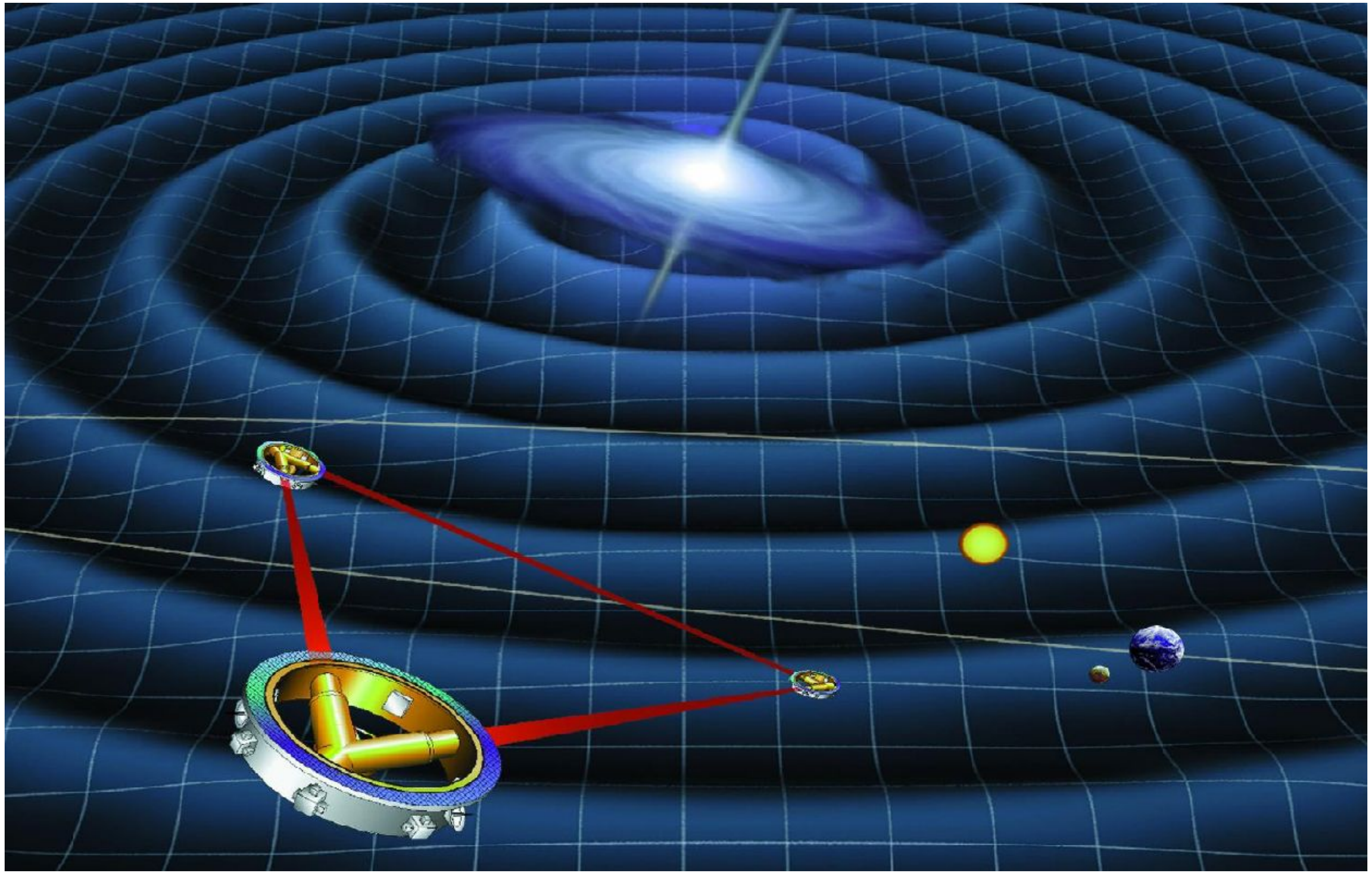
Stan Wojcicki Symposium

"TODAY: Exploring the Universe with Gravitational Waves"



Barry C Barish
Caltech
10-Nov-2023

Stan was a Leader in HEP for More than Five Decades

Pief and Stan

Who is telling who what?

Leon, Boyce and Stan
What's the story behind the orange?

Stan leading HEP study

Wood's Hole 1983: HEPAP (Wojcicki) sub-panel in session. Around the table, from 7 p.m., Earle Fowler (in red), Carlo Rubbia, Bruce Winstein, Lee Pondrom, Tom Appelquist, Jack Vandervelde and Maury Tigner (both hidden), Denis Keefe, Stan Wojcicki, Frank Sciulli, John Adams, Brig Williams, Mary Gaillard, Sam Treiman, Charlie Baltay, ?? (back of head).

