers
  High frequencies
  + Low frequencies

Low frequency

High frequency

Binary Black Holes coalescences up to cosmological distances

Extend the region of Black Holes masses

High masses (between 100 and 1000 $M_\odot$)

Low masses (below 1 $M_\odot$ => primordial)

Coalescence of Binary Neutron Star

Early warning
= Multi-messenger alert / observation

Up to the peak of star formation
Access to the merger phase
= Neutron Star Equation of State

Accurate tests of General Relativity

Low frequency — High frequency

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Accurate tests of General Relativity

New astrophysical sources (core collapse supernovae, isolated rotating Neutron Star, etc.)

Stochastic backgrounds from cosmological origin -> physics beyond the Standard Model

Test several dark matter candidates

Explore the nature of dark energy

Somes challenges of the data analysis

- High rate of Compact Binary Coalescence (CBC) detection:
  - LIGO-Virgo-KAGRA: ~1 signal per week to ~1 signal per day
  - Einstein Telescope: ~1 signal per minute
- As a consequence:
  - Overlapping signals: disentanglement and Parameter Estimation (PE)
  - CBC foreground mask other sources (stochastic background / other transients)
  - Computational cost: PE is expensive
    ➢ Need rapid PE for EM follow-up (chirp mass and sky position)

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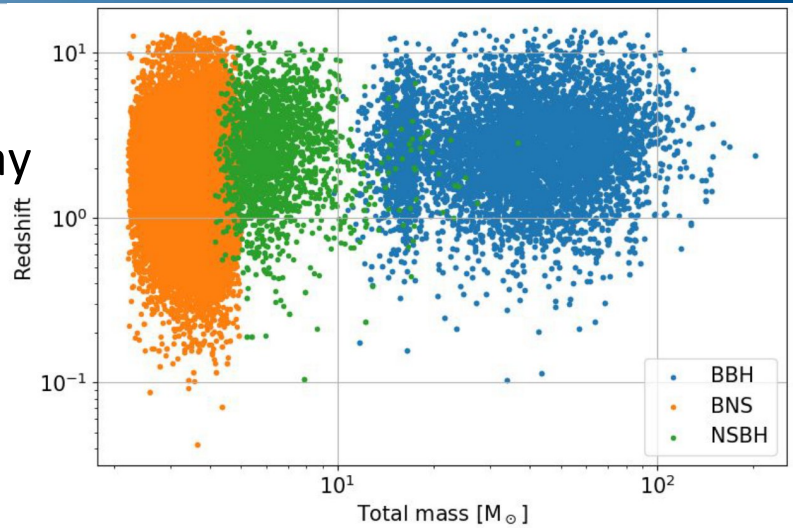
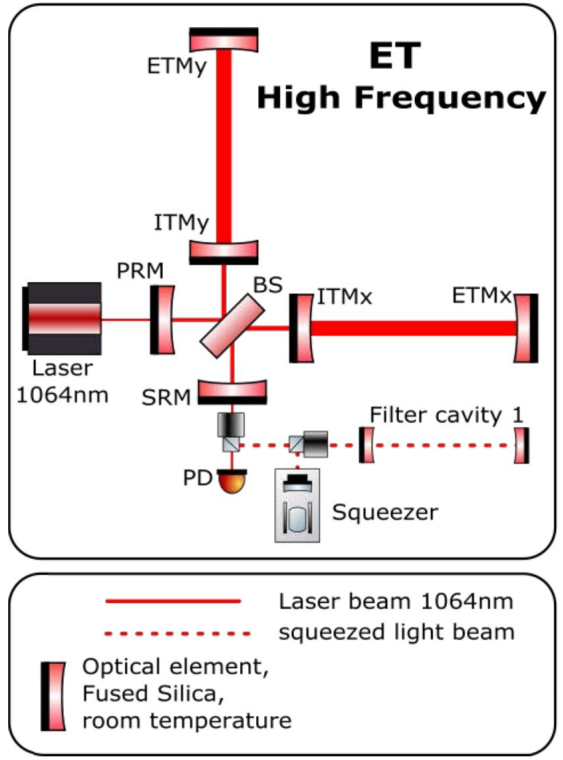
- Mock Data Challenges to prepare data analysis:
  - 2024: Dataset simulating 1 month of ET data (expected noise + realistic signal distribution = including long signals, overlapping signals, glitches, other source)
  - 2025: 2 new Mock Data Challenges to come



