Present and Near Future Gravitational Wave Observatories

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Instituto Nacional de Pesquisas Espaciais
pelas Colaborações LIGO (GWINPE- LSC) e Virgo

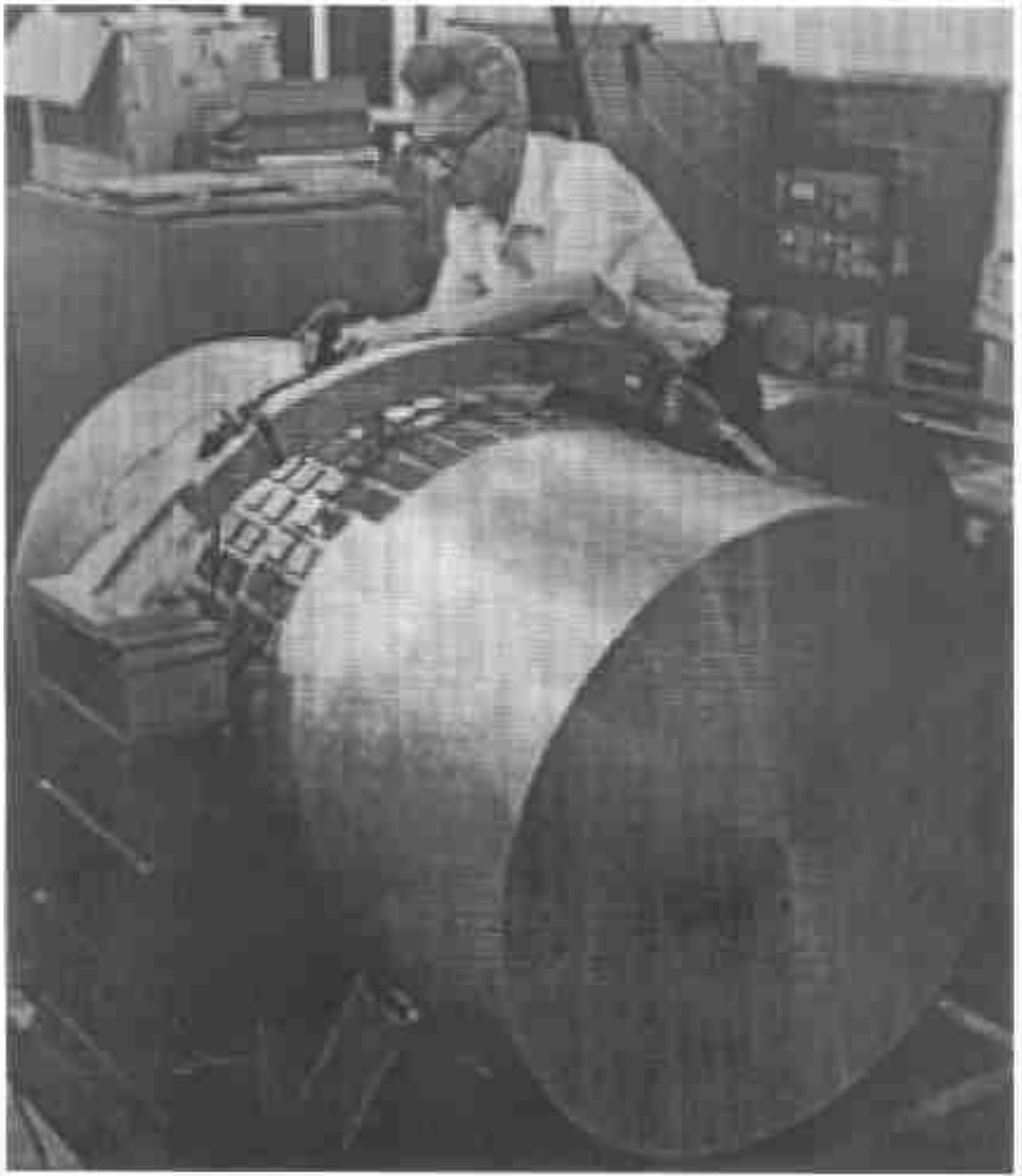
Joseph Weber

1ª geration

Cilíndrico

~ temp. ambiente

$h \sim 10^{-15}$



LSU (ALLEGRO)

2ª geração

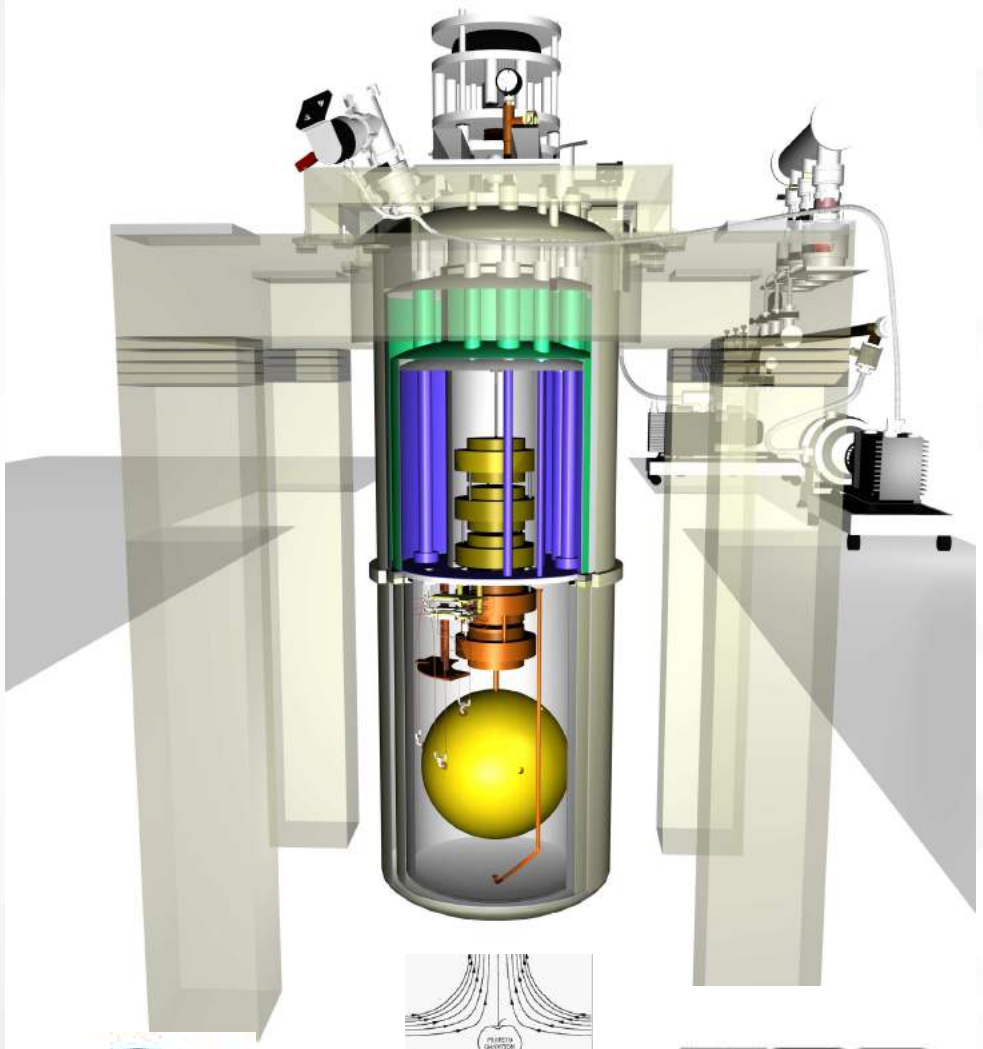
Cilíndrico
- 269 ºC

$h \sim 5 \times 10^{-19}$

http://www.phys.lsu.edu/

Mario Schenberg, Brazil (FAPESP)

MiniGRAIL Netherlands



GRAVITON GROUP

O Detector do Ondas Gravitationais

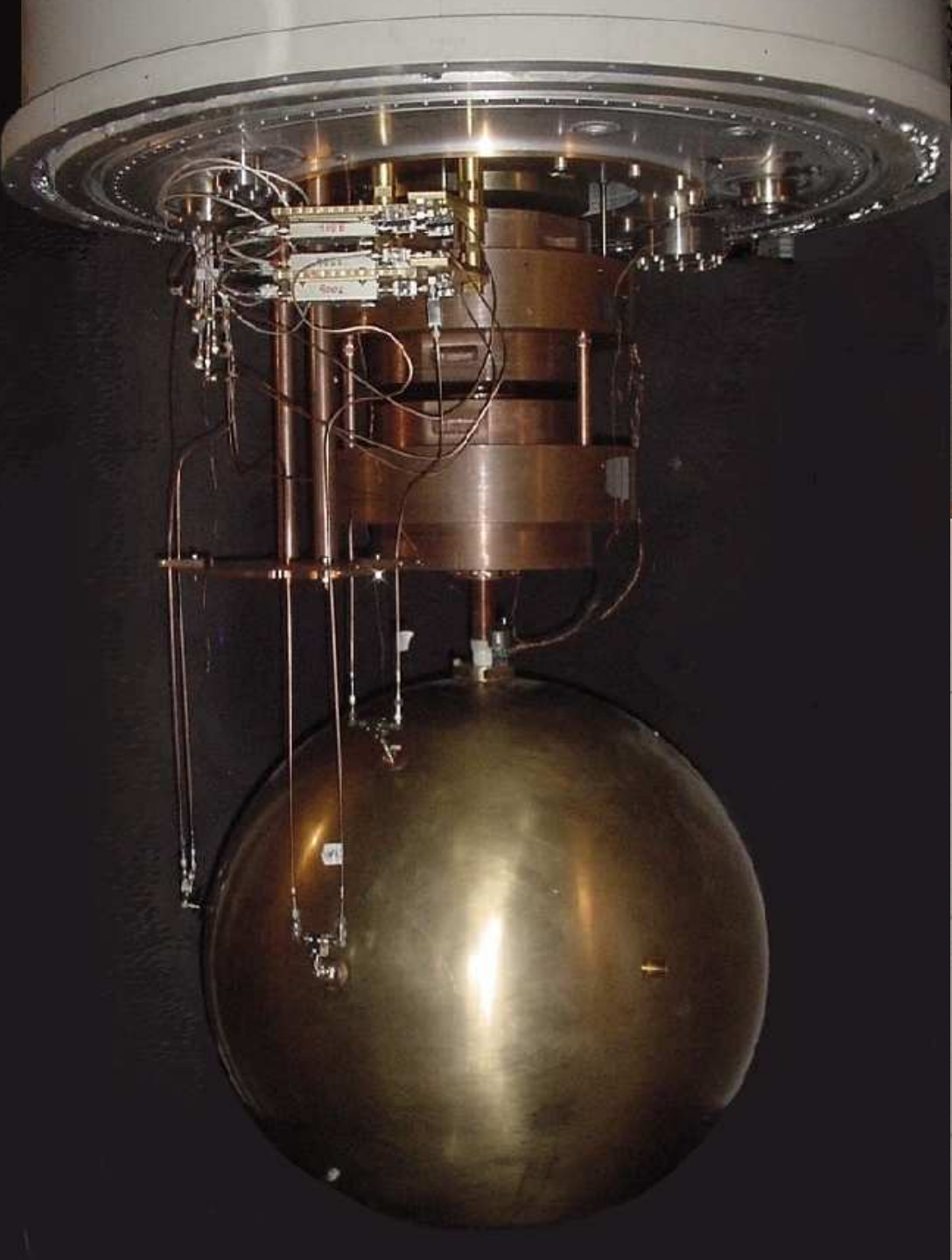
Mario SCHENBERG

iniciou operação comissionada em 8 de Setembro de 2006.

Ele envolve uma colaboração entre o

INPE, USP, ITA, IFSP, UNIFESP, UNESP, UNICAMP, UESC, IAE, UFABC, PUC-Rio, UNIPAMPA, CBPF Leiden Cryogenics, UWA, LSU, OCA,

e vem sendo apoiado pela




The antenna at its Sao Paulo city site
for the 2015 runs
h ~ 10-20 Hz-1/2

https://gravitationalwaveastronomy.org

GW Projects

LIGO
https://www.ligo.org
https://www.ligo.caltech.edu
Virgo
https://www.virgo-gw.eu
GEO600
https://www.geo600.org
KAGRA
https://gwcenter.icrr.u-tokyo.ac.jp/en/
LIGO India
https://www.ligo-india.in
ET - The Einstein Telescope
http://www.et-gw.eu
CE - Cosmic Explorer
https://cosmicexplorer.org
LISA
https://www.elisascience.org
DECIGO
http://tamago.mtk.nao.ac.jp/spacetime/decigo_e.html
BBO - Big Bang Observer
https://en.wikipedia.org/wiki/Big_Bang_Observer
IPTA - International Pulsar Timing Array
http://ipta4gw.org

EPTA - European Pulsar Timing Array
http://http//www.epta.eu.org/
NANOGrav - North American Nanohertz Observatory for Gravitational Waves
http://nanograv.org/
Indian Pulsar Timing Array Project
https://inpta.gitlab.io/profile/index.html
PPTA - Parkes Pulsar Timing Array
http://www.atnf.csiro.au/research/pulsar/ppta/
OzGrav
https://www.ozgrav.org
TianQin
https://en.wikipedia.org/wiki/TianQin
Taiji Program in Space
https://en.wikipedia.org/wiki/Taiji_Program_in_Space
BICEP and Keck Array
https://en.wikipedia.org/wiki/BICEP_and_Keck_Array
POLARBEAR - POLARization of the Background Radiation
https://en.wikipedia.org/wiki/POLARBEAR
Mario Schenberg
https://en.wikipedia.org/wiki/Mario_Schenberg_(Gravitational_Wave_Detector)

Other Important Links
GWIC - Gravitational Wave International Committee
https://gwic.ligo.org

Other GW Projects
AMIGO - Astrodynamical middle-frequency interferometric gravitational wave observatory https://arxiv.org/abs/1909.04995
Lunar Gravitational-Wave Antenna https://arxiv.org/abs/2010.13726 https://iopscience.iop.org/article/10.3847/1538-4357/abe5a7
Gravitational-wave Lunar Observatory for Cosmology https://iopscience.iop.org/article/10.1088/1475-7516/2021/06/044/meta
Bose-Einstein Condensates for Gravitational Wave Detection https://arxiv.org/pdf/2101.05051.pdf
MIGO - the Matter-wave Interferometric Gravitational-wave Observatory https://arxiv.org/abs/gr-qc/0312096
E-TEST https://www.etest-emr.eu

Videos
Gravitational Waves Explained https://www.youtube.com/watch?v=4GbWfNHtHRg
The Future of Gravitational Wave Astronomy https://www.youtube.com/watch?v=jKrOy4mC4wg

Lectures
School on Gravitational Waves: from data to theory and back https://www.ictp-saifr.org/school-on-gravitational-waves/

Tutorials
Gravitational Wave Open Science Center https://www.gw-openscience.org/tutorials/

Conferences
Kick off Workshop of the Einstein Telescope https://indico.ego-gw.it/event/240/timetable/#20210921
Dawn VI Meeting on Next Generation Observatories https://gwic.ligo.org/dawn-6/program.html
Ultra-High-Frequency Gravitational Waves http://www.ctc.cam.ac.uk/activities/UHF-GW.php
Ultra-High-Frequency GWs: A Theory and Technology Roadmap https://indico.cern.ch/event/1074510/
Gravitational wave detection at the Moon Workshop https://indico.ego-gw.it/event/263/timetable/

Schools
Gravitational Wave Challenges and Cosmology https://www.iip.ufrn.br/eventsdetail.php?inf=%3D%3DQTUFVM

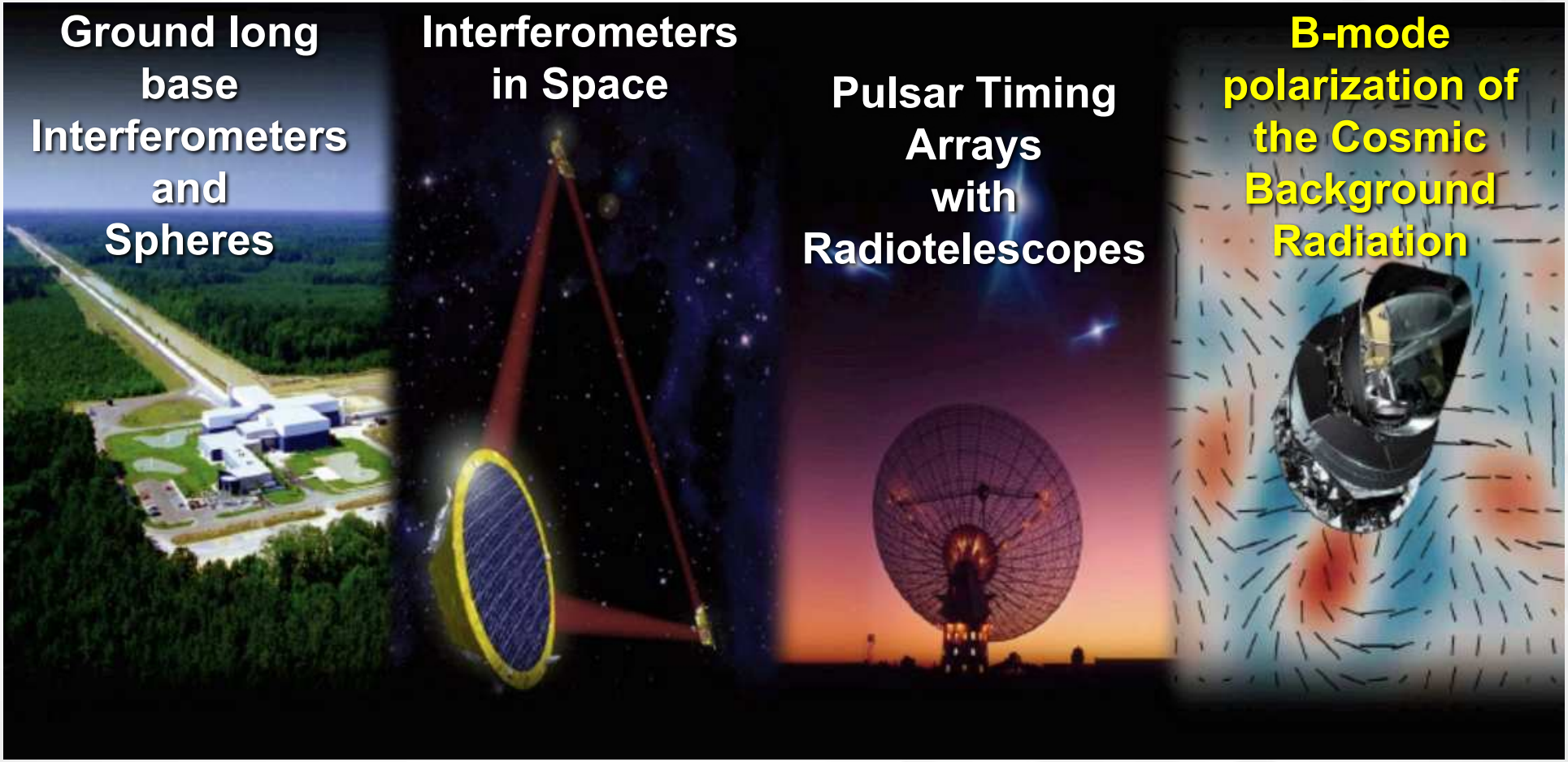
Job Opportunities
From the LAAC/LSC website https://wiki.ligo.org/LAAC/JobPostings

Facebook sites
Gravitational Wave Astronomy https://www.facebook.com/search/top?q=gravitational%20wave%20astronomy
Graviton (Mario Schenberg Detector) https://www.facebook.com/groups/MarioSchenberg

Wikipedia sites
Gravitational-wave astronomy https://en.wikipedia.org/wiki/Gravitational-wave_astronomy

Other important sites
European Gravitational Observatory https://www.ego-gw.it
IGrav https://www.igrav.org
Gravitational Wave Detectors and Sources http://gwplotter.com
Gravitational Wave Open Science Center https://www.gw-openscience.org/about/
LSC Academic Advisory Committee (LAAC) https://wiki.ligo.org/LAAC/EducationalResources