Stan's Retirement Event (2010)

SATURDAY, AUGUST 14, 2010

A CELEBRATION IN HONOR OF

STANLEY WOJCICKI

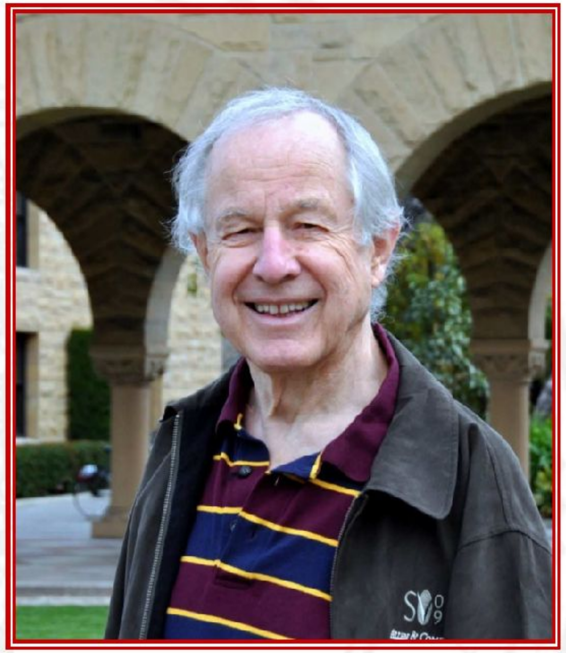
AS HE BECOMES PROFESSOR EMERITUS

All Day Symposium

Hewlett Teaching Center
370 Serra Mall
Stanford, CA 94305

Speakers

Barry Barish, *Caltech*
Robert N. Cahn, *LBNL*
George William "Bill" Foster, *U.S. Congressman, Illinois*
Boris Kayser, *Fermilab*
William Molzon, *UC Irvine*
Piermaria Oddone, *Fermilab*
Roberto Peccei, *UCLA*



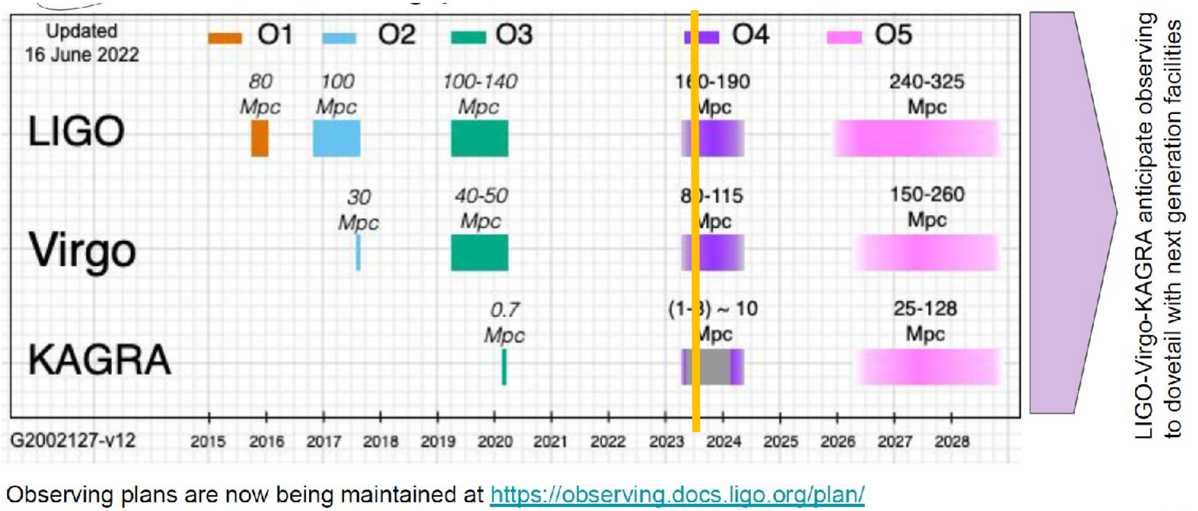
After wine speaker. Why me ????

- **The real reason: Stan assigned me !**
- **But, in the spirit of full disclosure ….**
  - » We've known each other 50 + years
  - » Parallel and intertwined careers
  - » Collaborated 3 times ---
    - – DELCO
    - – E595 Fermilab
    - – MINOS
  - » Co-authors (Stan on SPIRES): 53 / 169 = 31%
- **Despite all this, I was a bit stumped what to say.**

