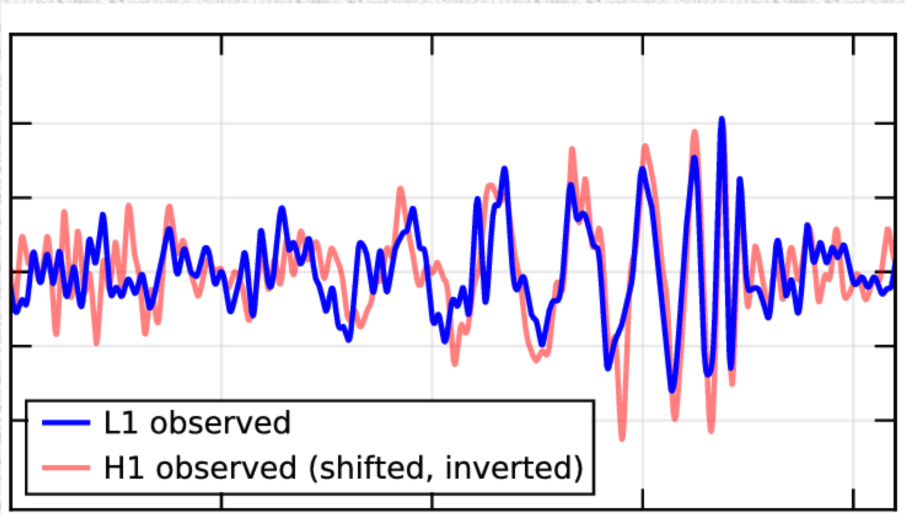
RAS DISCUSSION MEETING MAY 11, 2018



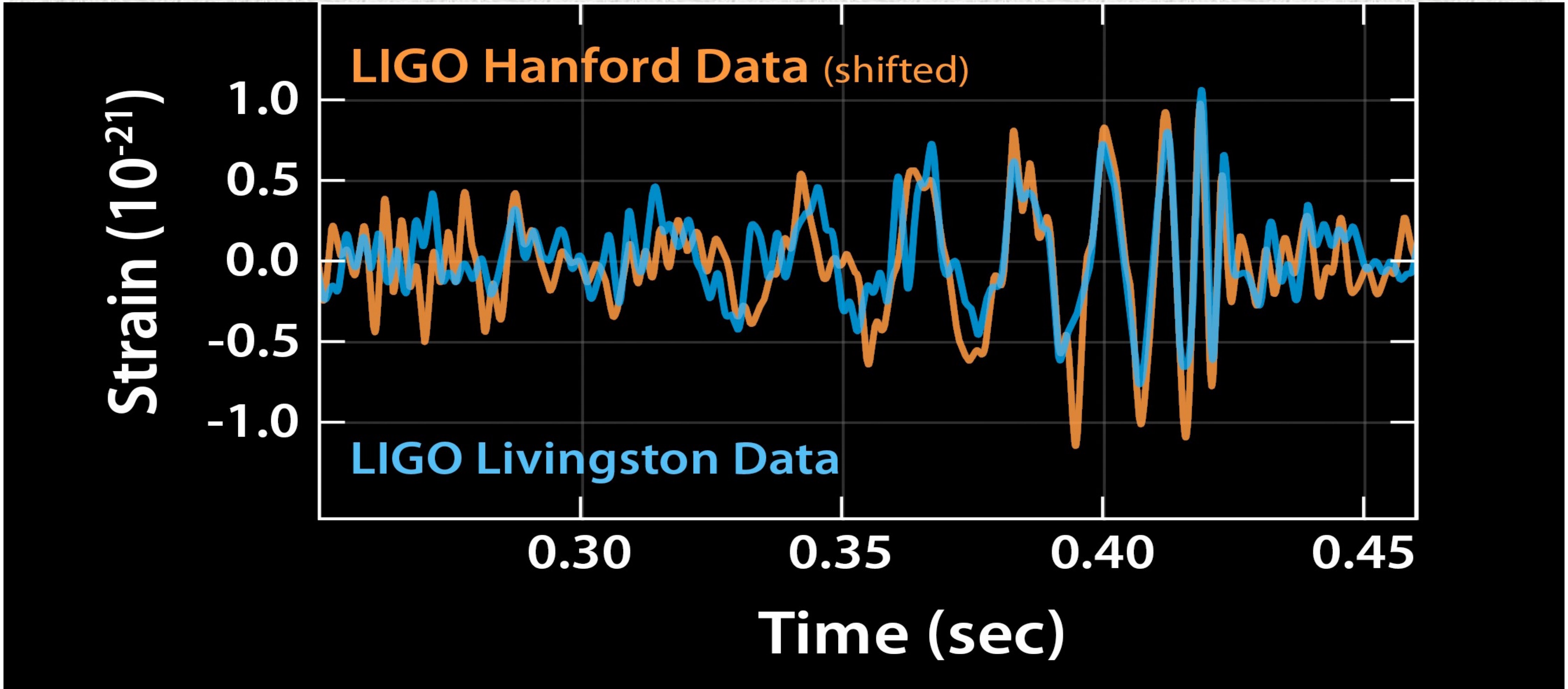
GRAVITATIONAL WAVE ASTRONOMY AND COSMOLOGY

Bernard Schutz
Cardiff University, Wales; Albert Einstein Institute, Germany

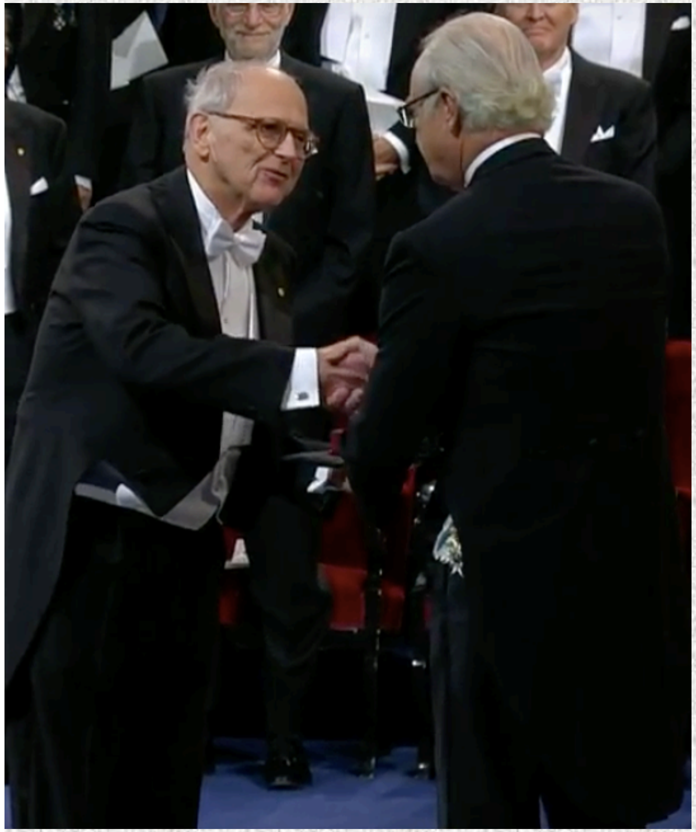
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

