Observing the Universe with Gravitational Waves

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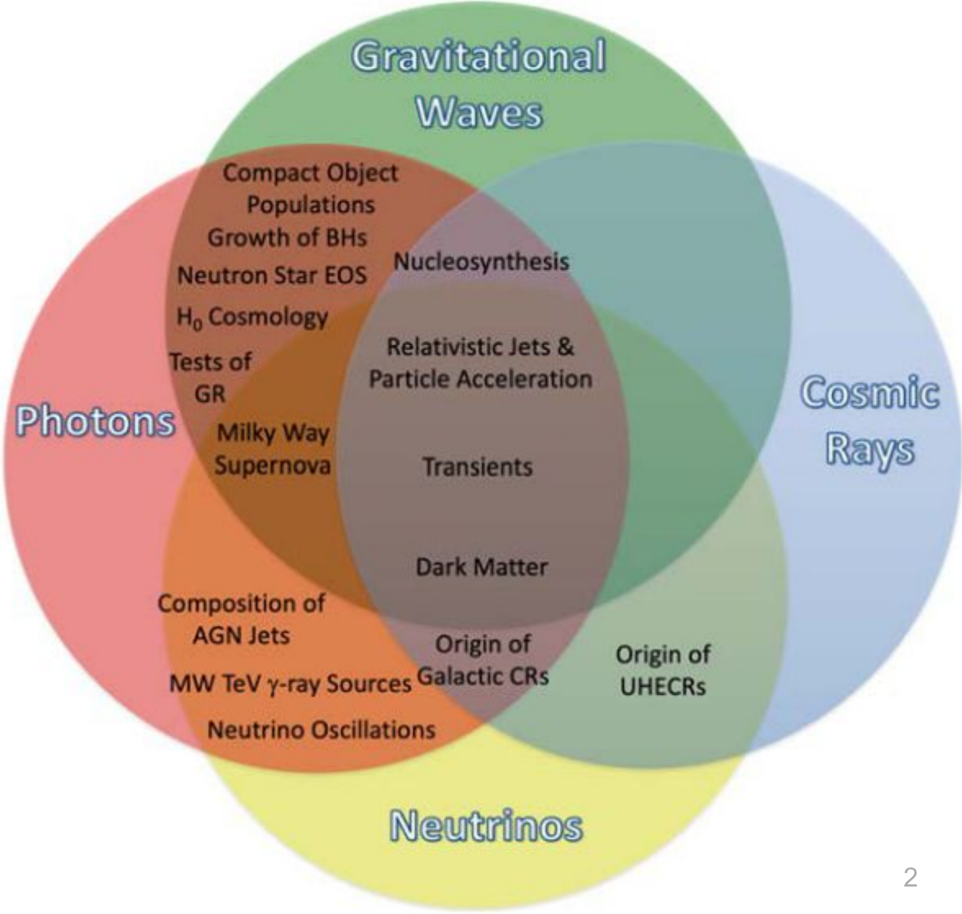
Multiple messengers to solve long standing questions

2015: birth of GW astrophysics

2017: birth of multimessenger astronomy:

- BNS merger observed with GWs and sGRB
- neutrino detected during a blazar flare

To enable discoveries and answer questions: build powerful observatories



Pathways to Discovery in Astronomy and Astrophysics for the 2020s (2021)
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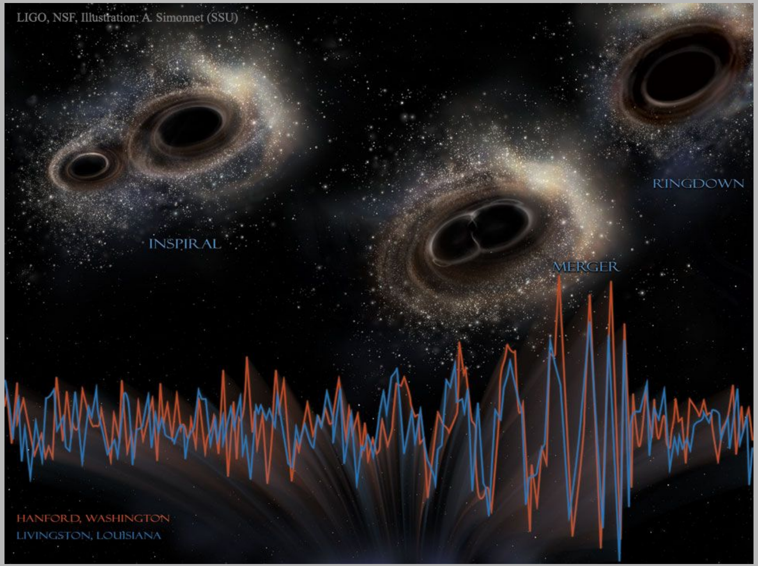
Outline

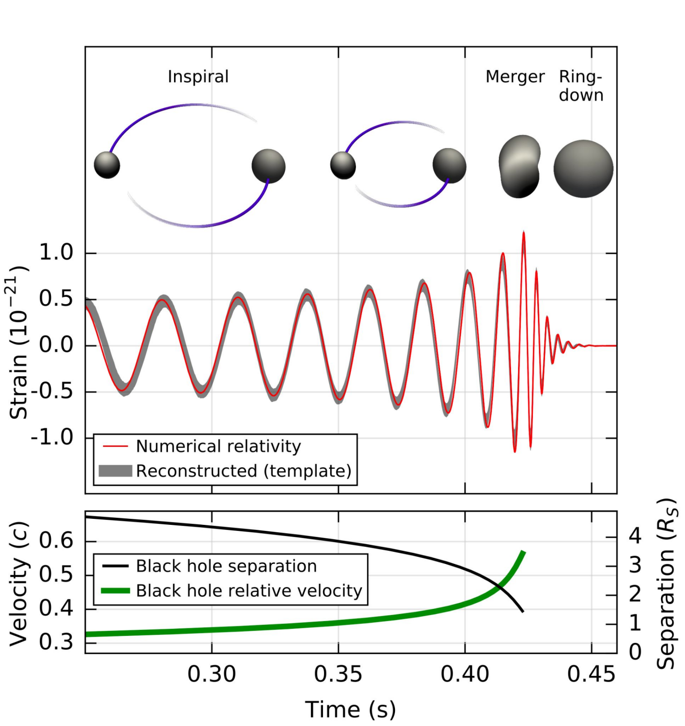
- From GW150914 to a full catalog of GW events: highlights
- How we can learn more with GWs
- The instruments for the future

GW150914

The first direct observation of a Gravitational Wave

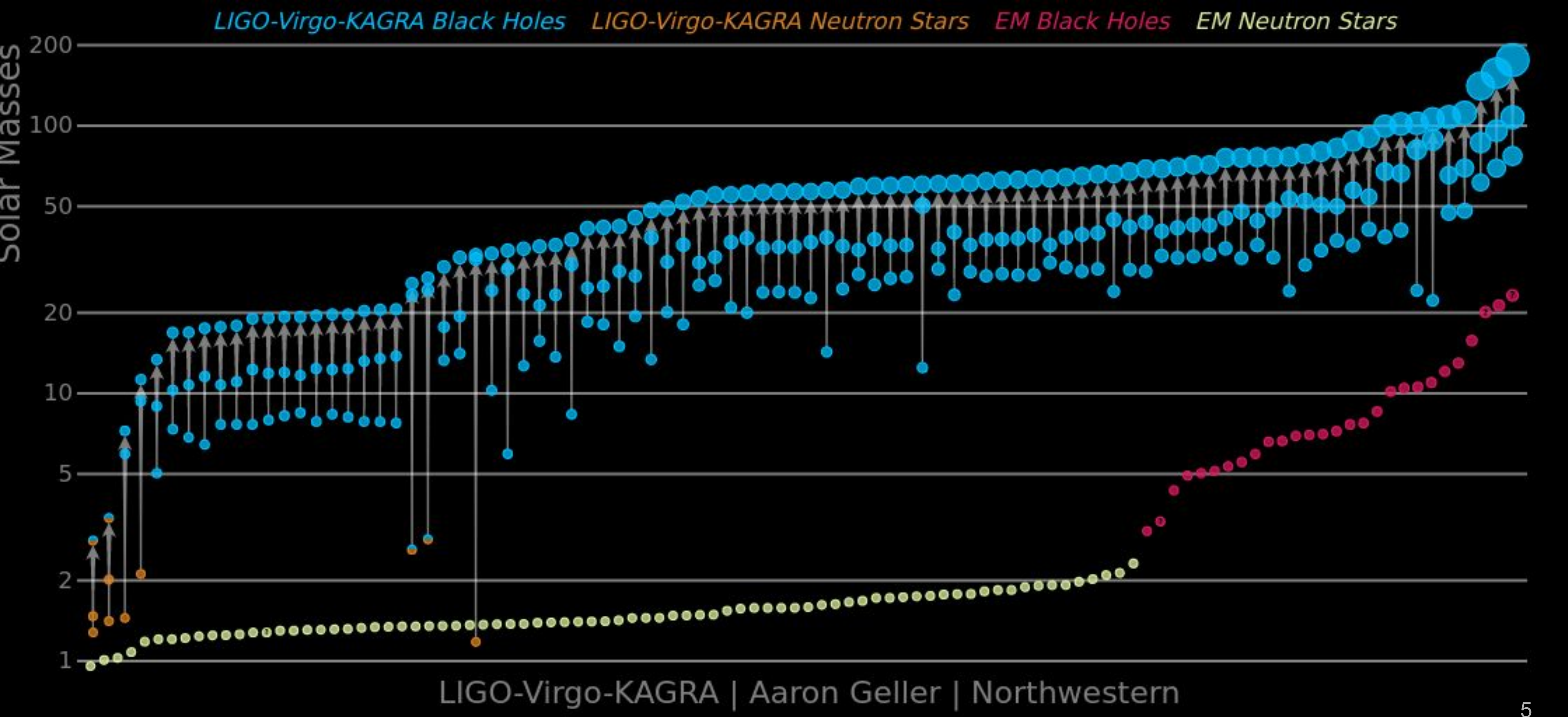
The coalescence of a binary system of black holes, 1.3 billion years ago





