Status of Gravitational-wave Observation

David Shoemaker
MIT

Thanks

- Colleagues who ‘lent’ slides and images
  - Dave Reitze, Jan Harms, Alessandra Buonanno, Daniel Reardon, Karan Jani, Many LIGO Lab folk, LVKfolk…
- NSF – a remarkable institution giving robust, sustained, courageous support for LIGO

Talk Roadmap

- Terrestrial Observatories/detectors
- Pulsar Timing Array observations
- Plans for free flying space observatories
- …the Moon

Early LIGO History

QUARTERLY PROGRESS REPORT

APRIL 15, 1972

No. 105

ELECTROMAGNETICALLY COUPLED BROADBAND GRAVITATIONAL ANTENNA

Rai Weiss, MIT
(1932-2025)

It's about:
i) Arm length
ii) Understanding and minimizing noises

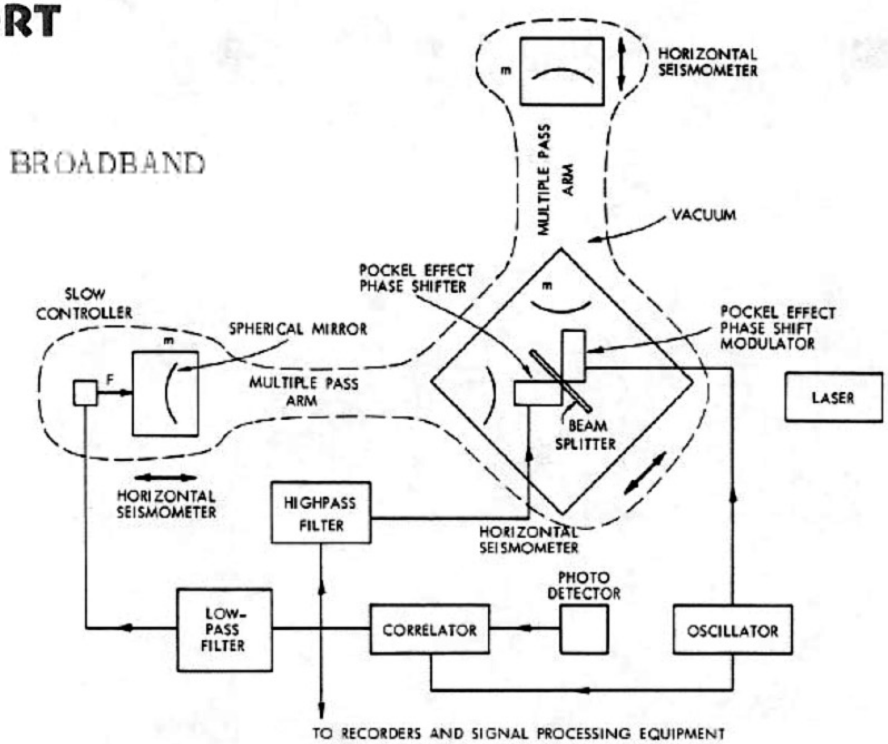
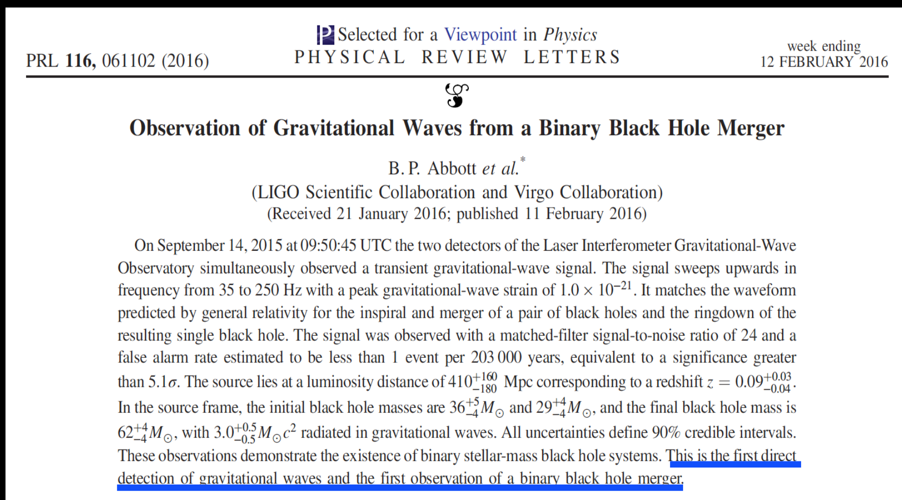


Fig. V-20. Proposed antenna.

This is the Seminal Paper in GW Interferometry. Yet wasn't published in an archival journal until 2022

R. Weiss, "Electromagnetically Coupled Broadband Gravitational Antenna", General Relativity and Gravitation (2022) 54:153

September 2015: The First Direct Observation of Gravitational Waves from a Binary Black Hole Merger



PRL **116,** 061102 (2016) — Selected for a Viewpoint in *Physics* — PHYSICAL REVIEW LETTERS — week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

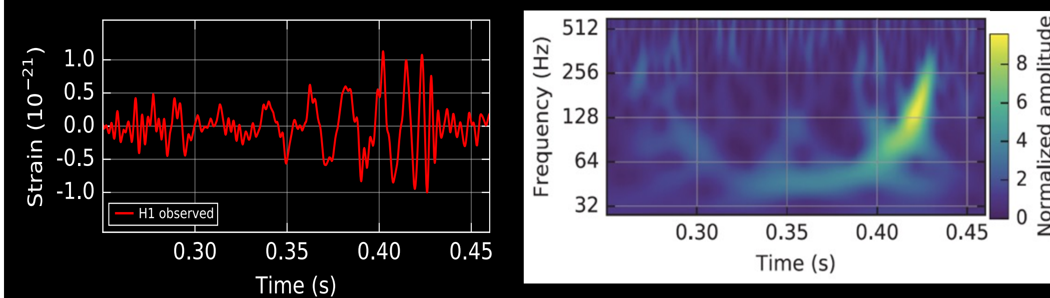
B. P. Abbott *et al.**

(LIGO Scientific Collaboration and Virgo Collaboration)

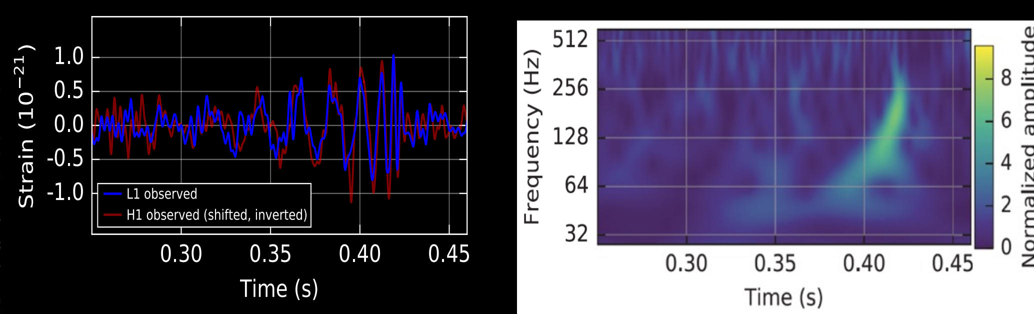
(Received 21 January 2016; published 11 February 2016)

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the wavefom predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

Hanford, Washington (H1)

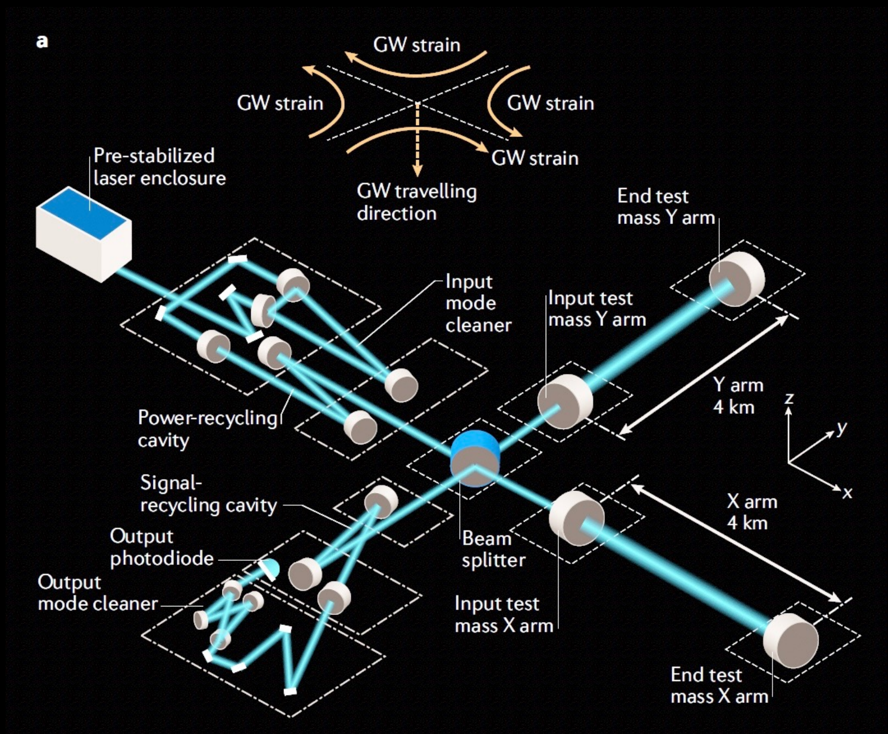


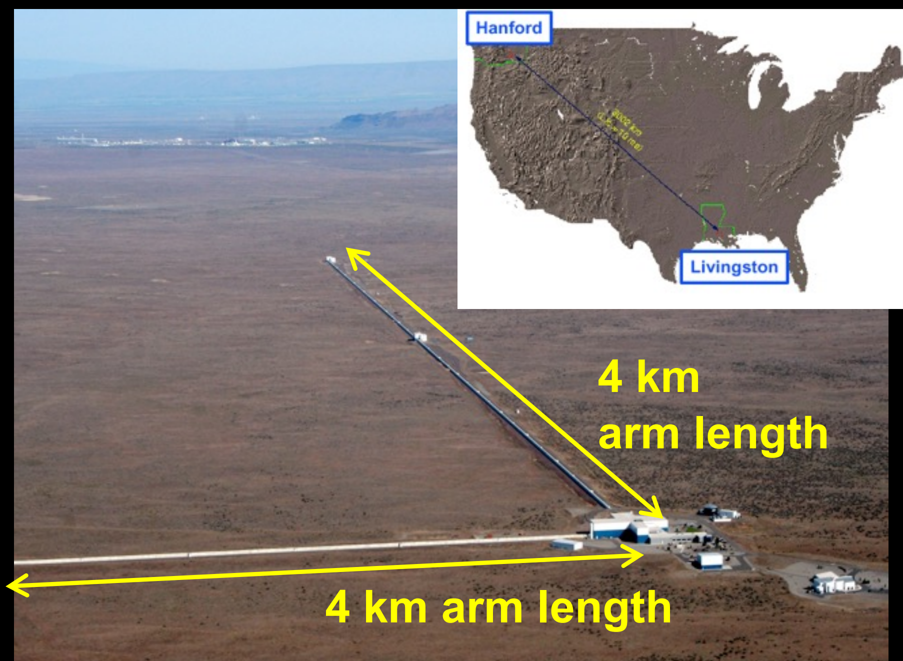
Livingston, Louisiana (L1)



Nature

Terrestrial detectors: LIGO, Virgo, KAGRA



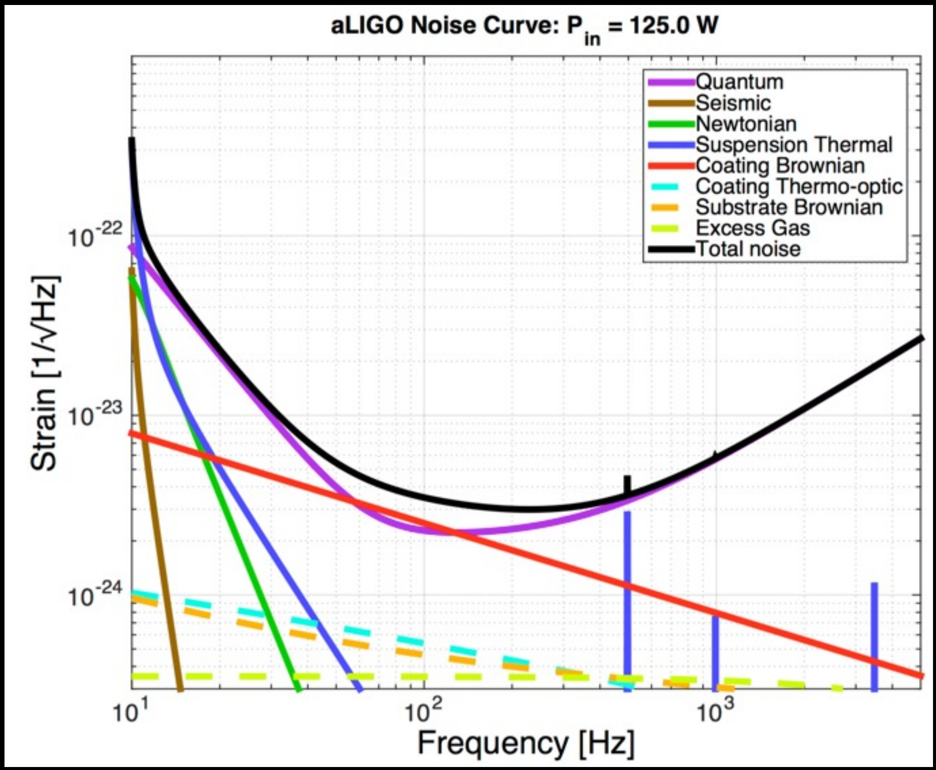


Passing GWs stretch and compress the distance between the end test mass and the beamsplitter, altering the arrival time of the light traveling in each arm --> One arm gets longer, one arm gets shorter

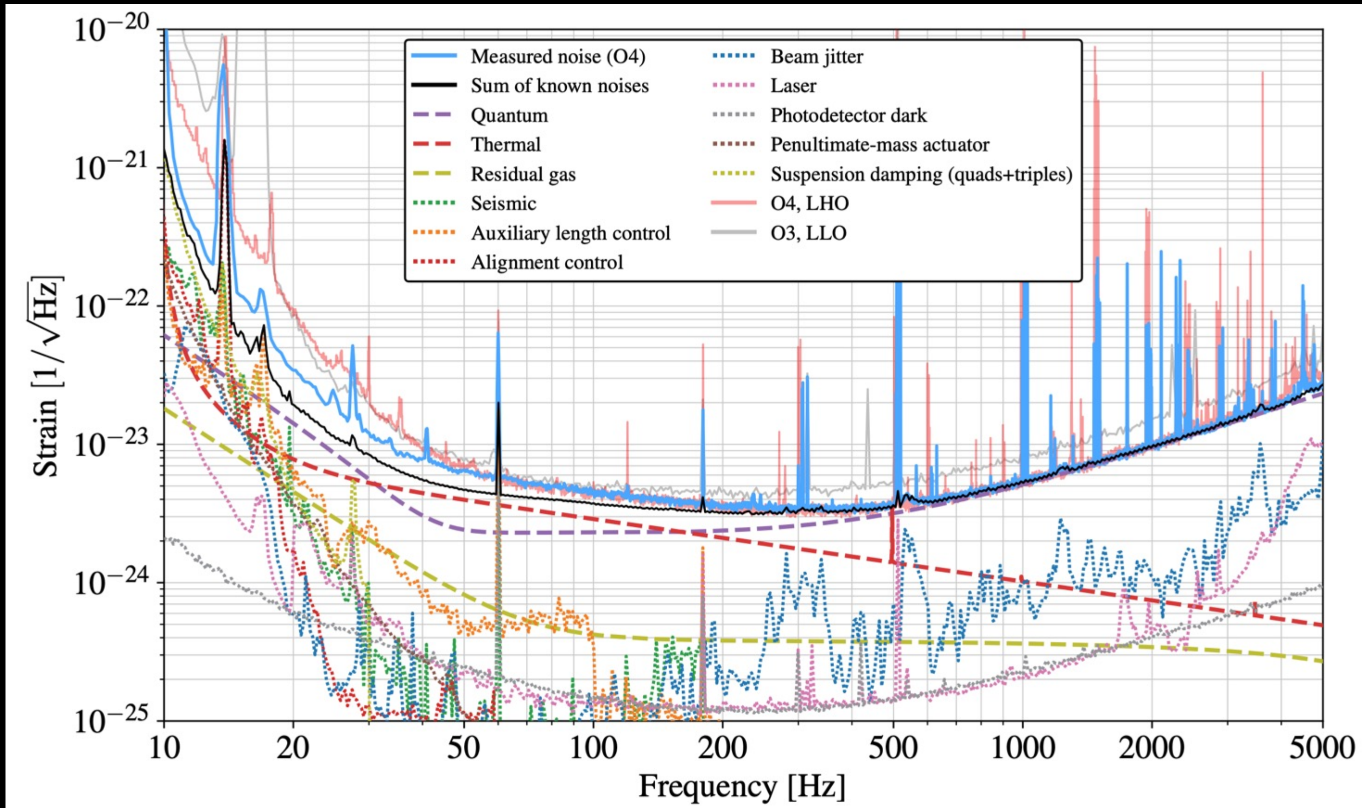
The interferometer acts as a transducer, turning GWs into photocurrent --> A coherent detector!