Some challenges of the High Frequency detectors

- High laser power in the arms:
  - 3MW (~100 kW now in Advanced Virgo)
  - Need a 300-500 W stabilized laser
  - Need to improve optical properties of the mirrors to avoid point absorbers



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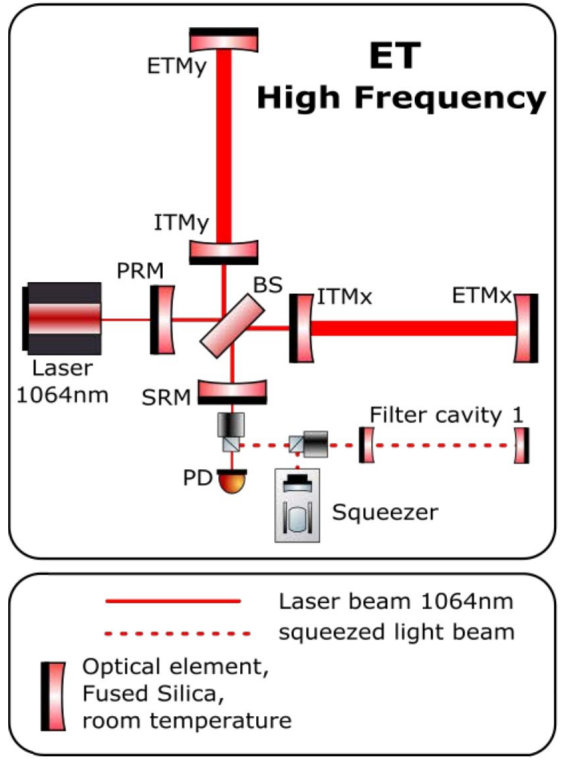
  - 62 cm diameter (35 cm now in Advanced Virgo)
  - 200 kg to be suspended (42 kg now in Advanced Virgo)



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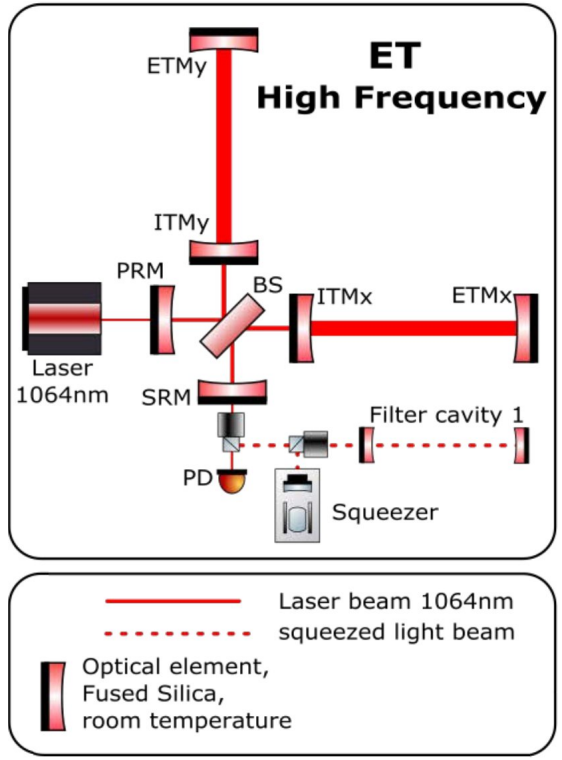
  - 10 dB effective (~3 dB now in Advanced Virgo)
  - 1 km-long filter cavity (285 m in Advanced Virgo)



