GRAVITATIONAL WAVE RESEARCH AND POSSIBLE CONNECTIONS WITH CHIPP AND CHAPS

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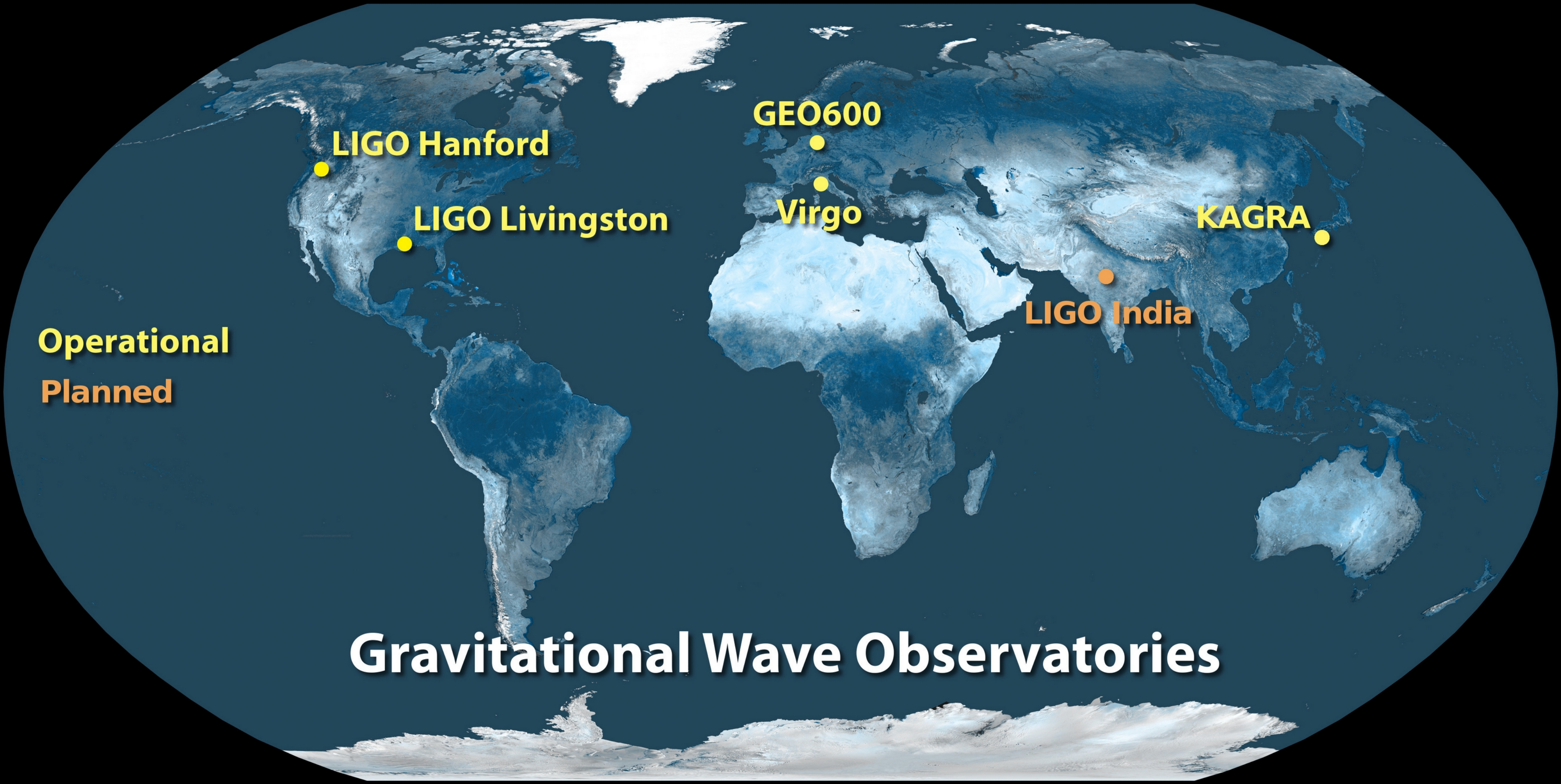
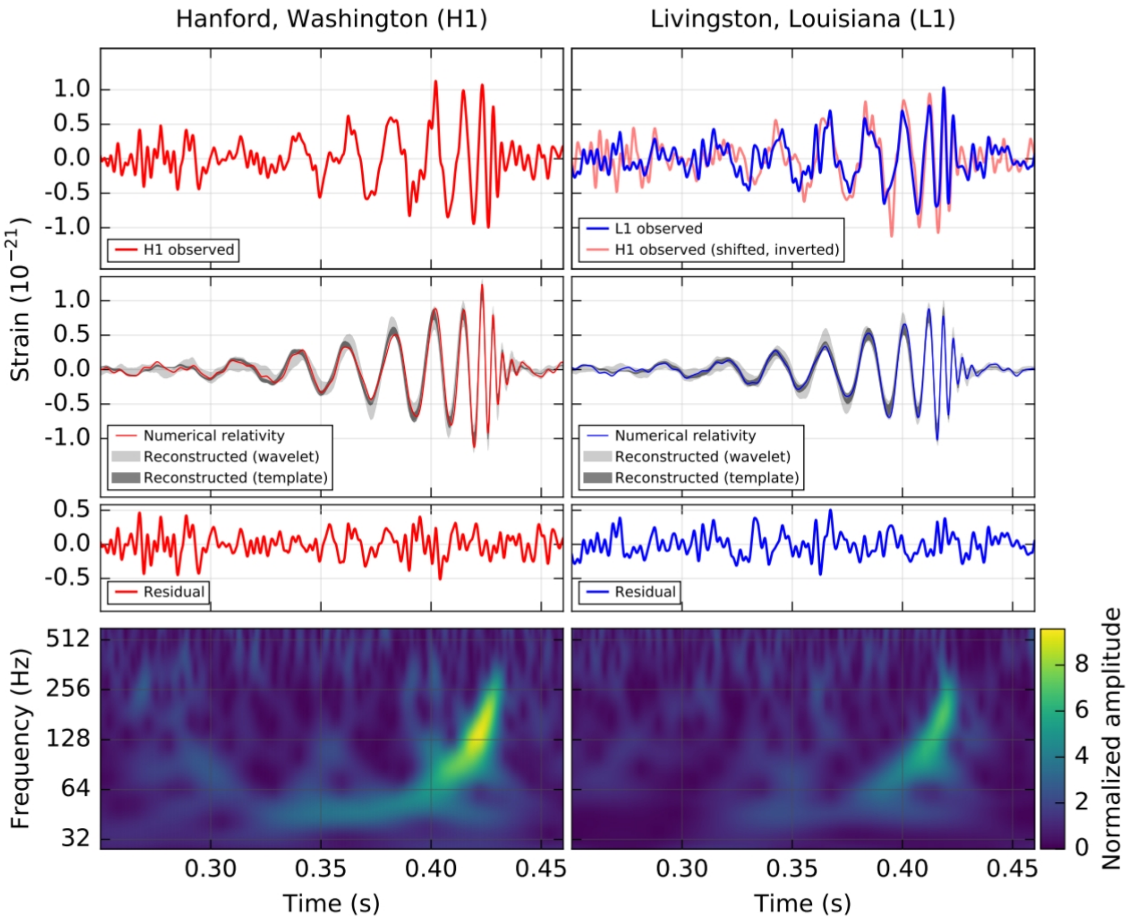
CHIPP Plenary meeting 2020

