MULTI-MESSENGER ASTRONOMY WITH ADVANCED LIGO AND VIRGO

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University of Maryland Department of Physics

LSC Open Data Workshop · March 26, 2018

LIGO DCC: G1800652

OUTLINE

- Progenitors of gravitational wave transients
- Low-latency searches
- Information for multi-messenger astronomy

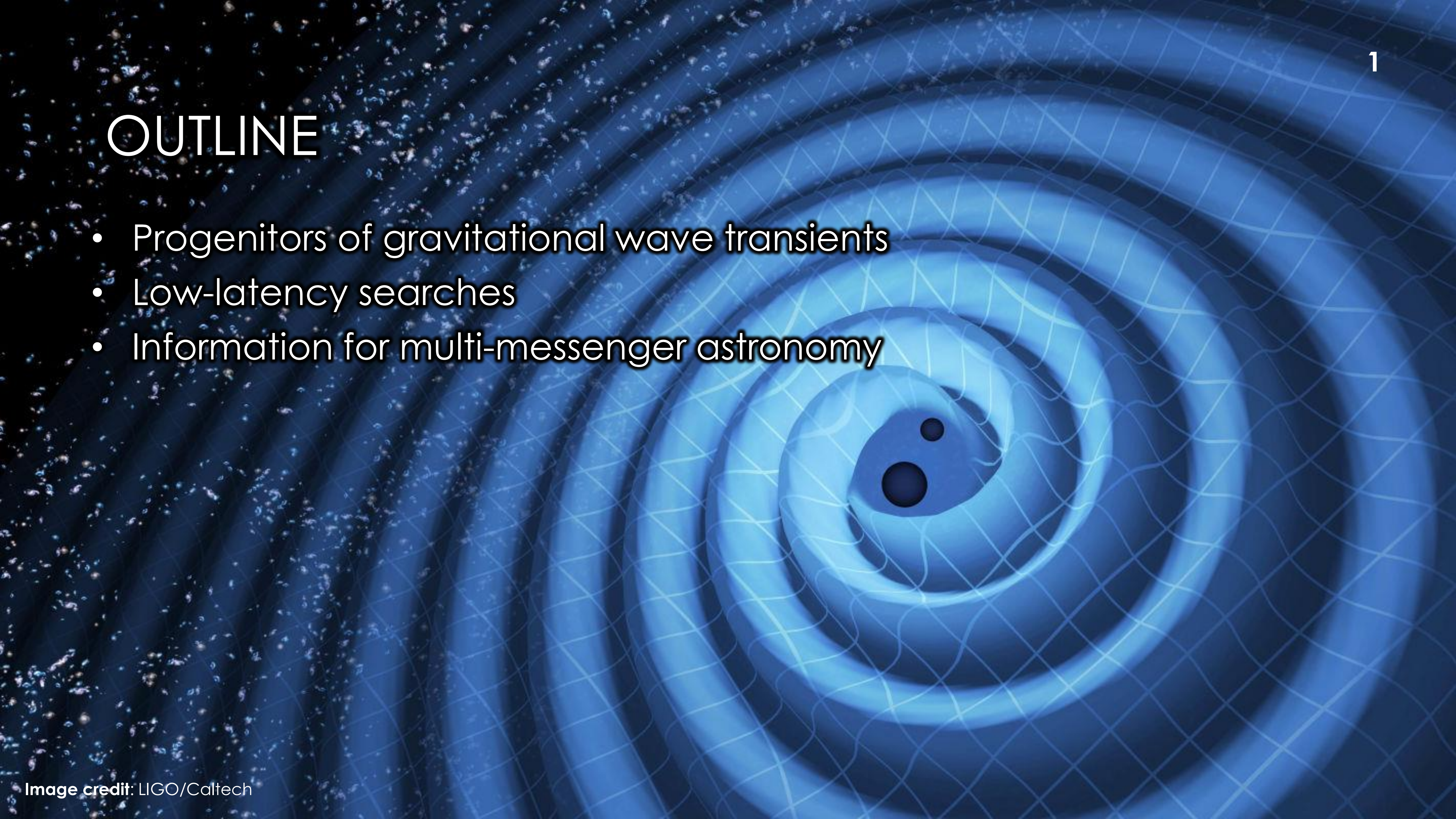

Image credit: LIGO/Caltech

THE GRAVITATIONAL WAVE SPECTRUM

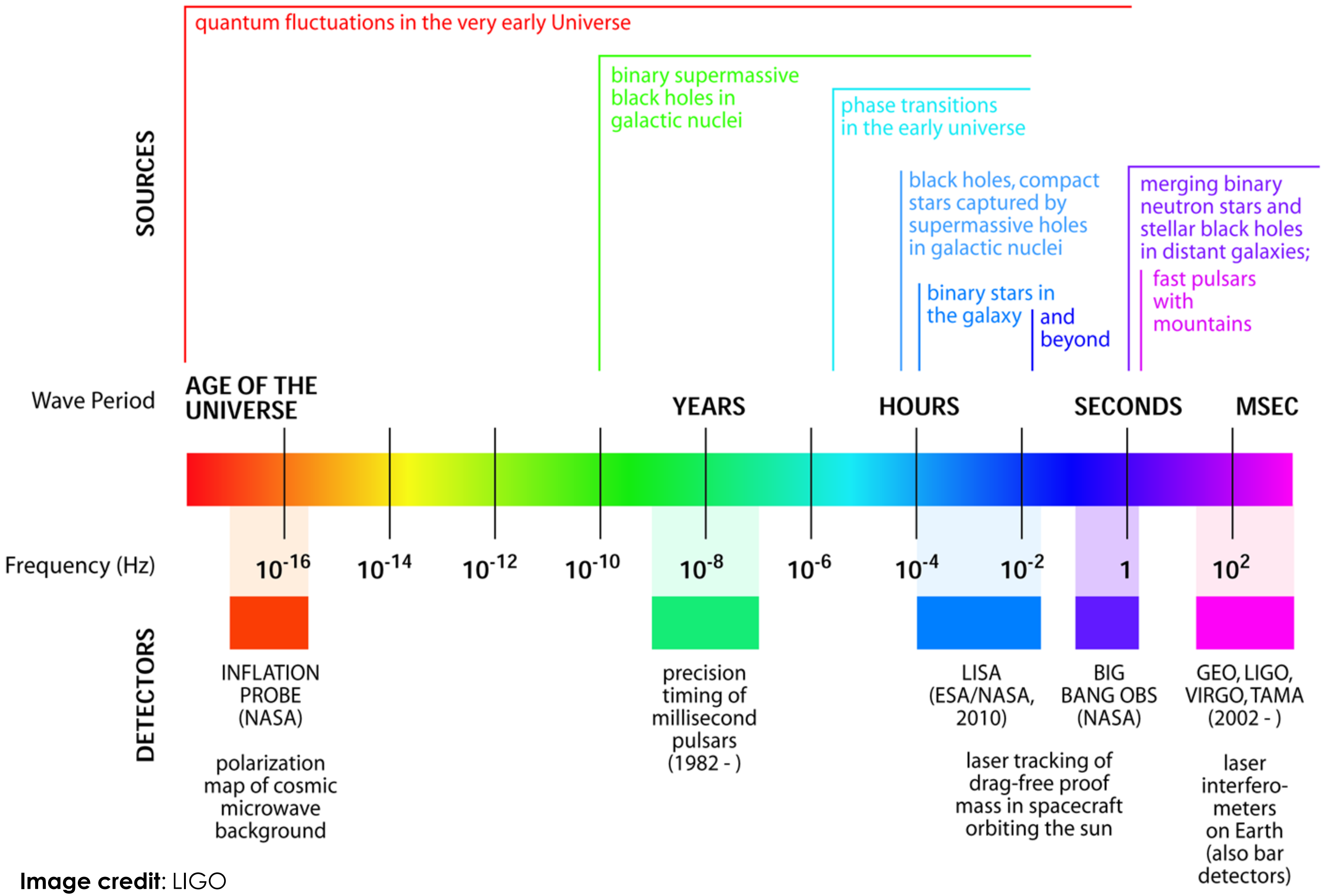

Image credit: LIGO

- The gravitational wave spectrum spans **over 18 orders of magnitude, *which is largely unexplored*** – we had our first direct detection on September 14, 2015!

Gravitational waves…

- Are excellent probes because they are not absorbed or scattered by matter and energy
- Come from the central engine of astrophysical objects
- Are only weakly beamed meaning detectors act as “microphones”

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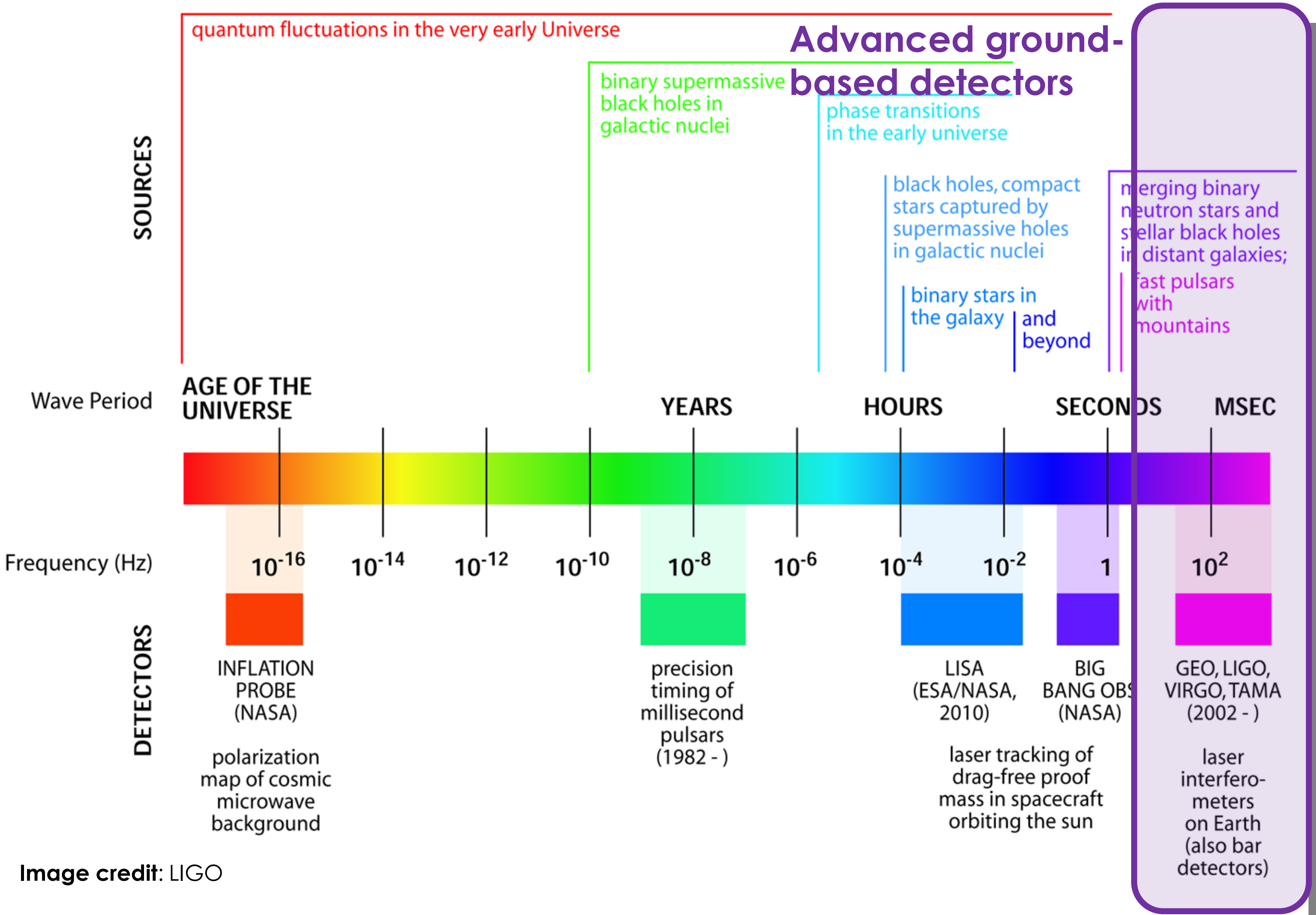

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COMPACT BINARY MERGERS

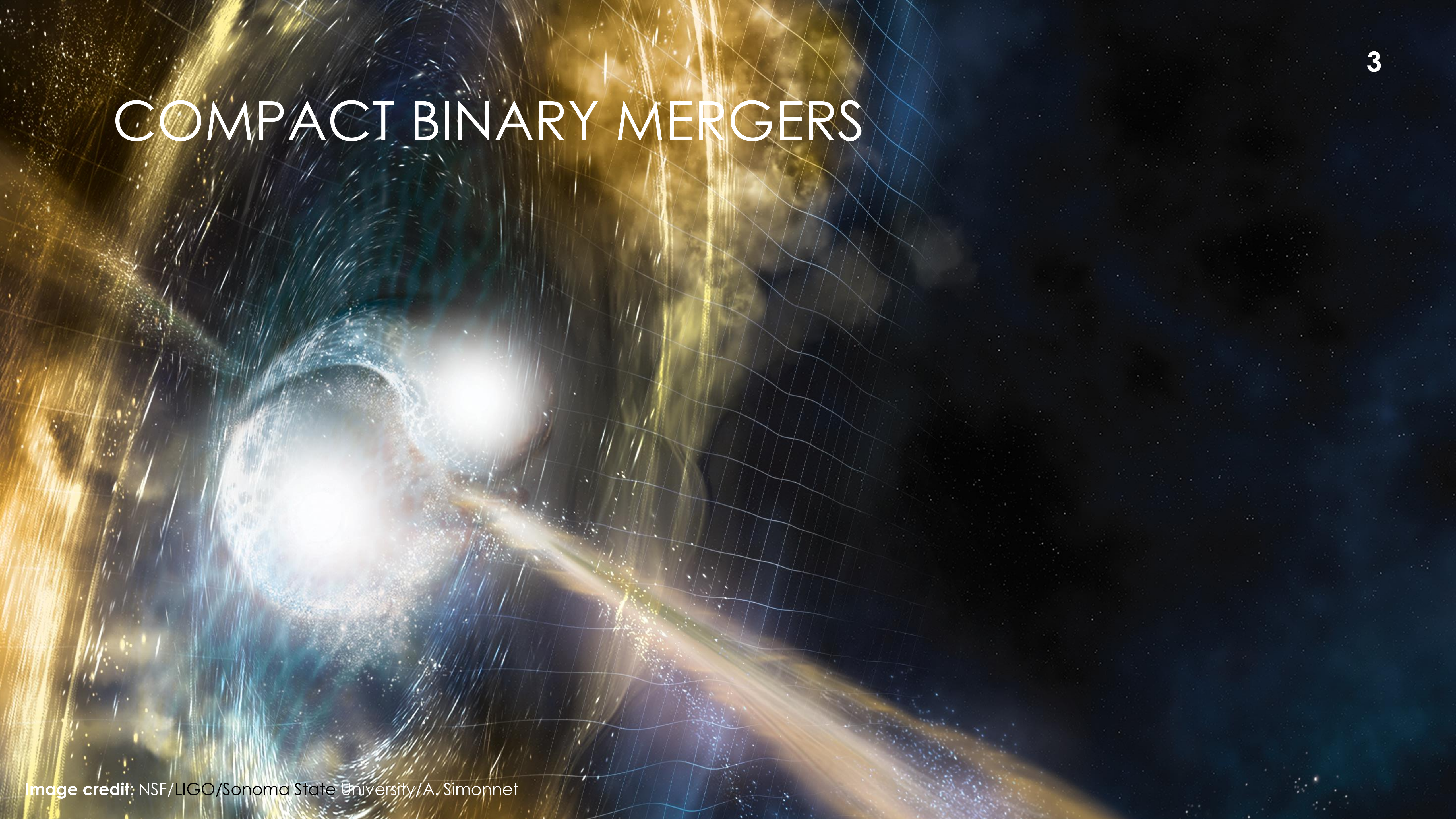

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

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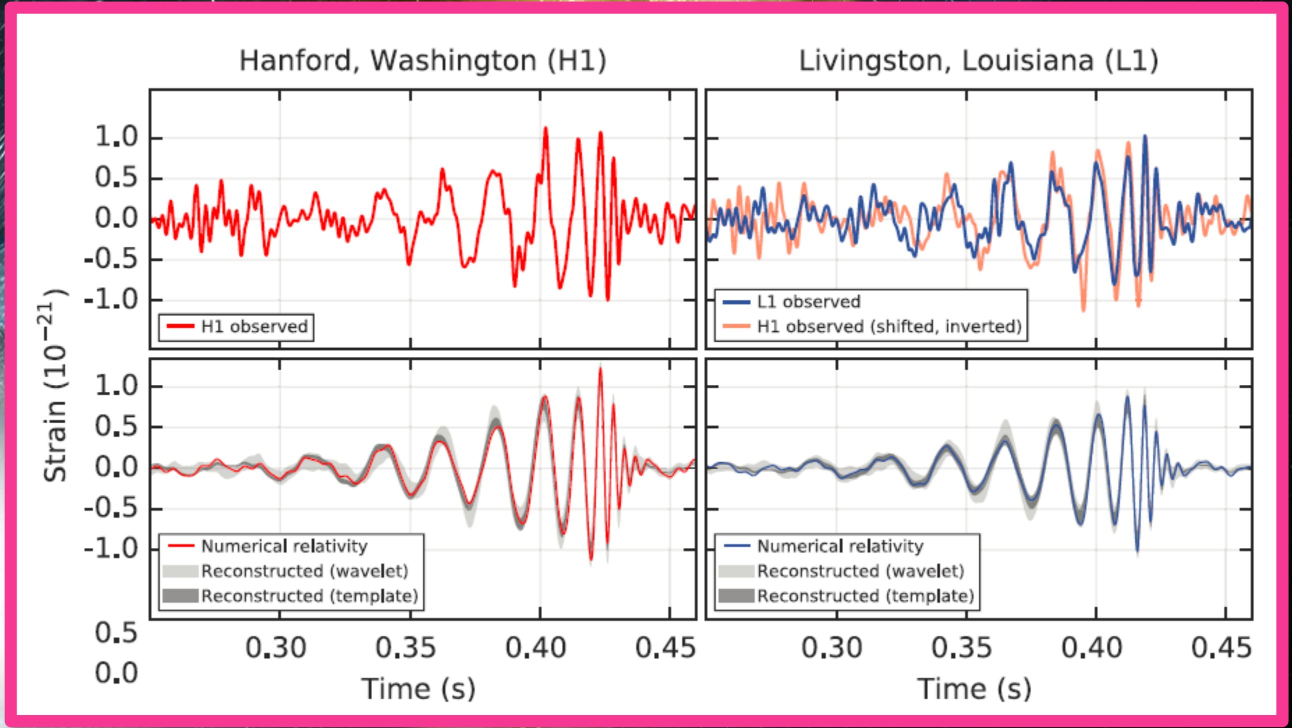

GW signal from GW150914, a BBH merger

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet, B. P. Abbott *et al.*, Phys. Rev. Lett. **116**, 061102 (2016)

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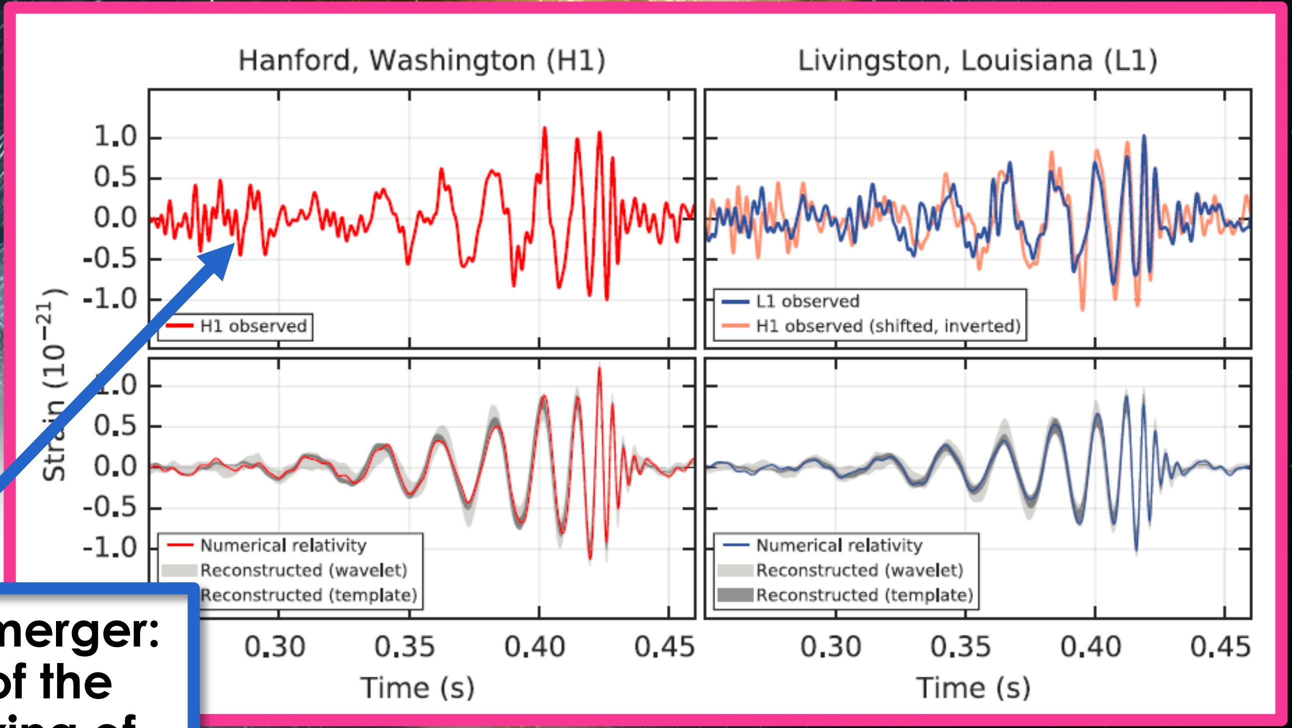

The waveform of the merger: the collected history of the stretching and squeezing of space by gravitational waves

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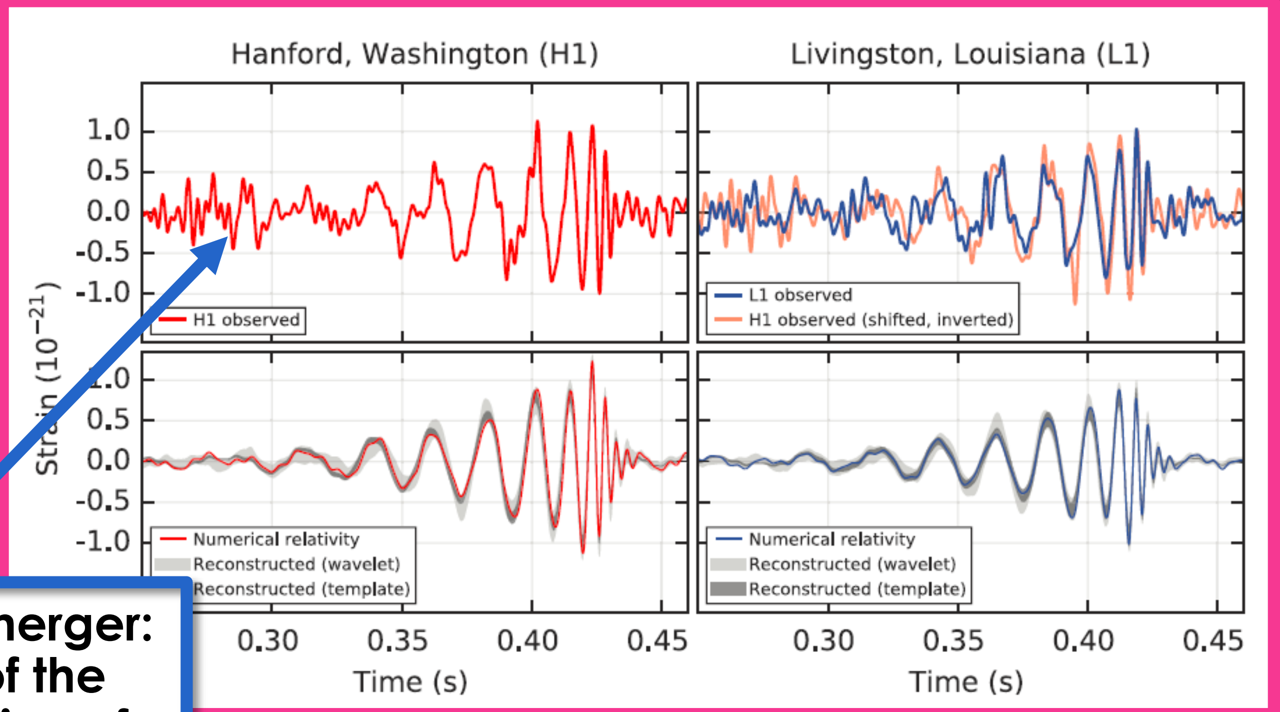

The **chirp**: rising frequency of the gravitational waves

The **waveform** of the merger: the collected history of the stretching and squeezing of space by gravitational waves

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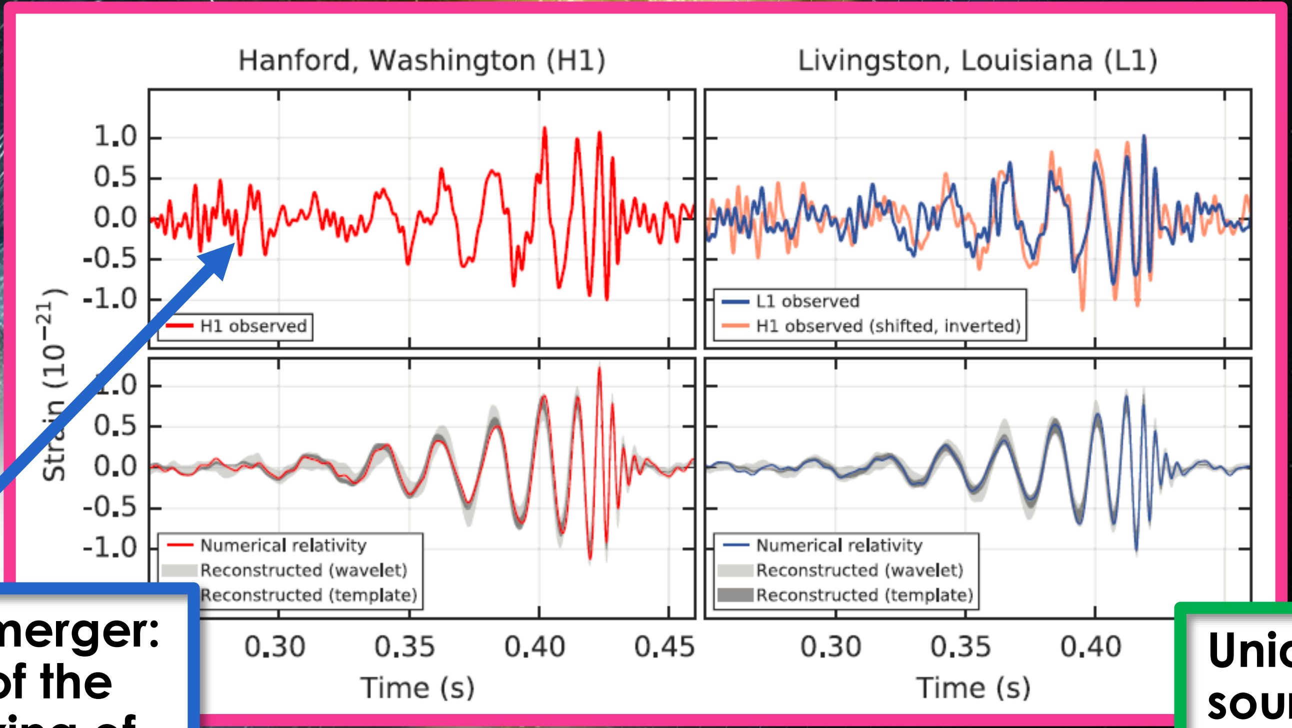

The waveform of the merger: the collected history of the stretching and squeezing of space by gravitational waves

GW signal from GW150914, a BBH merger

The chirp: rising frequency of the gravitational waves

Unique information about the source is encoded in the amplitude/phase evolution: masses, spins, and more…

Please see Katerina Chatziioannou's talk!

