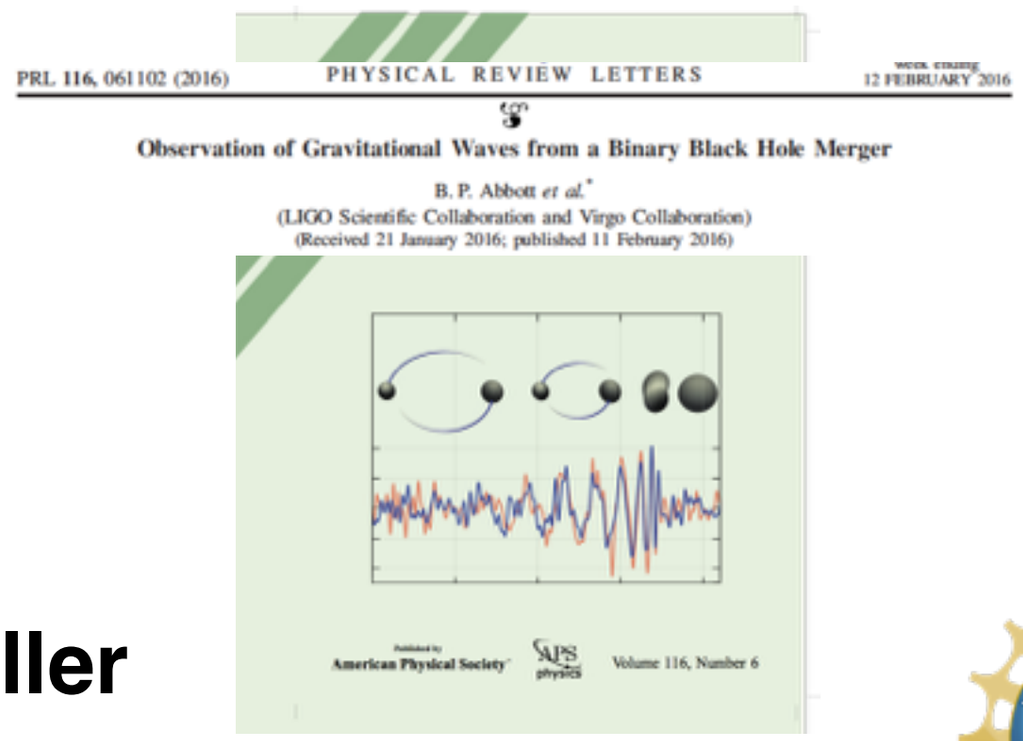
Gravitational Waves


PRL 116, 061102 (2016) PHYSICAL REVIEW LETTERS 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

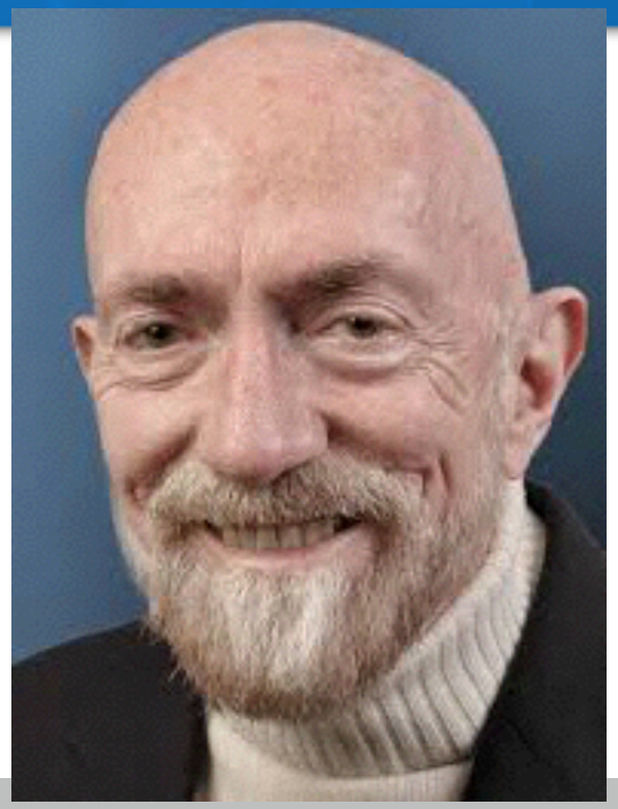
(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

American Physical Society Volume 116, Number 6

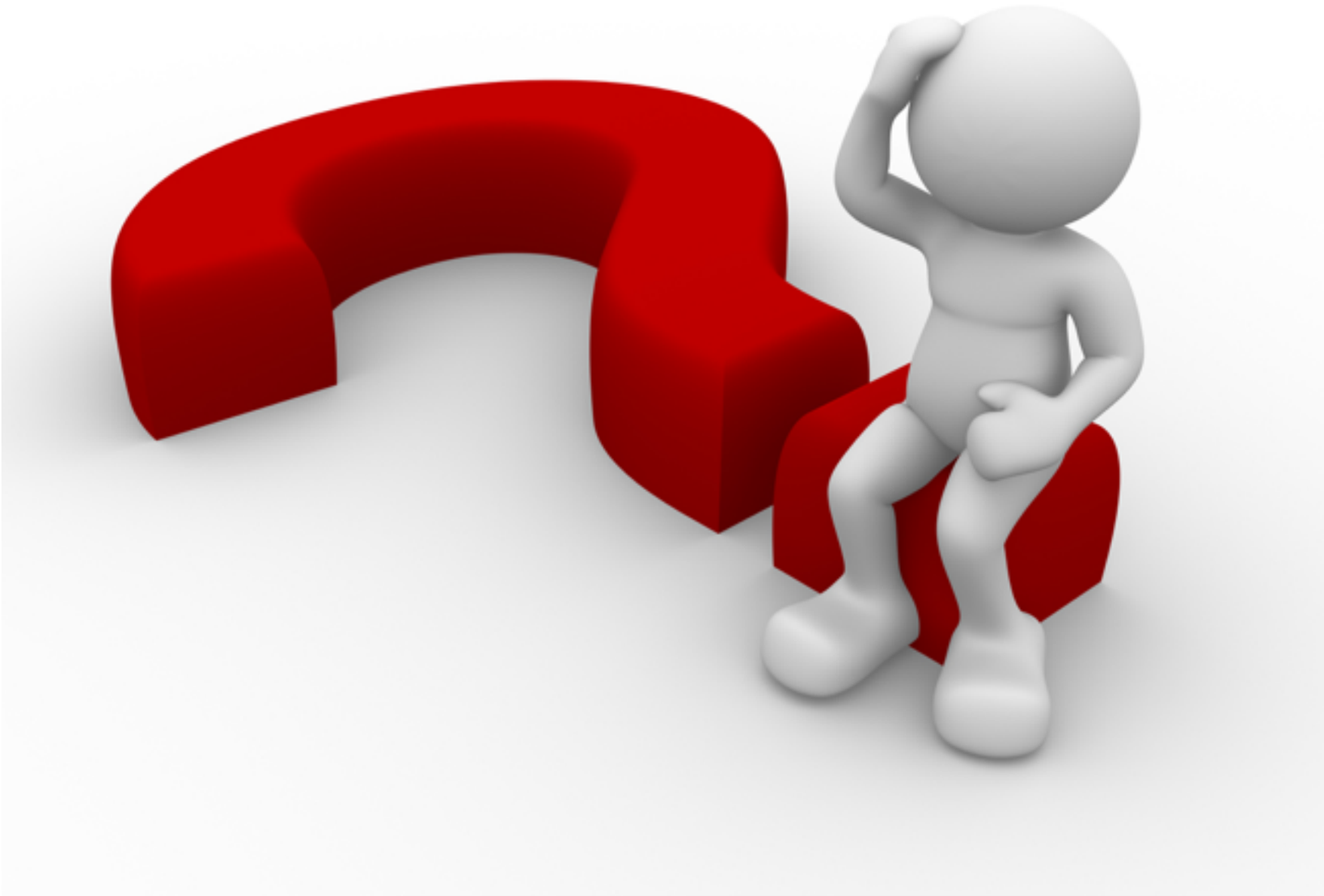
Guido Mueller

PHY1033, December 1st, 2016

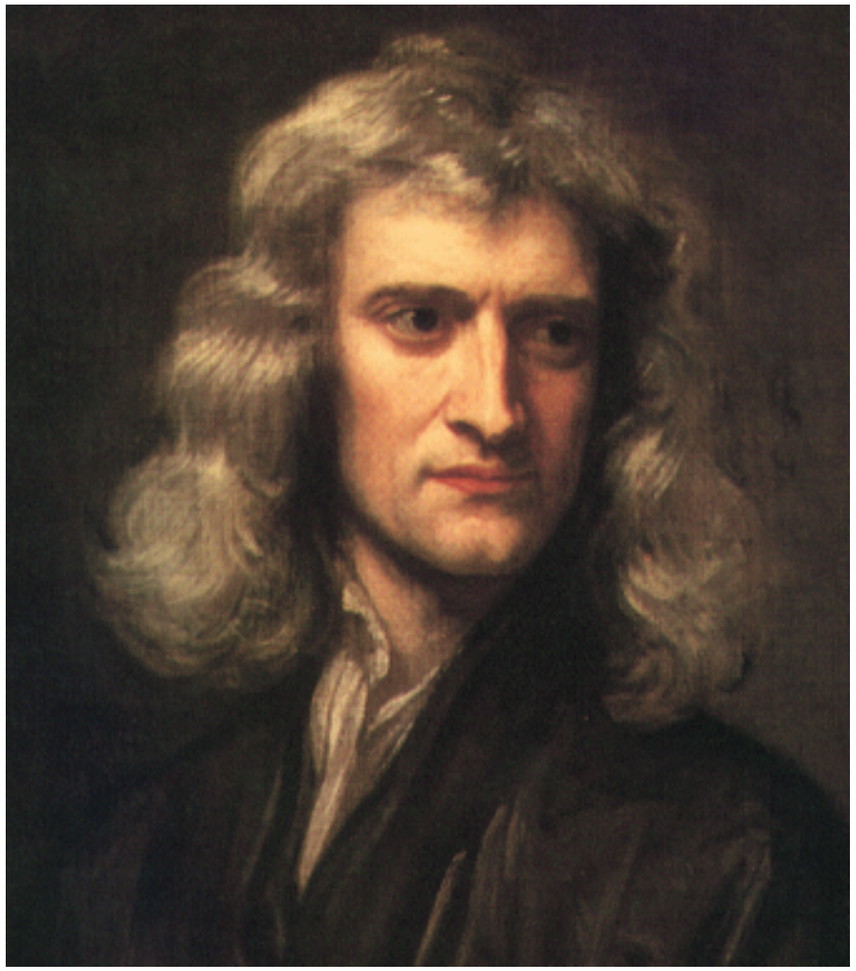


Breakthrough Prize	Ron Drever, Kip Thorne, Rainer Weiss	Authors of Paper (LVSC)
Gruber Prize for Cosmology	Ron Drever, Kip Thorne, Rainer Weiss	LIGO Discovery Team
Shaw Prize for Astronomy	Ron Drever, Kip Thorne, Rainer Weiss	
Kavli Prize for Astronomy	Ron Drever, Kip Thorne, Rainer Weiss	

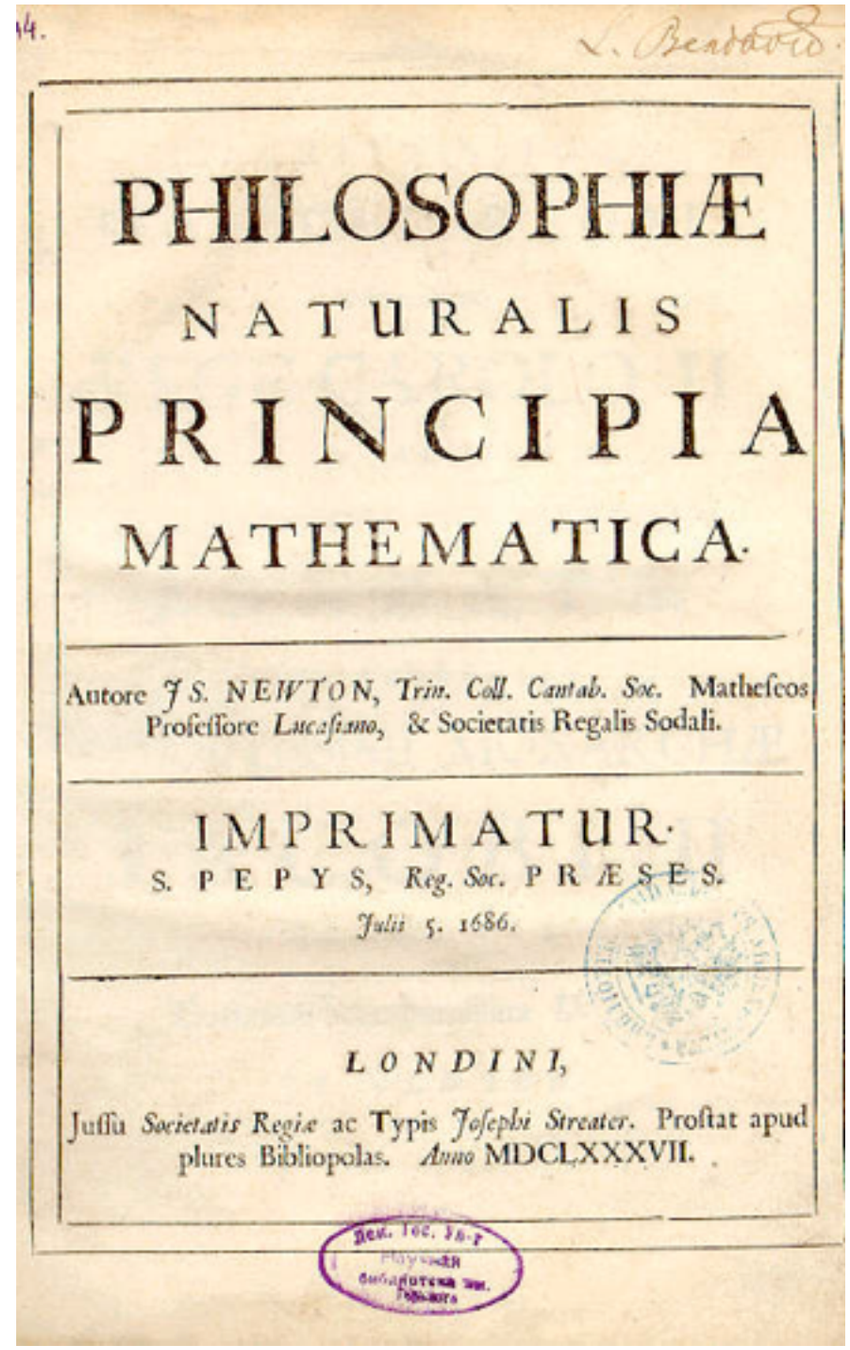
Big Deal?



Newtonian Gravity



Sir Isaac Newton
Theory of Gravity
(1686)



PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA.

Autore J S. NEWTON, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

IMPRIMATUR.
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

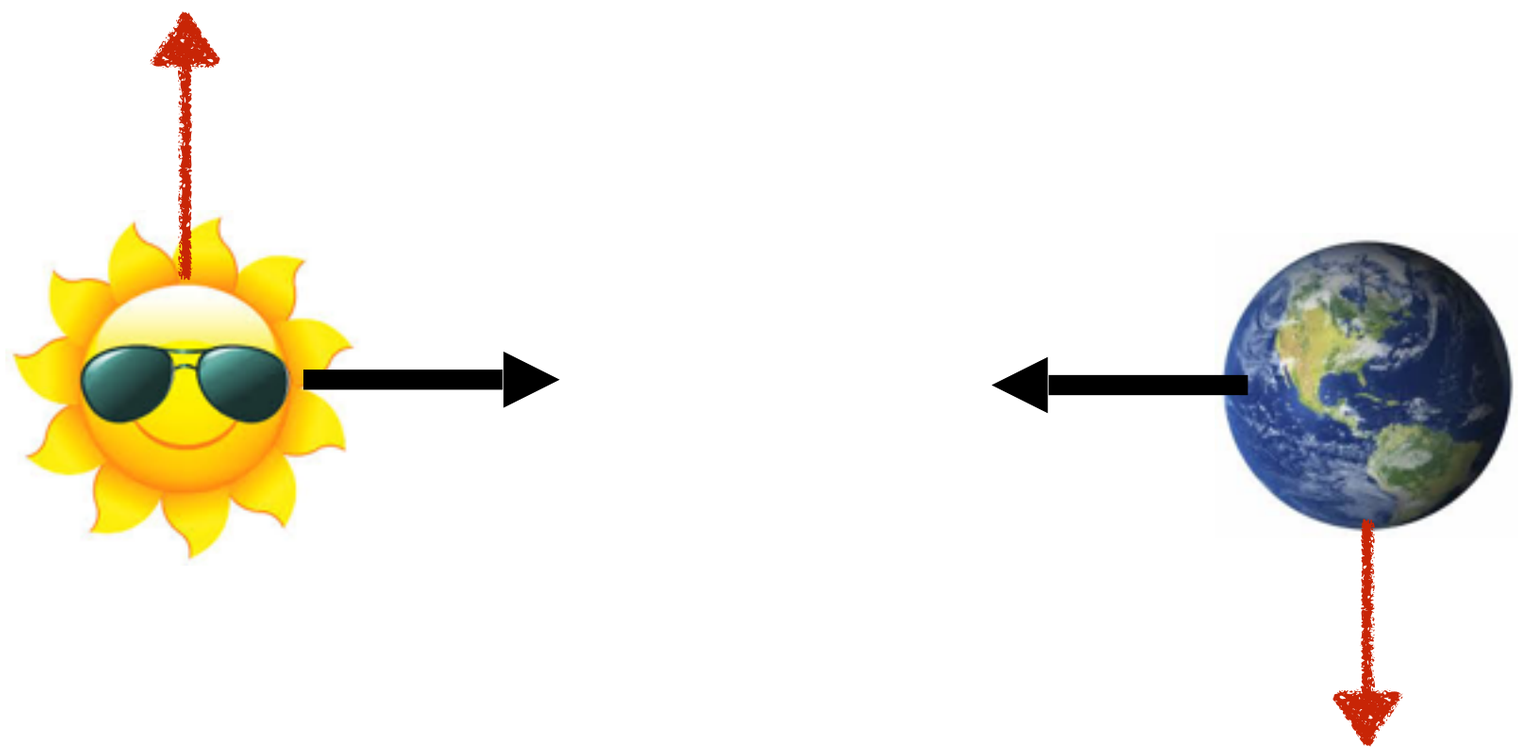
Newtonian Gravity

… has a fundamental problem

Newtonian Gravity

… has a fundamental problem

- Earth and Sun move relative to each other
- Light needs 8 minutes to travel from Sun to Earth



