Gravitational Waves and Black Holes

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Talk Outline

- News on GW detectors
- Highlights on GW discoveries and… new misteries
- Focus on Black Hole Physics
    - BH formation and Population Distribution
    - BH Thermodynamics
- GW perspectives of the next decade
- Conclusions

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News on the GW detectors

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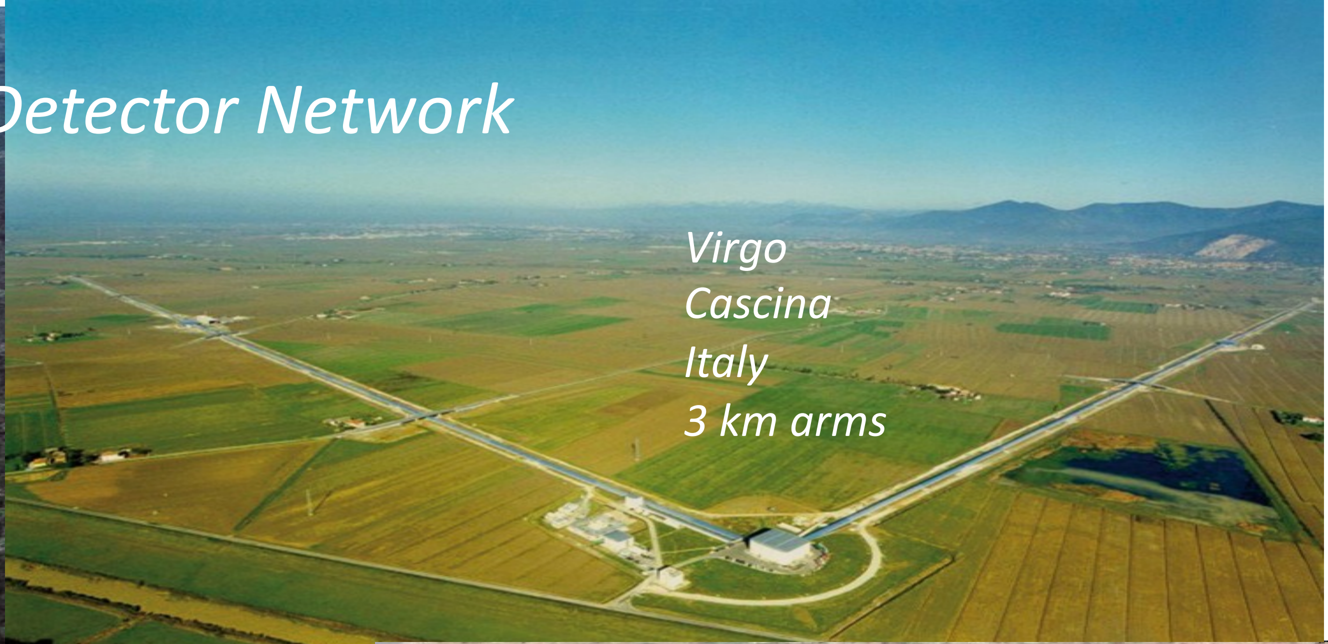
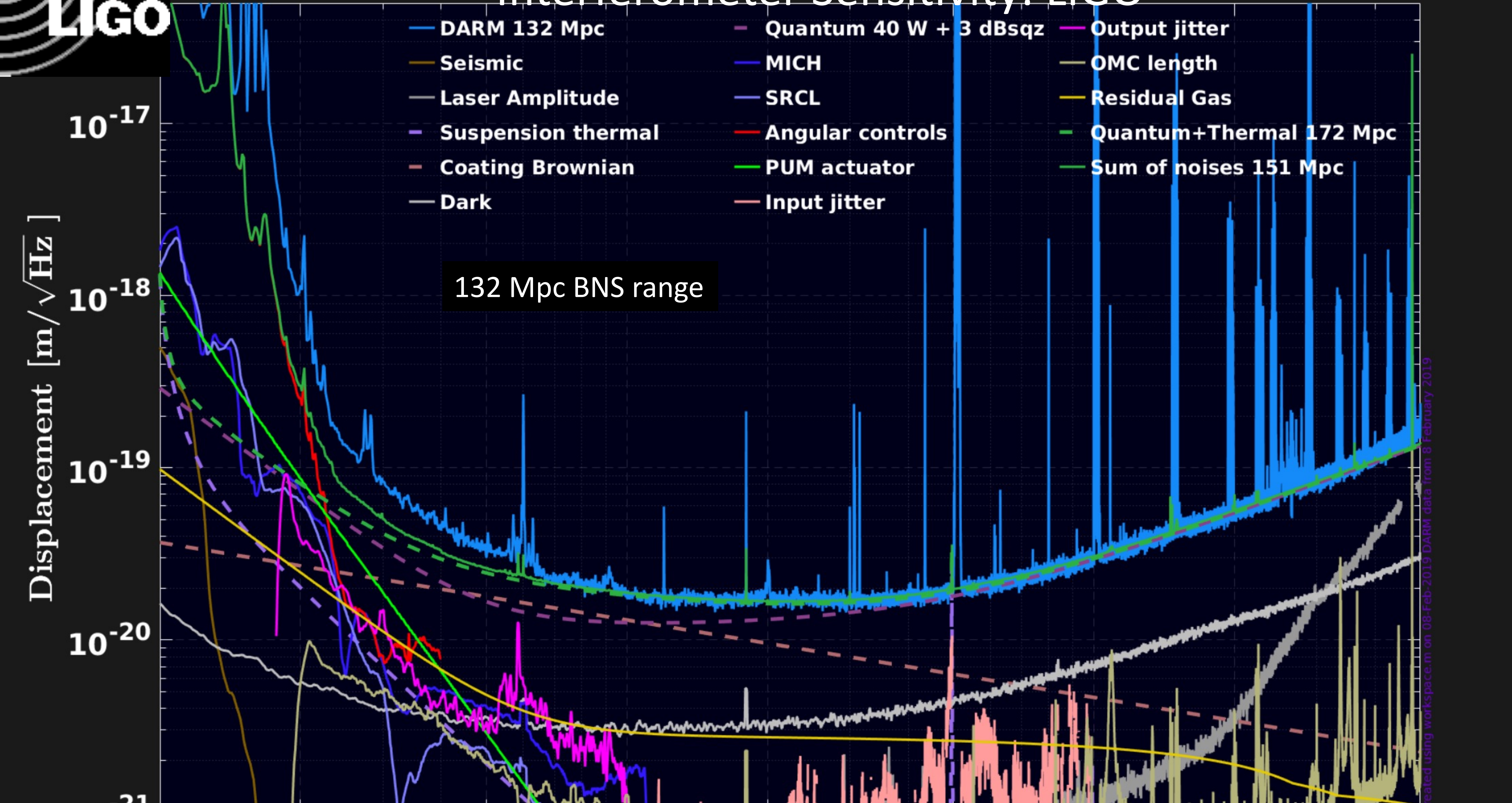
The Global GW Detector Network



Interferometer Sensitivity: LIGO



Standard Quantum Limit

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

wavelength

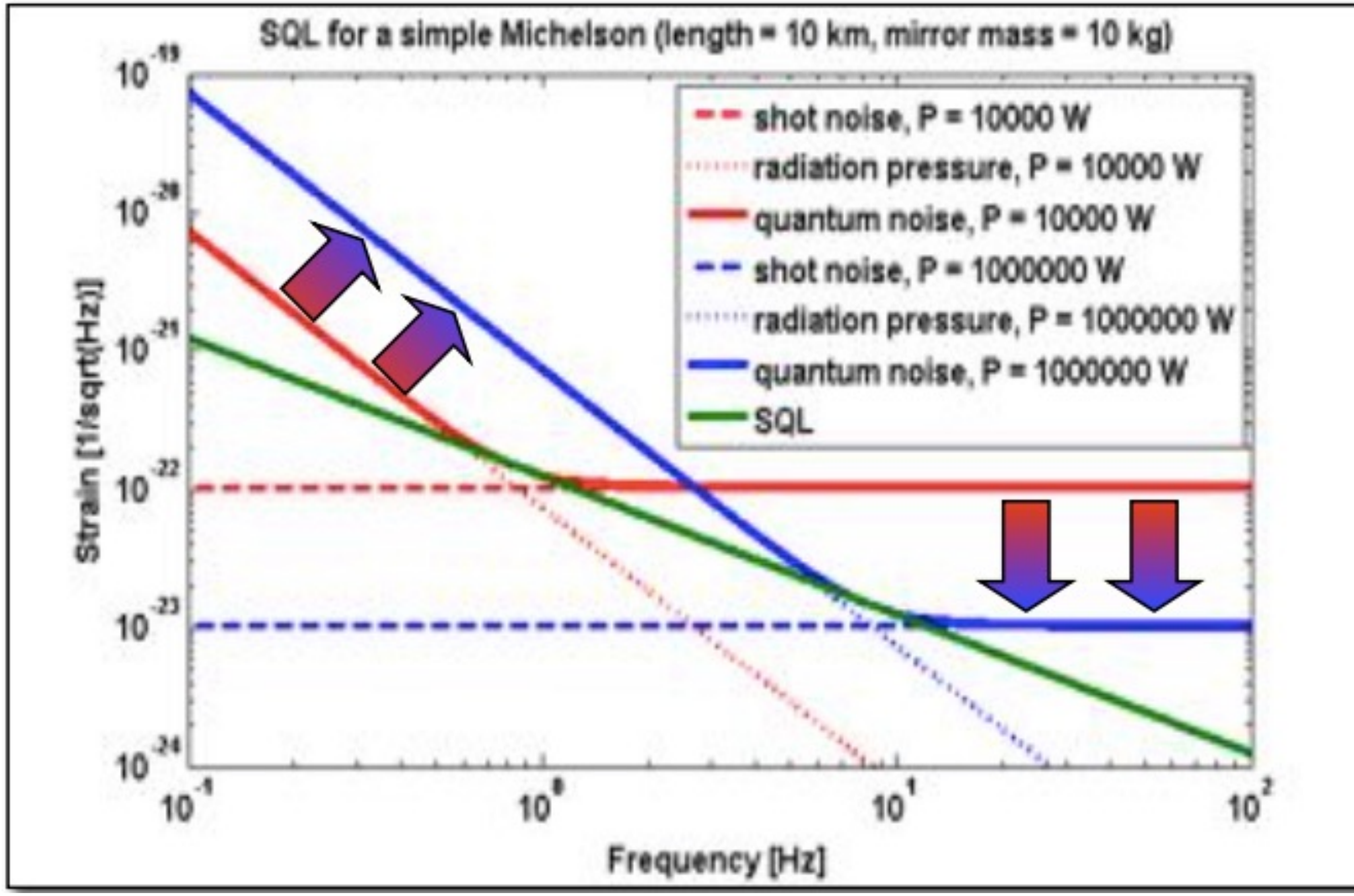
$$h_{\mathrm{sn}}(f) = \frac{1}{L}\sqrt{\frac{\hbar c \lambda}{2\pi P}}$$

optical power

Mirror mass

Arm length

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



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

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

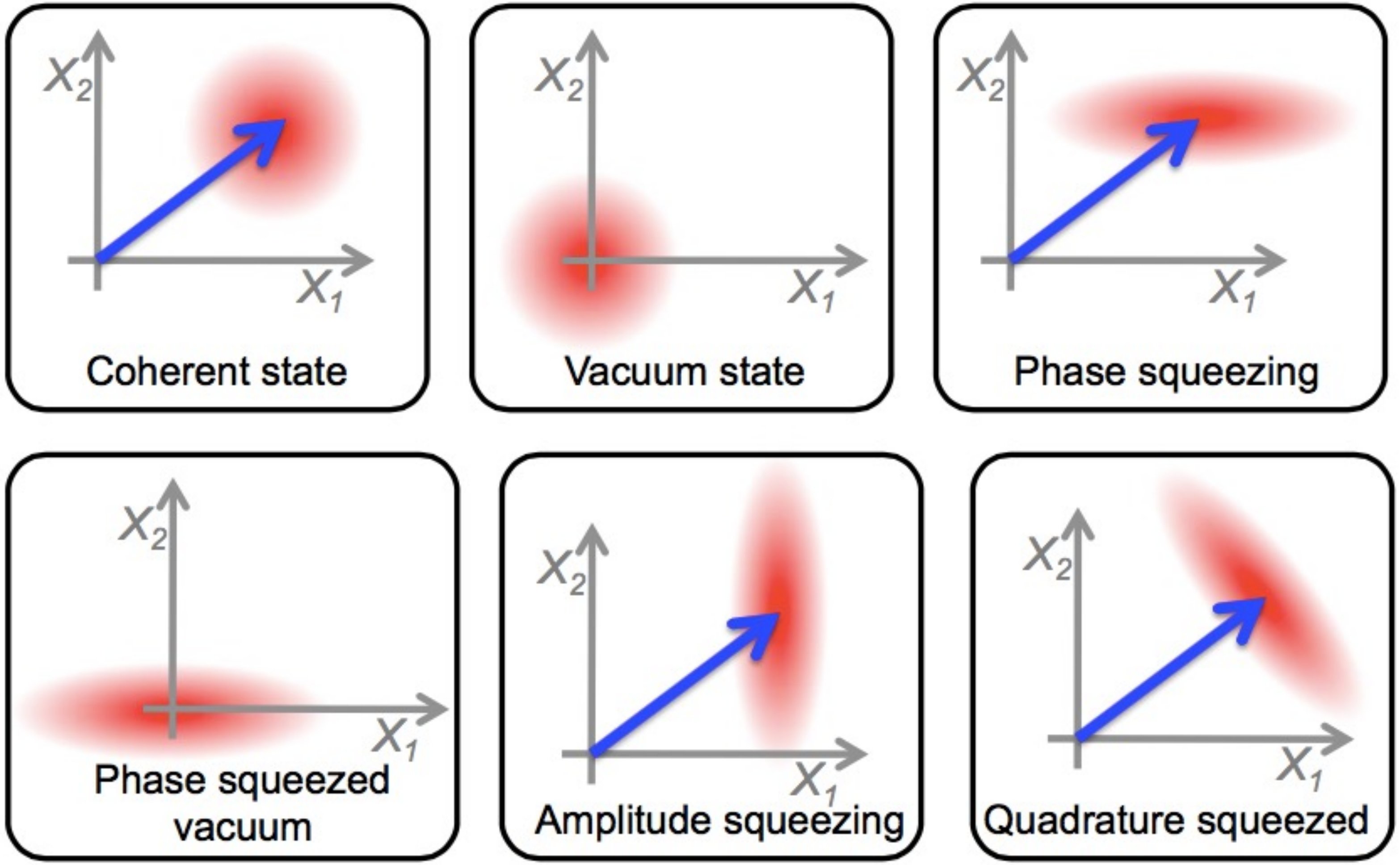
Quantum Interferometer with squeezed e.m. vacuum

- Electromagnetic fields are quantized:

