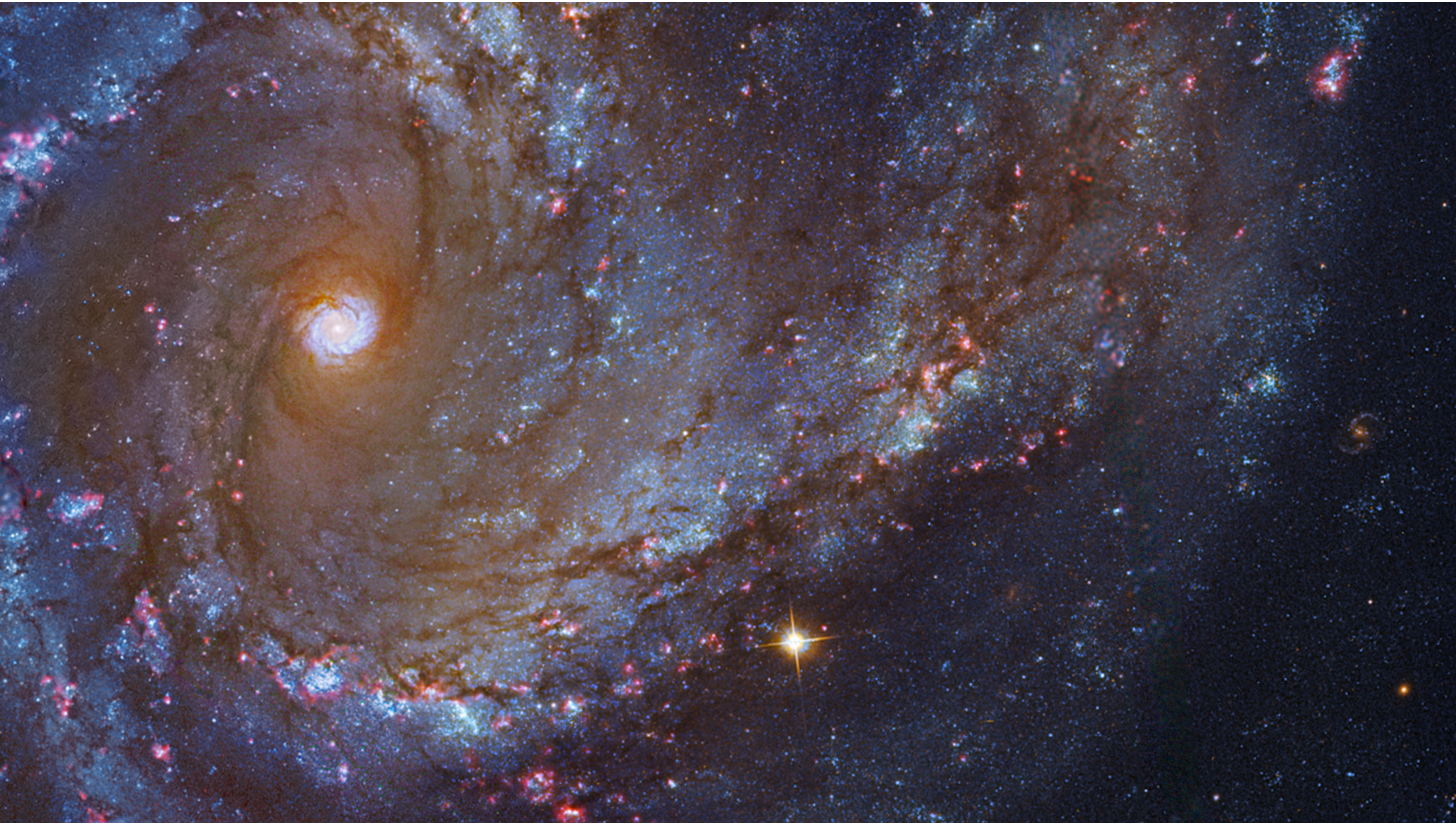
Astronomy: what next?

Musings on the past and future of astronomy

Presented by
A/Prof Helen Johnston
School of Physics

Quarks to the Cosmos, Spring 2019

THE UNIVERSITY OF SYDNEY



In tonight's lecture

- The parameters of astronomical discovery
- Three case studies:
  - ✳ the black hole at the Galactic centre
  - ✳ LIGO and the discovery of gravitational waves
  - ✳ the search for transients
- What next for astronomy?

Astronomical discoveries

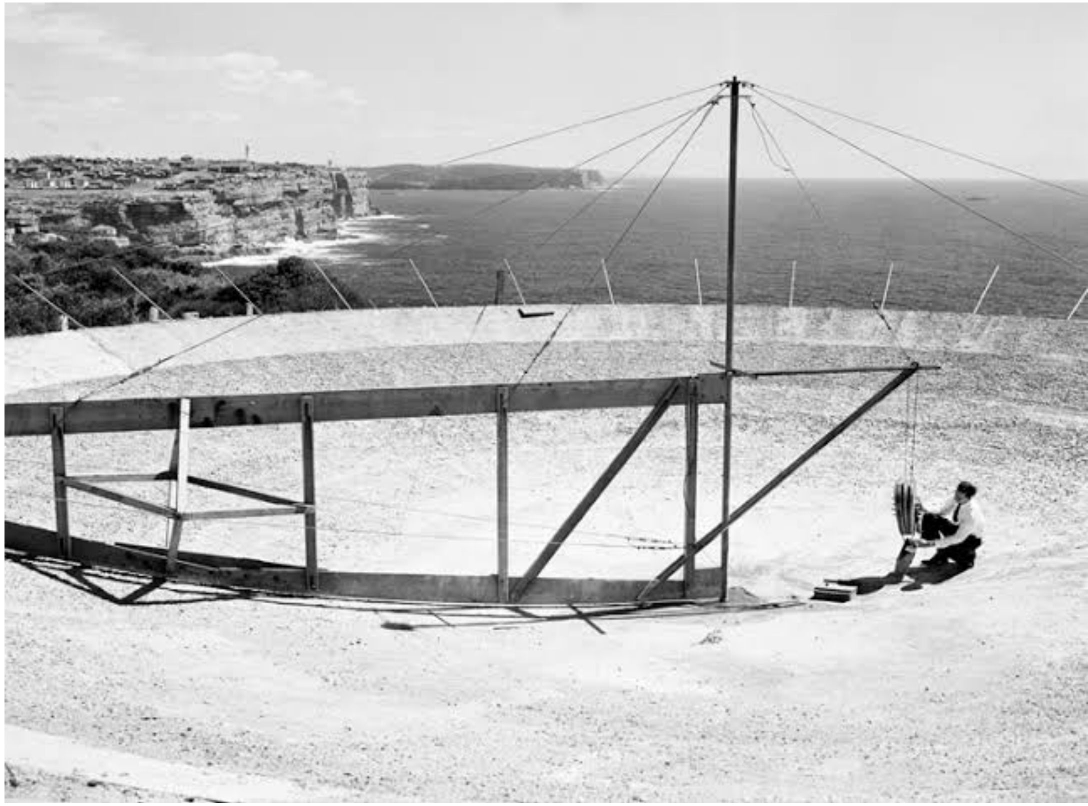
In his 1981 book "*Cosmic Discovery*", Martin Harwitt analysed when and how astronomical discoveries are made.

Astronomical discoveries

He came up with several surprising (?) suggestions:

1. *Most astronomical discoveries occur because of technological innovation*

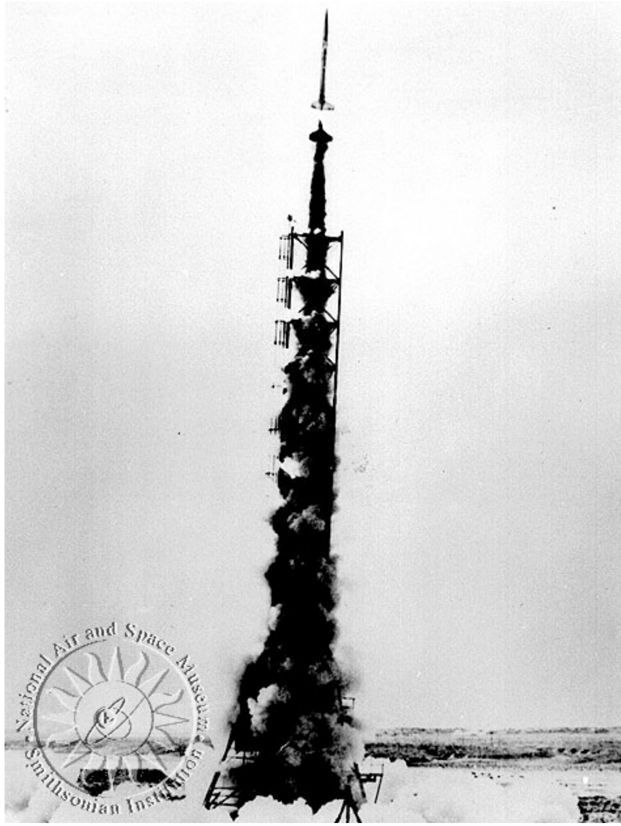
e.g. radio astronomy, developed because of research on radar during WWII



Astronomical discoveries

2. *Most new discoveries are made almost immediately the new technique becomes available, and often by a non-astronomer*

e.g. X-ray astronomy, which found most of the new types of sources within the first few years



Astronomical discoveries

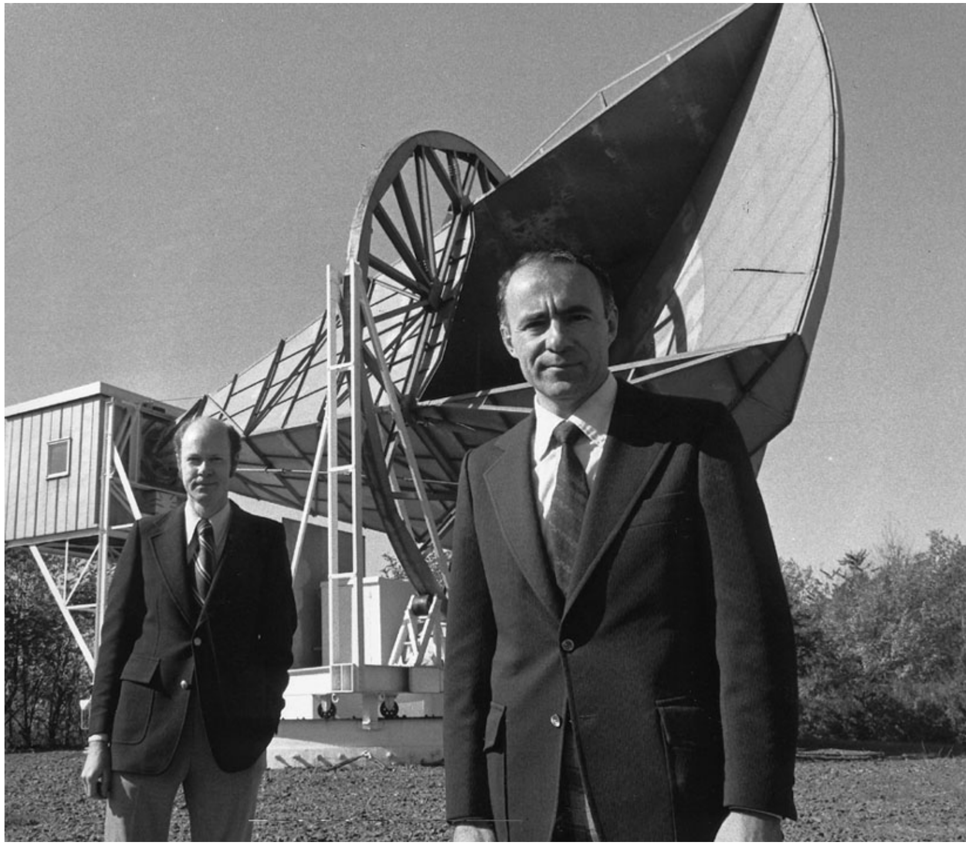
3. *Most discoveries are made using instruments built by the observer, who often has exclusive use. Few are made at national centers.*

e.g. Jocelyn Bell, who discovered pulsars using a telescope she had built

Astronomical discoveries

4. *Many discoveries of new phenomena happen by chance, combining a measure of luck with the will to pursue and understand an unexpected finding.*

e.g. Penzias and Wilson and the discovery of the cosmic microwave background radiation

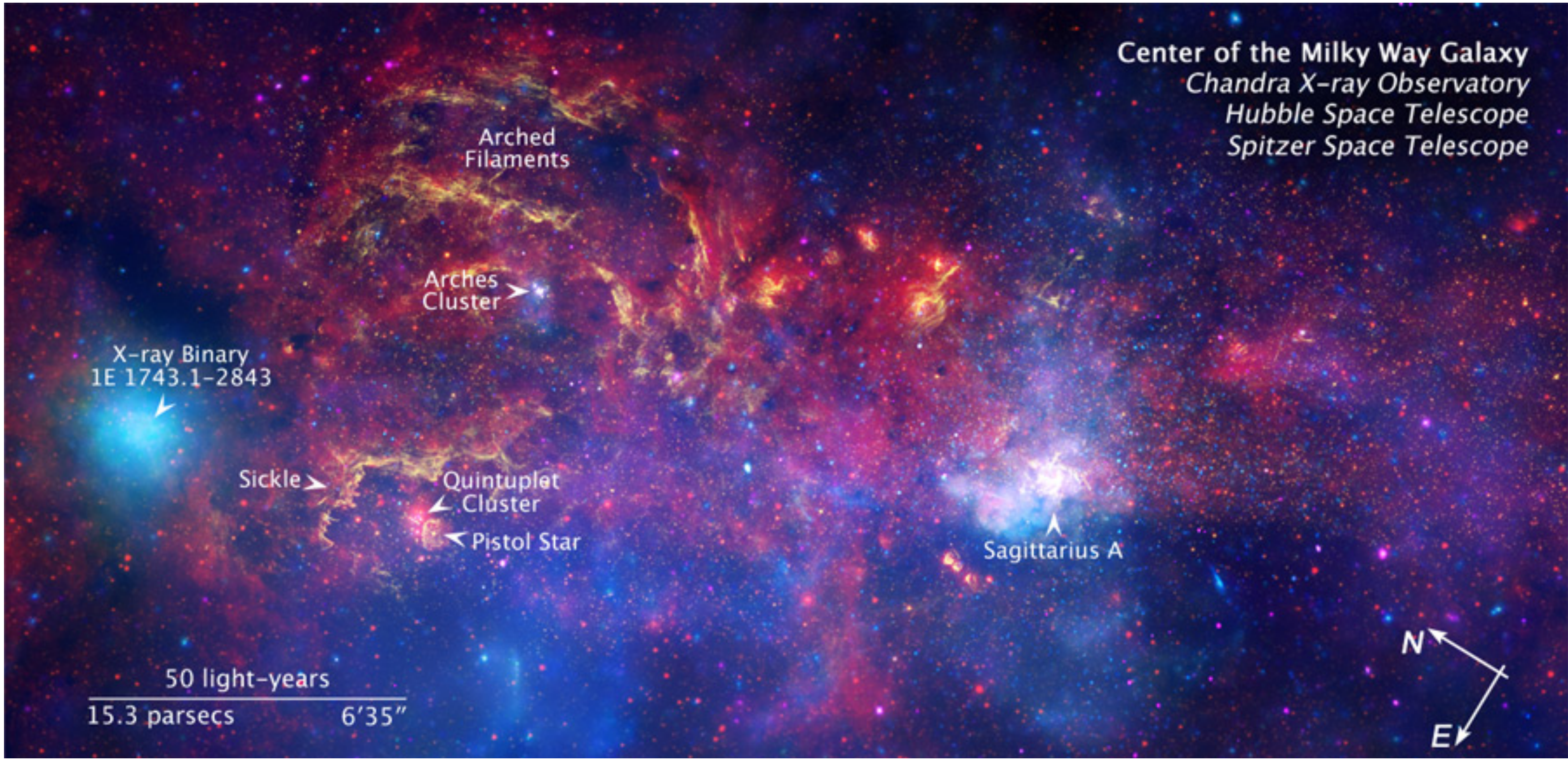


Have these observations remained true since he wrote his book in 1981?

What does this mean for the future of astronomy?

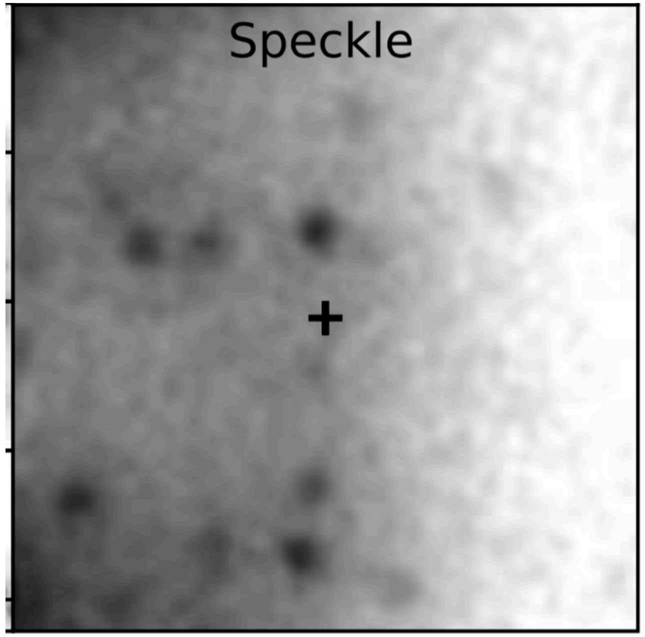
The black hole at the Galactic centre

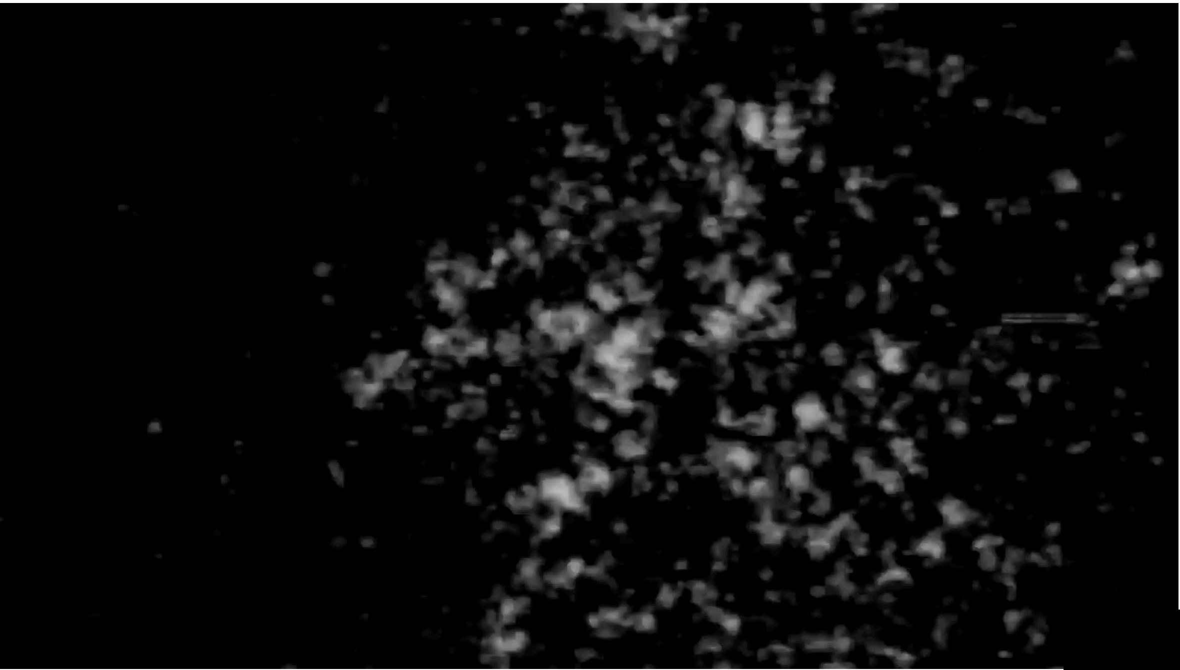
The centre of the Milky Way had long been suspected to contain a black hole; but proof was lacking.



