Multi-messenger Astronomy – Gravitational Waves

The Variable Universe – Lecture 11
Fall Semester 2022

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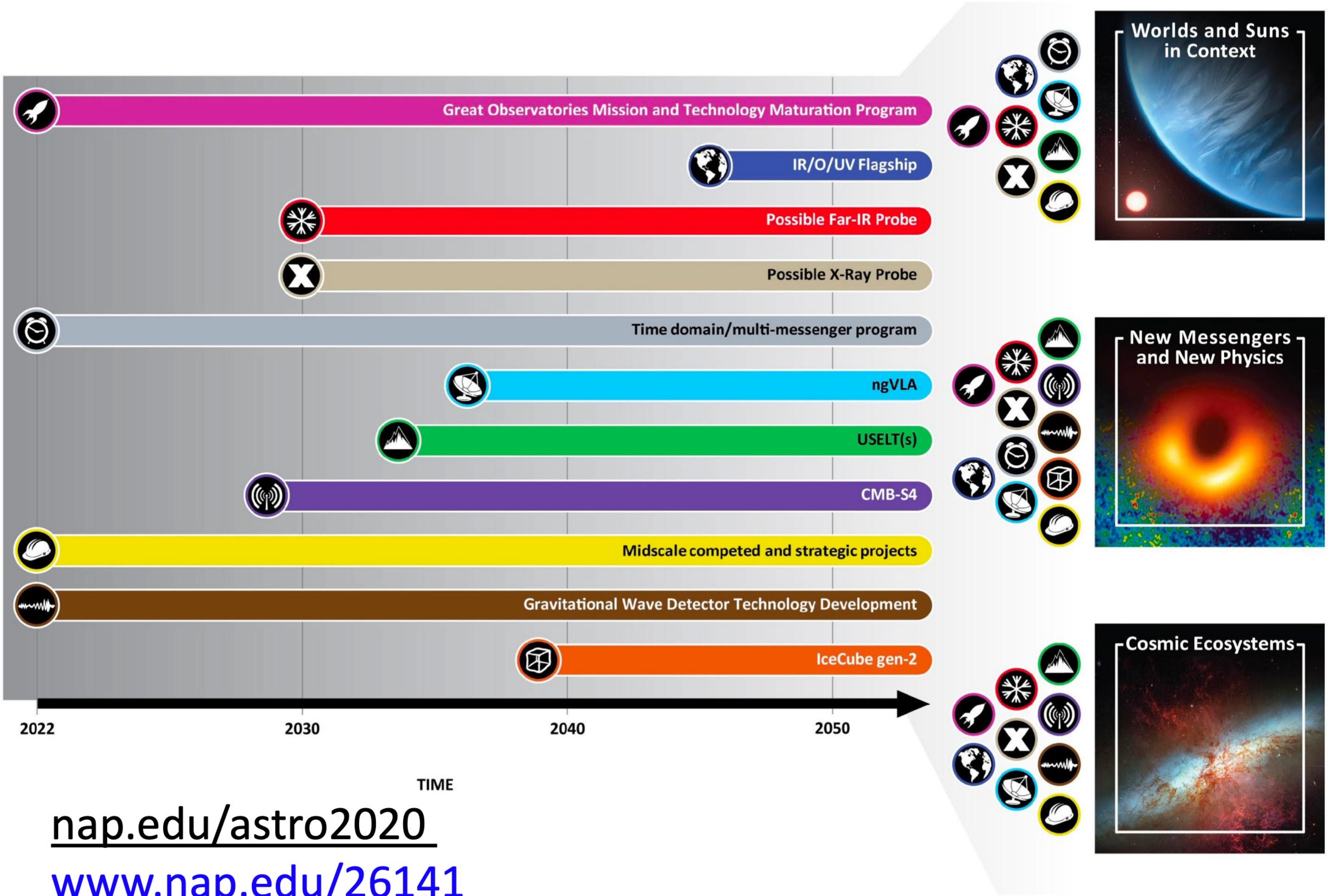
EPFL

“Gravitational wave detection is one of the most exciting and expanding scientific frontiers impacting central questions in astronomy “

US Decadal Survey – astro 2020 public briefing slides

Check out astro2020 – US decadal survey results!



nap.edu/astro2020

www.nap.edu/26141

LIGO's Impact on Science and Technology

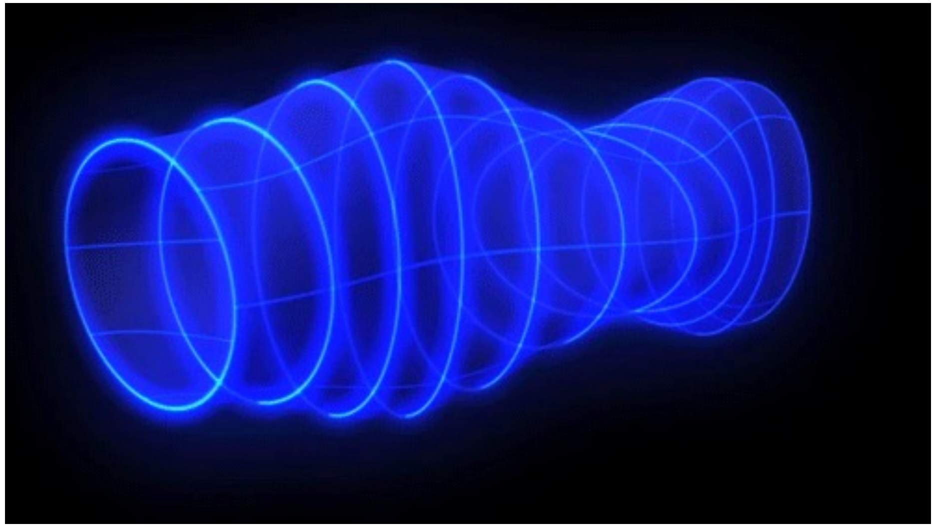
https://www.ligo.caltech.edu/page/science-impact

- Astronomy / Physics-related questions:
  - Is general relativity the correct theory of gravity?
  - How does matter behave under extreme densities and pressures?
  - How abundant are stellar-mass black holes?
  - What is the central engine driving gamma ray bursts?
  - What happens when a massive star collapses?
- Technology transfer/impact
  - High-precision metrology for quantum measurements
  - Optics, quantum mechanics, and laser systems
  - Cryogenics and related technology
  - Fast chirp transform
- And many more…

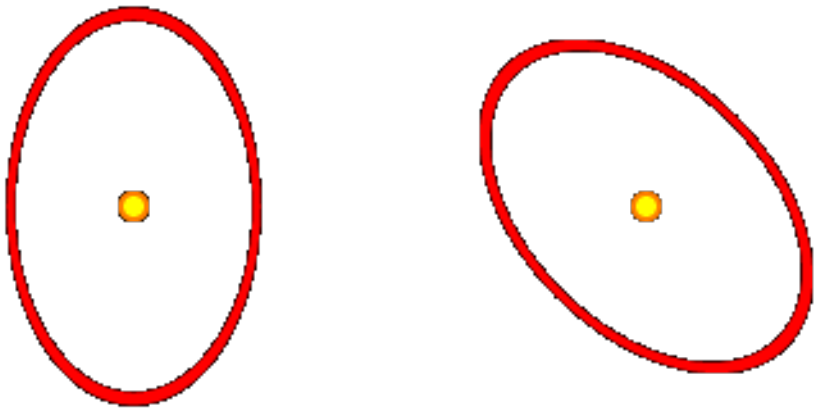
Fun facts about Gravitational Waves

- GWs penetrate all regions of spacetime; only significant changes incurred are amplitude decay and redshift
- Coupling constant to matter: $G = 6.67\times10^{-8}\ cm^3 s^{-2} g^{-1}$ is small
  - Little absorption of GWs by matter
  - Very hard to detect!
- GWs can be focused or diffracted by strong gravitational fields
- GWs have frequency, amplitude, phase, and polarization
- GWs predicted by Einstein in 1916
- First GW detected by LIGO in 2015
- Planned instrumentation (LISA) can detect massive BH mergers at *any* redshift!

Gravitational waves

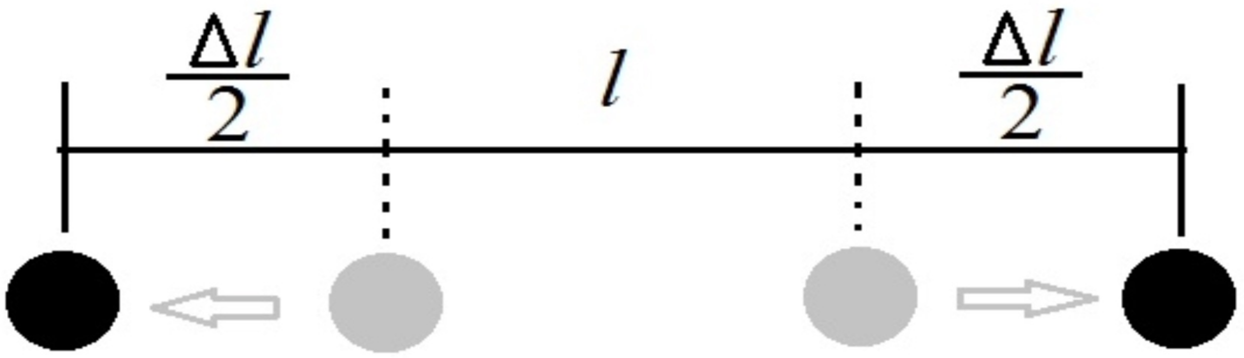


- Equivalence principle: inertial mass is same as gravitational mass
- Gravitational waves: changes in spacetime curvature between particles generated by time-varying quadrupole moment of gravitational tidal field
- GWs propagate at speed of light c
- GWs due to coherent bulk motion of matter
- Continuous GWs if perturbation is oscillatory: e.g., orbital motion
- GWs are "transverse traceless" (TT projection): force only perpendicular to direction of propagation & shearing causes no overall contraction or expansion

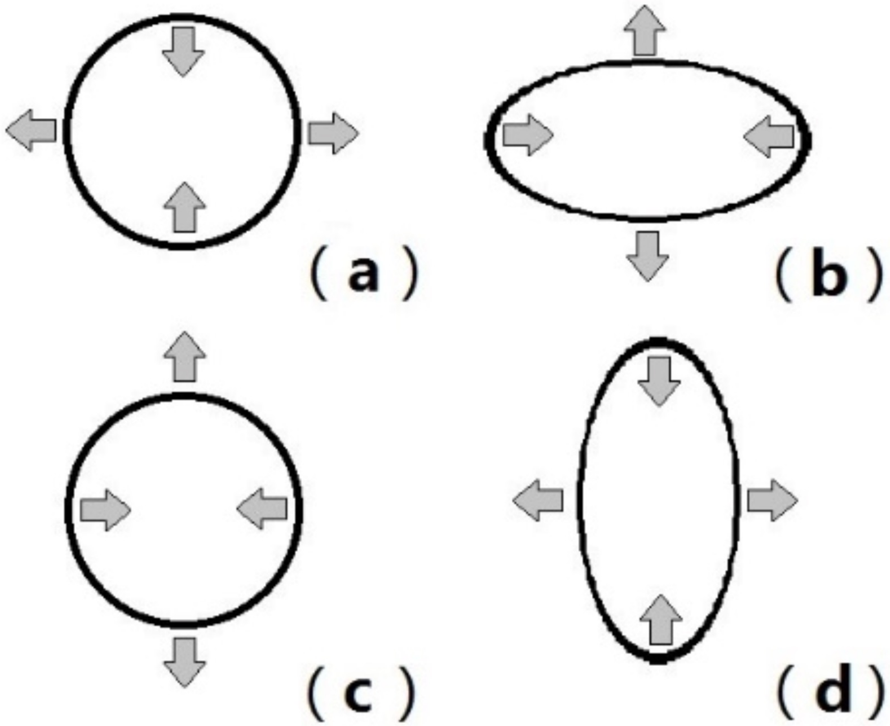


+ polarization x polarization

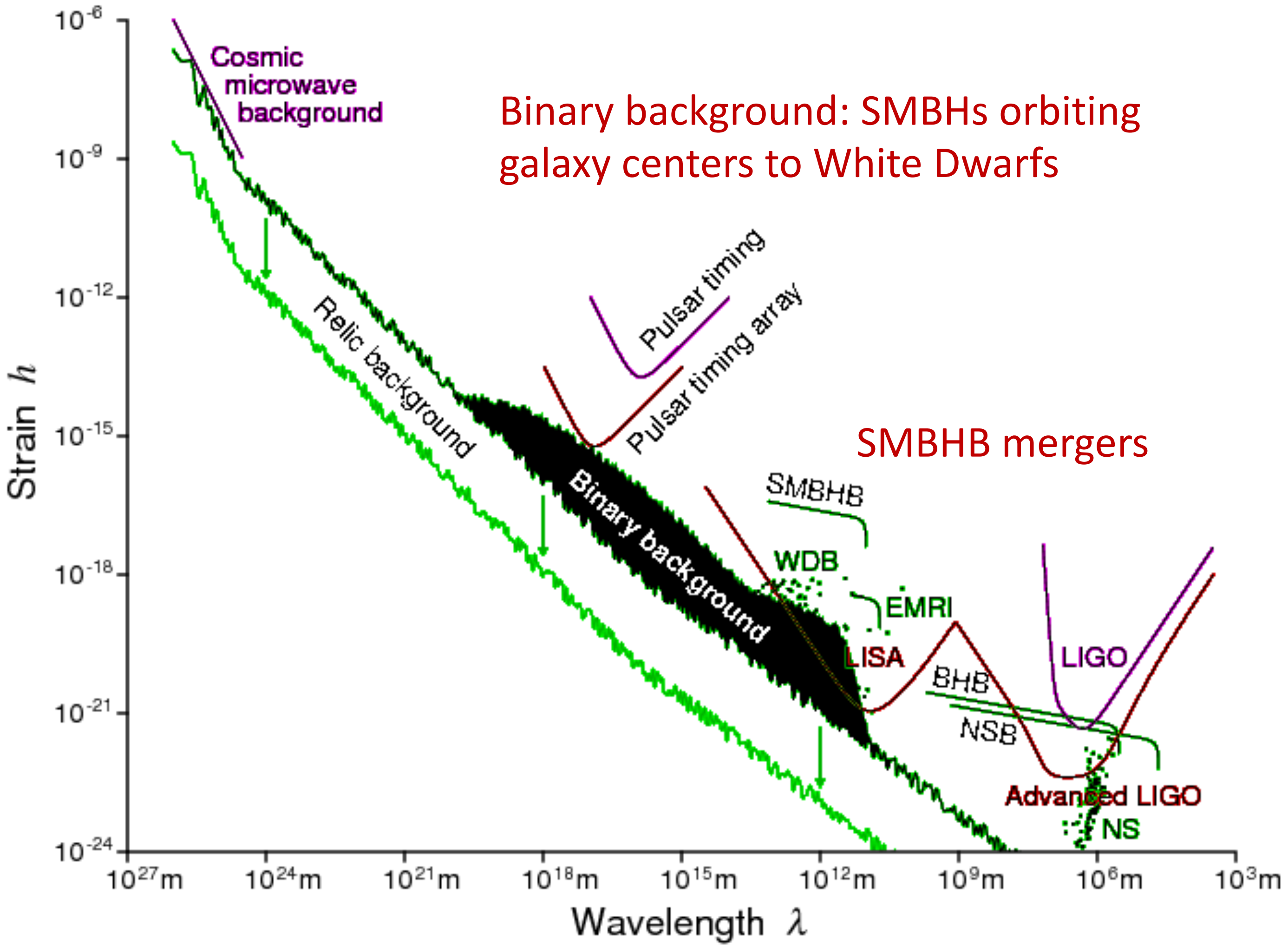
The Strain $h \approx \Delta l / l$



- Gravitational radiation accompanies quadrupolar acceleration of any kind of mass or energy
- Quadrupolar motion in system with mass M, size R, distance D perturbs space time with dimensionless metric-strain amplitude
- Strain = fractional variation in proper spatial separations
- $h \approx 10^{-22} \left(\frac{E_{GW}}{10^{-4} M_{\odot}}\right)^{\frac{1}{2}} \left(\frac{f}{1kHz}\right)^{-1} \left(\frac{\tau}{1ms}\right)^{-\frac{1}{2}} \left(\frac{r}{15Mpc}\right)^{-1}$
- GW observatories sense strain by monitoring distance variations among interial proof masses
- Critical: shielding proof masses from non-gravitational perturbations



The Gravitational Wave spectrum



Binary background: SMBHs orbiting galaxy centers to White Dwarfs

SMBHB mergers

EMRI: Extreme Mass Ratio Inspirals. WD, NS, BH of a few solar masses being swallowed by SMBHs

NSB: Merging Neutron Star binaries

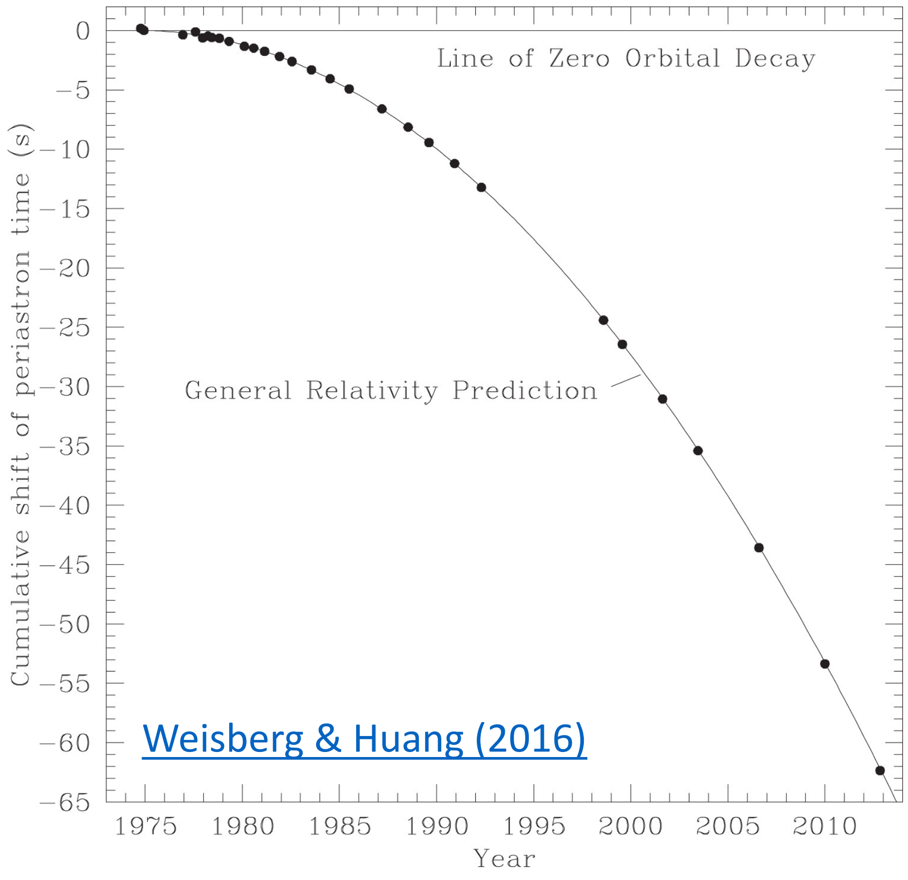
NS: single spinning Neutron Stars

Relic (upper limit): Big Bang Signal due to quantum fluxtucations amplified by expansion

A 50 year path to detections

- Einstein was not sure of reality of GWs at first
- First indirect detection by Taylor & Hulse (1974) by pulsar timing: matched predicted rate of orbital acceleration due to gravitational radiation emission
- Direct detection pioneered by Joseph Weber
- 1966 bar for GW detection reached strain sensitivity of 10^{-16}
- Laser interferometers proposed in the 1960s, first funding in the 1980s
- Collaborations between LIGO, VIRGO (Italo-French) and GEO600 (UK-Germany) crucial for technology development