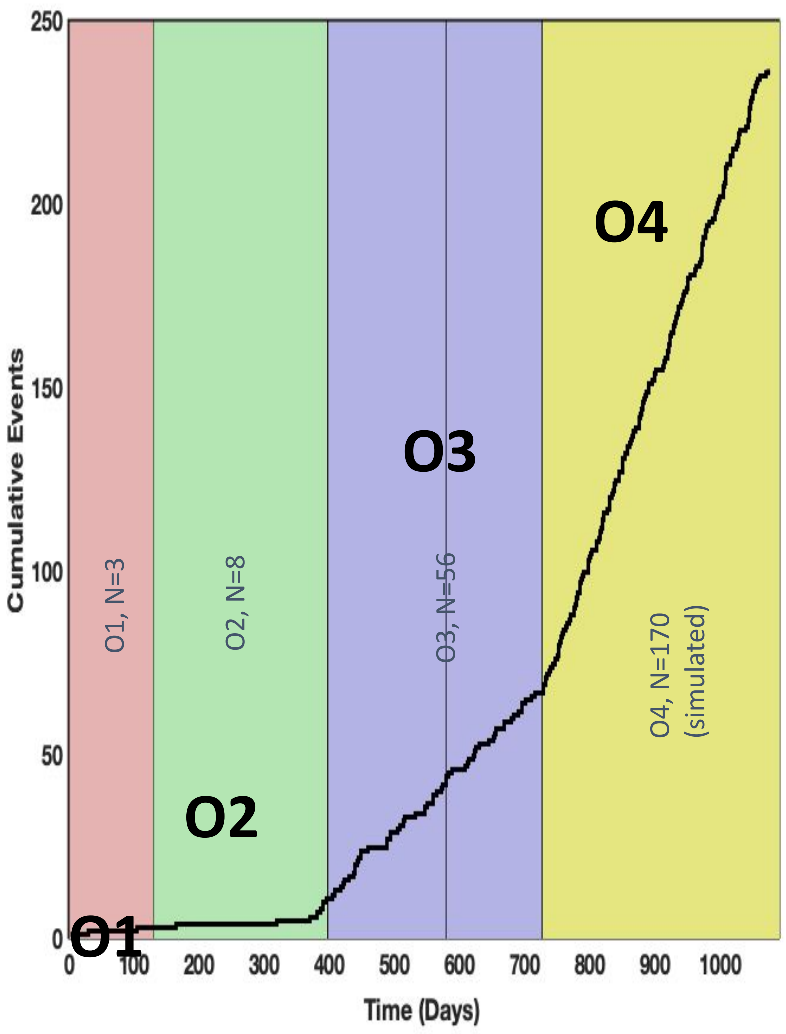
2

<u>TODAY</u> I will continue Stan and my dialogue. What we might discuss, if we were to meet today.

Technical/Sensitivity Advances over the Coming Decade



Run Plan Over Next 5-10 Years

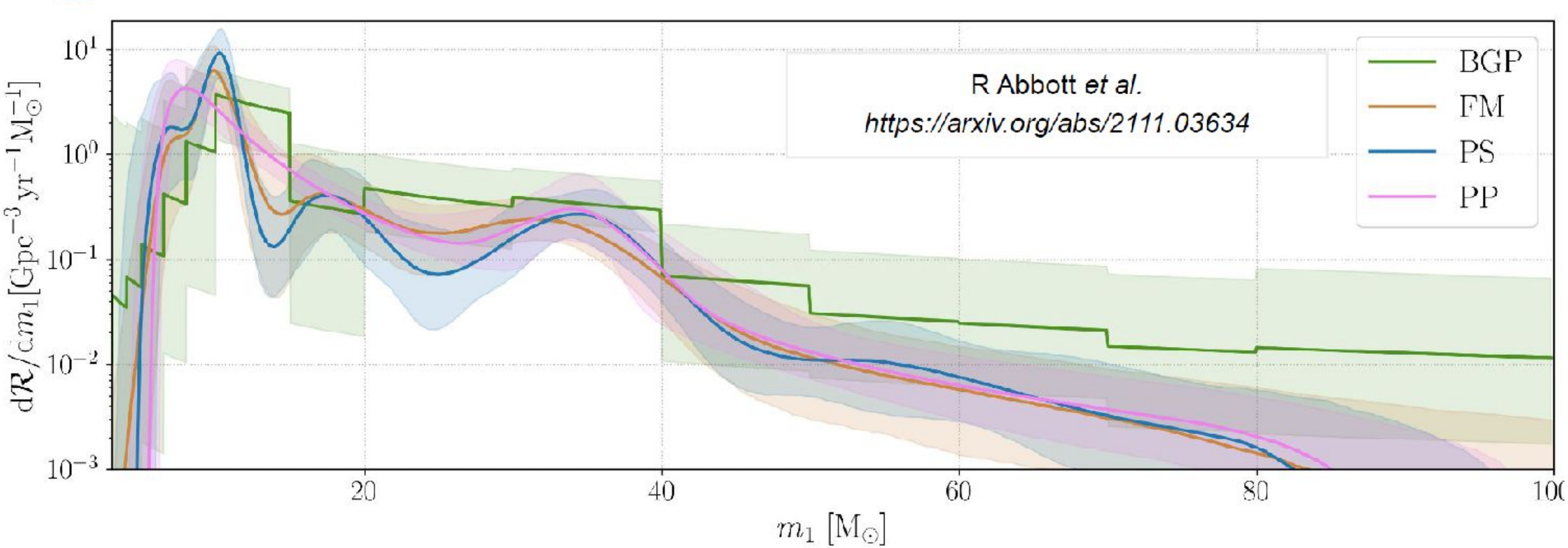


Incremental Increases in Sensitivity/Rate

LIGO India Funded - $320M India + $80M U.S.