Gravitational Wave Astronomy Bands



10 Hz to 10 kHz	10^{-4} Hz to 10^{0} Hz	10^{-9} Hz to 10^{-8} Hz	10^{-18} Hz to 10^{-15} Hz

Gravitational Waves Frequency

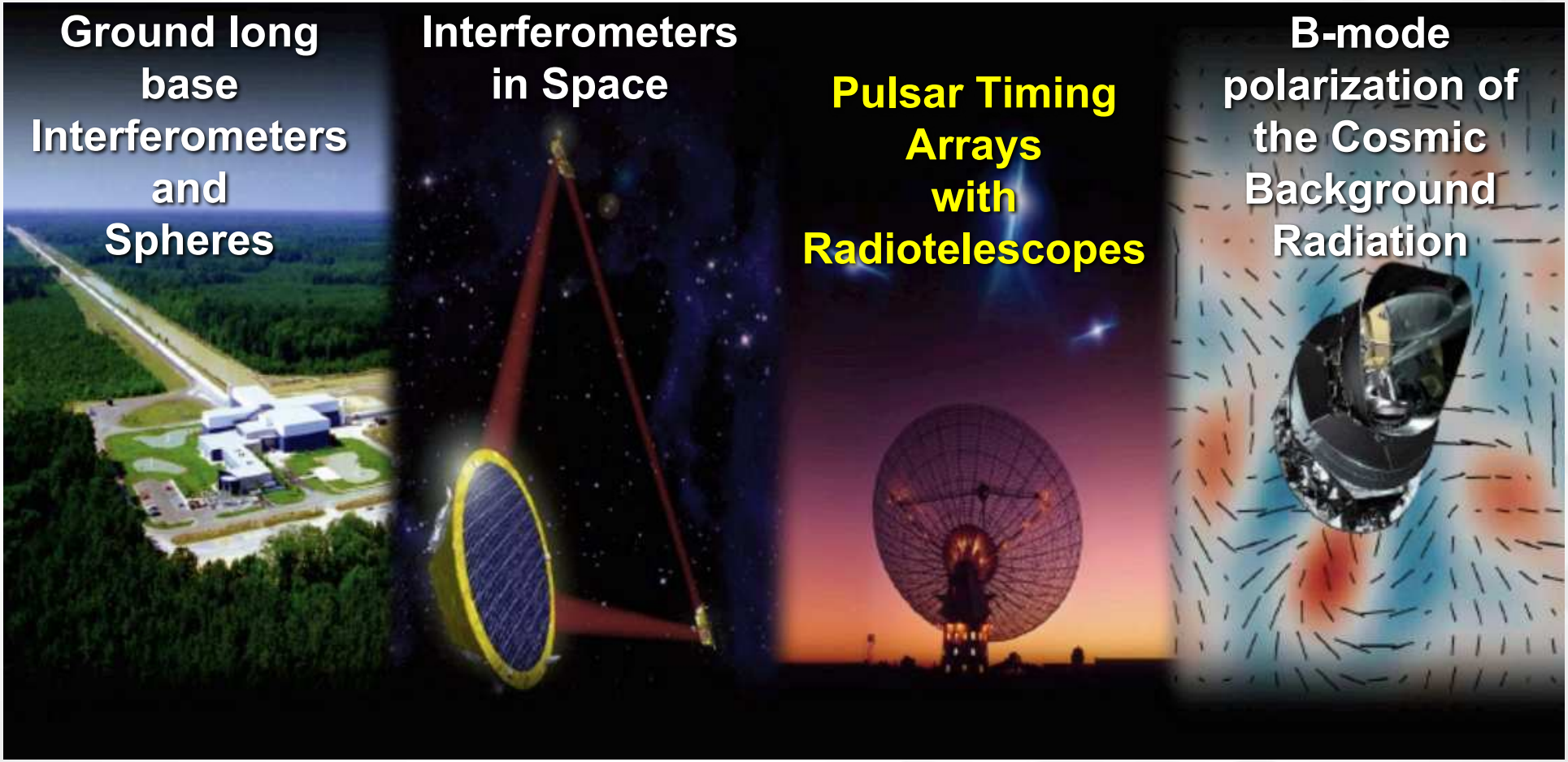
At the Amundsen–Scott South Pole Station

The **BICEP2** detector array under a microscope

POLARBEAR

at Atacama Desert

Gravitational Wave Astronomy Bands



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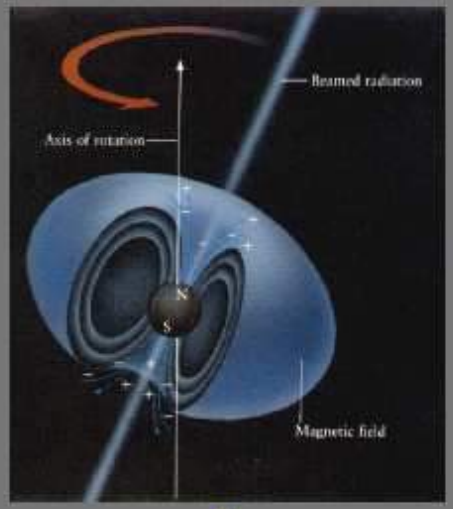
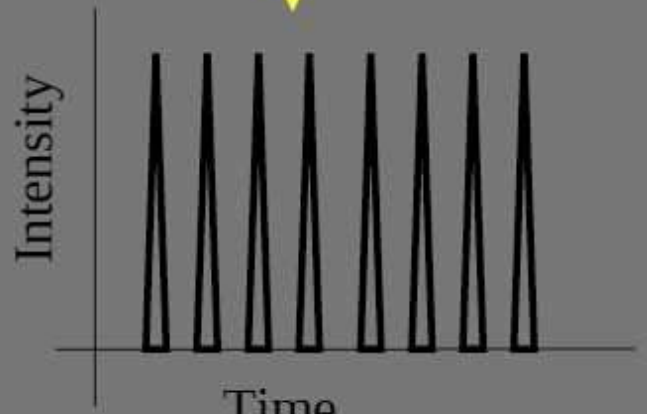
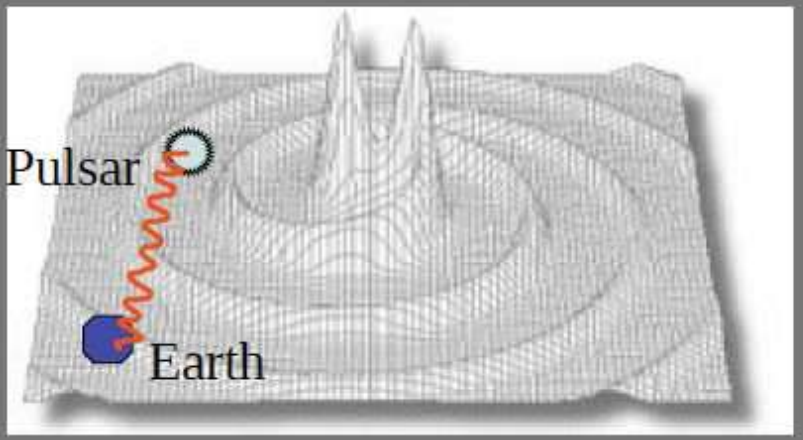
Gravitational Waves Frequency

Pulsar Timing Arrays







NRAO

International Pulsar Timing Array (IPTA)

- NANOGrav
- Parkes Pulsar Timing Array (PPTA)

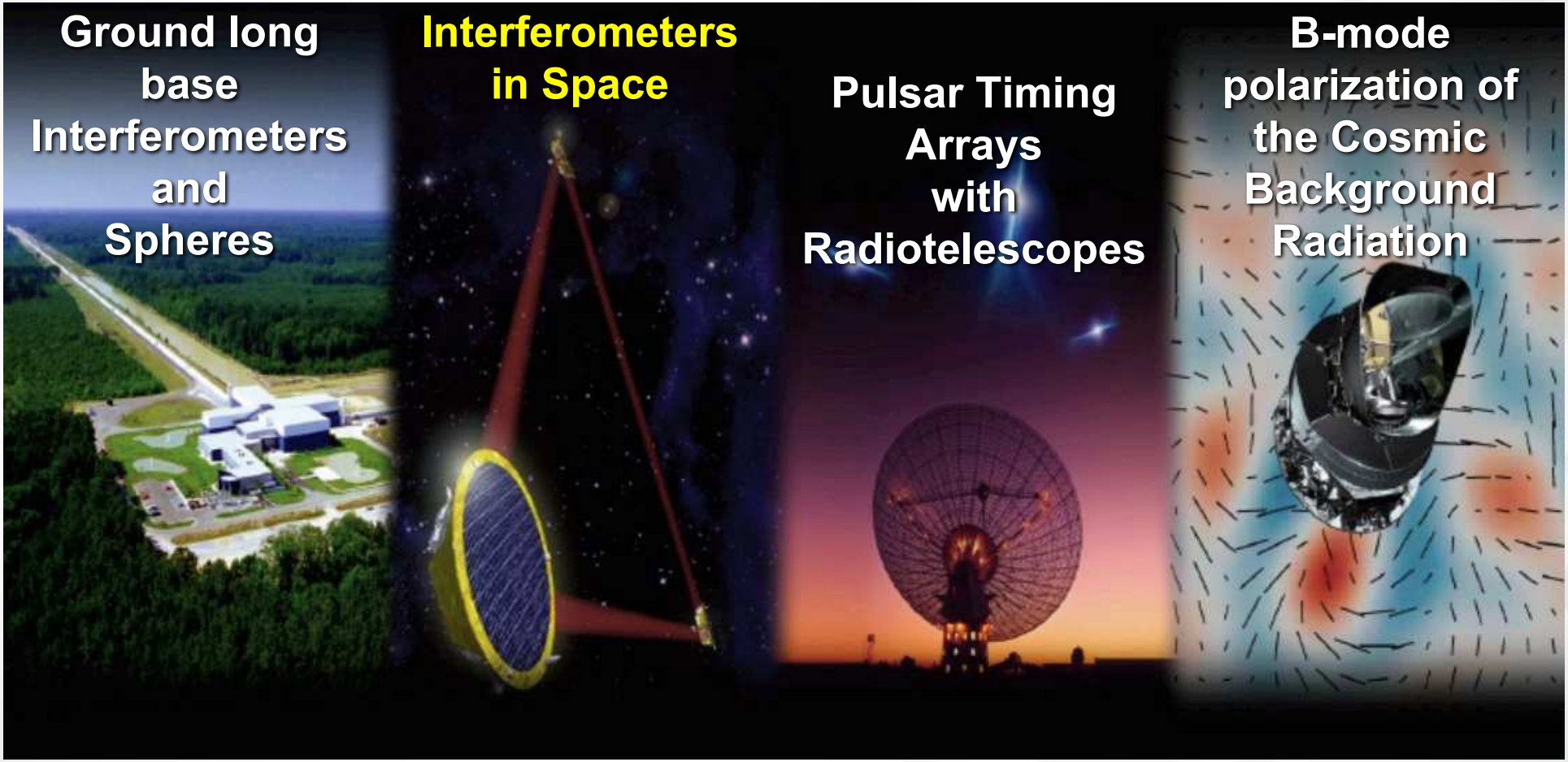
  (See talk by Joris Verbiest)
- European Pulsar Timing Array (EPTA)

  (See talk by Robert Ferdman)

All members of GWIC

Indian Pulsar Timing Array Project

Gravitational Wave Astronomy Bands



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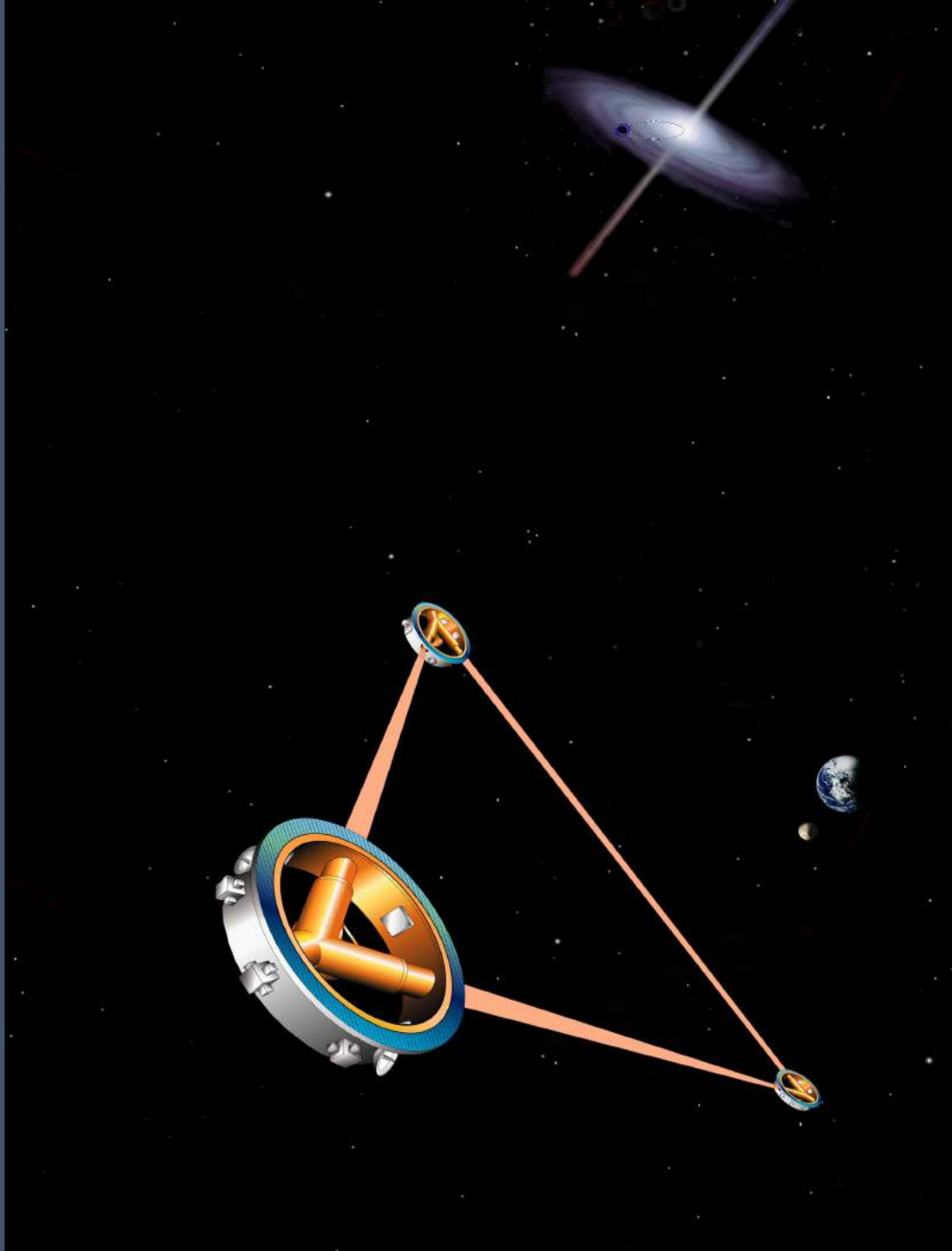
Gravitational Waves Frequency

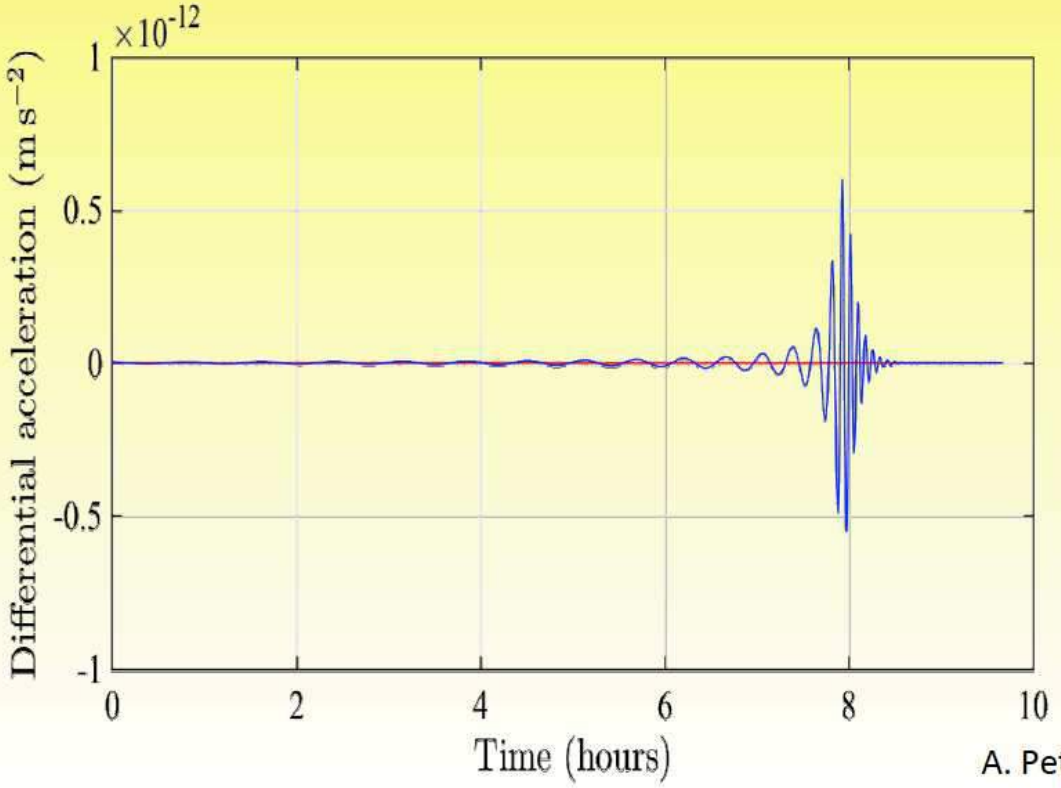
Interferometers in Space:

LISA, DECIGO BBO, TianQin, Taiji, and AMIGO



Black Hole Mergers far above Noise

- $10^5\ M_\odot$ BH binary merger at z=5
- In Red: Pathfinder instrumental noise



A. Petiteau 2016

Black Hole Merger far above Noise

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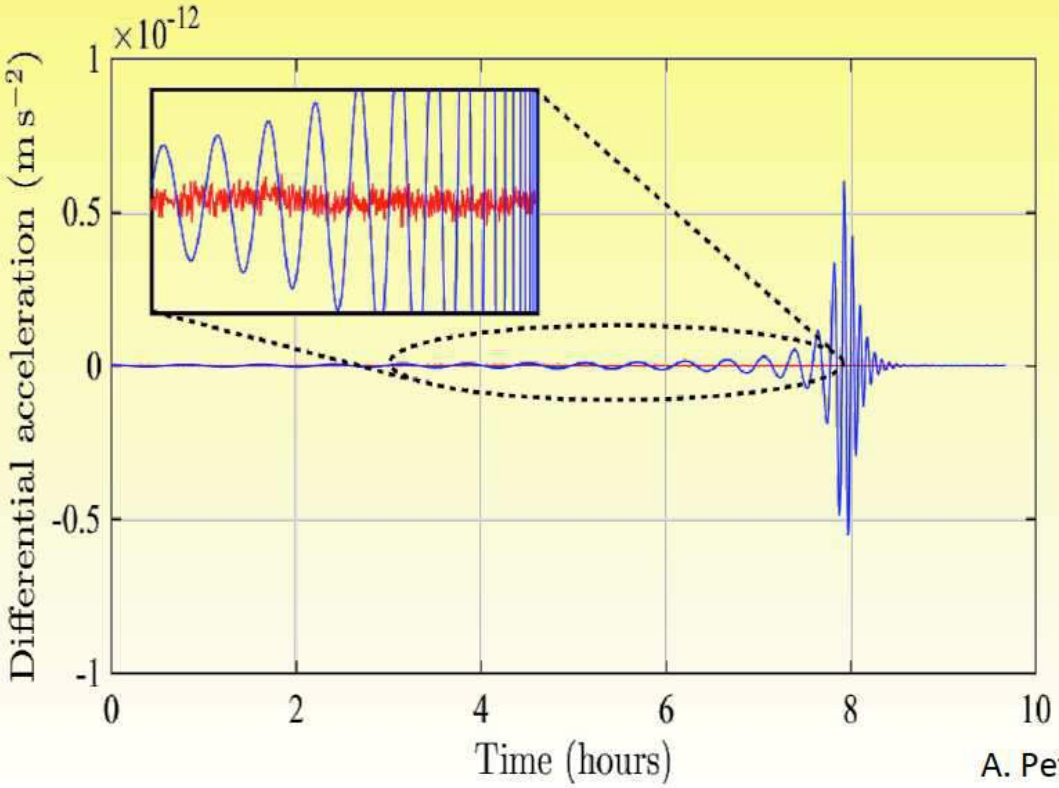
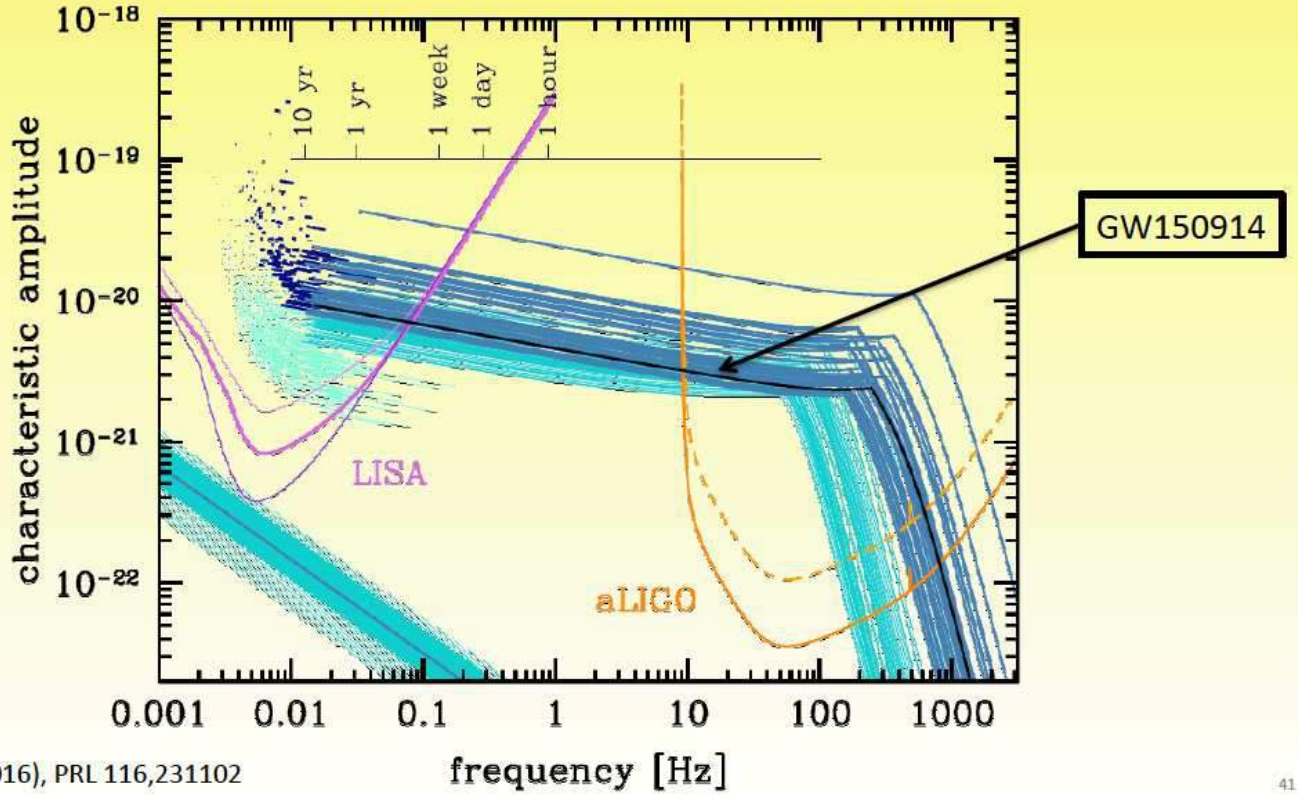


A. Petiteau 2016

LISA: LIGO Event Predicted 10 Years in Advance!