Hulse-Taylor binary: PSR 1913+16



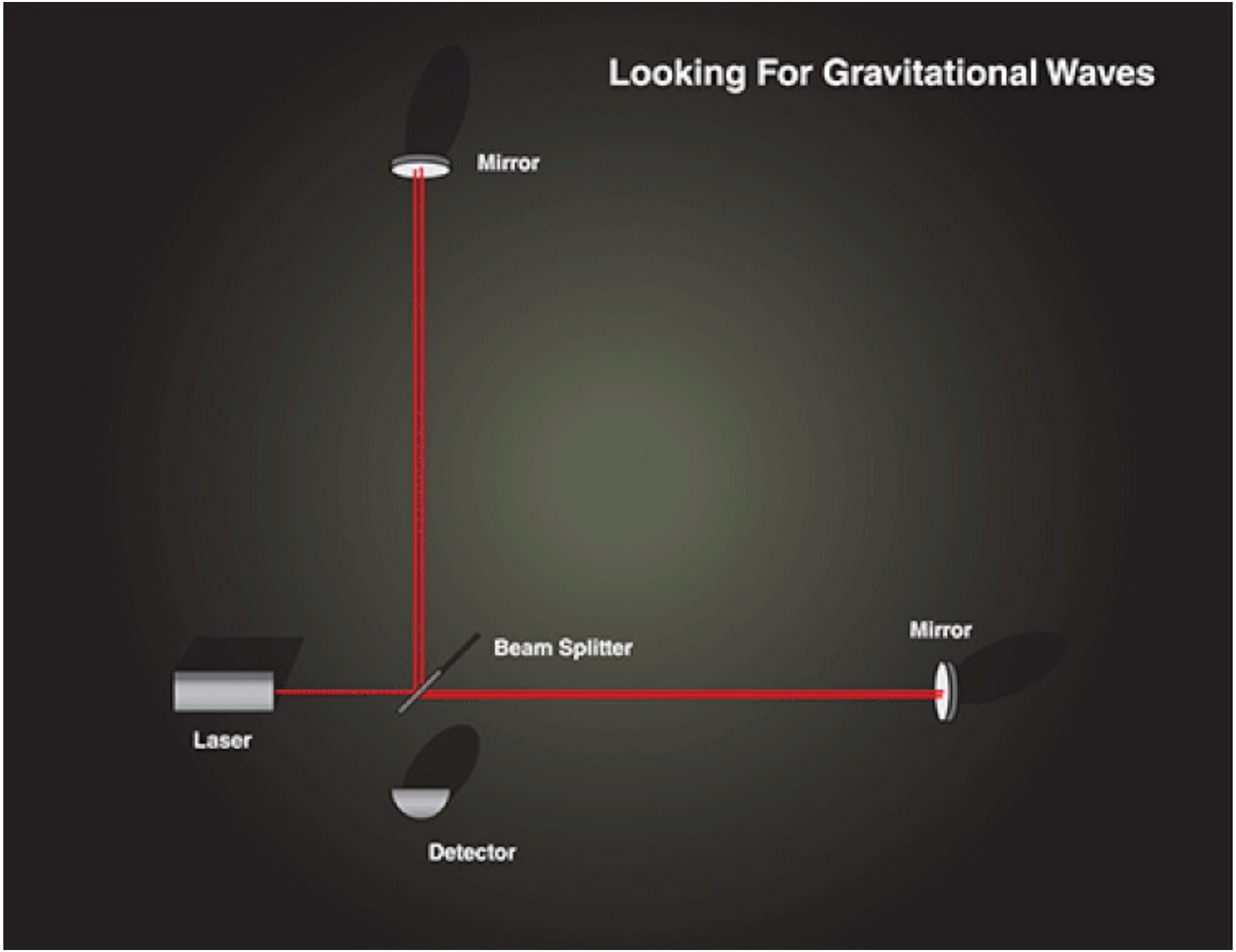
Weisberg & Huang (2016)

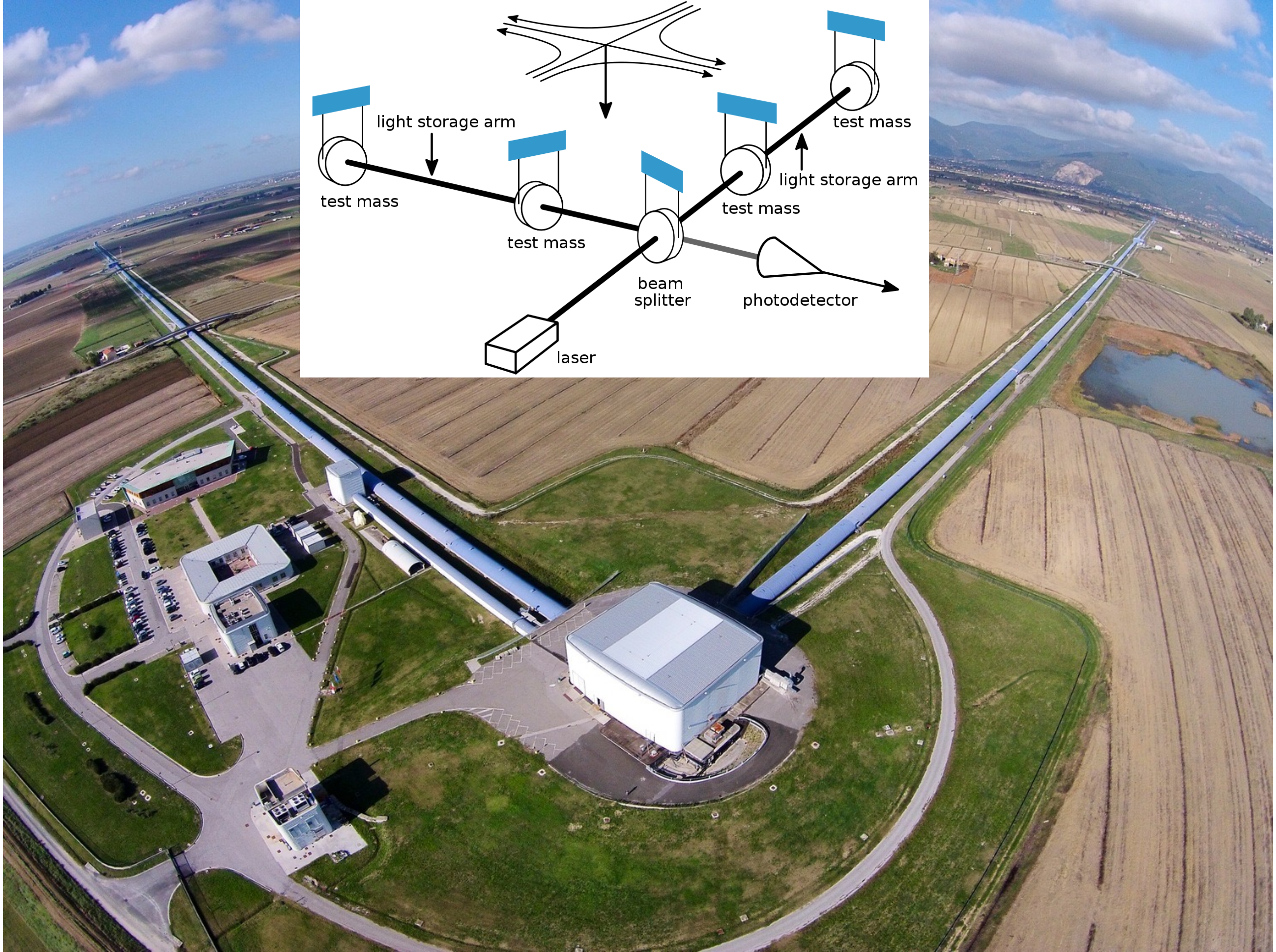
$L_{GW} \sim 0.02\, L_{\odot}$

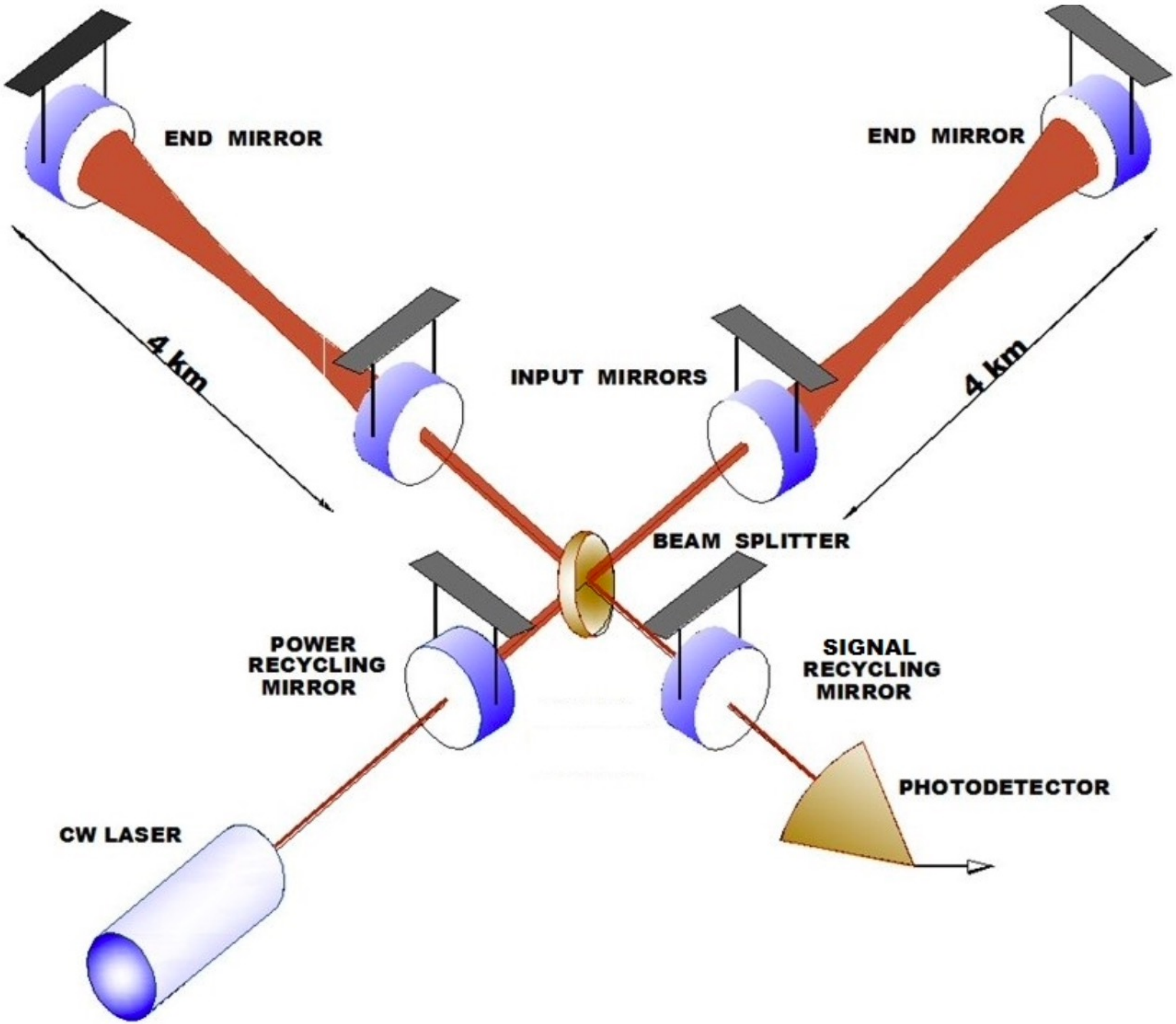
Laser Inferometer Gravitational Wave Observatory (LIGO)

https://www.ligo.caltech.edu/

Numbers given correspond to Advanced LIGO unless otherwise stated


Looking For Gravitational Waves
Mirror
Beam Splitter
Mirror
Laser
Detector


light storage arm
test mass
test mass
beam
splitter
test mass
test mass
light storage arm
photodetector
laser

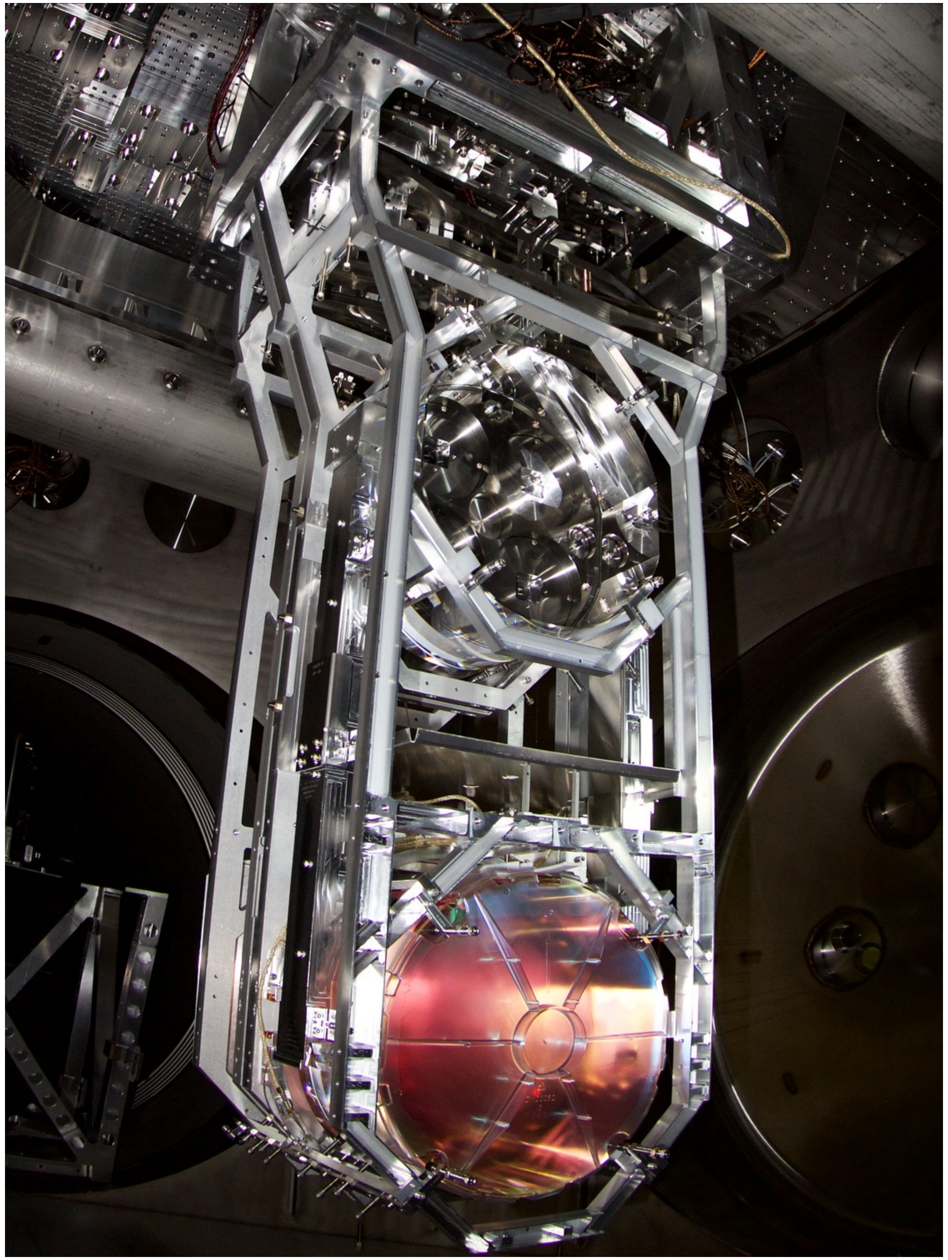


END MIRROR
END MIRROR
4 km
INPUT MIRRORS
4 km
BEAM SPLITTER
POWER RECYCLING MIRROR
SIGNAL RECYCLING MIRROR
PHOTODETECTOR
CW LASER

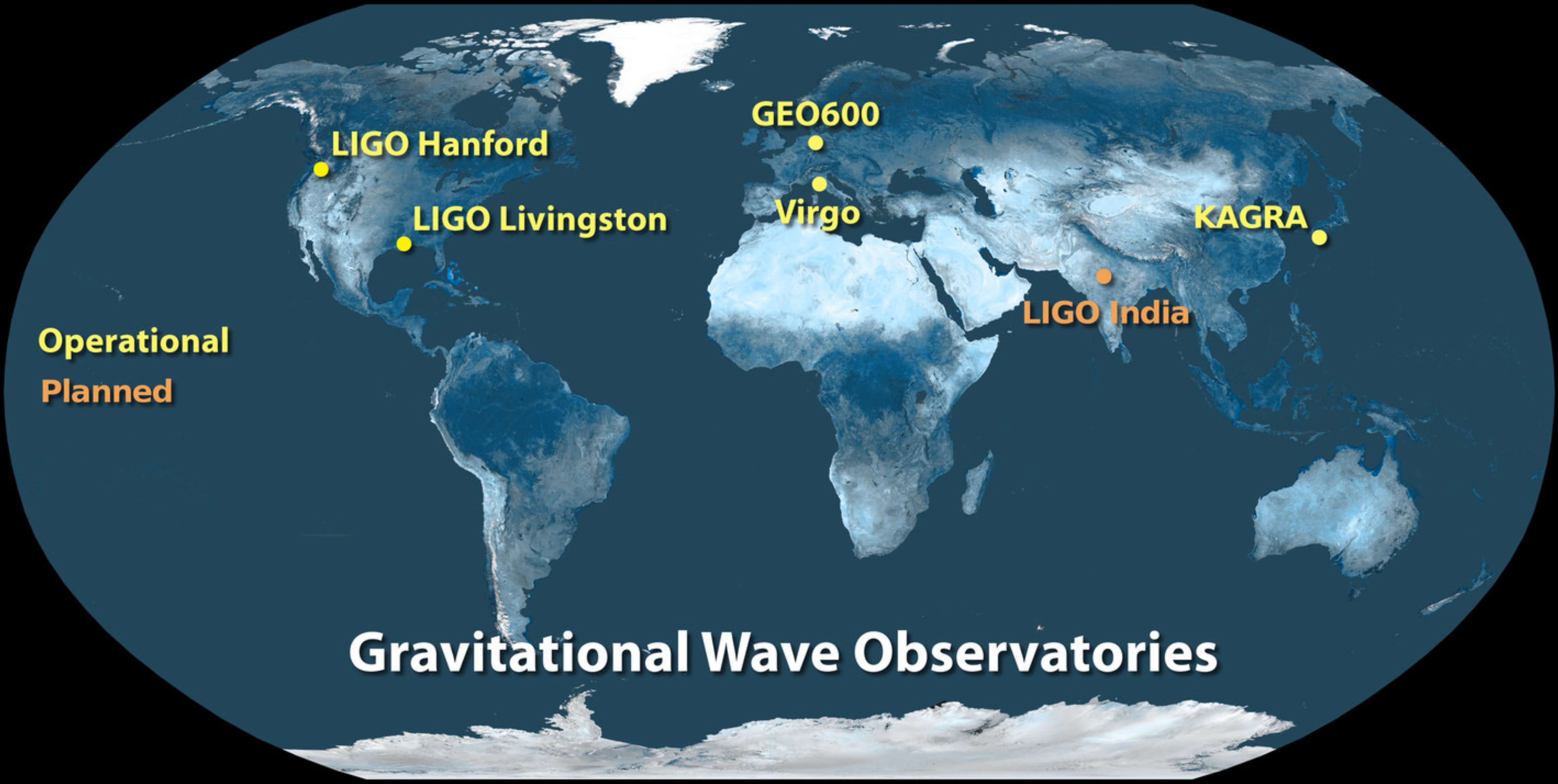
Isolating gravitational wave signals

https://www.ligo.caltech.edu/page/vibration-isolation

- LIGO’s arm cavities stable at a fraction of a picometer
- 4km long ultra-high vacuum chambers, diam=1.2m
- Seismic Isolation: counteract ground movements using permanent-magnet actuators (< 2×10^{-13}m)
  - Trucks driving by, ocean movement, earthquakes anywhere on Earth
- Suspension (10^{-19}m): 360kg quadruple-pendulum system (quad); test mass (40kg) suspended by 0.4mm fused silica threads (glass, lower internal motion than metal)
- Laser photons displace test masses & heat mirrors!
- Quad damping factor: 100 million



Credit: Caltech/MIT/LIGO Lab


GEO600
LIGO Hanford
Virgo
LIGO Livingston
KAGRA
LIGO India
Operational
Planned
Gravitational Wave Observatories

Gravitational Wave Open Science Center

https://www.gw-openscience.org/about/

- Good resource to get started on data analysis
- Includes learning materials, tutorials, workshops, etc.
- Check it out if you’re interested in working with GW data