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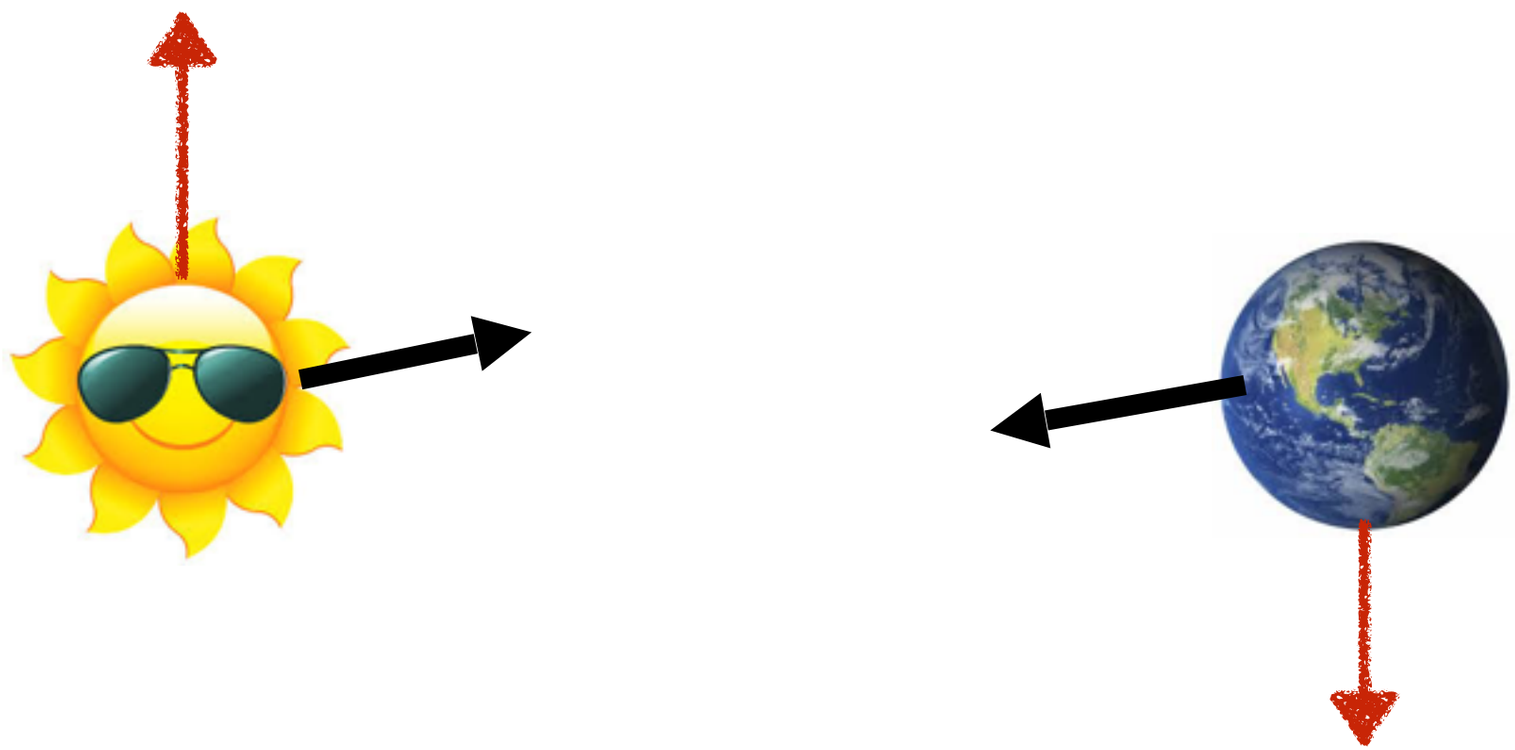

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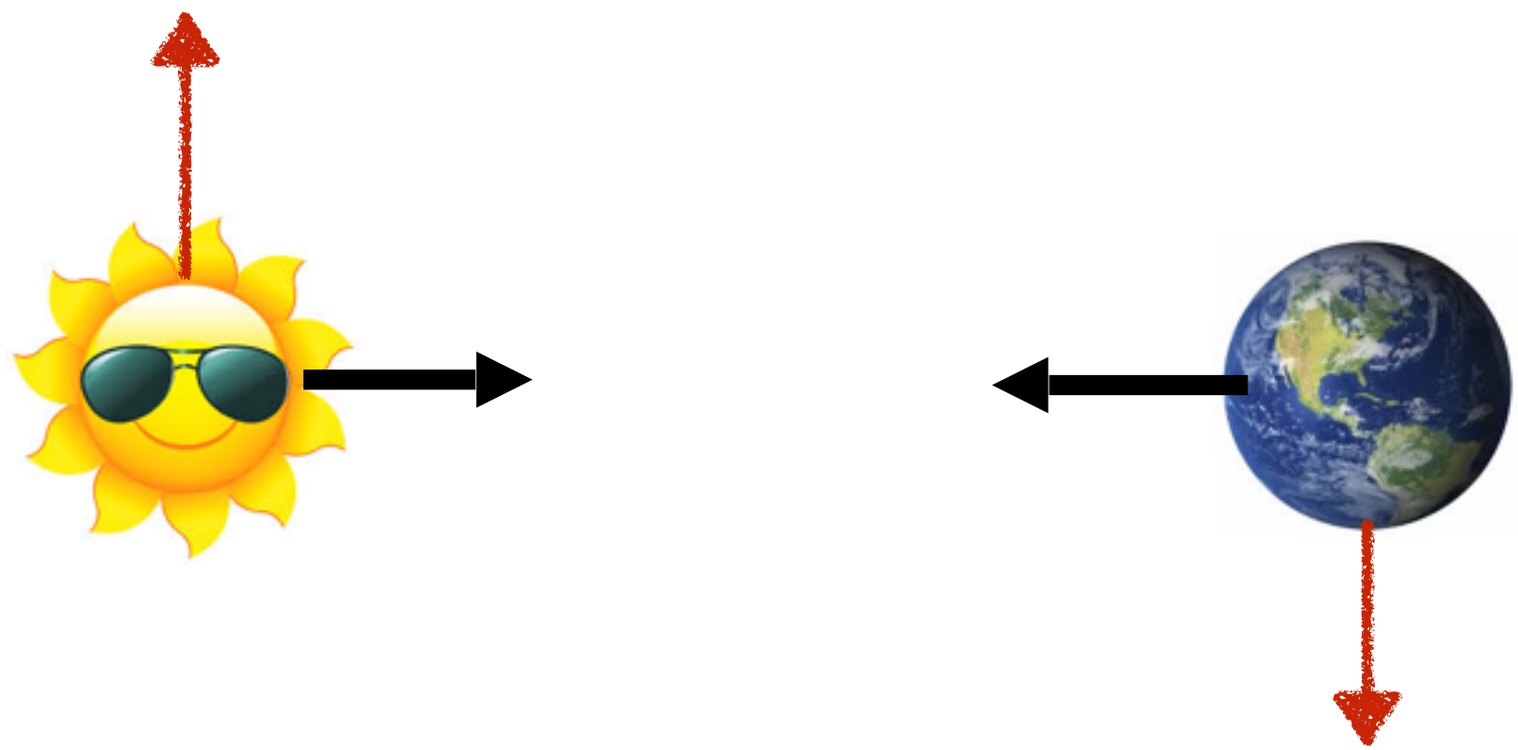


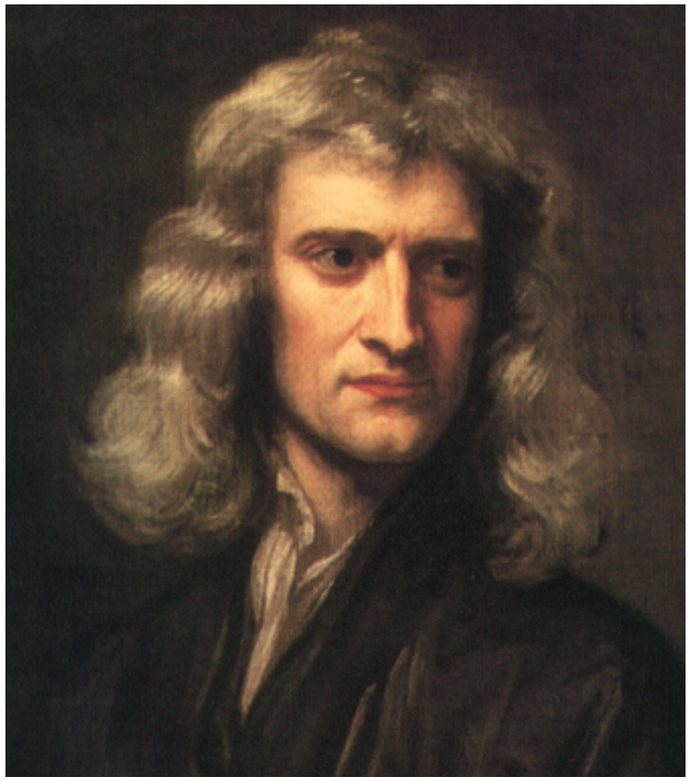
Newtonian Gravity

How do changes in the gravitational field change over large distances?

Newton's Theory:

Gravity changes everywhere immediately!

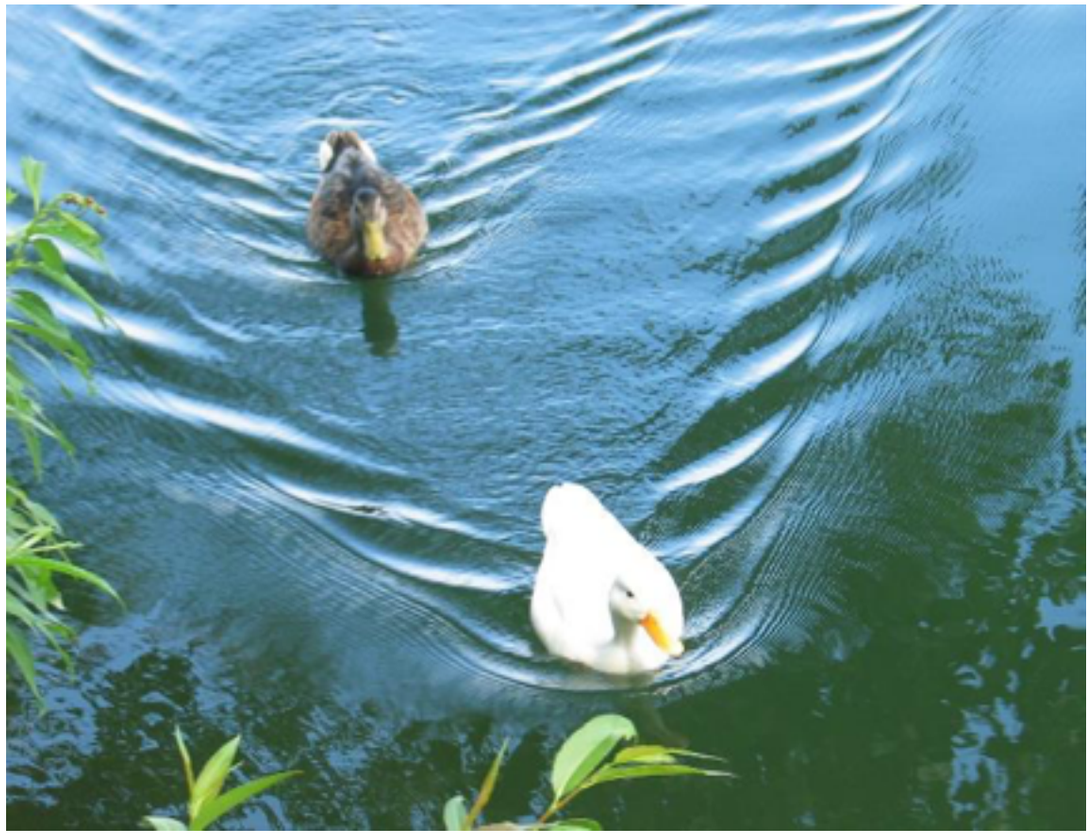
Gravity has no speed limit!

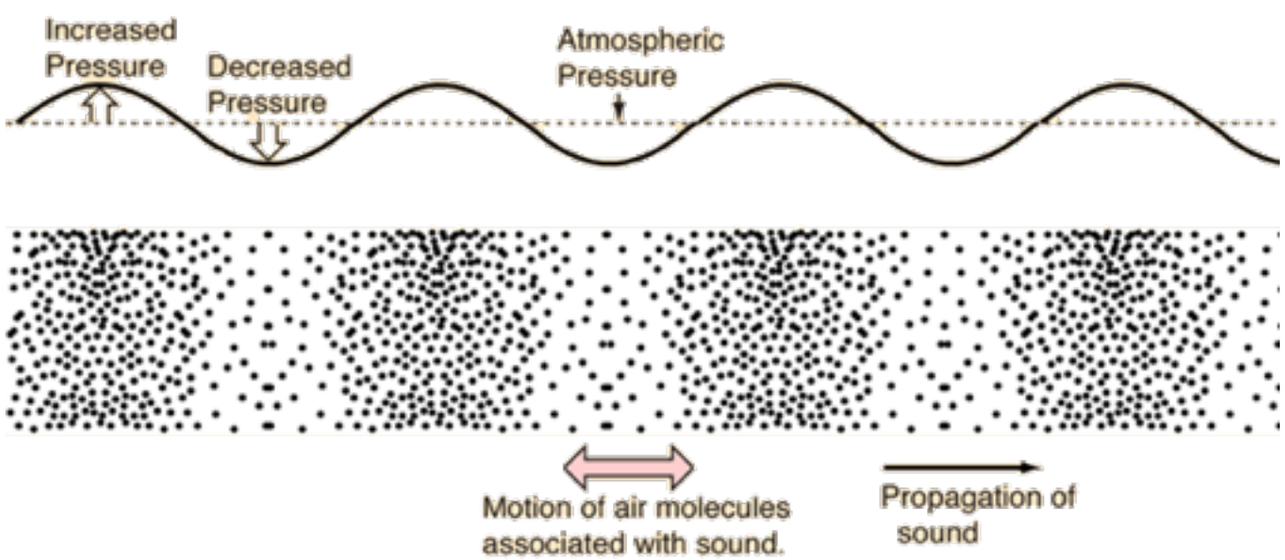


Newton knew that his Theory had a problem …

The speed limit in Nature

All other physical effects generate waves …





Newton's solution contradicts all we know about physics ….

Einstein's Theory of General Relativity

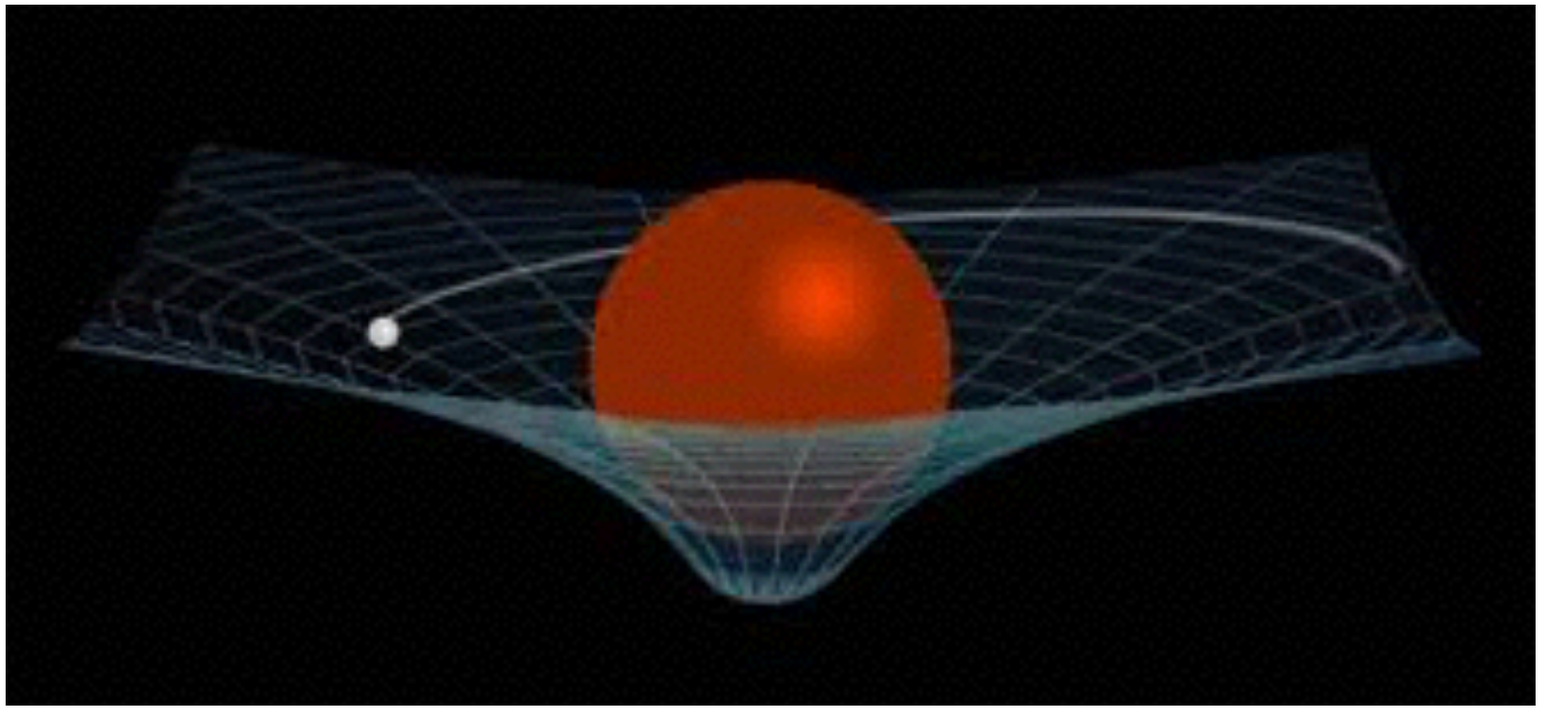
250 years later:

Albert Einstein (1879-1955)

Gravity is not a force!

Gravity is curved spacetime!

