Title: The Dawn of Gravitational Wave Astronomy

Date: May 18, 2016 02:00 PM

URL: http://pirsa.org/16050009

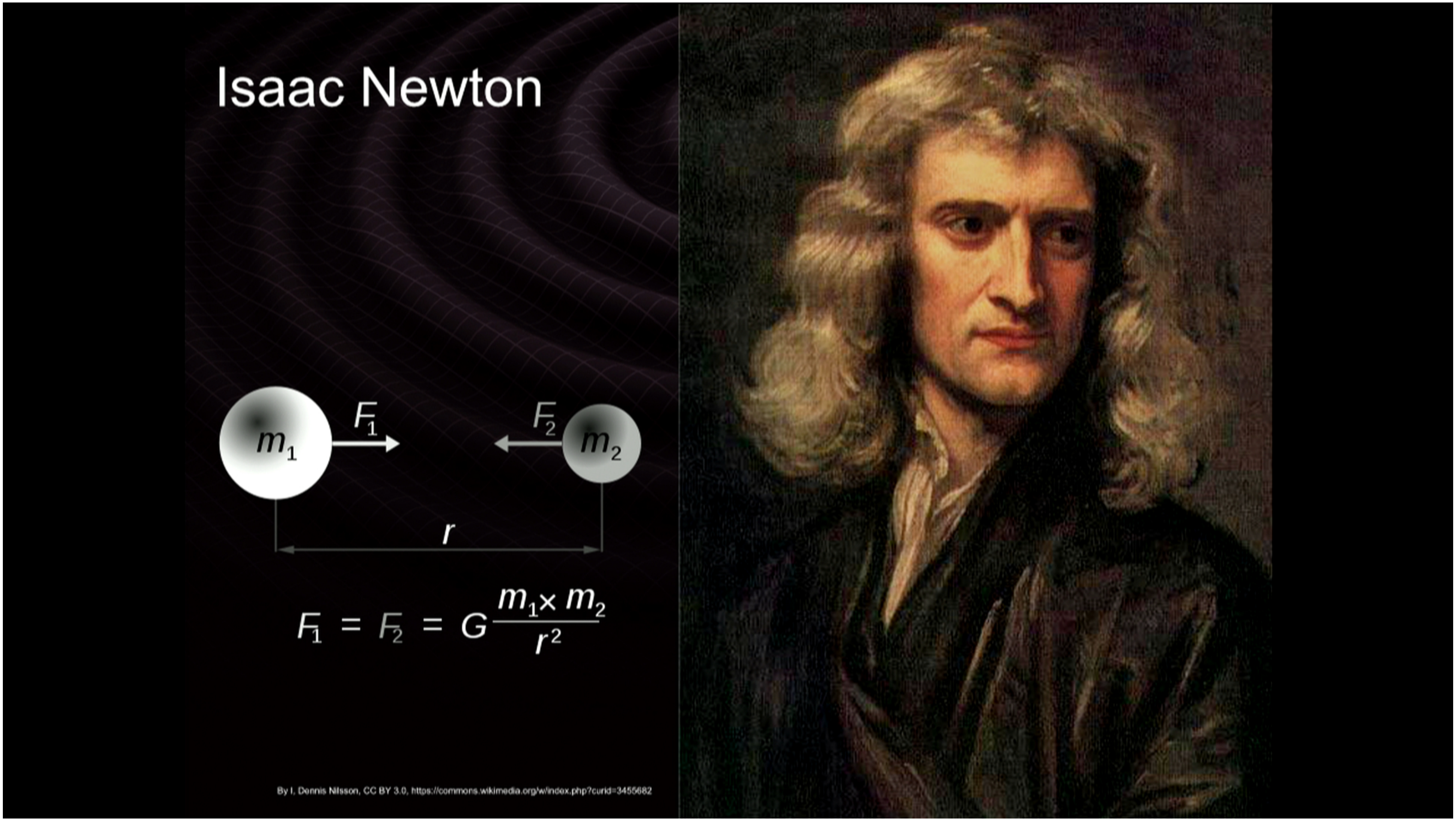
Abstract: <p>100 years after the existence of gravitational waves was first postulated by Albert Einstein, the LIGO and Virgo Collaborations detected gravitational waves for the first time on September 14, 2015. The gravitational waves originated from a pair of black holes that merged over one billion years ago. The merger was so powerful that it shook the very fabric of space and sent a ripple across the Universe that we observed here on Earth at present day. Although this event was but a blip in a sea of data taken by various experiments over the last several decades, it represents a paradigm shift in how we study our Universe.</p>

<p>In this colloquium, I will present some of the history of this great discovery and what it means for our future at the dawn of gravitational wave astronomy.</p>

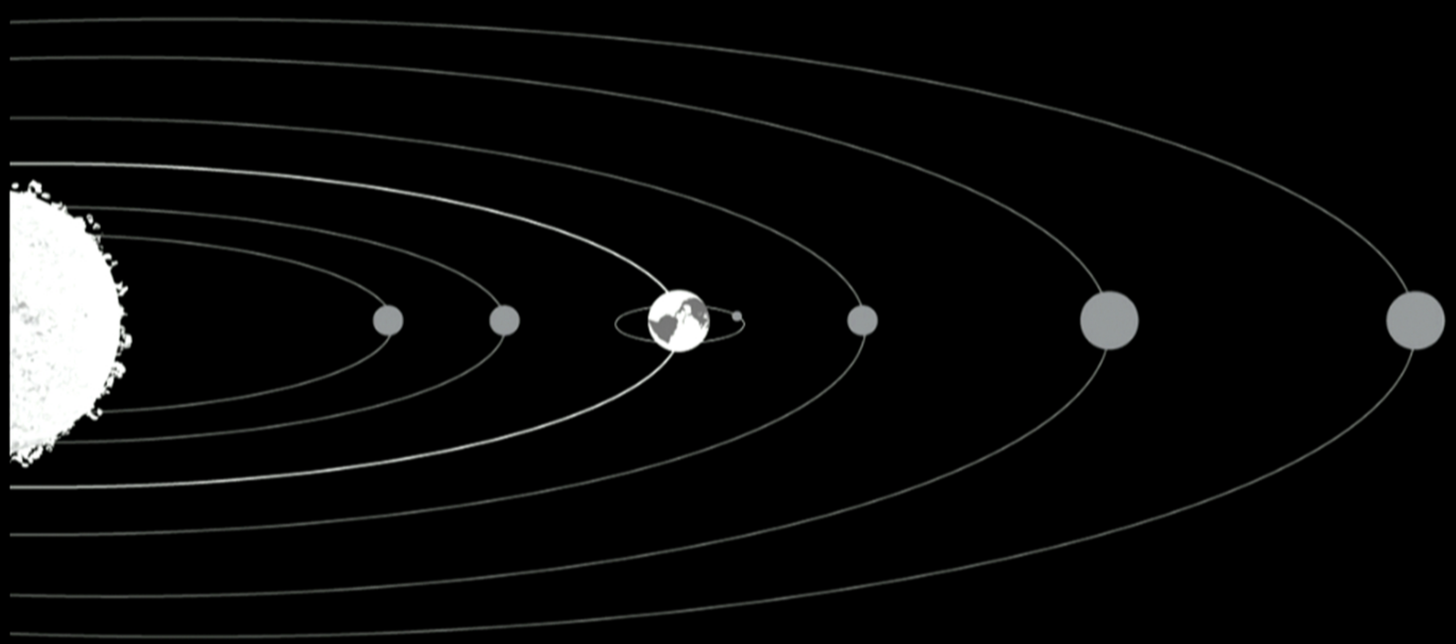
The Dawn of Gravitational Wave Astronomy

Chad Hanna

NSF
PennState
Eberly College of Science
Physics / Astronomy & Astrophysics
Institute for Gravitation & the Cosmos
LIGO


Isaac Newton
m_1
F_1
F_2
m_2
r
$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$
By I, Dennis Nilsson, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=3455682

Isaac Newton's theory of gravity explained Kepler's motion of the planets



But as we tried to understand other fundamental forces...

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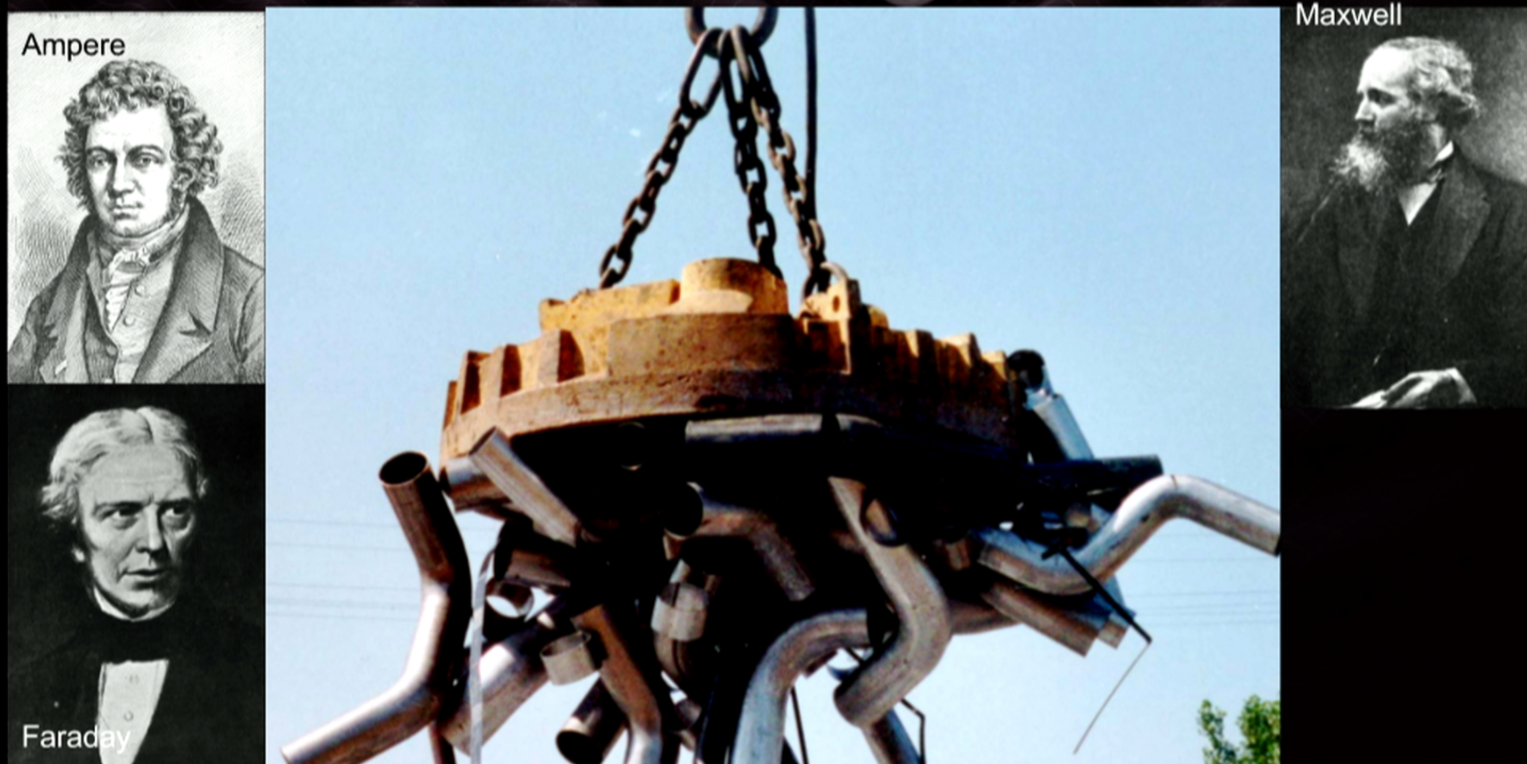
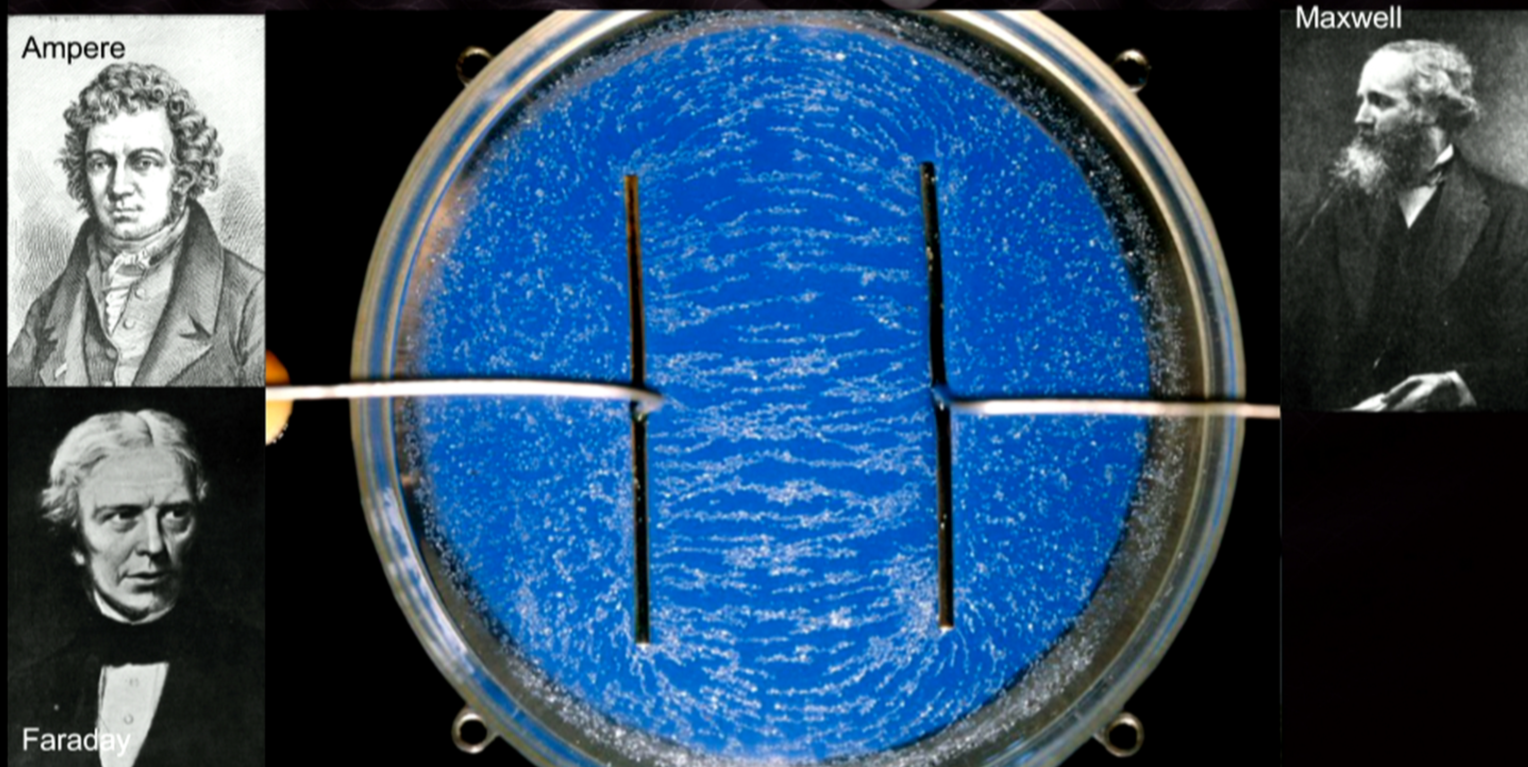


...new ideas emerged.

But as we tried to understand other fundamental forces...