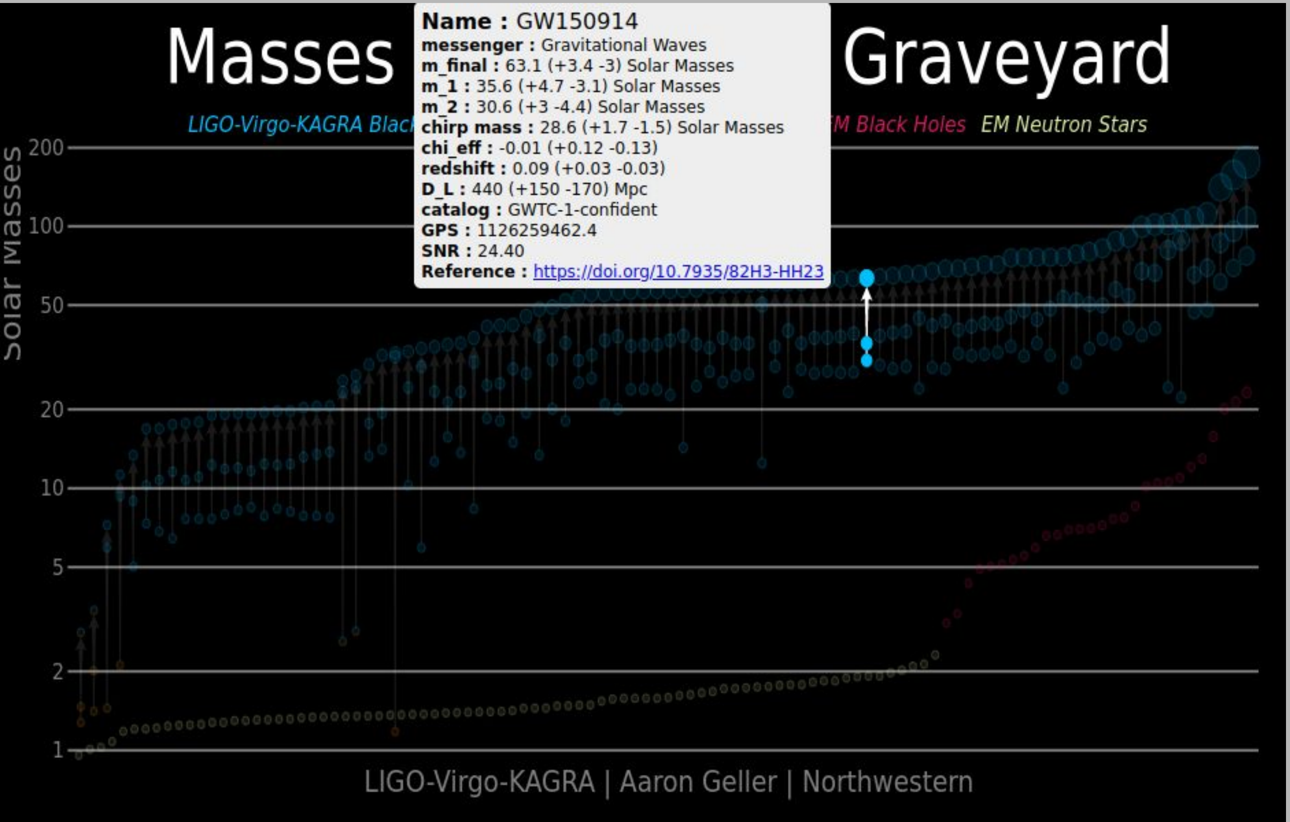
Phys. Rev. Lett. 116, 061102

GWTC-3 : 3rd catalog of GW observations! 90 events



GW150914

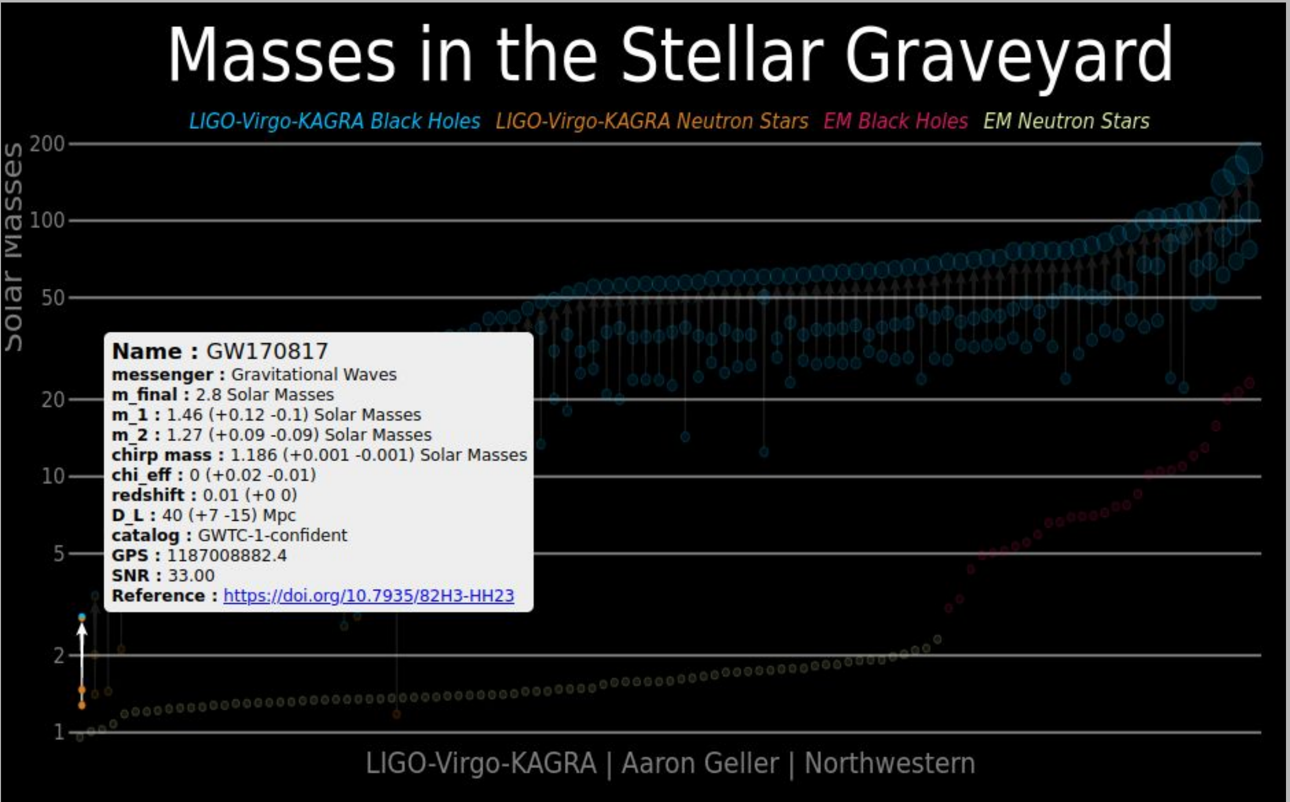
A Binary Black-Hole merger



- confirms a key prediction of Einstein's theory of general relativity
- demonstrates the existence of stellar-mass black holes more massive than ≃25$M_\odot$
- establishes that binary black holes can form in nature
- provides the first direct evidence that black holes merge within a Hubble time.

GW170817

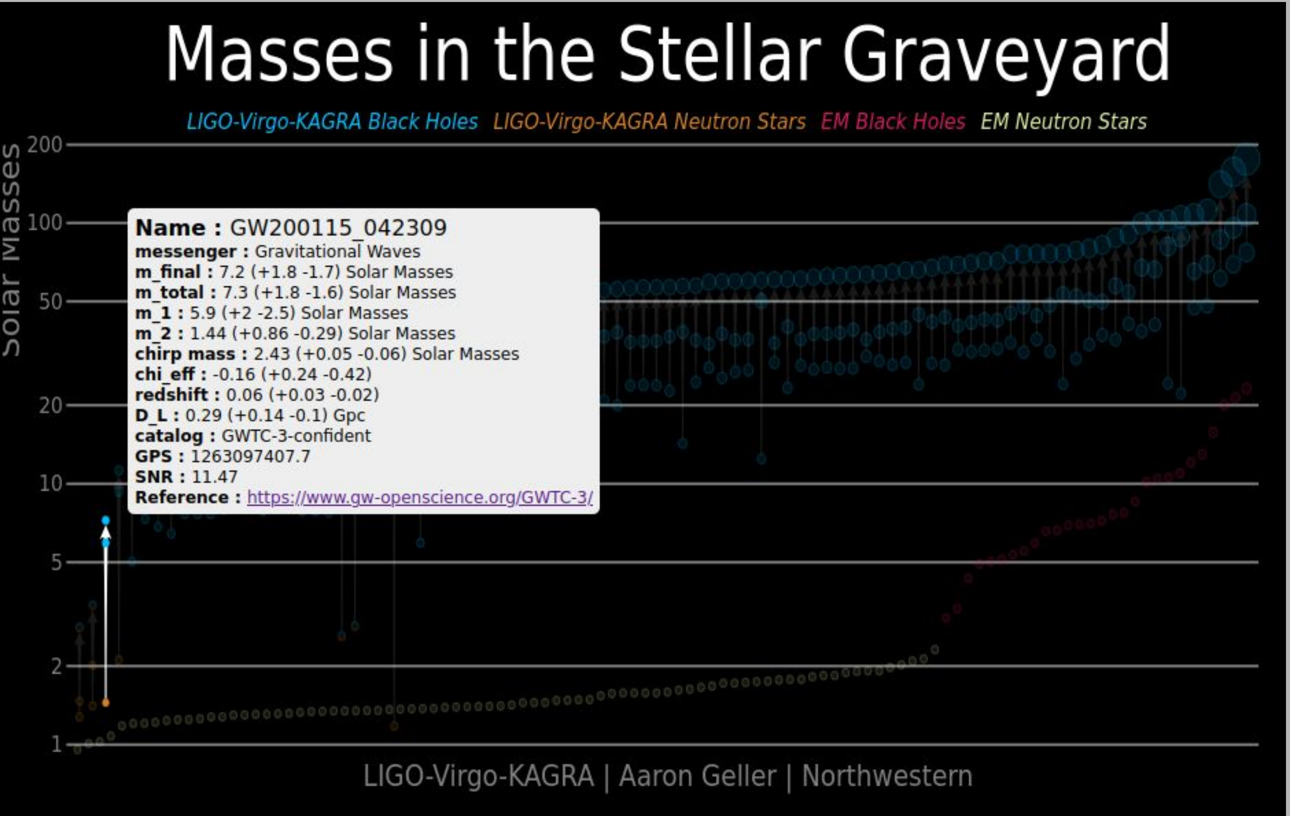
A Binary Neutron Star merger



- Localisation capabilities of a GW source (28 deg^2)
- First cosmic event viewed in both GW and light.
- First direct evidence that at least a fraction of sGRB have BNS system as progenitor
- Led to largest astronomical observation campaign
- Binary neutron star mergers produce kilonova explosions that generate heavy elements
- Constraining EOS of NS
- Measurement of the GW propagation speed
- Test of GR
- Alternative measurement of H_0
- ..

GW200115_042309

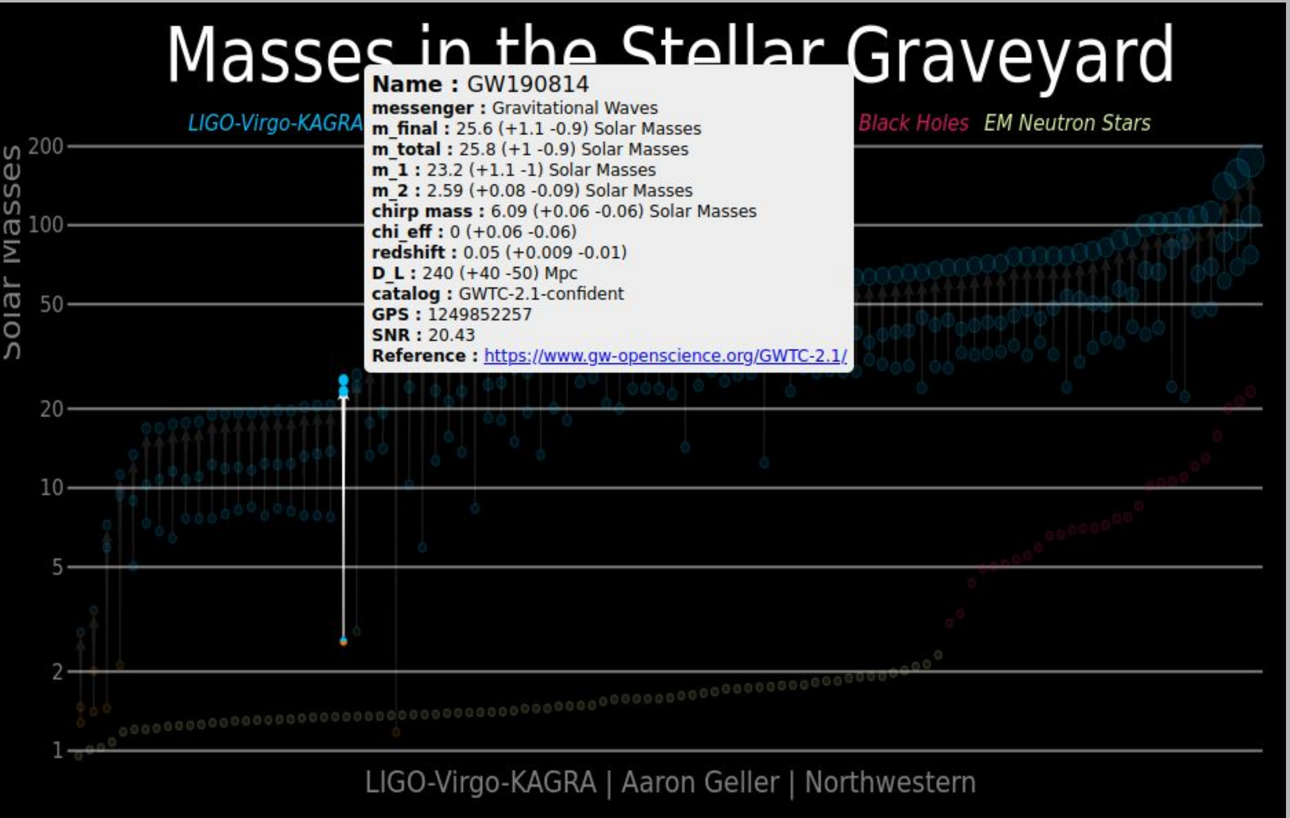
First confirmed detection of NSBH merger



- Finally found the missing type of binary! In fact NSBH were predicted to exist, but convincing observational evidence was missing
- Consistent with any plausible formation channels
- first direct measurements of the NSBH merger rate