Starting in 1995, Andrea Ghez at UCLA has been using the 10m Keck telescope to take high-resolution infrared images to track the positions of stars near the galactic centre.

Started with *speckle imaging* – technique to remove the effect of the atmosphere.

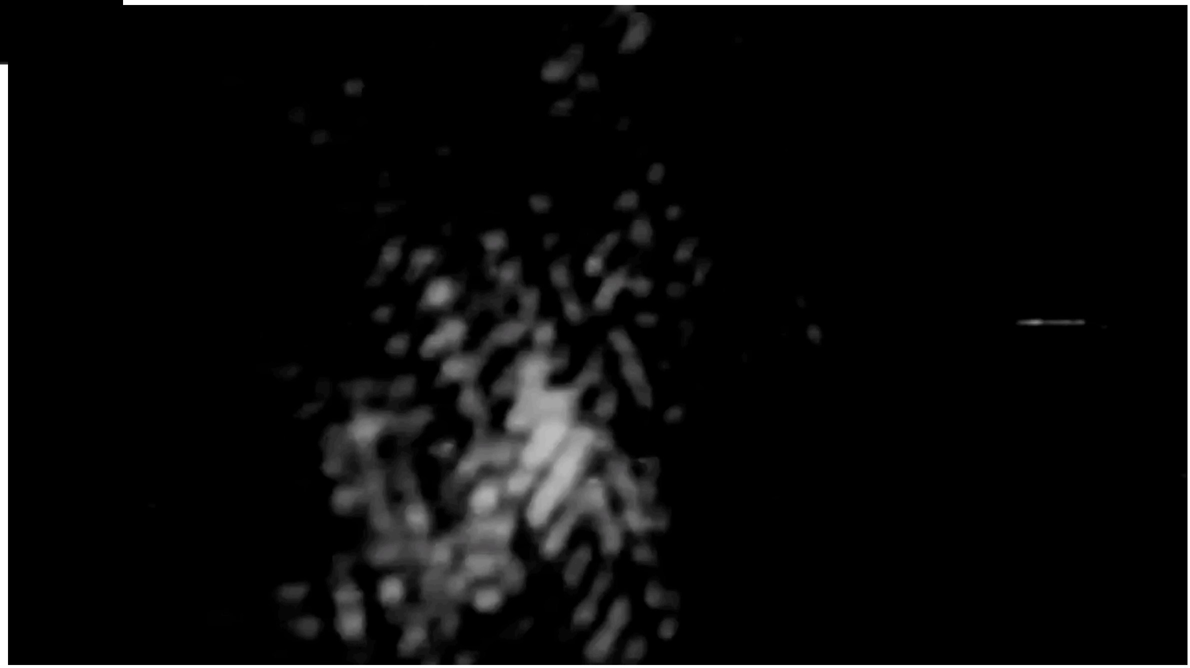


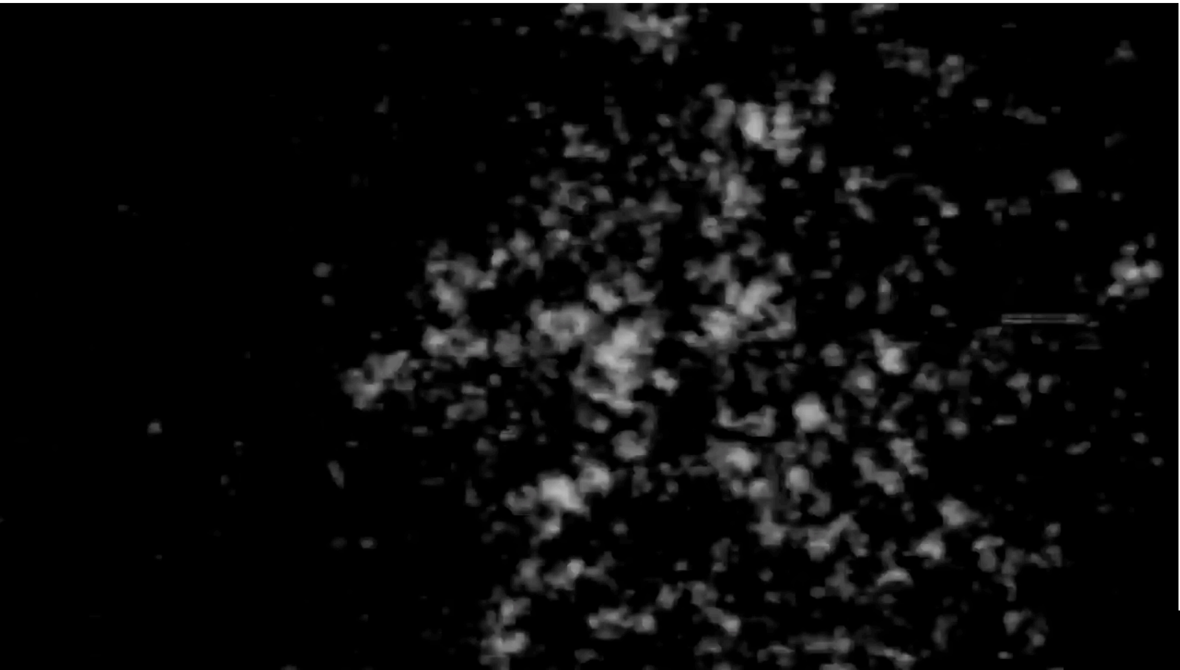


Speckles from a single star compared with speckles from a double star.

Most common separation = separation of binary

By taking hundreds of frames 10ms apart, can reconstruct the image





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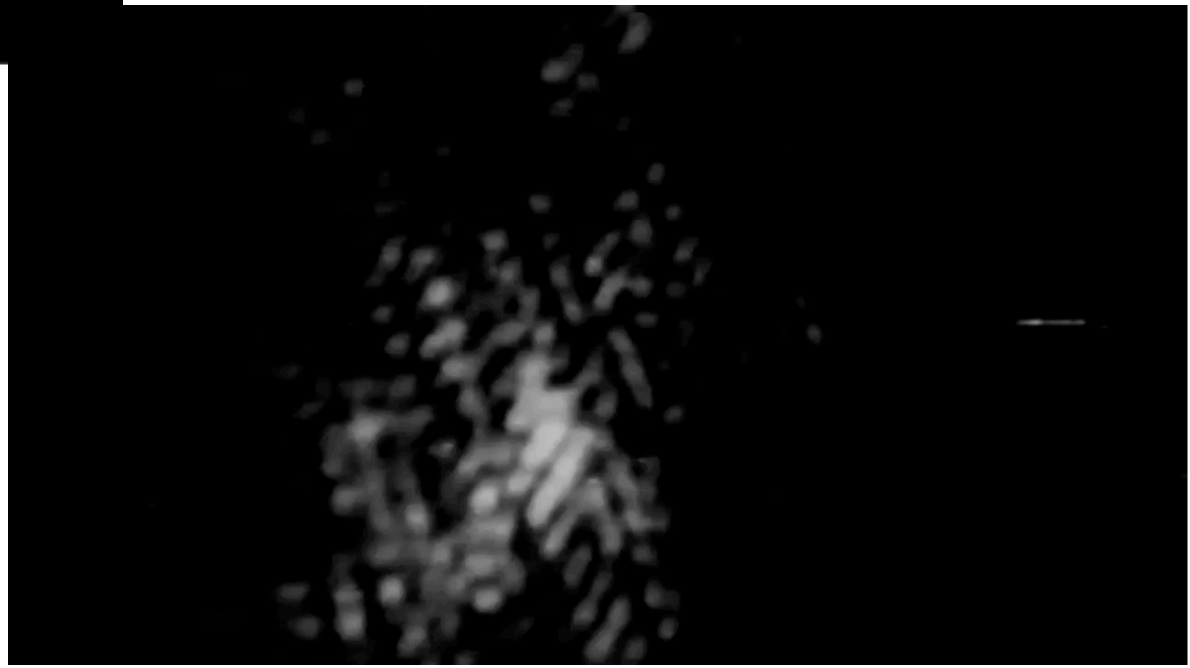

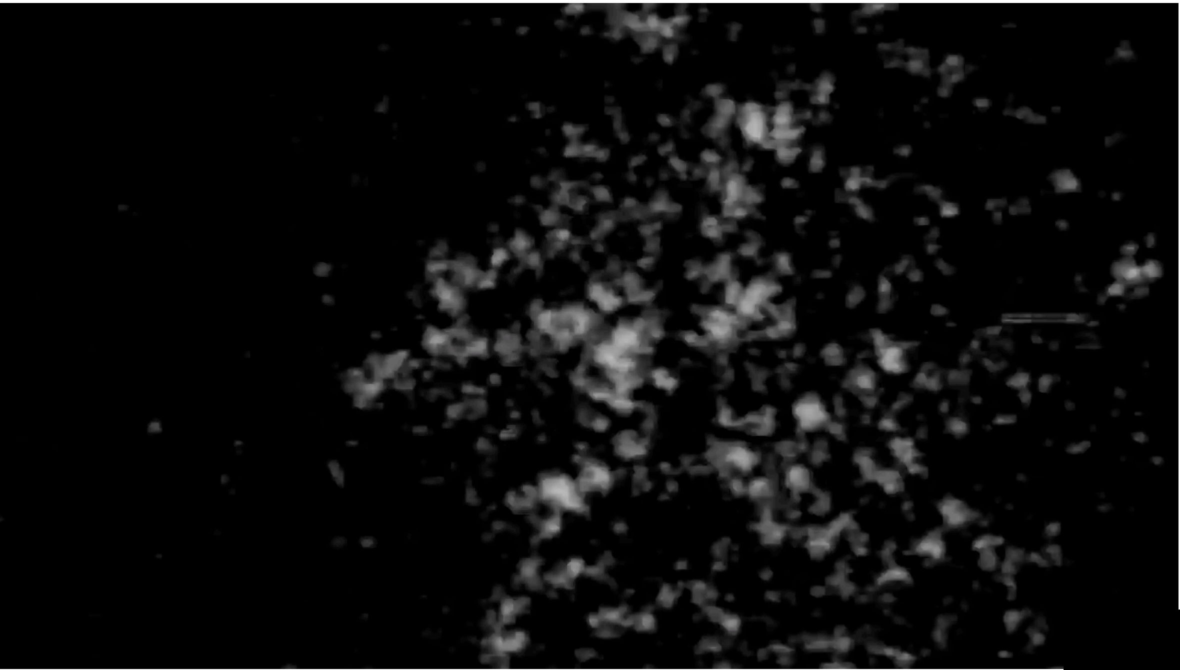

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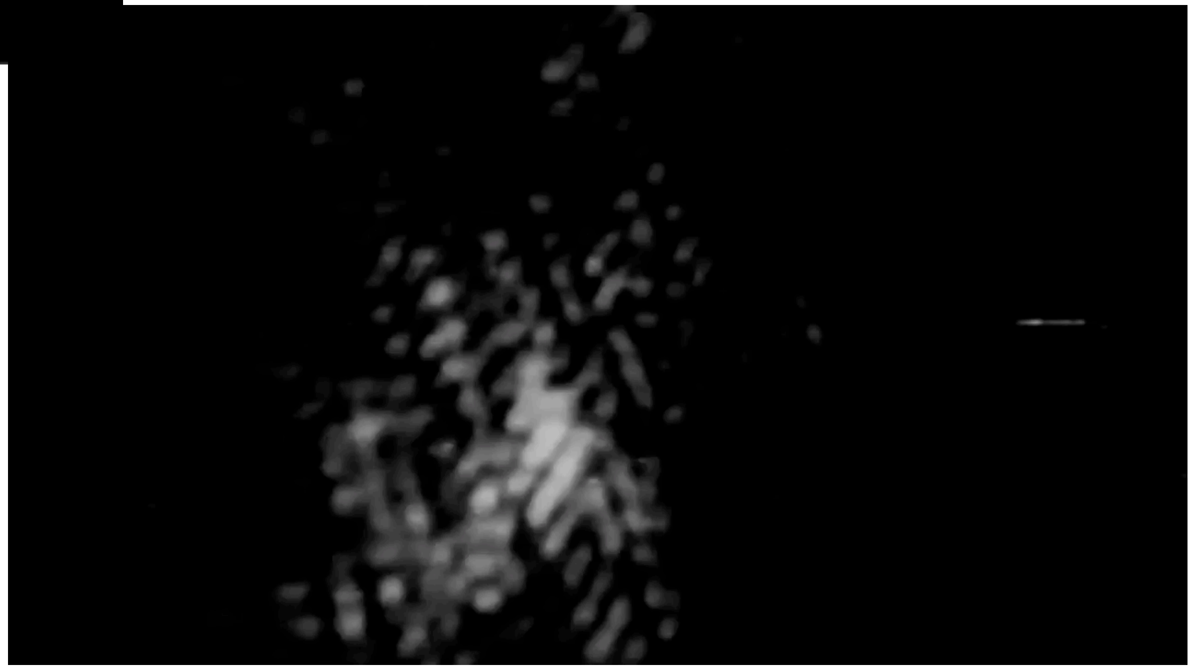
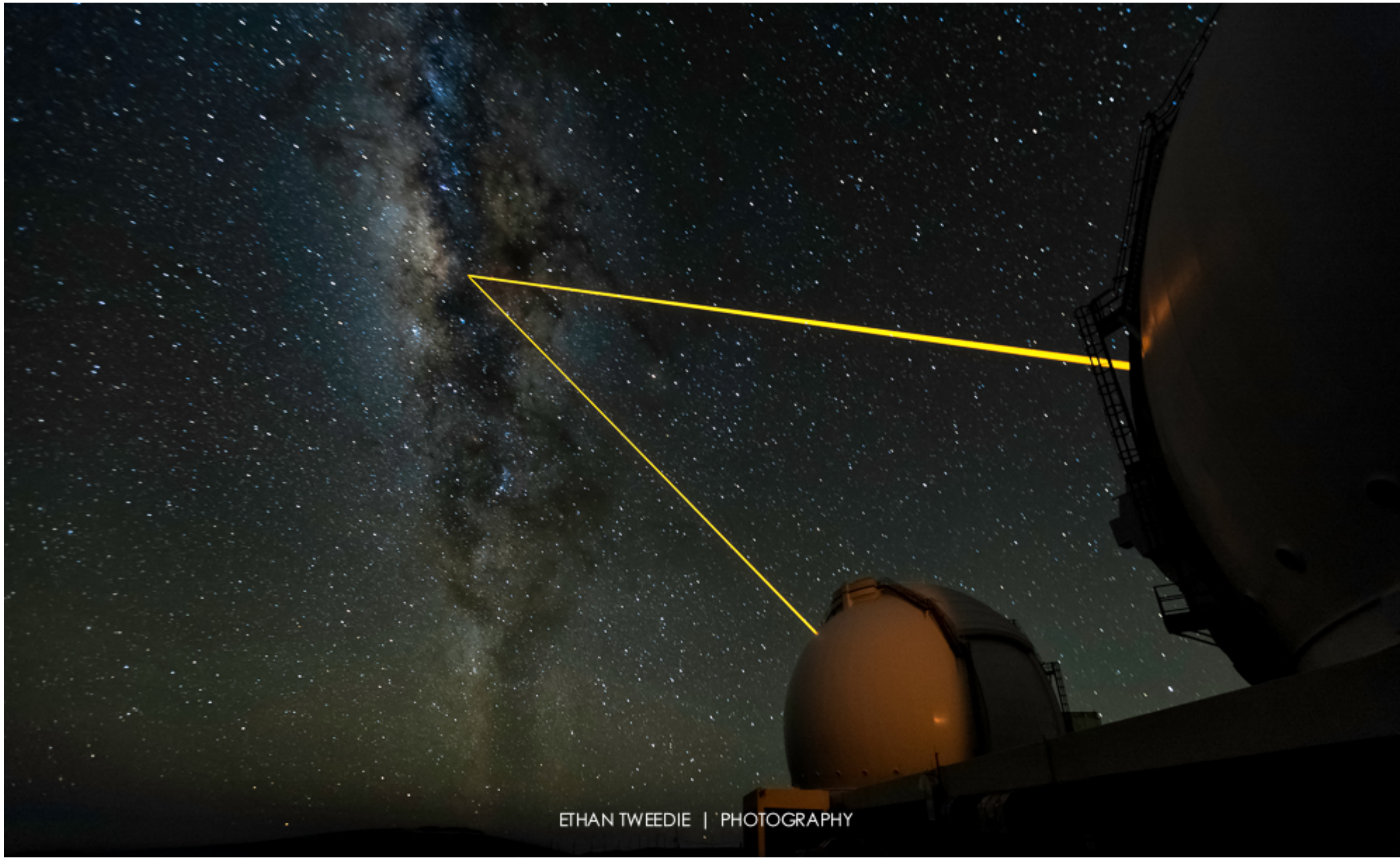
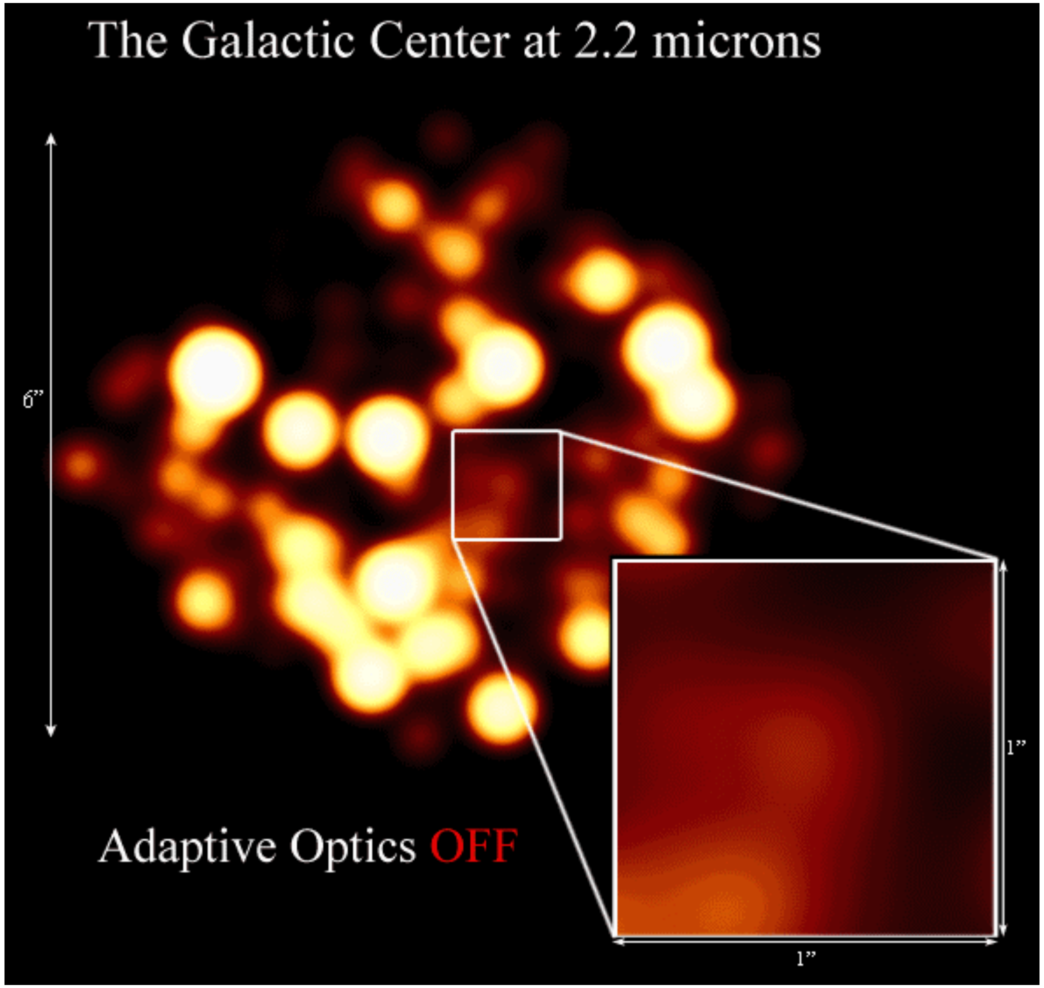
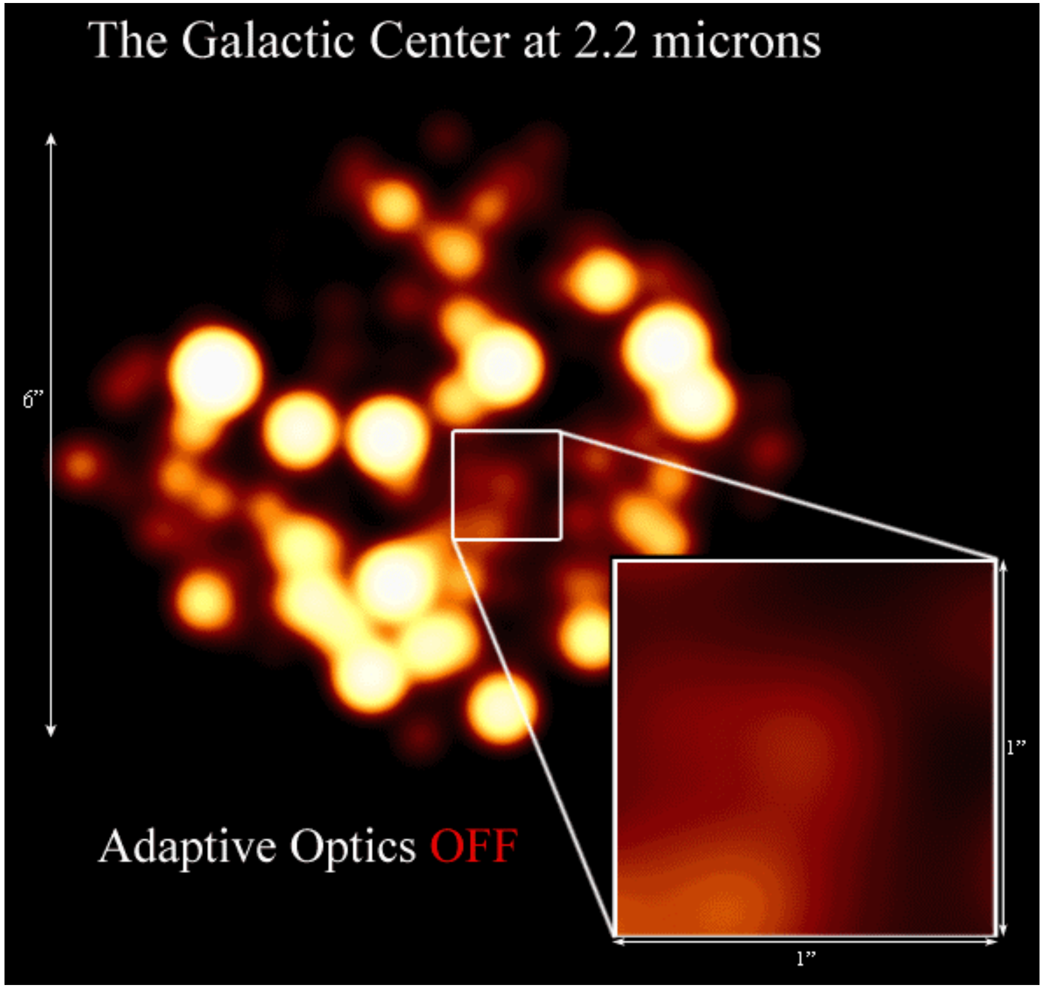