Einstein's Theory of General Relativity

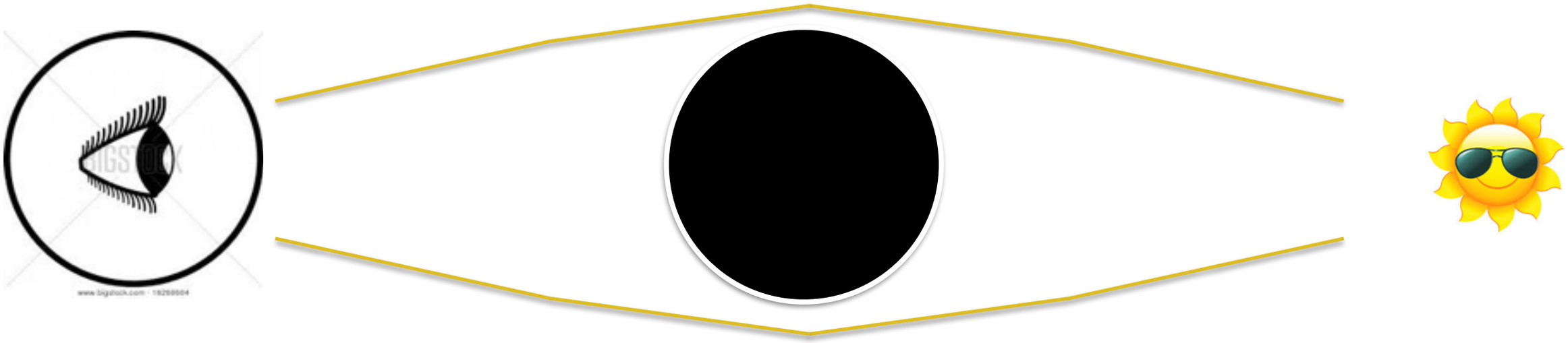


Spacetime tells matter how to move;
matter tells spacetime how to curve.
John A. Wheeler

Einstein's Theory of General Relativity

Curvature at the extreme: Black Holes

- Nothing escapes, not even light
  - Schwarzschild radius = event horizon
- Bends spacetime around it as well



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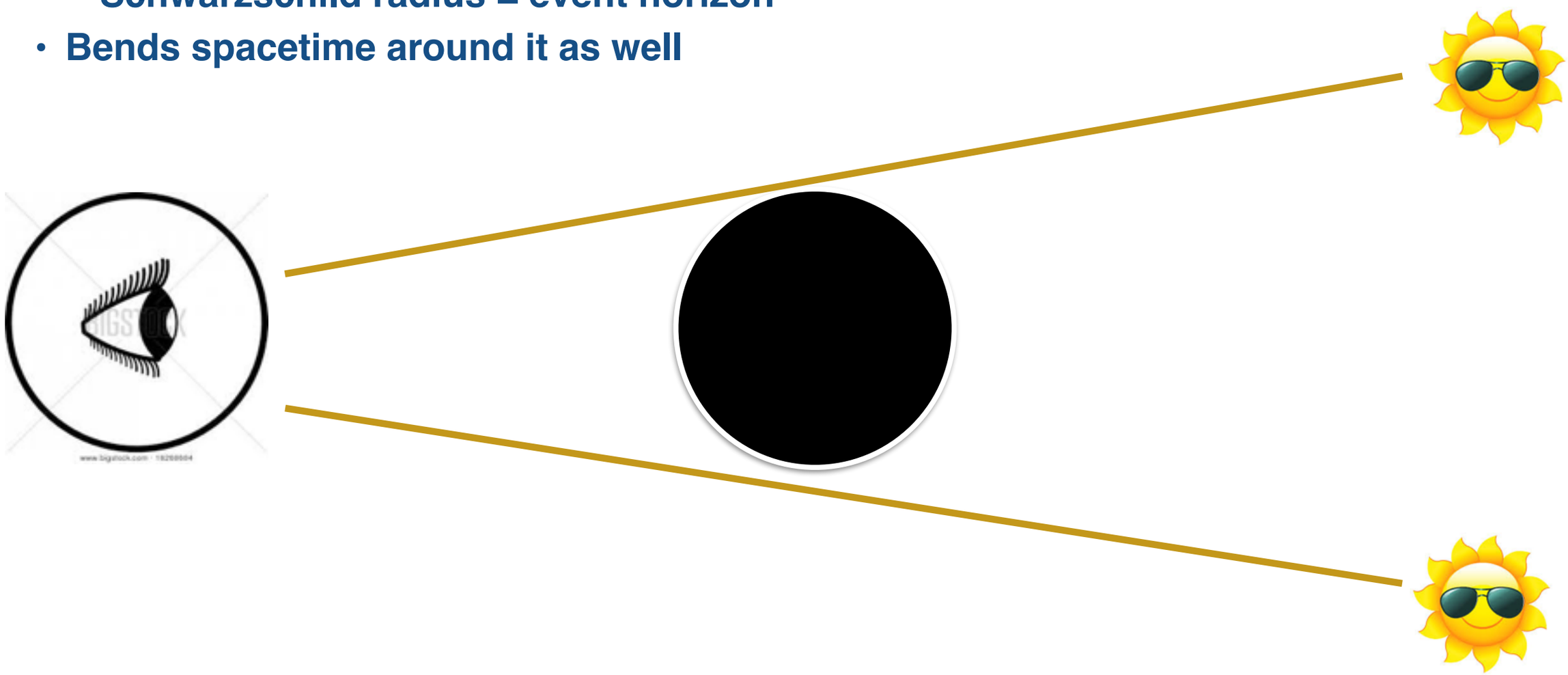


Einstein's Theory of General Relativity

Gargantus from Interstellar

Known stellar mass black holes

wikipedia (before LIGO):

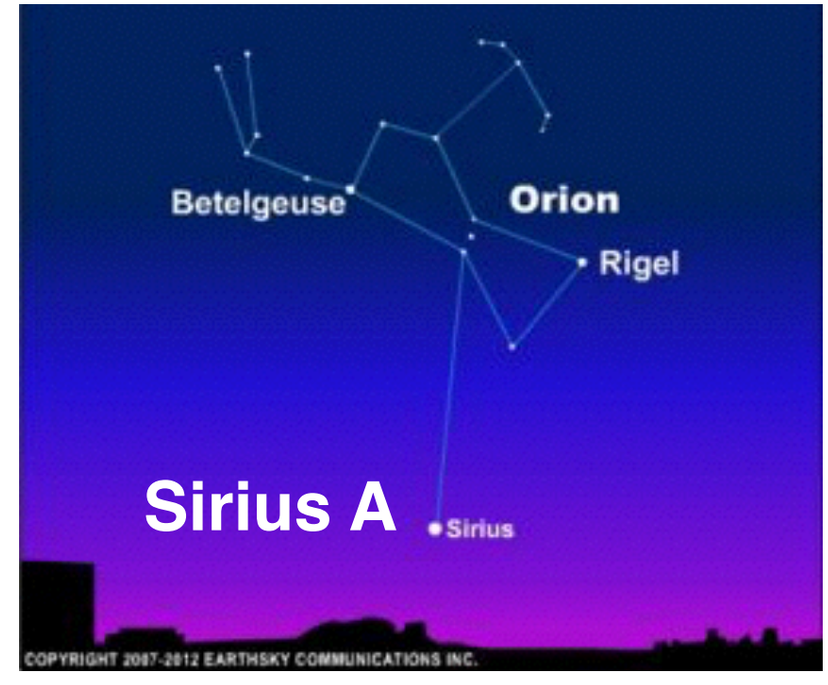
Name	BHC Mass (solar masses)	Companion Mass (solar masses)	Orbital period (days)	Distance from Earth (light years)	Location [14]
A0620-00/V616 Mon	11 ± 2	2.6–2.8	0.33	about 3500	06:22:44 -00:20:45
GRO J1655-40/ V1033 Sco	6.3 ± 0.3	2.6–2.8	2.8	5000–11000	16:54:00 -39:50:45
XTE J1118+480/KV UMa	6.8 ± 0.4	6–6.5	0.17	about 6200	11:18:11 +48:02:13
Cyg X-1	11 ± 2	≥18	5.6	6000–8000	19:58:22 +35:12:06
GRO J0422+32/V518 Per	4 ± 1	1.1	0.21	about 8500	04:21:43 +32:54:27
GRO J1719-24	≥4.9	~1.6	possibly 0.6[15]	about 8500	17:19:37 -25:01:03
GS 2000+25/QZ Vul	7.5 ± 0.3	4.9–5.1	0.35	about 8800	20:02:50 +25:14:11
V404 Cyg	12 ± 2	6.0	6.5	7800±460[16]	20:24:04 +33:52:03
GX 339-4/V821 Ara	5.8	5–6	1.75	about 15000	17:02:50 -48:47:23
GRS 1124-683/GU Mus	7.0 ± 0.6	~0.33	0.43	about 17000	11:26:27 -68:40:32
XTE J1550-564/V381 Nor	9.6 ± 1.2	6.0–7.5	1.5	about 17000	15:50:59 -56:28:36
4U 1543-475/IL Lupi	9.4 ± 1.0	0.25	1.1	about 24000	15:47:09 -47:40:10
XTE J1819-254/ V4641 Sgr	7.1 ± 0.3	5–8	2.82	24000 – 40000[17]	18:19:22 -25:24:25
GRS 1915+105/ V1487 Aql	14 ± 4.0	~1	33.5	about 40000	19:15;12 +10:56:44
XTE J1650-500	9.7 ± 1.6 [18]	.	0.32[19]		16:50:01 -49:57:45

Black Holes

How can we 'see' Black Holes?

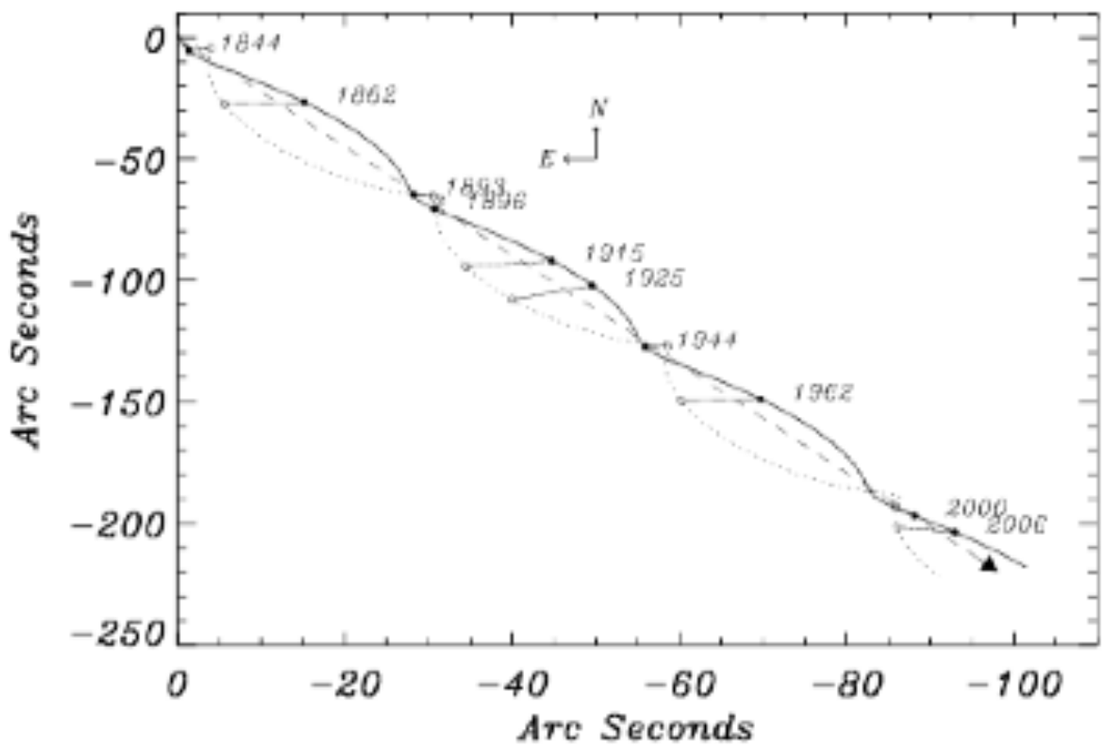
Indirectly:

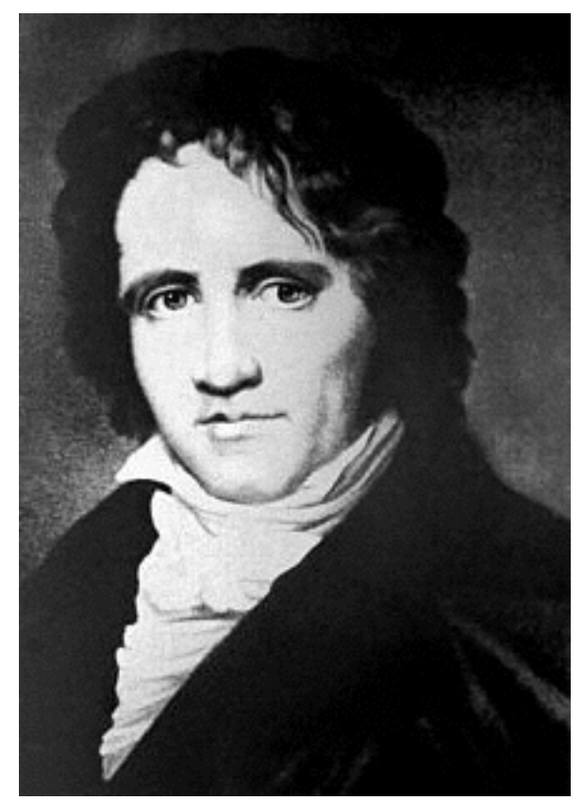
1. Through their influence on the motion of other stars.



Historical Example from 1844:

Sirius A motion





Friedrich Wilhelm Bessel (1784-1846)

Black Holes

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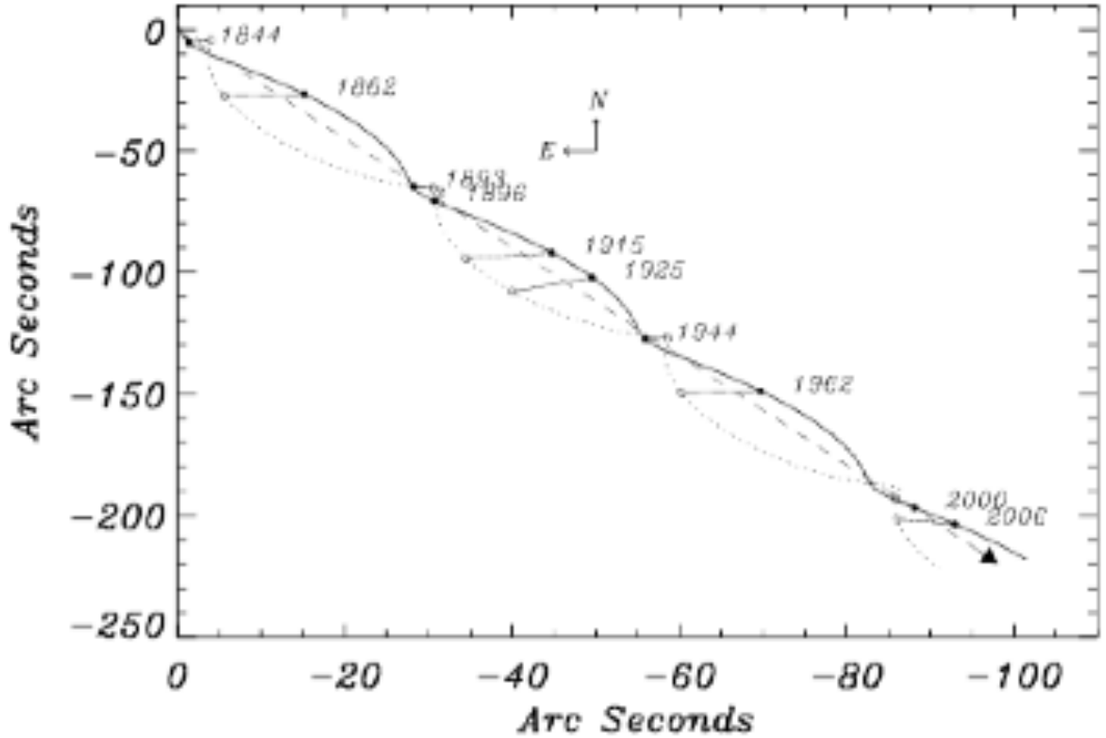
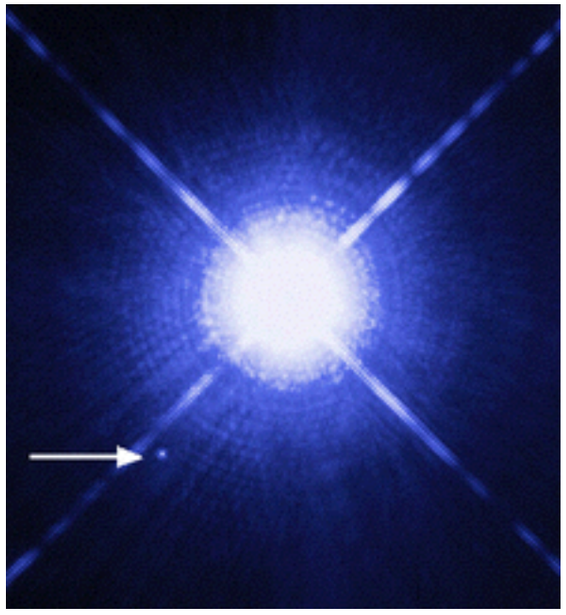
Historical Example from 1844:

Sirius A motion

explained by 2nd star: Sirius B (White dwarf)

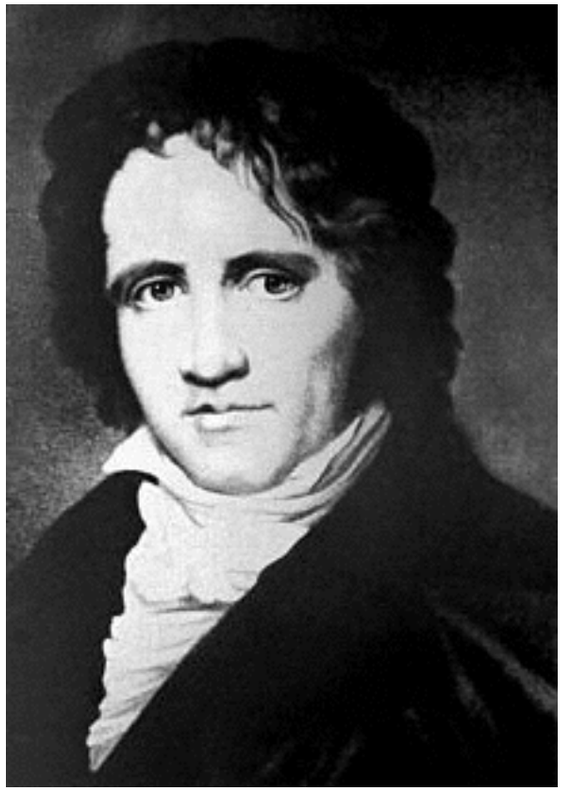


Sirius A:



Sirius B

1862 discovered



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Black Holes

How can we 'see' Black Holes?