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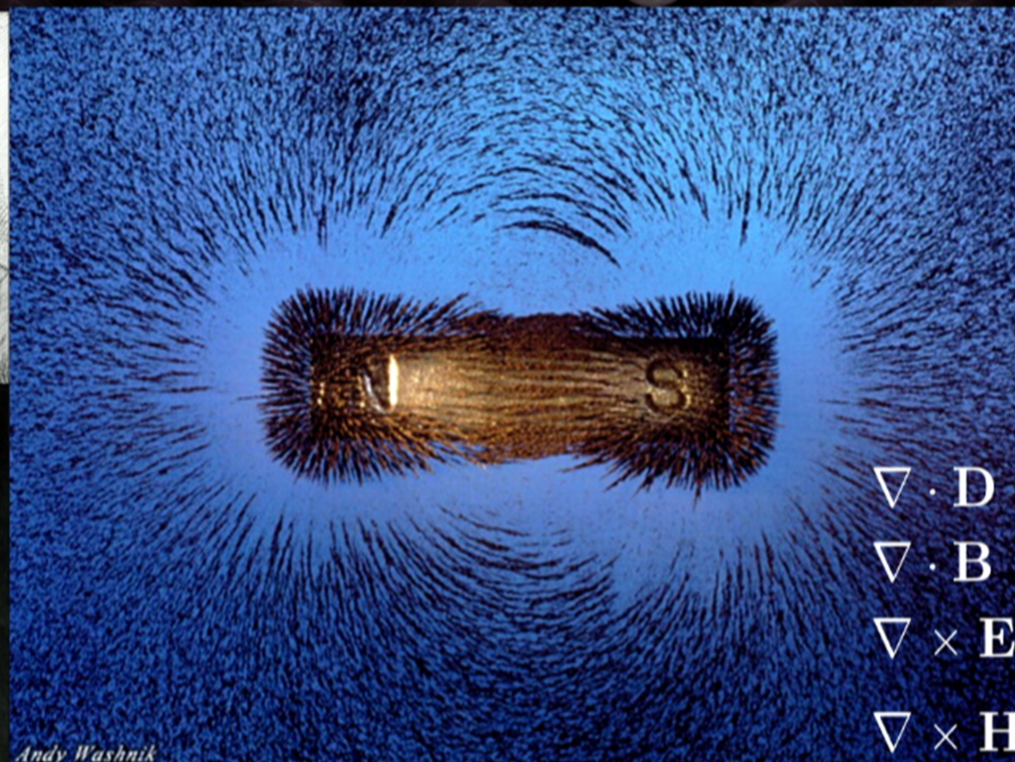
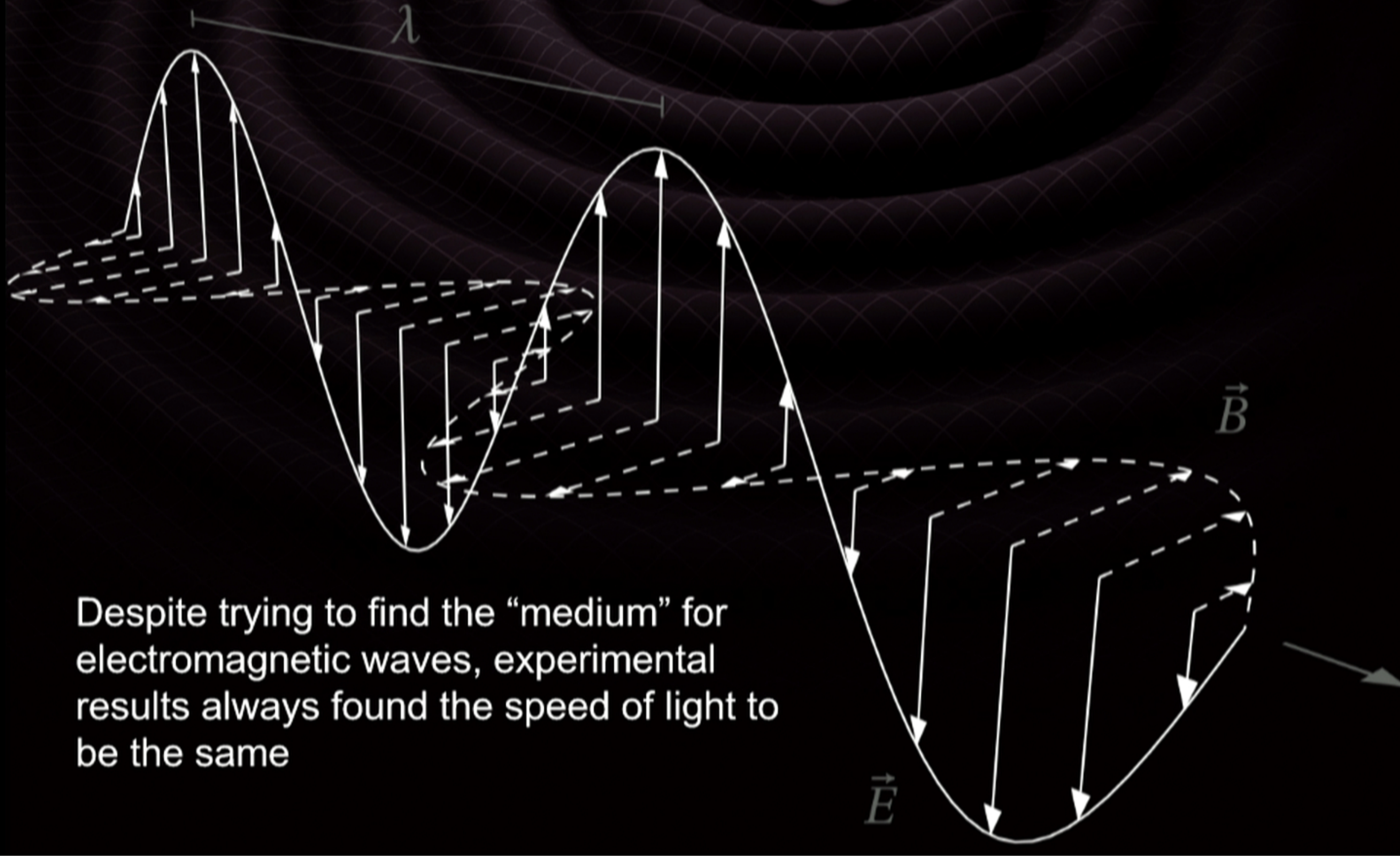


$$\nabla \cdot \mathbf{D} = \rho$$
$$\nabla \cdot \mathbf{B} = 0$$
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$
$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

...new ideas emerged.

Electromagnetism provided the possibility of a self-sustaining oscillation of fields

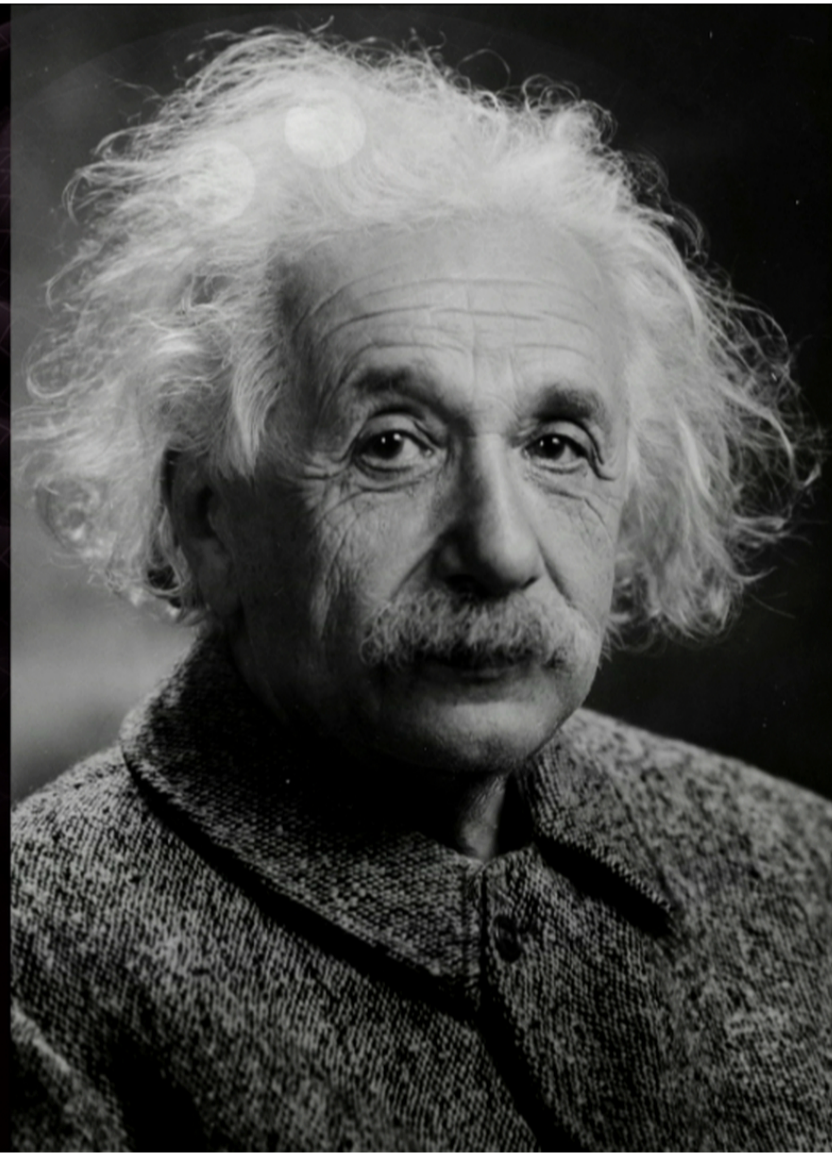


Despite trying to find the “medium” for electromagnetic waves, experimental results always found the speed of light to be the same

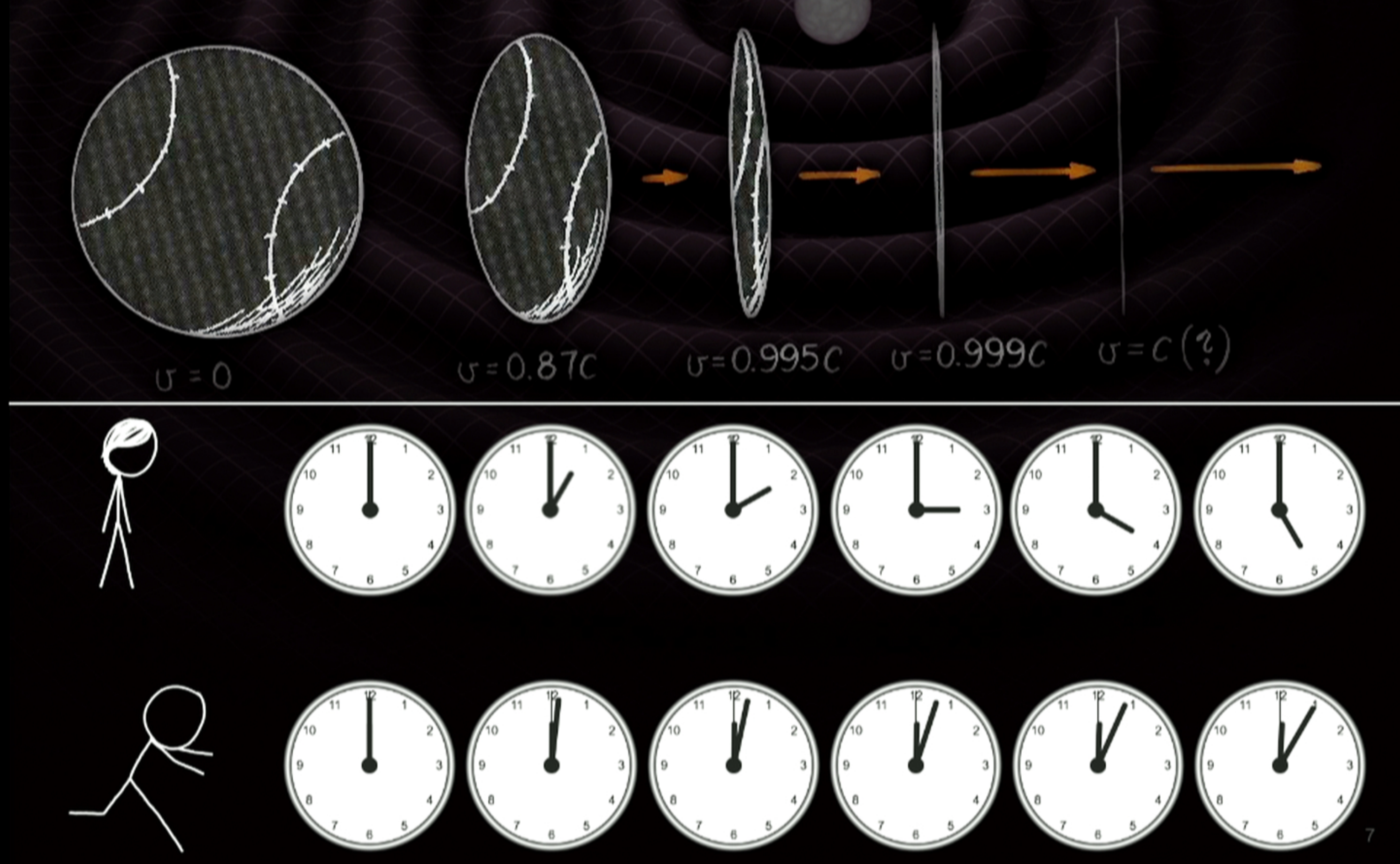
Albert Einstein

The velocity of light was the same regardless of the observer

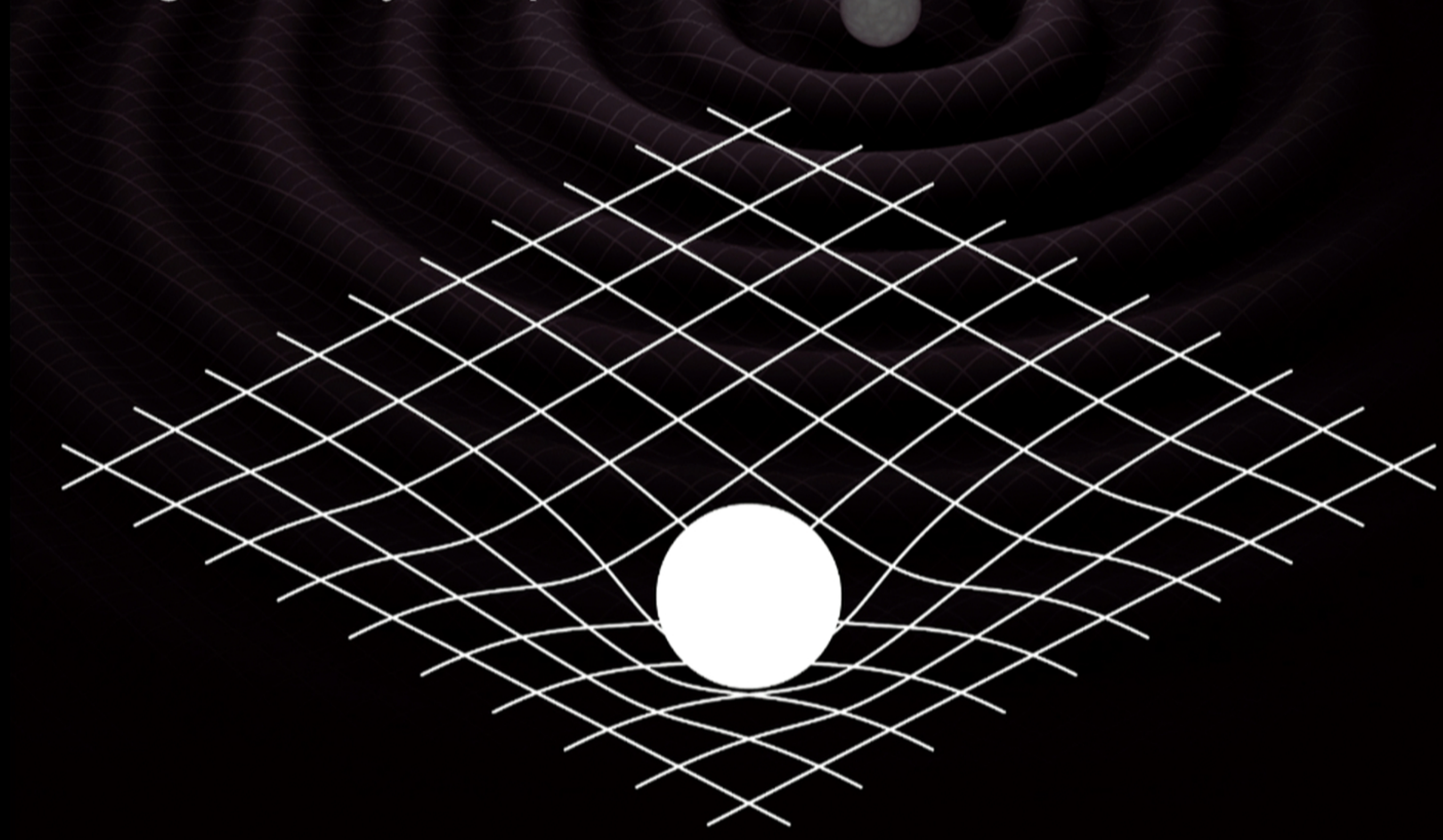
Adapted from XKCD



If the speed of light is the same for all observers, then space and time itself must be appear different.