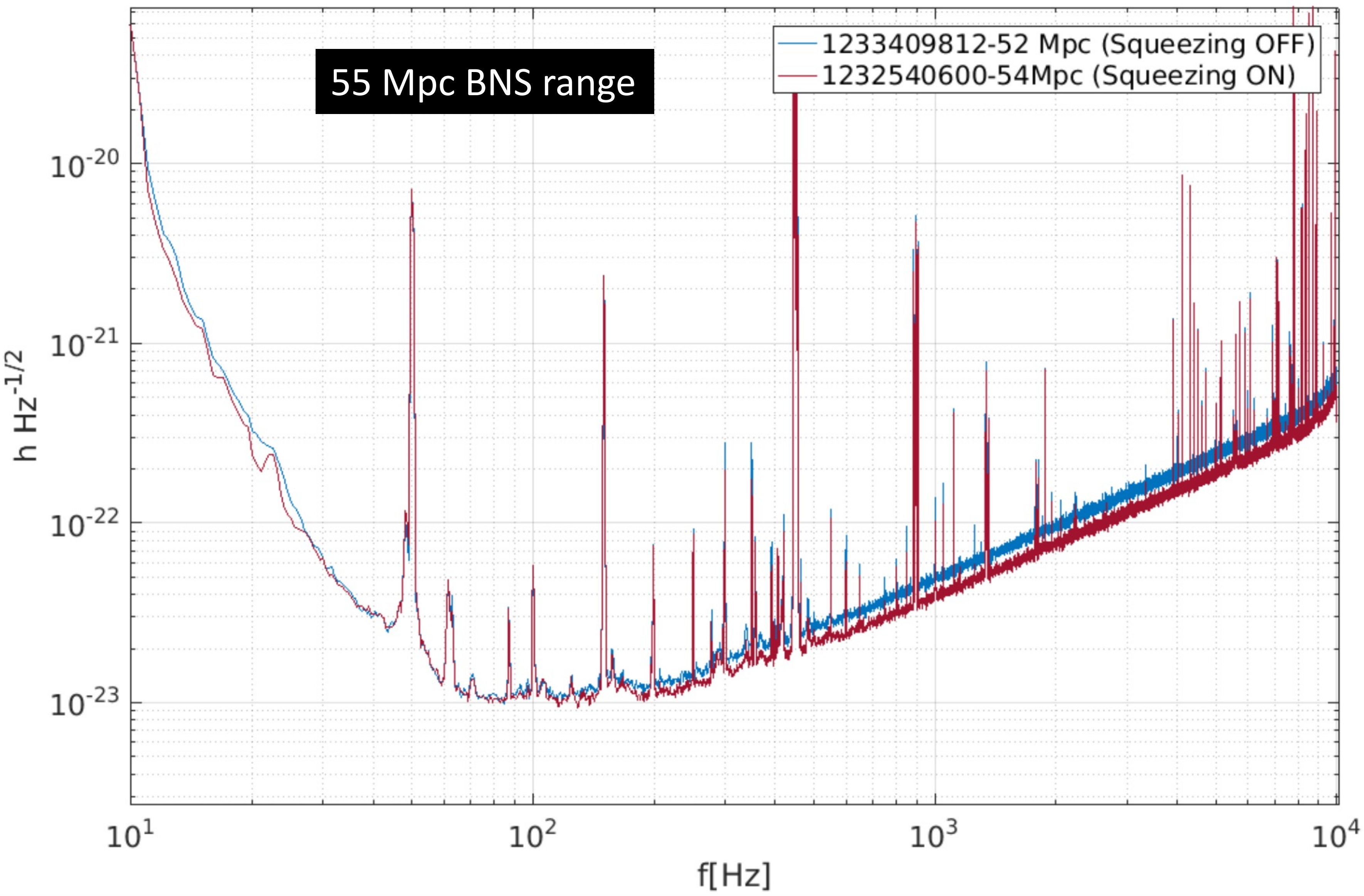
$$\hat{E} = \hat{X}_1 \cos\omega t + i\hat{X}_2 \sin\omega t$$

- Quantum fluctuations exist in the vacuum state:

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



Interferometer Sensitivity: Virgo

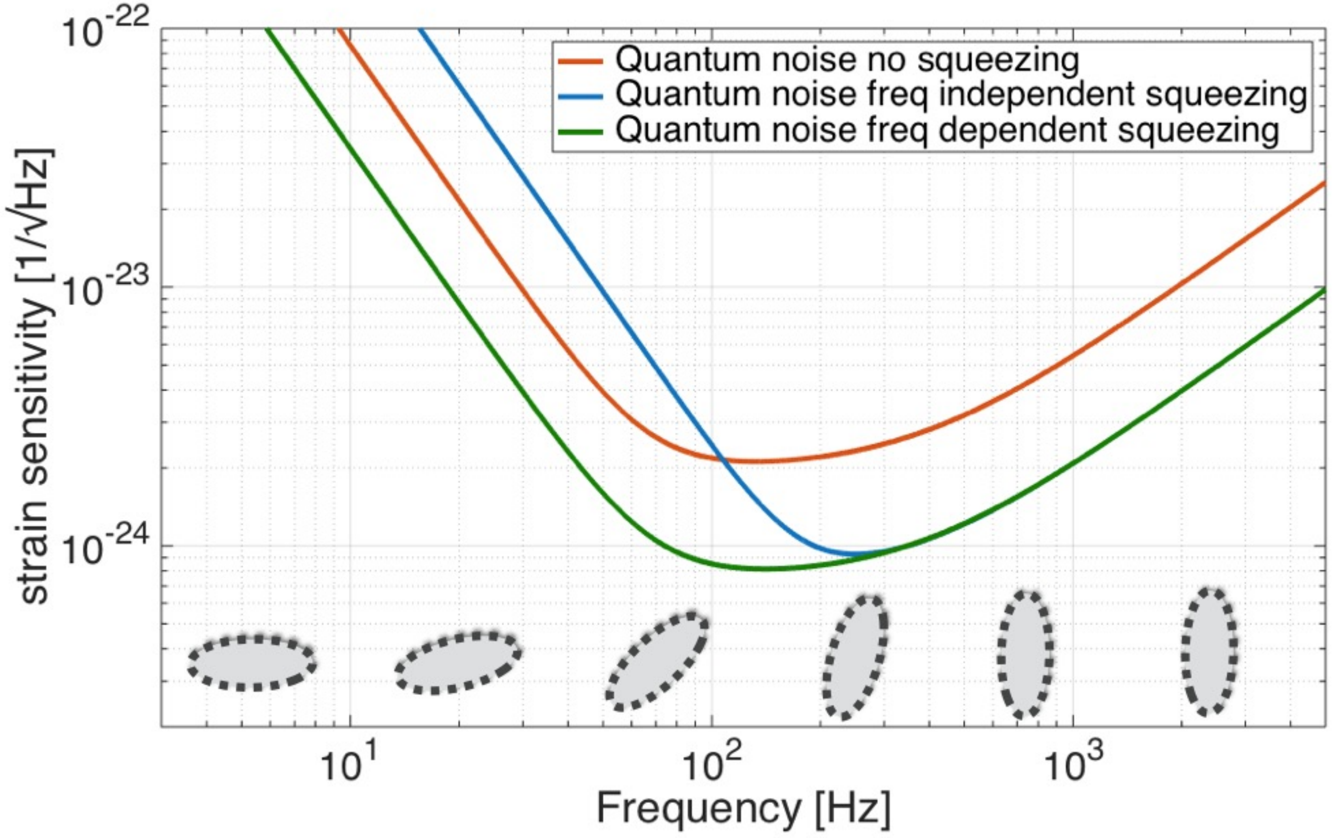


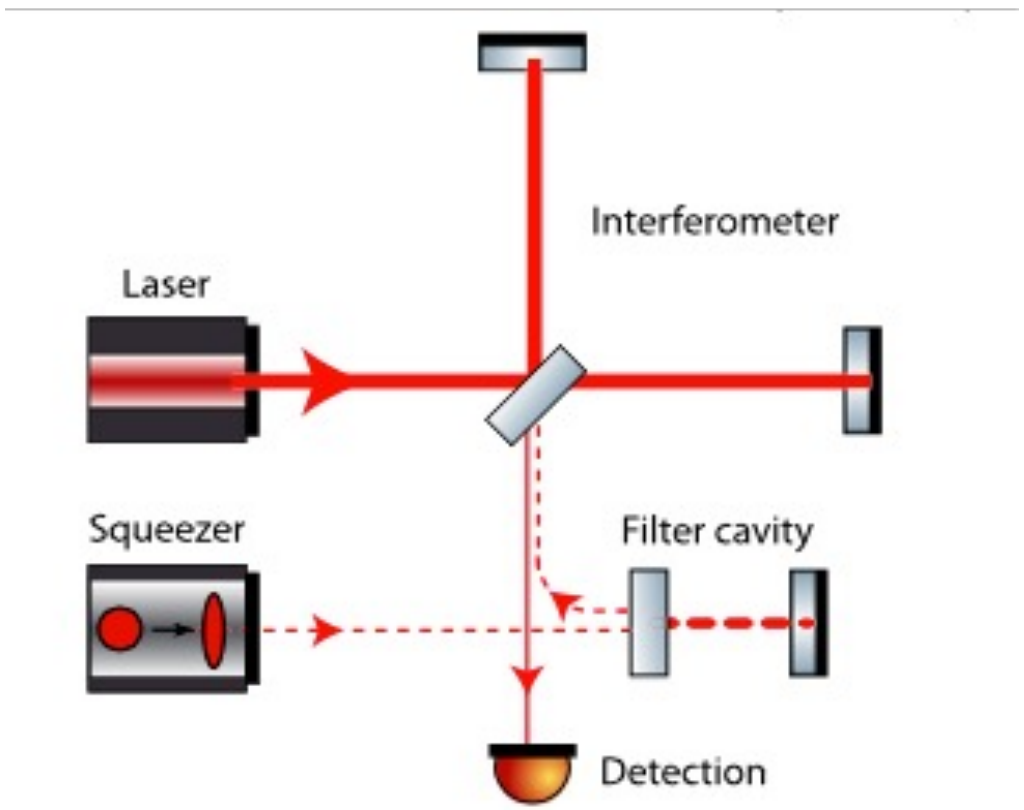
Next run O4. Main Improvement: higher laser power and frequency dependent squeezing

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

Adopted Method

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





Final Message:
stay tuned,
new run O4 will start at the beginning of the spring 2023

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Highlights on GW discoveries and… new misteries

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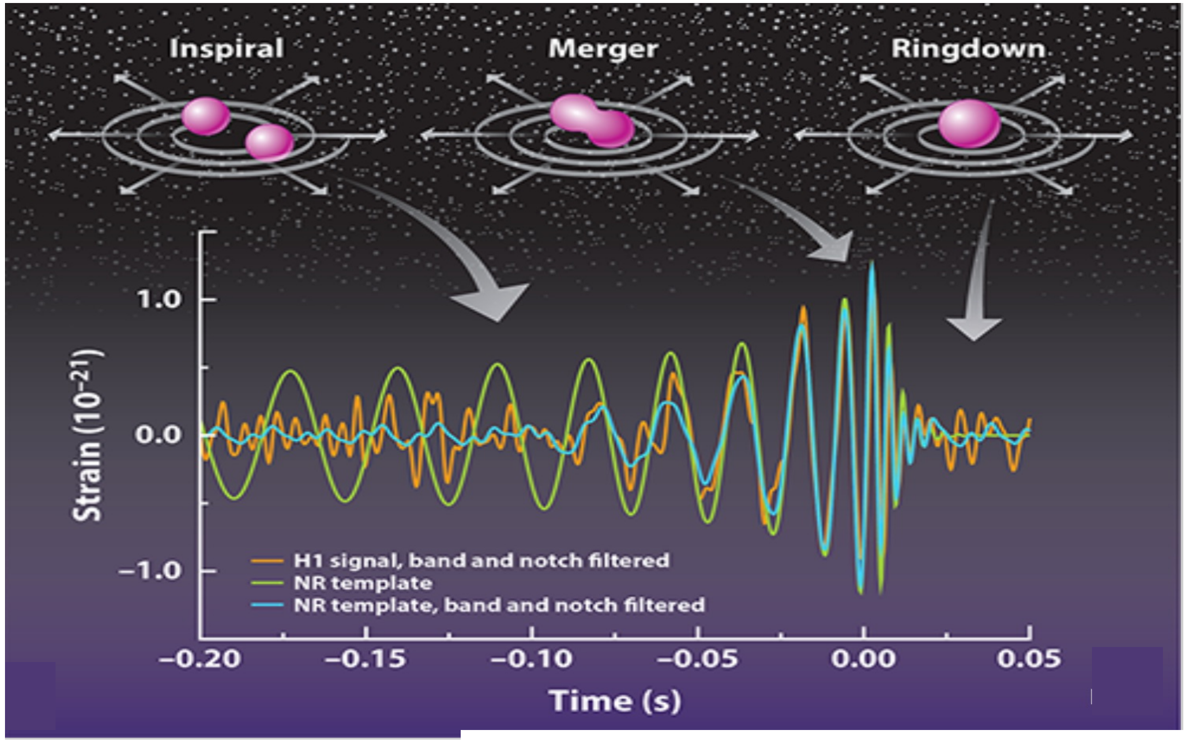
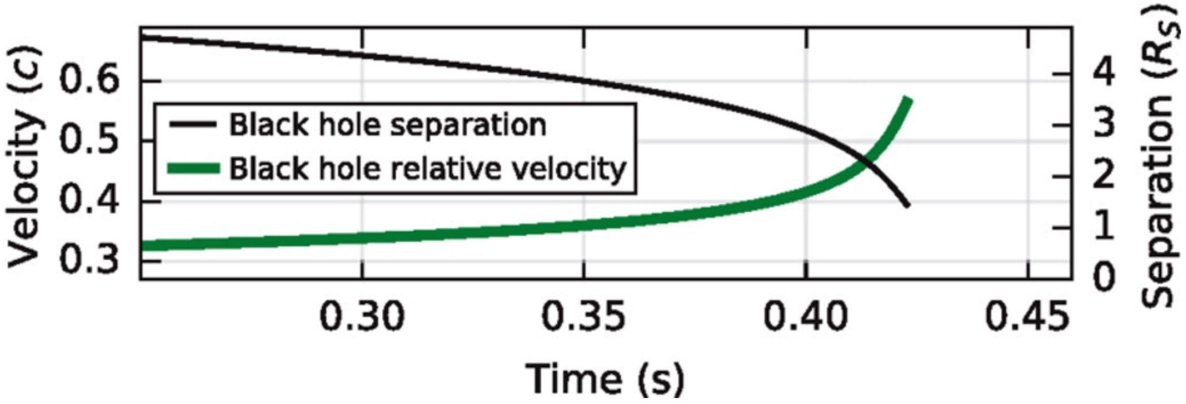
First Binary Black hole system detected on September 15th, 2015 by GW