Useful paradigm in considering limits to detector sensitivity

- **Ability to measure** the position of our test mass
  - **Quantum noise**
  - Scattered light
  - Laser light defects – intensity, position, mode shape, frequency noise
  - Laser path noise fluctuations
  - Electronics noise
- **True noise motions** of the reference surface on our 'free test mass' which can mask GWs
  - **Thermal noise**
  - Radiation pressure
  - Environmental mechanical forces – seismic, anthropogenic, weather
  - Stray electric, magnetic fields
  - Accidental noise forces from control systems and sensors



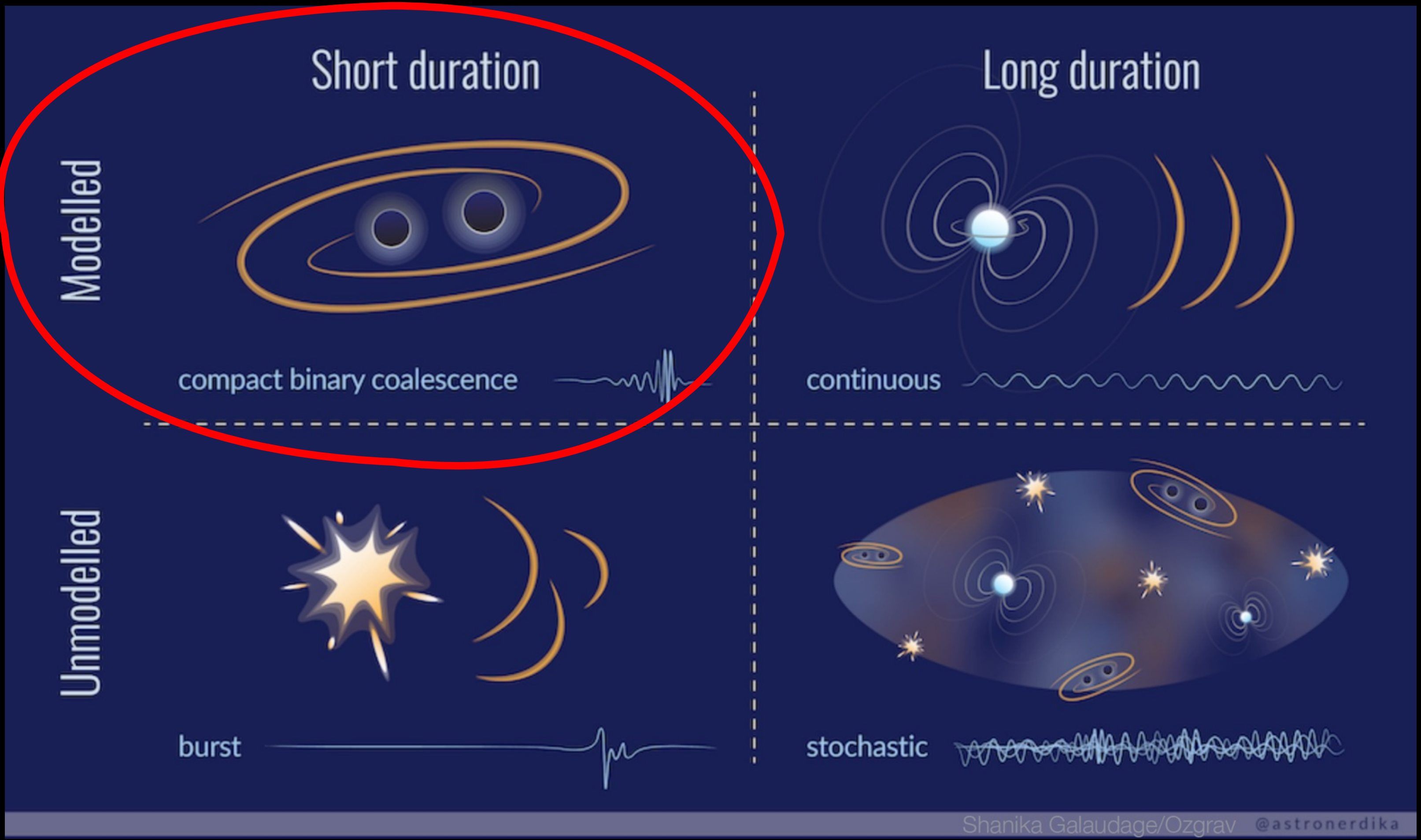
The more complete story



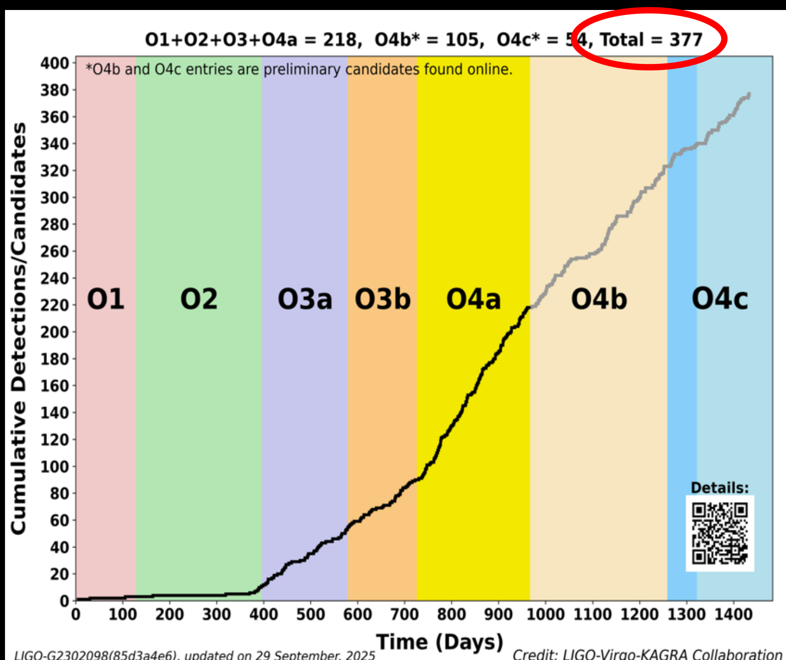
(b) Noise budget for the LIGO Livingston Observatory, as of October 2023.

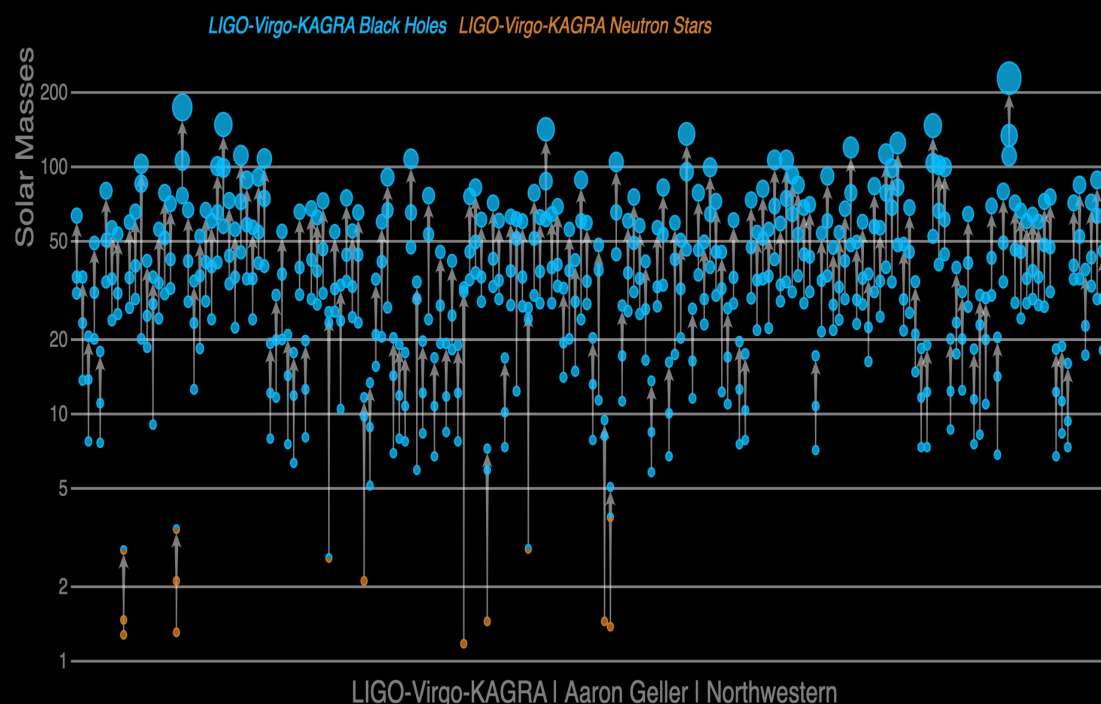

40 kg ‘Test
Mass’ Mirror
Quadruple Suspension
SOUTH
SHUMATE
HARLEY-DAVIDSON
INSTRUCTIONS