Distributions for BH Mergers -- Understand Origin/Characteristics

[redacted]



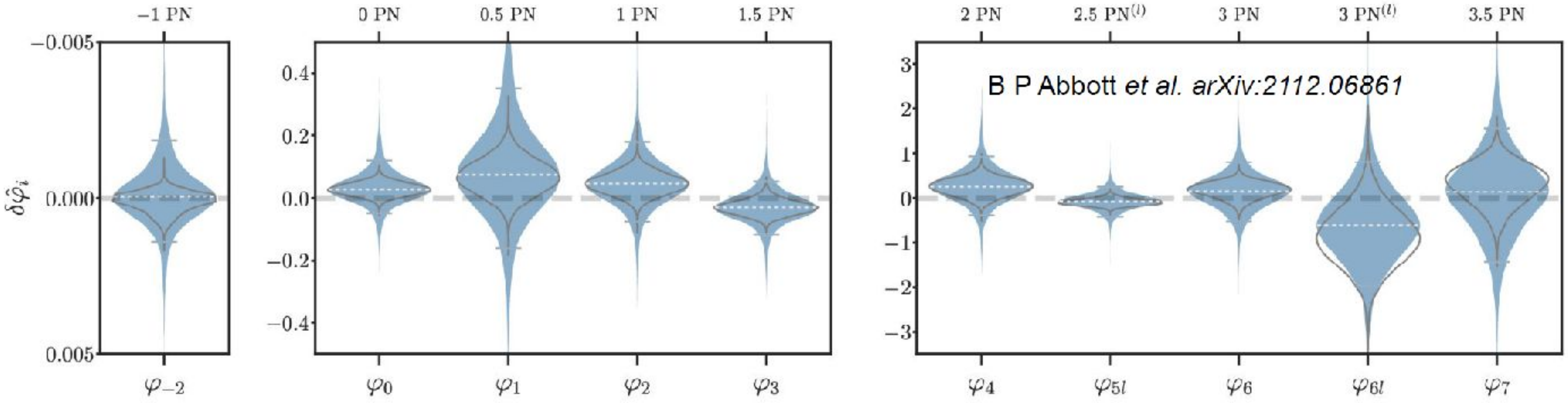
Merger rate density as a function of primary mass using 3 non-parametric models compared to the power-law+peak (pp) model.

[redacted]

Testing GW with Binary Black Hole Events

- Look for deviations in the phasing coefficients of a 3.5PN TaylorF2 phase:

$$\varphi_{\rm PN}(f) = 2\pi f t_{\rm c} - \varphi_{\rm c} - \frac{\pi}{4} + \frac{3}{128\eta}\left(\pi\tilde{f}\right)^{-5/3} \sum_{i=0}^{7} \left[\varphi_i + \varphi_{i\,l}\log(\pi\tilde{f})\right]\left(\pi\tilde{f}\right)^{i/3}$$



Testing General Relativity – Dispersion Term?

- In GR, there is no dispersion!