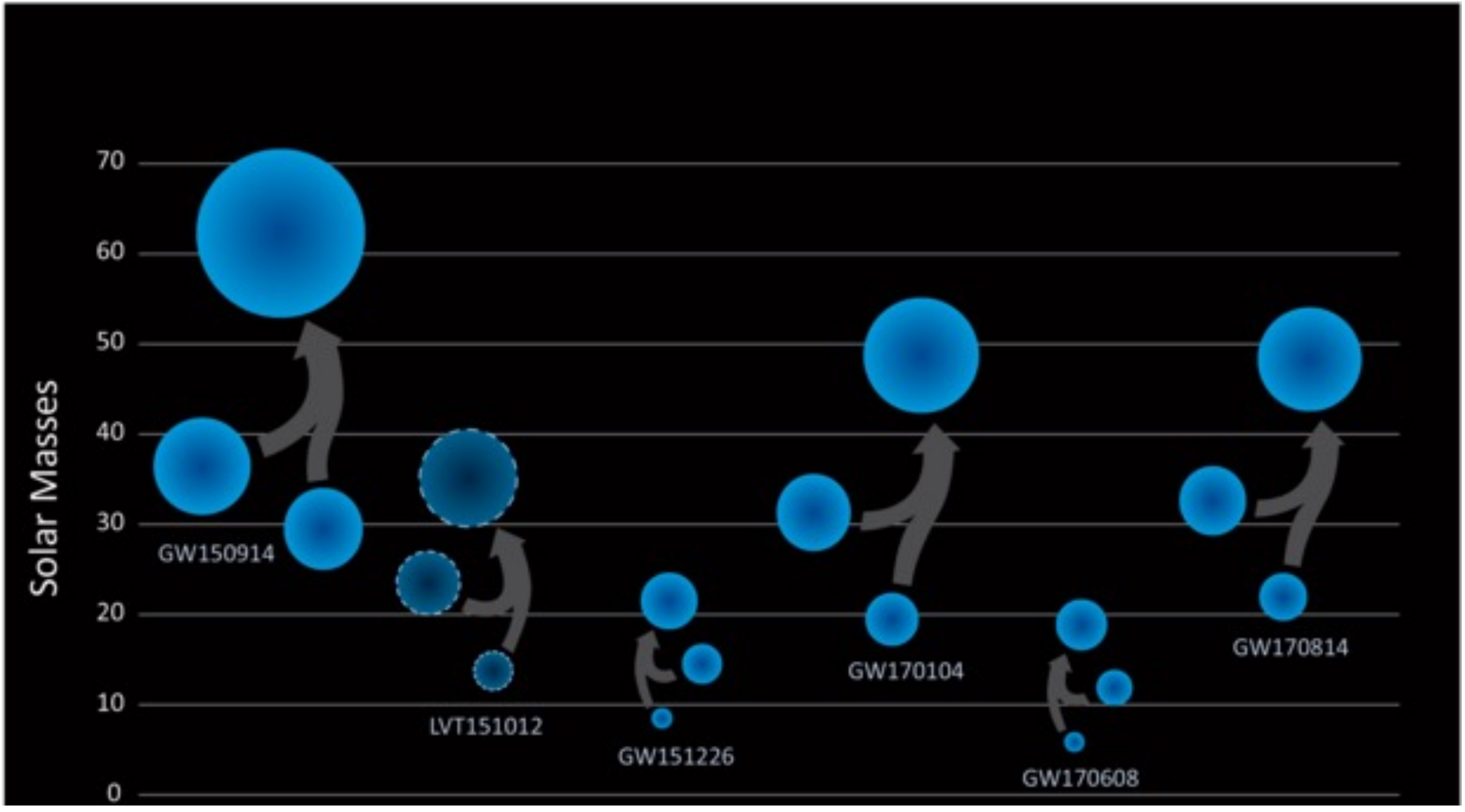


Credits F. Pretorius/APS Carin Caio

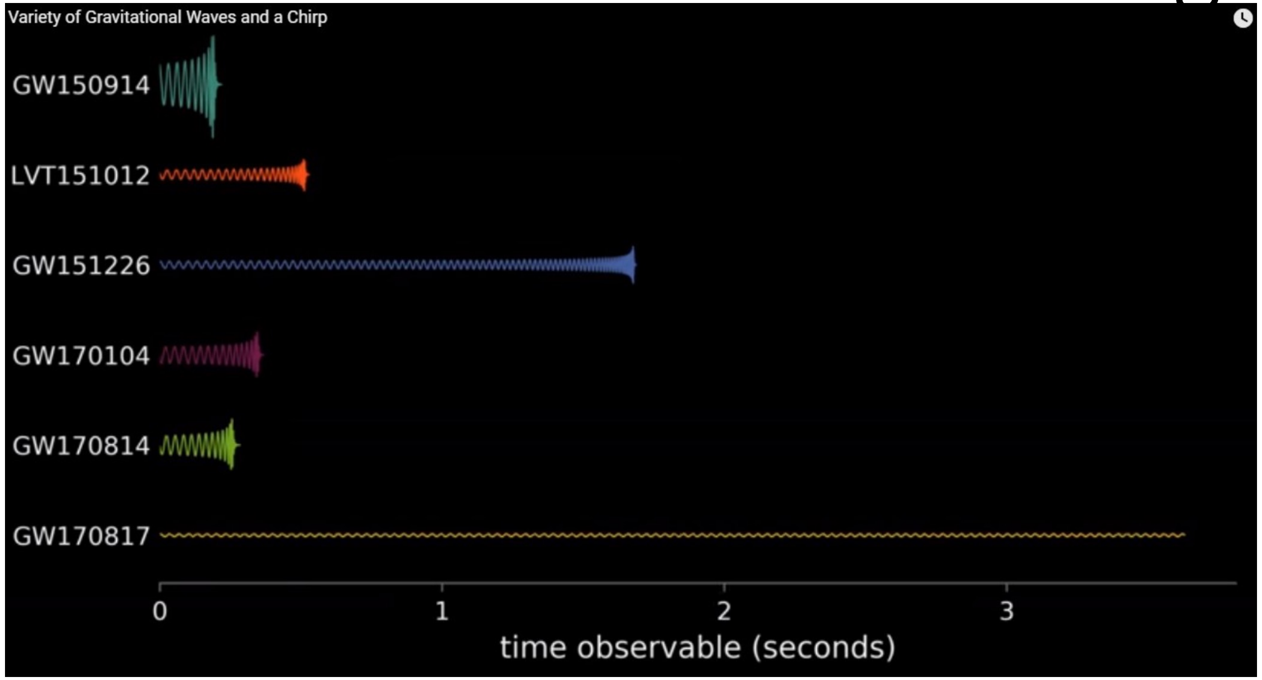
Primary black hole mass	$36^{+5}_{-4}\,\mathrm{M}_\odot$
Secondary black hole mass	$29^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole mass	$62^{+4}_{-4}\,\mathrm{M}_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift, z	$0.09^{+0.03}_{-0.04}$



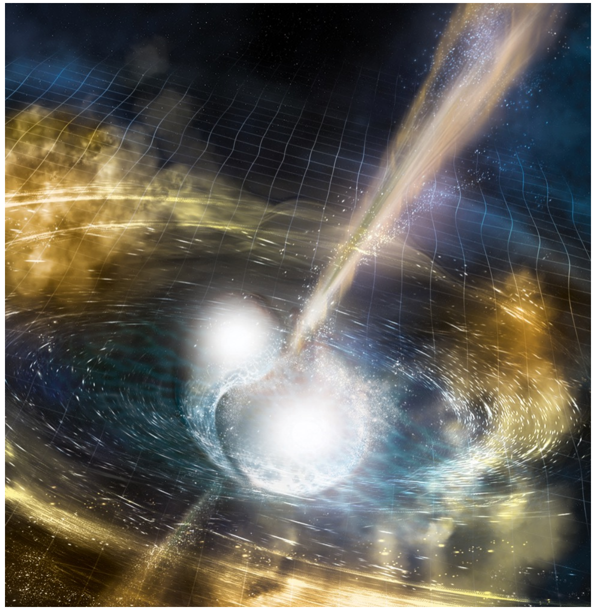
.. then other BBH signals



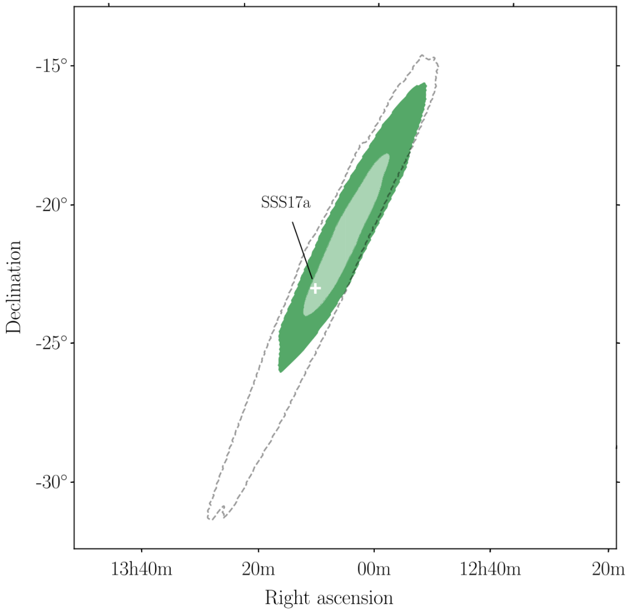
…and the first NS-NS merger GW170817



Event in NGC 4993: localisation area ~ 19 deg^2



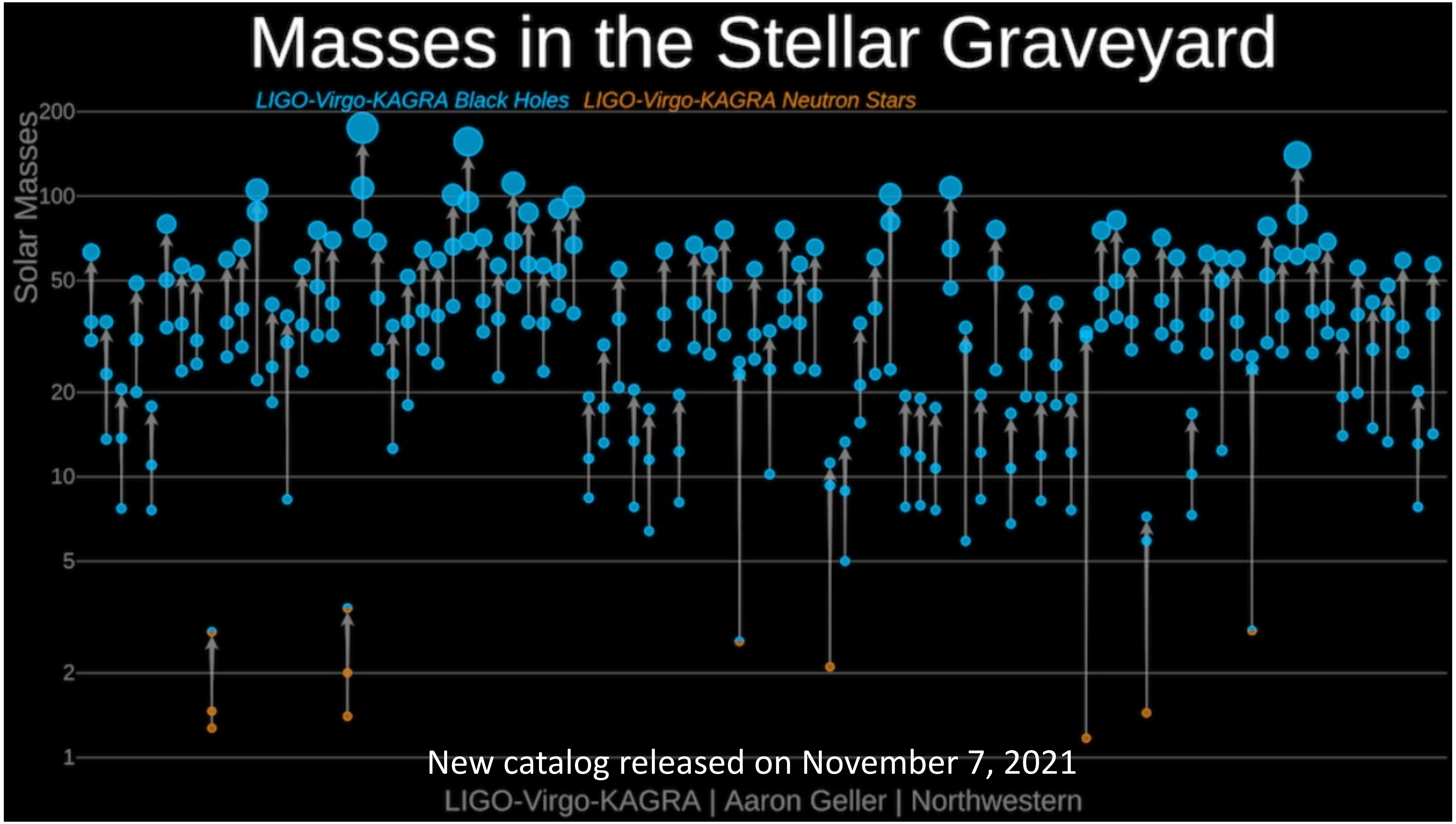
	Low-spin prior ($\chi \leq 0.05$)	High-spin prior ($\chi \leq 0.89$)
Binary inclination θ_{JN}	146^{+25}_{-27} deg	152^{+21}_{-27} deg
Binary inclination θ_{JN} using EM distance constraint [108]	151^{+15}_{-11} deg	153^{+15}_{-11} deg
Detector-frame chirp mass $\mathcal{M}^{\mathrm{det}}$	$1.1975^{+0.0001}_{-0.0001}$ $\mathrm{M}_\odot$	$1.1976^{+0.0004}_{-0.0002}$ $\mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}$ $\mathrm{M}_\odot$	$1.186^{+0.001}_{-0.001}$ $\mathrm{M}_\odot$
Primary mass m_1	$(1.36, 1.60)$ $\mathrm{M}_\odot$	$(1.36, 1.89)$ $\mathrm{M}_\odot$
Secondary mass m_2	$(1.16, 1.36)$ $\mathrm{M}_\odot$	$(1.00, 1.36)$ $\mathrm{M}_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}$ $\mathrm{M}_\odot$	$2.77^{+0.22}_{-0.05}$ $\mathrm{M}_\odot$
Mass ratio q	$(0.73, 1.00)$	$(0.53, 1.00)$
Effective spin χ_{eff}	$0.00^{+0.02}_{-0.01}$	$0.02^{+0.08}_{-0.02}$
Primary dimensionless spin χ_1	$(0.00, 0.04)$	$(0.00, 0.50)$
Secondary dimensionless spin χ_2	$(0.00, 0.04)$	$(0.00, 0.61)$
Tidal deformability $\tilde{\Lambda}$ with flat prior	300^{+500}_{-190}(symmetric)/300^{+420}_{-230}(HPD)	$(0, 630)$



Abbott et al. Phys Rev. X 9, 011001 (2019)

The prrogress → GWTC-1 → 11 events , GWTC-2 (*2.1 revisited*) → 55

GWTC-3 →90



Black holes are in blue, neutron stars are in orange, and compact objects of uncertain nature in both colors. Each event is represented by three points: the two coalescing objects and the final merger remnant. (Credit: LIGO Virgo Collaboration / Aaron Geller / Northwestern).

Focus on Black Hole Physics

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Short Recap on BH Physics

- GR BH: Schwarzschild prediction (1916) horizon radius $R_S = 2\,G\,M/c^2$
- No hair therorem.
  - a stationary black hole, as predicted by the Einstein–Maxwell equations of GR + e.m. theory are characterized just by mass M, electric charge Q and angular momentum .
  - *Example of a simple consequence: two BHs with the same M, Q and J, one made of anti-matter, the other made of matter are indistinguishable.*

- GR BH + Quantum Mechanics ➔ Bekenstein –Hawking Thermodynamics
  - BHs are more than simple geometrical objects. A distant observer sees a thermal distribution of particles emitted at a finite temperature: *Hawking radiation*
  - Entropy ➔ $S(M, \chi) = k_B A/(4\, l_P^{\,2}) = 2\pi k_B (M/m_P)^2[1+(1-\chi)^{1/2}]$ ($Q=0$, $\chi = [\,c\,J/(G\,M^2)\,]$)
  - *Hawking temperature* ➔ $T = (h\,c^3)/(16\,\pi^3\,k_B\,G\,M)$

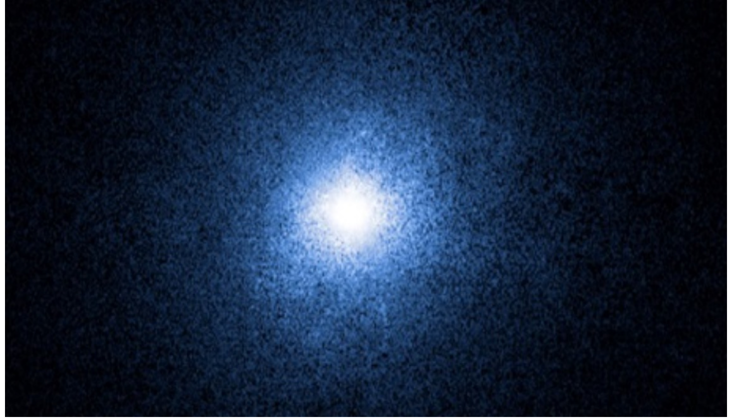
The first BH: CIGNUS X1

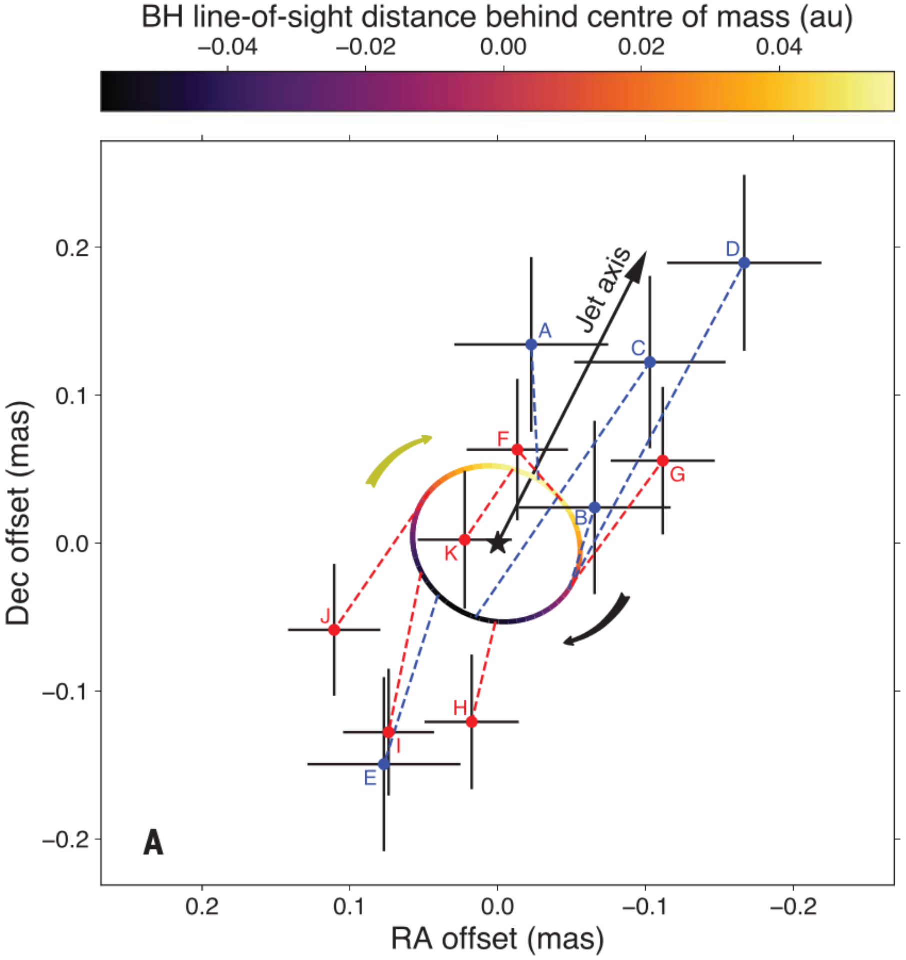
- In 1964 X-rays astronomers were able to trace back to a system containing a blue supergiant star orbiting another massive object some 7,200 light-years away.