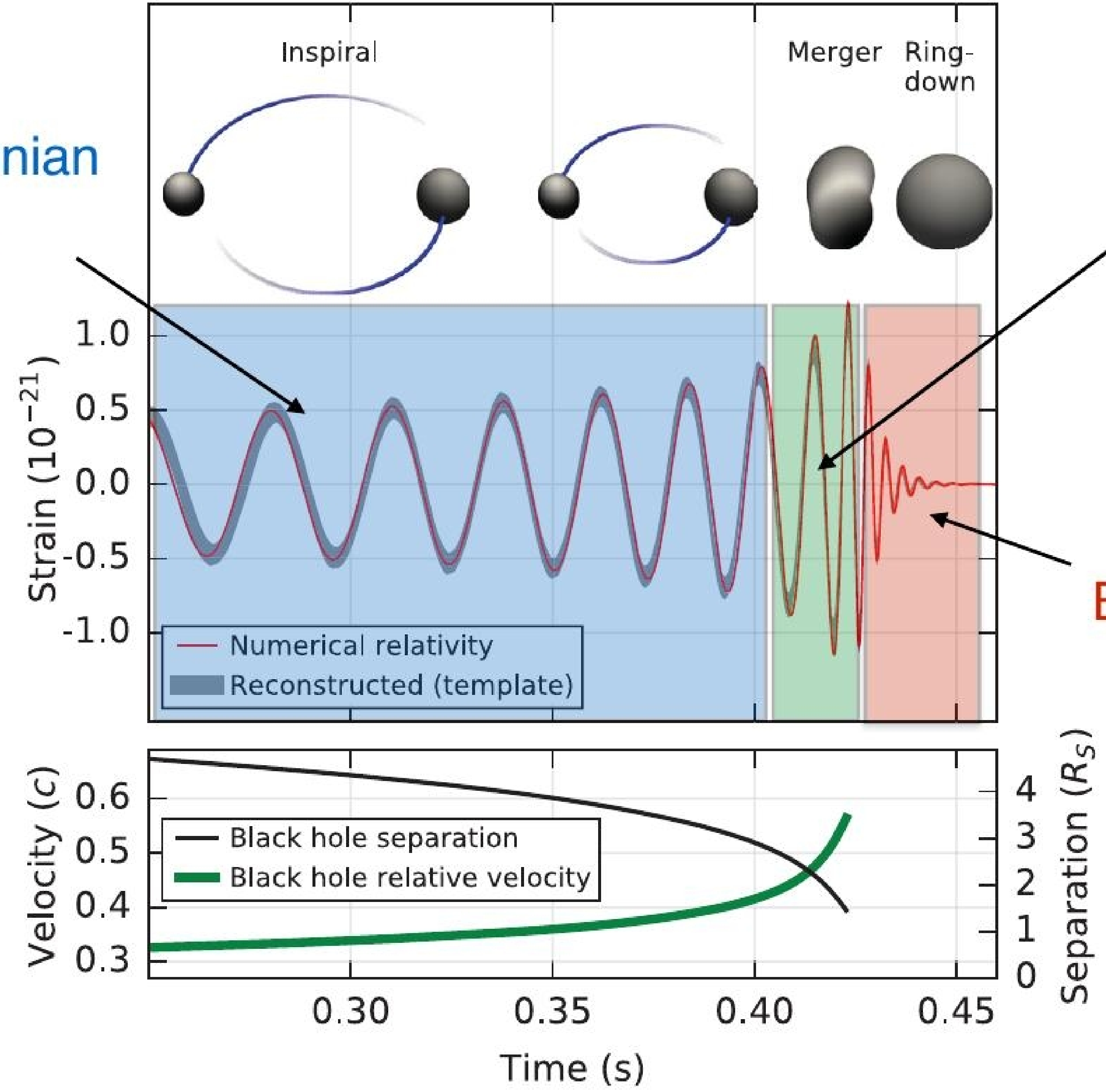
15 October 2020

Existing/ Planned Ground Based GW Detectors



Gravitational wave signal of 14 September 2015

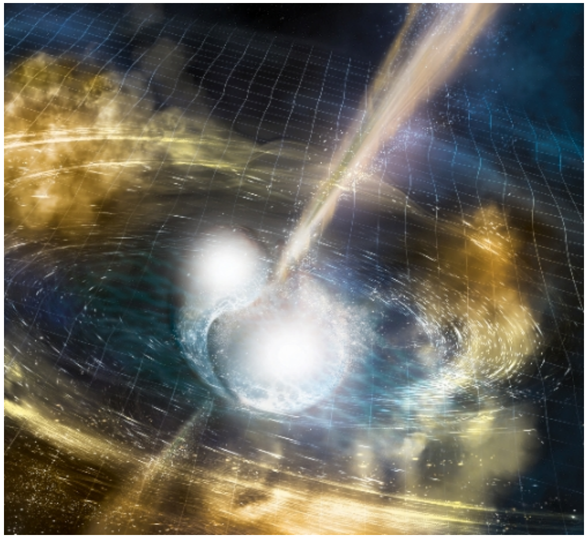




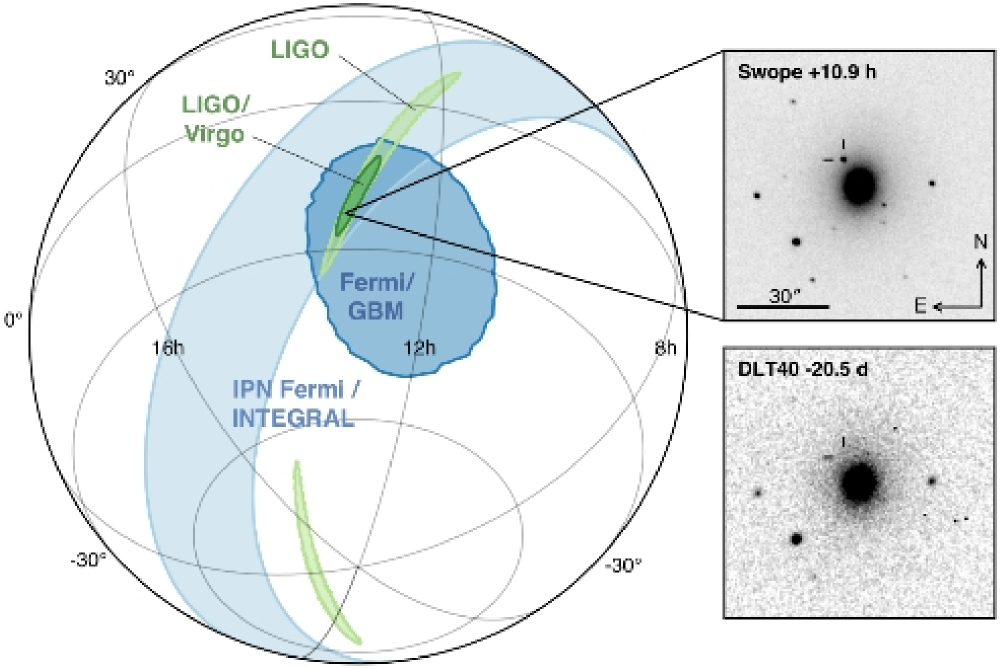
Post-Newtonian theory

Numerical relativity

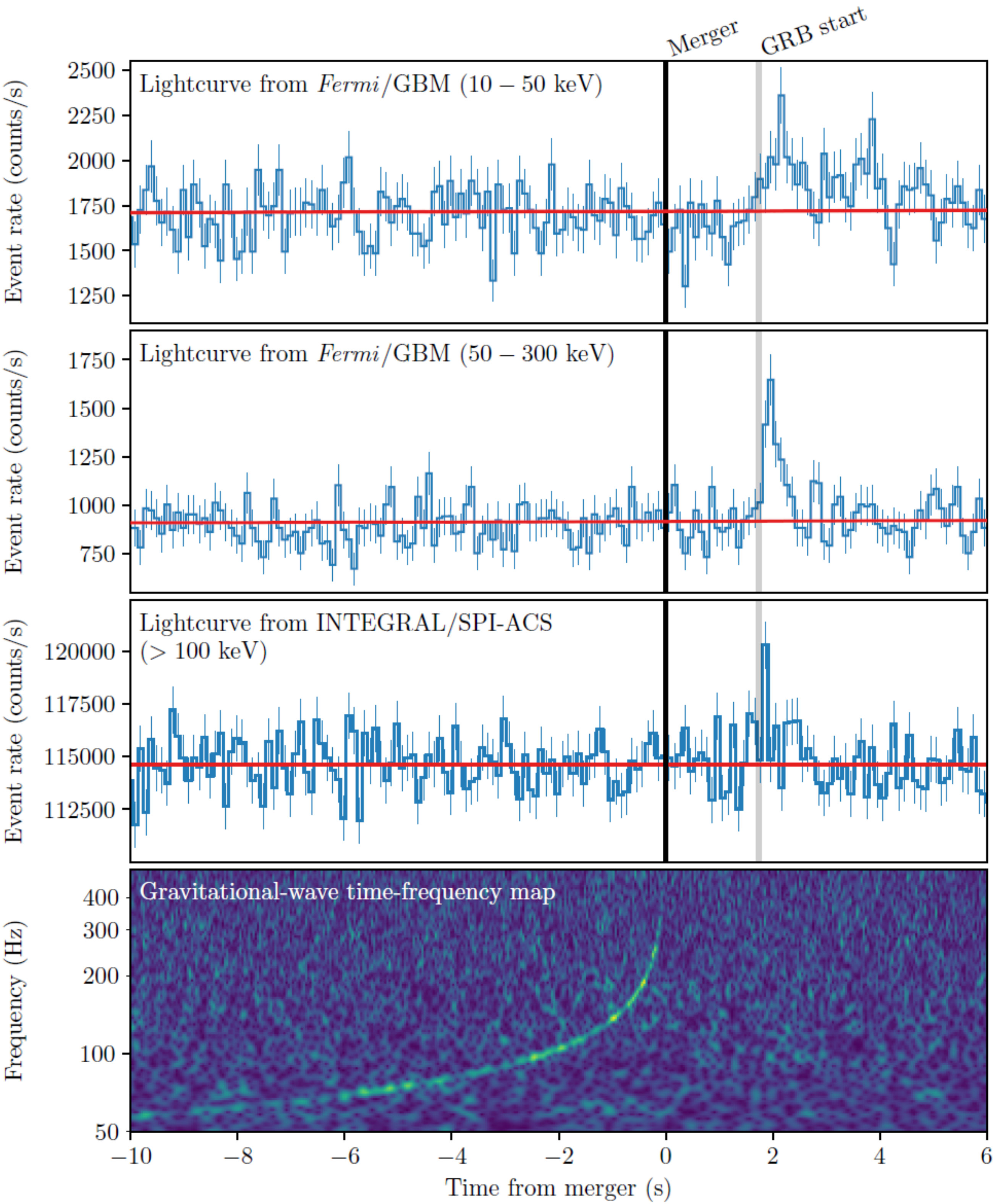
BH perturbations QNM

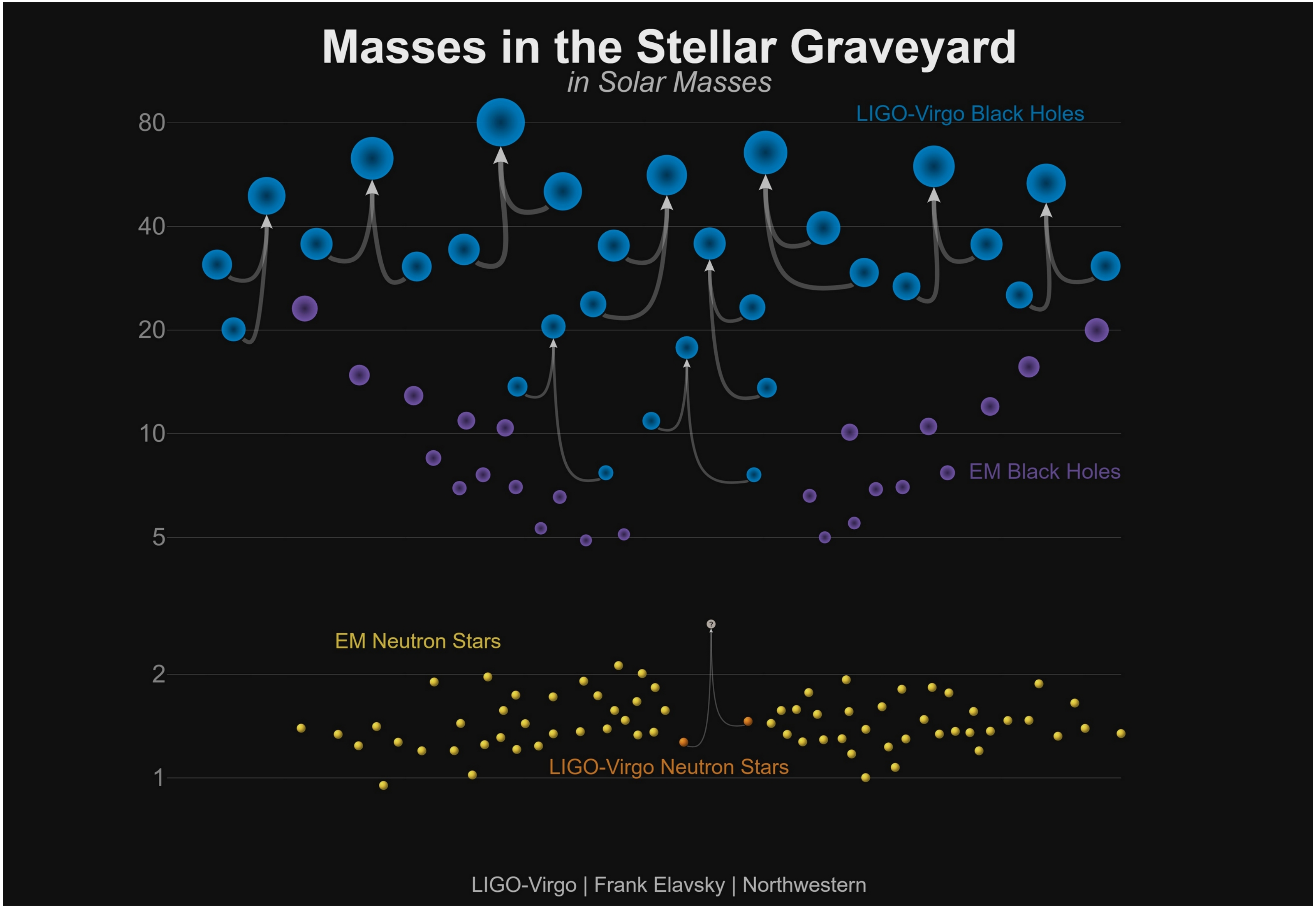


Artist's illustration of two merging Neutron stars.