MAX-PLANCK-GESELLSCHAFT

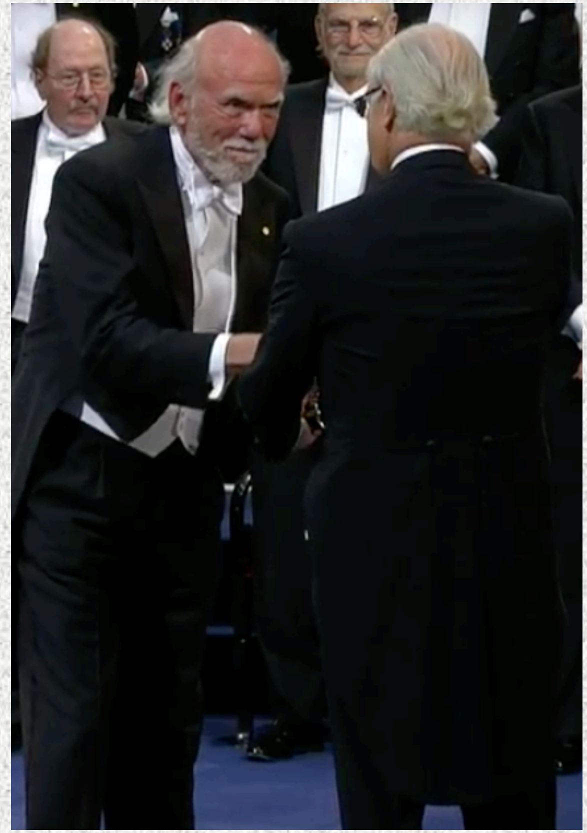
On 14 September 2015, we listened, for the first time, to a sound from the Universe, made by two BHs!



Just a year after the 2016 announcement, we celebrated the Nobel Prize.



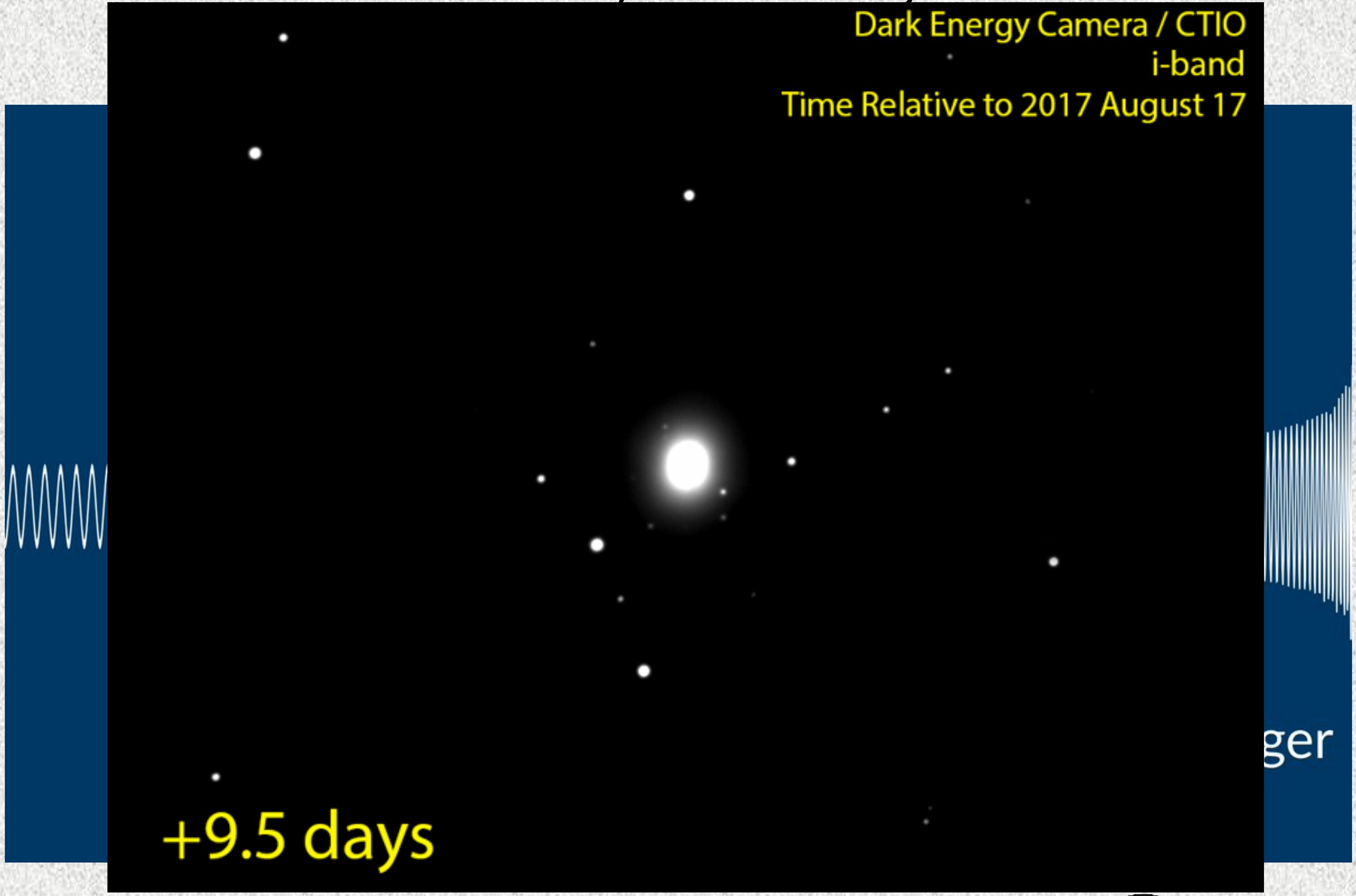
RAINER WEISS
(MIT)