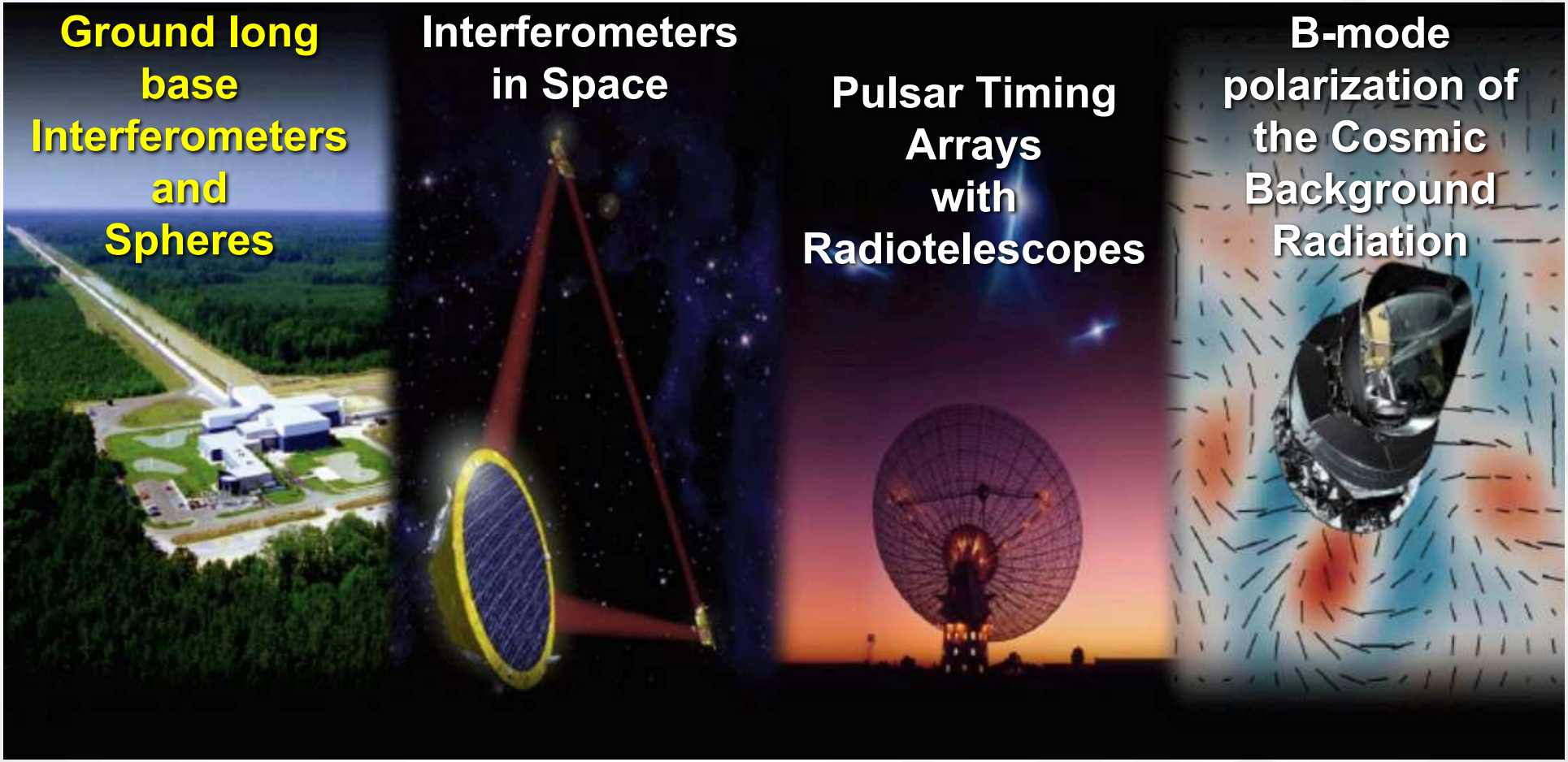
- Accurate to seconds and within a square-degree!



A. Sesana (2016), PRL 116,231102

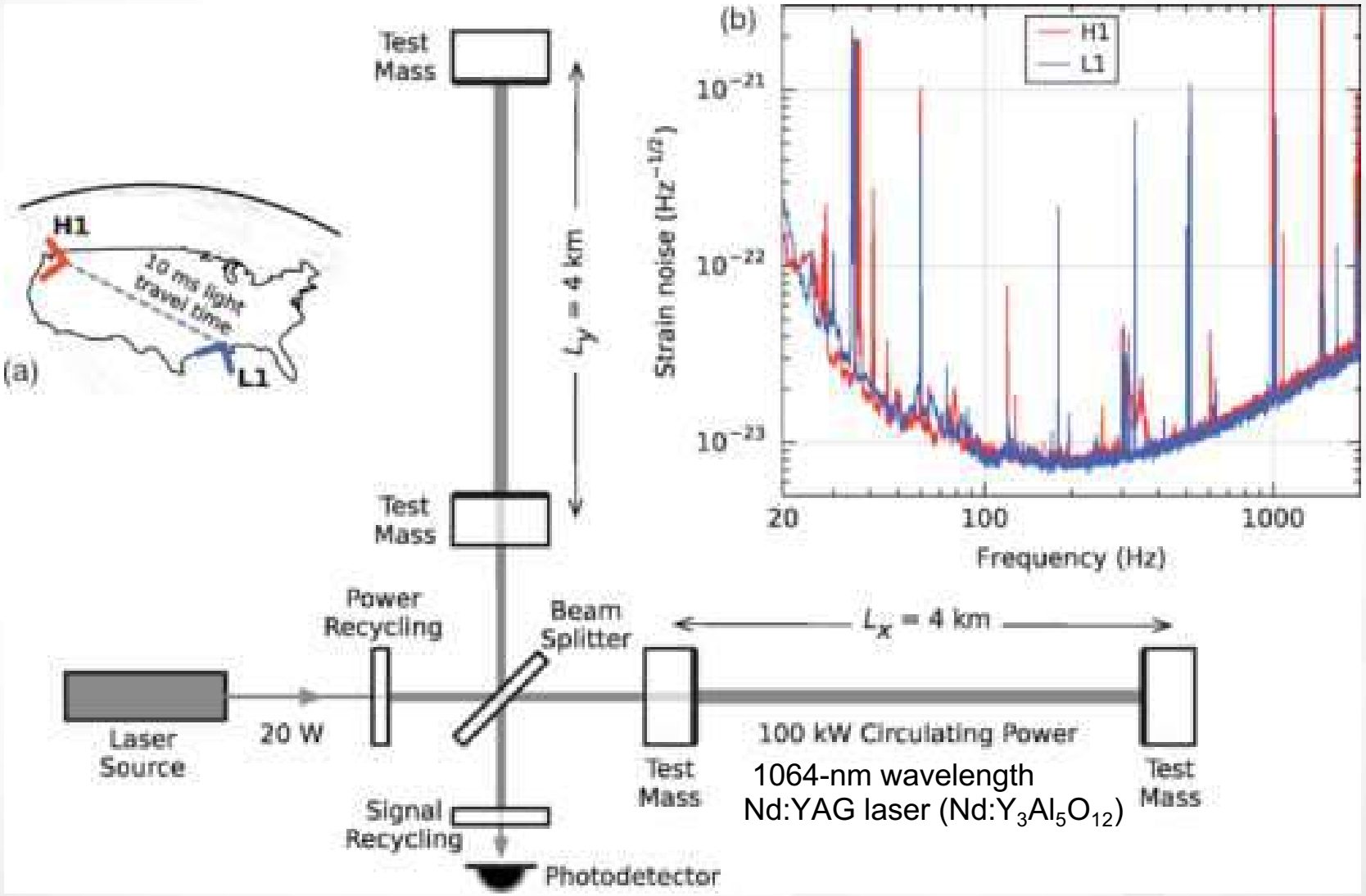
Gravitational Wave Astronomy Bands

There are also frequency bands above 10 kHz, they are called HFGW. There are many small groups trying them.



10 Hz to 10 kHz | 10^{-4} Hz to 10^{0} Hz | 10^{-9} Hz to 10^{-8} Hz | 10^{-18} Hz to 10^{-15} Hz

Gravitational Waves Frequency

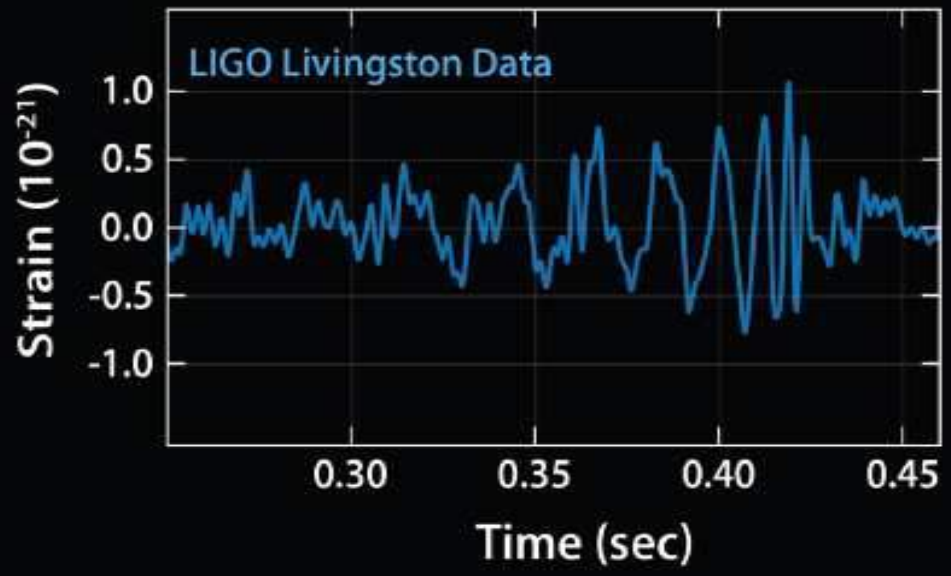


1064-nm wavelength
Nd:YAG laser ($Nd:Y_3Al_5O_{12}$)

http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102

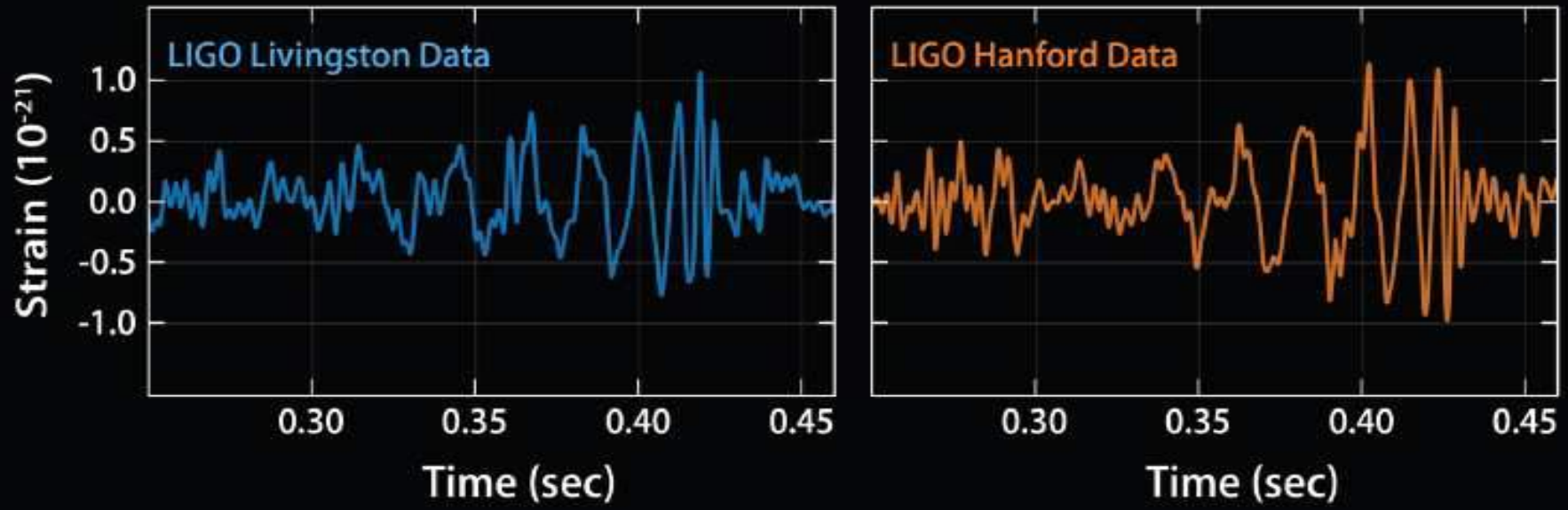
LIGO Scientific Collaboration

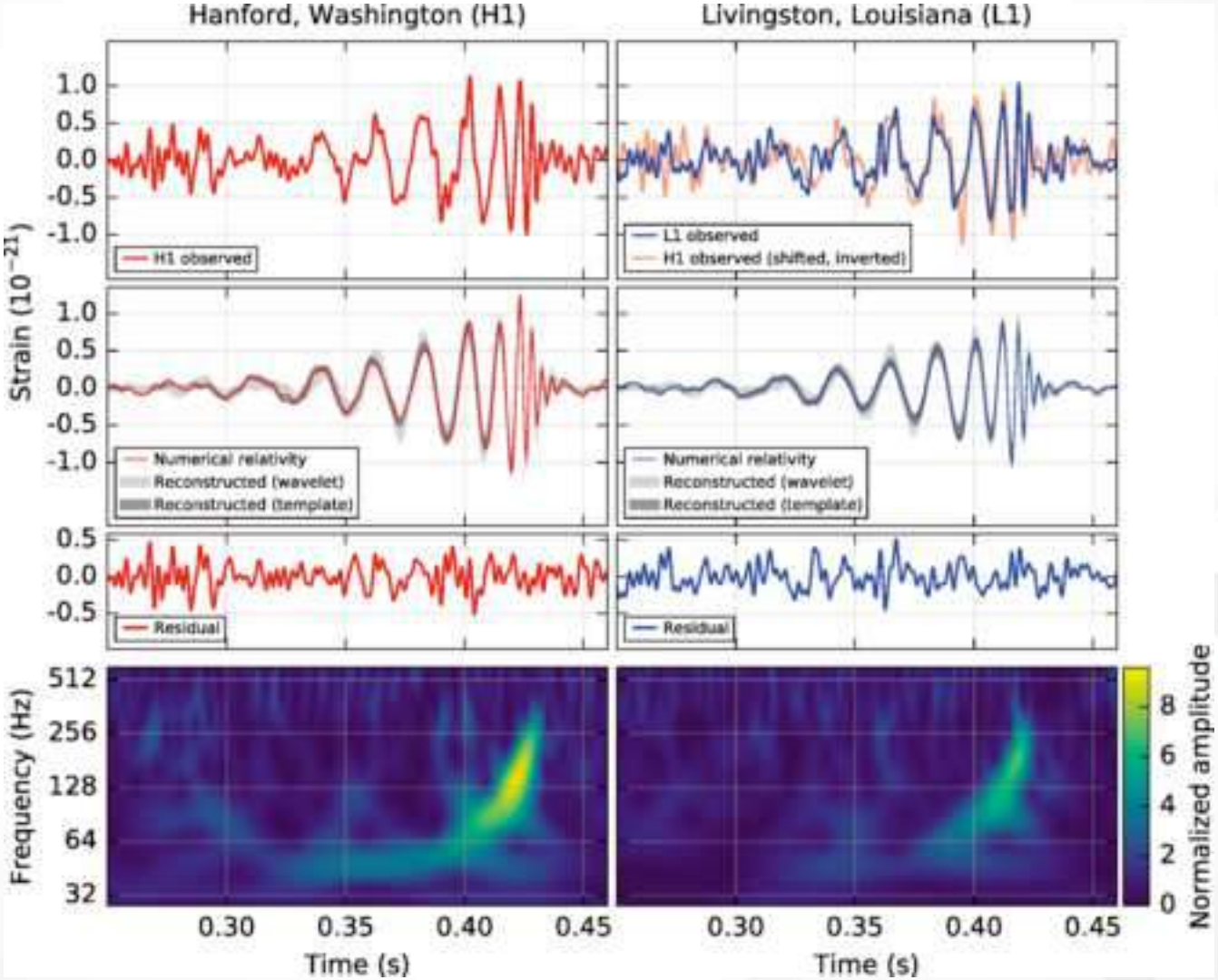
On September 14, 2015 at 09:50:45 UTC



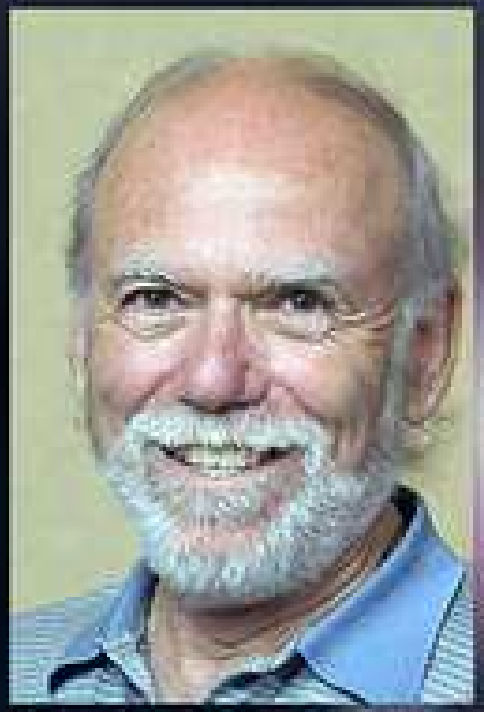
On September 14, 2015 at 09:50:45 UTC

e 7 milisegundos depois ...