- The second object, they determined, was also strongly radiating X-rays, which would make sense if it were a black hole

- Stars lose mass to their surrounding environment through stellar winds that blow away from their surface. The system emits x-rays and can form a radio jet. Then, using astrometric measurements carried on via VLBI technique the orbital parameters can be inferred.

- Recently it was stated that the Cignus X1 BH of a mass 21$\pm$2 $M_\odot$ is orbiting in 5.6 days around a supergiant star





Miller-Jones et al., Science 371, 1046–1049 (2021)

BH open questions

What is the nature of a BH and what is its origin?

- How well are these black holes described by General Relativity, and will new physics eventually be required, perhaps involving a quantum theory of gravity?

- Which physical processes and astrophysical conditions are responsible for the formation of the black holes we observe today?

- What is the detailed mass distribution of black holes as a function of cosmic history?

- Does this distribution have gaps or sharp features, and if so, what physical processes are responsible for them?

BH formation and Population Distribution

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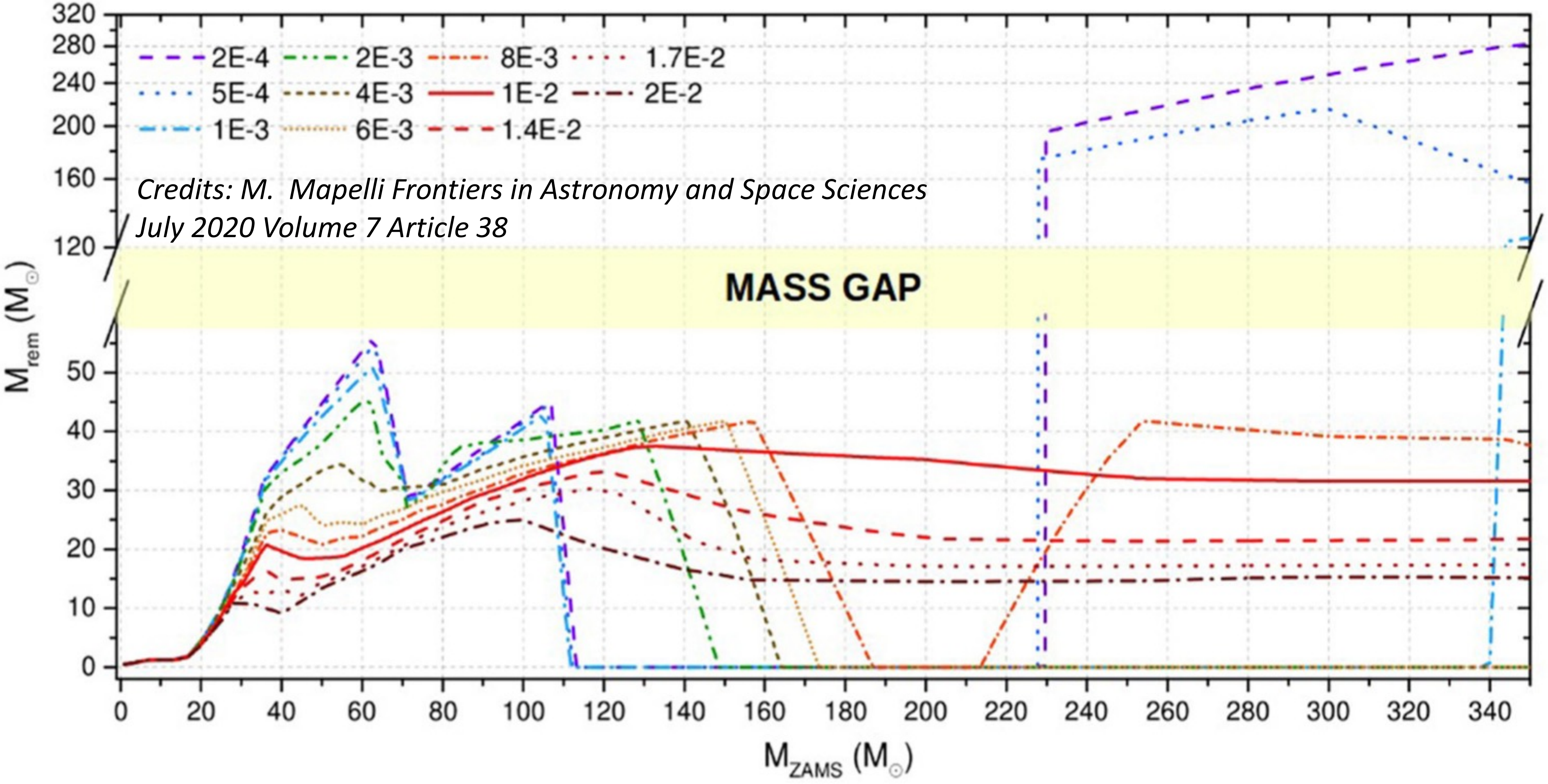
Simulations of stellar evolution in 11 different metallicity cases

(Astronomers use the word "metals" as a short term for "all elements except hydrogen and helium")

REM – Remenant

Mrem: Mass of the compact object

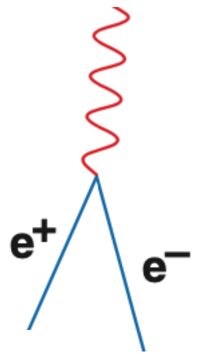


ZAMS - Zero Age Main Sequence is the is the time when a star first joins the main sequence on the Hertzsprung-Russell diagram (HR diagram) by burning hydrogen in its core through fusion reactions.

Why do they predict the existence of a mass gap ?

The model

- In stars with a main-sequence mass of approximately 150 $M_\odot$–260 $M_\odot$, the conversion of photons to e^+ / e^- pairs inside the hot dense core drives a runaway collapse.
- *When this collapse is halted by oxygen-burning nuclear reactions, the energy produced leads to an explosion powerful enough to completely destroy the star. The Supernova dominated by the pair instability mechanism do not leave any BH remnant.*
- Conclusion: the stellar evolution model tells us that there should be no black holes with masses in the range 50 $M_\odot$–140 $M_\odot$



Data from LIGO/Virgo

- GW190521 LIGO/Virgo event results from a BBH merger of black holes with masses of 66 $M_\odot$ and 85 $M_\odot$
- *At least one of the two BHs is well in the mass gap challenging the pair instability model.*

Attempts to conciliate model and data

- It is possible to move the boundaries of the mass gap by including rotation or magnetic fields in the calculation, but physically reasonable values of these seems not to permit that isolated stars populate the mass gap. (*D. Branch and J.C. Wheeler, Supernova Explosions, - Springer, New York, 2017*)

- If an energy source is added throughout the star in addition to nuclear fusion, it is possible to end up with a BH remnant: *J. Ziegler and K. Freese suggest as additive mechanism the case of dark matter annihilation (Phys. Rev. D 104, 043015 (2021)*

An other open problem: GW190814 and its ‘mystery object’

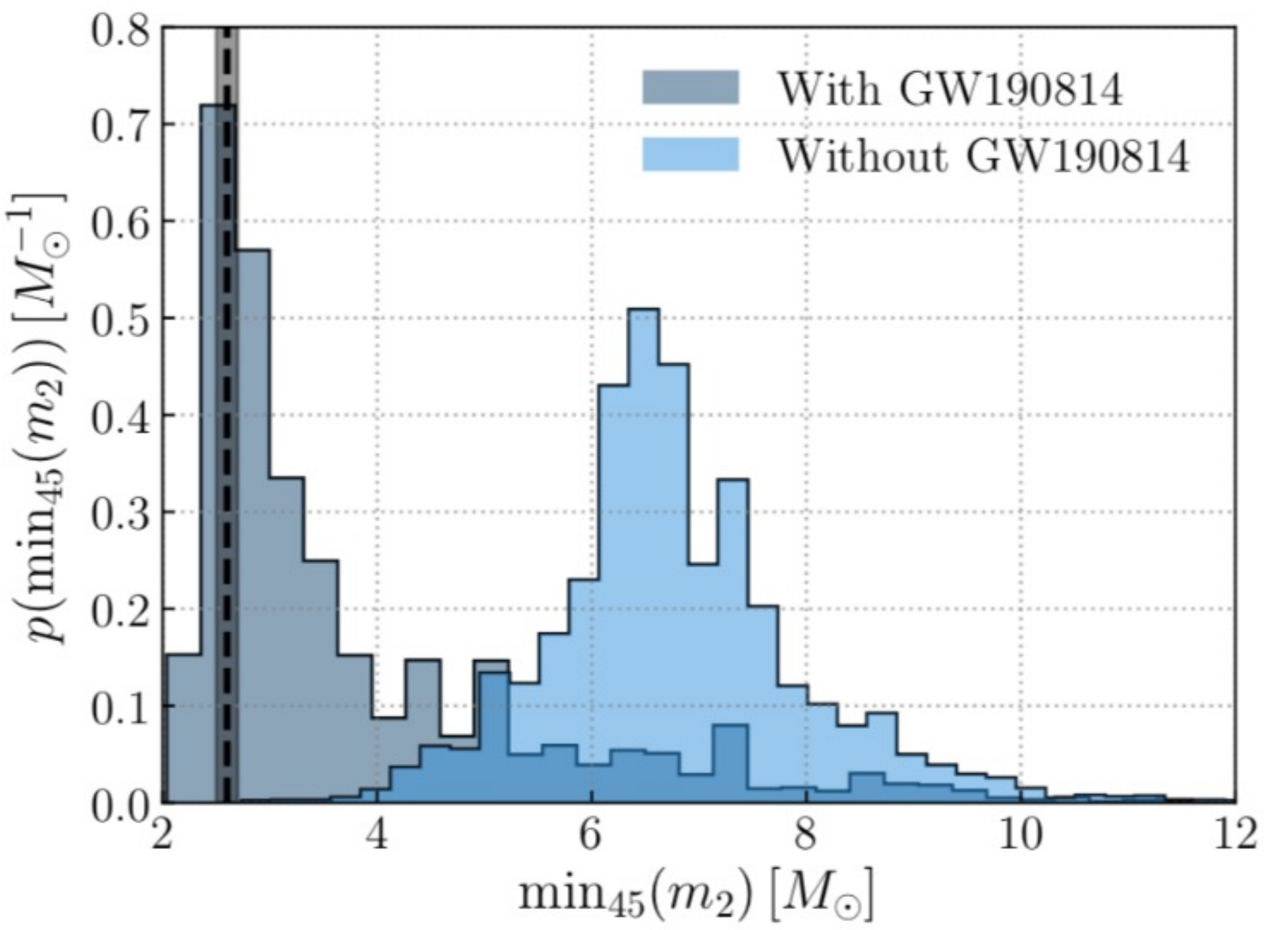
LVC, Astrophys.J.Lett. 896 (2020) 2, L44

Primary Object a BH of $\simeq$23 $M_\odot$,

Secondary Mass 2.50 -2.67 $M_\odot$:
a super-heavy NS or a super-light BH

Outlier in secondary mass & mass ratio distributions:
Probability <0.02% of seeing *as small* a m_2 or $q=m_2/m_1$ over 45 events

Indicates potential origin different from the majority of BBH detected up to now



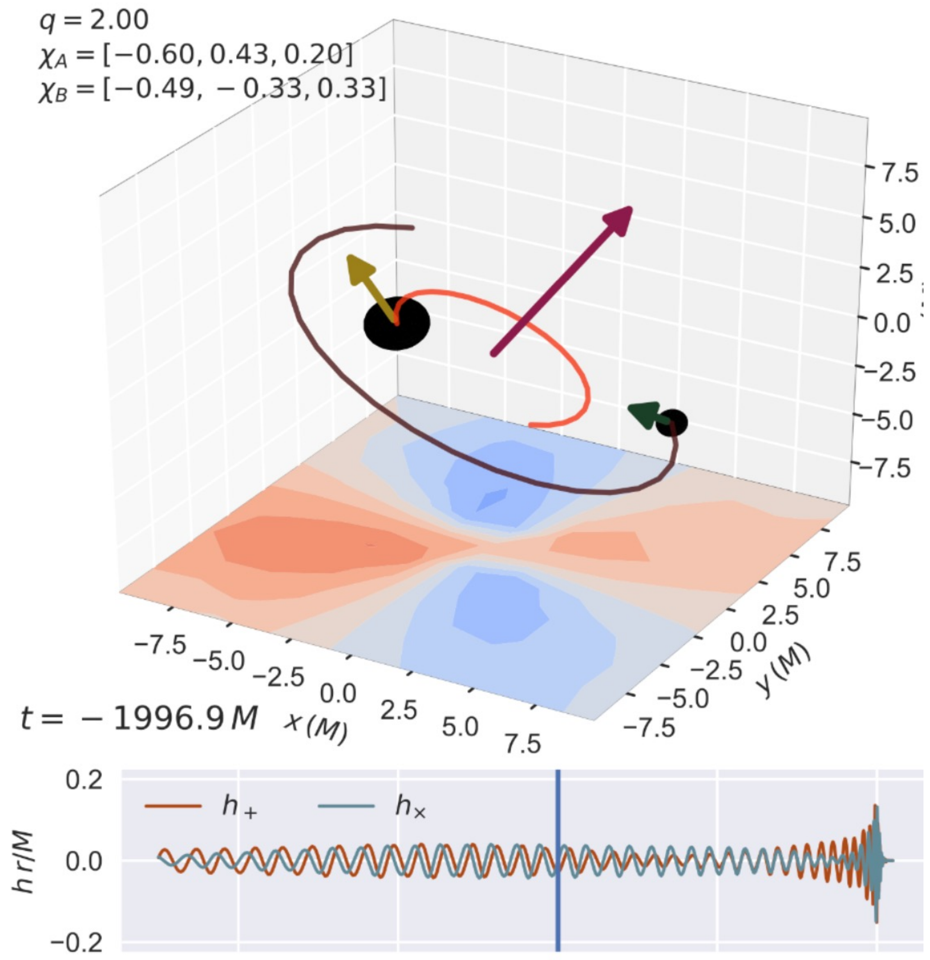
The role of the BH Spin in the Waveform analysis