GW190814

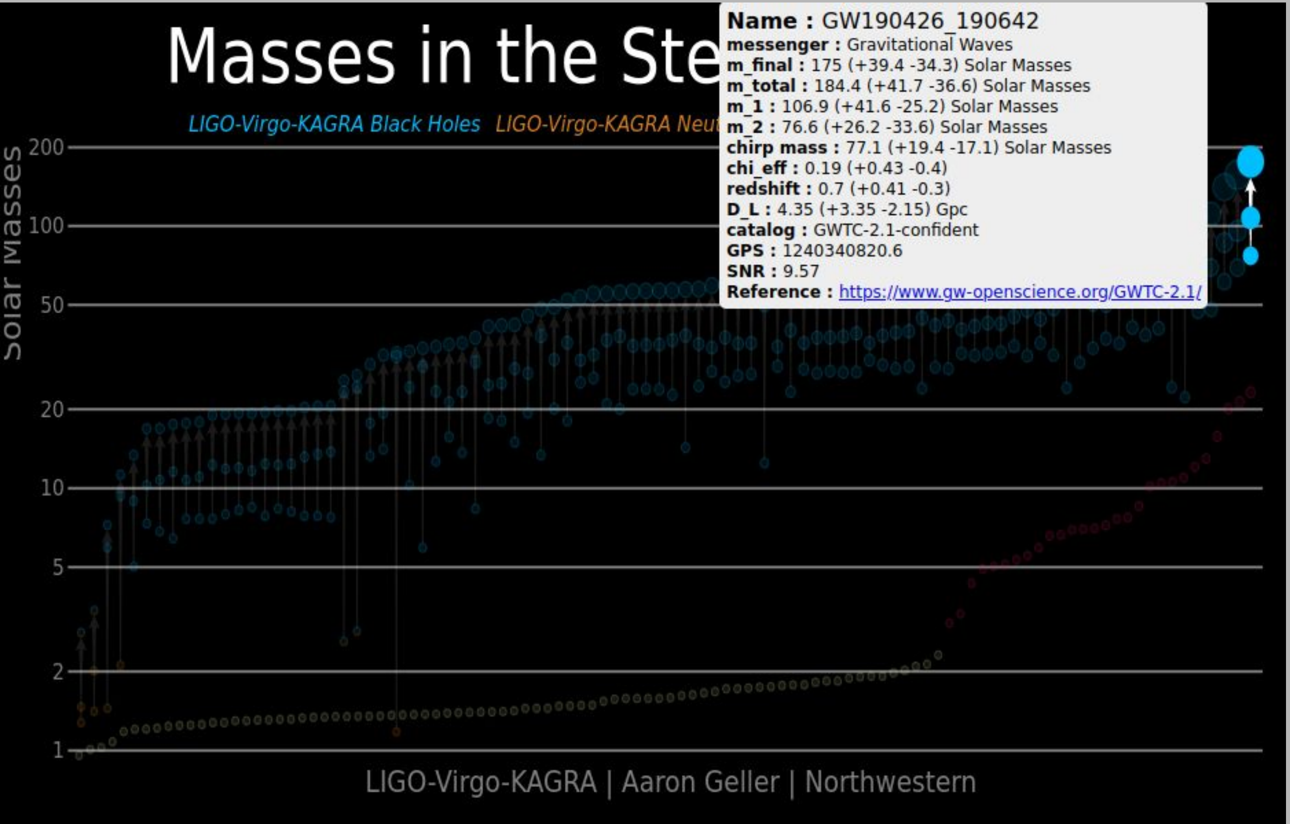
The most mass asymmetric GW event



- Best localised source (22 deg^2)
- Mass asymmetric GW event:
  - Primary is a BH;
  - secondary is in the lower mass gap: massive NS or very small BH?
- Compact objects exist with masses between 2-5 Msun
- Strongest evidence for higher-multipoles of Gravitational radiation
- Test of GR on strongly asymmetric mass distribution
- So good localization allows H_0 measurement only with GW signal (+ galaxies catalogues): best dark siren to date

GW190426_190642

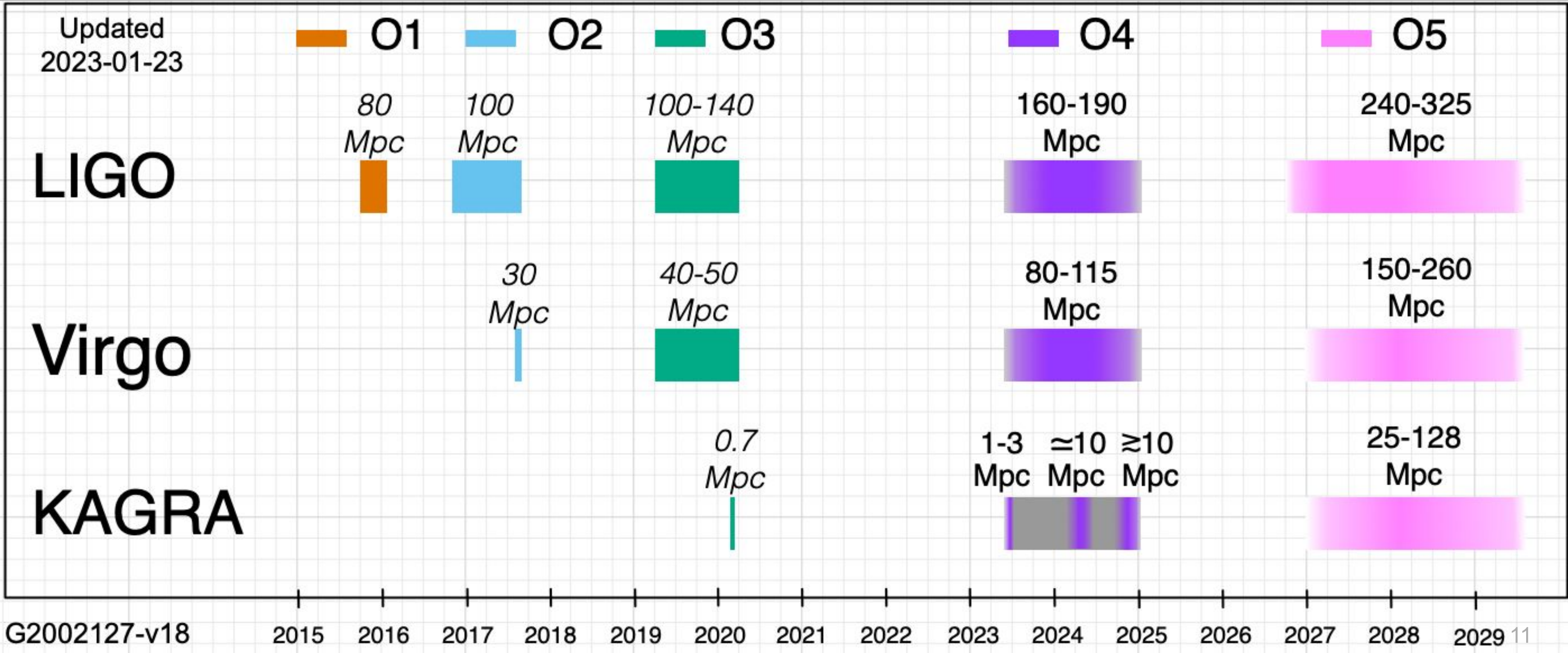
Most massive system detected with GWs



- The highest mass of all binary mergers reported by LVK
- Both components fall in the mass gap predicted by isolated evolution (pair-instability supernova theory)
- Final body is IMBH