From 2004, used *adaptive optics* with laser guide stars to remove the atmospheric effects.



Ethan Tweedy Photography - http://www.ethantweedie.com/


The Galactic Center at 2.2 microns
6"
1"
1"
Adaptive Optics OFF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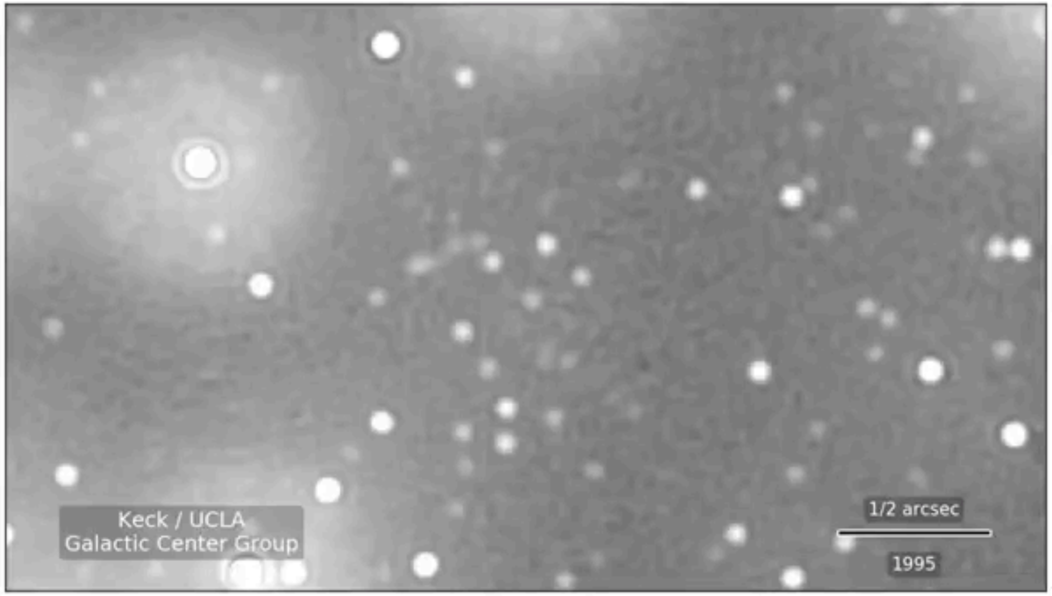
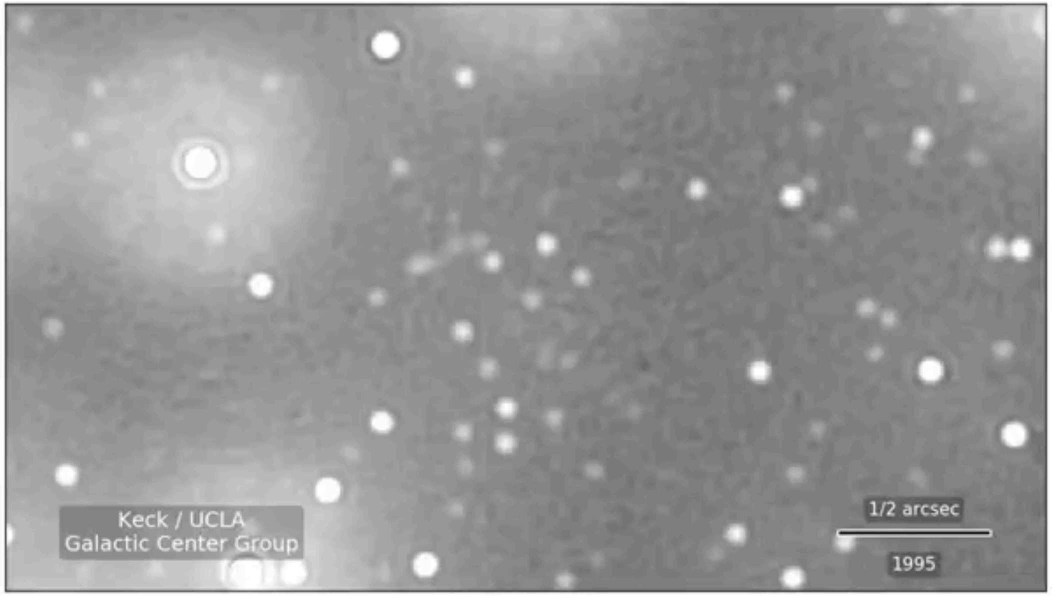

Keck / UCLA
Galactic Center Group
1/2 arcsec
1995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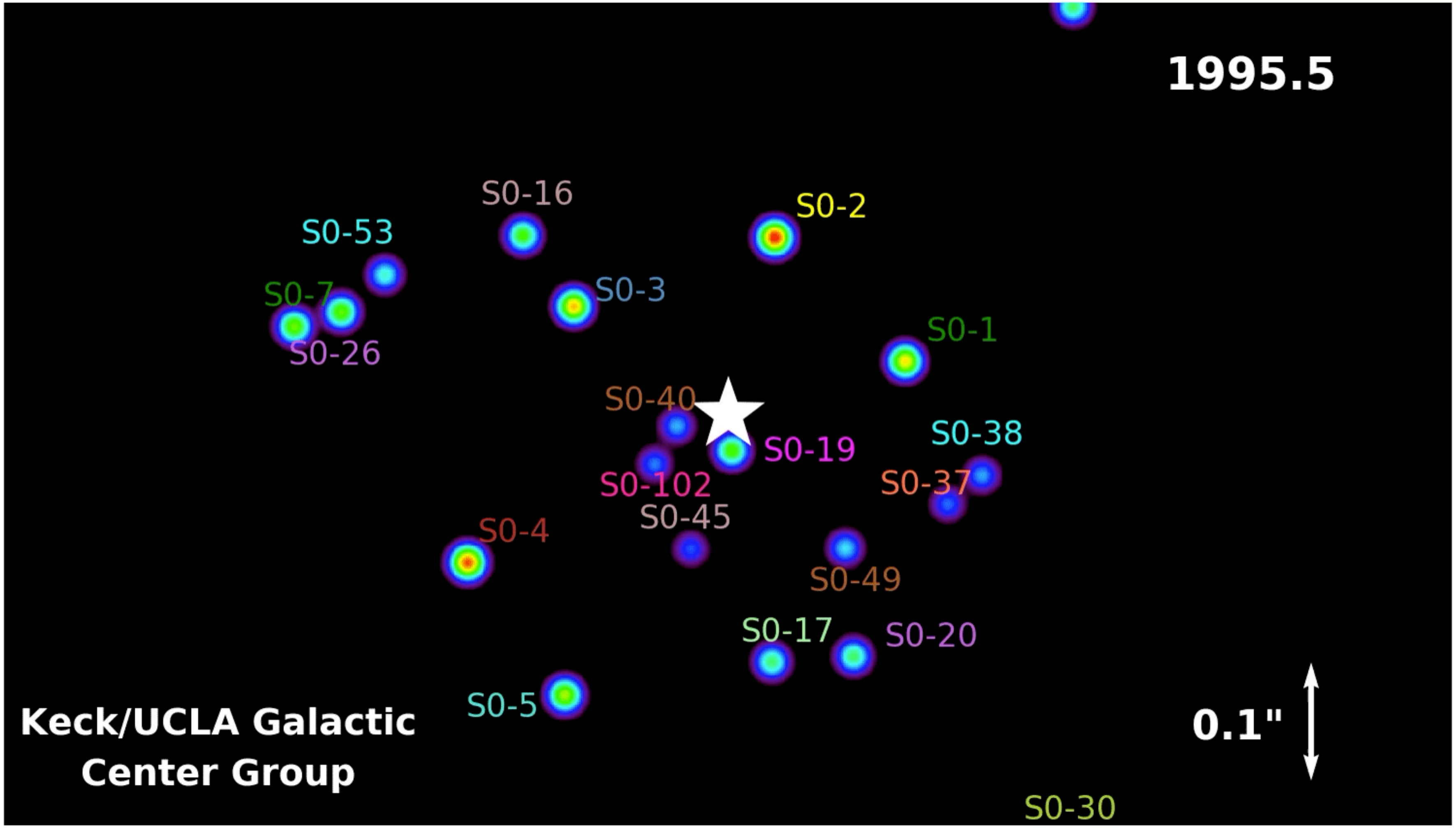
Now with 20+ years of data, the orbits of individual stars can be followed.



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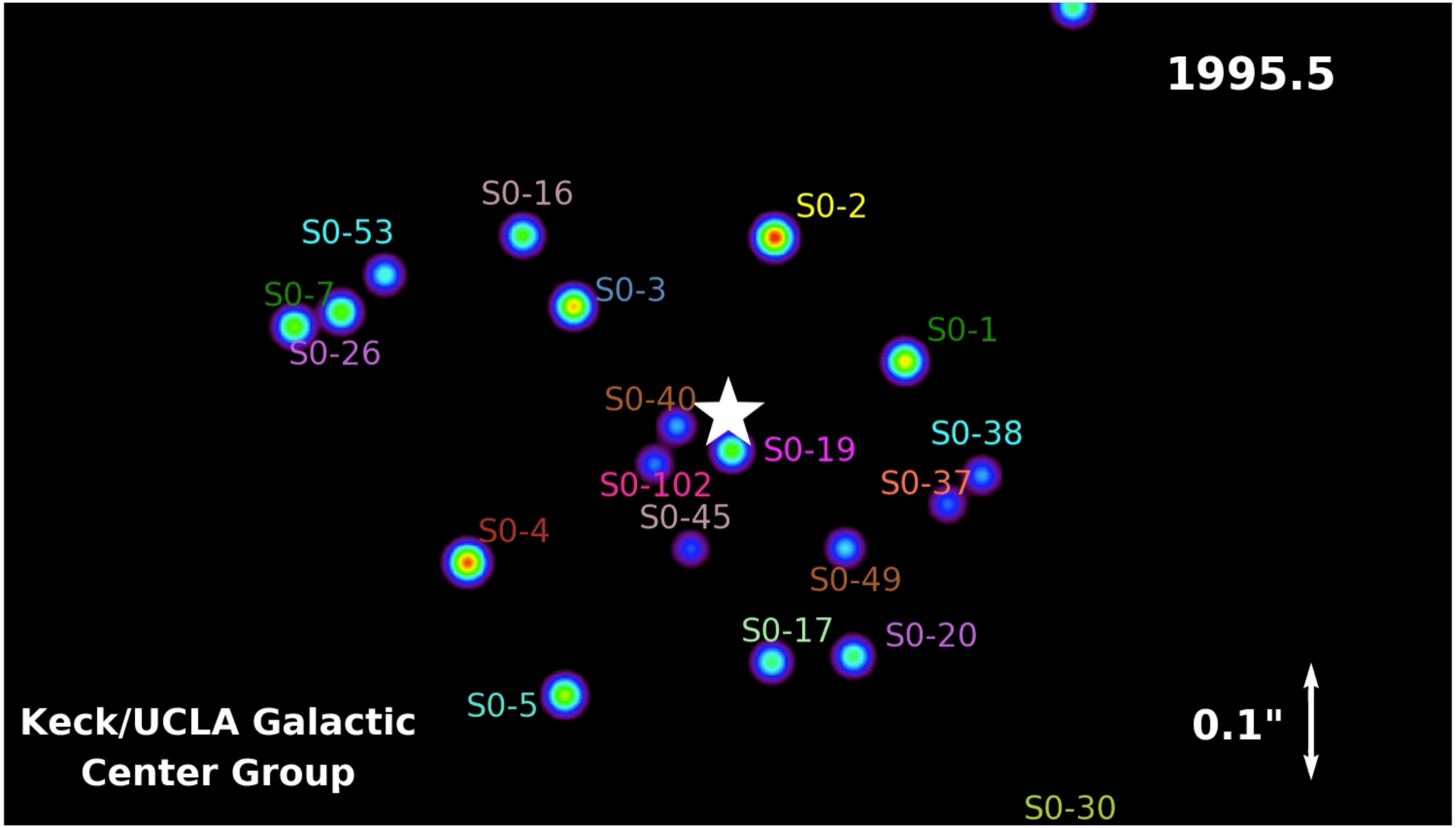
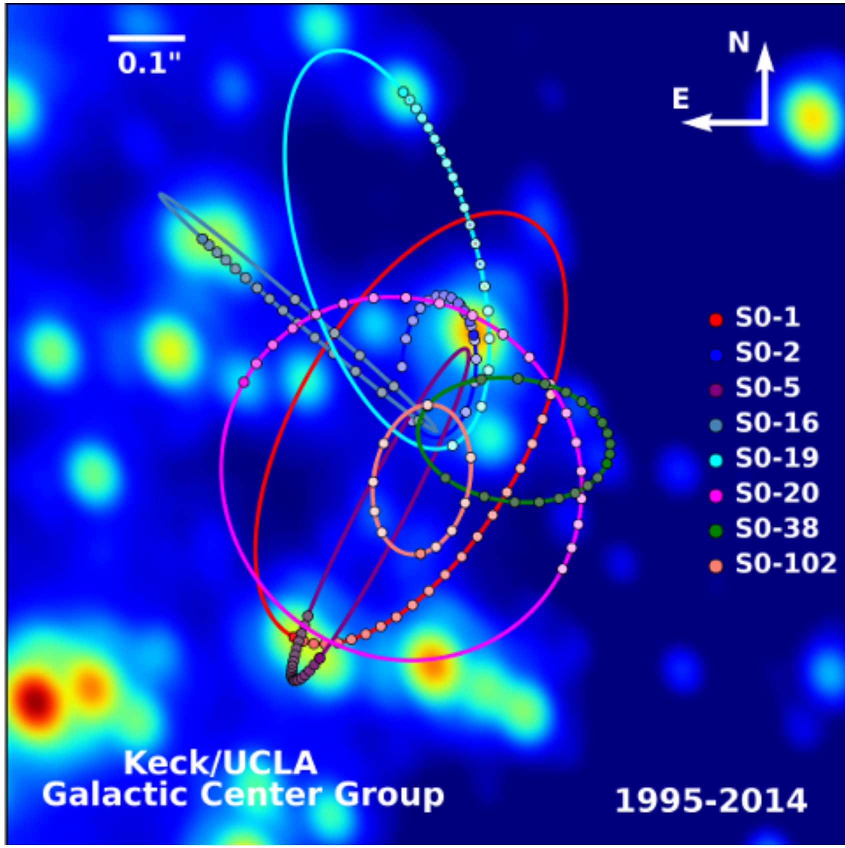