Discovery of the optical image by the Swope Telescope.
Host galaxy NGC 4993.
Top: 10.9 hr after the merger.
Bottom: 20.5 days before.


Merger
GRB start
Lightcurve from *Fermi*/GBM (10 – 50 keV)
Event rate (counts/s)
2500
2250
2000
1750
1500
1250
Lightcurve from *Fermi*/GBM (50 – 300 keV)
Event rate (counts/s)
1750
1500
1250
1000
750
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
120000
117500
115000
112500
Gravitational-wave time-frequency map
Frequency (Hz)
400
300
200
100
50
−10
−8
−6
−4
−2
0
2
4
6
Time from merger (s)

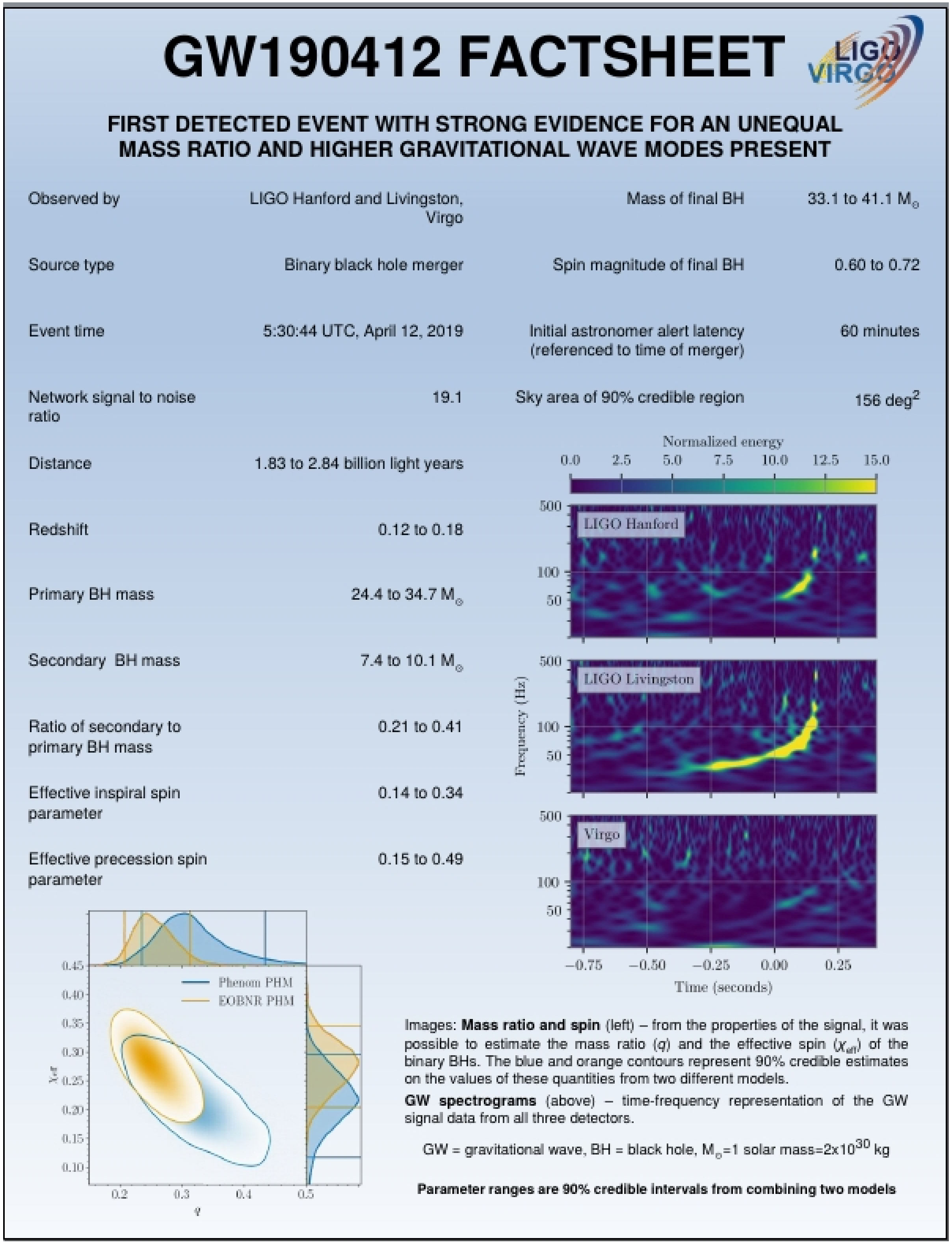


LIGO-Virgo events in O1 and O2: 10 BH events + 1 NS-NS event

- O3 started on 1 April 2019 and lasted till 27 March 2020.

- Some 56 alerts of candidate gravitational wave events were issued by LIGO-Virgo.

- KAGRA started the observation run on 25 February 2020.



GW190412 FACTSHEET

FIRST DETECTED EVENT WITH STRONG EVIDENCE FOR AN UNEQUAL MASS RATIO AND HIGHER GRAVITATIONAL WAVE MODES PRESENT

Observed by	LIGO Hanford and Livingston, Virgo
Source type	Binary black hole merger
Event time	5:30:44 UTC, April 12, 2019
Network signal to noise ratio	19.1
Distance	1.83 to 2.84 billion light years
Redshift	0.12 to 0.18
Primary BH mass	24.4 to 34.7 $M_\odot$
Secondary BH mass	7.4 to 10.1 $M_\odot$
Ratio of secondary to primary BH mass	0.21 to 0.41
Effective inspiral spin parameter	0.14 to 0.34
Effective precession spin parameter	0.15 to 0.49
Mass of final BH	33.1 to 41.1 $M_\odot$
Spin magnitude of final BH	0.60 to 0.72
Initial astronomer alert latency (referenced to time of merger)	60 minutes
Sky area of 90% credible region	156 deg^2

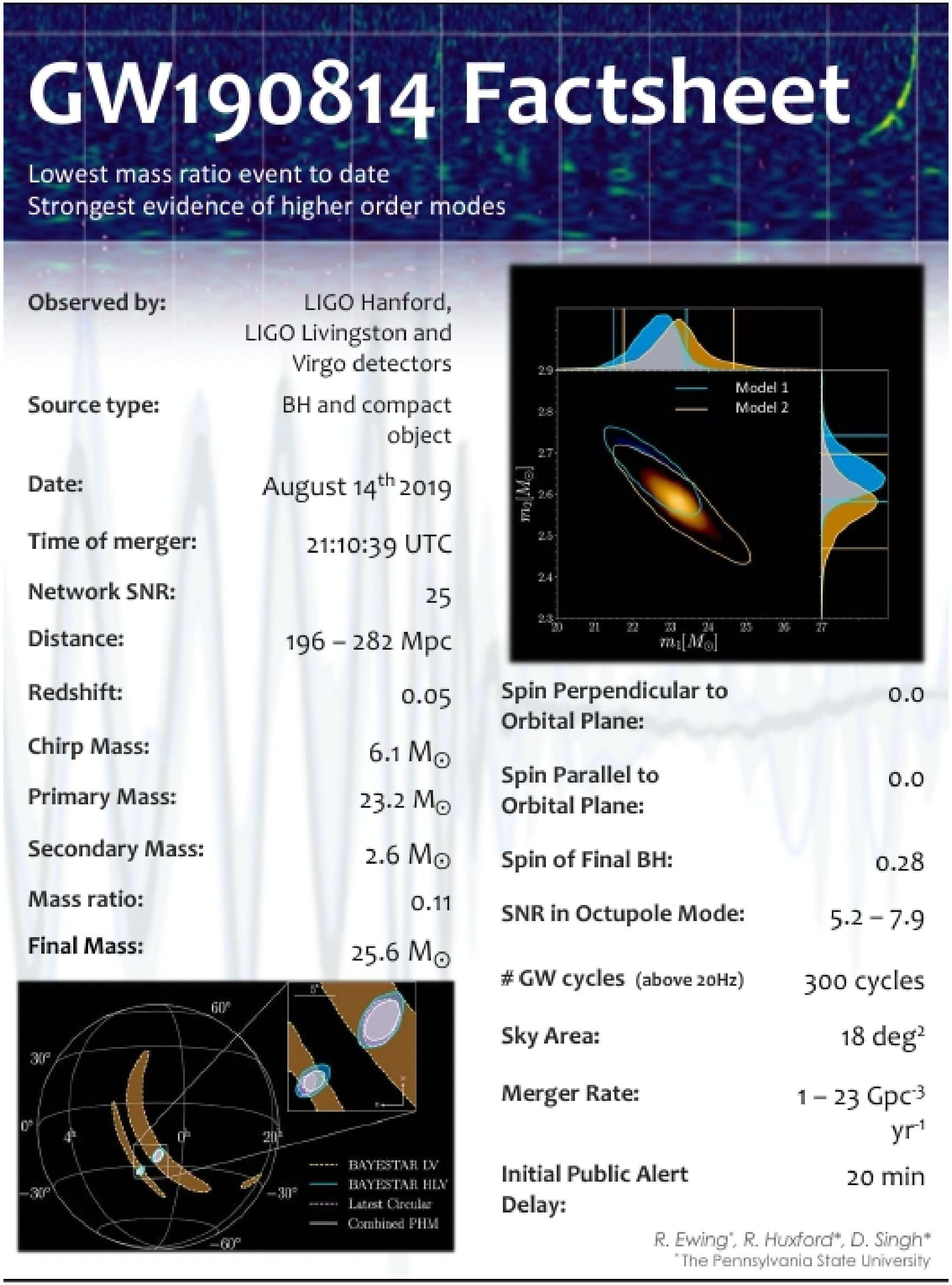
Images: **Mass ratio and spin** (left) – from the properties of the signal, it was possible to estimate the mass ratio (q) and the effective spin (χ_{eff}) of the binary BHs. The blue and orange contours represent 90% credible estimates on the values of these quantities from two different models.

