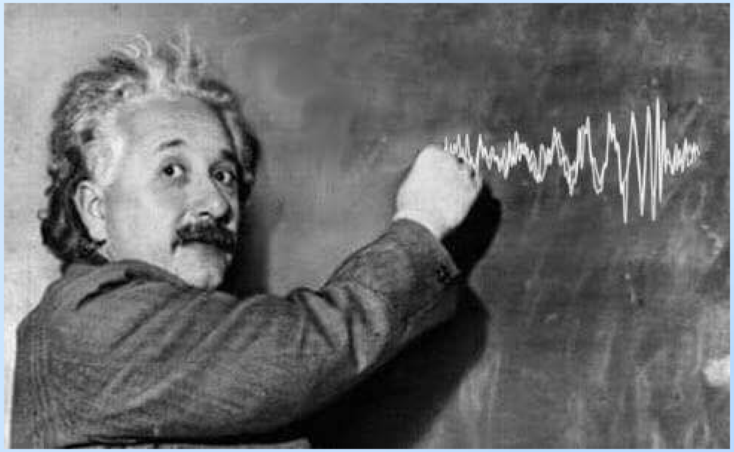
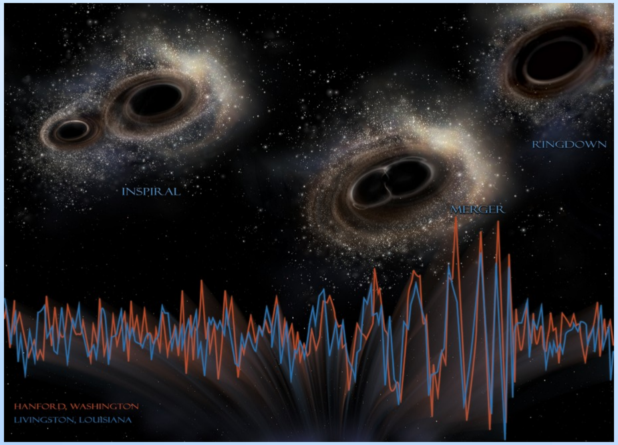
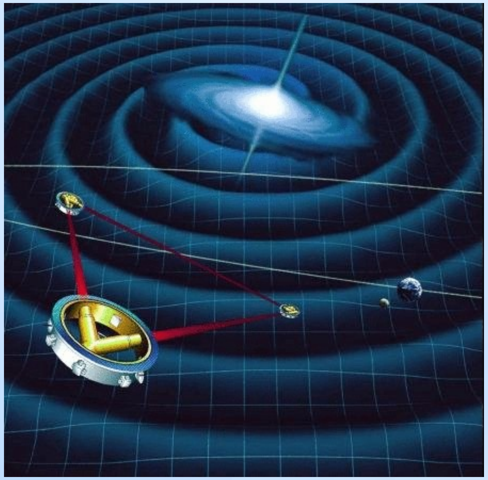






Overview: Science Goals and Future Detectors

Nelson Christensen
Artemis, Observatoire de la Côte d’Azur, Nice

Talk Outline

- Past:
  - Advanced LIGO- Advanced Virgo observing runs O1 and O2
  - Gravitational wave detections
  - Beginning of gravitational wave multimessenger astronomy
- Present:
  - Upcoming LIGO-Virgo searches
  - Further gravitational wave detections
  - Scientific implications
- Future:
  - LISA
  - Third generation detectors
  - Atom interferometers
  - Pulsar timing
  - CMB polarizations

Advanced LIGO – Advanced Virgo

O1: September 12 2015 to January 2016

O2: 30 November 2016 to 25 August 2017
Advanced Virgo 1 August – 25 August 2017

O3: February 2019

Talk by Nicolas Leroy, Advanced Virgo: present and future

The Results

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.**
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

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

GW170814 – 3 Detector Observation

GW170814 : A three-detector observation of gravitational waves from a binary black hole coalescence

The LIGO Scientific Collaboration and The Virgo Collaboration

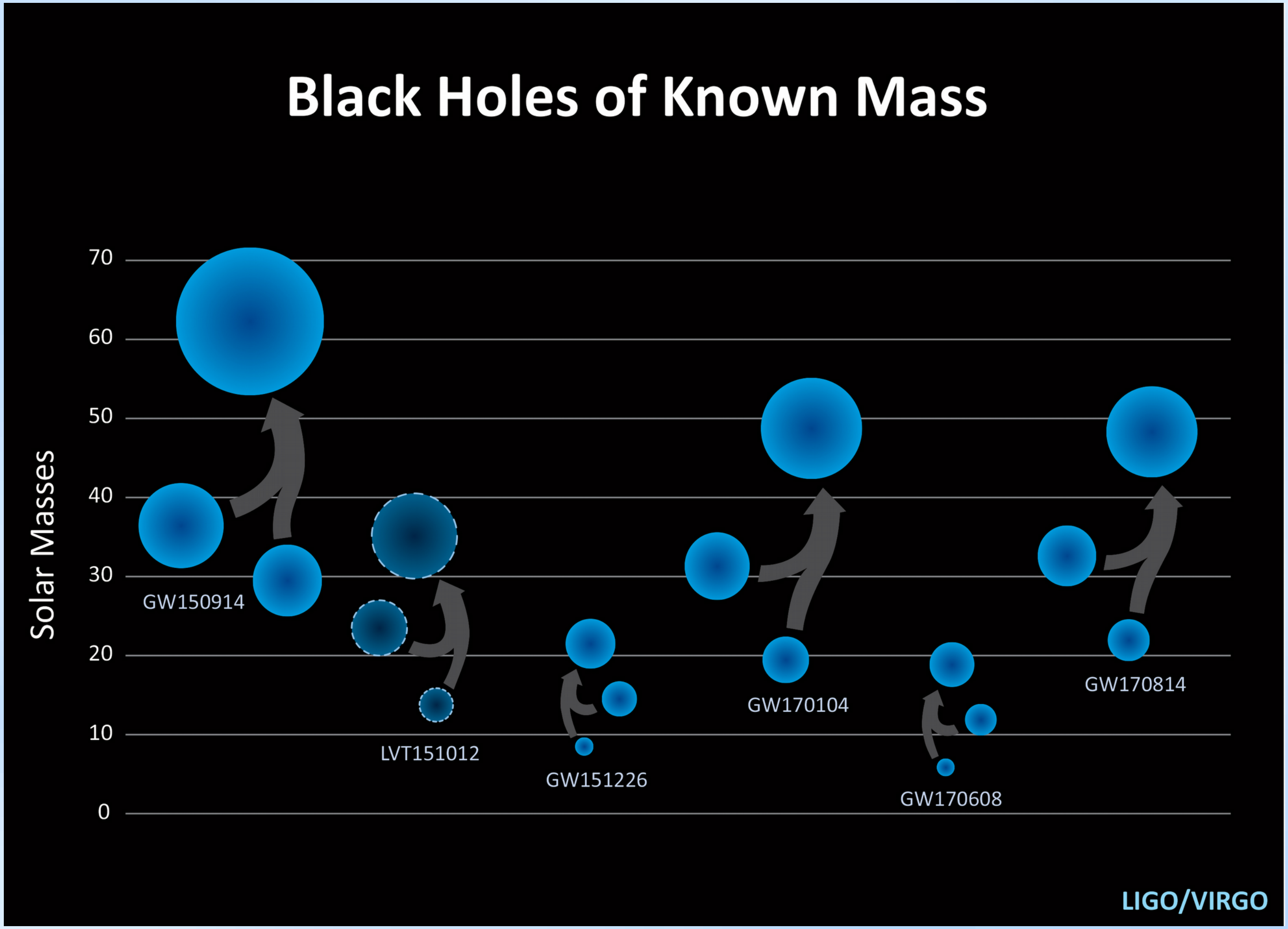
On August 14, 2017 at 10:30:43 UTC, the Advanced Virgo detector and the two Advanced LIGO detectors coherently observed a transient gravitational-wave signal produced by the coalescence of two stellar mass black holes, with a false-alarm-rate of $\lesssim 1$ in 27000 years. The signal was observed with a three-detector network matched-filter signal-to-noise ratio of 18. The inferred masses of the initial black holes are $30.5^{+5.7}_{-3.0}\,M_\odot$ and $25.3^{+2.8}_{-4.2}\,M_\odot$ (at the 90% credible level). The luminosity distance of the source is 540^{+130}_{-210} Mpc, corresponding to a redshift of $z = 0.11^{+0.03}_{-0.04}$. A network of three detectors improves the sky localization of the source, reducing the area of the 90% credible region from 1160 deg^2 using only the two LIGO detectors to 60 deg^2 using all three detectors. For the first time, we can test the nature of gravitational wave polarizations from the antenna response of the LIGO-Virgo network, thus enabling a new class of phenomenological tests of gravity.

Virgo has arrived!

A real world-wide network of gravitational wave detectors.

PRL

LIGO-Virgo Can Measure BH Mass Distributions



Population of Black Holes

GW170814 – 3 Detector Observation

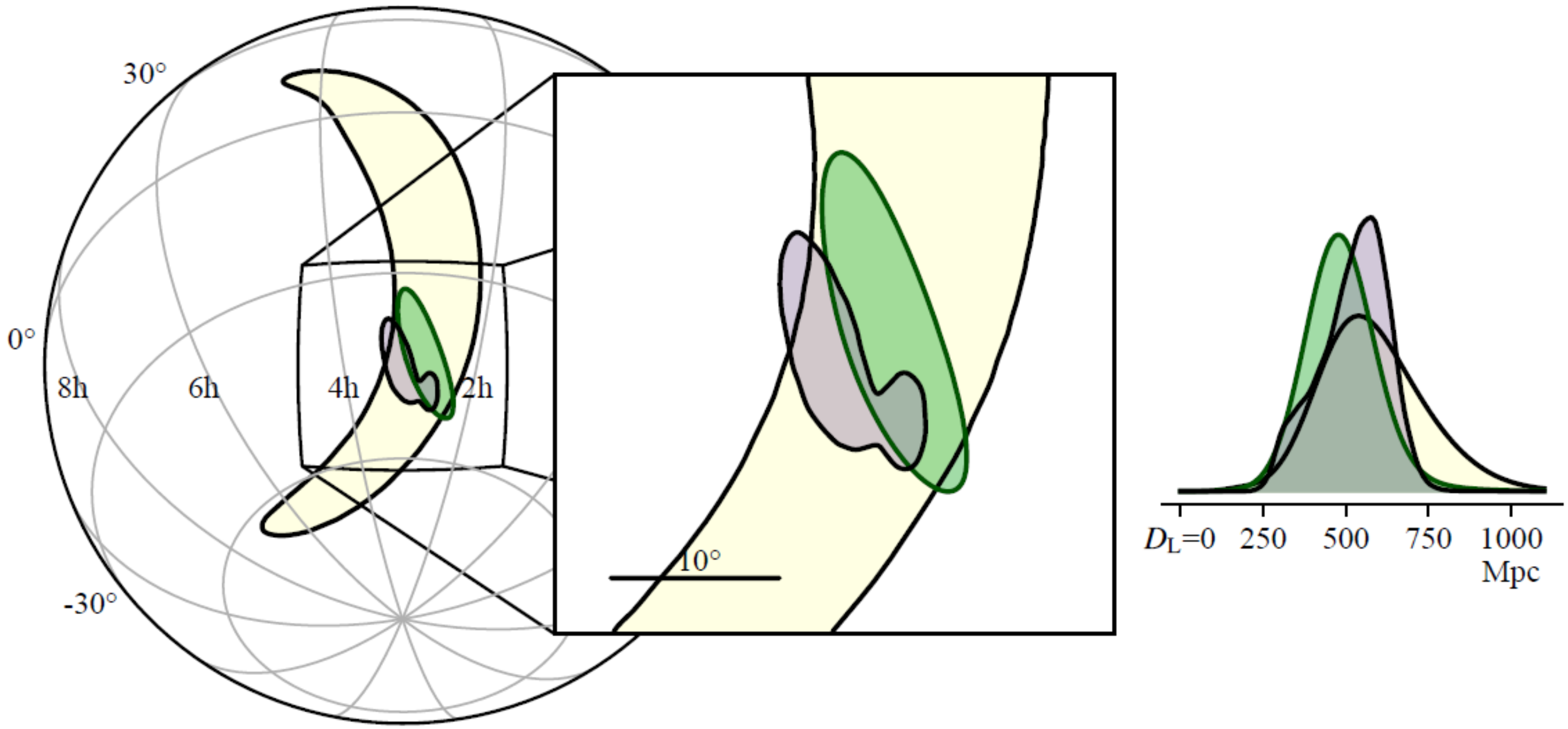
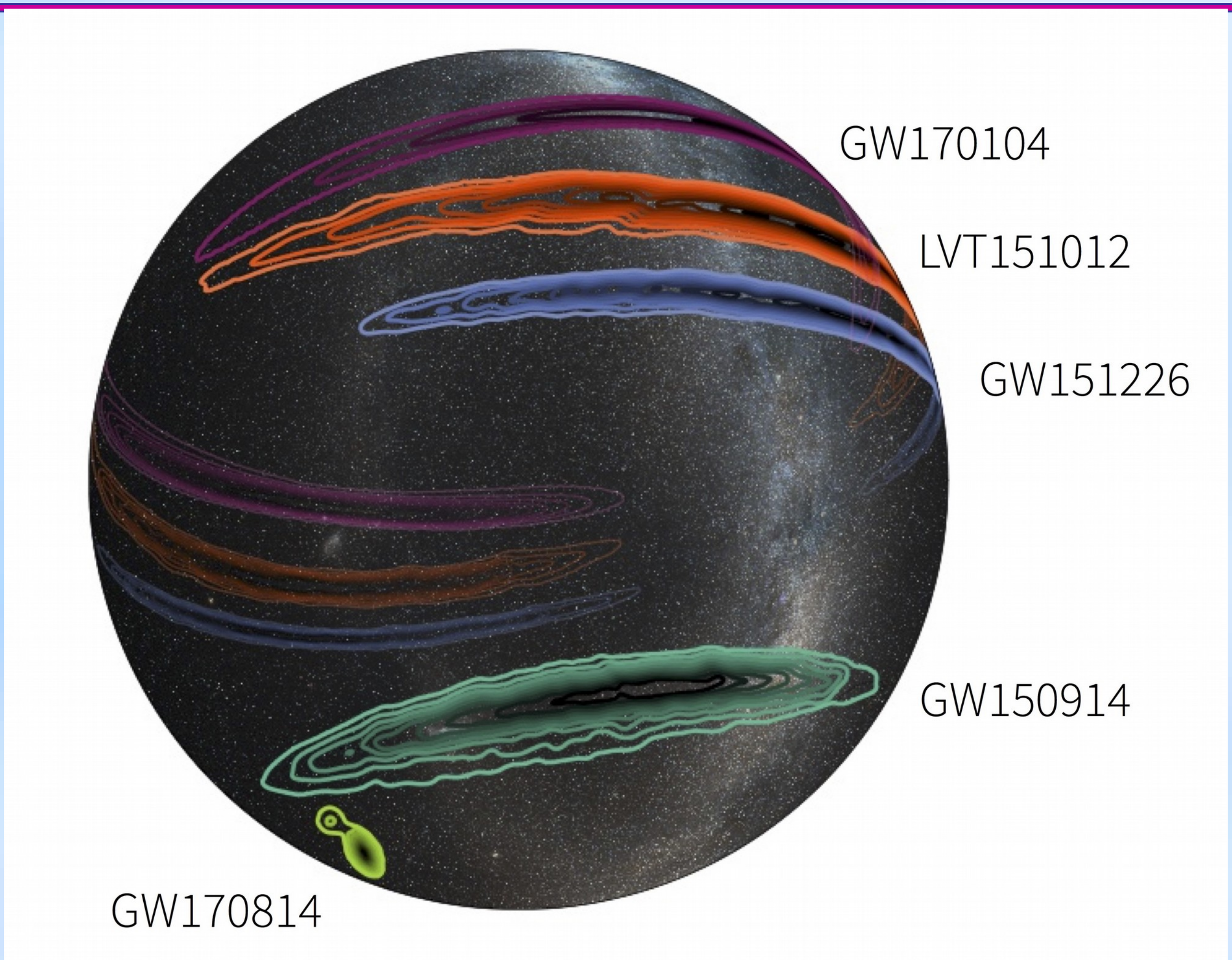


FIG. 3: Localization of GW170814. The rapid localization using data from the two LIGO sites is shown in yellow, with the inclusion of data from Virgo shown in green. The full Bayesian localization is shown in purple. The contours represent the 90% credible regions. The left panel is an orthographic projection and the inset in the center is a gnomonic projection; both are in equatorial coordinates. The inset on the right shows the posterior probability distribution for the luminosity distance, marginalized over the whole sky.

1160 sq. deg 2 LIGOs only →
60 sq. deg for 2 LIGOs + Virgo

Sky Position Estimation Comparison

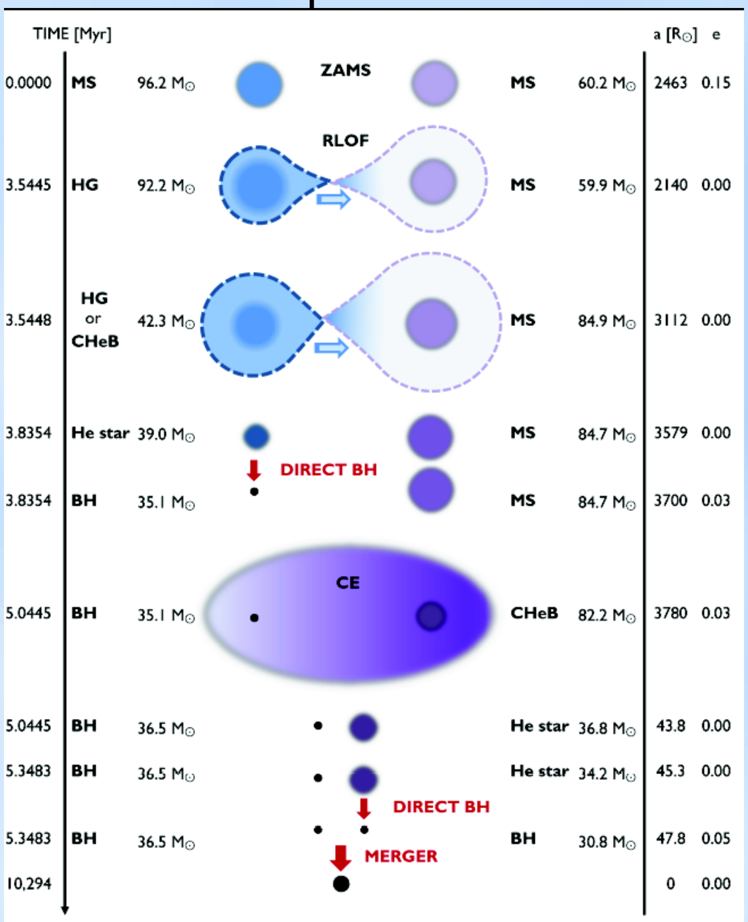
Skymap of the LIGO/Virgo black hole mergers. This three-dimensional projection of the Milky Way galaxy onto a transparent globe shows the probable locations of the black hole mergers.



LIGO/Virgo/Caltech/MIT/Leo Singer (Milky Way image: Axel Mellinger

Astrophysics: Binary Black Hole Formation

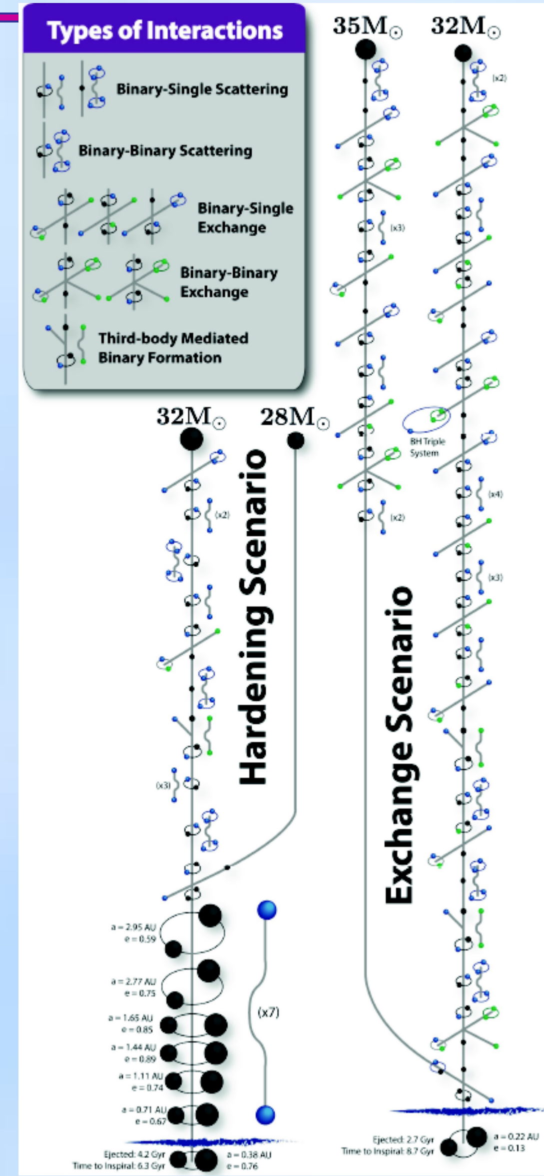
- Isolated Binaries
  - Solar to Population III
  - Rapid rotation



- Dense Clusters
  - Globular clusters
  - Young clusters
  - Galactic centers

Low metallicity environment needed for large stellar mass black hole formation

Belczynski et al. 2016

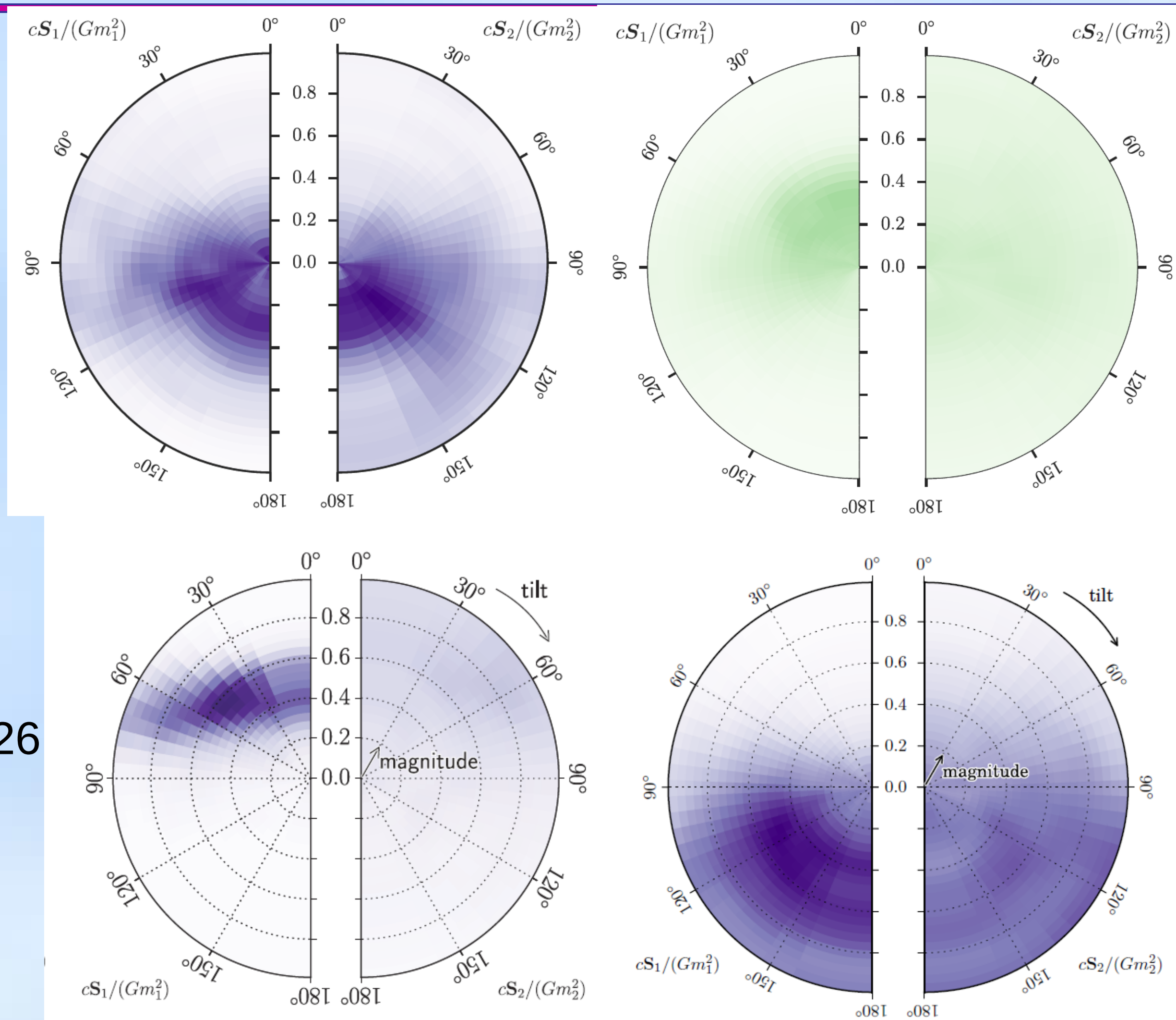


Arxiv 1602:02444, 1604:04254

Spin Observations Are Becoming Interesting

GW150914

LVT151012



GW151226

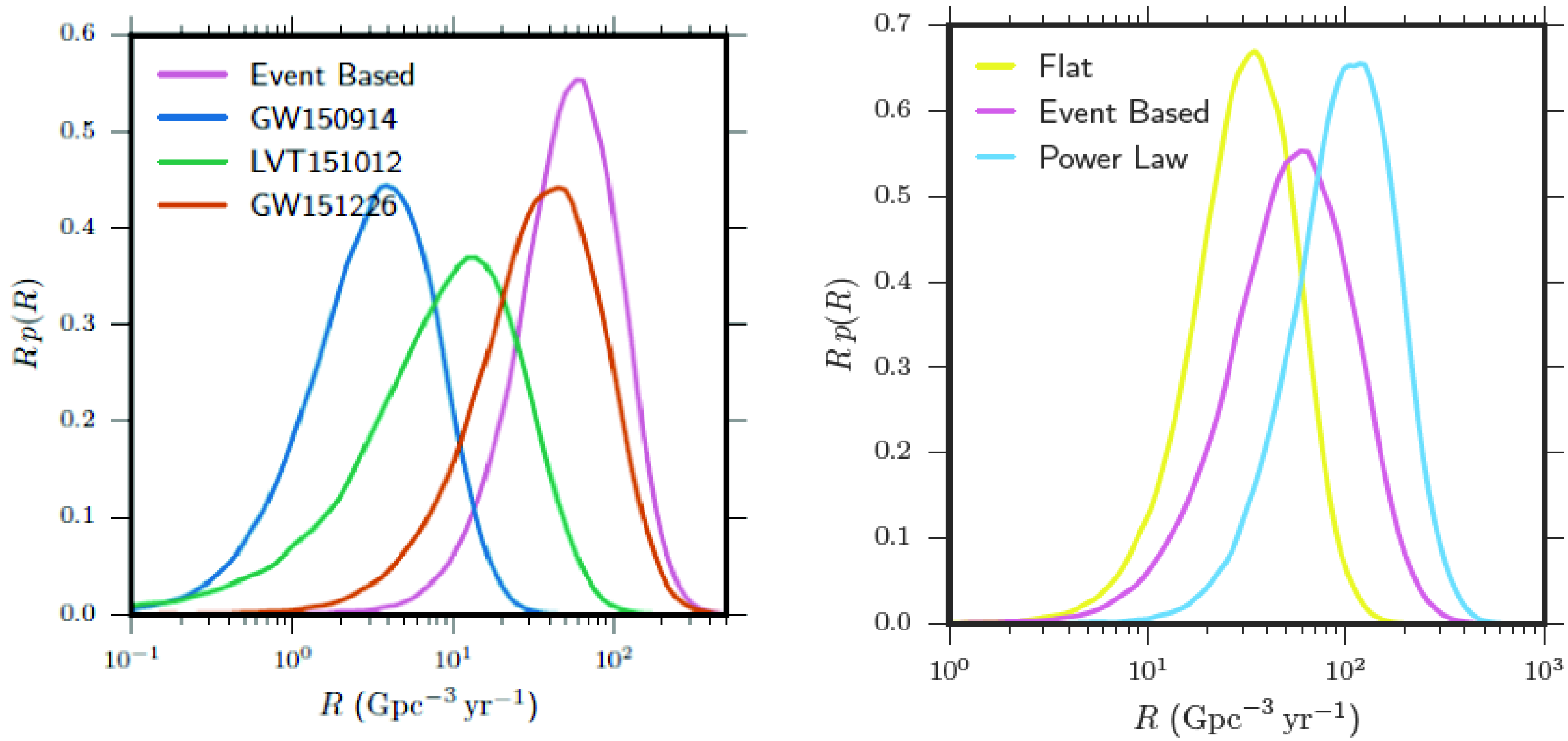
GW170114

No significant spin for GW170814

Isolated Binary Formation?