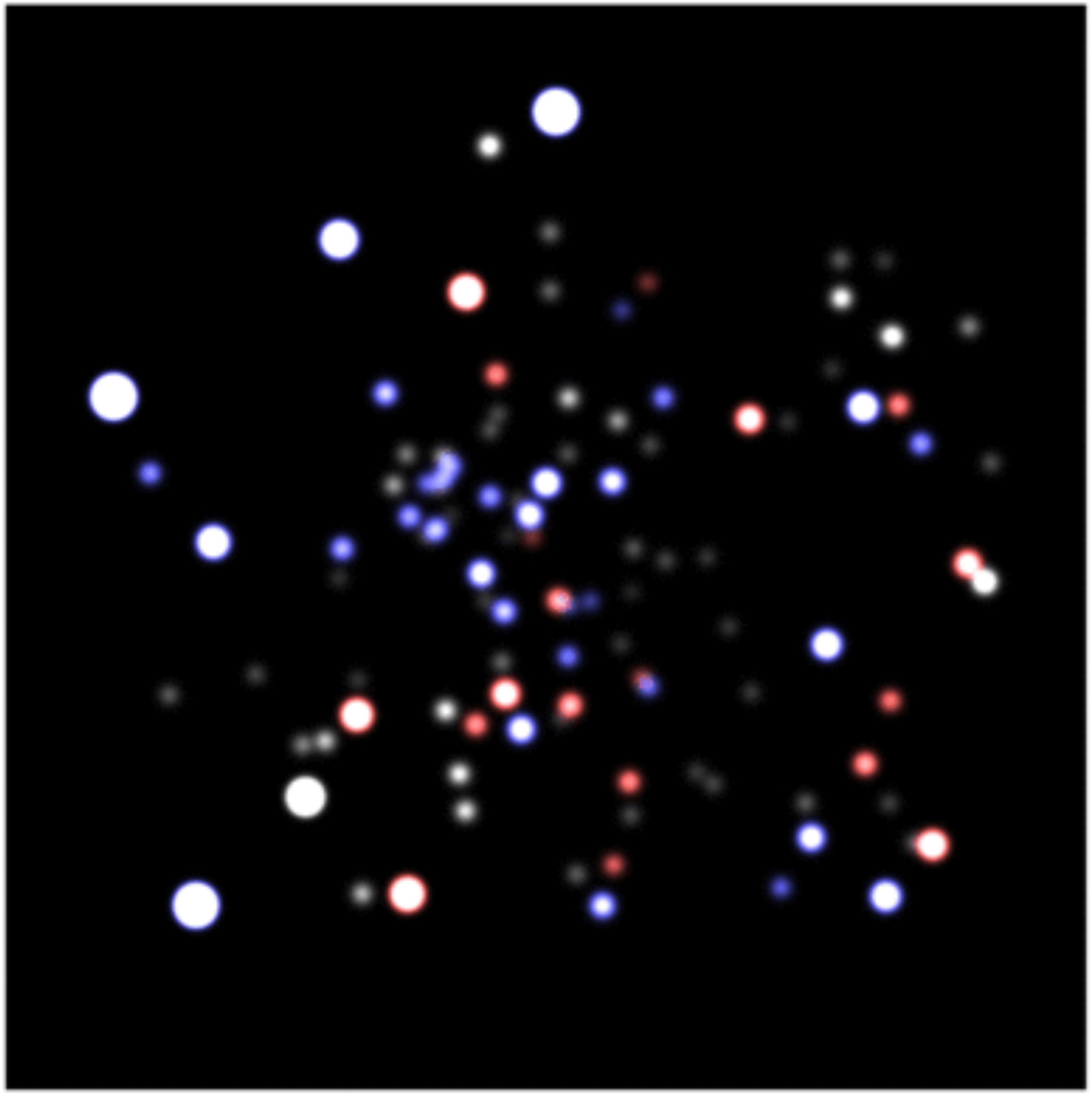
The black hole at the Galactic centre

Analysis of the stellar orbits reveal the mass of the central object to be 4 million times the mass of the Sun, with a Schwarzchild radius of 17 Solar radii (20% of the size of Mercury's orbit).

Measurements of the orbit of star S0-2 show the effect of general relativity.



A group led by Reinhard Genzel at MPE Garching has been making similar measurements over the same time period.



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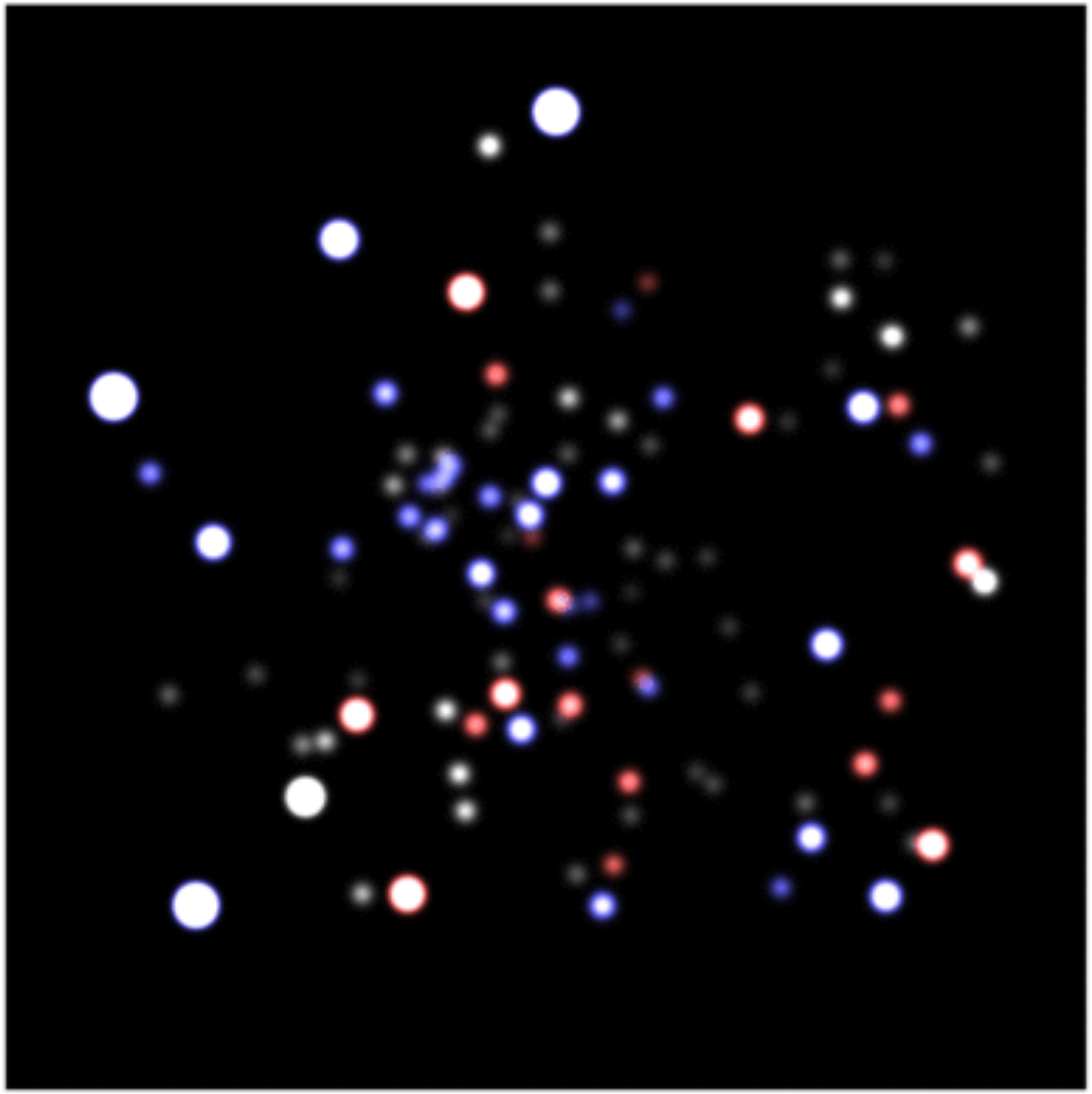
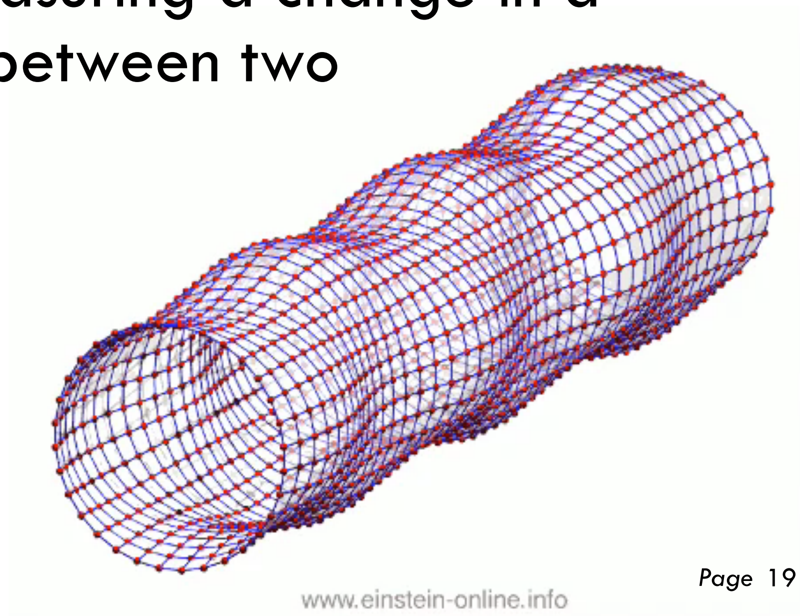


The search for gravitational waves

Einstein's General Theory of Relativity predicted the existence of *gravitational waves* in 1918 and described their properties: but their effects are tiny.

Gravitational waves are fluctuations in space-time which propagate as a wave, and in theory can be detected by measuring a change in a known length, e.g. the change in the distance between two objects.



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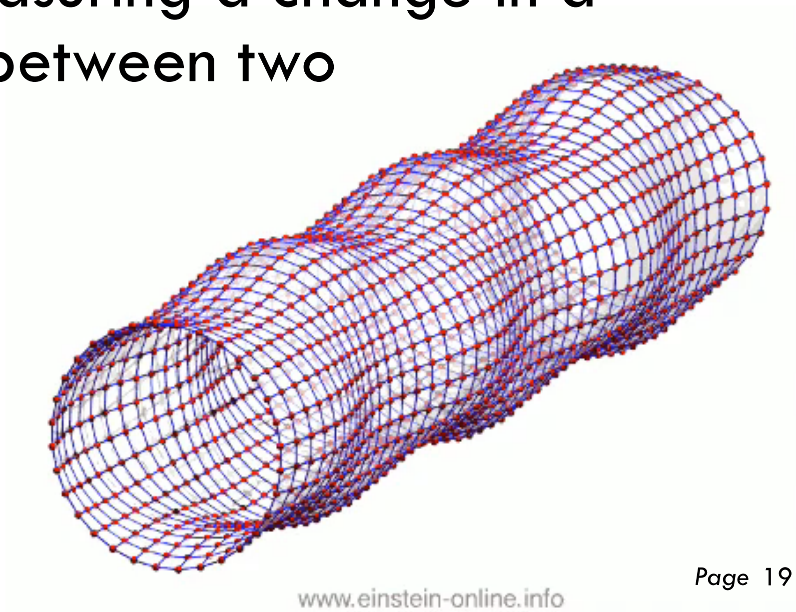
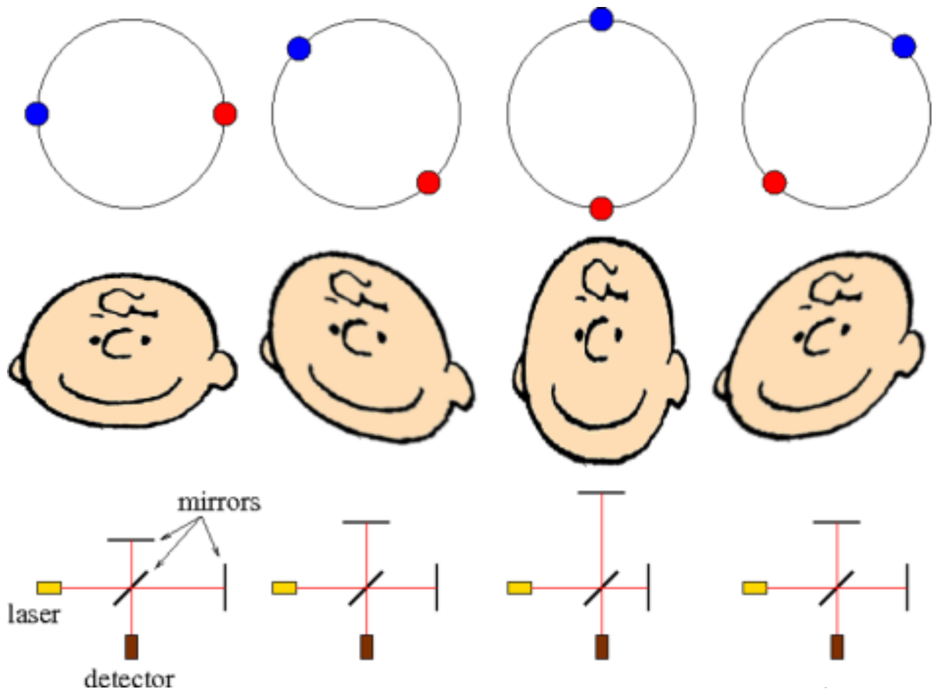
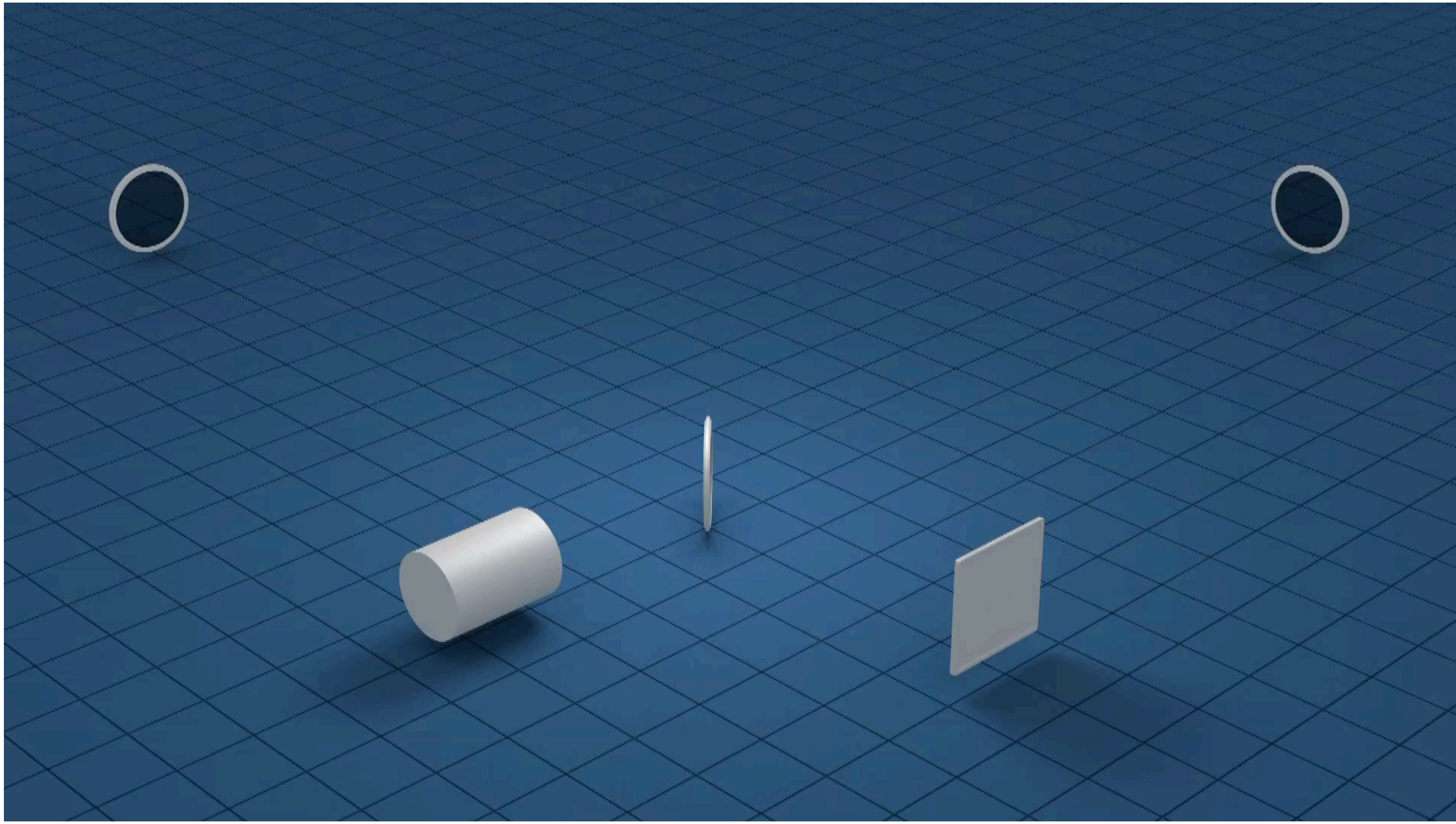


The effect is *extremely* weak: the most violent event produces changes of about 1 part in 10^{21}. To measure this, you need to be able to measure the change in length equal to 0.1% x diameter of a proton over 4 km.



Detecting gravitational waves by measuring a distortion (image by Matthew Francis)

In the 1980s, designs emerged for a laser interferometer to detect gravitational waves.