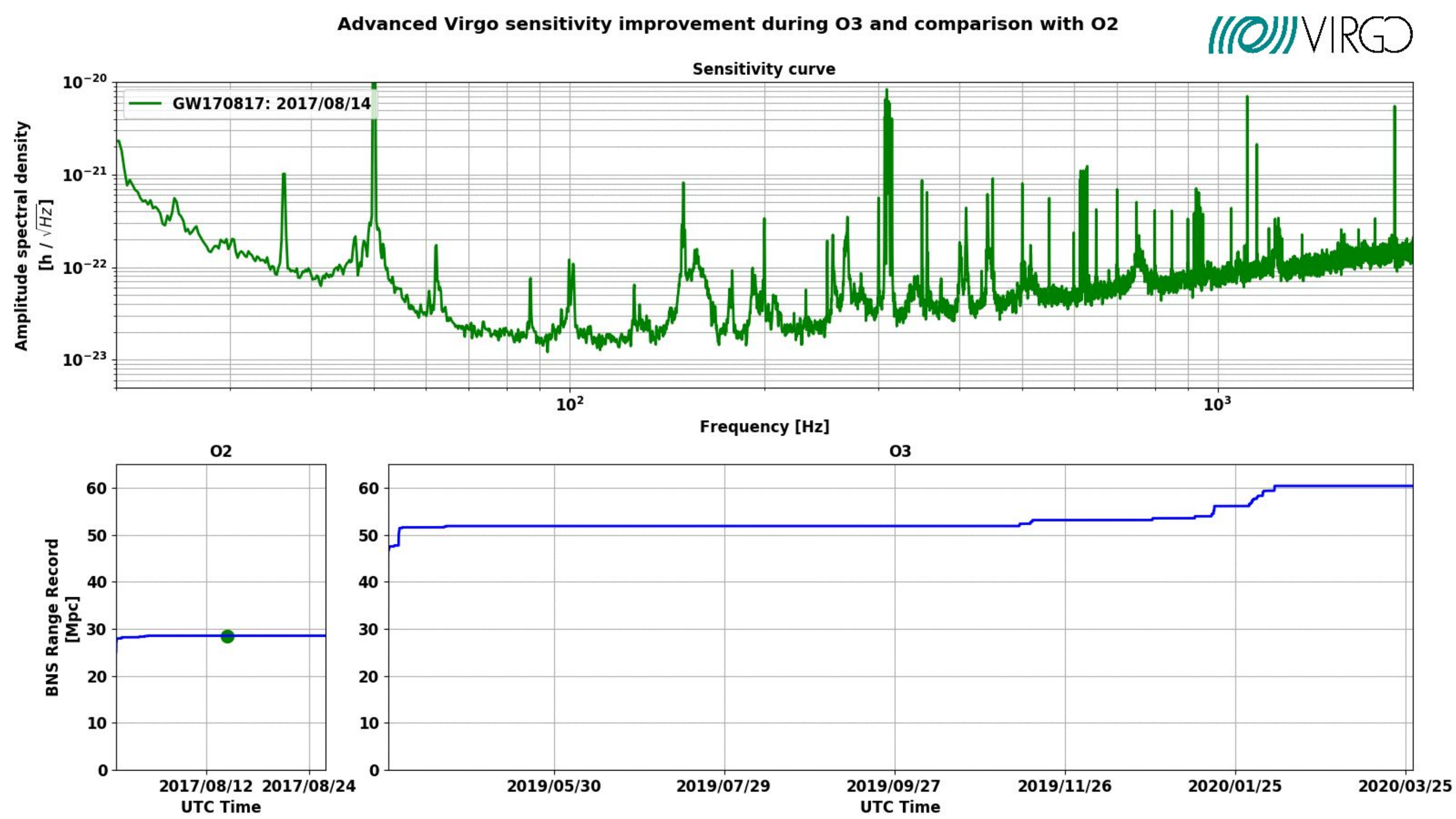
Near future

Current detectors have a well defined plan of upgrades and science runs

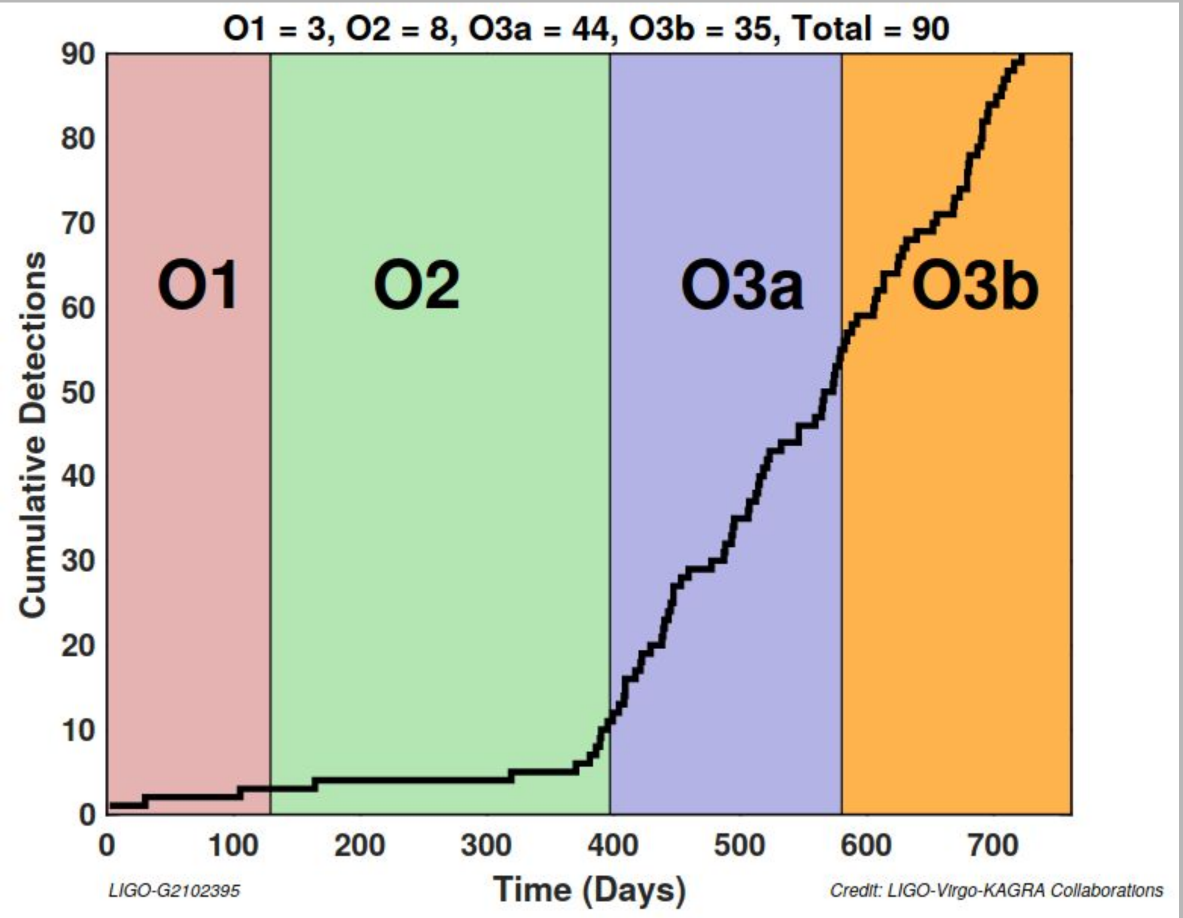


Evolution in sensitivity

Continuous effort to improve the detector performances over time



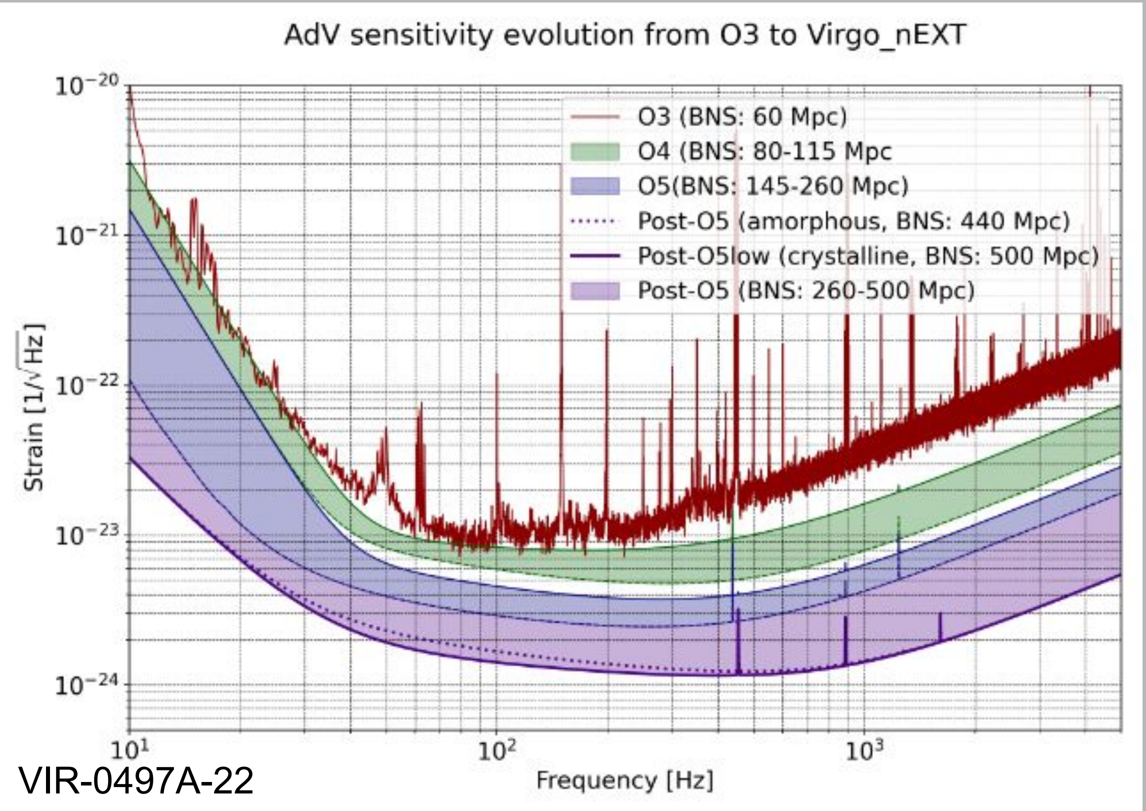
The past observing runs



Number of detectable events is the product of the event rate times the Time x Volume of reachout

More advantageous strategy is to increase the reachout (ie the sensitivity) than keep observing with a sensitivity that can be improved

Evolution in sensitivity



VIR-0497A-22

Advanced Virgo after O3:

- **Phase I:** reduce quantum noise, reach thermal noise limit.

BNS range: ~100 Mpc -> O4

- **Phase II**: lower the thermal noise wall.

BNS range: ≳200 Mpc -> O5

From 2nd to 3rd generation GW detectors

Advanced LIGO and Advanced Virgo have already achieved awesome results, even with a sensitivity below the nominal one.

This is **only a first step** toward our exploration of the Universe with GWs

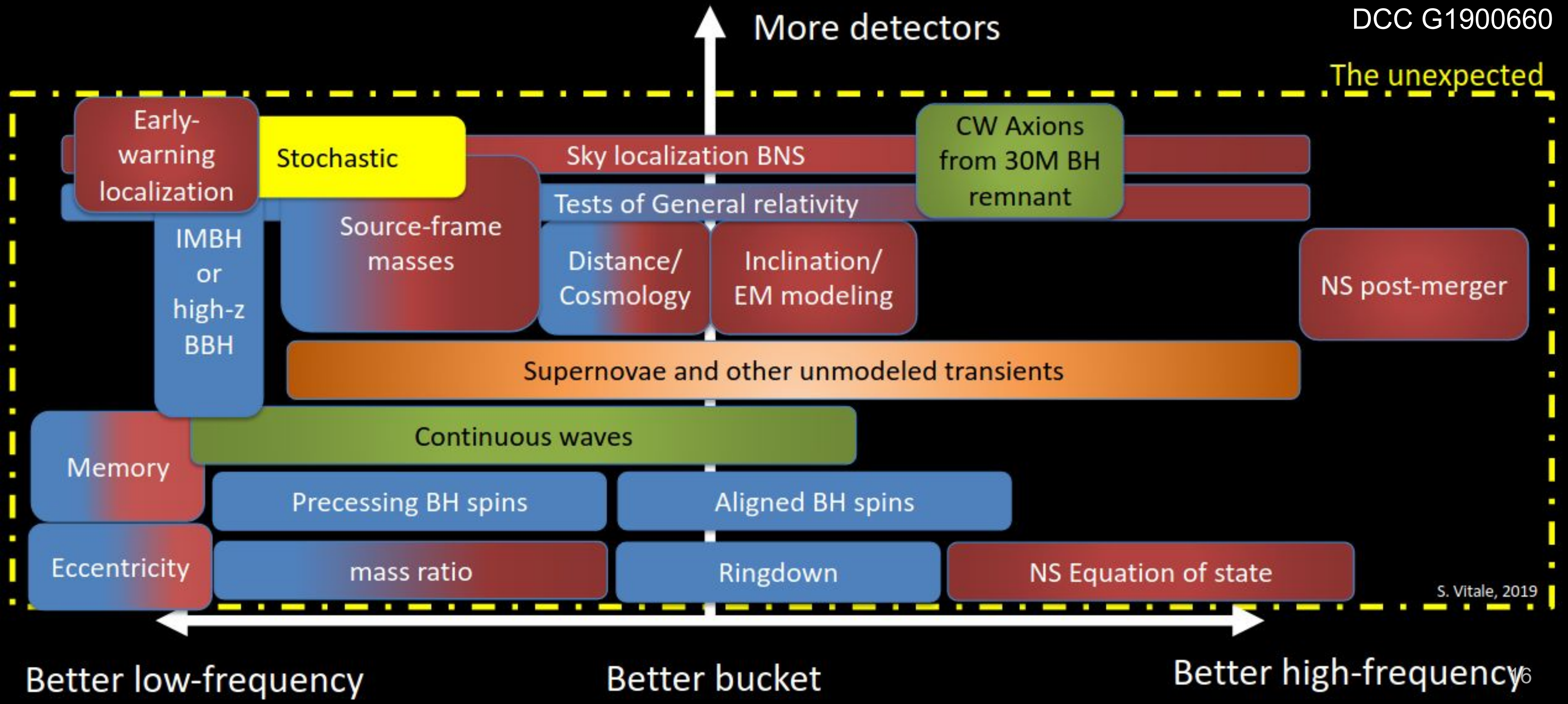
Even pushed to their (infrastructural) limits, **LIGO-Virgo-KAGRA can only explore the local Universe**.

To extend investigation to the cosmological scale and address more scientific questions, a major change is necessary:

this is the target of **3rd generation GW detectors**, such as the Einstein Telescope and Cosmic Explorer

The optimal network configuration depends on the scientific question to be addressed

DCC G1900660

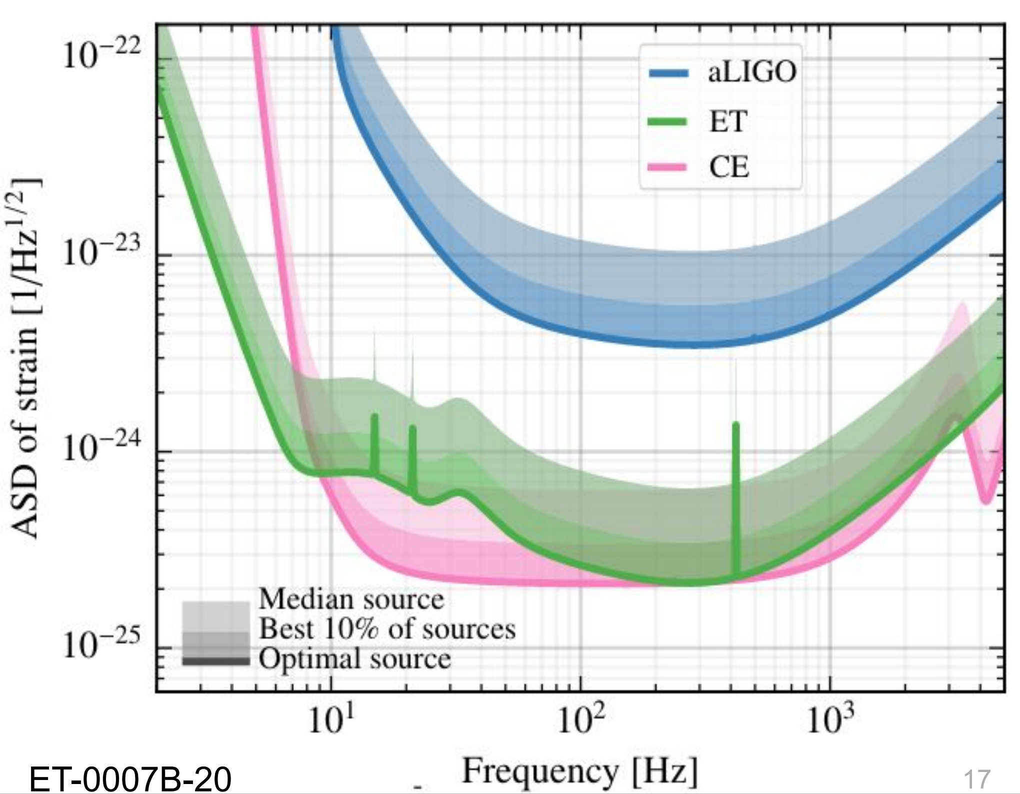


3rd generation GW detectors

3rd generation detectors will improve both the frequency range and the sensitivity

- an order of magnitude better sensitivity
- a wider accessible frequency band

Discovery machines !

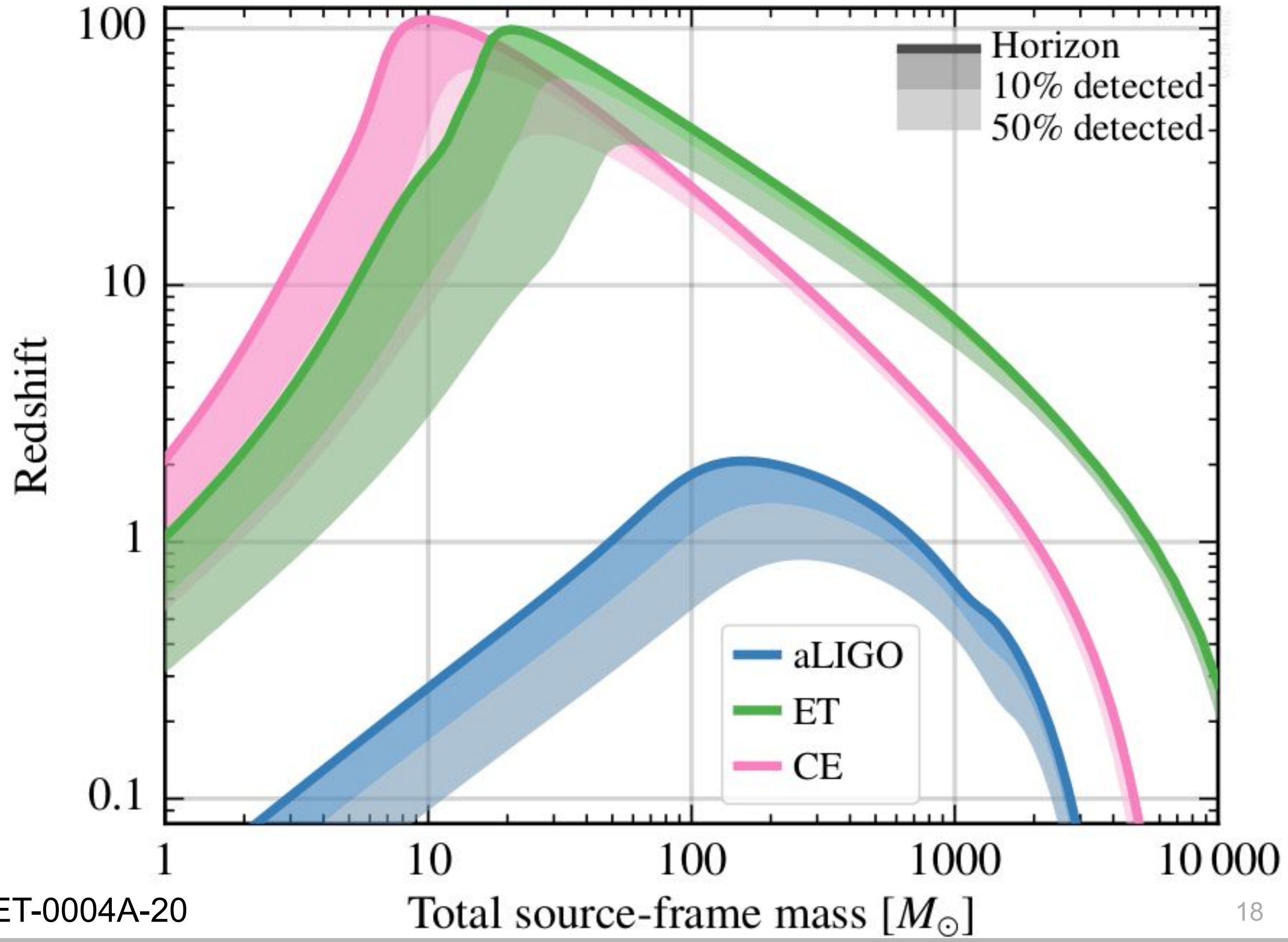


ET-0007B-20

Reach out

3rd generation:

- BBH up to z > 10 (up to primordial origin)
- BNS up to z > 1
- increase the accessible BBH mass range up to $>10^3\ M_{sun}$ out to z ~ 1 − 5.