Add dispersion term of form

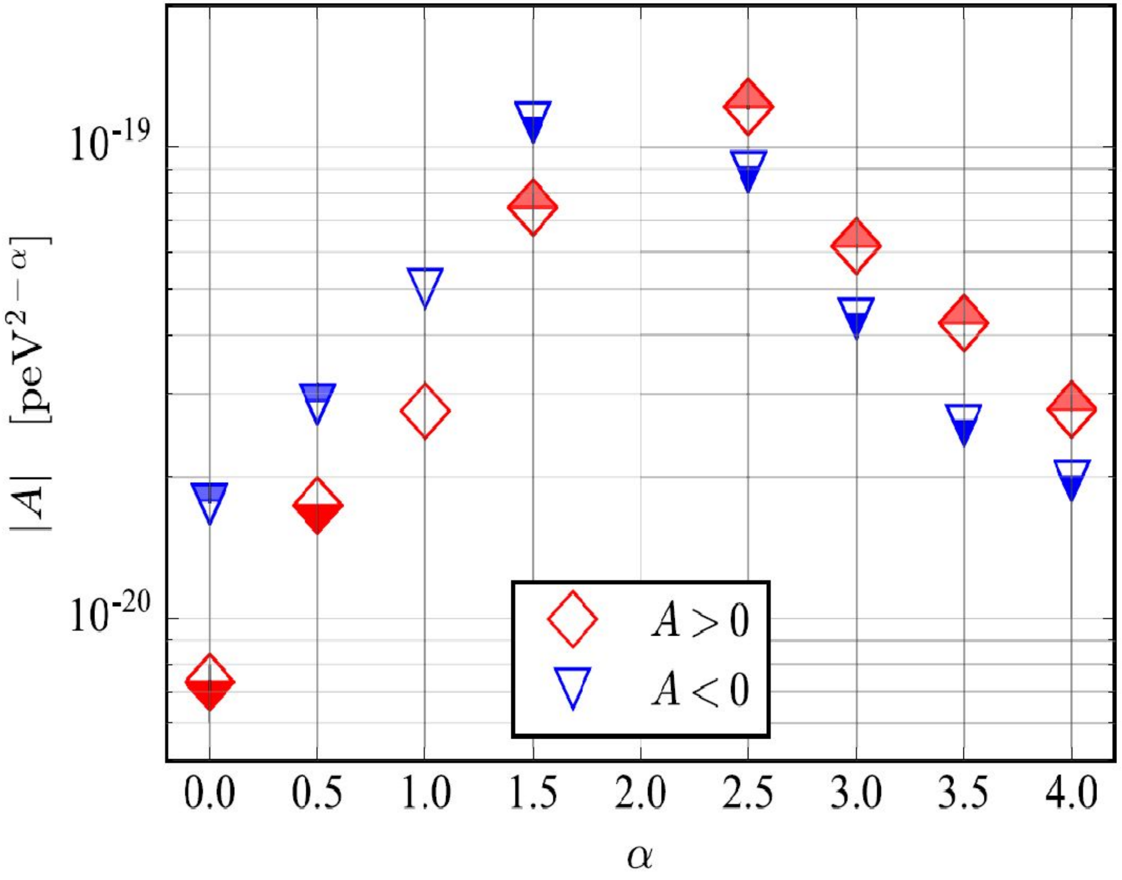
$$E^2 = p^2c^2 + Ap^{\alpha}c^{\alpha}, \quad \alpha \geq 0$$

(E, p are energy, momenturm of GW, A is amplitude of dispersion)

- Plot shows 90% upper bounds
- Limit on **graviton** mass

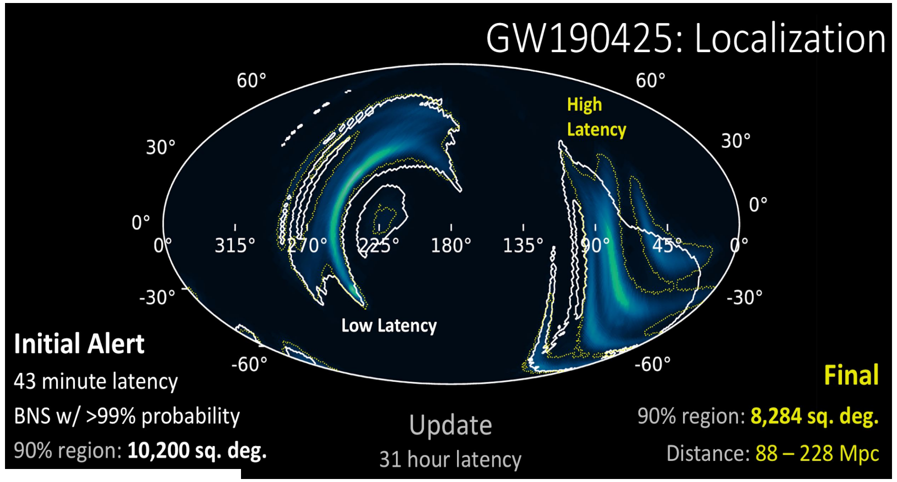
$$M_g \leq 7.7 \times 10^{-23}\ \mathrm{eV/c^2}$$