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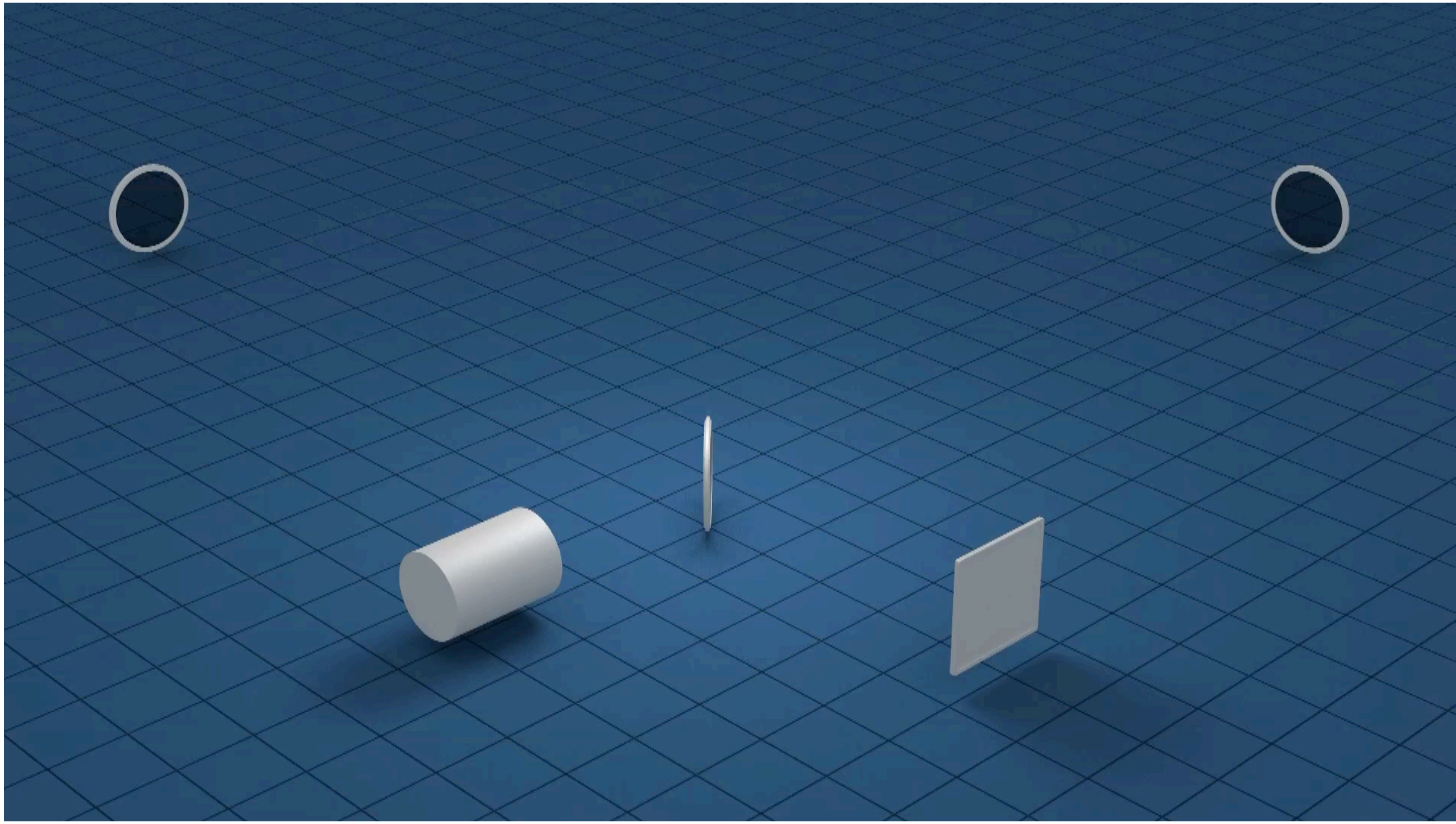
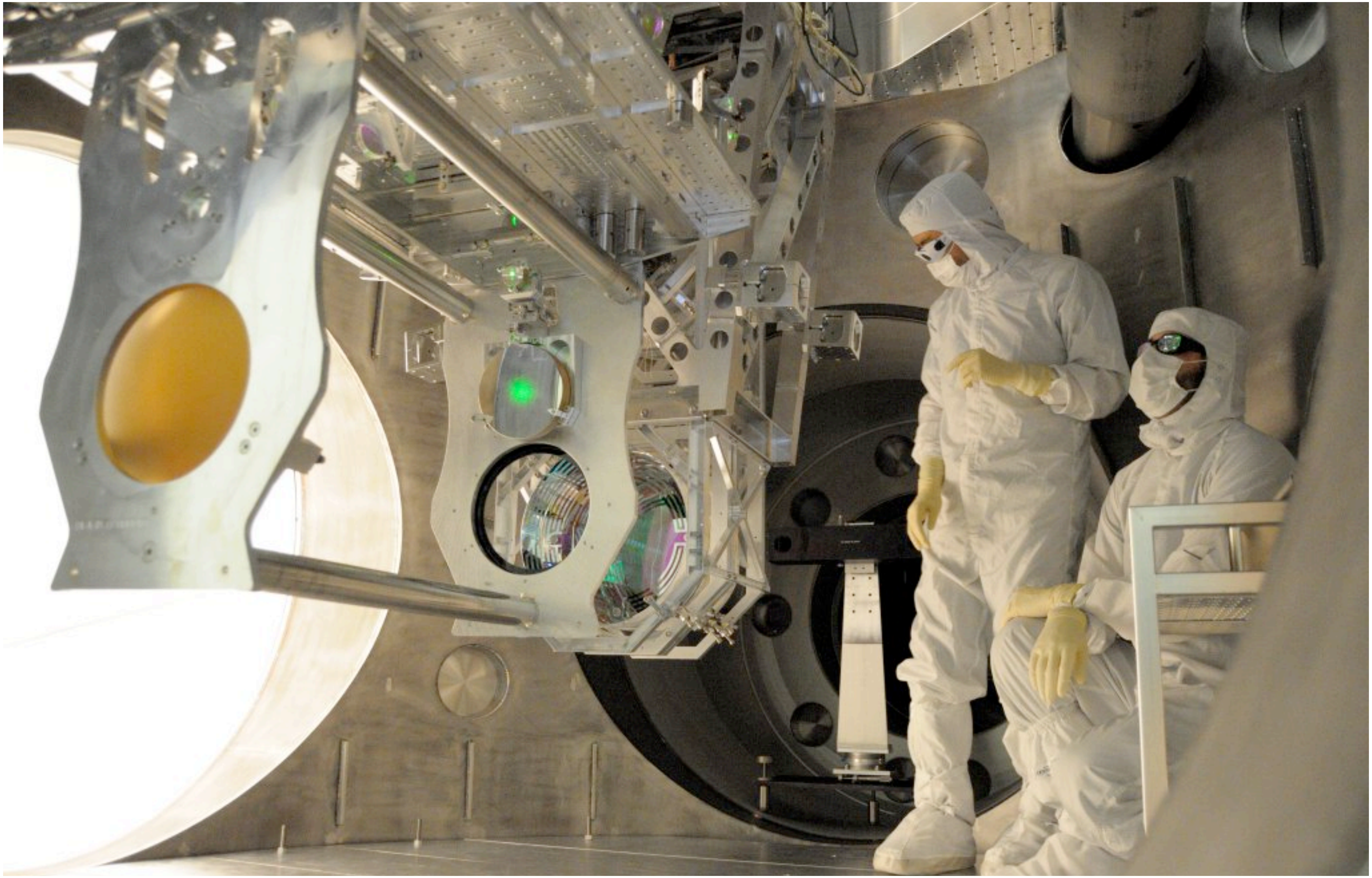


Construction of the LIGO observatory, with two antennas in Louisiana and Washington, began in 1994. Interferometers were installed between 1999 and 2002, and the facility began operation in 2002.

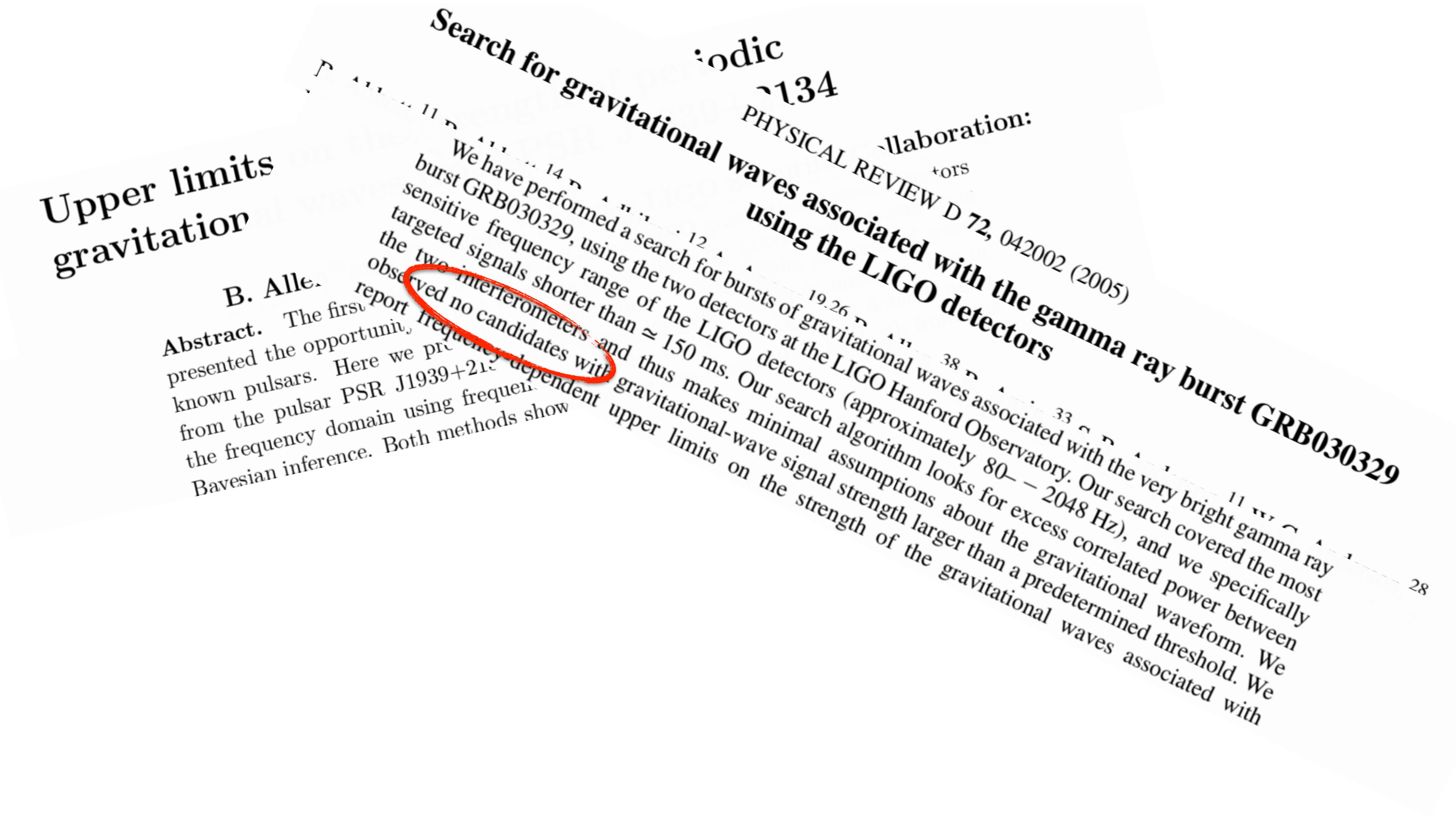
The plan was to construct an initial facility that *might* detect GW, with plans for an upgraded system that would *almost certainly* detect them.



Upper limits on the strength of periodic gravitational waves from PSR J1939+2134

B. Allen[39] and G. Woan[35], for the LIGO Scientific Collaboration:

Abstract. The first science run of the LIGO and GEO gravitational wave detectors presented the opportunity to test methods of searching for gravitational waves from known pulsars. Here we present new direct upper limits on the strength of waves from the pulsar PSR J1939+2134 using two independent analysis methods, one in the frequency domain using frequentist statistics and one in the time domain using Bayesian inference. Both methods show that the strain amplitude at Earth from this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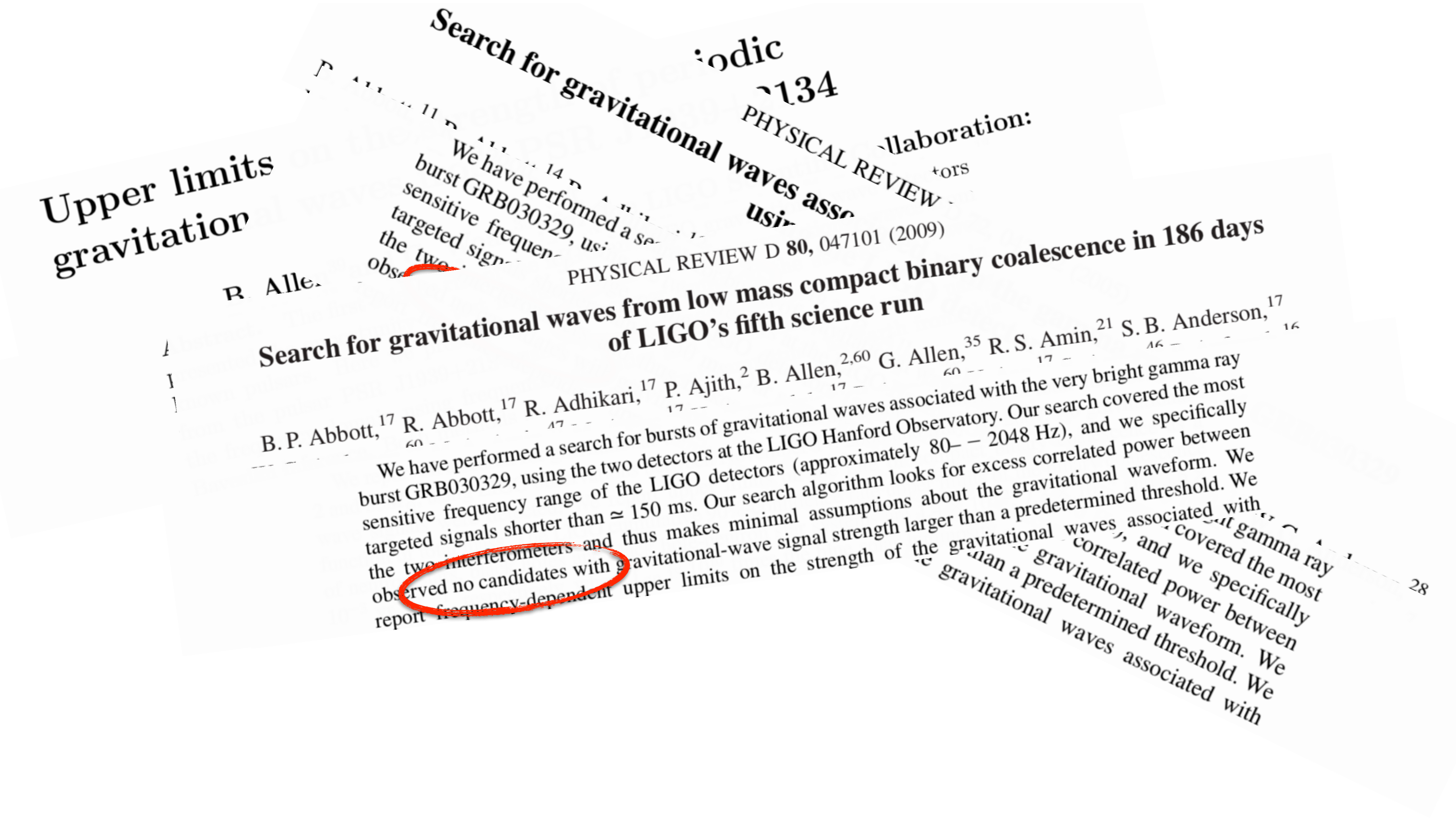
PHYSICAL REVIEW D 72, 042002 (2005)
Search for gravitational waves associated with the gamma ray burst GRB030329 using the LIGO detectors
We have performed a search for bursts of gravitational waves associated with the very bright gamma ray burst GRB030329, using the two detectors at the LIGO Hanford Observatory. Our search covered the most sensitive frequency range of the LIGO detectors (approximately 80– – 2048 Hz), and we specifically targeted signals shorter than ≃ 150 ms. Our search algorithm looks for excess correlated power between the two interferometers and thus makes minimal assumptions about the gravitational waveform. We observed no candidates with gravitational-wave signal strength larger than a predetermined threshold. We report frequency dependent upper limits on the strength of the gravitational waves associated with



Upper limits
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Search for gravitational waves ass
PHYSICAL REVIEW
llaboration:
PHYSICAL REVIEW D 80, 047101 (2009)
Search for gravitational waves from low mass compact binary coalescence in 186 days
of LIGO's fifth science run
B. P. Abbott, R. Abbott, R. Adhikari, P. Ajith, B. Allen, G. Allen, R. S. Amin, S. B. Anderson
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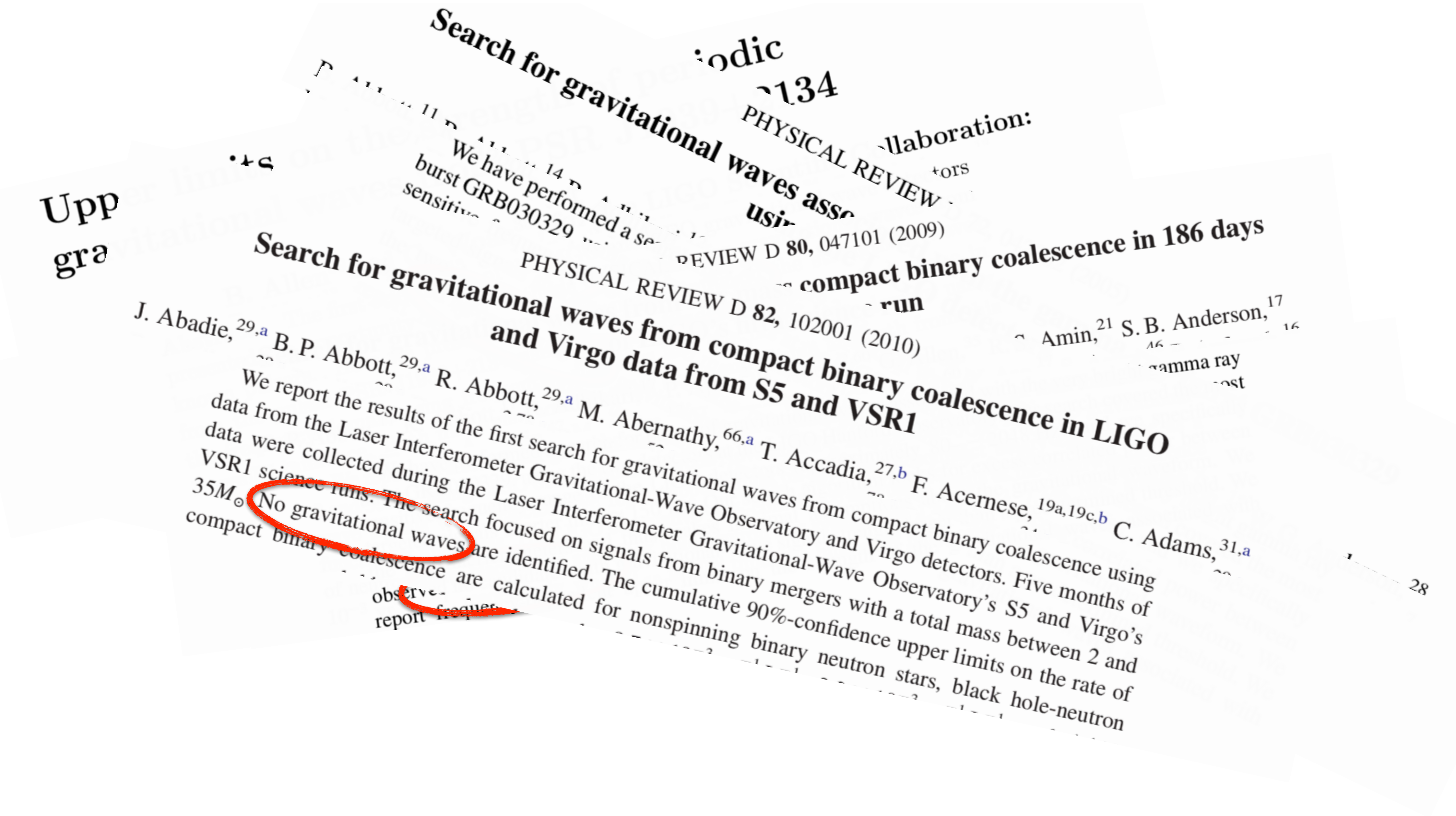
Search for gravitational waves from compact binary coalescence in LIGO and Virgo data from S5 and VSR1
PHYSICAL REVIEW D 82, 102001 (2010)
J. Abadie, B. P. Abbott, R. Abbott, M. Abernathy, T. Accadia, F. Acernese, C. Adams,
We report the results of the first search for gravitational waves from compact binary coalescence using data from the Laser Interferometer Gravitational-Wave Observatory and Virgo detectors. Five months of data were collected during the Laser Interferometer Gravitational-Wave Observatory's S5 and Virgo's VSR1 science runs. The search focused on signals from binary mergers with a total mass between 2 and 35M⊙. No gravitational waves are identified. The cumulative 90%-confidence upper limits on the rate of compact binary coalescence are calculated for nonspinning binary neutron stars, black hole-neutron
PHYSICAL REVIEW D 80, 047101 (2009)
compact binary coalescence in 186 days
Search for gravitational waves asso
PHYSICAL REVIEW
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We have performed a se
burst GRB030329
S. B. Anderson,
gamma ray

PHYSICAL REVIEW D **89**, 102006 (2014)