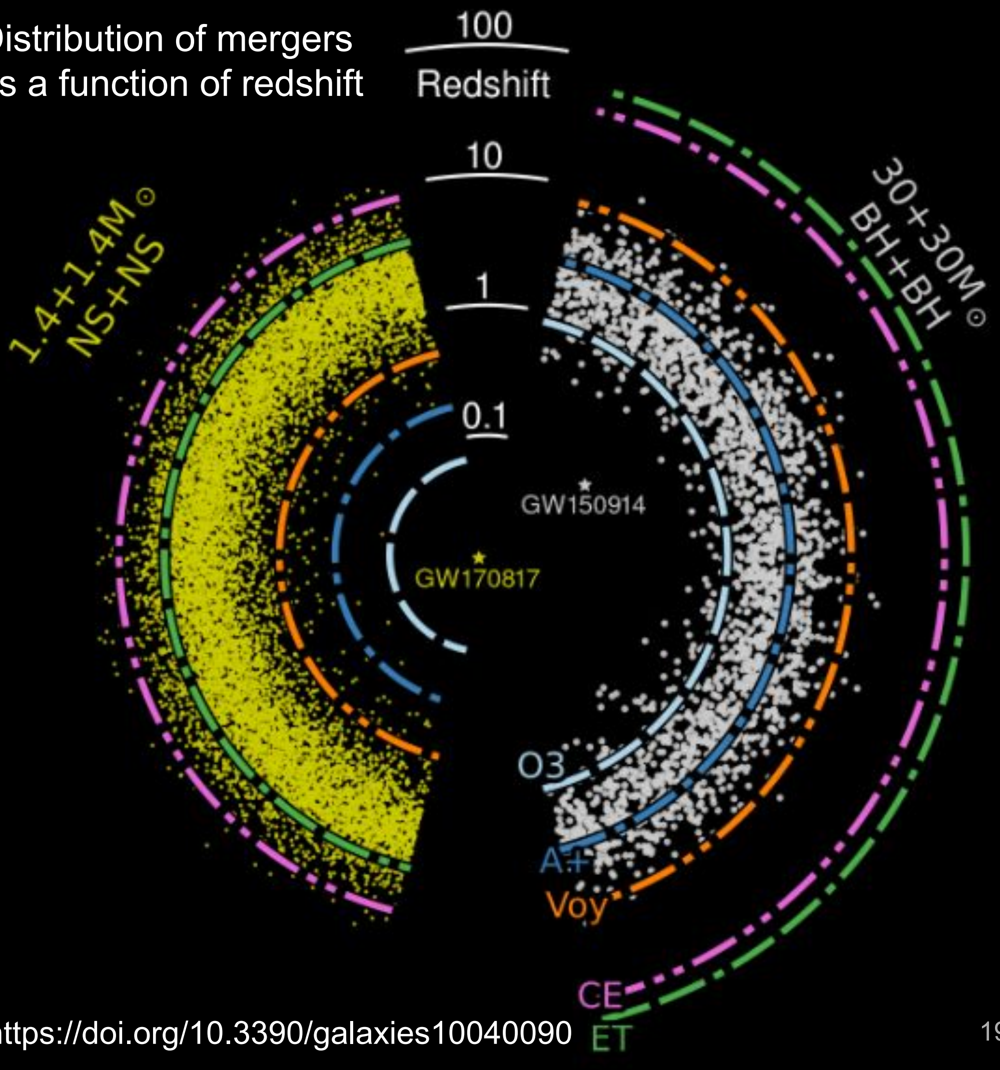
ET-0004A-20

Binary mergers

binary merger detections will **likely exceed 100,000 per year**, enabling detailed inferences about stellar remnant populations.

Individual merger signals, especially those in the local universe, will be detected with **greatly enhanced signal-to-noise ratio**, sometimes exceeding 1000 in amplitude, enabling precision observation of the dynamics at play in these systems.

Distribution of mergers as a function of redshift



https://doi.org/10.3390/galaxies10040090

ET Science in a nutshell

EINSTEIN TELESCOPE

ASTROPHYSICS

- **Black hole properties**
  - origin (stellar vs. primordial)
  - evolution, demography
- **Neutron star properties**
  - interior structure (QCD at ultra-high densities, exotic states of matter)
  - demography
- **Multi-band and -messenger astronomy**
  - joint GW/EM observations (GRB, kilonova,...)
  - multiband GW detection (LISA)
  - neutrinos
- **Detection of new astrophysical sources**
  - core collapse supernovae
  - isolated neutron stars
  - stochastic background of astrophysical origin

FUNDAMENTAL PHYSICS AND COSMOLOGY

- **The nature of compact objects**
  - near-horizon physics
  - tests of no-hair theorem
  - exotic compact objects
- **Tests of General Relativity**
  - post-Newtonian expansion
  - strong field regime
- **Dark matter**
  - primordial BHs
  - axion clouds, dark matter accreting on compact objects
- **Dark energy and modifications of gravity on cosmological scales**
  - dark energy equation of state
  - modified GW propagation
- **Stochastic backgrounds of cosmological origin**
  - inflation, phase transitions, cosmic strings

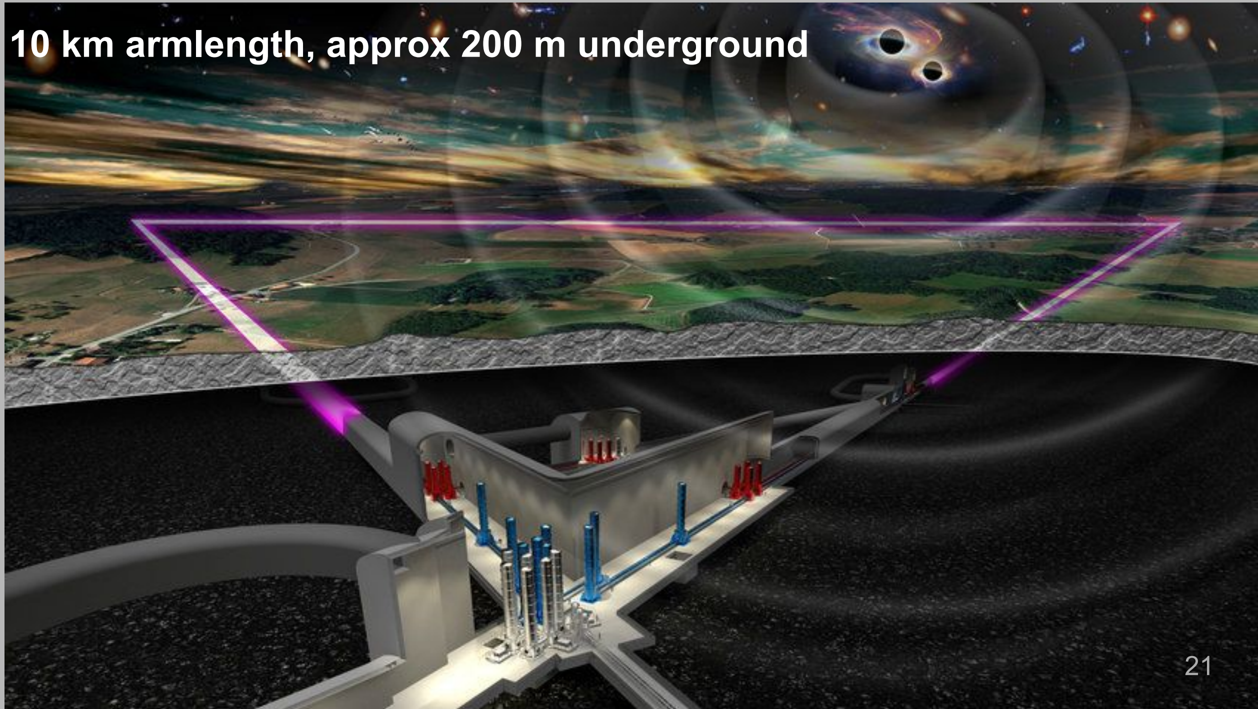
Einstein Telescope

A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities

ET is an observatory:

- **3 nested detectors** in a triangular arrangement.
- **Each detector consisting in two interferometers**:
  - a room T, HF one
  - a cryogenic, LF one

This is the multi-band configuration (also called ‘xylophone’)

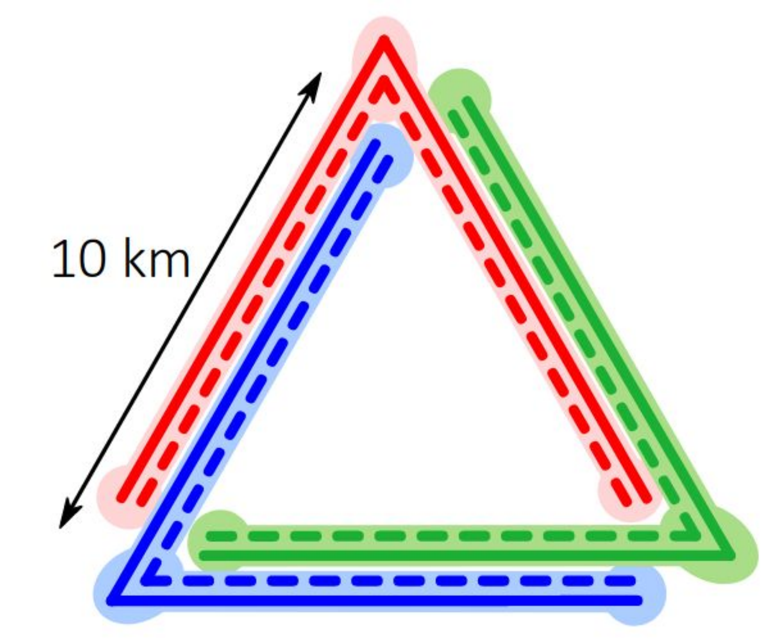


ET: three detectors in a single triangular site

The Einstein Telescope design has **three detectors hosted in a single triangular site**, providing a near-optimal configuration for a single-site observatory in a cost-efficient and prominent infrastructure.

Advantages:

- each side of the triangle can be deployed twice to build three V-shaped interferometers, 60 deg angle
- virtually complete sky coverage, with no blind spots
- equally sensitive to both polarizations of the GW
- redundancy and more uptime
- a null-stream in the sum of the responses of the three detectors in a triangle



ET site selection

Currently there are two sites in Europe, candidate to host ET:

- Italy, in the Sardinia island
- the EU Regio Rhine-Meusse area, close to the NL-B-D border

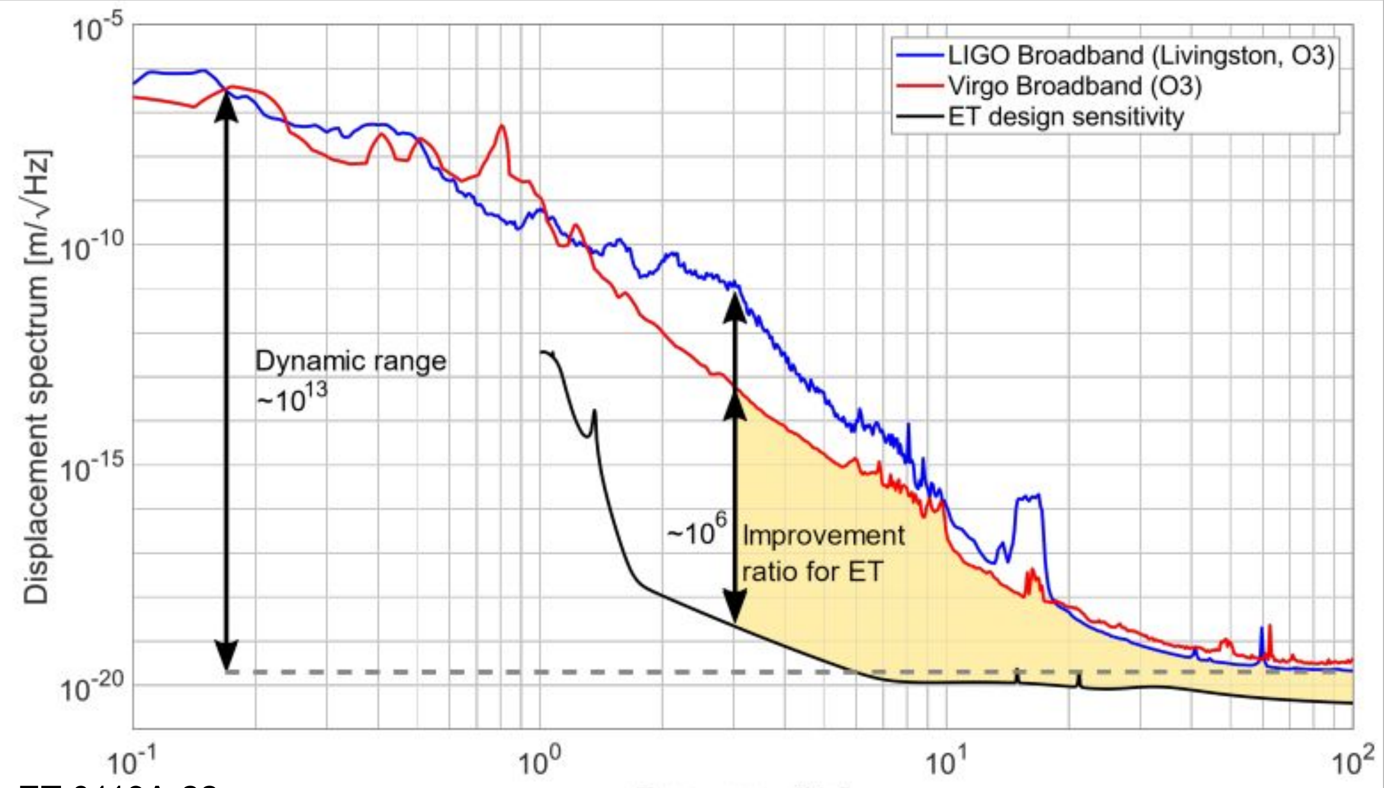
Both sites geologically and seismically suited. Investigations ongoing.