Indirectly:

1. Through their influence on the motion of other stars.
2. Through the emission of X-ray radiation from their accretion disc.

Not a picture, just an illustration!

Black Holes

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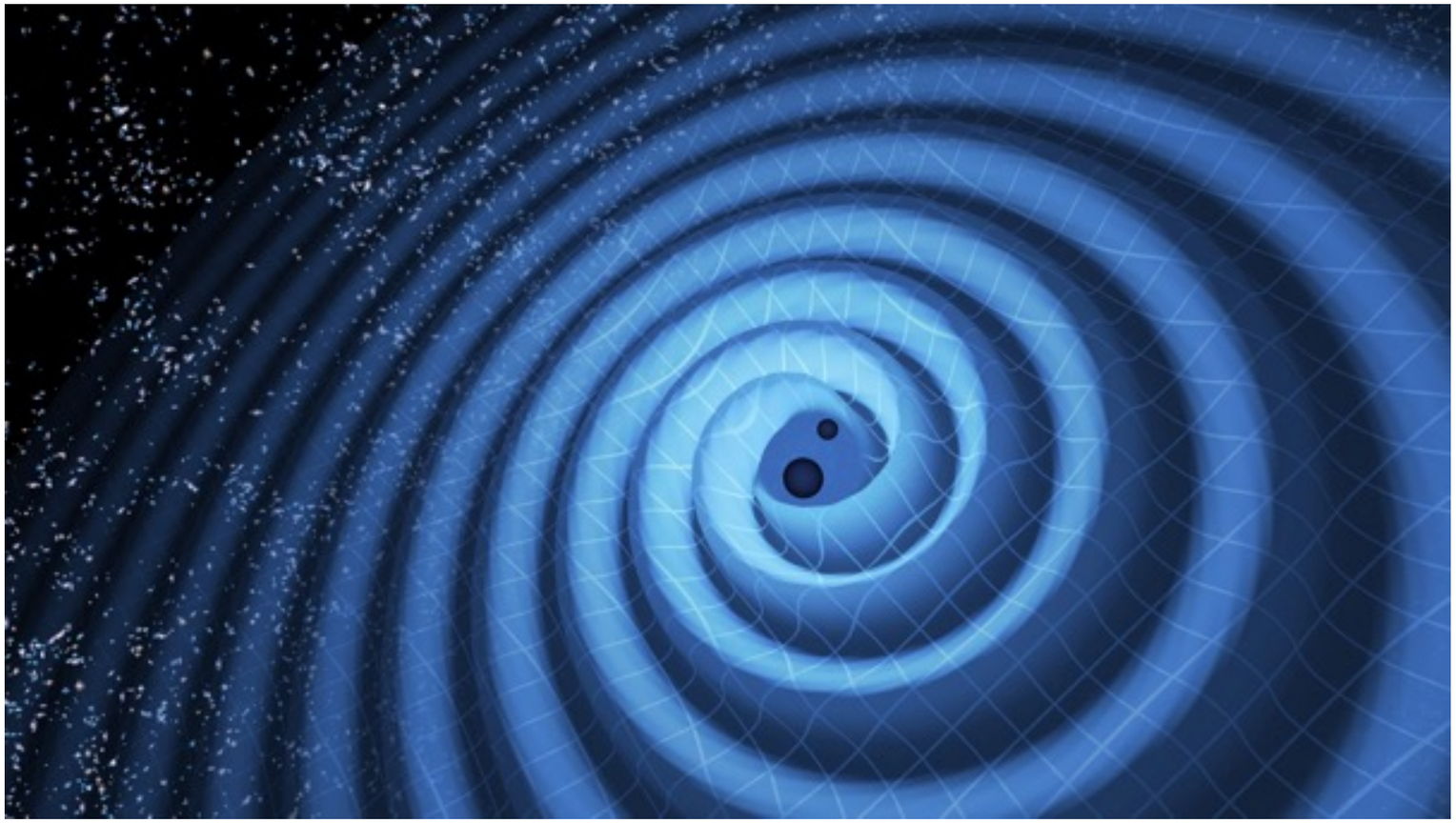
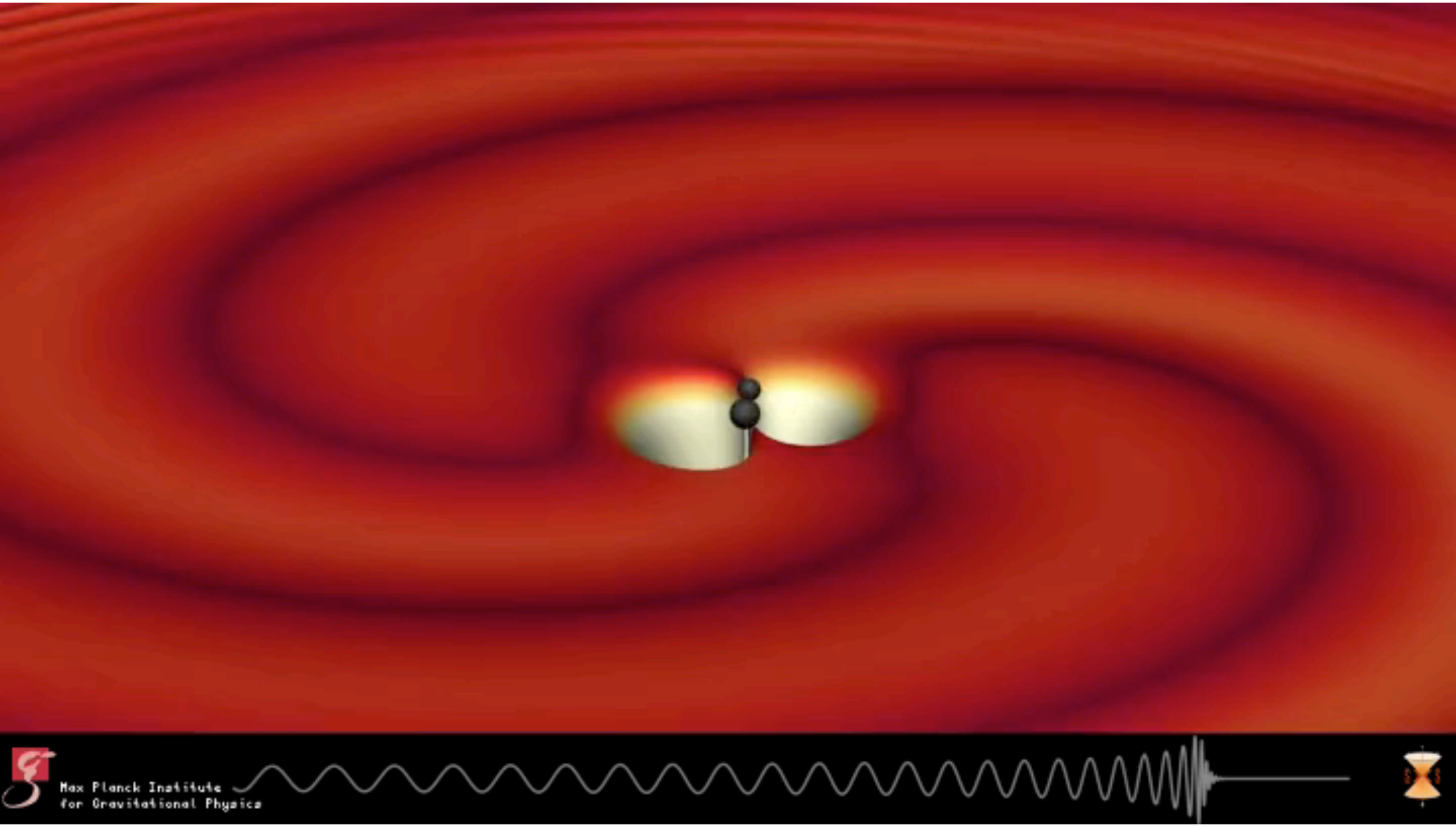
Directly:

1. In binary systems through their emission of gravitational waves



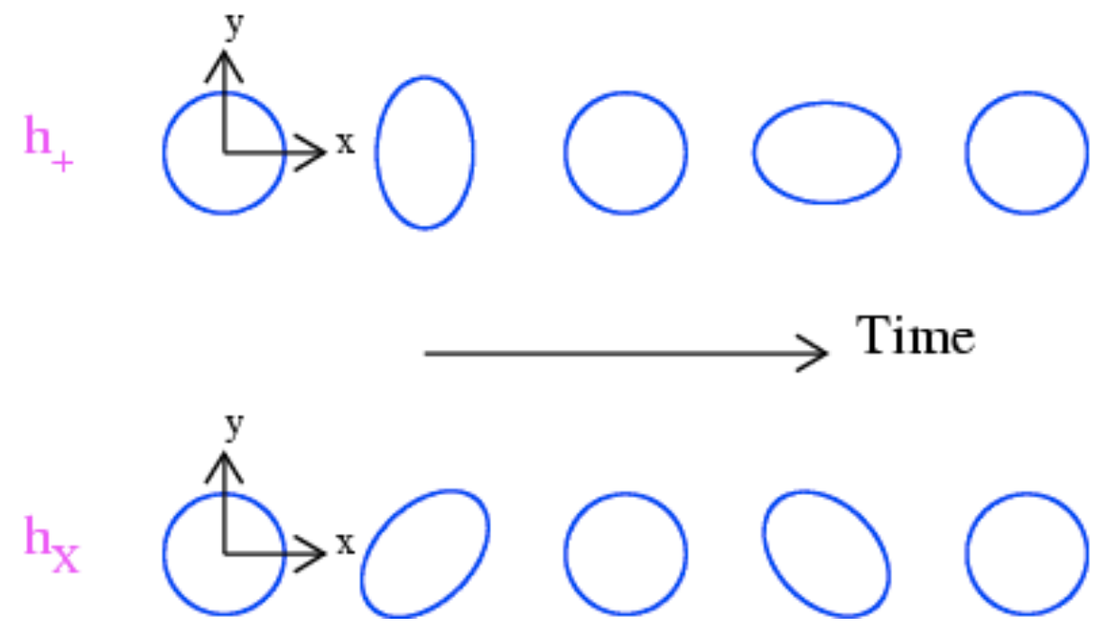
Gravitational Waves

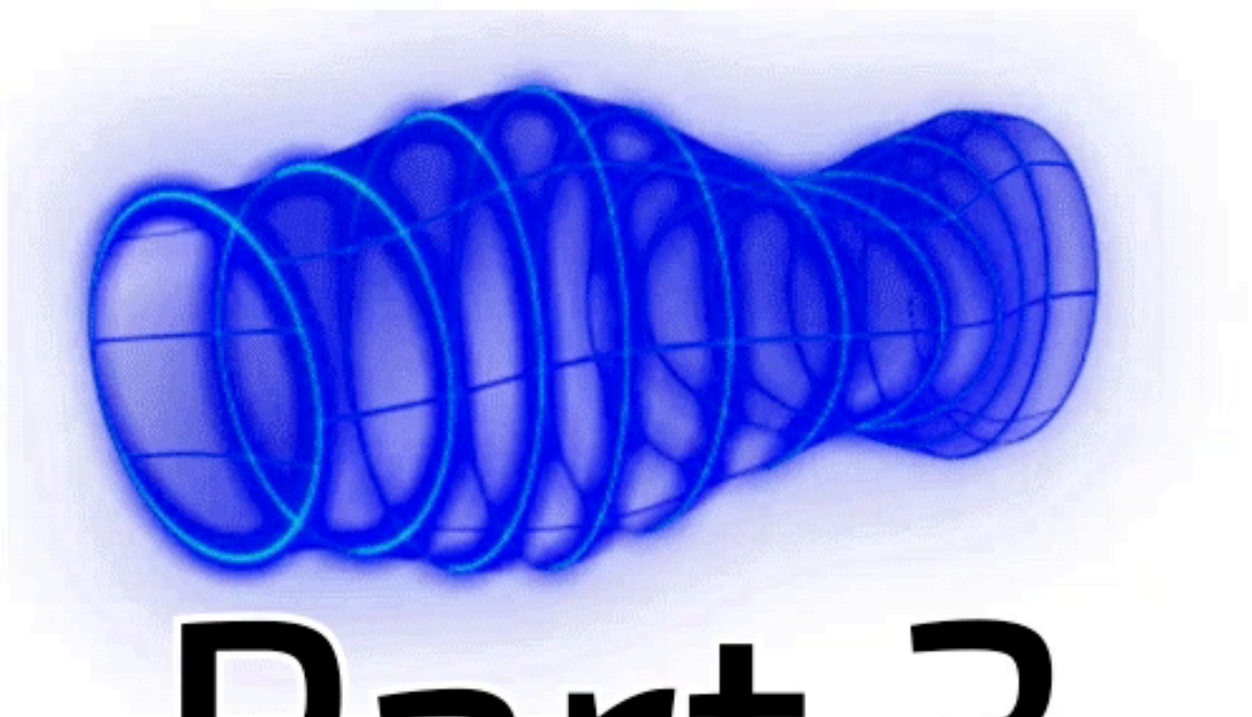


Gravitational Waves

What are GWs?

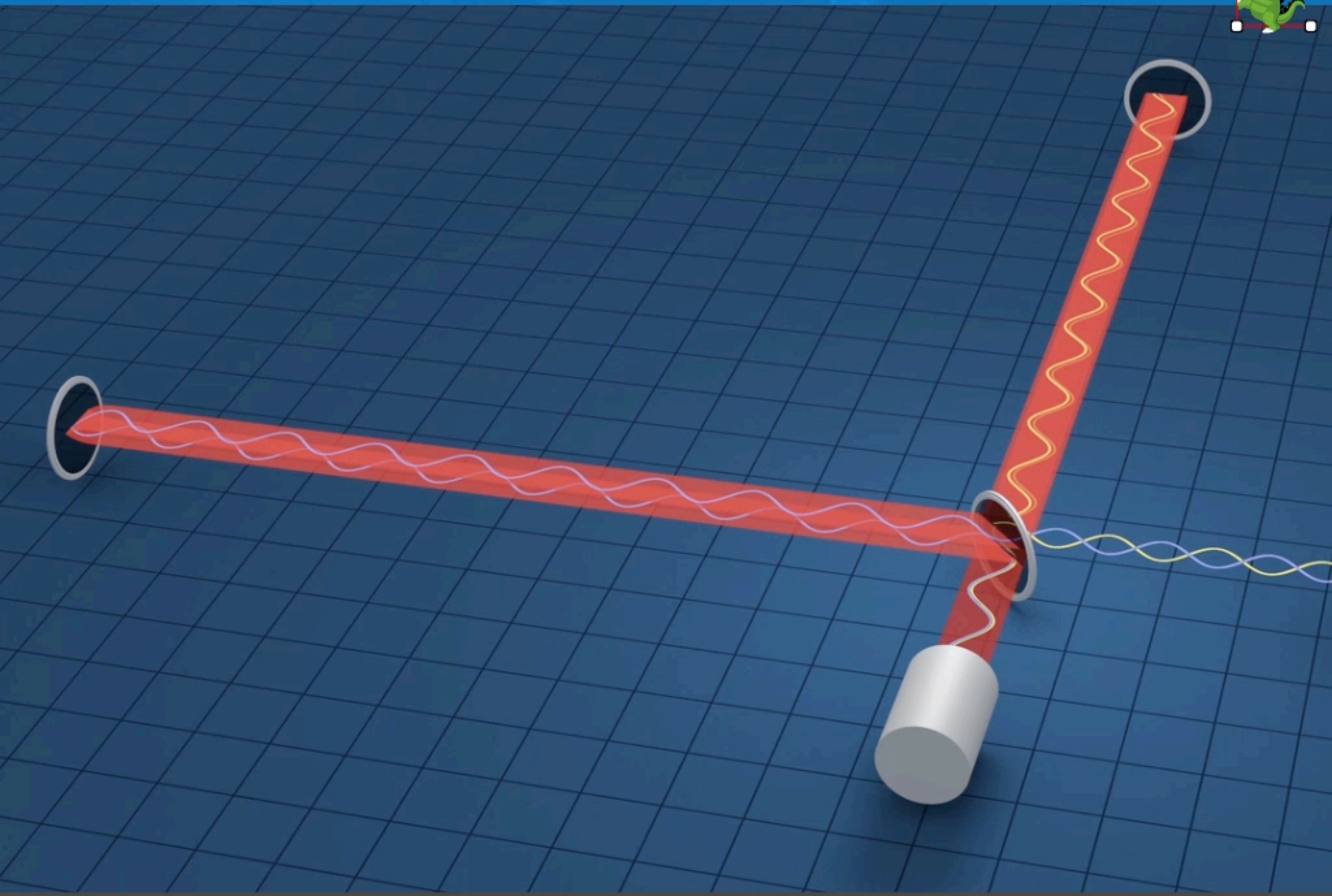
1. Strains of space time
   - Change distances
2. Propagate with c
3. Transversal
4. Two polarizations