Search for gravitational wave ringdowns from perturbed intermediate mass black holes in LIGO-Virgo data from 2005–2010

J. Aasi,[1] B. P. Abbott,[1] R. Abbott,[1] T. Abbott,[2] M. R. Abernathy,[1] F. Acernese,[3,4] K. Ackley,[5] C. Adams,[6] T. Adams,[7]

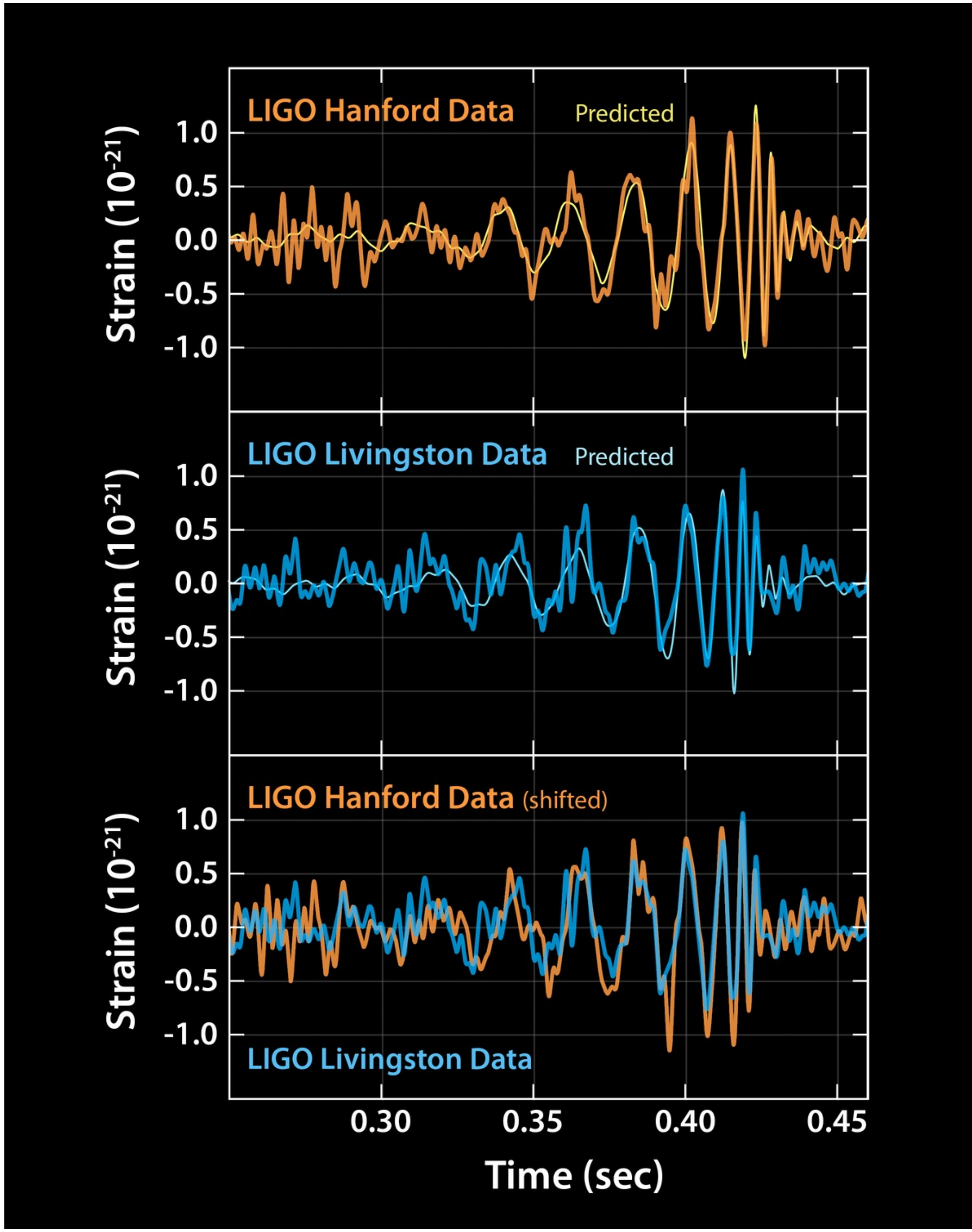
We report results from a search for gravitational waves produced by perturbed intermediate mass black holes (IMBH) in data collected by LIGO and Virgo between 2005 and 2010. The search was sensitive to astrophysical sources that produced damped sinusoid gravitational wave signals, also known as ringdowns, with frequency $50 \leq f_0/\mathrm{Hz} \leq 2000$ and decay timescale $0.0001 \lesssim \tau/\mathrm{s} \lesssim 0.1$ characteristic of those produced in mergers of IMBH pairs. No significant gravitational wave candidate was detected. We report upper limits on the astrophysical coalescence rates of IMBHs with total binary mass $50 \leq M/\mathrm{M}_\odot \leq 450$

In 2010, LIGO went offline for several years for a major upgrade: Advanced LIGO. Commissioning was complete by 2014, and in September 2015 both interferometers were ready to begin Advanced LIGO's first official gravitational wave search.

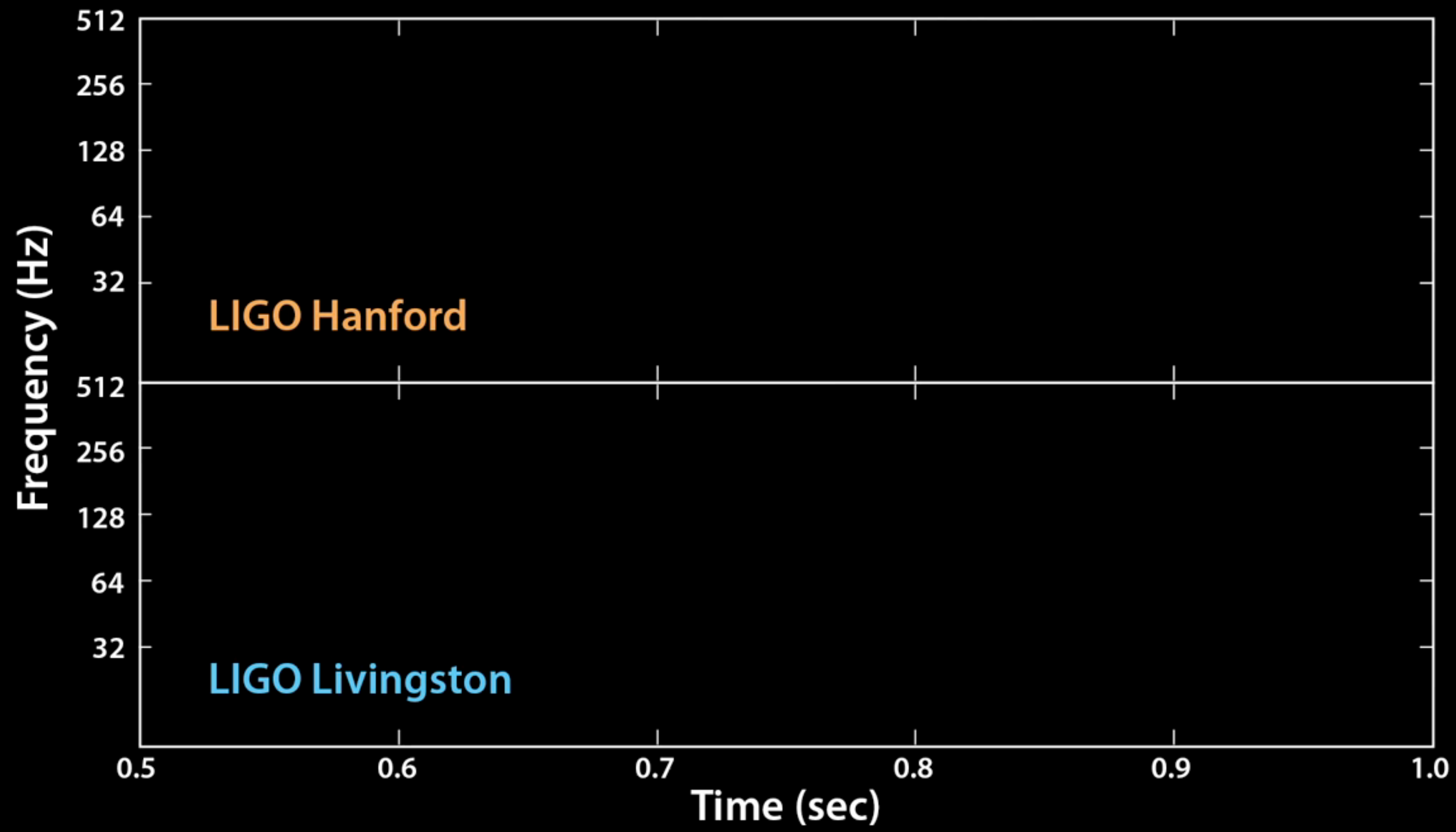
Just before the official observing run started, the first gravitational wave was detected, on 14 September 2015.

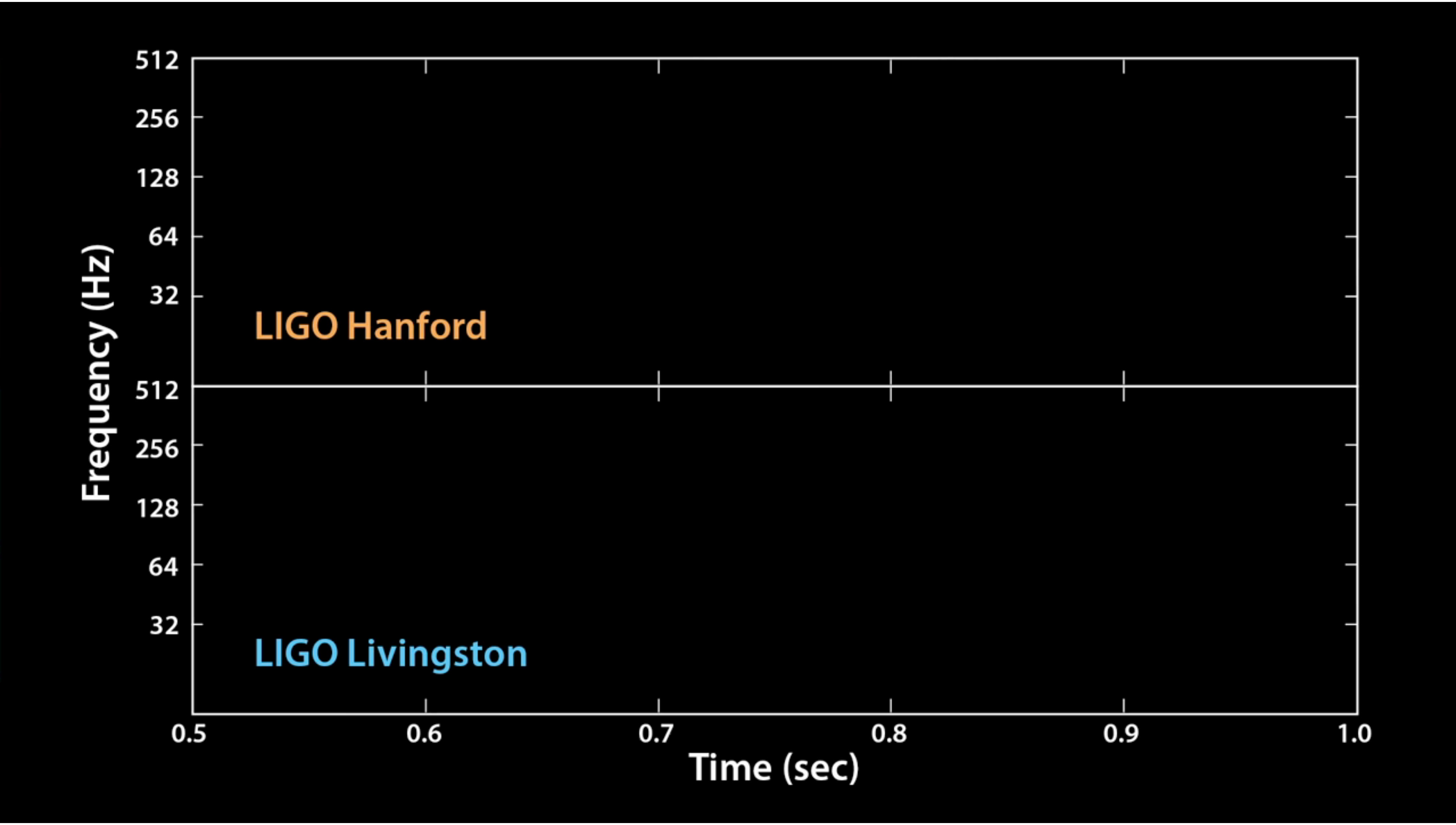
The gravitational wave event seen by the two LIGO detectors. Top two plots show the measured strain, compared to a numerical relativity waveform for two merging black holes.

The third plot shows the data from both detectors, with the data from H1 shifted by 6.9 ms and inverted.



Over 0.2 s, the signal increases in frequency and amplitude in about 8 cycles, from 35 to 150 Hz (the "chirp"). The most plausible explanation for this signal is the inspiral of two orbiting masses due to gravitational wave emission.


512
256
128
64
32
LIGO Hanford
512
256
128
64
32
LIGO Livingston
Frequency (Hz)
0.5
0.6
0.7
0.8
0.9
1.0
Time (sec)



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LIGO Livingston
Frequency (Hz)
0.5
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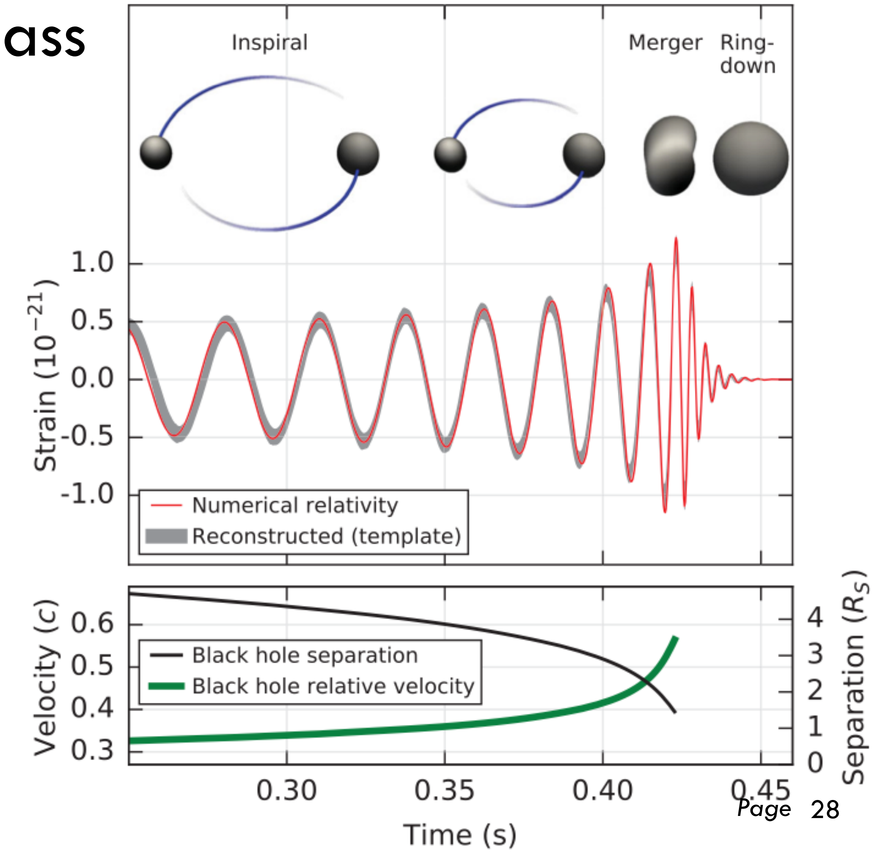
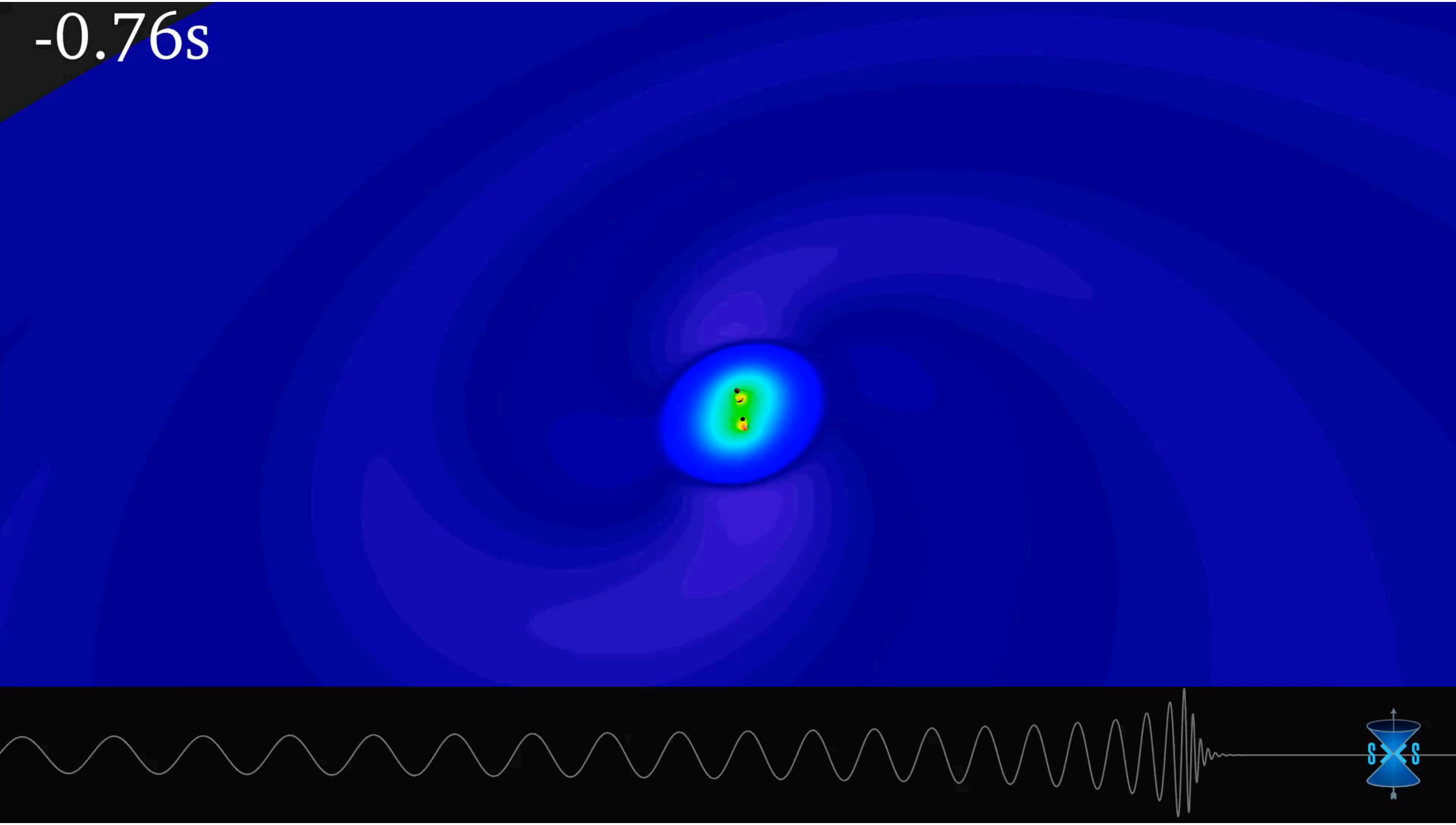
1.0
Time (sec)