A third option in Saxony (Germany) is under discussion

The challenge of low frequency sensitivity

At low freq ET needs to be million times better than 2nd generation ITF

→underground to reduce seismic and Newtonian noise



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ET Enabling Technologies

- The multi-interferometer approach asks for two parallel technology developments:
  - **ET-LF:**
    - Underground
    - Cryogenics
    - Silicon (Sapphire) test masses
    - Large test masses
    - New coatings
    - New laser wavelength
    - Seismic suspensions
    - Frequency dependent squeezing
  - **ET-HF:**
    - High power laser
    - Large test masses
    - New coatings
    - Thermal compensation
    - Frequency dependent squeezing

Parameter	ET-HF	ET-LF
Arm length	10 km	10 km
Input power (after IMC)	500 W	3 W
Arm power	3 MW	18 kW
Temperature	290 K	10-20 K
Mirror material	fused silica	silicon
Mirror diameter / thickness	62 cm / 30 cm	45 cm/ 57 cm
Mirror masses	200 kg	211 kg
Laser wavelength	1064 nm	1550 nm
SR-phase (rad)	tuned (0.0)	detuned (0.6)
SR transmittance	10 %	20 %
Quantum noise suppression	freq. dep. squeez.	freq. dep. squeez.
Filter cavities	1×300 m	2×1.0 km
Squeezing level	10 dB (effective)	10 dB (effective)
Beam shape	TEM_{00}	TEM_{00}
Beam radius	12.0 cm	9 cm
Scatter loss per surface	37 ppm	37 ppm
Seismic isolation	SA, 8 m tall	mod SA, 17 m tall
Seismic (for $f > 1$ Hz)	$5 \cdot 10^{-10}\ m/f^2$	$5 \cdot 10^{-10}\ m/f^2$
Gravity gradient subtraction	none	factor of a few

Challenging engineering

New technology in cryo-cooling

New technology in optics

New laser technology

High precision mechanics and low noise controls

High quality opto-electronics and new controls

Evolved laser technology

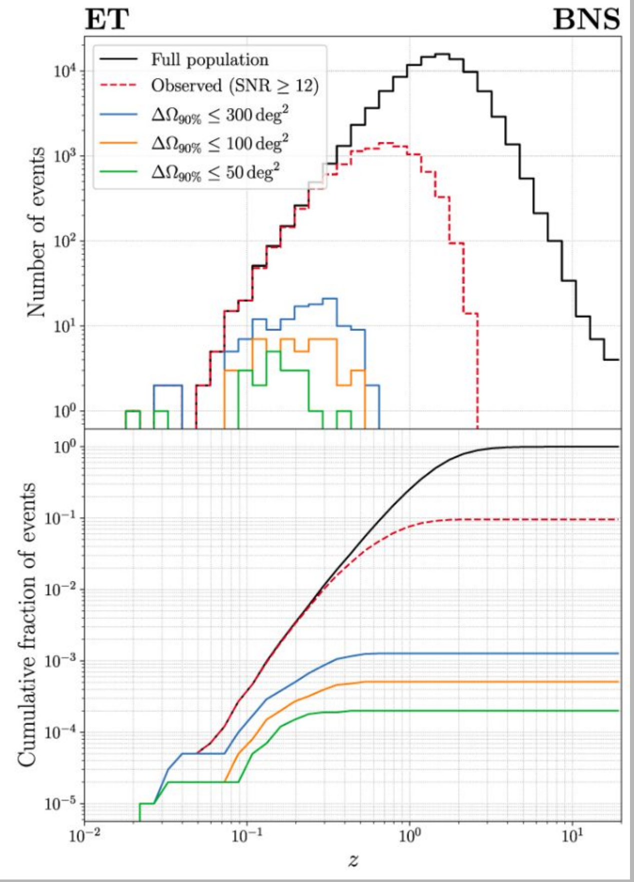
Evolved technology in optics

Highly innovative adaptive optics

High quality opto-electronics and new controls

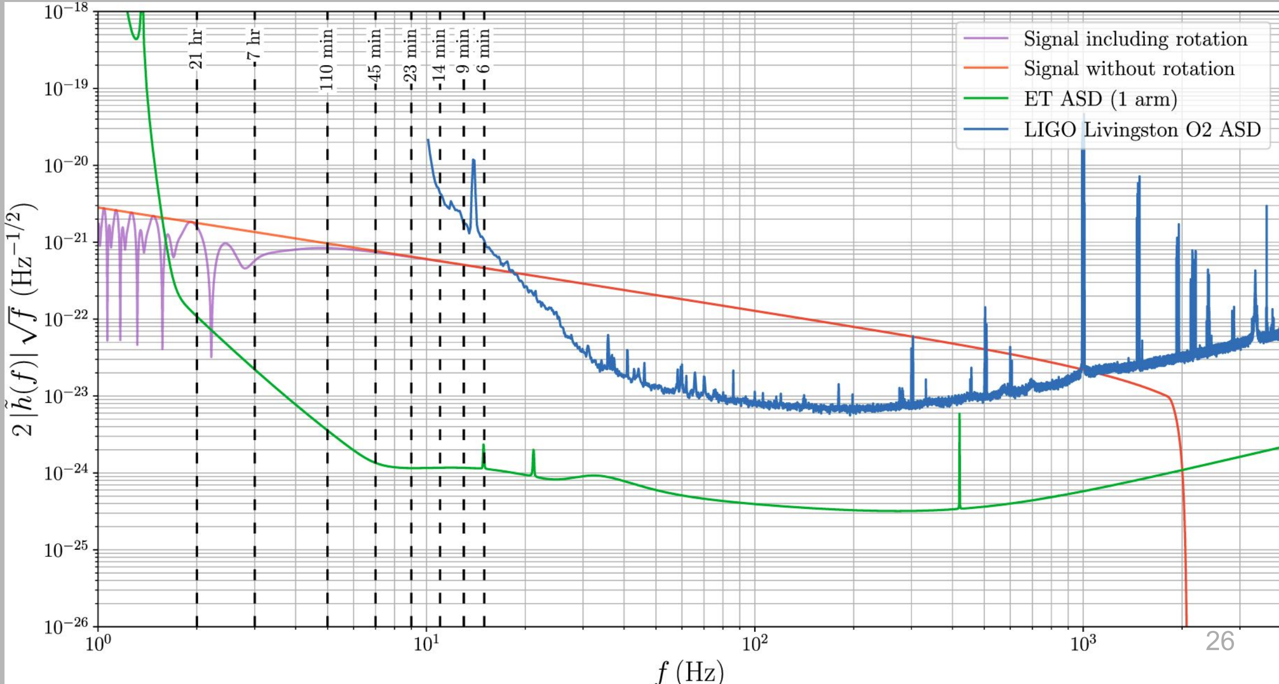
Punturo, Sept 2022

Enabling multimessenger observations, eg BNS



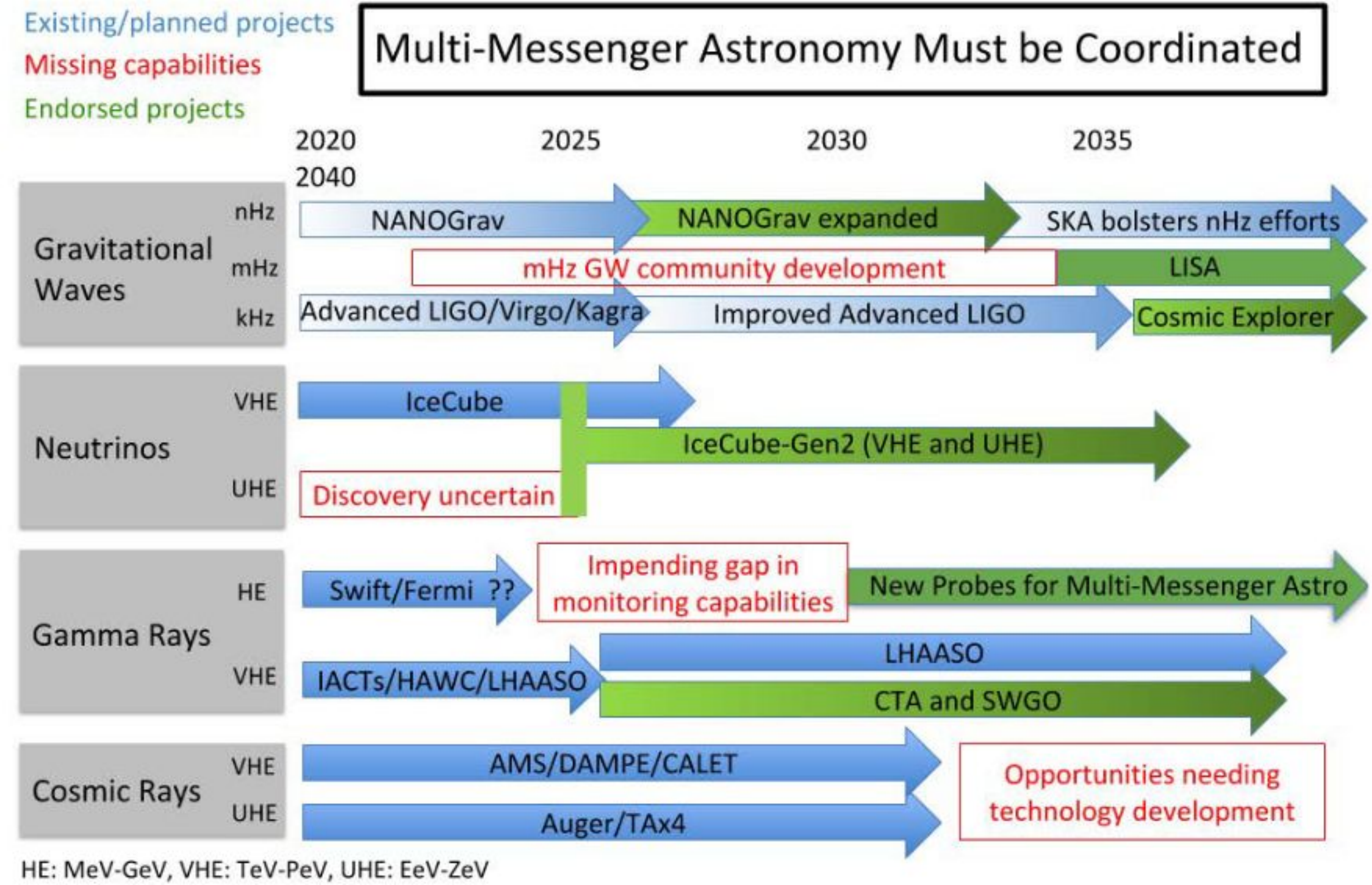
Thanks to the long time spent in the detector bandwidth at ET, the BNS localization can be improved by exploiting the rotation of the Earth.

If we are able to accumulate enough SNR before the merging phase, **we can trigger e.m. observations before the emission of photons**.



F Iacovelli *et al* 2022 *ApJ* **941** 208

Multimessenger science requires a great coordination!