An Abridged Astrophysical Gravitational-Wave Source Catalog



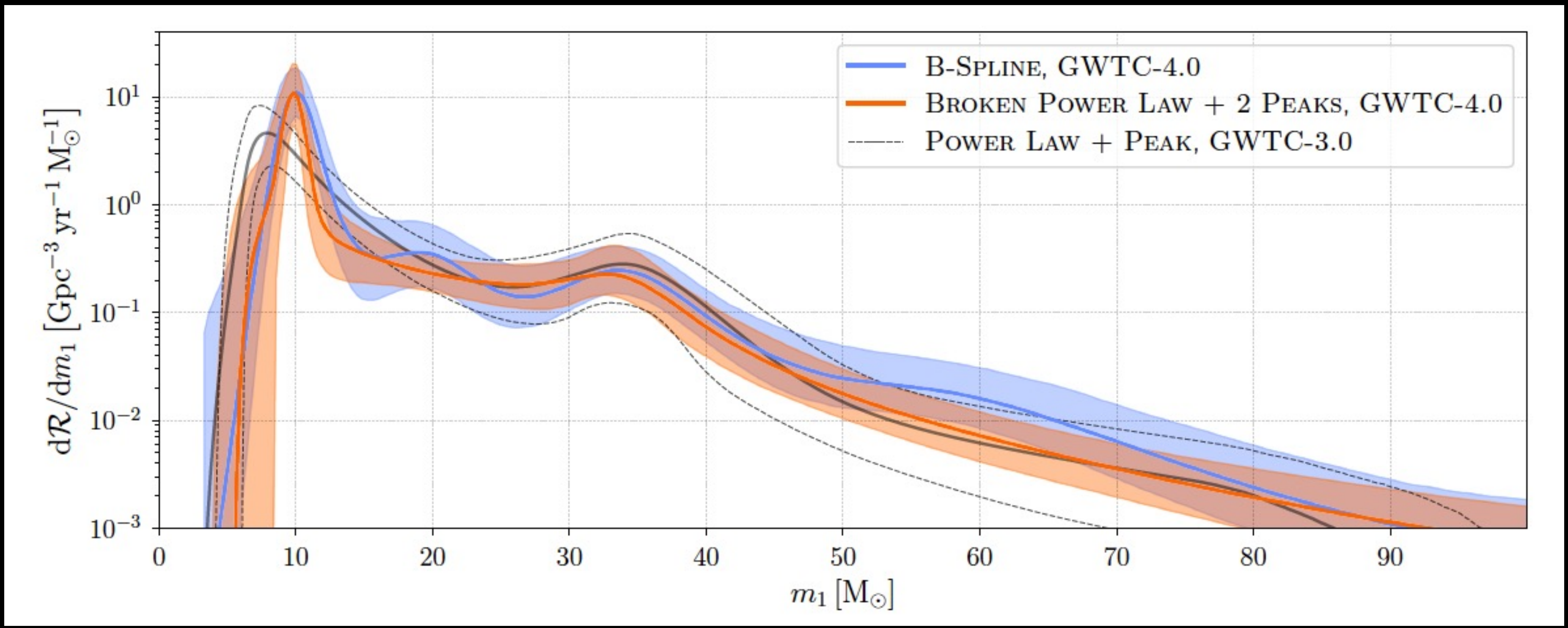
LIGO and Virgo observations through O4a





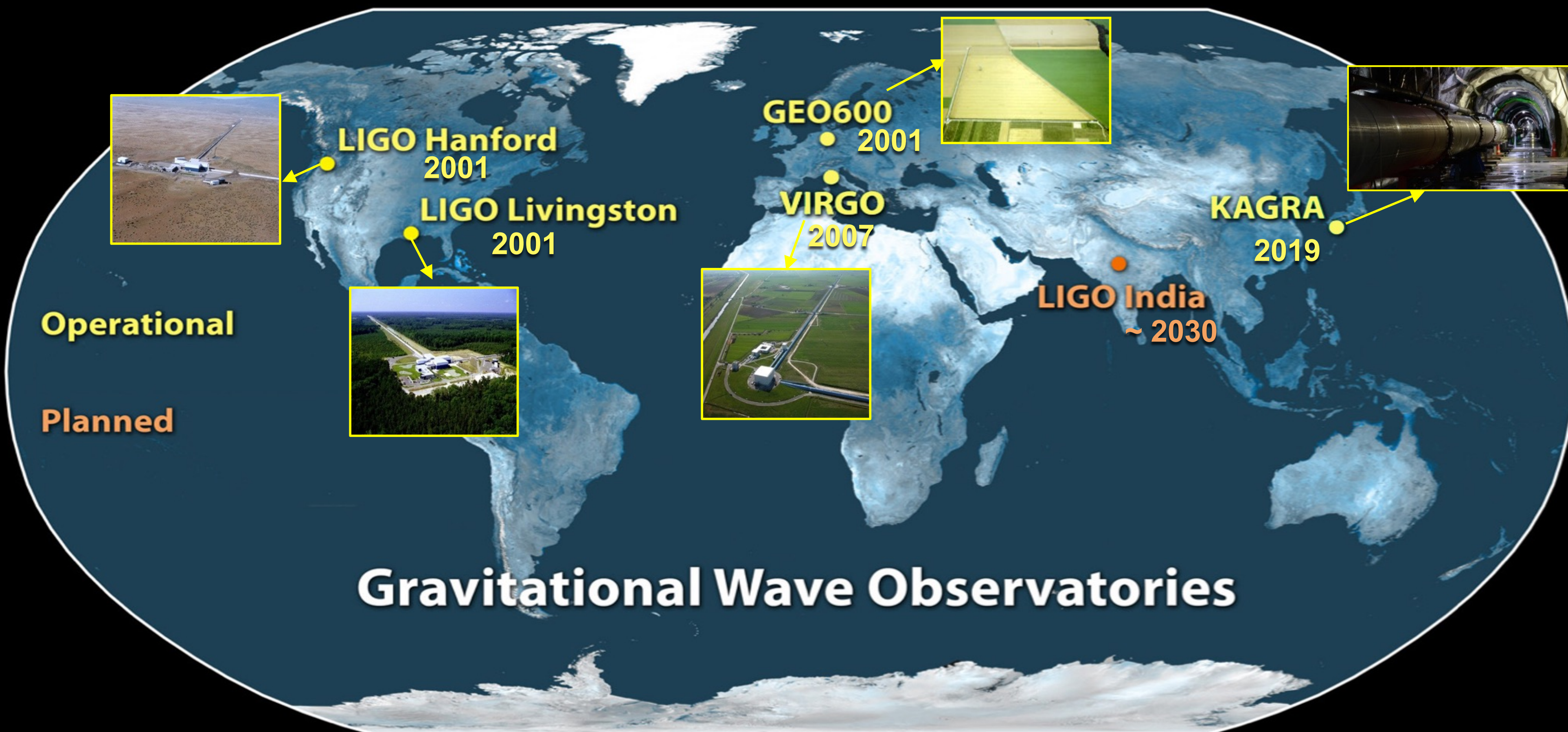
<Detector Strain Sensitivity> ~ Range # of detections ~ Range^3

Binary Black Hole (BBH) Properties: Population and Merger Rates



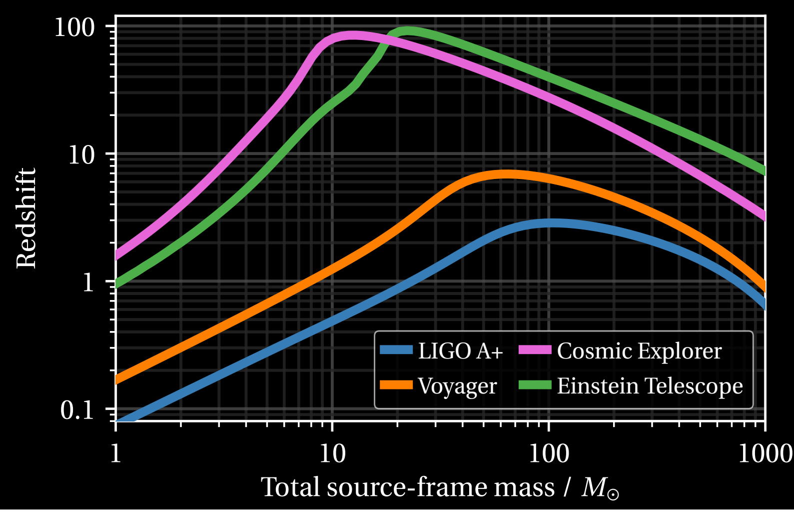
Abac, et al., (LIGO Scientific Collaboration, Virgo Collaboration, KAGRA Collaboration) “GWTC-4.0: Population Properties of Merging Compact Binaries”, https://arxiv.org/pdf/2508.18083

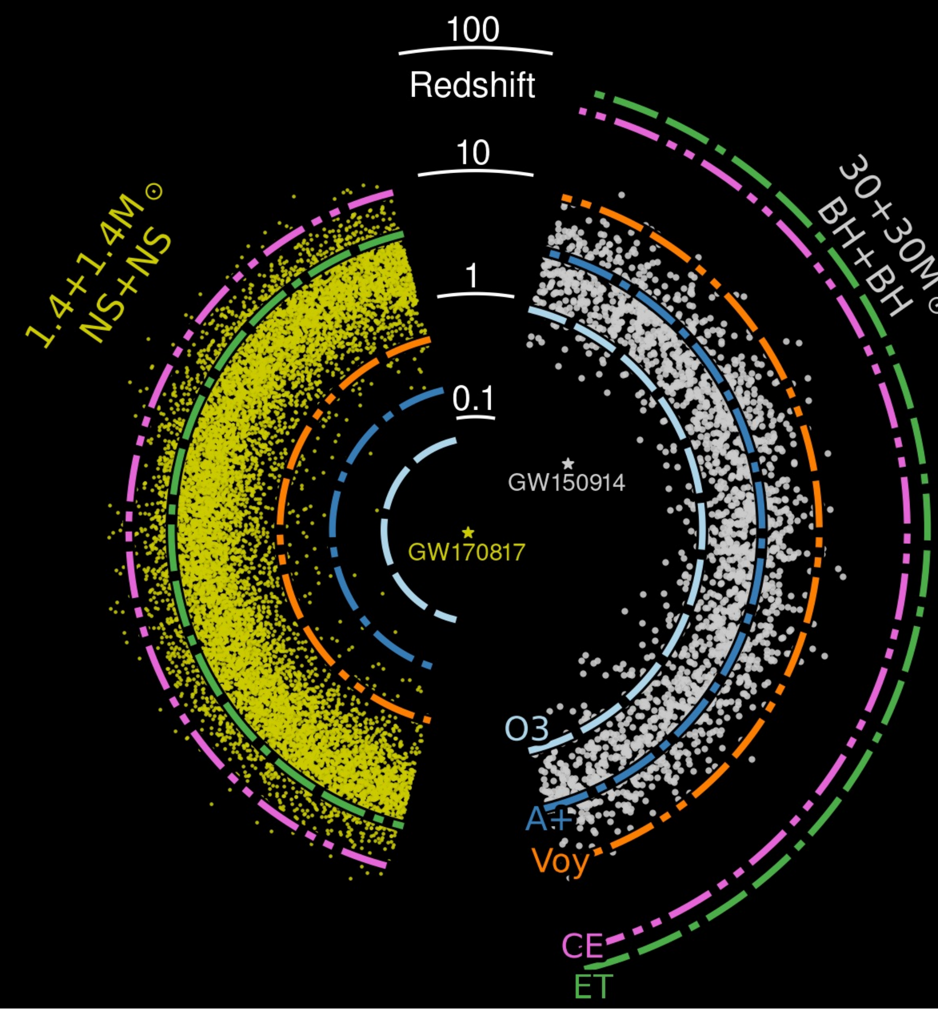
The Global Gravitational Wave Observatory Network



Black Holes and Neutron Stars throughout cosmic time

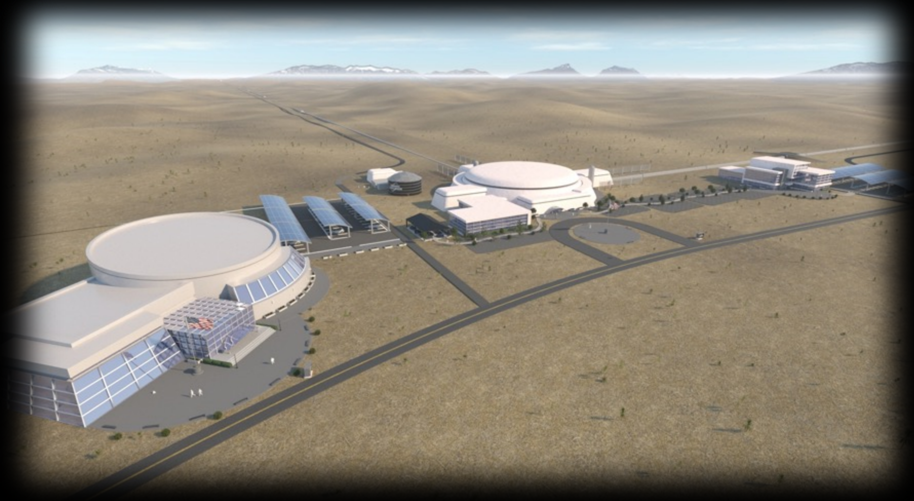
- The best understood source of gravitational wave emissions are compact binary systems.
- Can build a detector able see all binaries in a broad range of masses