GW spectrograms (above) – time-frequency representation of the GW signal data from all three detectors.

GW = gravitational wave, BH = black hole, $M_\odot$=1 solar mass=2x10^{30} kg

Parameter ranges are 90% credible intervals from combining two models

Unequal mass ratio event.



GW190814 Factsheet

Lowest mass ratio event to date
Strongest evidence of higher order modes

Observed by:	LIGO Hanford, LIGO Livingston and Virgo detectors
Source type:	BH and compact object
Date:	August 14th 2019
Time of merger:	21:10:39 UTC
Network SNR:	25
Distance:	196 – 282 Mpc
Redshift:	0.05
Chirp Mass:	6.1 $M_\odot$
Primary Mass:	23.2 $M_\odot$
Secondary Mass:	2.6 $M_\odot$
Mass ratio:	0.11
Final Mass:	25.6 $M_\odot$
Spin Perpendicular to Orbital Plane:	0.0
Spin Parallel to Orbital Plane:	0.0
Spin of Final BH:	0.28
SNR in Octupole Mode:	5.2 – 7.9
# GW cycles (above 20Hz)	300 cycles
Sky Area:	18 deg^2
Merger Rate:	1 – 23 $\mathrm{Gpc}^{-3}\,\mathrm{yr}^{-1}$
Initial Public Alert Delay:	20 min

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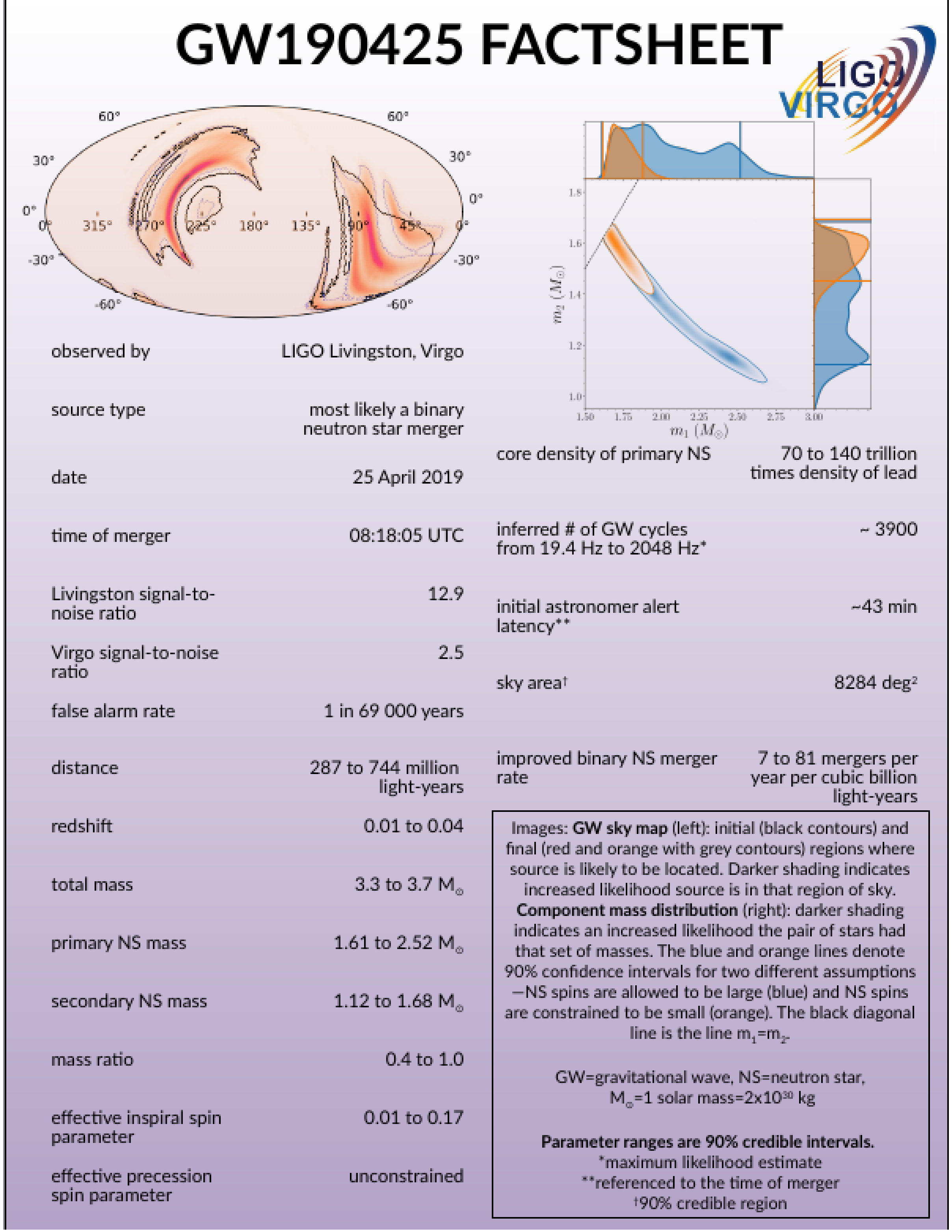
*The Pennsylvania State University

Secondary of
2.6 Solar masses
might either be a
neutron star or a black
hole.



GW190425 FACTSHEET

observed by	LIGO Livingston, Virgo
source type	most likely a binary neutron star merger
date	25 April 2019
time of merger	08:18:05 UTC
Livingston signal-to-noise ratio	12.9
Virgo signal-to-noise ratio	2.5
false alarm rate	1 in 69 000 years
distance	287 to 744 million light-years
redshift	0.01 to 0.04
total mass	3.3 to 3.7 $M_\odot$
primary NS mass	1.61 to 2.52 $M_\odot$
secondary NS mass	1.12 to 1.68 $M_\odot$
mass ratio	0.4 to 1.0
effective inspiral spin parameter	0.01 to 0.17
effective precession spin parameter	unconstrained

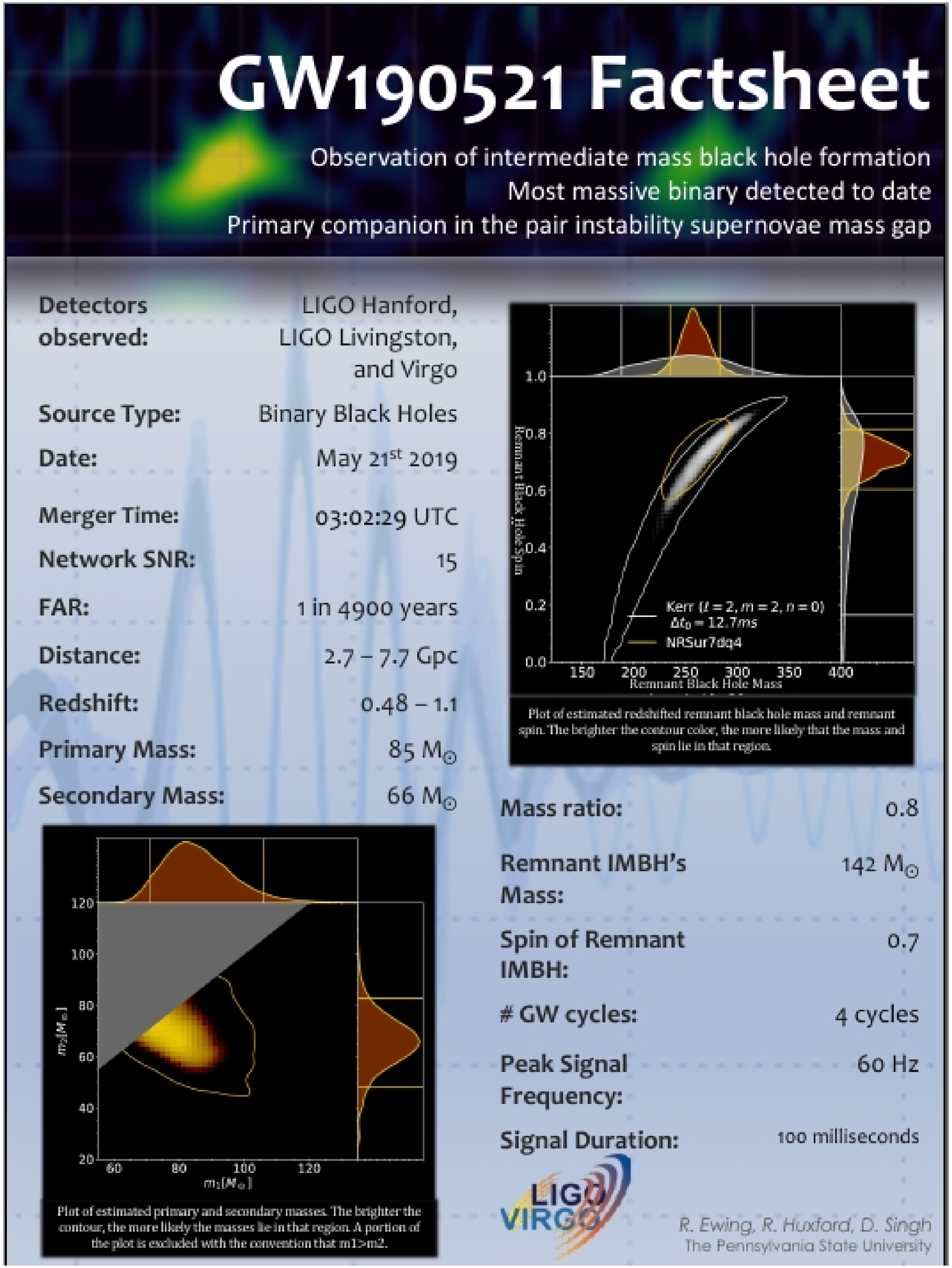
core density of primary NS	70 to 140 trillion times density of lead
inferred # of GW cycles from 19.4 Hz to 2048 Hz*	~ 3900
initial astronomer alert latency**	~43 min
sky area†	8284 deg^2
improved binary NS merger rate	7 to 81 mergers per year per cubic billion light-years

Images: **GW sky map** (left): initial (black contours) and final (red and orange with grey contours) regions where source is likely to be located. Darker shading indicates increased likelihood source is in that region of sky. **Component mass distribution** (right): darker shading indicates an increased likelihood the pair of stars had that set of masses. The blue and orange lines denote 90% confidence intervals for two different assumptions —NS spins are allowed to be large (blue) and NS spins are constrained to be small (orange). The black diagonal line is the line $m_1 = m_2$.

GW=gravitational wave, NS=neutron star,
$M_\odot$=1 solar mass=2×10^{30} kg

Parameter ranges are 90% credible intervals.
*maximum likelihood estimate
**referenced to the time of merger
†90% credible region

NS-NS event.