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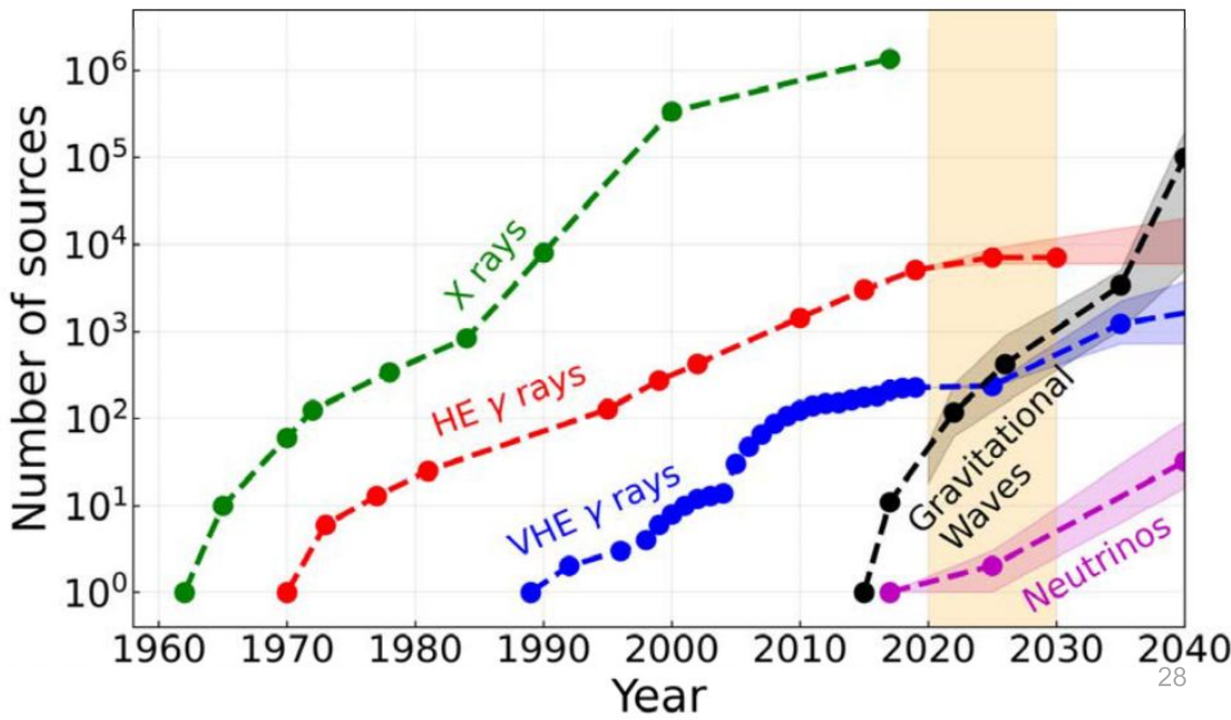
New astronomies for the future

Building on past successes, new astronomies can be opened now. The fields of X-ray and gamma-ray astronomy were built over decades, with the number of observed sources increasing by orders of magnitude.

GW astronomy has just started and holds the promise of a flourishing growth.



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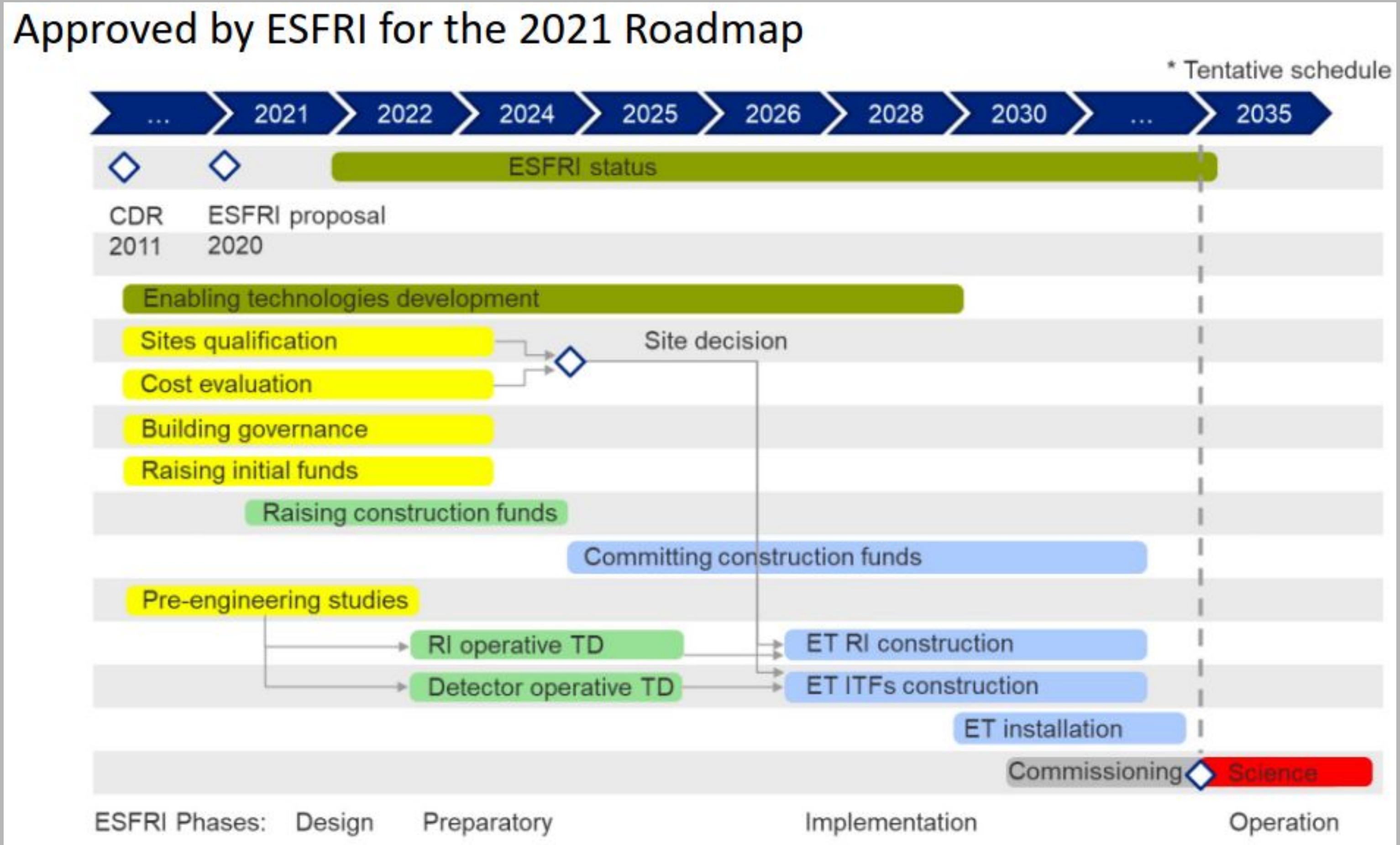
Thank you !

ET project Timeline approved by ESFRI (2021 roadmap)



Opening the low frequency region

Two key questions:

1)How, when and where do the first massive black holes form, grow and assemble, and what is the connection with galaxy formation?

(2)What is the nature of gravity near the horizons of black holes and on cosmological scales?

Laser Interferometry used to detect minute distance variations between free flying Test Masses

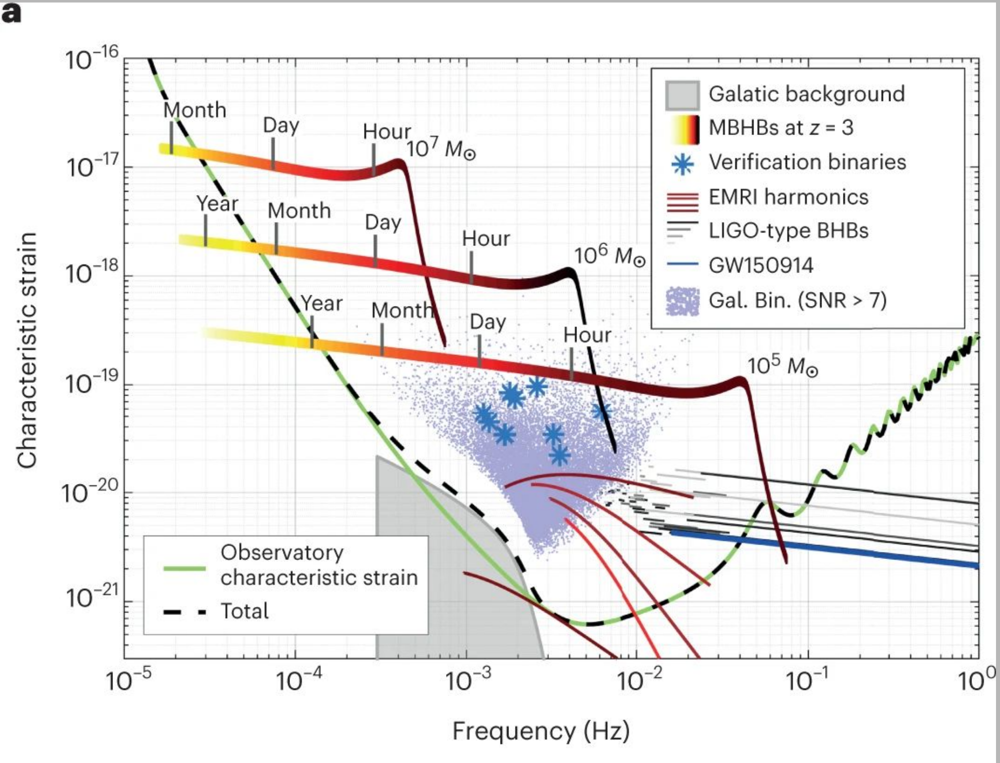
Launch: 2037

Lifetime: 4 years, with possible 6-year extension

- scan the entire sky by orbiting behind the Earth, obtaining both polarisations of the GW
- measure source parameters in the band 10^{-4} Hz - 10^{-1} Hz

LISA science

The majority of individual LISA sources will be binary systems covering a wide range of masses, mass ratios, and physical states

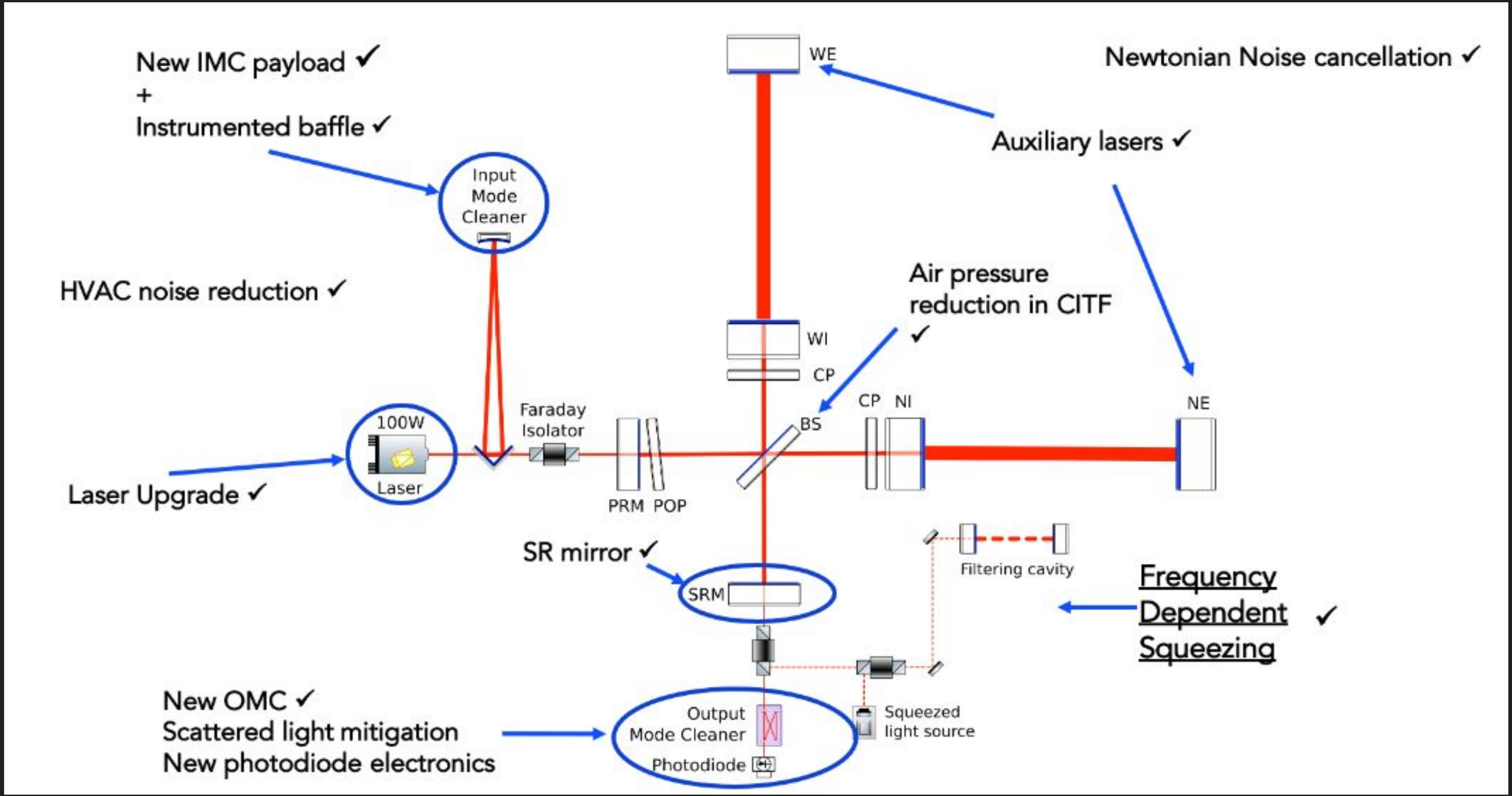


The Gravitational Universe objectives:

- Trace the formation, growth, and merger history of massive black holes
- Explore stellar populations and dynamics in galactic nuclei
- Test GR with observations
- Probe new physics and cosmology
- Survey compact stellar-mass binaries and study the structure of the Galaxy

LISA L3 proposal document (2017)