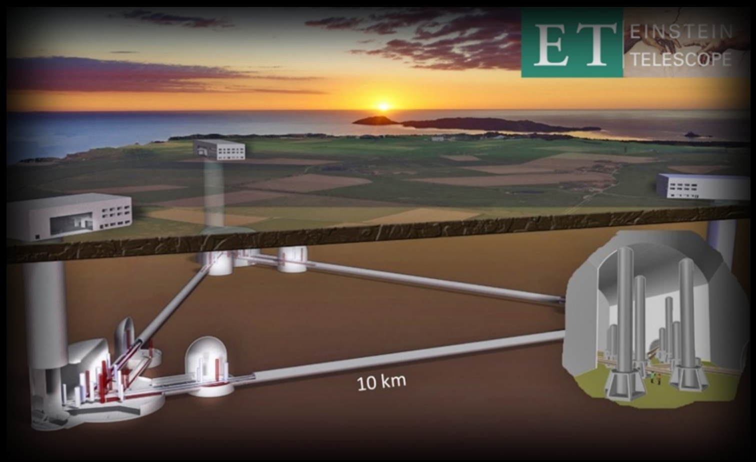


Evolution of terrestrial Observatories

LIGO-India: 2030+

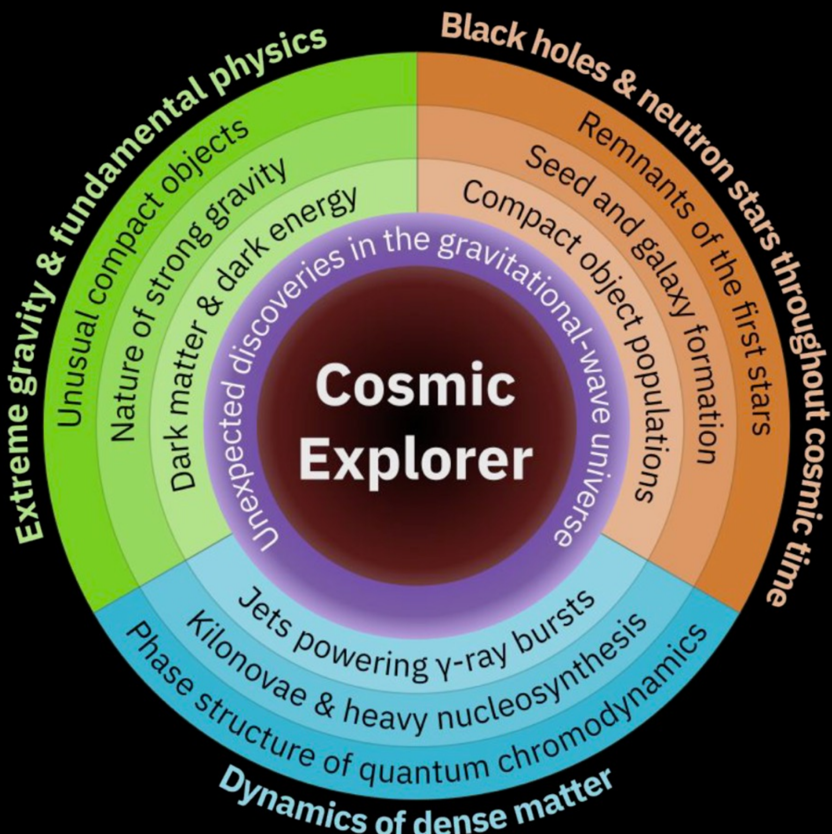


Cosmic Explorer (USA): 2035+
40 km arm lengths

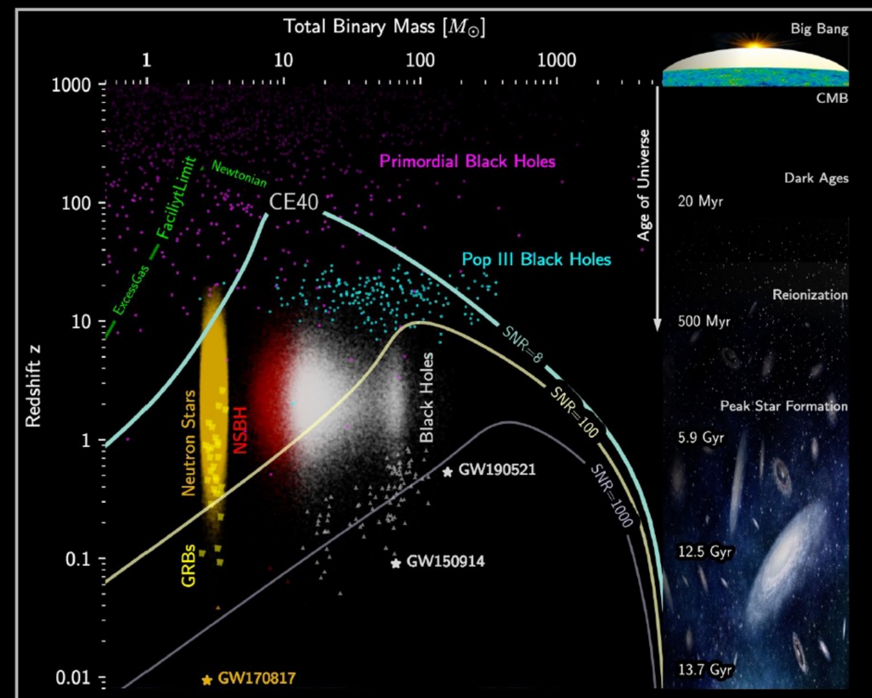


Einstein Telescope (Europe): 2035+
10-15 km arm lengths

ET+CE: All stellar-mass Black Holes in the Universe within reach



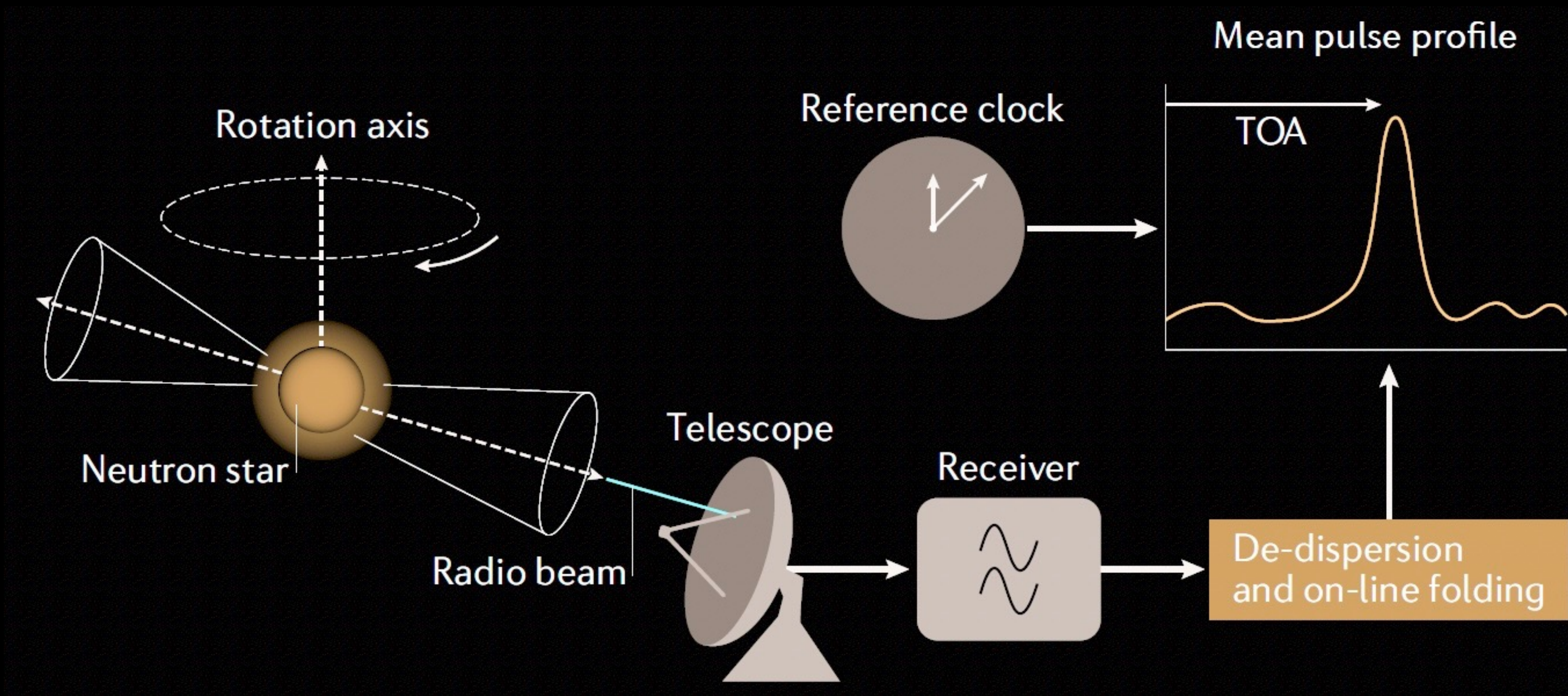
Cosmic Explorer: A Submission to the NSF MPSAC ngGW Subcommittee



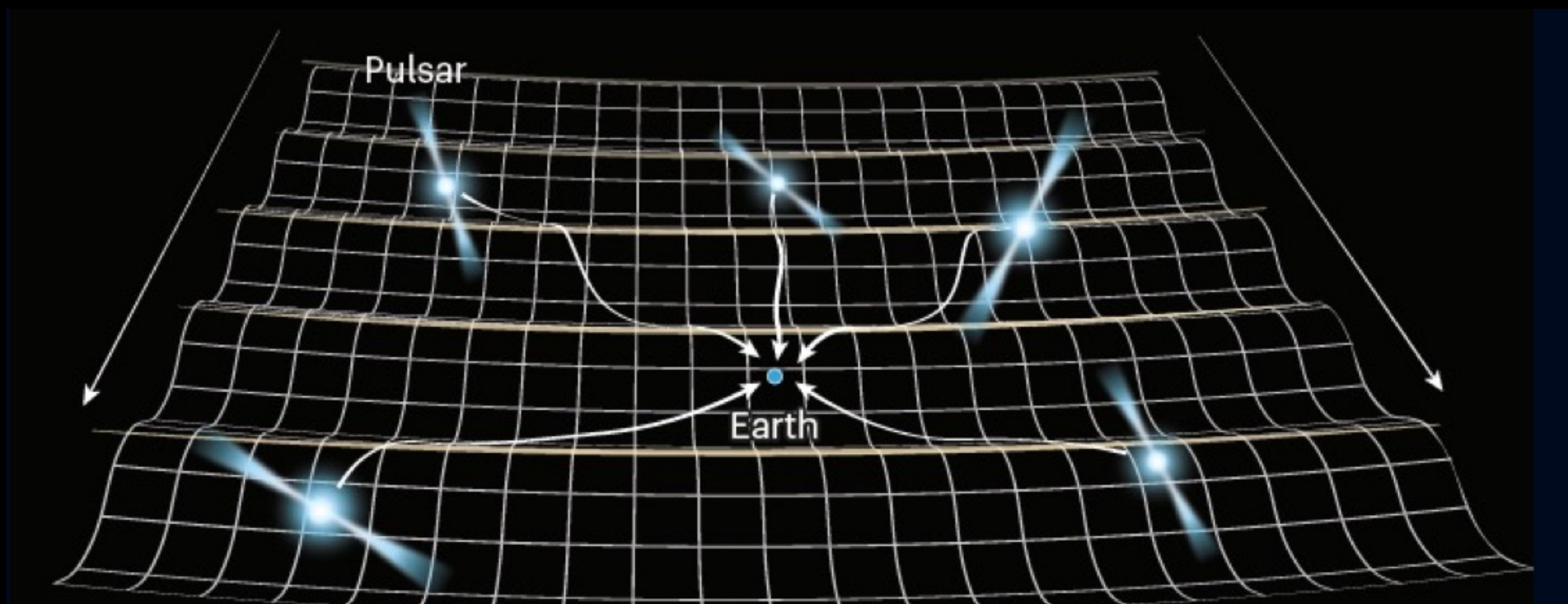
Credit: CE Team

The International Pulsar Timing Array (IPTA)

Using Neutron Stars as Test Masses: Pulsar Timing Array observations of GWs



Passing GW modulates signal phase



Nature

It is, at last, an international collaboration

IPTA third data release (IPTA-DR3)

Credit: Golam Shaifullah

PTA	Dataset	PSRs	Tspan (years)	$f_{GW,low}$ (nHz)	f_{radio} (MHz)
EPTA	DR3	60	24.5	1.3	283 - 5107
	LOFAR + NENUFAR	17	9.6	-	30 - 190
NANOGrav	15-yr	68	15.9	2.0	302 - 3988
	CHIME	11	2.5		400 - 800
PPTA	DR3	24	18.1	1.8	704 - 4032
InPTA	DR2	27	7.5	4.4	300 - 1460
MeerKAT	DR2	83	4.5	7.0	856 - 1712
CPTA	Subset of DR1	57	2.3	13.8	1050 - 1450
IPTA	**DR3**	**130**	**~27**	**1.2**	**30 - 5107**

Data processing is not simple

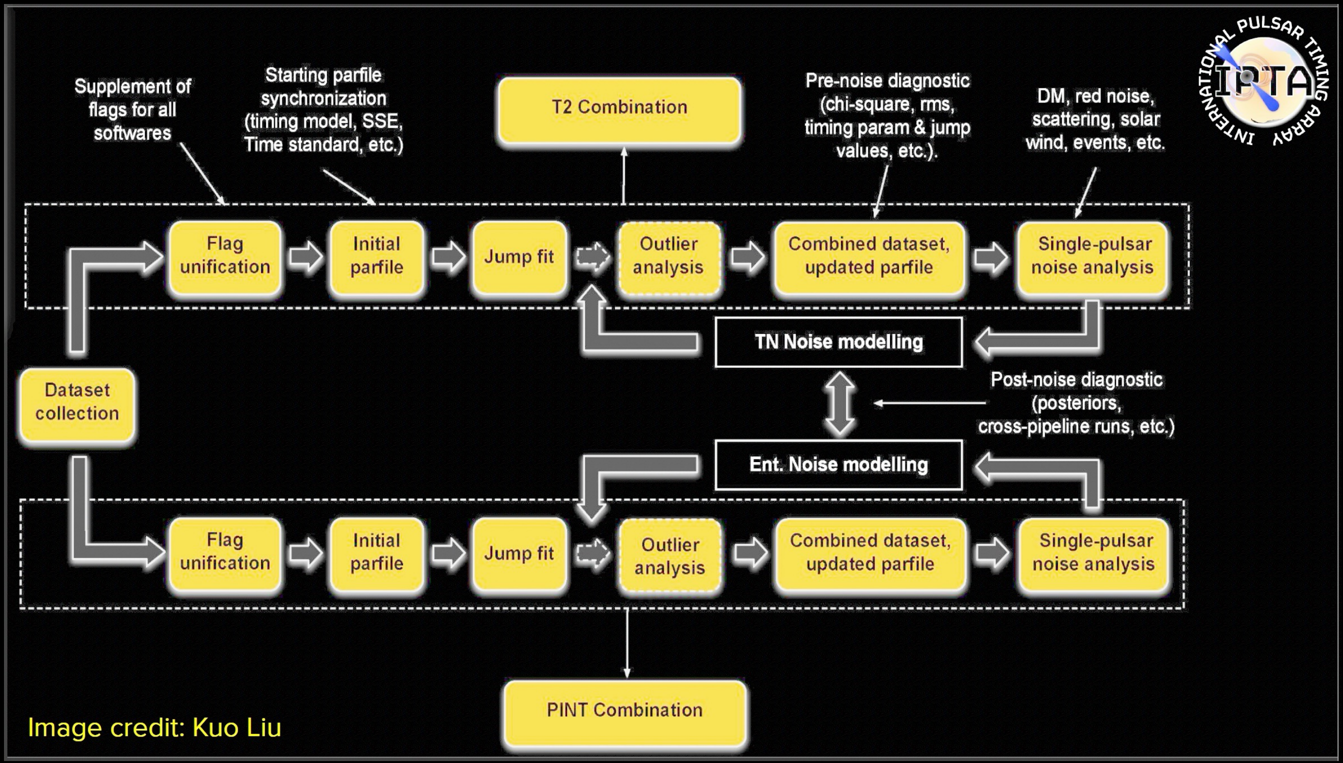


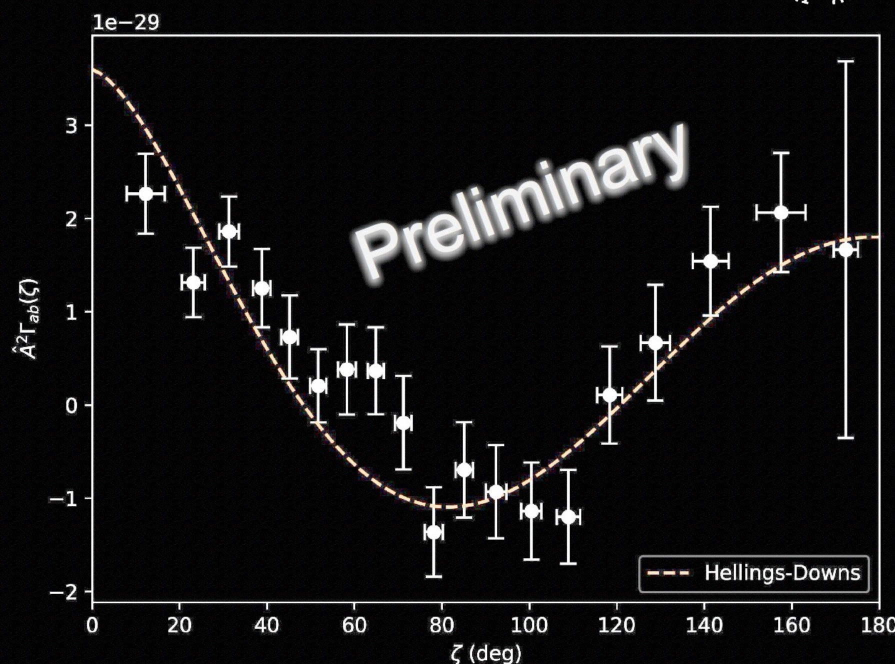
Image credit: Kuo Liu

But there is now clear evidence of a GW signal

IPTA-DR3 challenges and solutions

- Large data volume
- Complex noise environments
- Final data combination now underway

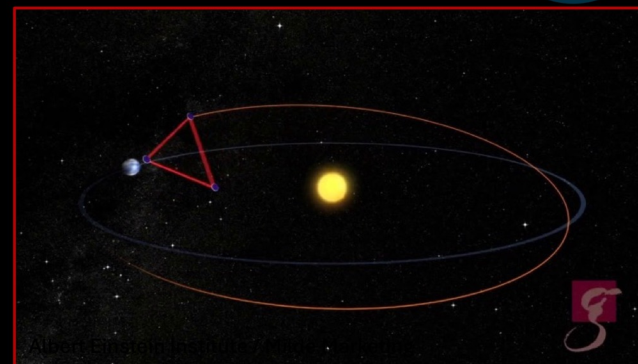
- New codes, models, and techniques
    - GPU-accelerated Bayesian inference with *Discovery*
    - Methods to do rapid inference without full data combination, e.g. “*Frankenstat*”
- Expect greater GWB significance than individual component data sets

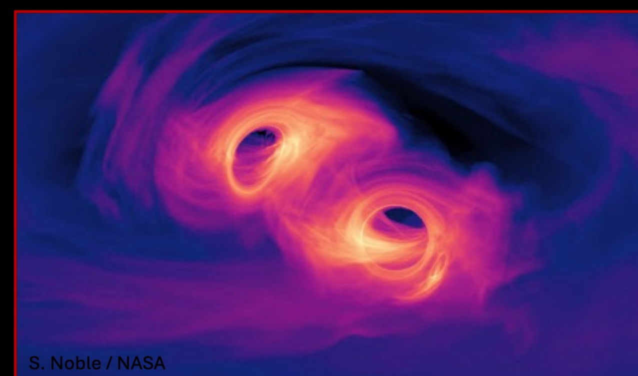


Above: “Frankenstat” IPTA-DR3 analysis preview.
Credit: Wright, Wayt, Hazboun, Siemens, Romano, Vigeland