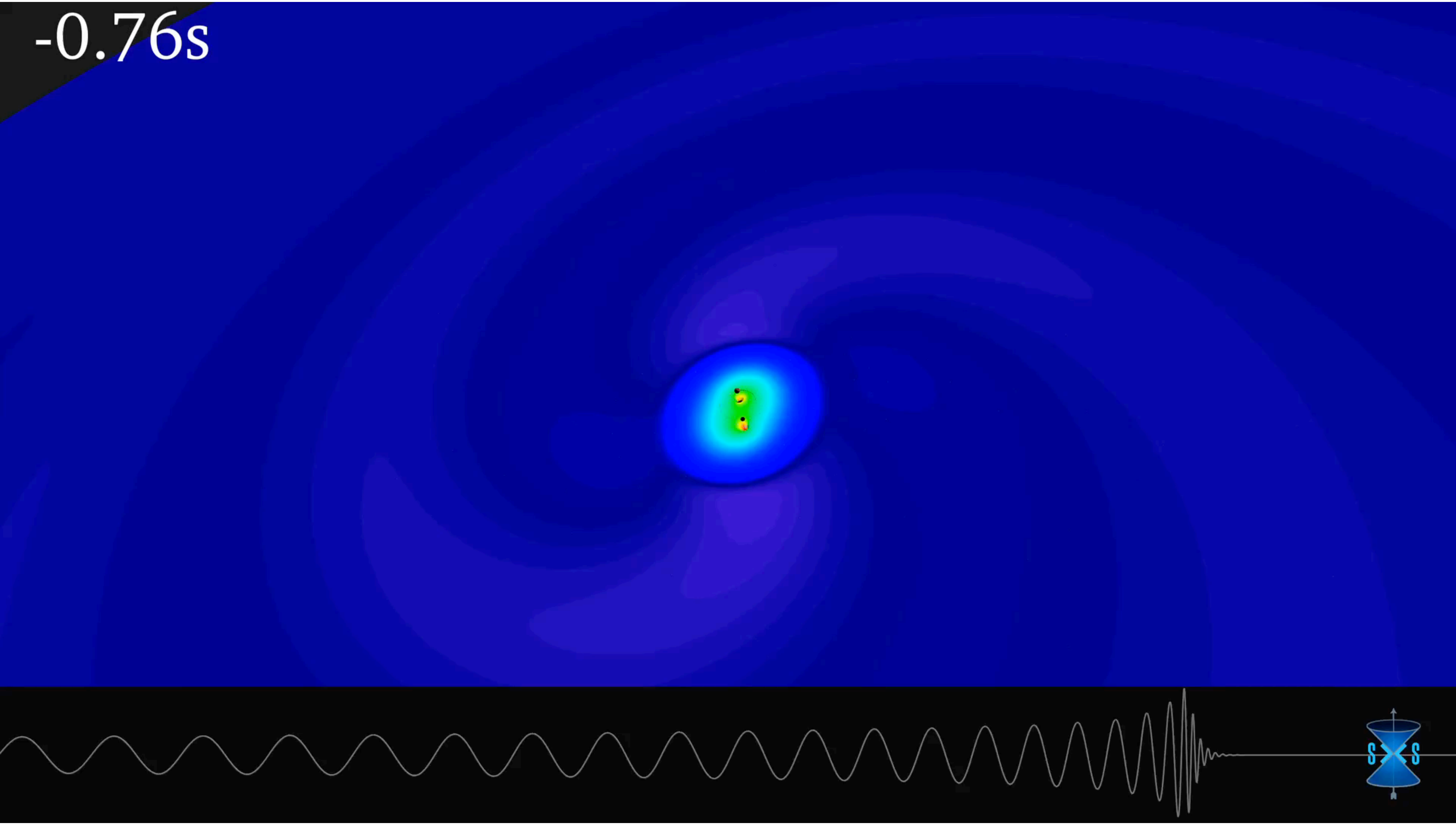
From the shape of the signal, we can determine that two black holes, with masses $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$

merged, to form a single black hole with mass

$62^{+4}_{-4} M_\odot$



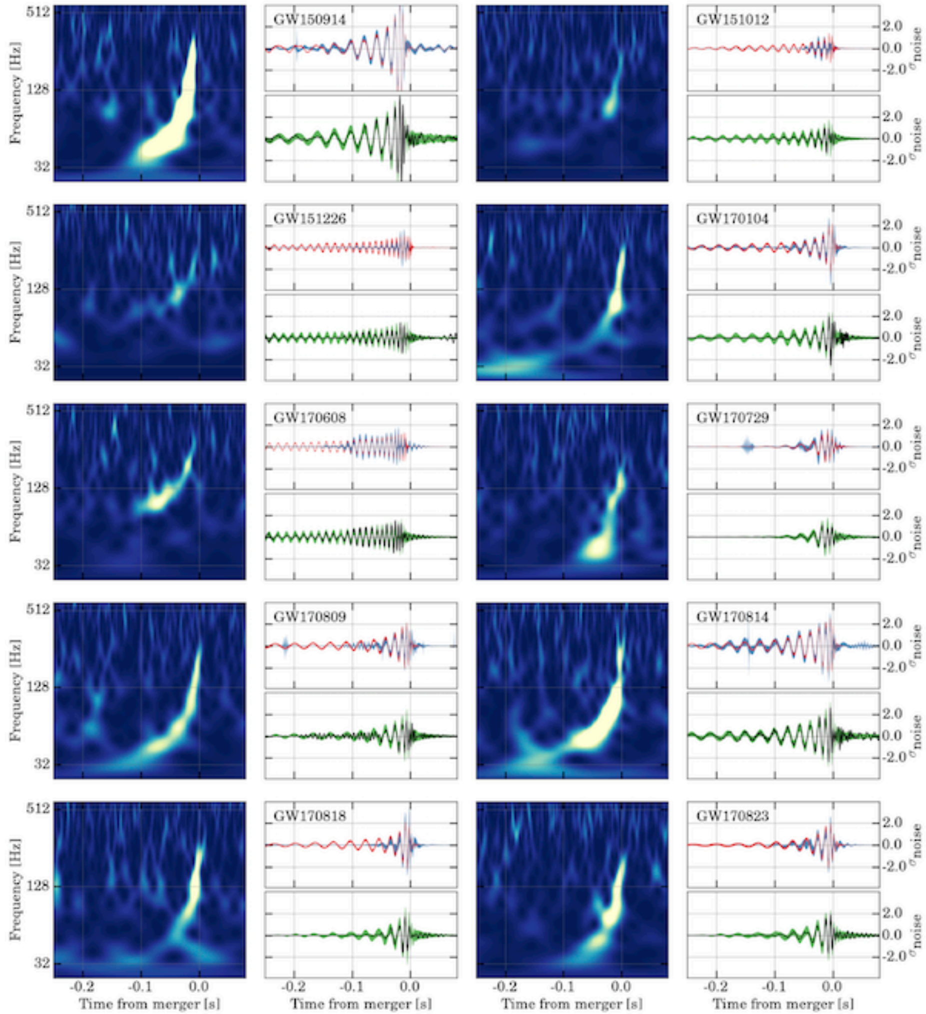

-0.76s


-0.76s

Since that initial discovery, LIGO has detected

- the first neutron star-neutron star merger, with its associated kilonova explosion (*see Tara's talk*)
- ten confirmed binary black hole mergers
- around 20 candidate events so far in O3

LIGO third observing run will conclude in April next year.



"Chirp" signals from the ten BBH events in O1/O2

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  mergers
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LIGO third obse
in April next ye...


Gijs Nelemans
@gijsnelemans
Follow

Who would have believed we would have quotes like this any time soon "Last week was quite uneventful, with only one BBH detected...". @LIGO @ego_virgo

6:14 AM - 4 Jun 2019

2 Retweets 24 Likes

2 24

“Chirp” signals from the ten BBH events in O1/O2

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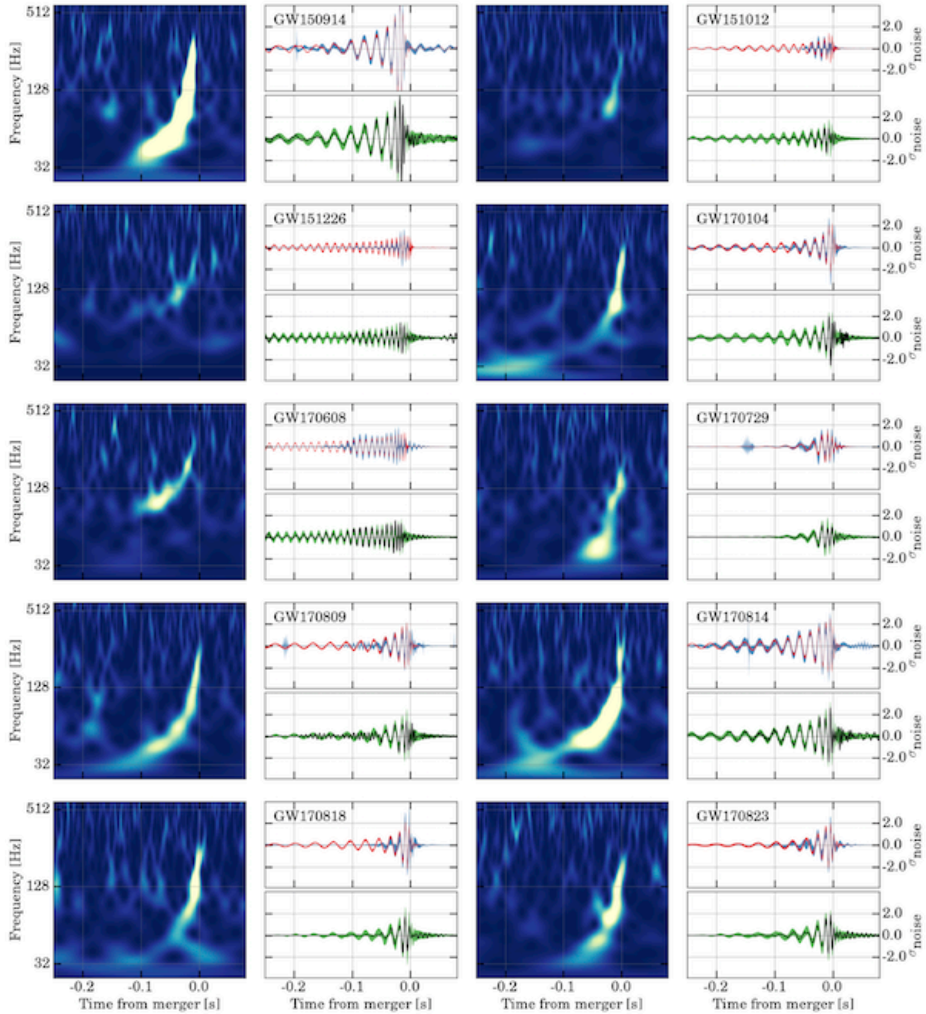
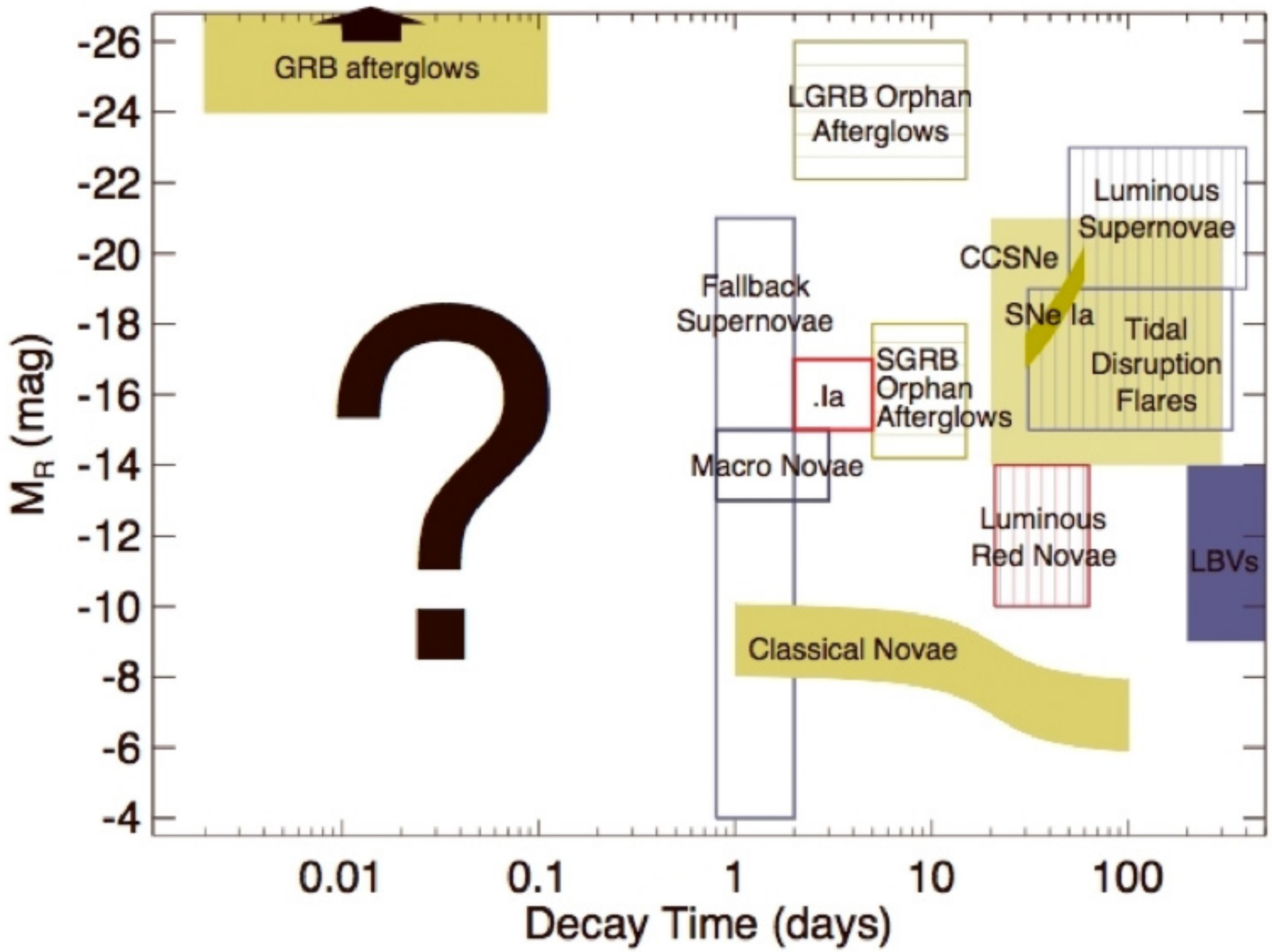


"Chirp" signals from the ten BBH events in O1/O2

The search for transients

Many processes in astronomy are *transient* – they occur rarely, or for a short time, or randomly, or all three.



GRB afterglows
LGRB Orphan Afterglows
Luminous Supernovae
CCSNe
Fallback Supernovae
SNe Ia
Tidal Disruption Flares
SGRB Orphan Afterglows
.Ia
Macro Novae
Luminous Red Novae
LBVs
Classical Novae
?
M_R (mag)
Decay Time (days)
-26
-24
-22
-20
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-16
-14
-12
-10
-8
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100

In the 1990s, the mystery of the gamma-ray bursts was solved using robotic telescopes that could slew automatically to the position of a GRB when an email alert was sent out.

In 1999, ROTSE-1 detected the afterglow from a GRB only *22 seconds* after the burst.

But the other way to do transient searches is to look at the whole sky as often as possible, and look for objects that change.

Many programs:

- *UTMOST*, using the Molonglo telescope
- *SkyMapper*, using a dedicated telescope at Siding Spring
- The *Palomar Transient Factory*
- The *Large Synoptic Survey Telescope*, which will photograph the whole sky every few nights with an 8-m mirror

Search for failed supernovae

Inverse transient search: looking for *failed supernovae*.

We know that stars with masses ~10 $M_\odot$ explode as a supernova, leaving behind a neutron star. We also know that really massive stars (bigger than 40 $M_\odot$) explode as a supernova, leaving behind a black hole.

Several lines of evidence suggest that stars between these two limits might not explode at all, but might collapse directly into a black hole, without an accompanying explosion.

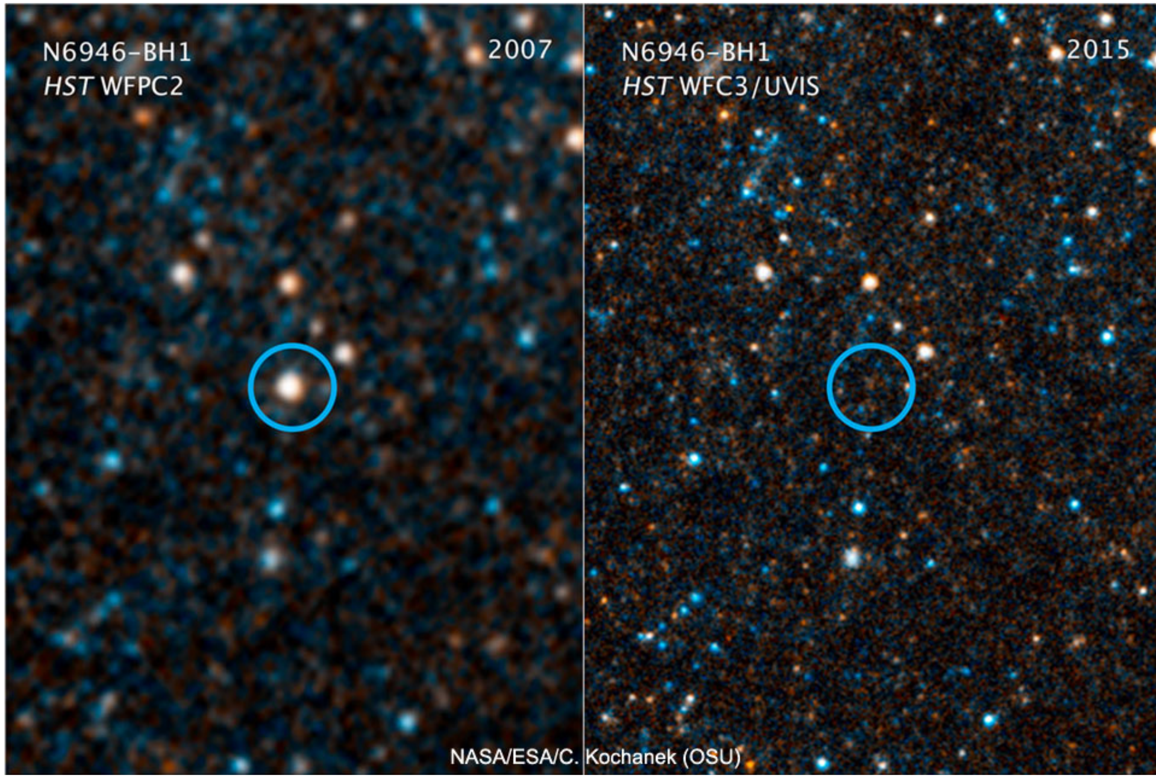
Unfortunately, to find these, we need to look for stars that disappear.

Since the progenitor stars live for about 10^6 y, need to monitor 10^6 stars to have reasonable chance of seeing one in a few years.

Kochanek et al: monitoring 27 galaxies for years, looking for stars that disappear.

They found one star that disappeared in this time (confirmed by Hubble data).