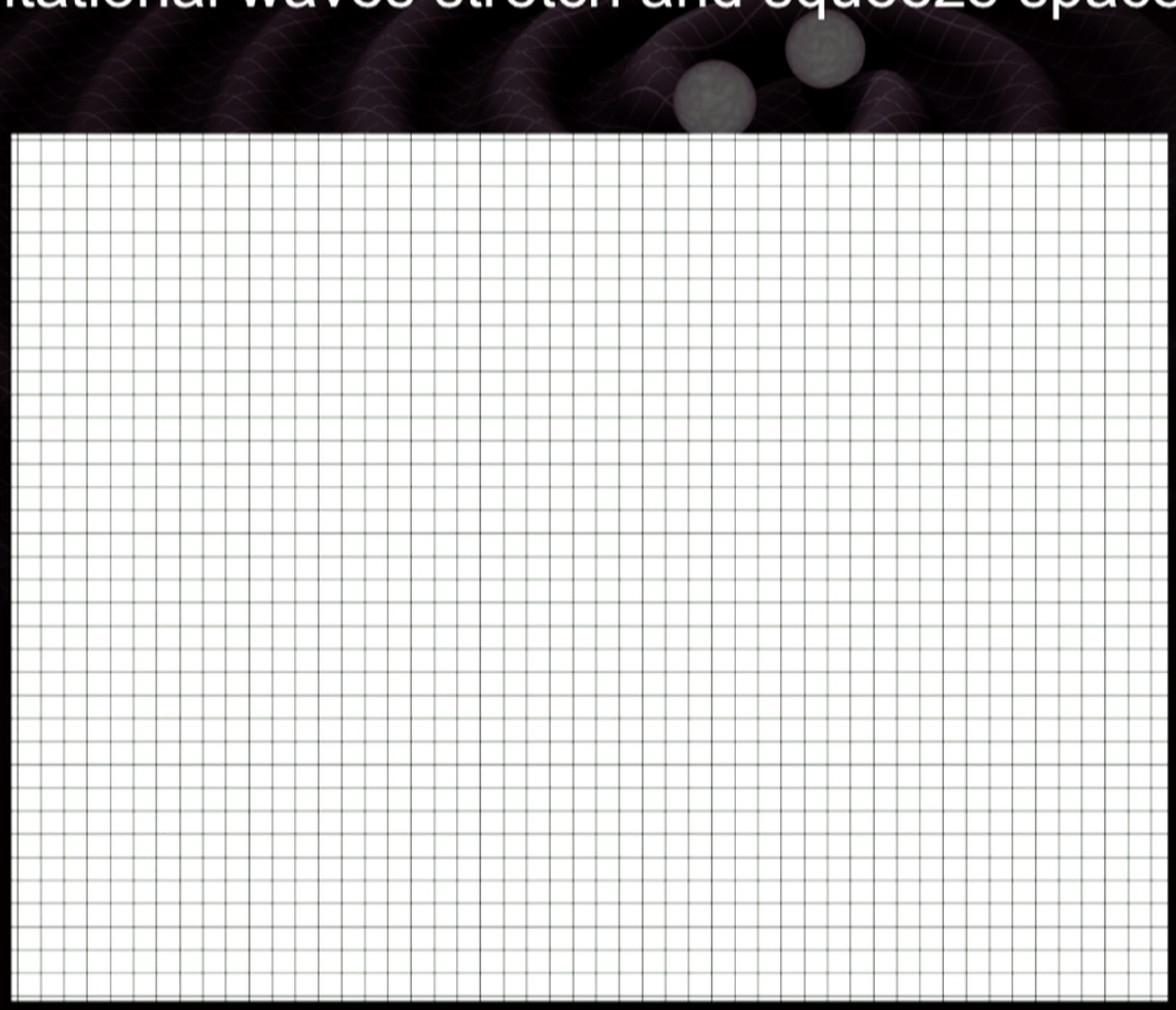


Einstein didn’t stop there. He related gravity to the geometry of space and time too.

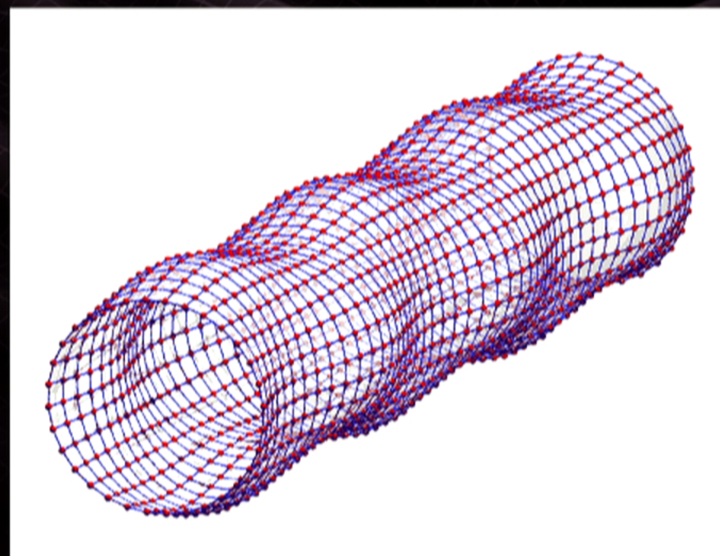


The geometry is dynamic and just like electromagnetism it has waves

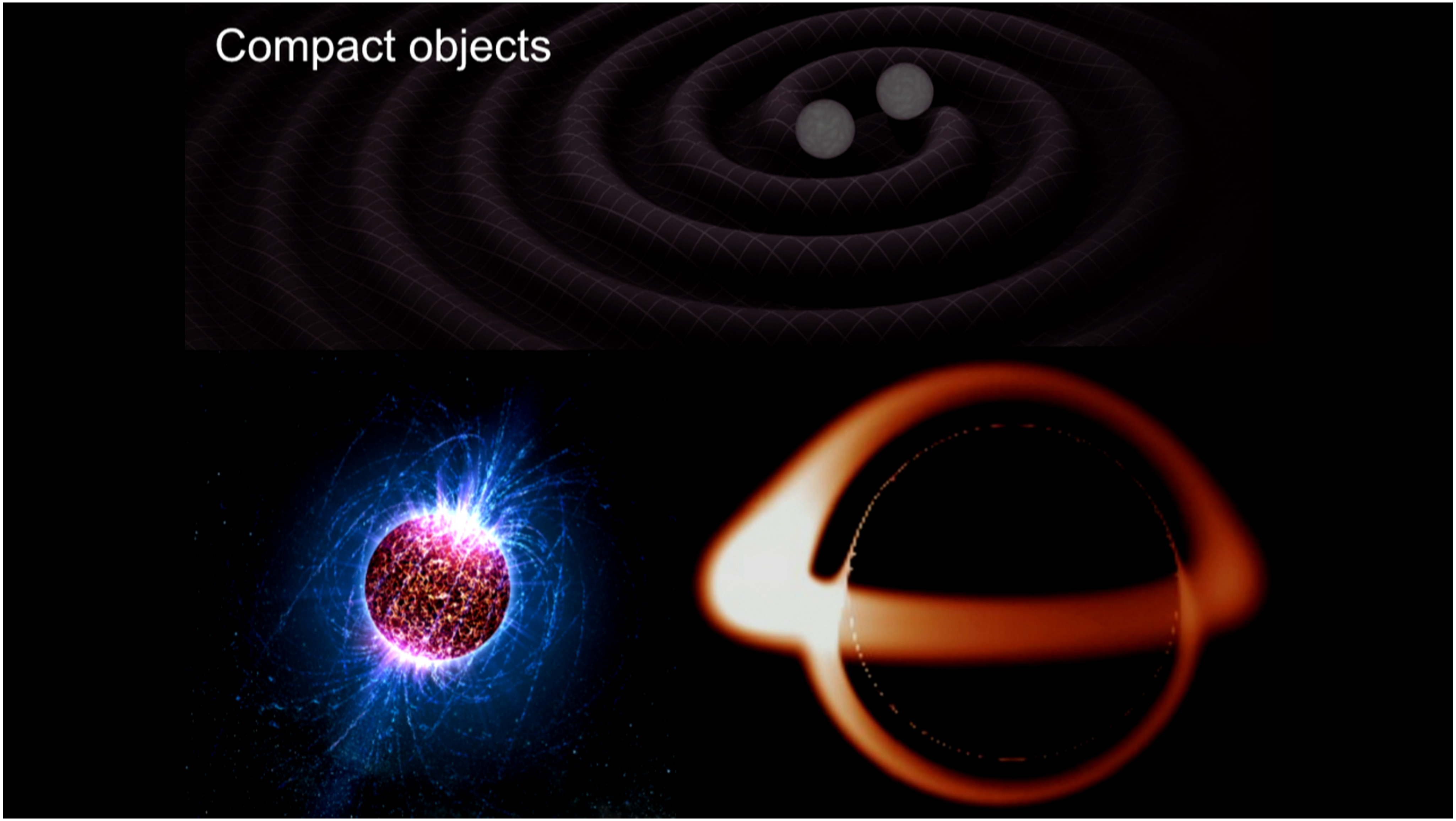
Gravitational waves stretch and squeeze space itself



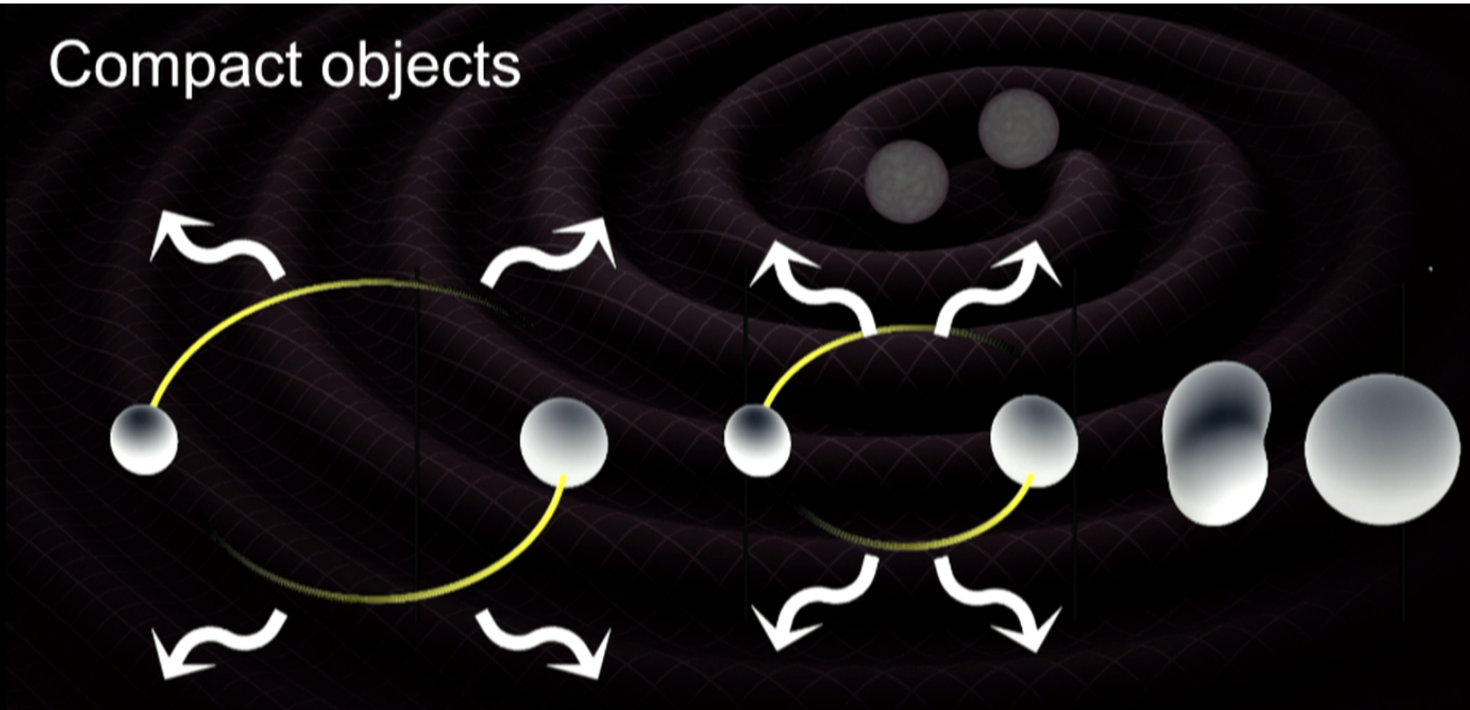
Gravitational waves stretch and squeeze space itself



Although predicted in 1916, there were no plausible sources or detection technology.

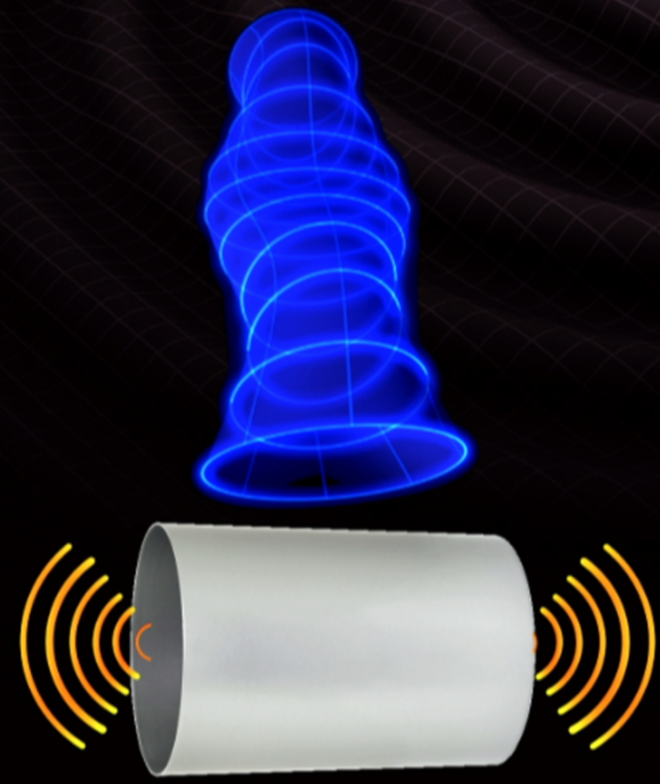

Compact objects

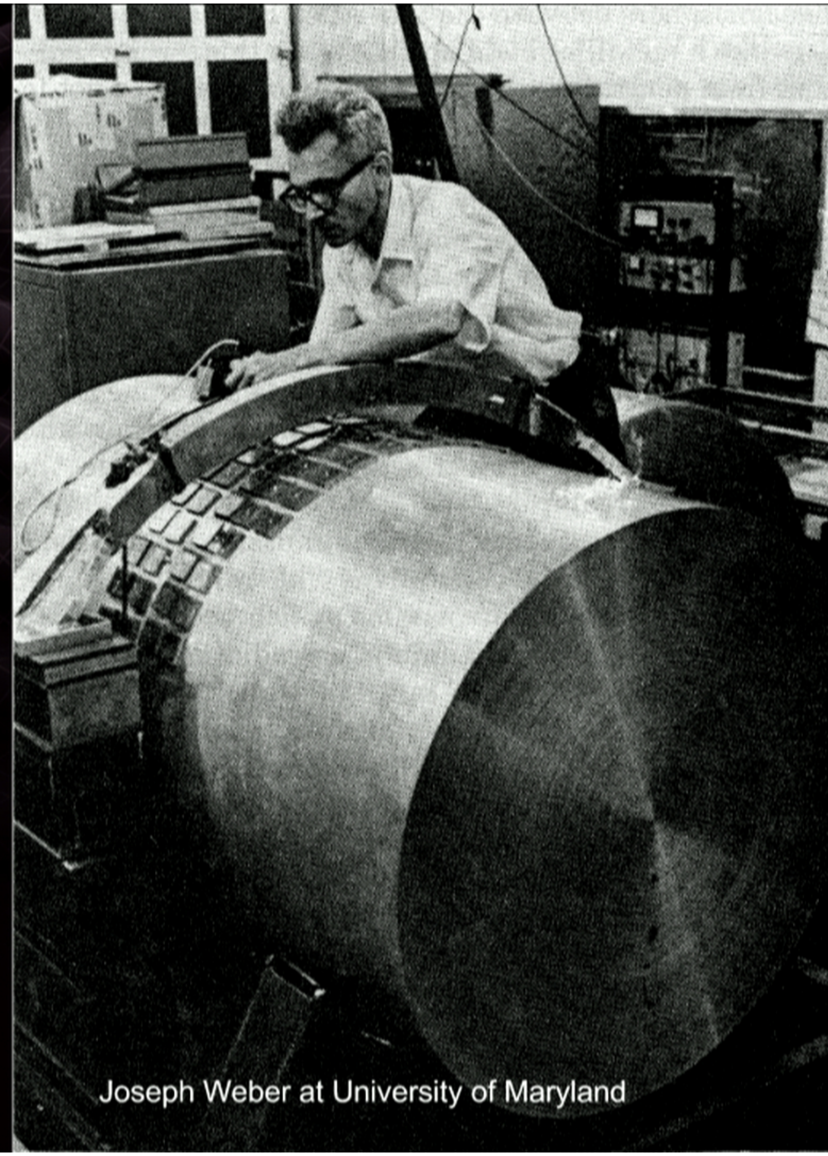
Compact objects



By the 1960s compact objects and aspects of their dynamics under gravitational wave emission were well on their way to being understood.