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet, B. P. Abbott *et al.*, Phys. Rev. Lett. **116**, 061102 (2016)

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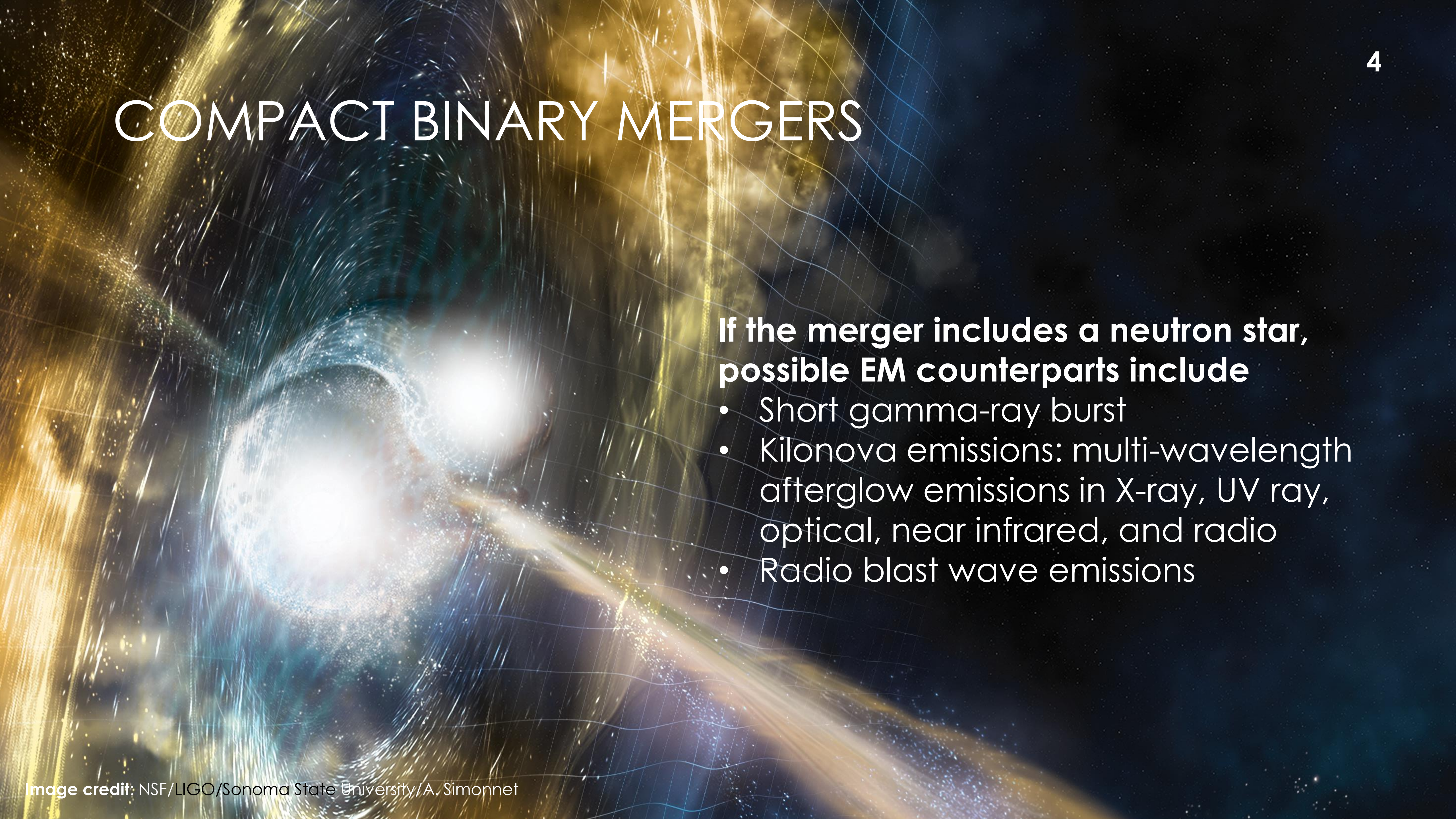
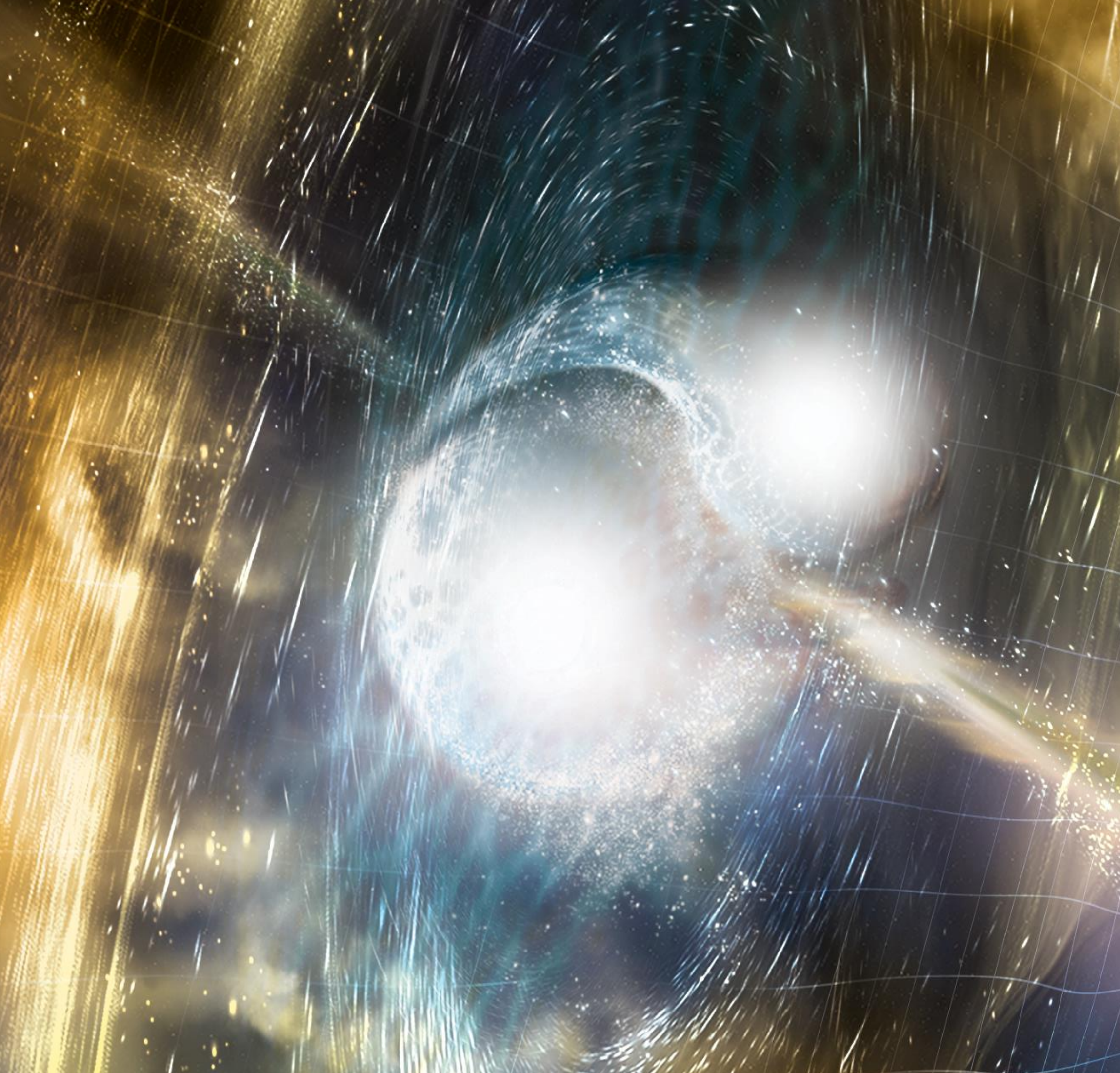


If the merger includes a neutron star, possible EM counterparts include

- Short gamma-ray burst
- Kilonova emissions: multi-wavelength afterglow emissions in X-ray, UV ray, optical, near infrared, and radio
- Radio blast wave emissions

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

COMPACT BINARY MERGERS



Scientific motivation for joint observations

- Confirm short gamma-ray burst/BNS/NSBH connection
- Learn about energetics of short gamma-ray bursts from the beaming angle of the burst
- Independently measure the Hubble constant

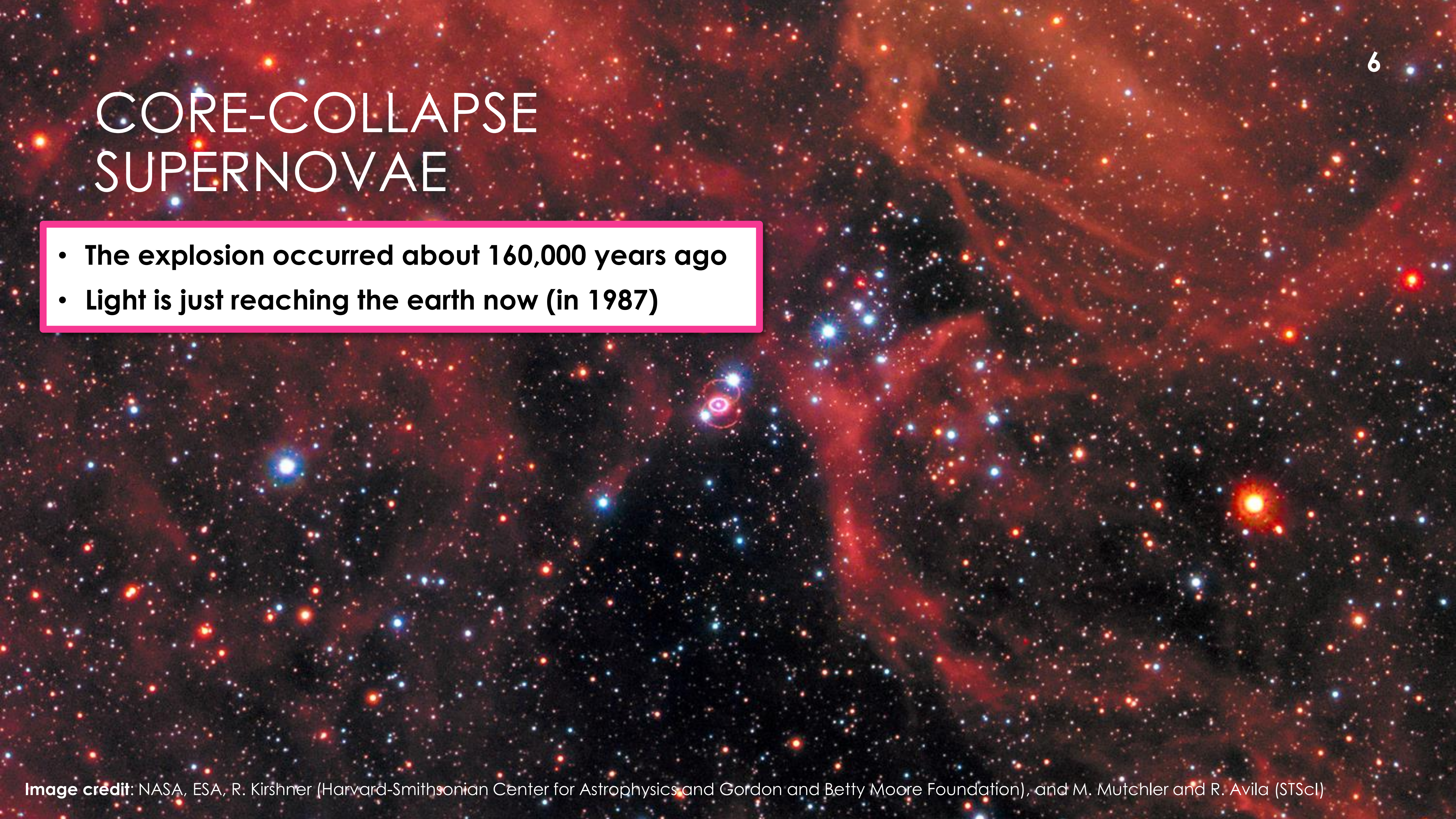
Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

CORE-COLLAPSE SUPERNOVAE

Image credit: NASA, ESA, R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation), and M. Mutchler and R. Avila (STScI)

CORE-COLLAPSE SUPERNOVAE

- **The explosion occurred about 160,000 years ago**
- **Light is just reaching the earth now (in 1987)**



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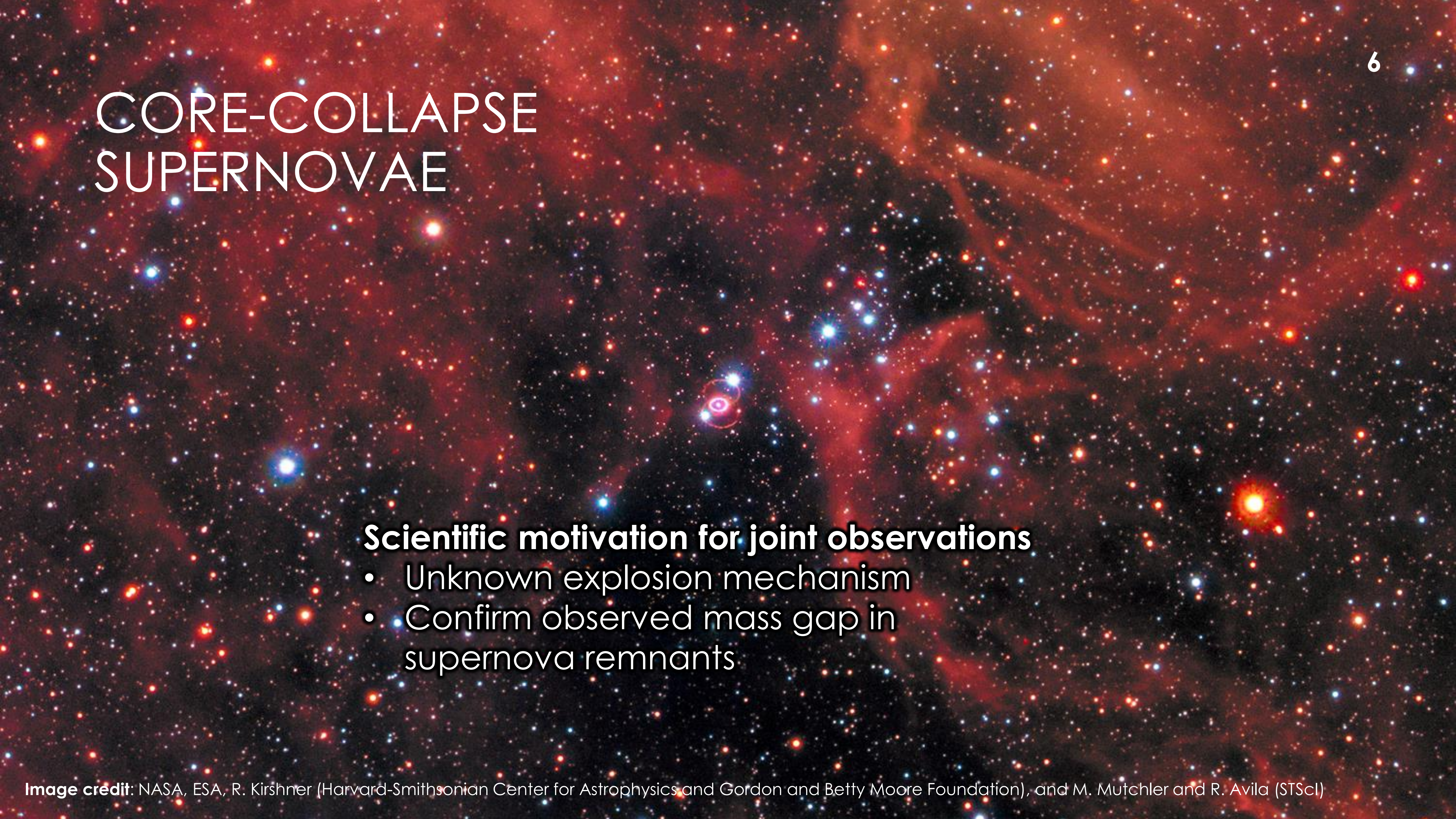

Scientific motivation for joint observations

- Unknown explosion mechanism
- Confirm observed mass gap in supernova remnants

Image credit: NASA, ESA, R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation), and M. Mutchler and R. Avila (STScI)

GW'S FROM CORE-COLLAPSE SUPERNOVAE

The key to the resultant gravitational waves is the initial rotation rate (Ω_0) of the iron core!

GW'S FROM CORE-COLLAPSE SUPERNOVAE

	Neutrino mechanism	**MHD mechanism**
Progenitor	Non-rotating or slowly rotating stars $\Omega_0 < \sim 0.1$ rad/s ~99% of the progenitors -- these are the main players!	Rapidly rotating star with strong magnetic fields $\Omega_0 > \sim \pi$ rad/s, $B_0 > 10^{11}$ G ~1% (hypothetical link to magnetars and collapsars)
Main origin of gravitational wave emission	Turbulent convection and SASI (Standing Accretion Shock Instability)	Rotating bounce and non-axisymmetric instabilities
Gravitational wave signatures	**Three generic phases**: prompt convection, neutrino-driven convection & SASI, and explosion	Rotating bounce (< 20 ms post-bounce) and non-axisymmetric instabilities (< ? ms)
Detection prospects	• Requires 3rd generation detectors to see every galactic event with high SNR • Close by events (2~3 kpc) are detectable with Advanced LIGO • If detected, critical information about the supernova engine (convection vs. SASI dominant) can be obtained	• **Bounce GW signal**: requires design sensitivity of Advanced LIGO • **GW's from non-axisymmetric instabilities**: "quasi-periodicity" of the signal enhances chances of detection • **Detection of circular polarization**: important probe of core rotation

See reviews in: Janka (2017), Mezzacappa *et al.* (2015), Burrows (2013), Kotake *et al.* (2012)

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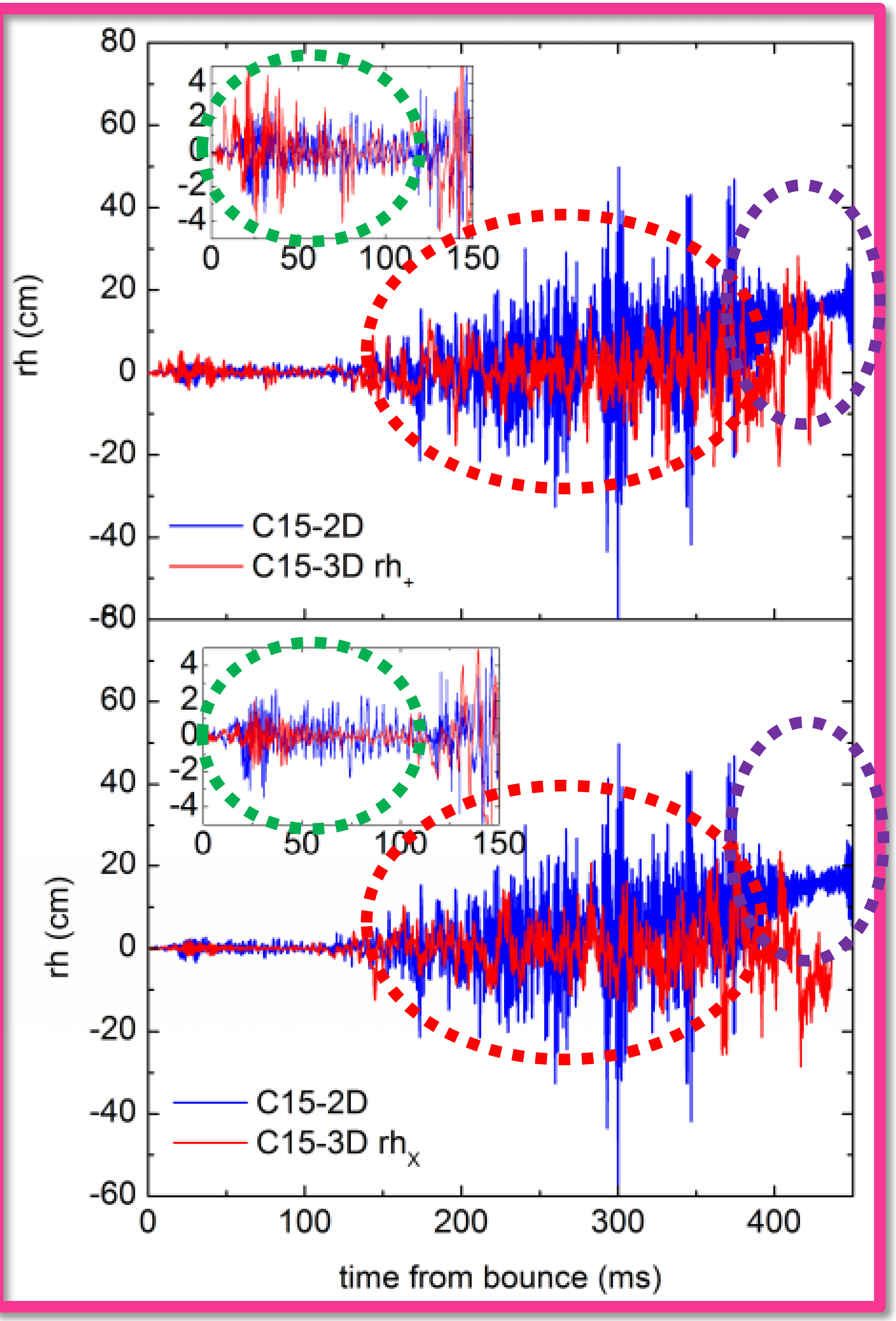

See reviews in: Janka (2017), Mezzacappa *et al.* (2015), Burrows (2013), Kotake *et al.* (2012), Yakunin *et al.* (2017), arXiv: 1701.07325v1

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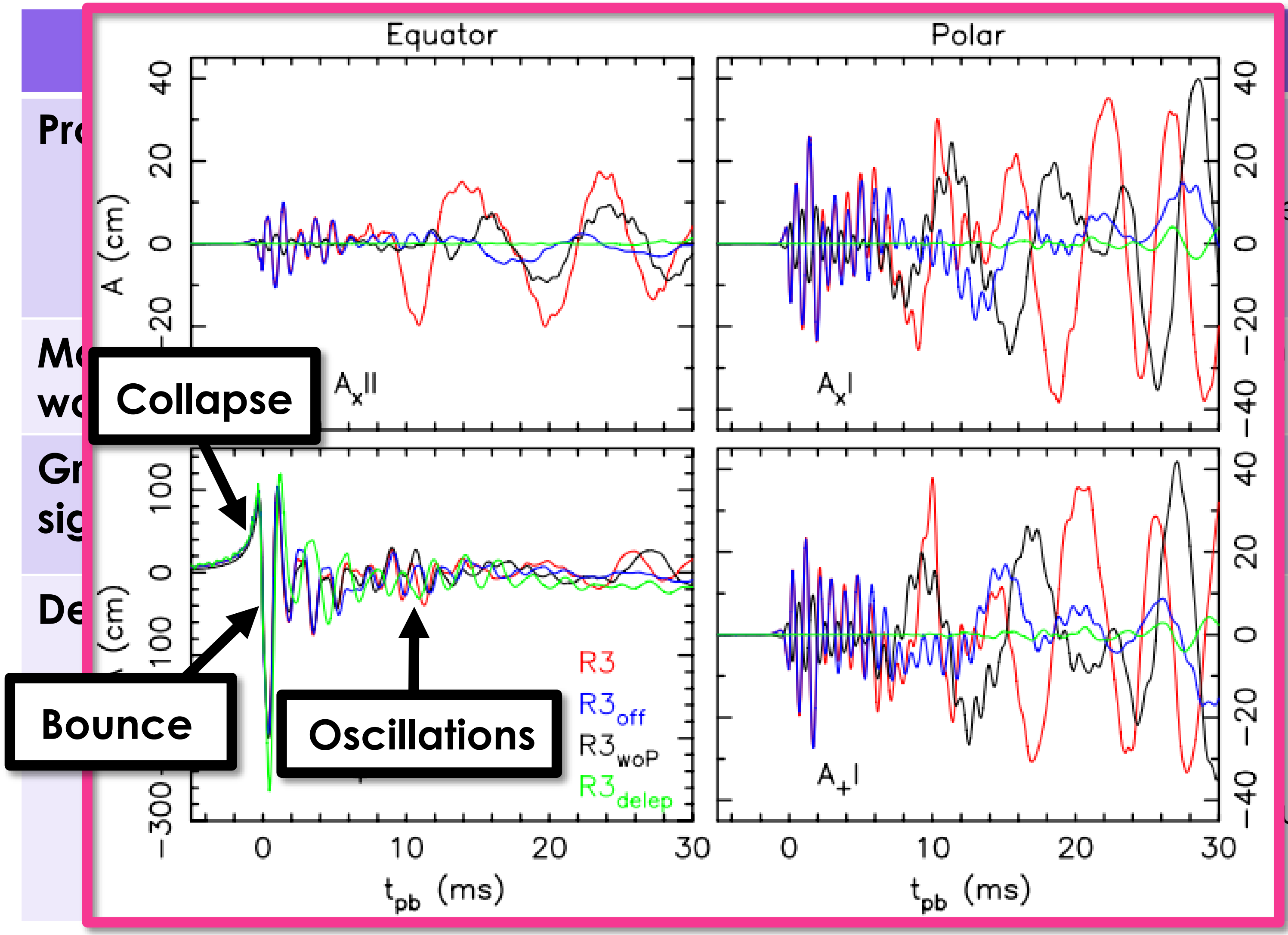
There are 11 long GRB—core-collapse supernovae associations
The neutrino mechanism is inefficient; it can't deliver hyper-energetic supernovae

See reviews in: Janka (2017), Mezzacappa *et al.* (2015), Burrows (2013), Kotake *et al.* (2012)