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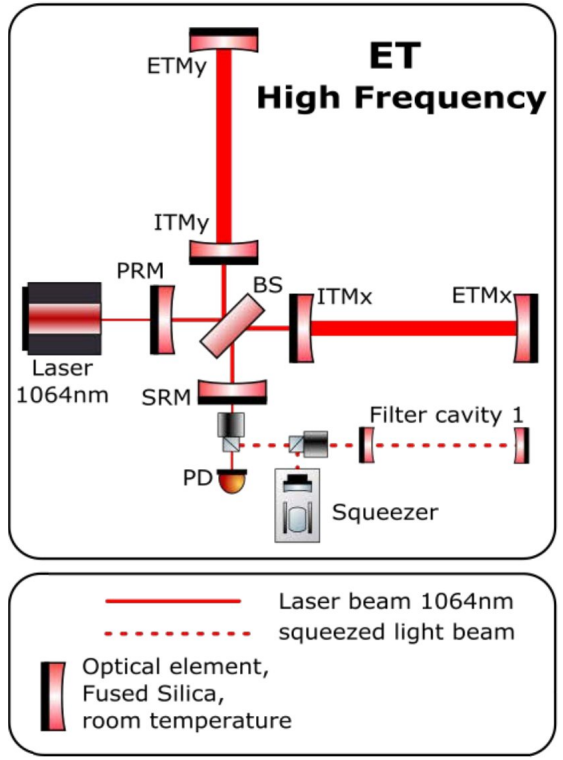
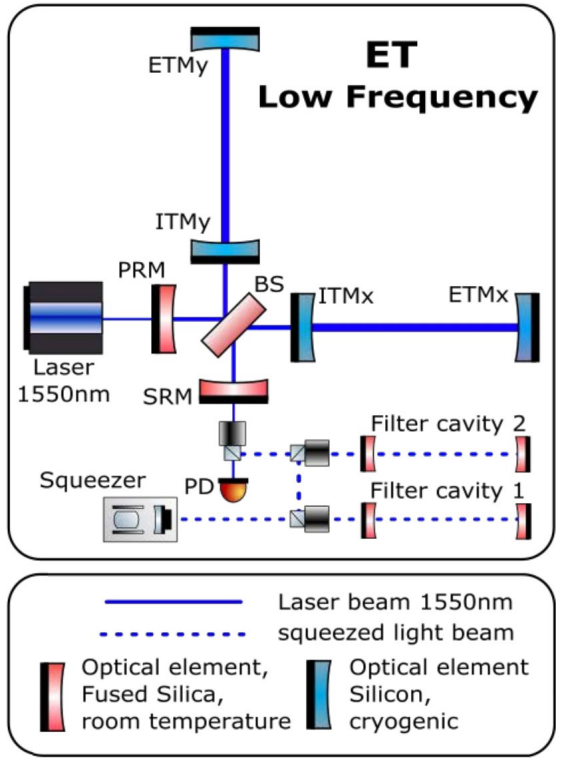
Similar to current generation but bigger!



Some challenges of the Low Frequency detectors

- Test masses at cryogenics temperature:
  - Cool down test mass mirrors (and only them) at 10-20 K without introducing vibration (for instance via the suspensions)
  - Develop huge cryostat at 2K (surrounded by 2 thermal shields at respectively 50-80K and 5K)
  - Change of mirror substrate (silicon or sapphire) and wavelength in the case of silicon (1550 nm or 2 µm) (1064 nm in Advanced Virgo)
  - New coatings to be developed
  - 45 cm diameter, 211 kg (at the technology limit)



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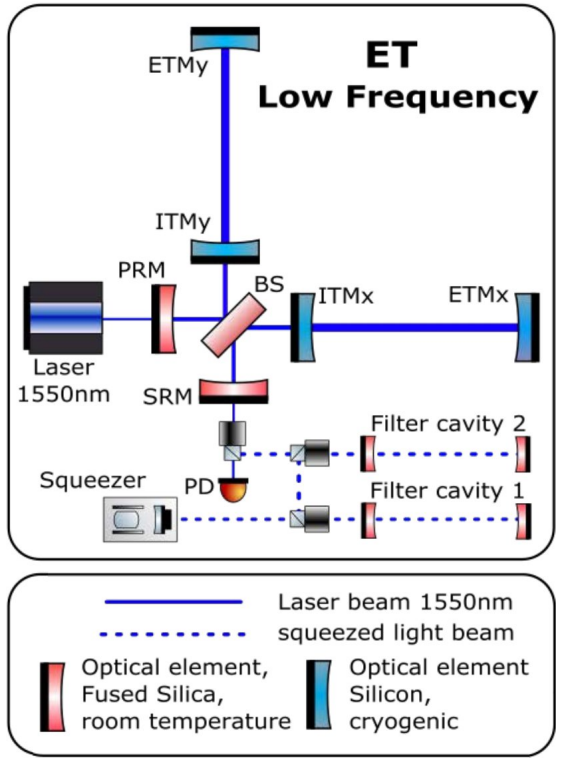