O3b Bulk Data Now Available

GWTC-3 Catalog Data Now Available

Start with a Learning Path

Browse the Event Portal

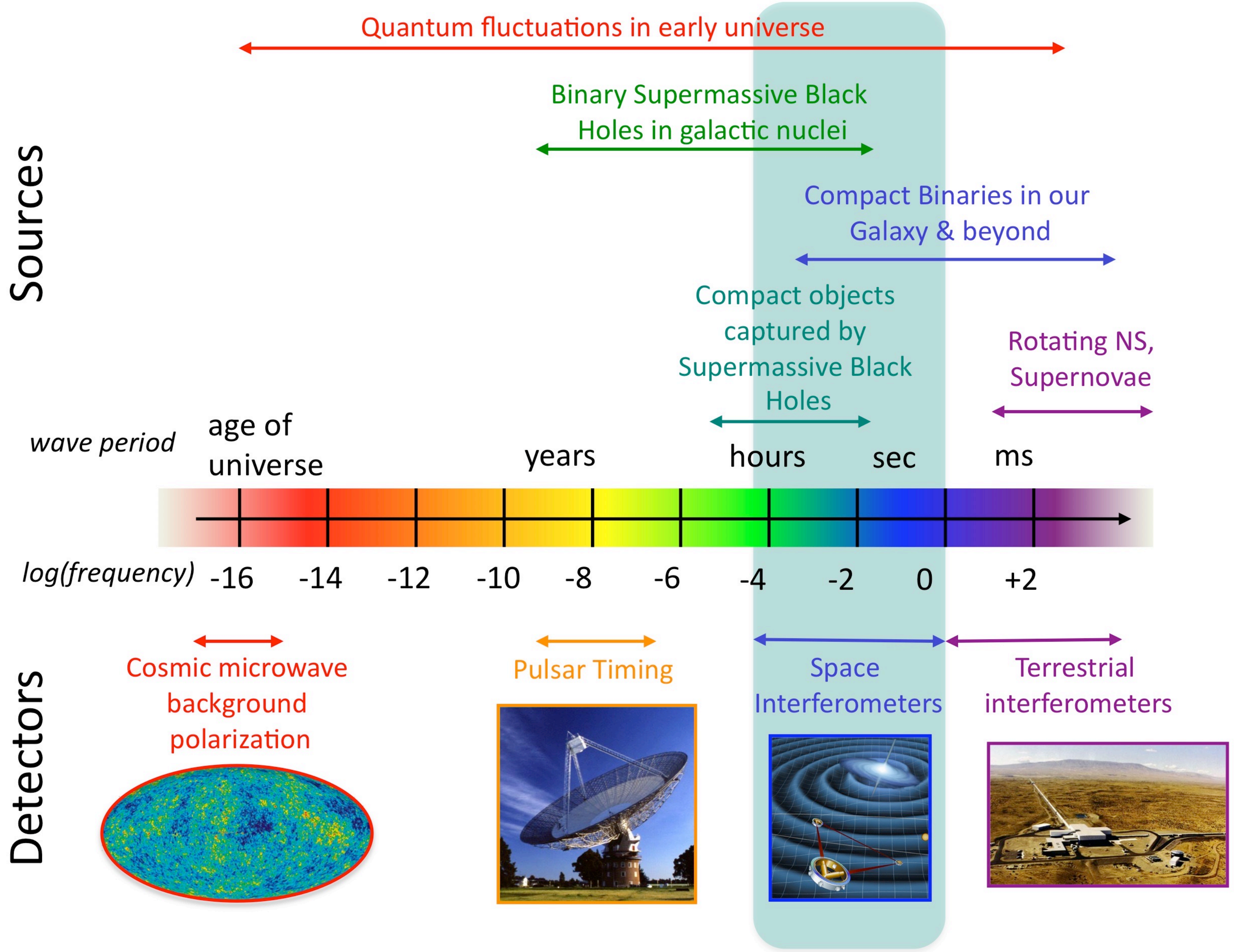
Download data

Join the email list

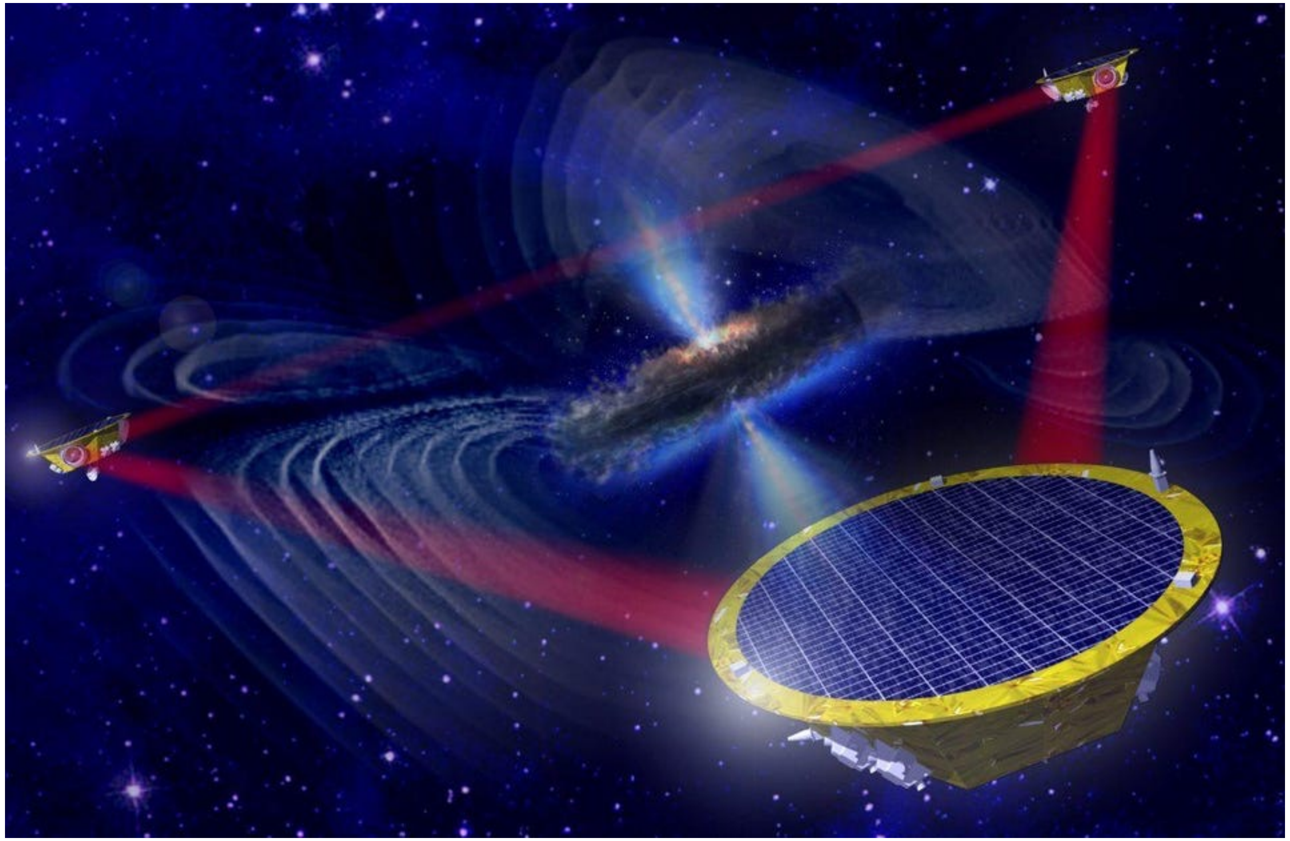
Open Data Workshops

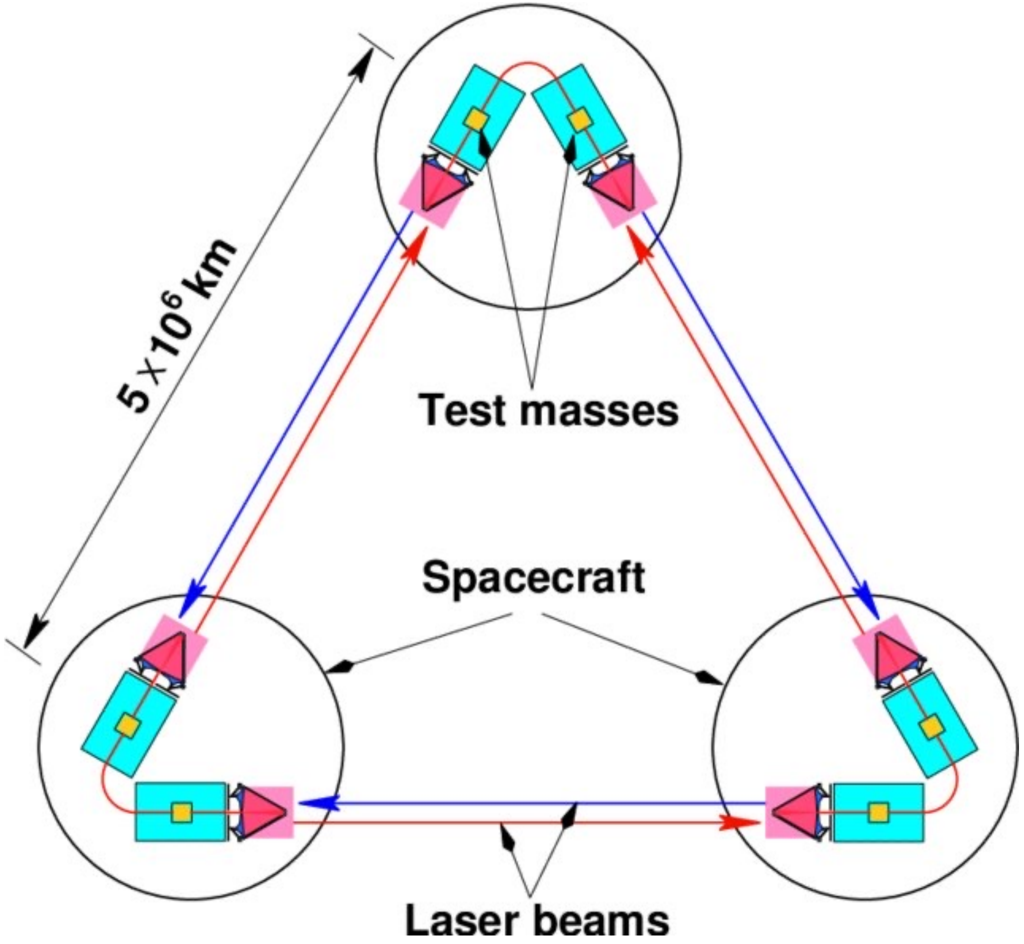
Attend Office Hours

The Gravitational Wave Spectrum



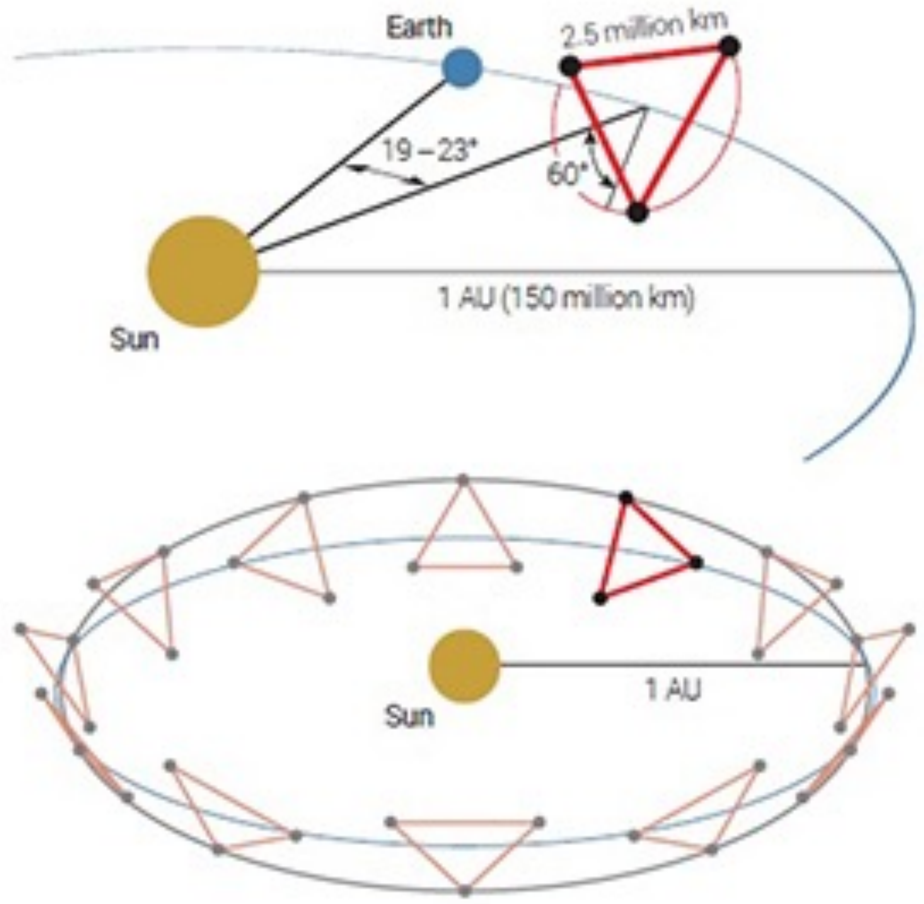
Laser Interferometer Space Antenna (LISA)

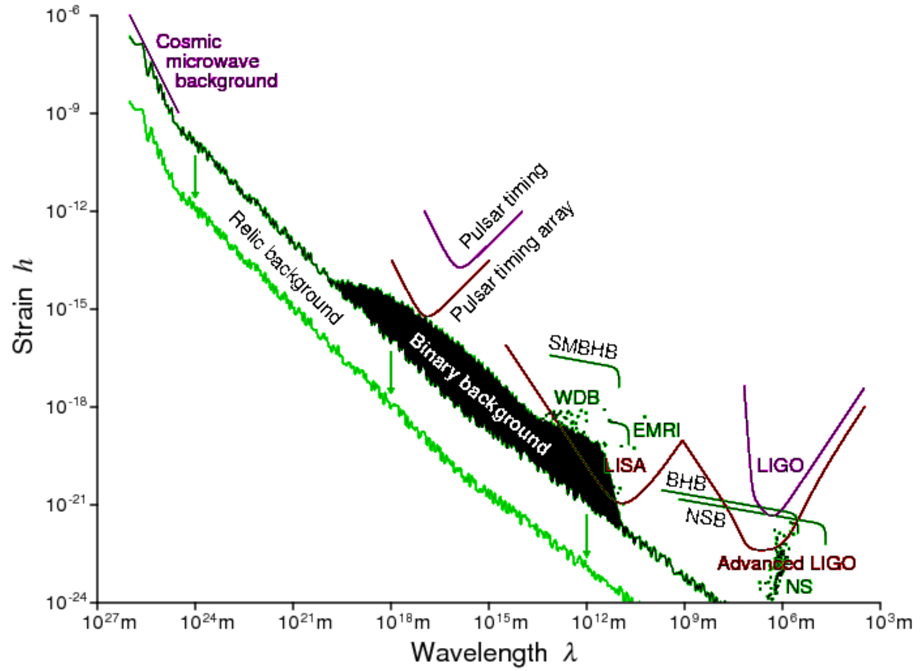




Laser Interferometer Space Antenna (LISA)

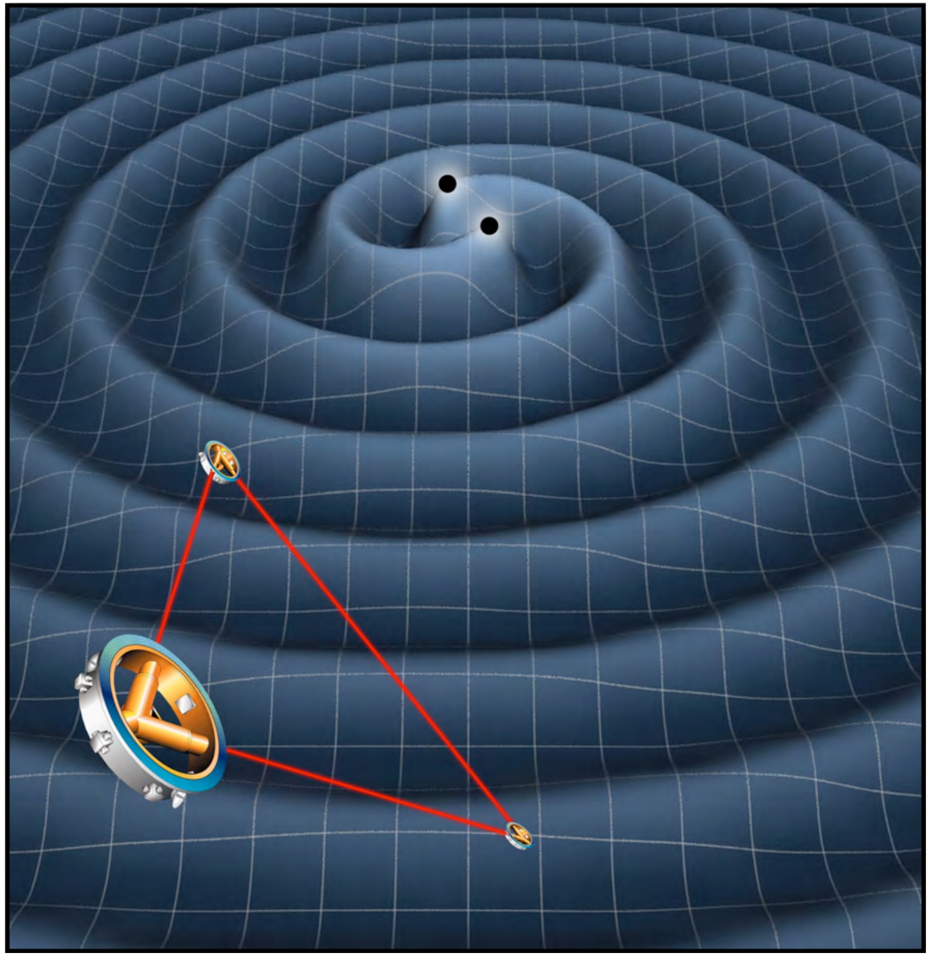
- ESA L-class mission (< 900M EUR)
- Launch: 2037, 4yr (+ 6 yr extension?)
- Earth-trailing orbit, 50M km distant





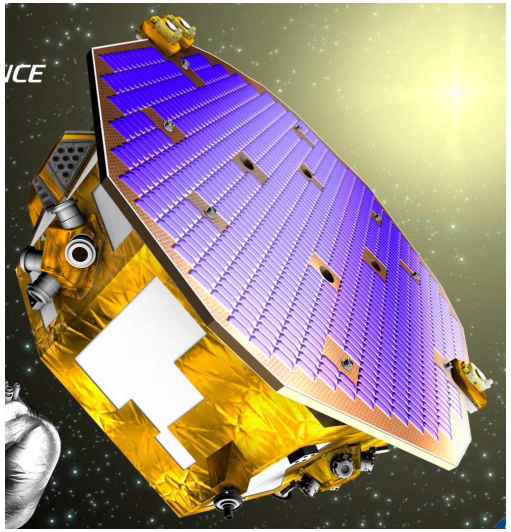
Laser Interferometer Space Antenna (LISA)

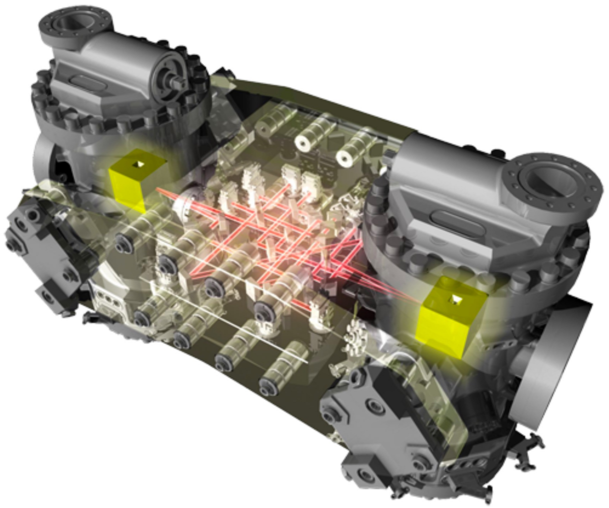
- Separation $\mathrm{L} \approx 2.5 \times 10^6 km$
- Precision: $\sigma_d \approx 0.05 \times 10^{-12} m$
- Strain sensitivity $h \approx L/\sigma_d \approx 10^{-23}$
- LISA measures spacetime strain variations coherently, including frequency, phase, polarization
- LISA has all—sky field of view
- Triangulation allows on-sky localization
- Huge dynamic range: $\Delta A/A = 10^5$ or $\Delta E/E = 10^{10}$
- At LISA frequencies, IMBH & SMBH are strongest sources with $M \sim 10^4 - 10^7 M_\odot$

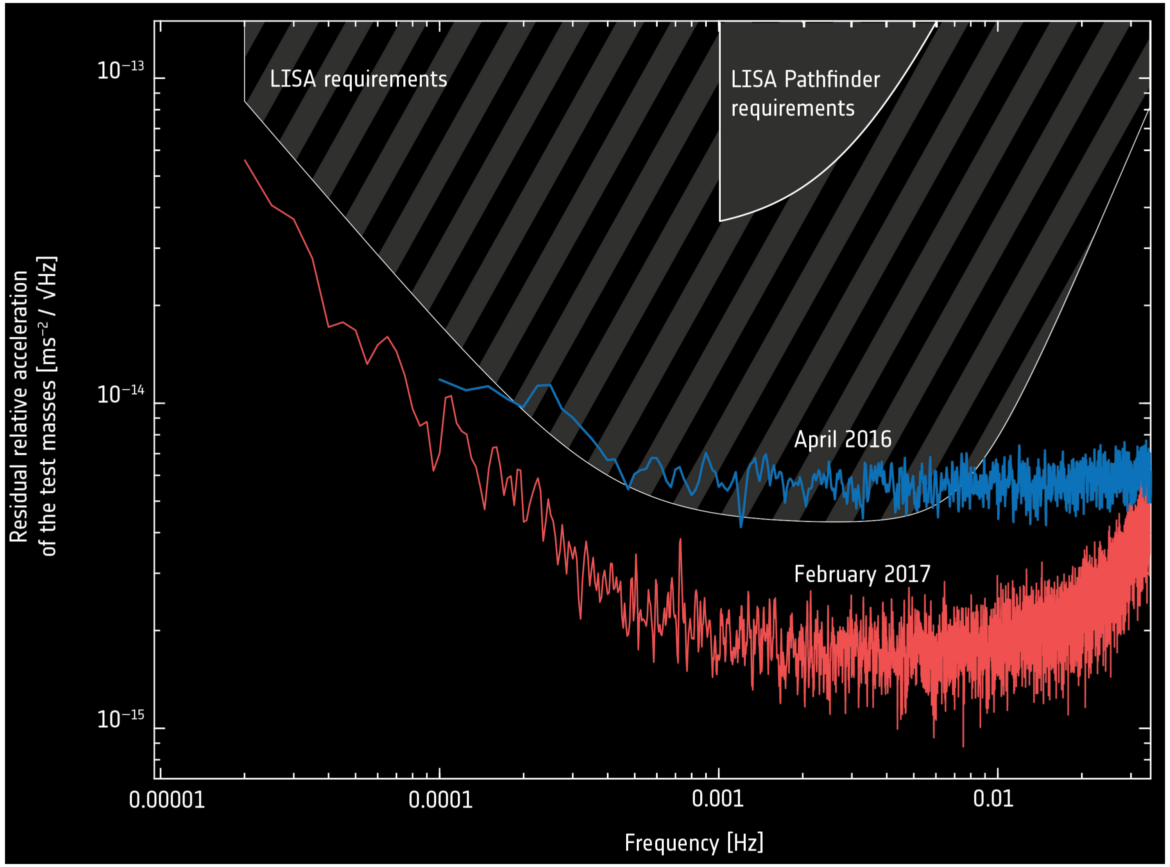


LISA Pathfinder

- Technology demonstration experiment
- Miniature version of LISA's concept, shrunken from 5M km to 38 cm
- Mission goal: in-flight test of low frequency GW metrology
- Demonstration: free-falling bodies follow geodesics in space-time
- Two free-falling test masses measured by pico-meter resolution laser interferometer near 1mHz
- April 2016: LISA mission is feasible!