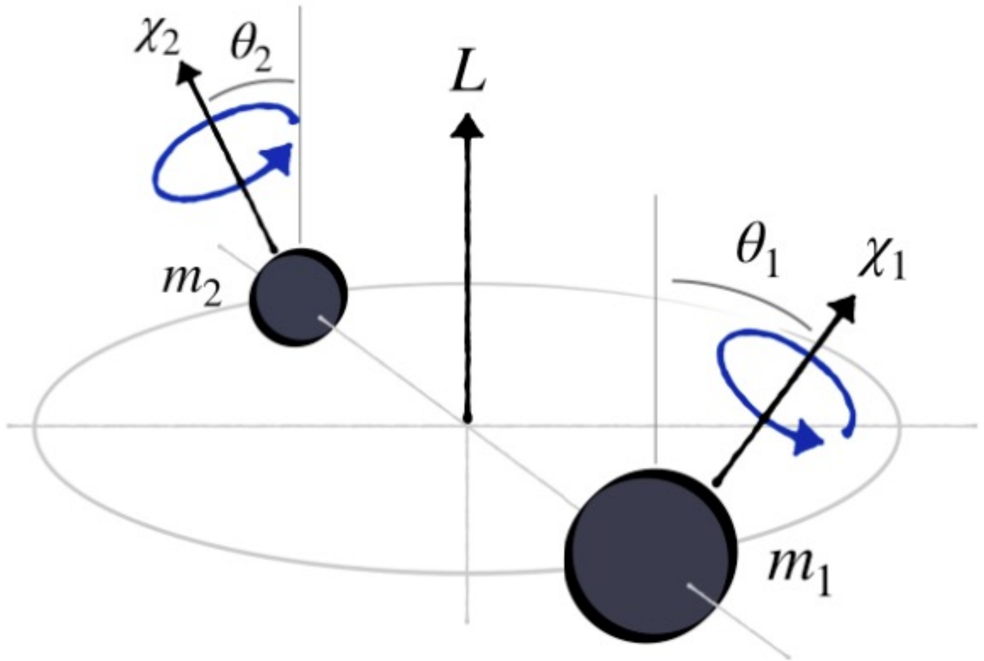
Effective spin

$$\chi_{\rm eff} = \frac{\chi_1 \cos\theta_1 + q\,\chi_2 \cos\theta_2}{1+q}$$

Effective precession spin

$$\chi_{\rm p} = \max\left[\chi_1 \sin\theta_1, \left(\frac{4q+3}{4+3q}\right) q\,\chi_2 \sin\theta_2\right]$$

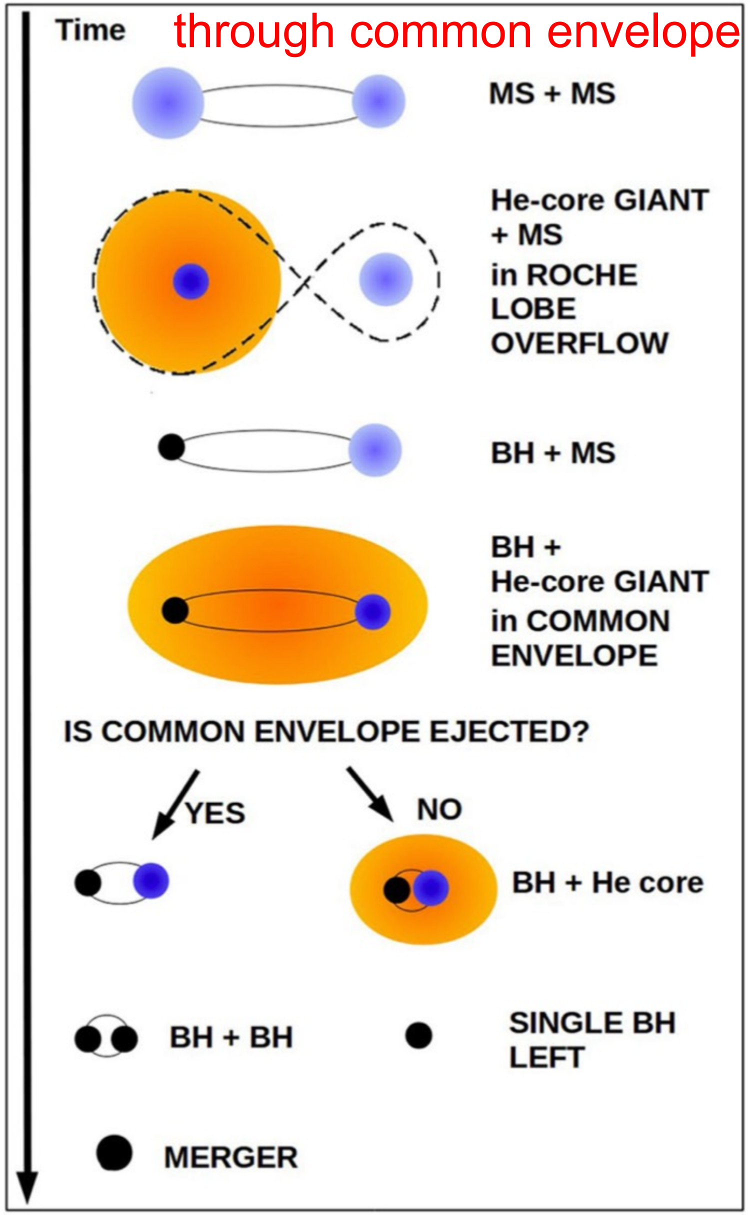




$q = m_2 / m_1$

Two scenarios of formation for stellar mass BBHs

Isolated BBH formation through common envelope



Isolated Formation

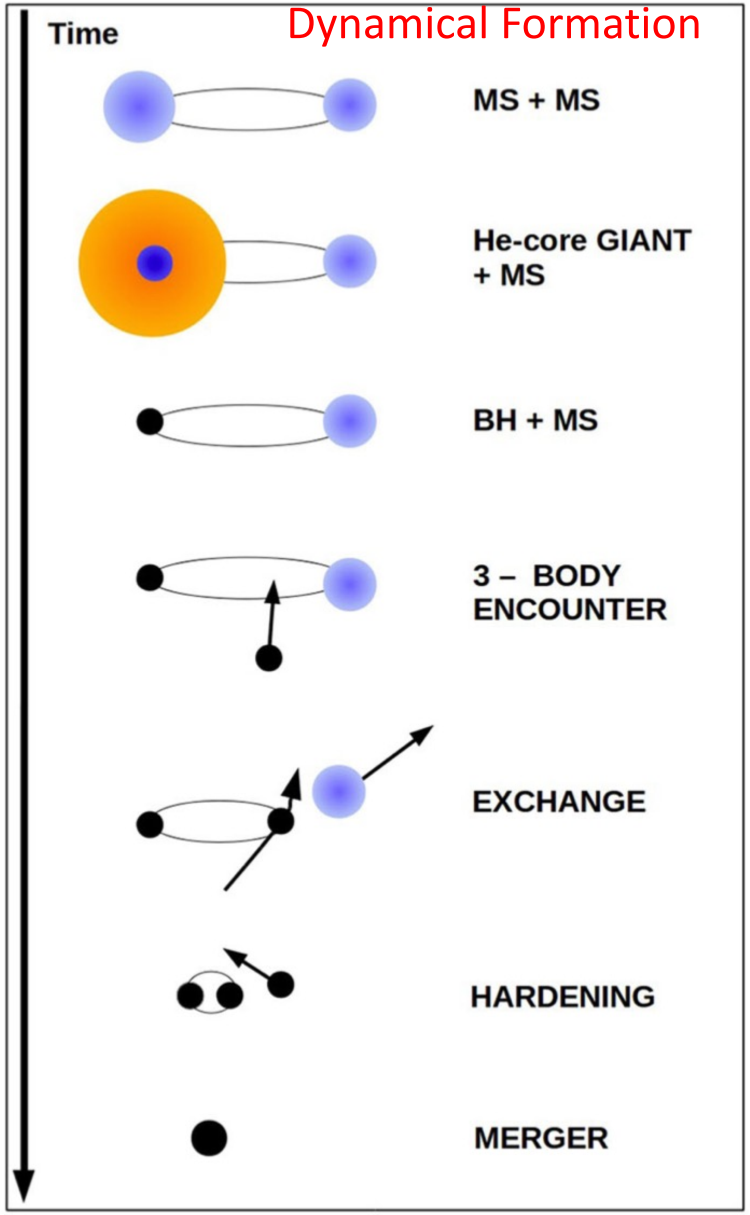
Strong gas drag from the envelope and loss of kinetic energy:

- inspiraling about each other and form a single BH
- If the envelop is ejected and the natal chick is low, BBH is formed

Dynamical Formation

During a three-body encounter, a binary star exchanges a fraction of its internal energy with the third body. If the binary is particularly tight (hard binary), such encounters tend to harden the binary star, i.e., to increase its binding energy by reducing its semi-major axis (*dynamical hardening*).

Dynamical Formation

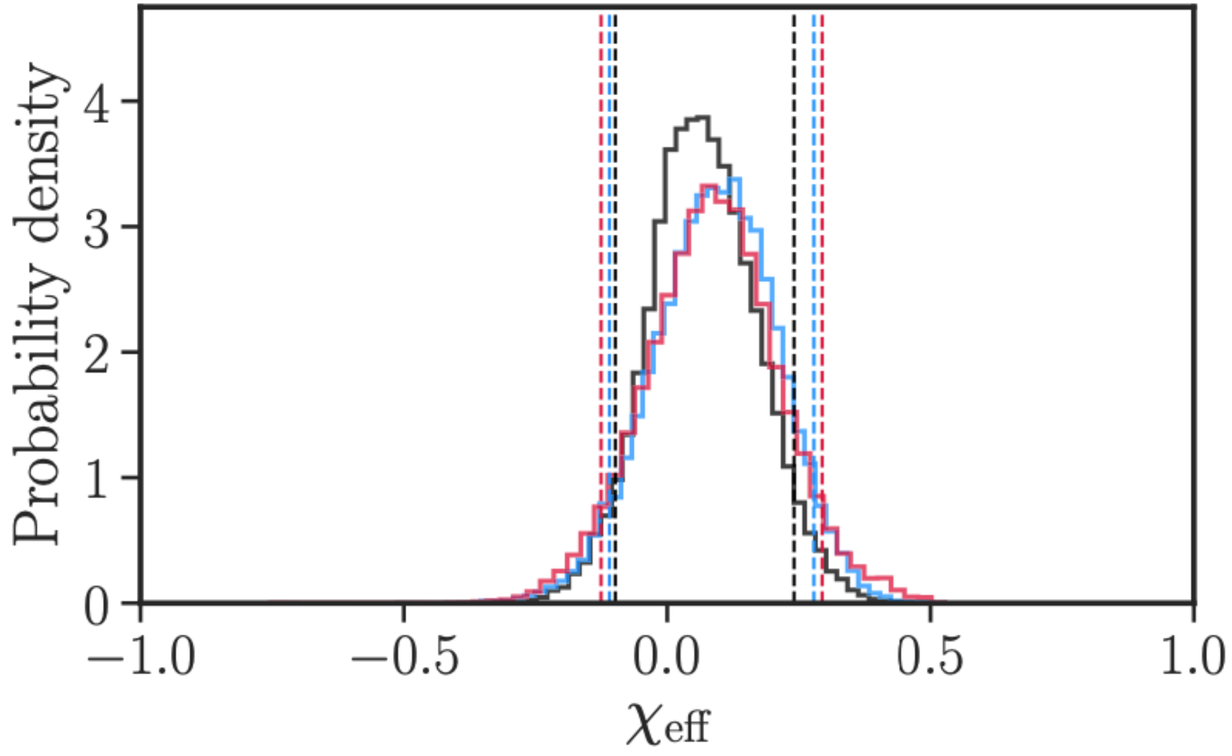


Spin and hints on BH population

- BHs in dynamically formed binaries in dense stellar environments expected to have spins distributed isotropically

- BHs formed in the isolated scenario of the stellar evolution are expected to induce BH spins preferentially aligned with the orbital angular momentum

- In almost all the BBHs mergers events, the inferred probability posterior of χ_{eff} clusters around zero and is rather narrowly peaked.



B. P. Abbott et al Phys. Rev X 9, 031040 (2019)

BH Thermodynamics

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Why is it interesting?

- Thermodynamics of the equilibrium states is a macroscopic description of an ensemble of many microscopic states, corresponding to the different possible ways of forming the same macroscopic solution.
- Enumerating these microstates we can derive the laws of thermodynamics from the kinetic theory of gases

- BH entropy and temperature are intrinsically related to the quantum nature of the system, but are related to macroscopic quantities: horizon area and surface gravity as provided by GR.

- <u>Starting from a fundamental theories of Quantum Gravity, in an appropriate average limit, should permit to derive BH Thermodynamics</u>.

- Conclusion: thermodynamic behaviour of BHs gives insights into the nature of quantum phenomena occurring in strong gravitational fields.

Bekenstein Hawking Thermodinamics

- Entropy

$$S\,(M,\chi) = k_B\, A/(4\, l_P{}^2) = 2\,\pi\, k_B\, (M/m_P)^2\, [1+(1-\chi)^{1/2}]$$

- Temperature

$$T = (h\, c^3)\,/\,(16\,\pi^3\, k_B\, G\, M)$$

Hawking has theorized that during pair production occurring just outside the event horizon, a black hole slowly loses mass or *evaporates* as particles are radiated away.

The temperature increase with loss of mass and the rate at which the energy is radiated from the black hole should also increase.

S should behave really as the Entropy of Classical Thermodinamics!

Attempt to verify the entropy increase in a irreverseble process: the area theorem

- Assuming the point of view of classical Thermodynamics, the *merger of two black hole* can be modeled as *an adiabatic irreversible process*:

  - *the entropy difference between final and initial state of the must be positive* for the Second law of Thermodynamics.

$$k_B/(4\,l_P^{\,2})\ (A_1 + A_2) < k_B/(4\,l_P^{\,2})\ A_f$$

$S(M_i, \chi_i) = k_B A/(4\, l_P^{\,2}) = 2\pi k_B (M_i/m_P)^2\,[1+(1-\chi_i)^{1/2}]$ *with i=1,2 and f*

The case of GW150914:

$(A_1 + A_2) < (2.36\pm0.48)\times10^{11}\ m^2$ $<$ $A_f \geq (3.61\pm0.47)\times10^{11}\ m^2$

Few other examples:

GW200112	$2.255\times10^{11}\pm0.016\times10^{11}$	$3.434\times10^{11}\pm0.010\times10^{11}$
GW200128	$3.100\times10^{11}\pm0.030\times10^{11}$	$4.596\times10^{11}\pm0.026\times10^{11}$
GW200129	$2.208\times10^{11}\pm0.020\times10^{11}$	$3.337\times10^{11}\pm0.008\times10^{11}$
GW200202	$1.693\times10^{10}\pm0.015\times10^{11}$	$2.639\times10^{10}\pm0.025\times10^{10}$

Salerno Valeria, *Il segnale di onde gravitazionali GW150914 e la variazione di entropia associata*, Bachelor Thesis in Physics of *Sapienza* University of Rome a.a. 2021/2022, March 2022

The main remark affecting the test and …how to overcome it

Cabero M., Collin M., Capano D., Fischer-Birnholtz O., Krishnan B., Nielsen A.B., Nitz A. H., and Biwer C. M., *Observational tests of the black hole area increase law*, Phys Rev D 97, 124069 (2018)

- M and χ obtained fitting the GW data with numerica relativity formulas and even the increase of the Bekenstein-Hawking entropy is GR.
  - ➢ The test is still dependent on GR

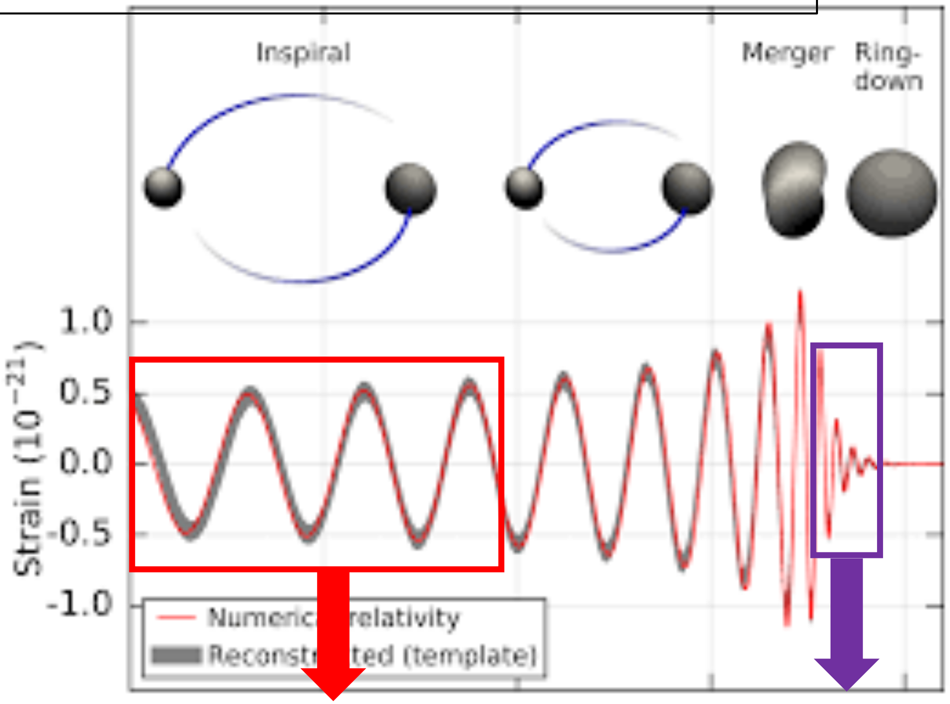
- We should be able to measure the initial and final parameters (masses and spin) independently, without assuming GR during the merger process.