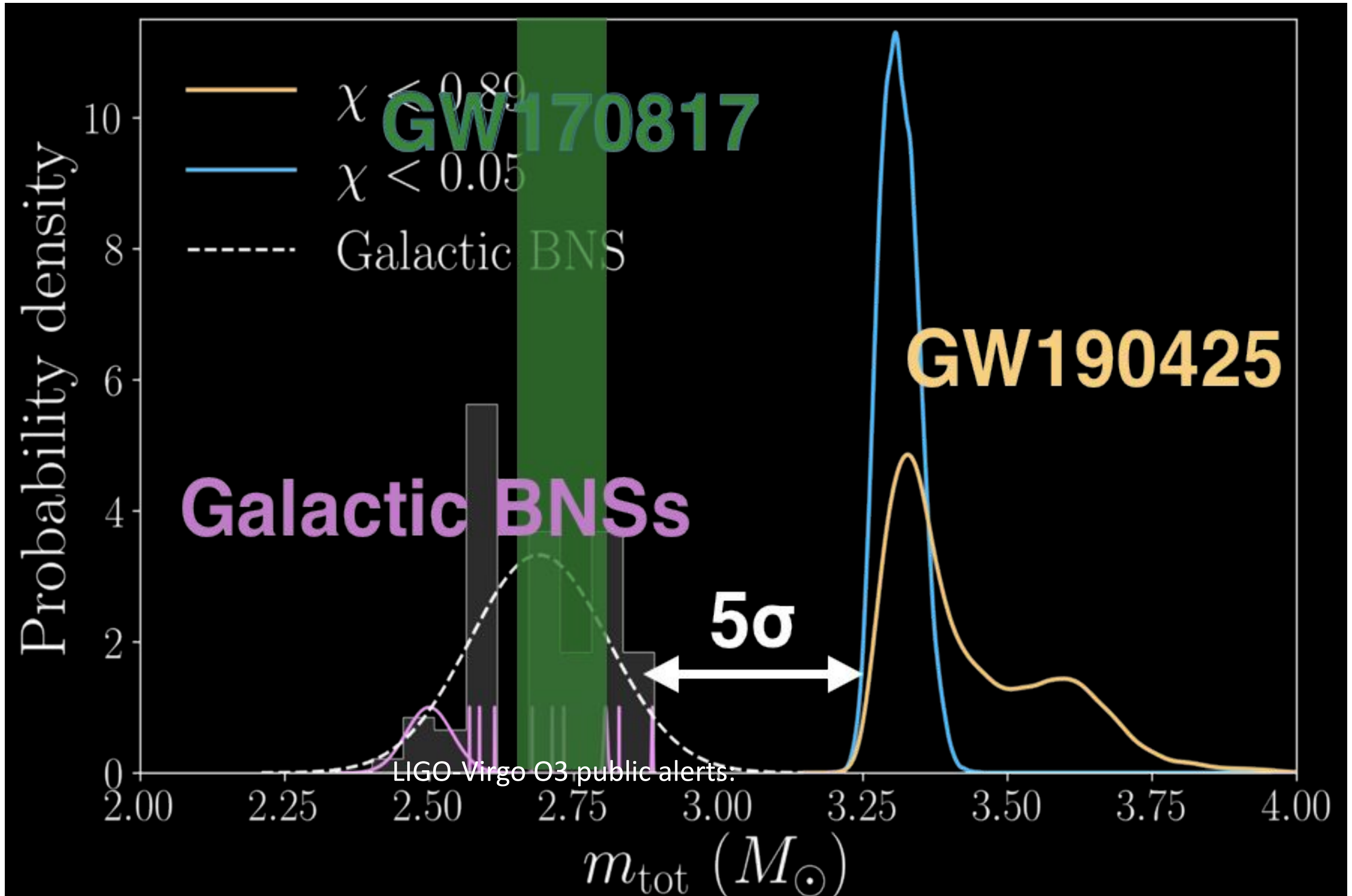
- Null tests to quantify generic deviations from GR



PhysRevLett.118.221101

Exceptional Events





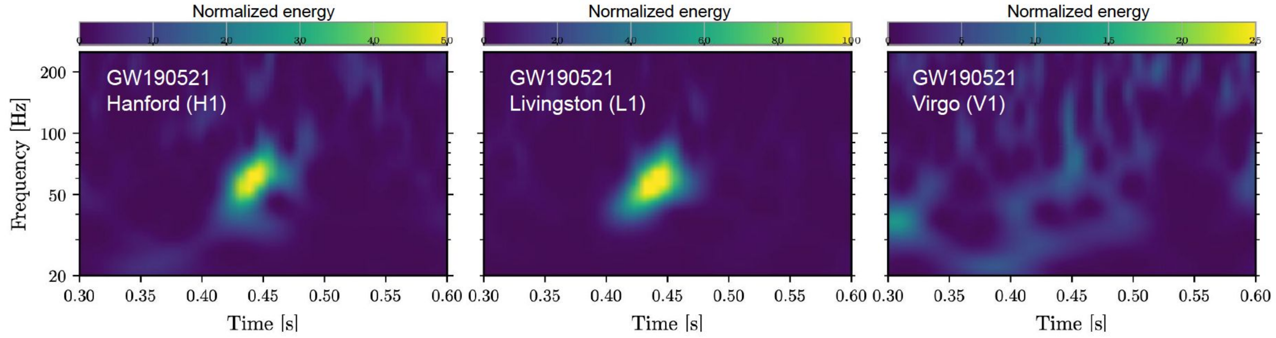
The signal was detected by only the LIGO Livingston interferometer