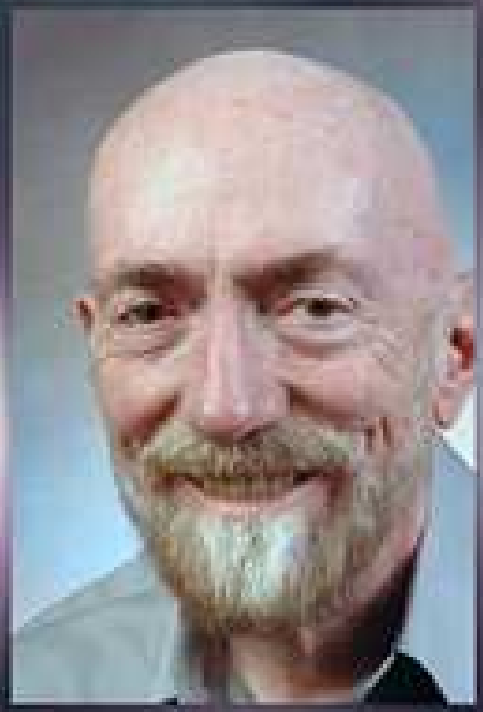




http://journals.aps.org/prl/abstract/10.1103/PhysRevLett.116.061102



Barry C. Barish (Caltech)

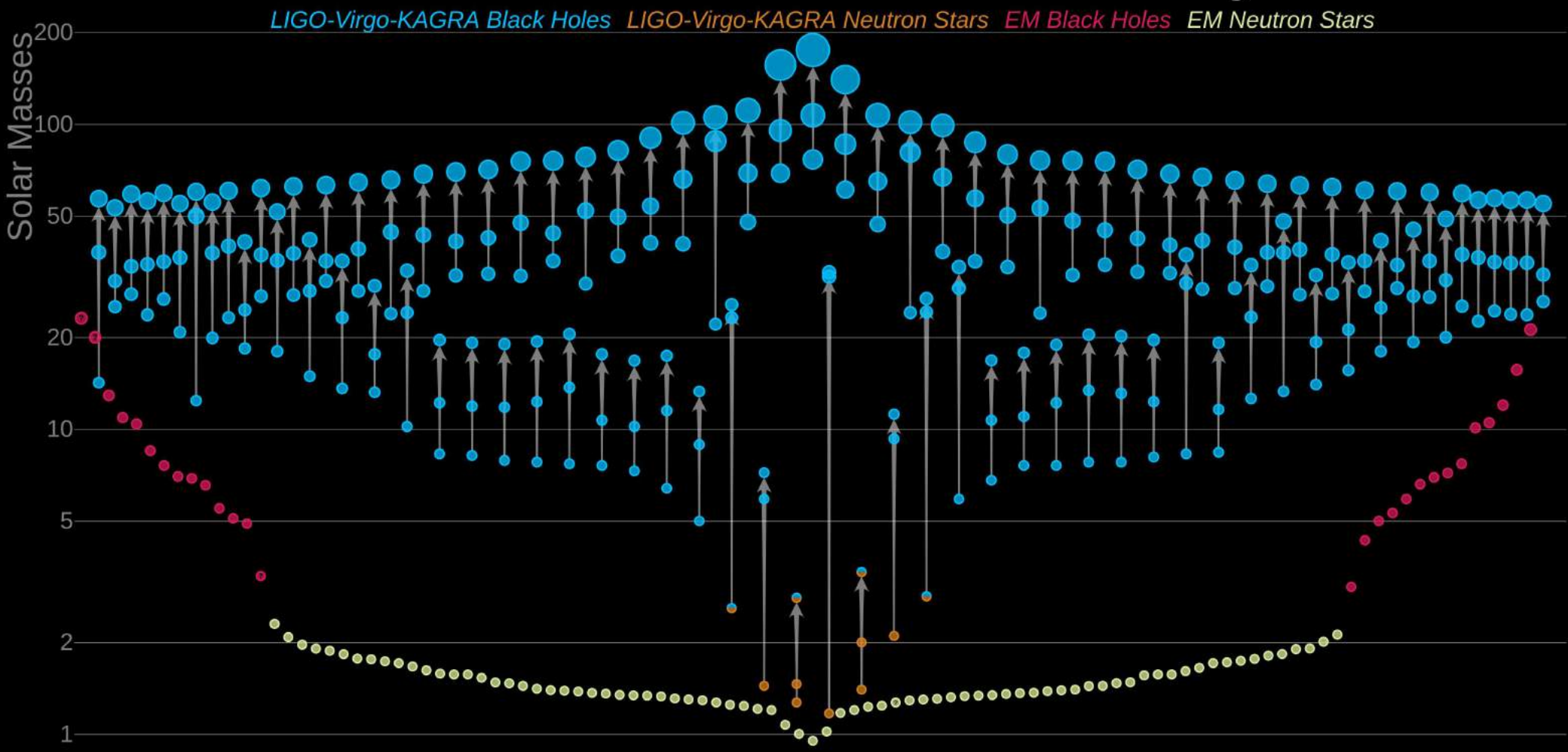


Kip S. Thorne (Caltech)

Rainer Weiss (MIT)

2017 Nobel Prize in Physics

Masses in the Stellar Graveyard

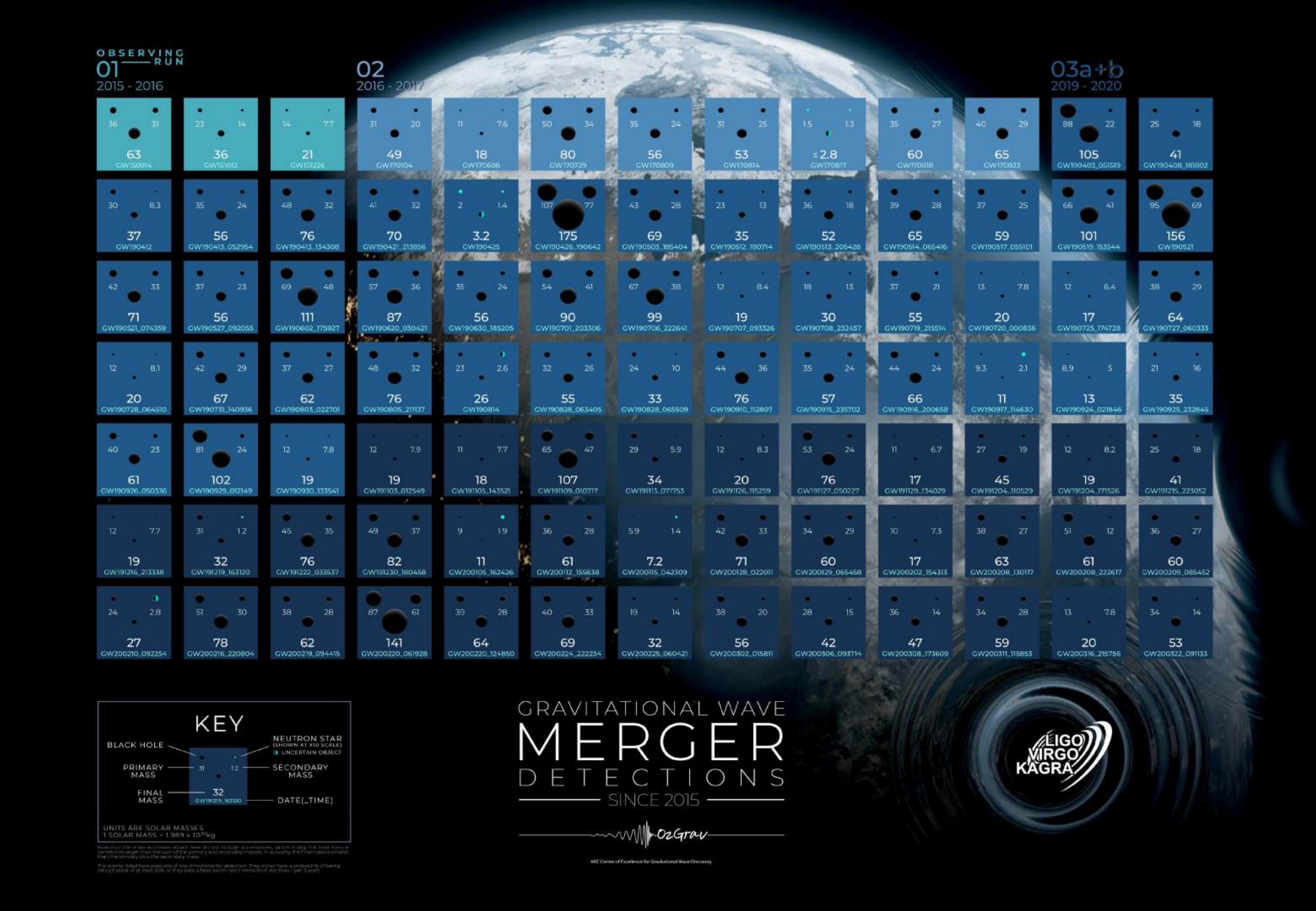


Gravitational-Wave Transient Catalog

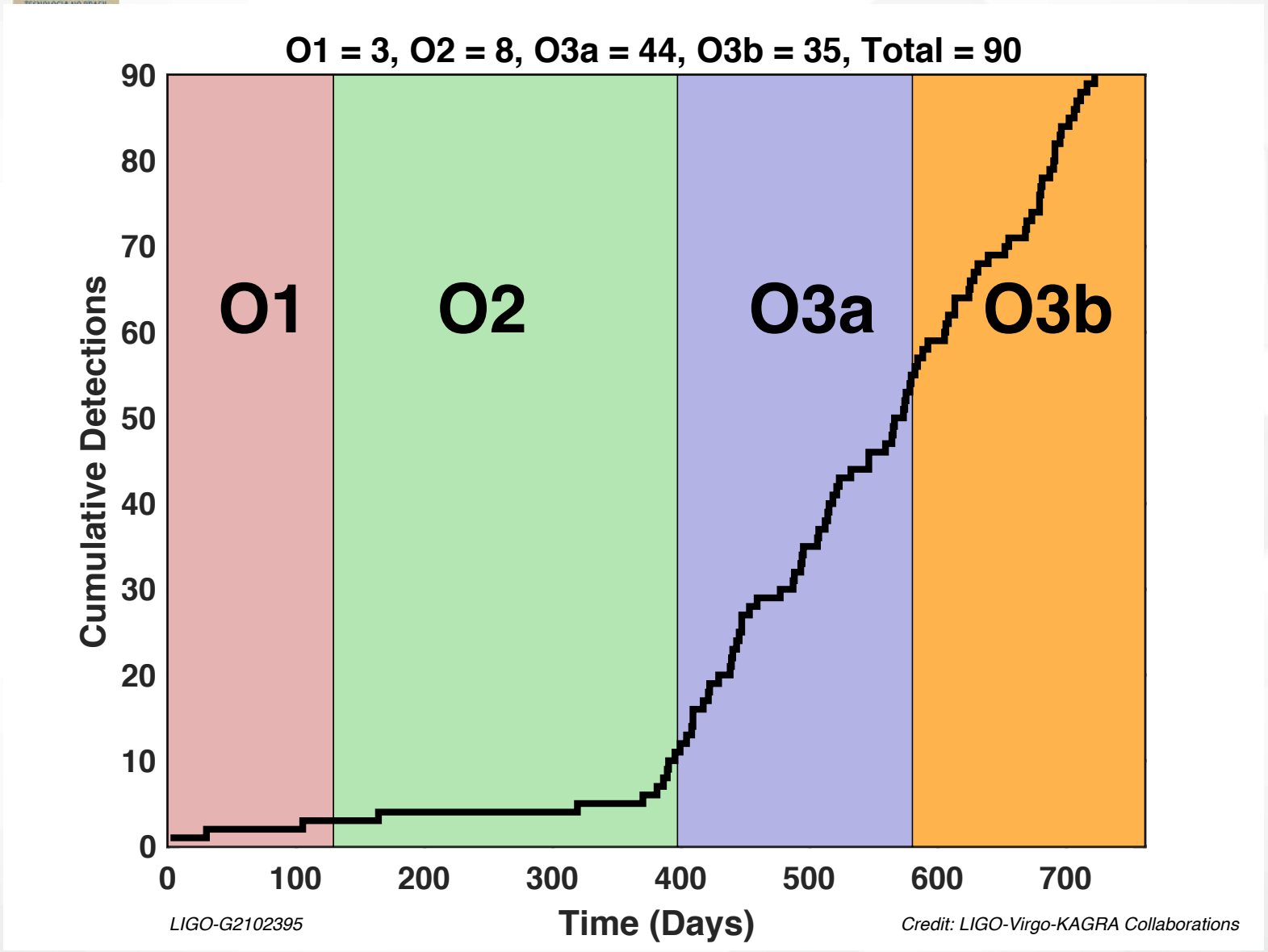
Detections from 2015-2020 of compact binaries with black holes & neutron stars

Sudarshan Ghonge | Karan Jani

LIGO VIRGO KAGRA
NSF
Georgia Tech
VANDERBILT UNIVERSITY



OBSERVING RUN
01
2015 - 2016
02
2016 - 2017
O3a+b
2019 - 2020
36 31 63 GW150914
23 14 36 GW151012
14 7.7 21 GW151226
31 20 49 GW170104
11 7.6 18 GW170608
50 34 80 GW170729
35 24 56 GW170809
31 25 53 GW170814
1.5 1.3 ≤2.8 GW170817
35 27 60 GW170818
40 29 65 GW170823
88 22 105 GW190403_051519
25 18 41 GW190408_181802
30 8.3 37 GW190412
35 24 56 GW190413_052954
48 32 76 GW190413_134308
41 32 70 GW190421_213856
2 1.4 3.2 GW190425
107 77 175 GW190426_190642
43 28 69 GW190503_185404
23 13 35 GW190512_180714
36 18 52 GW190513_205428
39 28 65 GW190514_065416
37 25 59 GW190517_055101
66 41 101 GW190519_153544
95 69 156 GW190521
42 33 71 GW190521_074359
37 23 56 GW190527_092055
69 48 111 GW190602_175927
57 36 87 GW190620_030421
35 24 56 GW190630_185205
54 41 90 GW190701_203306
67 38 99 GW190706_222641
12 8.4 19 GW190707_093326
18 13 30 GW190708_232457
37 21 55 GW190719_215514
13 7.8 20 GW190720_000836
12 6.4 17 GW190725_174728
38 29 64 GW190727_060333
12 8.1 20 GW190728_064510
42 29 67 GW190731_140936
37 27 62 GW190803_022701
48 32 76 GW190805_211137
23 2.6 26 GW190814
32 26 55 GW190828_063405
24 10 33 GW190828_065509
44 36 76 GW190910_112807
35 24 57 GW190915_235702
44 24 66 GW190916_200658
9.3 2.1 11 GW190917_114630
8.9 5 13 GW190924_021846
21 16 35 GW190925_232845
40 23 61 GW190926_050336
81 24 102 GW190929_012149
12 7.8 19 GW190930_133541
12 7.9 19 GW191103_012549
11 7.7 18 GW191105_143521
65 47 107 GW191109_010717
29 5.9 34 GW191113_071753
12 8.3 20 GW191126_115259
53 24 76 GW191127_050227
11 6.7 17 GW191129_134029
27 19 45 GW191204_110529
12 8.2 19 GW191204_171526
25 18 41 GW191215_223052
12 7.7 19 GW191216_213338
31 1.2 32 GW191219_163120
45 35 76 GW191222_033537
49 37 82 GW191230_180458
9 1.9 11 GW200105_162426
36 28 61 GW200112_155838
5.9 1.4 7.2 GW200115_042309
42 33 71 GW200128_022011
34 29 60 GW200129_065458
10 7.3 17 GW200202_154313
38 27 63 GW200208_130117
51 12 61 GW200208_222617
36 27 60 GW200209_085452
24 2.8 27 GW200210_092254
51 30 78 GW200216_220804
38 28 62 GW200219_094415
87 61 141 GW200220_061928
39 28 64 GW200220_124850
40 33 69 GW200224_222234
19 14 32 GW200225_060421
38 20 56 GW200302_015811
28 15 42 GW200306_093714
36 14 47 GW200308_173609
34 28 59 GW200311_115853
13 7.8 20 GW200316_215756
34 14 53 GW200322_091133
KEY
BLACK HOLE
NEUTRON STAR (SHOWN AT X10 SCALE)
UNCERTAIN OBJECT
PRIMARY MASS
SECONDARY MASS
FINAL MASS
DATE(_TIME)
31 1.2 32 GW191219_163120
UNITS ARE SOLAR MASSES
1 SOLAR MASS = 1.989 x 10^30 kg
GRAVITATIONAL WAVE
MERGER
DETECTIONS
SINCE 2015
OzGrav
LIGO VIRGO KAGRA


O1 = 3, O2 = 8, O3a = 44, O3b = 35, Total = 90
O1
O2
O3a
O3b
Cumulative Detections
0
10
20
30
40
50
60
70
80
90
0
100
200
300
400
500
600
700
Time (Days)
LIGO-G2102395
Credit: LIGO-Virgo-KAGRA Collaborations

https://doi.org/10.3847/2041-8213/aa920c

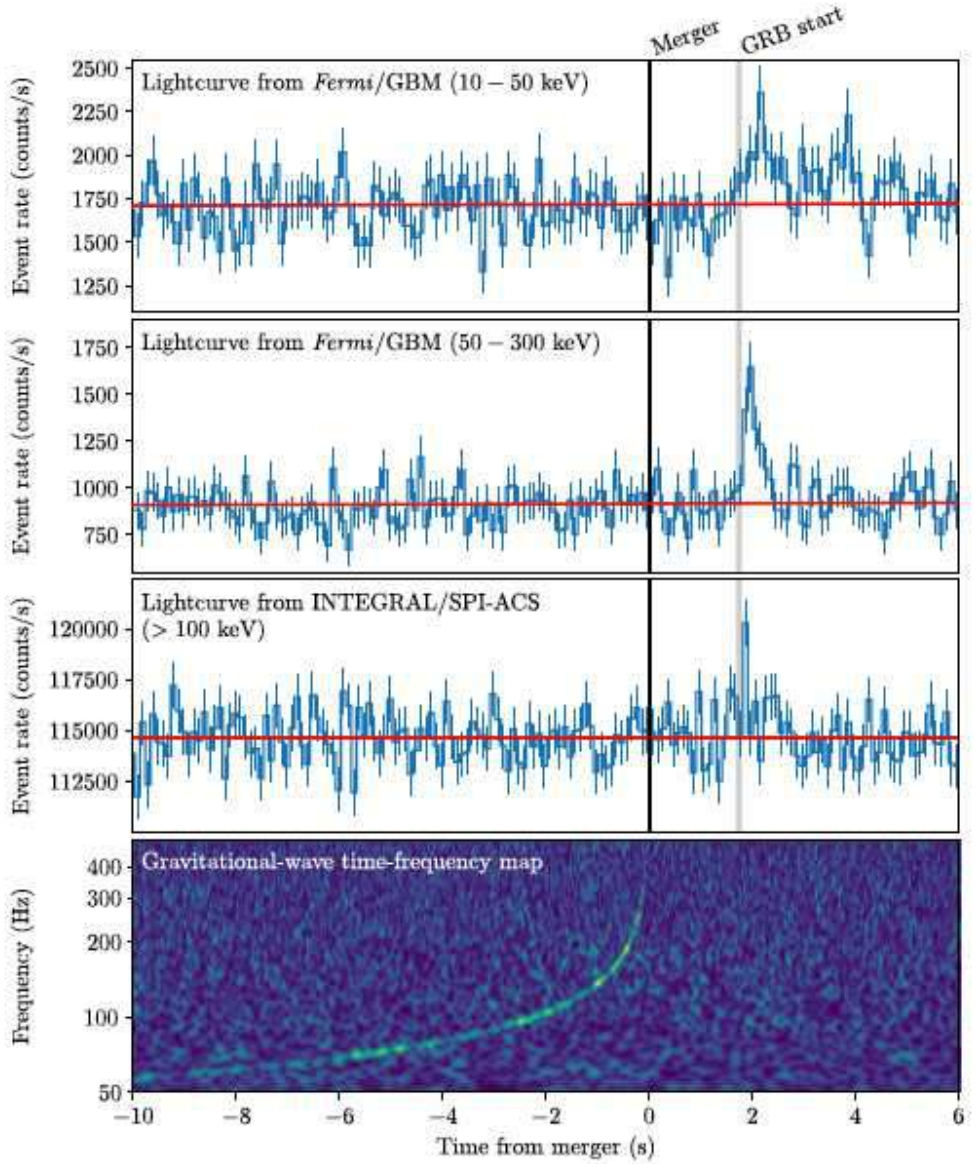


Figure 2. Joint, multi-messenger detection of GW170817 and GRB 170817A. Top: the summed GBM lightcurve for sodium iodide (NaI) detectors 1, 2, and 5 for GRB 170817A between 10 and 50 keV, matching the 100 ms time bins of the SPI-ACS data. The background estimate from Goldstein et al. (2016) is overlaid in red. Second: the same as the top panel but in the 50–300 keV energy range. Third: the SPI-ACS lightcurve with the energy range starting approximately at 100 keV and with a high energy limit of least 80 MeV. Bottom: the time-frequency map of GW170817 was obtained by coherently combining LIGO-Hanford and LIGO-Livingston data. All times here are referenced to the GW170817 trigger time T_0^{GW}.