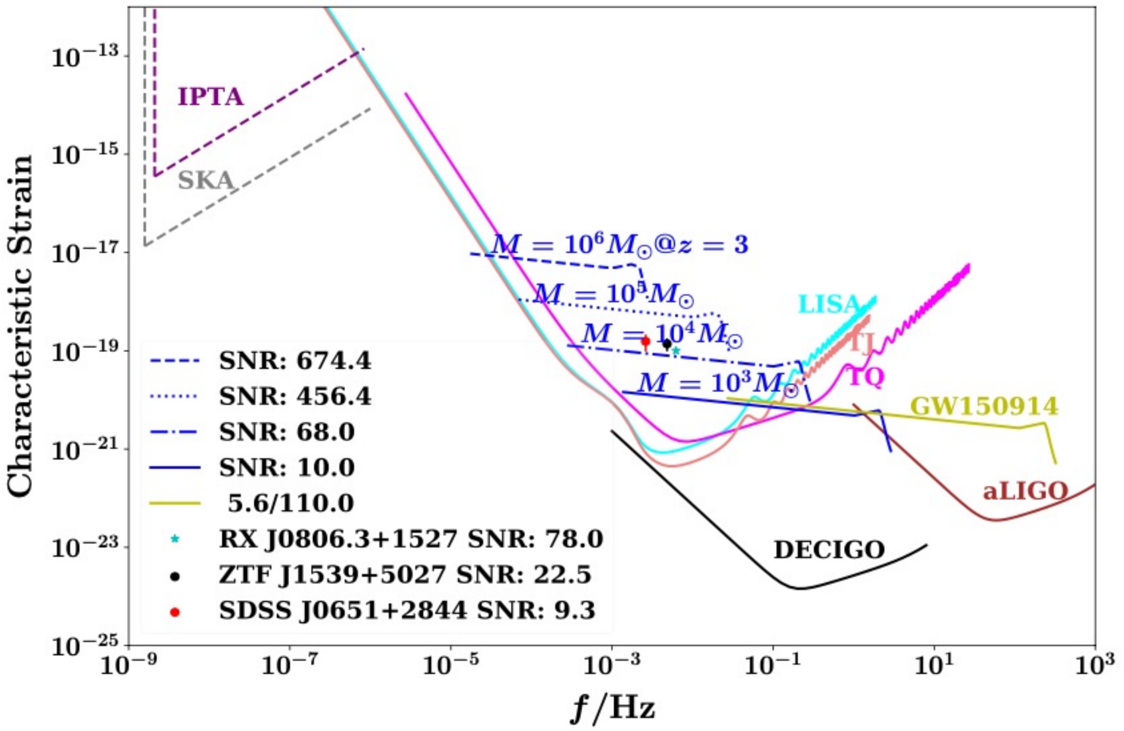


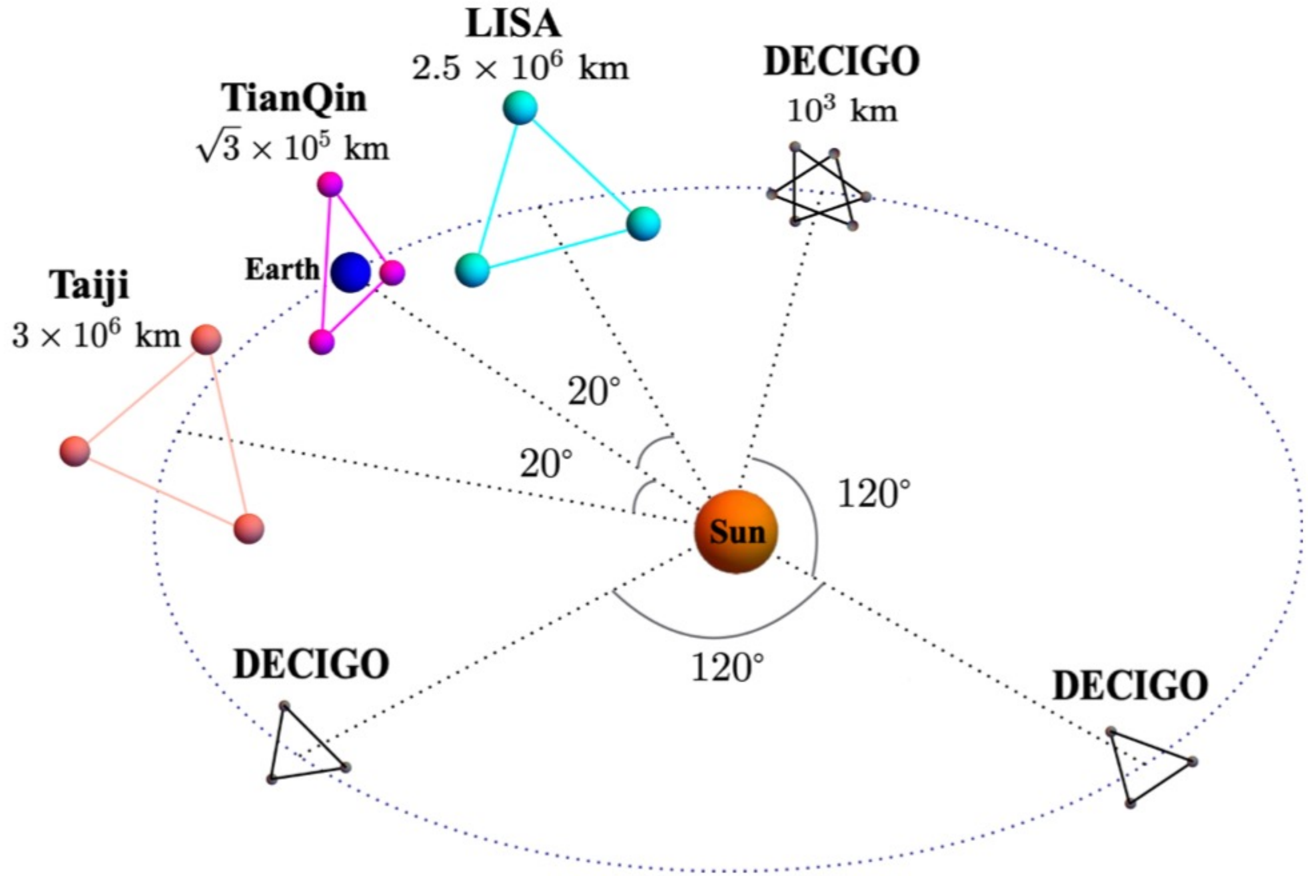




From naught to many in a decade

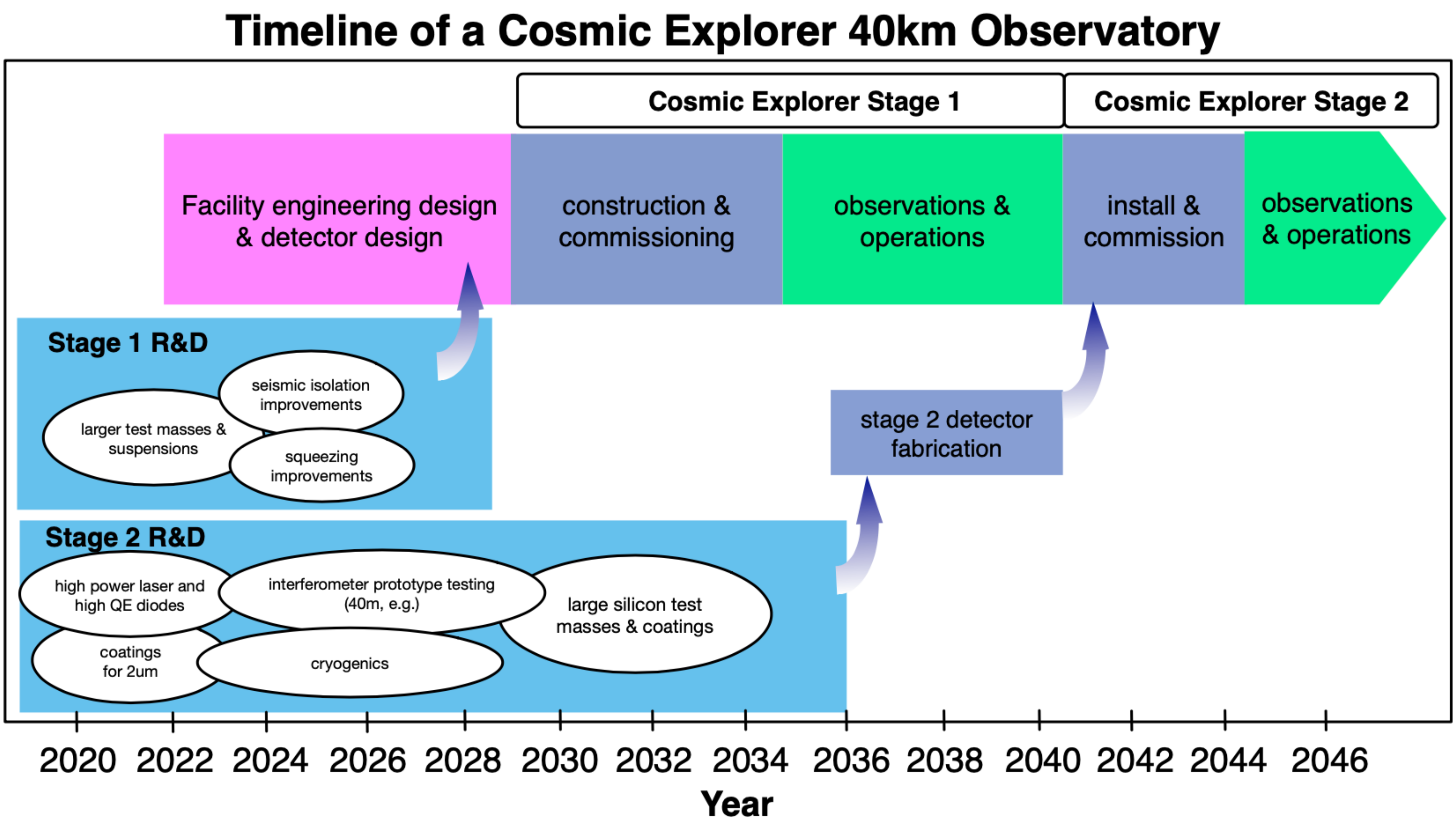
Gong et al. (2021), NatAs, arXiv: 2109.07442

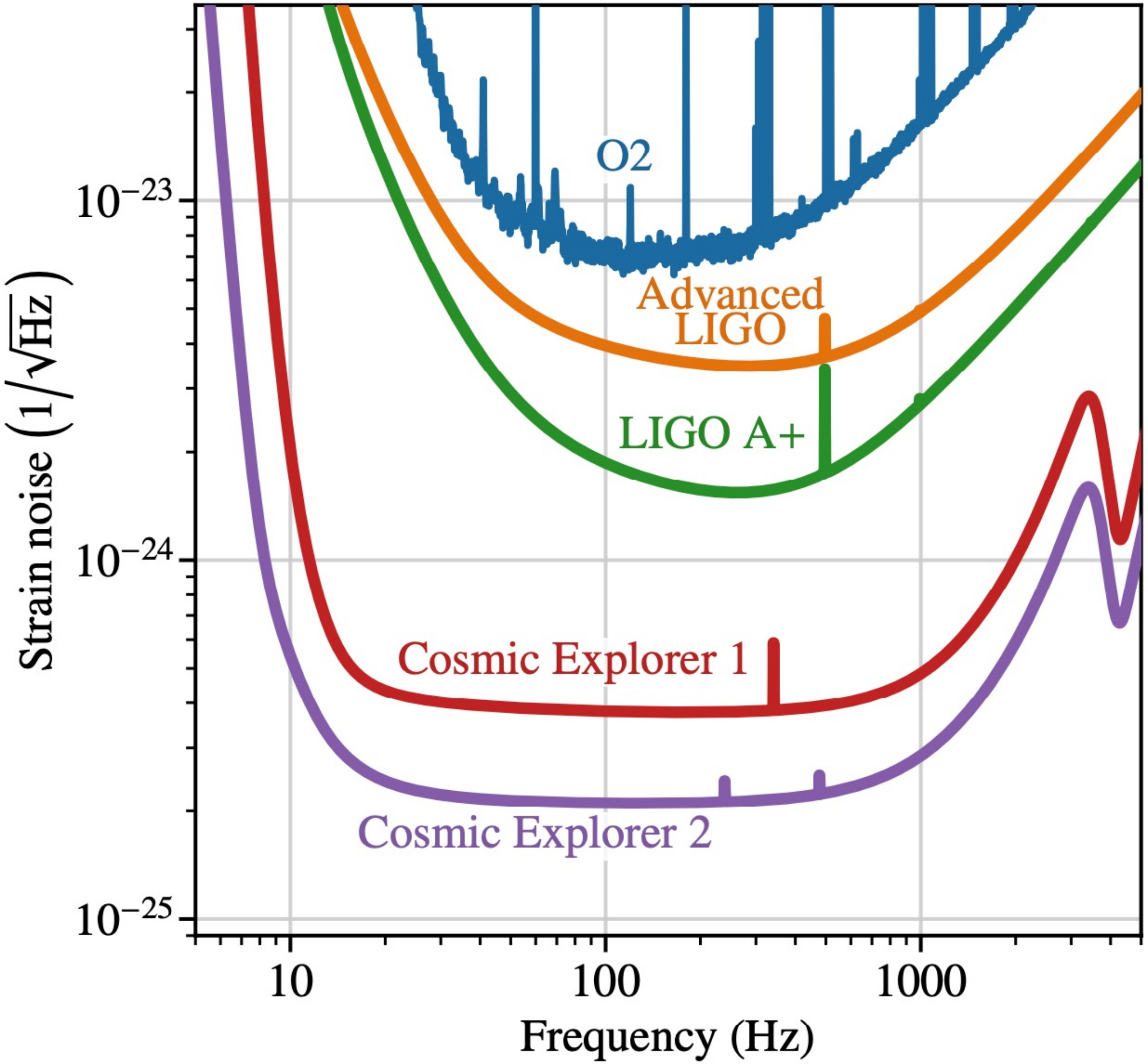


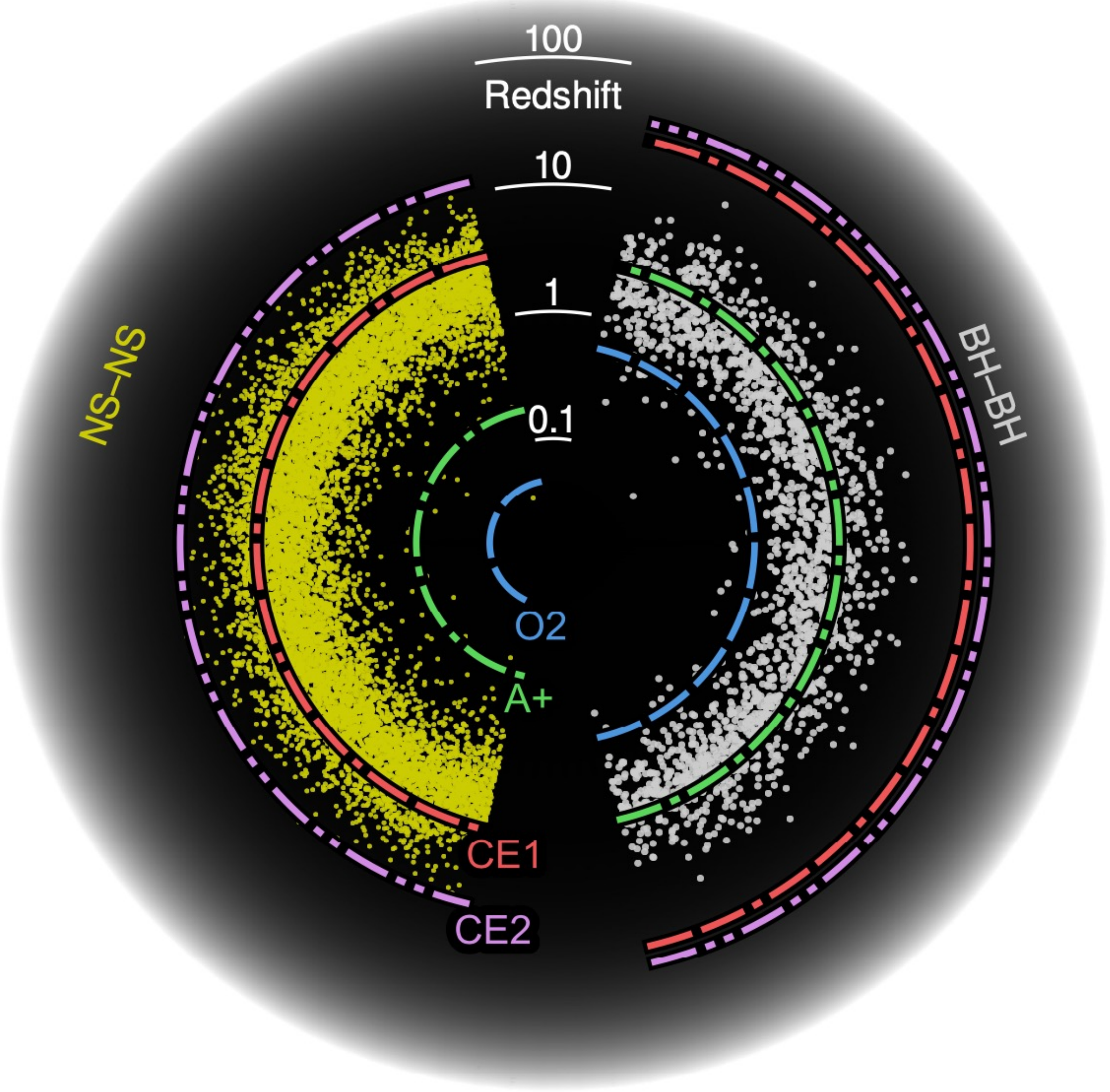


Cosmic Explorer: a 40km GW Observatory

A clear endorsement for NSF/PHYS programs by the US decadal survey astro2020


Timeline of a Cosmic Explorer 40km Observatory
Cosmic Explorer Stage 1
Cosmic Explorer Stage 2
Facility engineering design & detector design
construction & commissioning
observations & operations
install & commission
observations & operations
Stage 1 R&D
seismic isolation improvements
larger test masses & suspensions
squeezing improvements
stage 2 detector fabrication
Stage 2 R&D
high power laser and high QE diodes
interferometer prototype testing (40m, e.g.)
large silicon test masses & coatings
coatings for 2um
cryogenics
2020 2022 2024 2026 2028 2030 2032 2034 2036 2038 2040 2042 2044 2046
Year



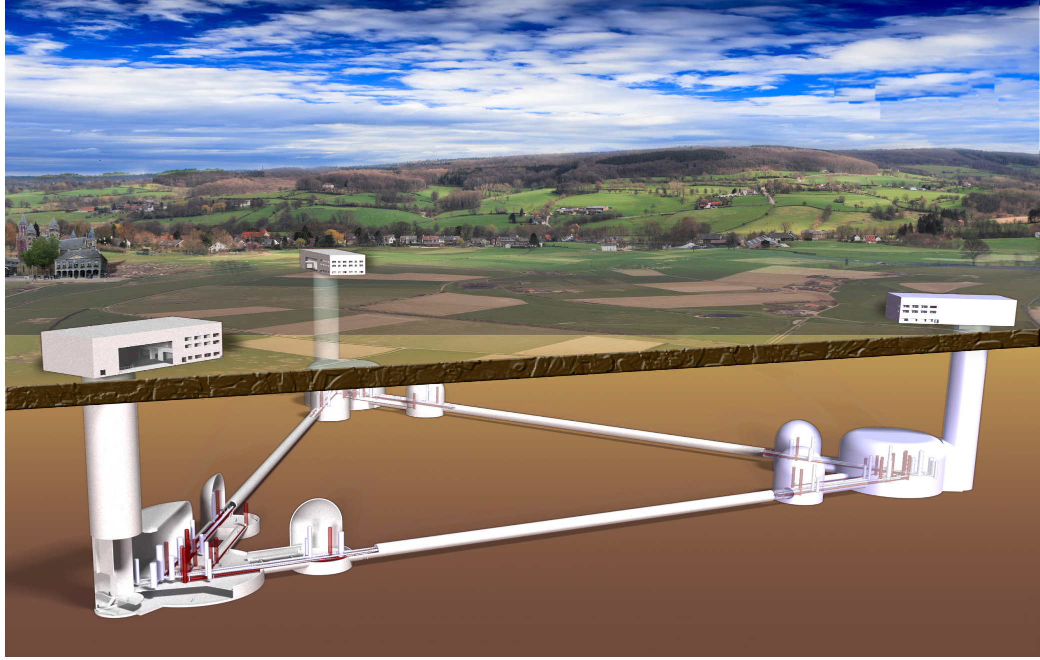


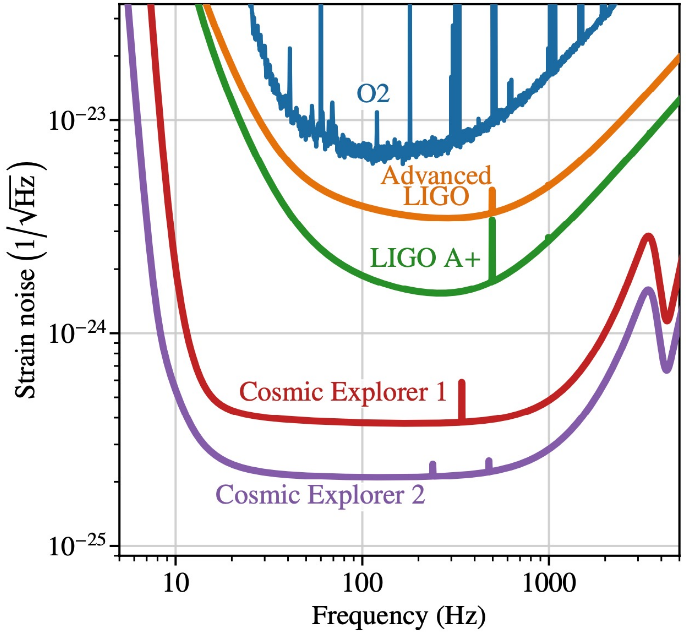
Reitze et al. (2019) - Astro2020 White Paper