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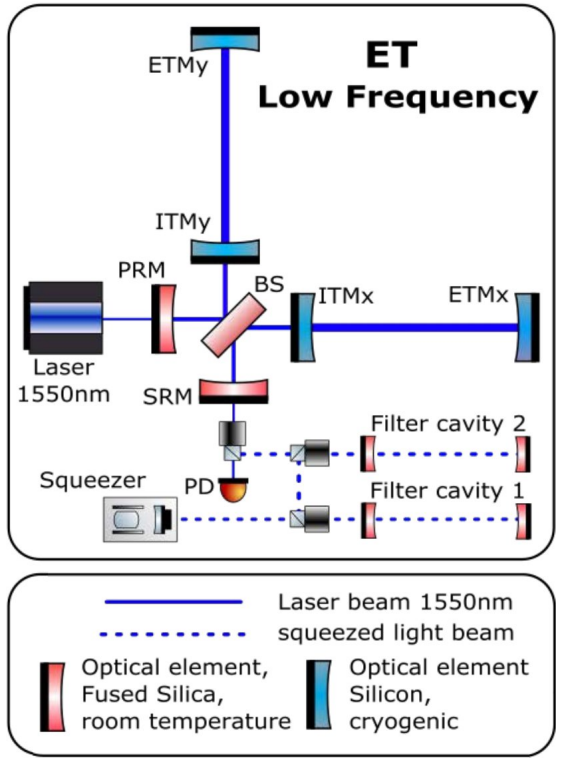
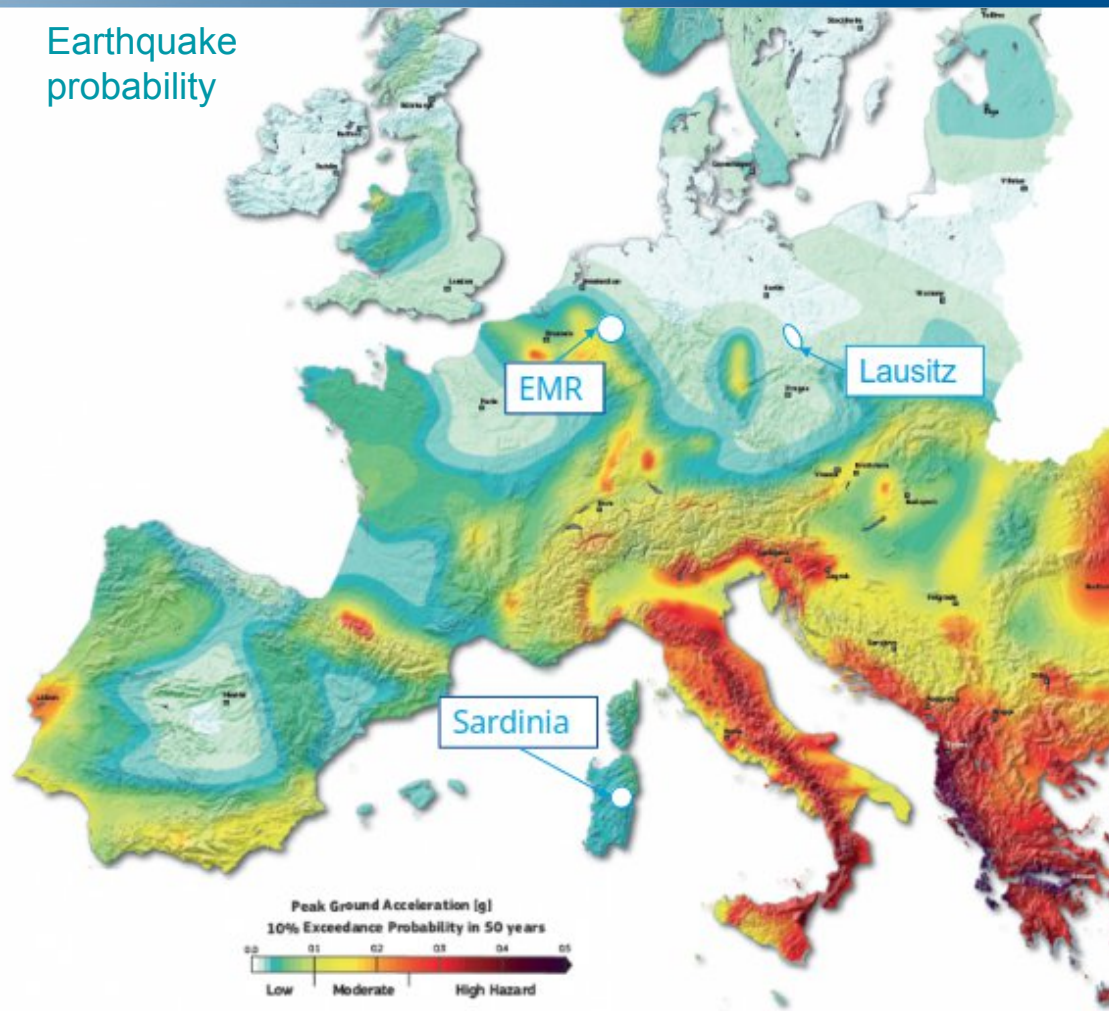