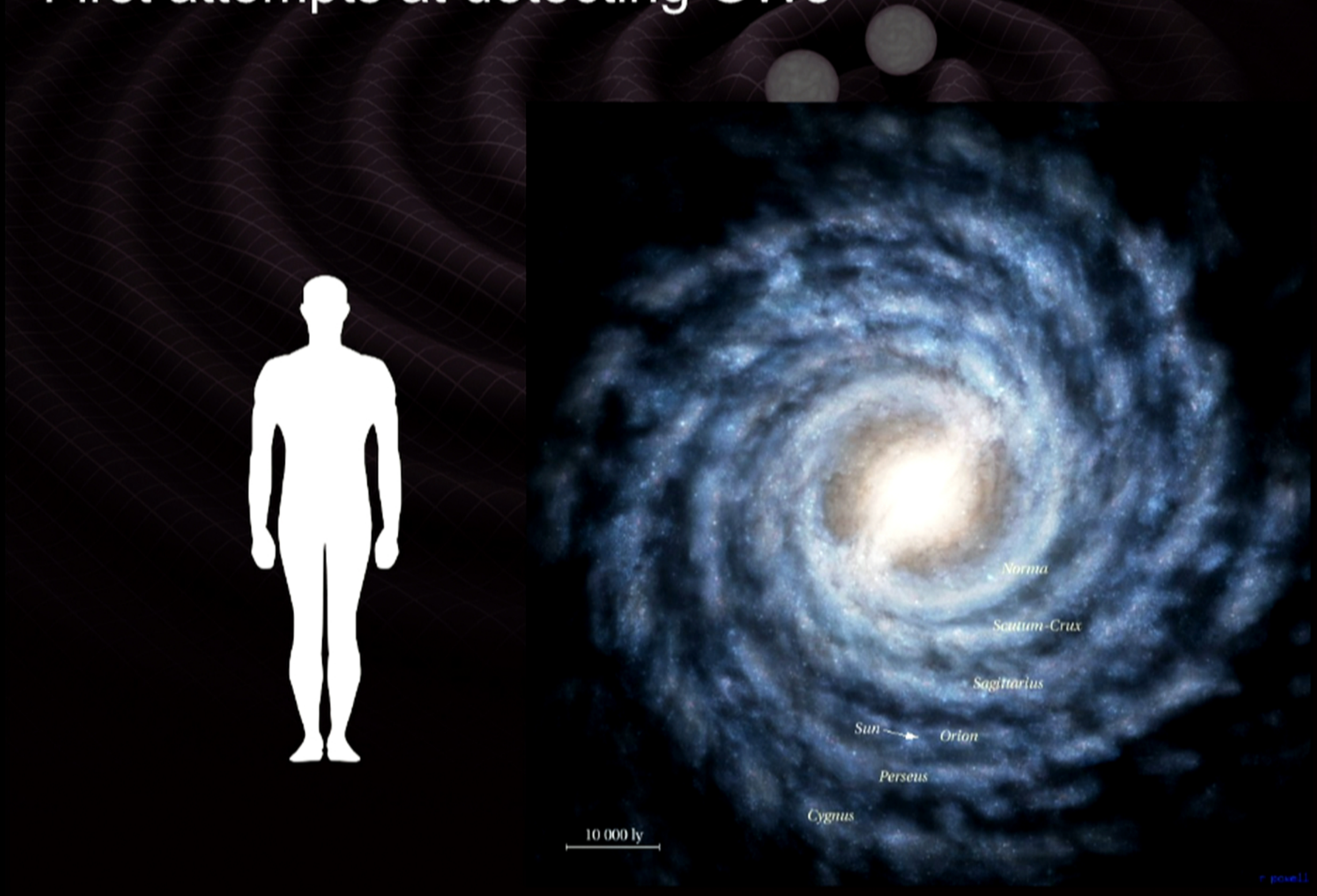
First attempts at detecting GWs



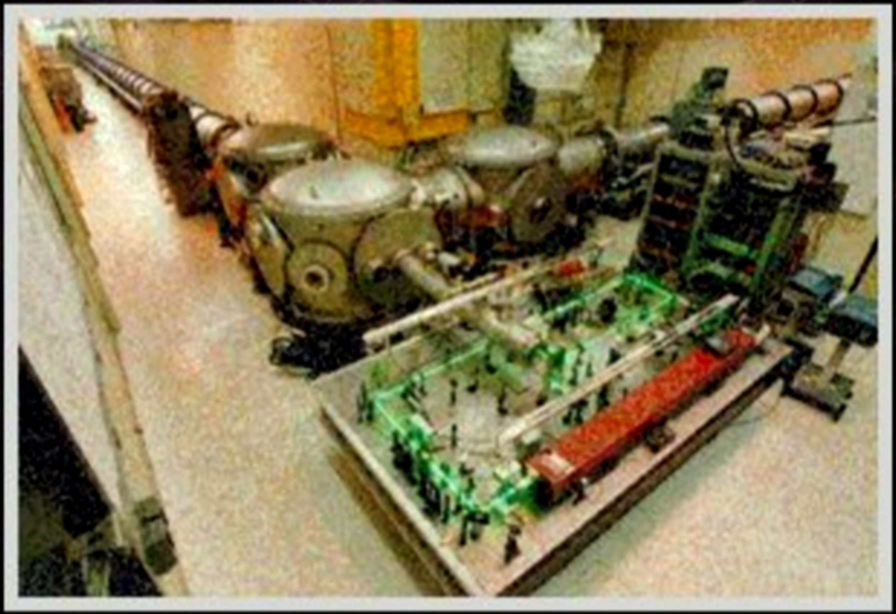


Joseph Weber at University of Maryland

First attempts at detecting GWs



Modern attempts at detecting GWs



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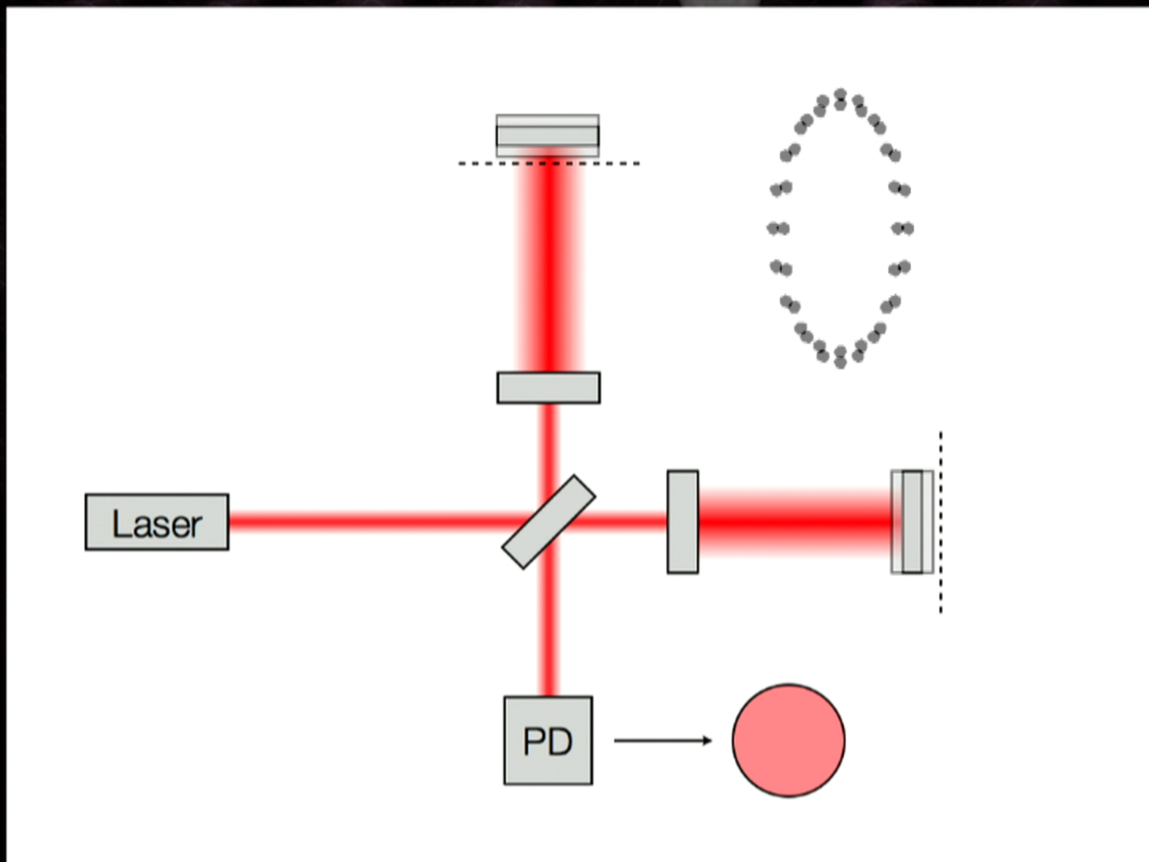
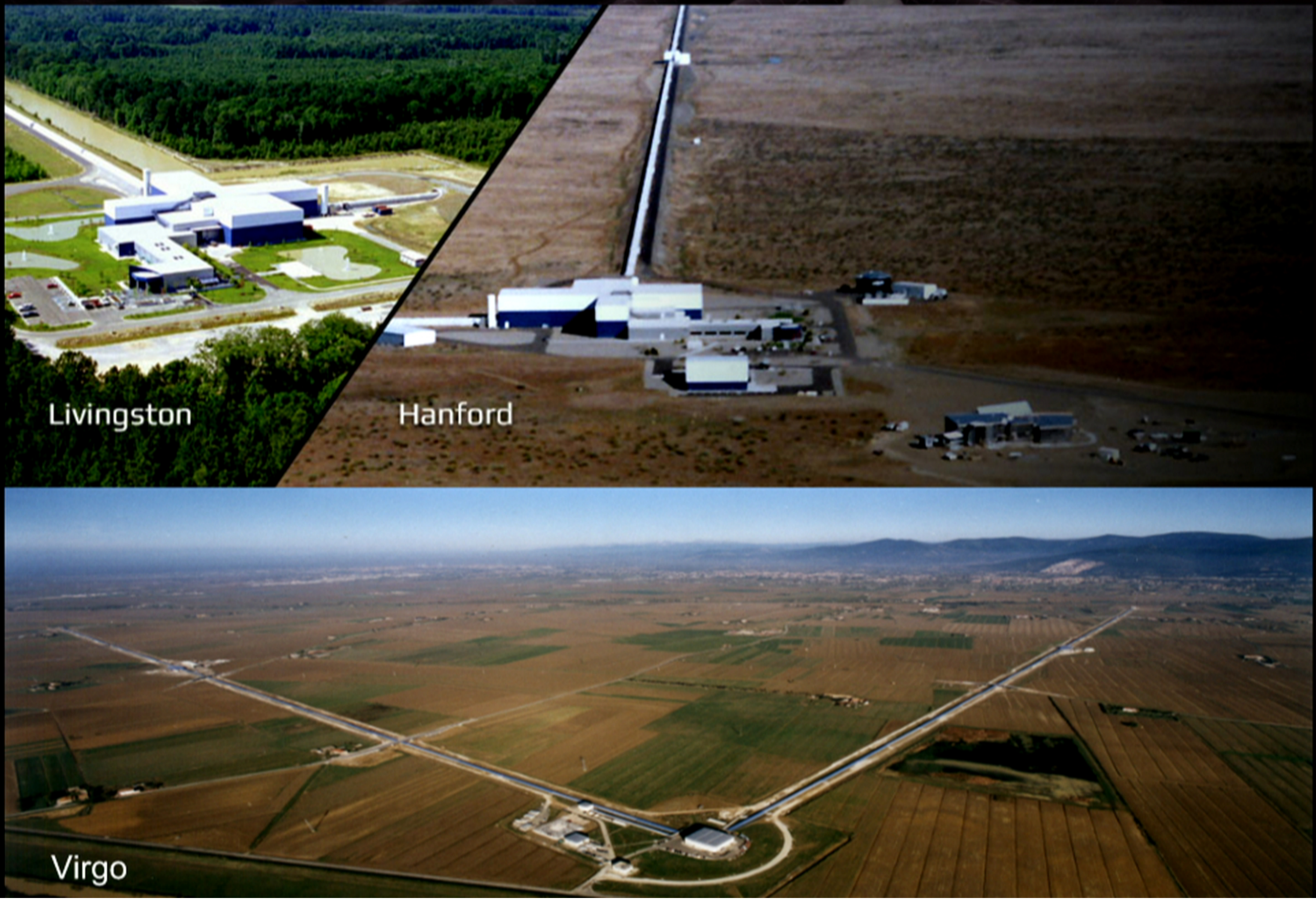
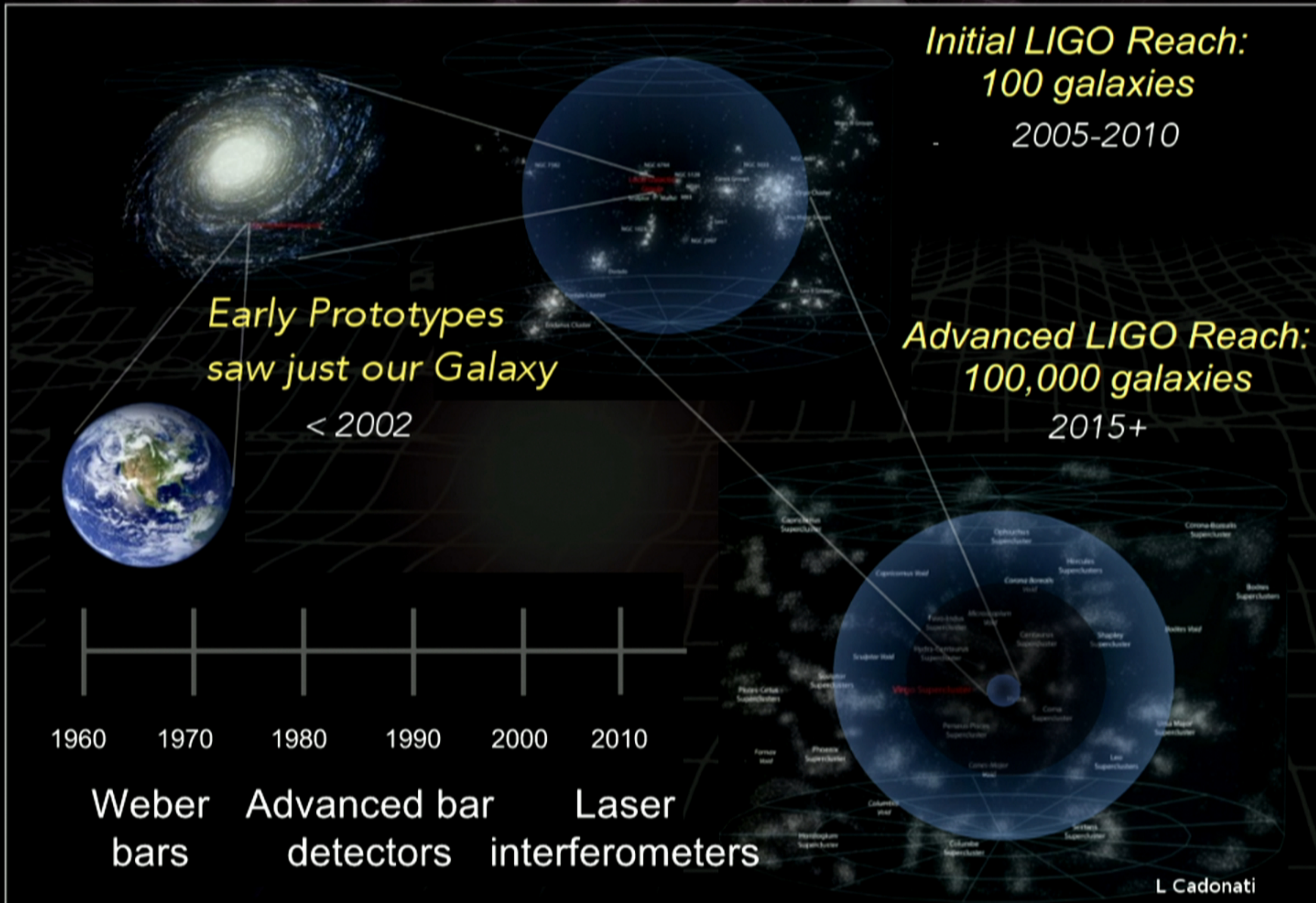