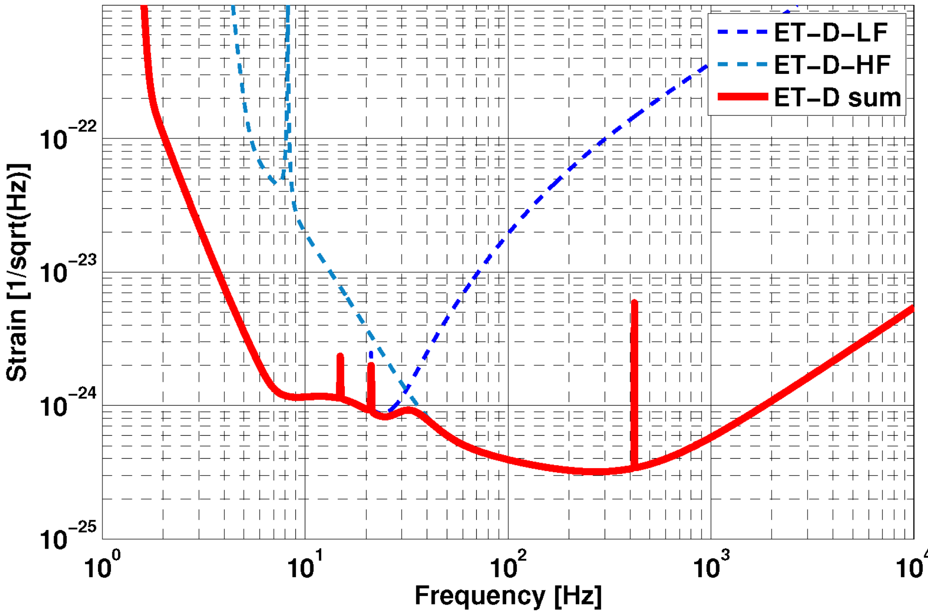
Einstein Telescope

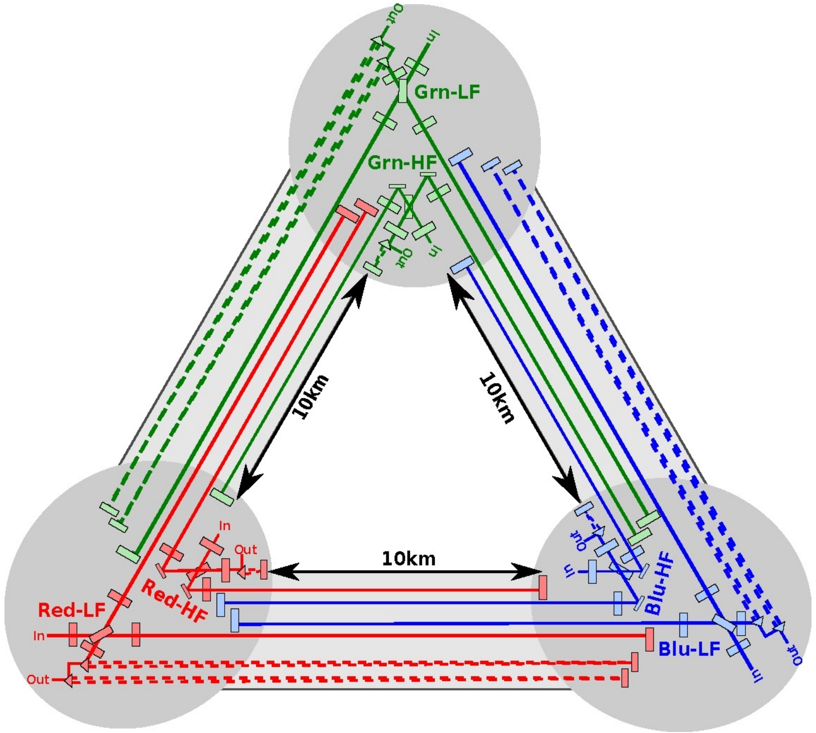
www.et-gw.eu

- Triangular like LISA
- 10km arm length
- A key European priority
- ET Science Collaboration established on June 2022





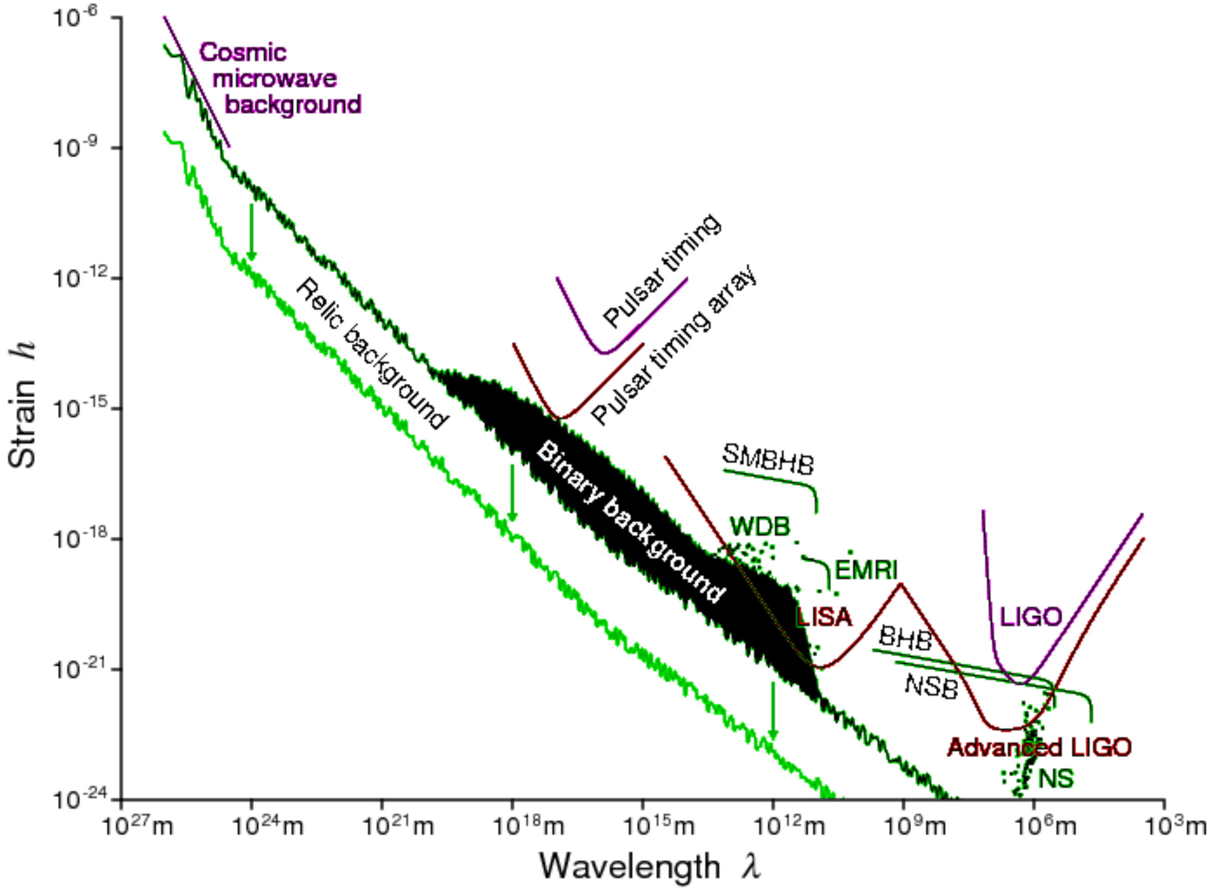


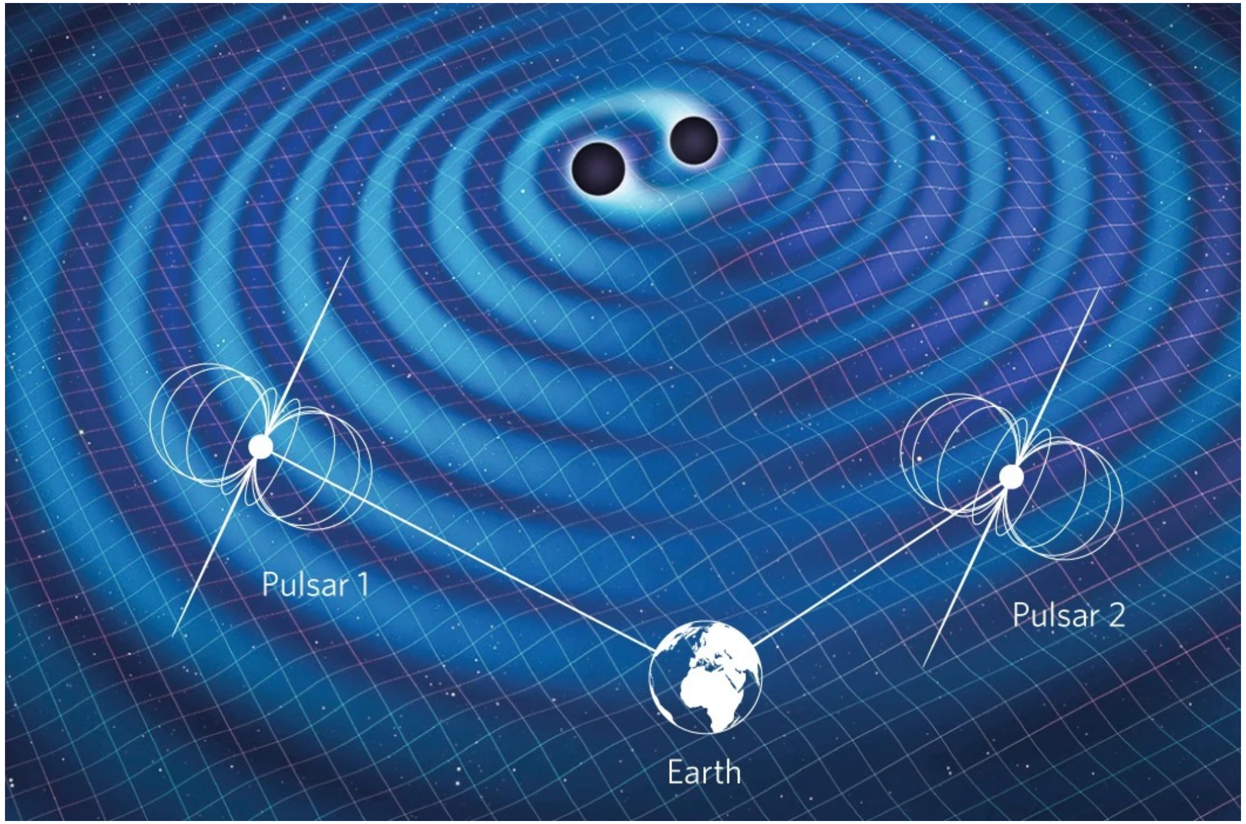


Pulsar Timing Arrays: Natural interferometers with galaxy scale arm lengths!

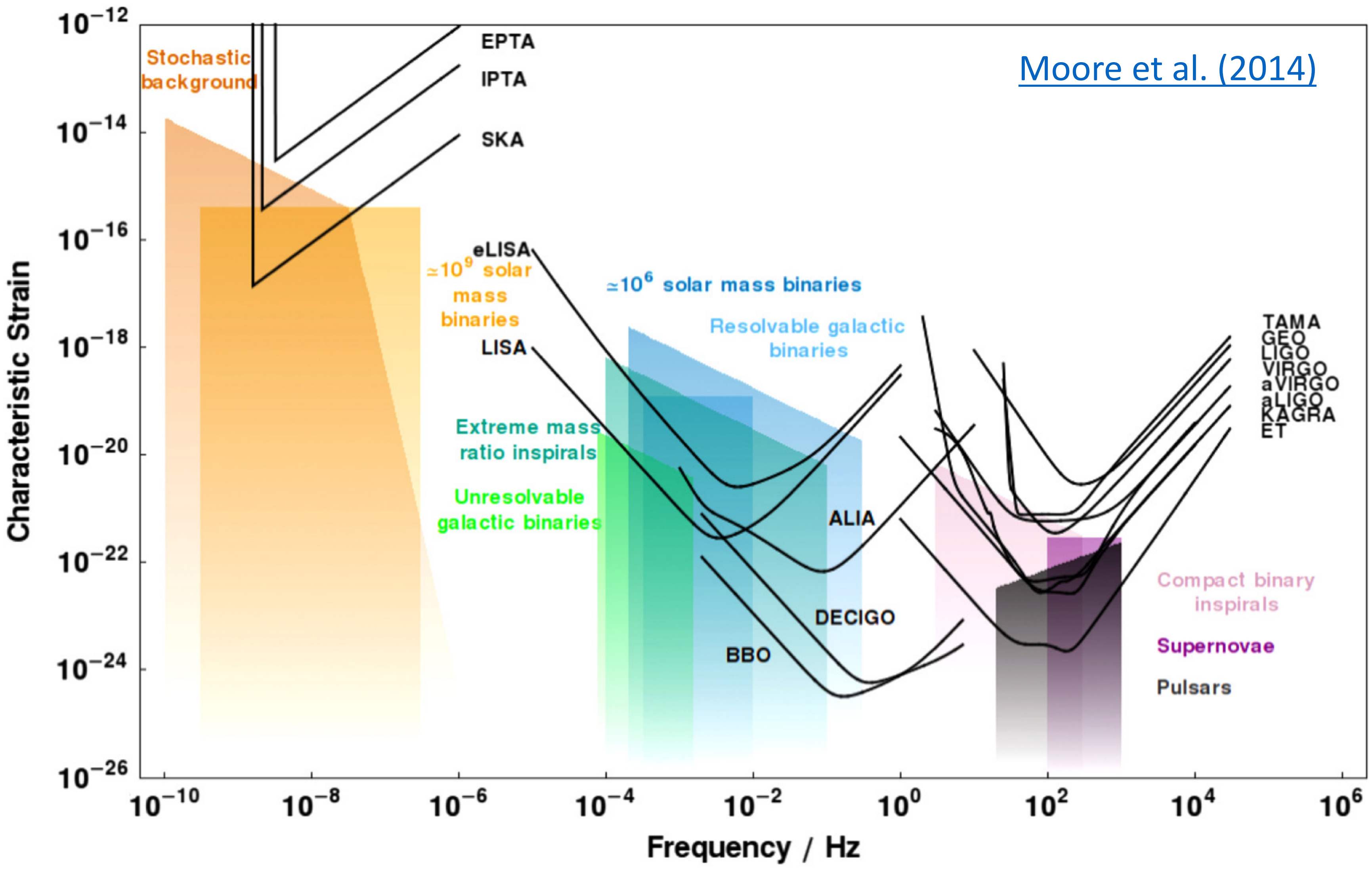
- Longer arms = larger chirp mass

$$T \sim \sqrt{\frac{R^3}{GM}} \;\rightarrow\; f = \frac{2\pi}{T} \;\rightarrow\; \lambda = \frac{c}{f} \sim \frac{c}{2\pi}\sqrt{\frac{R^3}{GM}} \sim \frac{GM}{\pi c}\sqrt{2}$$





Gravitational Waves and Pulsar Timing



The first detection

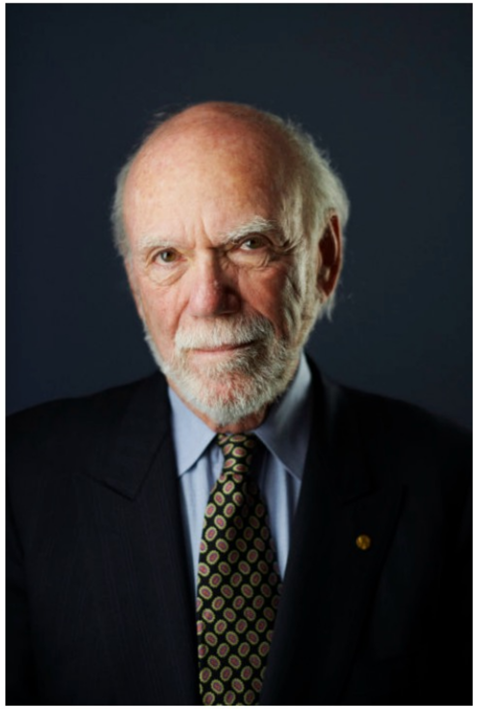
… 50 years in the making!