Telescopes contributing to the next IPTA data release

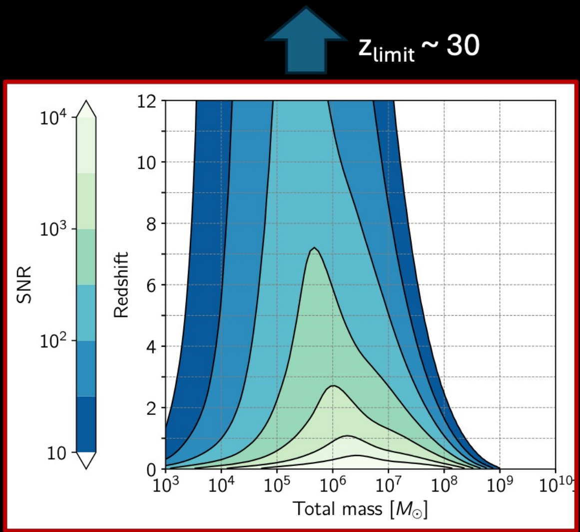
Laser Interferometer Space Antenna



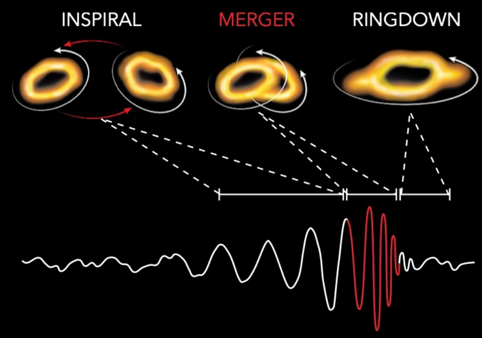


Joey Shapiro Key
University of Washington Bothell
for the LISA Science Team

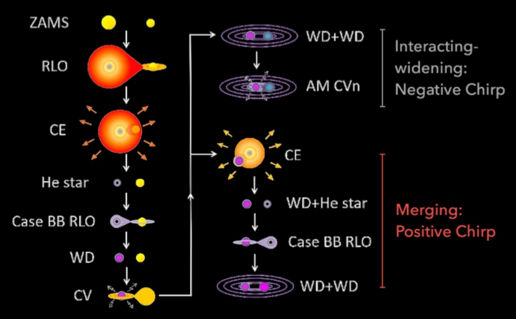
Science Highlights



Census of massive black hole mergers into the cosmic dark ages

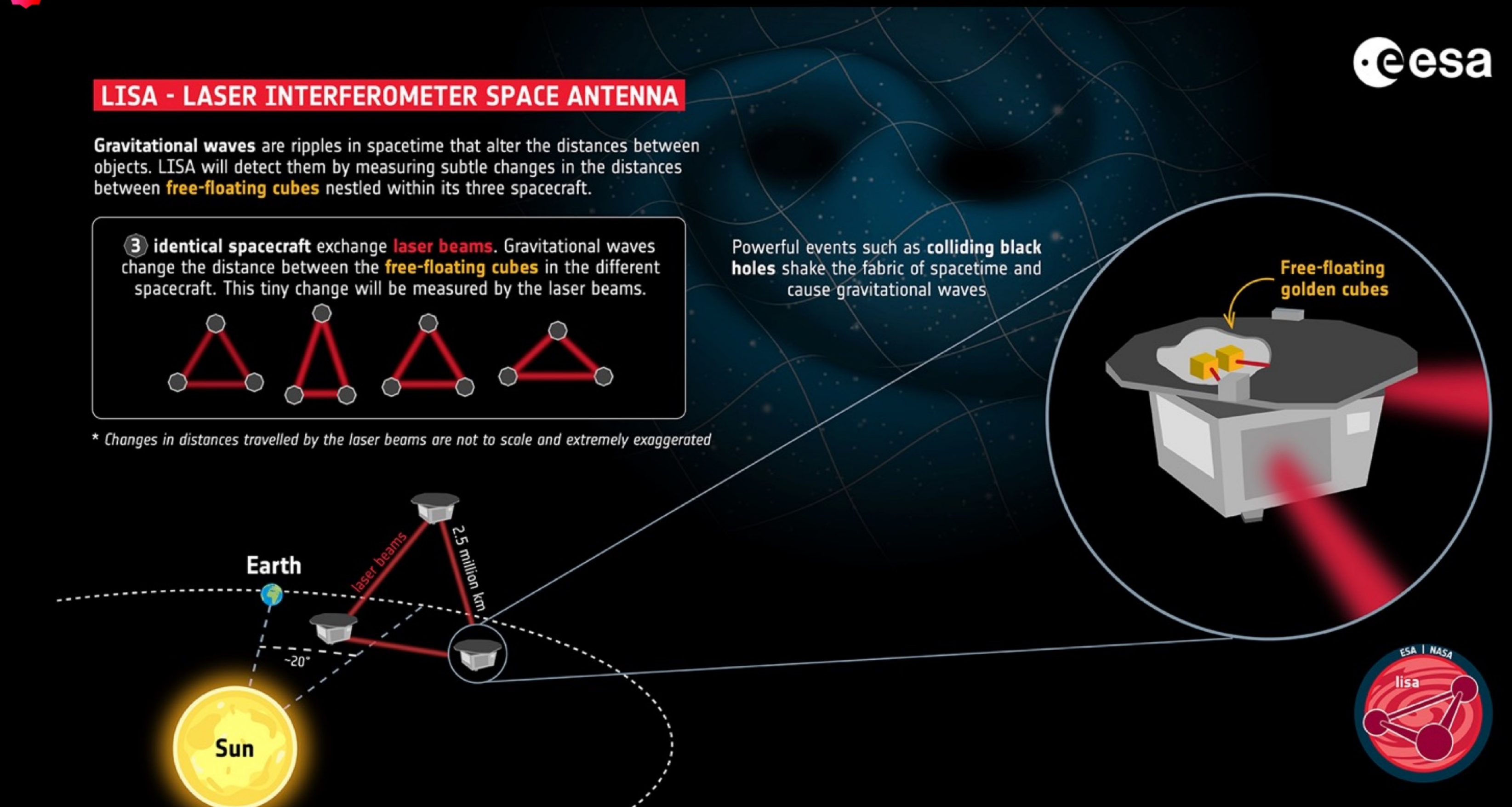


Precision tests of GR in extreme gravitational environments



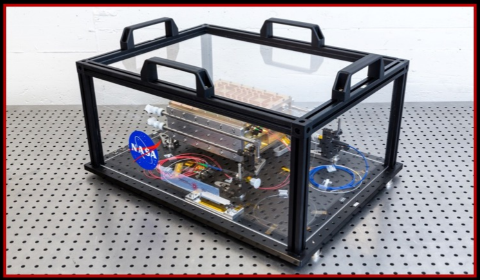
Tens of thousands of compact binary systems in the Milky Way

Measurement Principle

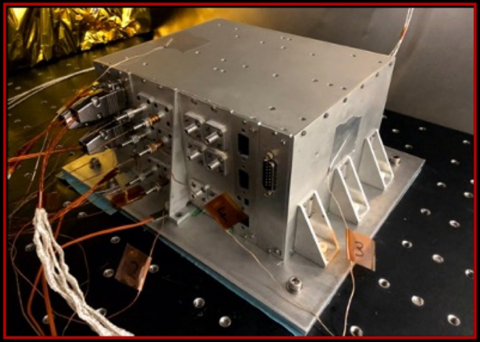


Hardware Progress

EDU Telescope (NASA/GSFC/L3 Harris Corp)



TRL-5 Laser Demonstrator (GSFC/ Avo photonics / Fibertek)

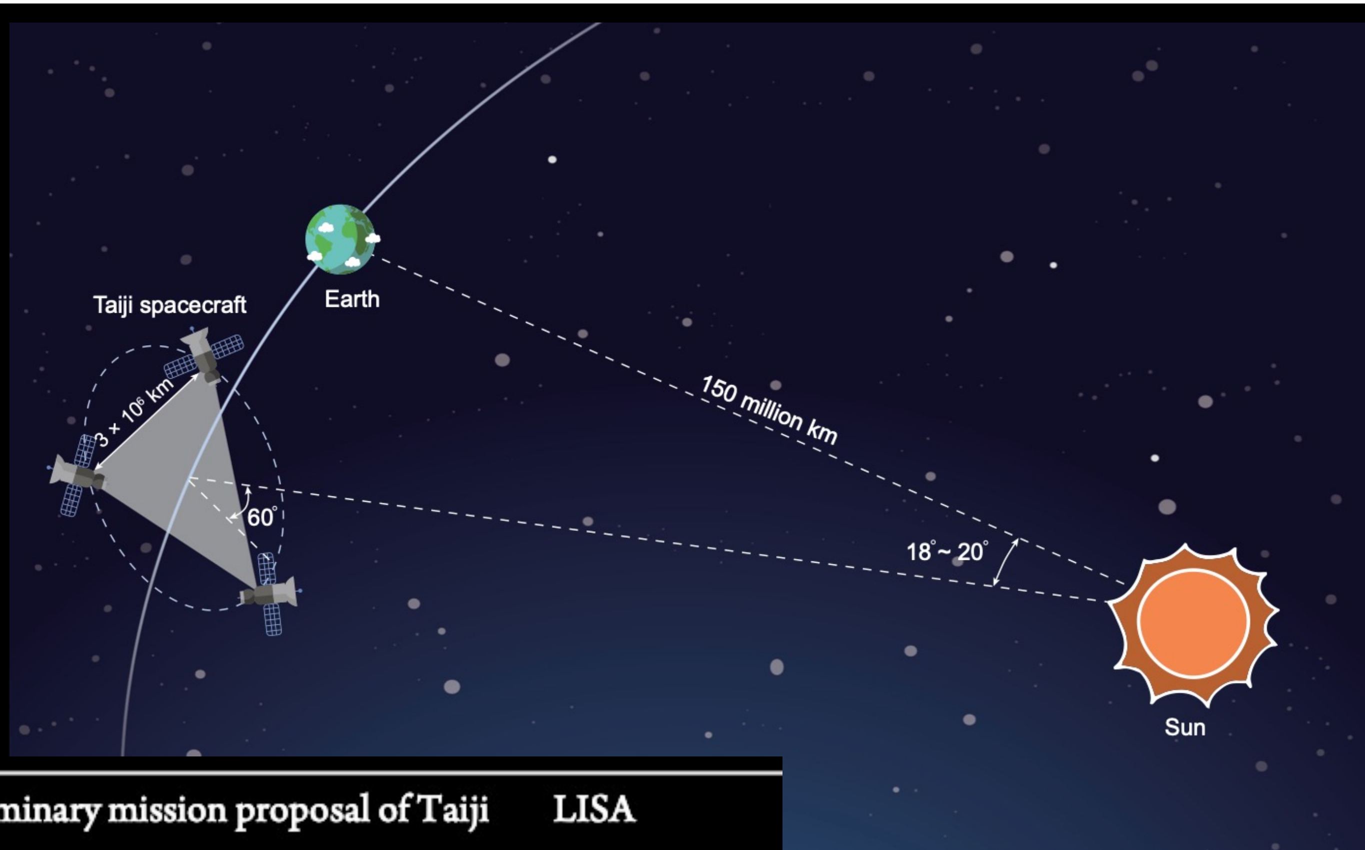


TRL-5 Charge Management Device (UF)

LISA planned launch 2035; data 2037-8

- LISA is moving forward
  - 50 years since Bender & Weiss discussed space-based GW detector at a NASA meeting!
  - ESA has selected a spacecraft vendor
  - NASA and ESA MS are completing technology development and preparing for flight procurements
- NASA is moving full speed ahead with a LISA project
  - Project structure and personnel in place
  - First milestone review complete, first key decision point in July
- Groundwork laid for robust US science participation
  - Negotiated data policy consistent with open science principles
  - US representation in ESA-NASA LISA Science Team provides "seat at the table"
  - NASA developing science ground segment contribution

Taiji – A Chinese mission like LISA

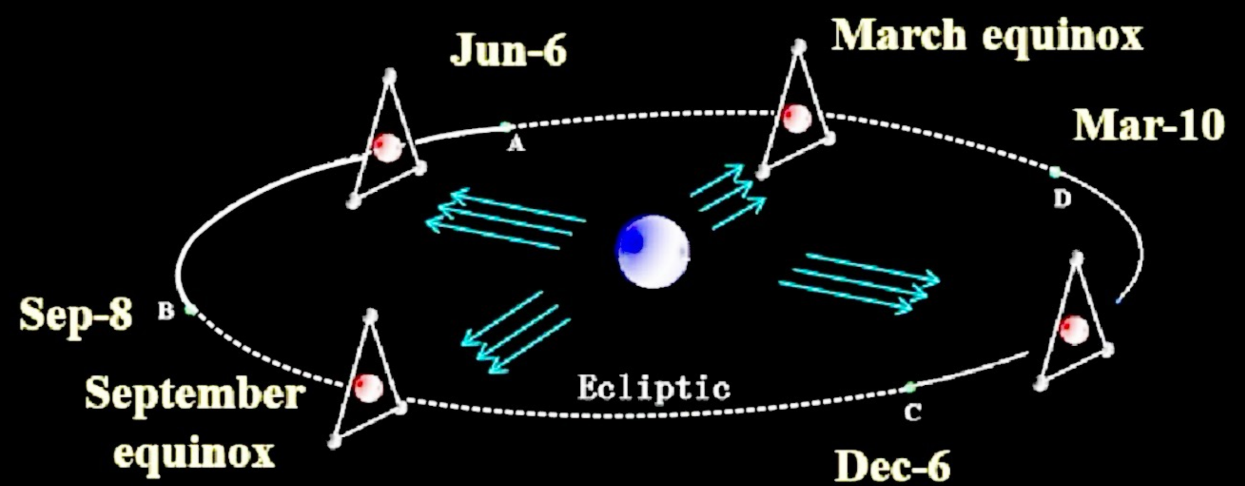


	Preliminary mission proposal of Taiji	LISA
Arm length	$3 \times 10^9\ m$	$5 \times 10^9\ m$
1-way position noise budget	$5 \sim 10\ \mathrm{pm\ Hz}^{-\frac{1}{2}}$	$18\ \mathrm{pm\ Hz}^{-\frac{1}{2}}$
Laser power	2 W	2 W
Telescope diameter	~ 50 cm	40 cm

…And a second Chinese effort:

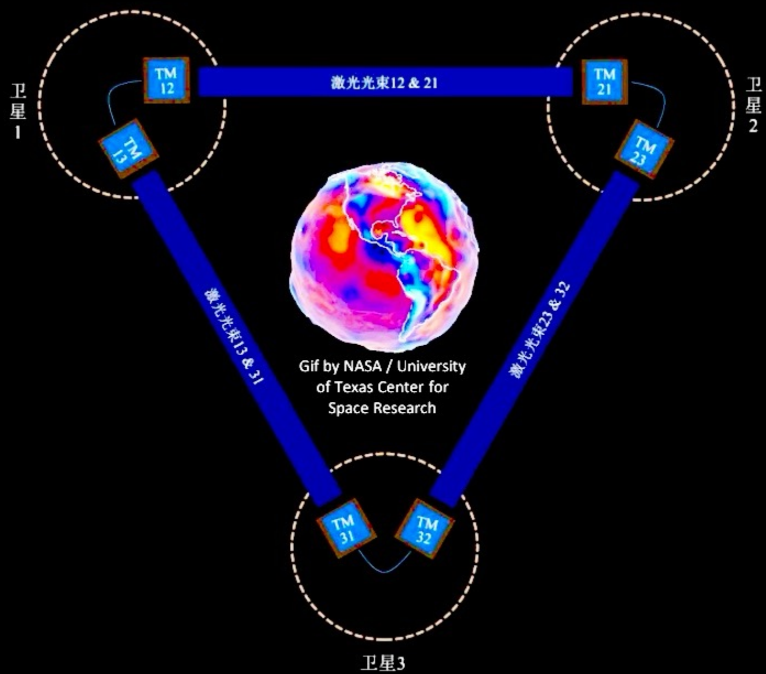
Solution from TianQin

Vertical orbital plane and "3 month on + 3 month off" detection scheme

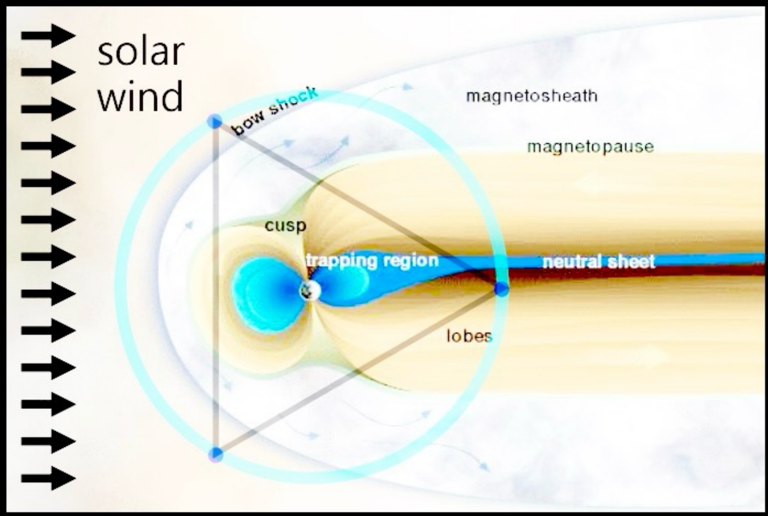


Challenging environment

Near Earth gravity environment



Near Earth plasma environment



Wei Su, Modified from ESA

Free flyers for the near future

- Similar *design* sensitivities
- Potentially similar timelines
- Some discussion of collaboration
- Could e.g., enable stochastic background measurement