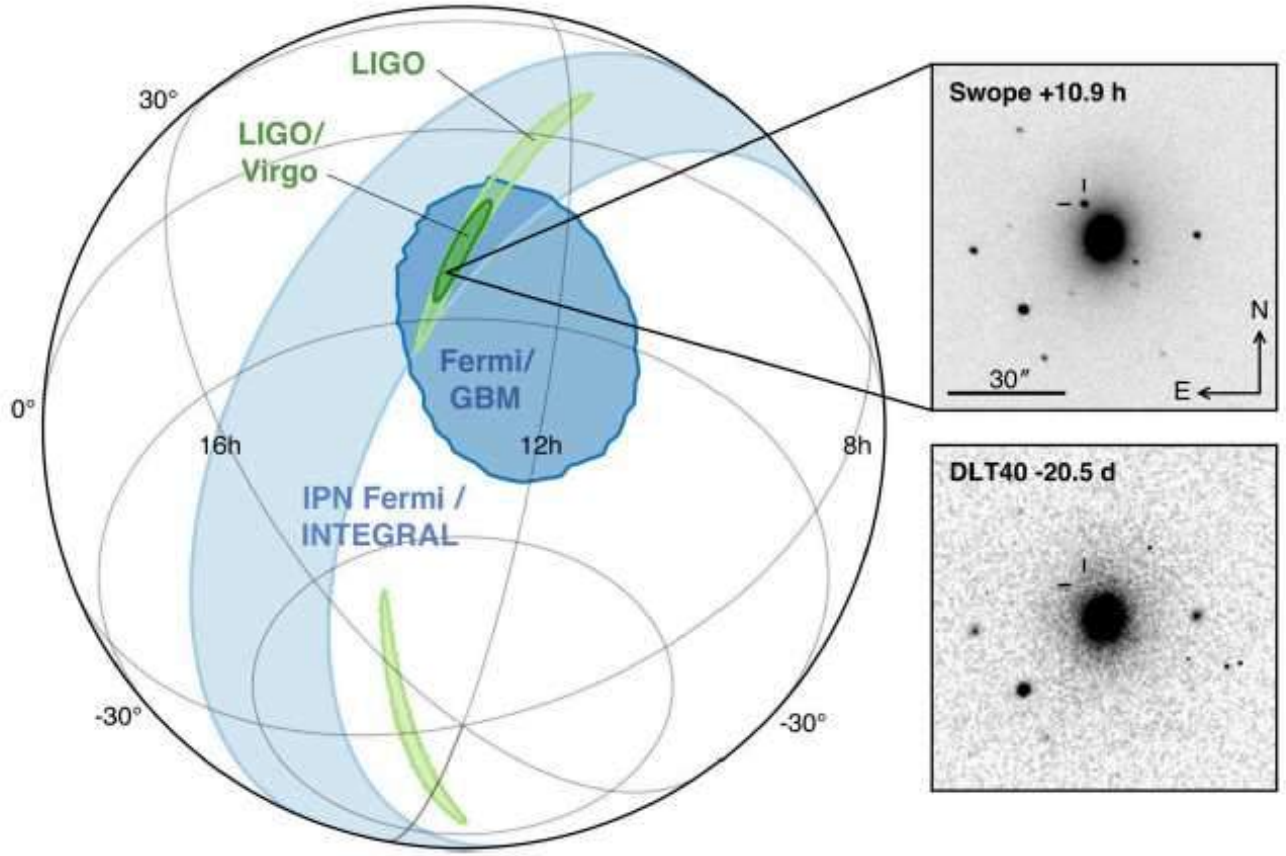
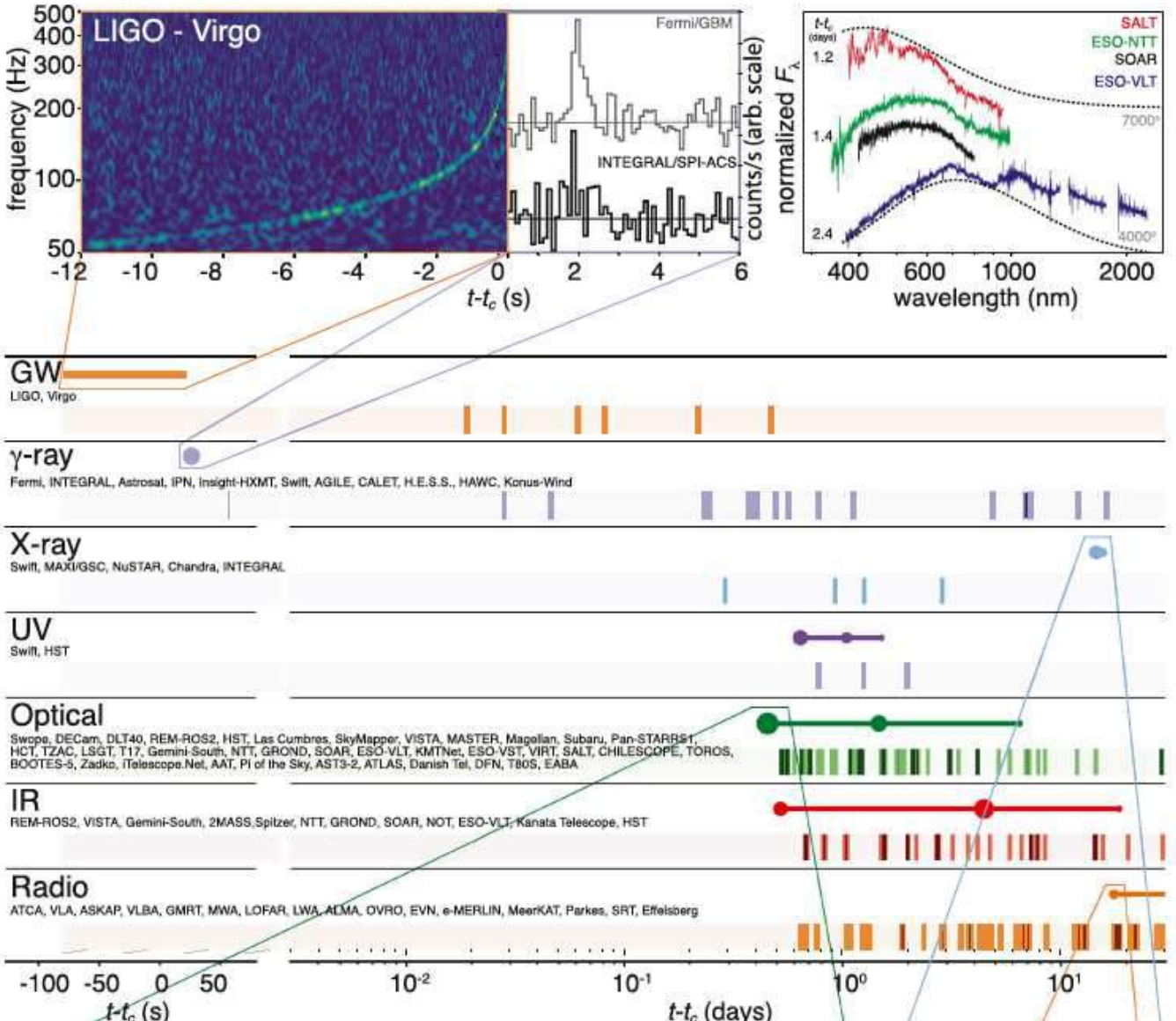


Figure 1. Localization of the gravitational-wave, gamma-ray, and optical signals. The left panel shows an orthographic projection of the 90% credible regions from LIGO (190 deg^2; light green), the initial LIGO-Virgo localization (31 deg^2; dark green), IPN triangulation from the time delay between *Fermi* and *INTEGRAL* (light blue), and *Fermi*-GBM (dark blue). The inset shows the location of the apparent host galaxy NGC 4993 in the Swope optical discovery image at 10.9 hr after the merger (top right) and the DLT40 pre-discovery image from 20.5 days prior to merger (bottom right). The reticle marks the position of the transient in both images.

https://doi.org/10.3847/2041-8213/aa91c9


LIGO - Virgo
frequency (Hz)
500
400
300
200
100
50
-12 -10 -8 -6 -4 -2 0 2 4 6
t-t_c (s)
Fermi/GBM
INTEGRAL/SPI-ACS
counts/s (arb. scale)
normalized F_λ
t-t_c (days)
1.2
1.4
2.4
SALT
ESO-NTT
SOAR
ESO-VLT
7000°
4000°
400 600 1000 2000
wavelength (nm)
GW
LIGO, Virgo
γ-ray
Fermi, INTEGRAL, Astrosat, IPN, Insight-HXMT, Swift, AGILE, CALET, H.E.S.S., HAWC, Konus-Wind
X-ray
Swift, MAXI/GSC, NuSTAR, Chandra, INTEGRAL
UV
Swift, HST
Optical
Swope, DECam, DLT40, REM-ROS2, HST, Las Cumbres, SkyMapper, VISTA, MASTER, Magellan, Subaru, Pan-STARRS1, HCT, TZAC, LSGT, T17, Gemini-South, NTT, GROND, SOAR, ESO-VLT, KMTNet, ESO-VST, VIRT, SALT, CHILESCOPE, TOROS, BOOTES-5, Zadko, iTelescope.Net, AAT, PI of the Sky, AST3-2, ATLAS, Danish Tel, DFN, T80S, EABA
IR
REM-ROS2, VISTA, Gemini-South, 2MASS,Spitzer, NTT, GROND, SOAR, NOT, ESO-VLT, Kanata Telescope, HST
Radio
ATCA, VLA, ASKAP, VLBA, GMRT, MWA, LOFAR, LWA, ALMA, OVRO, EVN, e-MERLIN, MeerKAT, Parkes, SRT, Effelsberg
-100 -50 0 50
t-t_c (s)
10^-2
10^-1
10^0
10^1
t-t_c (days)

ASTROFÍSICA MULTIMENSAGEIRA:
Busca simultânea com instrumentos da janela eletromagnética

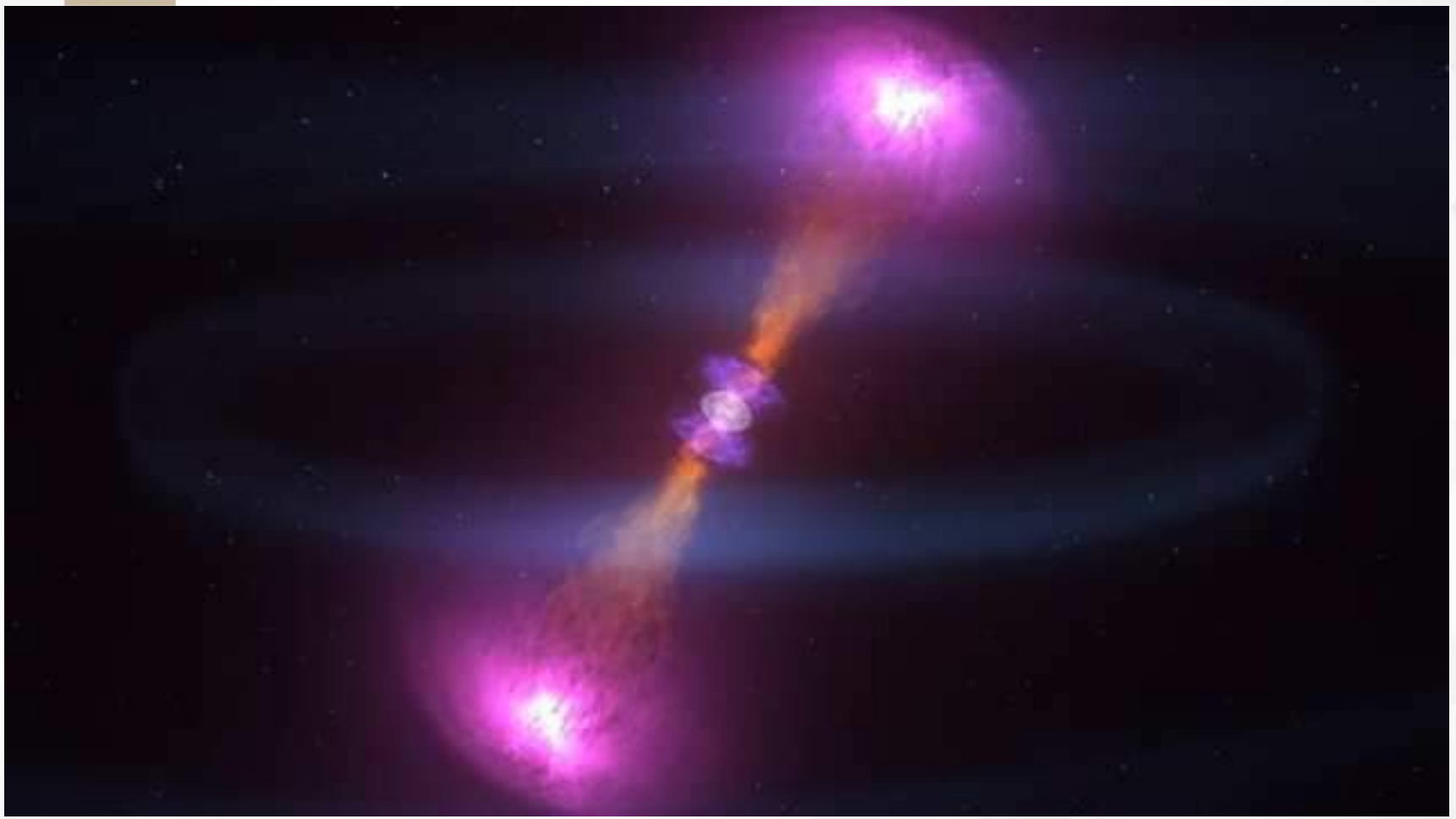
Menos de dois anos após a estréia da astronomia de ondas gravitacionais, GW170817
marca o início de uma nova era de descoberta.

optical

gamma rays,
x-rays

radio

neutrinos



This still from a NASA animation shows the aftermath of a collision of two neutron stars, which merged into an objected called GW170817. Gravitational waves from the collision were detected on Aug. 17, 2017.

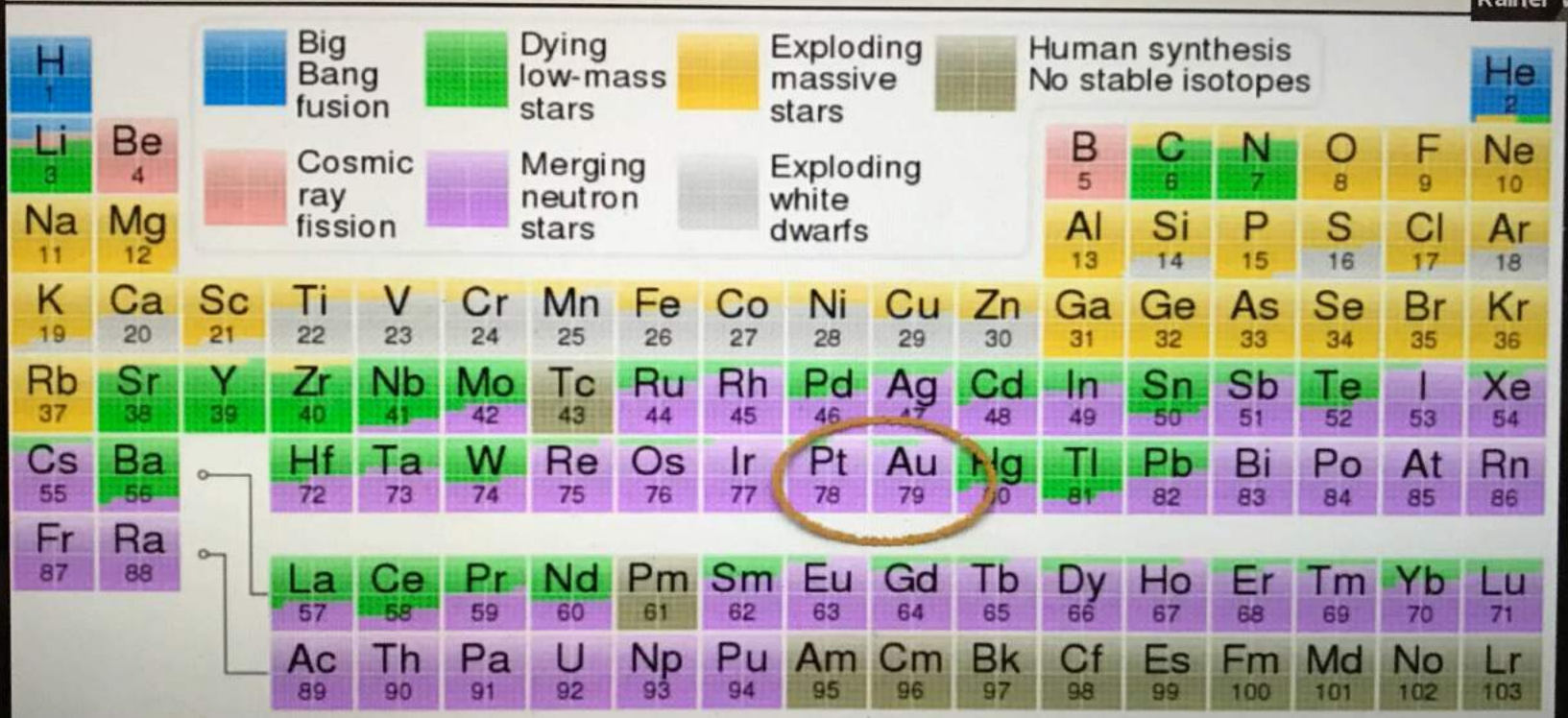
Credit: NASA's Goddard Space Flight Center/CI Lab

Rai Weiss: The future of gravitational wave astronomy | Webinar 100

Watch later Share

Rainer Weiss

Origin of the elements



MORE VIDEOS

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48:21 / 1:31:45

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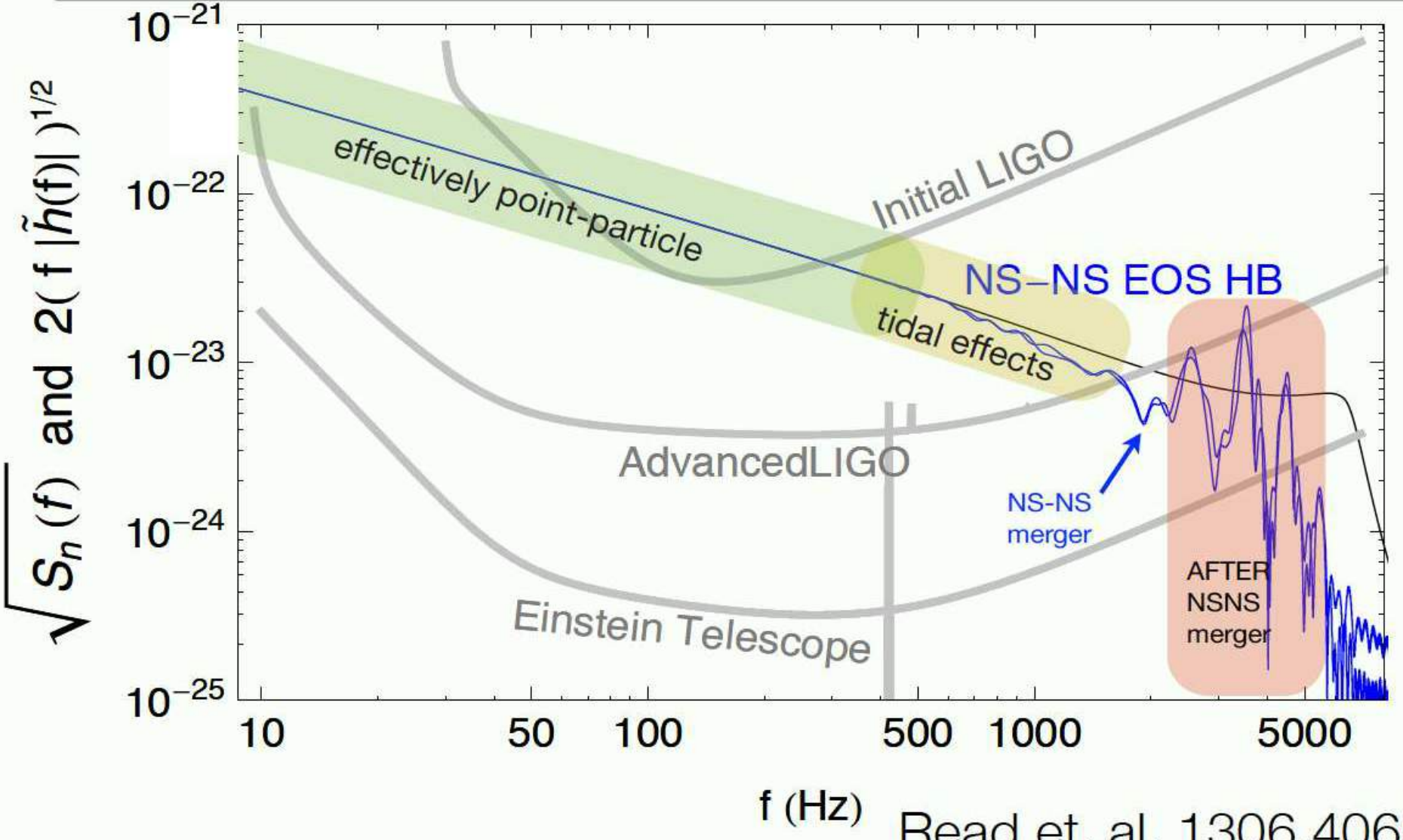
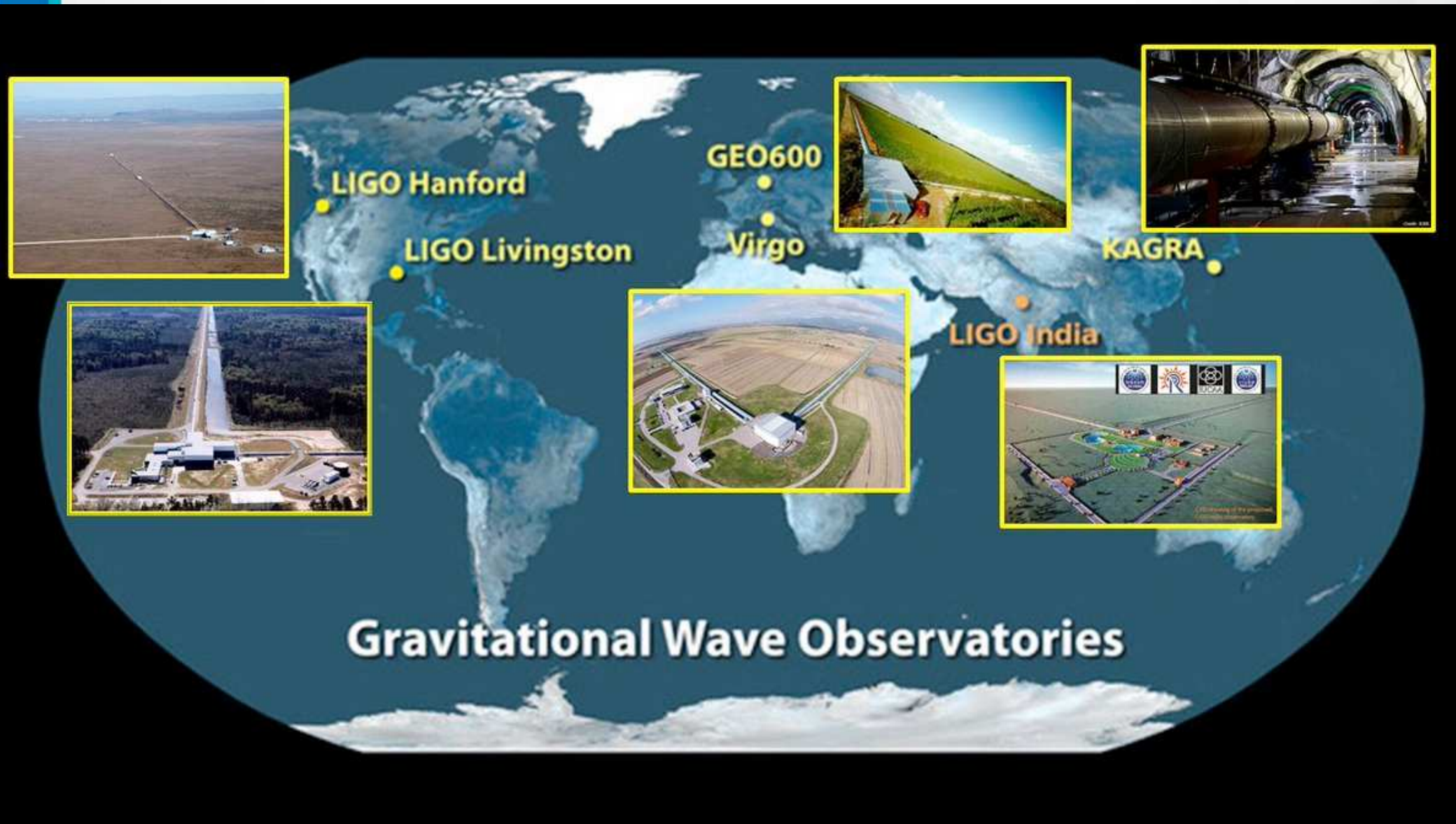
Gravitational-wave spectrum of BNS