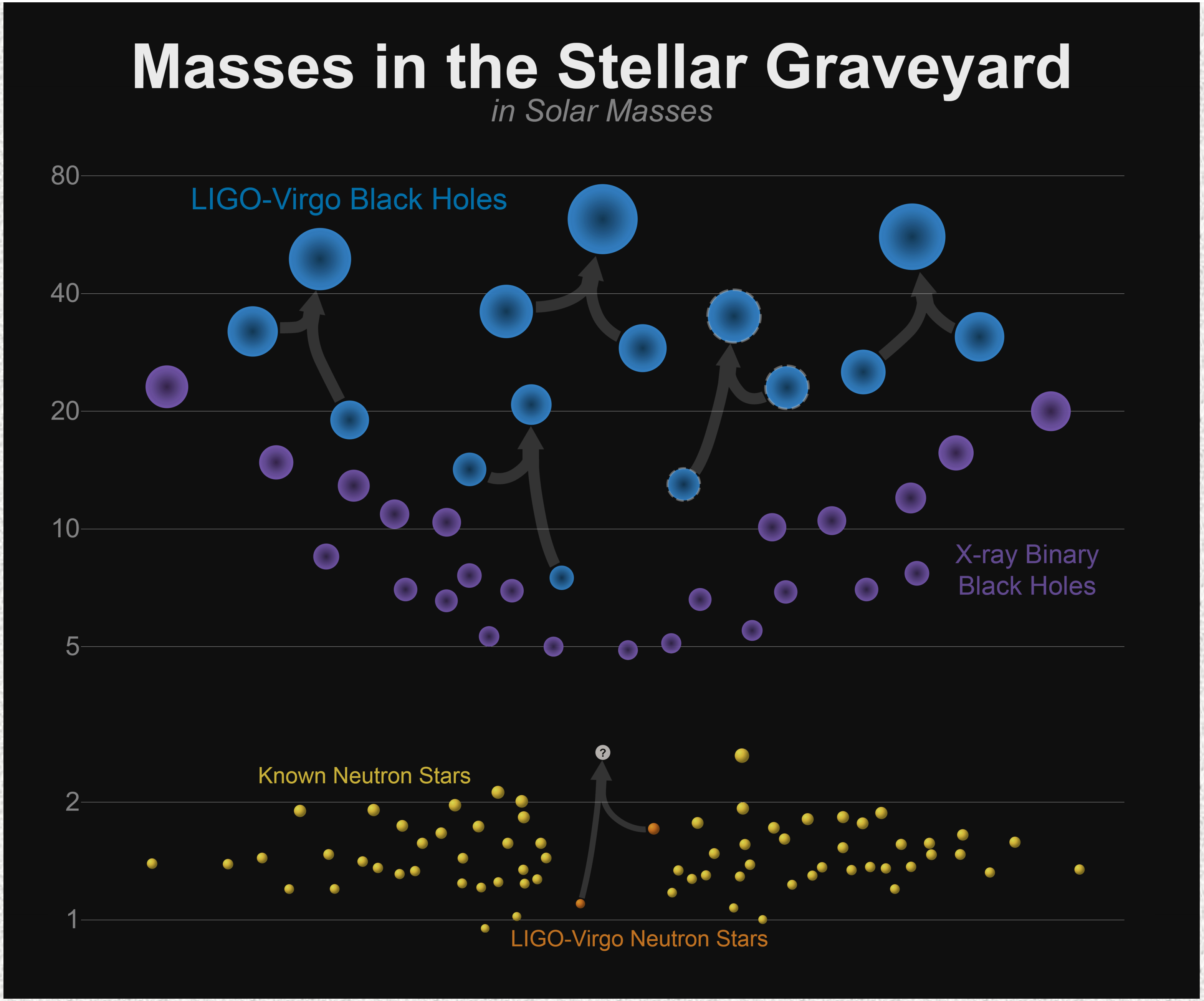


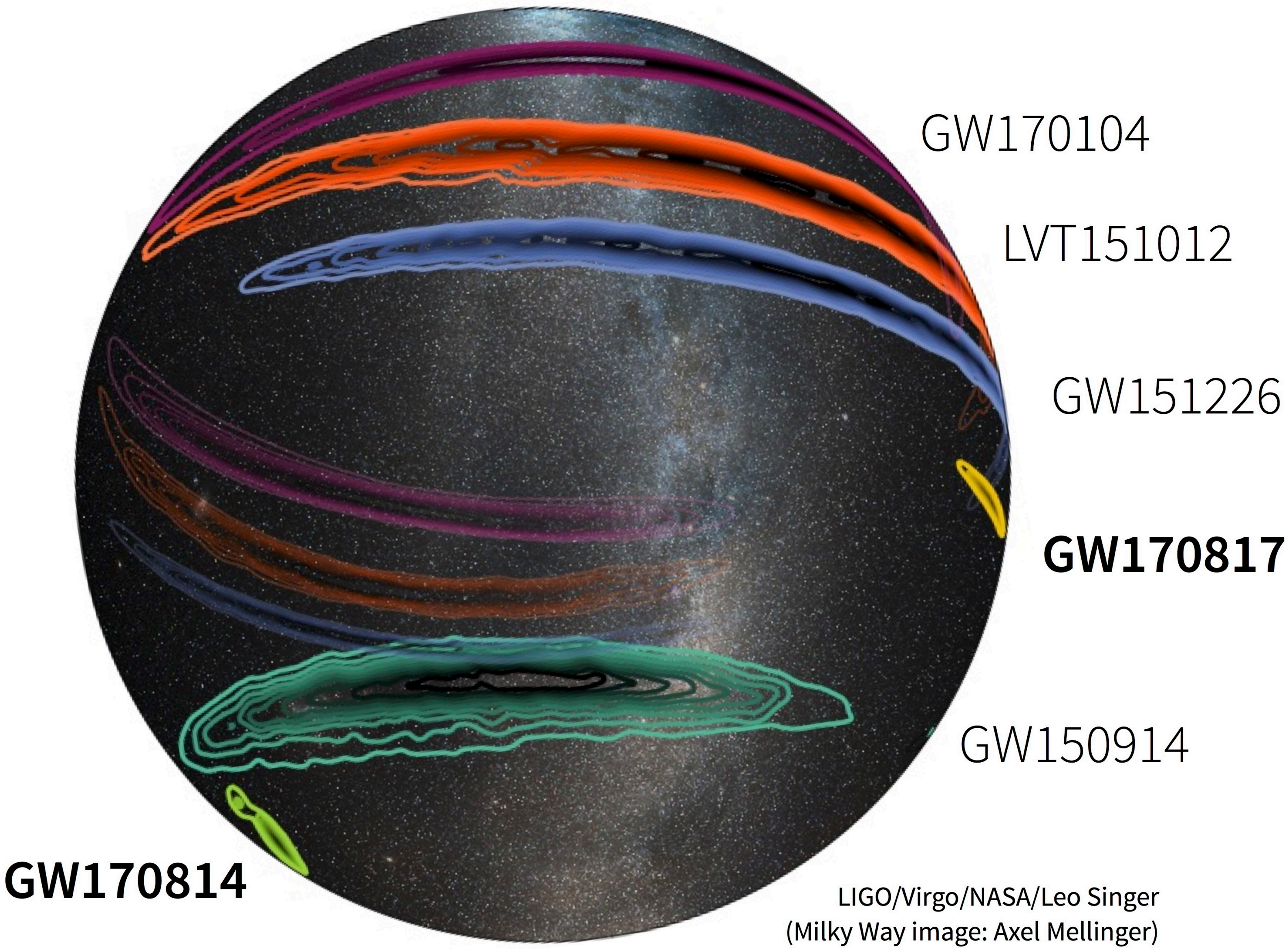
BARRY BARISH
(CALTECH)