This suggests that as many as 1/3 of stars with masses around 25 $M_\odot$ collapse directly to a black hole without exploding.



Lessons learned

Do these three examples fit with Harwit's analysis?

✳ the black hole at the Galactic centre

– *specialised equipment*

✳ LIGO and the discovery of gravitational waves:

– *no! huge NSF-funded project*

✳ the search for transients

– *something new: Big Data*


What next for astronomy?

Extremely large telescopes

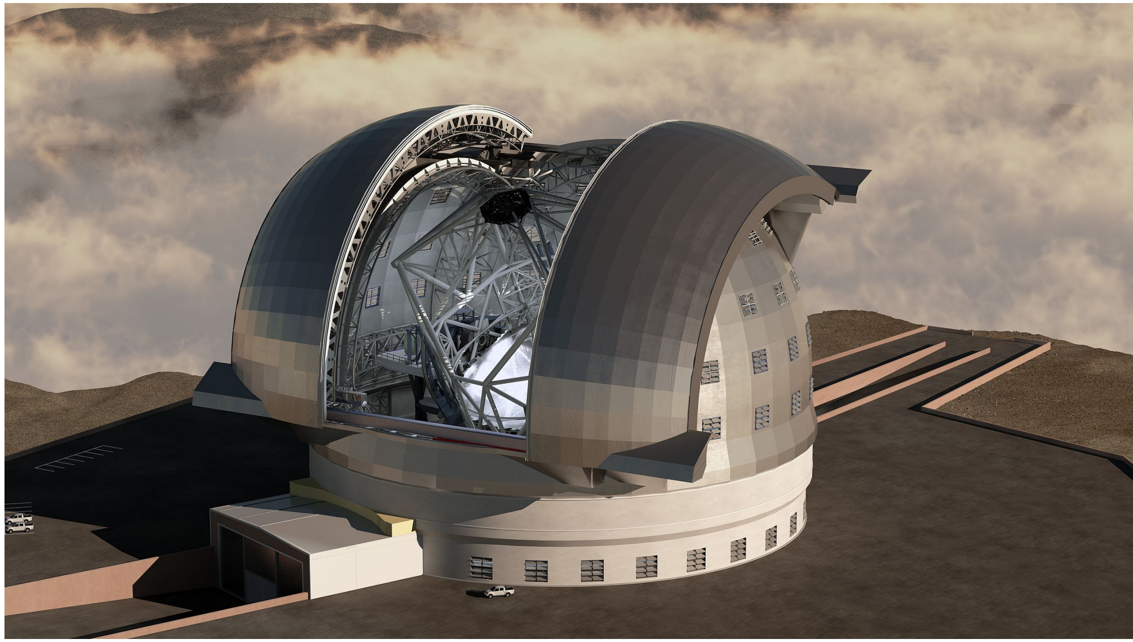
A whole new generation of enormous telescopes, both optical and radio, is currently under construction.

Here are a few of the telescopes due to come online in the next decade.

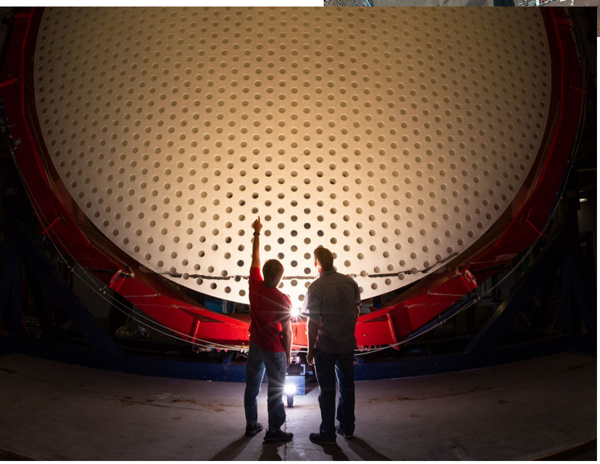
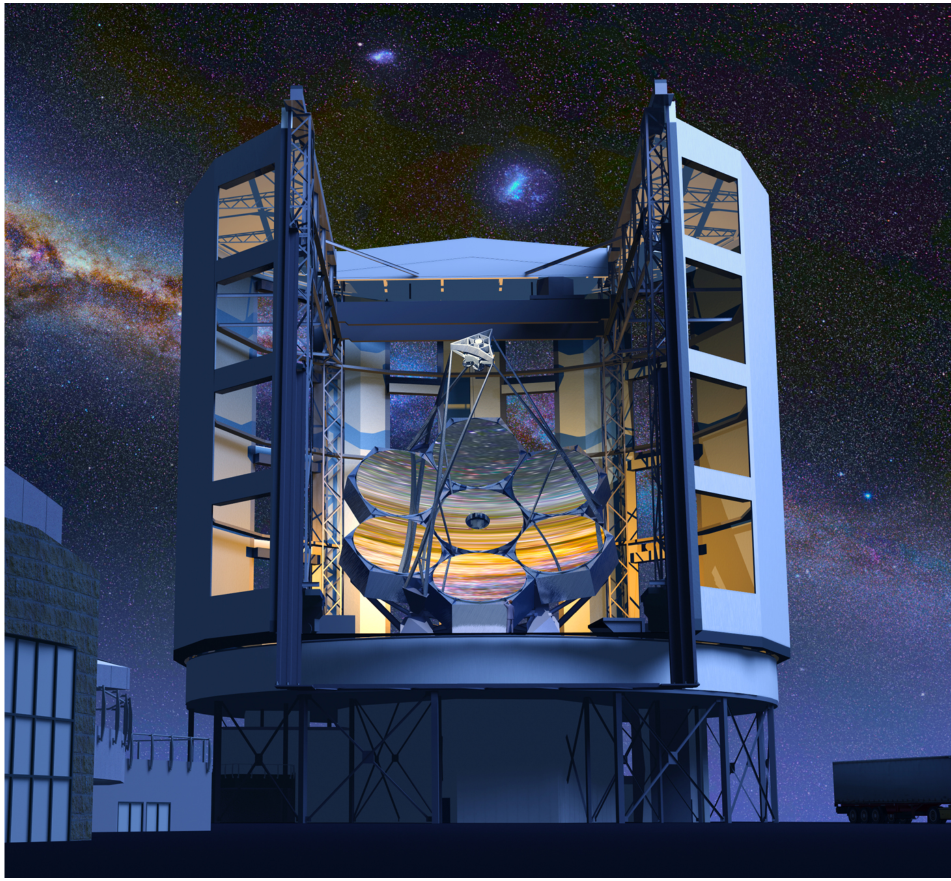
Optical telescopes

- The *Extremely Large Telescope*, under construction in Chile by ESO
  - 39.3 m mirror with 798 hexagonal segments, first light 2025

The Unive



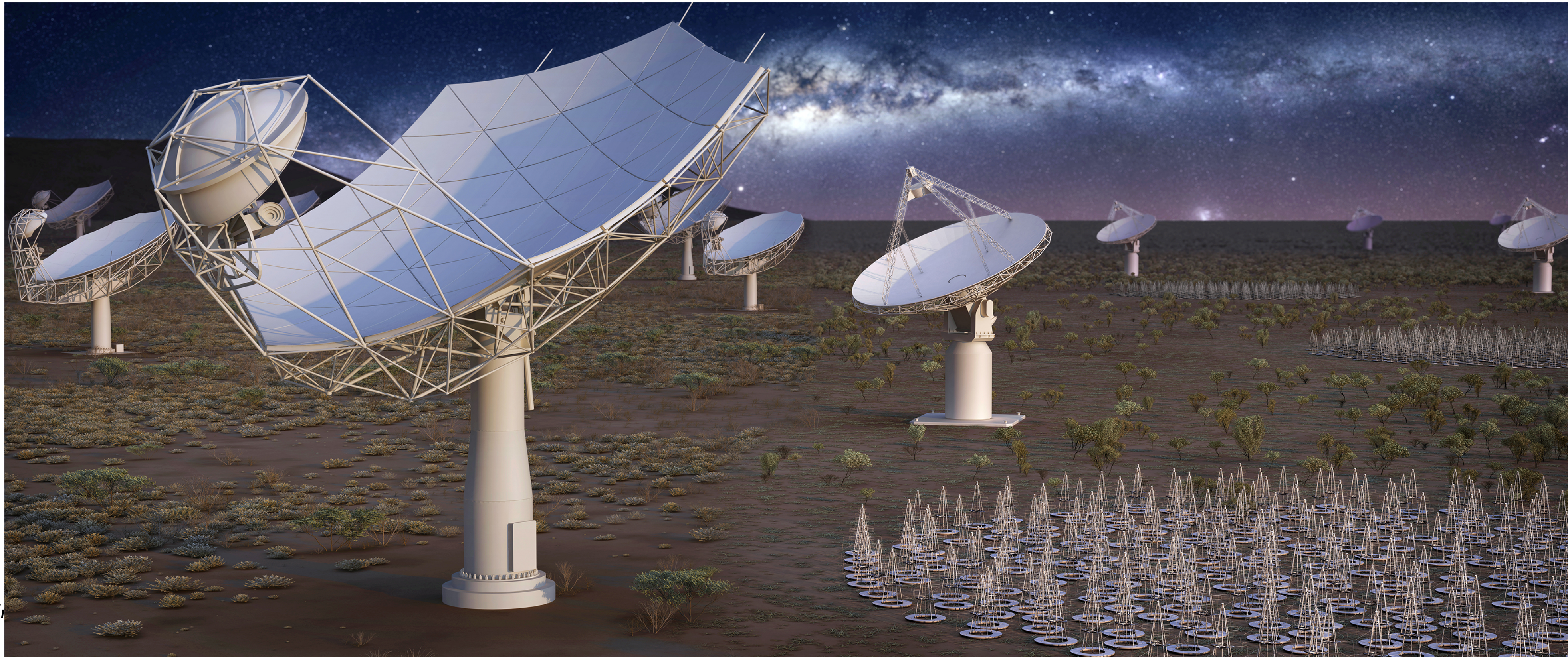
- The *Giant Magellan Telescope*, under construction in Chile by a US-led consortium, including Australia
  - 24.5 m diameter with seven circular 8.4 m mirrors, first light 2029

- The *Thirty Meter Telescope*, to be built on Mauna Kea, Hawai’i. Construction halted due to protests.
  – 30.0 m mirror with 492 hexagonal segments

Radio telescopes

- The *Square Kilometre Array*, to be built in Australia and South Africa
  - collecting area 1 km^2, with baselines up to 3000 km. Construction to begin in 2021



Precursors to the SKA have been in operation for several years:

- The *Murchison Widefield Array*, 800 km north of Perth
  - 4096 dipole antennas arranged in 4x4 tiles, Phase II completed in 2017

- The *Australian Square Kilometre Array Pathfinder (ASKAP)*, also at the Murchison Observatory site in WA
  - 36 parabolic antennas, each 12 m in diameter, began operation in 2012 (adding antennas as it goes)

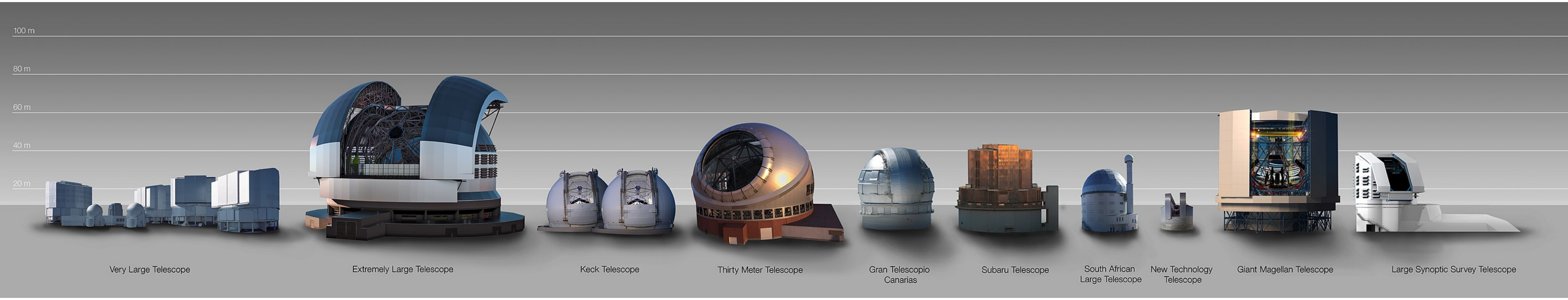
- *MeerKAT*, in South Africa
  - 64 parabolic antennas, each 13.5 m in diameter, began operation in 2016

The University of Sydney

These telescopes cost US$1–2 billion each, and thus are all being built by groups of nations.

We may be reaching the maximum size of telescope that can be reasonably built.

Here are my thoughts about some trends in the way astronomy is heading.



What next for astronomy?

Big Astronomy is approaching.

1. *Fewer and fewer astronomers will ever actually observe at a telescope personally*

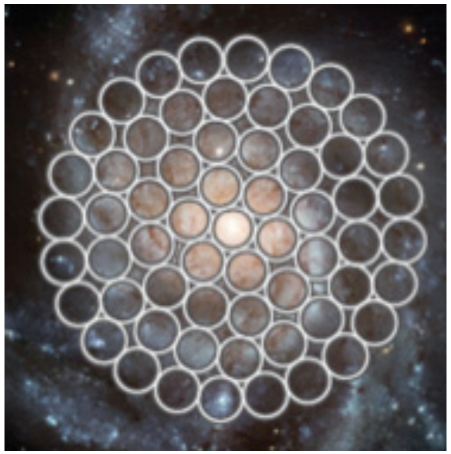
The era of service observing is well underway

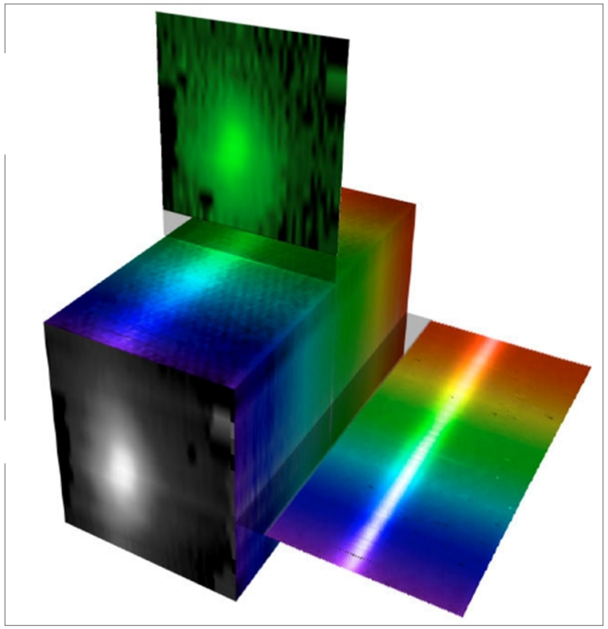
- queue scheduling: better use of resources
- increased science productivity
- less training of users
- lower cost

2. *More data reduction will take place through automated pipelines, with astronomers only seeing final data*

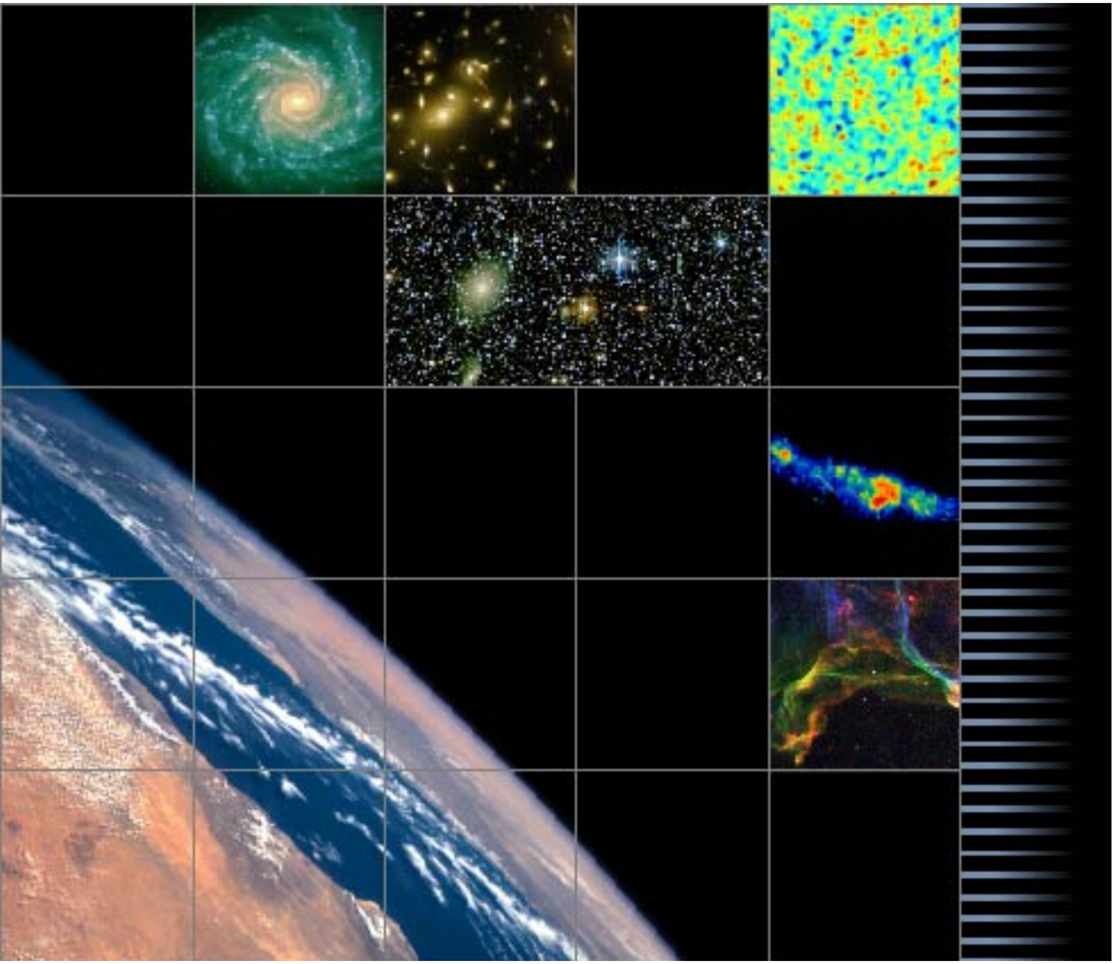
Many new instruments offer automatic data reduction pipelines

- reproducible
- users no longer need to be master arcane knowledge – focus on science, not technique
- reduction can be "best practice"





3. *Much research will be mining vast quantities of existing data instead of taking new observations*



Large-scale surveys in the public domain mean that there will be less need to propose new observation.

Instead, astronomers will mine survey databases, combining at a from different wavelengths or regions of parameter space.

Creating new algorithms may be more important than new instruments.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Sign up for the "Sydney Ideas" lectures

http://sydney.edu.au/sydney_ideas/

which have lectures about a vast range of topics, including astronomy.

Particularly watch out for the "Professor Walter Stibbs Lectures", a public lecture on astronomy each year in about April.

- 2019: Jocelyn Bell Burnell, "Pulsars and the universe"
- 2018: Brian Schmidt, "The State of the Universe"
- 2017: David Reitze, "LIGO, Gravitational Waves, and the Final Ballet of a Pair of Black Holes"
- 2016: Natalie Batalha, "A planet for Goldilocks"
- 2015: Andrea Ghez, "The monster at the heart of our Galaxy"

And, of course, attend more Continuing Education courses! Next course will be

Modern Astronomy: Lives of the Stars

A detailed look at how stars live and die

(semester 2, 2020)


That’s all, folks!