GW'S FROM CORE-COLLAPSE SUPERNOVAE



MHD mechanism
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Rotating bounce and non-axisymmetric instabilities
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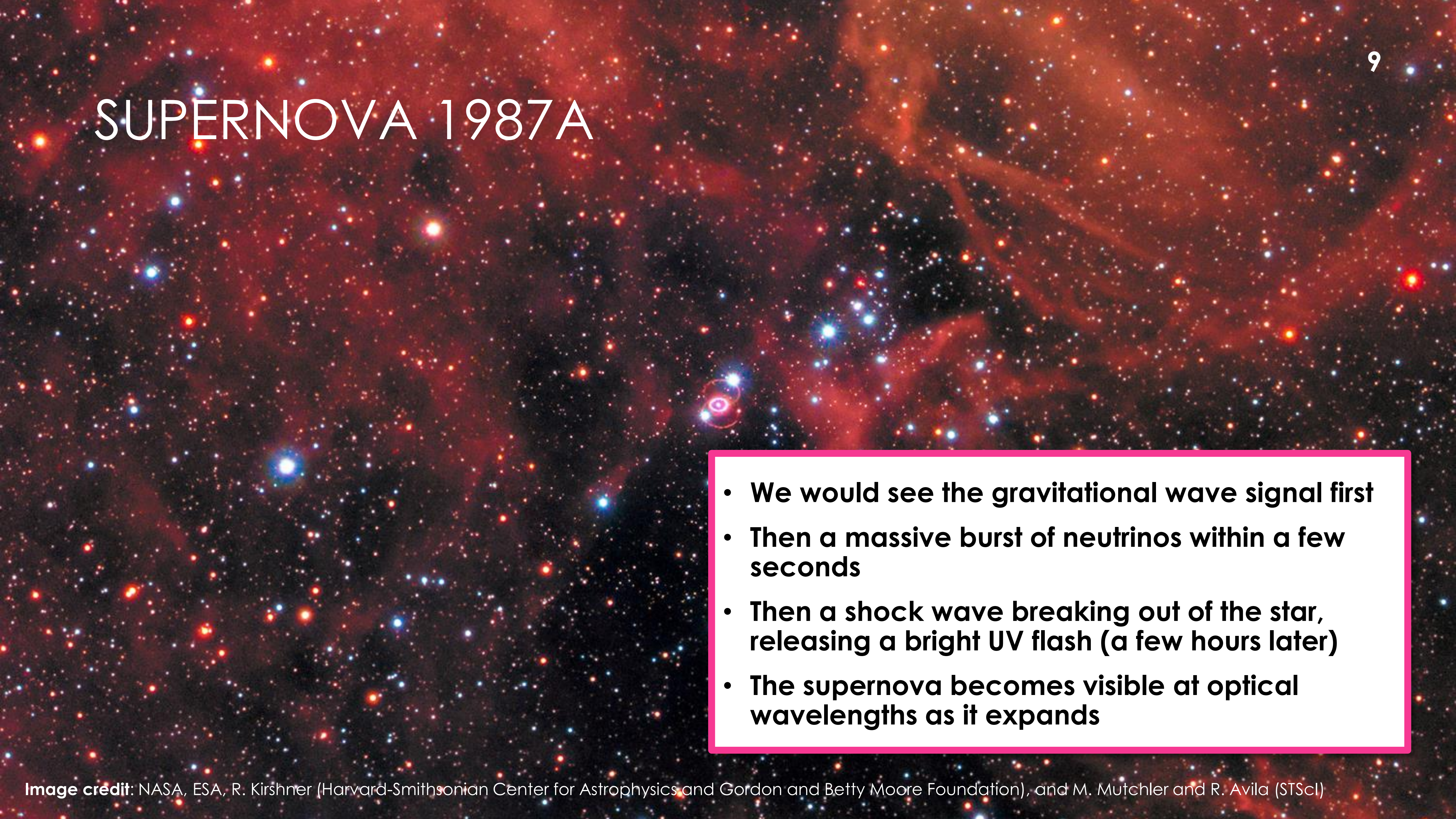
See reviews in: Janka (2017), Mezzacappa *et al.* (2015), Burrows (2013), Kotake *et al.* (2012), Kuroda, Takiwaki, and Kotake PRD **89** 044011 (2014)

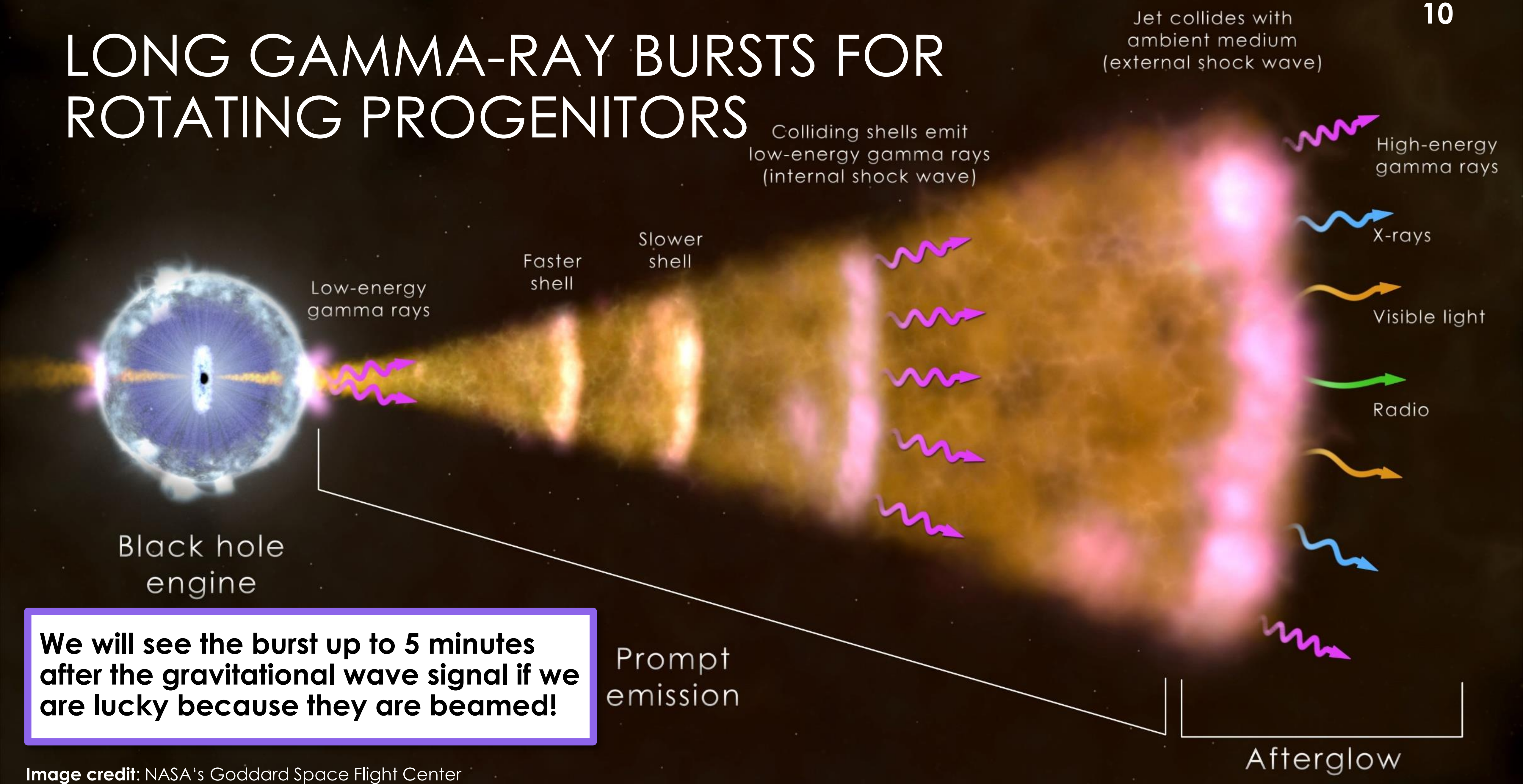
SUPERNOVA 1987A



- We would see the gravitational wave signal first
- Then a massive burst of neutrinos within a few seconds
- Then a shock wave breaking out of the star, releasing a bright UV flash (a few hours later)
- The supernova becomes visible at optical wavelengths as it expands

Image credit: NASA, ESA, R. Kirshner (Harvard-Smithsonian Center for Astrophysics and Gordon and Betty Moore Foundation), and M. Mutchler and R. Avila (STScI)

LONG GAMMA-RAY BURSTS FOR ROTATING PROGENITORS



We will see the burst up to 5 minutes after the gravitational wave signal if we are lucky because they are beamed!

Image credit: NASA's Goddard Space Flight Center

MAGNETAR STARQUAKES

Image credit: NASA

MAGNETAR STARQUAKES

Possible electromagnetic counterparts:

- Soft gamma repeaters
- Anomalous X-ray pulsars
- Radio/X-ray pulsar glitches

Image credit: NASA

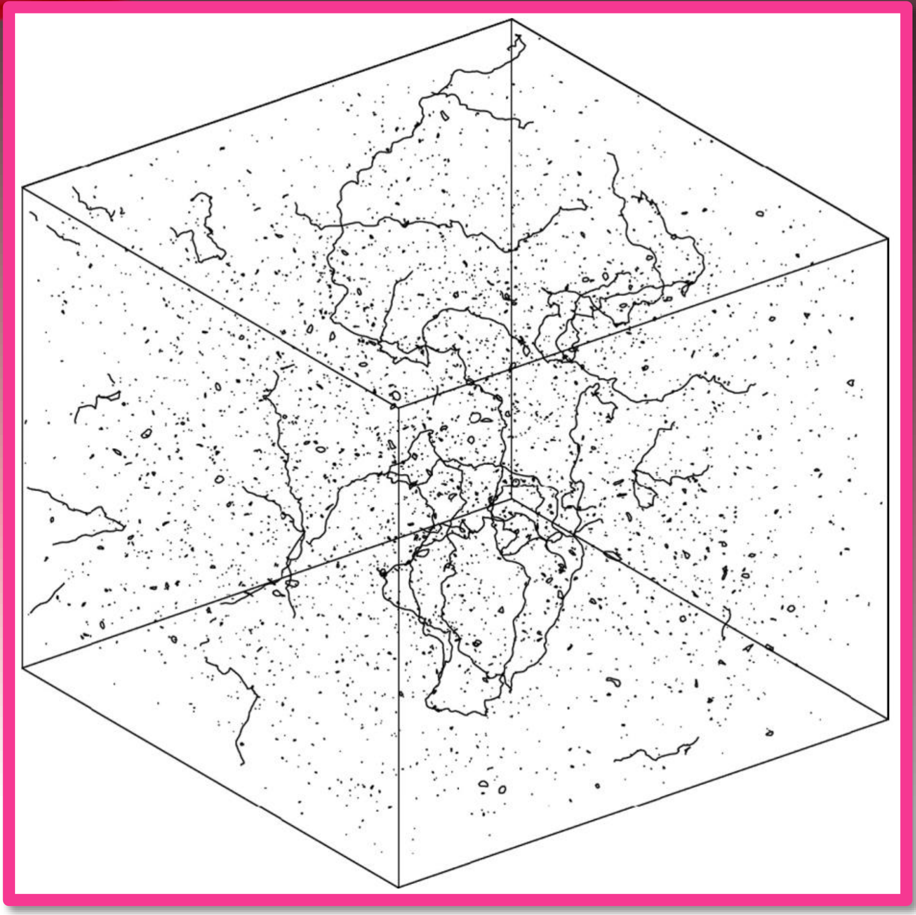
MAGNETAR STARQUAKES

Scientific motivation for joint observations:

- Unknown GW signal → Neutron star asteroseismology → Possible constraints on the equation of state

Image credit: NASA

OTHER SOURCES OF GW TRANSIENTS

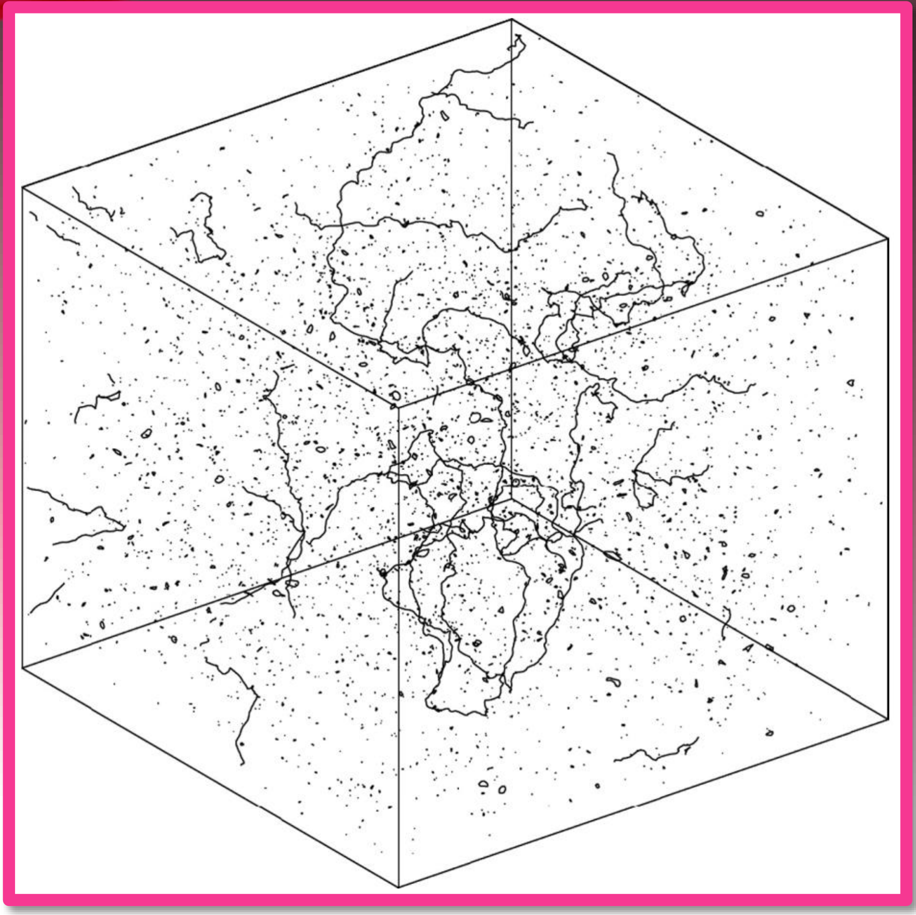


Simulation of a cosmic string network

More speculative sources

- Intersecting cosmic strings

Image credit: Allen & Shellard (1990)



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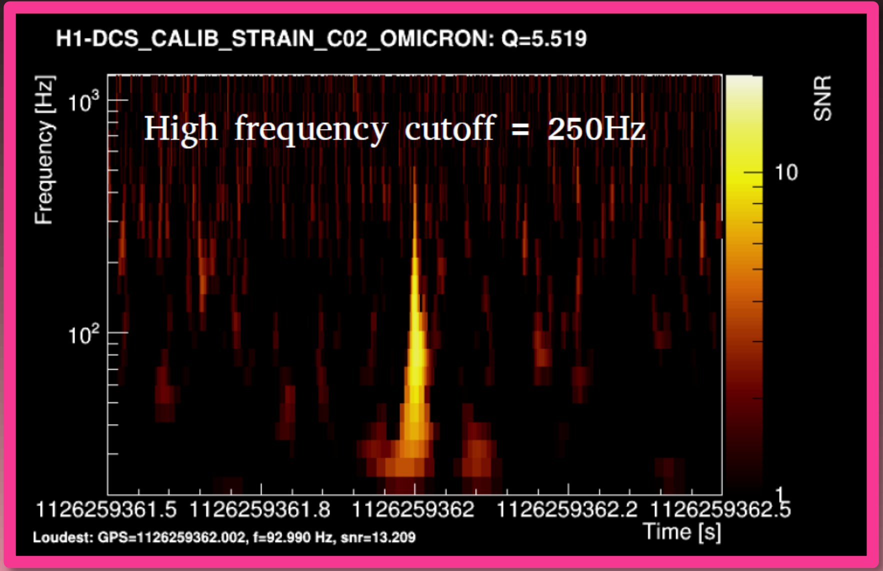
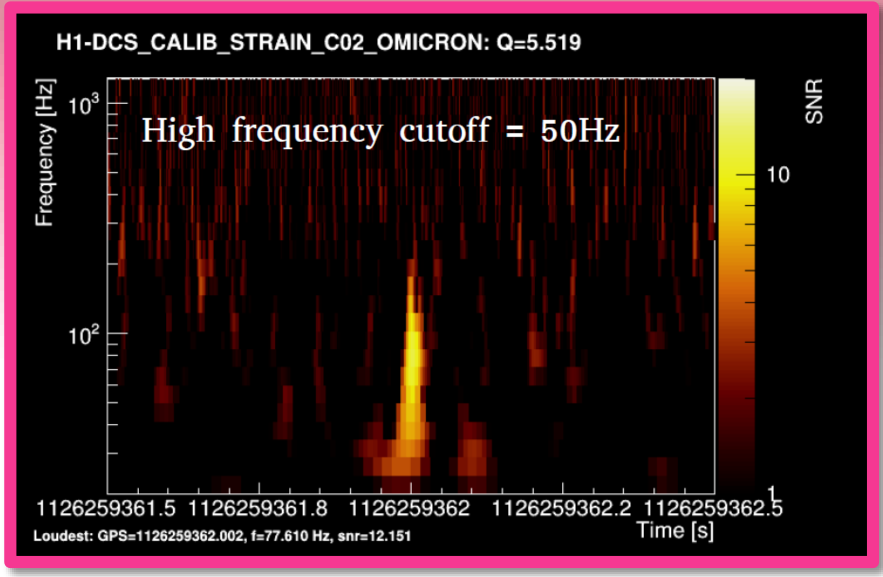
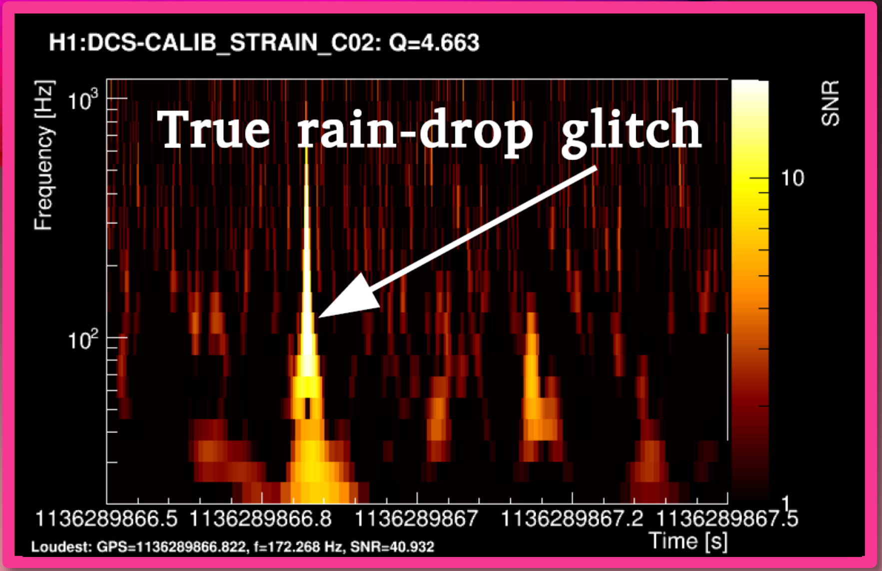
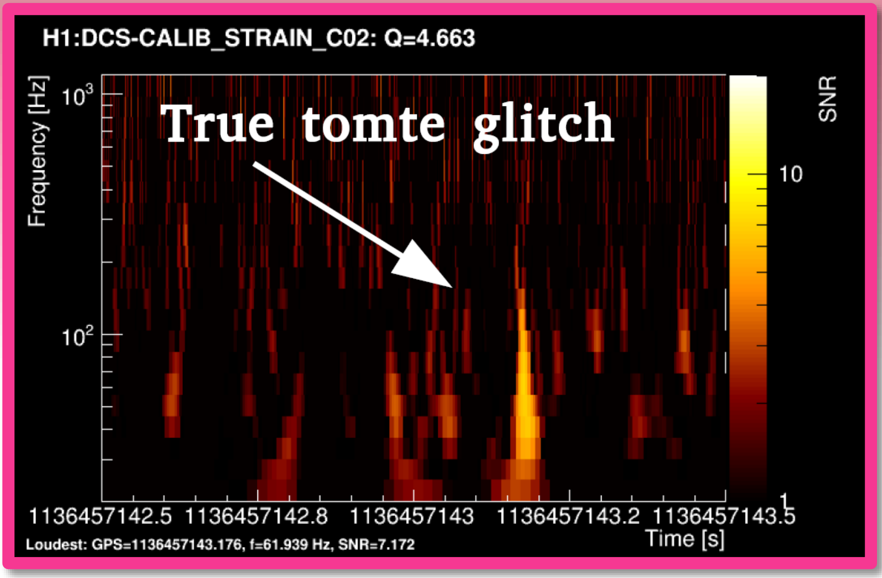


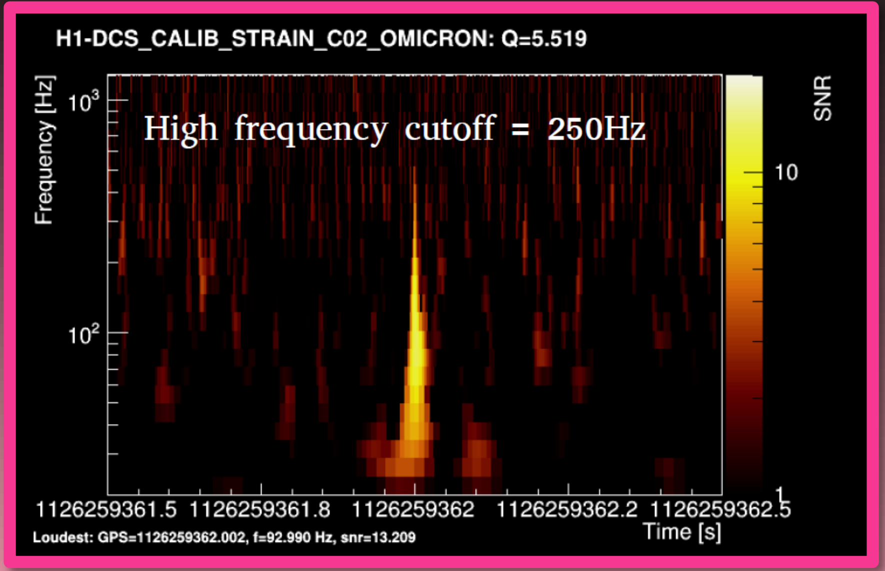


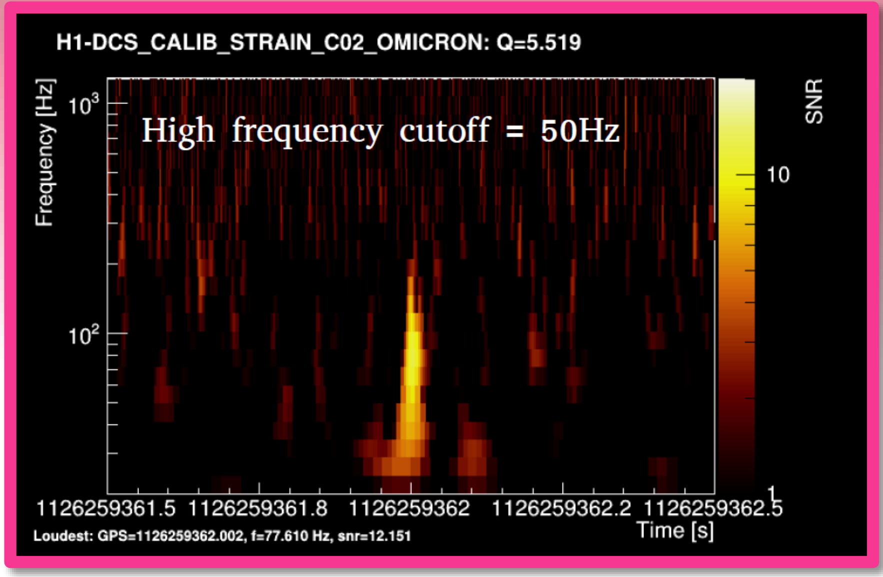
Cosmic string cusp injections

Image credit: Allen & Shellard (1990), LIGO DCC G1602392









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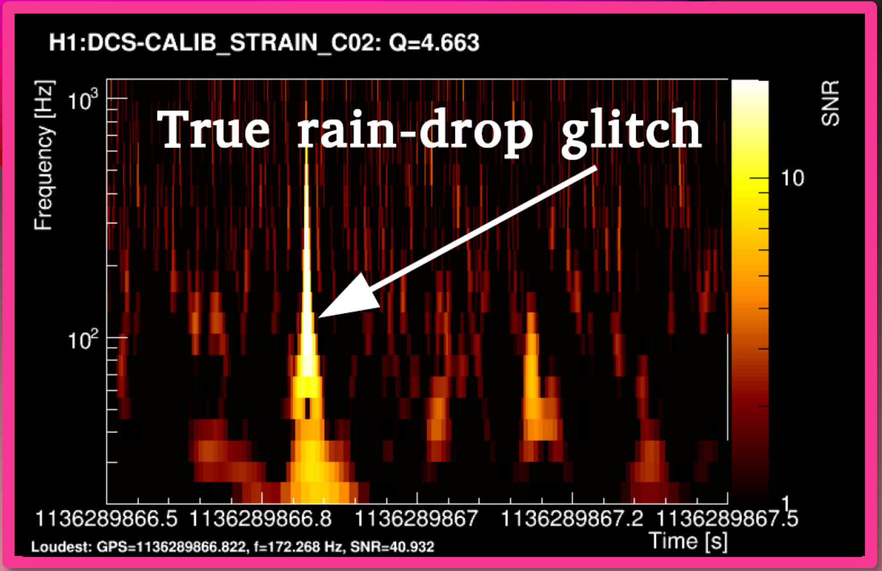