  - Initial phase: keplerian mechanics to evaluate masses and spins.

  - Final oscillation used to extract mass and spin

No obvious separation between the two phases.

<u>SNR must be high in both sections of the GW signal</u>



The two bodies are relatively far from each other in a quasi stationary state

the quasi normal mode oscillations of the final object to

Spin population and BH Thermodynamics

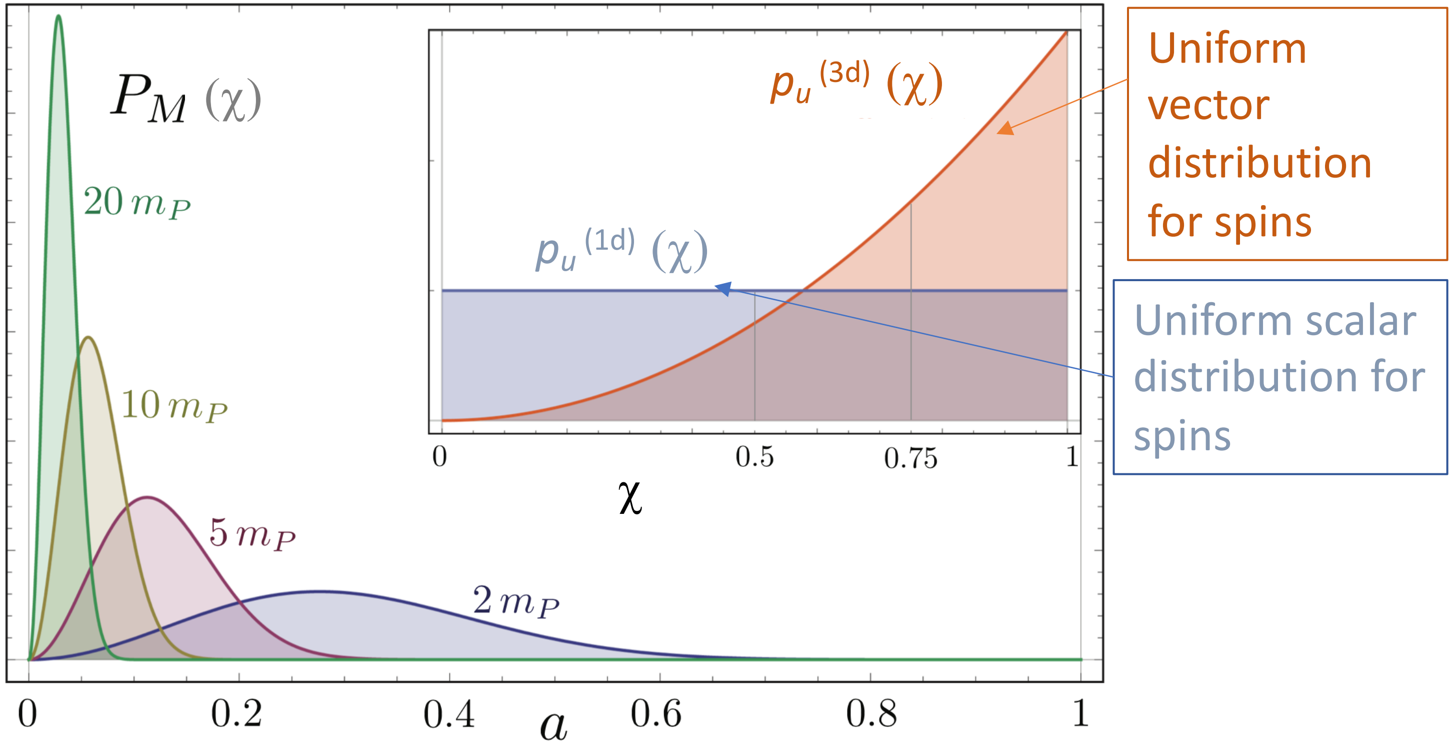
Bianchi et al. arXiv:1812.05127v

Probability to find a spin a in a fixed microcanonical ensemble of mass M is

$$P_M(\chi) = \chi^2 \, e^{S(M,\chi)} / N$$

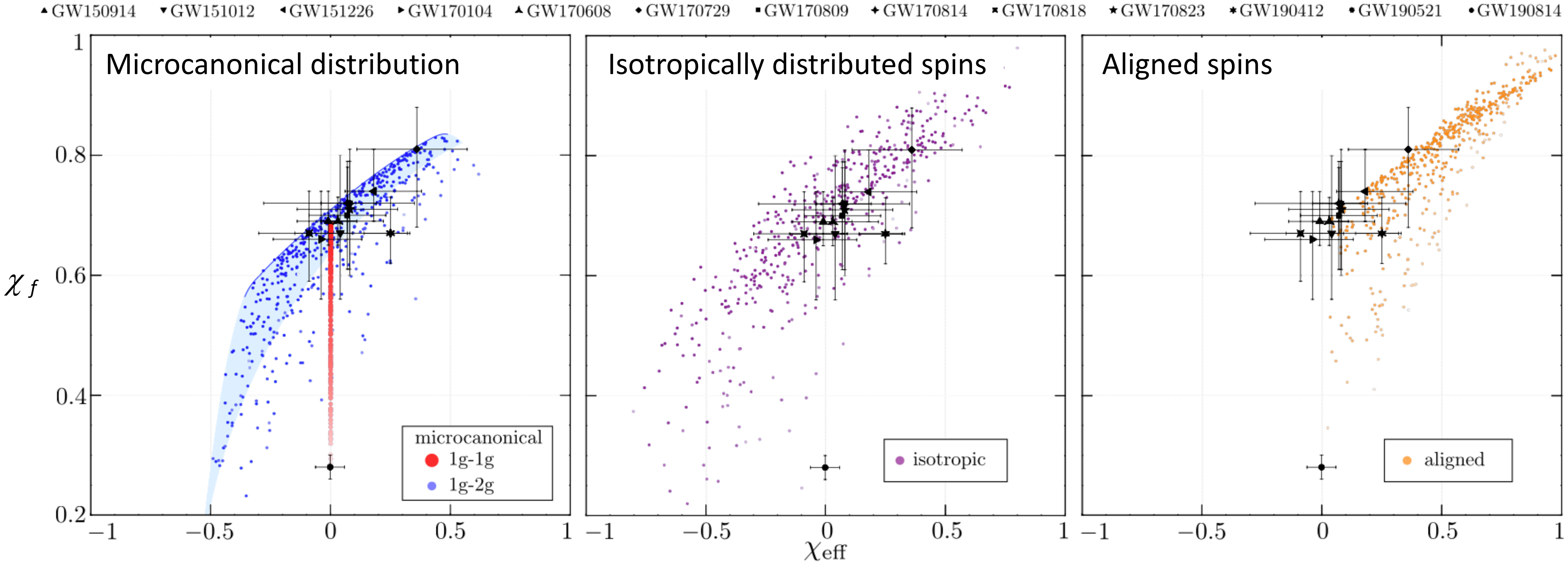
N ➔ normalization factor and $S(M, \chi) = k_B A/(4 l_P^2) = 2\pi k_B (M_i/m_P)^2 \, [1+(1-\chi)^{1/2}]$

For equal masses (M), higher spins (χ) correspond to lower entropy values, i.e. we should have fewer microstates with large spin than with small spin.



A first attempt to compare data with the spin distribution computed on the base of P(χ) derived assuming the microcanonical ensamble formula

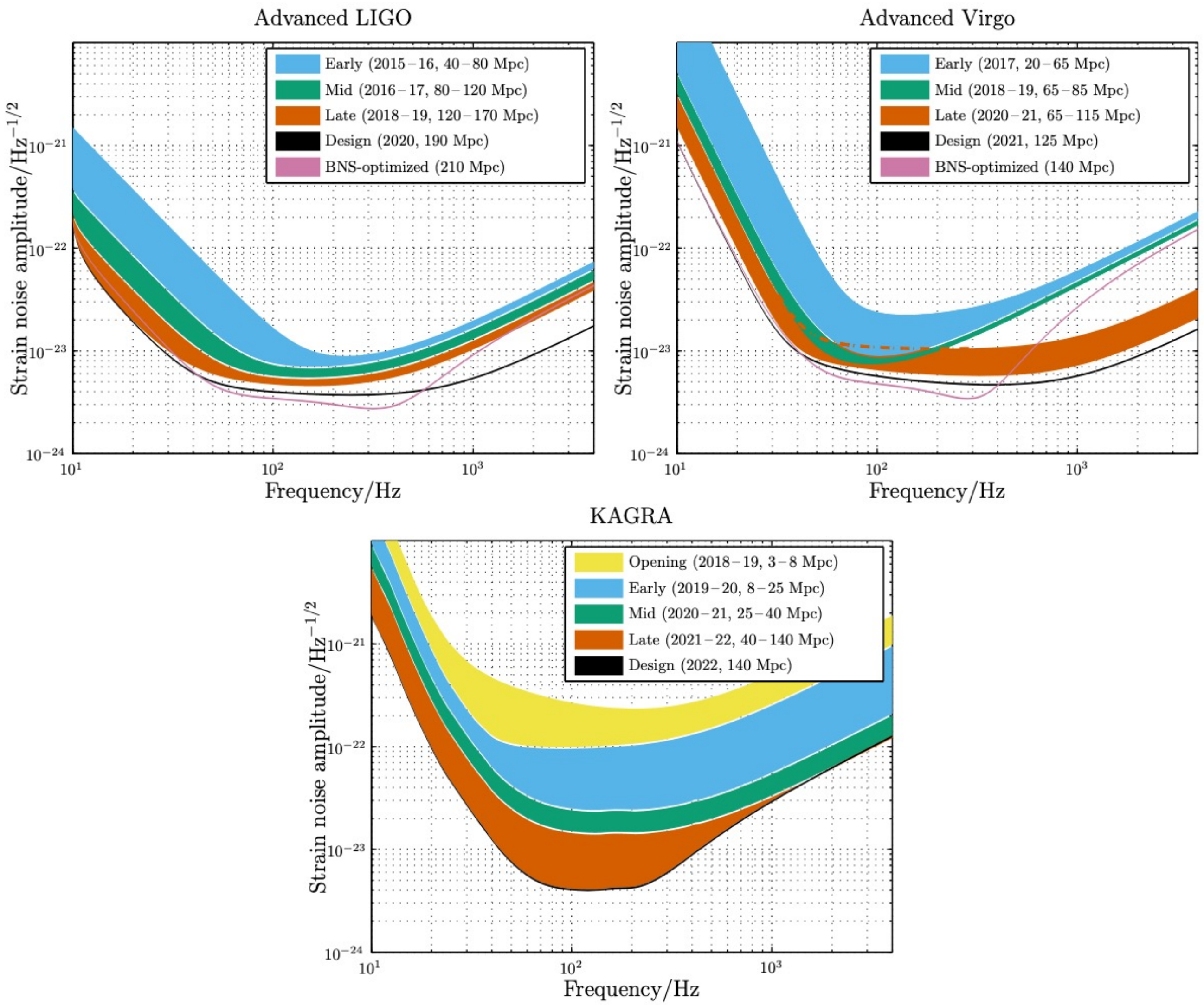
Bianchi et al. arXiv:1812.05127v



BH formation modeling

- 1g => BH of first generation,
- 2g => BH of second generation

More events at high SNR needed to progress on BH physics



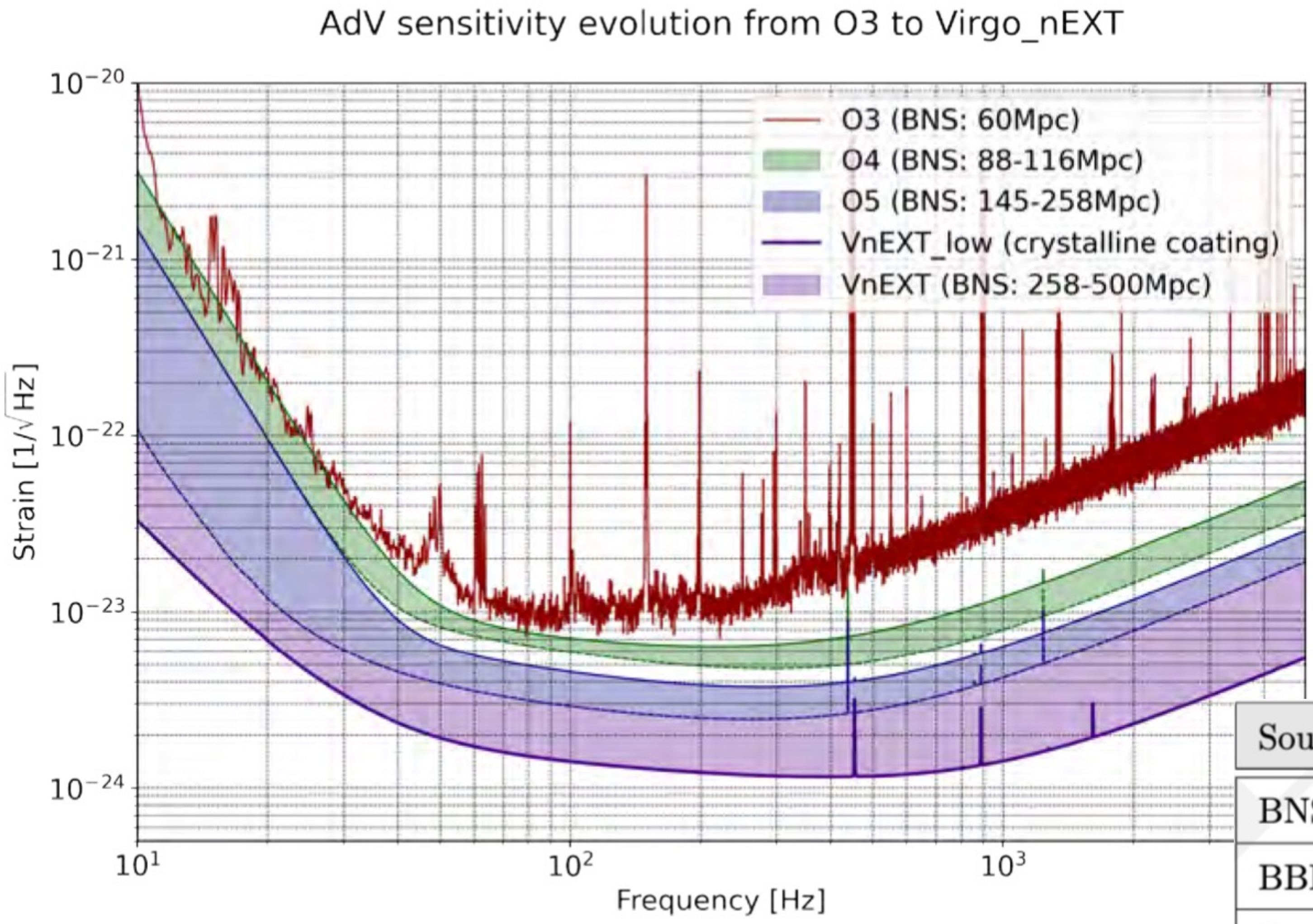
…and even to detect other kind of signals: neutron star emitters , supernovae, GW stocastic background

GW perspectives of the next decade

➔ Advanced Detectors +

➔ 3G detectors

Advanced Detectors in the post O5 era: the Virgo_nEXT case



Source	O5 low	"post-O5low"
BNS range (Mpc)	258	500
BBH range ($30 + 30\,M_\odot$) (Mpc)	590	3320
Stochastic Omega	7.5e-10	2.3e-10
Supernova (kpc) [217]	18.3	51.0

From Advanced Virgo + to Virgo_nEXT: the system upgrades

Parameter	**O4 high**	**O4 low**	**O5 high**	**O5 low**	**VnEXT_low**
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