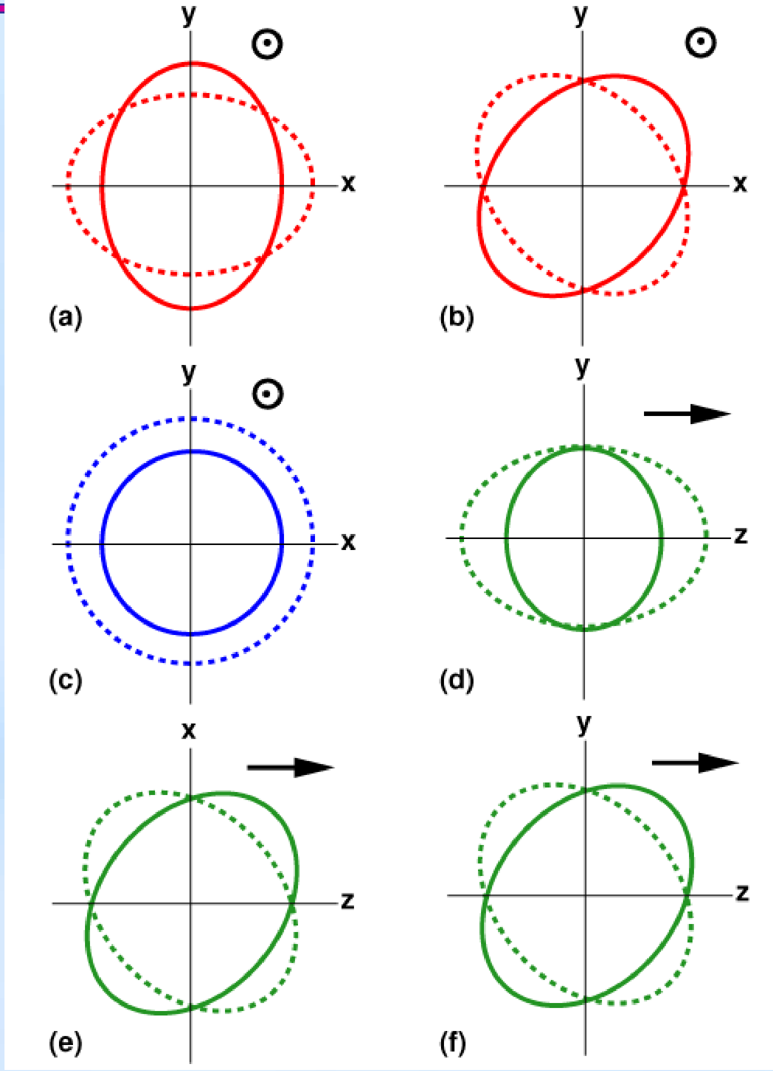
Cluster Formation?

Binary Black Hole Merger Rate



90% allowed range: [9-240] /Gpc^3/yr

Testing General Relativity With GW170814



Clifford Will, Living Reviews in Relativity)

We now have a network of detectors with different orientations (2 LIGO are almost co-aligned, Virgo is not).

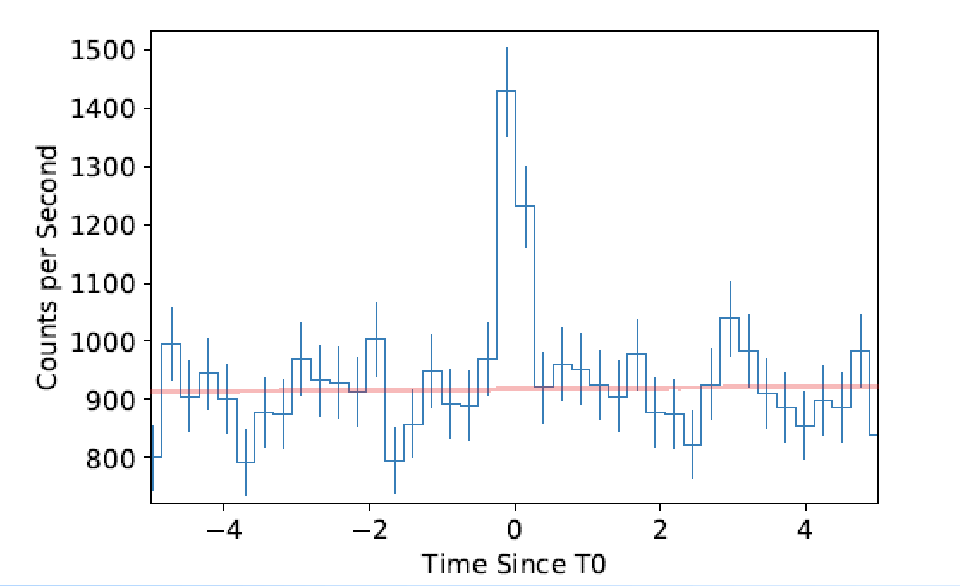
Allows the study of polarization of the gravitational waves.

Results favor purely tensor polarization against purely vector and purely scalar.

Tests of GR performed similar to those carried out for the previous confirmed detections — similar results, consistent with the predictions of Einstein's theory.

Post-Newtonian tests, signal consistency, ...

GW170817 – The Birth of Multi-Messenger Astronomy



17 August 2017, 12:41...

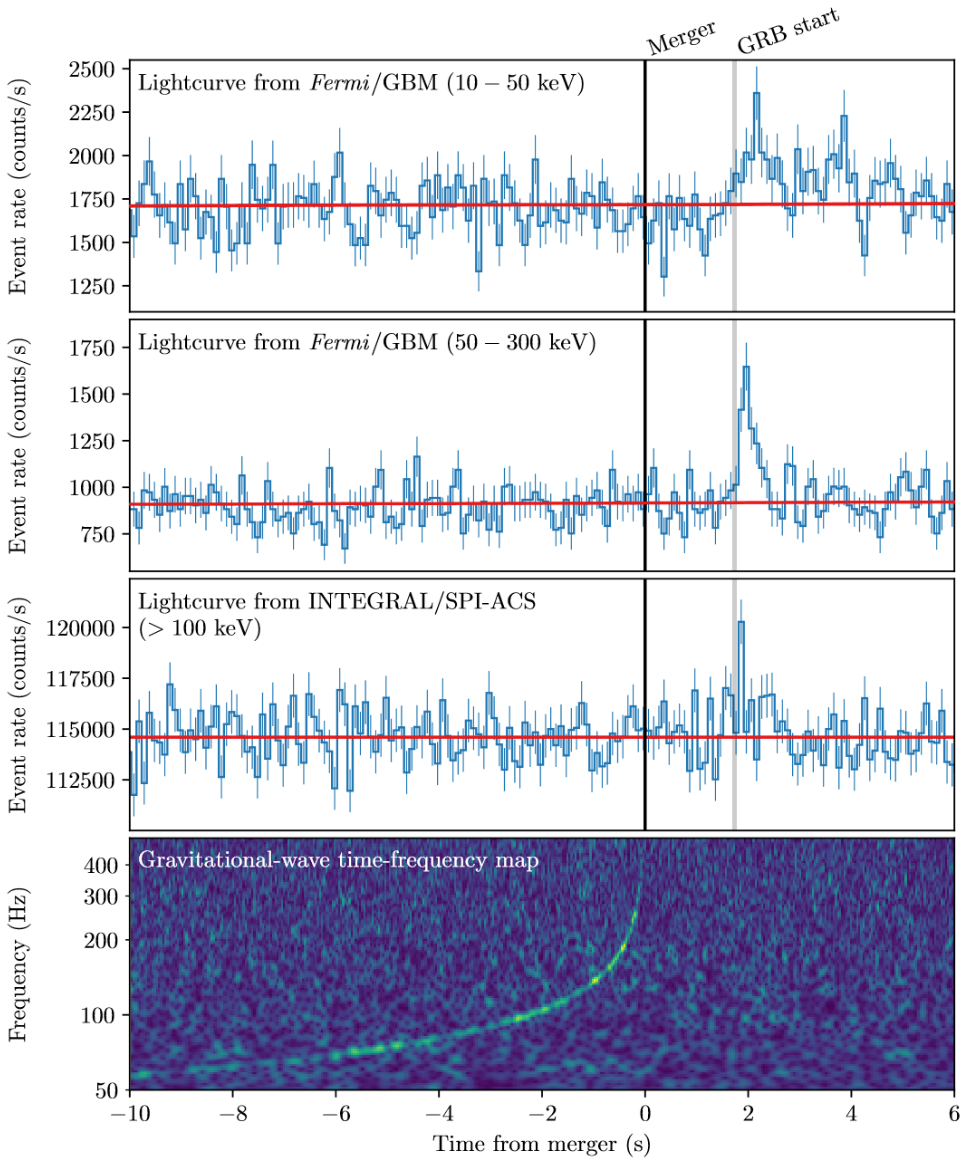
```
//////////////////////////////////////////////////////////////////////
TITLE:           GCN/FERMI NOTICE NOTICE_DATE:     Thu 17 Aug 17 12:41:20 UT
NOTICE_TYPE:     Fermi-GBM Alert RECORD_NUM:      1
TRIGGER_NUM:     524666471
GRB_DATE:        17982 TJD;    229 DOY;   17/08/17
GRB_TIME:        45666.47 SOD {12:41:06.47} UT
TRIGGER_SIGNIF:  4.8 [sigma]
TRIGGER_DUR:     0.256 [sec]
E_RANGE:         3-4 [chan]   47-291 [keV]
...
COMMENTS:        Fermi-GBM Trigger Alert.
COMMENTS:        This trigger occurred at longitude,latitude = 321.53,3.90 [deg].   COMMENTS:
   The LC_URL file will not be created until ~15 min after the trigger.
//////////////////////////////////////////////////////////////////////
```

GRB 170817A and GW170817

- 6 minutes later a single interferometer trigger was seen by LIGO
- The LVC reported GW170817 to LV-EM collaborators as a possible joint detection about 40 minutes after event time
- The first constrained skymap for this event was the initial GBM localization
- The combine LIGO/Virgo skymap agreed with the GBM location, and reduced the area to about 30 deg^2

- **Further work shows an association significance of 5.3σ**

$$\Delta t = 1.74 +/- 0.05$$



GW170817 – Host Galaxy Found

T_0 + 12 hours :
Alert sent from 1m2H Swope

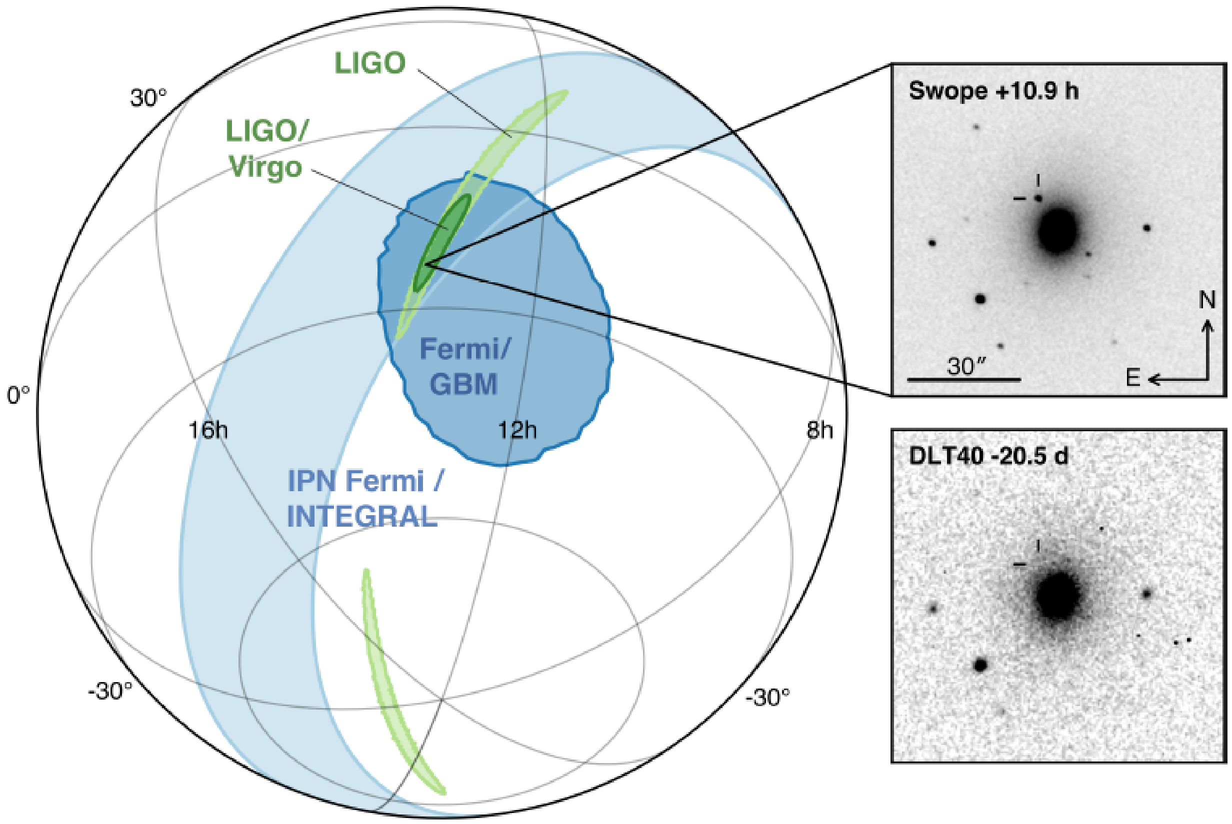
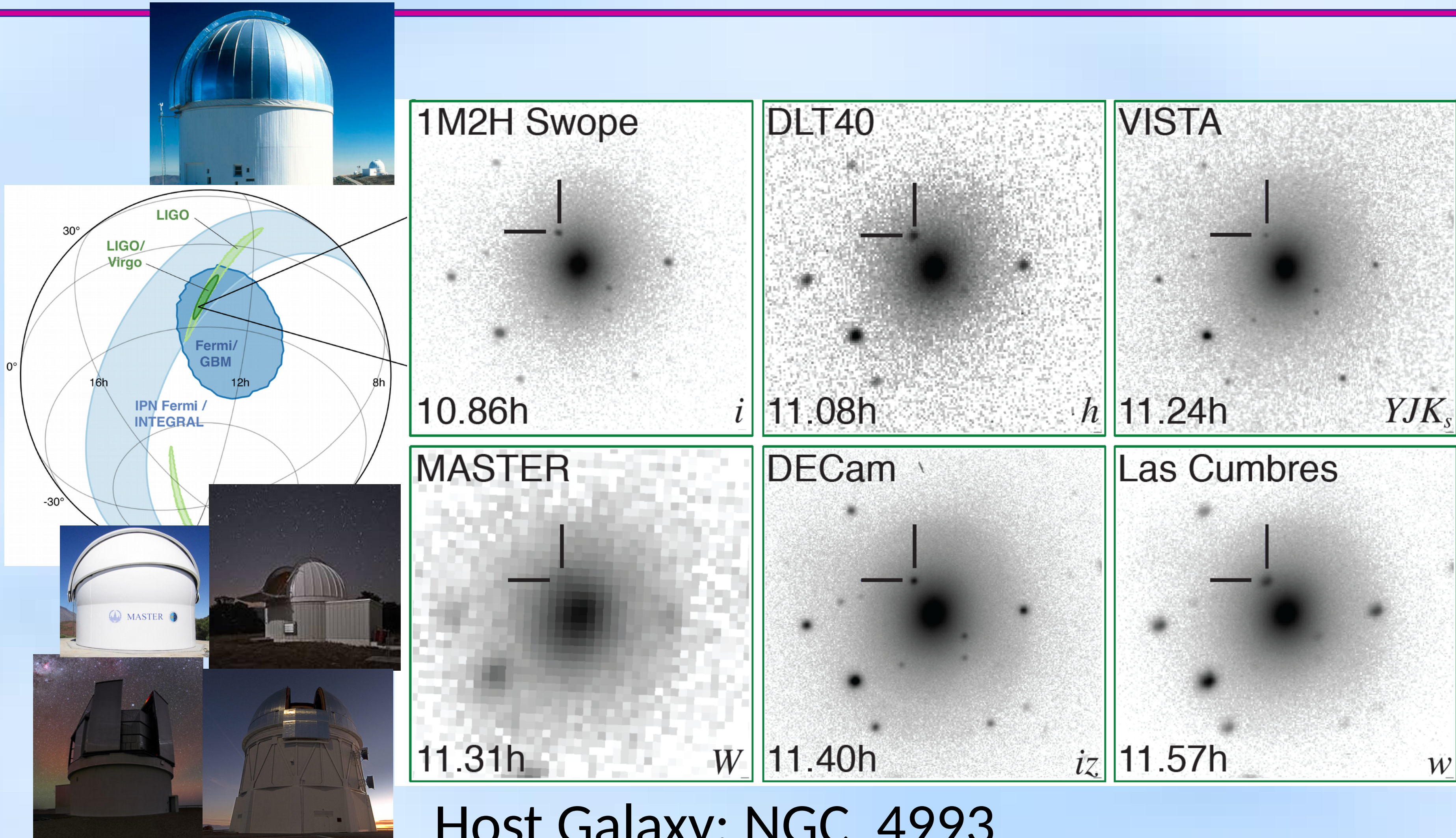


Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2, light green), the initial LIGO-Virgo localization (31 deg^2, dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi* GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hours after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

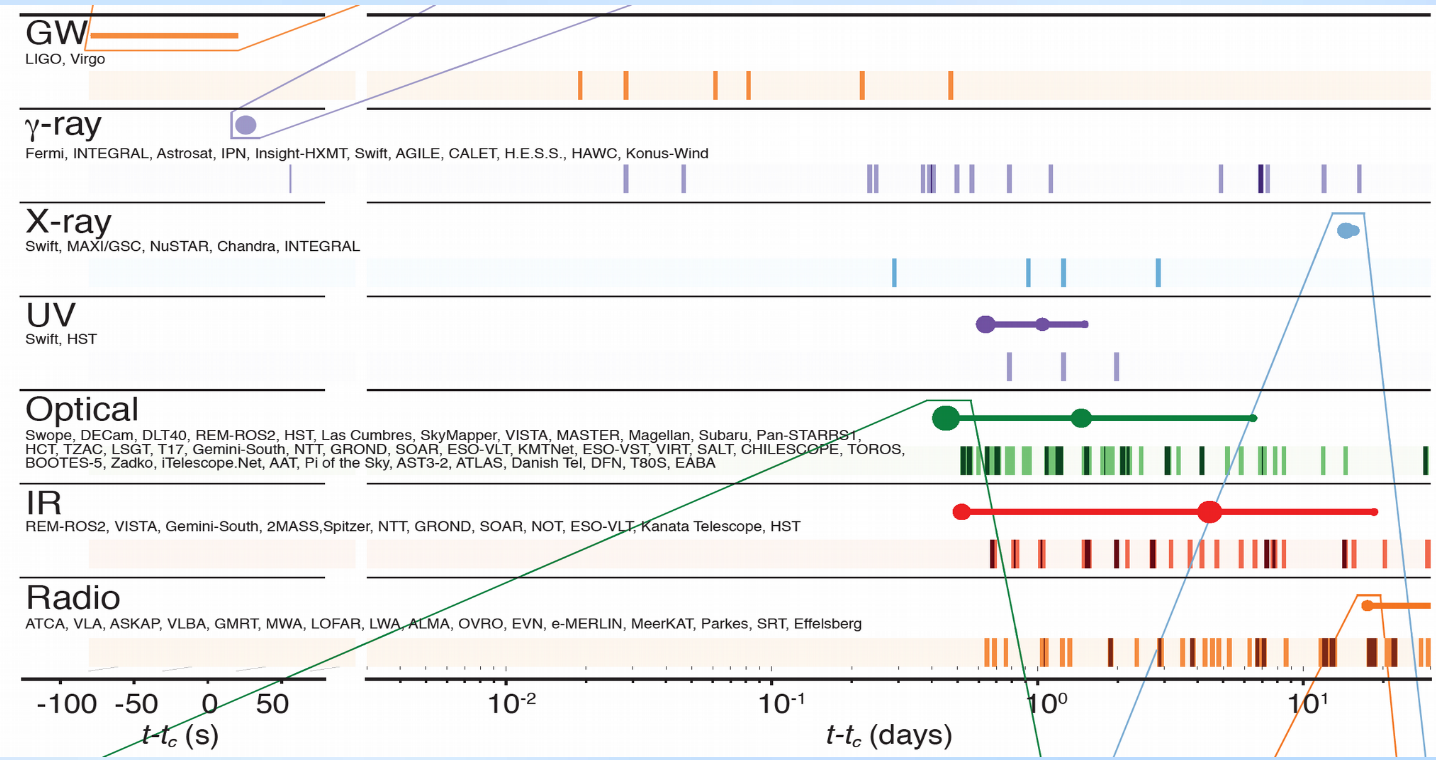
GW170817 – Host Galaxy Found

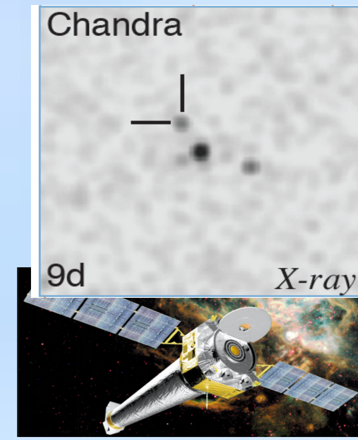


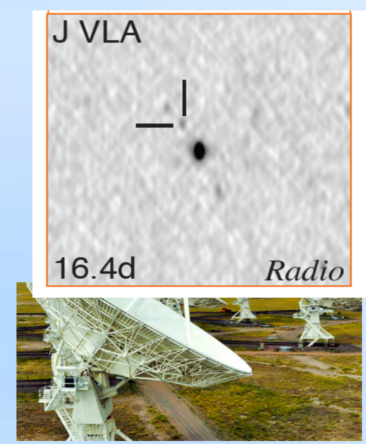
Host Galaxy: NGC 4993
Distance 42.9 +/- 3.2 Mpc, (140 +/- 10 Mly)

An Unprecedented Follow-up

70 observatories
192 “GCN” circulars
76 papers on arxiv on 16-10-2017.

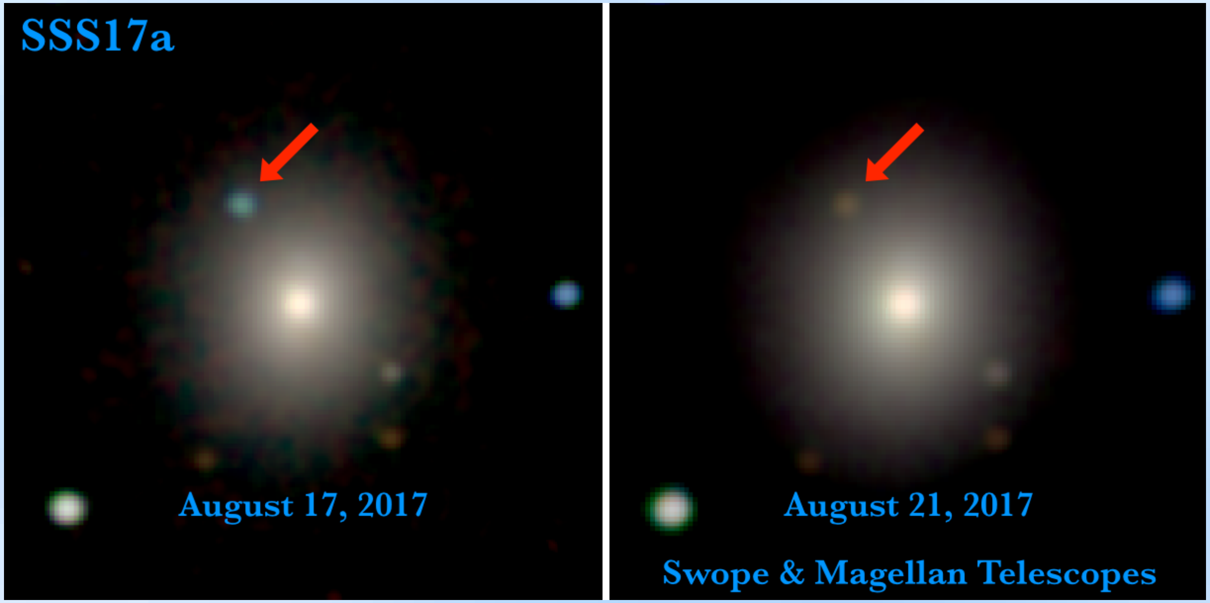


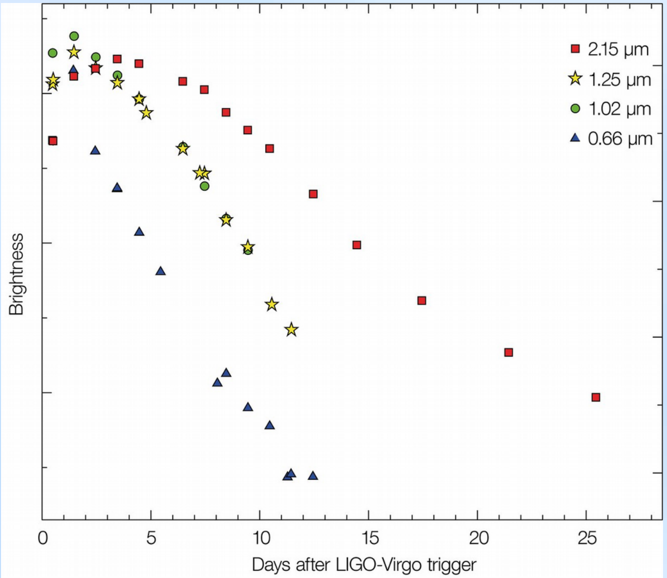




ApJ Lett

Kilonova





An initially blue signals that fades and turns to red.

All that glisters is not gold—
Often have you heard that told.

ApJ Lett

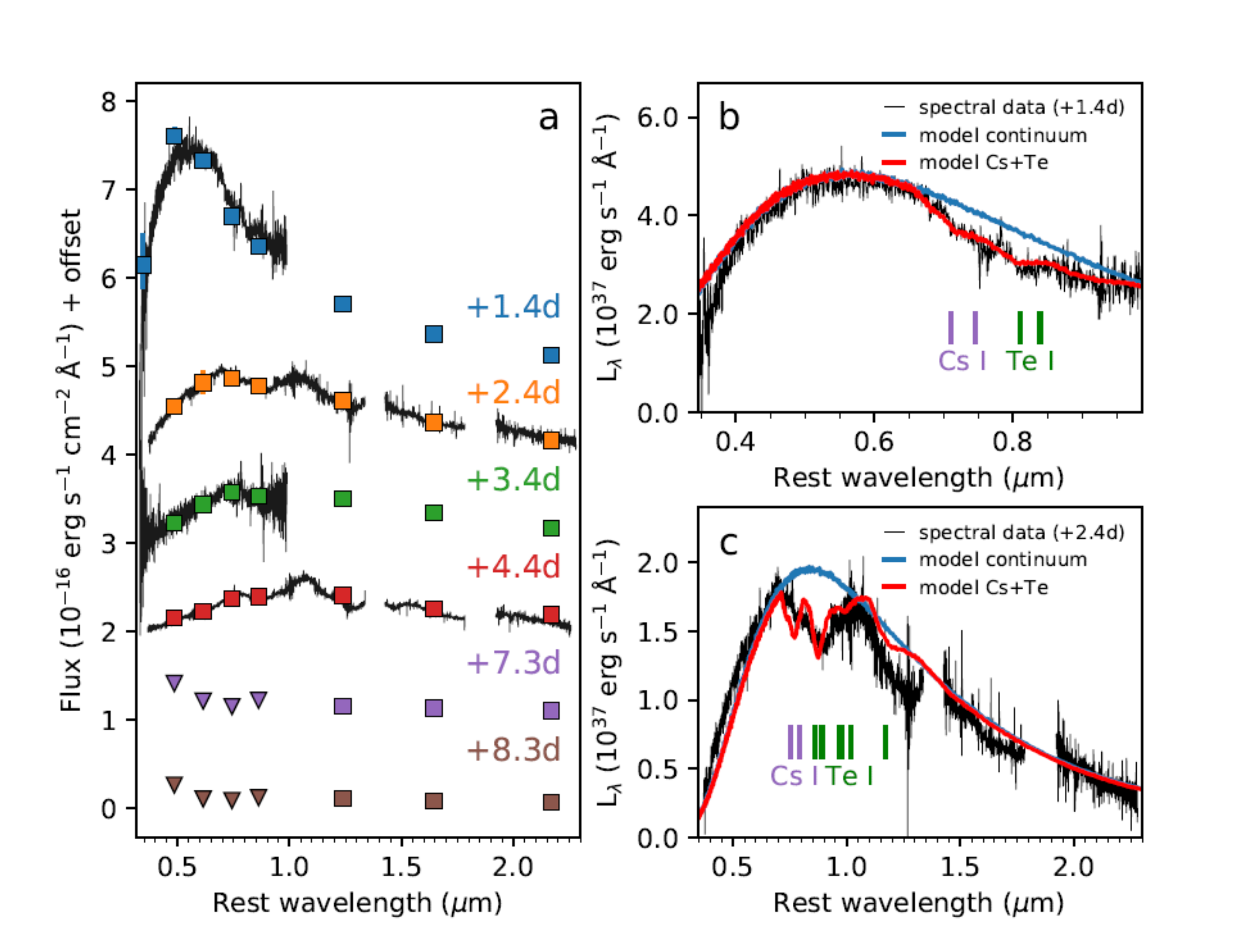
Kilonova

Ejected mass of 0.04 Mo

Velocity 0.2 c

Line feature for r-process with elements 90<A<140

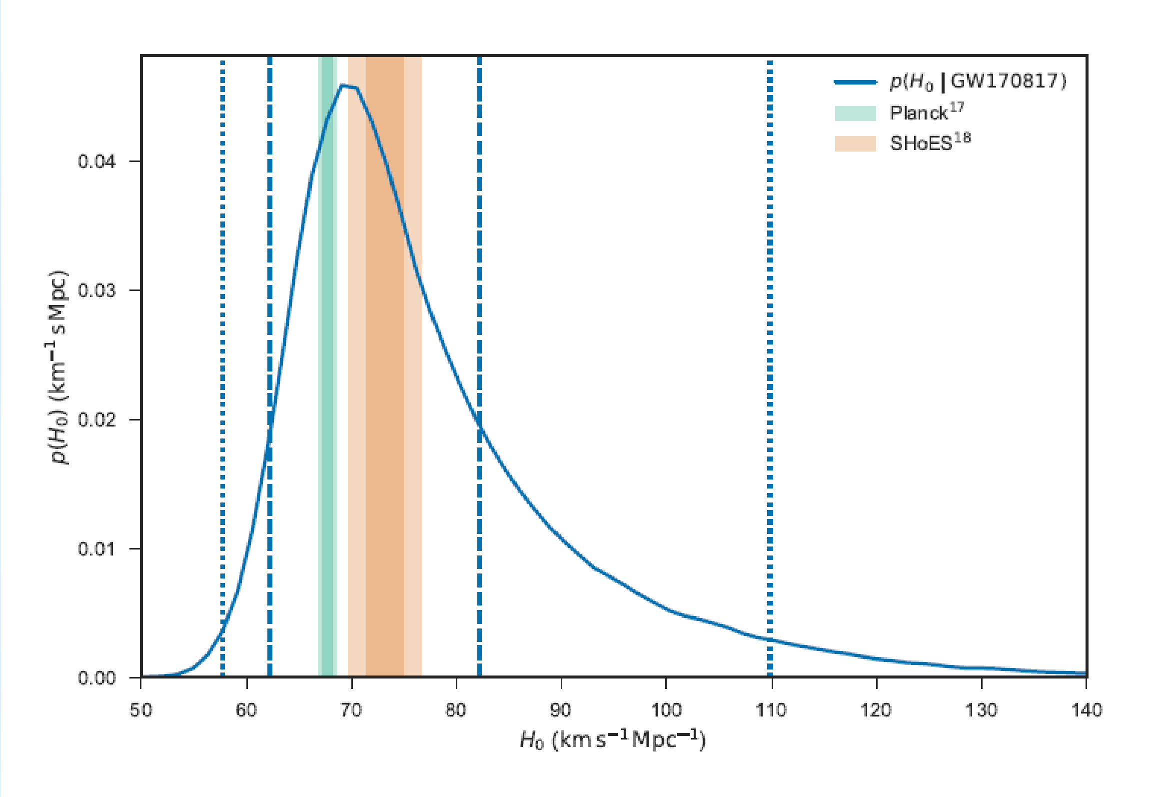
"This indicates that neutron star mergers produce gravitational waves, radioactively powered kilonovae, and are a nucleosynthetic source of the r-process elements."