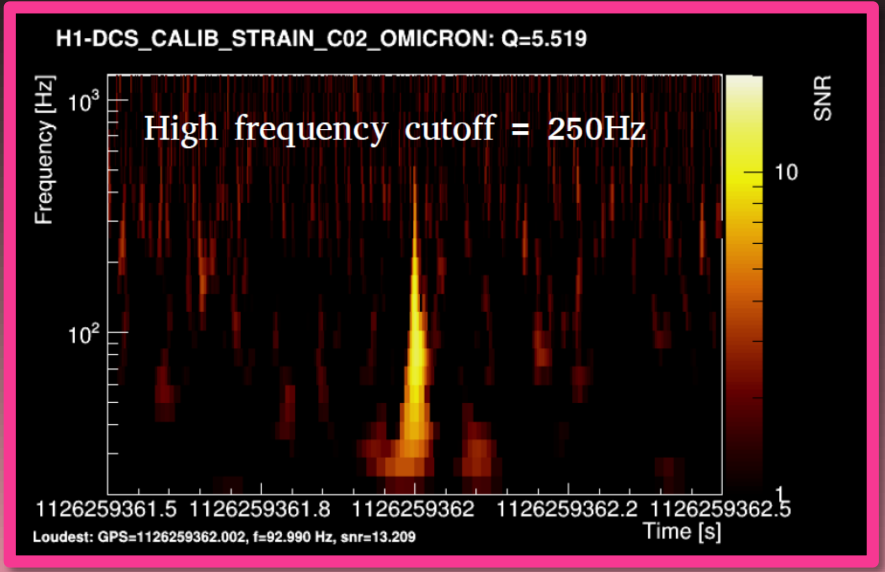

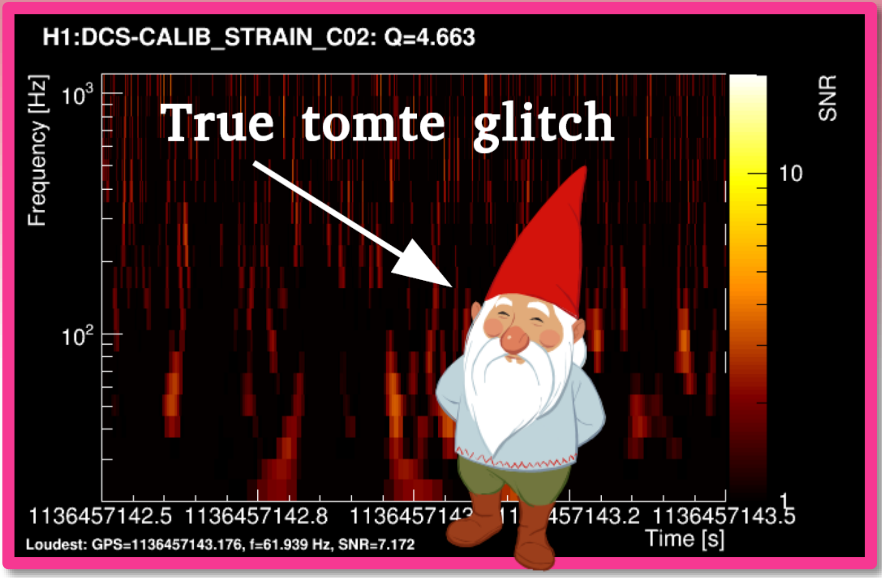

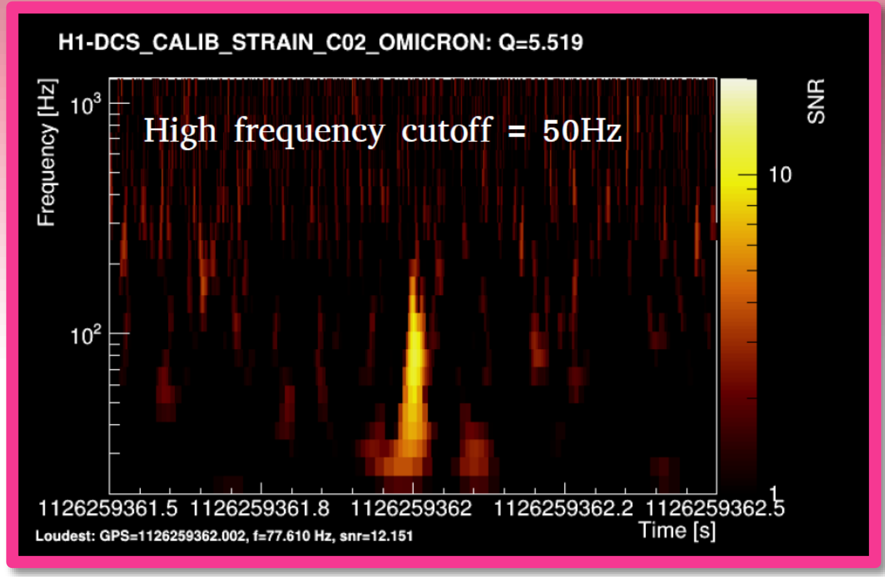

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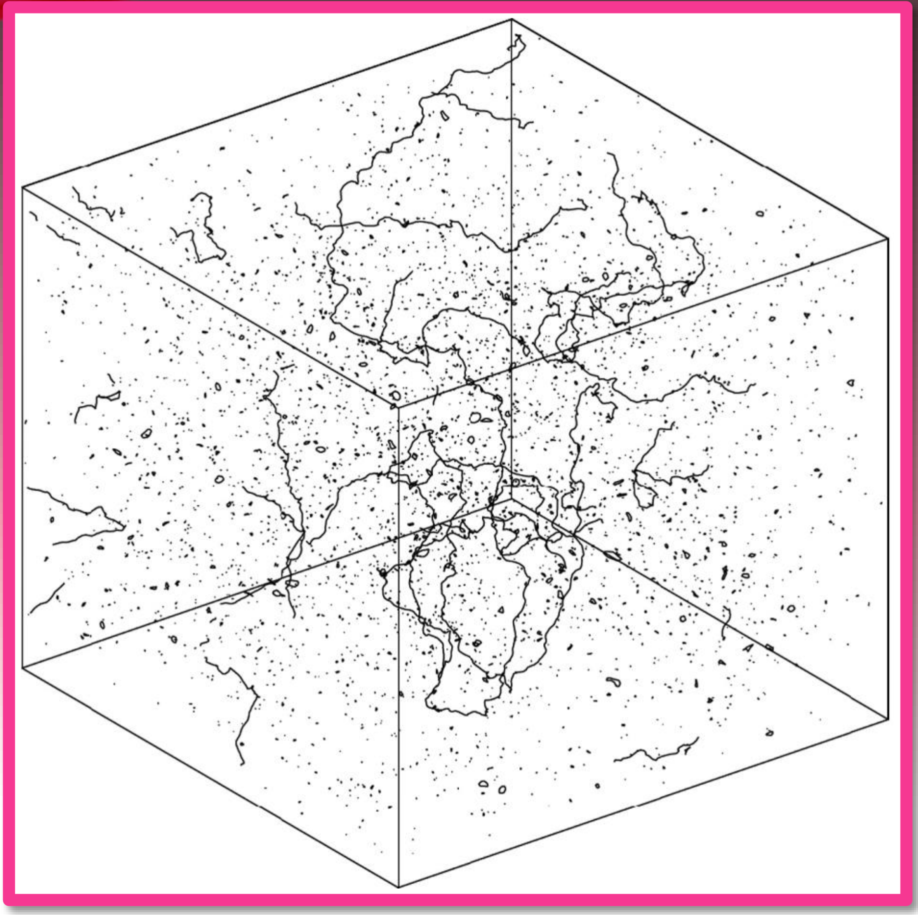

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Yet known GW sources

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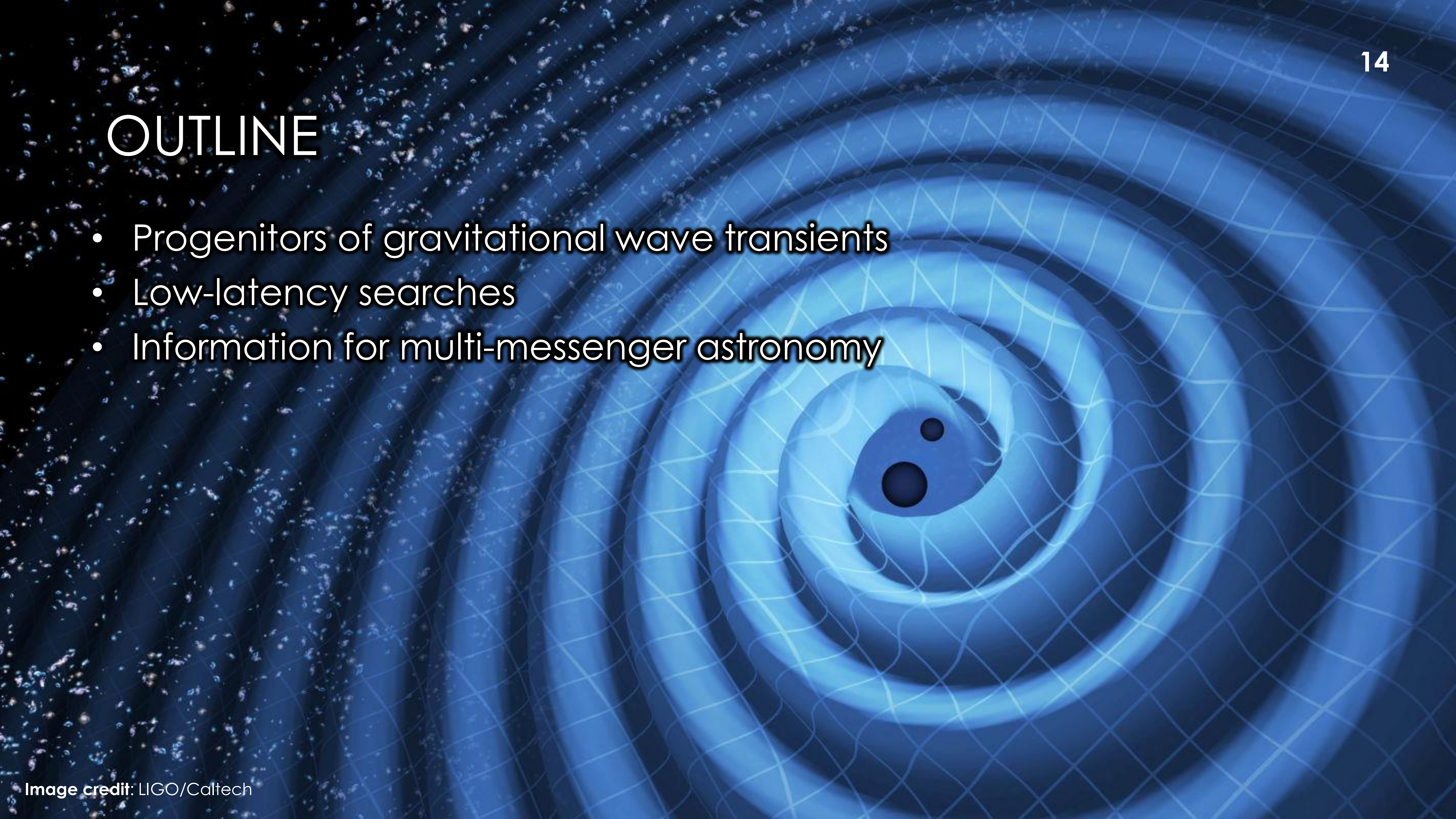

Image credit: LIGO/Caltech

LIGO: LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

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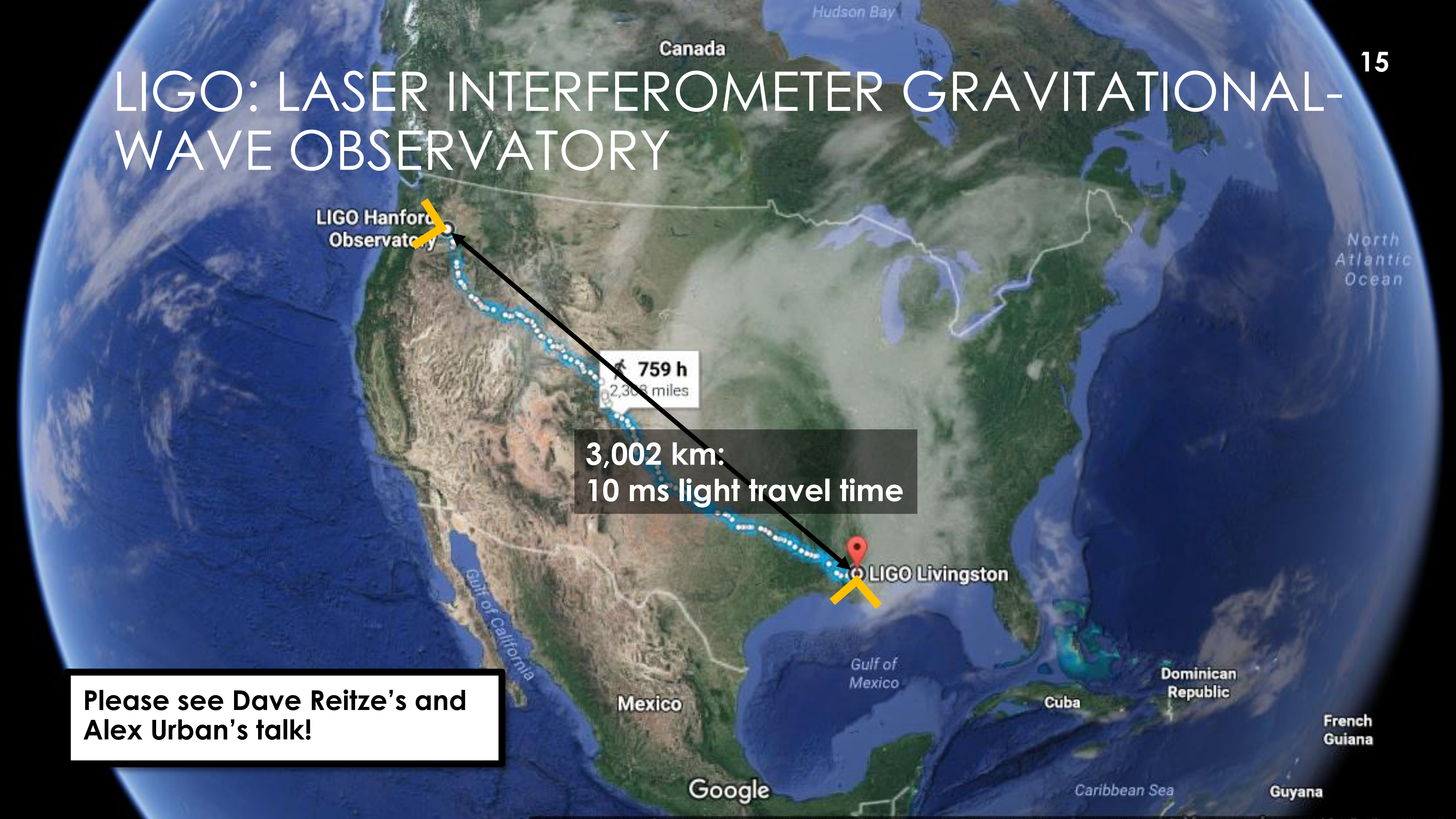


3,002 km:
10 ms light travel time

Please see Dave Reitze's and Alex Urban's talk!

LIGO HANFORD

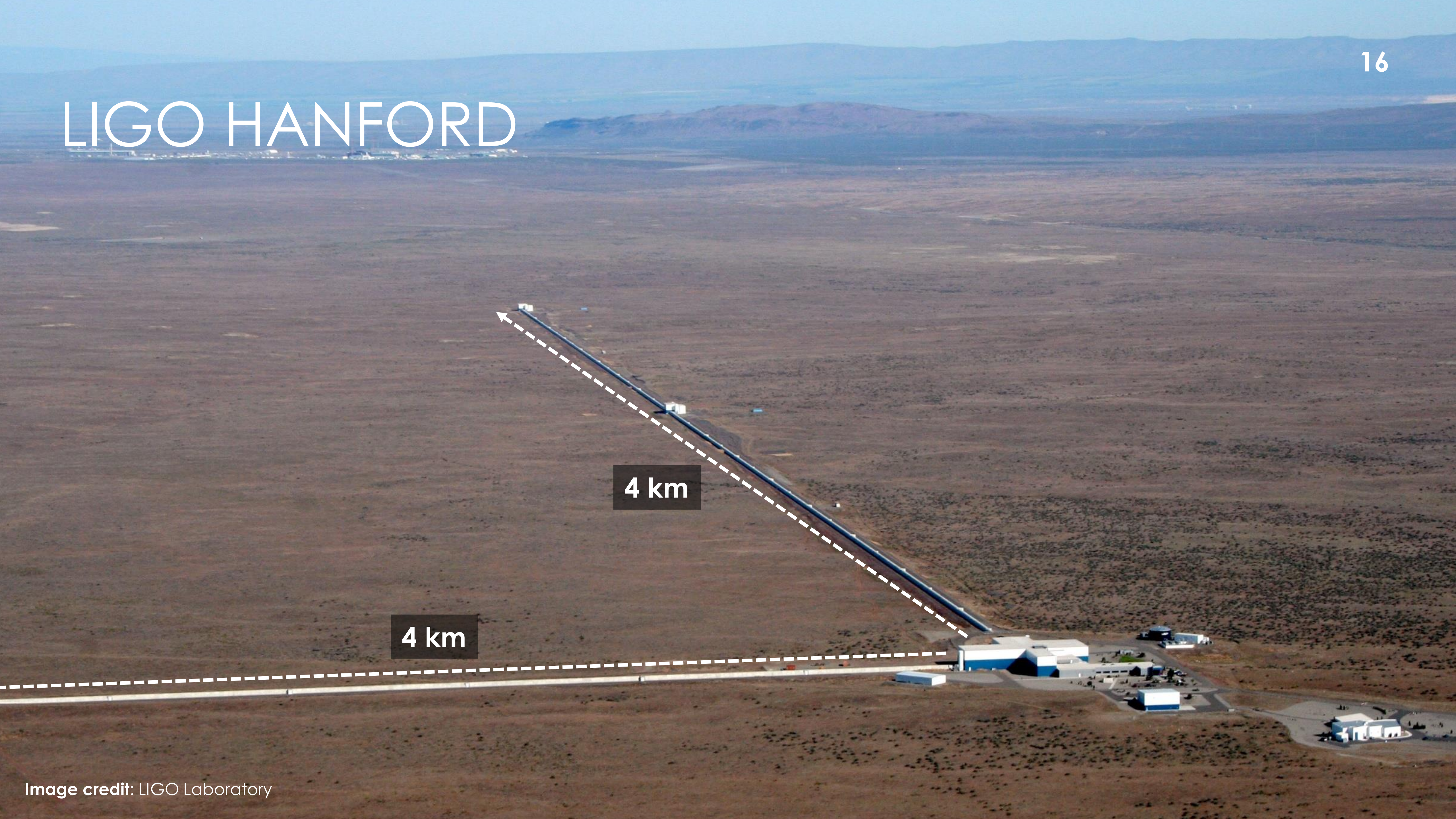


Image credit: LIGO Laboratory

LIGO LIVINGSTON

Image credit: Science Magazine

VIRGO

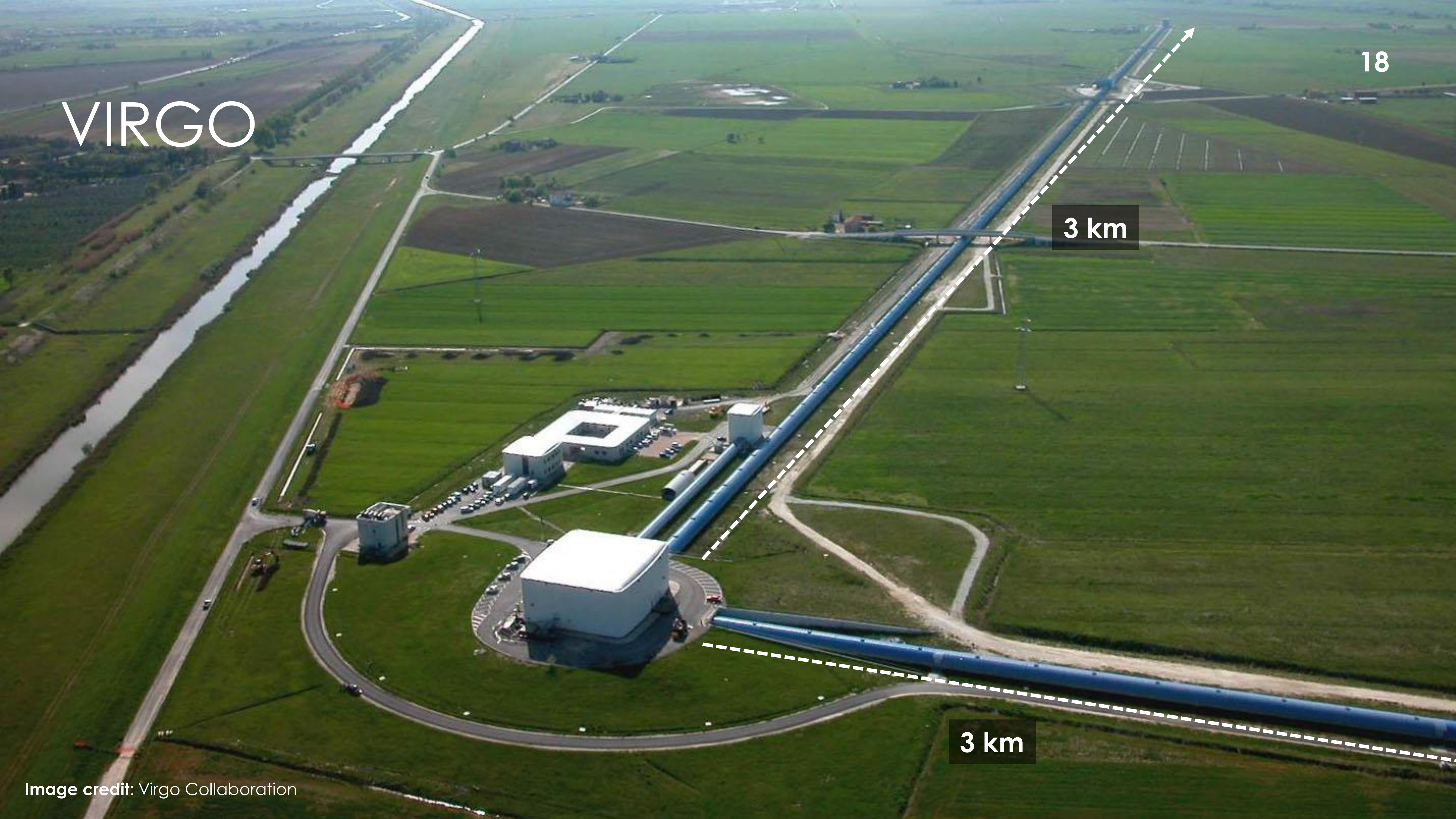
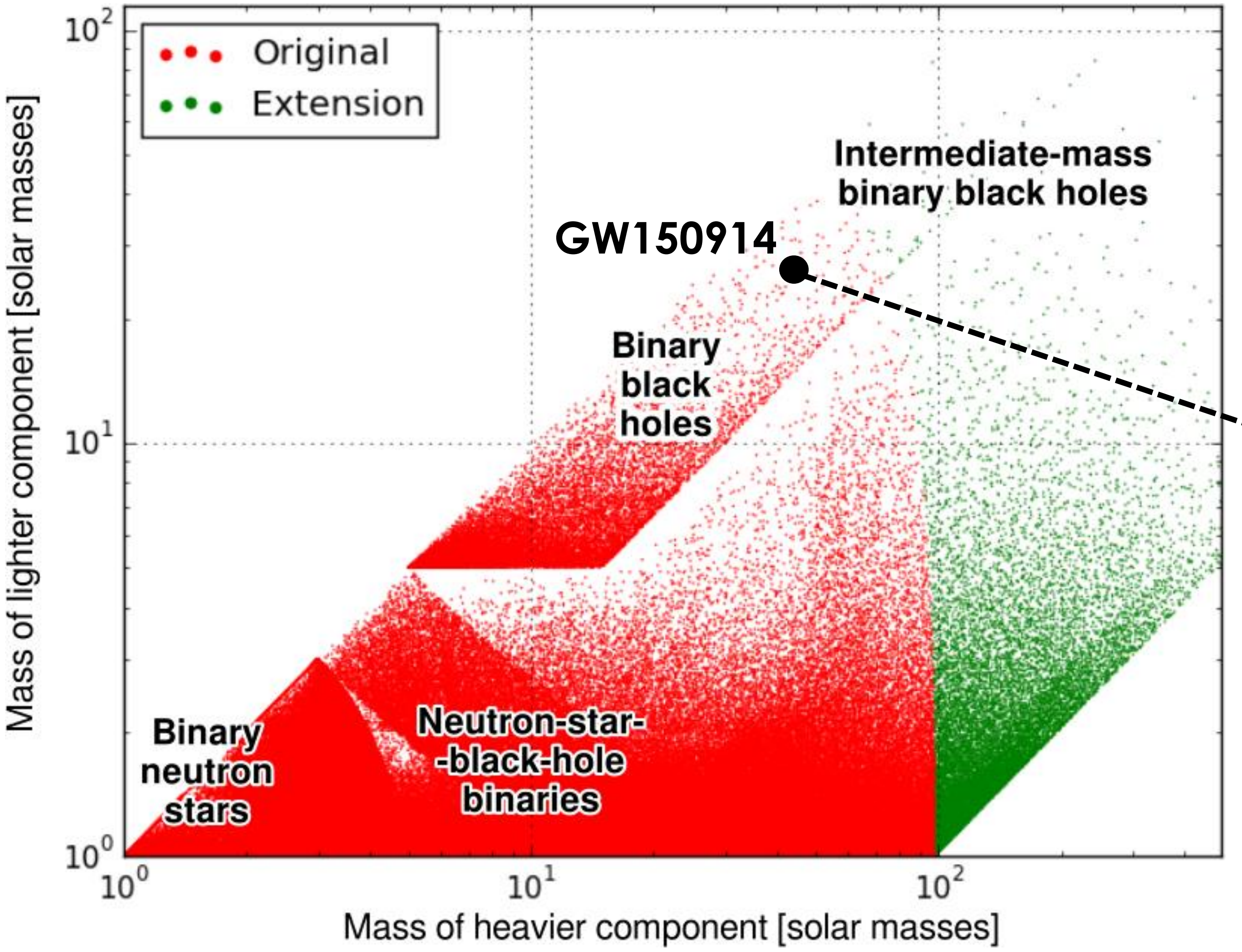


Image credit: Virgo Collaboration

MODELED (CBC) SEARCHES: MATCHED FILTERING

Please see Alex Nitz's and Alan Weinstein's talk!