The Nobel Prize in Physics 2017

© Nobel Media AB. Photo: A. Mahmoud

Rainer Weiss

Prize share: 1/2



© Nobel Media AB. Photo: A.Mahmoud

Barry C. Barish

Prize share: 1/4

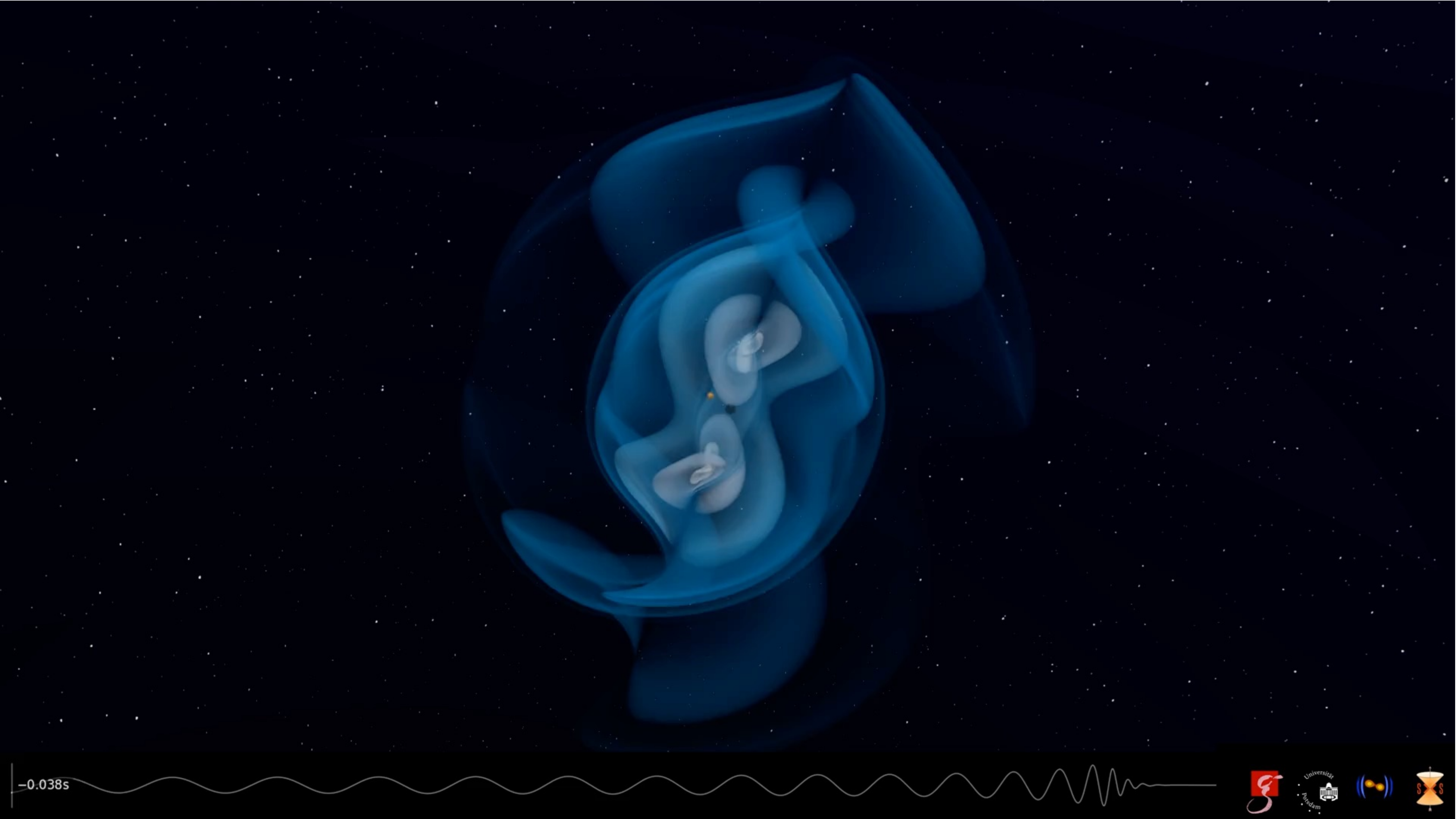
© Nobel Media AB. Photo: A.Mahmoud

Kip S. Thorne

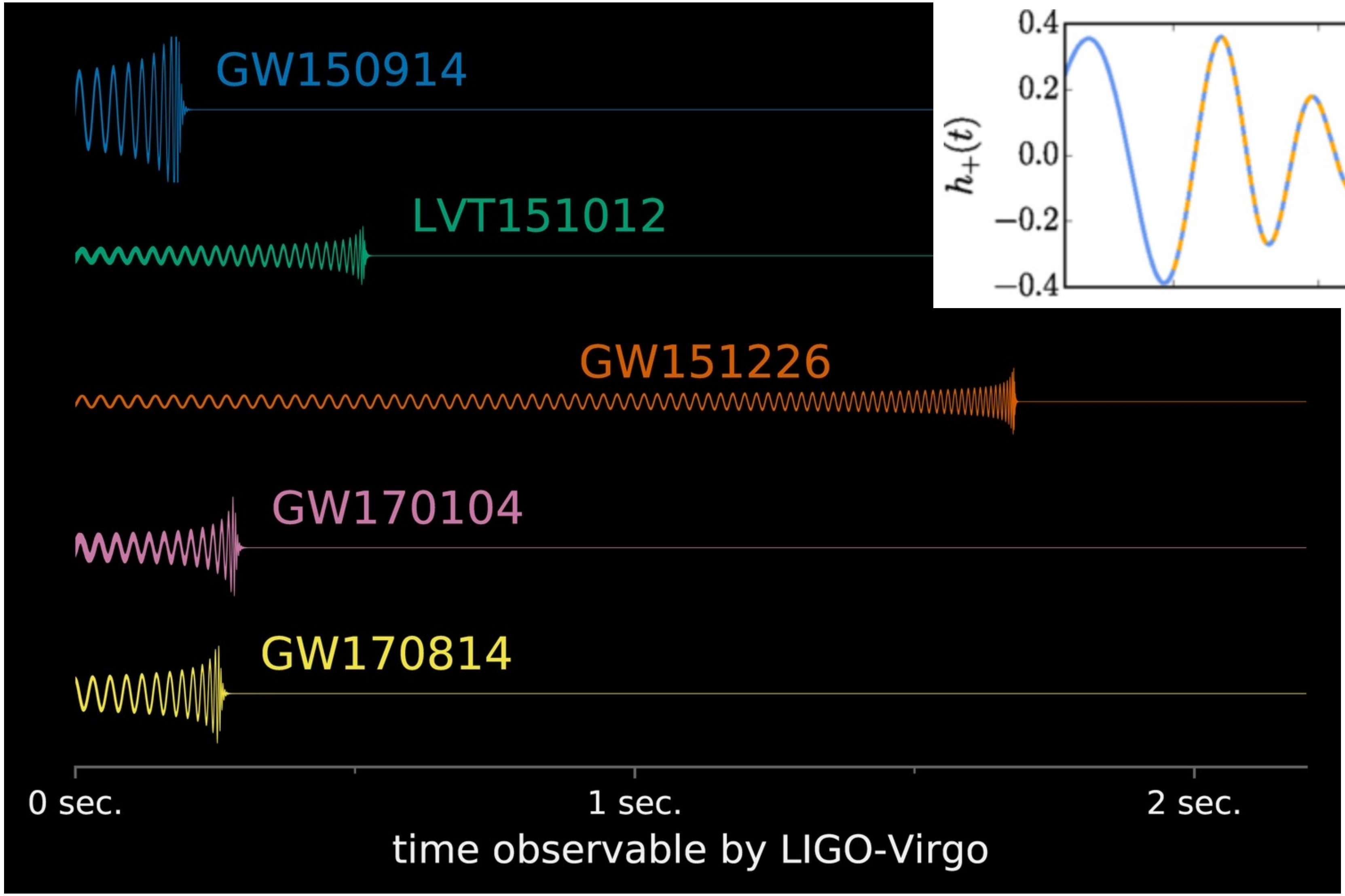
Prize share: 1/4

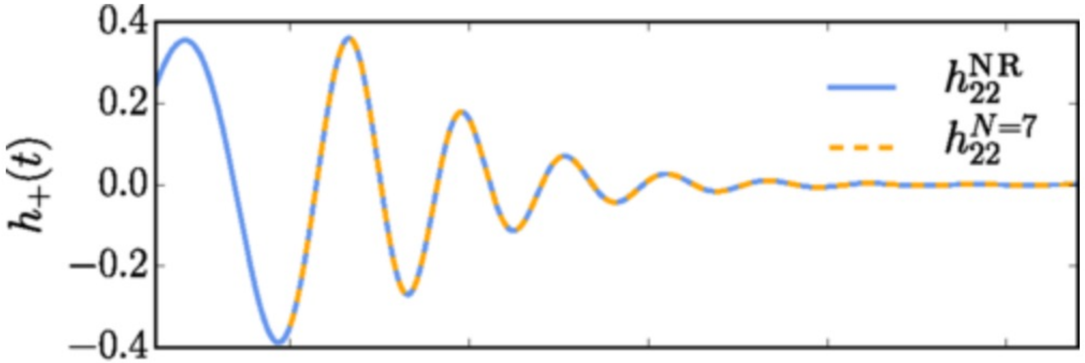
"for decisive contributions to the LIGO detector and the observation of gravitational waves."

GWs from Coalescing Compact Objects


−0.038s

Gravitational waves detected by LIGO (2017)





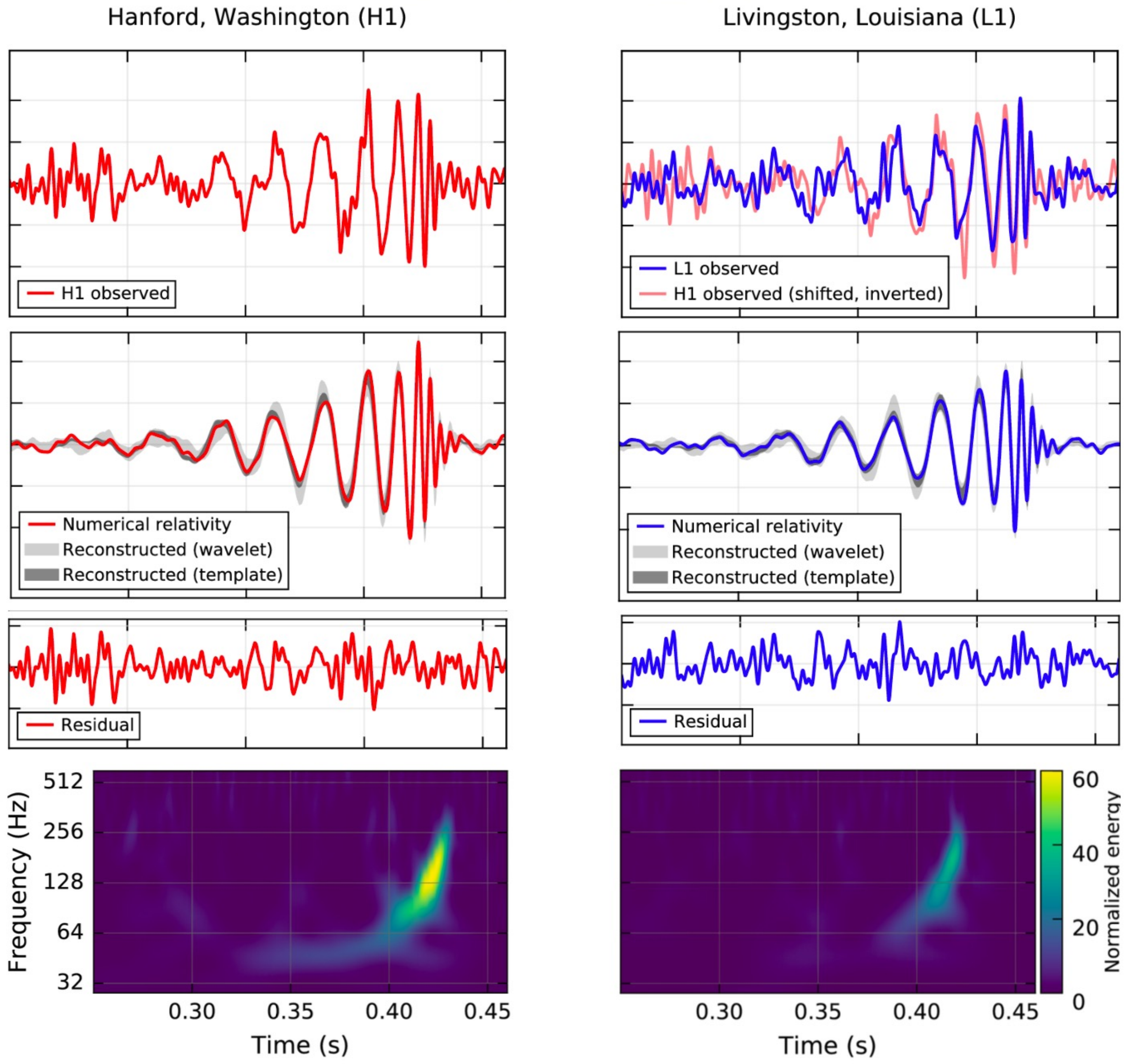
$$T \sim \sqrt{\frac{R^3}{GM}}$$

Gravitational Wave Chirp Spectrogram

GW150914; GR waveform, whitened, +400 Hz

GW170104; GR waveform, whitened, +400 Hz

www.blackholehunter.org



Gravitational waves

- $L_{GW} \propto \frac{c^5}{G}\left(\frac{R_S}{R}\right)^2\left(\frac{v}{c}\right)^6 \rightarrow L_{Univ} \sim \frac{c^5}{G} = 3.6\times10^{59} erg\ s^{-1}$
- Luminosity highest for highly relativistic objects of $R_S = 2GM/c^2$
- Energy radiated during merger
  - $\mathrm{L} \approx 10^{-3}c^5/G \sim 10^{49}W$ in a few wave cycles
  - Timescale: $\tau \approx 100\ GM/c^3$; 500s for a $10^6 M_\odot$ BH merger
  - Peak power is approx. 1000 times all stars in the visible Universe!
- Amplitude: $h \sim \frac{G}{c^4}\frac{\epsilon E_{kin}}{r}$; decrease as $1/r$, not $1/r^2$
- Source asymmetry $0 \leq \epsilon \leq 1$ determines fraction of kinetic energy that emits
- Quadrupolar fields only: spherically symmetric events = no GWs

GW primary observables – chirp mass

Orbital evolution:

- $\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}$

Chirp Mass:

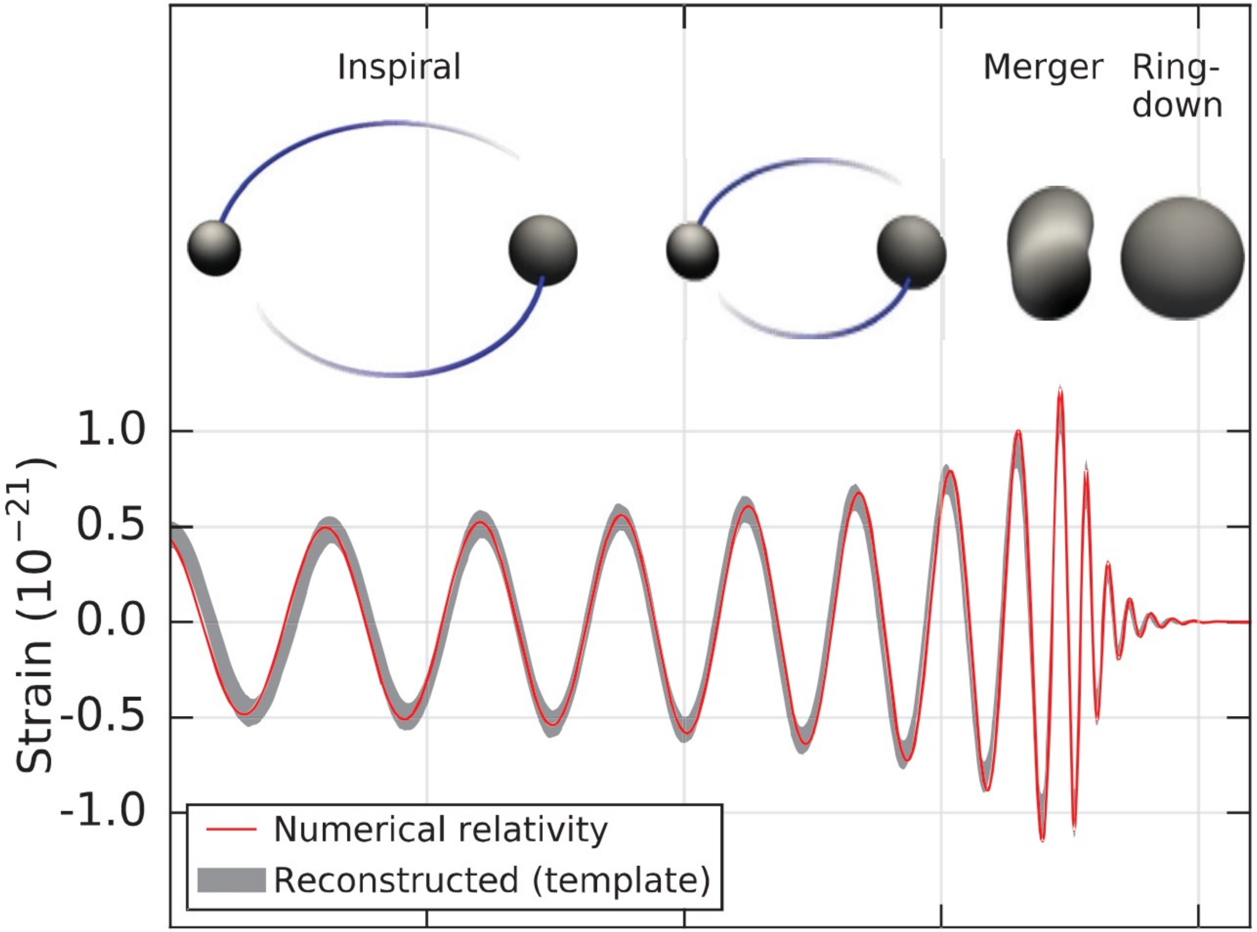
- $\mathcal{M} = \frac{(m_1 m_2)^{\frac{3}{5}}}{(m_1+m_2)^{\frac{1}{5}}} = \mu^{3/5} M^{2/5};$

$with\ M = m_1 + m_2;\ \mu = \frac{m_1 m_2}{M}$

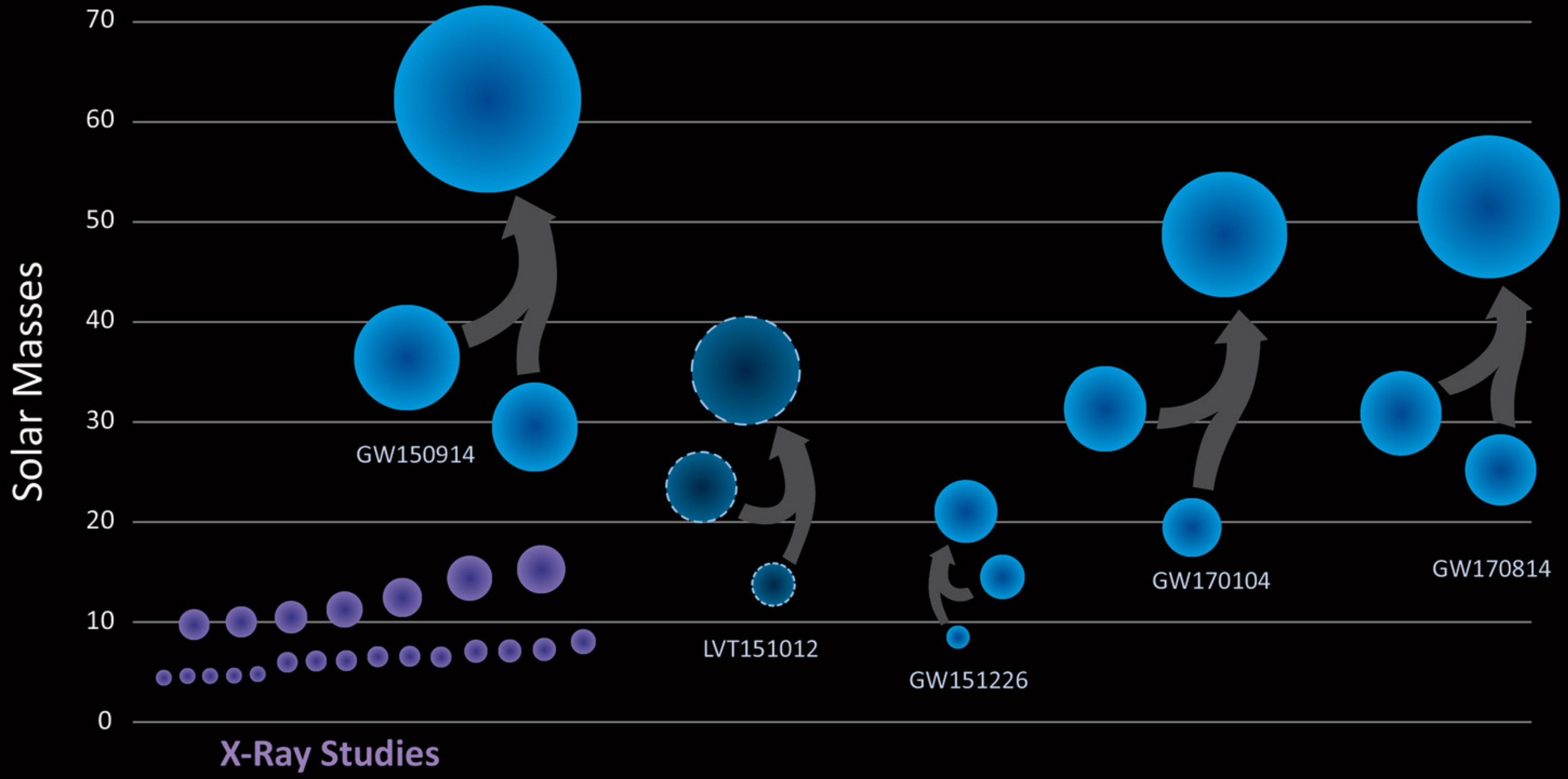
Mass-redshift degeneracy:

- $\mathcal{M}_{obs} = \mathcal{M}_{true}(1+z)$

Need to measure f and df/dt to determine chirp mass



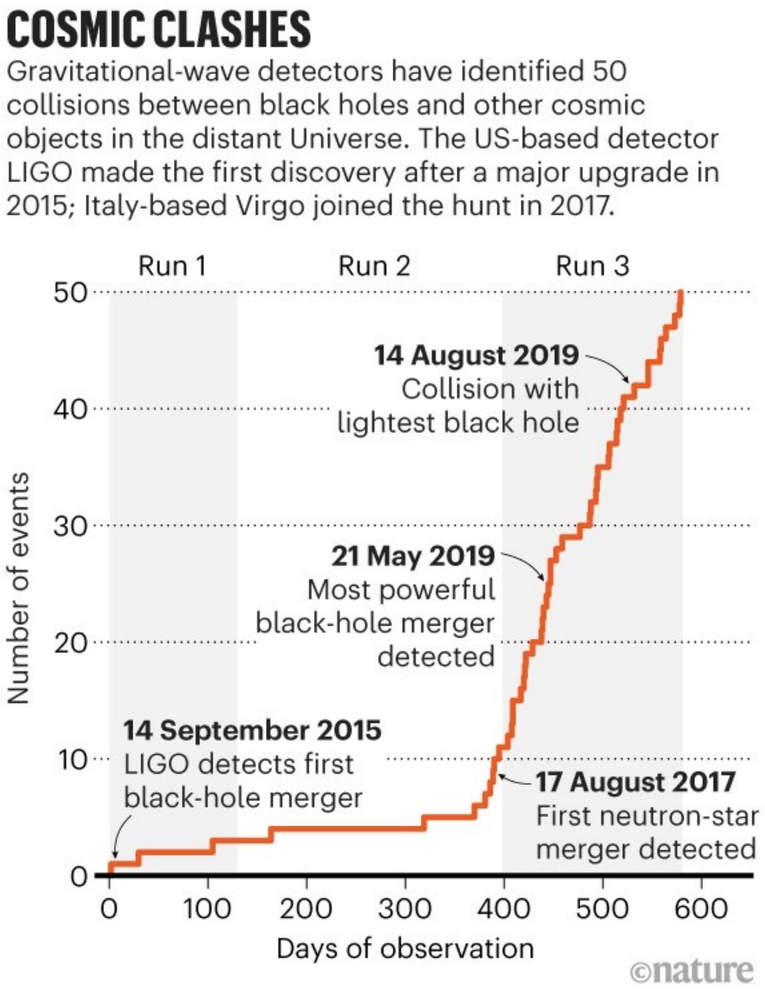
Black Holes of Known Mass



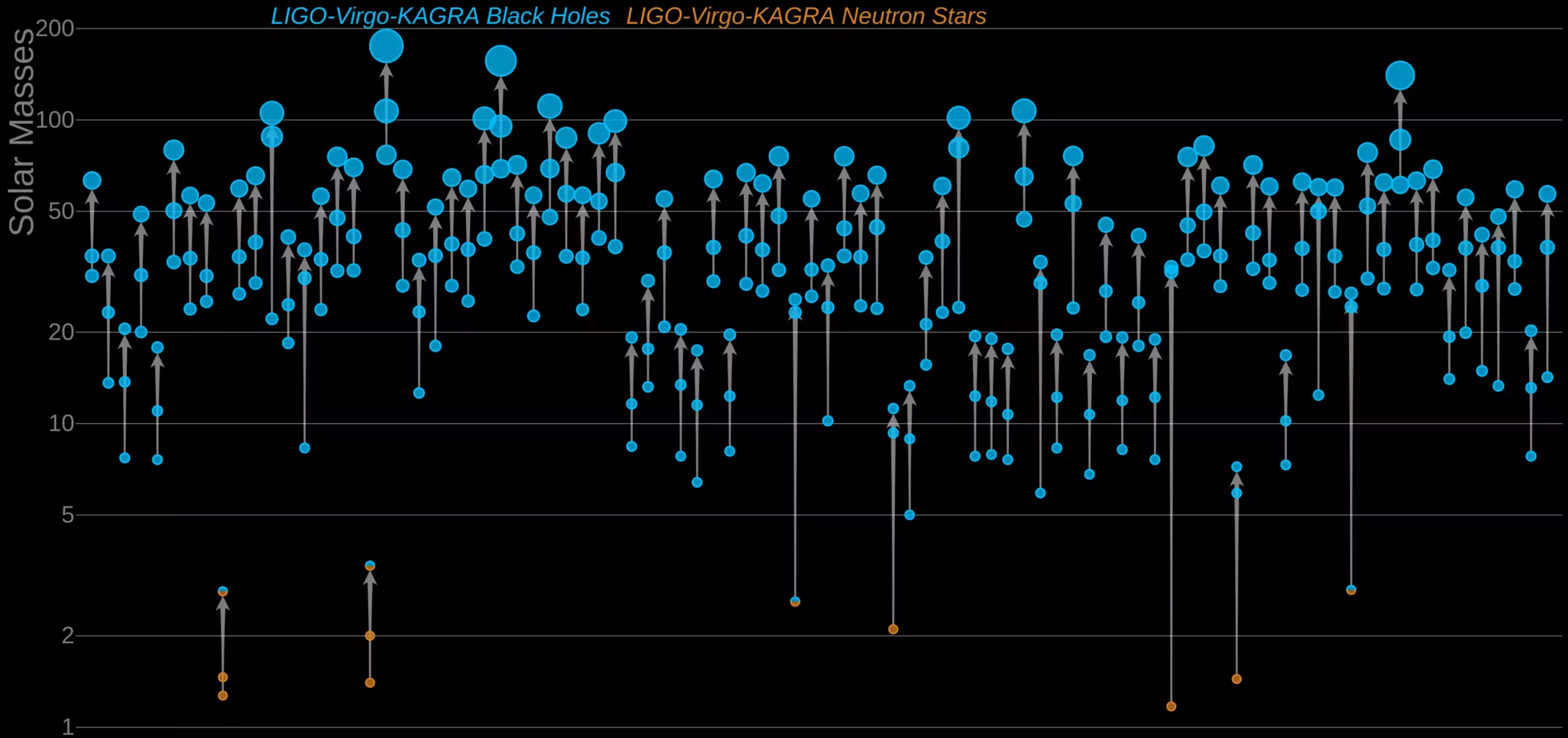
LIGO/VIRGO

November 2021: 3rd LIGO-Virgo-Kagra run

35 new GW events for a total of 90 confirmed



Masses in the Stellar Graveyard

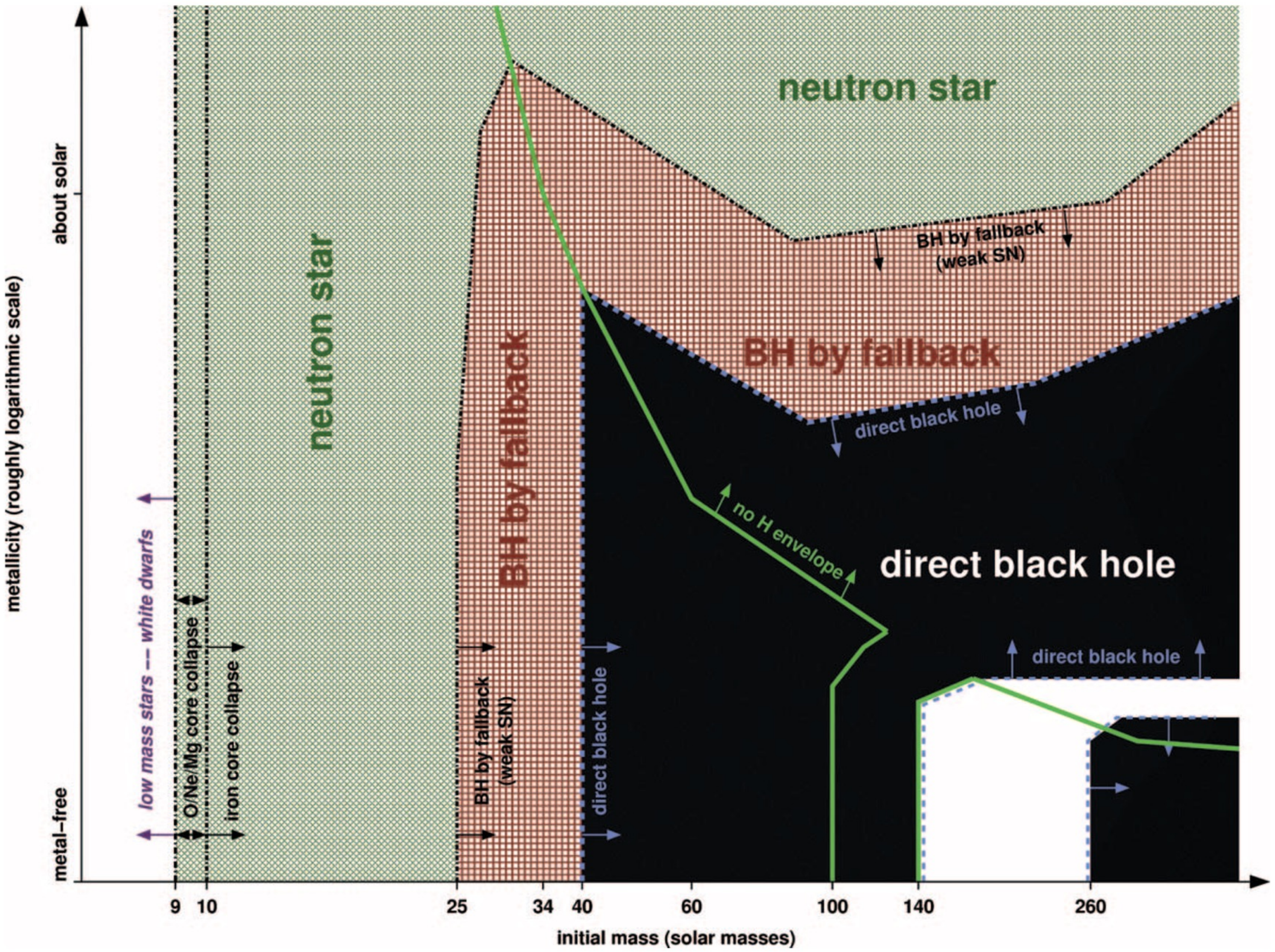


LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

“Forbidden” masses?

Woosley & Heger (2021)

- Black holes are expected from core-collapse supernovae that produce neutron stars too massive for further collapse; $\mathrm{M_{ns}} \geq 2.2 M_{\odot}$; $M_{\star} \geq 20\ M_{\odot}$
- But: mass gap predicted around 50 – 130 Msun. Lower bound perhaps 70 Msun (rotation). Upper bound set by (pulsational) pair instability supernovae. Mass ranges depend on metallicity & many other things.
- GWs determine black hole masses empirically & challenge theory
- Alternative origins: primordial black holes? “second-generation” binaries?



Heger+2003, ApJ 591, 288

“Forbidden” masses?

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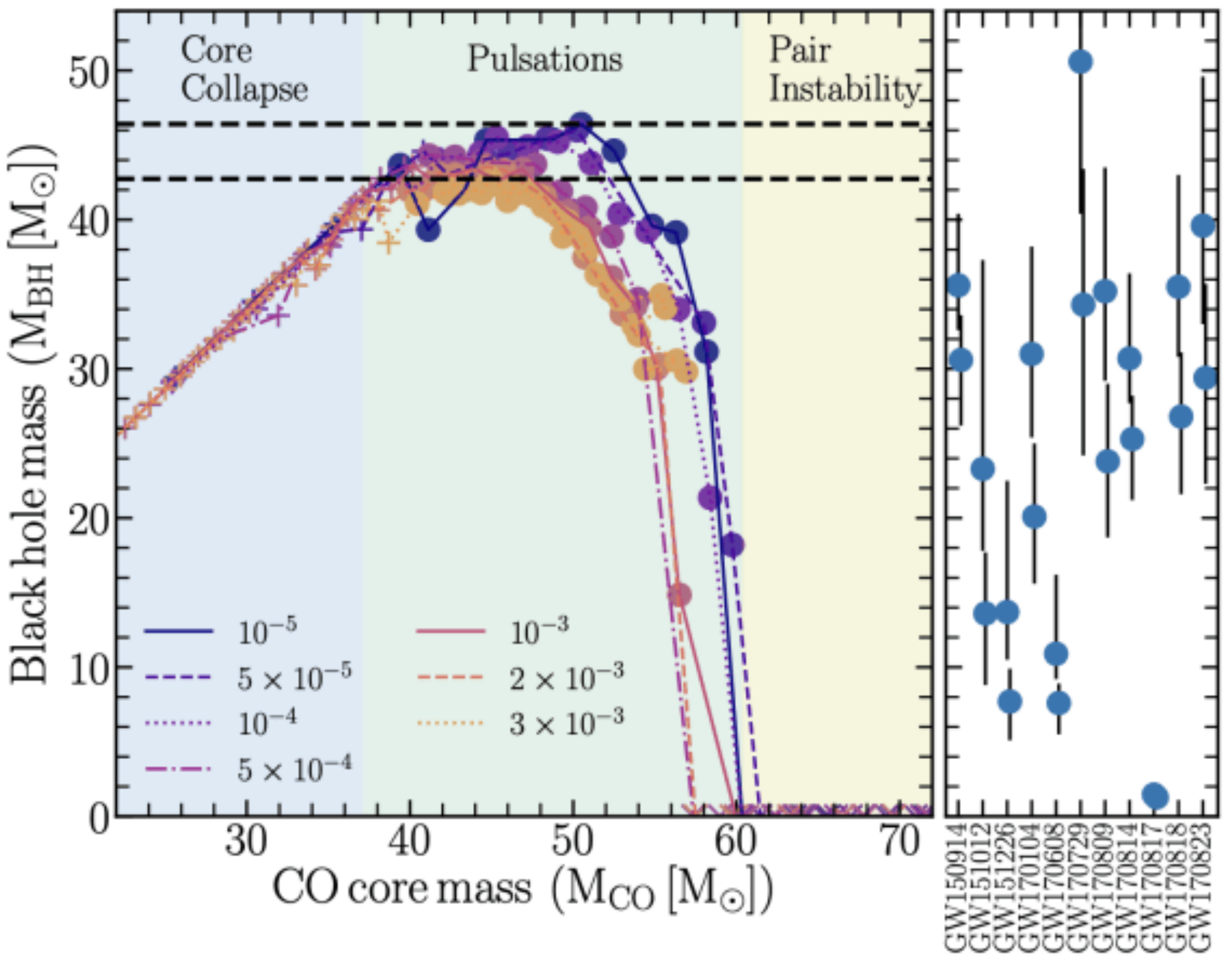
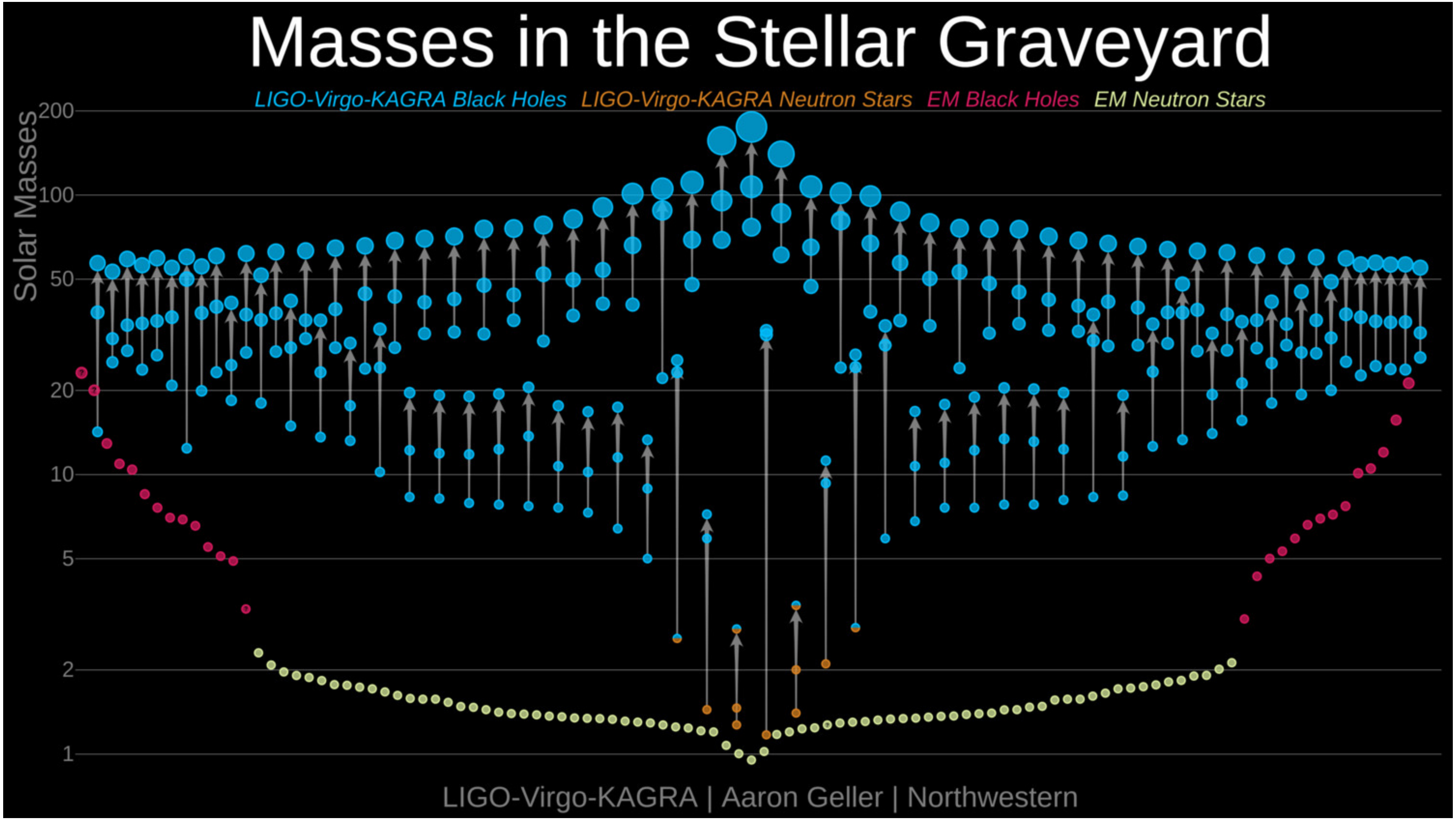


Farmer+2019, ApJ 887, 53


Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
EM Black Holes
EM Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

GW170817: The first GW Multimessenger event

Multi-messenger astrophysics = international cooperation!

THE ASTROPHYSICAL JOURNAL LETTERS, 848:L12 (59pp), 2017 October 20 https://doi.org/10.3847/2041-8213/aa91c9

OPEN ACCESS

CrossMark

Multi-messenger Observations of a Binary Neutron Star Merger*

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-HXMT Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave Inaf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OzGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUGE Collaboration, MASTER Collaboration, J-GEM, GROWTH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, Pi of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RIMAS and RATIR, and SKA South Africa/MeerKAT
(See the end matter for the full list of authors.)

Received 2017 October 3; revised 2017 October 6; accepted 2017 October 6; published 2017 October 16

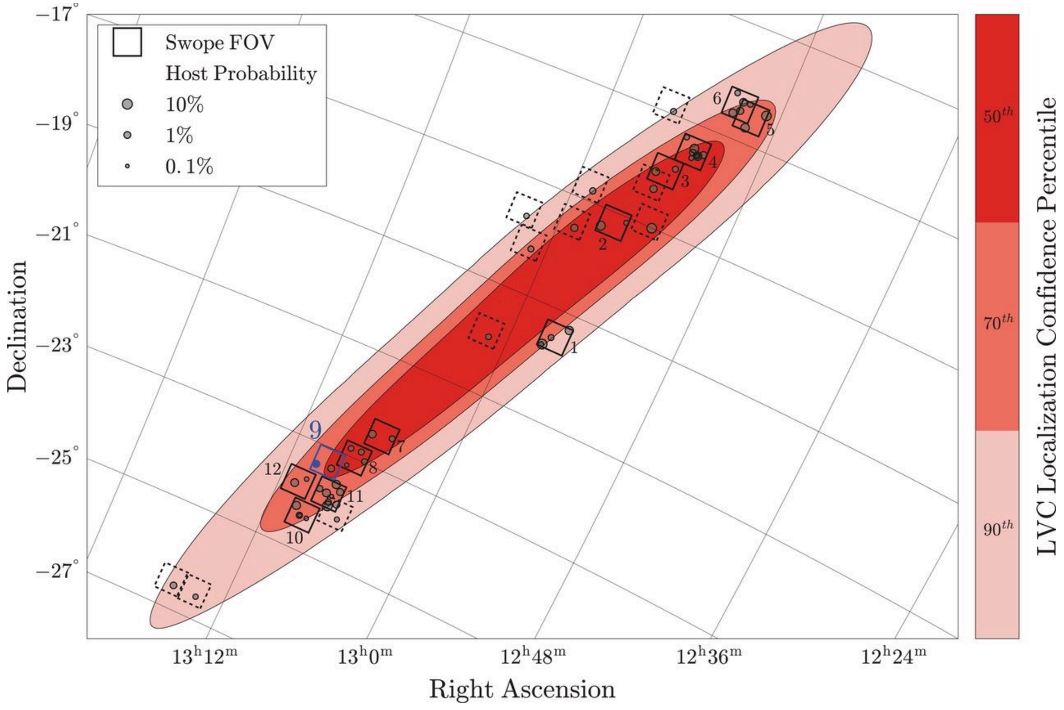
Abbott et al. (2017)