GW190521 Factsheet

Observation of intermediate mass black hole formation
Most massive binary detected to date
Primary companion in the pair instability supernovae mass gap

Detectors observed:	LIGO Hanford, LIGO Livingston, and Virgo
Source Type:	Binary Black Holes
Date:	May 21st 2019
Merger Time:	03:02:29 UTC
Network SNR:	15
FAR:	1 in 4900 years
Distance:	2.7 – 7.7 Gpc
Redshift:	0.48 – 1.1
Primary Mass:	85 $M_\odot$
Secondary Mass:	66 $M_\odot$

Plot of estimated redshifted remnant black hole mass and remnant spin. The brighter the contour color, the more likely that the mass and spin lie in that region.

Mass ratio:	0.8
Remnant IMBH's Mass:	142 $M_\odot$
Spin of Remnant IMBH:	0.7
# GW cycles:	4 cycles
Peak Signal Frequency:	60 Hz
Signal Duration:	100 milliseconds

Plot of estimated primary and secondary masses. The brighter the contour, the more likely the masses lie in that region. A portion of the plot is excluded with the convention that m1>m2.

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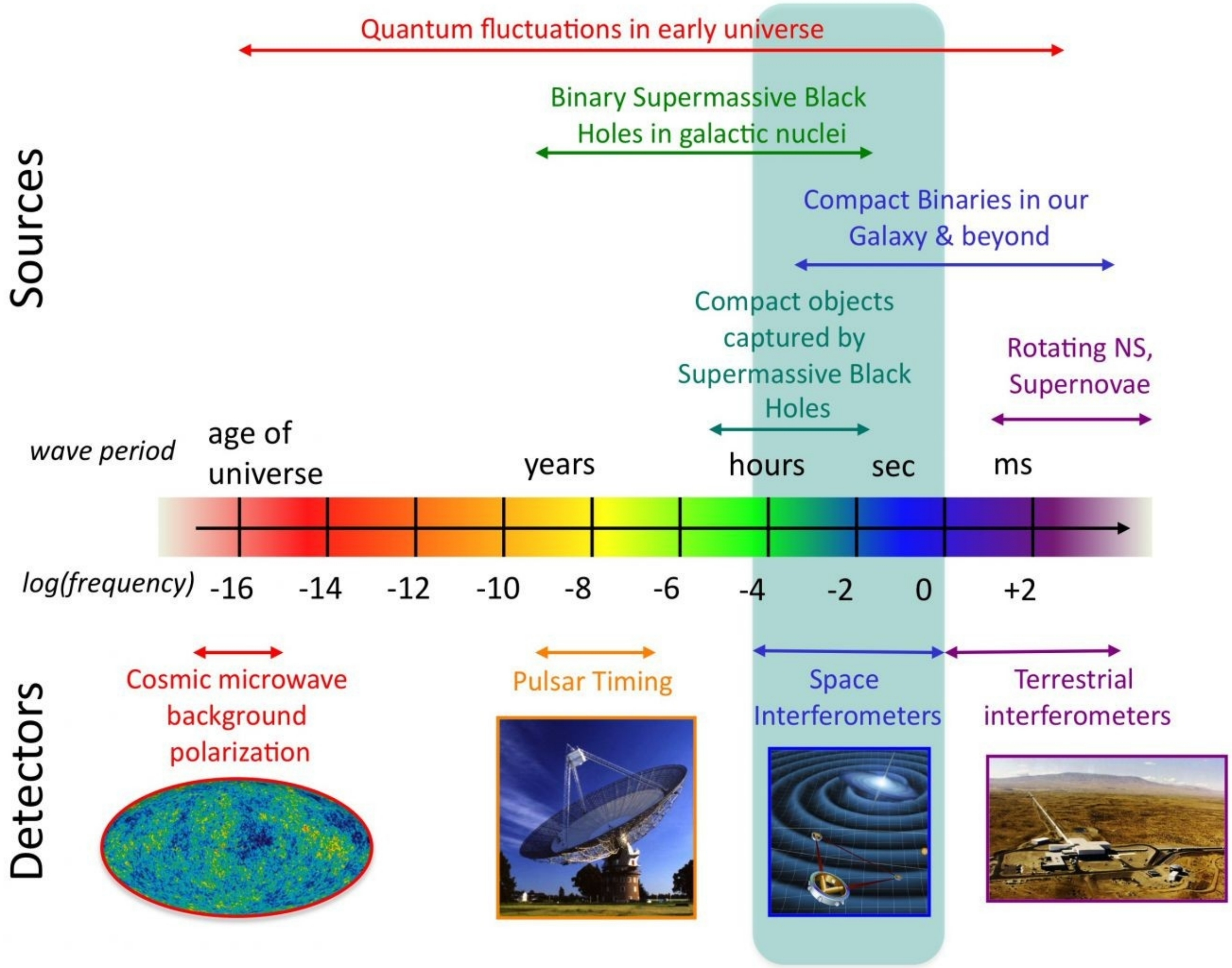
The Pennsylvania State University

Most massive BH event.

The Gravitational Wave Spectrum



Sources

Quantum fluctuations in early universe

Binary Supermassive Black Holes in galactic nuclei

Compact Binaries in our Galaxy & beyond

Compact objects captured by Supermassive Black Holes

Rotating NS, Supernovae

wave period age of universe — years — hours — sec — ms

log(frequency) -16 -14 -12 -10 -8 -6 -4 -2 0 +2

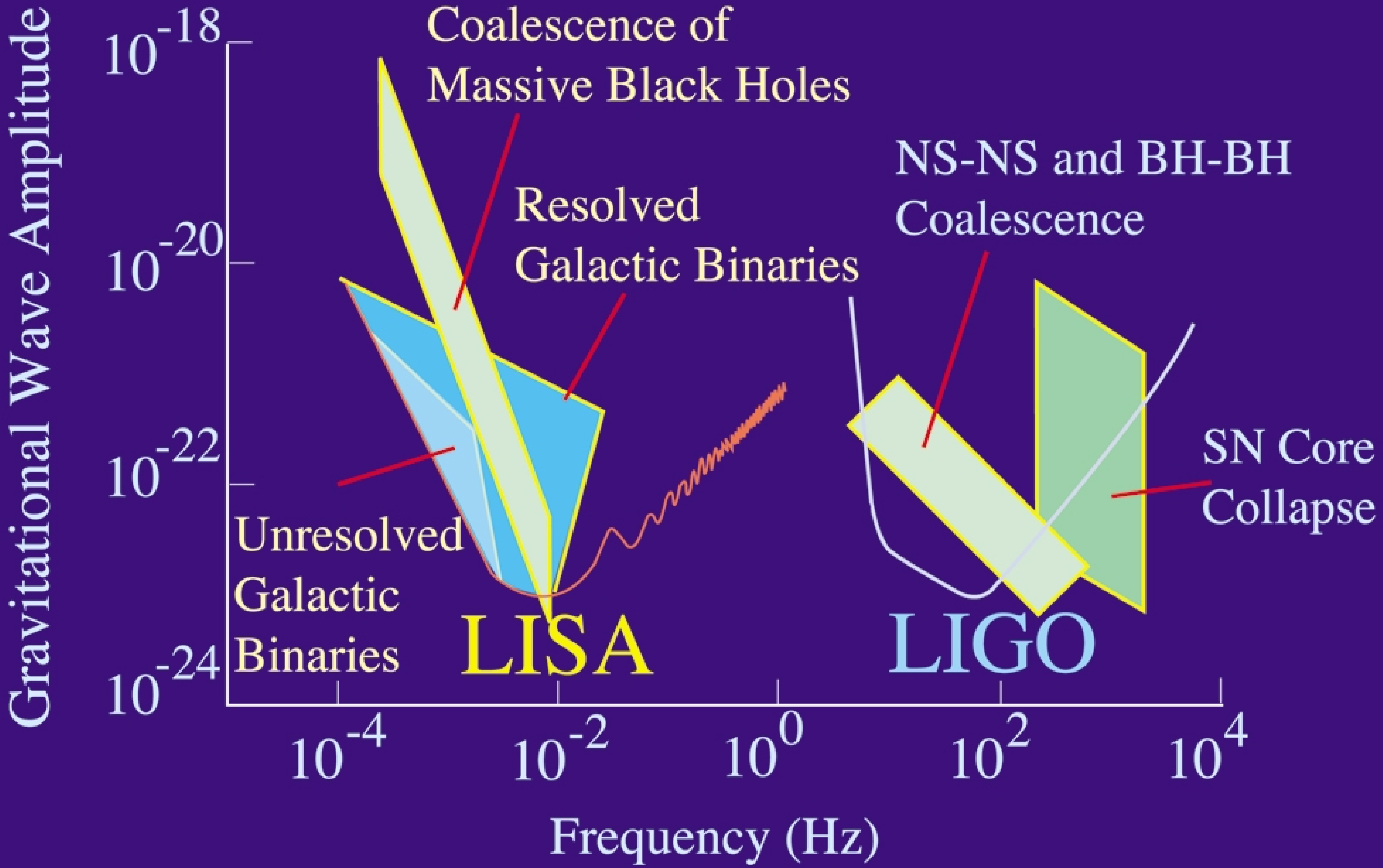
Detectors

Cosmic microwave background polarization

Pulsar Timing

Space Interferometers

Terrestrial interferometers

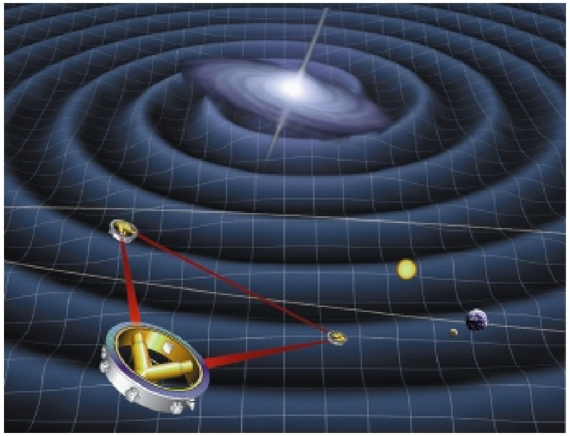

Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coalescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
NS-NS and BH-BH
Coalescence
SN Core
Collapse
LISA
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)

GRAVITATIONAL WAVE DETECTION IN SPACE: LISA

- LISA will be the first gravitational wave observatory **in space**
- selected in 2017 as the third large class mission in ESA's Science Programme
- **to be launched in 2034** (likely earlier)

- The LISA Consortium has been joined by more than 1000 scientists worldwide

- **Jetzer's group:** active member of the **LIGO Scientific collaboration and the LISA Consortium**