Pan-STARRSS. Smartt et al, Nature

A New Measurement of the Hubble Constant

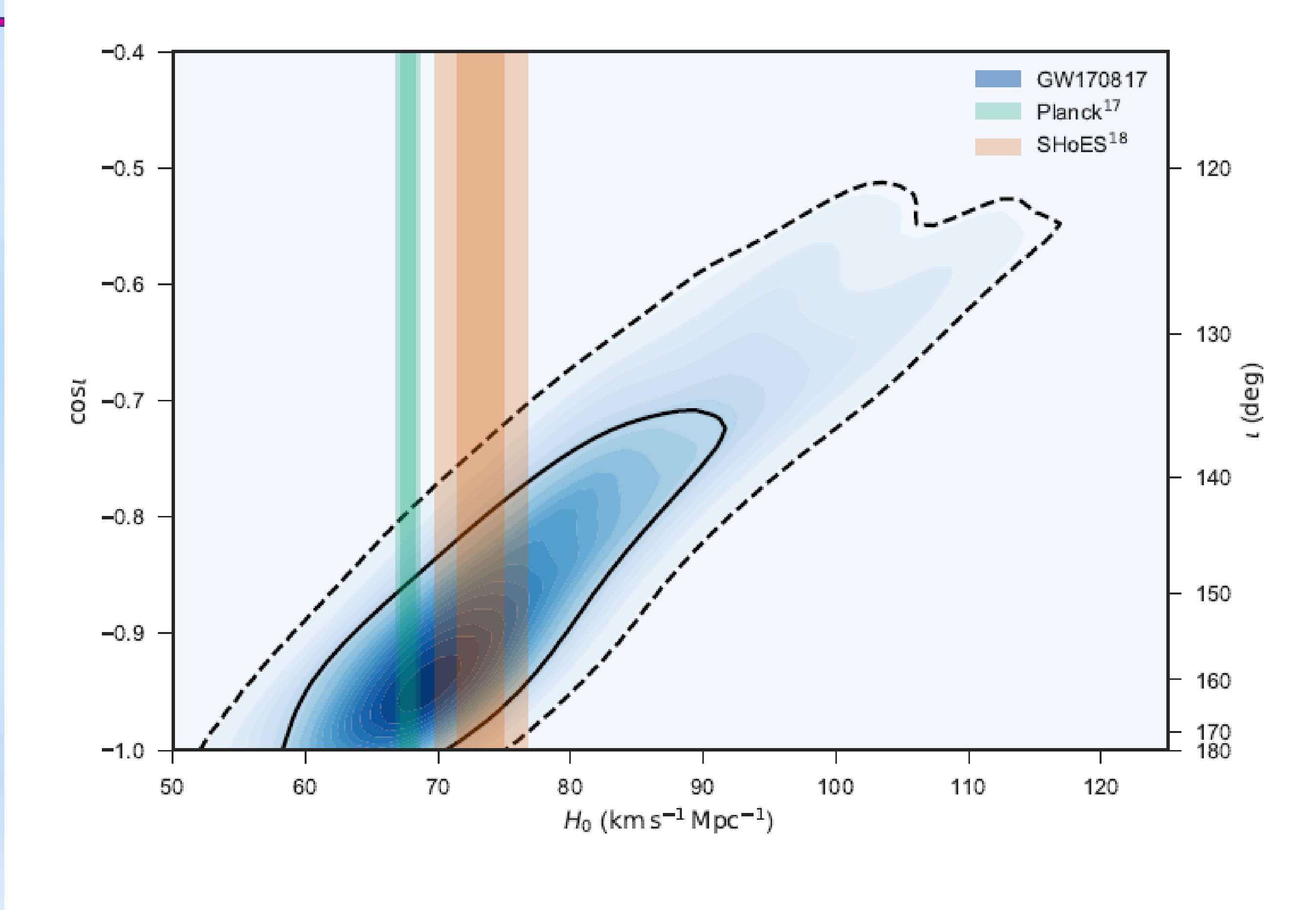
We determine the Hubble constant to be $70.0^{+12.0}_{-8.0}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$



“Our measurement combines the distance to the source inferred purely from the gravitational-wave signal with the recession velocity inferred from measurements of the redshift using electromagnetic data.”

Nature

A New Measurement of the Hubble Constant



Inclination angles near 180 deg (cos ἰ = -1) indicate that the orbital angular momentum is anti parallel with the direction from the source to the detector.

Tidal Effects and Equation of State of Nuclear Material

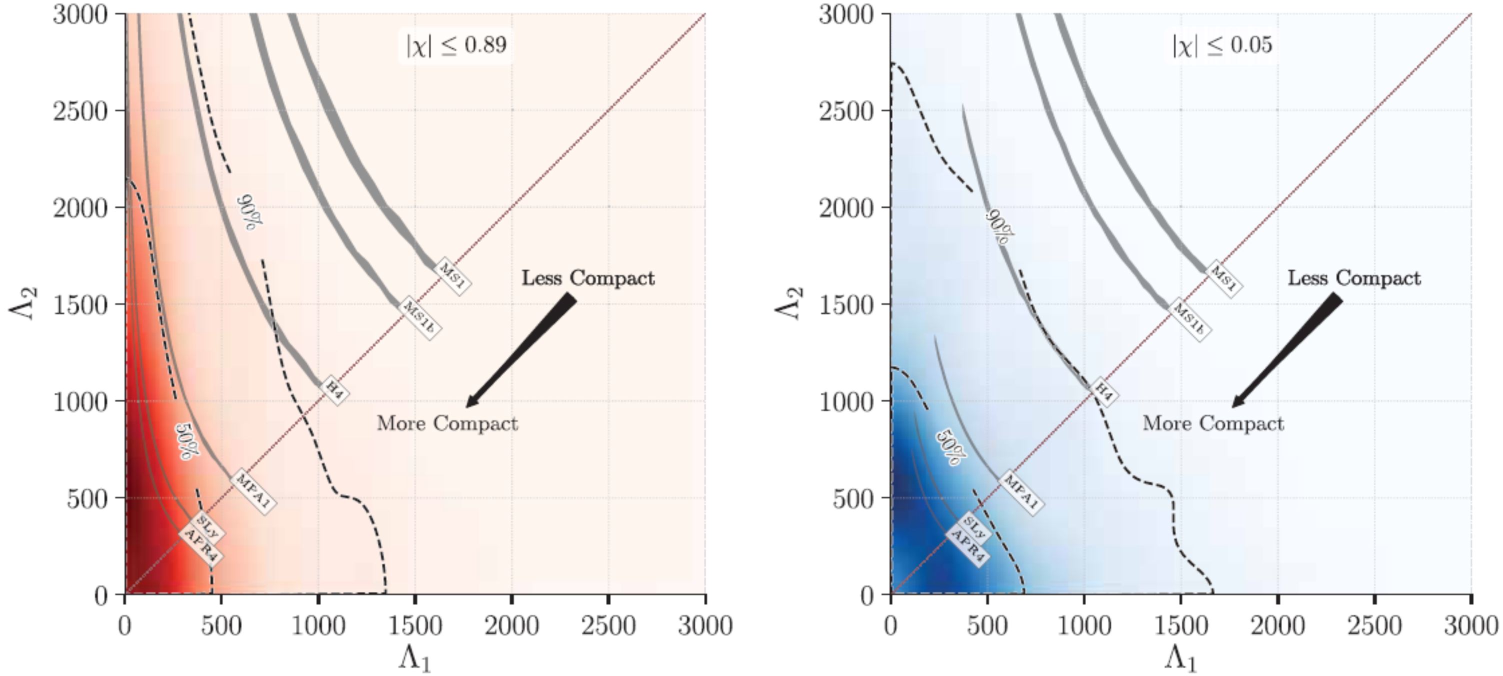


FIG. 5. Probability density for the tidal deformability parameters of the high and low mass components inferred from the detected signals using the post-Newtonian model. Contours enclosing 90% and 50% of the probability density are overlaid (dashed lines). The diagonal dashed line indicates the $\Lambda_1 = \Lambda_2$ boundary. The Λ_1 and Λ_2 parameters characterize the size of the tidally induced mass deformations of each star and are proportional to $k_2(R/m)^5$. Constraints are shown for the high-spin scenario $|\chi| \leq 0.89$ (left panel) and for the low-spin $|\chi| \leq 0.05$ (right panel). As a comparison, we plot predictions for tidal deformability given by a set of representative equations of state [156–160] (shaded filled regions), with labels following [161], all of which support stars of $2.01 M_\odot$. Under the assumption that both components are neutron stars, we apply the function $\Lambda(m)$ prescribed by that equation of state to the 90% most probable region of the component mass posterior distributions shown in Fig. 4. EOS that produce less compact stars, such as MS1 and MS1b, predict Λ values outside our 90% contour.

PRL

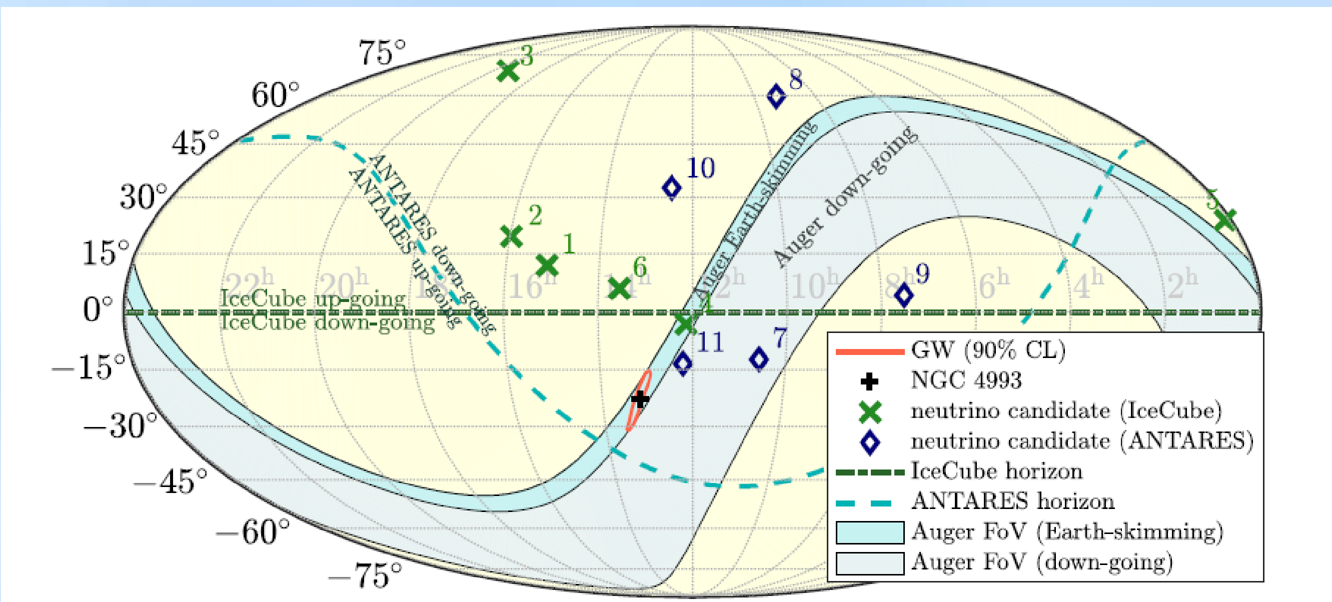
No neutrinos … but we looked!

The Astrophysical Journal Letters, 850:L35 (18pp), 2017 December 1
https://doi.org/10.3847/2041-8213/aa9aed

CrossMark

Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

ANTARES Collaboration, IceCube Collaboration, The Pierre Auger Collaboration,
and LIGO Scientific Collaboration and Virgo Collaboration



No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission

The Speed of Gravity

$$\Delta v = v_{\rm GW} - v_{\rm EM}$$

$$\Delta v / v_{\rm EM} \approx v_{\rm EM} \Delta t / D$$

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\rm EM}} \leq +7 \times 10^{-16}$$

Assuming D = 26 Mpc (the lower bound on the 90% confidence interval for distance based on GW data alone, and bounding t between [-10, +1.74] s, where the -10 s is a reasonably conservative assumption.

ApJ Lett

New Test of the Equivalence Principle

$$\delta t_{\mathrm{S}} = -\frac{1+\gamma}{c^3}\int_{\mathbf{r}_{\mathrm{e}}}^{\mathbf{r}_{\mathrm{o}}} U(\mathbf{r}(l))dl$$

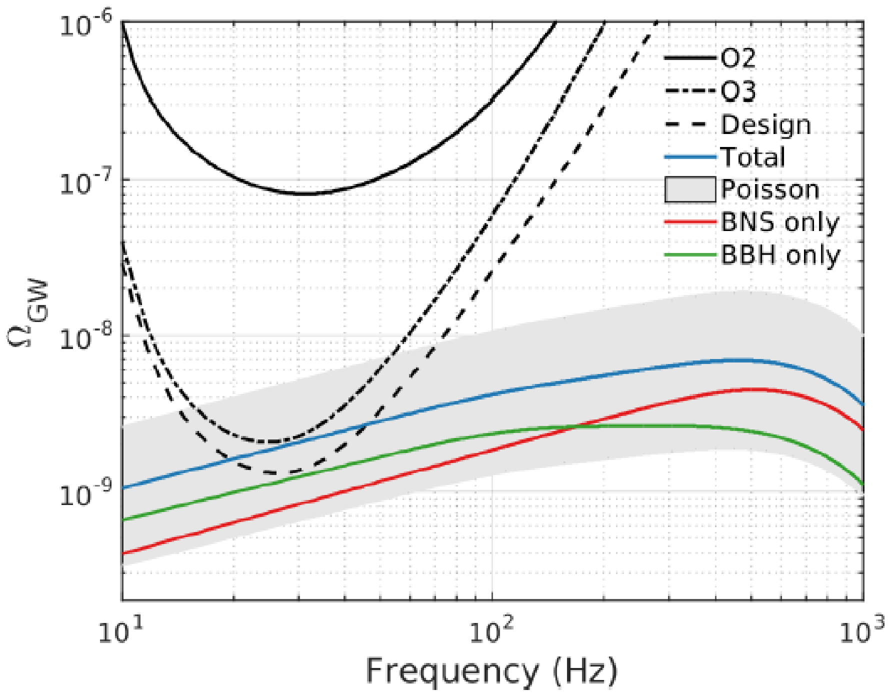
δt_S = Shapiro delay using the same time bounds
$\mathbf{r}_o$ = observation positon, $\mathbf{r}_e$ = emission position
$U(\mathbf{r})$ = gravitational potential (here the Milky Way's)
= wave path
γ = deviation from Einstein-Maxwell theory
(where γ_{EM} and γ_{GW} are both equal to 1)

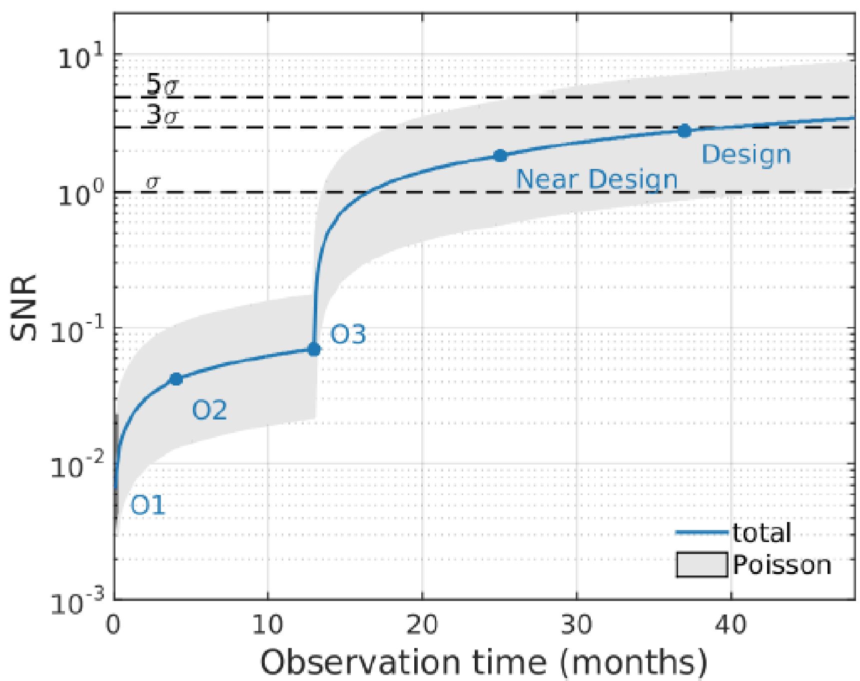
$$-2.6\times 10^{-7} \leq \gamma_{\mathrm{GW}} - \gamma_{\mathrm{EM}} \leq 1.2\times 10^{-6}$$

The best absolute bound on γ_{EM} is $\gamma_{\mathrm{EM}} - 1 = (2.1 \pm 2.3)\times 10^{-5}$, from the measurement of the Shapiro delay (at radio wavelengths) with the Cassini spacecraft (Bertotti et al. 2003).

ApJ Lett

Implications for a Stochastic Background

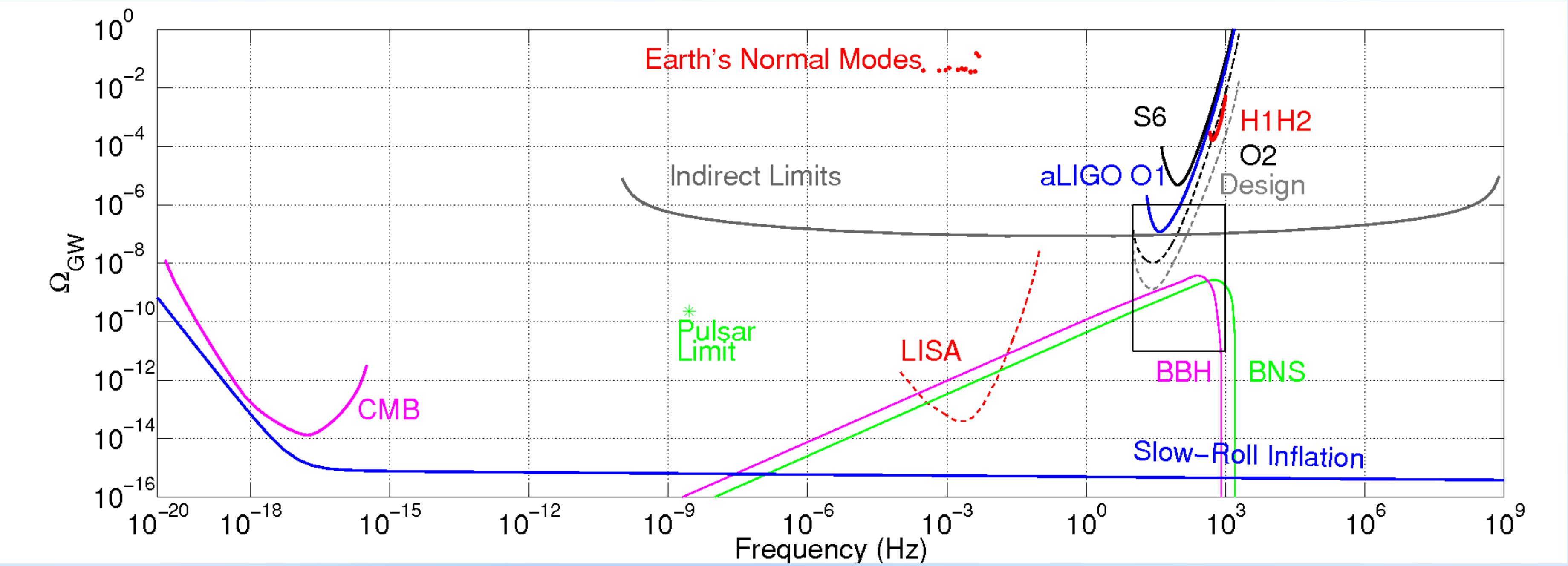




"Assuming the most probable rate for compact binary mergers, we find that the total background may be detectable with a signal to-noise-ratio of 3 after 40 months of total observation time."

Submitted PRL

O1 isotropic stochastic search



Phys. Rev. Lett. 118, 121101 (2017)

Indirect limits: PhysRevX.6.011035

"CMB temperature and polarization power spectra, lensing, BAOs and BBN"

$$\Omega_{gw}(25\text{Hz}) < 1.7 \times 10^{-7}$$

Gamma Rays with Fermi GBM

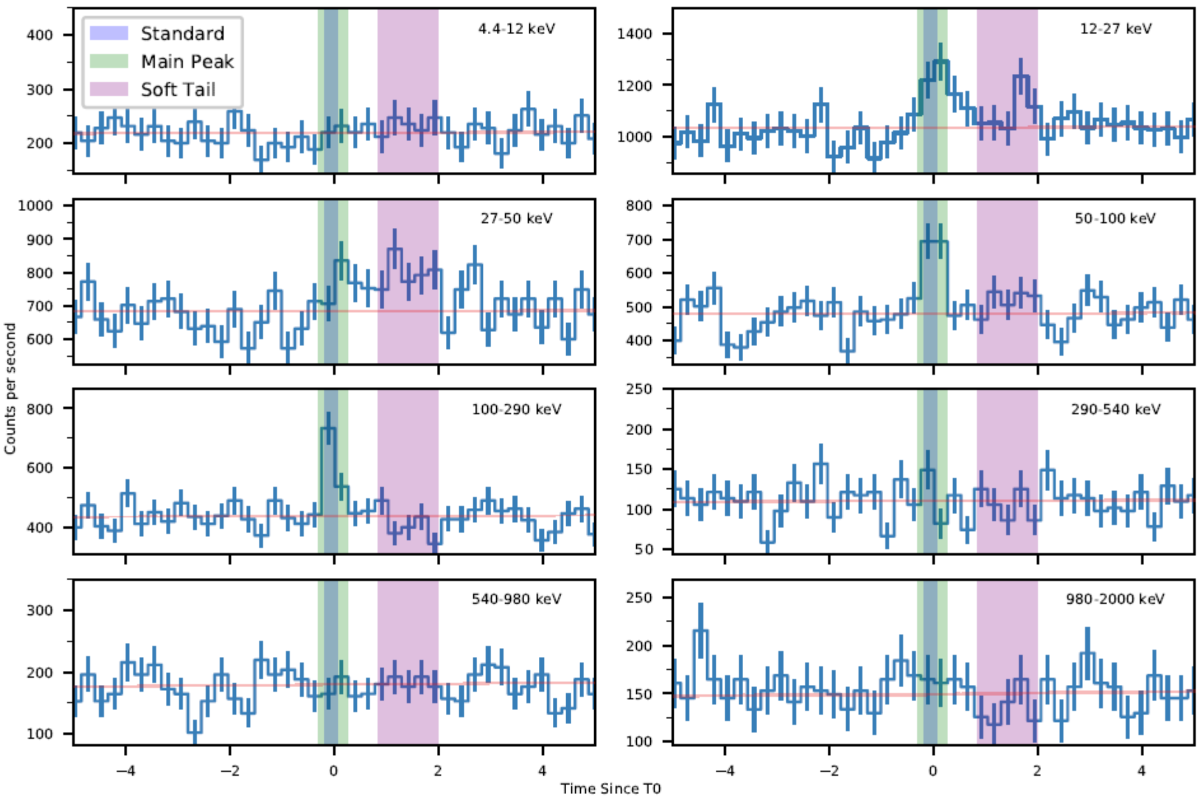
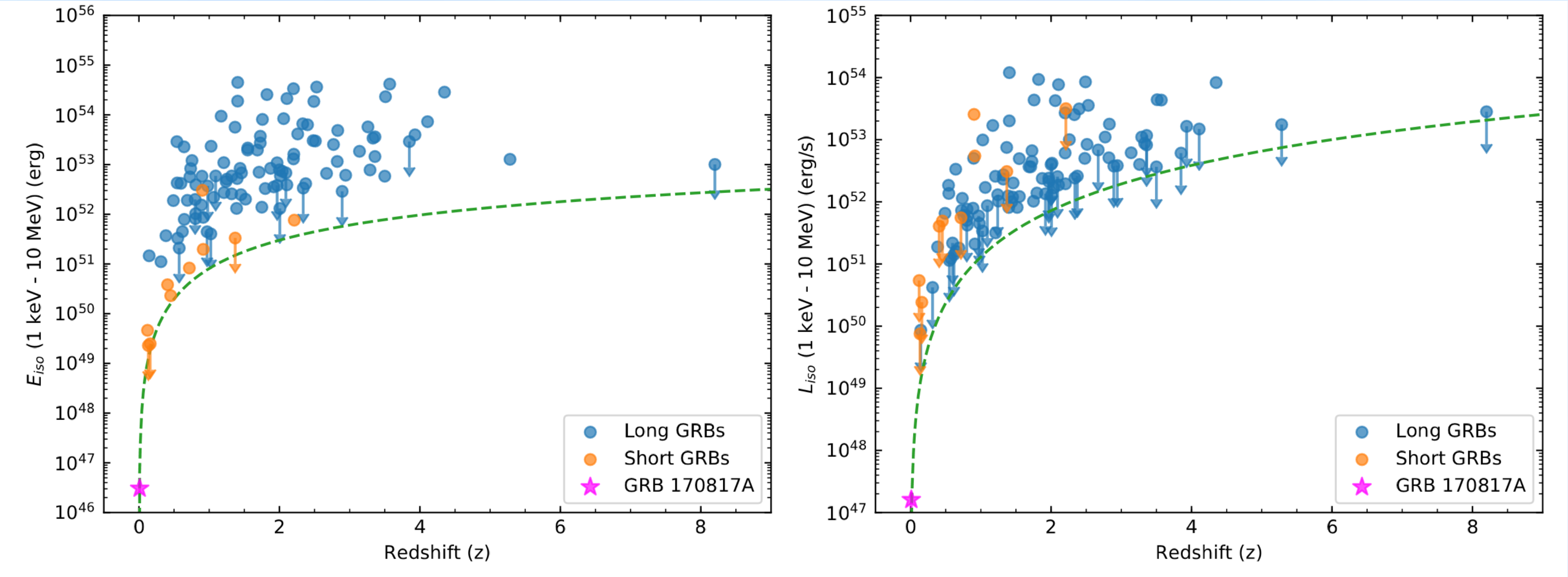


Figure 6. The 256 ms binned lightcurve of GRB 170817A for NaI 1, 2, and 5 over the standard 8 CTIME energy channels. The shaded regions are the different time intervals selected for spectral analysis. The inclusion of the lower energies shows the soft tail out to T0+2 s.