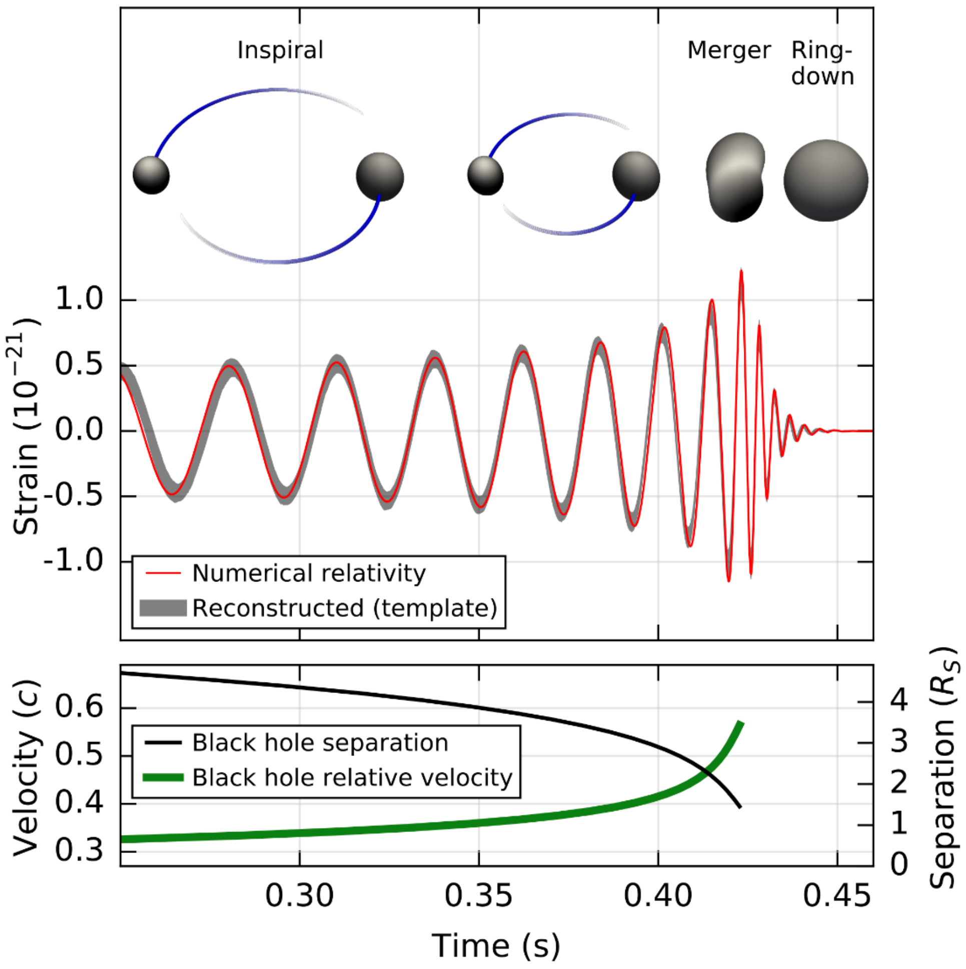


Image credit: LIGO/Caltech, Tito Dal Canton, Sennett, Phys. Rev. Lett. **116**, 061102 (2016), Phys. Rev. Lett. **116**, 241103 (2016)

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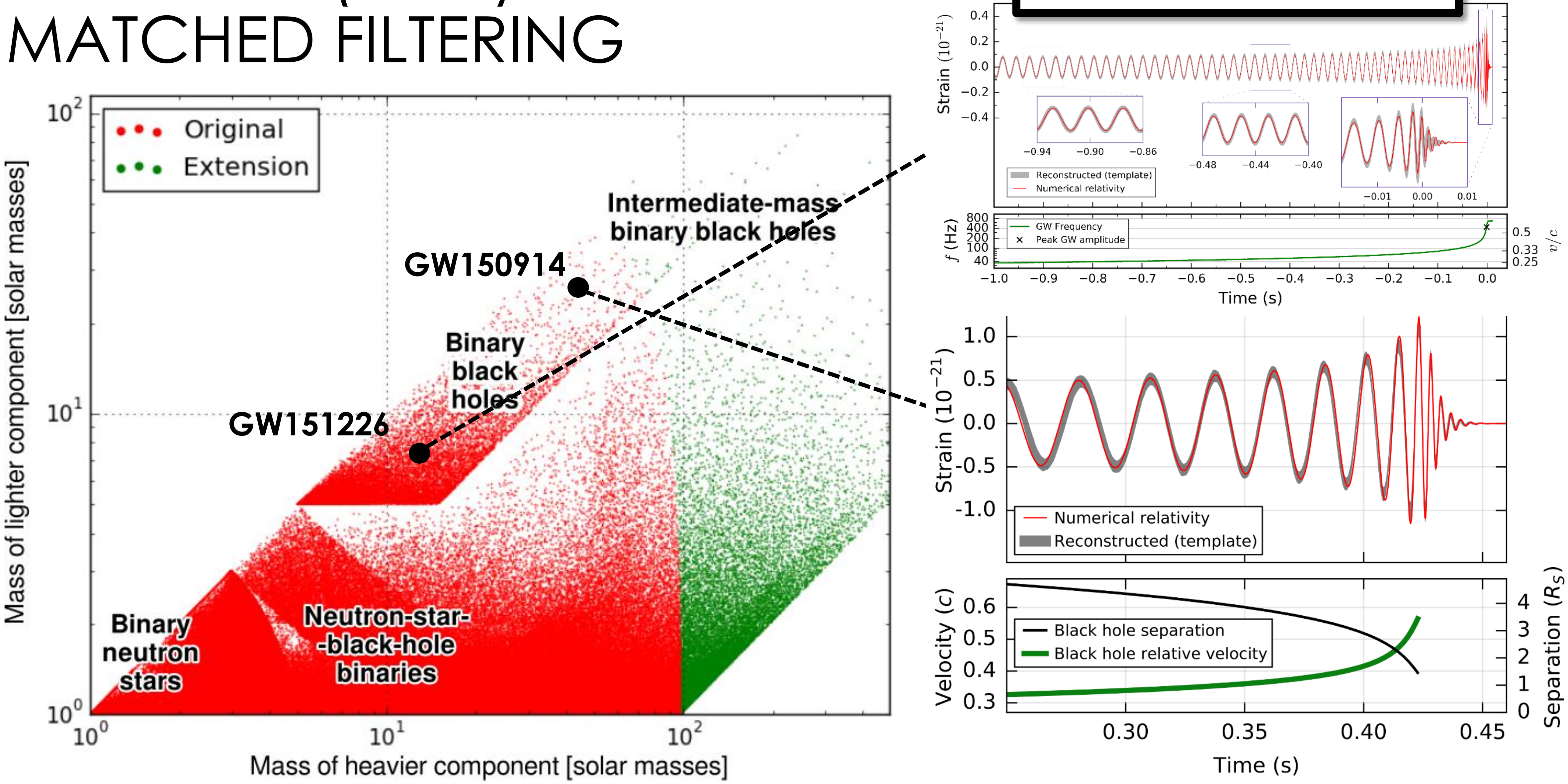

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UNMODELED (BURST) SEARCHES: EXCESS POWER

GW150914

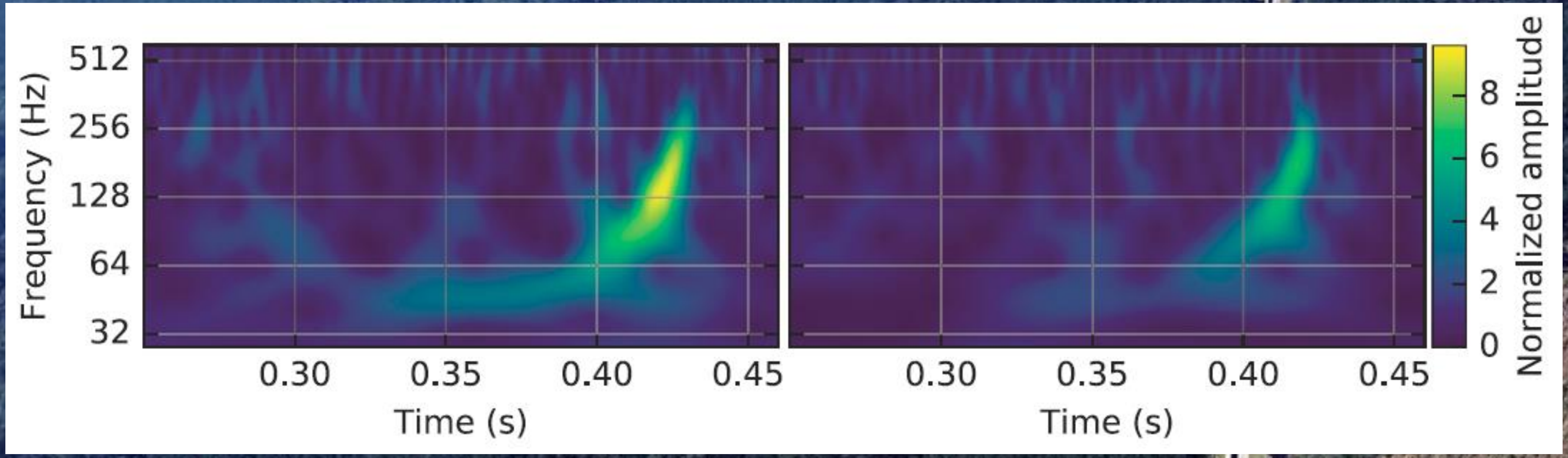
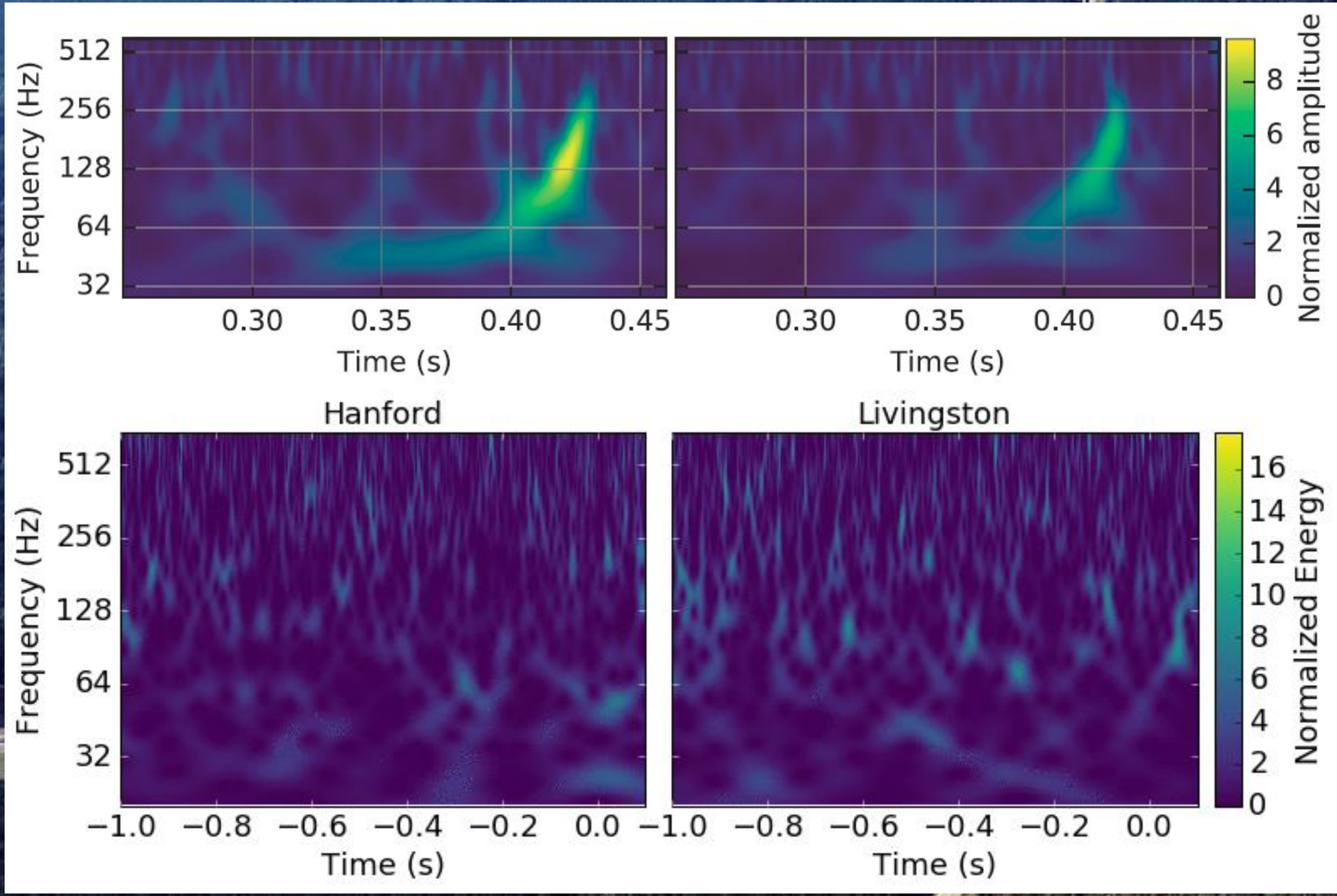


Image credits: Science Magazine, B. P. Abbott *et al.*, Phys. Rev. Lett. **116**, 061102 (2016)

UNMODELED (BURST) SEARCHES: EXCESS POWER

GW150914

GW151226



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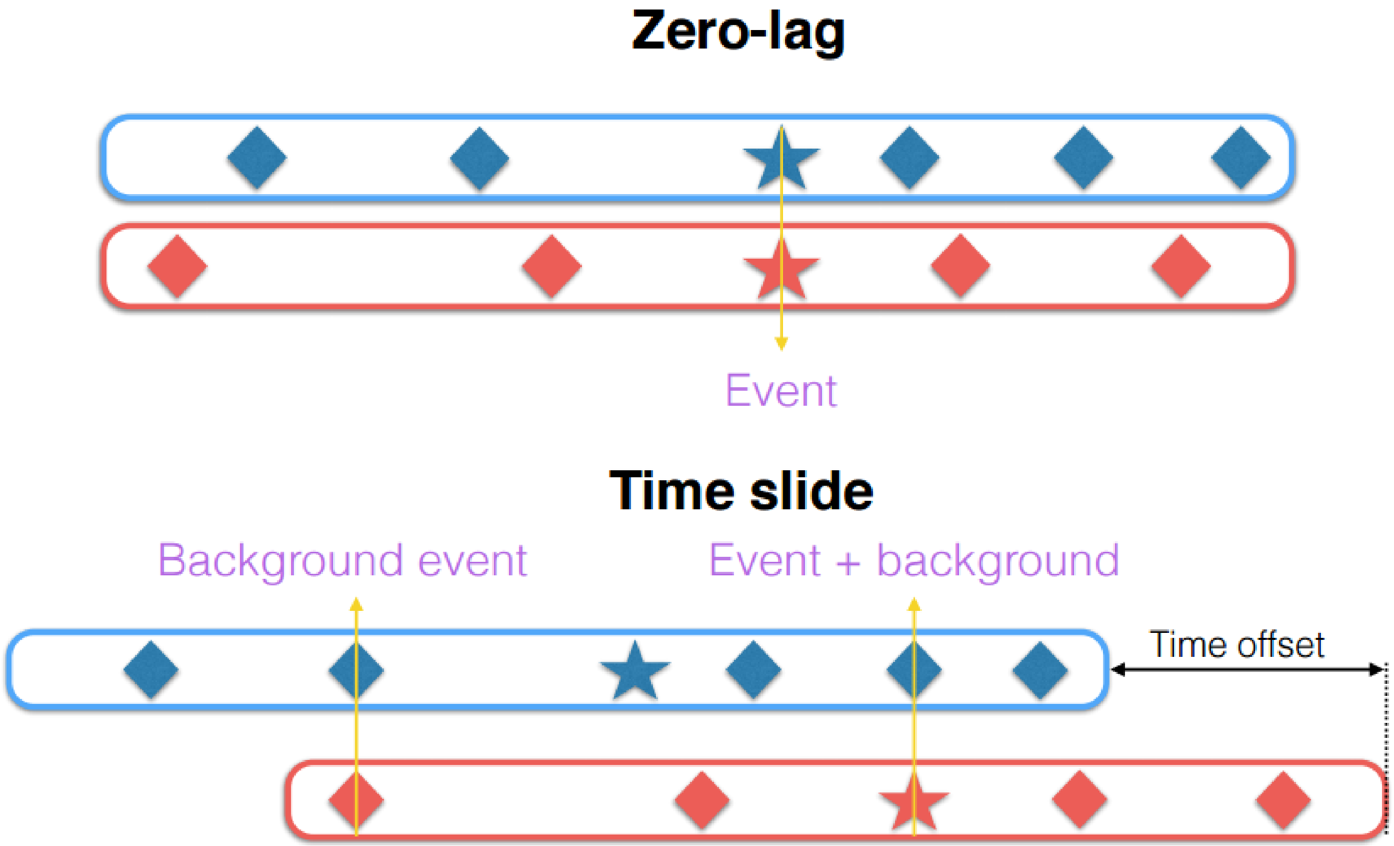
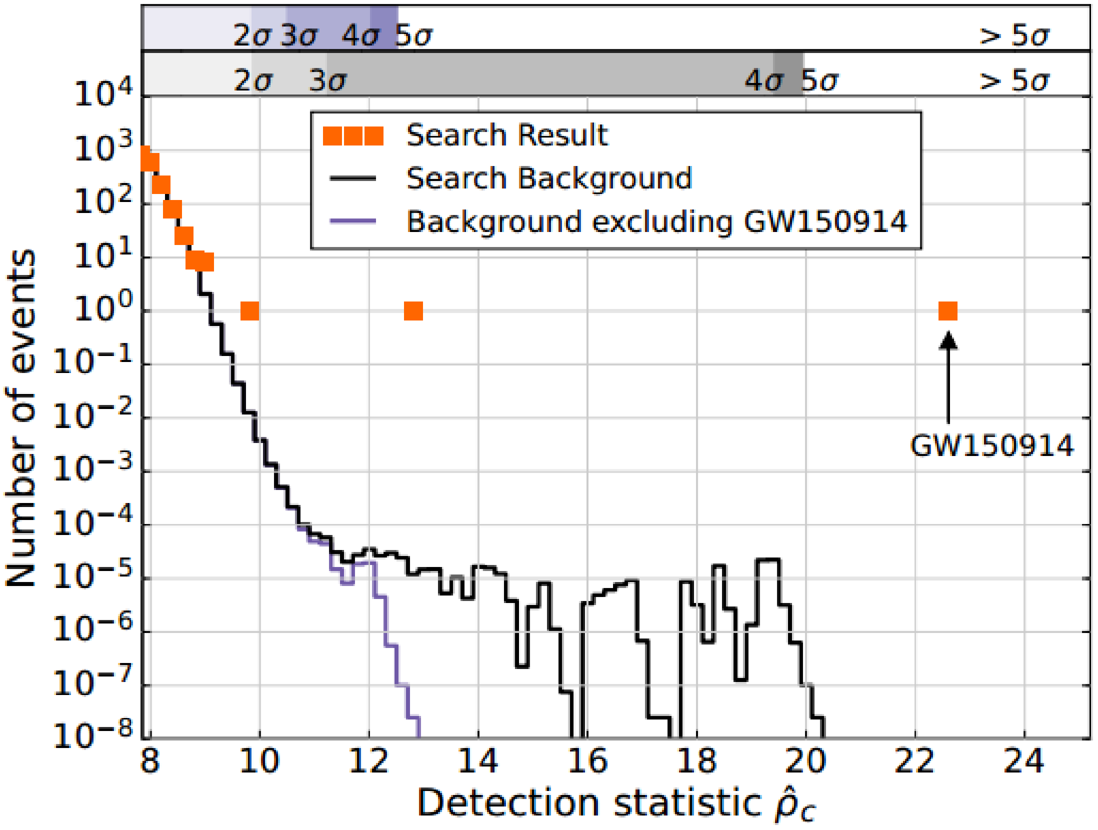
MEASURING BACKGROUNDS TO DETERMINE SIGNIFICANCE





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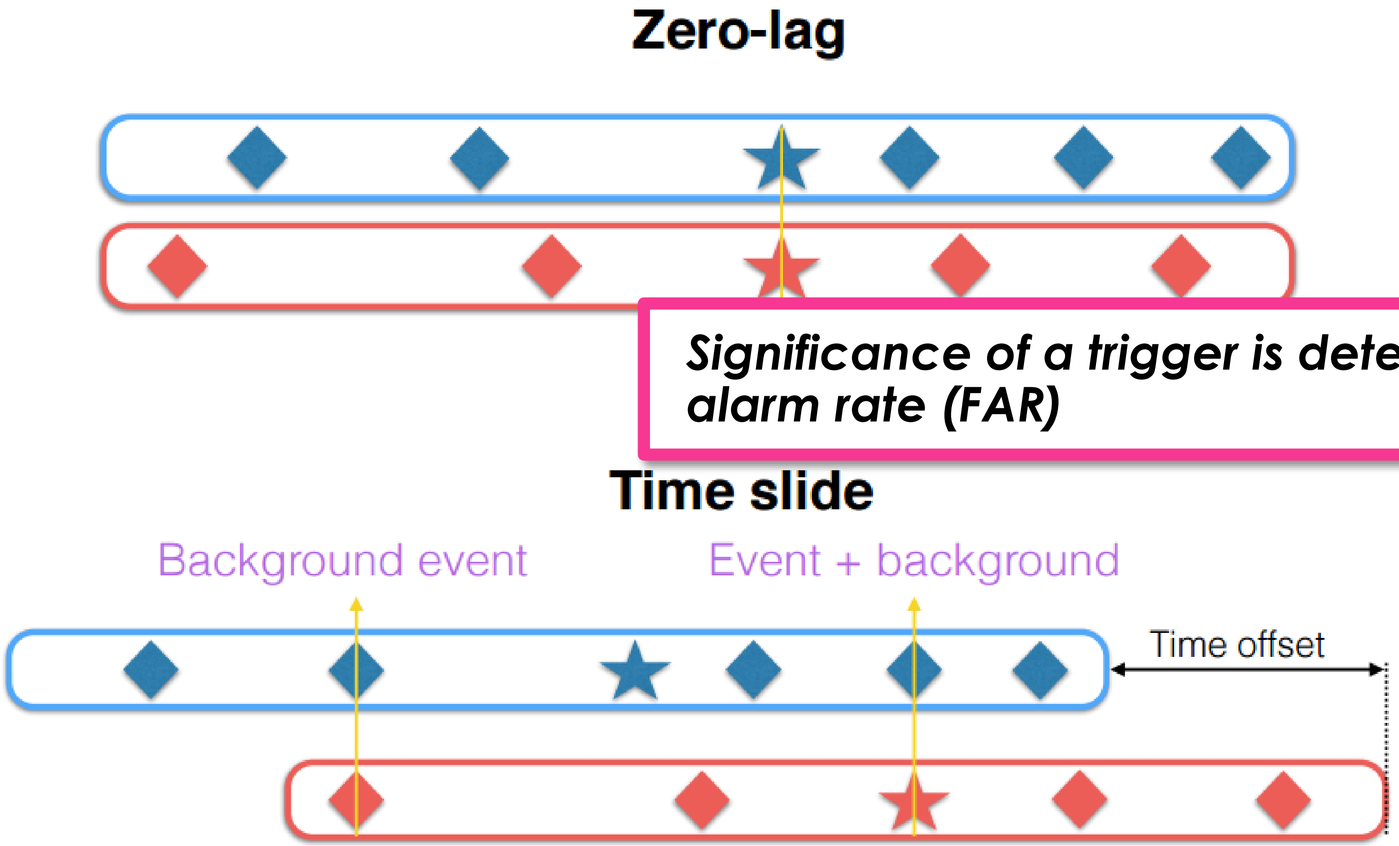
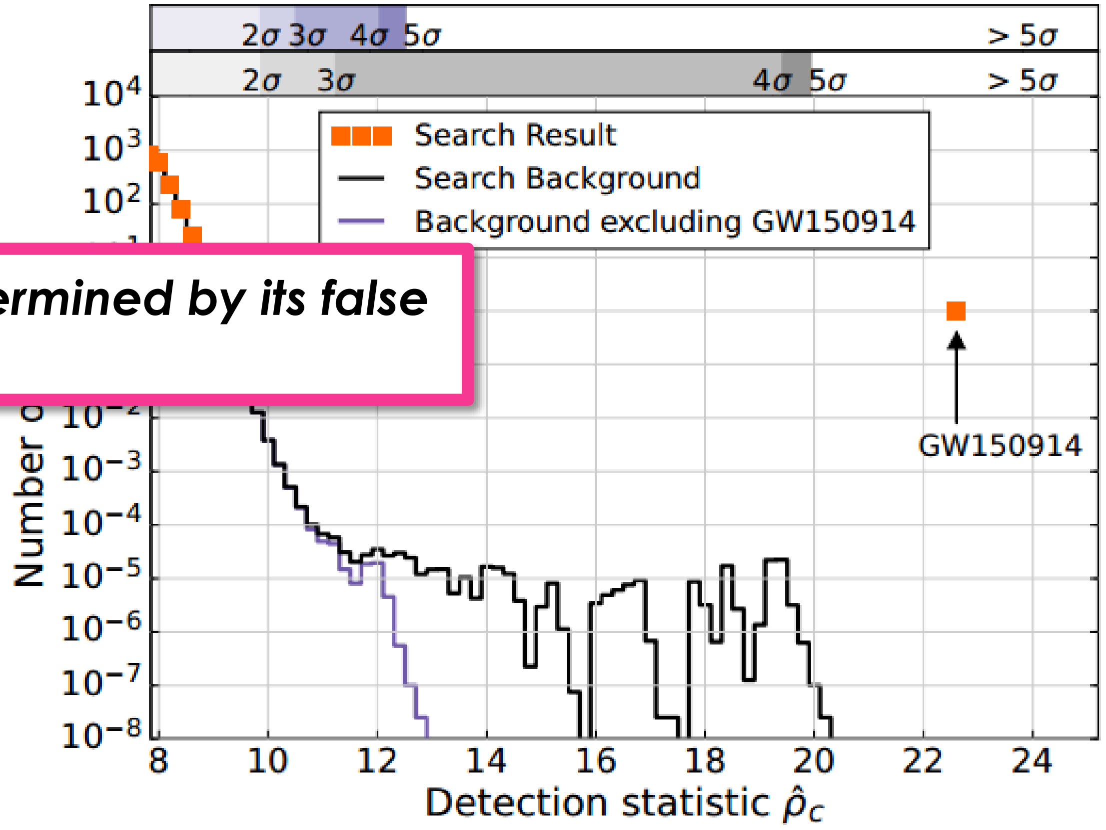




Significance of a trigger is determined by its false alarm rate (FAR)

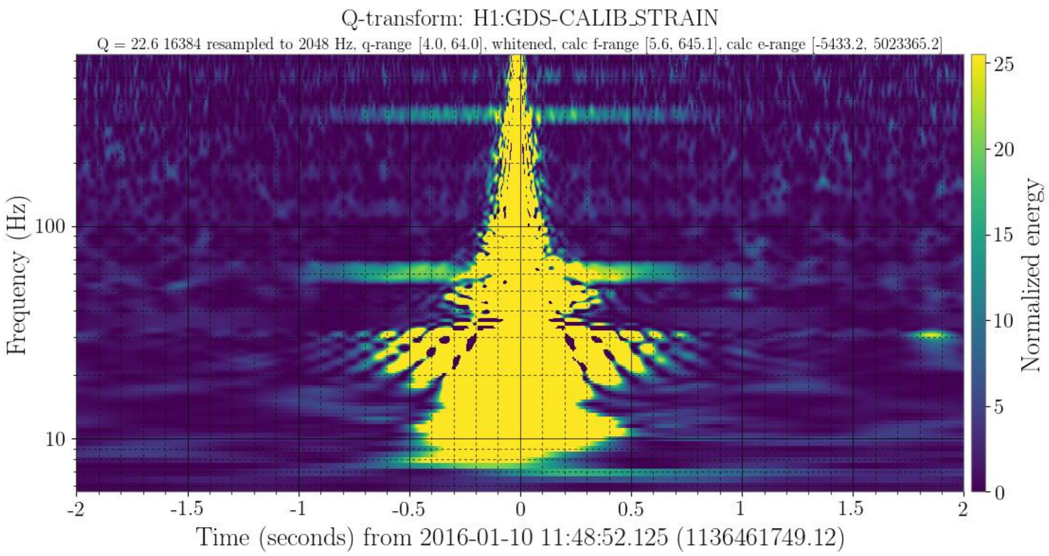
Image credits: Laura Nuttall, B. P. Abbott *et al.*, Phys. Rev. Lett. **116**, 061102 (2016)

Please see Jess McIver's and Katerina Chatziioannou's talk!