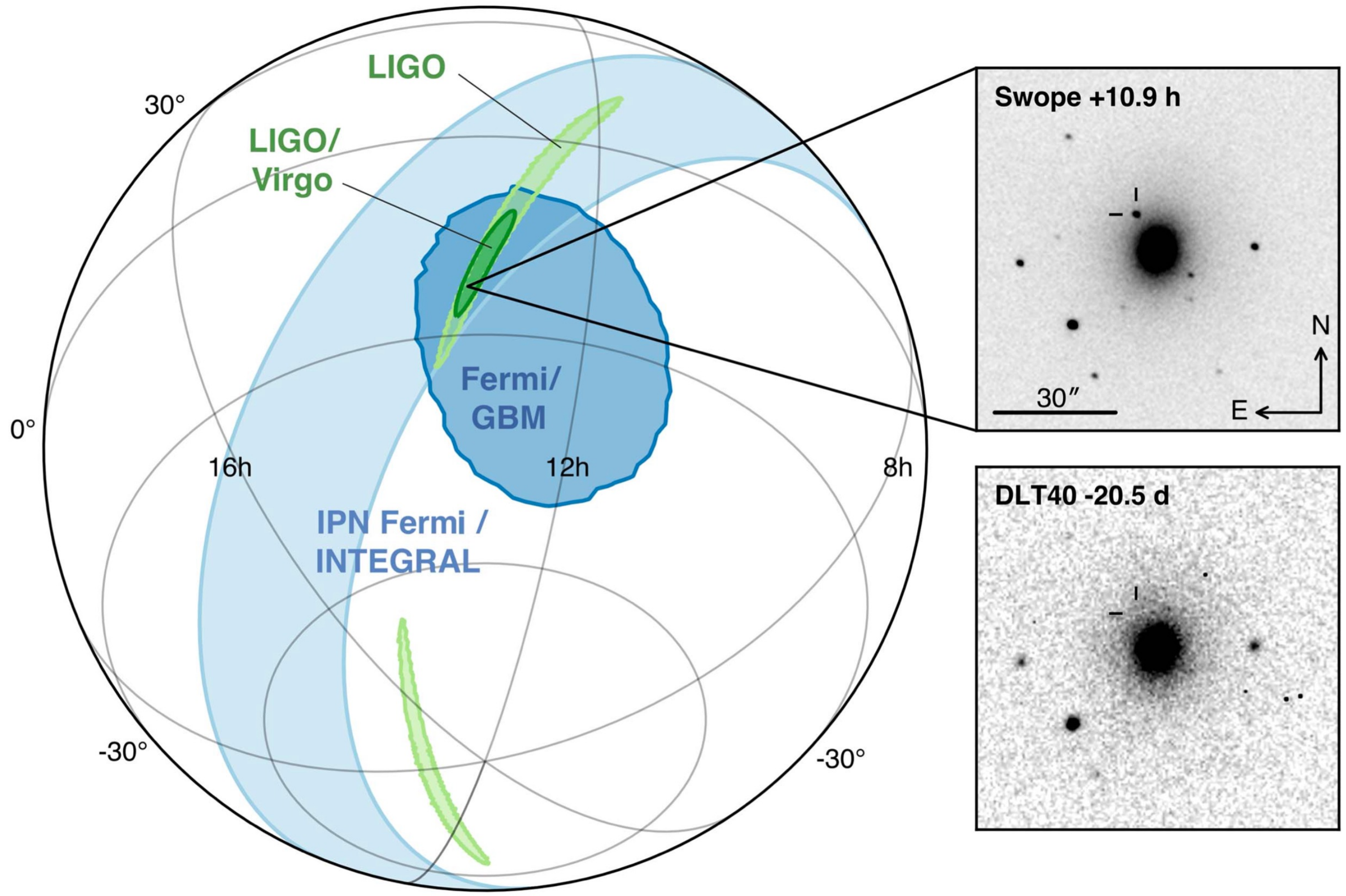
GW170817 : the BNS kilonova

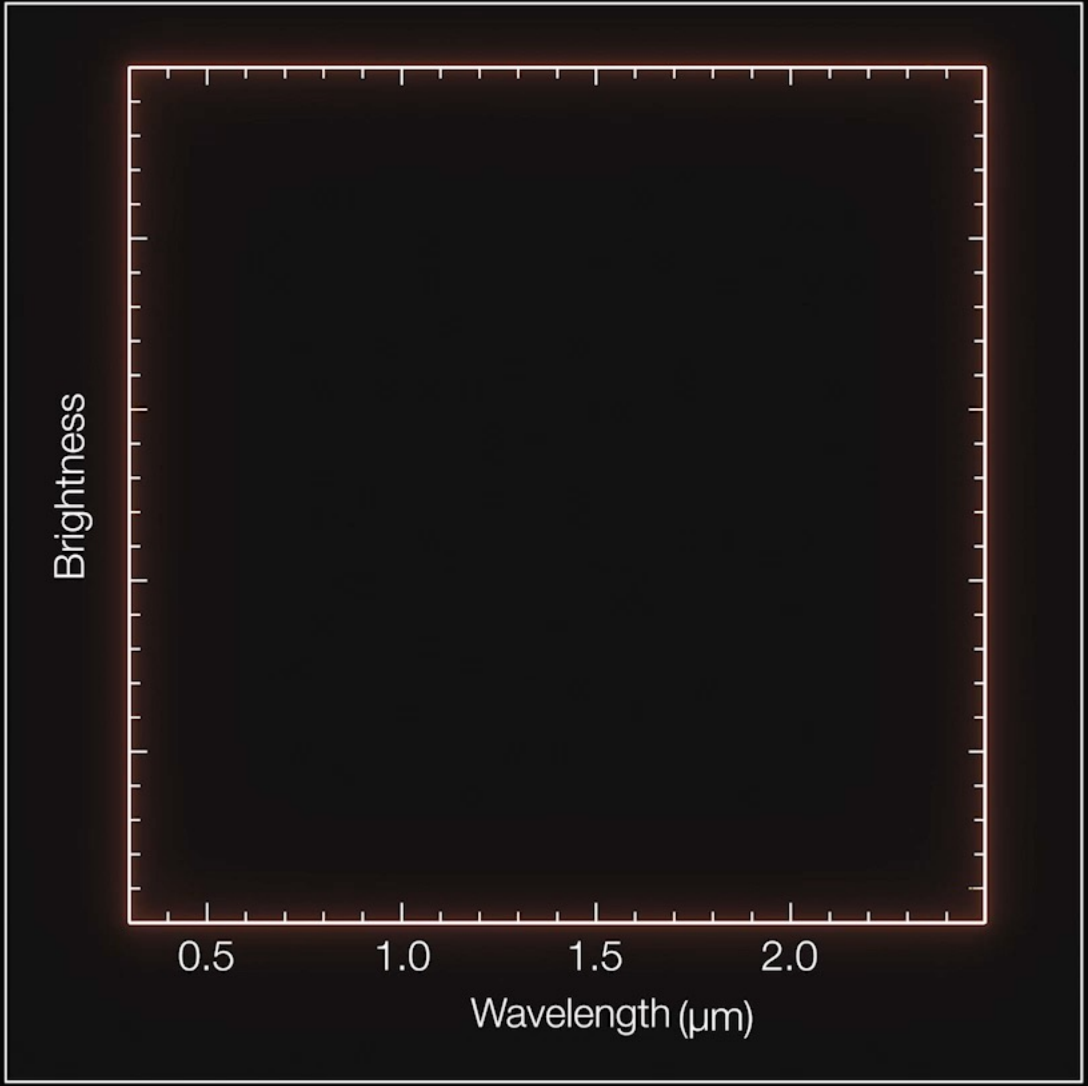
Abbott et al. (2017)

- GW trigger at 2017-08-17T12:41:04.4
- Wave signal duration: ca. 100s (3000 cycles)
- First at Virgo, 22ms at LIGO-Livingston, 3ms later at LIGO-Hanford
- 1.7s later: Fermi Gamma-ray Burst Monitor triggered
- 40 minutes post event: LIGO/Virgo preliminary alert
- Follow-up area approx. 150 times area of full moon
- Swope Supernova Survey found source 10h52m after GW event using 1m telescope
- UV detection 15.3h by Swift
- X-ray 9 days later by Chandra, Radio 16 days later by VLA

Identifying NGC4993 as the host







Time: -1225 days

GW170817 properties

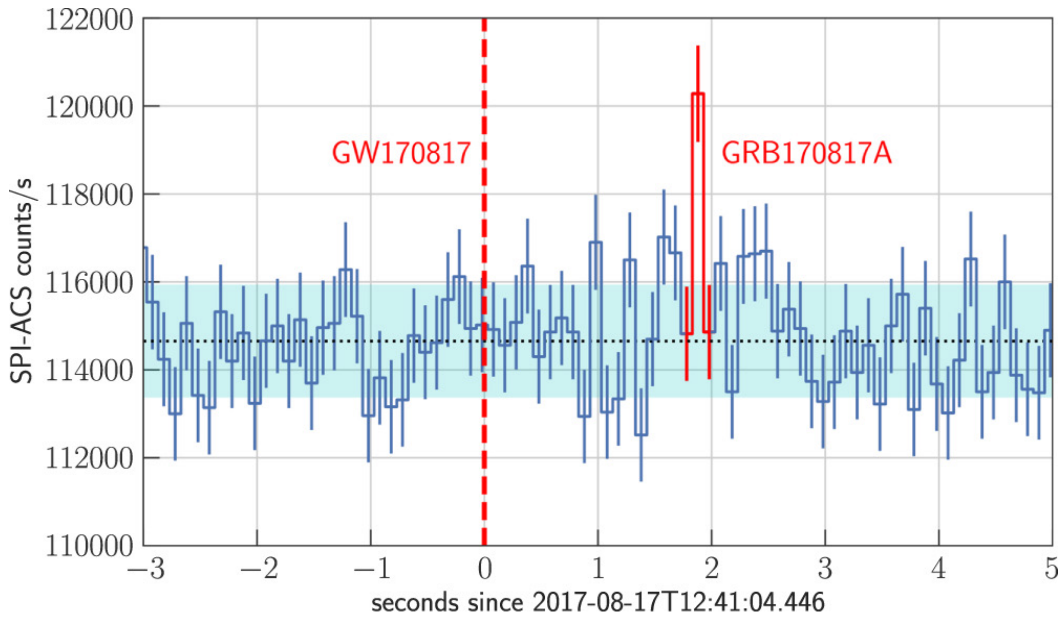
Abbott et al. (2019)

Low-spin prior, $\chi_i \leq 0.05$	SEOBNRv4T
Detector-frame chirp mass $\mathcal{M}^{\mathrm{det}}$	$1.1975^{+0.0001}_{-0.0001}\ \mathrm{M}_\odot$
Chirp mass $\mathcal{M}$	$1.186^{+0.001}_{-0.001}\ \mathrm{M}_\odot$
Primary mass m_1	$(1.36, 1.56)\ \mathrm{M}_\odot$
Secondary mass m_2	$(1.19, 1.36)\ \mathrm{M}_\odot$
Total mass m	$2.73^{+0.04}_{-0.01}\ \mathrm{M}_\odot$
Mass ratio q	(0.76, 1.00)
Effective spin χ_{eff}	$0.00^{+0.02}_{-0.01}$
Primary dimensionless spin χ_1	(0.00, 0.03)
Secondary dimensionless spin χ_2	(0.00, 0.03)
Tidal deformability $\tilde{\Lambda}$ with flat prior (symmetric/HPD)	$280^{+430}_{-220}/280^{+280}_{-280}$

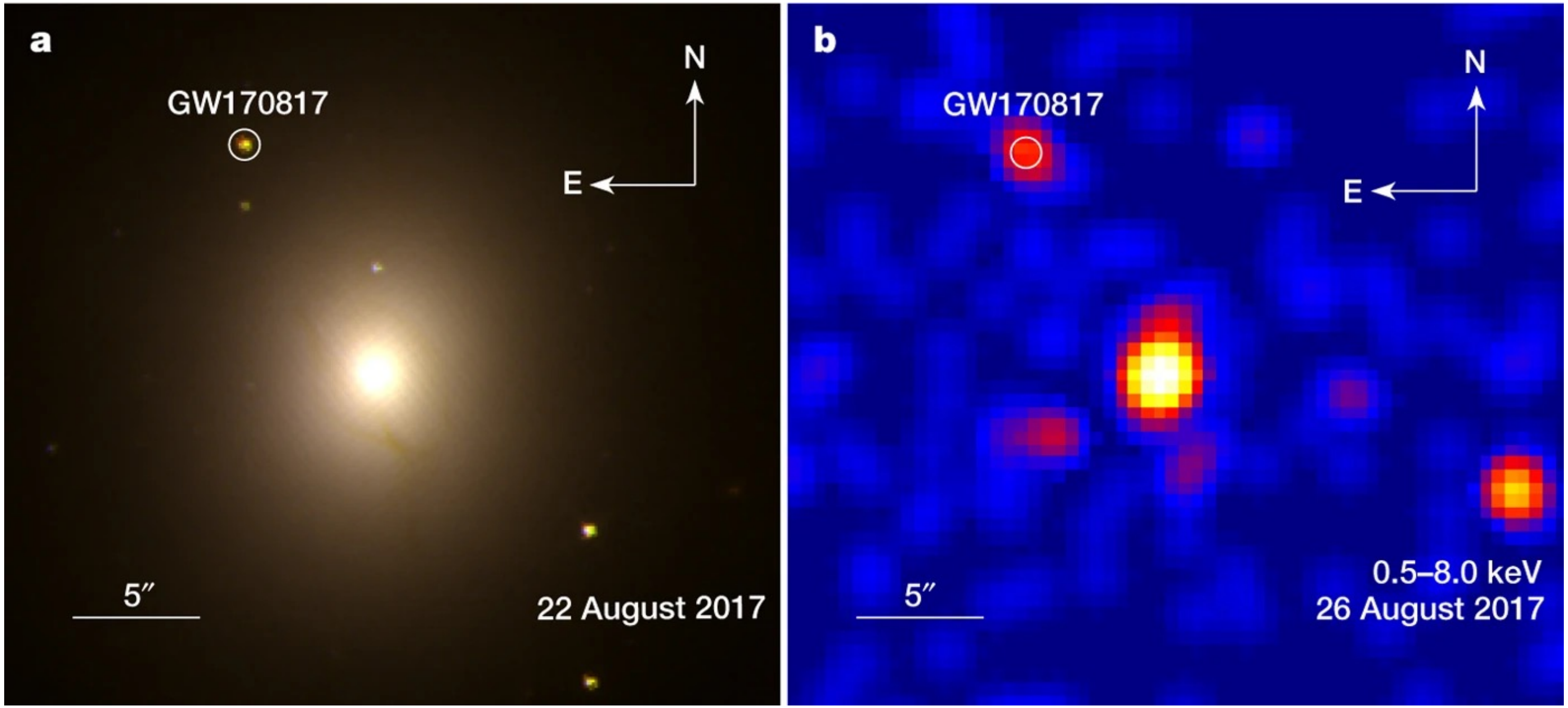
Prompt gamma rays: gravitational waves propagate at speed of light

- GW trigger at 2017-08-17T12:41:04
- Gamma-ray signal detected 1.74s after GW
- Known distance (26 Mpc)
- GW propagate with c to within $\Delta v / c \sim 10^{-16}$
- Excludes a large range of gravitational theories beyond GR

Savchenko et al. (2017)



Delayed x-rays

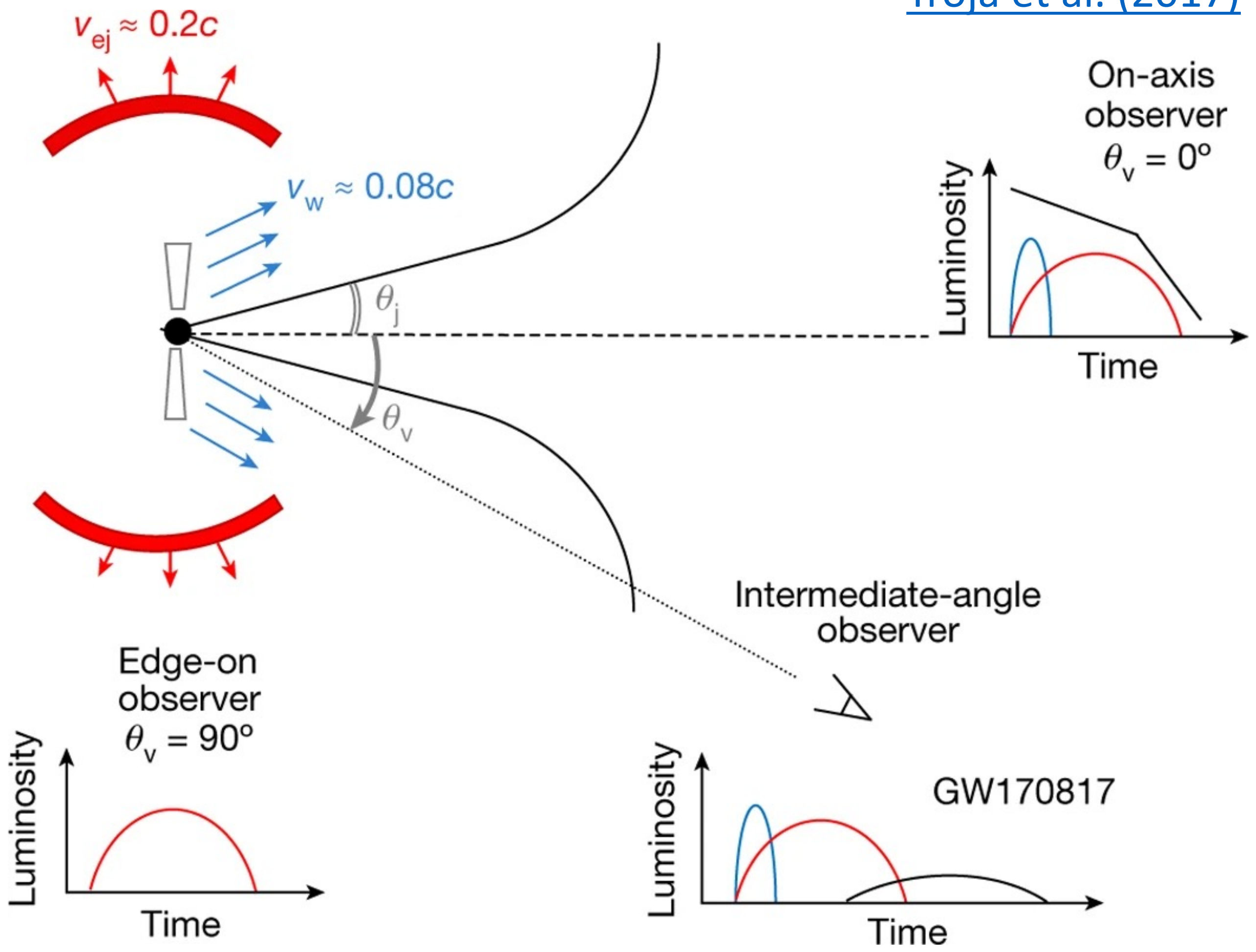


A coherent picture from prompt gamma-ray emission and multi—wavelength afterglow (X-ray, optical, radio)

Ciolfi (2020)

Troja et al. (2017)

- Merger remnant launched highly relativistic jet (matches GRB paradigm)
- Burst was off-axis by 15-30deg, low-energy gamma rays from mildly relativistic outflow, not from jet
- On-axis observer would have seen a short GRB
- Binary Neutron Star mergers can generate SGRBs!



Kilonovae as r-process engines

- GW170817 is first clear photometric & spectroscopic kilonova
- Kilonova: UV/optical/IR transient powered by radioactive decay of heavy r-process elements synthesized within matter ejected by merger process
- Implications for EM kilonovae where source not as cleanly identified
- Optical light curve confirms BNS mergers to produce significant amount of heavy elements up to high atomic mass (A>140)
- 1-5 Earth masses Eu, 3-13 Earth masses Au
- Challenges AGB stars as primary sites of heavy element production, but depends on merger rate

Next exercise:

A gravitational-wave standard siren measurement of the Hubble constant

The LIGO Scientific Collaboration and The Virgo Collaboration, The 1M2H Collaboration, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, The Las Cumbres Observatory Collaboration, The VINROUGE Collaboration & The MASTER Collaboration

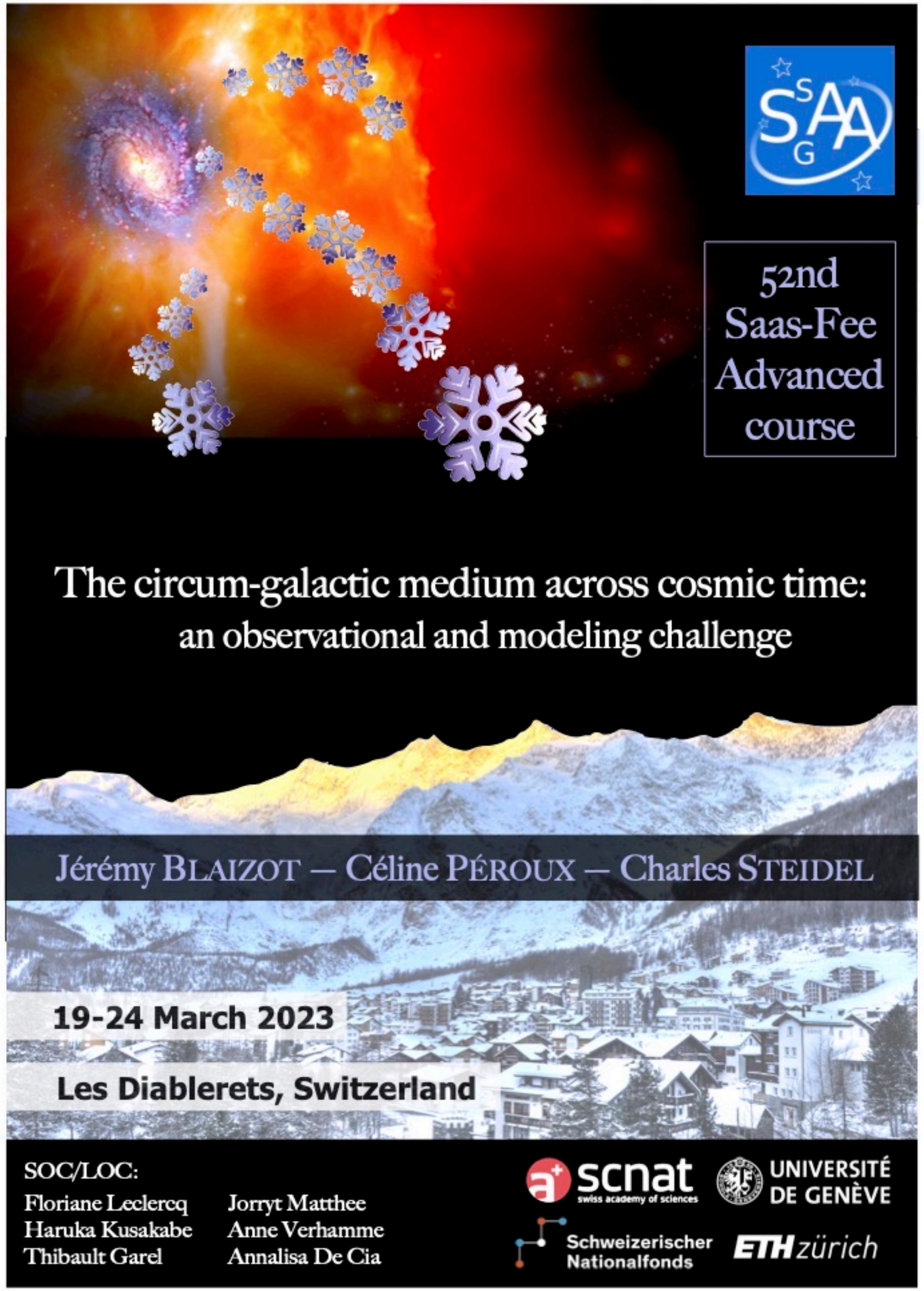
Nature **551**, 85–88 (2017) | Cite this article

Summary Gravitational Waves

- Technology development opening new field: priority in US, EU, CN, JP, IN
- GW detections are intrinsically time-domain
- Amplitude decays as 1/r : sensitive to entire observable Universe
- Mergers vs continuous sources
- Surprise: BHs found too massive for stellar evolution
- Detection of EM counterparts: multi-messenger
- Kilonova GW170817 is rosetta stone for
  - General Relativity
  - Heavy-element production
  - Hubble constant
  - Neutron star physics
- Next LIGO run starts March 2023: prepare for many more kilonovae!

Upcoming Saas Fee Courses

- Formal lectures, interactive hands-on sessions (observational and simulation data).
- Several-hour-long afternoon break for winter sports or participant interactions
- 2023:
  - https://www.astro.unige.ch/saasfee2023/
  - Deadline 15 Jan 2023
- 2024:
  - From stars to planets in the space-based photometry eras
  - Vincent Bourrier, Patrick Eggenberger, Gael Buldgen, and Svetlana Berdyugina
- 2022: was on gravitational waves https://www.astro.unige.ch/saasfee2022/



Questions?