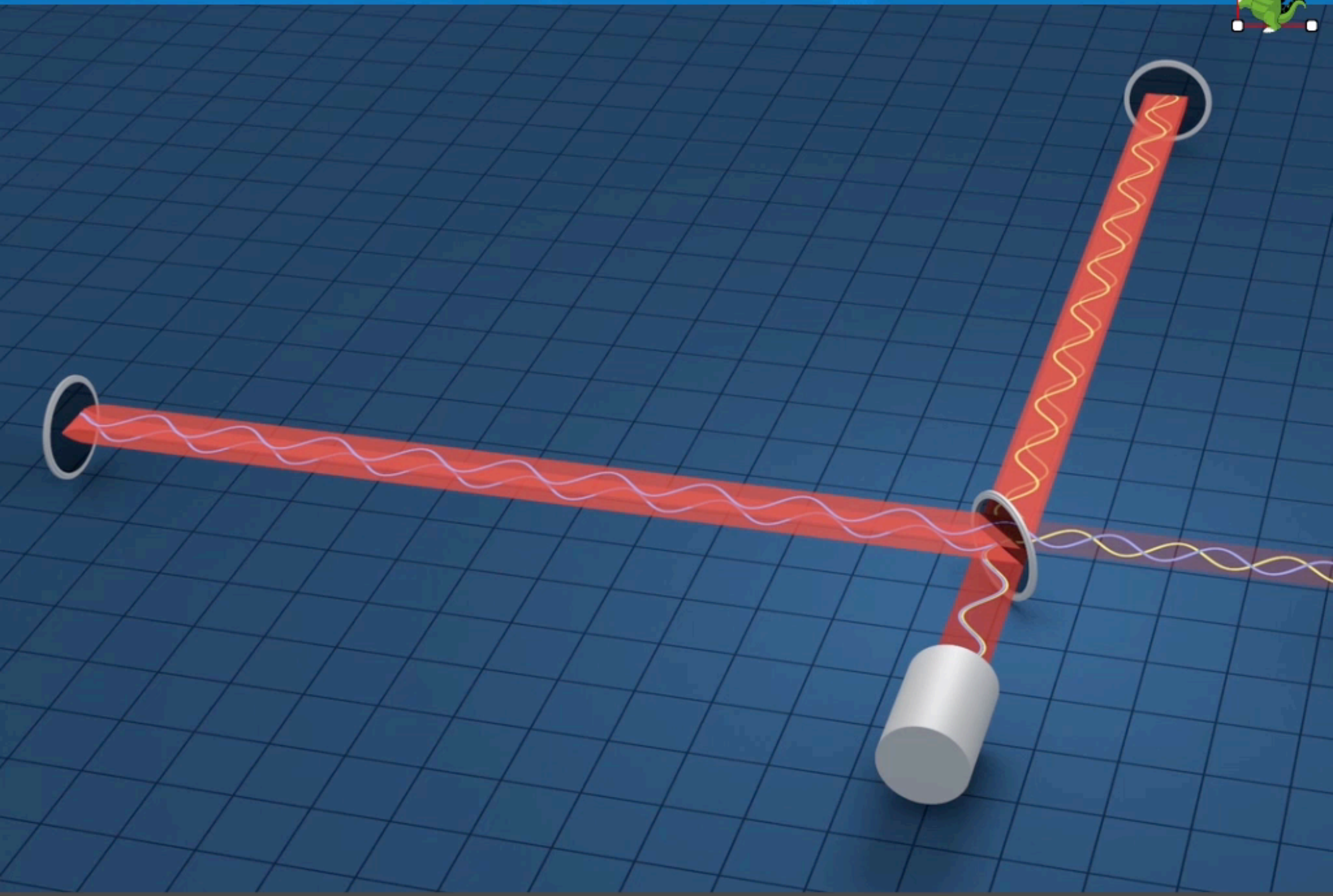




Part 3

THE FIRST DETECTION





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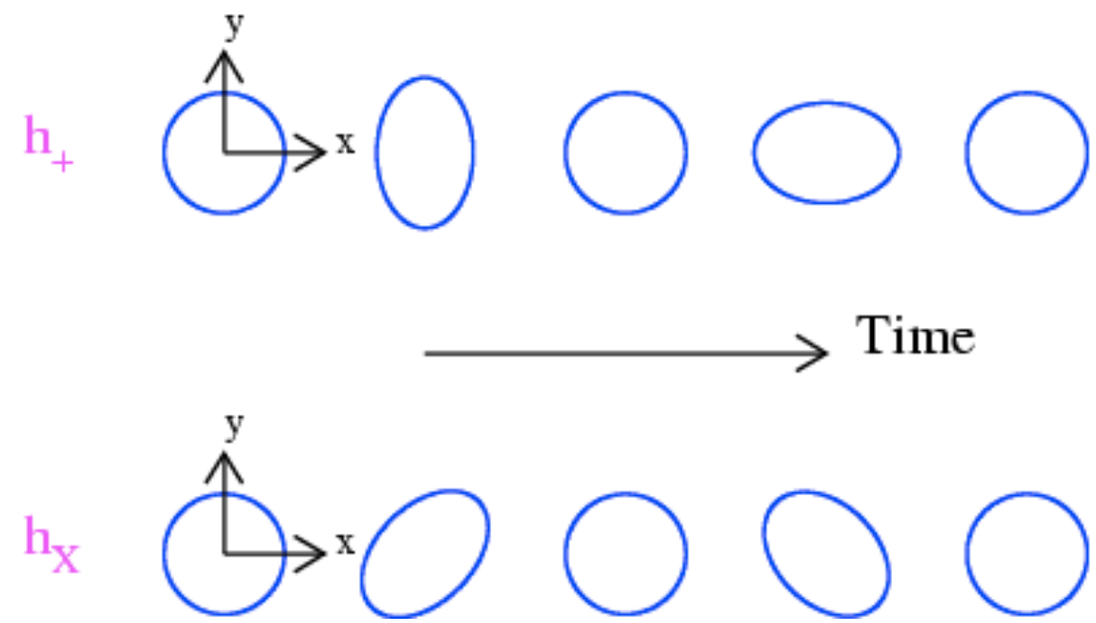


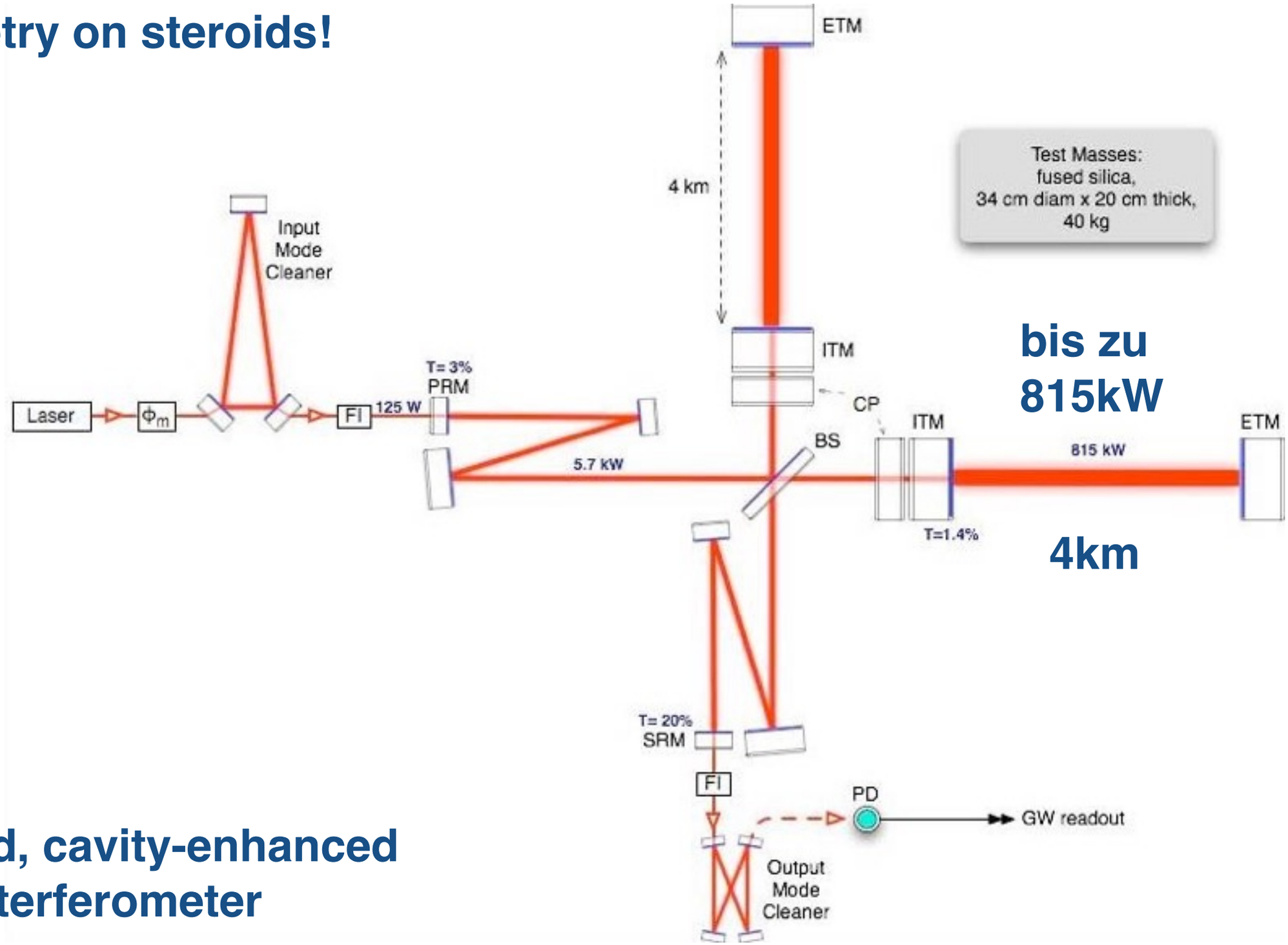
Problem:

$$h \approx 10^{-21}$$

Over 4km by 0.00000000000000004m

Advanced LIGO Design

Interferometry on steroids!



bis zu 815kW

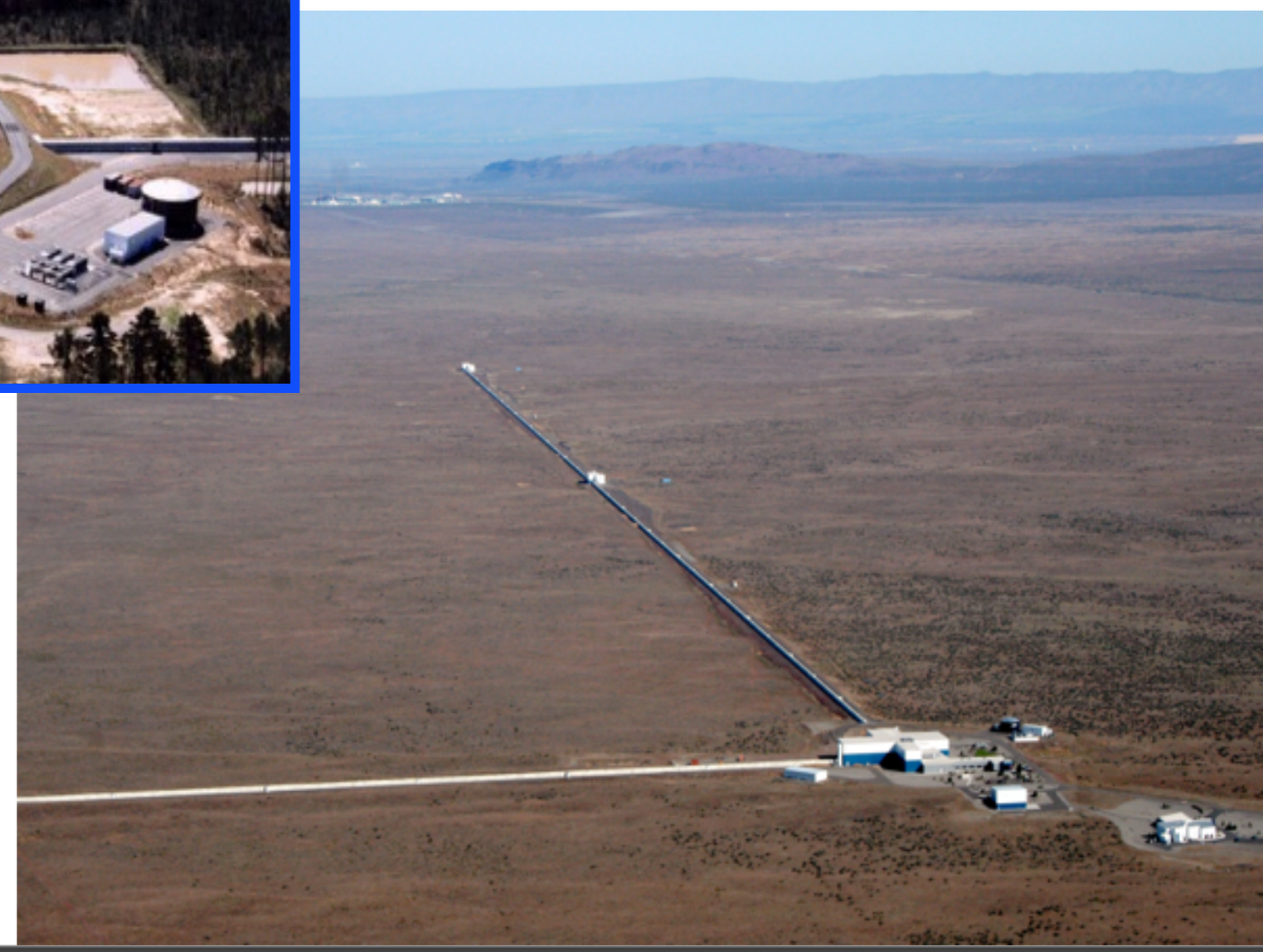
4km

Dual-recycled, cavity-enhanced Michelson interferometer

Advanced LIGO

LLO, Livingston, LA

LHO, Hanford, WA



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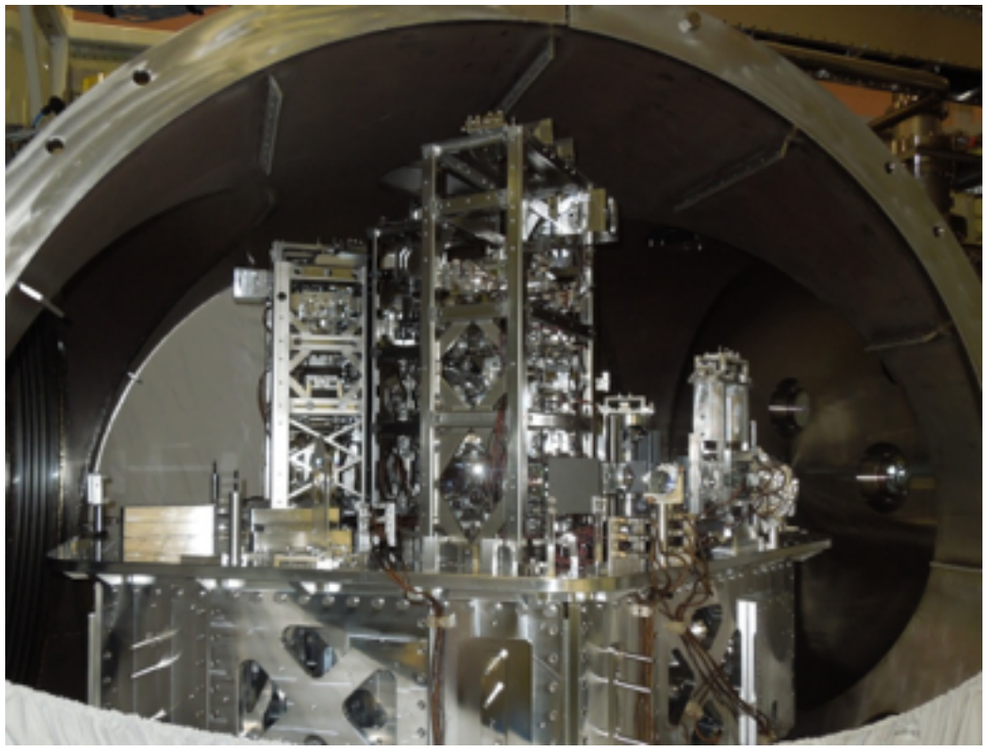
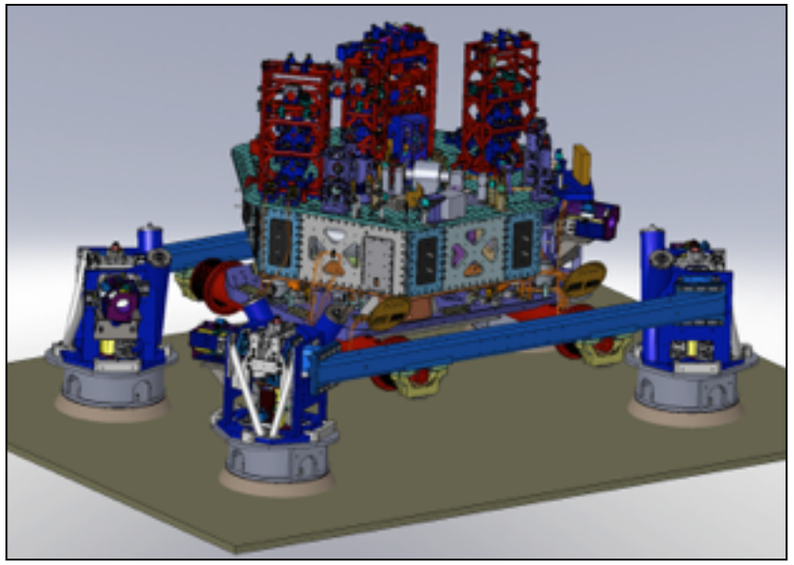
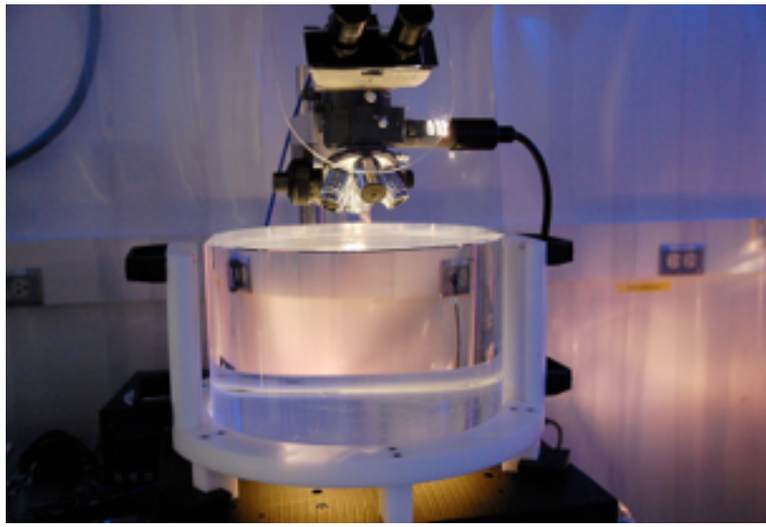