Read et. al. 1306.4065

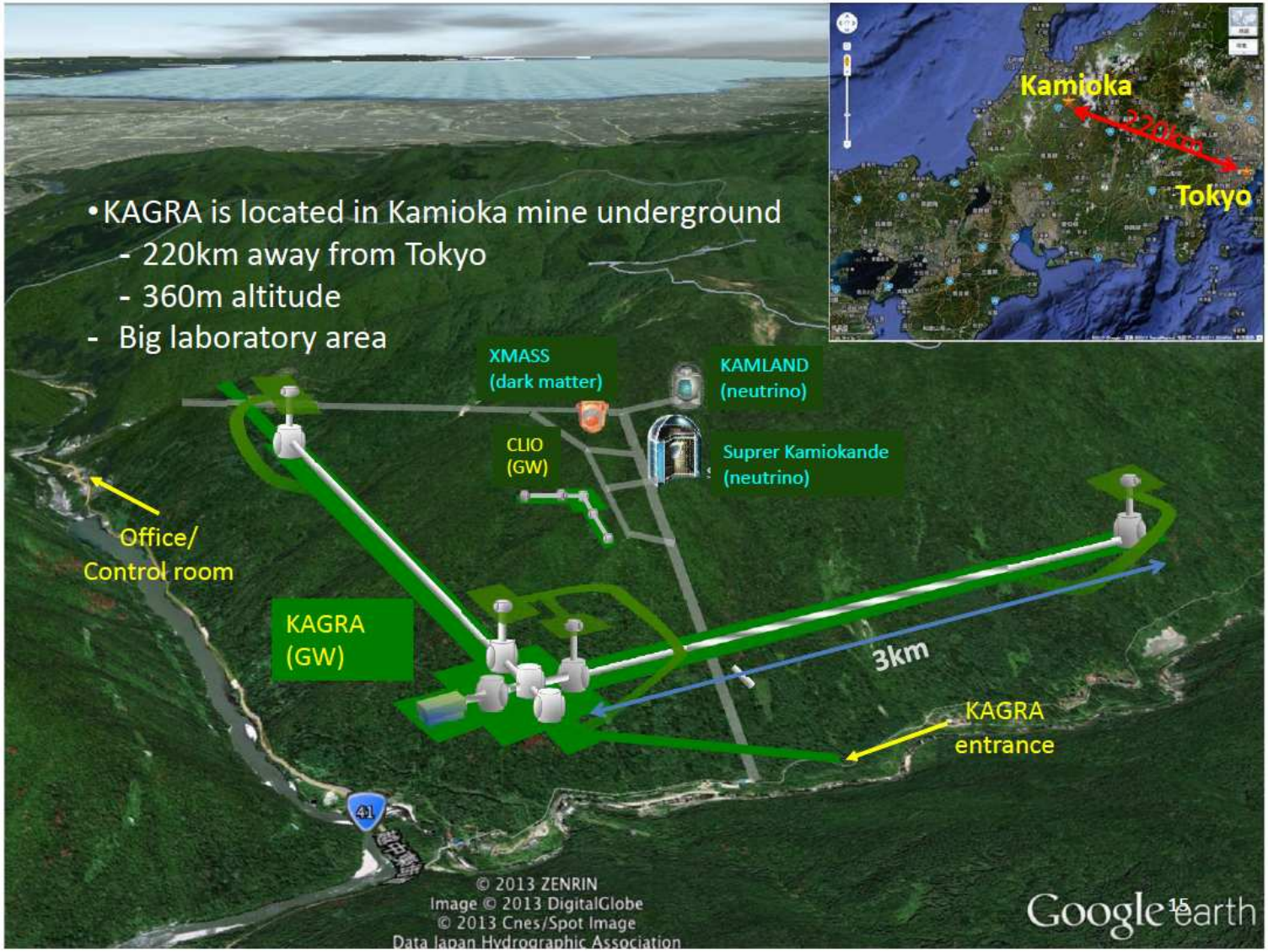
https://web.facebook.com/LigoScientificCollaboration/photos/a.217122835061847/4029977737109652/?_rdc=1&_rdr



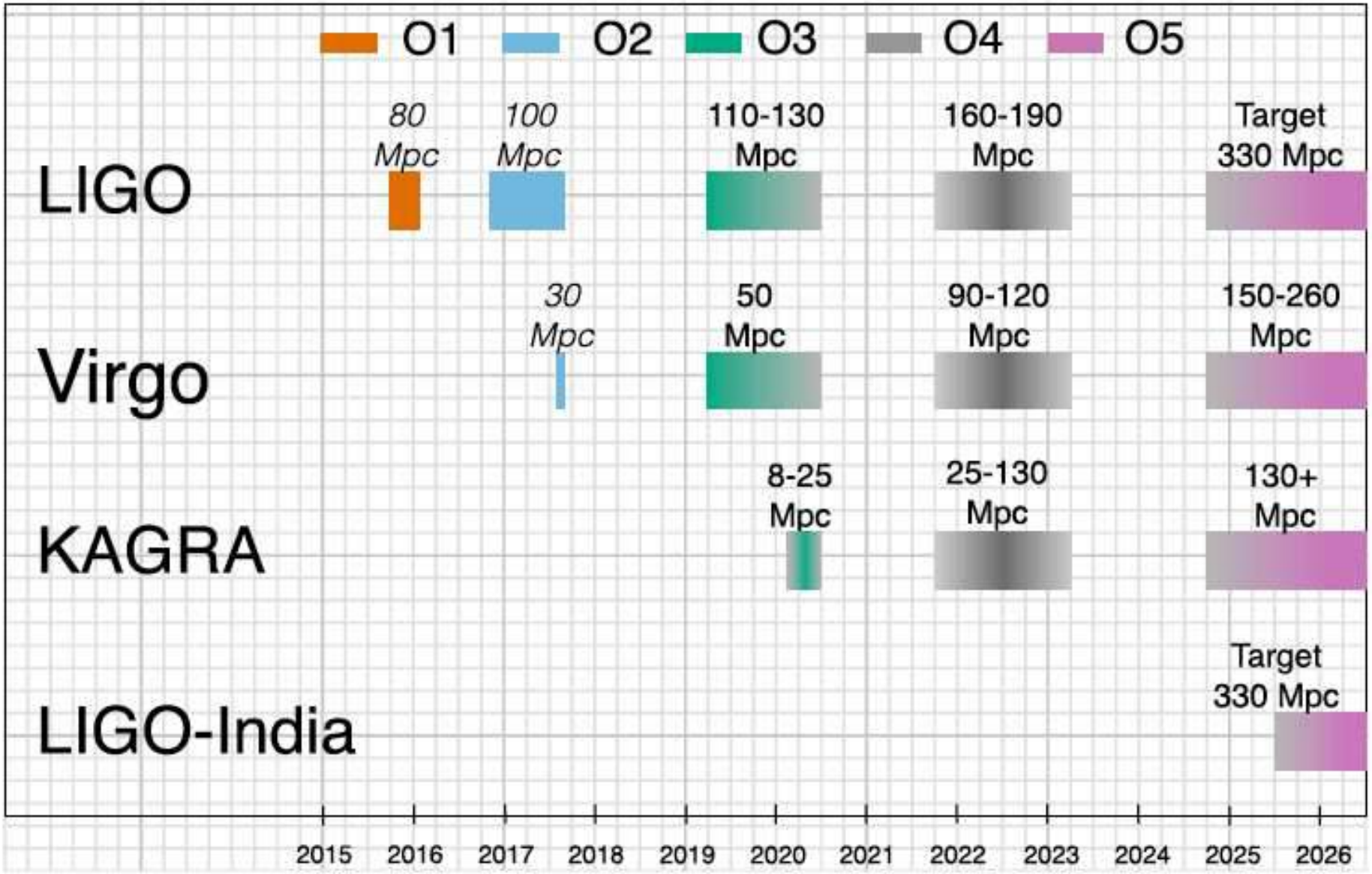
GEO600

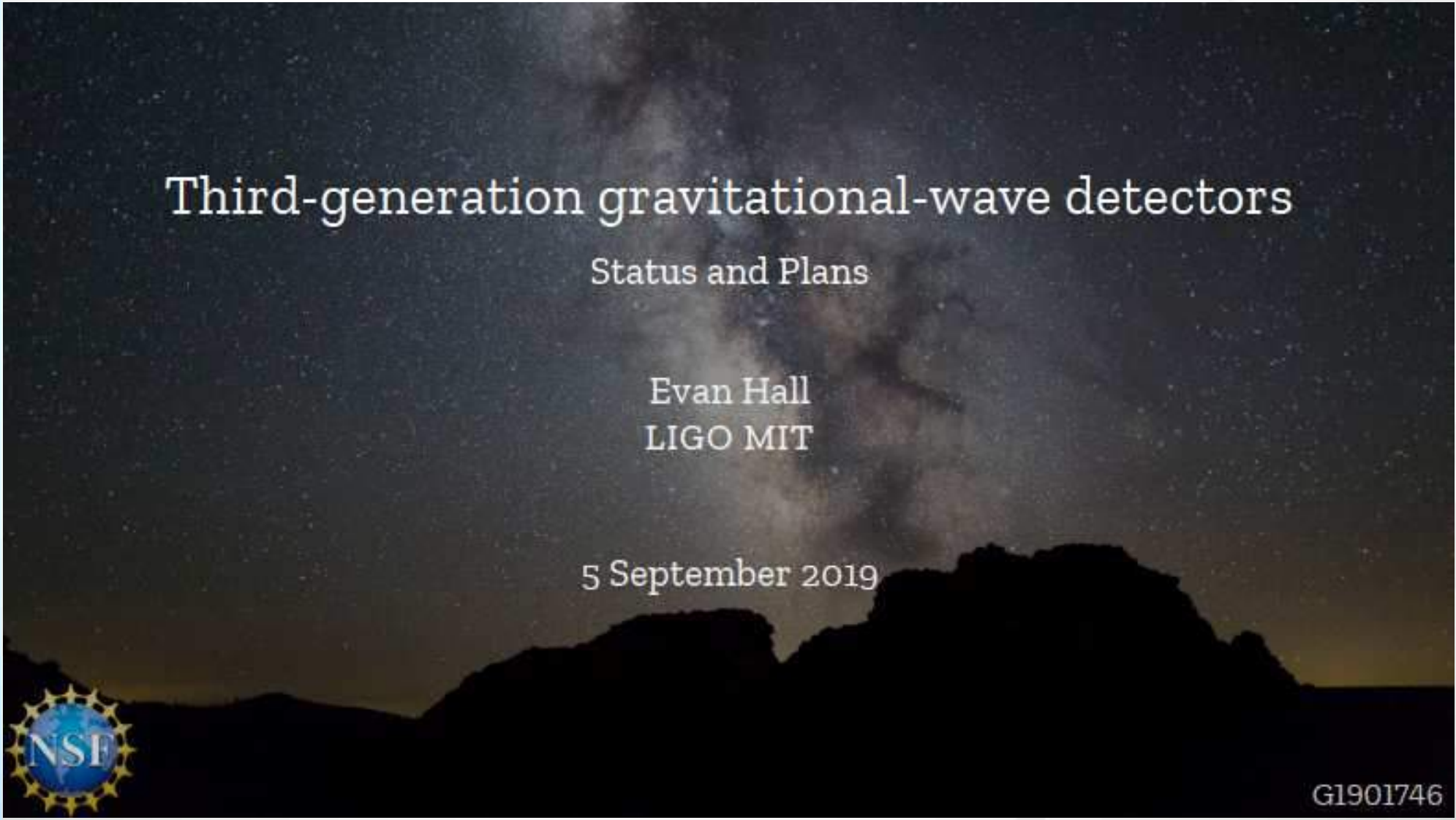
crédito: LIGO lab

Presented at Amaldi12 by Sheila Rowan
http://www.amaldi12.org/talks

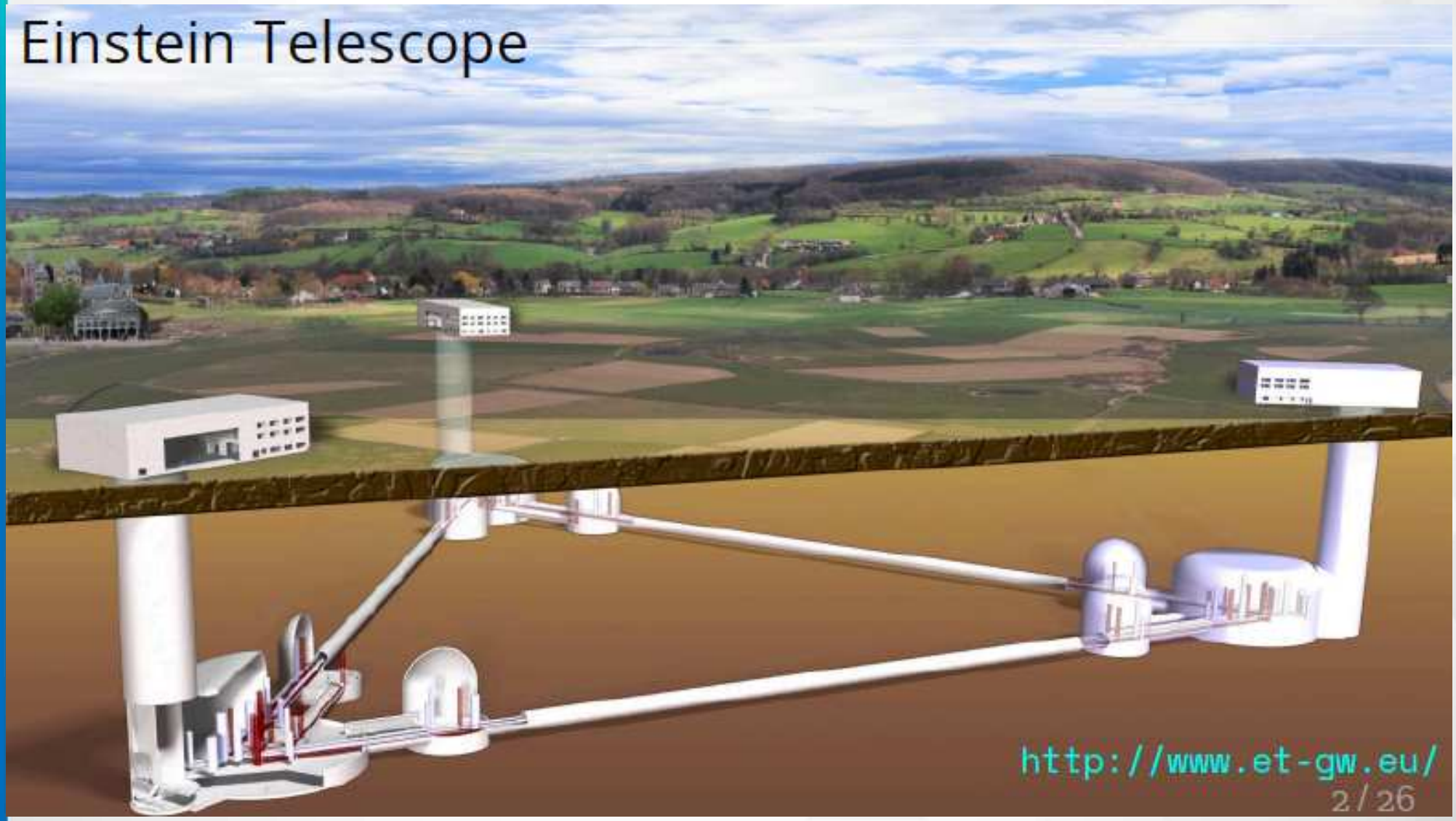


Living Reviews in Relativity
https://doi.org/10.1007/s41114-020-00026-9

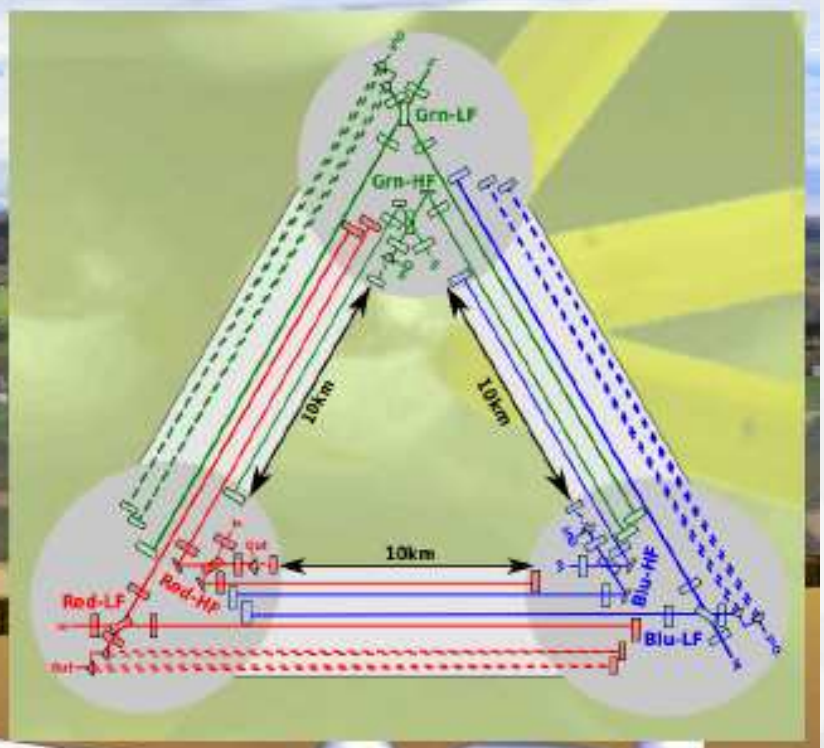



Third-generation gravitational-wave detectors
Status and Plans
Evan Hall
LIGO MIT
5 September 2019
G1901746