Lot's of new technologies to be developed!

- Still 2 big question marks:
  - **What will be the final geometry of Einstein Telescope?**
    ➢ A triangle (completely new)
    ➢ Two L (like current generation)
    ➢ First physics analysis : JCAP07(2023)068
    ➢ Risk analysis and mitigation strategies to follow

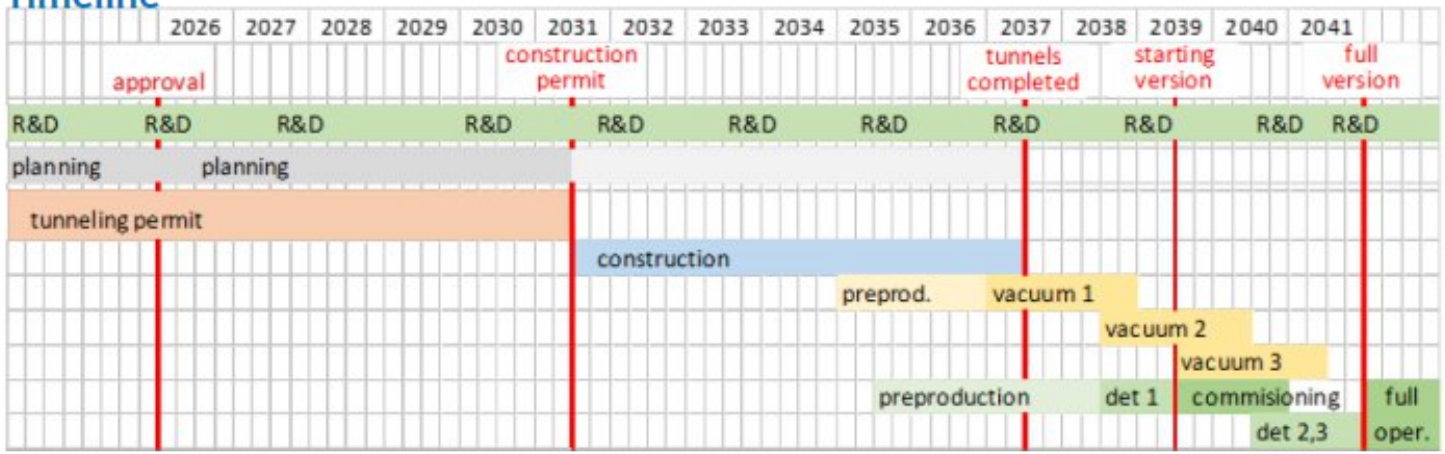
Einstein Telescope Configuration and localization

- Still 2 big question marks:
  - **What will be the final geometry of Einstein Telescope?**
    ➢ A triangle (completely new)
    ➢ Two L (like current generation)
    ➢ First physics analysis : JCAP07(2023)068
    ➢ Risk analysis and mitigation strategies to follow
  - **Where will be constructed Einstein Telescope?**
    ➢ 2(+1) candidate site: EMR, Sardinia (+Lausitz)
    ➢ One or two sites (in case of L-shape)?