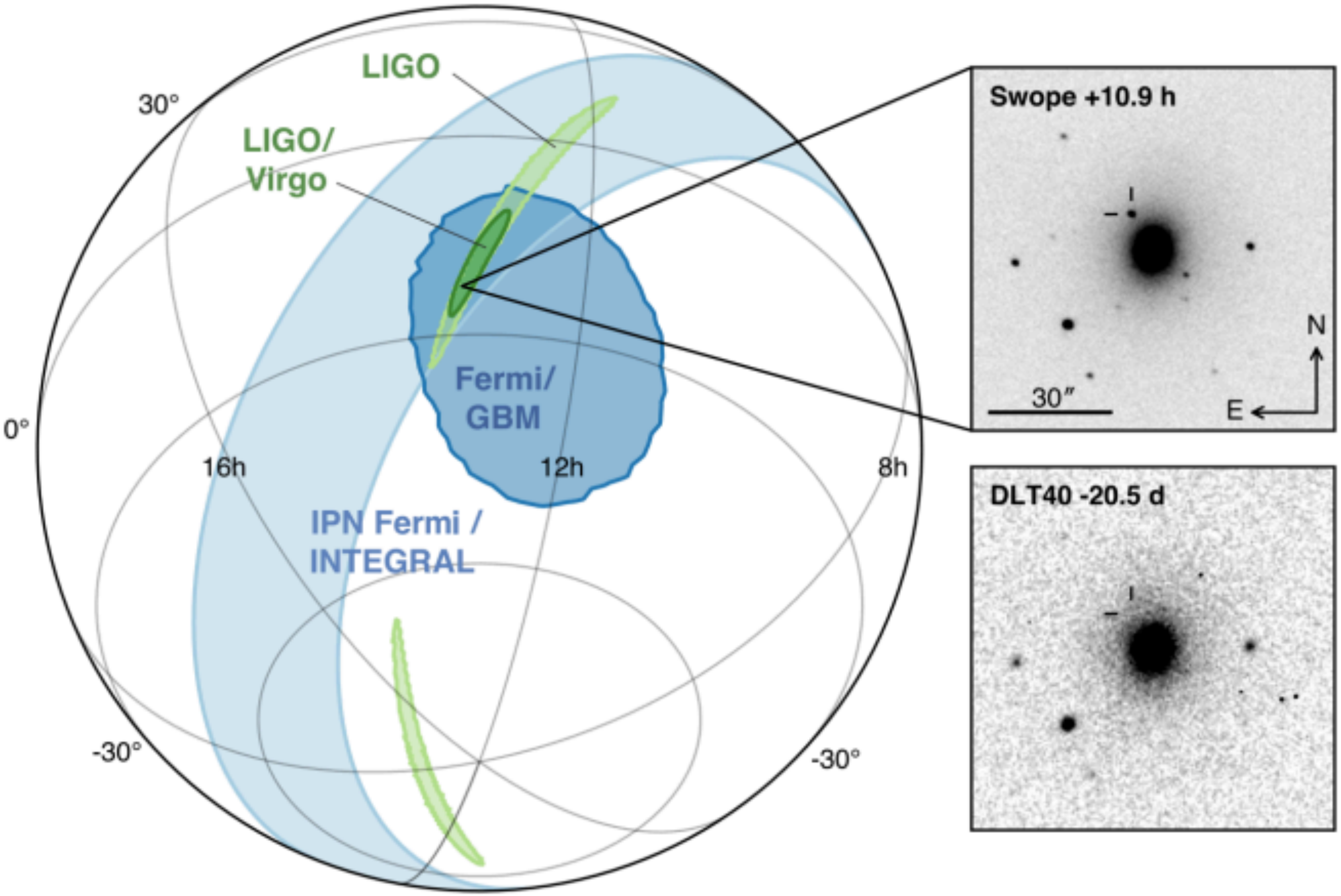
KIP THORNE
(CALTECH)

And even before Stockholm, on 17 August 2017, we saw the explosion associated with another sound, made by two NSs!




Masses in the Stellar Graveyard
in Solar Masses
80
40
20
10
5
2
1
LIGO-Virgo Black Holes
X-ray Binary
Black Holes
Known Neutron Stars
LIGO-Virgo Neutron Stars
?


GW170104
LVT151012
GW151226
GW170817
GW150914
GW170814
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)


LIGO
30°
LIGO/
Virgo
Fermi/
GBM
0°
16h
12h
8h
IPN Fermi /
INTEGRAL
-30°
-30°
Swope +10.9 h
30″
N
E
DLT40 -20.5 d

Standard Sirens

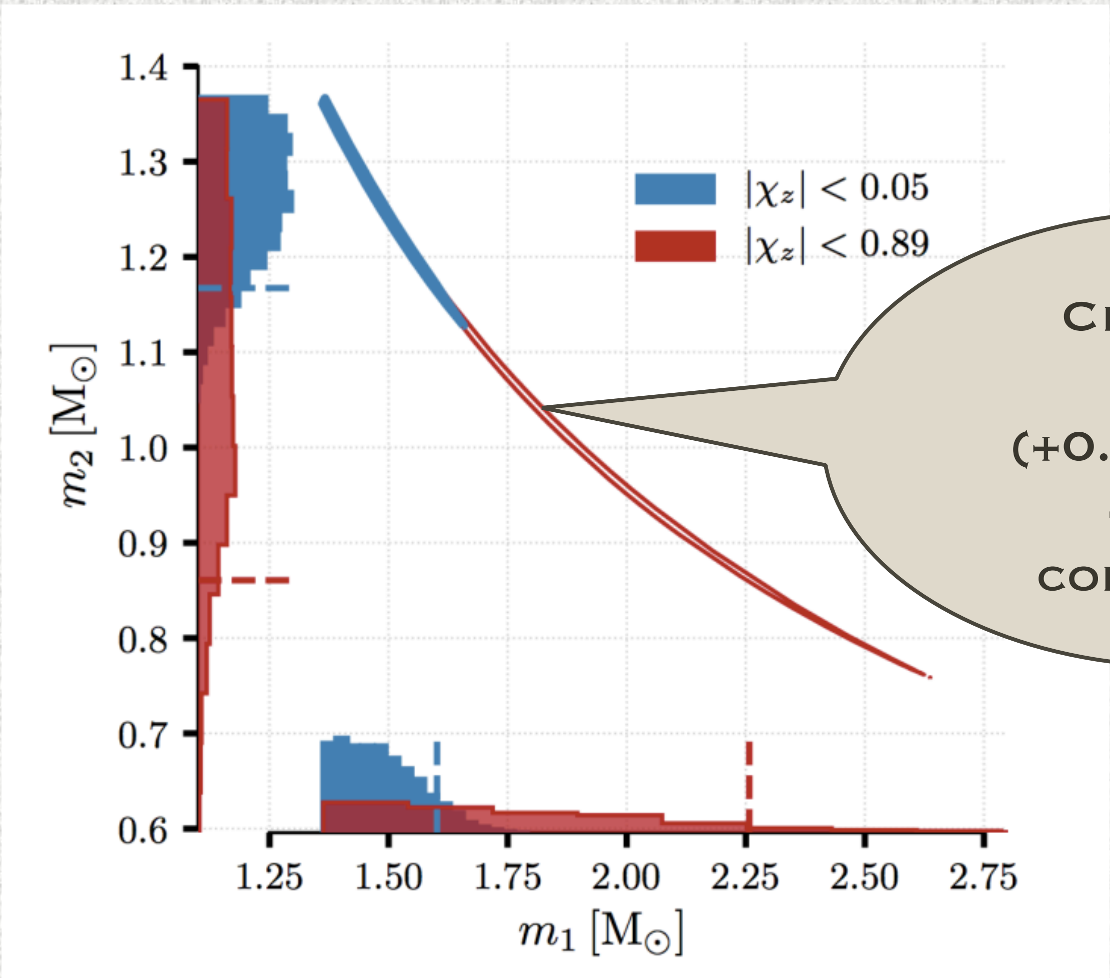
Binary system signals carry the information about their distance: they are called standard sirens (Schutz; Holz & Hughes; Nissanke; …).

The formula for the radiation amplitude *h* depends on 3 intrinsic variables that determine the Newtonian orbit, (m_1, m_2, Ω), and of course *h* falls off as $1/r$. But at the lowest pN order, it happens that h depends only *one* mass, the chirp mass

$$\mathcal{M} := (m_1 * m_2)^{3/5} / (m_1 + m_2)^{1/5}$$

There is enough information in the phase of the signal to solve for these lowest order variables: f and $\mathrm{d}f/\mathrm{d}t$ determine $\mathcal{M}$. Then $h \sim \mathcal{M} / r$. But to determine *h* accurately, one needs all orientations: location on sky, inclination of binary orbit. For GW170817, we did not get the inclination accurately.