- development of **gravitational-wave templates** for the identification and interpretation of gravitational-wave events in detector data
- dynamics and gravitational radiation of **merging black holes and neutron stars** within the framework of General Relativity
- methods developed for ground-based detectors will be applied for **future LISA data analysis**

Observational facts

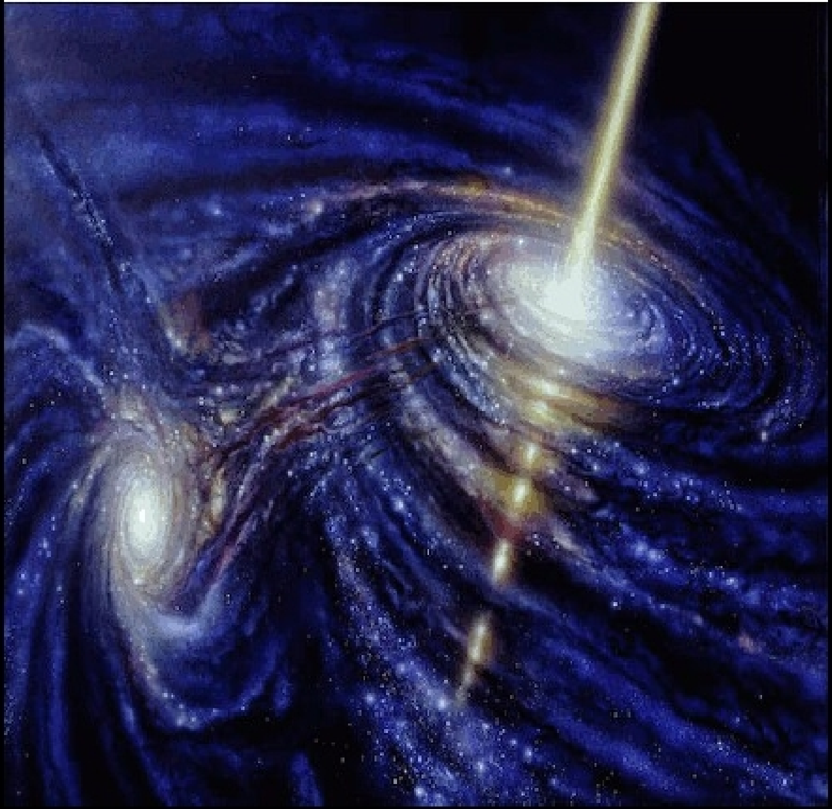
1- In all the cases where the inner core of a galaxy has been resolved (i.e. In nearby galaxies), a massive compact object (which I'll call Massive Black Hole, MBH for convenience) has been found in the centre.

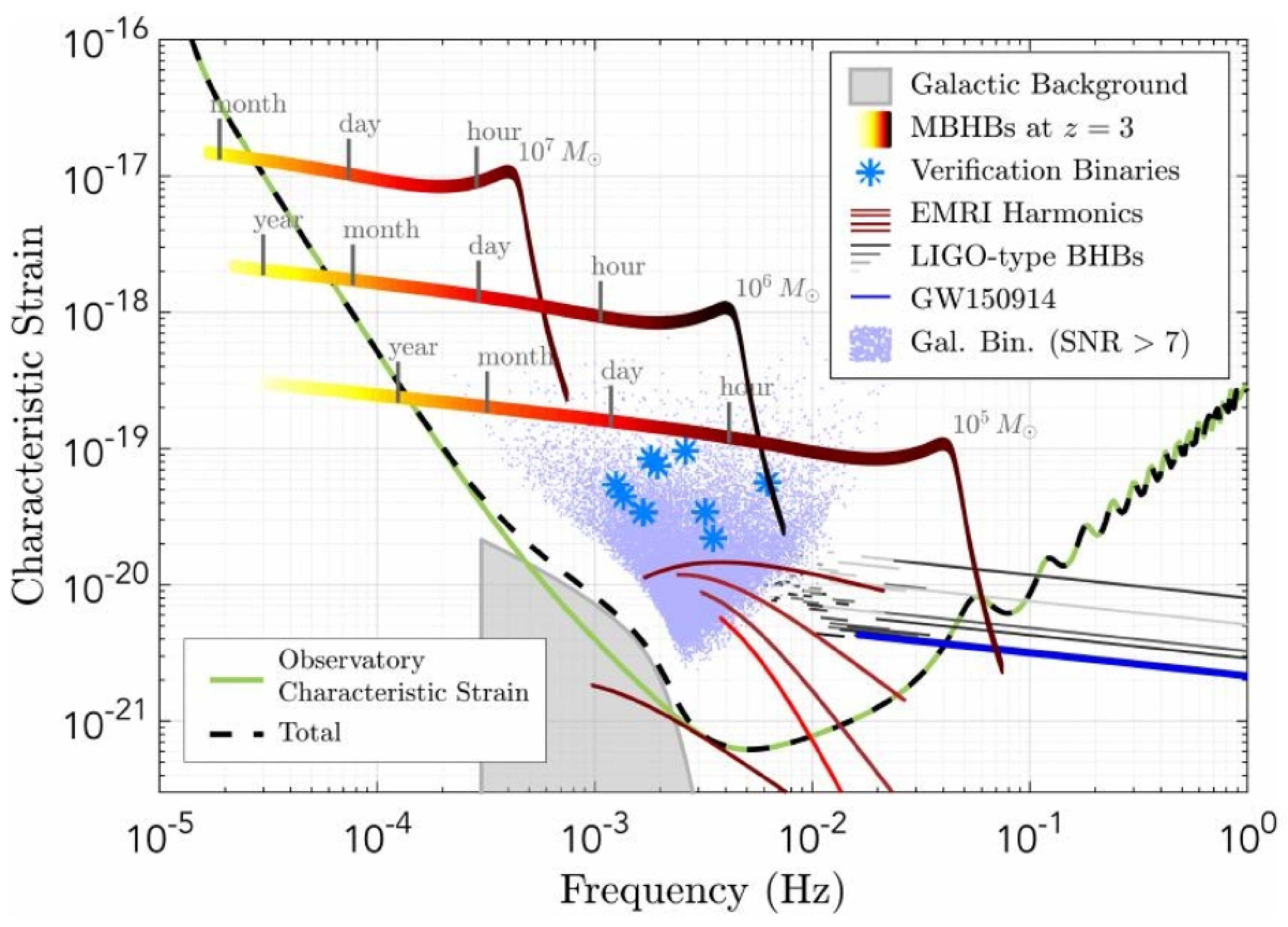
2- MBHs must be the central engines of Quasars: the only viable model to explain this cosmological objects is by means of gas accretion onto a MBH.

3- Quasars have been discovered at z~7, their inferred masses are ~10^9 solar masses!

THERE WERE 10^9 SOLAR MASS BHs WHEN THE UNIVERSE WAS <1Gyr OLD!!!

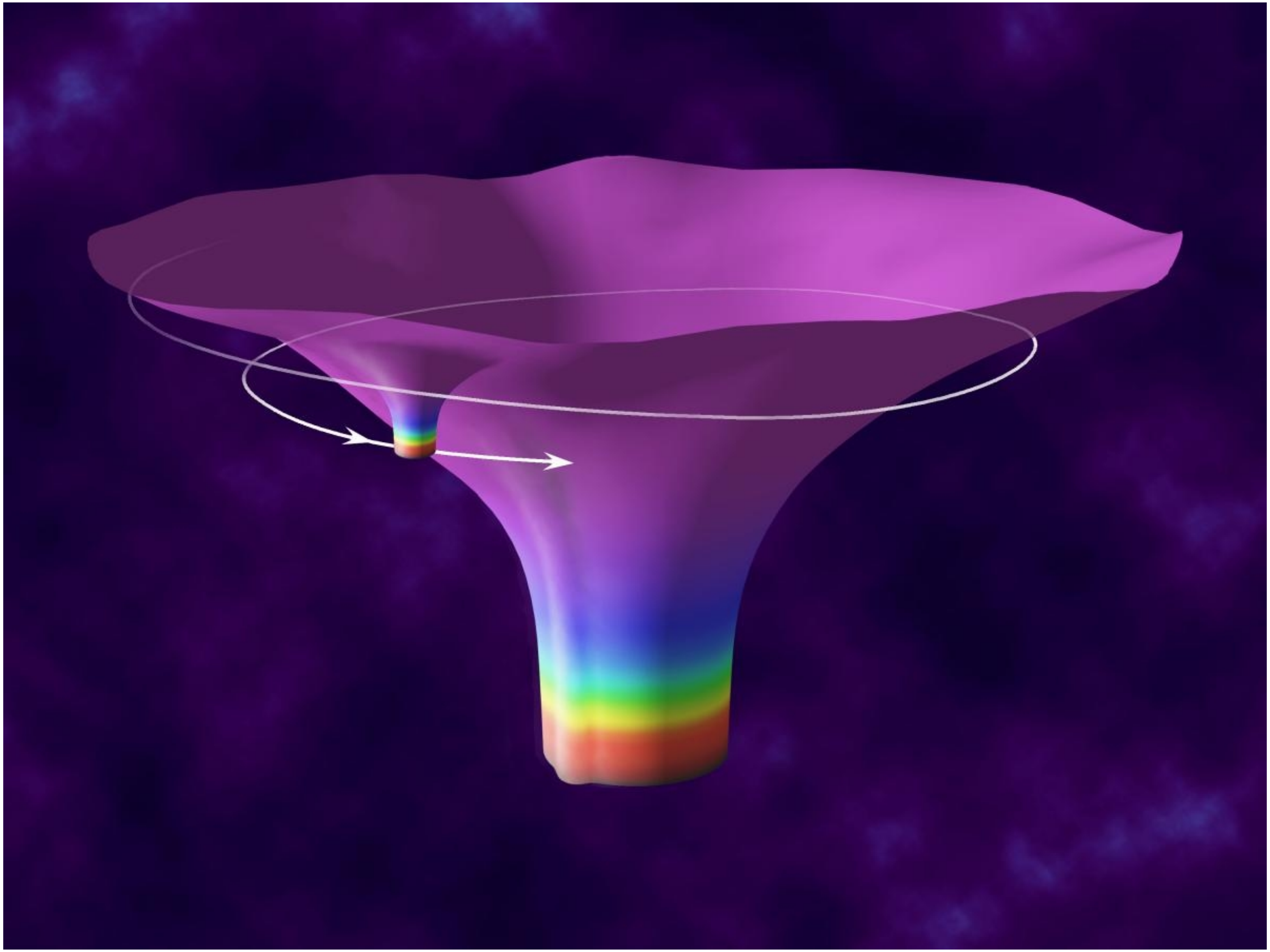
MBH formation and evolution have profound consequences for GW astronomy