Modern attempts at detecting GWs



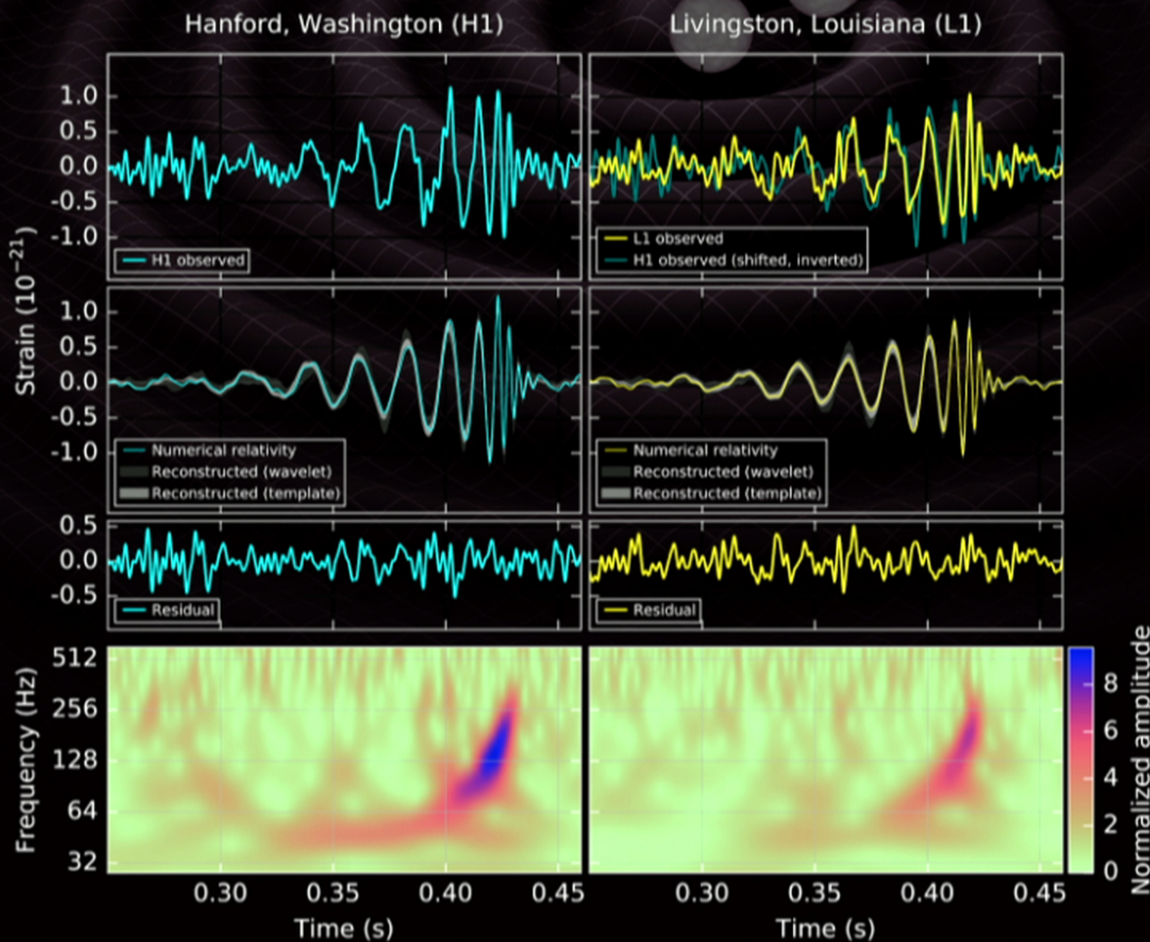
Modern attempts at detecting GWs

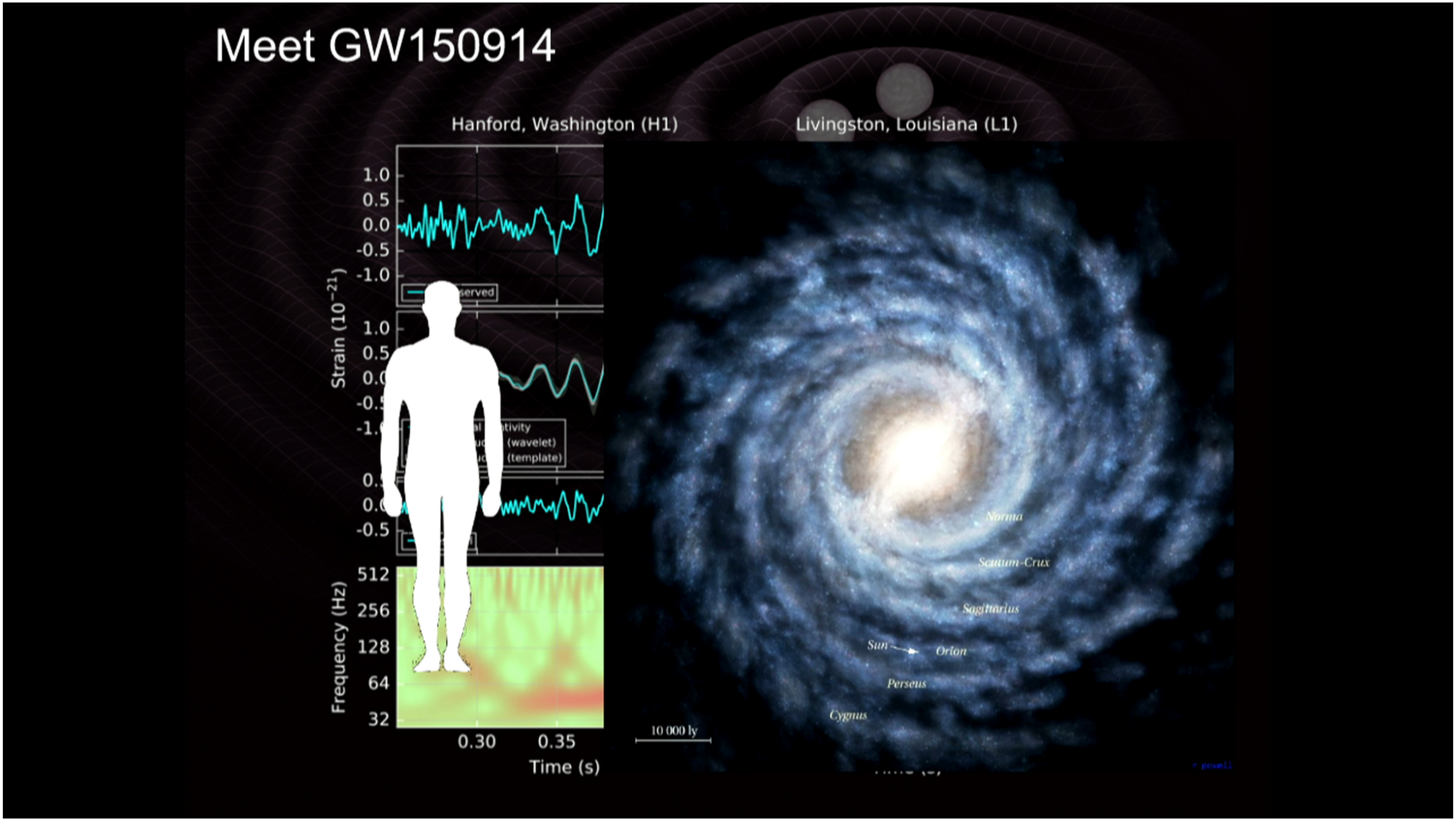


Finally a breakthrough!

Slide 21 | Presenter view | Exit

Meet GW150914




Meet GW150914
Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
(wavelet)
(template)
Frequency (Hz)
512
256
128
64
32
0.30
0.35
Time (s)
Norma
Scutum-Crux
Sagittarius
Sun
Orion
Perseus
Cygnus
10 000 ly

GW150914 was detected within about three minutes of the signal arriving at Earth by a low-latency search.

- Approximately 8 hours later, the event was confirmed by another online burst search

GraceDB — Gravitational Wave Candidate Event Database

HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION

AUTHENTICATED AS: CHAD HANNA

Basic Info

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	FAR (Hz)	Links	UTC Submitted
G184098	H1OK L1OK	Burst	CWB	AllSky	H1,L1	1126259462.3910	1.178e-08	Data	2015-09-14 09:53:51 UTC

Analysis-Specific Attributes

start_time	1126259461	central_freq	123.8285	false_alarm_rate	
start_time_ns	750000000	bandwidth	51.8386	ligo_axis_ra	130.9219
duration	2.477e-02	amplitude	1.410e+01	ligo_axis_dec	4.4808
peak_time	None	snr	23.4521	ligo_angle	None
peak_time_ns	None	confidence		ligo_angle_sig	None

Neighbors [-5,+5]

UID	Labels	Group	Pipeline	Search	Instruments	GPS Time Event Time	Δgpstime	FAR (Hz)	Links	UTC Submitted

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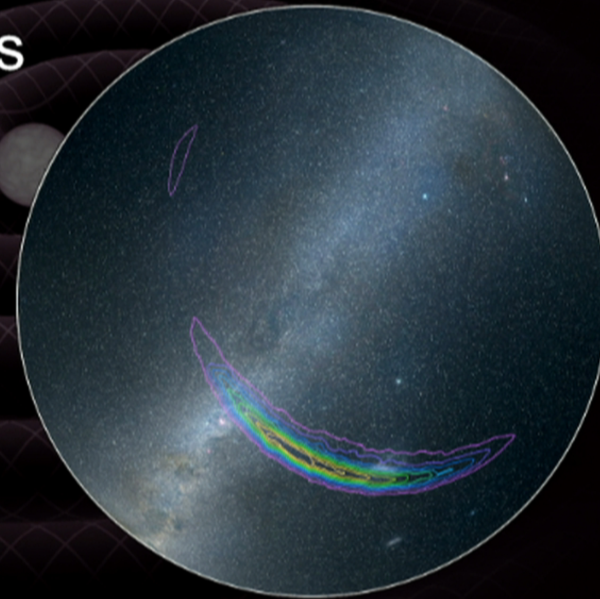
Connecting GW and EM skies

- Sent alert to 63 partners < 2 days.
- 25 followed-up : satellites, ground-based telescopes around the globe : 19 orders of magnitude across the EM spectrum.



25

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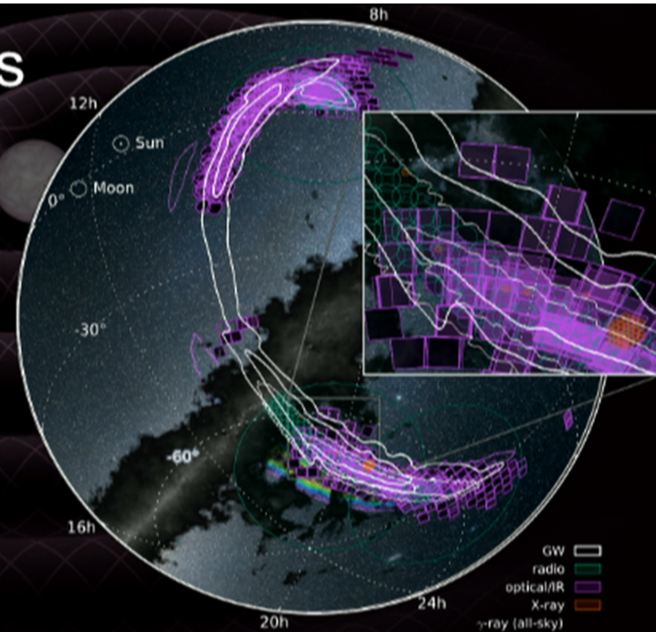

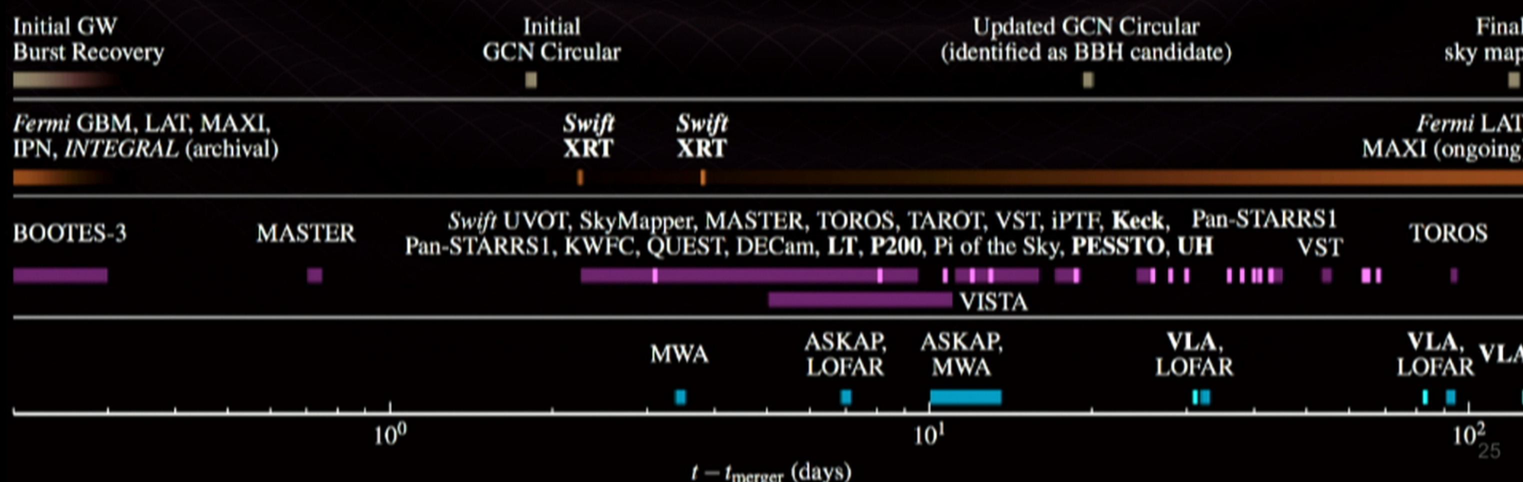

Two types of transient searches

Unmodeled “burst” searches

- Makes minimal assumptions about waveform morphology apart from approximate timescales and frequency content.
- Use coherence between detectors
- Best possible search for sources without exact models, e.g., supernova searches

Modeled “CBC” searches

- Use waveforms predicted by general relativity that match the target signal.
- Generally more sensitive to longer duration lower amplitude signals.
- Best search for sources with precisely known models. Demands the signal matches model to > 90%

Two types of transient searches

Unmodeled "burst" searches	Modeled "CBC" searches
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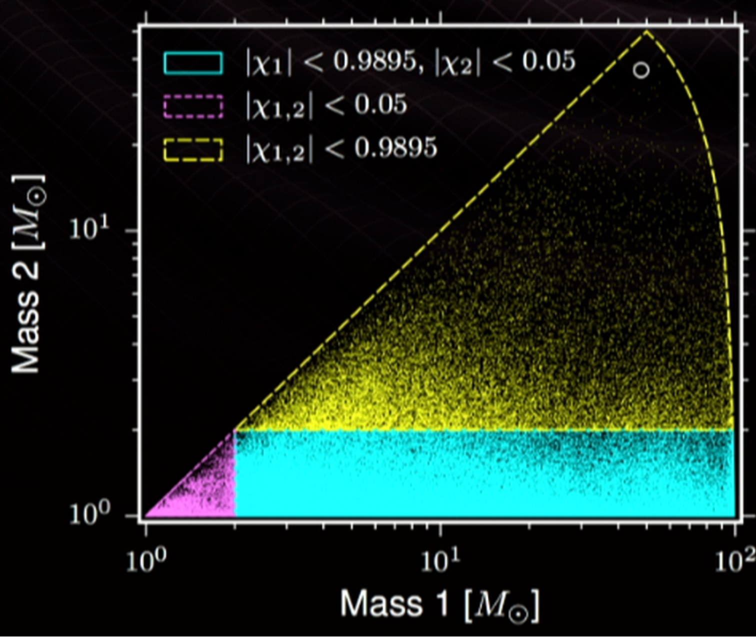
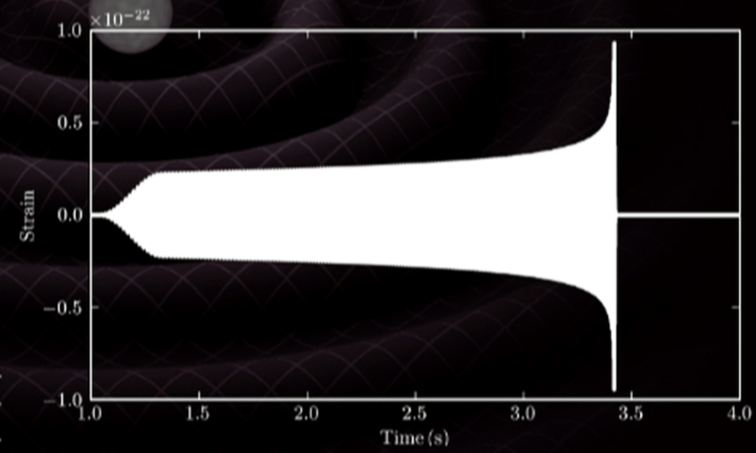
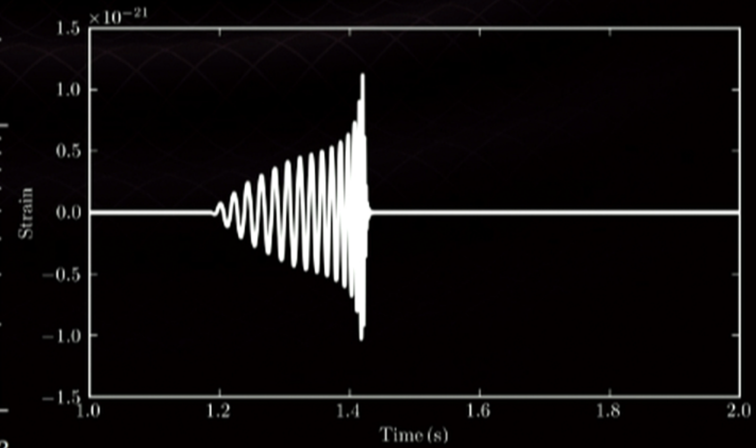
Both searches are sensitive to high mass binary black hole mergers

CBC ("modeled") searches

- Use GR predicted waveforms
- Convolve waveforms with data, called "matched filtering"
- Demand coincidence between detectors
- Reject glitches w/ consistency checks