The event has an estimated total mass of 3.4 M_{sun}

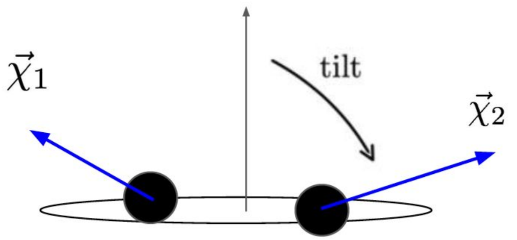
The combined mass of the neutron stars is greater than all known neutron star binaries (galactic, GW170817)

The Most Massive and Distant Black Hole Merger Yet: GW190521 (142 M_{sun})

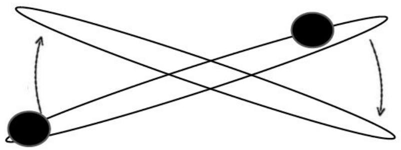
- The furthest GW event ever recorded: ~ 7 Glyr distant
- At least one of the progenitor black holes (85 M_{sun}) lies in the pair instability supernova gap
  - » Stars with helium cores in the mass range 64 - 135 M_{sun} undergo an instability and obliterate upon explosion
- **The final black hole mass (142 M_{sun}) places it firmly in the intermediate mass category (between 10^2 – 10^5 M_{sun}) □ *<u>the first ever observation of an intermediate mass black hole</u>***
- Strong evident for spin precession; both progenitor black holes were spinning
  - □ Implications for how these black holes formed