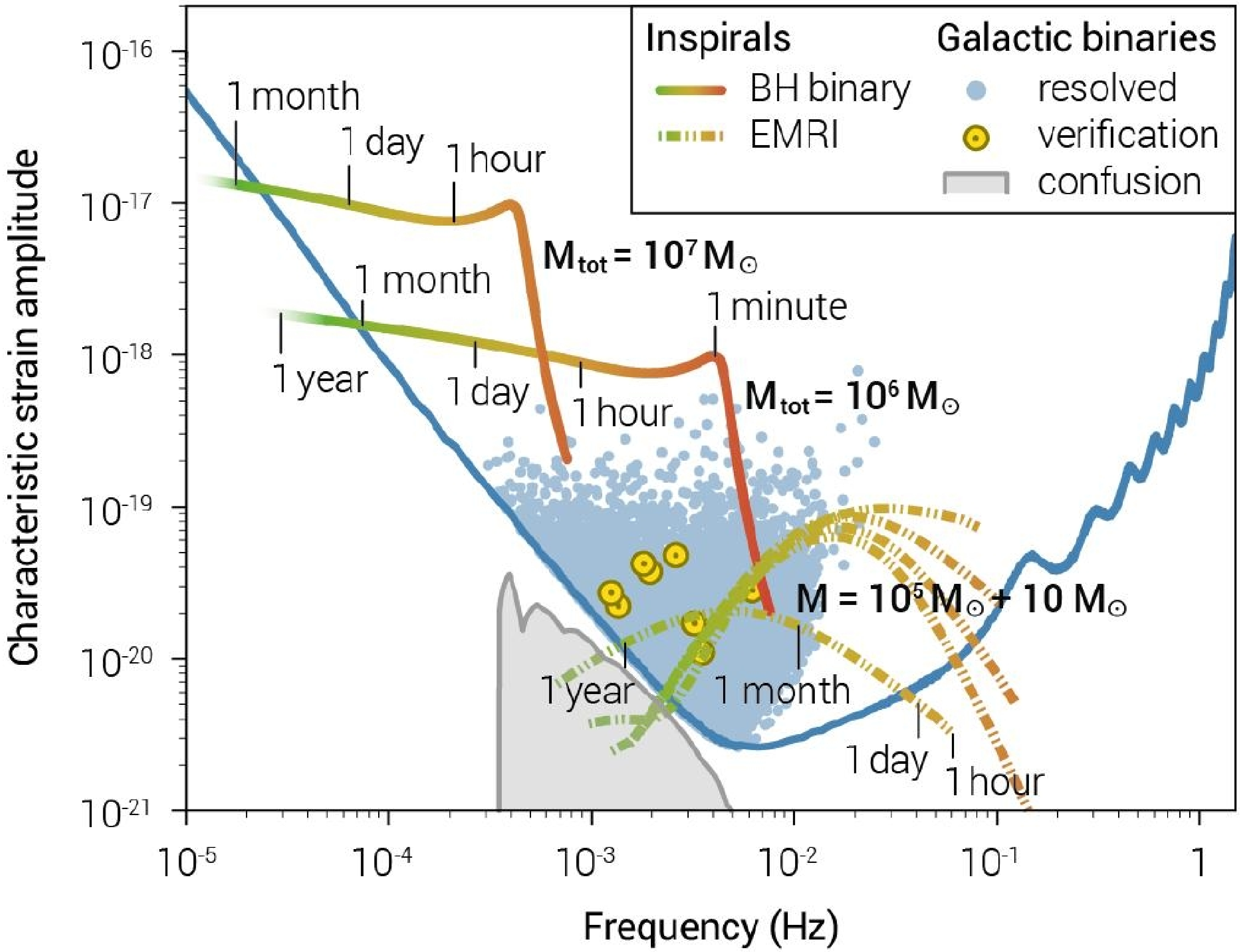
Possible other sources (not shown): cosmic strings (kink, cusps) cosmological backgrounds (non-standard inflation, phase transitions)

Extreme Mass Ratio Inspirals (EMRIs)



A smaller black hole orbits around a supermassive black hole

LISA sensitivity: EMRI , ultra-compact binaries in the Milky Way



The Laws of Nature

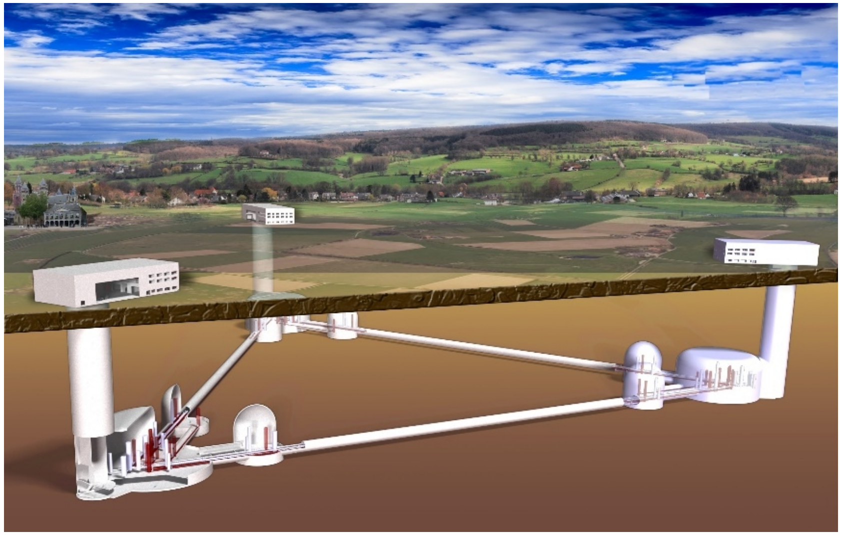
Confronting general relativity with high-precision measurements of strong gravity:

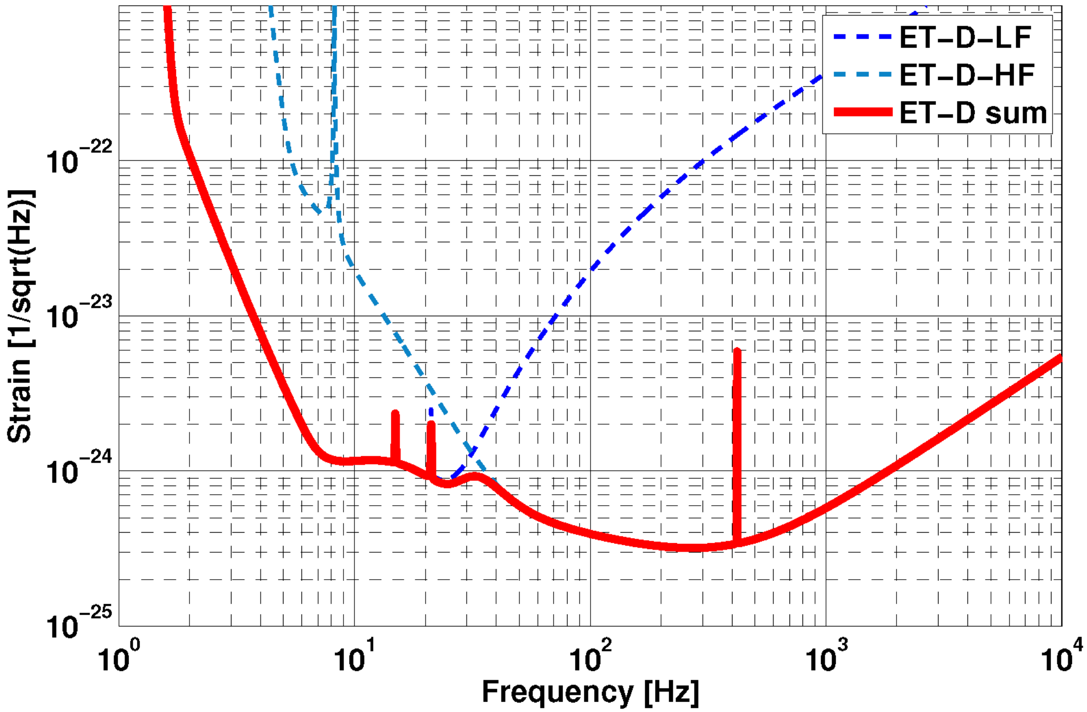
- Does gravity travel at the speed of light?
- Does the graviton have mass?
- Are there more than two transverse modes of propagation?
- Does gravity couple to other dynamical fields, e.g., massless or massive scalars?
- What is the structure of spacetime just outside astrophysical black holes?
- Do black holes have an horizon?
- Are astrophysical black holes described by the Kerr metric, As predicted by GR?

Outlook 2030’s

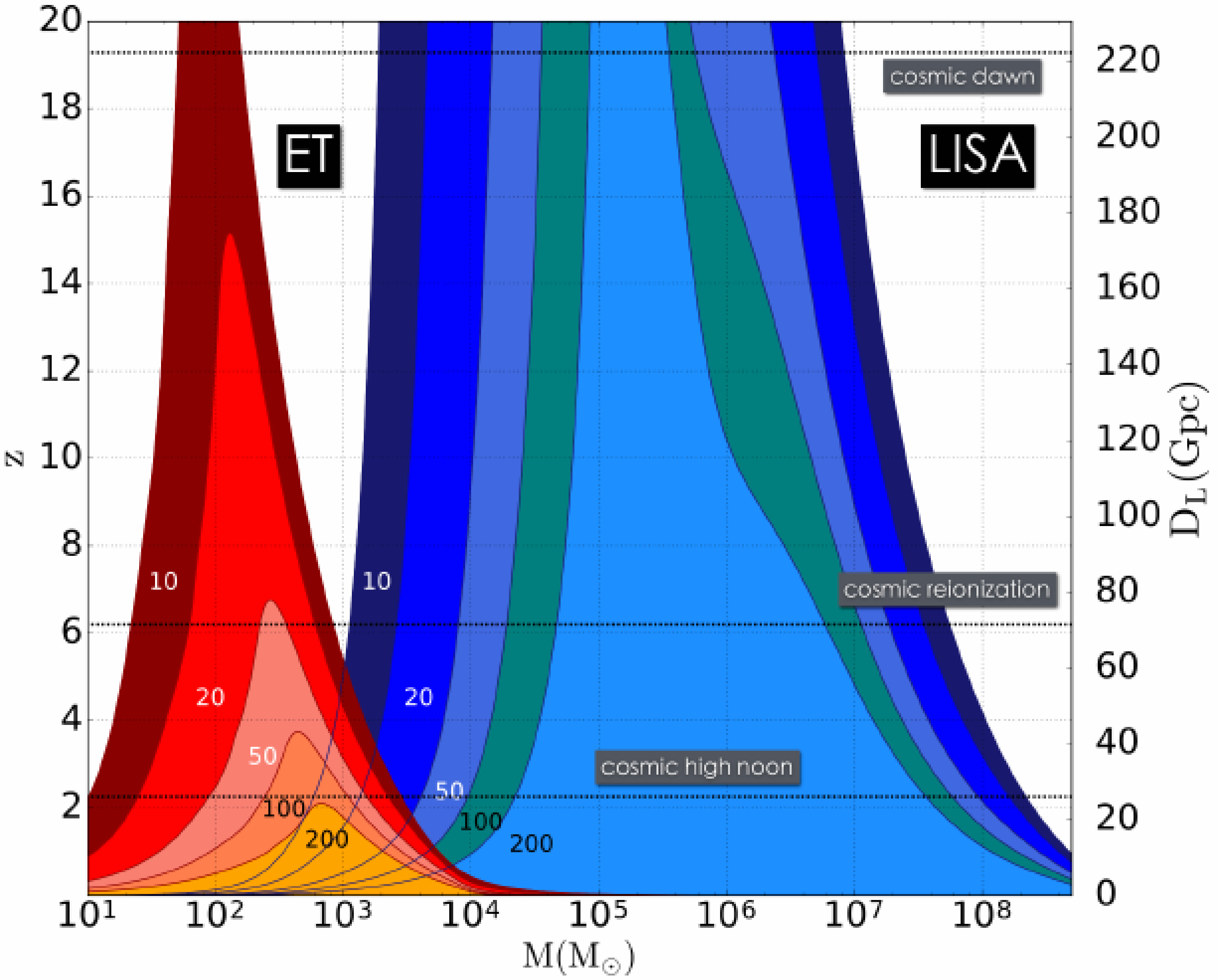
Underground infrastructures for ≥ 10*km* arms:
Einstein Telescope: 3 arms, each about 10 km in length