Two components: Main peak 0.5s and a soft tail ~2s

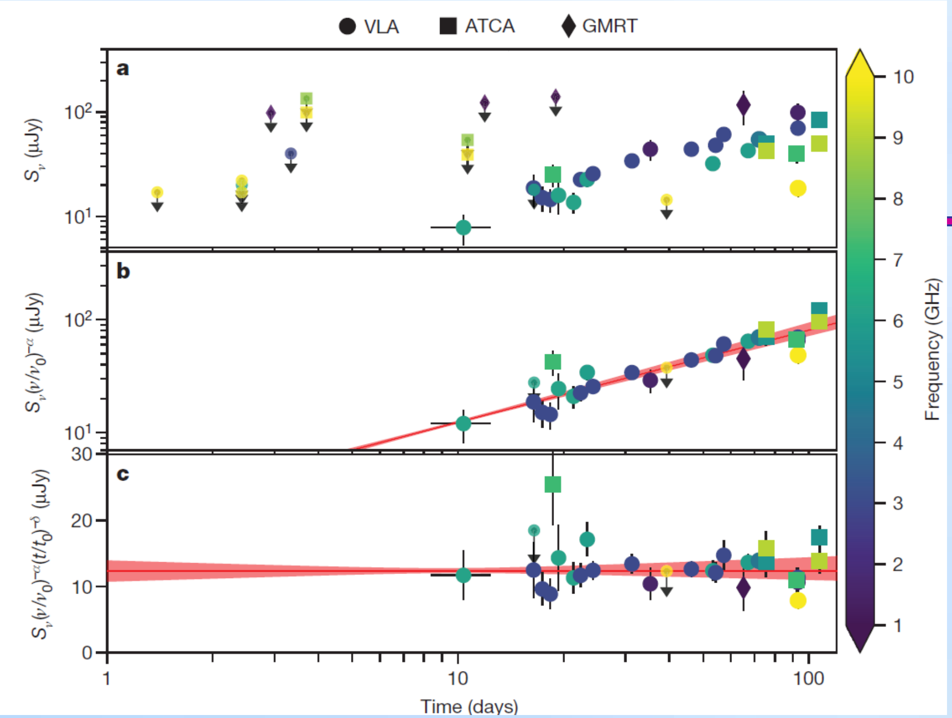
GRB 170817A – Very Dim

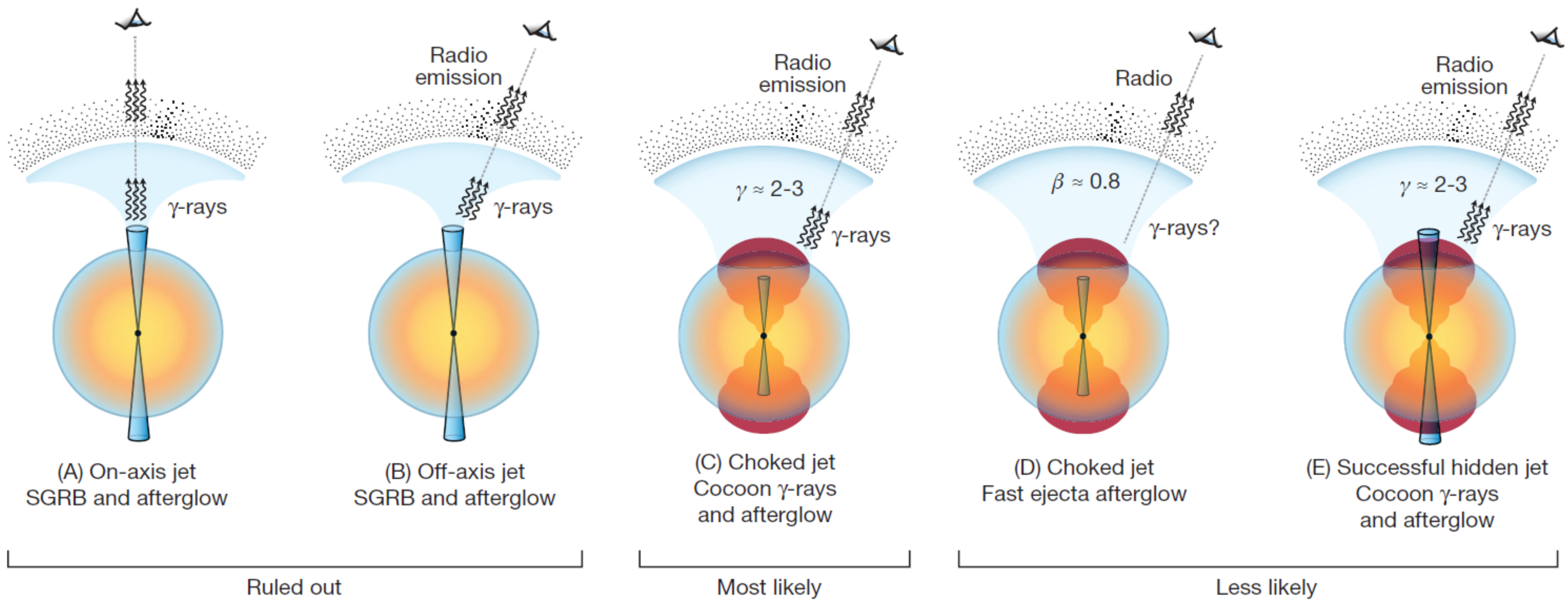


GRB 170716A is 2 to 6 orders of magnitude less energetic than previously known sGRBs with firm redshifts.

Cocoon Model Likely?

Nature **554**, p. 207 (2018)





No neutrinos … but we looked!

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Search for High-energy Neutrinos from Binary Neutron Star Merger GW170817 with ANTARES, IceCube, and the Pierre Auger Observatory

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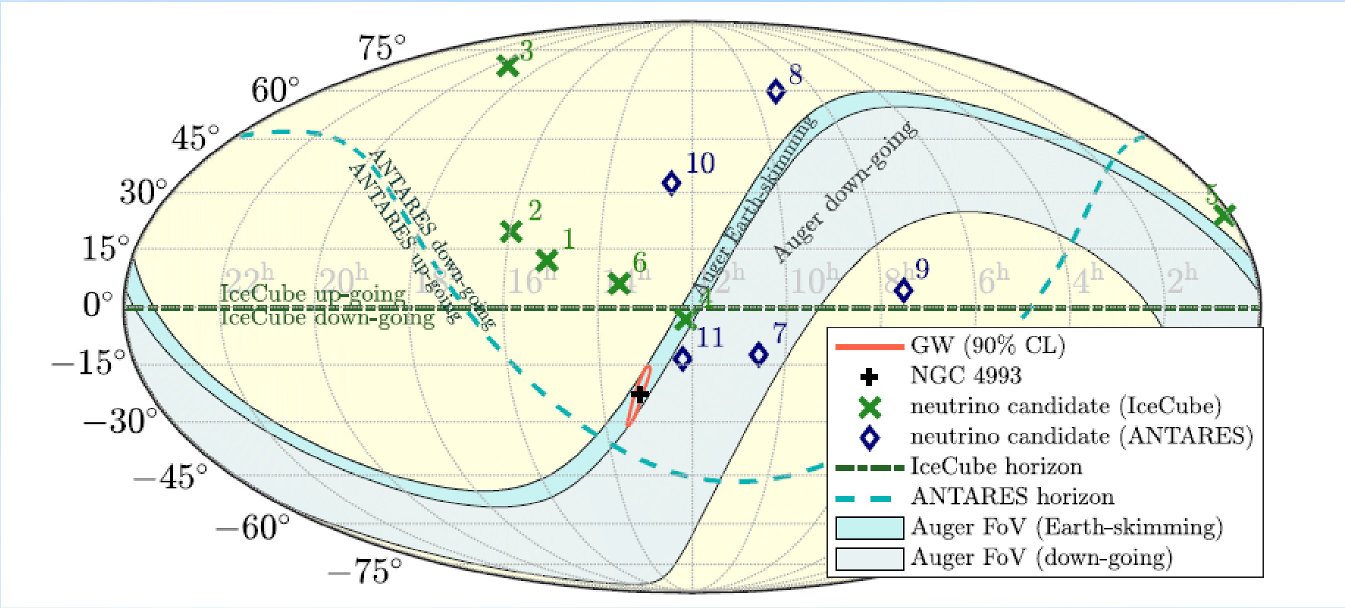
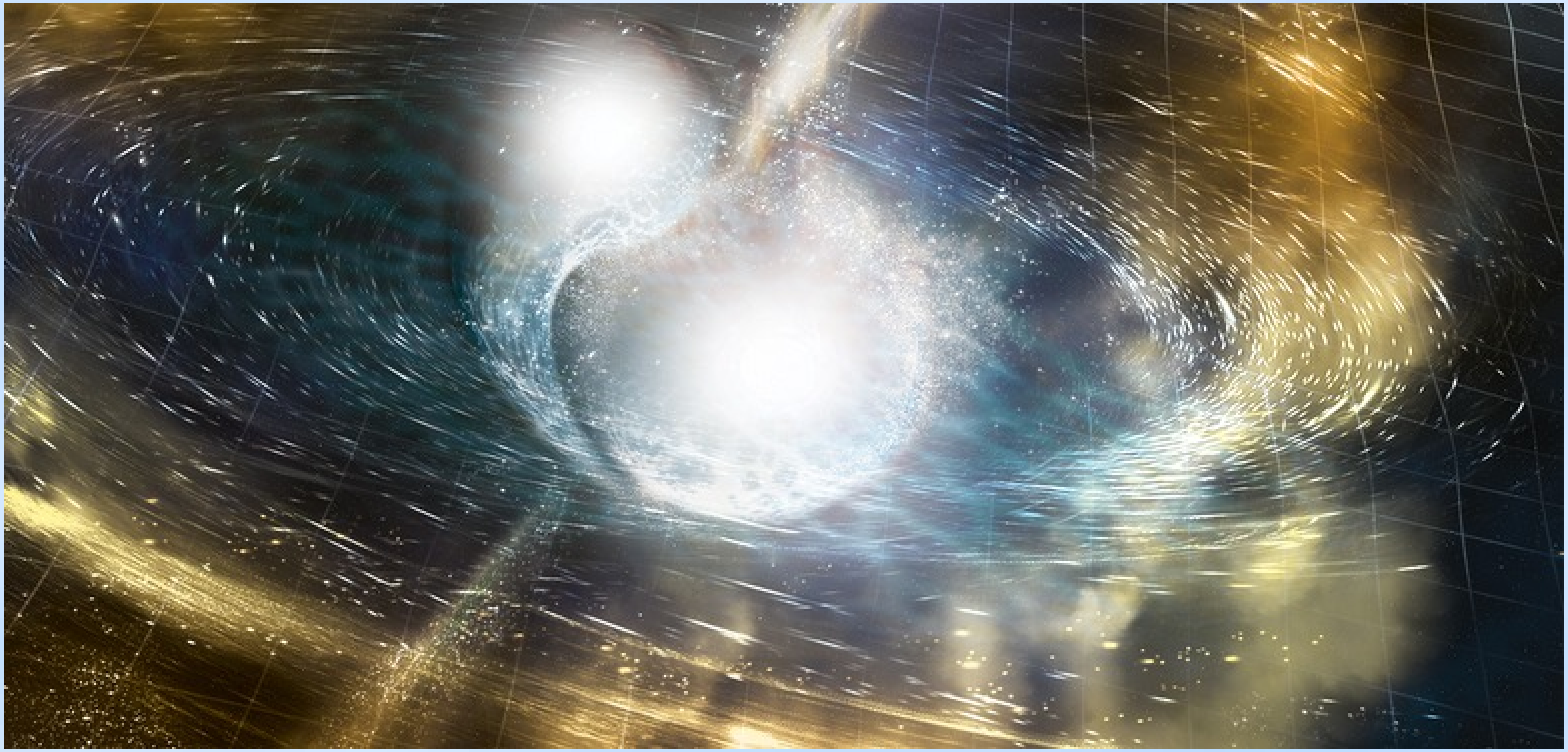


No neutrinos directionally coincident with the source were detected within ±500 s around the merger time. Additionally, no MeV neutrino burst signal was detected coincident with the merger. We further carried out an extended search in the direction of the source for high-energy neutrinos within the 14 day period following the merger, but found no evidence of emission

LIGO – Virgo Summary

- Gravitational waves have been observed
- The universe has more stellar mass black holes than expected
- Binary neutron star merger, kilonova, multimessenger astronomy started
- A stochastic background of gravitational waves from throughout the history of the universe could be observed in a few years
- Intensive effort to find burst (CCSN, cosmic string, etc), compact binary coalescence, continuous wave, and stochastic signals.
- Looking for signals in coincidence with electromagnetic and neutrino signals.
- Observing run O3 to start in February 2019 – 1 year run.
- KAGRA and LIGO-India will join in the coming years
- The future looks bright for ground based detectors

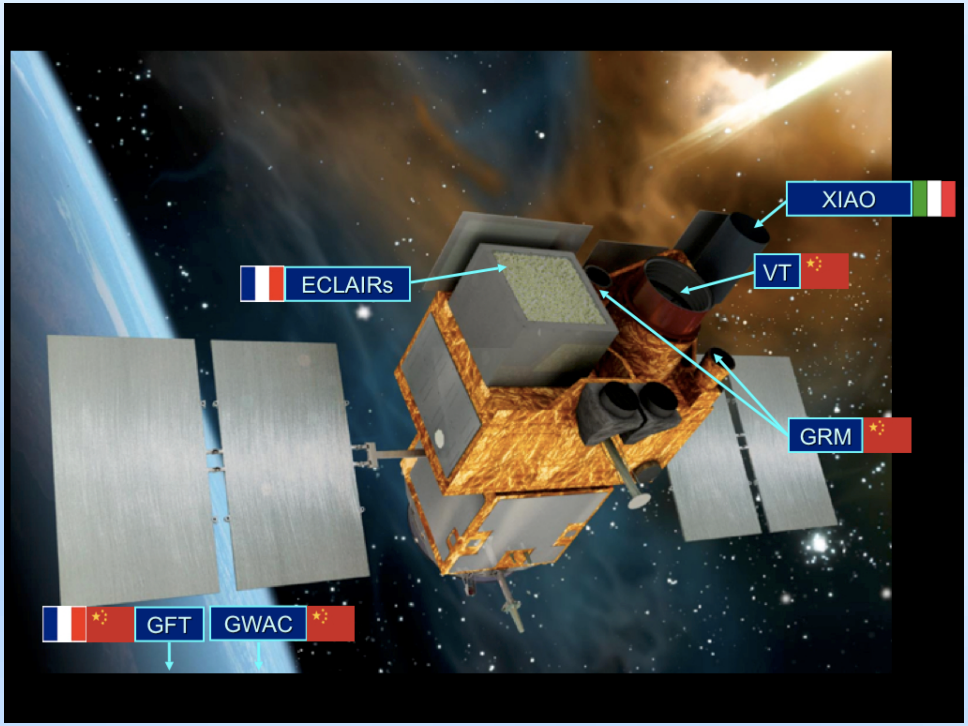
What's Next?



Future – More Multimessenger Astronomy

TAROT-Zadko: optic follow-up.

Calern France, Réunion Island, Chile, Western Australia
To come? Algeria, Tahiti

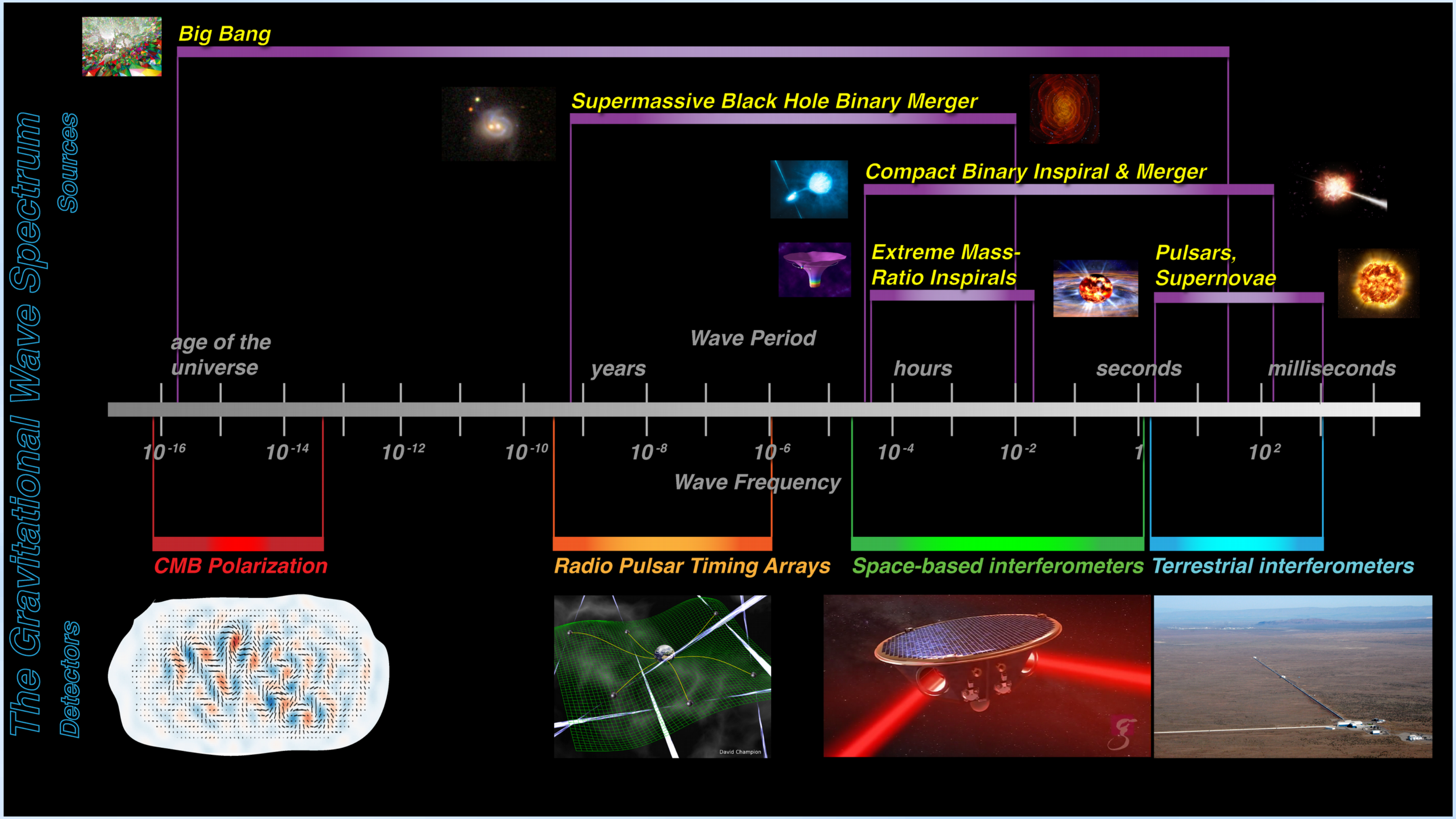


SVOM (Space-based multi-band astronomical Variable Objects Monitor)

France – China.

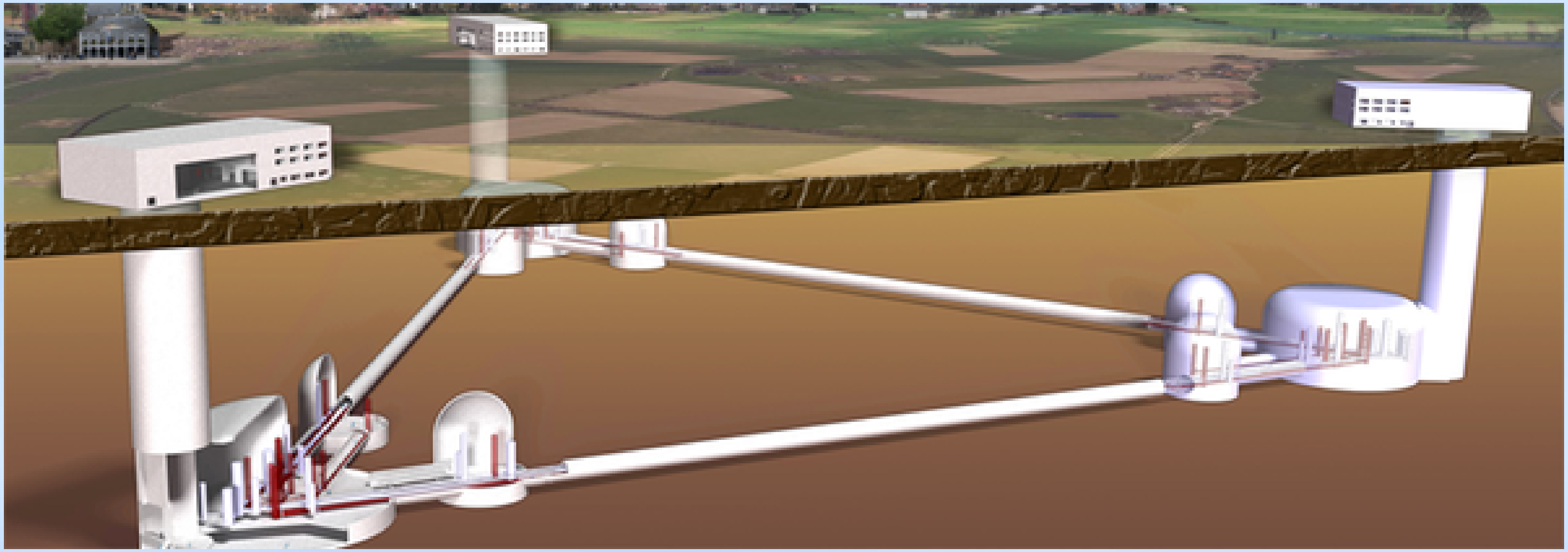
3 – 5 year mission. ~ 2021 launch

Gravitational Wave Spectrum



Third Generation Gravitational Wave Detectors

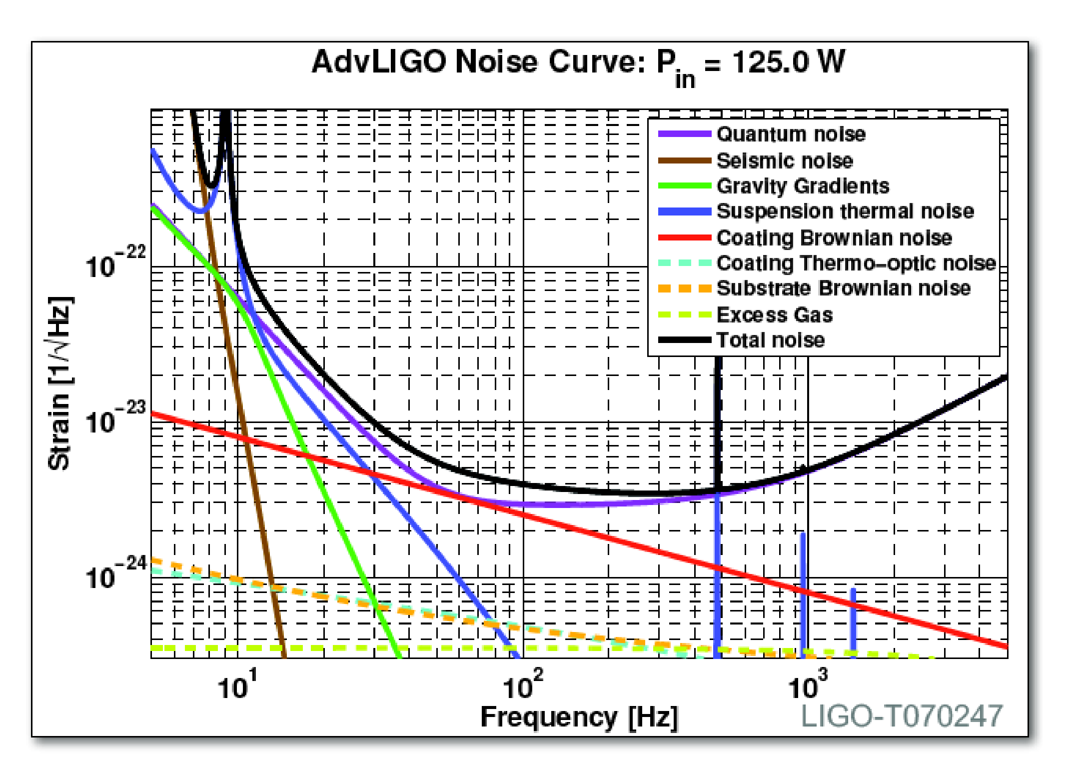
Einstein Telescope



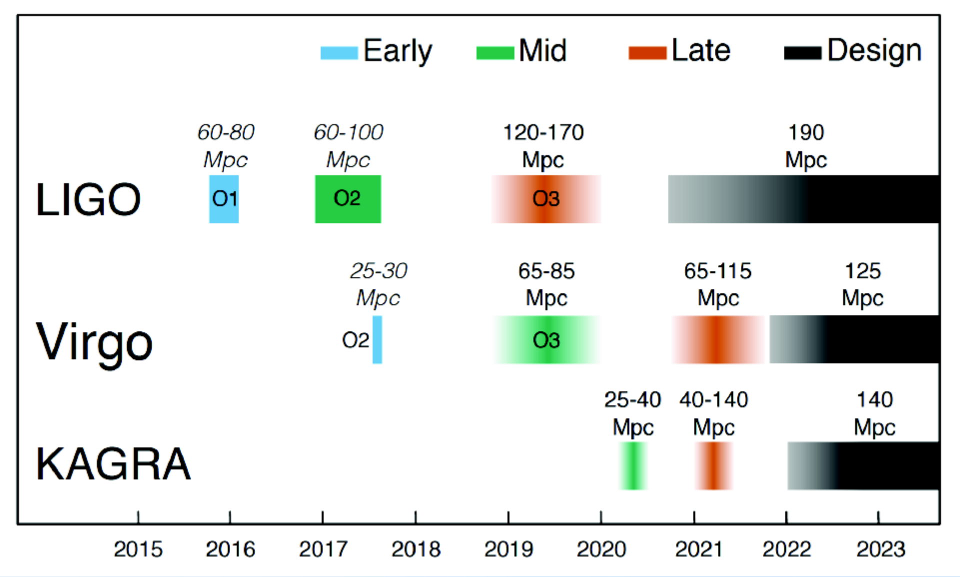
Underground to reduced seismic noise.
10 km arms
Cryogenic mirrors
Lower frequency limit – 1 Hz
10 x better sensitivity than 2nd generation detectors
Farther back in the universe

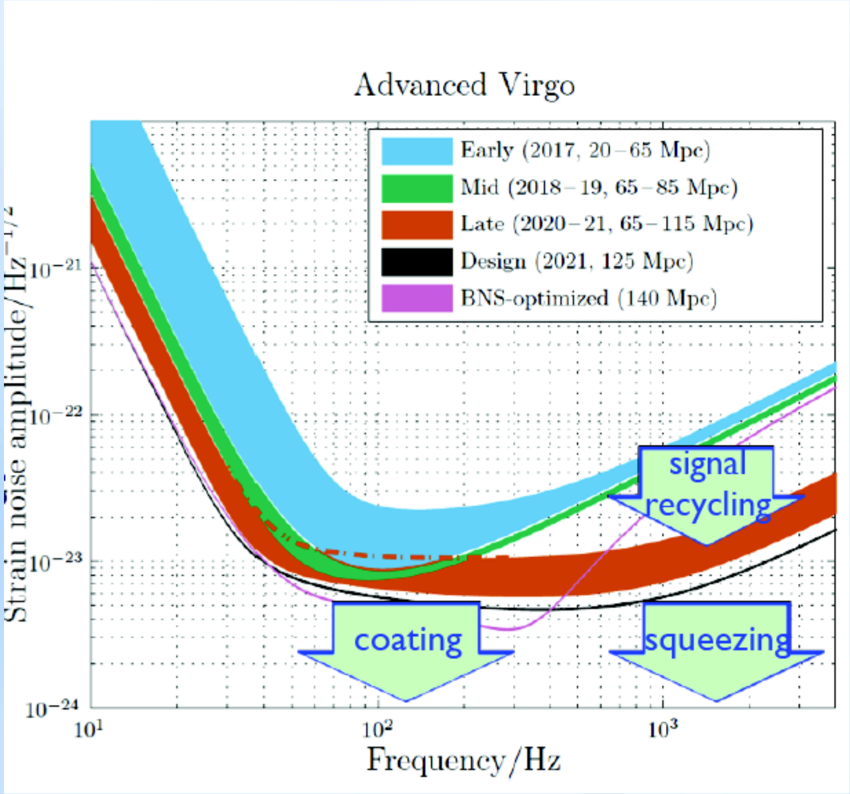
Noise Sources Limiting the 2G Detectors

- Quantum noise limits most of the frequency range.
- Coating Brownian noise limits in the range from 50 to 100Hz.
- Below ~15Hz we are limited by ‘walls’ made of Suspension Thermal, Gravity Gradient and Seismic noise.
- And then there are the, often not mentioned, ‘technical’ noise sources which trouble the commissioners so much.



Advanced Virgo +





Advanced Virgo design: BNS range 125 Mpc

Do better?