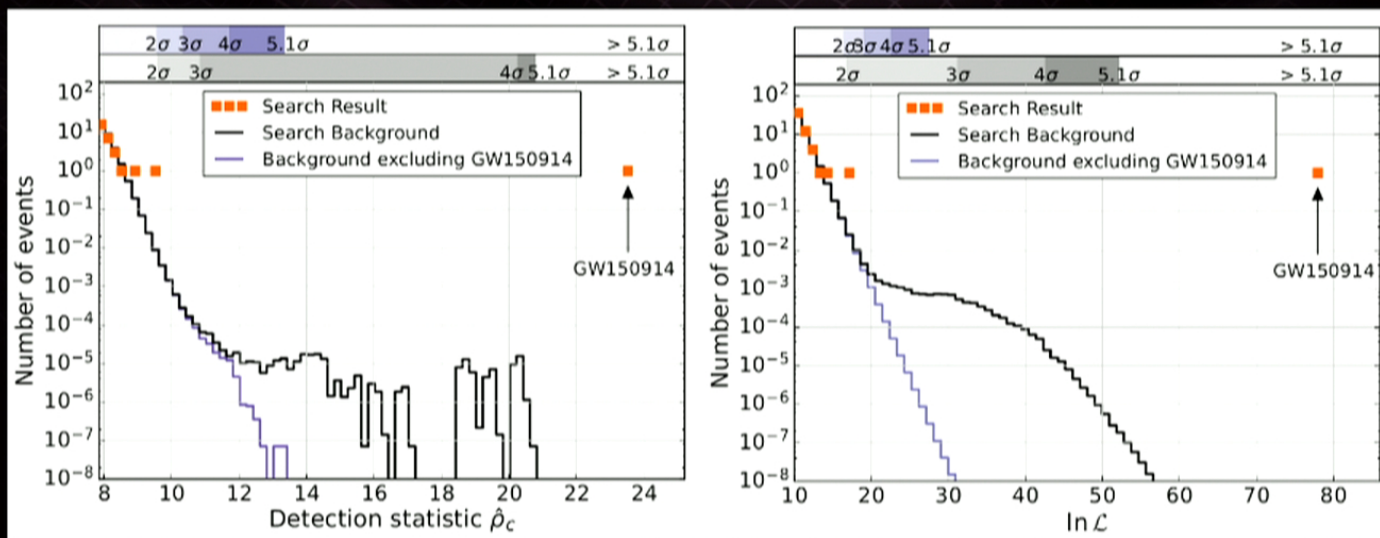






GW150914: Offline binary search

Two independently implemented matched filter analyses with different statistical techniques ranked GW150914 as "off the charts" **> 5 sigma with a false rate < 1 / 200,000 years**



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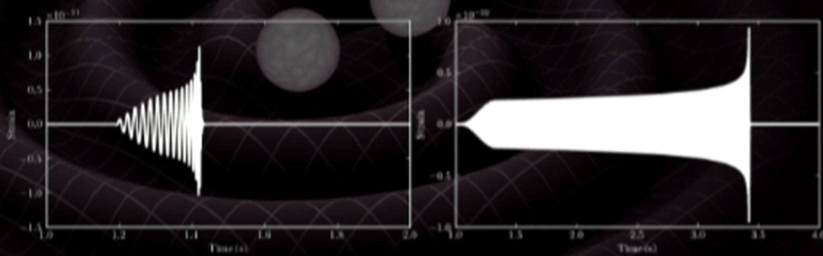
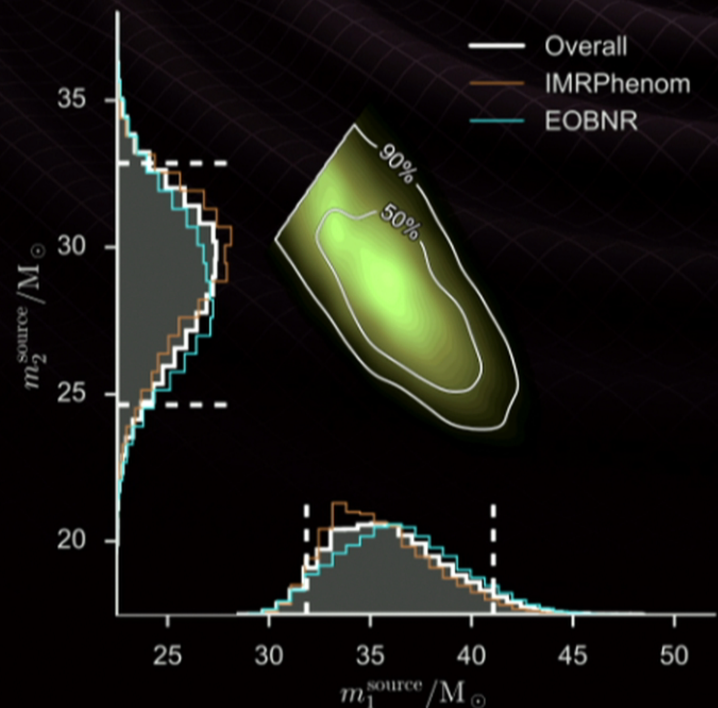
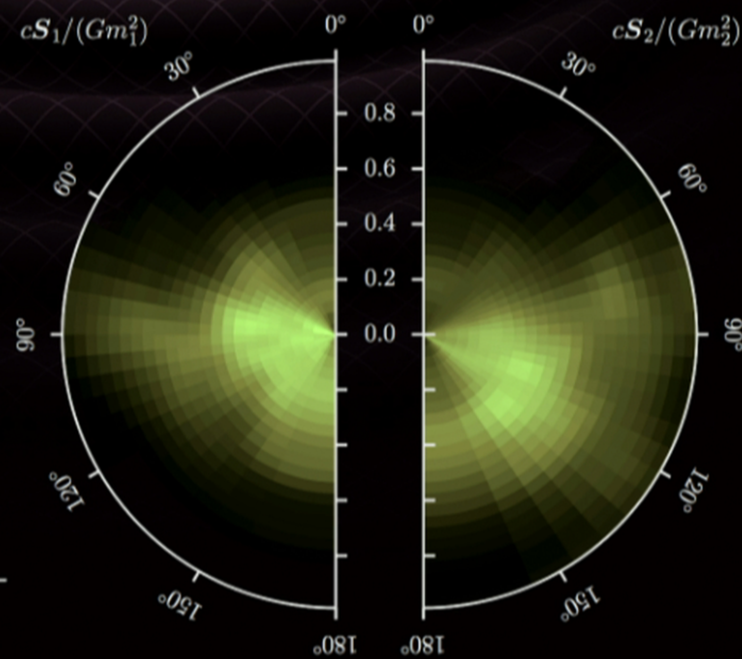
GW150914: Parameter estimates

Mass 1: 32 - 41 Msun
Mass 2: 25 - 33 Msun

Little constraint on spin, but effective spin is small

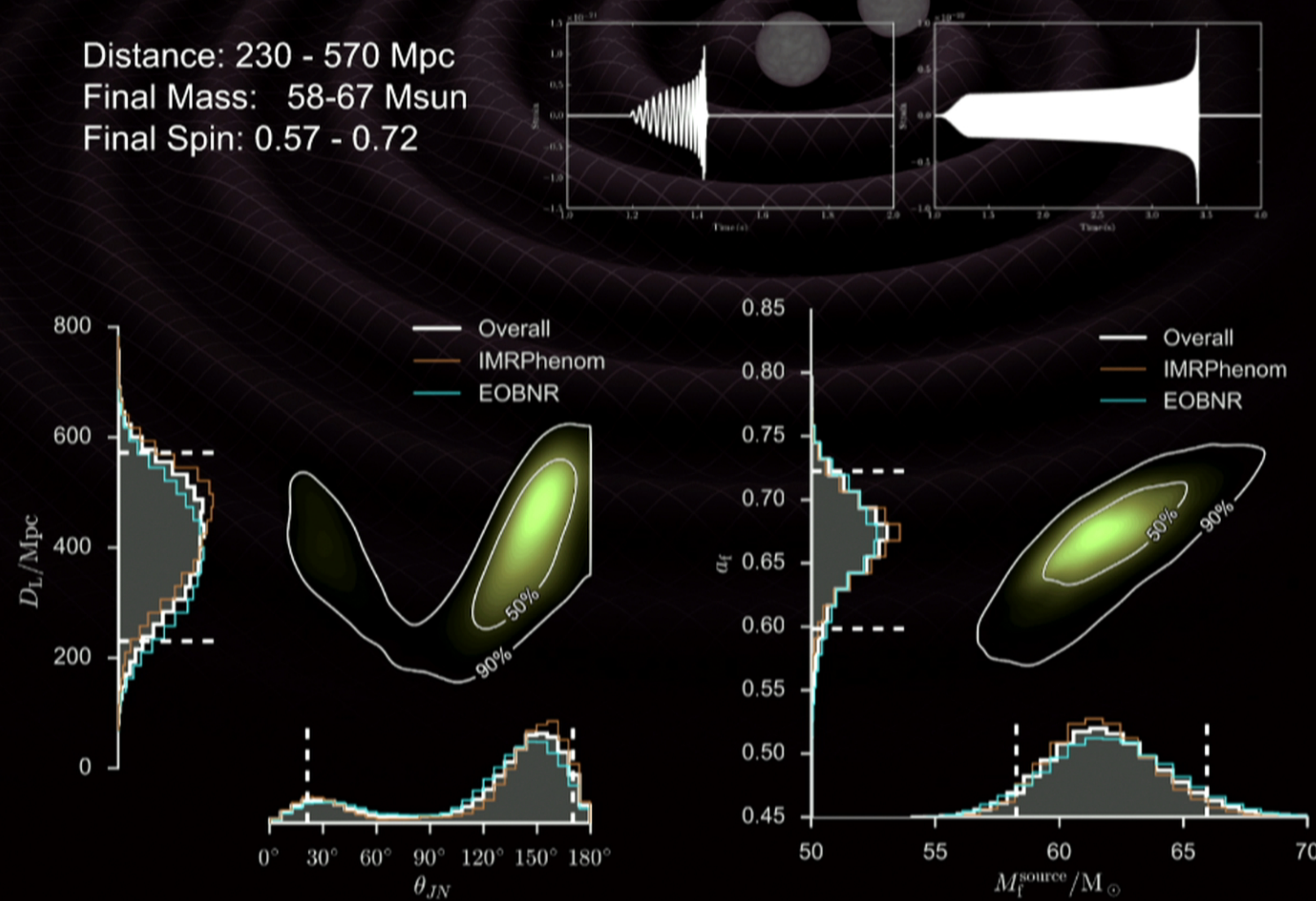






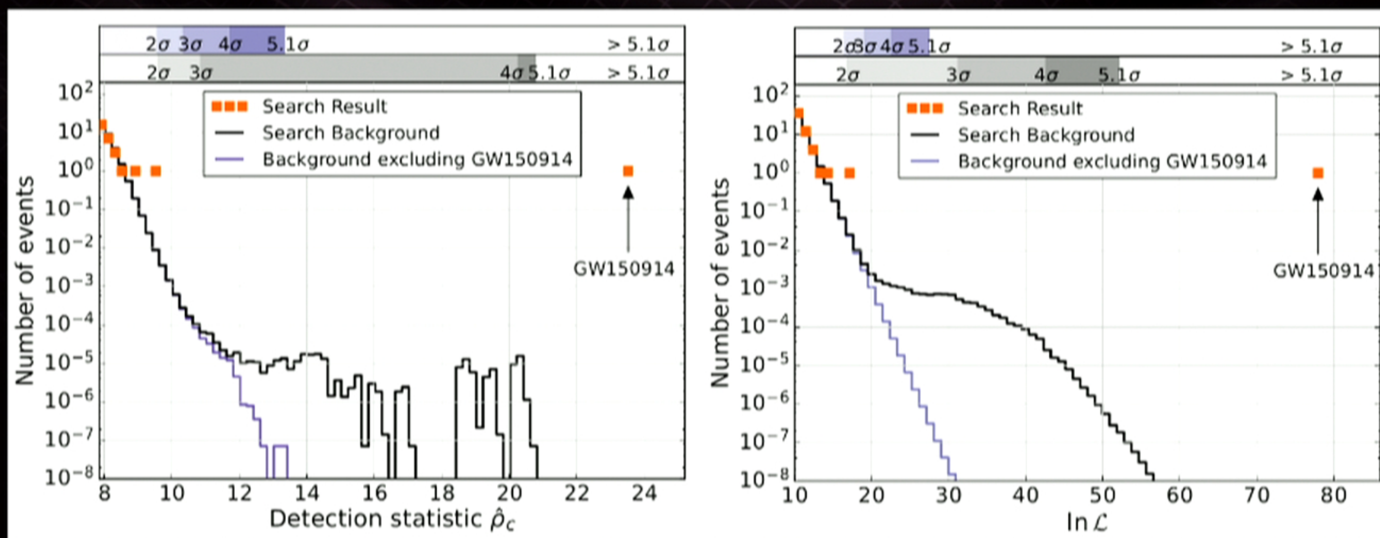
GW150914: Parameter estimates

Distance: 230 - 570 Mpc
Final Mass: 58-67 Msun
Final Spin: 0.57 - 0.72



LVT151012: An interesting event

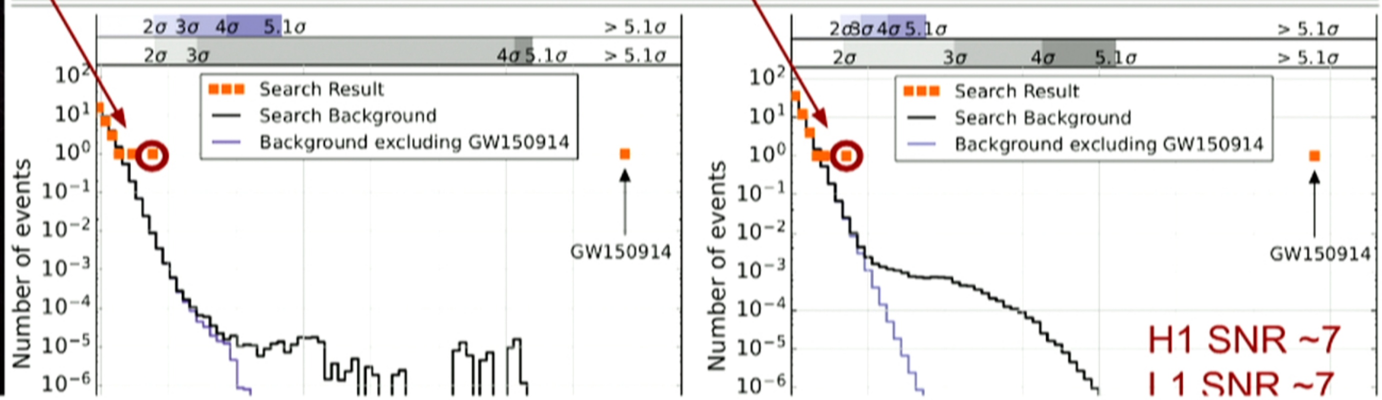
Second trigger found with similar parameters by both matched filter pipelines.



LVT151012: An interesting event

Second trigger found with similar parameters by both matched filter pipelines.

Event	Time (UTC)	FAR (yr^{-1})	$\mathcal{F}$	$\mathcal{M}$ ($M_\odot$)	m_1 ($M_\odot$)	m_2 ($M_\odot$)	χ_{eff}	D_L (Mpc)
GW150914	14 September 2015 09:50:45	$< 5 \times 10^{-6}$	$< 2 \times 10^{-7}$ ($> 5.1\sigma$)	28^{+2}_{-2}	36^{+5}_{-4}	29^{+4}_{-4}	$-0.06^{+0.17}_{-0.18}$	410^{+160}_{-180}
LVT151012	12 October 2015 09:54:43	0.44	0.02 (2.1σ)	15^{+1}_{-1}	23^{+18}_{-5}	13^{+4}_{-5}	$0.0^{+0.3}_{-0.2}$	1100^{+500}_{-500}



The BBH situation before: $0.1–300\ Gpc^{-3}\ yr^{-1}$ [Abadie et al. (2010)]

The BBH situation after: $2–400\ Gpc^{-3}\ yr^{-1}$ [1602.03842]

Extremely conservative range, likely rates between ~30-100

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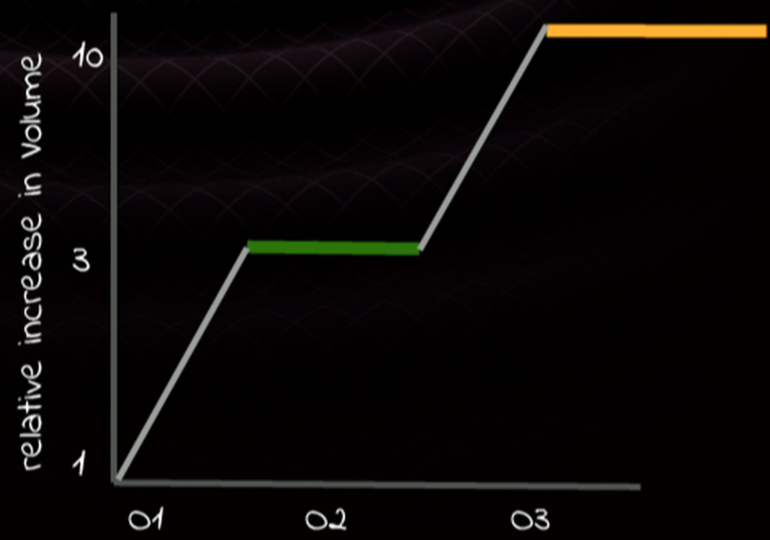
Just the beginning for black hole detections...