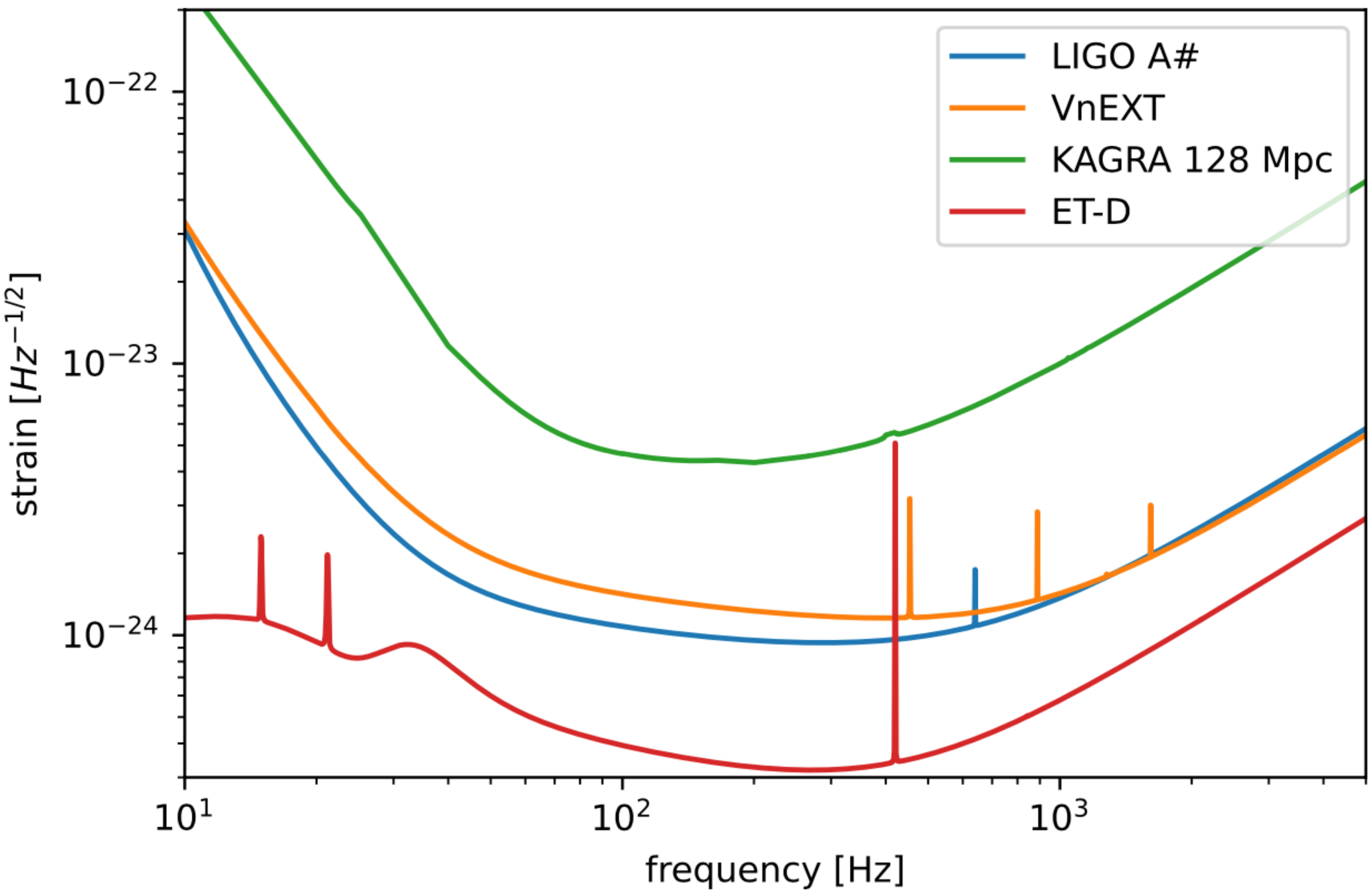
3G detectors: Einstein Telescope and 2G sensitivities

- Mirror Mass 200 kg

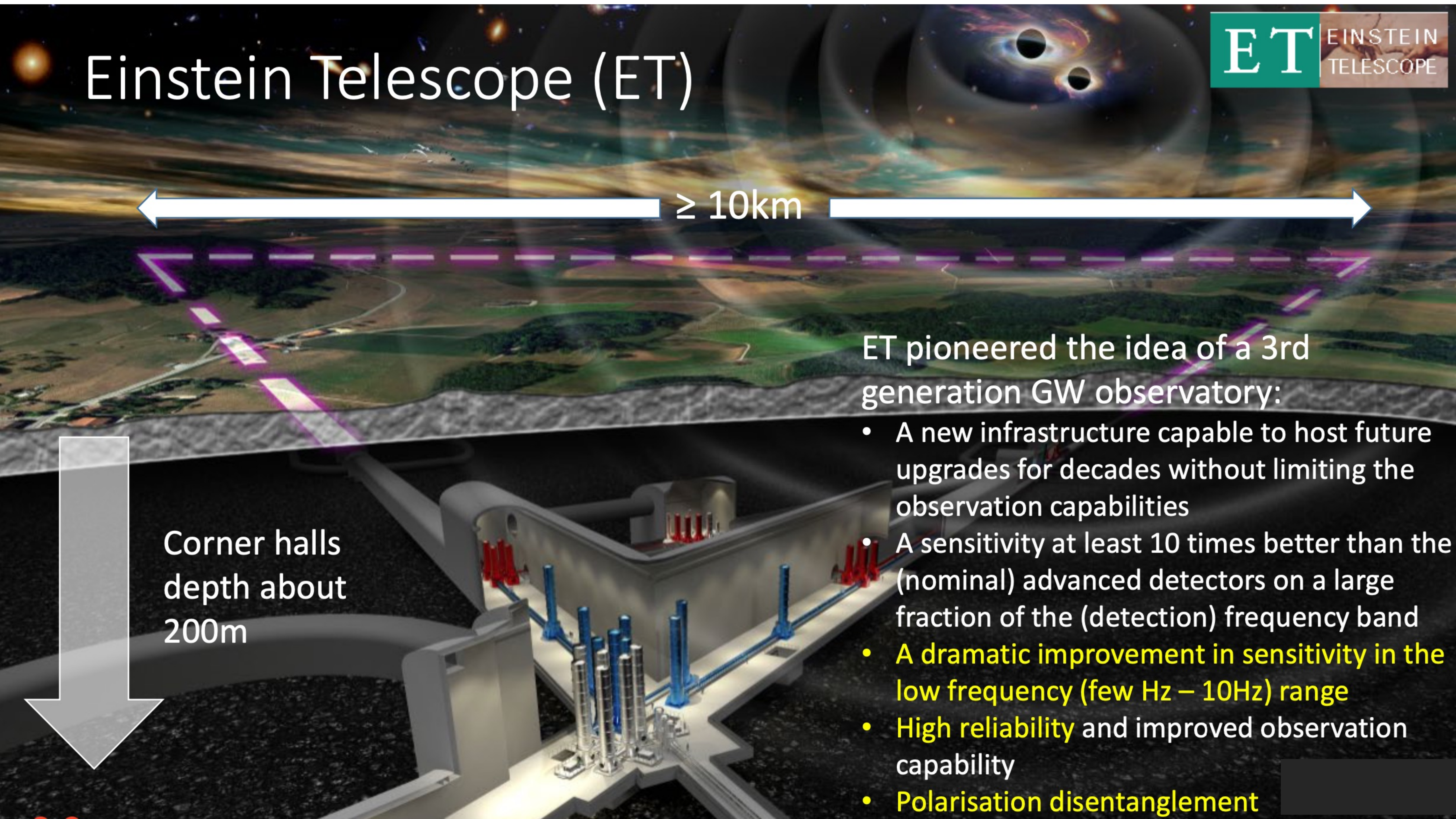
- Double Interferometer: xilophone concept based on Hot and Cold Interferometer

    - ➢ Hot ➔ High power laser ~700 W to traget high frequency

    - ➢ Cold ➔ Cryogenic Mirror and the last suspension stage to target low frequency



Einstein Telescope (ET)



ET pioneered the idea of a 3rd generation GW observatory:

- A new infrastructure capable to host future upgrades for decades without limiting the observation capabilities
- A sensitivity at least 10 times better than the (nominal) advanced detectors on a large fraction of the (detection) frequency band
- A dramatic improvement in sensitivity in the low frequency (few Hz – 10Hz) range
- High reliability and improved observation capability
- Polarisation disentanglement

40 km and 20 km L-shaped surface observatories
10x sensitivity of today's observatories (Advanced LIGO+)
Global network together with Einstein Telescope

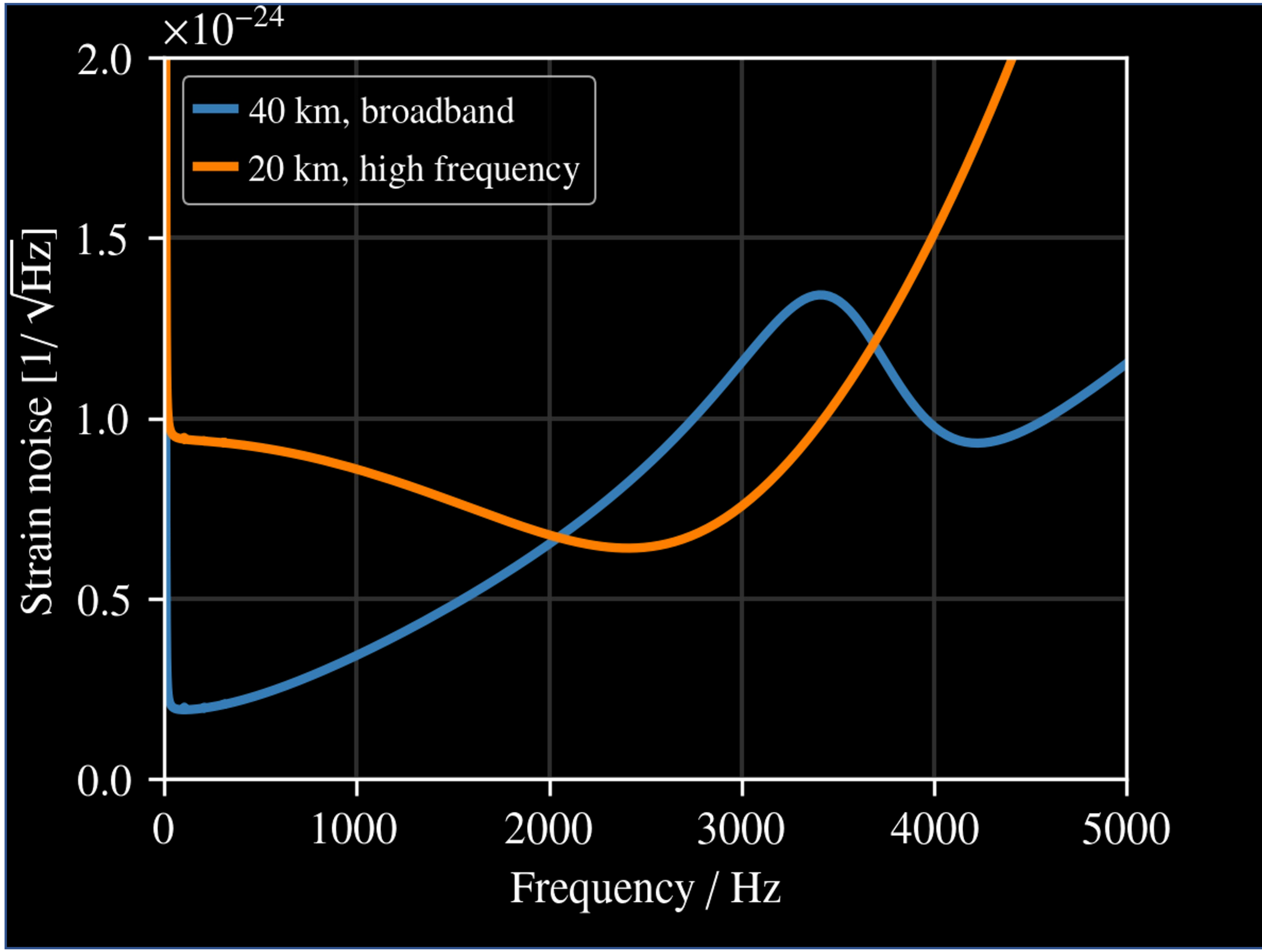
Artist: Eddie Anaya (Cal State Fullerton)

Cosmic Explorer: conceptual detector

Two widely separated interferometers of different arm length, installed on surface in two USA locations

- 40 km: deep broadband sensitivity from few Hz to kHz
  ($c/2L_{\mathrm{arm}} \approx 3.7\mathrm{kHz}$)

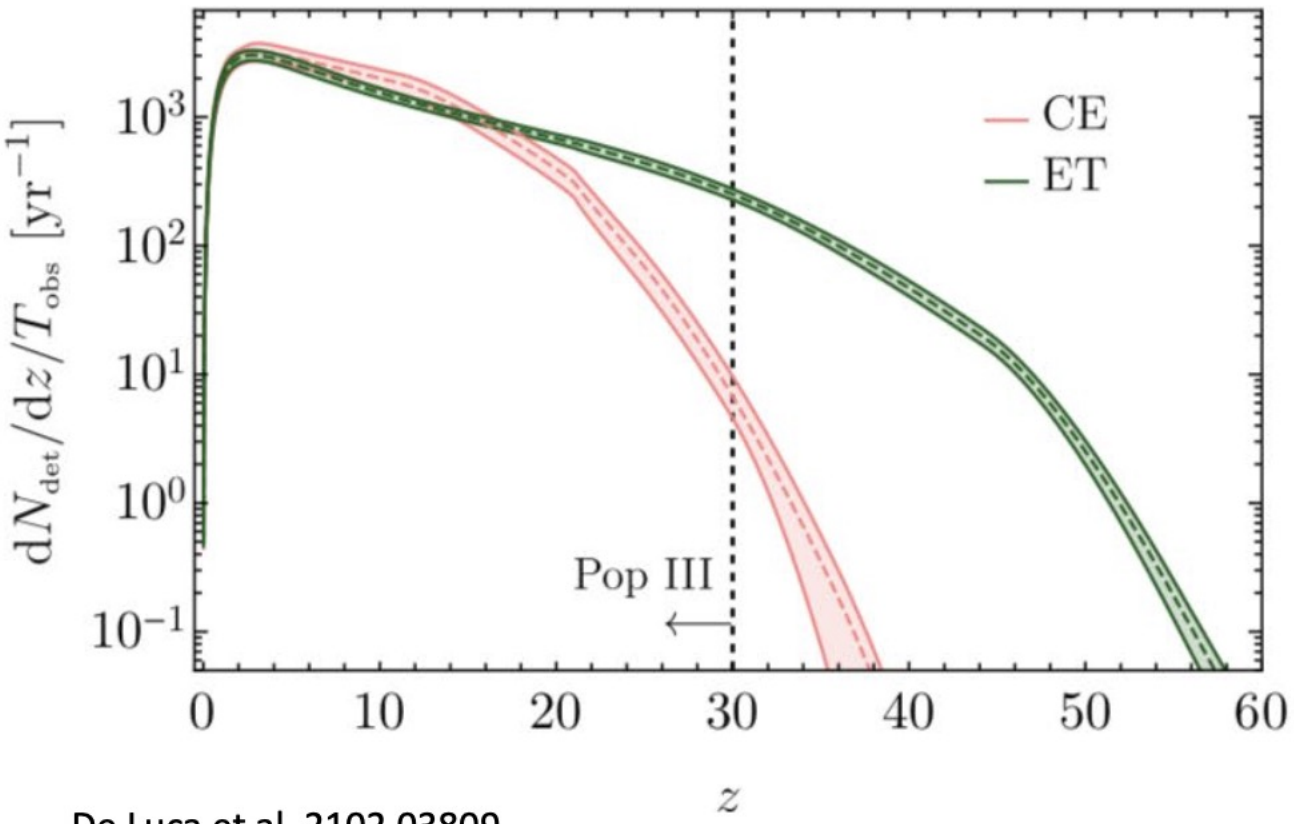
- 20 km: sensitivity improvement in the kHz range, to optimize the post-merger physics (hadron-quark phase transition)