Masses of the stars



CHIRP MASS

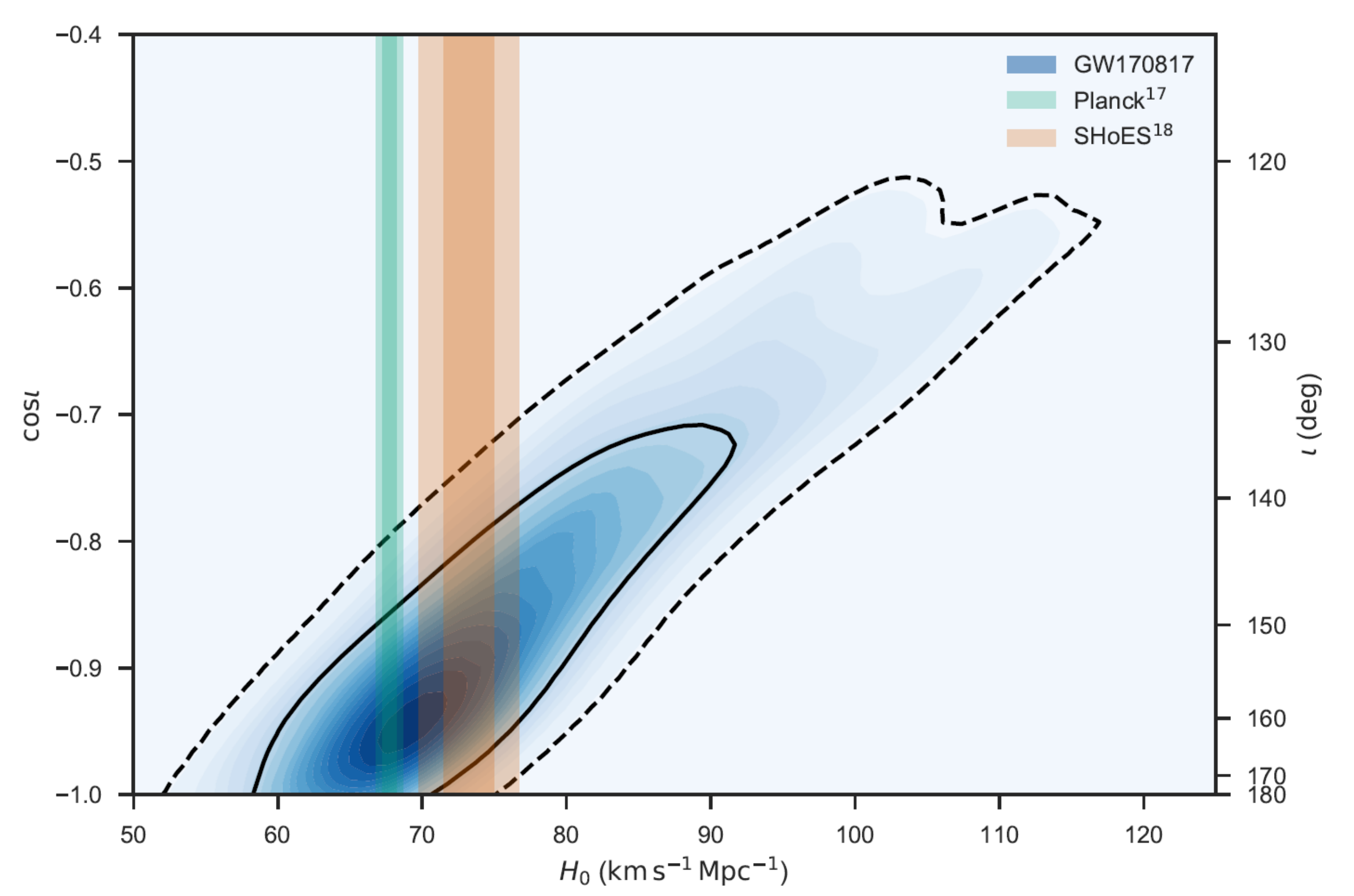
1.188

(+0.004,-0.002)

-- TIGHT

CORRELATION.

With a standard siren, you measure H_0 … if you can measure inclination



LIGO-Virgo future

When LIGO and Virgo come back online after current upgrade work (end 2018?), we hope for sensitivity improvement × 2, detection volume × 8. NS-NS binary rate could be ~ 1/month. BH-BH rate ~ 1 or 2 per week.

Important to understand that GW detections are declared after passing both of 2 different significance tests:

1. local SNR (Gaussian noise significance at time of detection);
2. chance coincidence probability (non-Gaussian glitch noise).

Having 3 detectors improves SNR but improves glitch rejection even more! Laura Nuttall will discuss the detectors in detail, and look at what we can expect from the future network.

Expanded IFO network 2020+

Science Goals of Ground-based Detectors

NS-NS and BH-BH events will be plentiful, GW pulsars will be detected in the long term, so will a stochastic GW background.

Astrophysics: origin of binaries, markers of cosmic evolution, feedback.

Nuclear physics: NS's are laboratories for physics we cannot duplicate on the ground.

GR: Cosmic censorship, non-GR propagation ($v<c$, birefringence), look for extra polarisations.

Cosmology: Local H_0 to 1% or better; anisotropy tests; lensing; stochastic GW background.

Discovery space: Networks veto glitches well, making searches for unmodelled bursts much more sensitive. Cosmic strings? Completely unexpected sources?

LIGO is just the beginning! Over next 20 years:

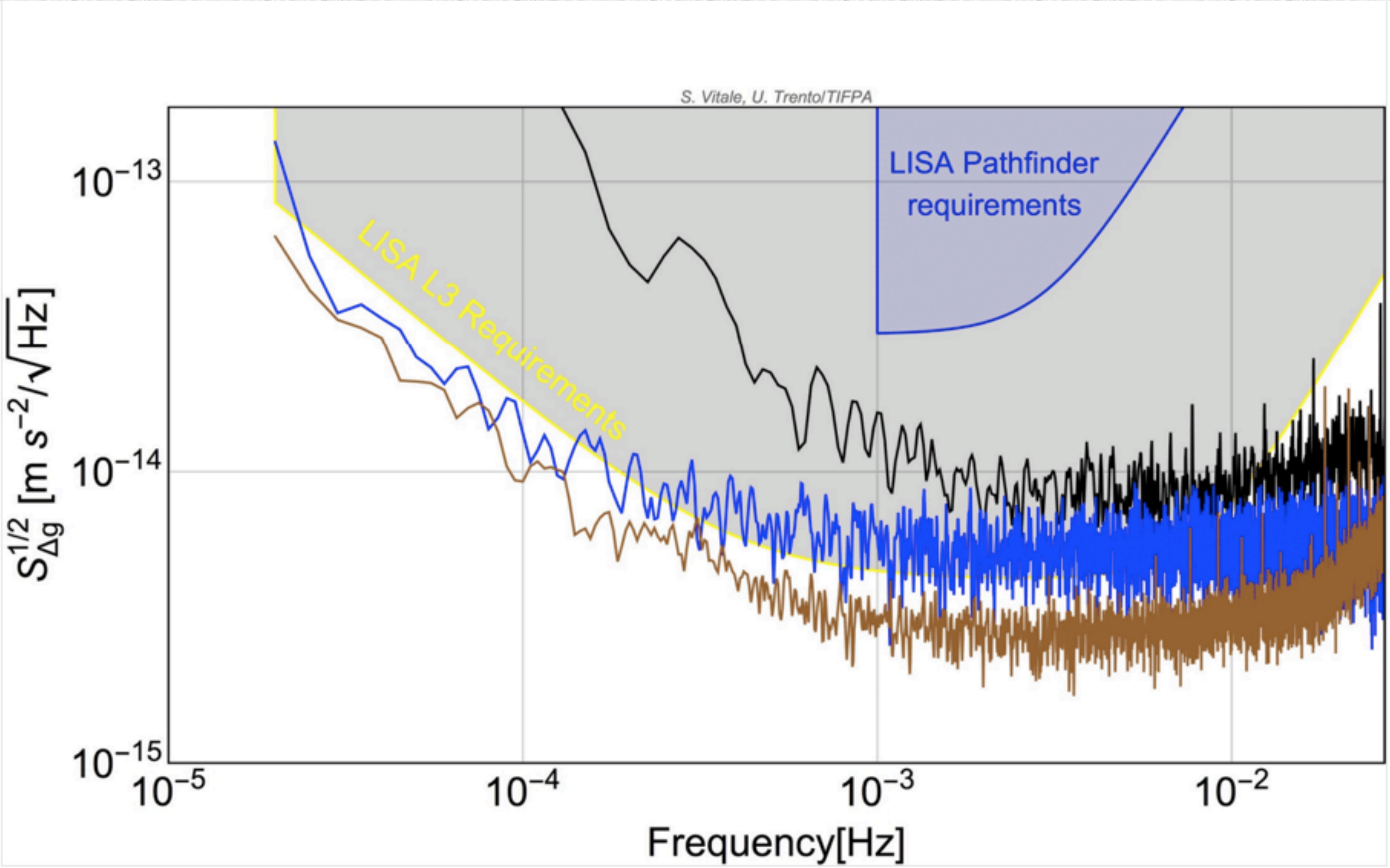
Big improvements in LIGO and partners, including 2.5G and new-build 3G instruments, bringing the reach for BNS to z > 2. (Nuttall talk).

ESA's space-based detector LISA opening up the richest frequency band (0.1 -100 mHz) for GW observations; LISA Pathfinder (2016-18) was enormously successful, exceeding sensitivity goal by ×10, proving the technology and energizing ESA to put LISA on the fast track.

Detections at very low frequencies by pulsar timing arrays, with SKA becoming a nHz observatory of SMBH binaries.

Detection of GWs from the Big Bang by their signature in the polarization of the CMB.

The amazing LISA Pathfinder



LISA: Hunting Black Holes

Remember the LIGO chirp?

Here is what we expect LISA to hear!

By detecting MBHB mergers out to z = 20, LISA will trace hierarchical galaxy formation and measure H0 to 1%, w to 15% [Tamanini et al, 1601.07112].

LISA will listen as supermassive BHs capture smaller black holes (EMRIs), which gradually spiral closer and closer for months or years before merging. These will provide exquisite high-precision tests of general relativity.

GW Astronomy is here!

The experimental teams have delivered –
- LIGO & Virgo have made the first direct observation of GWs.
- LISA Pathfinder worked "out of the box"; fewer faults than any previous ESA sciencecraft; exceeded spec by x10.

Nature has delivered too –
- We were conservative predicting BBH numbers, maybe also BNS.
- Data analysis algorithms, supported by numerical relativity, work!

While we extract the science from the current observations, this is also the right time to work toward the future:
- Upgrade LIGO, Virgo; bring KAGRA online; build LIGO-India.
- Join the LISA Consortium.
- Form the international collaboration to build 3G detectors.
- Press on with pulsar timing and CMB detection programmes.

THANK YOU!

Further on GWs

• Review: Sathyraprakash & Schutz, Liv Rev Relativity.
• Help us with our data analysis – discover the first pulsar signals! Download Einstein@Home: http://www.aei.mpg.de/154894/03_Einstein_Home

- Science outreach online
  - Einstein Online: http://www.Einstein-Online.info
  - Scienceface (interviews): http://www.scienceface.org
- Science outreach books
  - B Schutz, *Gravity from the ground up*
  - other authors: H Collins, M Bartusiak, T Bührke, L Smolin, J Ehlers, J Levin

The facts about GW150914

- Time: 14 Sept 2015 09:50:45 UTC (GMT)
- System: inspiral and merger of two BHs.
  - Duration: ~100 ms
  - BH1 mass: 36 $M_\odot$
  - BH2 mass: 29 $M_\odot$
  - Remnant mass: 62 $M_\odot$, spinning at 70% maximum
- Energy radiated in GWs by merger: 3 $M_\odot$
- Luminosity: 3.6 x 10^{49} W = 10^{23} $L_\odot$ > 10 x Universe!
- Distance: 410 Mpc, z = 0.09
- Detection: LIGO instruments in WA and LA
  - Combined SNR = 24 (amplitude), or 570 (energy)
- False alarm rate << 1 per 200,000 years

The facts about GW151226

- Time: 26 Dec 2015 03:38:53 UTC (GMT) – Boxing Day
- System: inspiral and merger of two BHs.
  - Duration: ~2 s
  - BH1 mass: 14.2 $M_\odot$
  - BH2 mass: 7.5 $M_\odot$
  - Remnant mass: 20.8 $M_\odot$, spinning at 74% maximum
- Energy radiated in GWs by merger: 1 $M_\odot$
- Luminosity: 3.3×10^{49} W = 10^{23} $L_\odot$ ~ 10^3 x Universe!
- Distance: 440 Mpc, z = 0.09
- Detection: LIGO instruments in WA and LA
  - Combined SNR = 13 (amplitude), or 169 (energy)
- False alarm rate < 1 per 200,000 years