Increased volume of future runs implies favorable rate

O2 could have BBH detection **> 1 per month**

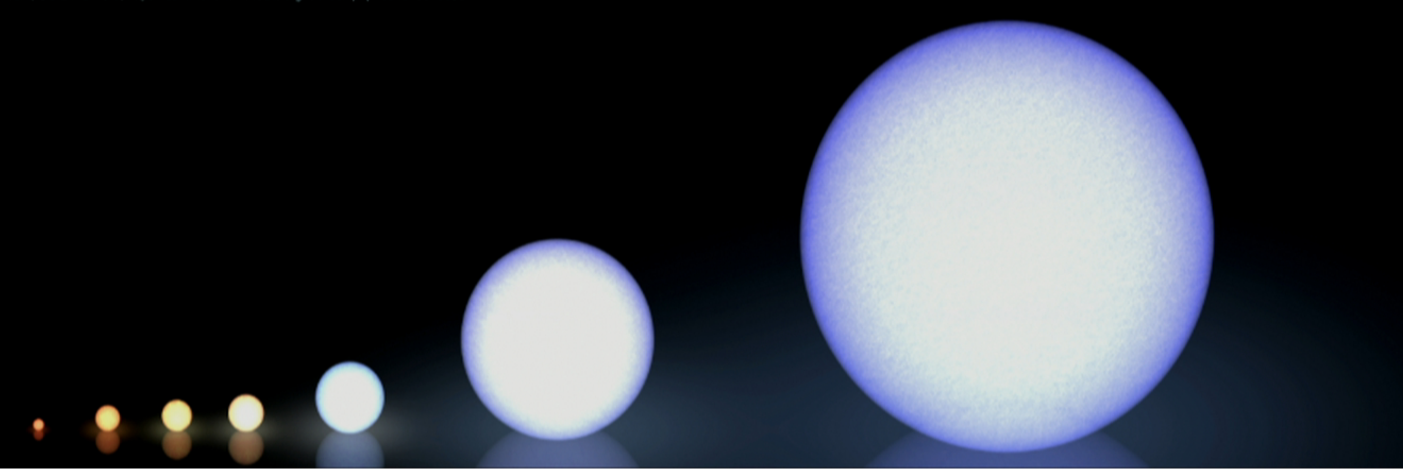
O3 could have BBH detection **once per week**



Population inference and formation scenarios

GW150914 is heavier than had been expected.

- ❖ Implies progenitor stars were very big.
- ❖ Couldn't have shed to much mass from stellar wind
- ❖ Metalicity less than half of solar metalicity
- ❖ Either low metalicity environment in recent Universe or a really long merger time



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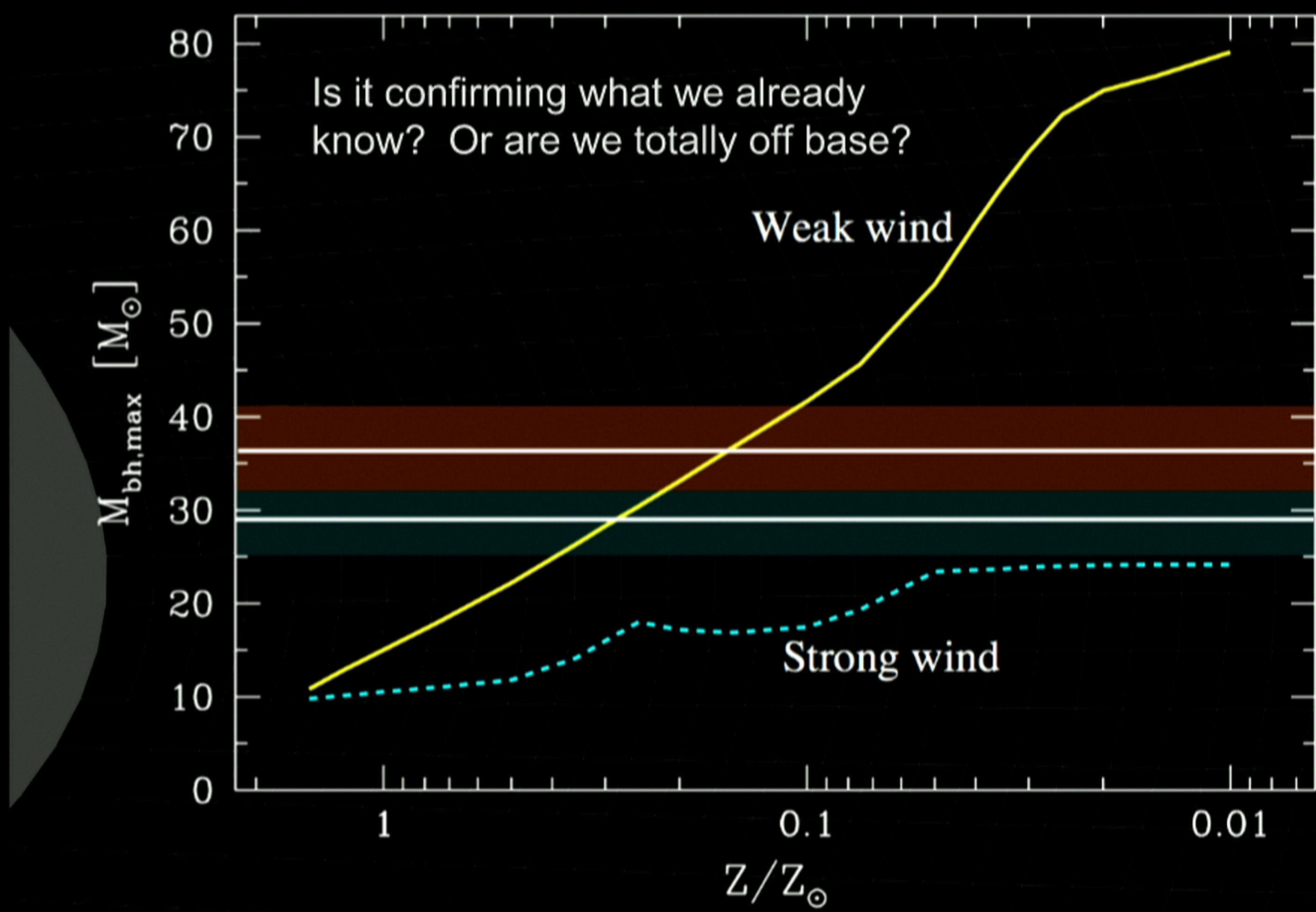
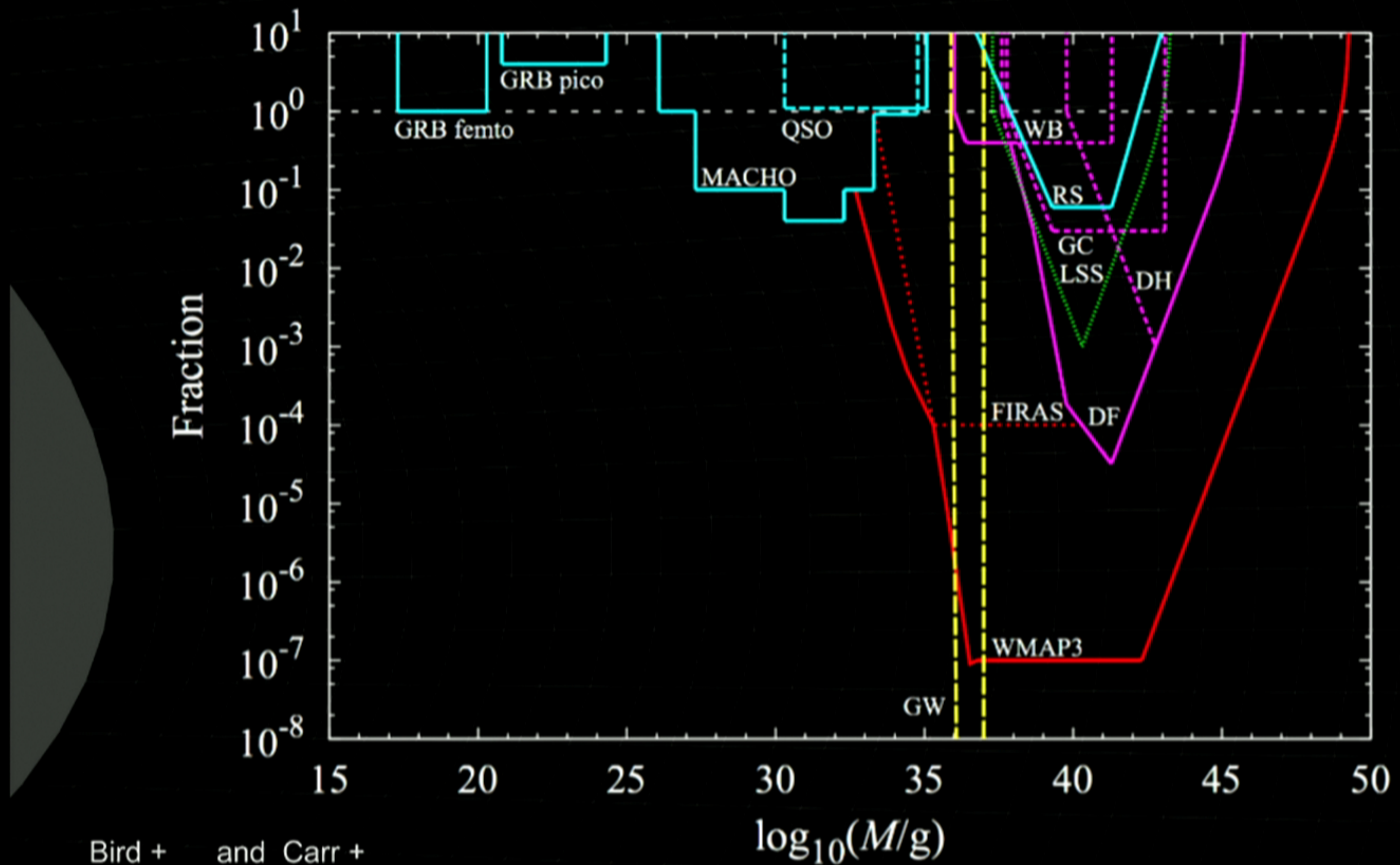


Tweaking our understanding of stellar evolution might be the most boring outcome ever.



Bird + and Carr +
1603.00464 and 1001.3144

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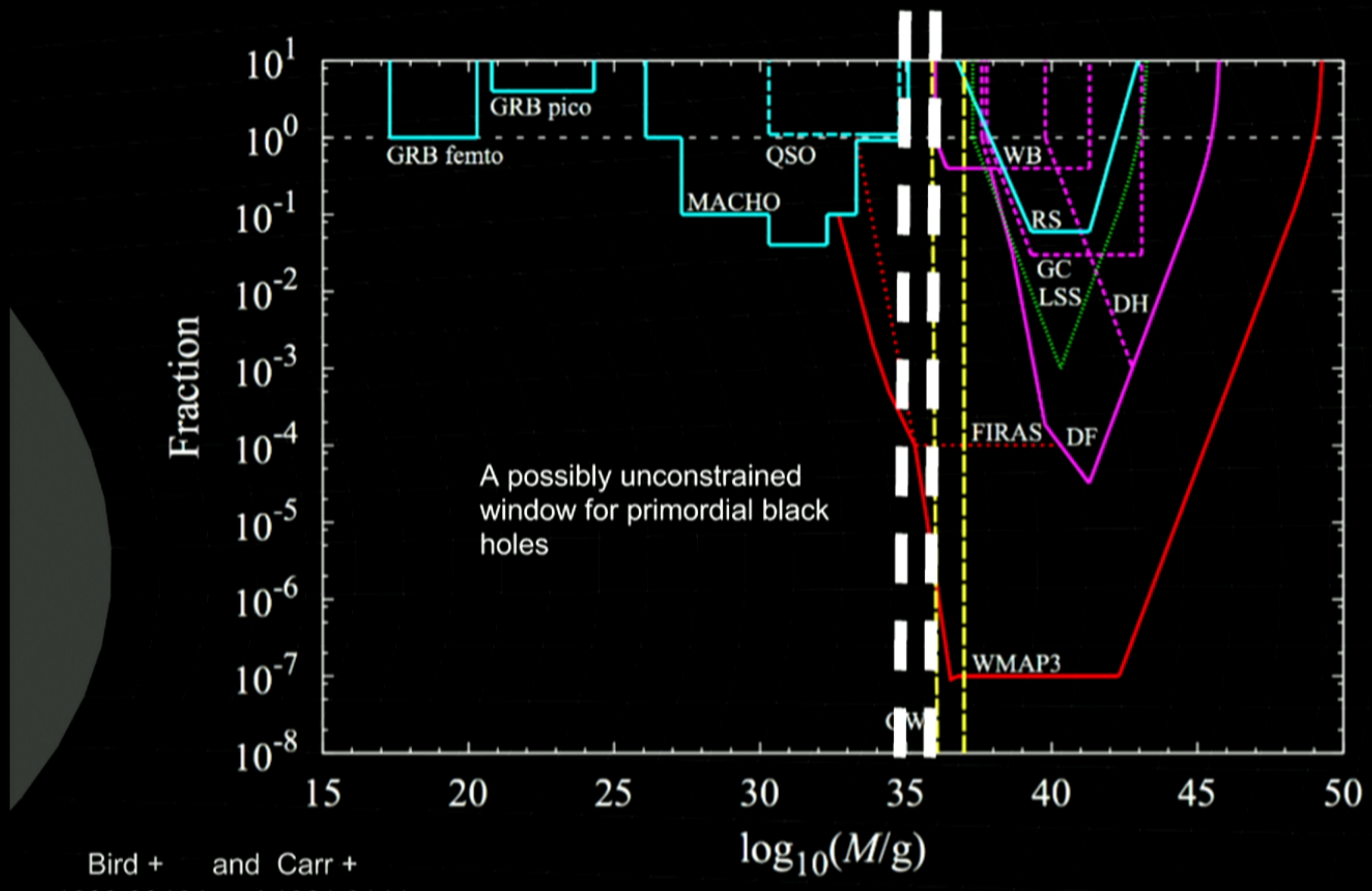
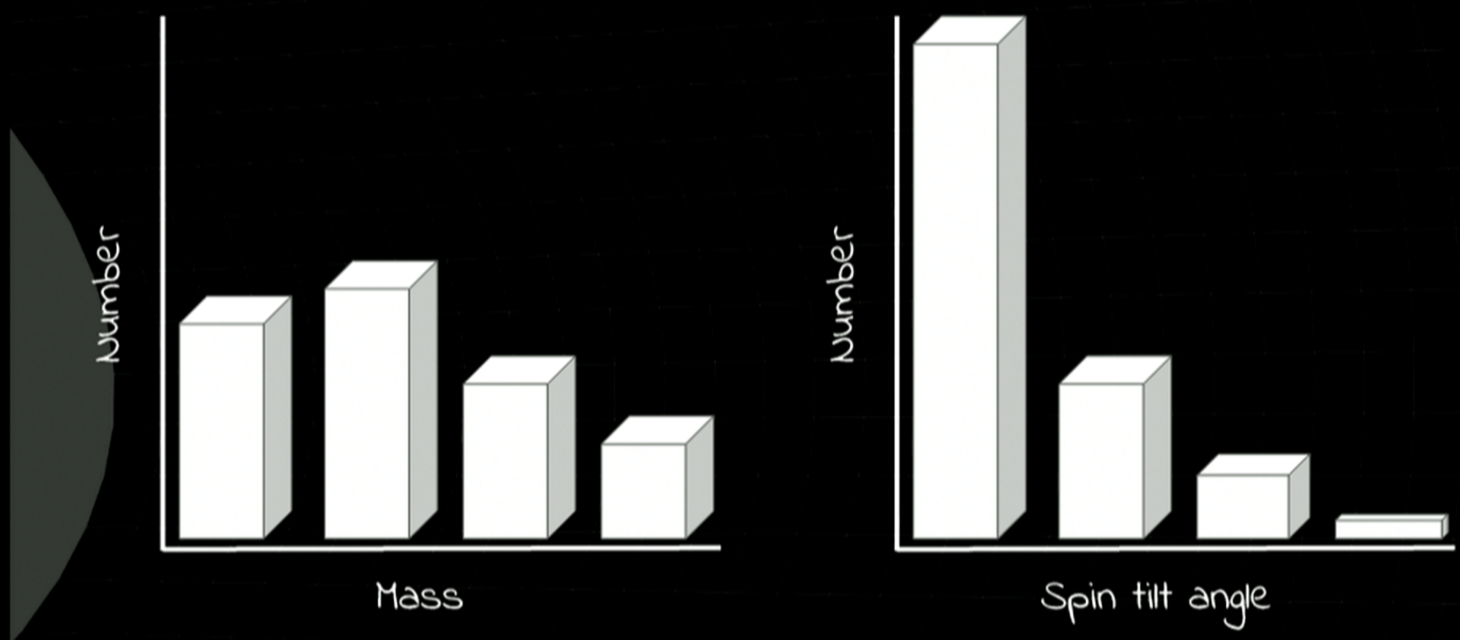