Einstein Telescope

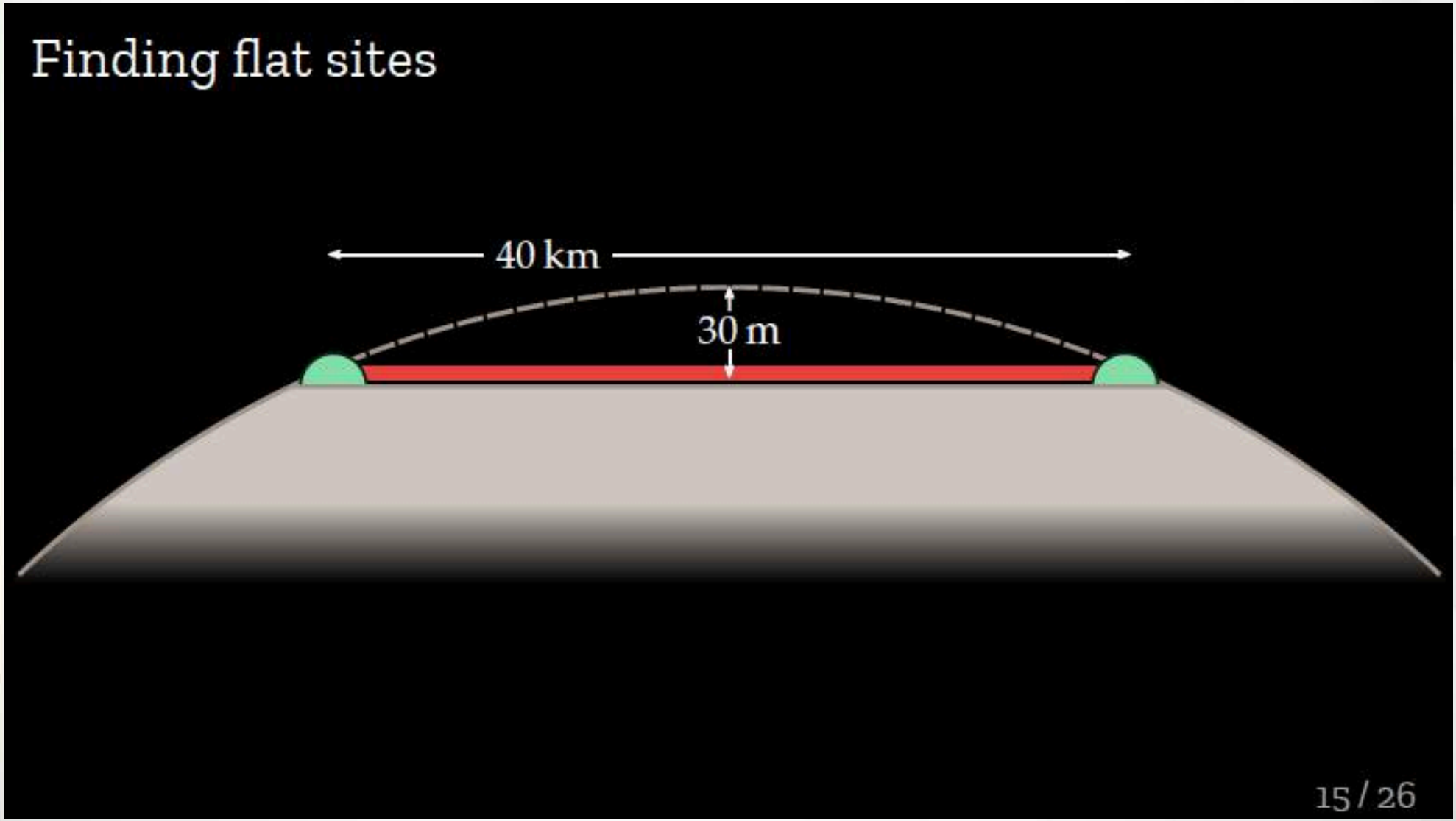


Einstein Telescope

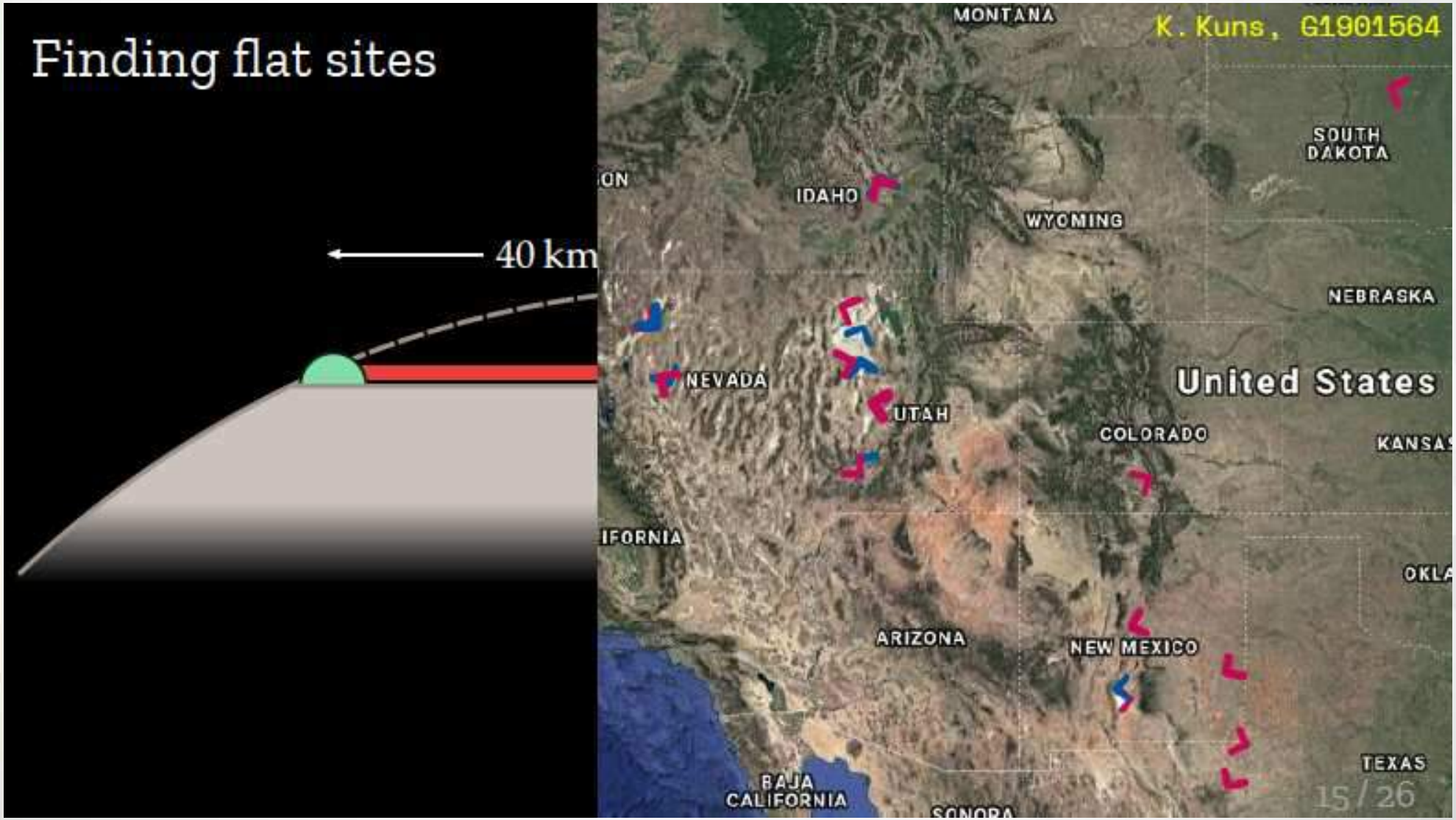


http://www.et-gw.eu/

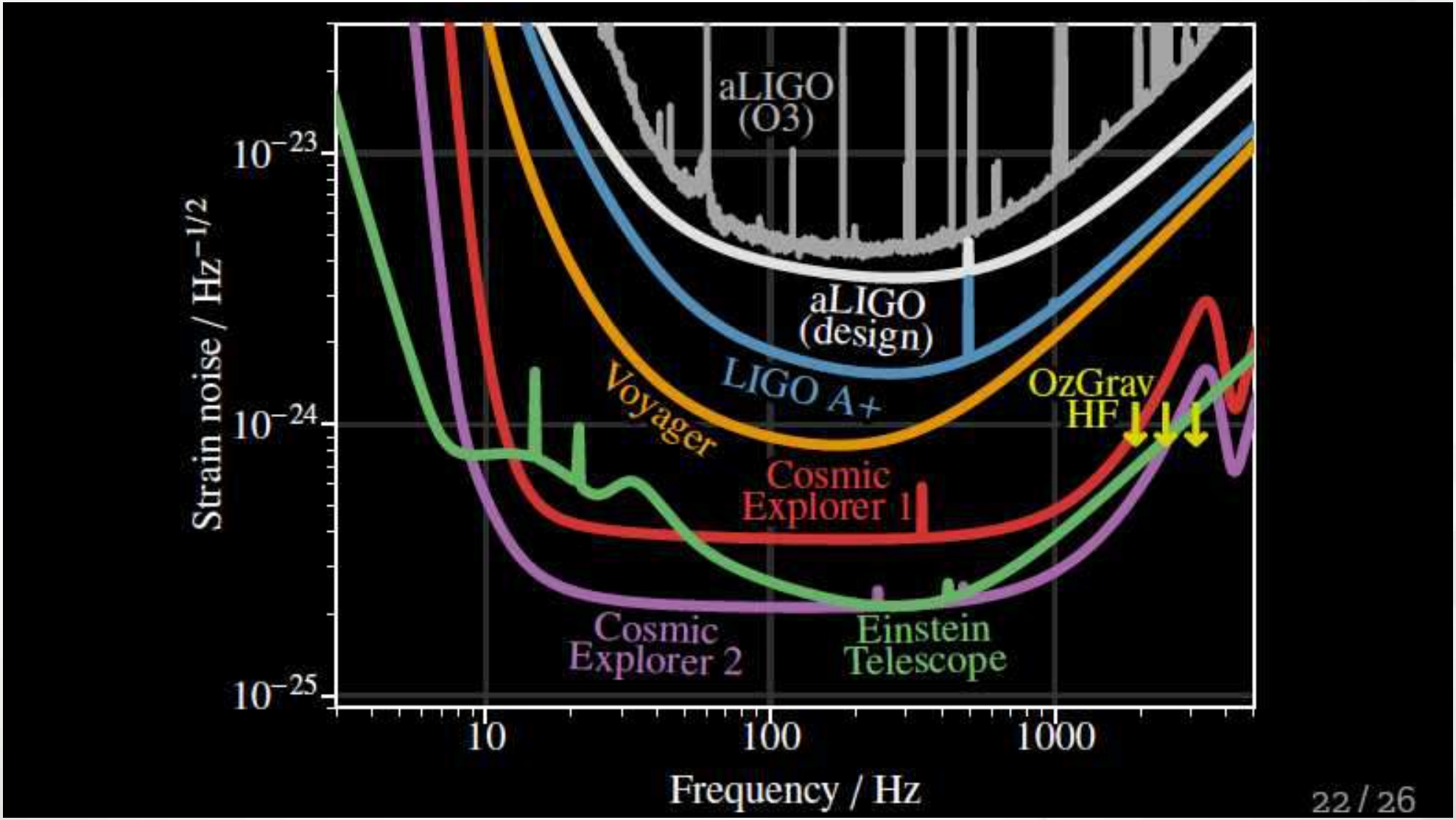

Cosmic Explorer
https://www.cosmicexplorer.org/


Finding flat sites
40 km
30 m
15 / 26

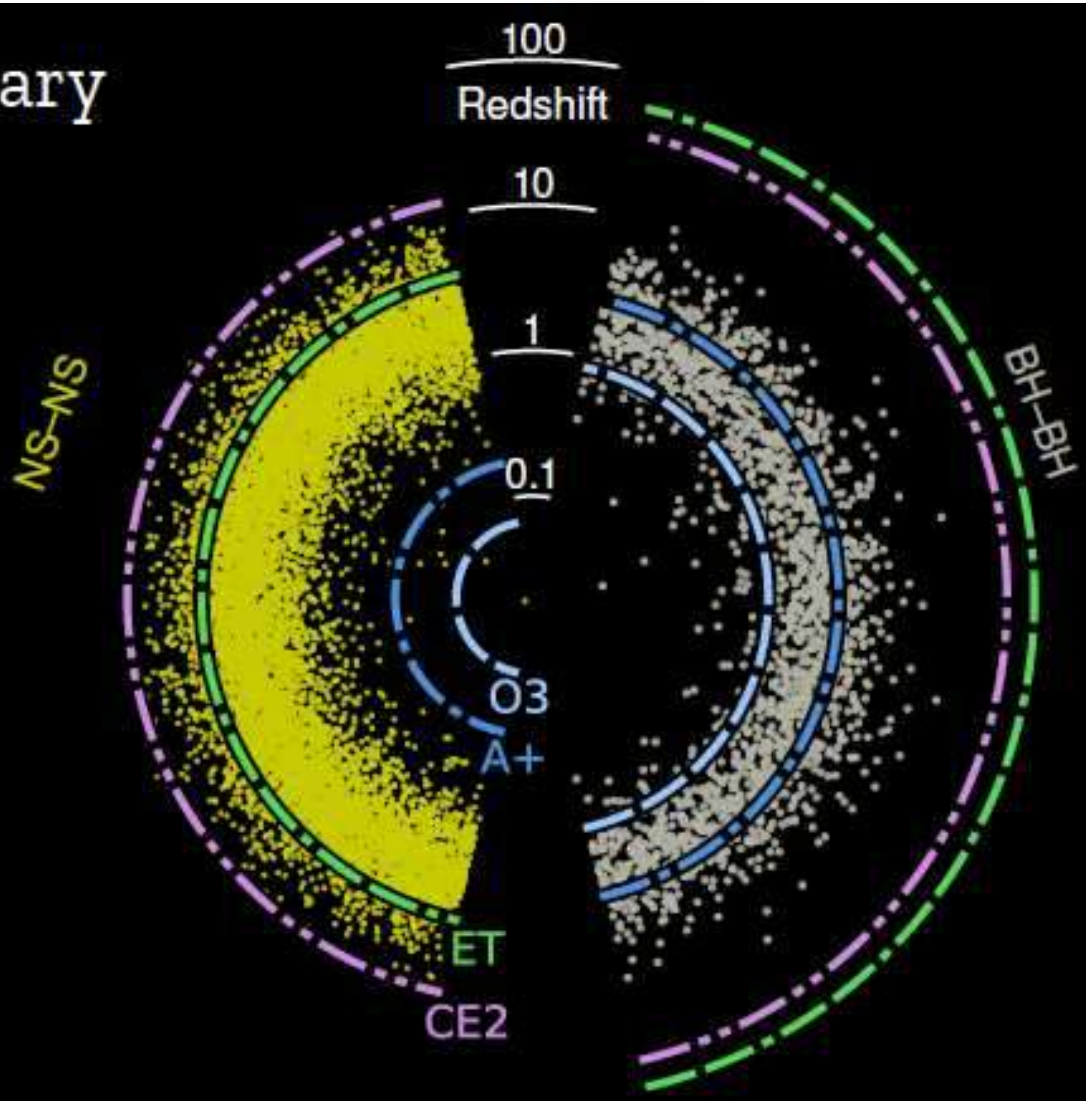
Credit: Evan Hall (LIGO, MIT)



Credit: Evan Hall (LIGO, MIT)



Compact binary horizons



Hall/Vitale, G1900803

3G R&D

- the current status of R&D
- Foreseeable requirements
- Paths towards these goals
- Coordination requirements

https://gwic.ligo.org/3Gsubcomm/documents/GWIC_3G_R_D_Subcommittee_report_July_2019.pdf

GWIC, GWIC-3G, GWIC-3G-R&D-Consortium

H. Lück, G1901698

Contents

- Facilities & Infrastructures
- Core Optics
- Coatings
- Cryogenics
- Newtonian Noise
- Light Sources
- Quantum Enhancements
- SAS & SUS
- Auxilliary Optics
- Simulation and Controls
- Calibration

https://gwic.ligo.org/3Gsubcomm/

SAGO – South American Gravitational wave Observatory

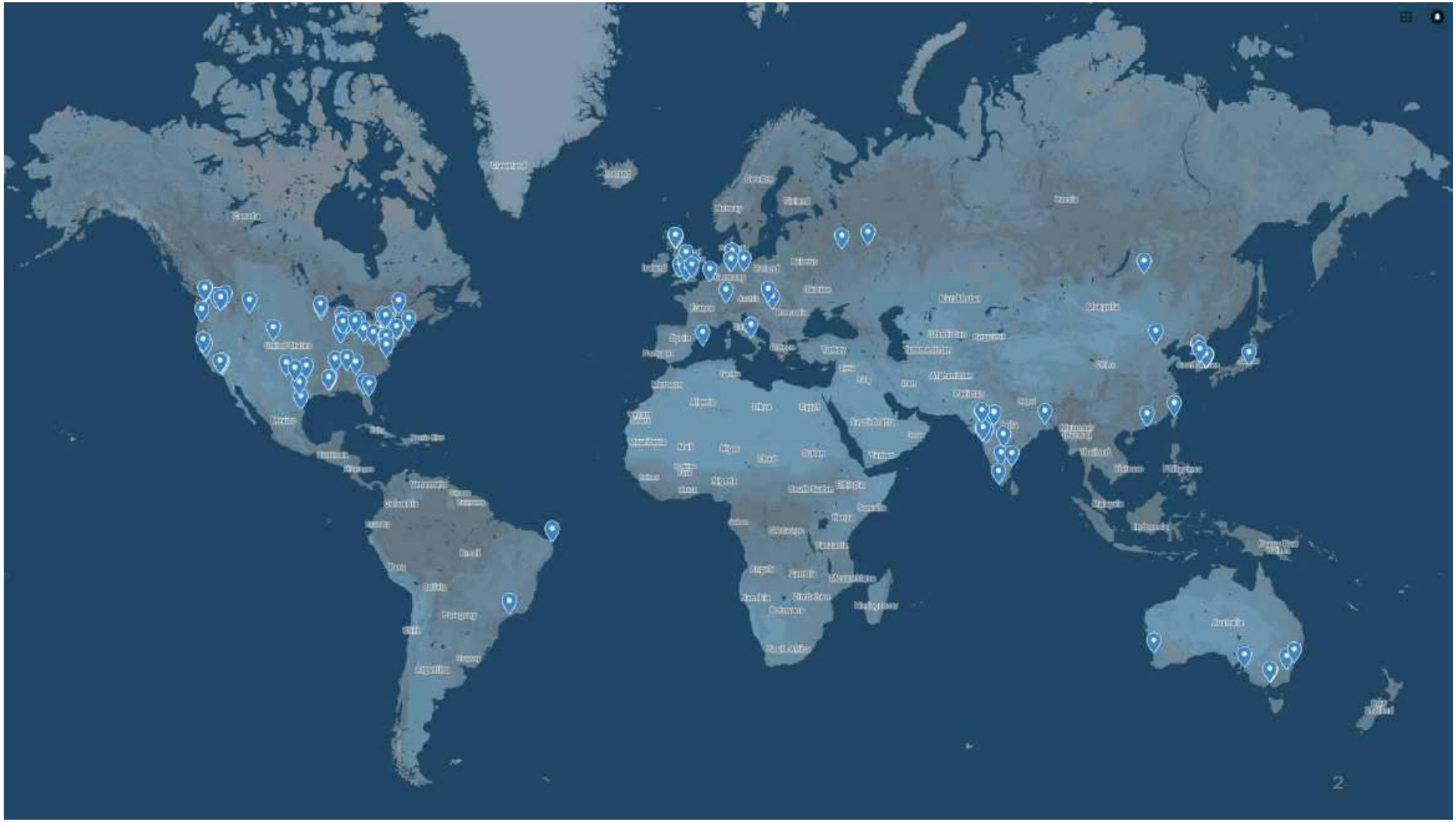
Google Maps

500 km

Google Maps

Google Maps

Imagens ©2019 Landsat / Copernicus, Data SIO, NOAA, U.S. Navy, NGA, GEBCO, Imagens ©2019 TerraMetrics, Dados do 100 km
mapa ©2019 Google



LSC/GWINPE: 6 members; **LSC/IIP/UFRN:** 2 members; **LSC/AEI:** Marina Neri (Brazil);
LSC/USA: Claudia Moreno (Mexico); **Virgo/Italy**: Iara Tosta e Melo (Brazil); **Virgo/Belgium**: Elvis C. Ferreira (Brazil);
Virgo/Netherlands: Enzo Tapia (Chile), **Virgo/Brazil:** Edison Santos (Brazil);
KAGRA: Fabian Peña Arellano (Peru). **TOTAL :** 15+ We will need about 100 or more for a successful proposal.