Timeline and Cost estimation

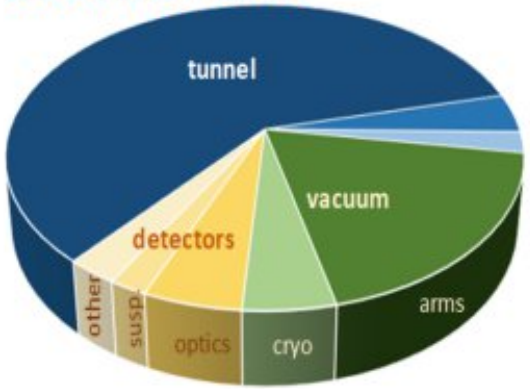
Timeline



Milestones

year	major milestone
2026	Temporary legal entity installed
2031	Tunneling permit granted
2037	Underground construction completed
2038	Vacuum system of the first detector completed
2039	First GW detector installed
2040	Commissioning of first detector completed
2041	All GW detectors installed
2041	Operation of full ET version started

Construction Costs



tunnel	1.438 M€
surface buildings	98 M€
underground services	53 M€
	1.589 M€
arm vacuum	450 M€
cryo vacuum	117 M€
	567 M€
optics	125 M€
suspensions	48 M€
others	65 M€
	238 M€
	2.394 M€

Based on Amberg/Tractel Study 2023

Operational costs

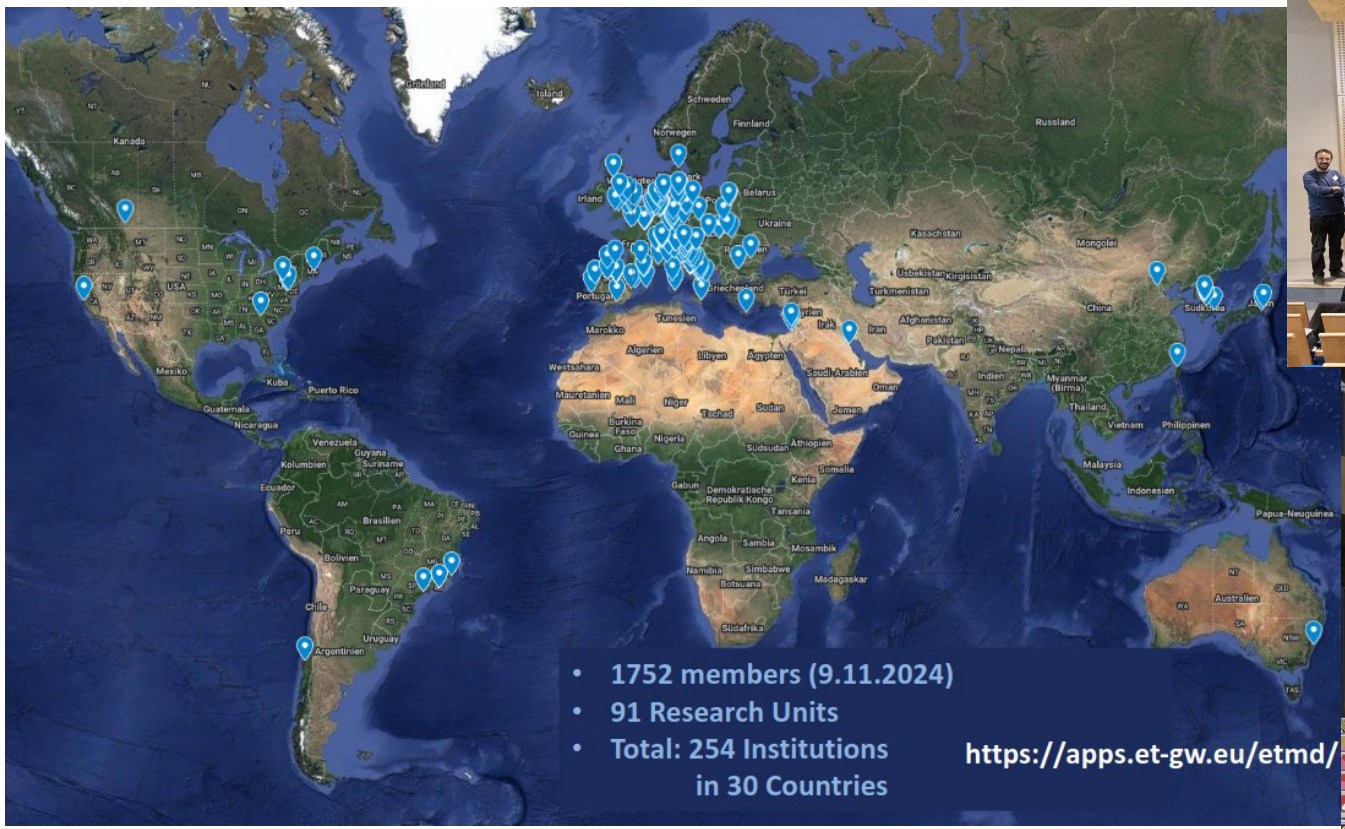
50M€/y Ramping up until start of operation