- Clearly also a competitive environment

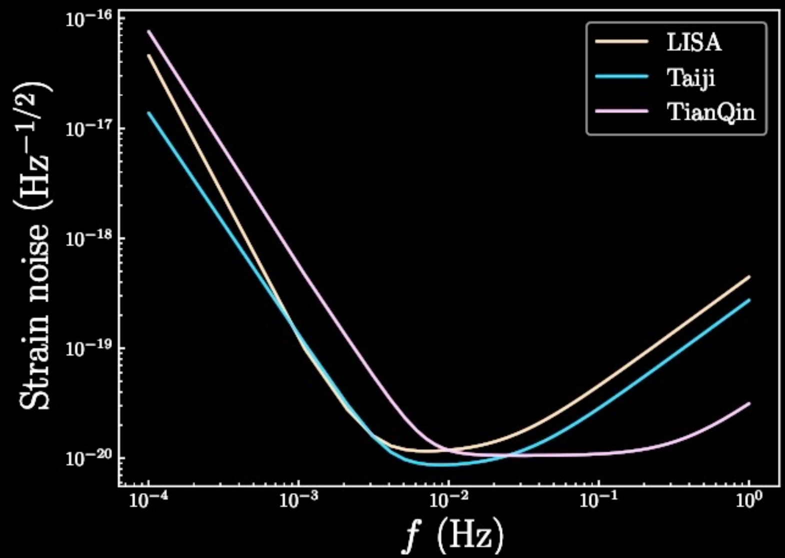


FIG. 1. The sensitivity curves of Taiji, TianQin, and LISA. More details about these sensitivity curves can be found in Refs. [125, 129, 159].

LGWA
LUNAR GRAVITATIONAL
WAVE ANTENNA

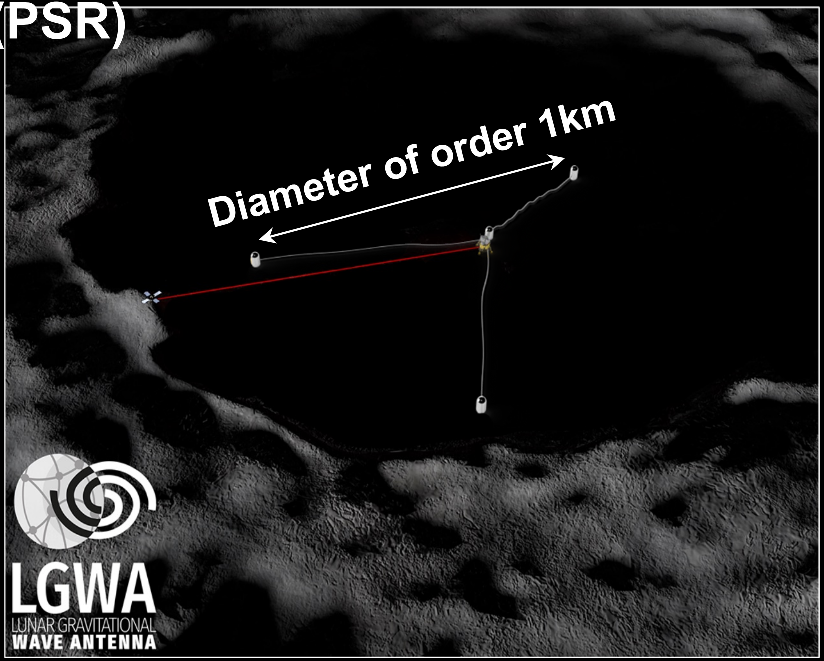
Jan Harms

Gran Sasso Science Institute
INFN - LNGS

lgwa.unicam.it

Mission Concept

Deployment of sensor array inside a permanently shadowed region (PSR)



LGWA is an evolution of the Lunar Surface Gravimeter deployed on the Moon with Apollo 17 in 1972

Measure oscillations of the Moon caused by GWs

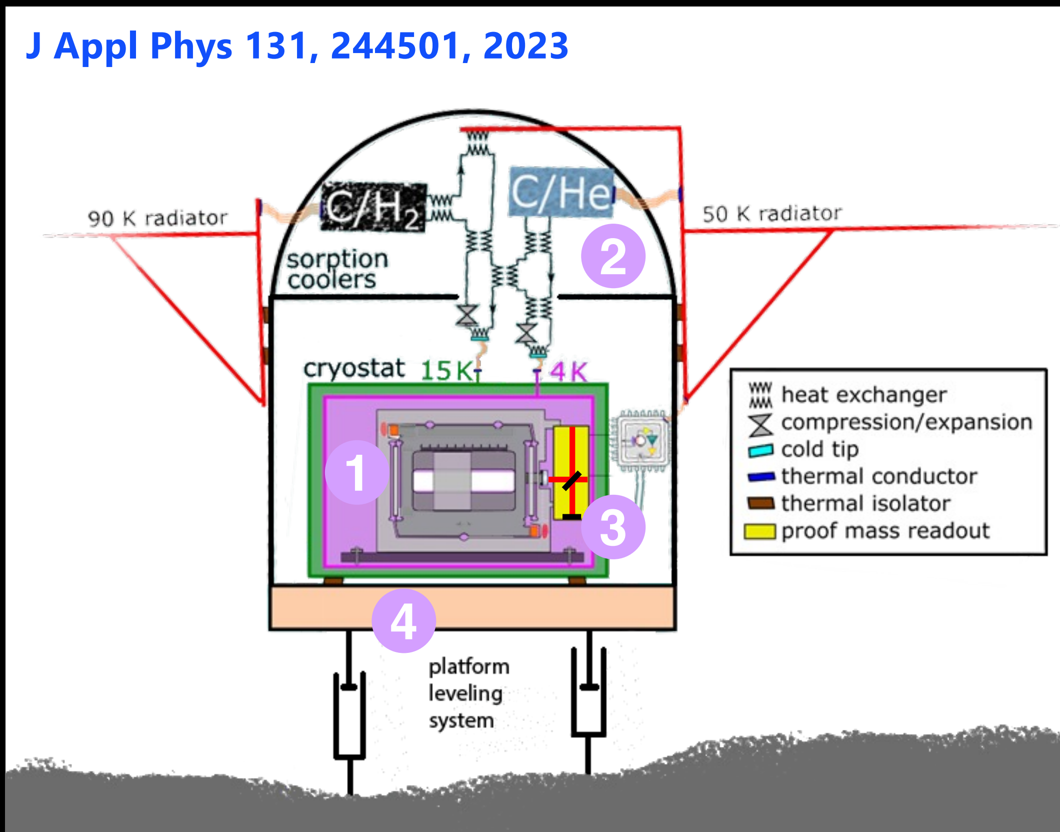
Key Mission Features

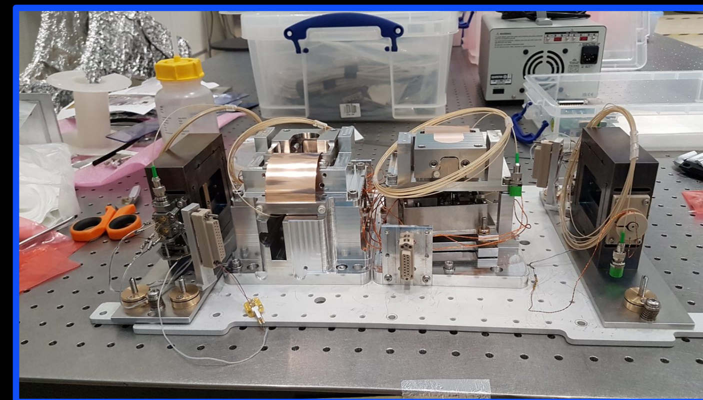
- **Femtometer precise ground-vibration measurement to observe the lunar response to gravitational waves (GWs)**
- **Exploiting the extremely low seismic background on the Moon**
- **Exploiting the extremely low temperature and high temperature stability inside permanently shadowed regions at the lunar poles**
- **Station array to mitigate the noise from the seismic background in post-processing**

Soundcheck selected in 2020 by ESA into the Reserve Pool of Science Activities for the Moon

	Soundcheck (PSR geophysical explorer)	**LGWA** (GW observatory)
Number of seismic stations	1 seismic station (two horizontal channels) deployed on ground	4 seismic stations (each with two horizontal channels) deployed on ground and forming a kilometer-scale array
Displacement sensitivity	$<1\text{pm/Hz}^{1/2}$ between 0.1-1Hz	$<1\text{pm/Hz}^{1/2}$ at 0.1Hz, $<\text{fm/Hz}^{1/2}$ at 1Hz
Deployment site	Inside any PSR (<100K)	Inside PSR with T<40K
Proof-mass material	Niobium	Niobium or silicon
Proof-mass temperature	Ambient PSR temperature (<100K)	Cooled to 4K with low-vibration cryocooler
Readout	Laser interferometric	Laser interferometric or through superconducting coils and SQUIDs
Targeted mission lifetime	2 months	10 years

The LGWA Payload Concept

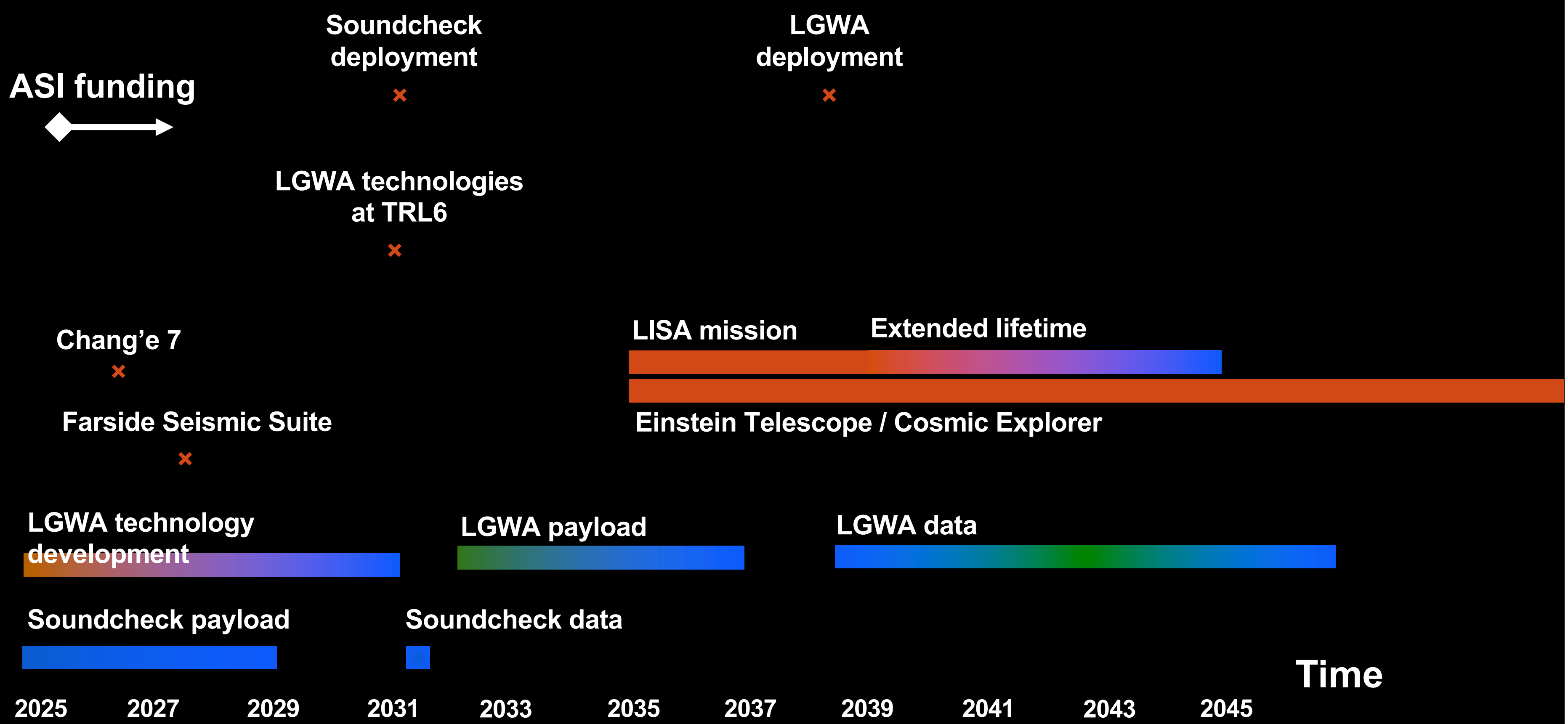




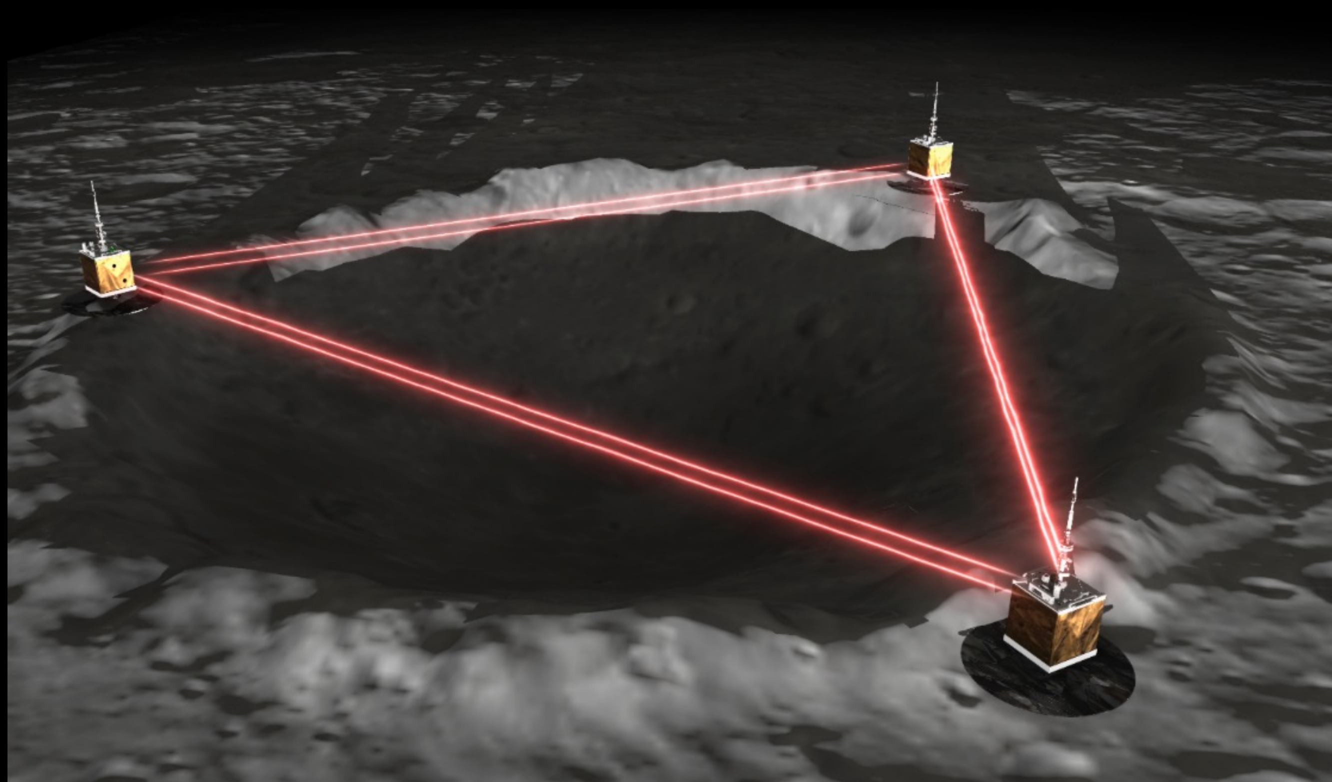
J van Heijningen, VU Amsterdam

1. Ultra-high quality mechanical structure
2. Vibration free sorption cooling
3. Quantum limited readout
4. Microradian precision leveling at cryo-temperatures