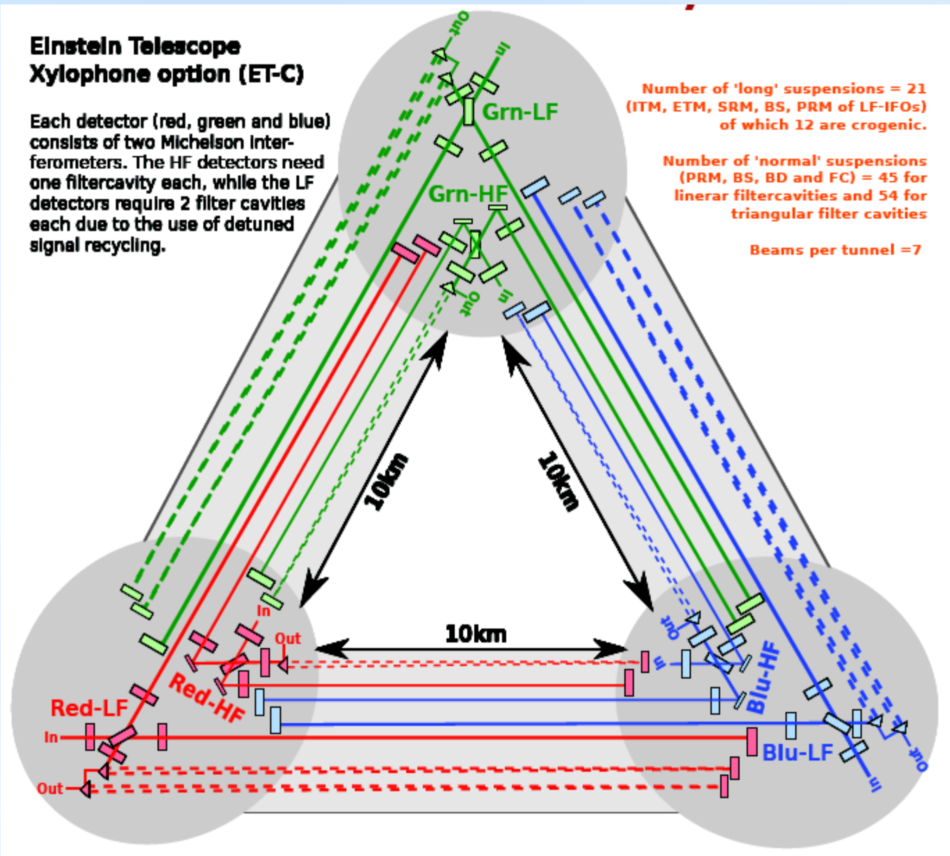
Frequency dependent squeezing
Newtonian noise cancellation
Larger mirrors
Mirror coating improvements

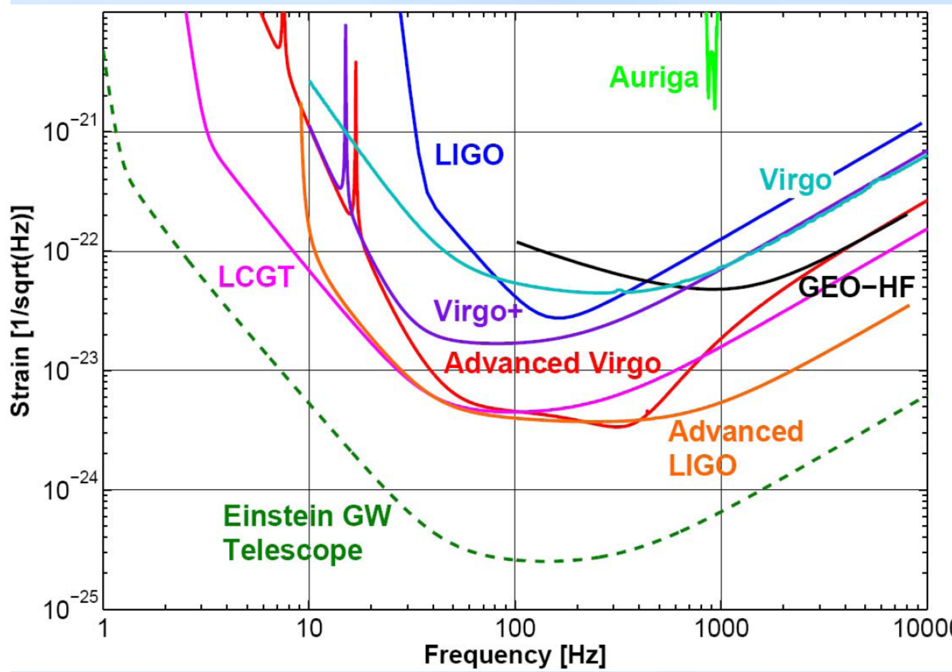
3^{rd} Generation Detectors, To Do List

- Increase arm length, 3km → 10 km: decrease all displacement noises by ~ 3
- Optimizing signal recycling (tuned SR)
- Increase laser power: 125 W to 500 W at IFO input. Reduce shot noise but increase radiation pressure
- Quantum noise suppression: squeezed light
- Increase the beam size → decrease coating Brownian noise
- Cool the test masses: 20 K and decrease Brownian noise
- Longer suspensions: 50 m, 5 stage, corner frequency 0.16 Hz and bring seismic noise wall from 10 Hz down to 1.5 Hz
- Go underground: decrease seismic noise and gravity gradient noise
- Gravity gradient suppression (seismic arrays)
- Heavier mirrors: 42 kg → 120 kg, reduce radiation pressure noise

Talk by Michele Punturo, 3rd generation of ground-based detectors: Einstein Telescope

Einstein Telescope – Very Ambitious Goals



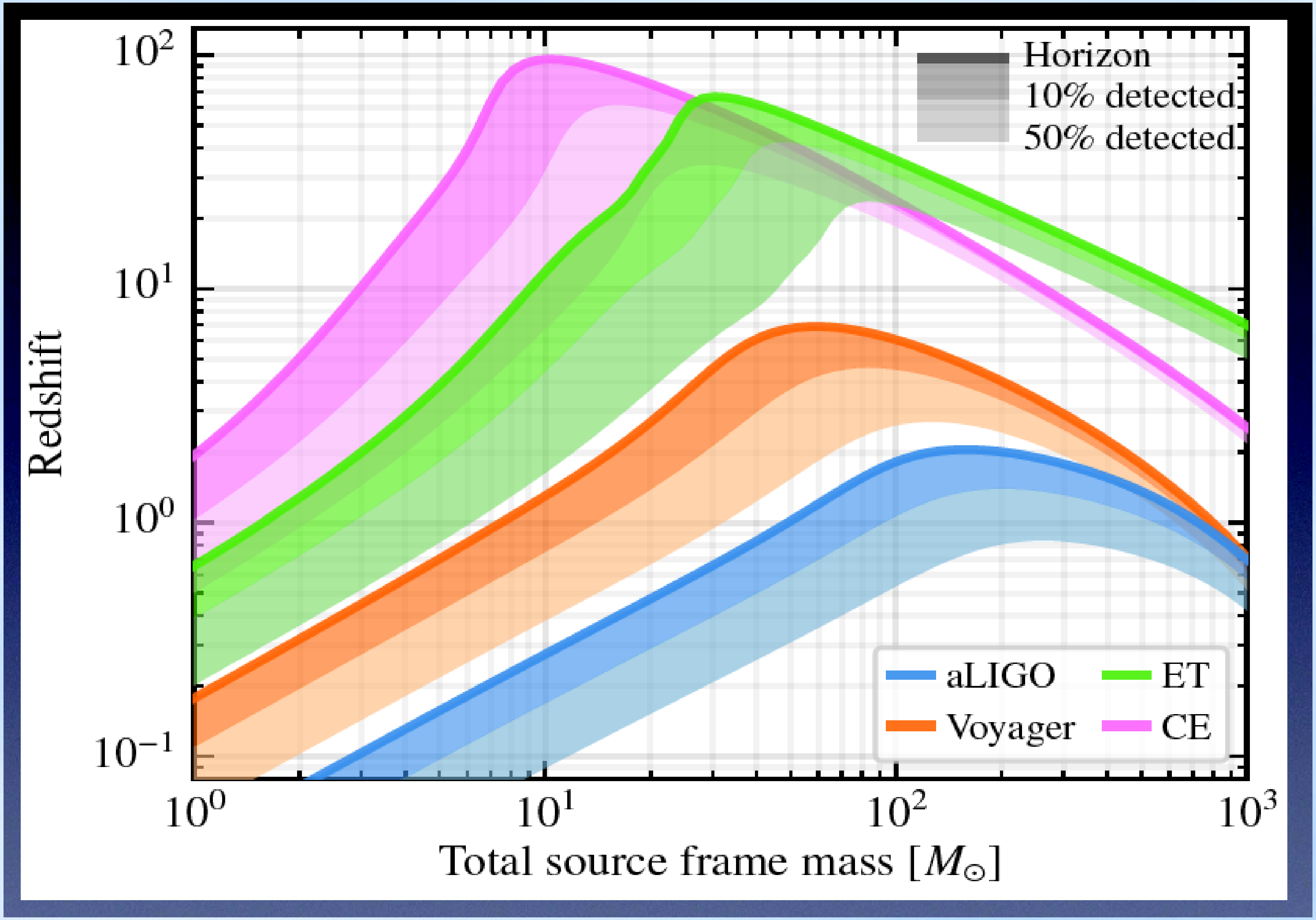


Other 3G Projects:
Voyager : A 4 km cryogenic detector, 200 kg masses
Cosmic Explorer: 40 km interferometer

3G Science

- Advance exploration of extremes of gravity and astrophysics
- Address fundamental questions in physics and astronomy
- Provide insights into most powerful events in the Universe
- Reveal new objects and phenomena
- Try to identify observations that:
  - Will lead to breakthrough science
  - Are uniquely available with gravitational wave observations, possibly in conjunction with EM observations
  - Can only be achieved with the sensitivity of 3rd generation detectors such as Einstein Telescope

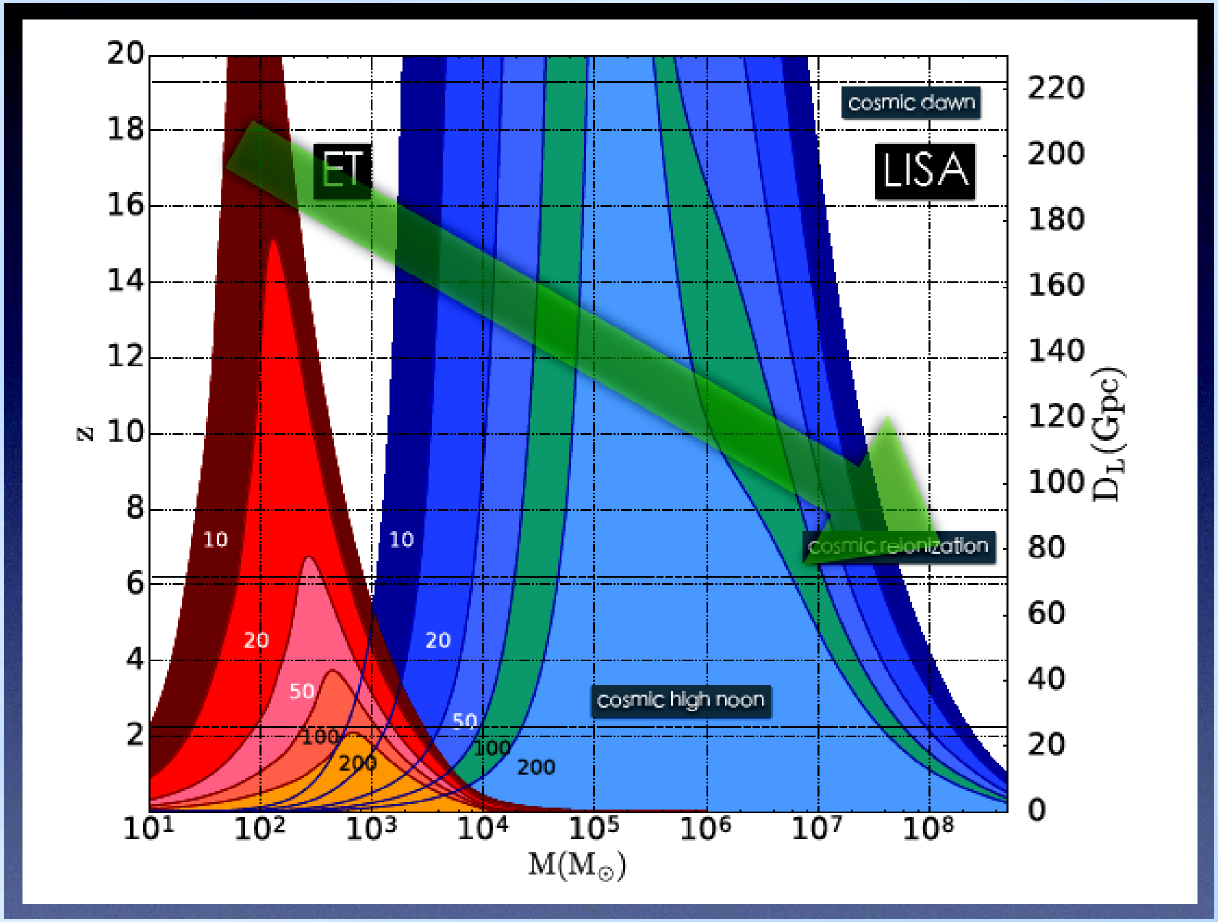
3G Science - Compact Binaries



Credit: Evan Hall

What is the mass and spin distribution of compact objects through cosmic time?

3G Science - Seed black holes

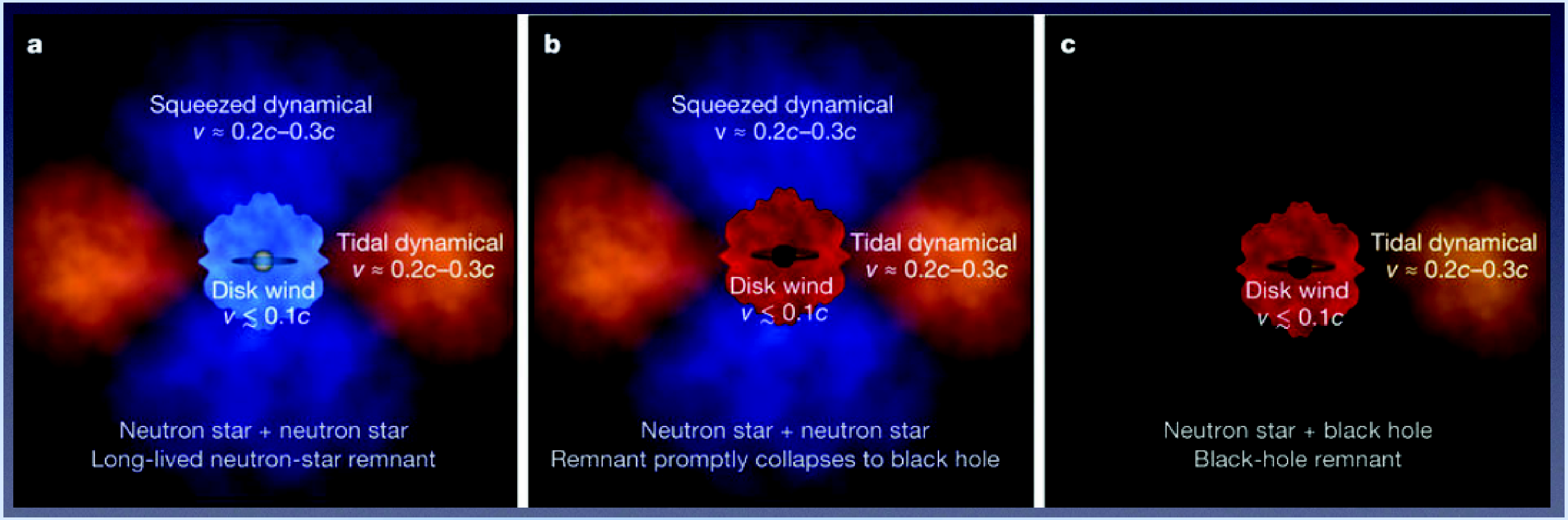


Credit:
Monica Colpi

When and where do the first binary seeds form?

How fast do seed BHs grow hand-in-hand with the growth of cosmic structures?

3G Science - Multi-messenger observations



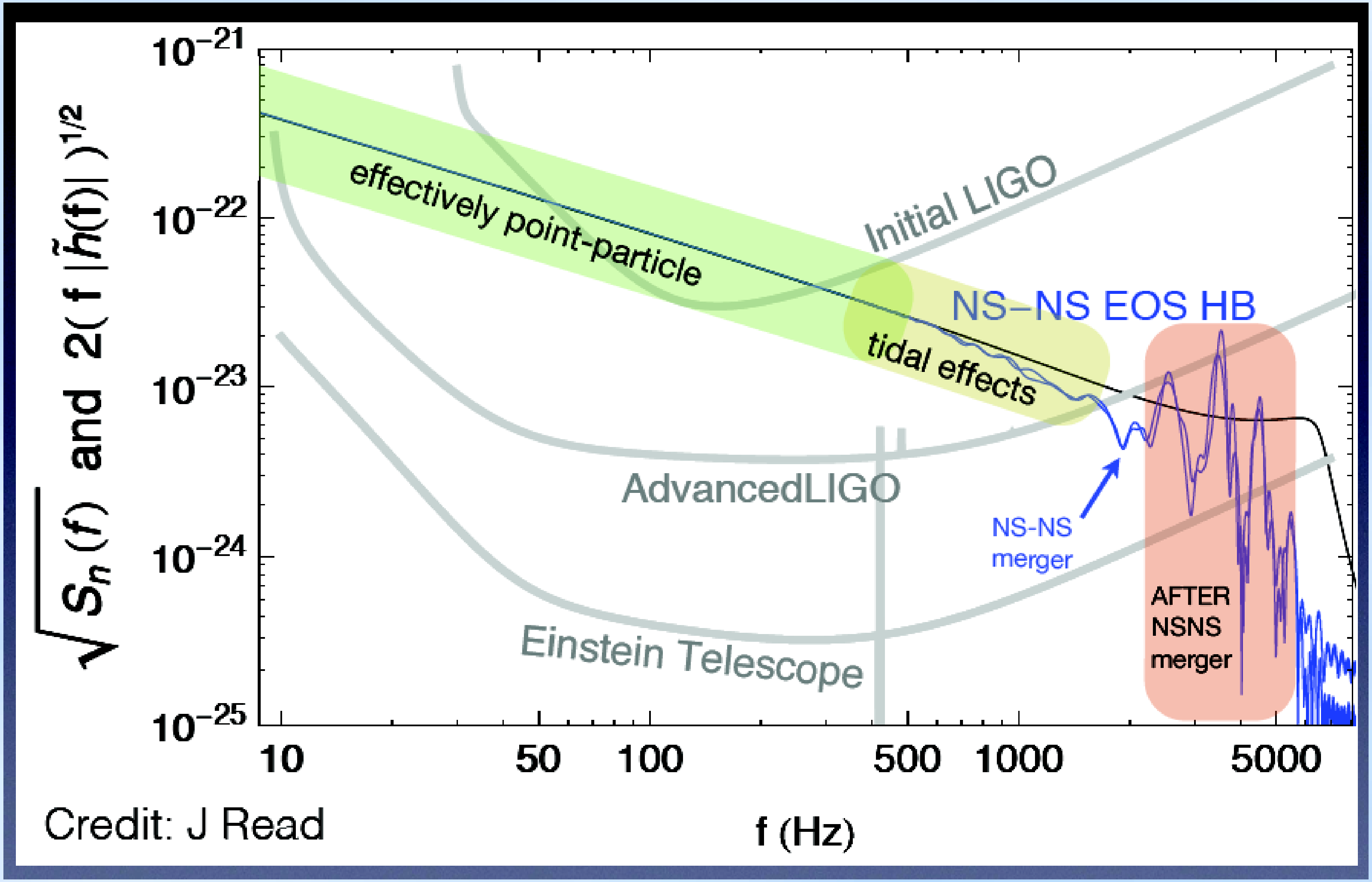
Kasen et al 2017

- What is the contribution of NS-NS and/or NS-BH mergers to r-process elemental production?

- How does this vary with redshift?

- Where in the galaxies do these mergers occur and what does the location tell us?

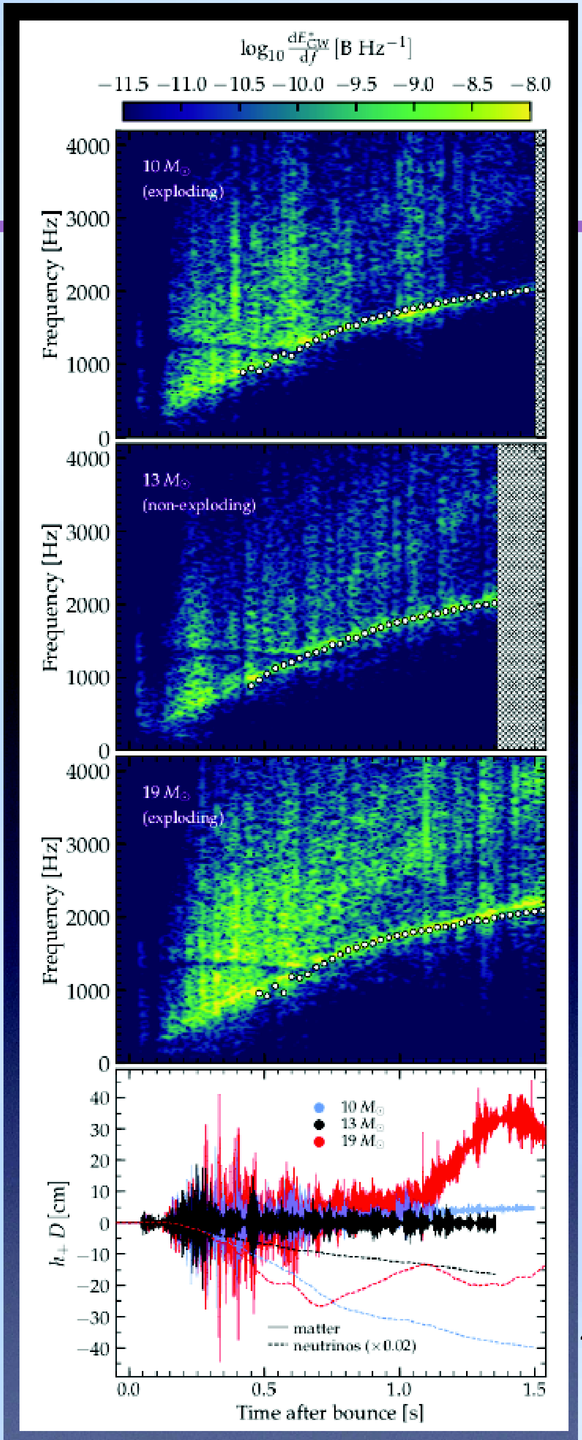
3G Science – Neutron Stars



Neutron star structure from observation of binaries, and continuous waves.

3G Science - Supernovae

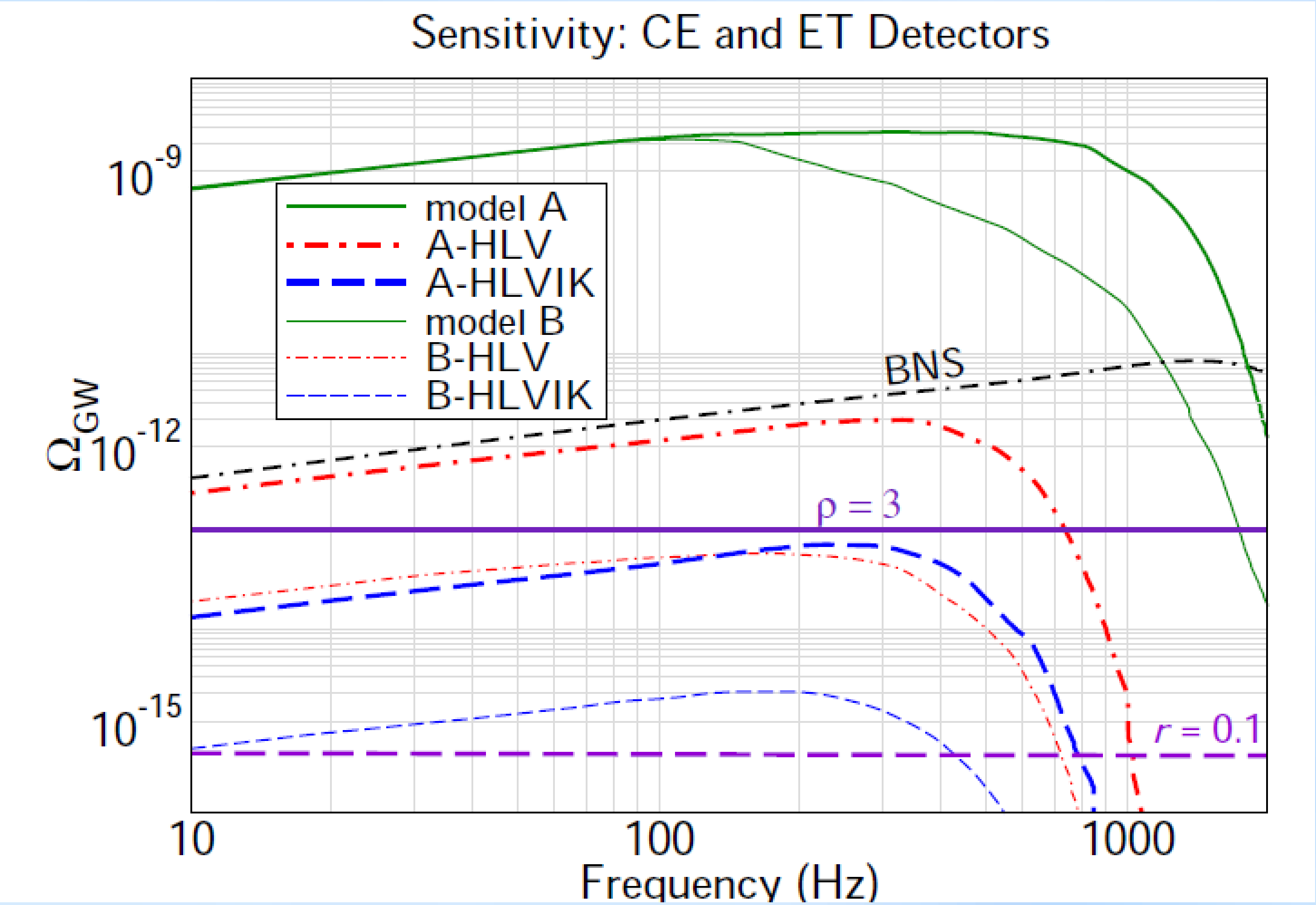
- Can we distinguish the various phases of the supernova explosion?
- Can we determine the nuclear equation of state?
- Can we determine the progenitor mass?



Morozova et al 2018

Third Generation Gravitational Wave Detectors

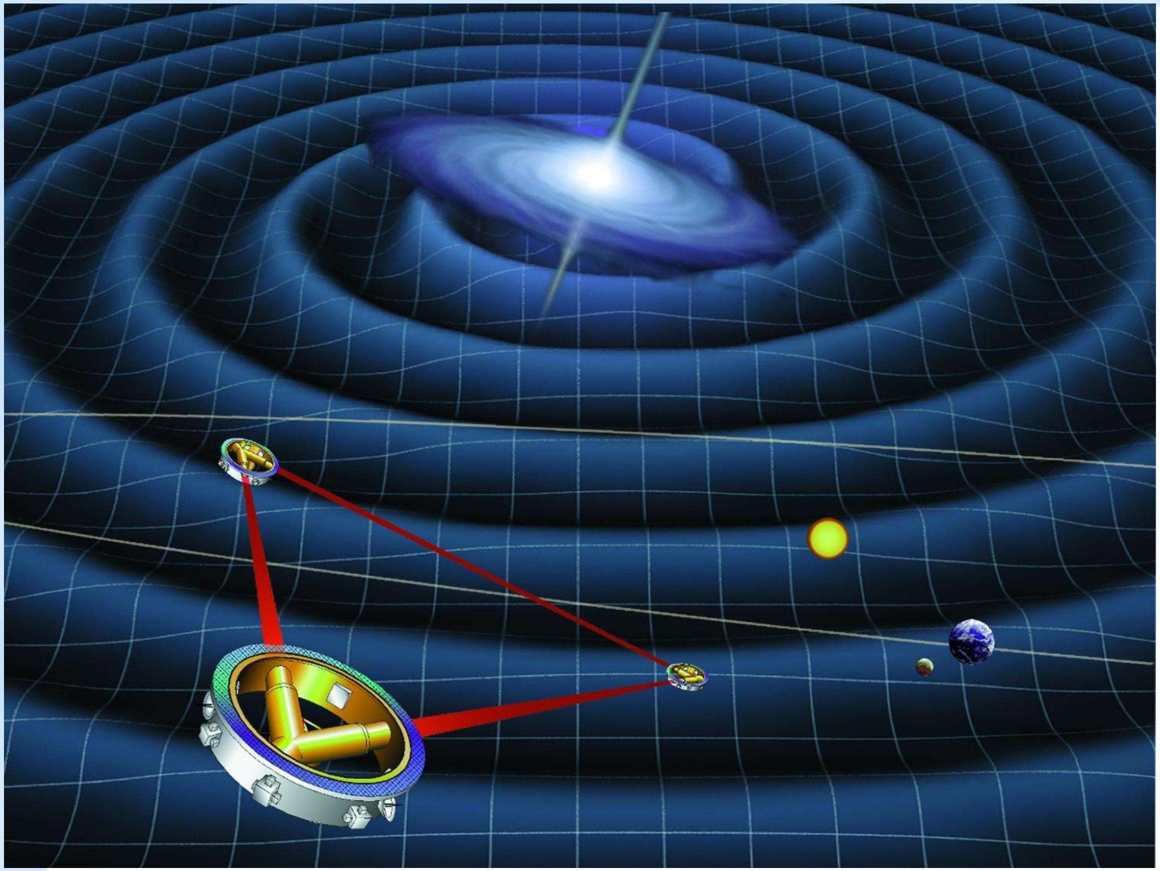
With Einstein Telescope (European) or Cosmic Explorer (US) almost every stellar mass binary black hole merger in the observable universe will be detectable.