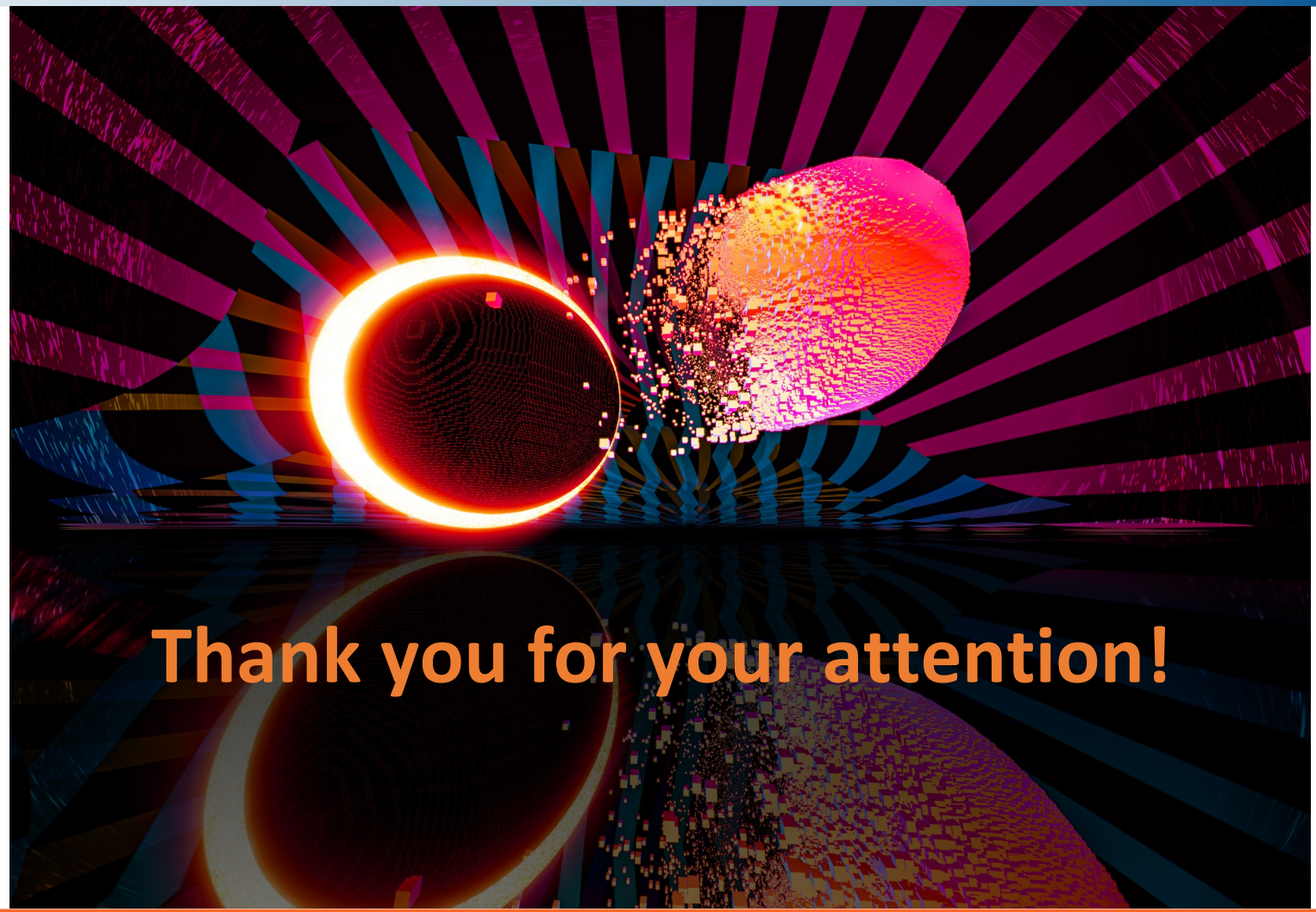
→ Sum= 1075M€ (Until start of operation + first 15 years)

Deep data analysis not included

Based on LVK

The Einstein Telescope Collaboration




Thank you for your attention!