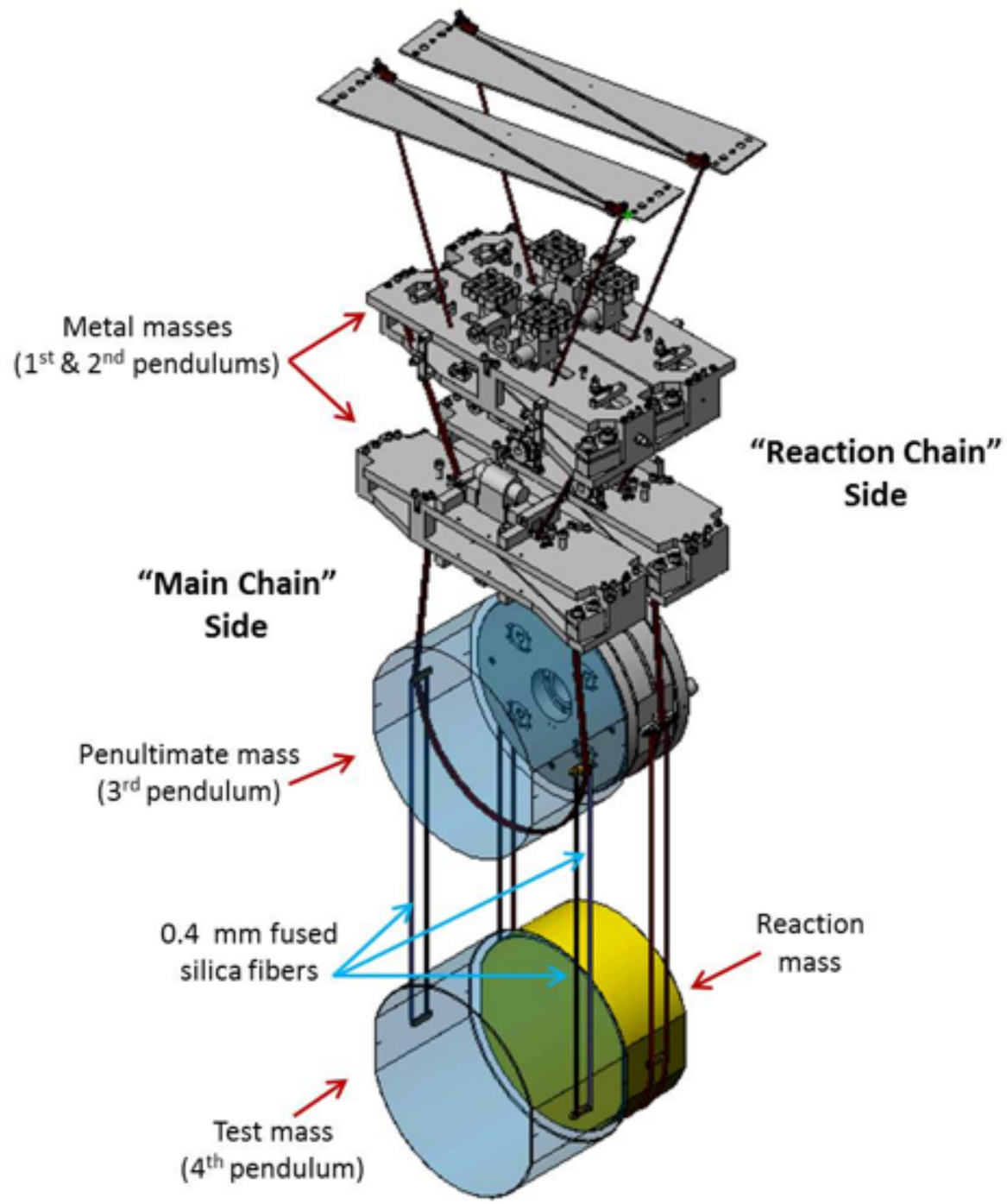


Gravitational Waves

Suspension system:

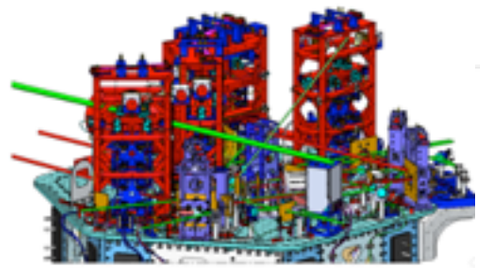
Combination of masses, pendula, and springs!

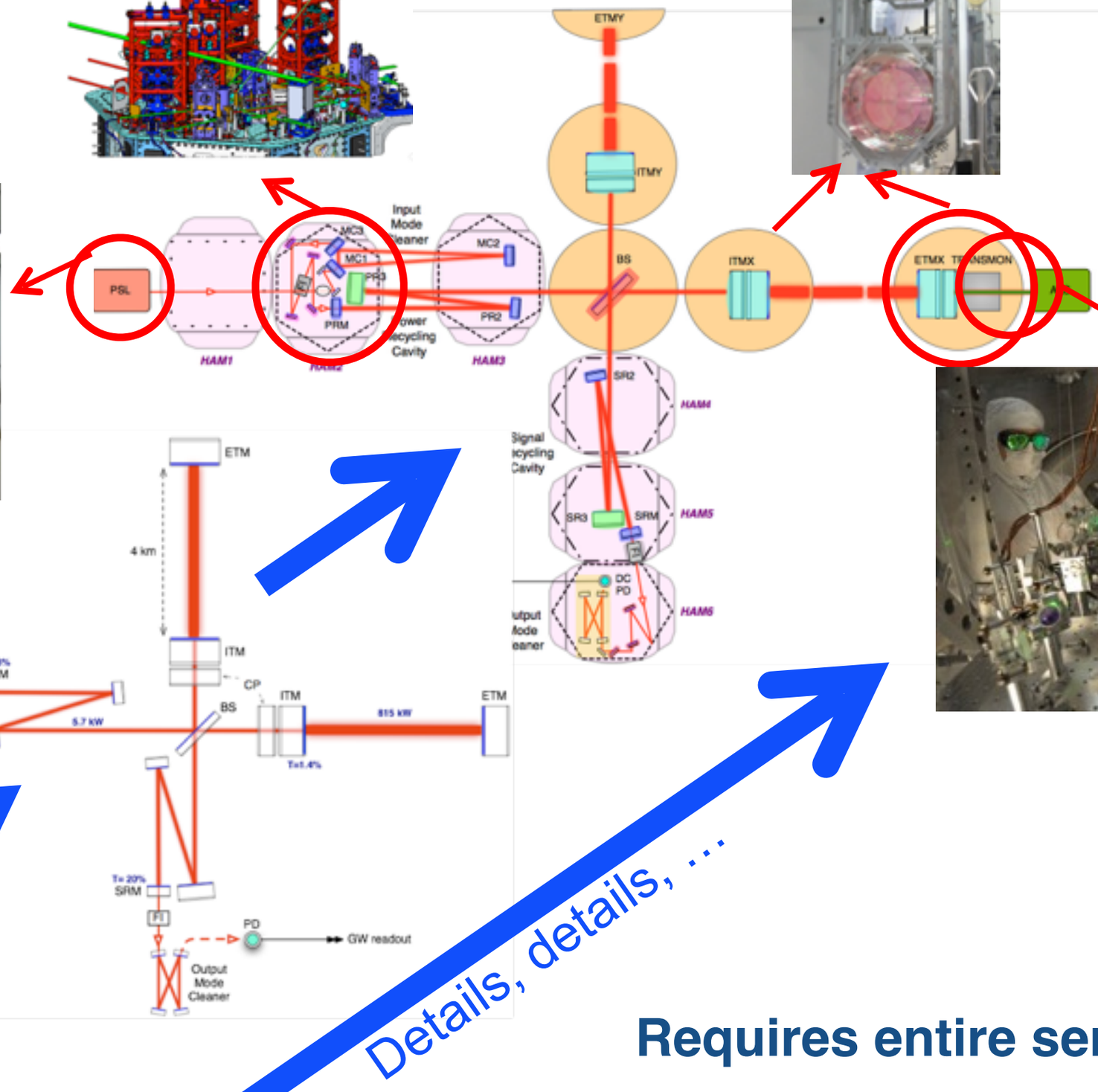
Isolates mirrors from ground-motion!

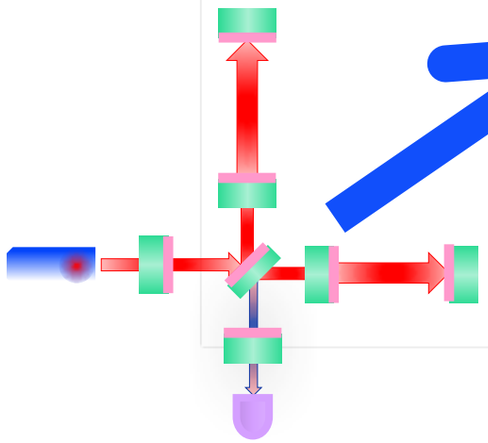


Advanced LIGO

Details how all of this works:





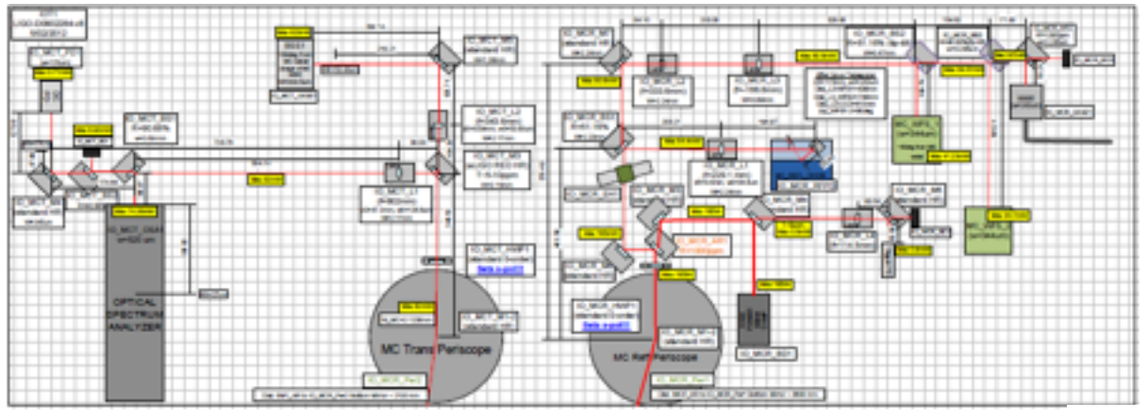


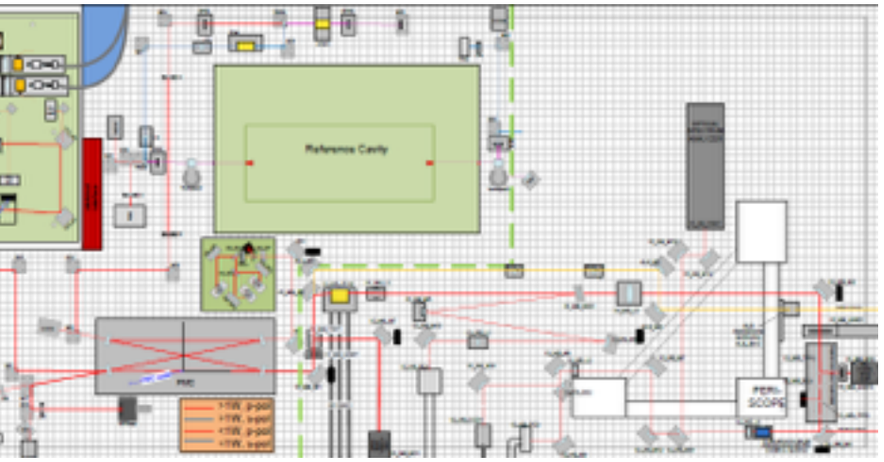
Details, details, …

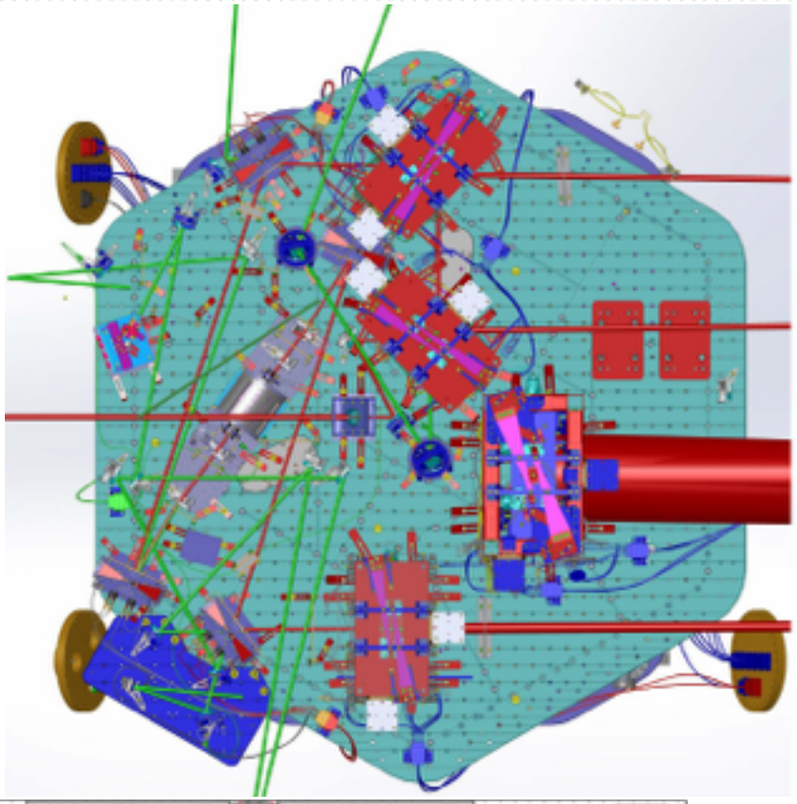
Requires entire semester …

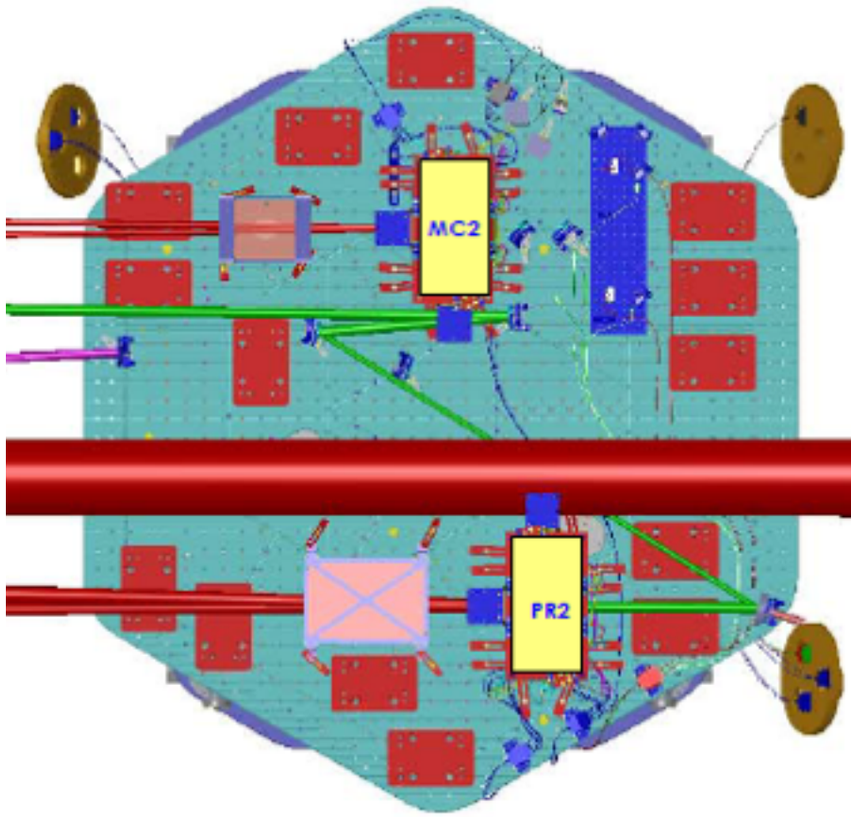
Advanced LIGO

Advanced LIGO Input Optics:

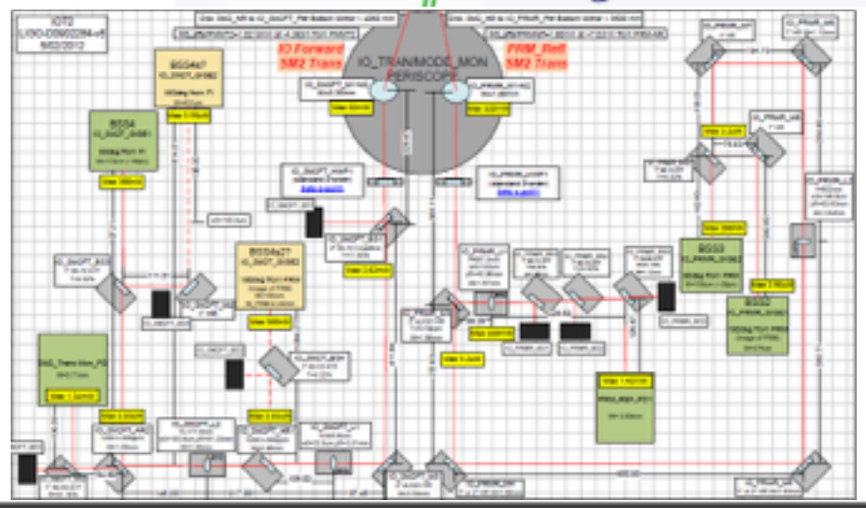








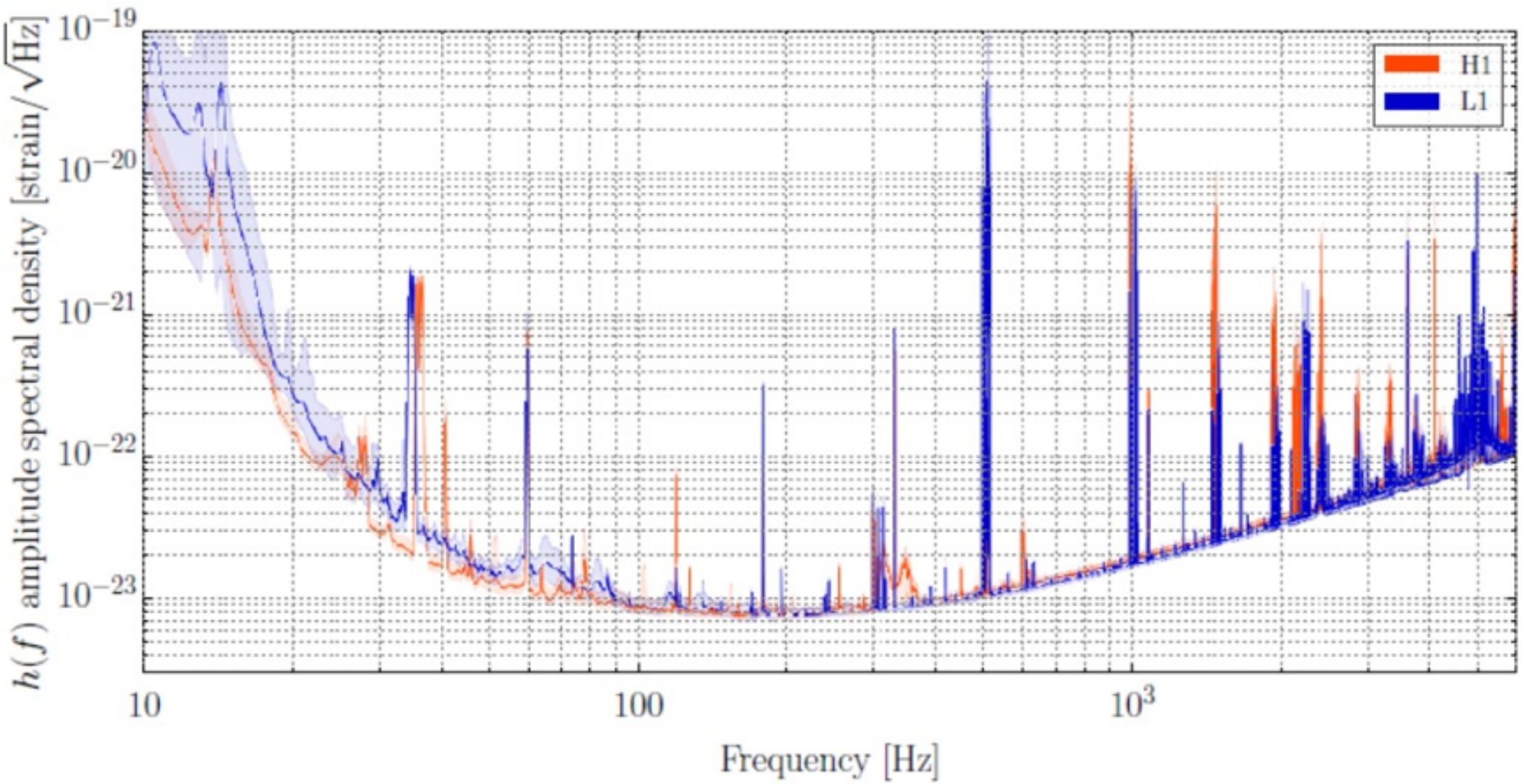
- Just to prepare the laser field



Advanced LIGO Performance O1

Sensitivity in Autumn 2015: Better than expected!