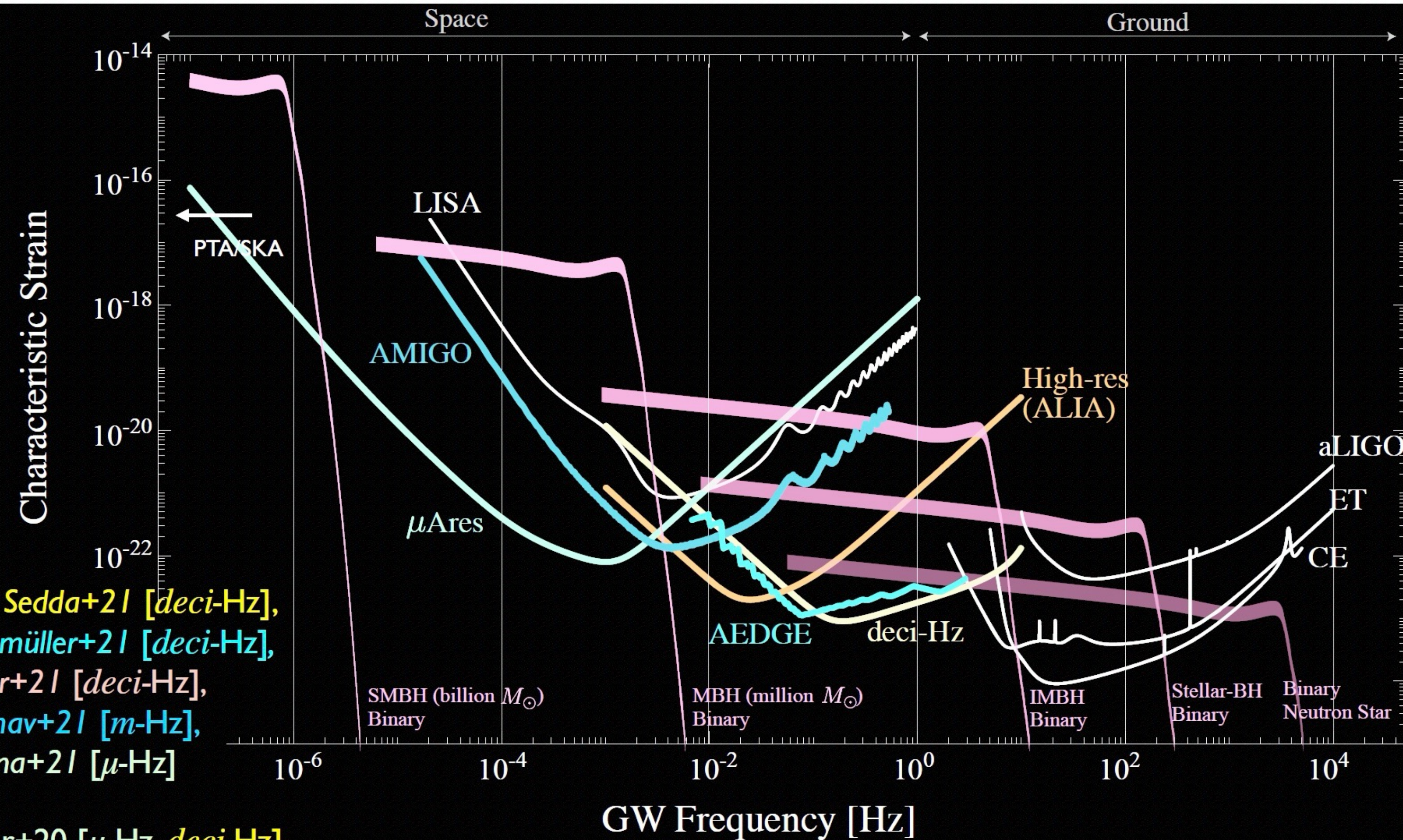
Conceivable Timeline



…and LILA, of course!



Adding Color and Depth to the Gravitational-Wave Sky

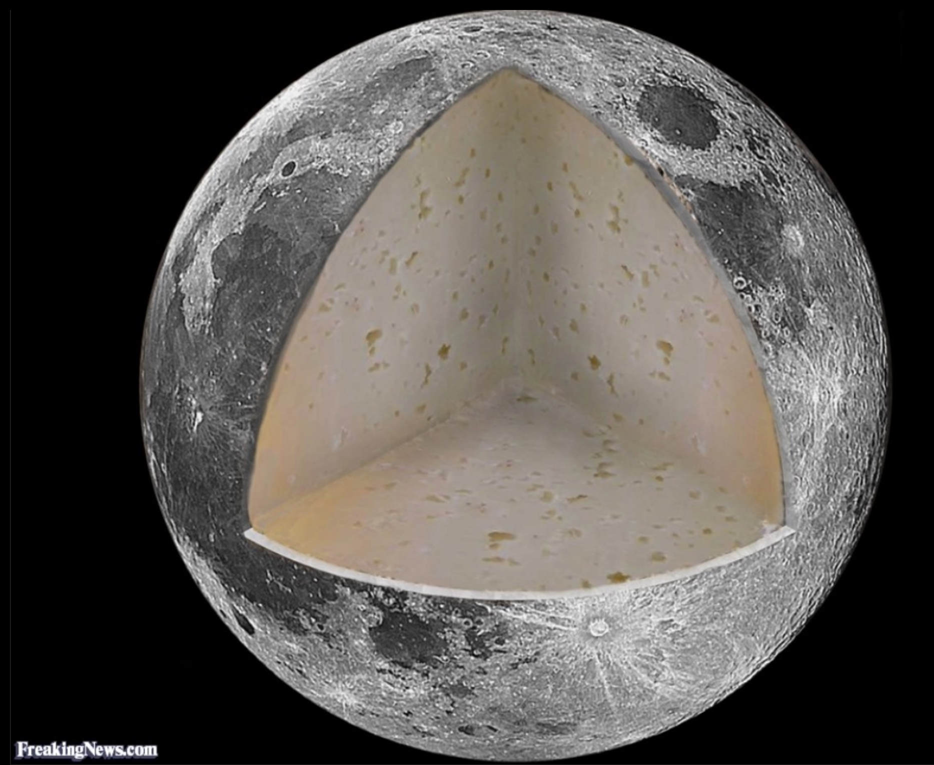


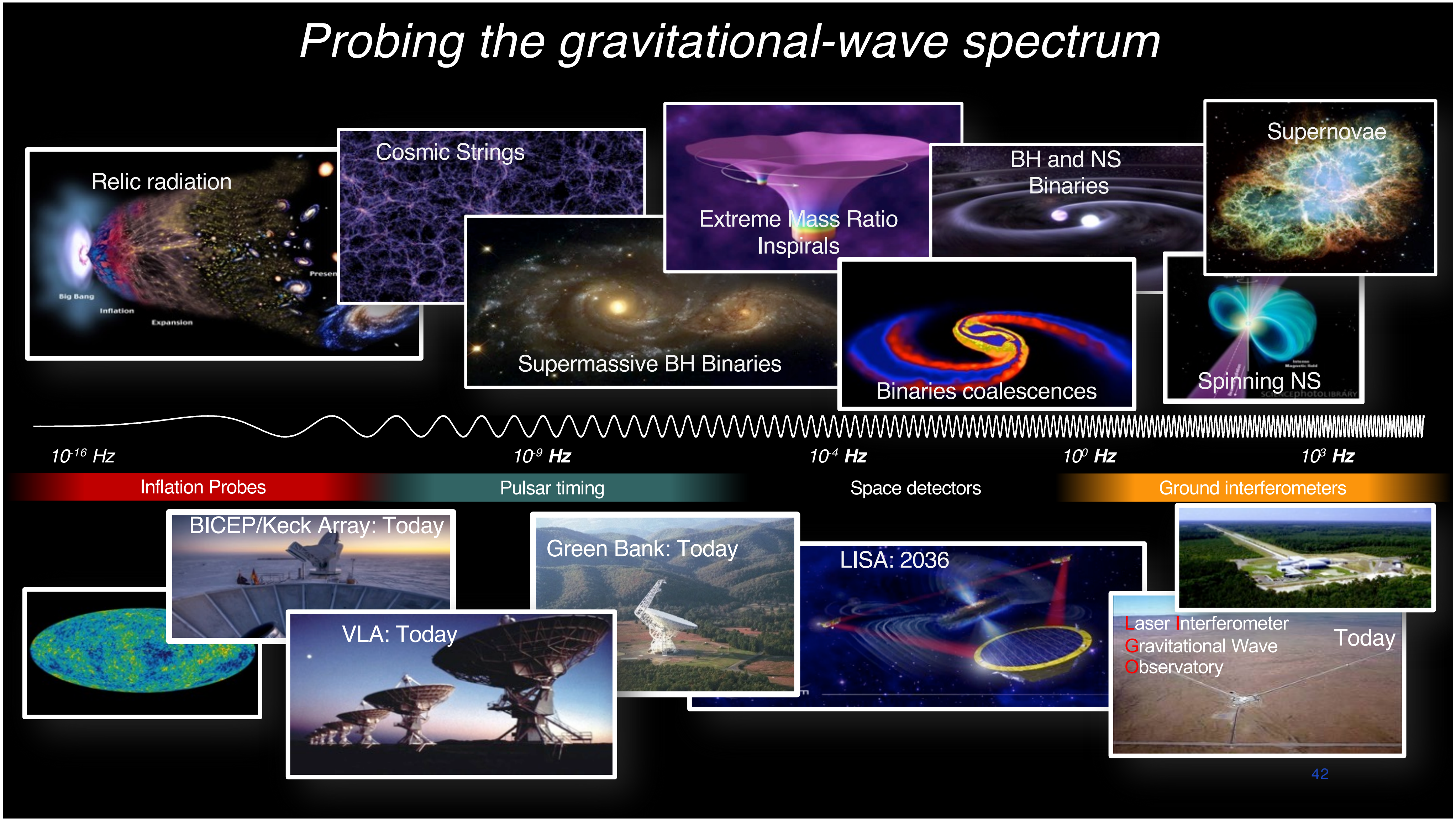
(credit: Jani)

DSAA-2020 & Voyage-2050 WPs

Arca Sedda+21 [*deci*-Hz],
Buchmüller+21 [*deci*-Hz],
Baker+21 [*deci*-Hz],
Baibhav+21 [*m*-Hz],
Sesana+21 [μ-Hz]

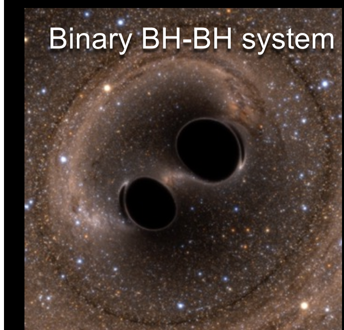
Baker+20 [μ-Hz, *deci*-Hz].


FreakingNews.com

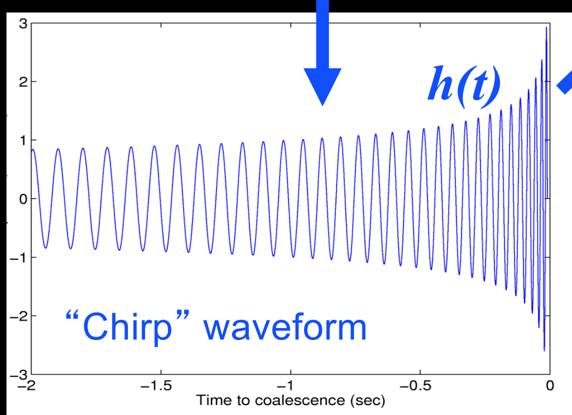

Probing the gravitational-wave spectrum
Relic radiation
Big Bang
Inflation
Expansion
Cosmic Strings
Supermassive BH Binaries
Extreme Mass Ratio Inspirals
BH and NS Binaries
Binaries coalescences
Supernovae
Spinning NS
10-16 Hz
10-9 Hz
10-4 Hz
100 Hz
103 Hz
Inflation Probes
Pulsar timing
Space detectors
Ground interferometers
BICEP/Keck Array: Today
VLA: Today
Green Bank: Today
LISA: 2036
Laser Interferometer Gravitational Wave Observatory
Today
42

Searching for Compact Binary Coalescences

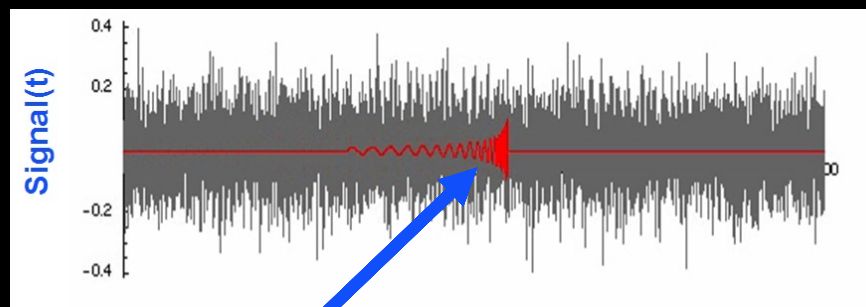
This source:



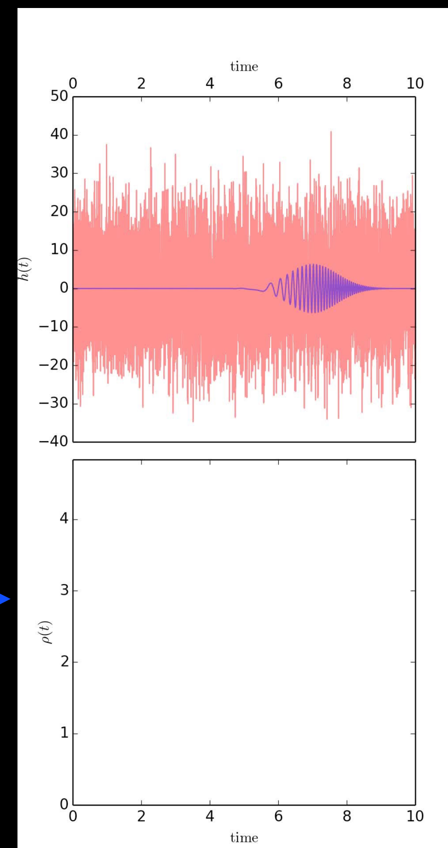
Produces this waveform:



Buried in this noise stream:



We use different methods (in this case optimal Wiener filtering using matched templates) to pull these signals from the noise:

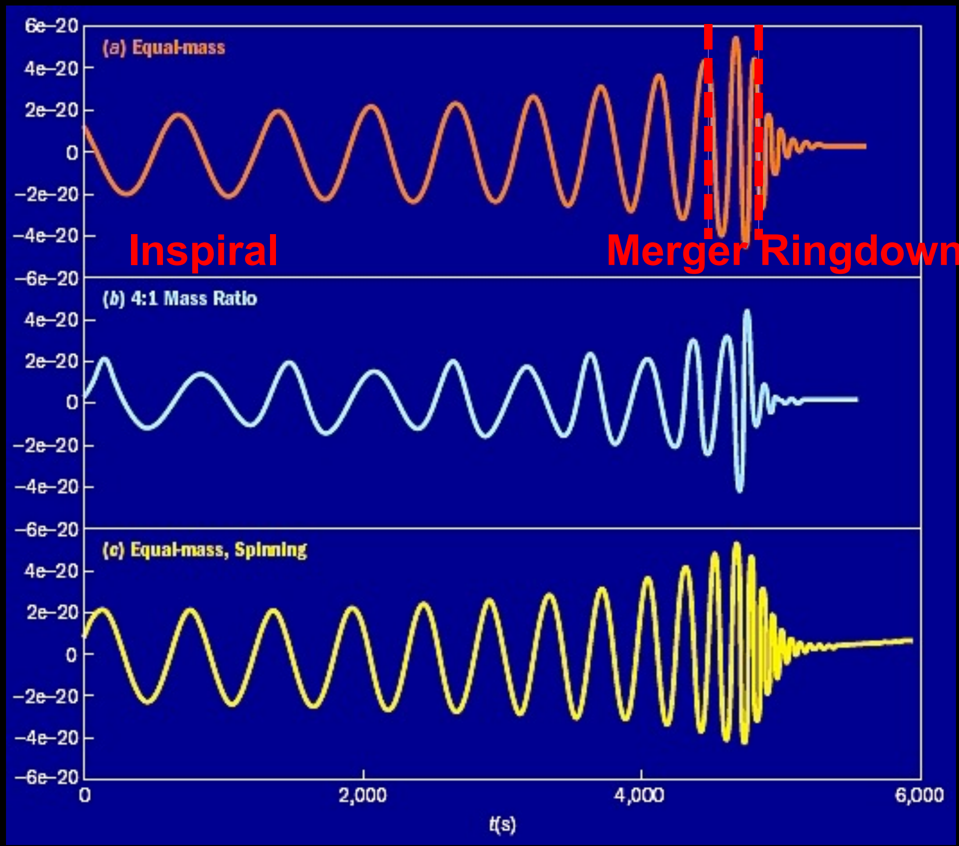


Simulation: Reed Essick, LIGO MIT

Compact binary inspiral, merger, ringdown

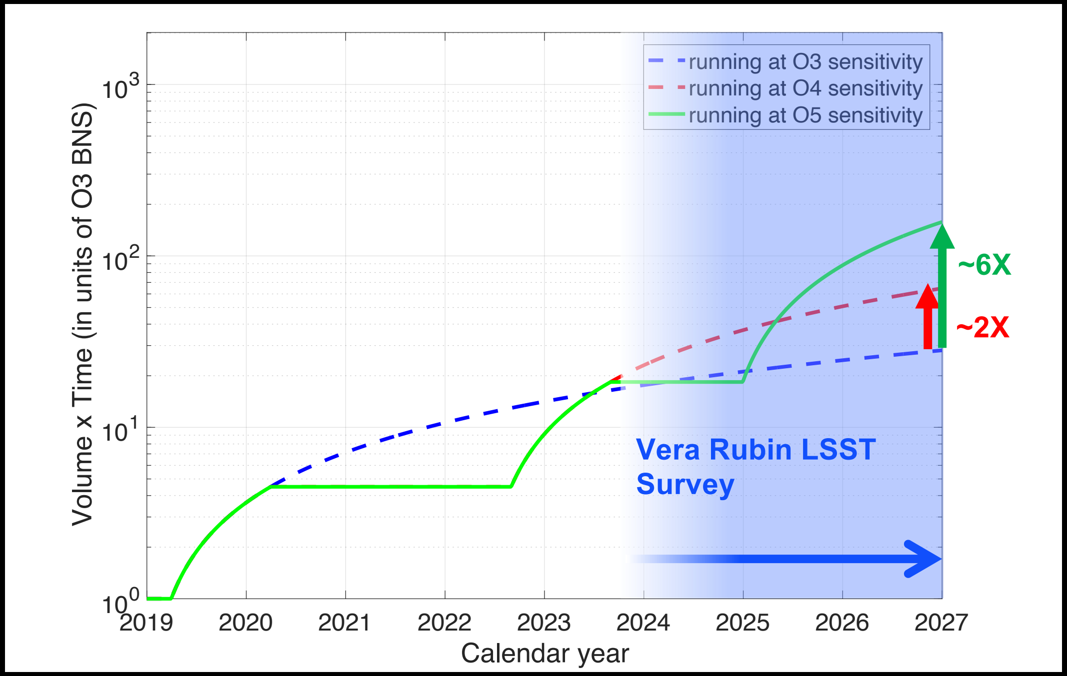
- NS/BH parameters encoded in the waveforms:
  - Constituent masses, constituent spins, sky location, luminosity distance, orbital inclination, time of arrival
  - A 15 total of parameters
    - Initial masses: inspiral phase ~ chirp mass
    - Final mass ~ merger frequency
    - Distance: GW amplitude + masses
    - (most difficult) Spin ~ precession
- Intrinsic degeneracies make parameter estimation difficult
- The SNR of the waveform matters
  - often buried in detector noise; lower SNR obscures parameter estimation

chirp mass: $\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$



Gravitational-wave Science is Sensitivity Driven

Binary Neutron Stars



1) *Rates*

N_{events} = <R>VT

<R>: average astrophysical rate

V: volume of the universe probed → $(Range)^3$

T: observing time

2) Many sources require higher SNR to uncover new astrophysics

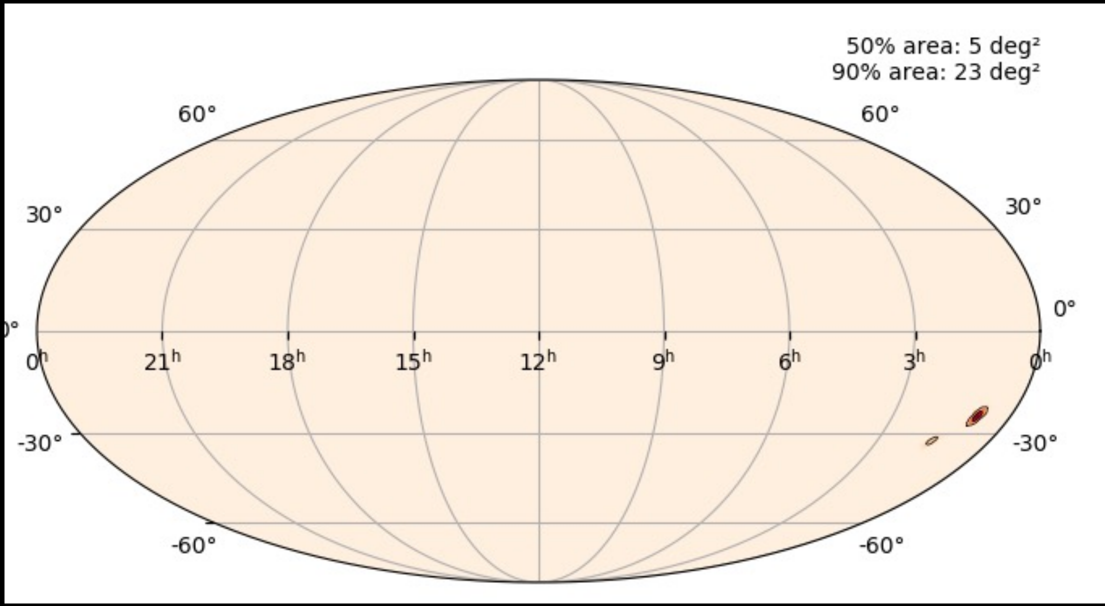
- tidal disruption in BNS mergers
- tests of alternative theories of gravity
- Black hole ringdowns
- Stochastic background
- Isolated neutron stars
- Galactic supernova
- ....

Localizing Gravitational-wave Events: 'It's Complicated'

The ability to localize GW events depends on:

- The number of GW detectors online
  - More is better!
  - Also depends on sensitivities of the observatories
- Location of the GW source on the sky
  - Optimal positions for GW observatory network
- Distance to event -> larger ('louder') signal
  - Closer is better!
- The parameters of the GW source -> larger ('louder') signal
  - Masses, orbital orientation
- *Coincidence with other 'messengers'*
  - *Gamma rays, X-ray, UV, optical/IR, radio, neutrinos*

GW190814 (black hole - ?? merger)
90% localization contour: 23 deg^2
50% localization contour: 5 deg^2



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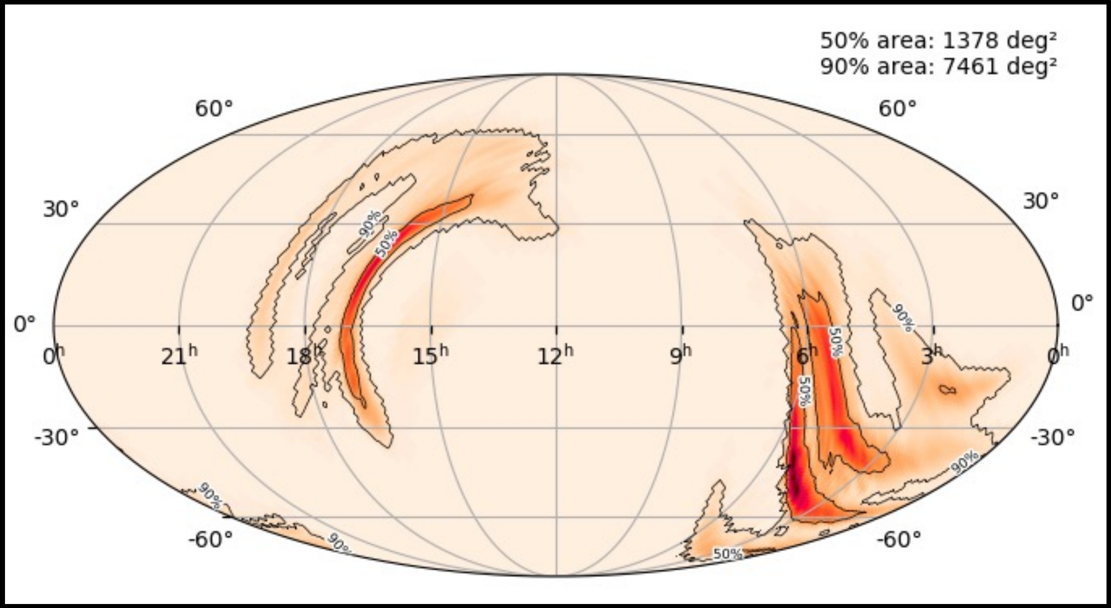
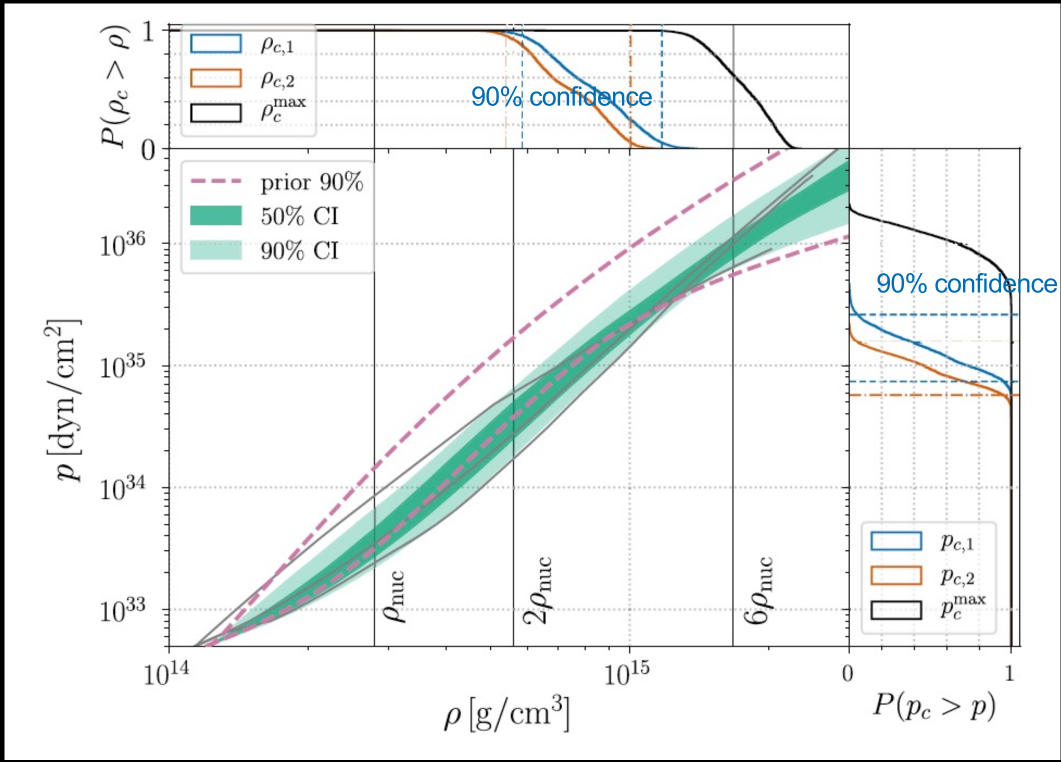
GW190425 (neutron star – neutron star merger)
90% localization contour: 7461 deg^2
50% localization contour: 1378 deg^2



What GW170817 Reveals About Nuclear Matter (II)

- GW data constrains pressure-density for the NS interior.
  - Consistent with NS equations of state (EoS) and upper limits on observed NS masses
- GW170817 supports central densities (ρ_c) up to ~ 5$\rho_{nuclear}$ and central pressures up to ~3x10^{35} dyn/cm^3
  - *90% confidence: 2$\rho_{nuclear}$*



Abbott, et al., "GW170817: Measurements of Neutron Star Radii and Equation of State" Phys. Rev. Lett. **121**, 161101 (2018)

What GW170817 Reveals About Nuclear Matter (III)

From limits on tidal deformabilities, we obtain posterior limits on NS masses and radii

- Using Λ–C relation,
  - Compactness $C = \dfrac{GM}{Rc^2}$ For NSs, *C ~ 0.05 - 0.25*