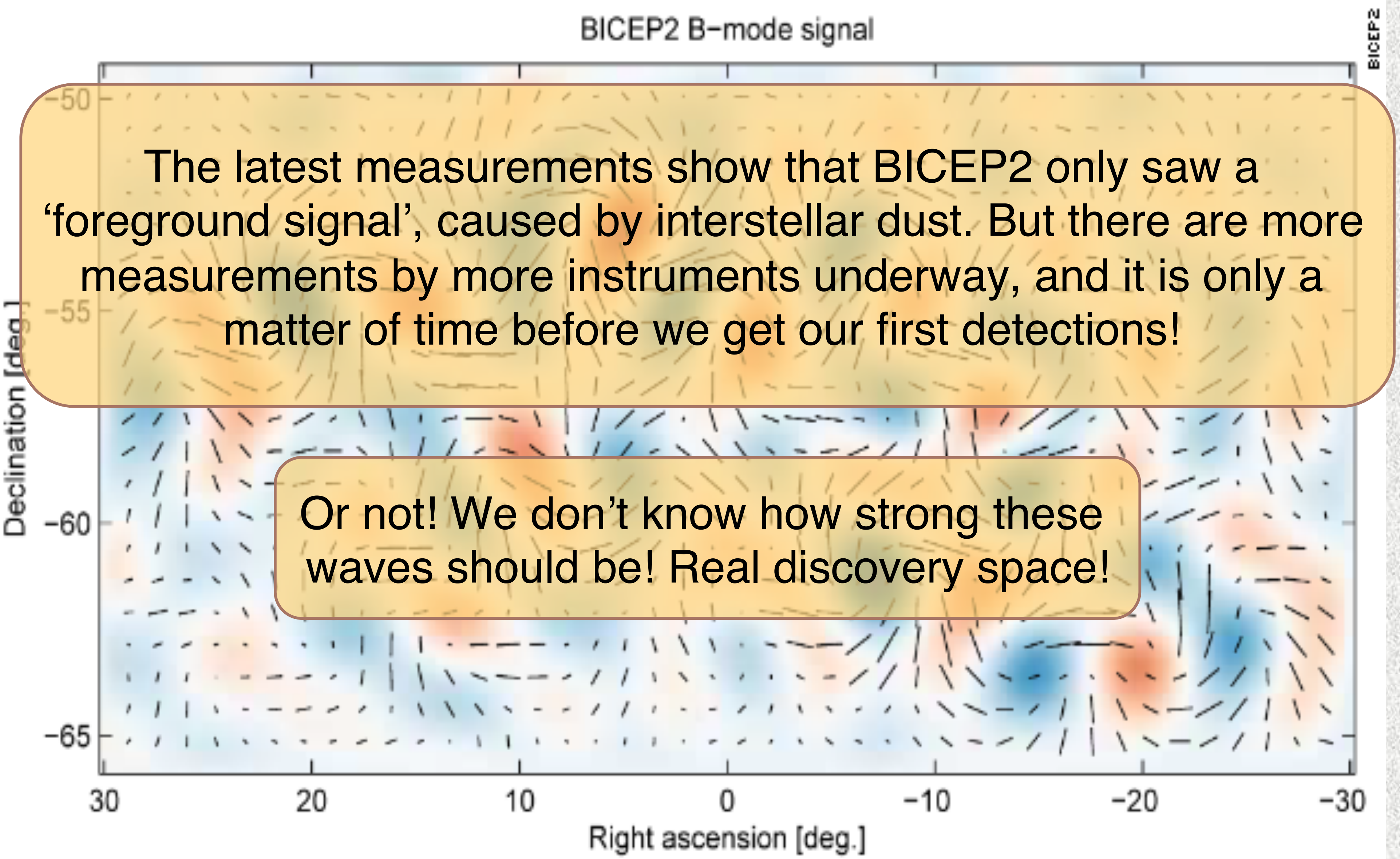
The facts about LVT151012

- Time: 26 Dec 2015 03:38:53 UTC (GMT) – Boxing Day
- System: inspiral and merger of two BHs.
  - Duration: ~0.5 s
  - BH1 mass: 23 $M_\odot$
  - BH2 mass: 13 $M_\odot$
  - Remnant mass: 35 $M_\odot$, spinning at 66% maximum
- Energy radiated in GWs by merger: 1.5 $M_\odot$
- Luminosity: 3.1 x 10^{49} W = 10^{23} $L_\odot$~ 10^3 x Universe!
- Distance: 1000 Mpc, z = 0.2
- Detection: LIGO instruments in WA and LA
  - Combined SNR = 9.7 (amplitude), or 95 (energy)
- False alarm rate 1 per 3 years

The facts about GW170104

- Time: 04 January 2017 10:11:58.6 UTC (GMT)
- System: inspiral and merger of two BHs.
  - Duration: ~0.5 s ***
  - BH1 mass: 31.2 $M_\odot$
  - BH2 mass: 19.4 $M_\odot$
  - Remnant mass: 48.7 $M_\odot$, spinning at 66% maximum
- Energy radiated in GWs by merger: 2 $M_\odot$
- Luminosity: 3.1 x 10^{49} W = 10^{23} $L_\odot$~ 10^3 x Universe!
- Distance: 880 Mpc, z = 0.18
- Detection: LIGO instruments in WA and LA
  - Combined SNR = 13 (amplitude), or 169 (energy)
- False alarm rate 1 per 70,000 years

BICEP2: GWs & Big Bang?



The latest measurements show that BICEP2 only saw a 'foreground signal', caused by interstellar dust. But there are more measurements by more instruments underway, and it is only a matter of time before we get our first detections!

Or not! We don't know how strong these waves should be! Real discovery space!

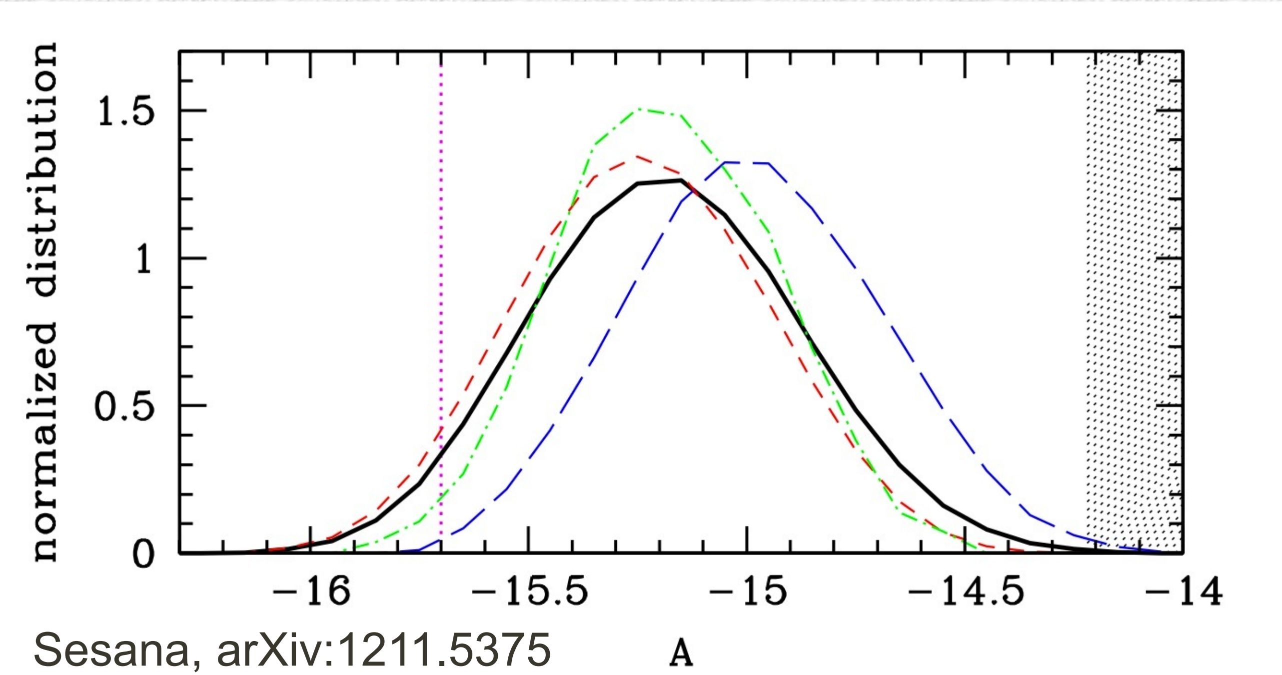
Pulsar Timing Arrays

Radio astronomers around the world are precisely recording the arrival times of pulses of ultra-stable millisecond pulsars to find the tiny variations produced by GWs passing the Earth. They should this decade detect GWs from the most massive BHs: 10^9 times the mass of the Sun!