BBH confusion background can potentially be subtracted to observe the primordial background at the level of $\Omega_{GW} \sim 10^{-13}$ after five years of observation.

Regimbau et al 2017

Laser Interferometer Space Antenna - LISA



ESA – All Systems GO!

NASA coming back

LIGO GW events and Lisa Pathfinder success have helped significantly

Tremendous activity at present

Planned launch 2034

Earlier launch? 2030?

4 year mission → 10 years?

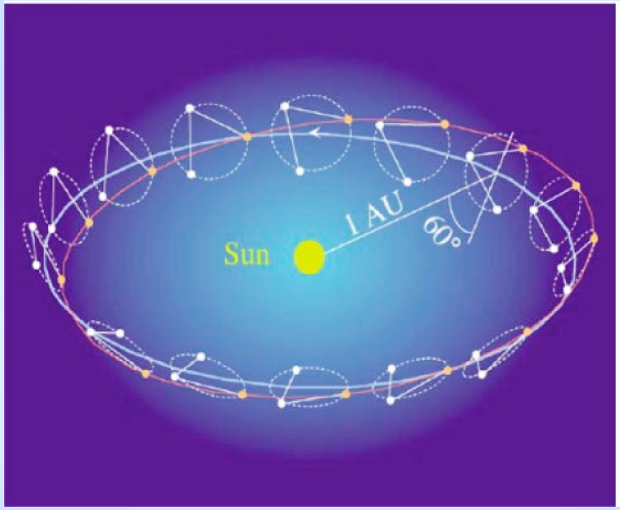
Present plan: 3 Interferometers
2.5 x 10^6 km arm lengths

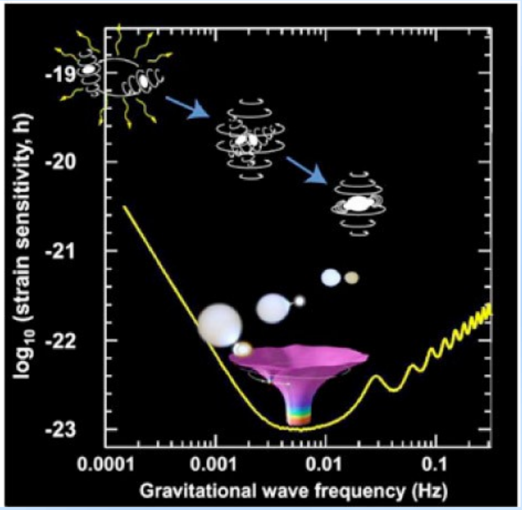
Talk by Antoine Petiteau, Space detectors: LISA

LISA physics

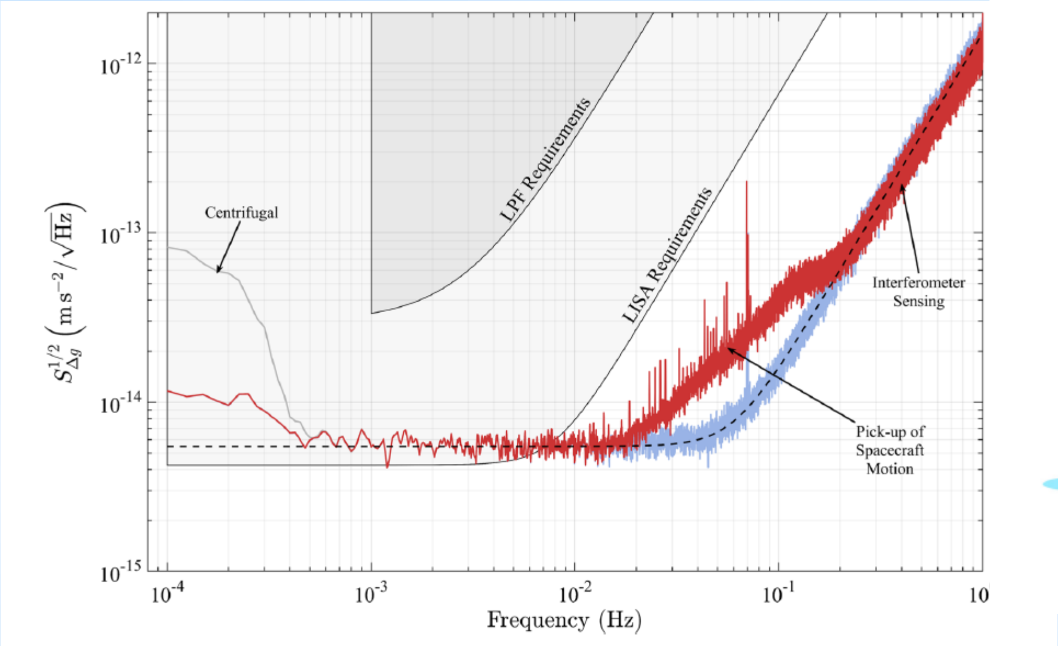
- the nature of gravity
- the fundamental nature of black holes
- black holes as sources of energy
- nonlinear structure formation
- dynamics of galactic nuclei
- formation and evolution of stellar binary systems
- the very early universe
- cosmography (specifically, the cosmic distance scale)

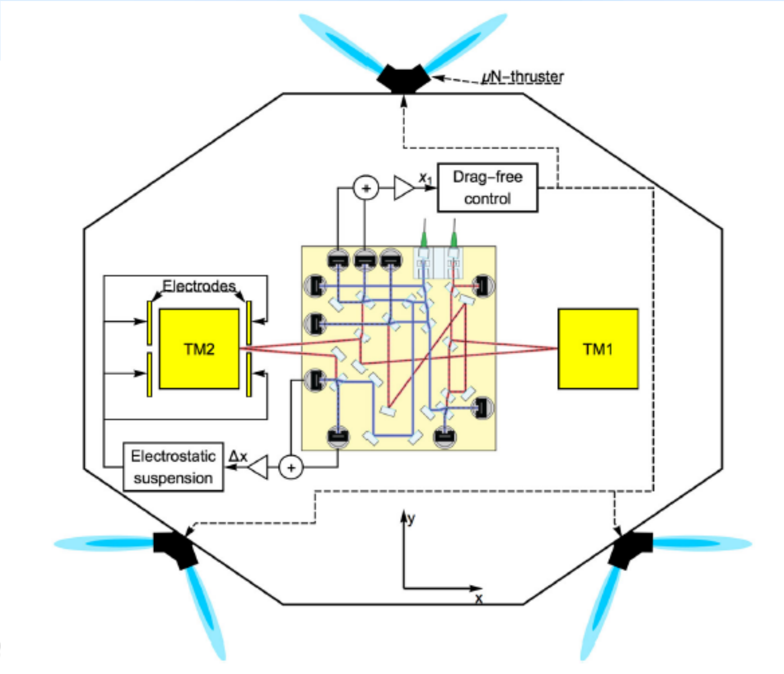
Gravitational Observatory Advisory Team – GOAT (ESA web site)





LISA Pathfinder – Demonstrating LISA Technology



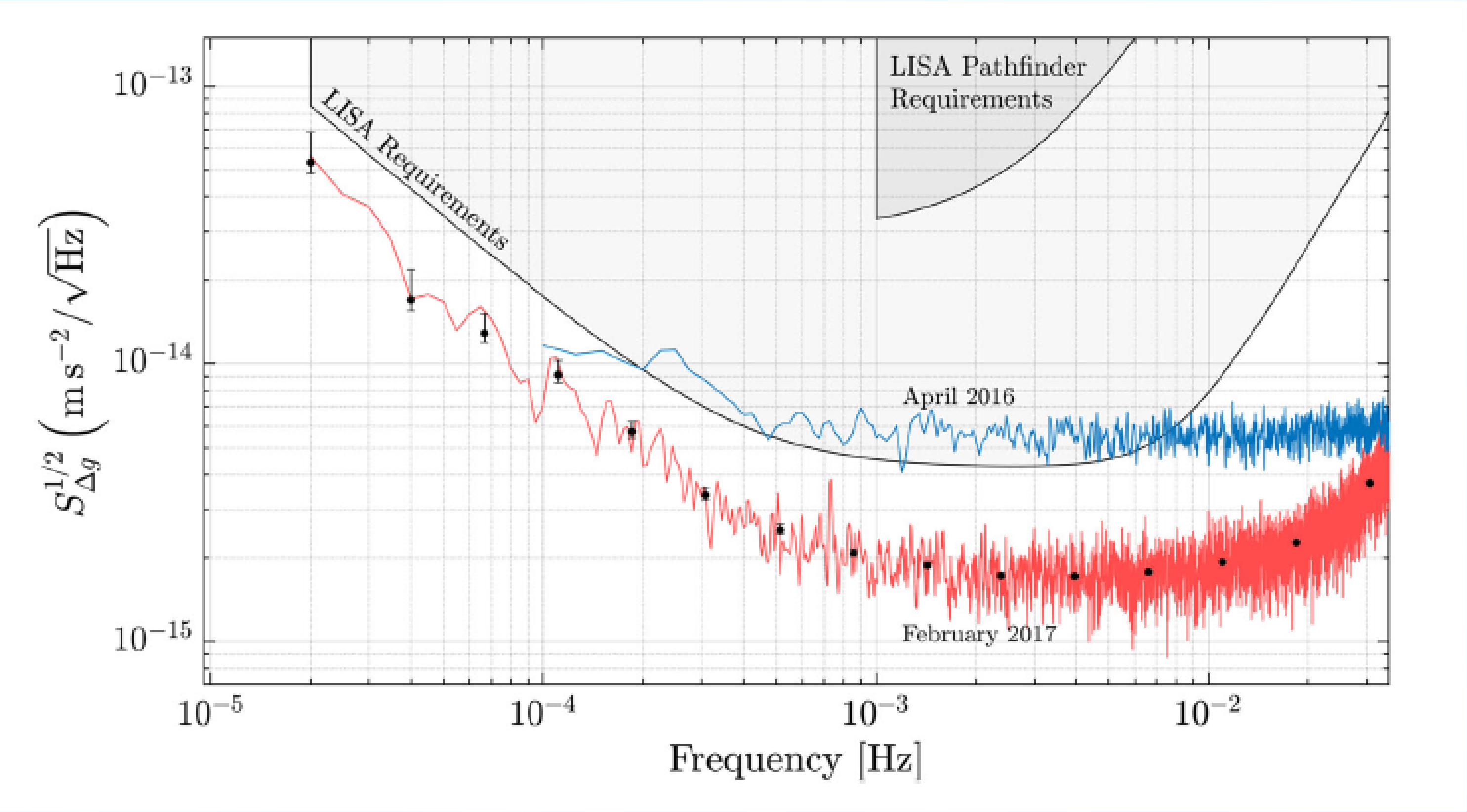


LISA Pathfinder worked! Exceeded requirements. Still, operation was not perfect, and there is lots of experimental work to do before LISA.

A set of cold gas micro-newton thrusters to ensure the spacecraft follows TM1. A second control loop forces TM2 to stay at a fixed distance from TM1 and thus centered in its own electrode housing.

PRL **116**, 231101 (2016)

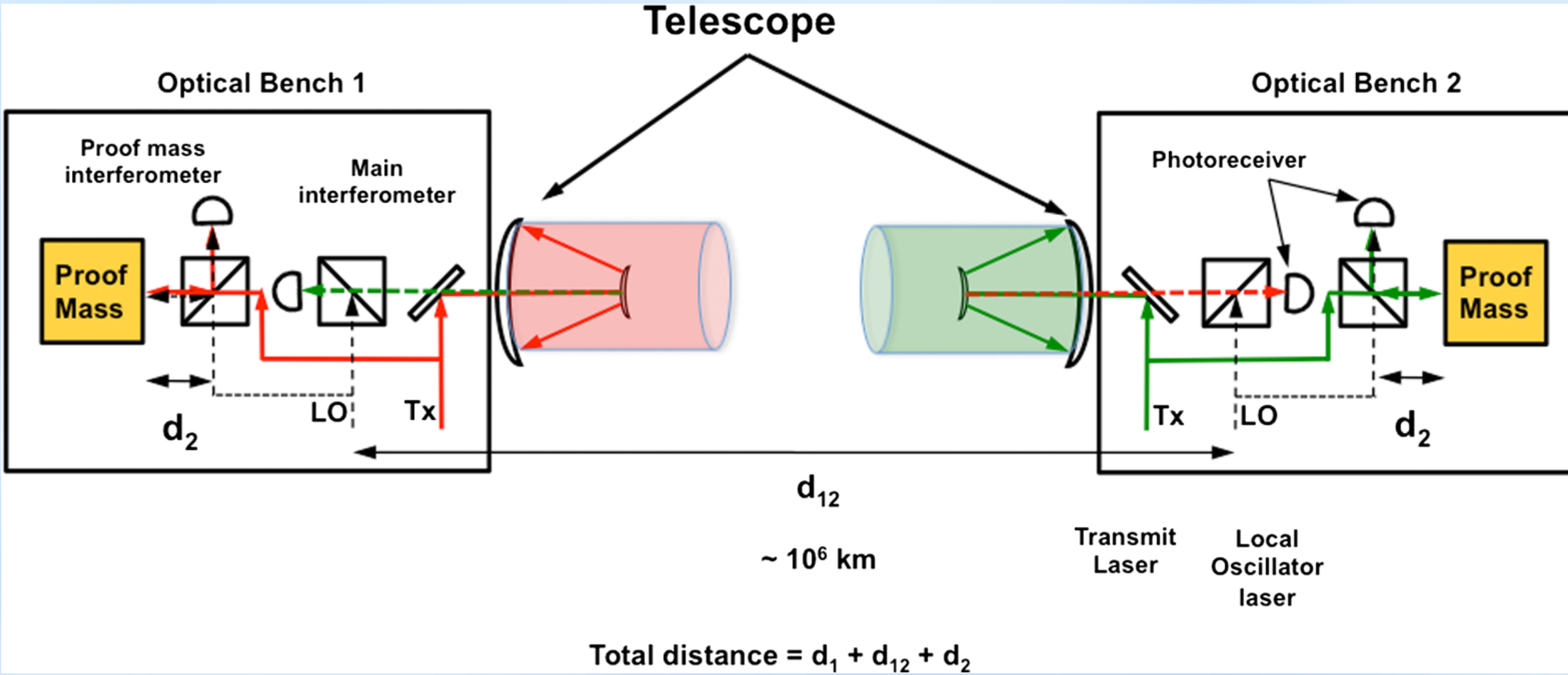
LISA Pathfinder – Demonstrating LISA Technology



The noise performance of LISA Pathfinder has improved because of reduced Brownian noise due to the continued decrease in pressure around the test masses, from a better correction of noninertial effects, and from a better calibration of the electrostatic force actuation.

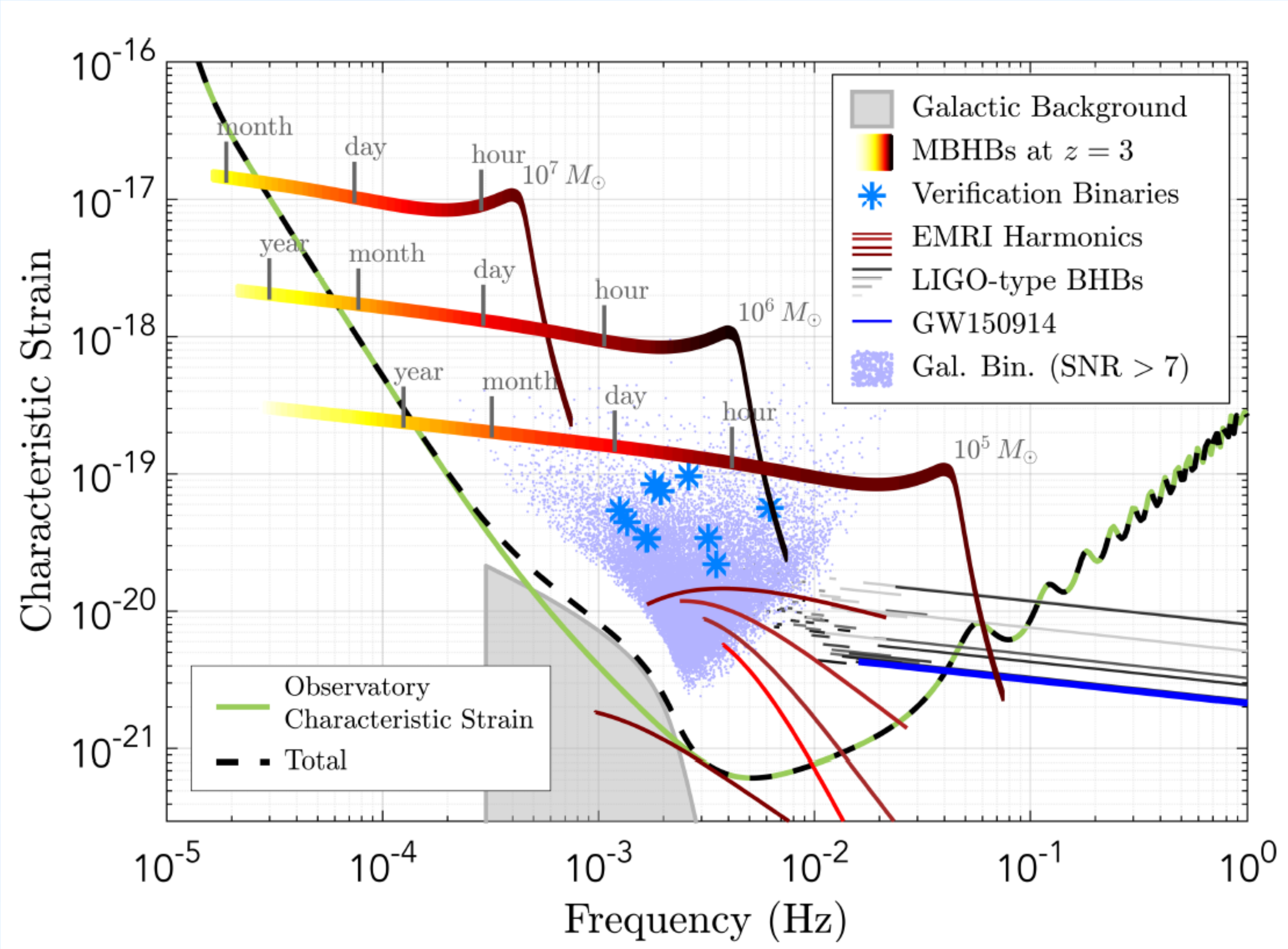
PRL **120**, 061101 (2018)

LISA Proof Masses, Optical Bench, Interferometry and Telescopes



Livas et al, Opt. Eng. 52(9), 091811 (2013)

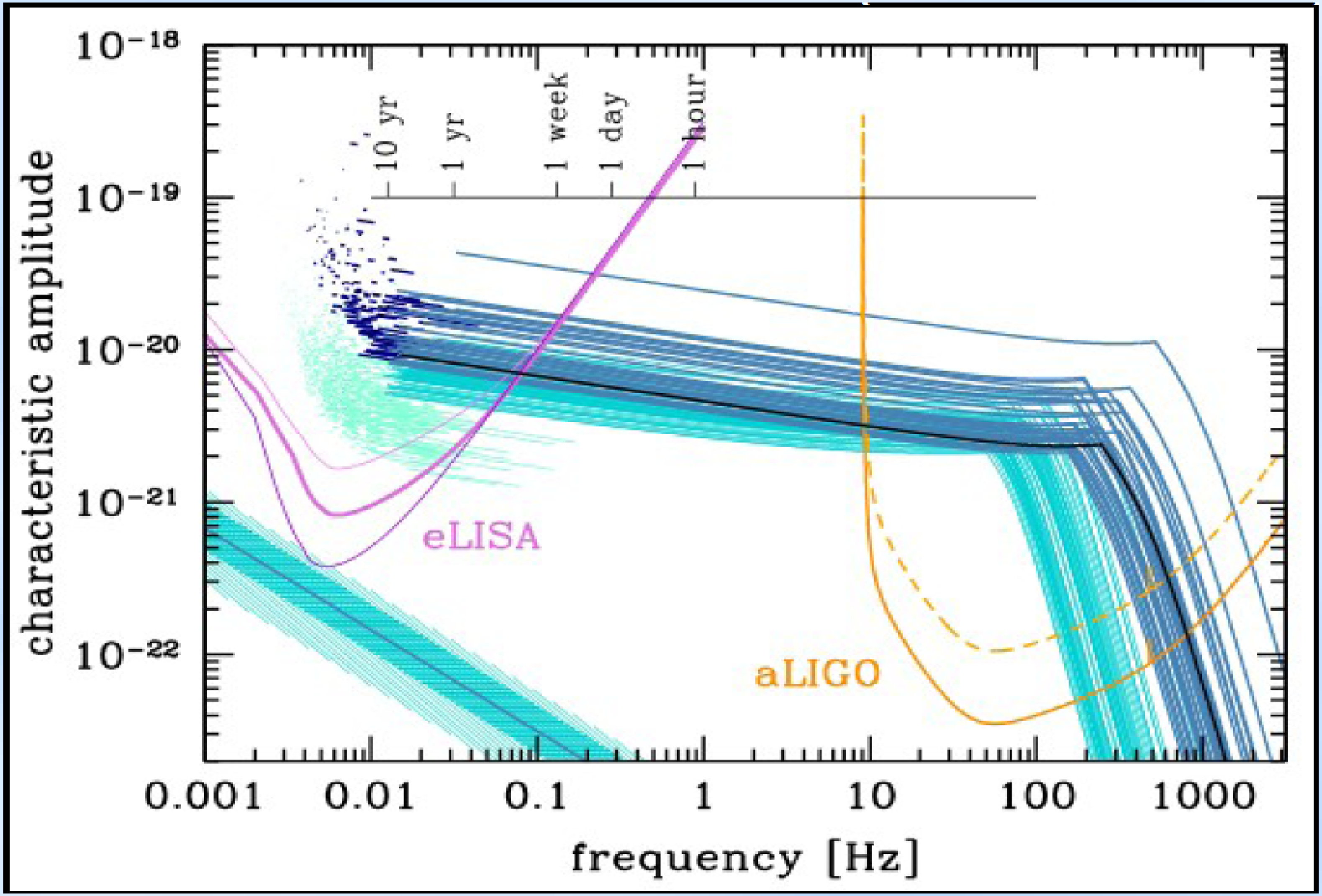
LISA Physics



1702.00786

Characteristic strain amplitude versus frequency (arm length 2.5 x 10^6 km, 1-yr observations).

LISA Physics

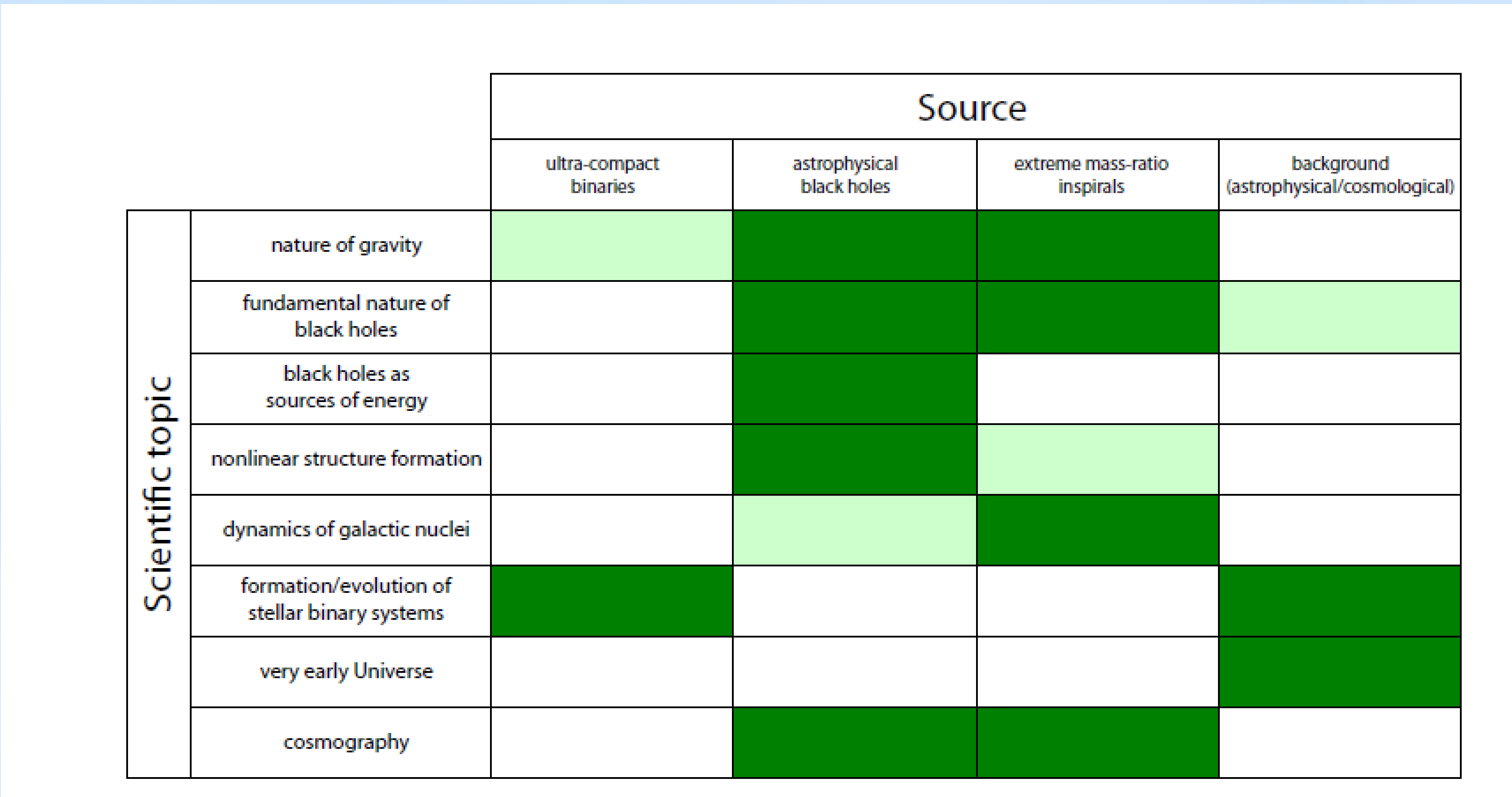


Gravitational wave signals from a heavy stellar black hole binaries. BBH systems can be observed by both LISA and Advanced LIGO – Advanced Virgo.

LISA GOAT, A. Sesana

Testing the Early Universe

- Inflation
- Electro-weak phase transition, or phase transitions related to new physics
- Cosmic strings (phase transitions, topological defects, cosmic superstrings)



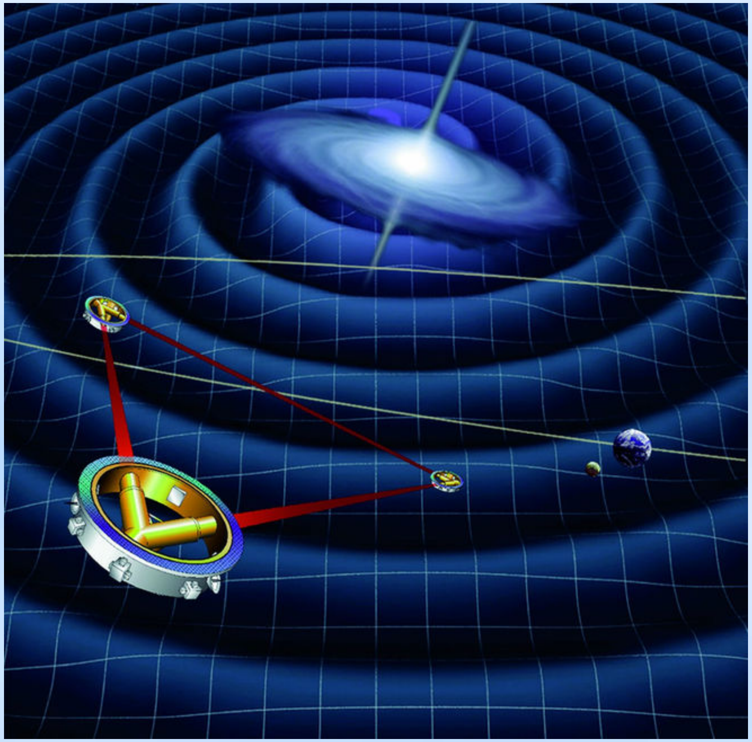
LISA – France

- France has the responsibility for ...
- LISA Data Procession Center
- Assembly, Integration, Verification, Testing (AIVT)
- Exciting work ahead!!!!