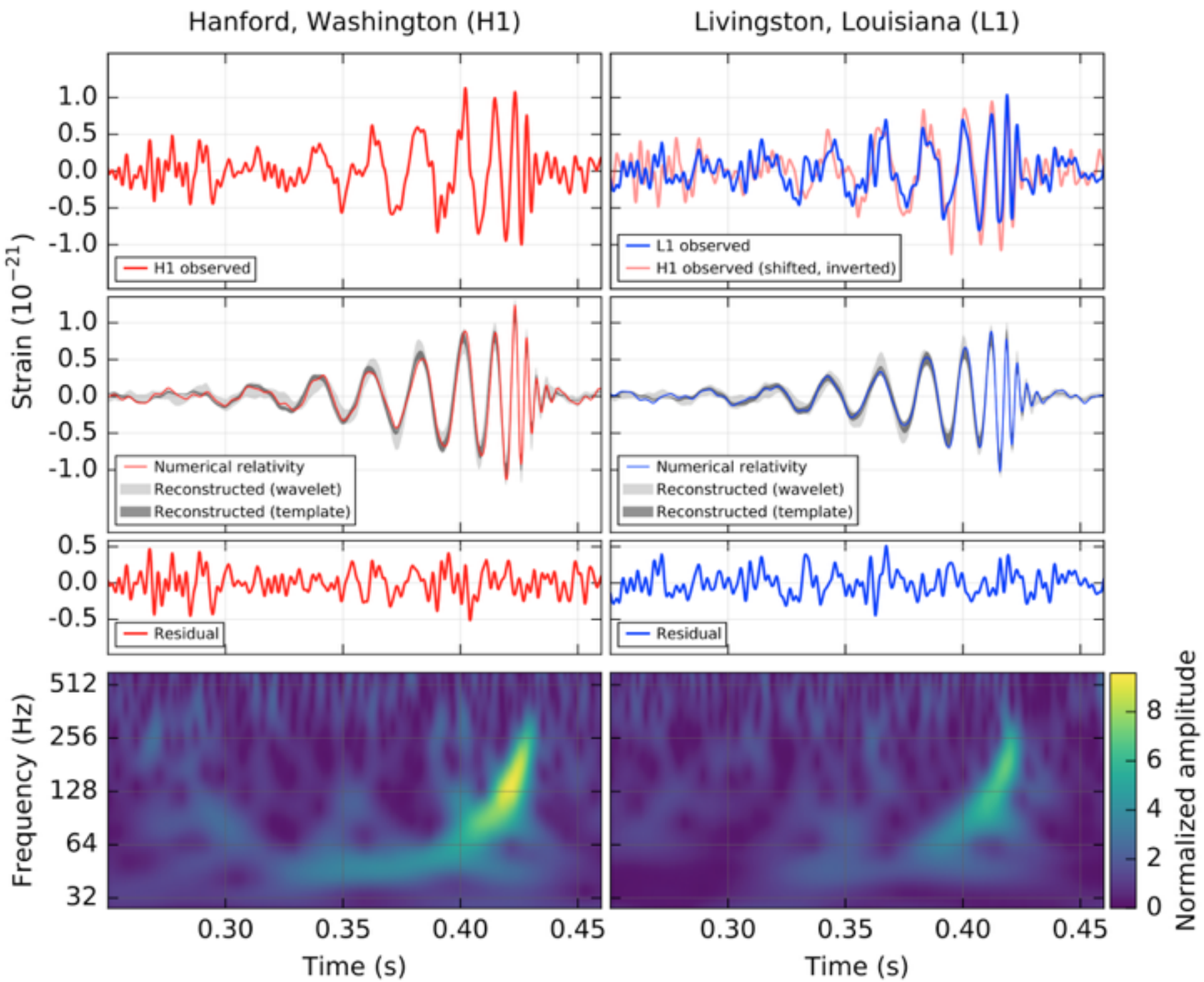
- 4×10^{-20} m/√Hz between 60 and 600Hz



1. Signal: 14 September 2015

GW150914:

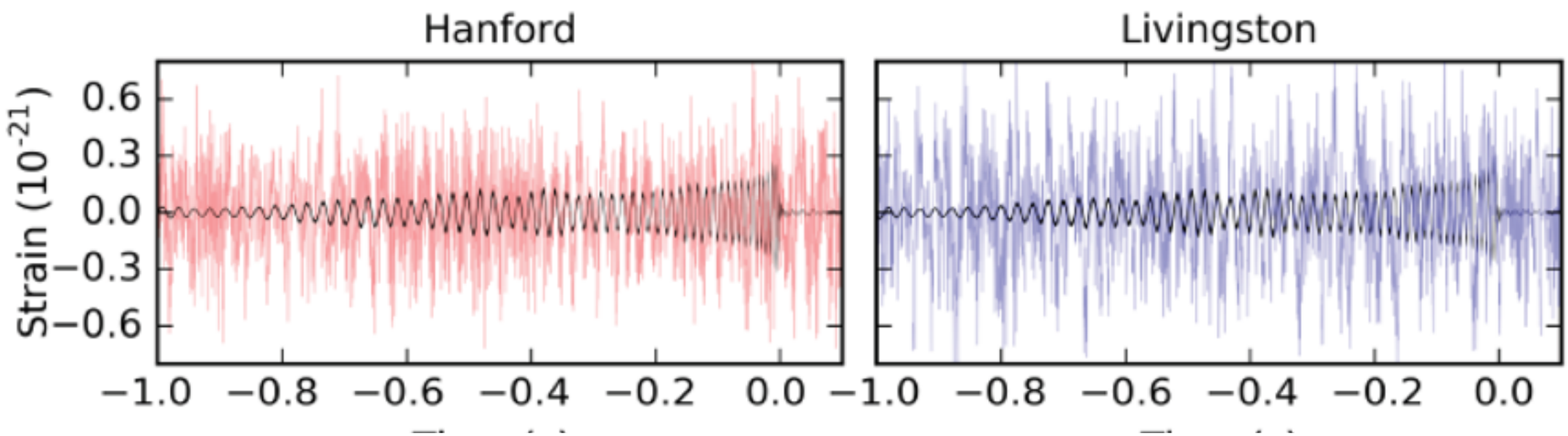
- high amplitude
- 300ms long
- 30-300Hz
- visible by eye



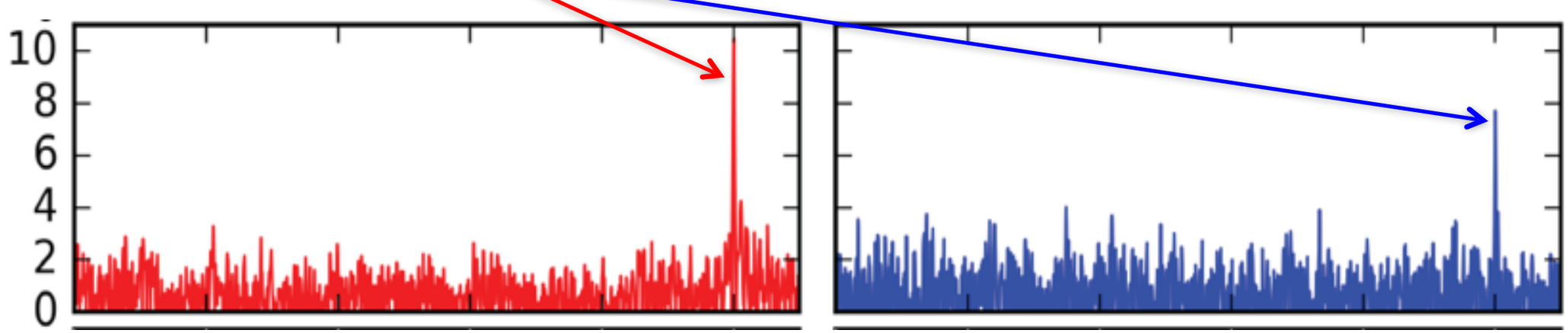
2. Signal: 26 Dezember 2015

GW151226:

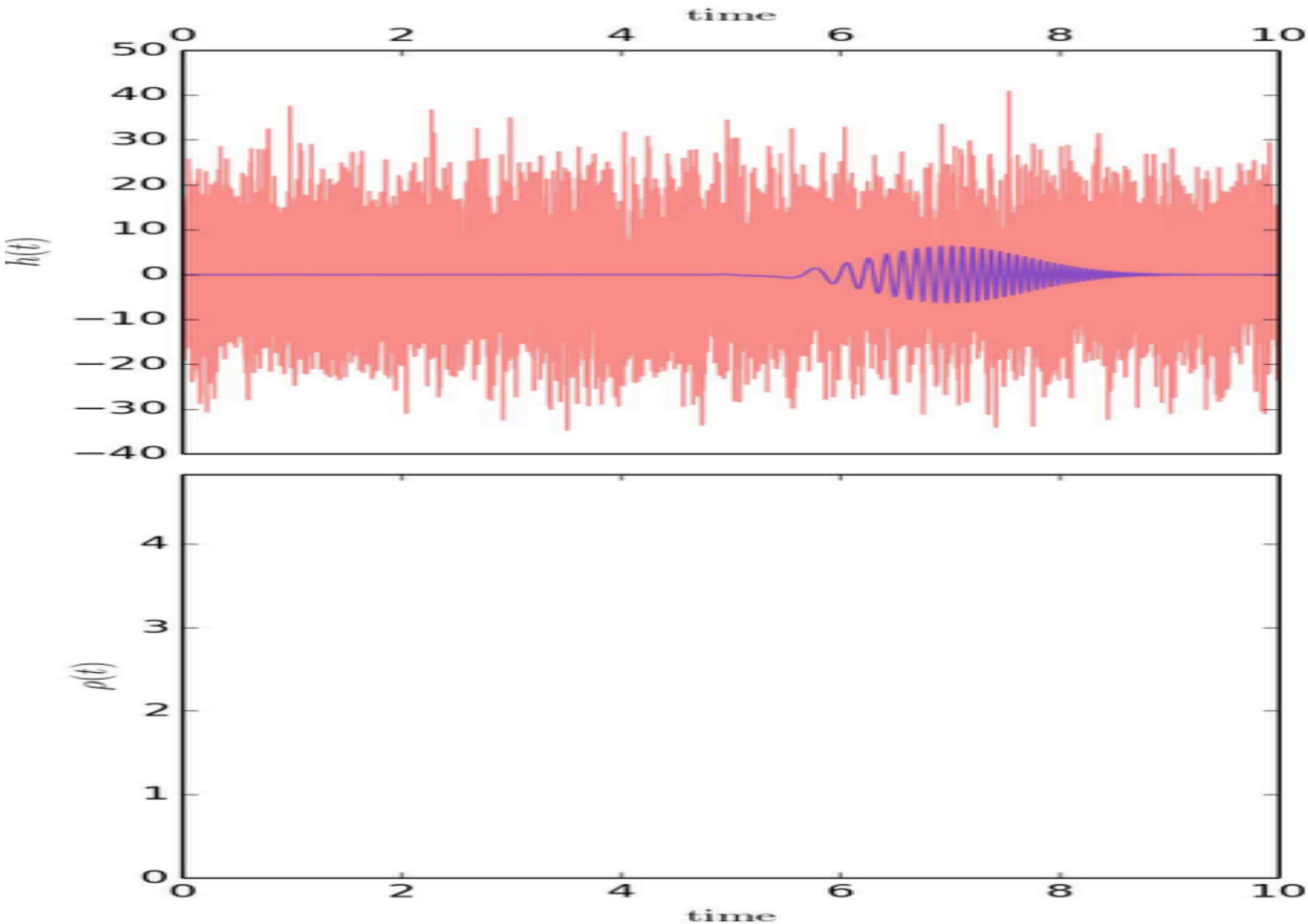
- lower amplitude
- 1s long
- 35-700Hz
- Template search



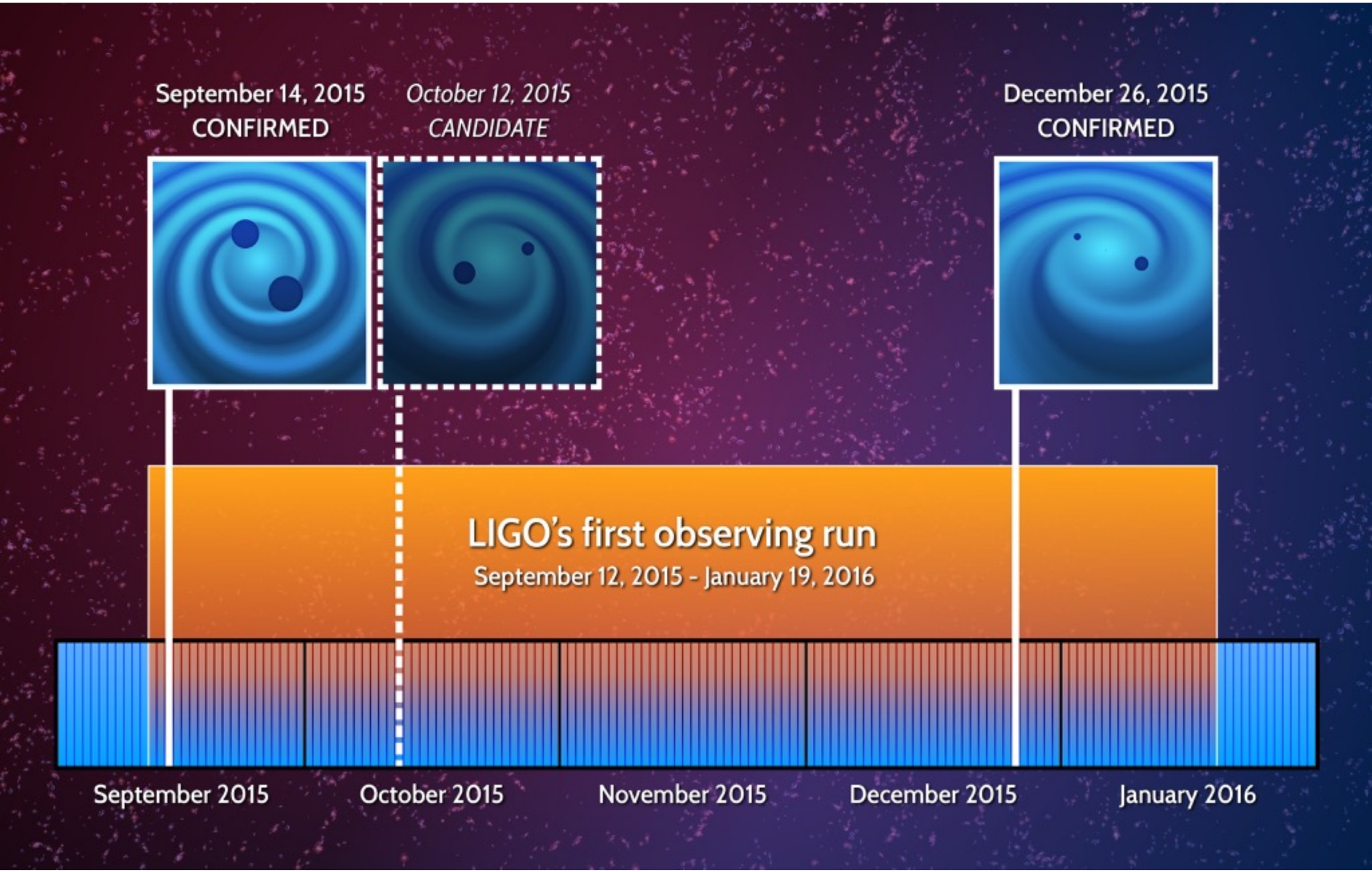
Signal-to-noise (SNR) when best template matches at