GW amplitude pdf based on large ensemble of evolutionary models.

Shaded: current PTA limits.

Black: PTA with 20 MSPs for 10 years.



Sesana, arXiv:1211.5375

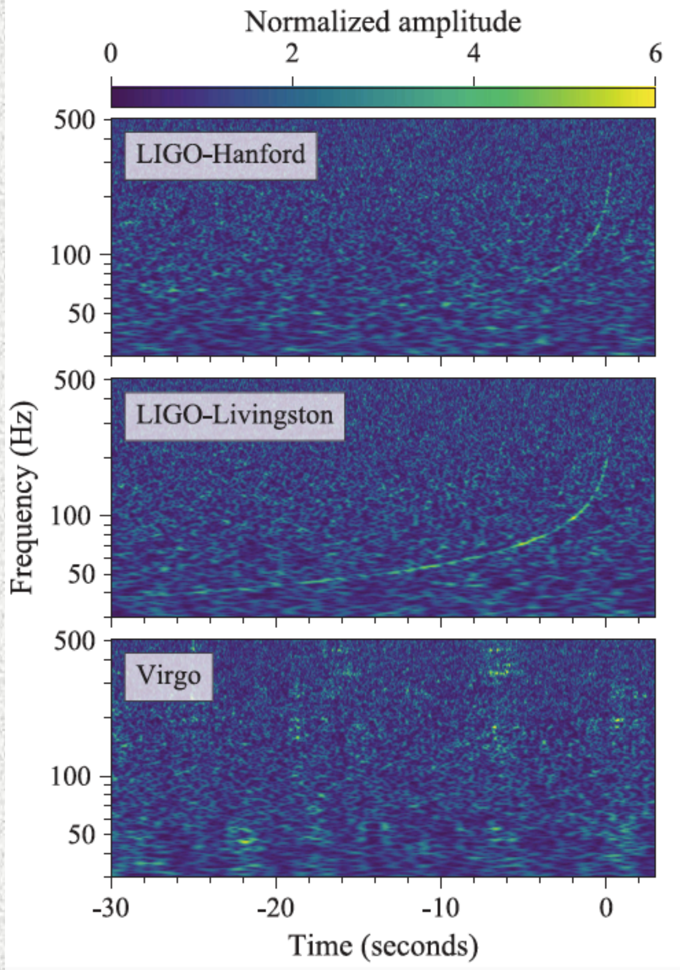
Binaries are standard sirens

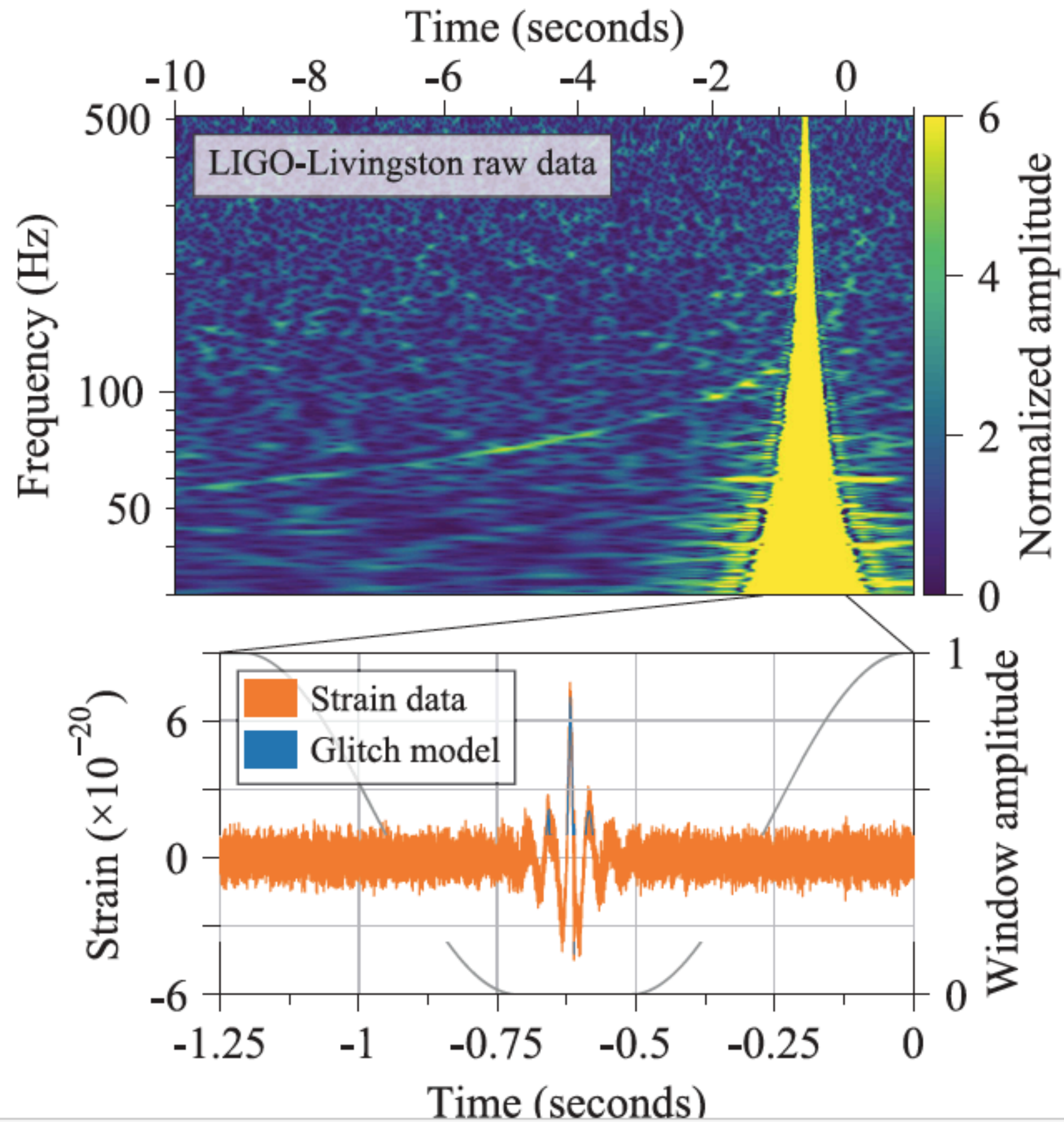
Binaries are *clean* systems: we have accurate models even in full general relativity.

Loss of energy to GWs causes orbit to decay, orbital frequency to go up. So the GWs will chirp up in frequency. Chirp time $t_{\text{chirp}} \sim f\,/\,[\mathrm{d}f\,/\,\mathrm{d}t\,]$.

Signal contains both apparent brightness (from h and f) and intrinsic luminosity (from t_{chirp}), from which we can compute the distance to the source:

$$\text{Distance} \propto c\,\frac{}{\text{frequency}^2 \times t_{\text{chirp}}}$$


Normalized amplitude
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
Time (seconds)


Time (seconds)
LIGO-Livingston raw data
Frequency (Hz)
Normalized amplitude
Strain data
Glitch model
Strain (×10^−20)
Window amplitude
Time (seconds)

Audio and visual chirp