Extend the sensitivity band to larger mass BHs at low frequency and to NS at high frequency





Black hole coalescence sensitivity for ET and LISA



Adv-Virgo to Adv-Virgo+ to ET

- Upgrading the detectors leads to larger time volume visibility, hence higher detection rates
- Advanced Virgo will operate at design sensitivity till 2025
- Advanced Virgo+ is proposed as an intermittent detector between Advanced Virgo and ET, which can also serve as an R&D for ET
- In the first approximation the cost for Advanced Virgo + can be 80M Euros

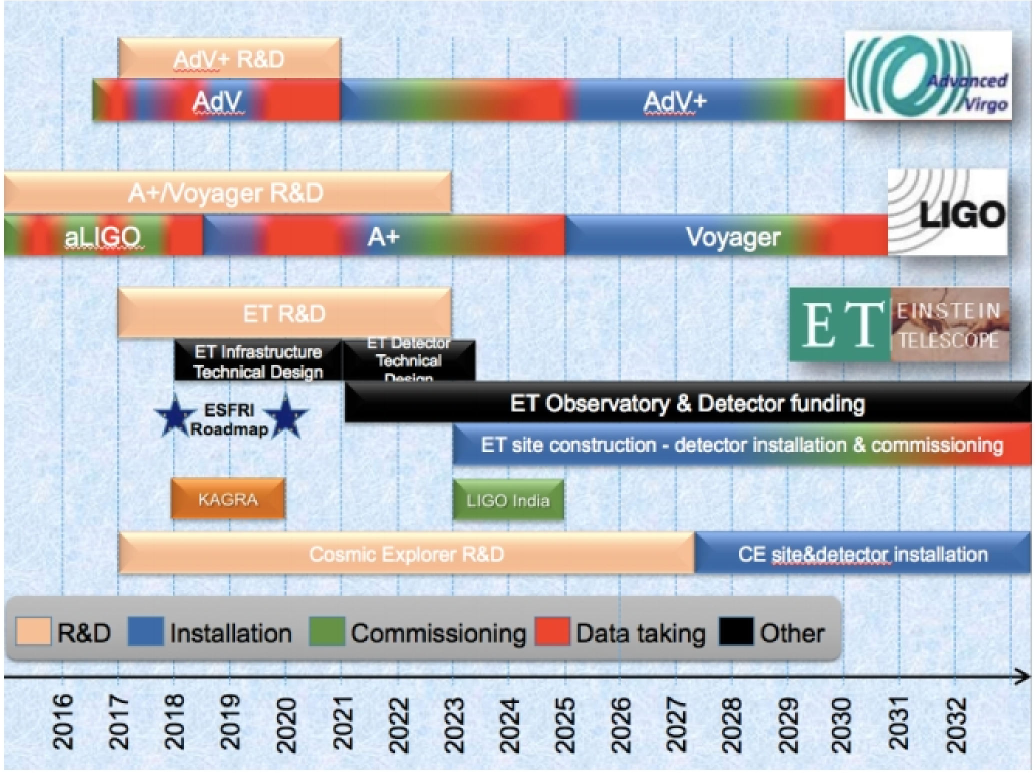
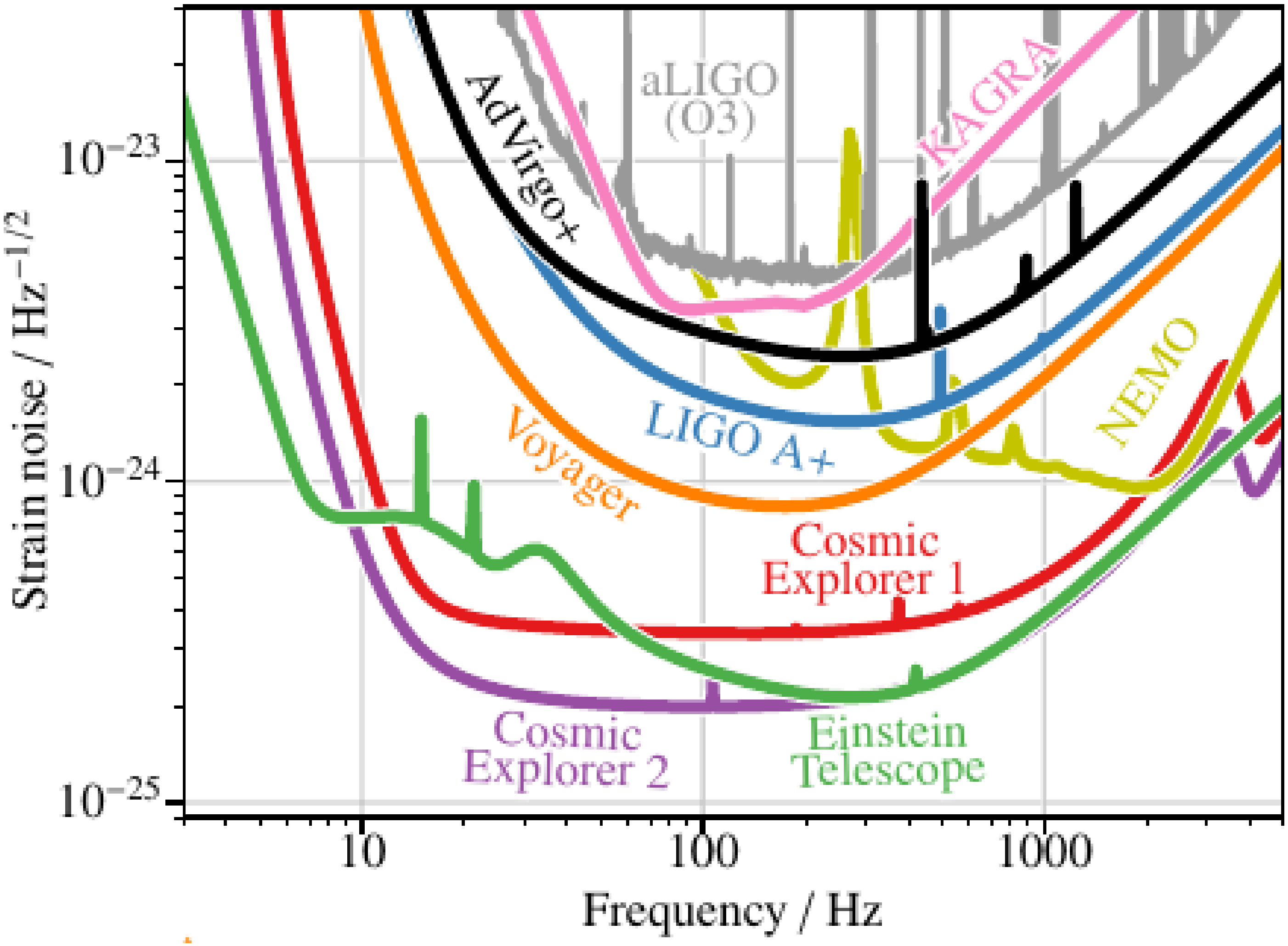


Figure 5: *Roadmap of the GW detectors in the next 15 years. The first two lines represent the evolution of the Advanced Virgo and Advanced LIGO detectors in the current infrastructures. The last two lines represent the evolution of the 3G level infrastructures, ET and LIGO 3G. The color code is specified in the figure.*



ET could observe BNS up to z ~ 2 (Advanced LIGO only up to ~ 200 Mpc)

Will improve substantially our knowledge on the matter equation of state in Neutron stars.

GRAVITATIONAL WAVE RESEARCH IN SWITZERLAND

At present both groups are working on Phase A of LISA (D. Giardini is the PI and P. Jetzer the co-PI of the Swiss Prodex Contribution).

Roles in LISA:
- D. Giardini: LISA board and executive board member
- P. Jetzer: LISA board and ESA Science Study Team member
- L. Ferraioli: co-lead of the Simulation management group
- L. Mayer: co-lead of the Astrophysics Working group
- P. Jetzer: co-lead of the Fundamental Physics Working group

Since 2017 the group of P. Jetzer is member of the LIGO Scientific Collaboration (LVC). Maria Haney is the LIGO council delegate of the Group.

GRAVITATIONAL WAVE RESEARCH IN SWITZERLAND

- Michele Maggiore is member of the ET steering committee and leads the science working team

- Several swiss scientists in Geneva and Zurich are members of various LISA Working groups. In particular Prof. S. Paltani and his group is involved in the project of a data center for LISA to be set up in the Geneva Observatory (in the Integral Data Center ISDC)

From the industry (besides RUAG) there is CSEM (Neuchatel) with the group of S. Lecomte who is involved (with an ESA contract) in the laser metrology for LISA.

Outlook

- GW is a tool for astrophysics but also for investigating topics in fundamental physics:

  from dark matter to quantum gravity, stochastic background produced in the big bang, equation of state of neutron stars and thus QCD at ultra-high density.
- Many technologies developed for particle physics are needed for building GW detectors: cryogenics, optics, data acquisition etc.
- This is truly a topic at the interface between CHIPP and CHAPS.