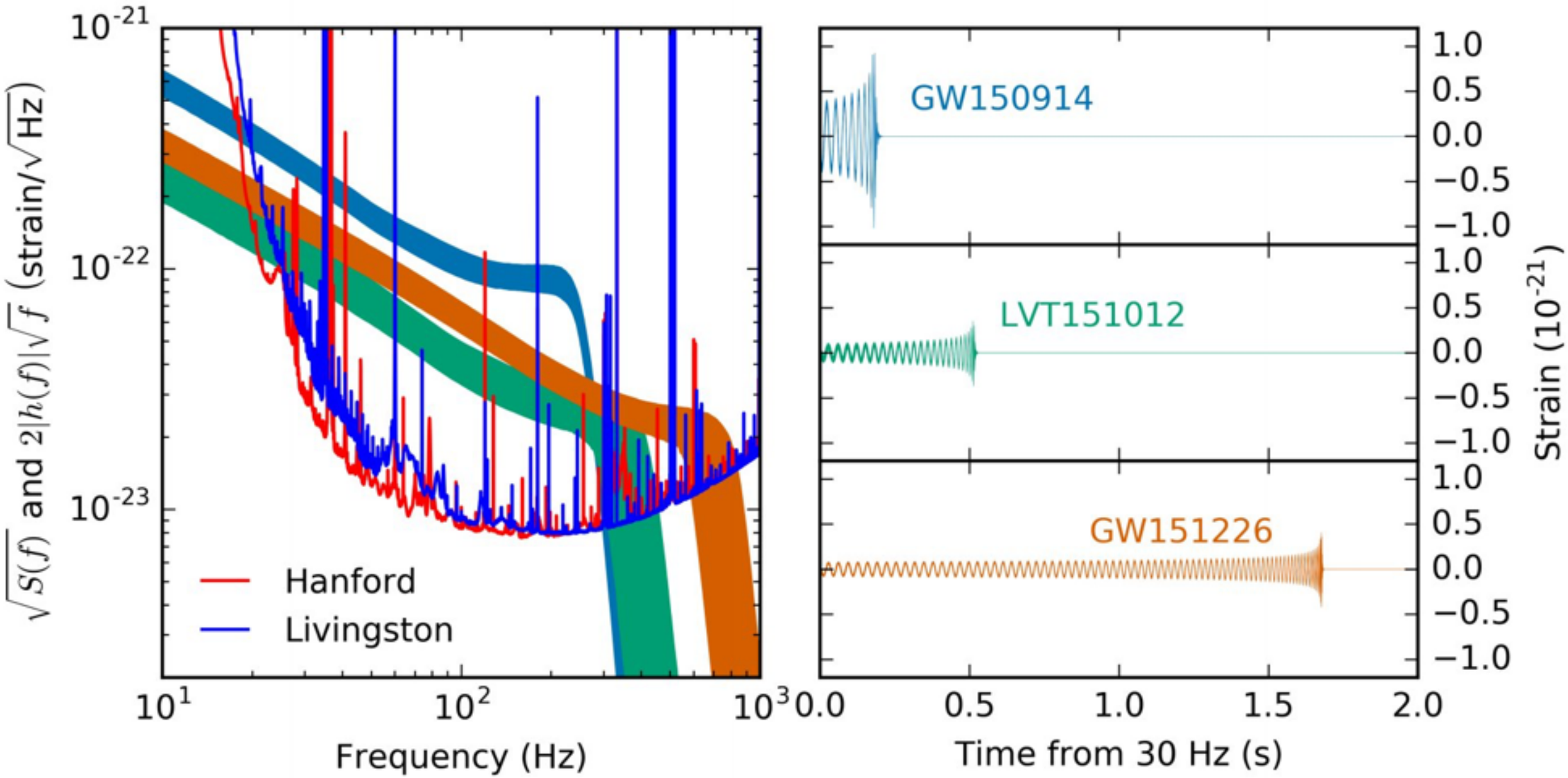
Template search



First Science Run: 2.98 Signals



First Science Run: 2.98 Signals

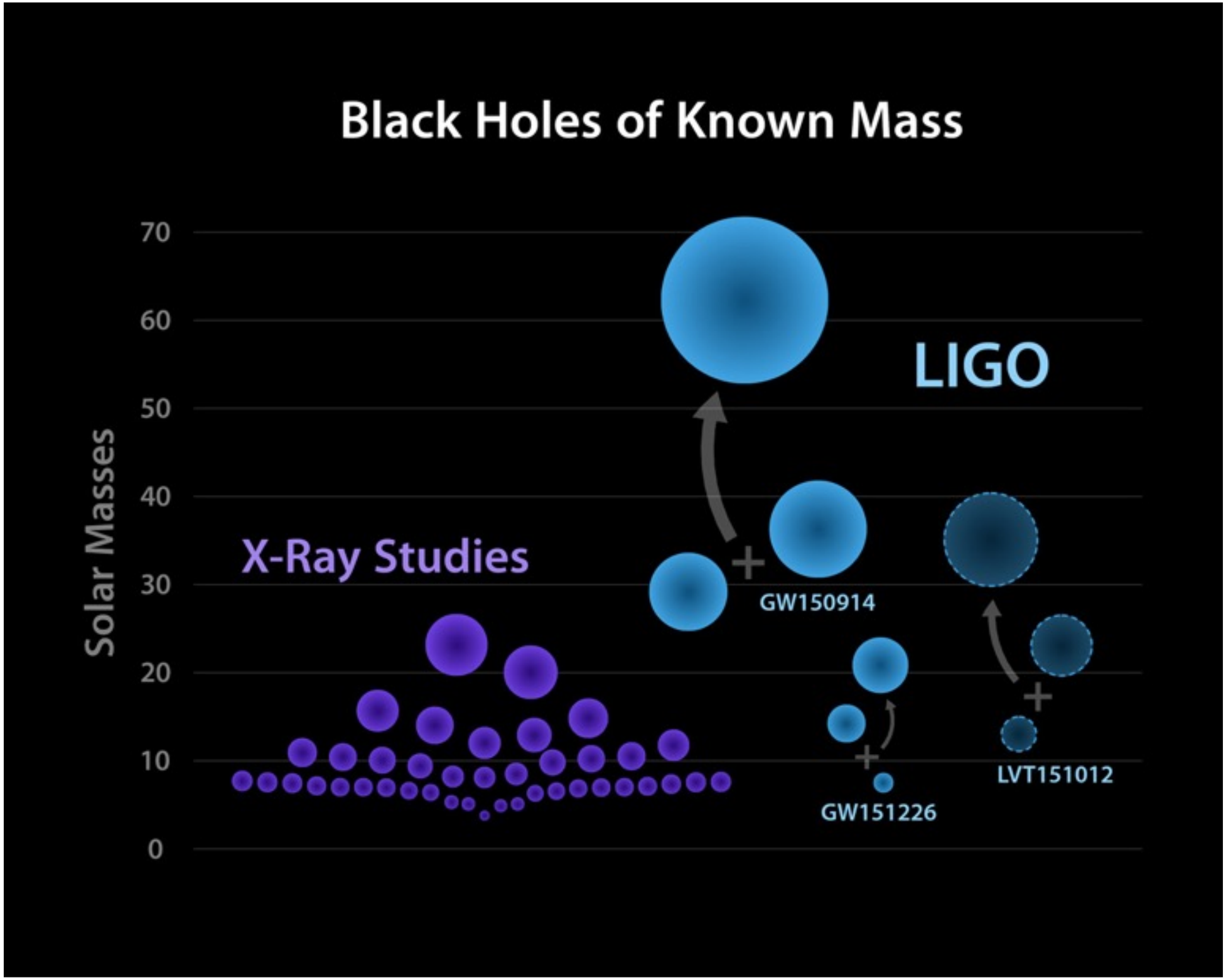


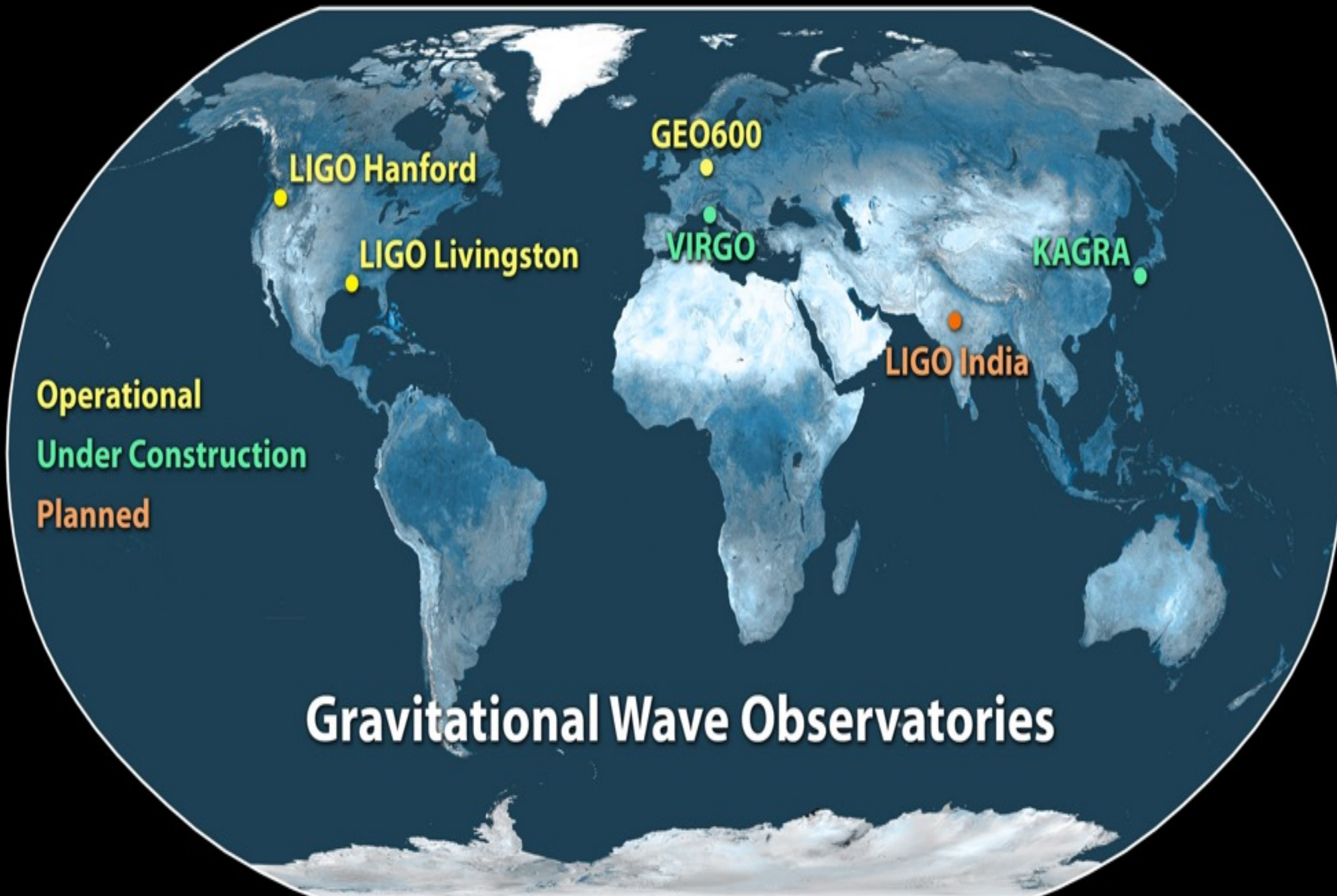
Little Black Holes

wikipedia + LIGO:

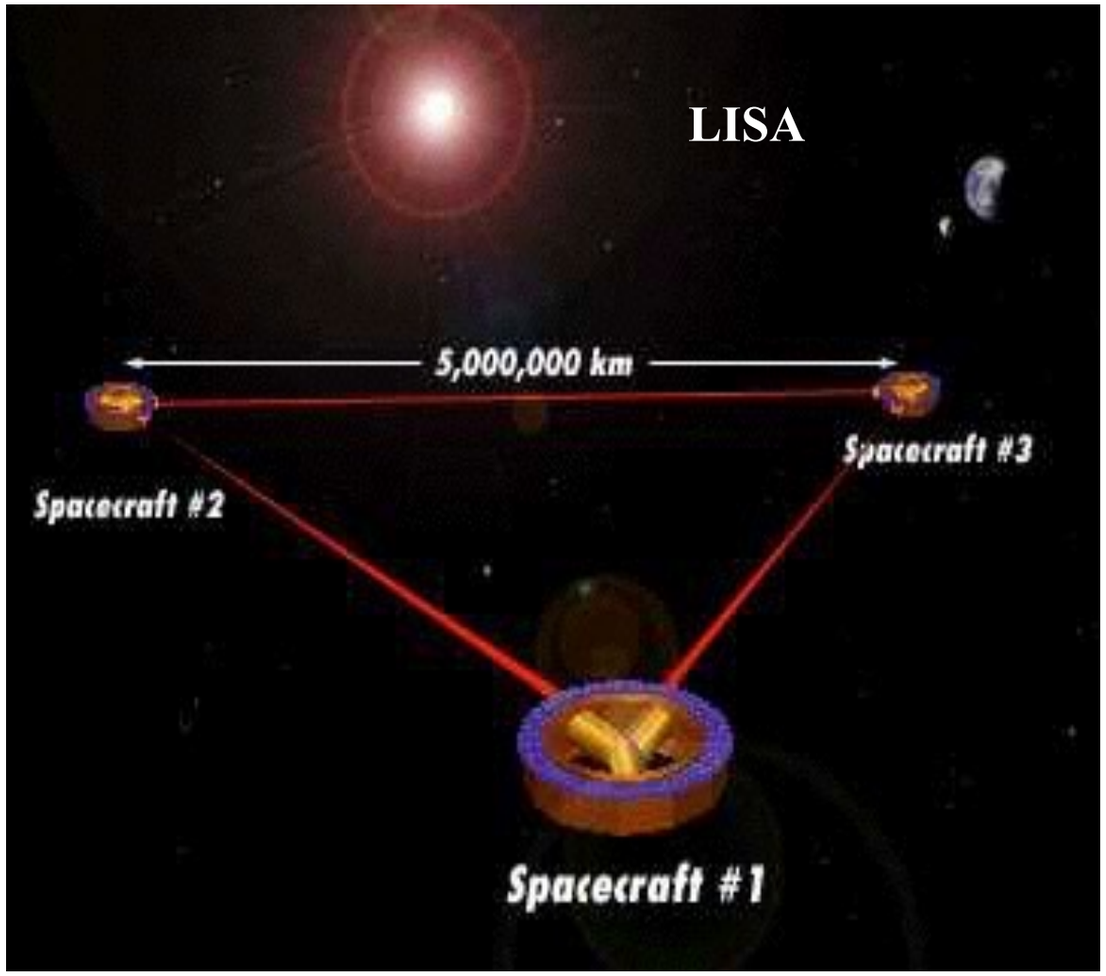
Name	BHC Mass (solar masses)	Companion Mass (solar masses)	Orbital period (days)	Distance from Earth (light years)	Location [14]
A0620-00/V616 Mon	11 ± 2	2.6–2.8	0.33	about 3500	06:22:44 -00:20:45
GRO J1655-40/V1033 Sco	6.3 ± 0.3	2.6–2.8	2.8	5000–11000	16:54:00 -39:50:45
XTE J1118+480/KV UMa	6.8 ± 0.4	6–6.5	0.17	about 6200	11:18:11 +48:02:13
Cyg X-1	11 ± 2	≥18	5.6	6000–8000	19:58:22 +35:12:06
GRO J0422+32/V518 Per	4 ± 1	1.1	0.21	about 8500	04:21:43 +32:54:27
GRO J1719-24	≥4.9	~1.6	possibly 0.6[15]	about 8500	17:19:37 -25:01:03
GS 2000+25/QZ Vul	7.5 ± 0.3	4.9–5.1	0.35	about 8800	20:02:50 +25:14:11
V404 Cyg	12 ± 2	6.0	6.5	7800±460[16]	20:24:04 +33:52:03
GX 339-4/V821 Ara		5–6	1.75	about 15000	17:02:50 -48:47:23
GRS 1124-683/GU Mus	7.0 ± 0.6		0.43	about 17000	11:26:27 -68:40:32
XTE J1550-564/V381 Nor	9.6 ± 1.2	6.0–7.5	1.5	about 17000	15:50:59 -56:28:36
4U 1543-475/IL Lupi	9.4 ± 1.0	0.25	1.1	about 24000	15:47:09 -47:40:10
XTE J1819-254/V4641 Sgr	7.1 ± 0.3	5–8	2.82	24000 – 40000[17]	18:19:22 -25:24:25
GRS 1915+105/V1487 Aql	14 ± 4.0	~1	33.5	about 40000	19:15;12 +10:56:44
XTE J1650-500	9.7 ± 1.6 [18]	.	0.32[19]		16:50:01 -49:57:45
GW150914 (62 ± 4)$M_\odot$	**36 ± 4**	**29 ± 4**	**Merger**	**1.3 billion light years**	
GW151226 (21 ± 4)$M_\odot$	**14 ± 6**	**8 ± 2**	**Merger**	**1.3 billion light years**	
LVT151012 (~35)$M_\odot$	**~23**	**~13**	**Merger**	**3.5 billion light years**	

The new catalogue:

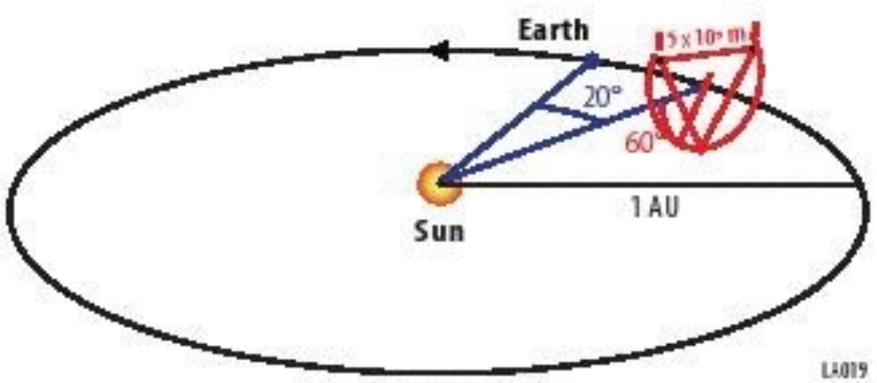


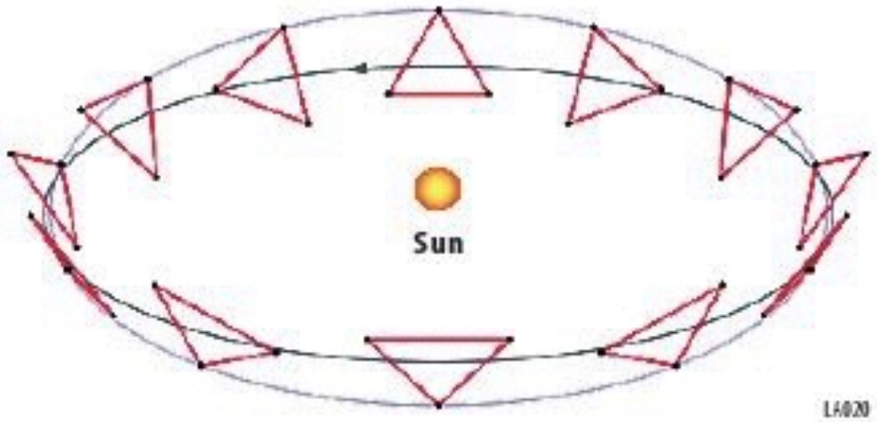

GEO600
LIGO Hanford
LIGO Livingston
VIRGO
KAGRA
LIGO India
Operational
Under Construction
Planned
Gravitational Wave Observatories

LISA



- ESA mission
  - NASA: Junior partner
- Laser interferometry
- Mergers between 10.000 - 100.000.000 SM black holes
- ~100.000 compact binary systems in Milkyway
- Launch: ~2033/34





Summary

'Wrap-Up'

- GW
  - expected to exist since Newton
  - predicted by Einstein
  - finally measured
- Black Holes
  - Known since Einstein/Schwarzschild (1917)
  - Controversial at least until the 1960s
  - Discovered first small black holes outside MW
  - Heaviest of solar mass type BHs
  - First observed merger between BHs
  - Largest energy release ever measured
- New observational method, new window to the universe
- …