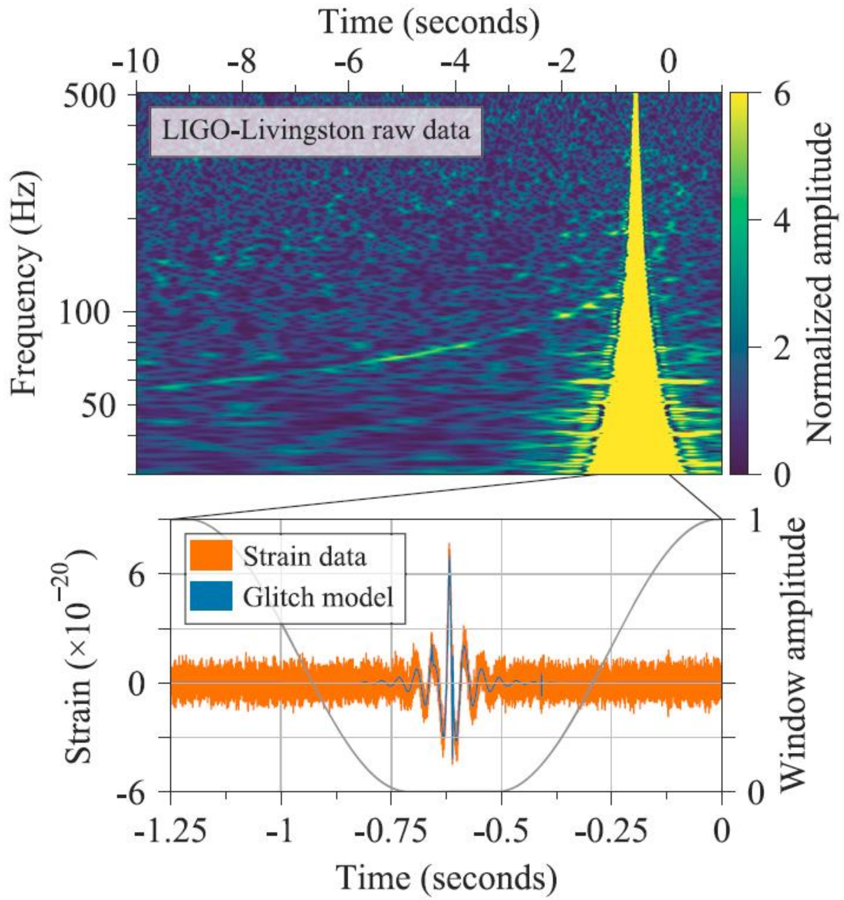
CHECKING FOR GLITCHES AND NOISE

1. Could transient noise account for a trigger that we see? → If yes, veto

2. Could transient noise bias the estimate of the source parameter/properties? → If yes, mitigate

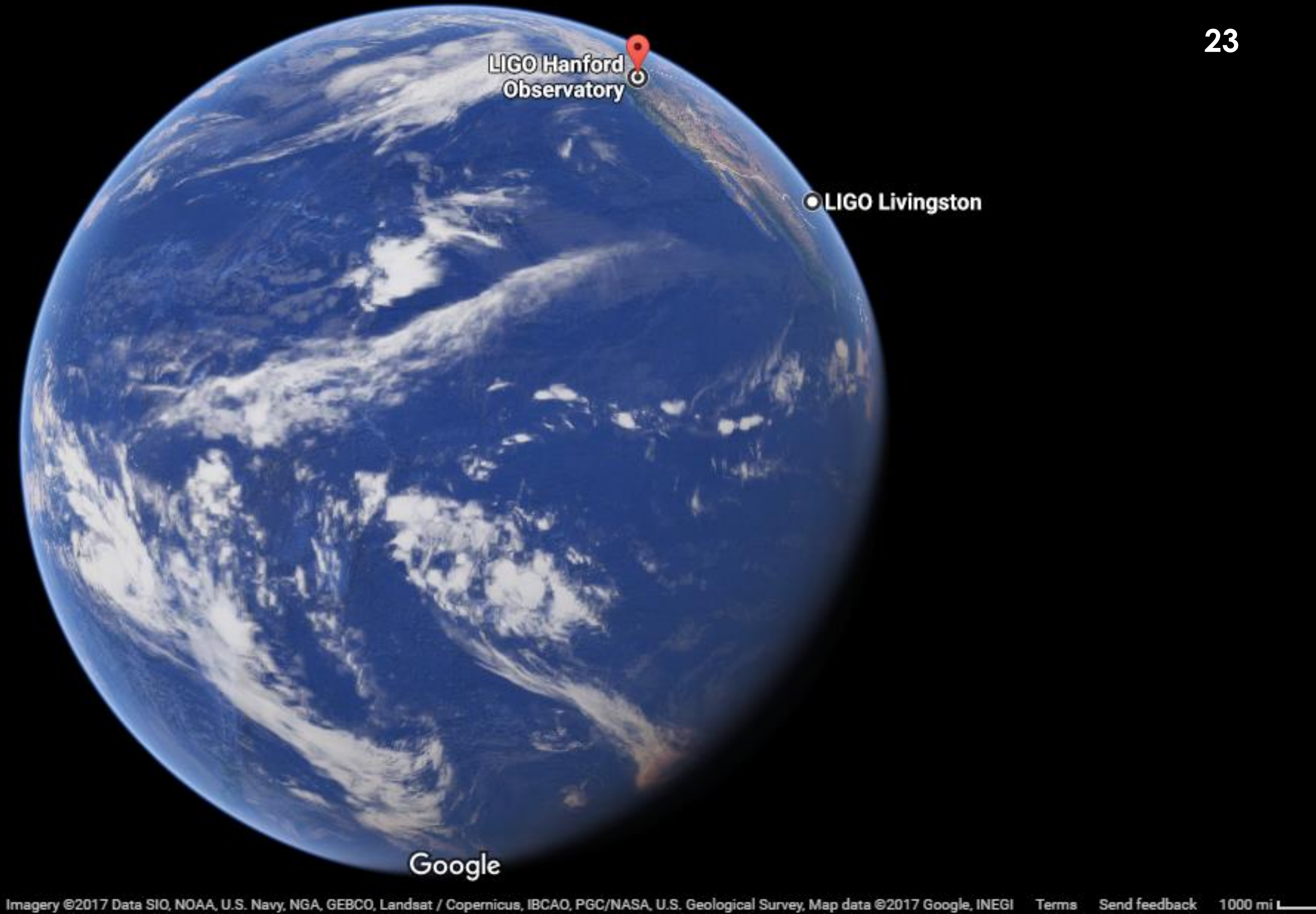


Q-transform of a glitch at Hanford caused by an overflow in the Y-end test mass control loop



Q-transform of data containing GW170817

Image credits: B. P. Abbott *et al.*, Phys. Rev. Lett. **119**, 161101 (2017)


LIGO Hanford Observatory
LIGO Livingston
Google
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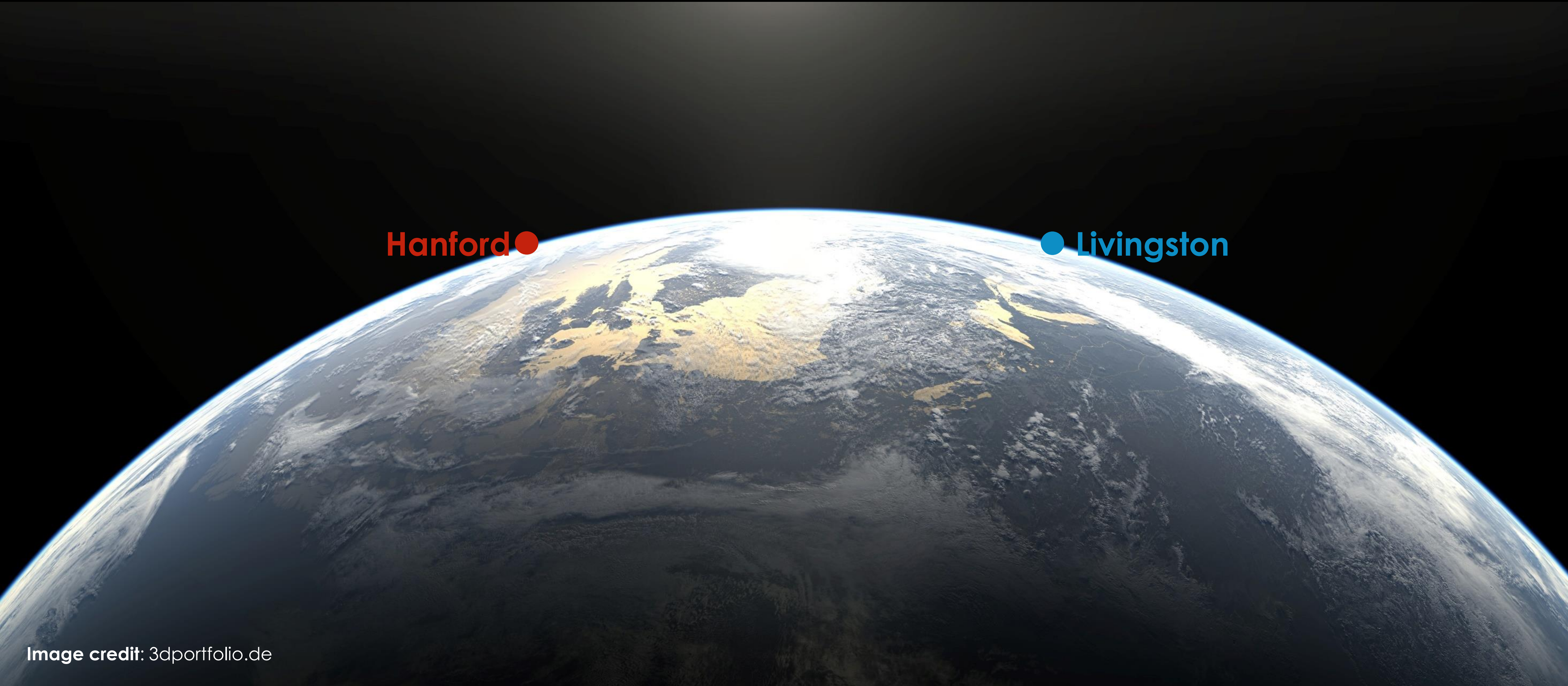
IDEA BEHIND DETECTION AND LOCALIZATION W/ 2 DETECTORS



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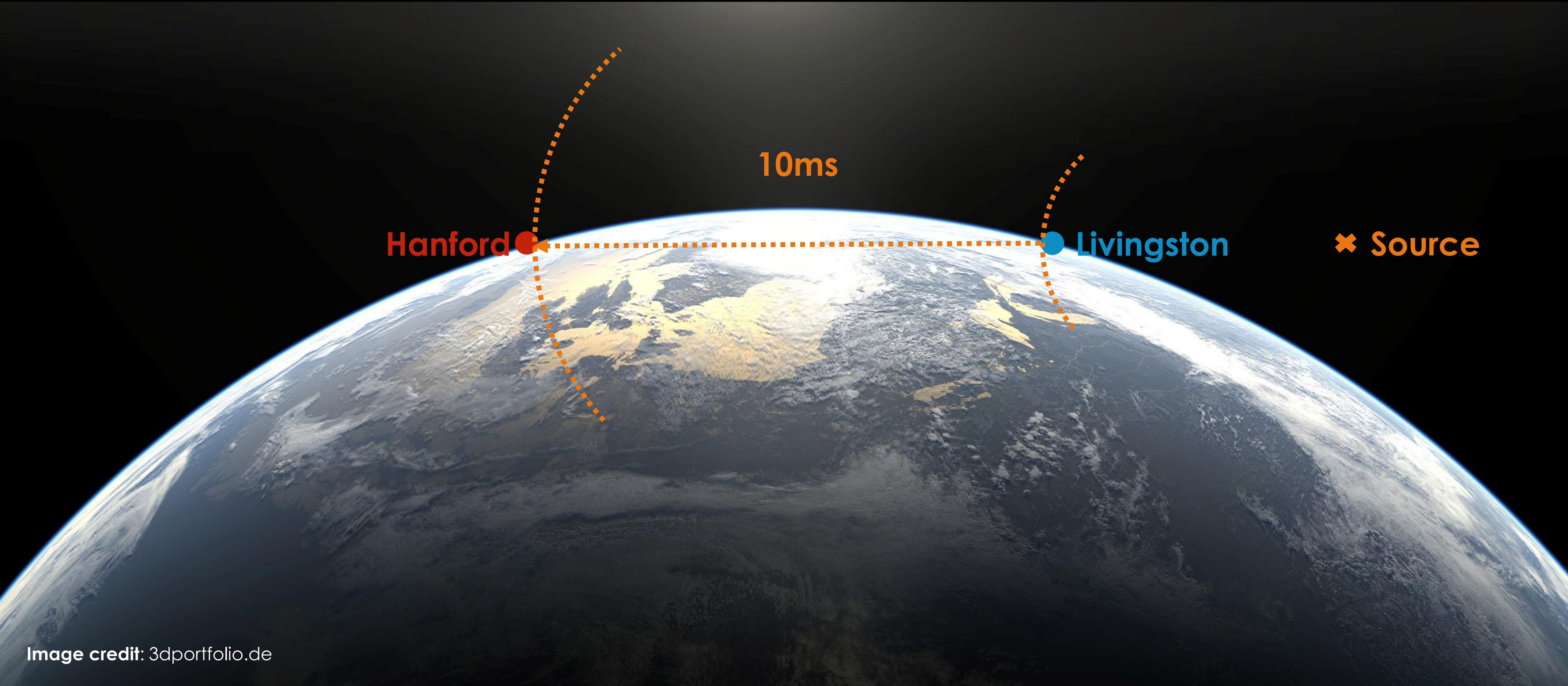

Image credit: 3dportfolio.de

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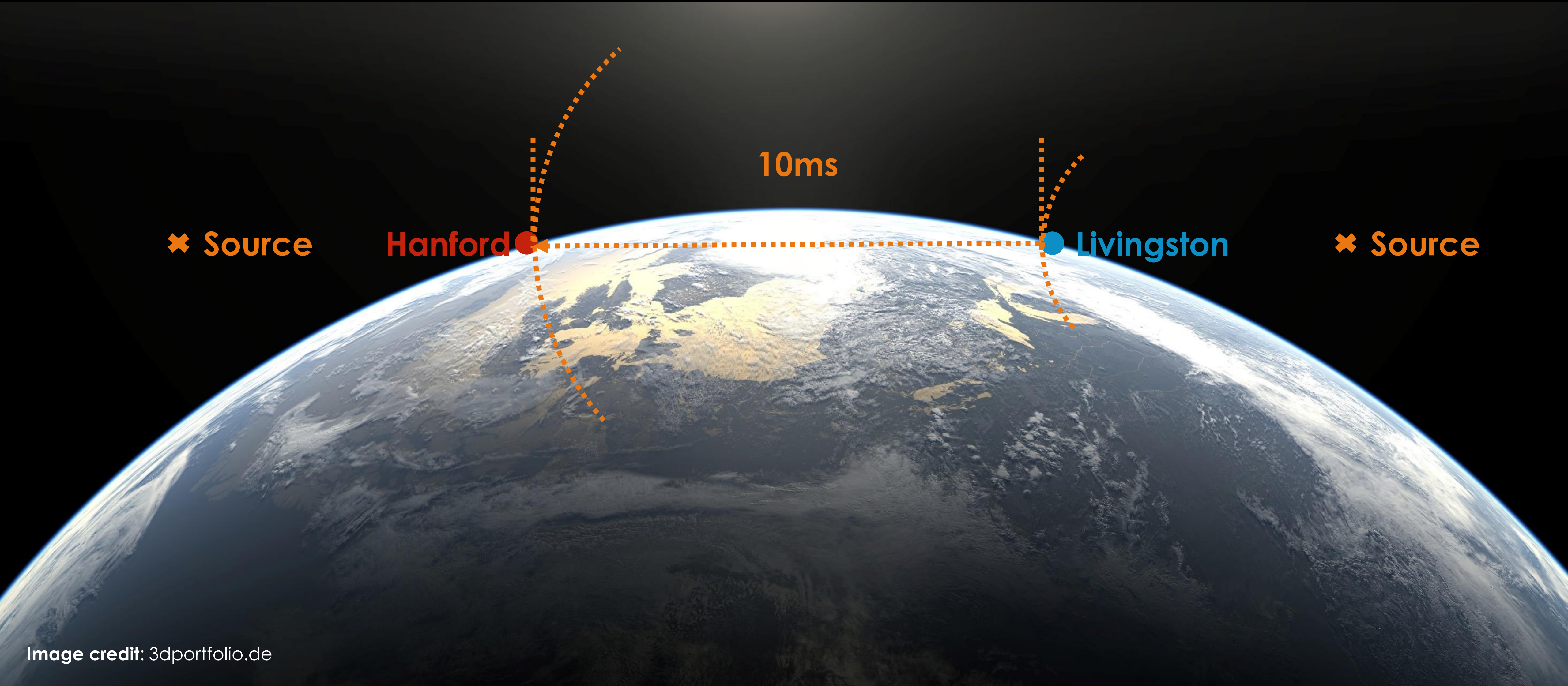

Image credit: 3dportfolio.de

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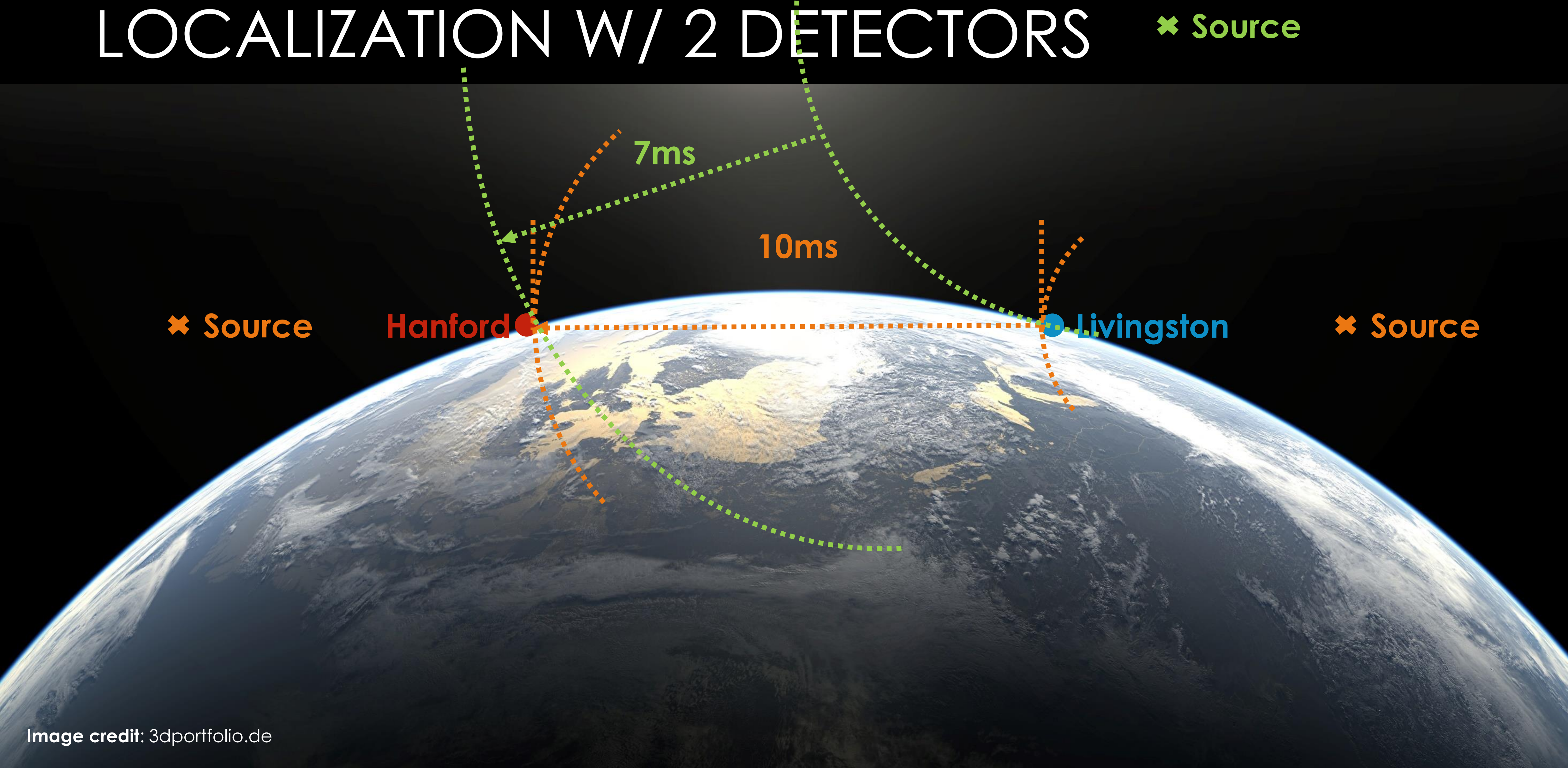


Image credit: 3dportfolio.de

IDEA BEHIND DETECTION AND LOCALIZATION W/ 2 DETECTORS

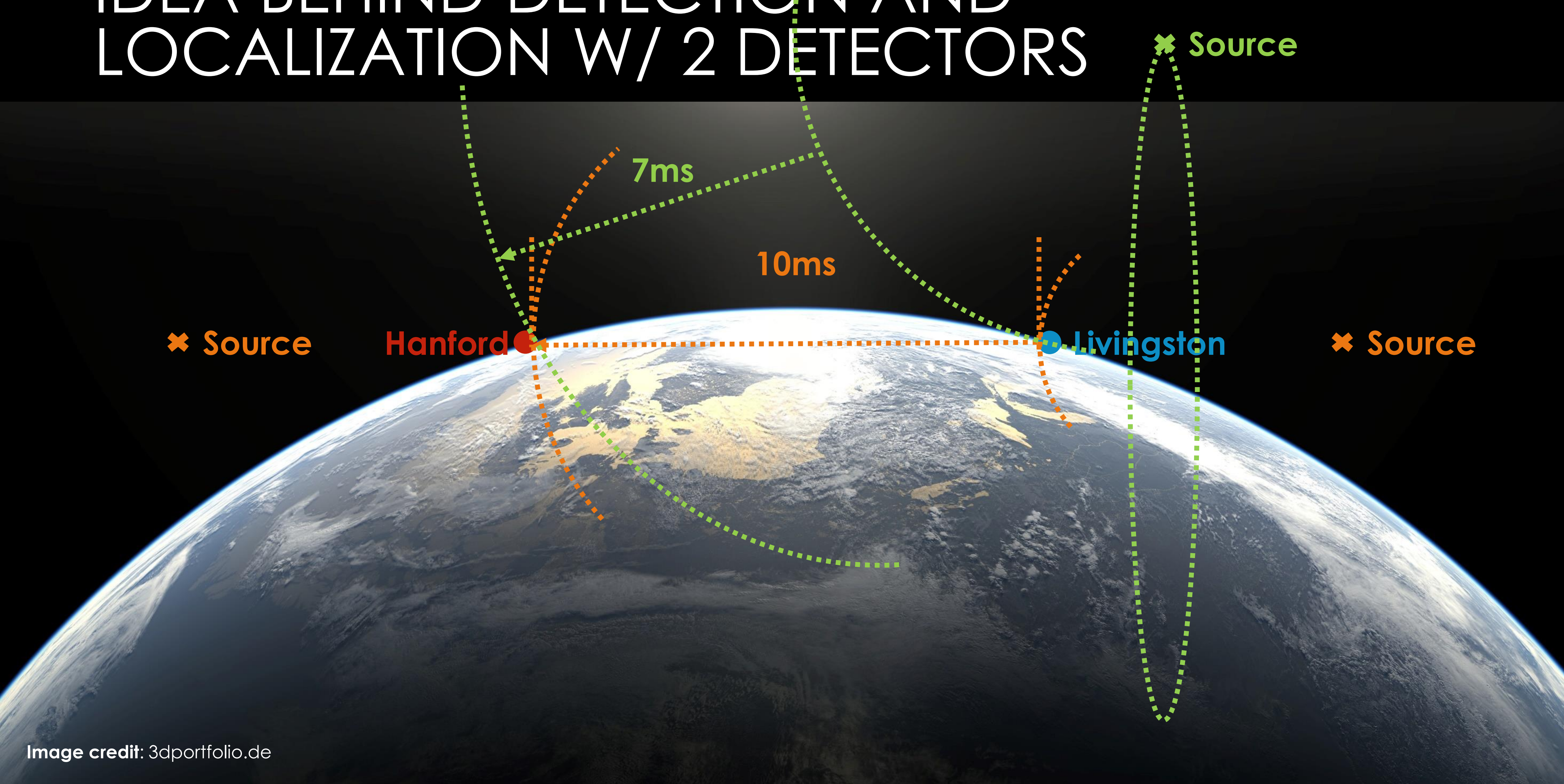


Image credit: 3dportfolio.de

IDEA BEHIND DETECTION AND LOCALIZATION W/ 2 DETECTORS

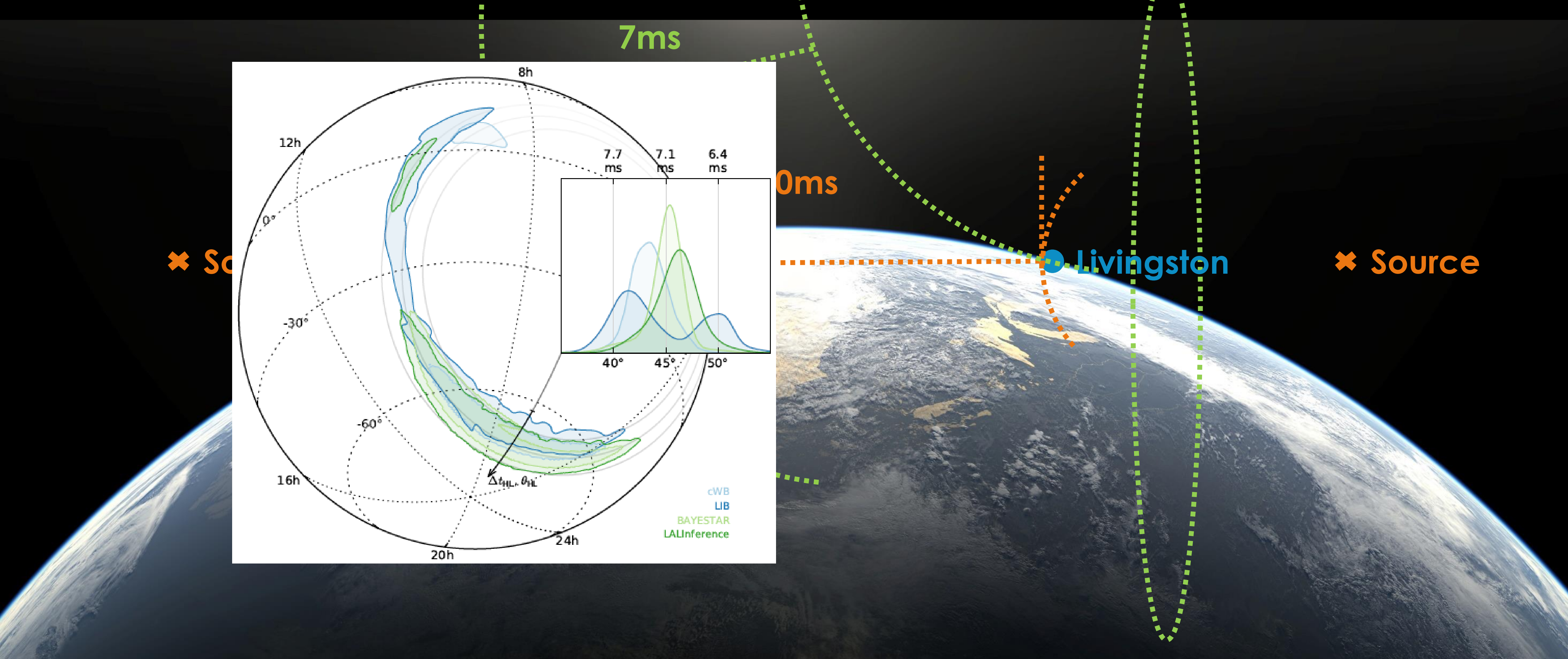


Image credits: 3dportfolio.de, B. P. Abbott *et al.*, ApJ Letters, Volume **826**, Number 1 (2016), L. P. Singer *et al.*, ApJ Letters, **829**:L15, (2016)