APC
ARTEMIS/OCA
CEA/DSM/IPhT
CEA/IRFU/DAp
CEA/IRFU/DEDIP
CEA/IRFU/DIS
CEA/IRFU/DPhN
CEA/IRFU/DPhP
CNES
CPPM
IAP
LAM
LMA
LPC Caen
LPC2E
LUTh/OBSPM
ONERA
SYRTE/OBSPM
Institut Fresnel

https://signup.lisamission.org/

LISA Summary



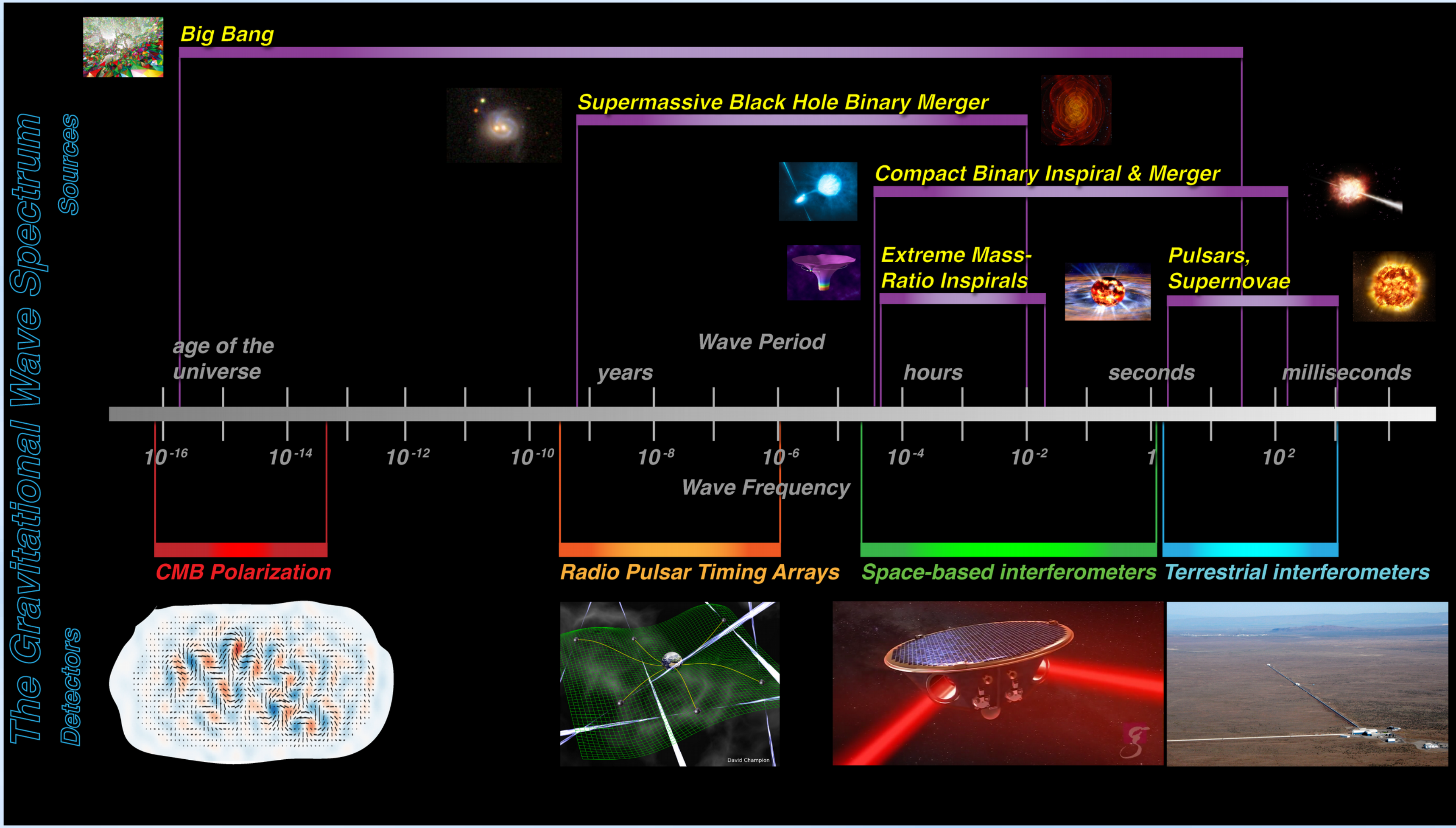
The LISA project is presently moving forward rapidly.

ESA and NASA see this as a high priority.

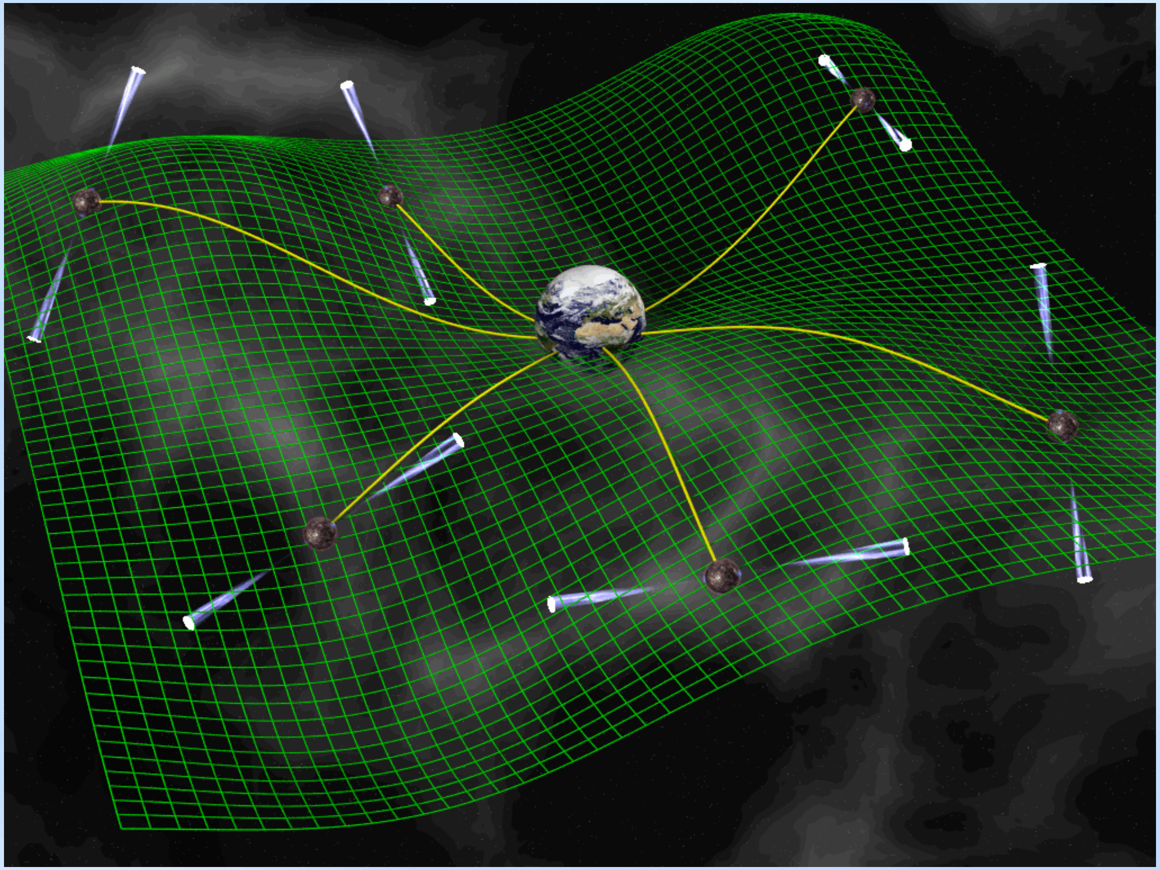
A tremendous amount of R&D still needs to be done for LISA, and there is much experimental activity.

After the LHC, LISA may offer the best opportunity to observe the high energy physics that describes the universe.

Gravitational Wave Spectrum



Pulsar Timing



arXiv:1211.4590

Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

Numerous collaborations around the world. Interesting upper limits and likely detections in the near future.
Talk by Antoine Petiteau, Detecting gravitational waves with pulsars: PTA

Pulsar Timing

EPTA
The Radio Telescope Effelsberg in Germany
The Lovell Telescope in the UK,
The Nancay Decimetric Radio Telescope in France
The Sardinia Radio Telescope in Italy
The 14-dish Westerbork Synthesis Radio Telescope in the Netherlands.

A ~ 3 x 10^{-15} 10^{-7} to 10^{-9} Hz over 18 years

THE WESTERBORK SYNTHESIS RADIO TELESCOPE in the Netherlands brings 14 dishes, each 25 m in diameter, to the European Pulsar Timing Array project. Together, they have an effective diameter of 94 m.

NANOgrav, EPTA, IPTA.

Square Kilometer Arrary – France is Back

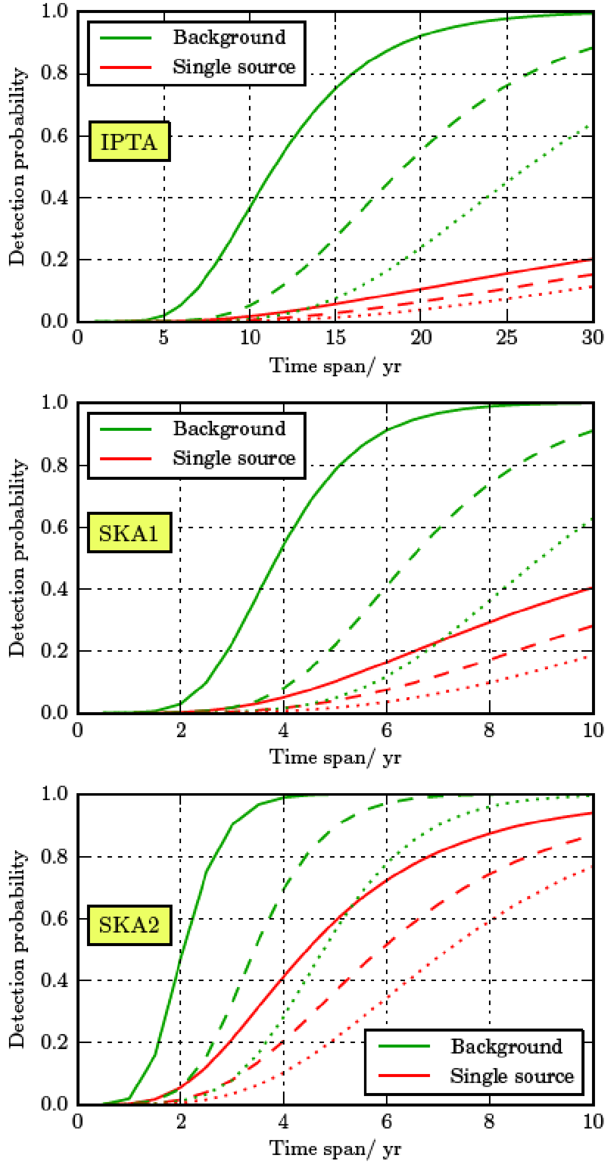


Figure 2. Detection probability (averaged over all realisations of the ensemble of SBHBs) versus observing time of a GWB (green lines) and a single source (red lines) assuming the IPTA (upper panel) SKA1 (middle panel) and SKA2 (lower panel). Solid lines show DPs integrated over all the frequency range $[T^{-1}, \Delta t^{-1}]$, whereas the dashed (dotted) lines show the result when the lowest frequency bin (two lowest bins) are removed from the calculation.

Pulsar Timing

Expected GW Signals

Detections are very likely.

Super-massive black hole binaries

Cosmic strings

GW periods of years

Rosado, Sesana & Gair 2015

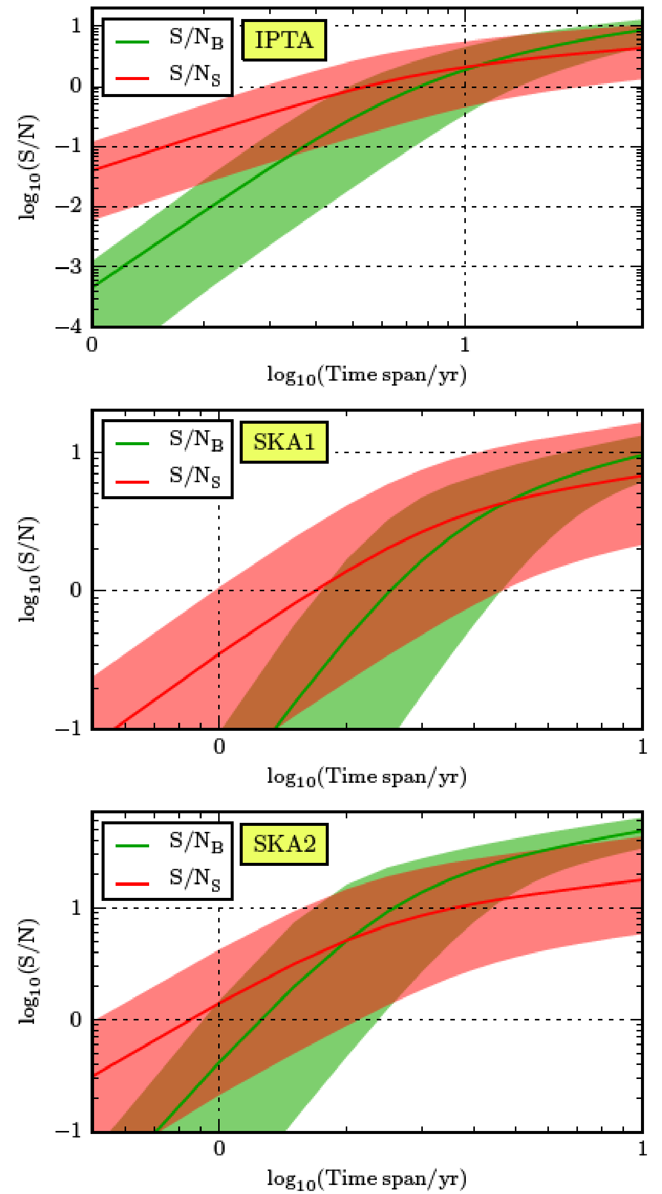
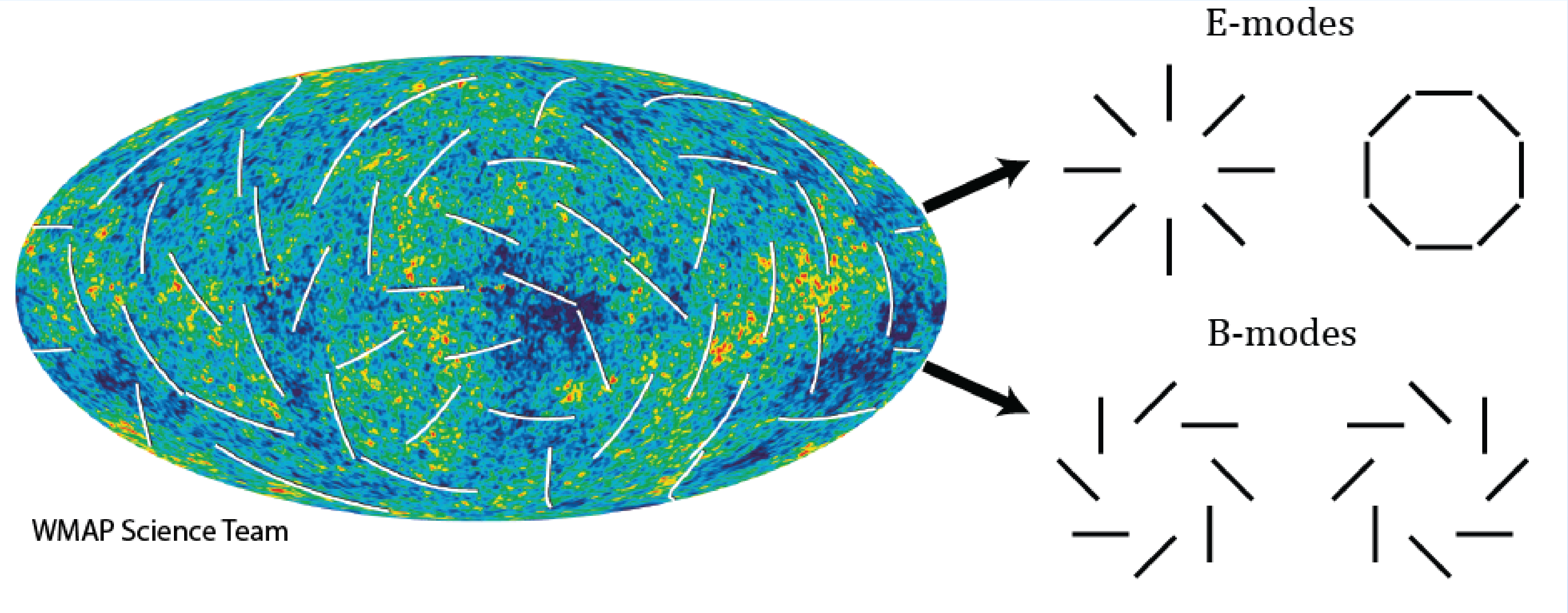


Figure 4. S/N versus observation time, for an IPTA (top), SKA1 (central), and SKA2 (bottom). The red area covers the values between the 5th and 95th percentiles of S/N_S of all realisations; the red line is the average over realisations. The green area covers values between the 5th and 95th percentiles of S/N_B, and the green line is the average.

Polarization Map of the Cosmic Microwave Background

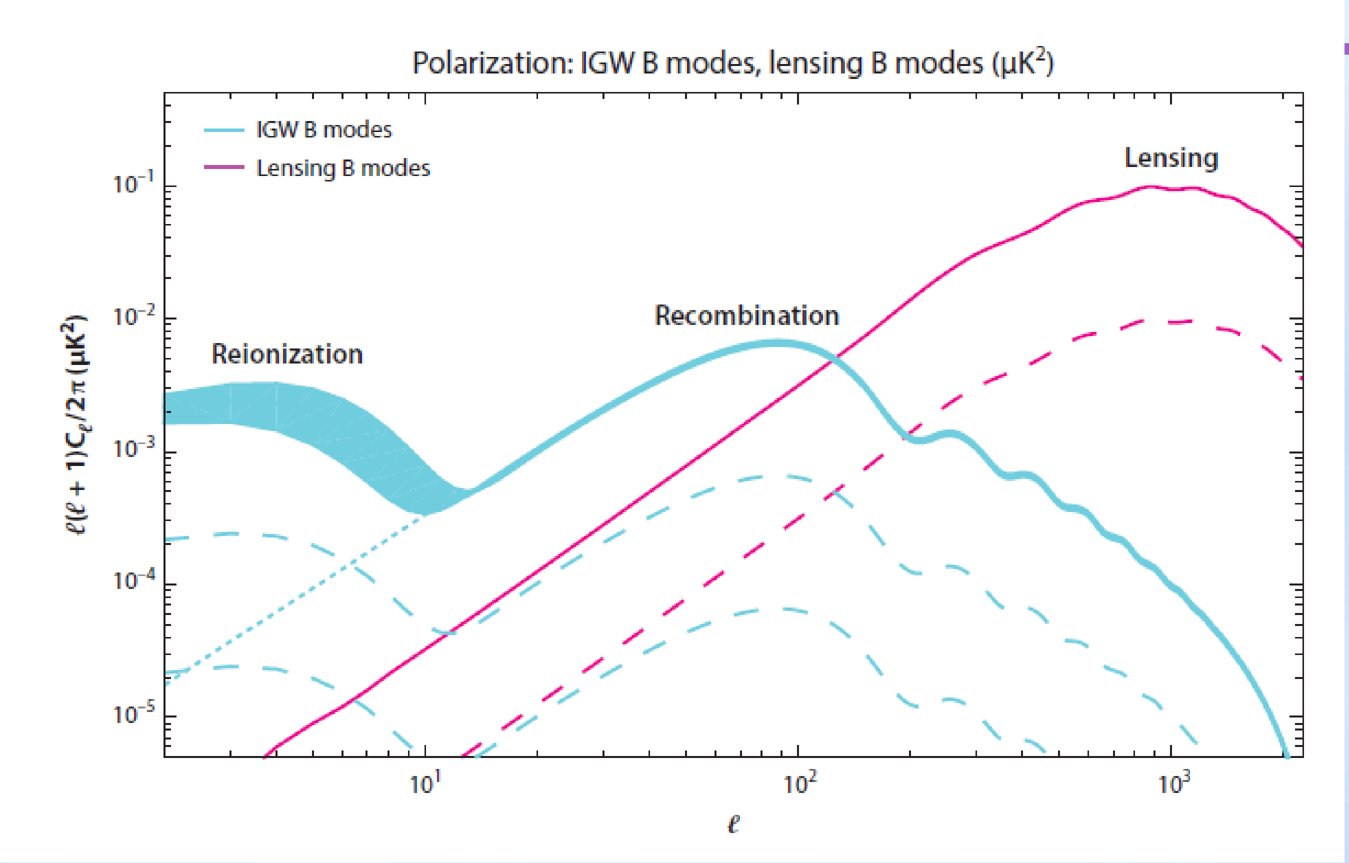


The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence-free odd-parity B-modes.

Gravitational waves in the early universe imparts a “curl” on CMB polarization.
ArXiv:1407.2584

BICEP2, KECK Array, Planck

Polarization Map of the Cosmic Microwave Background



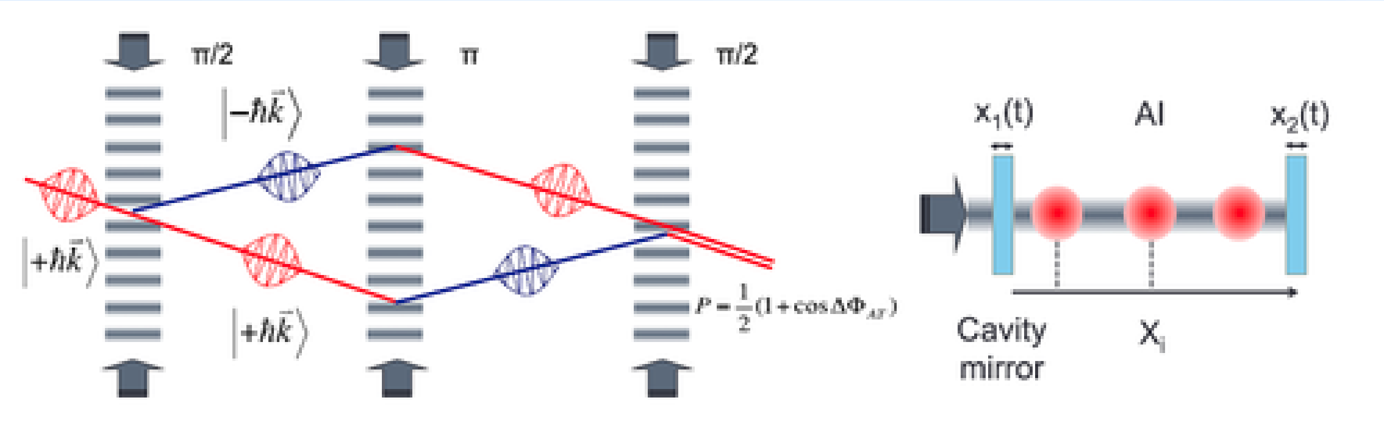
The GW amplitude is often reported as a tensor-to-scalar ratio,

$$r \equiv \frac{\Delta_h^2}{\Delta_{\mathcal{R}}^2} = 16\epsilon \simeq 0.1 \left[\frac{V}{(2 \times 10^{16}\,\mathrm{GeV})^4} \right], \tag{16}$$

where the measured value of $\Delta_{\mathcal{R}}^2$ was used in the last step. The current bound $r \lesssim 0.1$ (Ade et al. 2015a,d) thus provides a slightly stronger constraint on the energy density than the bound from measurement of the scalar amplitude.

M. Kamionkowski and E.D. Kovetz, 2016

Atom Interferometers

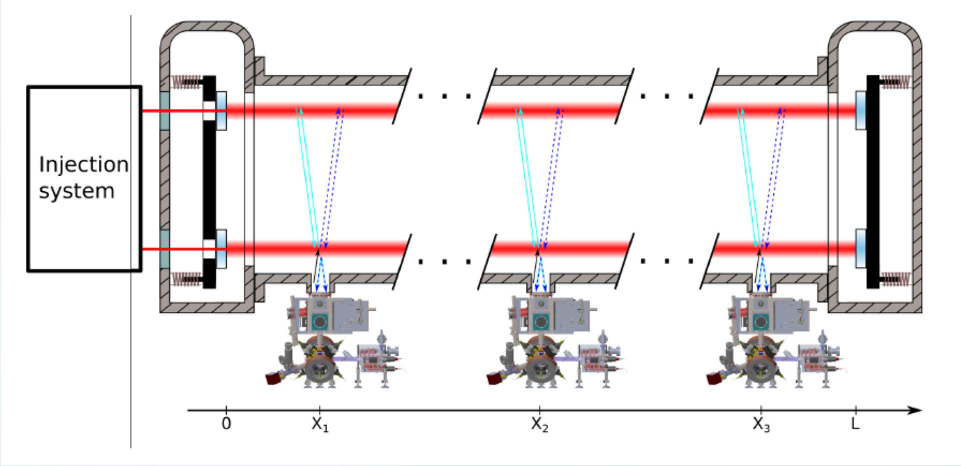


Use a long optical cavity to interrogate atom interferometers.

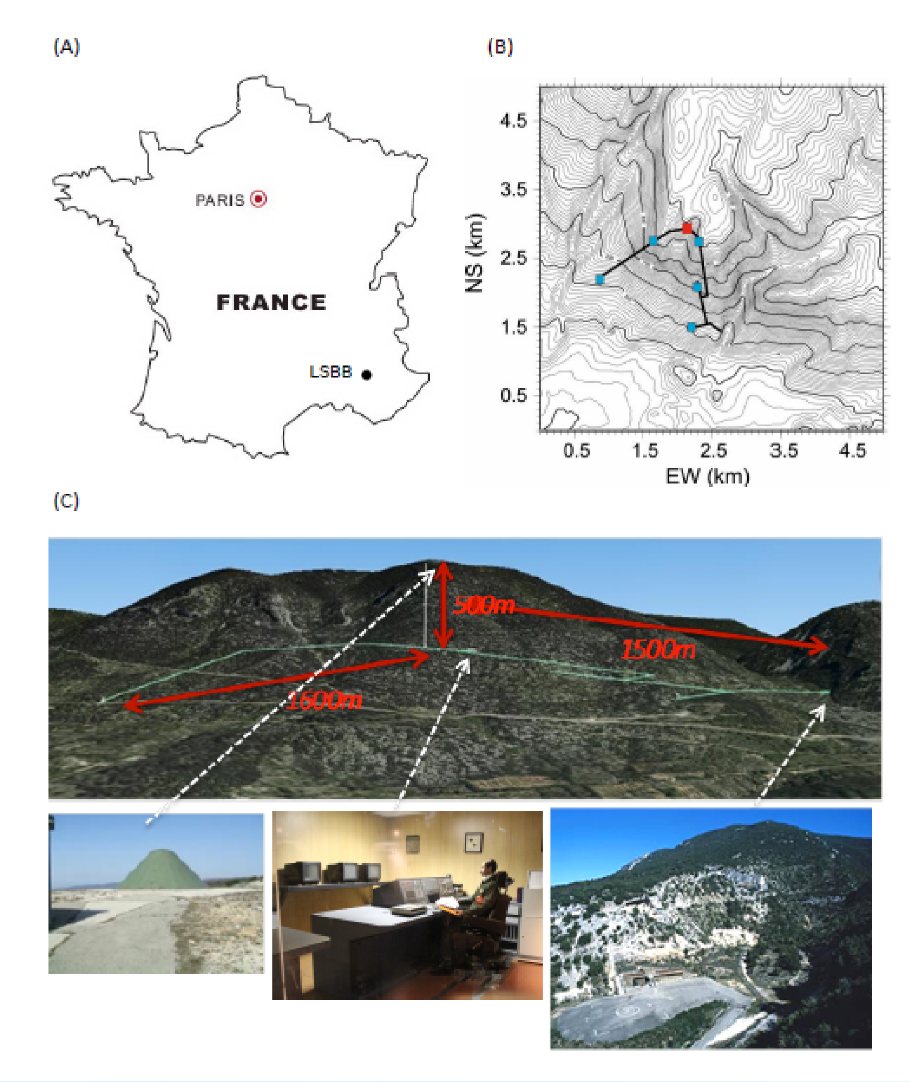
It may be possible to use this method to build a gravitational wave detector in the 0.1 Hz – 10 Hz band, between LISA and LIGO-Virgo.

Arxiv 1505:07137

MIGA: Matter Wave laser Interferometric Gravitation Antenna



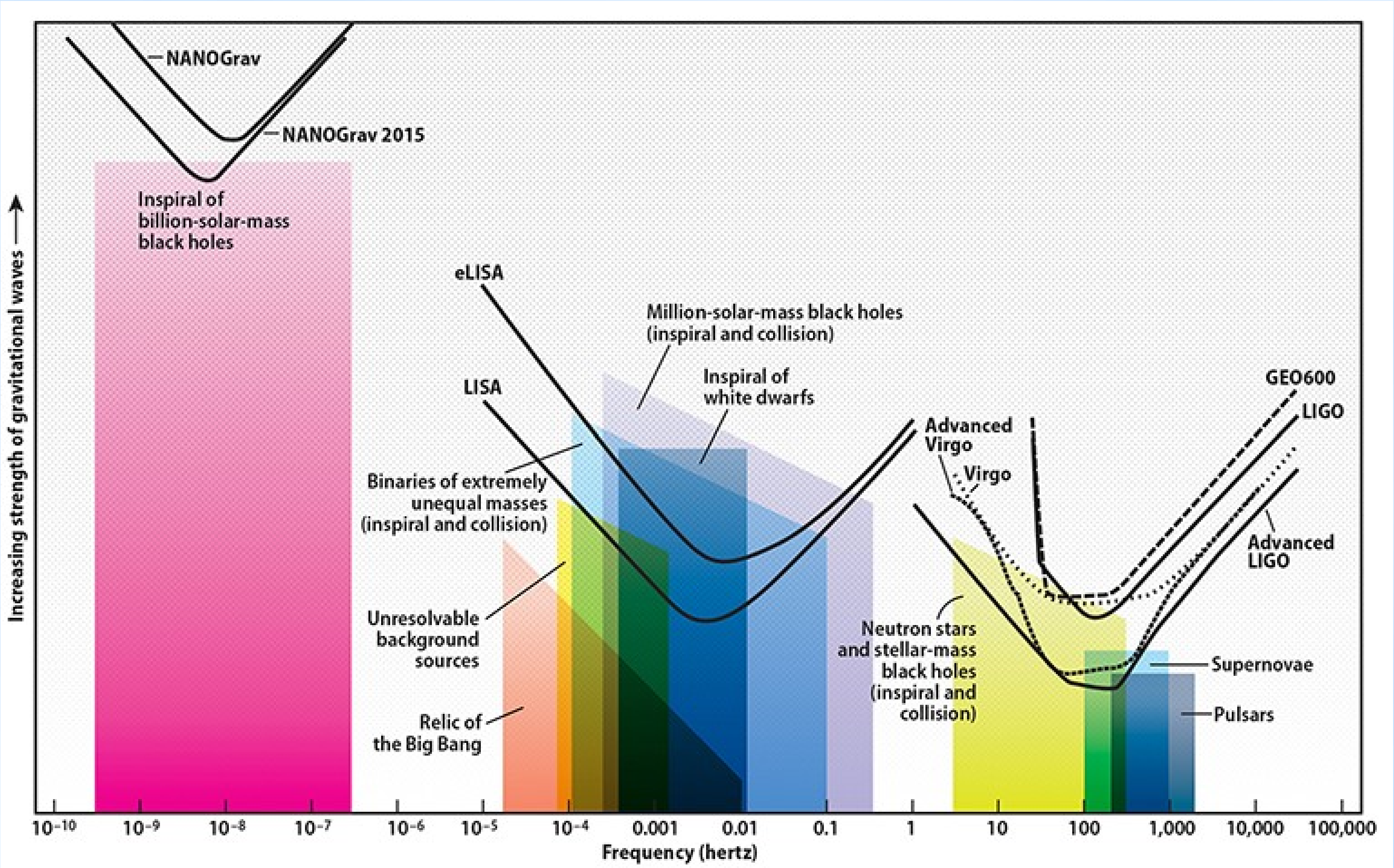
200 m arms



a peak strain sensitivity of $2{\cdot}10^{-13}/\sqrt{\mathrm{Hz}}$ at 2 Hz.