Bird + and Carr +
1603.00464 and 1001.3144

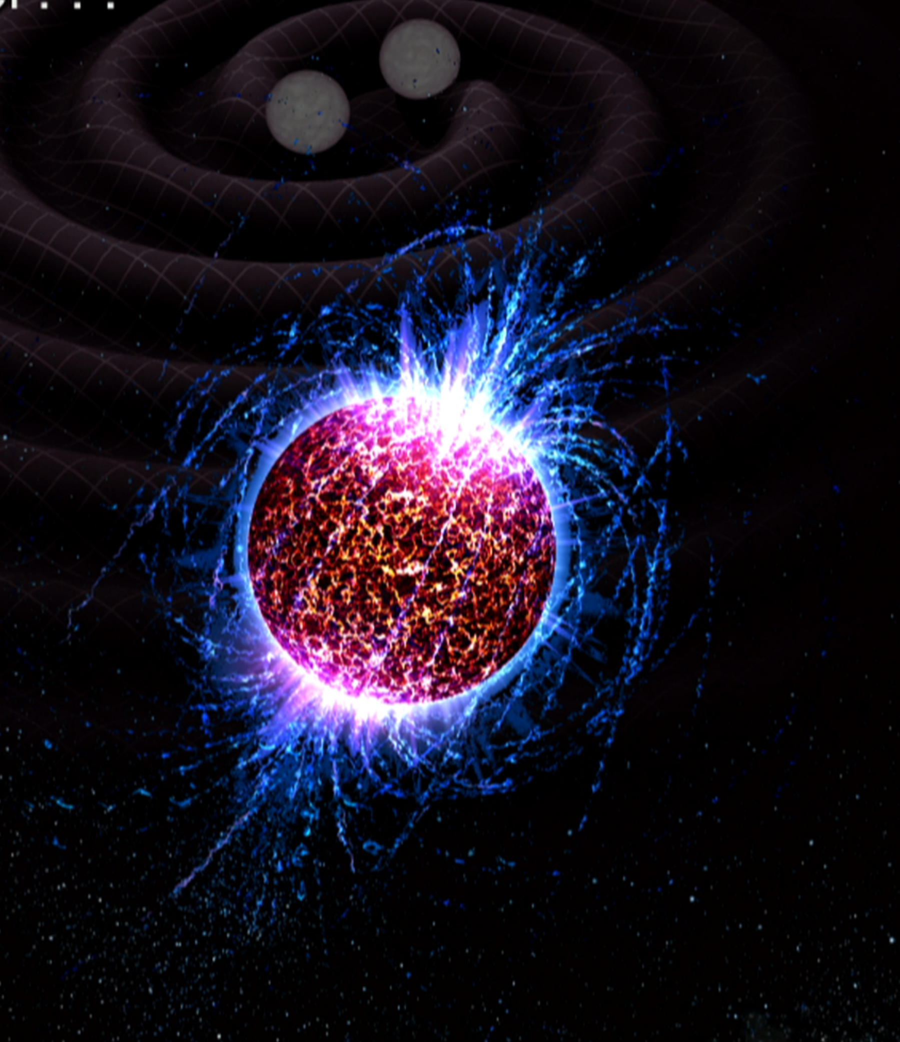
We will disentangle the origin once we measure the mass and spin distributions



Where's the matter???

Binary black holes are simple objects with few degrees of freedom

Neutron star binaries offer tremendous possibility for understanding matter at extreme densities in a highly relativistic regime.



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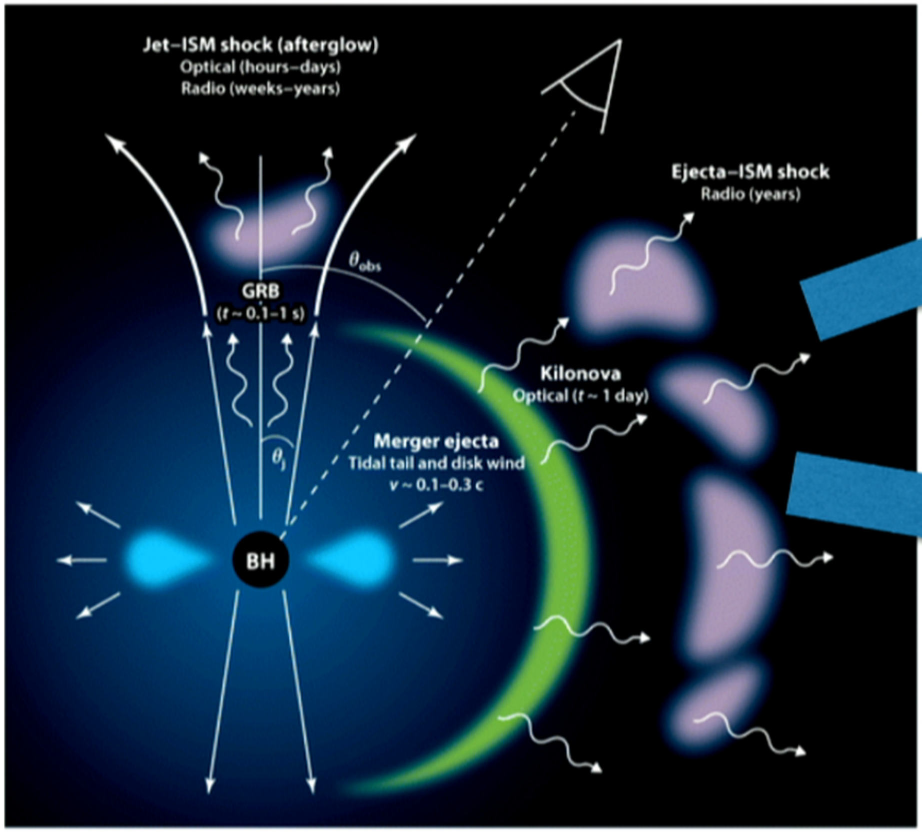
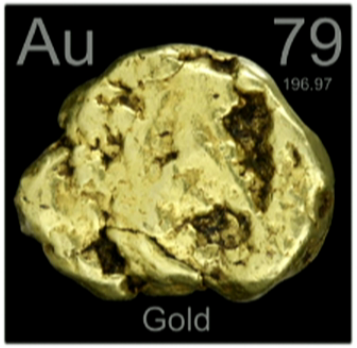
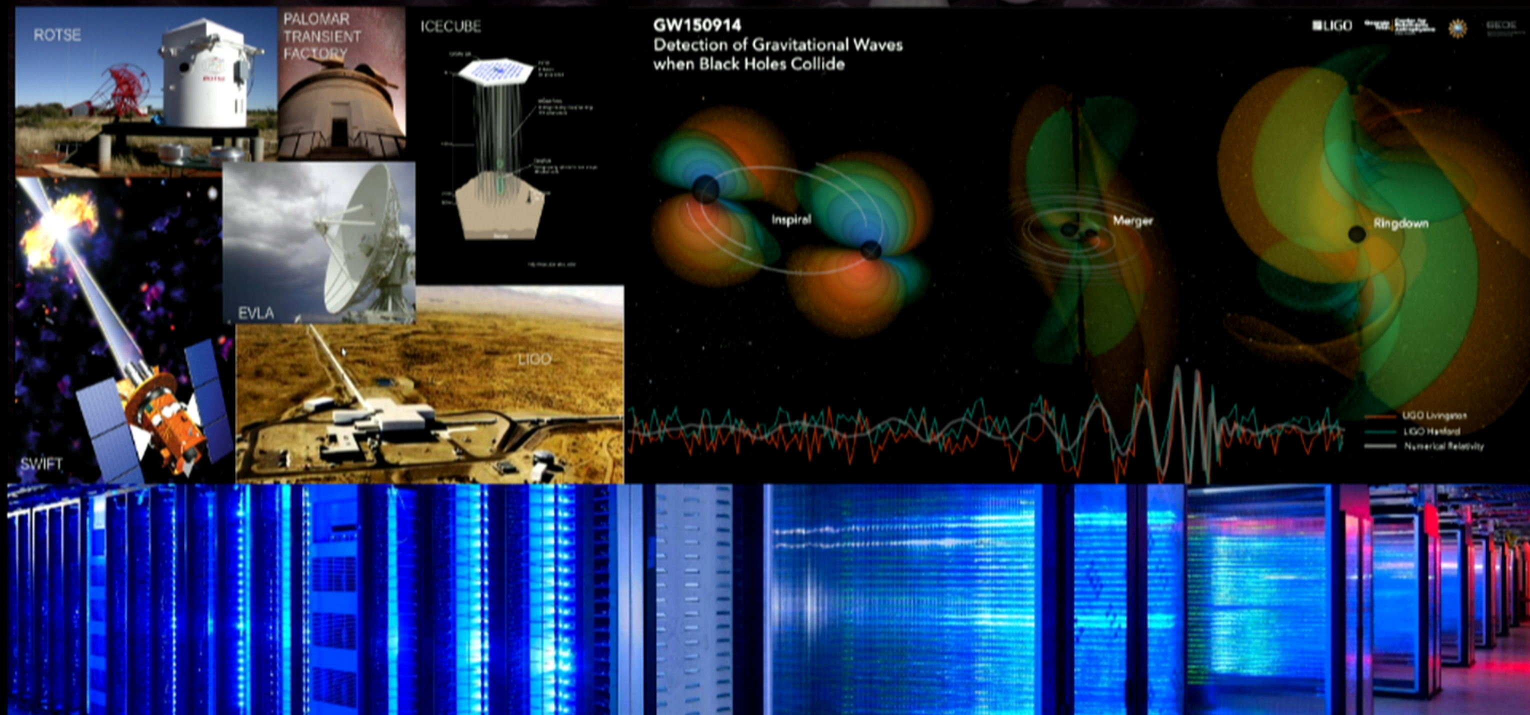




Berger E. 2014.
Annu. Rev. Astron. Astrophys. 52:43–105

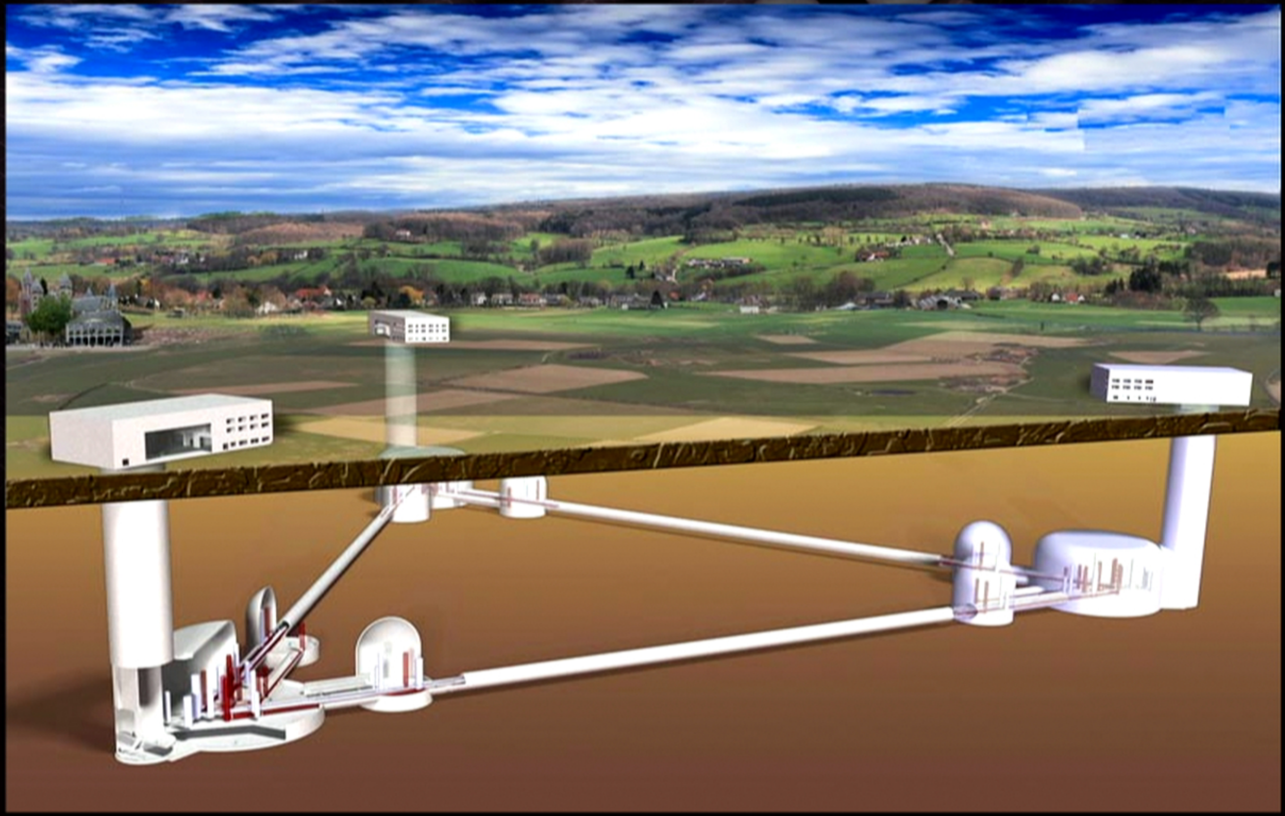
Leo Singer

Multimessenger astrophysics + Computational Modeling



Multimessenger observations + numerical modeling is the key to putting our Universe under a microscope and not just a telescope.

Beyond LIGO

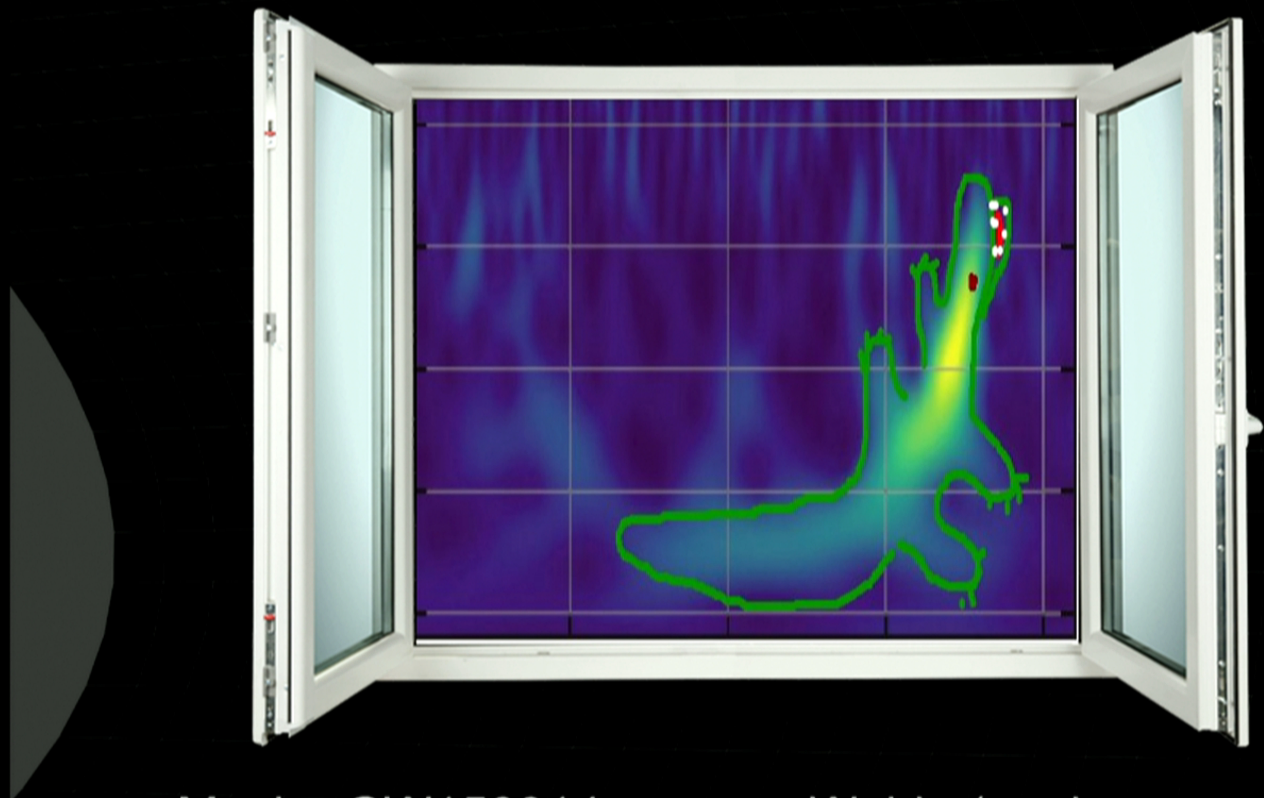


To advance this field, we must not only ponder the physics of the cosmos, but also the terrestrial problem of precision measurement.

We have opened a new window on the Universe

Maybe GW150914 was our Waldo (or close enough)

We have opened a new window on the Universe



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