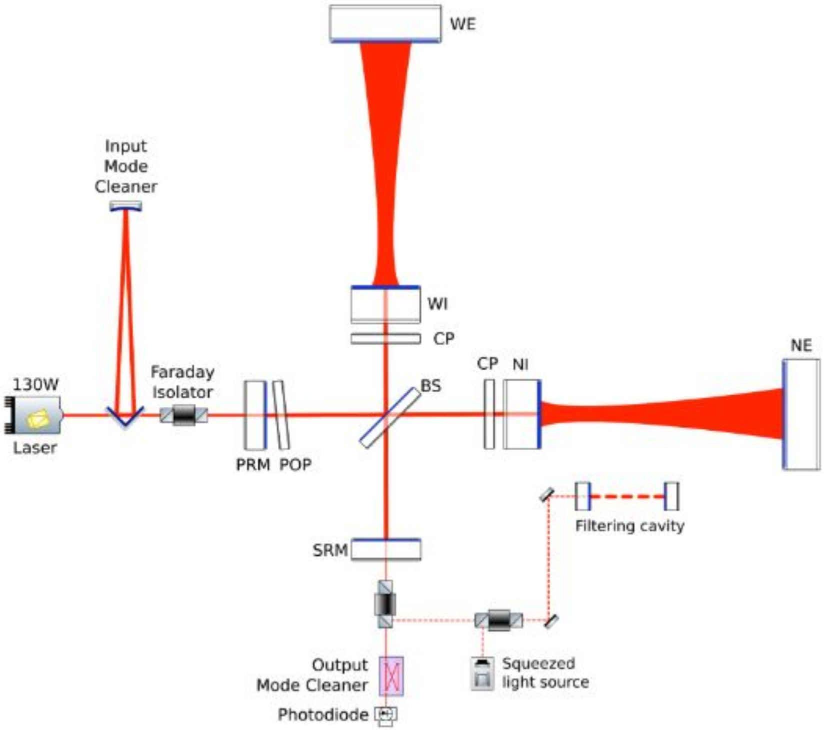
Advanced Virgo Phase I

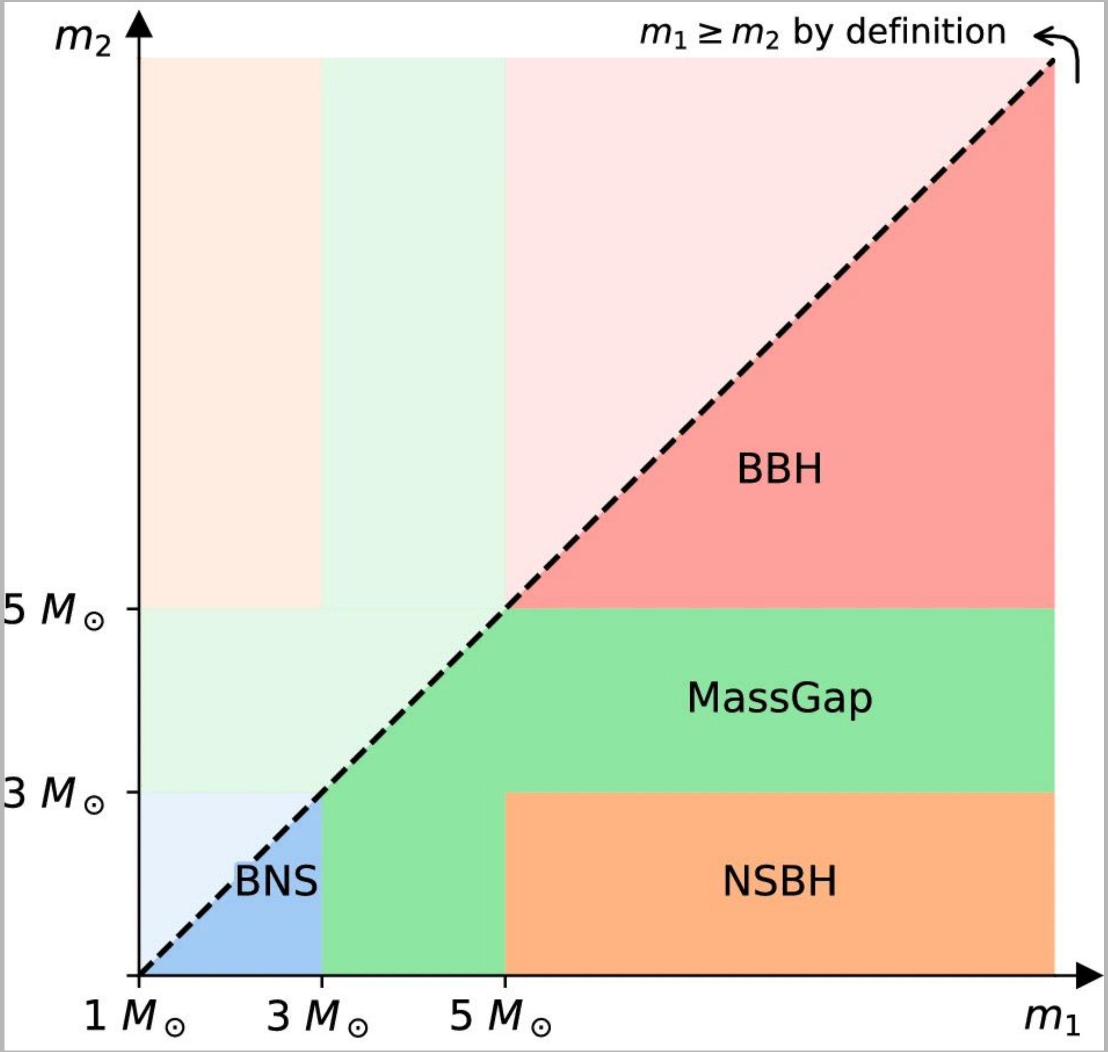


Advanced Virgo Phase II

- Larger beams on end test masses
  - 6 cm radius ⇒ 10 cm radius
- Larger end mirrors
  - 35 cm diameter ⇒ 55 cm diameter
  - 40 kg ⇒ 100 kg
- Better mirror coatings
  - Lower mechanical losses, less point defects, better uniformity
- New suspensions/seismic isolators for large mirrors
- Further increase of laser power

  40W ⇒ 60W ⇒ 80 W





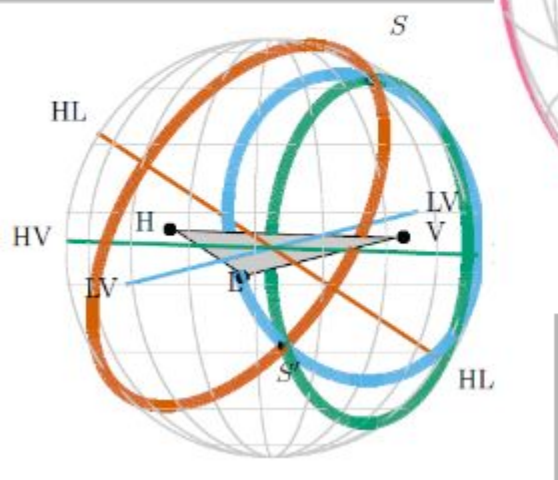
m_2
$m_1 \geq m_2$ by definition
BBH
MassGap
BNS
NSBH
$5\ M_\odot$
$3\ M_\odot$
$1\ M_\odot$
$3\ M_\odot$
$5\ M_\odot$
m_1

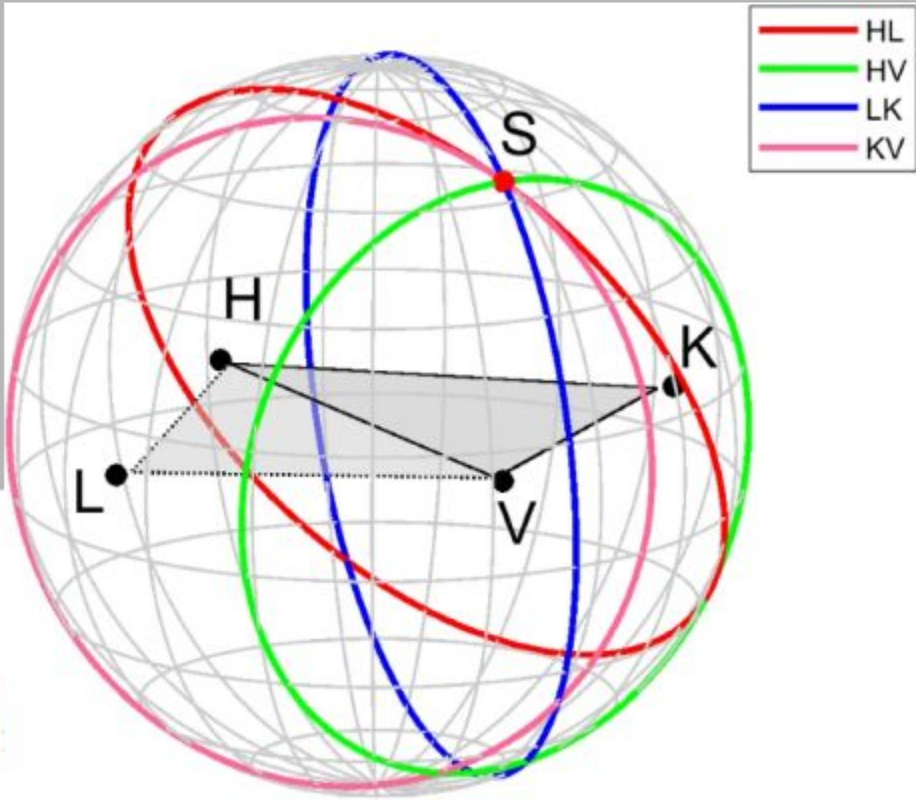
The locus of constant time delay (with associated timing uncertainty) between two detectors forms an annulus on the sky concentric about the baseline between the two sites (labeled by the two detectors).

Here the HK and LV combinations are omitted for clarity.

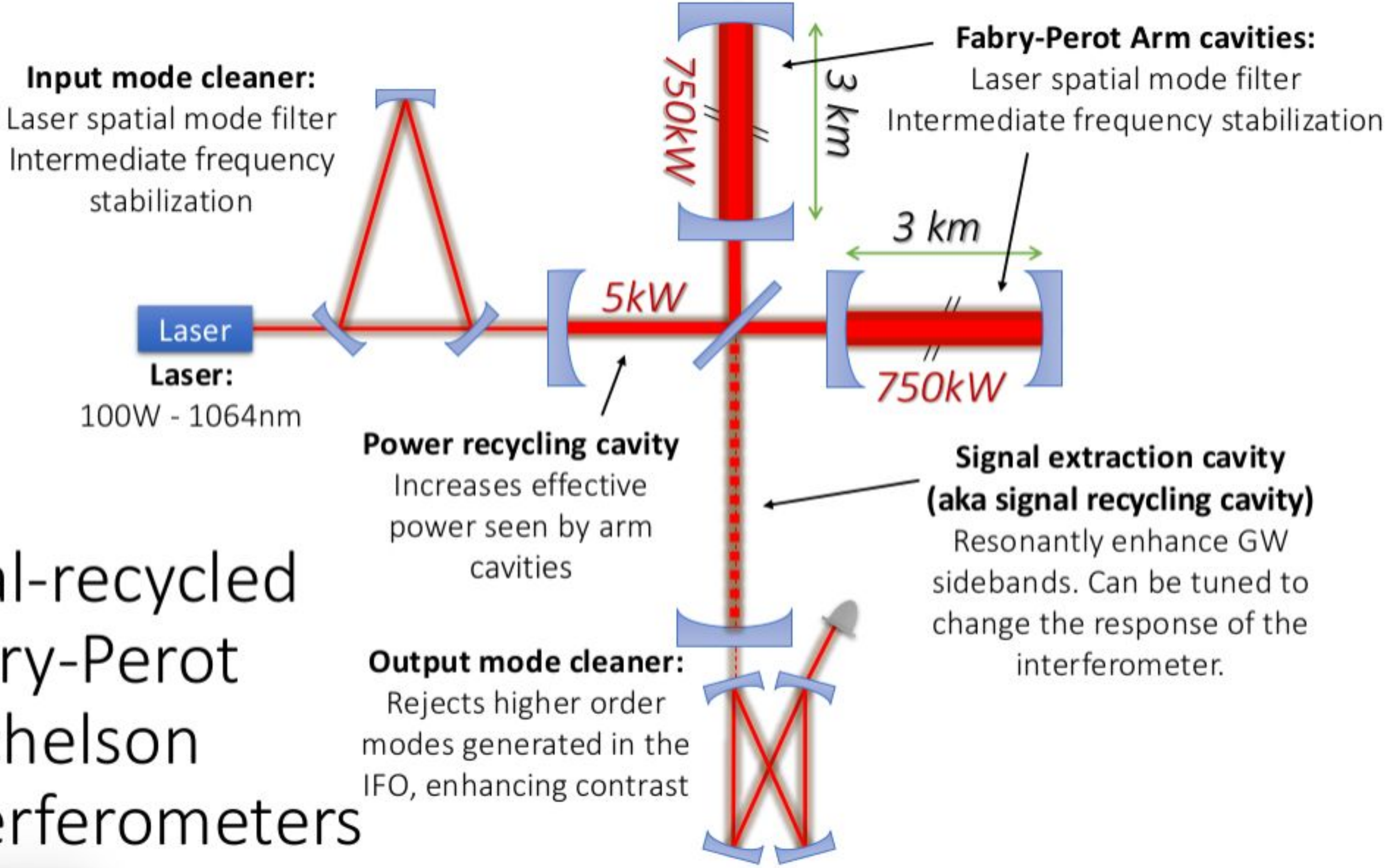
Degeneracy along the rin
by using variability of ante

For four or more detectors there is a unique intersection region, S.





3 detector case: 2 regions S



Dual-recycled Fabry-Perot Michelson Interferometers

Timeline di sviluppo (da NSF) con anche altri segnali

Slide di BNS segnale nel tempo

Accenno a lisa

Segnali lisa -> terra