IDEA BEHIND DETECTION AND LOCALIZATION W/ 2 DETECTORS

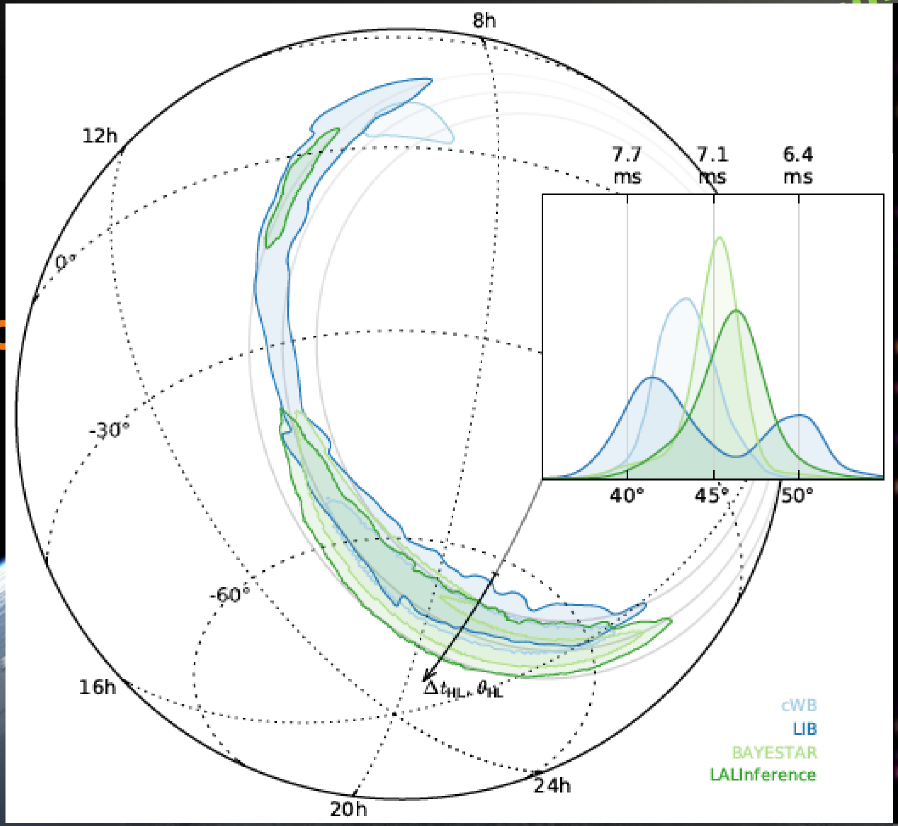


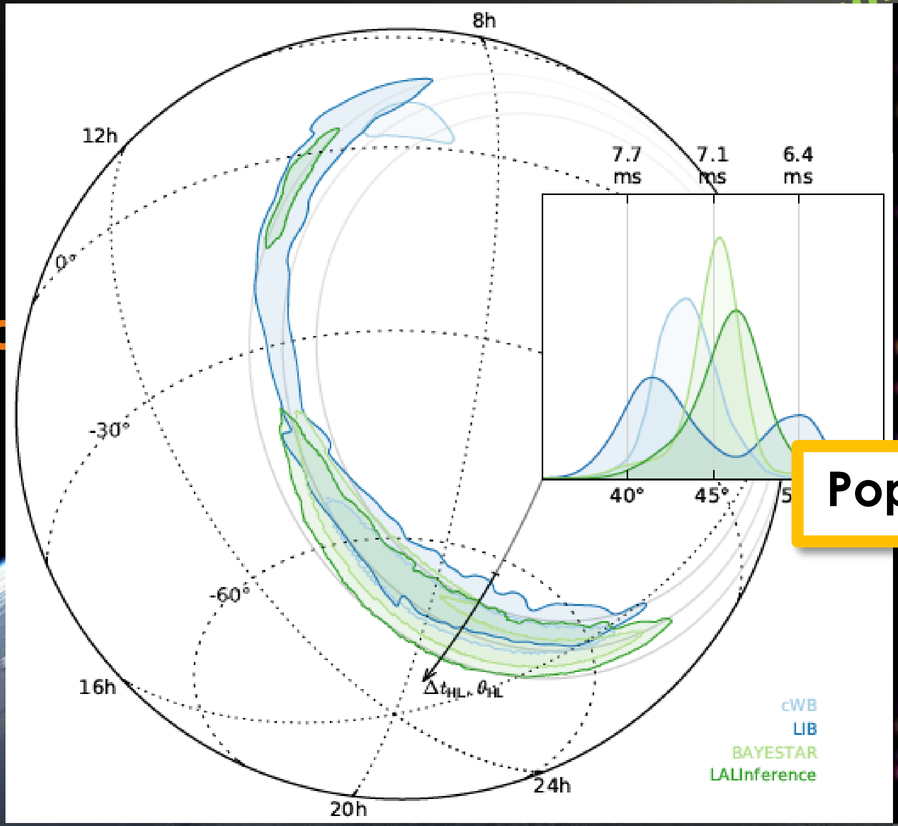
Image credits: 3dportfolio.de, B. P. Abbott *et al.*, ApJ Letters, Volume **826**, Number 1 (2016), L. P. Singer *et al.*, ApJ Letters, **829**:L15, (2016)

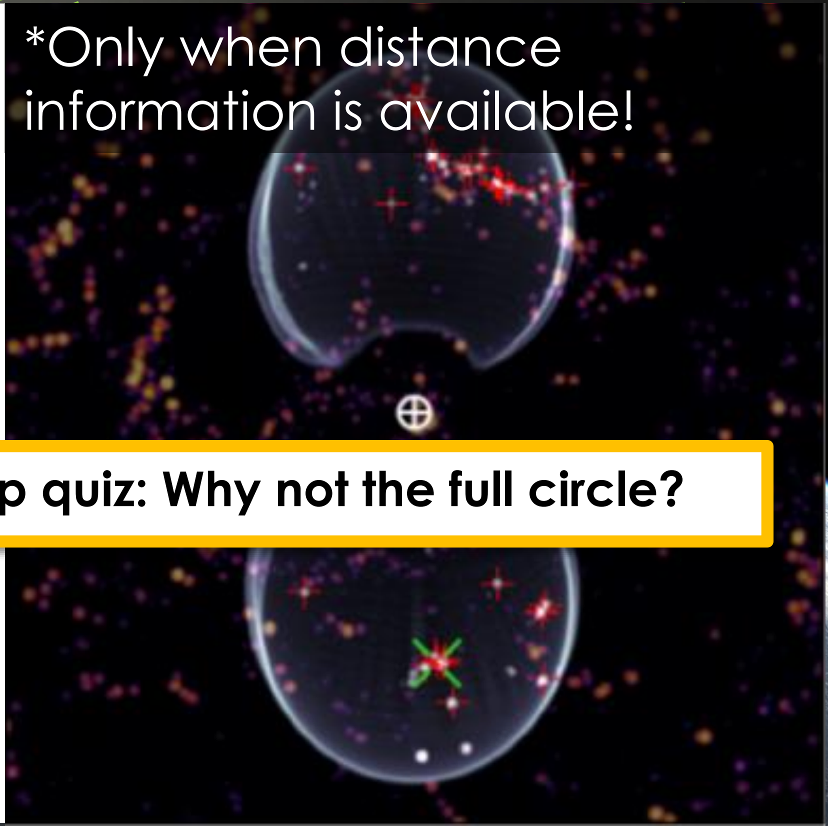
IDEA BEHIND DETECTION AND LOCALIZATION W/ 2 DETECTORS

Source

7ms

✖ Sc





*Only when distance information is available!

Pop quiz: Why not the full circle?

✖ Source

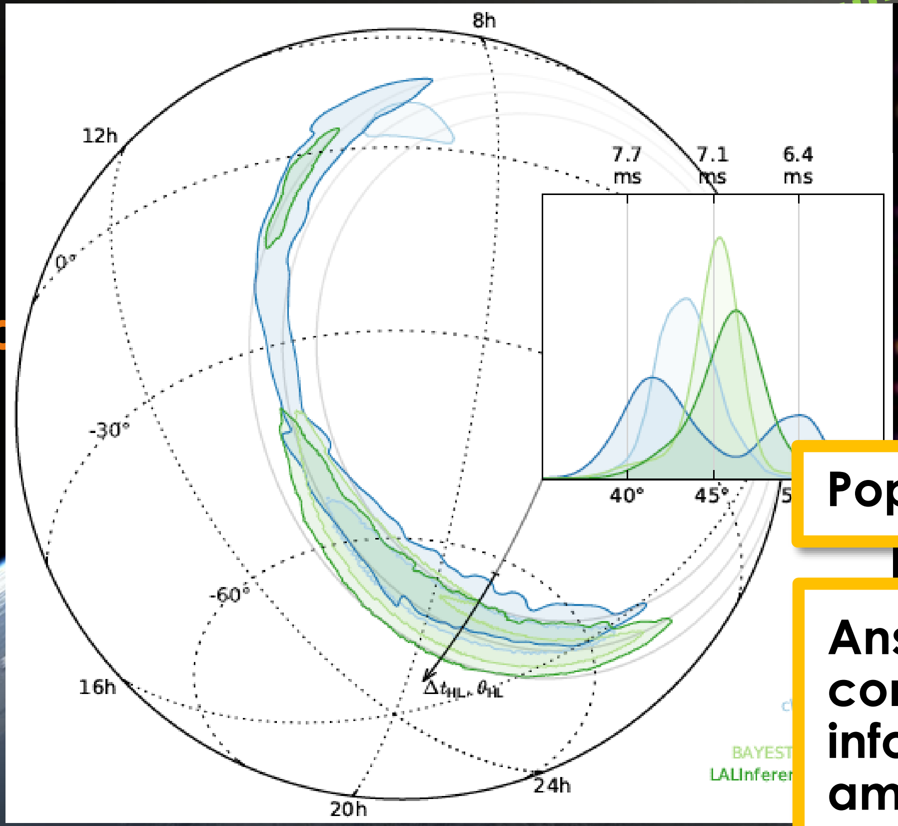
Image credits: 3dportfolio.de, B. P. Abbott *et al.*, ApJ Letters, Volume **826**, Number 1 (2016), L. P. Singer *et al.*, ApJ Letters, **829**:L15, (2016)

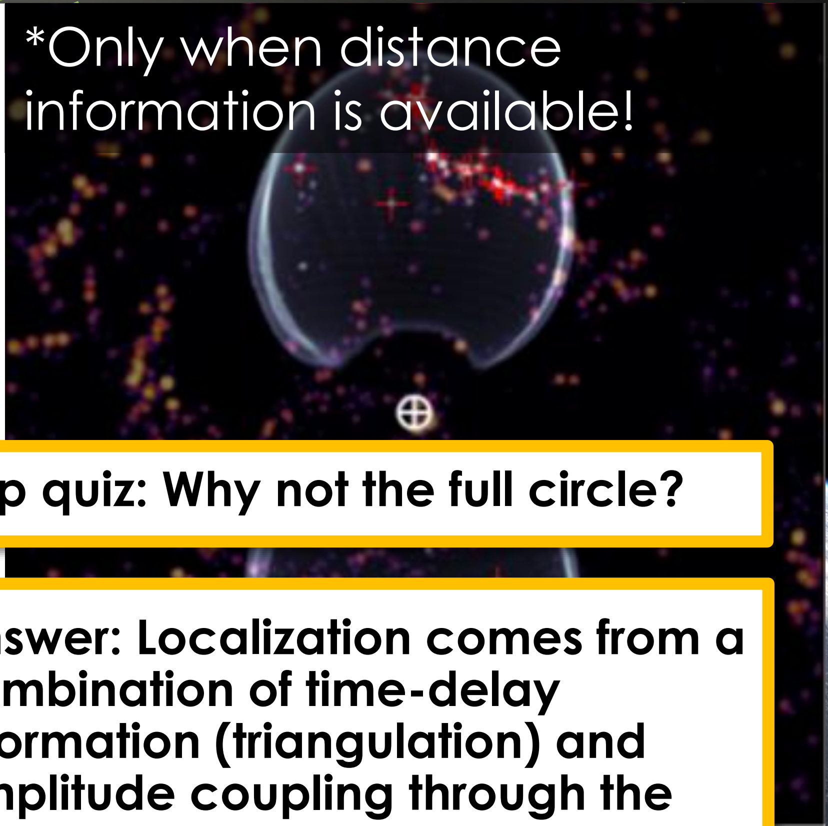
IDEA BEHIND DETECTION AND LOCALIZATION W/ 2 DETECTORS

✖ Source

7ms

✖ Sc





*Only when distance information is available!

✖ Source

Pop quiz: Why not the full circle?

Answer: Localization comes from a combination of time-delay information (triangulation) and amplitude coupling through the antenna patterns

Image credits: 3dportfolio.de, B. P. Abbott *et al.*, ApJ Letters, Volume **826**, Number 1 (2016), L. P. Singer *et al.*, ApJ Letters, **829**:L15, (2016)

INTERFEROMETER ANTENNA RESPONSE

A detector in a plane that is perpendicular to the incident gravitational waves has a response tensor in the reference frame of the beam splitter:

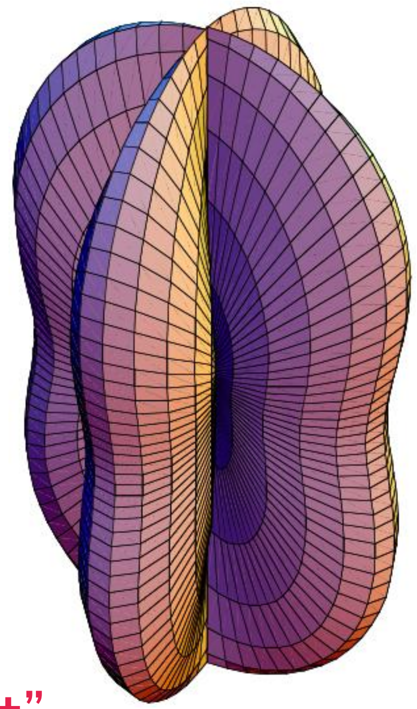
$$R^{\alpha\beta} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

where the resulting response of the detector is given by:

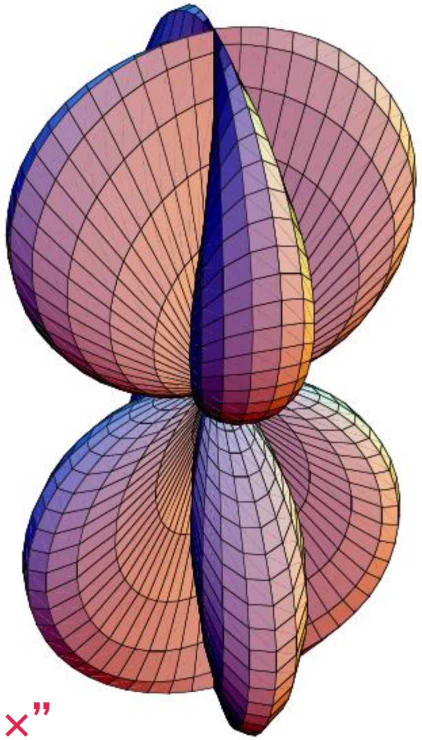
$$\frac{\Delta L}{L} = \frac{1}{2} h_{\alpha\beta} R^{\alpha\beta}$$

Key point: ***gravitational waves from arbitrary directions*** **(given by the Euler angles, φ, θ, ψ)** ***will have different projections onto this response tensor that can be described as antenna patterns***

For polarization angle ψ = 0:



"+" polarization



"×" polarization

Image credit: Keppel, Drew Garvin (2009) Ph.D. Dissertation

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A LIGO interferometer is a microphone, not a telescope, where sensitivity depends on propagation direction and polarizations

where the resulting response of the detector is given by:

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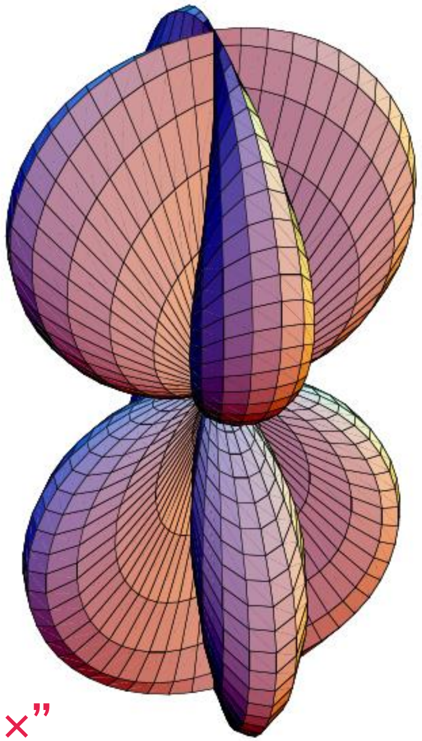


“×” polarization

Image credit: Keppel, Drew Garvin (2009) Ph.D. Dissertation

INTERFEROMETER ANTENNA RESPONSE

For polarization angle = 0:

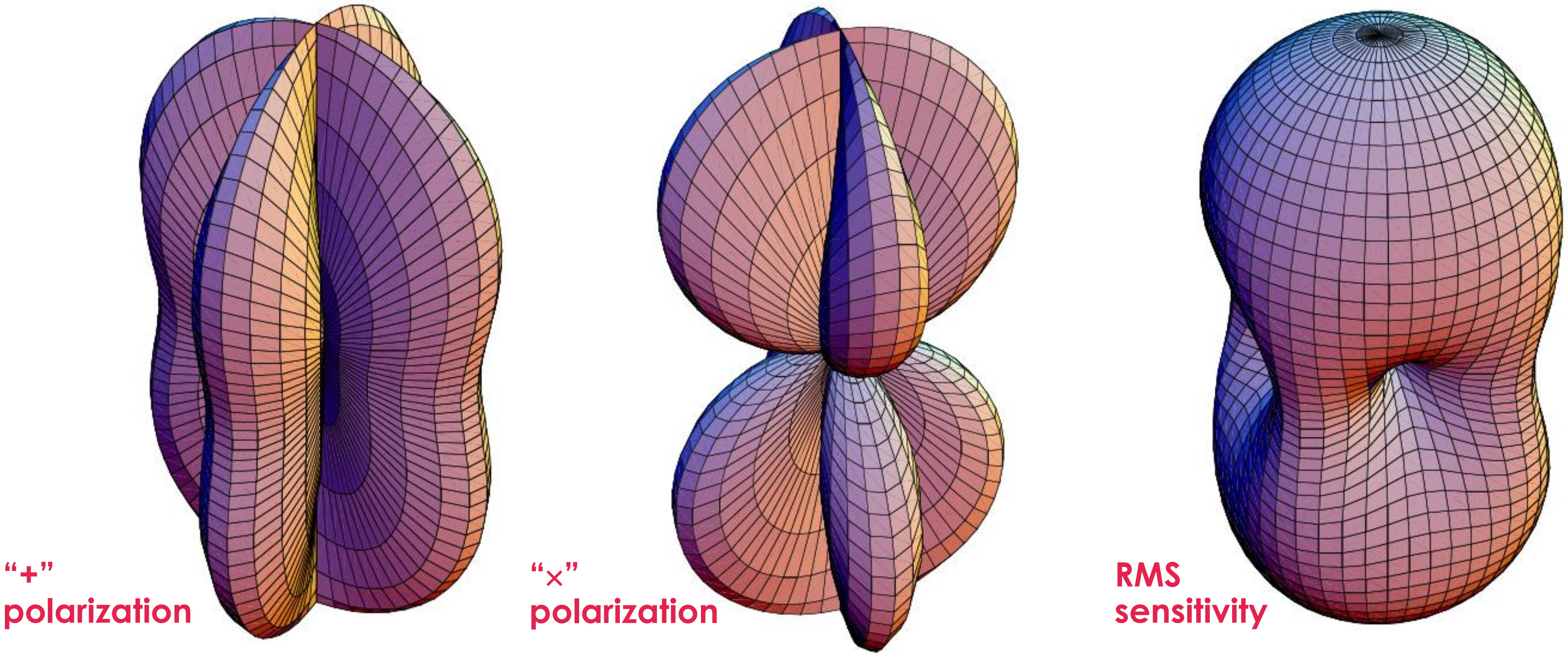
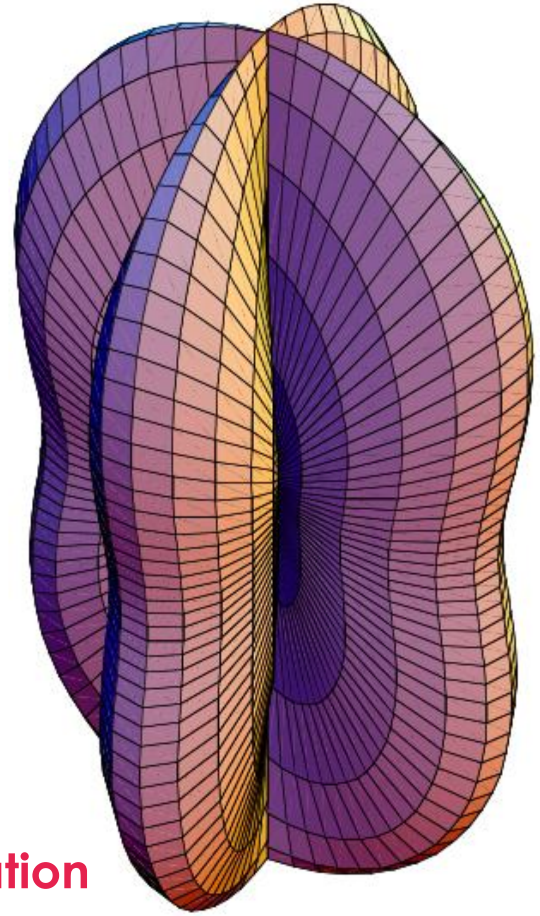


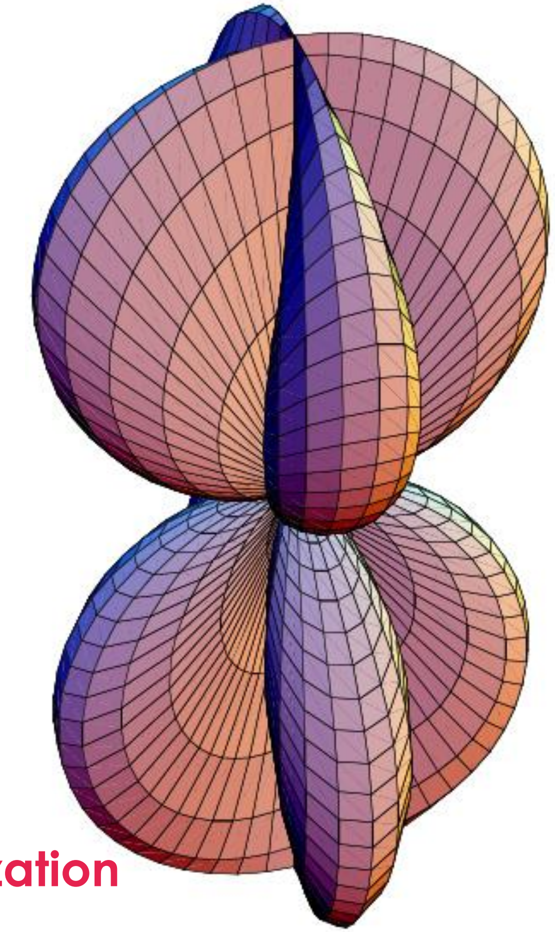
Image credit: Keppel, Drew Garvin (2009) Ph.D. Dissertation

INTERFEROMETER ANTENNA RESPONSE

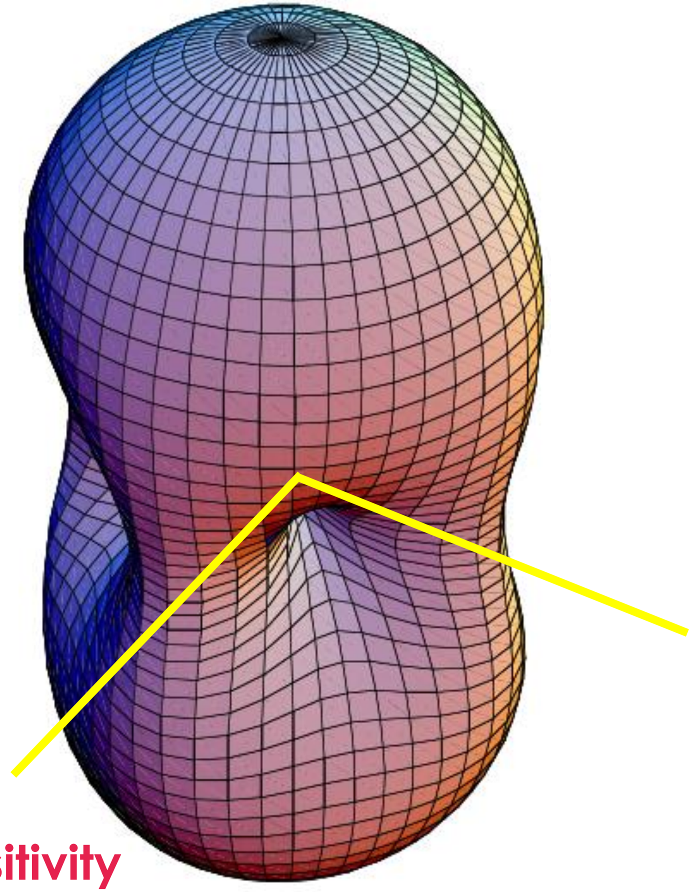
For polarization angle = 0:



"+"
polarization



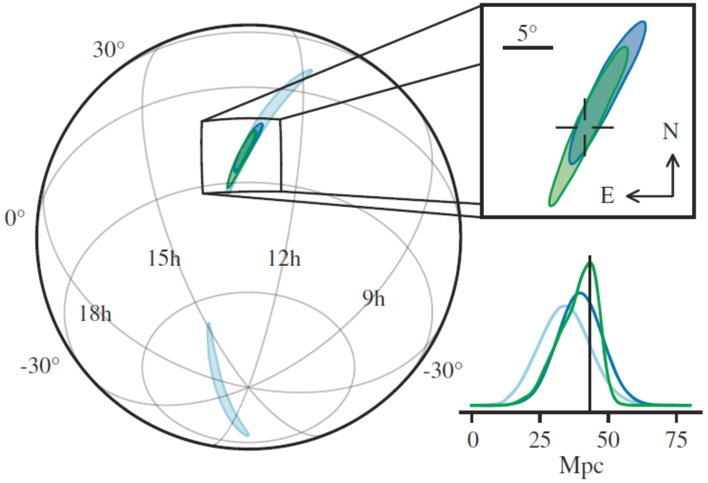
"×"
polarization

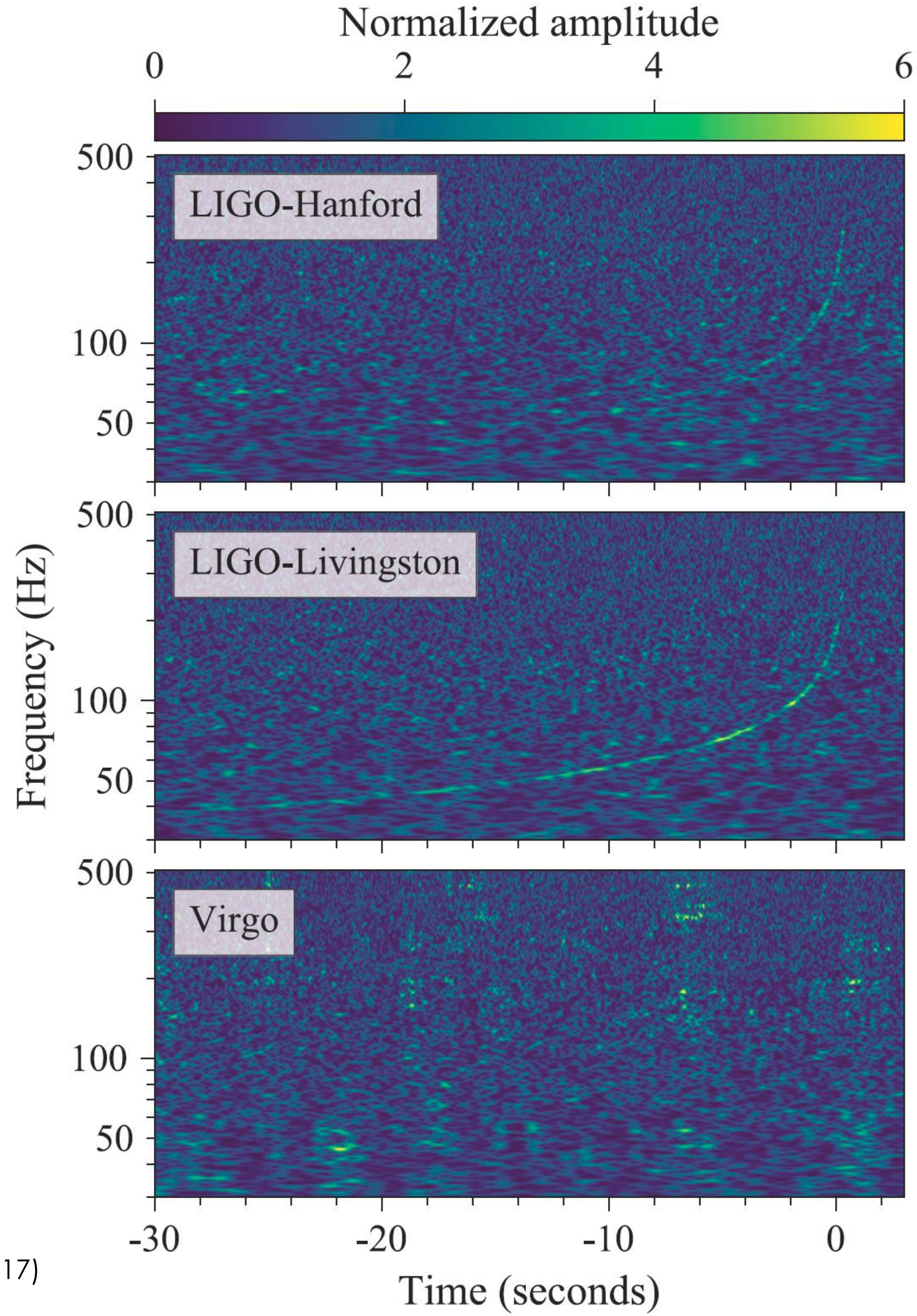


RMS
sensitivity

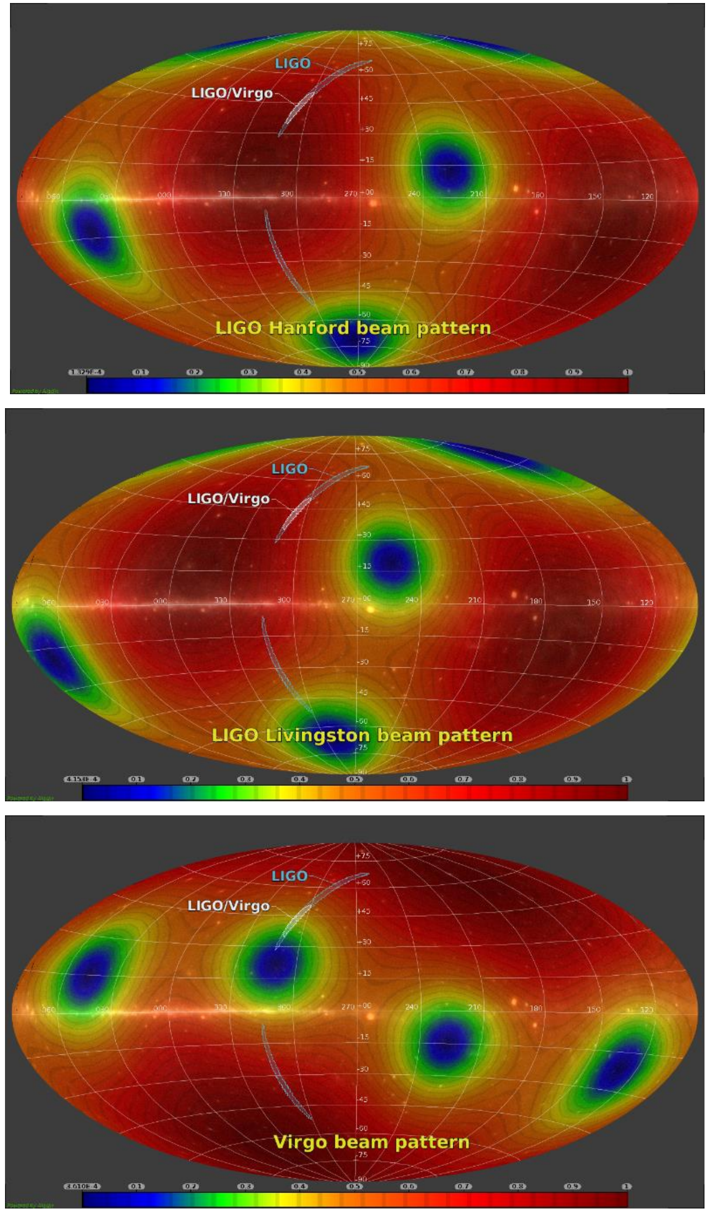
Image credit: Keppel, Drew Garvin (2009) Ph.D. Dissertation