Credits: Matt Evans et al arXiv:2109.09882

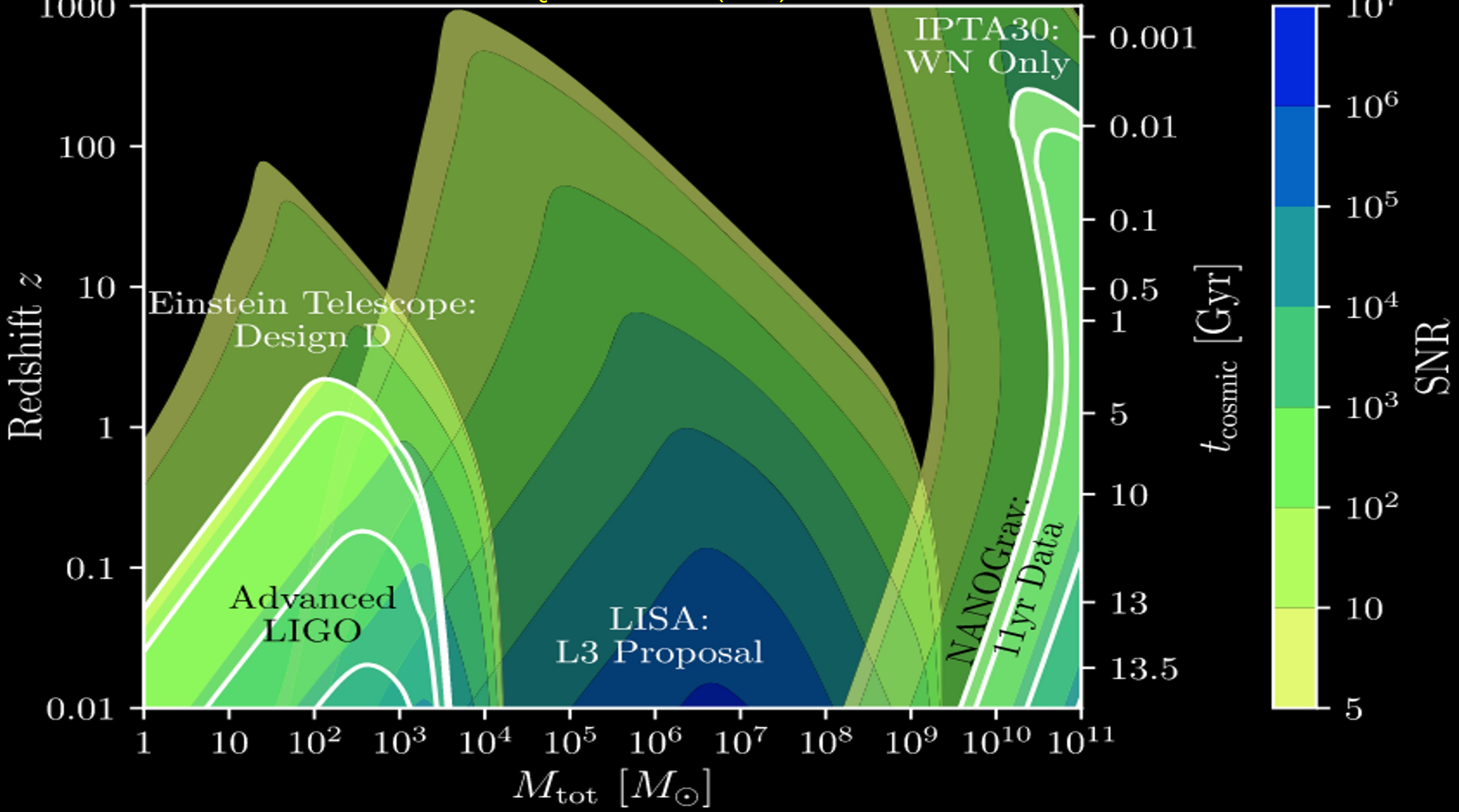
Primordial BHs

- ET will detect BH well beyond redshift $z \simeq 2$
- If we will compare the redshift dependence of the BBH merger rate with the cosmic star formation rate we can disentangle the contribution of BHs of stellar origin from that of primordial BHs (BHs uncorrelated to the star formation density
- BBH merger at z>30 will be of primordial origin



De Luca et al. 2102.03809

Credit : Kaiser+ *CQG* **38** 055009 (2021)



Conclusions

GW experiments and the recent visualization of the black hole at the center of our galaxy by the Event Horizon Telescope, seem to confirm GR

Each potential experimental test of general relativity could provide hints toward new directions for the theory, or even - in the extreme case - refutation of it.

Black holes are a great laboratory for such experiments !

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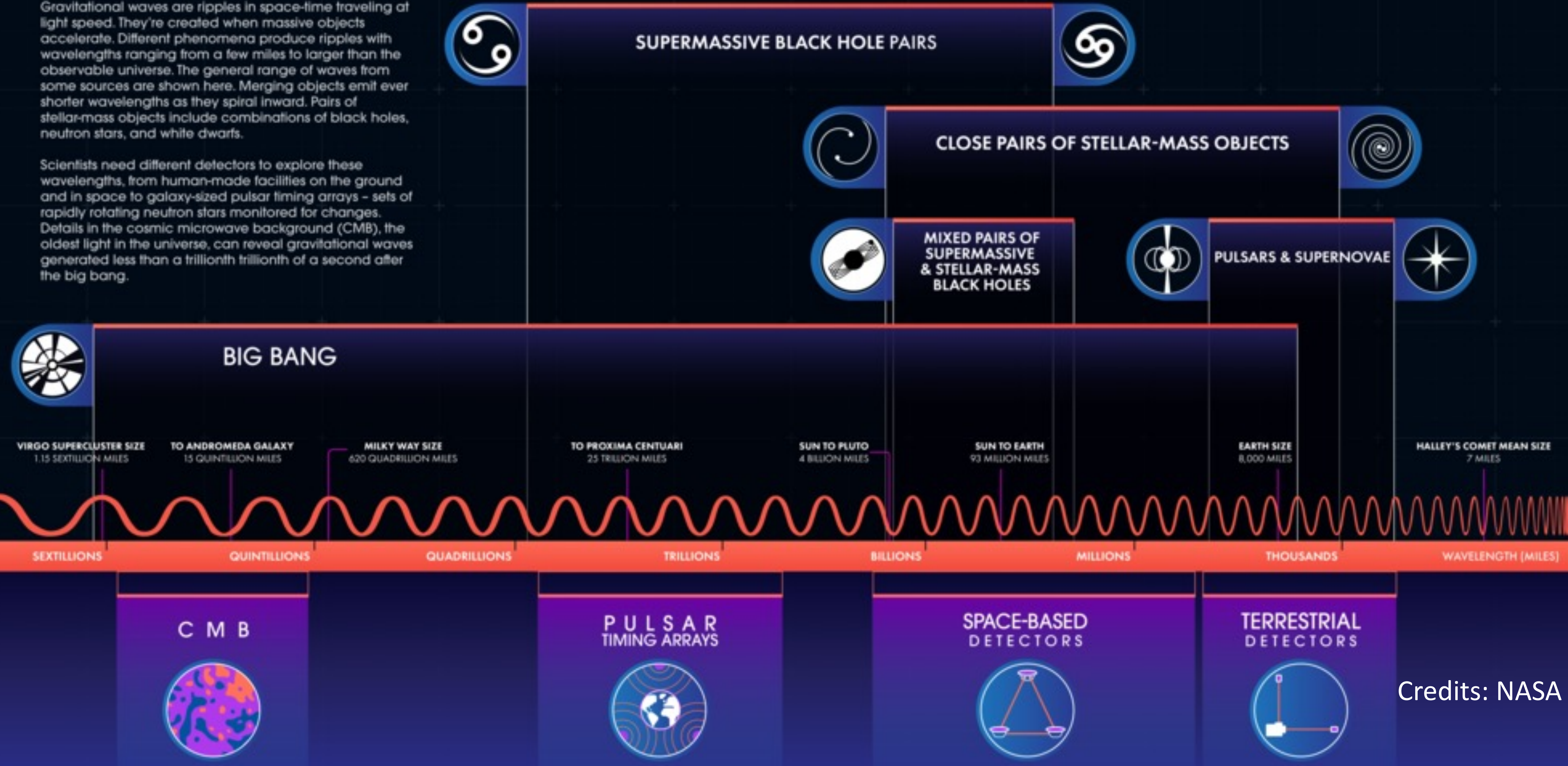
Istituto Nazionale di Fisica Nucleare

EXTRA SLIDES

THE GRAVITATIONAL WAVE SPECTRUM

Gravitational waves are ripples in space-time traveling at light speed. They're created when massive objects accelerate. Different phenomena produce ripples with wavelengths ranging from a few miles to larger than the observable universe. The general range of waves from some sources are shown here. Merging objects emit ever shorter wavelengths as they spiral inward. Pairs of stellar-mass objects include combinations of black holes, neutron stars, and white dwarfs.

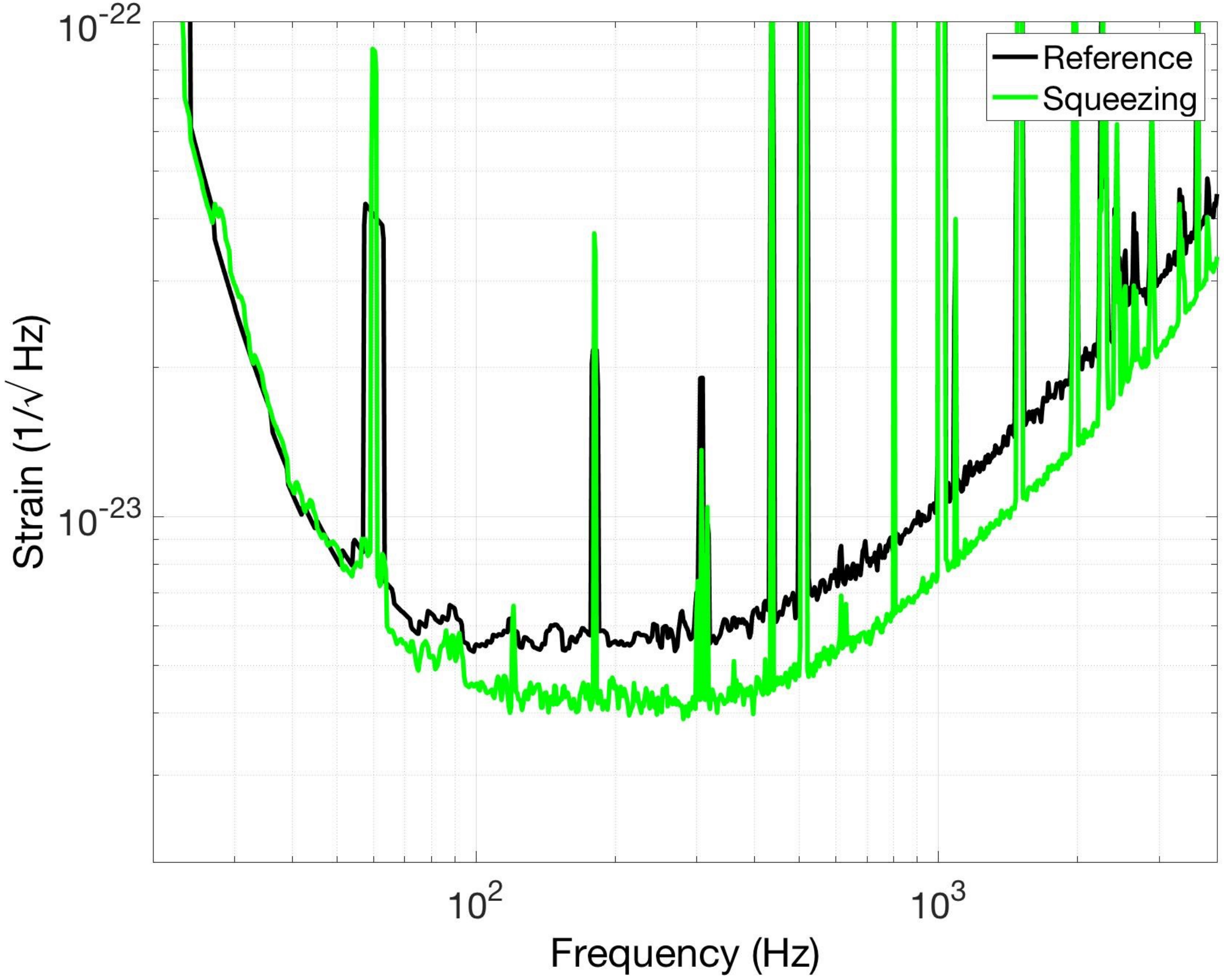
Scientists need different detectors to explore these wavelengths, from human-made facilities on the ground and in space to galaxy-sized pulsar timing arrays – sets of rapidly rotating neutron stars monitored for changes. Details in the cosmic microwave background (CMB), the oldest light in the universe, can reveal gravitational waves generated less than a trillionth trillionth of a second after the big bang.

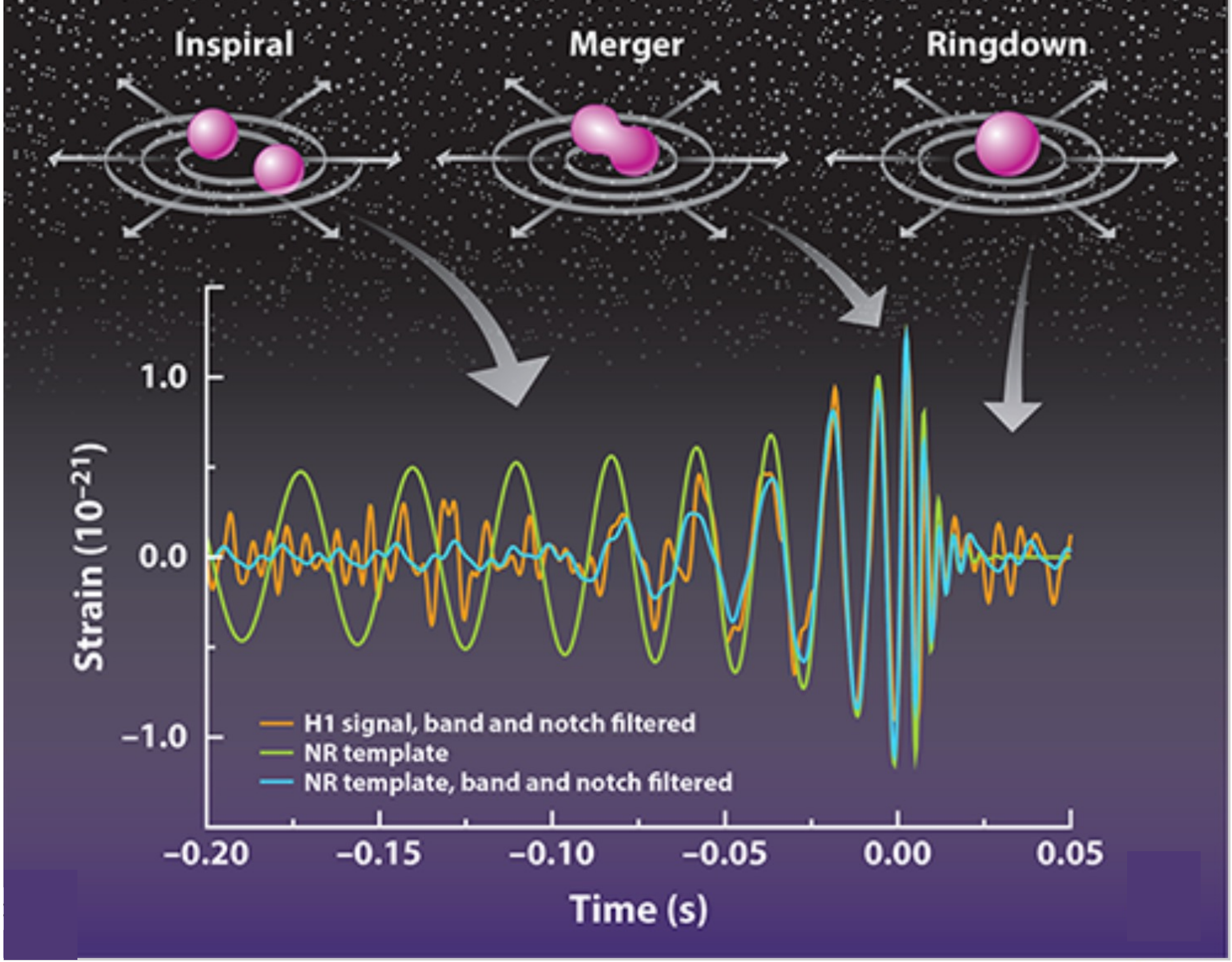


Credits: NASA

Reducing Sensing Noise with Squeezed Light

3 dB Squeezed Light Injection, LIGO Livingston, Feb 2019





Frans Pretorius, APS/Carin Cain