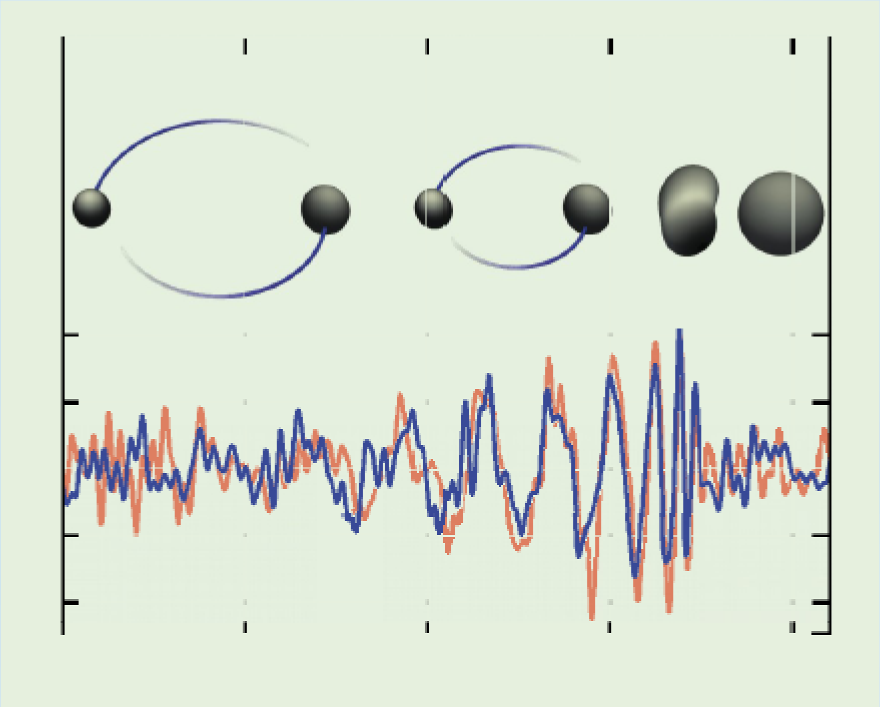
arXiv:1703.02490

Gravitational Wave Spectrum



Atom interferometric detectors would fill a critically important region of the GW spectrum. Between LISA and LIGO-Virgo

Conclusion on Gravitational Waves



A new window on the universe has opened.

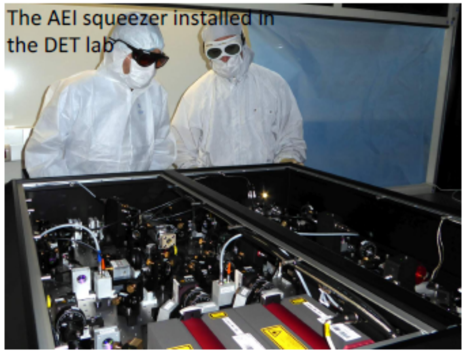
We are just beginning!

Extra Slides

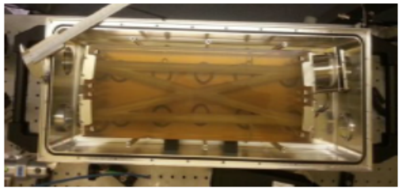
Upgrades for O3 - Virgo

Main upgrades: Nov 2017-Mar 2018

- All test masses suspended with fused silica fibers;
- Will boost the low frequency sensitivity.



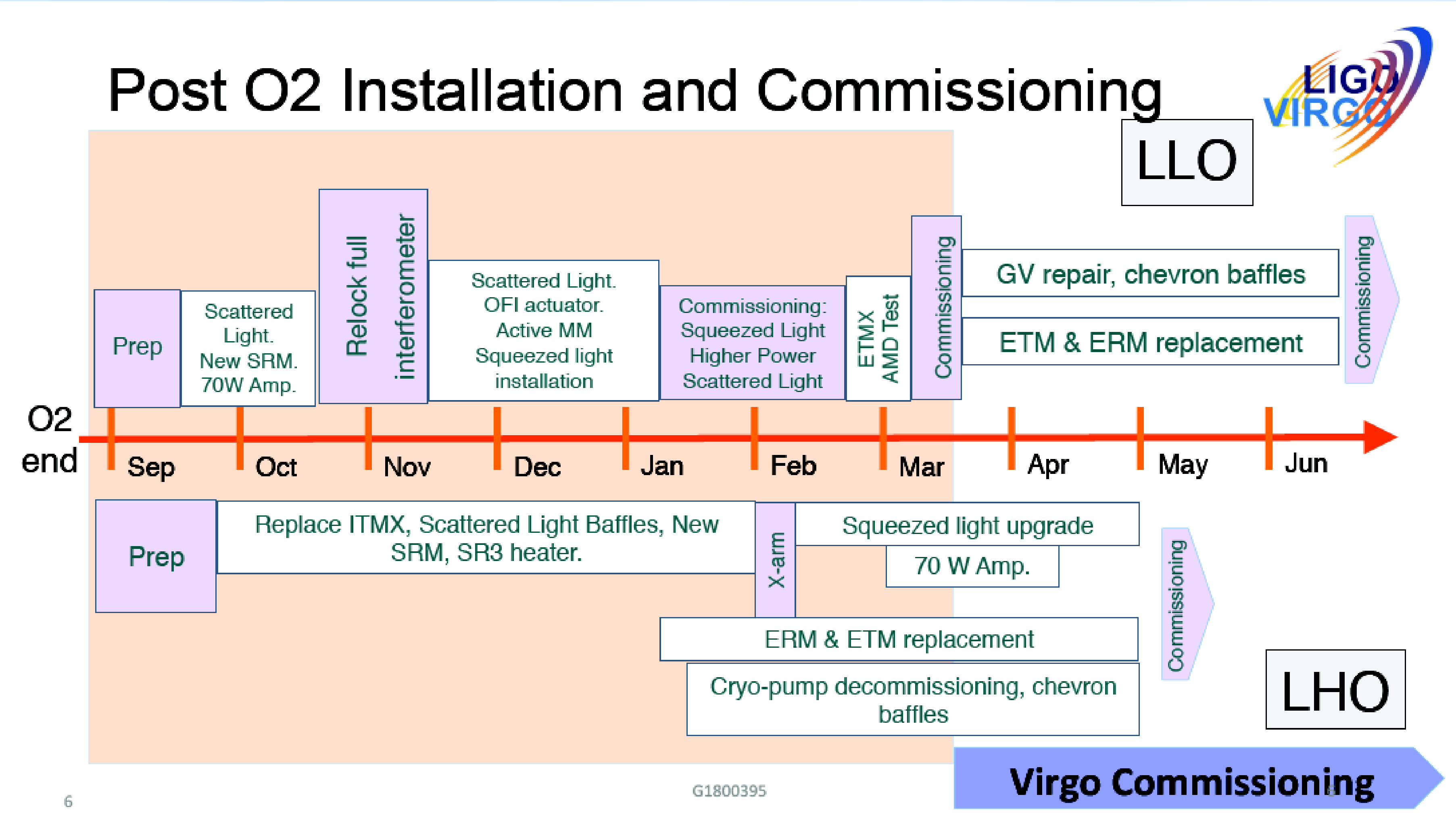
- On-site measured squeezing: around 10 dB;
- Improves high frequency sensitivity.



- New high power laser amplifier: delivers up to 60 W to the ITF;
- New monolithic pre-mode-cleaner.

G1800395 3

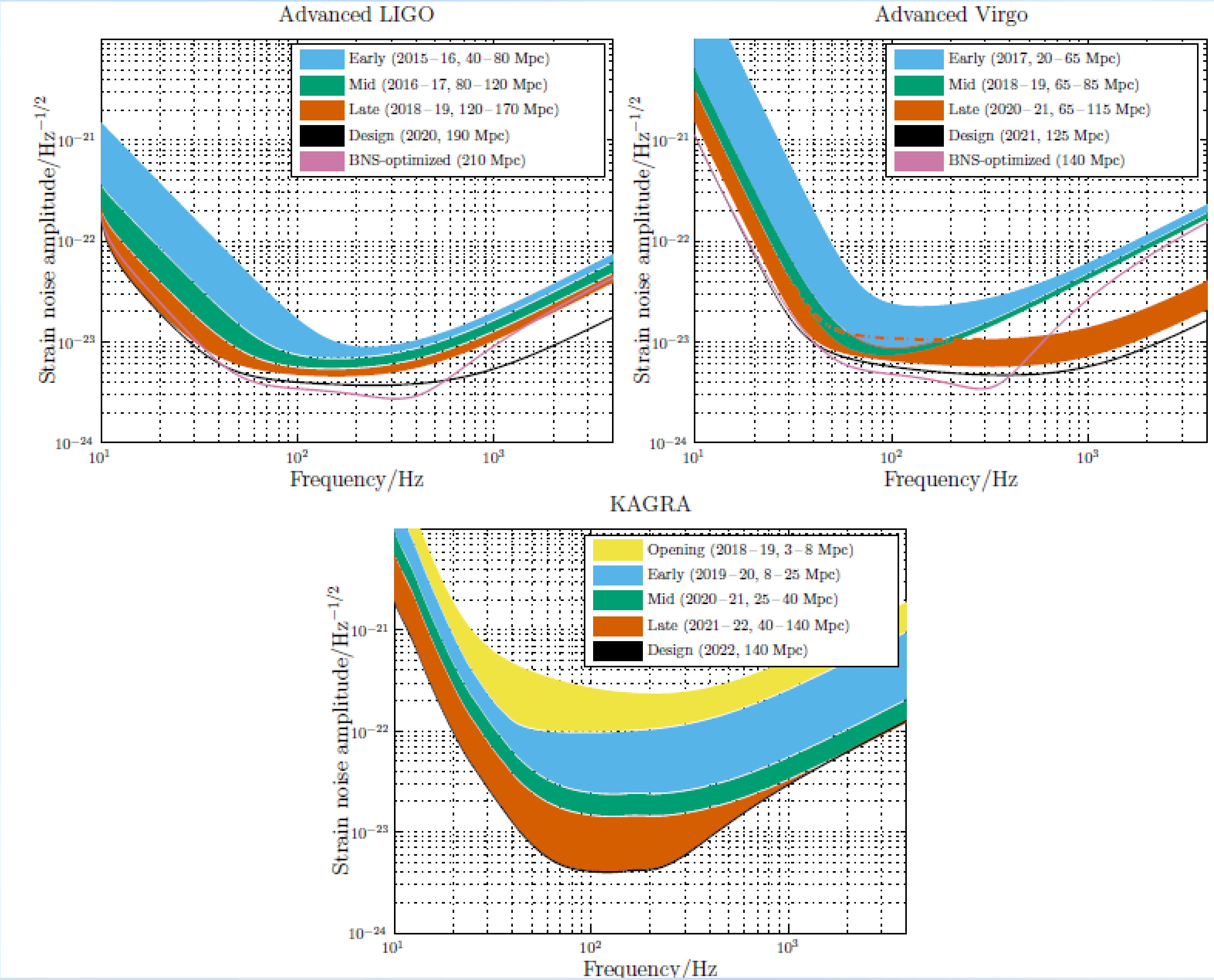
Upgrades for O3 - LIGO



Observing Run O3

- Plan to start at the end of January 2019
- Run will last for one year
- KAGRA may join near the end if they achieve sufficient sensitivity
- Public alerts will be issued
- GW transient triggers below the detection standard that may improve a specific science/source search when analyzed jointly with the EM/neutrino sectors
- Several MOUs with this scope exercised are still in place:
  - High Energy Neutrinos (Antares, Icecube)
  - Gamma-Ray/X-ray transients sources (Fermi-GBM)
  - Core-collapse Supernova low energy neutrinos (Borexino, Icecube, KamLAND, LVD)

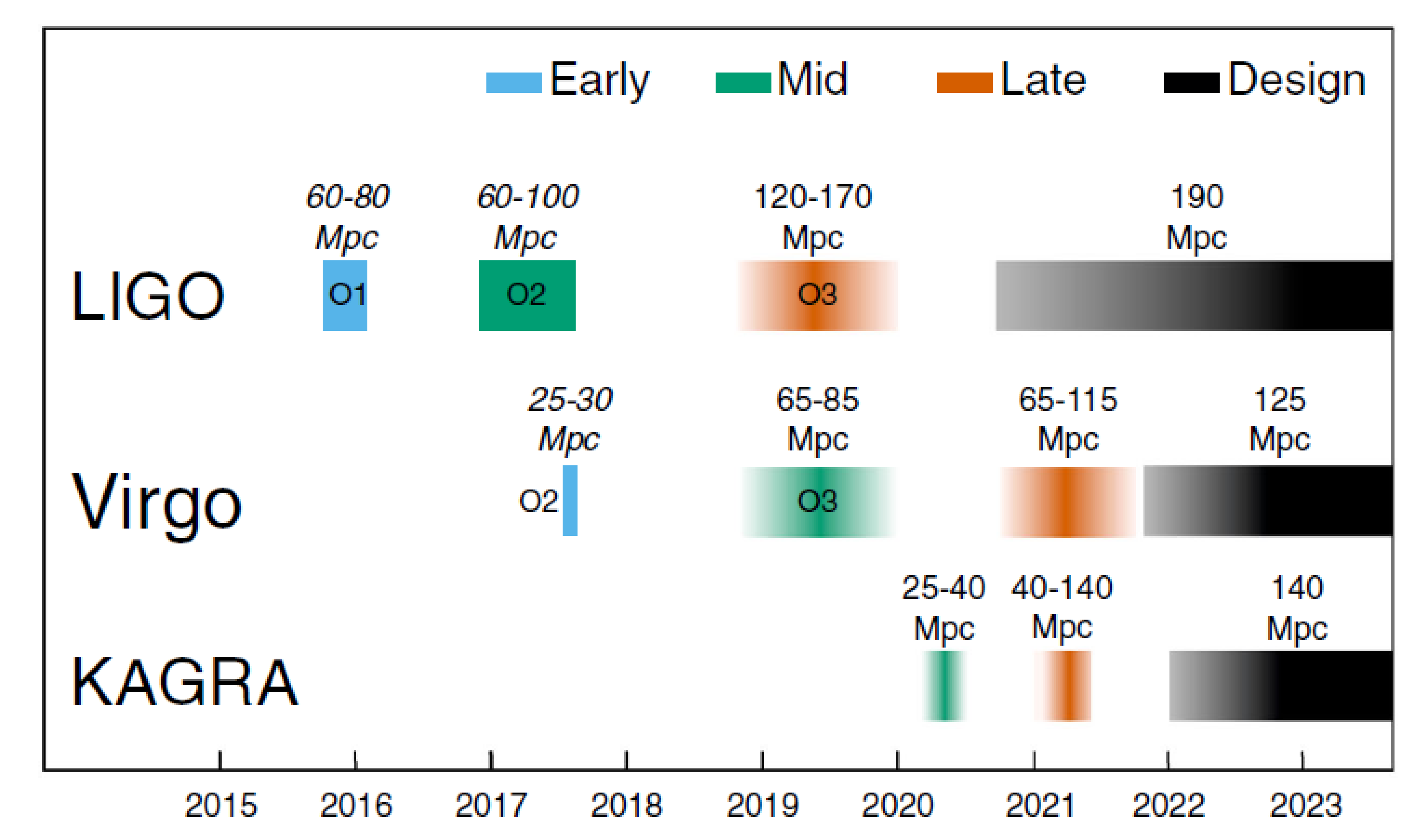
Expected Advanced LIGO-Virgo-KAGRA Sensitivities



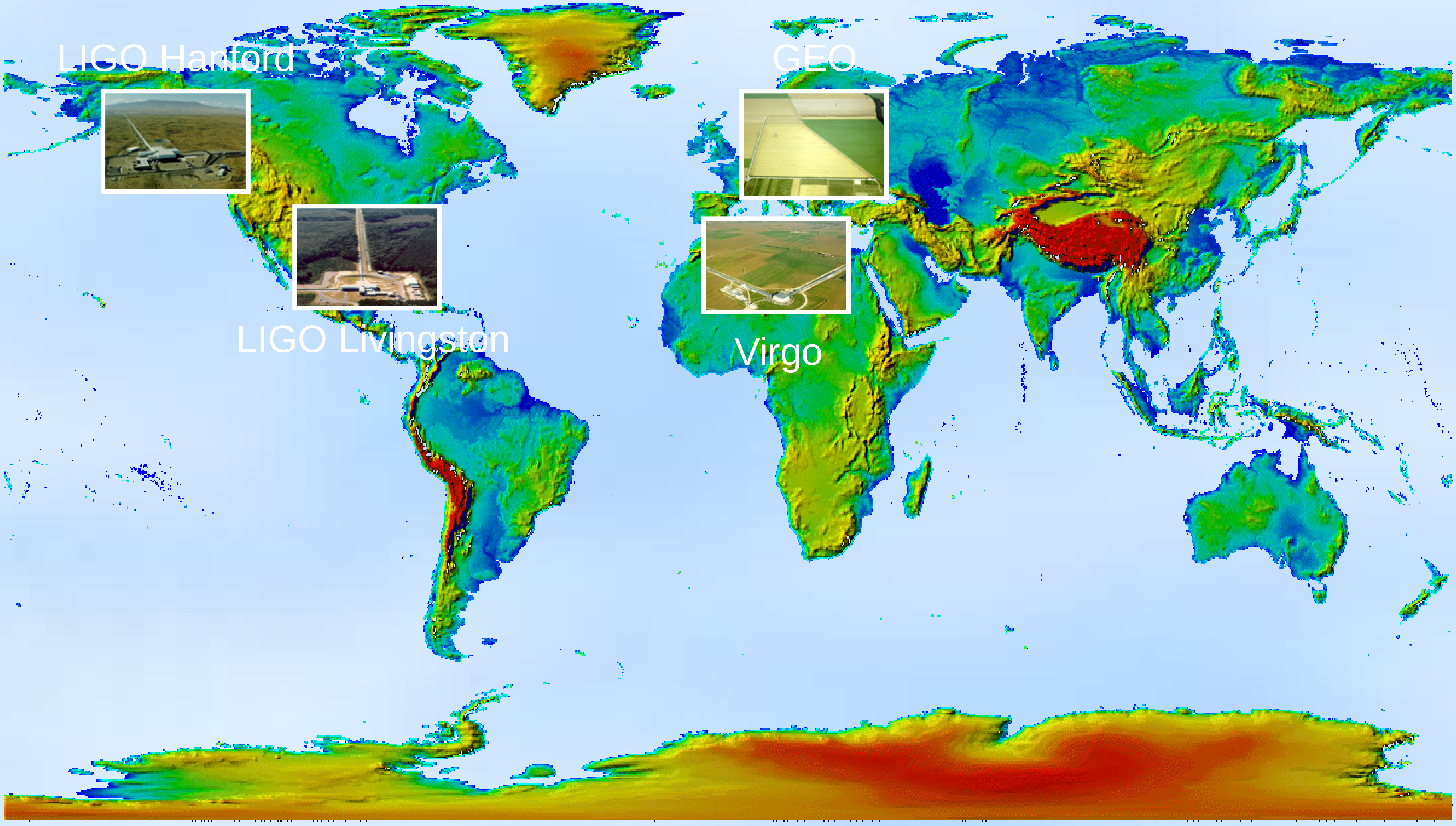
Future Observing Runs

	LIGO		Virgo		KAGRA	
	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc	BNS range/Mpc	BBH range/Mpc
Early	40–80	415–775	20–65	220–615	8–25	8–250
Mid	80–120	775–1110	65–85	615–790	25–40	250–405
Late	120–170	1110–1490	65–115	610–1030	40–140	405–1270
Design	190	1640	125	1130	140	1270

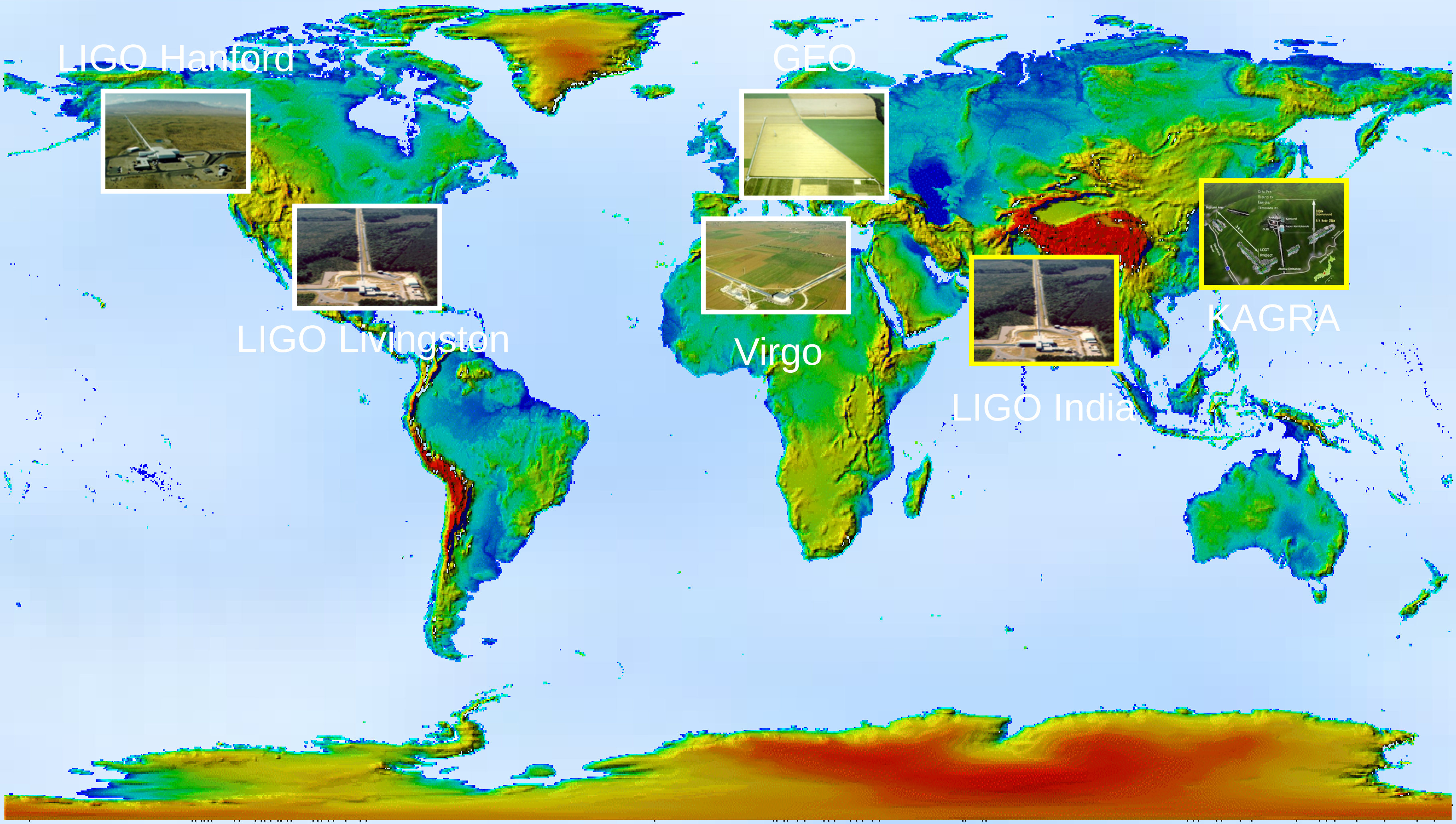
The different phases match those in Fig. 1. We quote the range, the average distance to which a signal could be detected, for a 1.4 $M_\odot$+1.4 $M_\odot$ binary neutron star (BNS) system and a 30 $M_\odot$+30 $M_\odot$ binary black hole (BBH) system



A detector network



An even better detector network

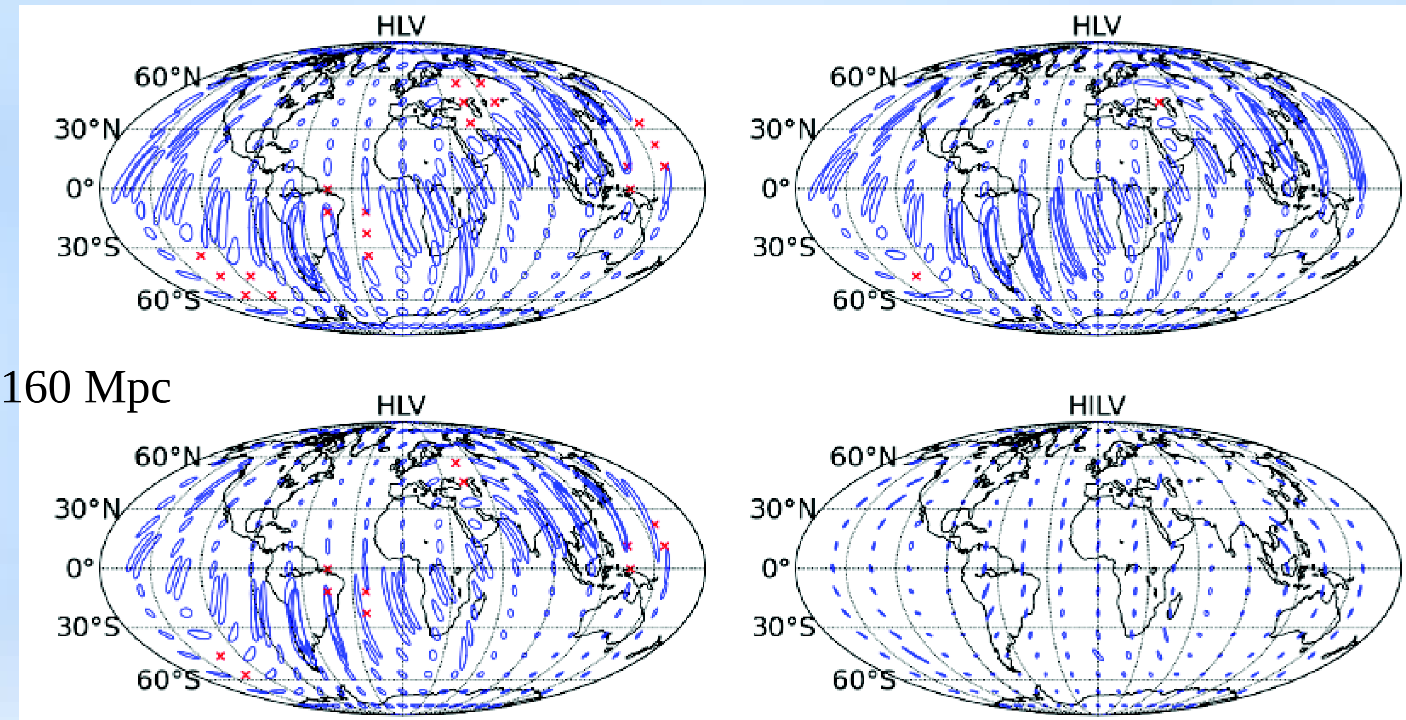


Advanced LIGO/Virgo sky localization

BNS source @ 80 Mpc

2016-2017 runs

2018-2019 runs



BNS source @ 160 Mpc

2019+ runs

HLV + LIGO India 2022+

Living Rev. Relativity, **19**, (2016), 1
DOI 10.1007/lrr-2016-1

GW170817 – LIGO and Virgo

- Calculate the sky position of the source
- Contribution of Virgo is decisive
  - LIGO alone: 190 deg^2
  - LIGO + Virgo: 28 deg^2
- LIGO-Virgo sky map much smaller than GRB (Fermi GBM + INTEGRAL)
- Gravitational waves give a distance: ~40 Mpc, ~140 million light years
- 17:54 the improved skymap is distributed to observing partners.
- Frantic preparations for observing at sunset in Chile