GW170817





Galactic coordinates



Aitoff projection

Image credit: Giuseppe Greco using GWSky;
B. P. Abbott *et al.*, Phys. Rev. Lett. **119**, 161101 (2017)

LOCALIZATION W/ 3 DETECTORS ADVANCED LIGO + VIRGO

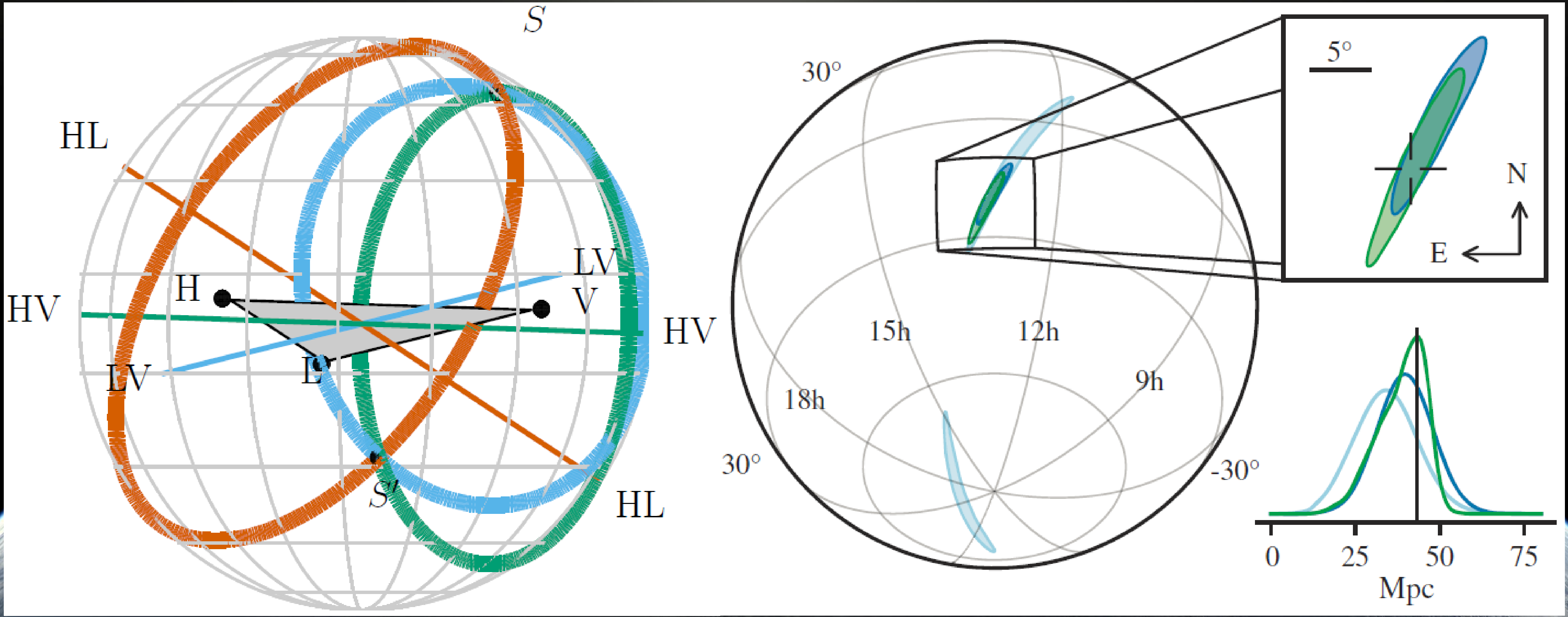


Image credits: 3dportfolio.de, , B. P. Abbott *et al.*, Living Rev. Relativity 19 (2016) 1; B. P. Abbott *et al.*, Phys. Rev. Lett. **119**, 161101 (2017)

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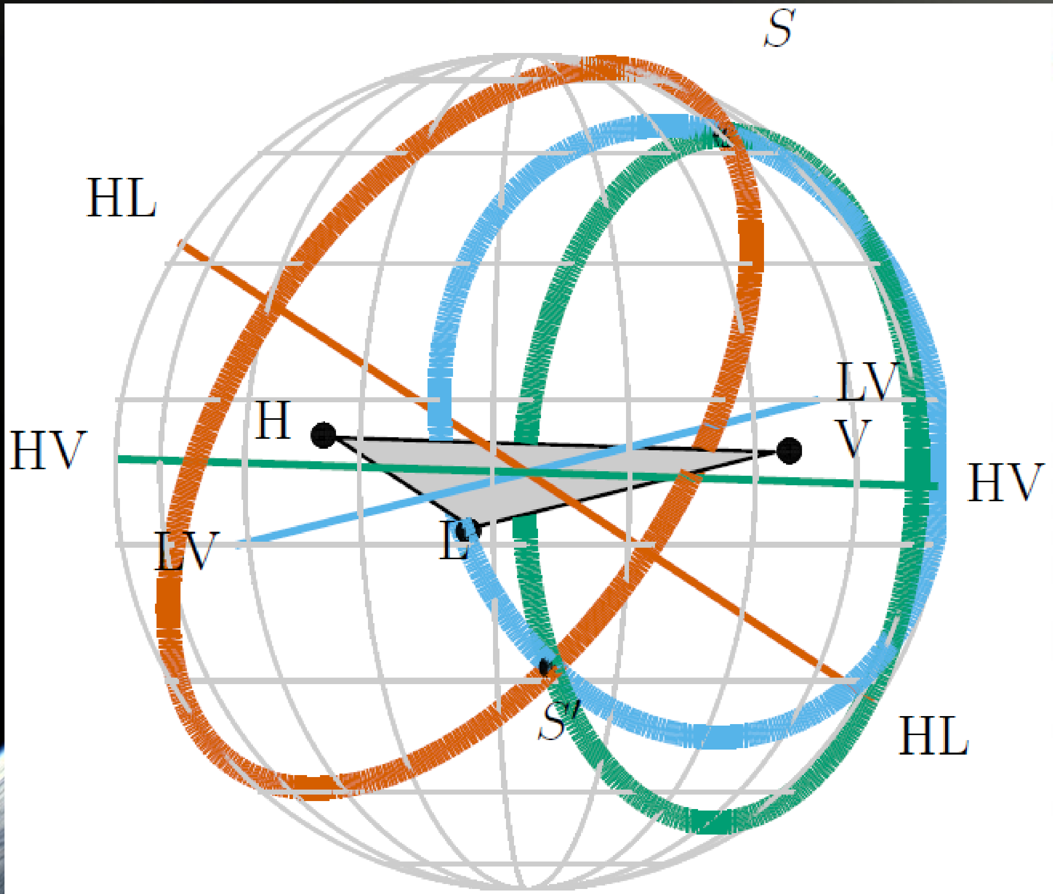

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Image credits: 3dportfolio.de, , B. P. Abbott *et al.*, Living Rev. Relativity 19 (2016) 1; B. P. Abbott *et al.*, Phys. Rev. Lett. **119**, 161101 (2017); mielkesfiberarts.com

OUTLINE

- Progenitors of gravitational wave transients
- Low-latency searches
- Information for multi-messenger astronomy

Image credit: LIGO/Caltech

OPEN PUBLIC ALERTS

From the LSC Town Hall meeting at MIT on 3/16/18:

> ***We (LIGO/Virgo) will release public alerts for all event candidates in which we have a reasonable confidence and feel we can stand behind.***

What is an open, public alert?

For more, see:

https://gw-astronomy.org/wiki/pub/OpenLVEM/TownHallMeetings2018/what-is-an-opa.pdf

OPEN PUBLIC ALERTS

Two types of GCN alerts:

"Notices": **automated, machine-readable packets. Available as VOEvent XML, binary, and plain text. Listen anonymously or pre-register for connection and delivery tracking.**

"Circulars": **human-readable, citable, non-refereed astronomical bulletins. Pre-register in order to receive and submit by email.**

Sign-up for alerts here:

https://gw-astronomy.org/registry/pages/public/lv-em-user

ALERT INFORMATION

For modeled (CBC) triggers:

Significance, time, GW signal classification, 3D sky position + distance

FAR >= 1/100 years: number will be stated in Circulars

FAR <= 1/100 years: will be described simply as “highly significant”

P_astro (higher latency): probability that the signal is astrophysical in origin accounting for both observed merger rate distribution and background distribution

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

ALERT INFORMATION

For modeled (CBC) triggers:

Significance, time, GW signal classification, 3D sky position + distance

Simple statement of signal consistency with a BNS, BBH, or NSBH signal

ProbHasNS: probability that the less massive companion has a mass consistent with a neutron star

ProbHasRemnant (higher latency): probability that there is matter left outside of the remnant

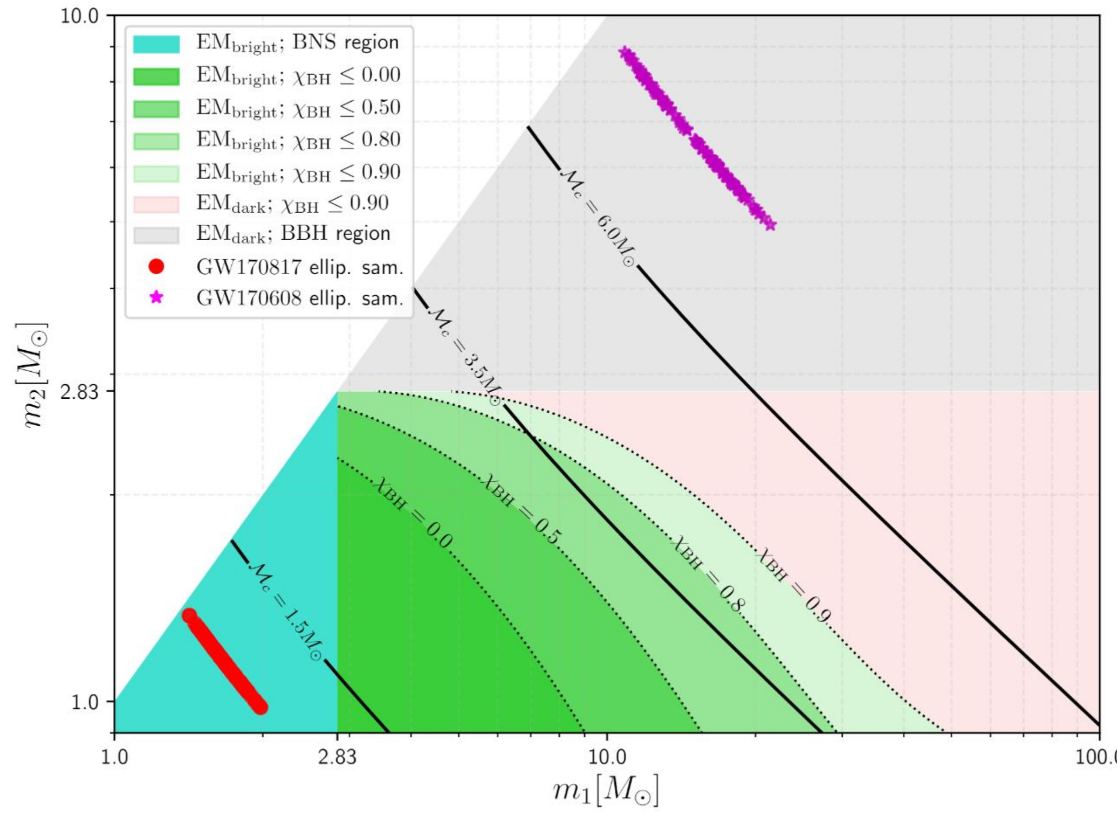

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet, Deep Chatterjee/Shaon Ghosh

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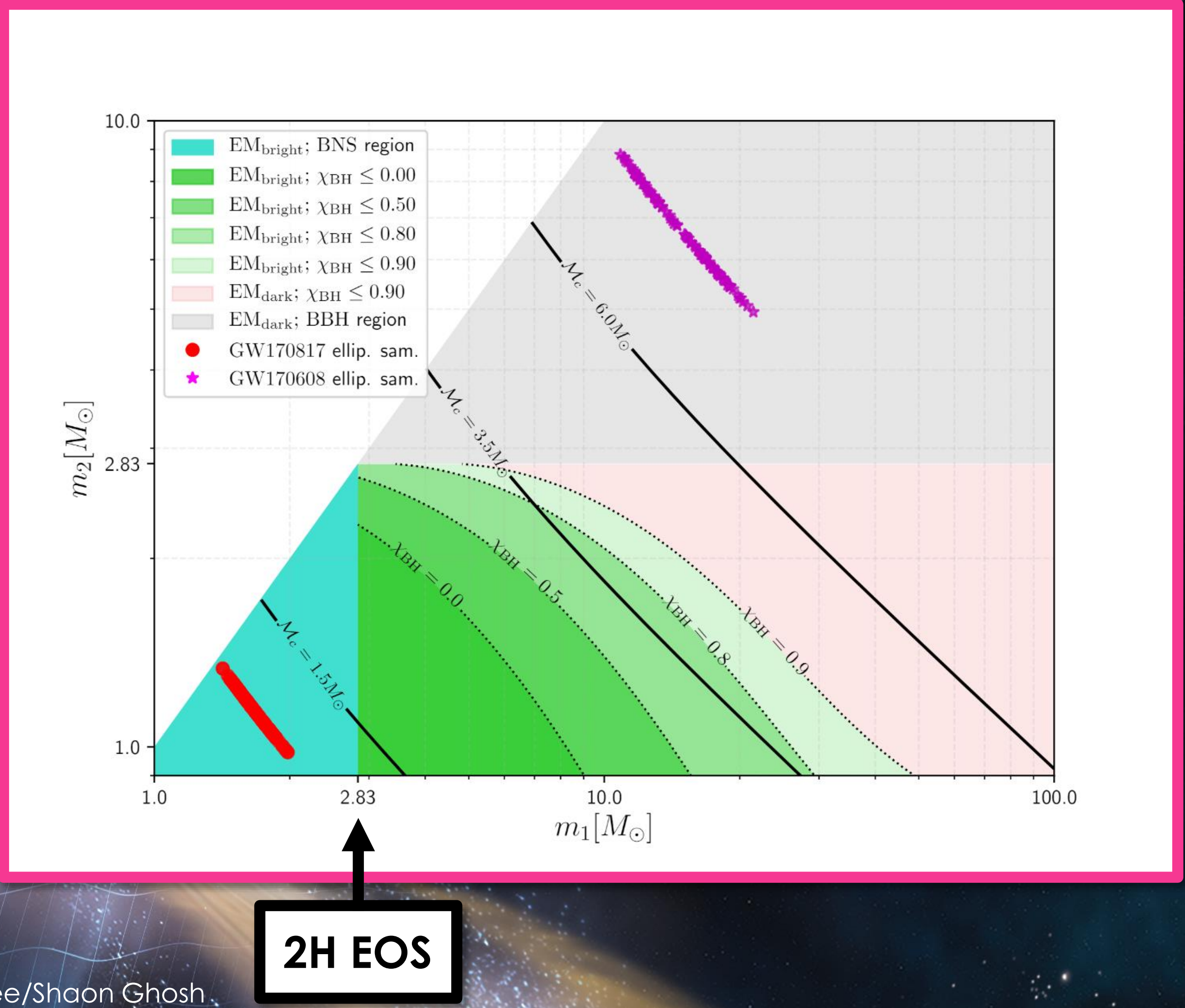

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet, Deep Chatterjee/Shaon Ghosh

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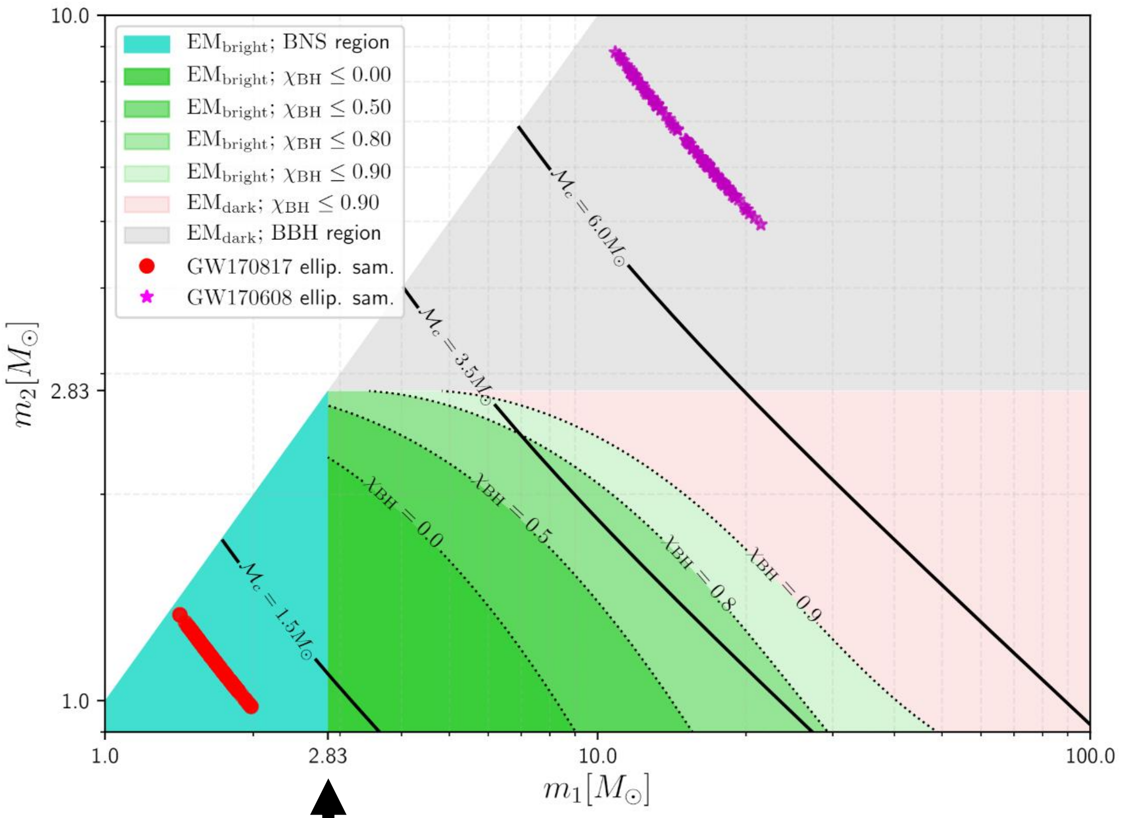


2H EOS

Foucart's fitting formula

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet, Deep Chatterjee/Shaon Ghosh

ALERT INFORMATION

For modeled (CBC) triggers:

We will not release quantitative estimates of masses and spins

We will not release the GW strain or the waveform regressed from the data

Image credit: NSF/LIGO/Sonoma State University/A. Simonnet

ALERT INFORMATION

For unmodeled (Burst) triggers:

Significance, time, 2D sky position

FAR threshold for sending Burst trigger alerts will be more restrictive, on the order of 1/10 years – 1/100 years (in comparison with 1/month – 1/year for CBC triggers)

Image credit: NASA

GCN NOTICES: BASIC INFO

	CBC	Burst
IVORN	ivo://nasa.gsfc.gcn/LVC#{G, M}nnnnnn-{1, 2, 3}-{Preliminary, Initial, Update}	
Who	LIGO Scientific Collaboration and Virgo Collaboration	
What	GraceDB: {G, M}nnnnnn	
Search group	CBC	Burst
Pipeline	{Gstlal, MBTA, PyCBC}	{CWB, LIB}
FAR	Estimated false alarm rate in Hz	
Network	Flag for each detector that participated	
Sky map	URL of HEALPix FITS localization file	
WhereWhen	Arrival time (UTC, ISO-8601)	

GCN NOTICES: INFERENCE (CBC ONLY)

	CBC
What	GraceDB ID: {G, M}nnnnnn
…	…
Distance	a posteriori mean luminosity distance in Mpc
DistanceError	a posteriori standard deviation of luminosity distance in Mpc
ProbHasNS	Probability (0-1) that the 2nd mass companion has a source frame mass < 2.83 $M_\odot$
ProbHasRemnant	Probability (0-1) that there is any remnant matter left outside the remnant
P_astro	Probability (0-1) that the signal is astrophysical in origin accounting for both observed merger rate distribution and background distribution

GCN CIRCULARS: GCN 21509

"A binary neutron star candidate was identified in data from the LIGO Hanford detector at gps time 1187008882.4457 (Thu Aug 17 12:41:04 GMT 2017). The signal is clearly visible in time-frequency representations of the gravitational-wave strain in data from H1. The current significance estimate of ~1/10,000 years is based on data from H1 alone. Information about this candidate is available in GraceDb here..."

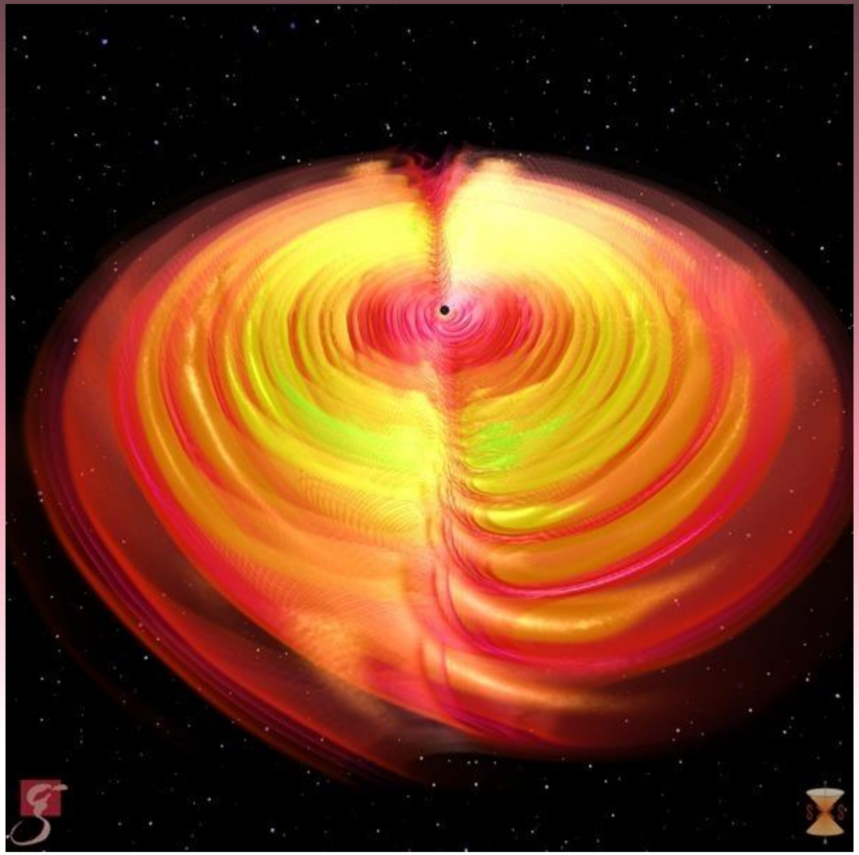
GCN CIRCULARS: GCN 21513

"…Investigation of L1 data identified a noise transient from a known class of instrumental glitches during the inspiral signal. The duration of this glitch is a small fraction of a second and does not appear to affect the signal at times away from the glitch. To make an improved preliminary estimate of the sky position, we re-analyzed the data, removing the L1 noise transient at GPS time 1187008881.389 by multiplying the strain data with a Tukey window, such that the total duration of the zeroed data is 0.2 s and the total duration of the Tukey window is 1.2 s…"

GCN CIRCULARS: GCN 21513

"…An updated BAYESTAR sky map (Singer et al. 2016, ApJL 829, 15) that uses data from all three gravitational-wave observatories (H1, L1, and V1) is available for retrieval from the GraceDB page (https://gracedb.ligo.org/events/view/G298048): bayestar-HLV.fits.gz. The centroid (maximum a posteriori) sky location is R.A.=12h57m, Dec.=-17d51m. The 50% credible region spans about 9 deg2 and the 90% region about 31deg2. The luminosity distance is 40 +/- 8 Mpc (all-sky a posteriori mean +/- standard deviation). This is the preferred sky map at this time…"

CONCLUSION



Gravitational waves as emitted during a black hole merger

……….Thank you for listening!

Questions?

Image credits: S. Ossokine, A. Buonanno, R. Haas (Max Planck Institute for Gravitational Physics), Simulating eXtreme Spacetime project