A Astronomia de Ondas Gravitacionais (AOG) vai revolucionar o nosso conhecimento da física e astrofísica e, provavelmente, nos ajudar a responder às principais questões da atualidade: a matéria escura, a energia escura e como o Universo teve início.

Gravitational Wave Astronomy (AOG) will revolutionize our knowledge of physics and astrophysics and will probably help us to answer main current questions: dark matter, dark energy and how the Universe got started.

DUAS VISÕES DO PRINCÍPIO

Em nosso Universo em expansão, as galáxias se afastam rapidamente umas das outras, a uma velocidade proporcional à distância entre elas: duas galáxias separadas por uma distância de 500 milhões de anos-luz se afastam a uma velocidade duas vezes maior do que duas galáxias separadas por uma distância de 250 milhões de anos-luz. Por isso, todas as galáxias que vemos devem ter se originado em um mesmo ponto e ao mesmo tempo — o Big Bang. A conclusão é válida mesmo quando a expansão cósmica passou por períodos de aceleração e desaceleração; em diagramas de espaço-tempo (*abaixo*), as galáxias seguem trajetórias sinuosas que as levam para dentro e para fora da região observável do espaço (*triângulo amarelo*). No entanto, a situação torna-se incerta no instante exato em que as trajetórias das galáxias (ou suas predecessoras) começaram a divergir.

SAMUEL VELASCO

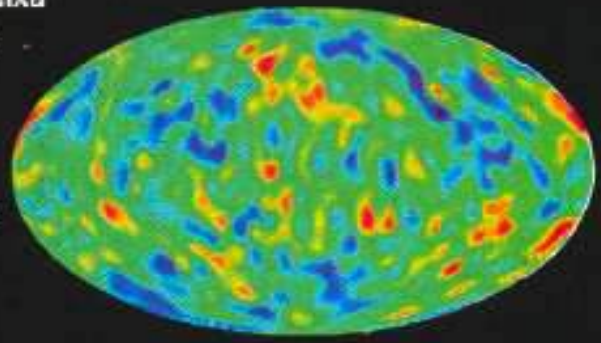
Na cosmologia do Big Bang convencional, que se baseia na teoria da relatividade geral de Einstein, a distância entre quaisquer duas galáxias era zero há um tempo finito. O tempo perde significado antes desse instante.

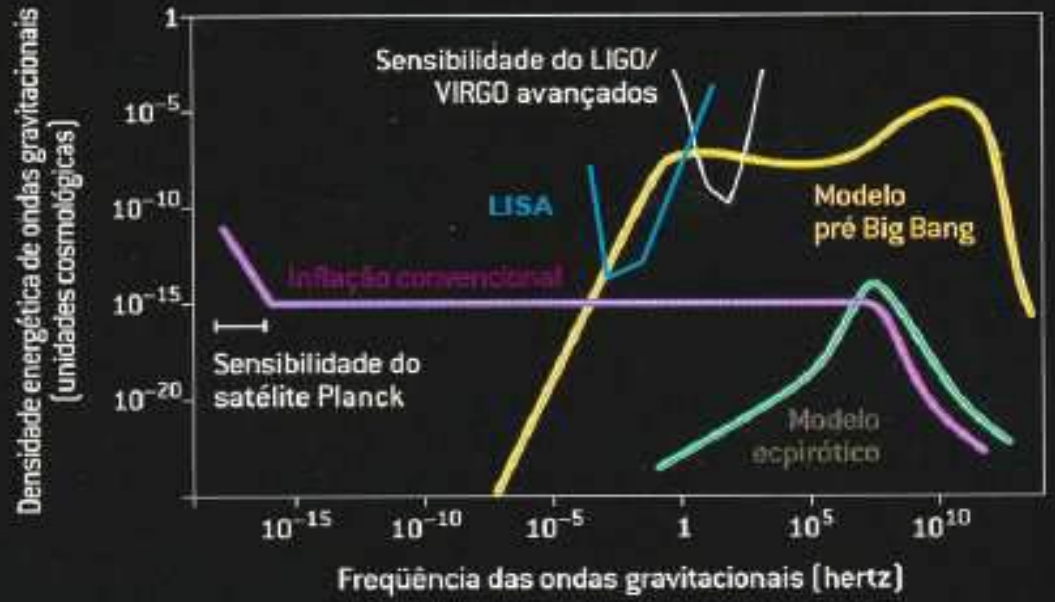
Nos modelos mais sofisticados, que incluem efeitos quânticos, quaisquer duas galáxias devem ter surgido a uma certa distância mínima uma da outra. Esses modelos abrem a possibilidade de um Universo pré-Big Bang.

Gabriele Veneziano, 2004
Scientific American Brasil

EFEITO DE FUNDO

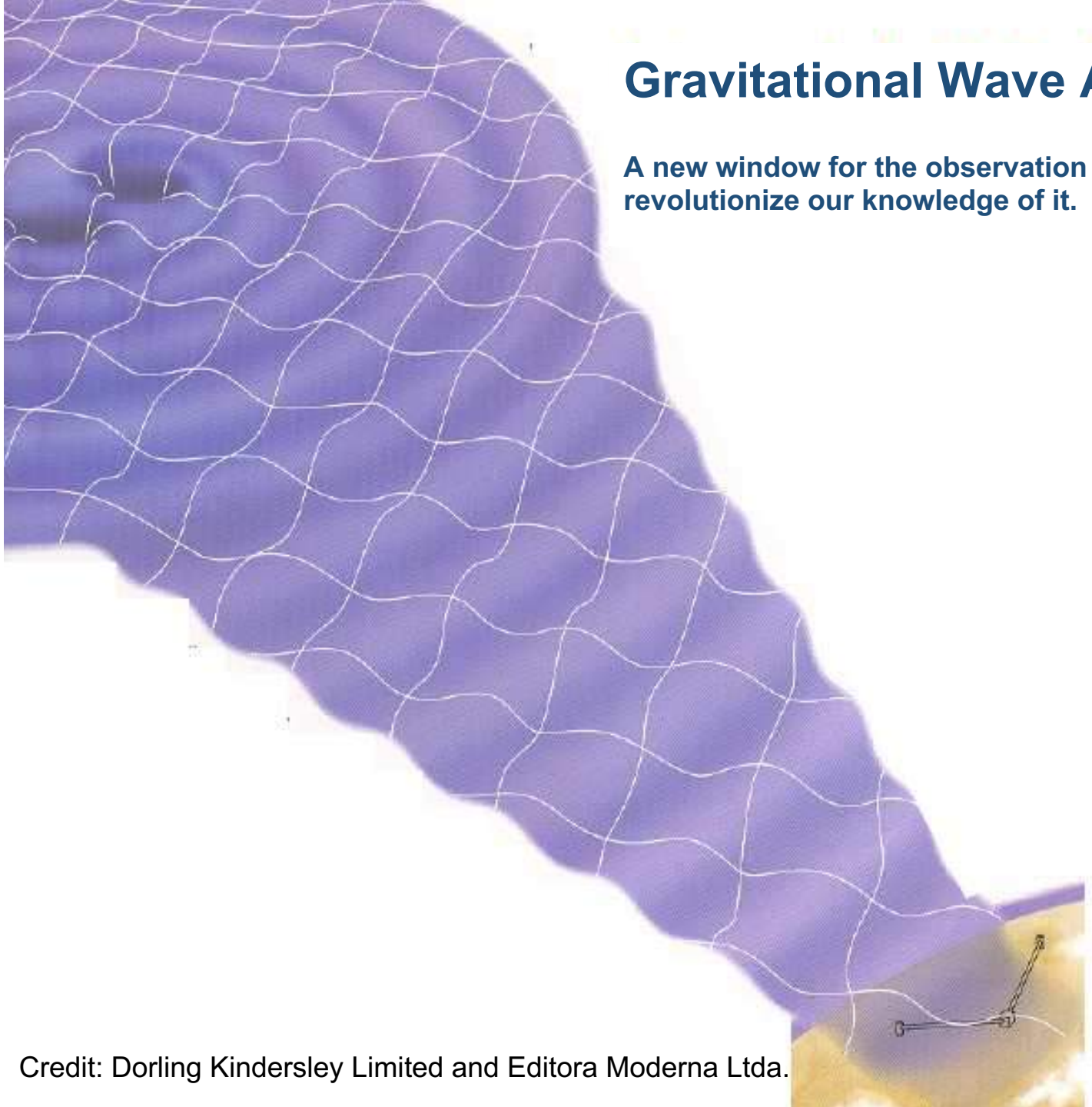
Observar o Universo pré-Big Bang pode parecer uma tarefa sem futuro, mas uma forma de radiação poderia sobreviver desde aquela época: a radiação gravitacional. Essas variações periódicas na campo gravitacional poderiam ser detectadas indiretamente, por seu efeito na polarização do fundo cósmico de microondas (*vista simulada, abaixo*), ou diretamente, em observatórios terrestres. Os cenários pré-Big Bang e ecpirótico prevêem mais ondas gravitacionais de alta freqüência e menos de baixa freqüência do que os modelos convencionais de inflação (*abaixo*). Medidas existentes de vários fenômenos astronômicos não conseguem fazer a distinção entre esses modelos, mas futuras observações do satélite Planck, assim como dos observatórios LIGO e VIRGO, devem ser capazes disso.





Gravitational Wave Astronomy

A new window for the observation of the universe that will revolutionize our knowledge of it.



Credit: Dorling Kindersley Limited and Editora Moderna Ltda.

https://gravitationalwaveastronomy.org

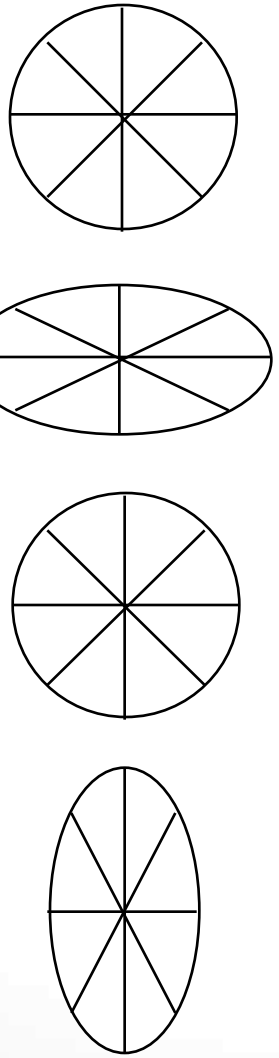
www.gov.br/**mcti** /mctic

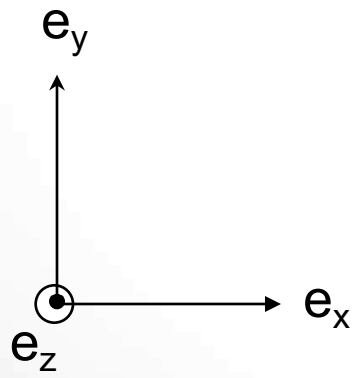
Thanks for your attention!

Gravitational Waves are ripples in the spacetime that travel in the tissue of the spacetime with the speed of light

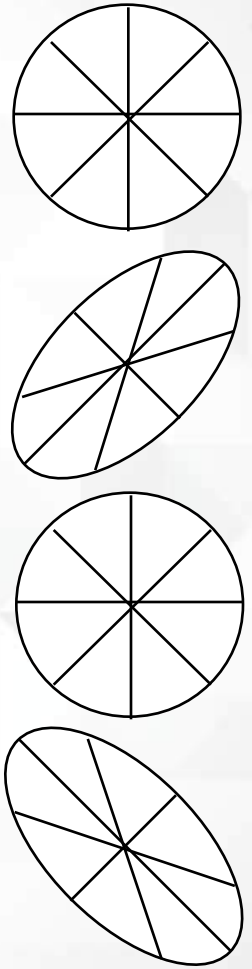
Two polarizations "+" e "x"

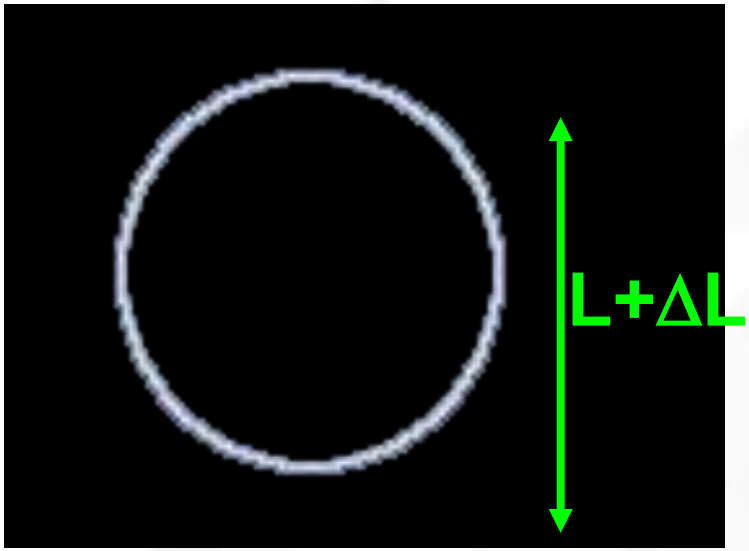
h_+





h_x





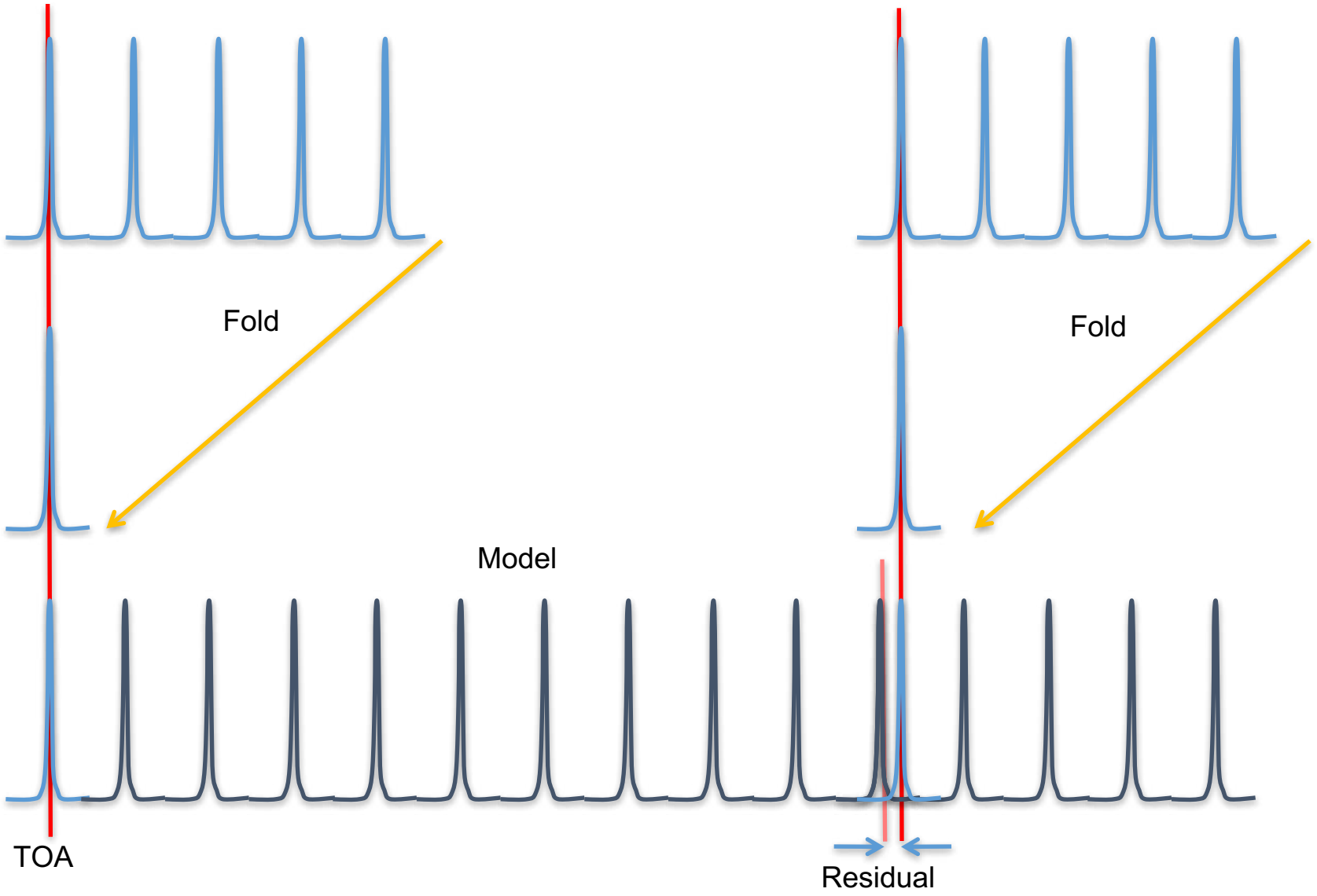
Deformations on a ring

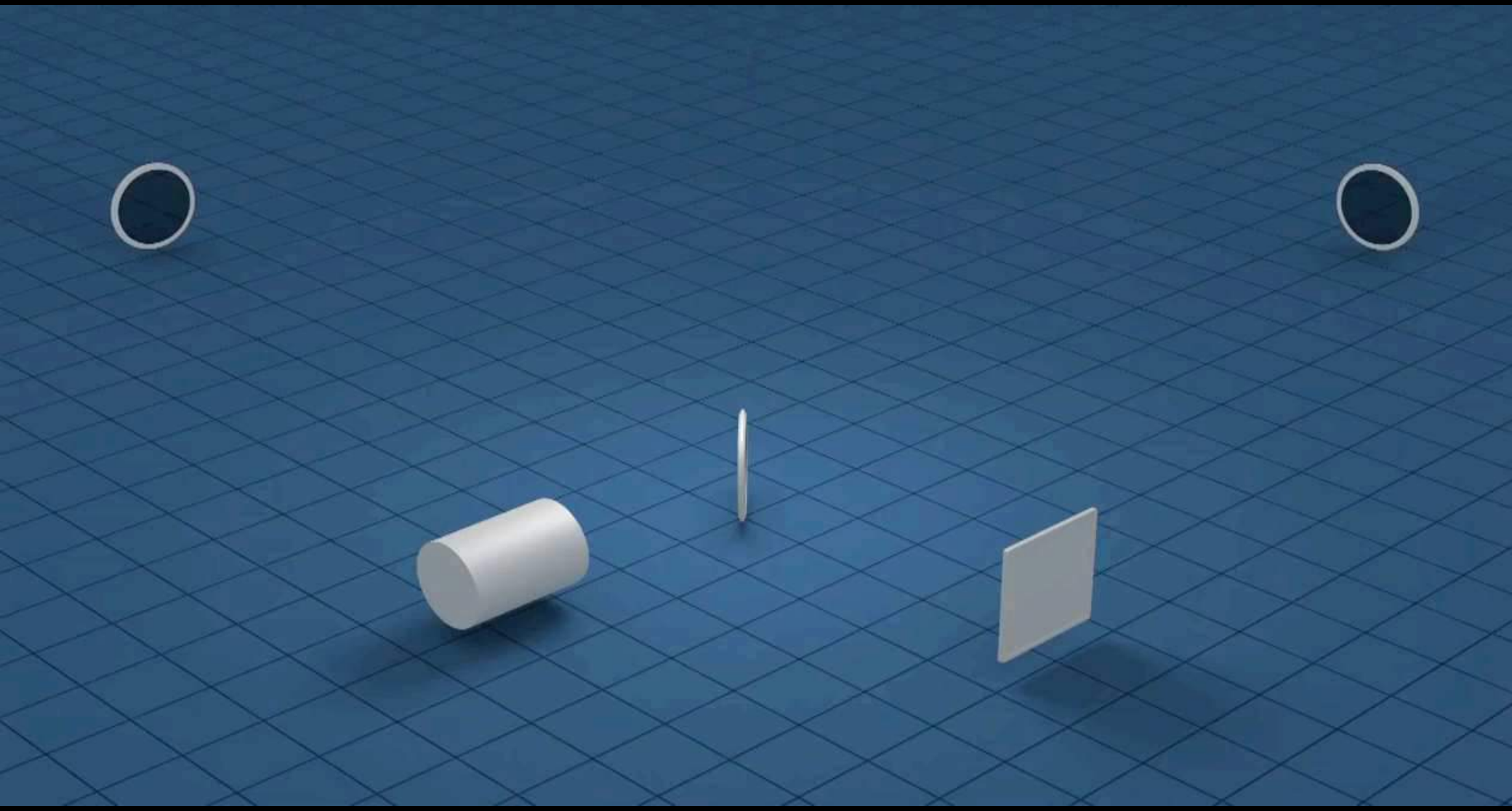
$$h = \Delta L/L = ((h_+)^2 + (h_x)^2)^{1/2}$$

credit: Arlette de Ward

Slide from D. Champion

Pulsar timing





Before asking money for a proposal, we need to ask fellowships and research money in order to create a critical mass of researchers in Latin America with knowledge on the 3G technology. So, we need to involve Latin American students and post-docs in the present projects (LIGO, Virgo, KAGRA, LIGO India, ET, and Cosmic Explorer) and attract them and foreign post-docs with knowledge on 3G to form groups in Latin America.