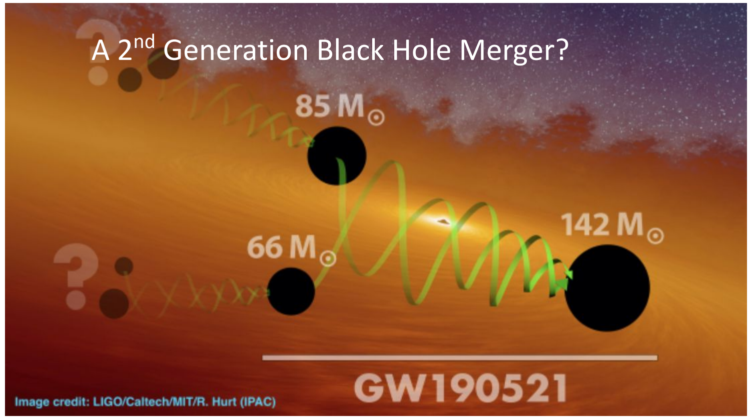


Orbital Angular Momentum



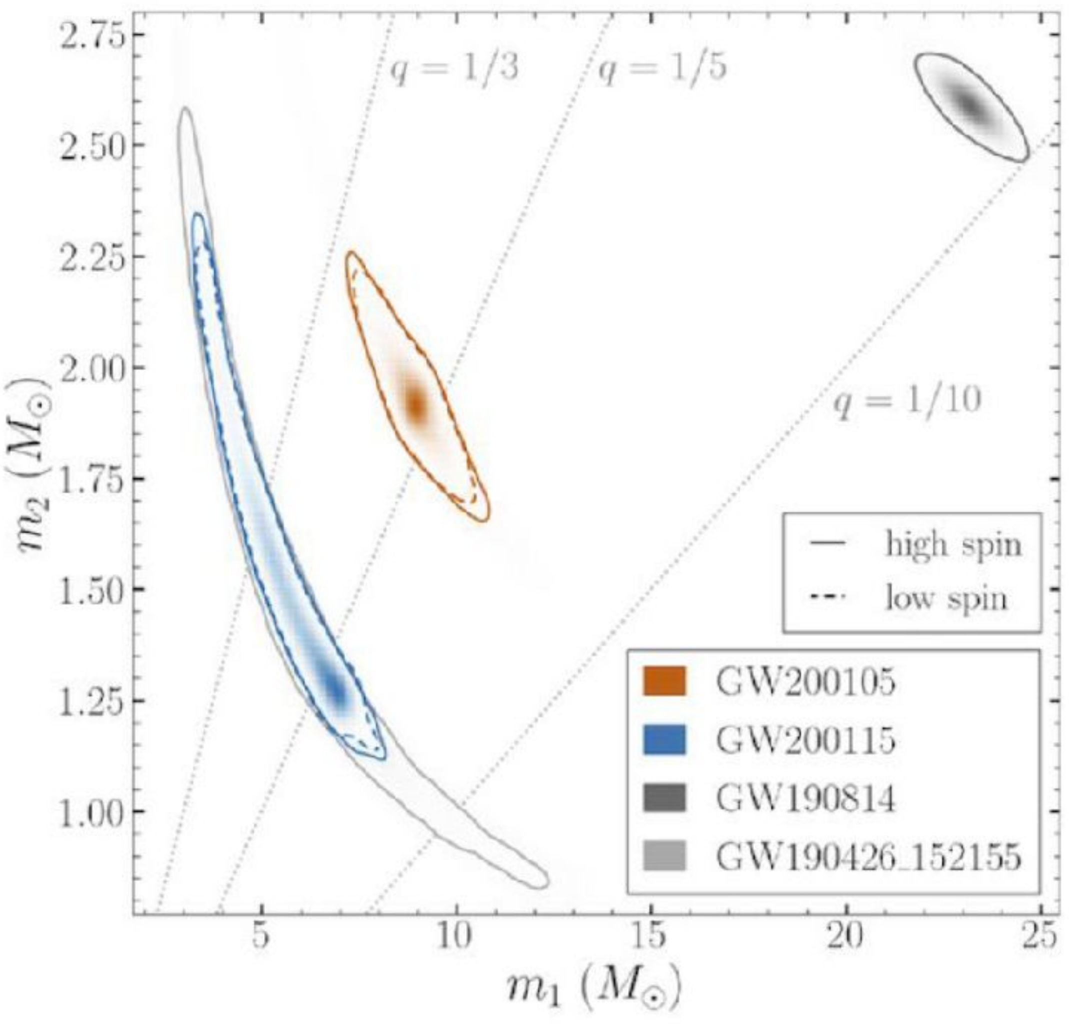
Orbital Plane Precession



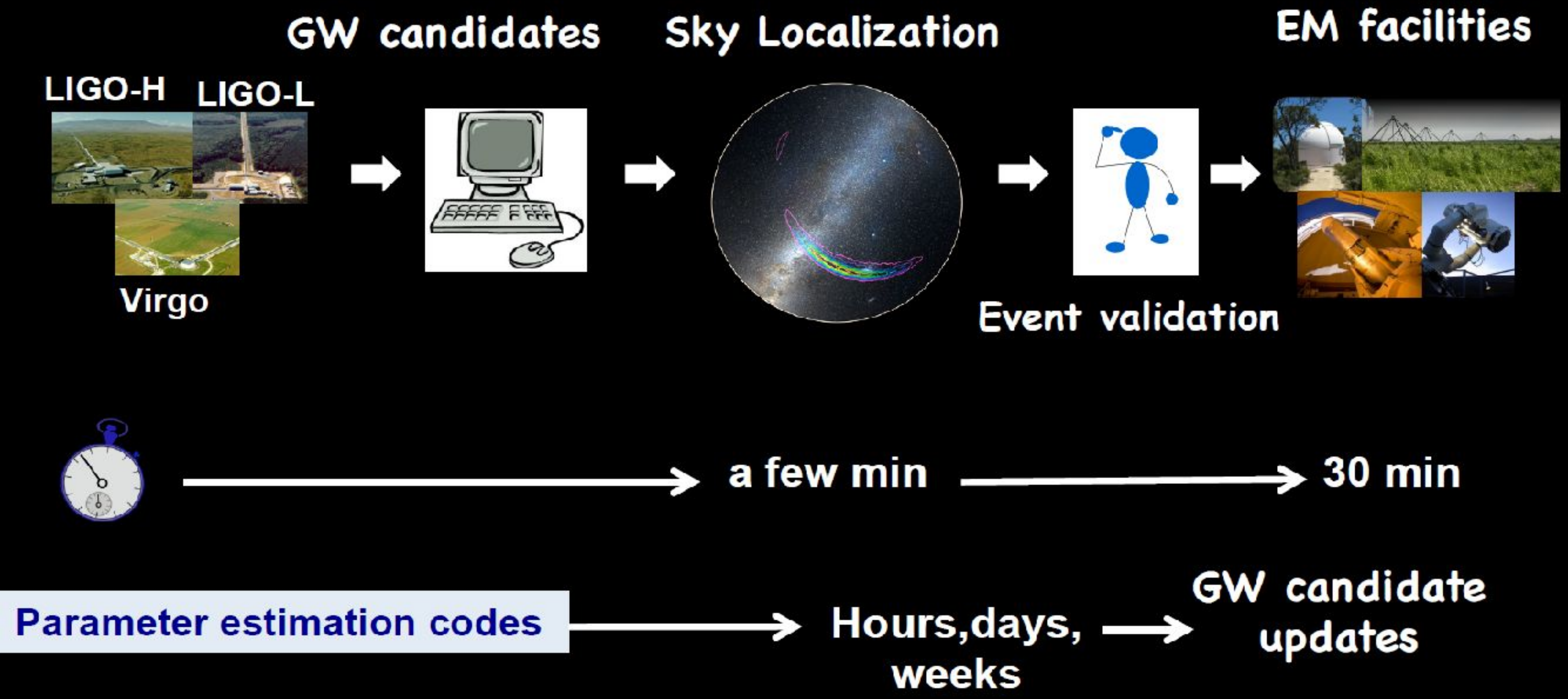


First Observed Neutron Star / Black Hole Mergers

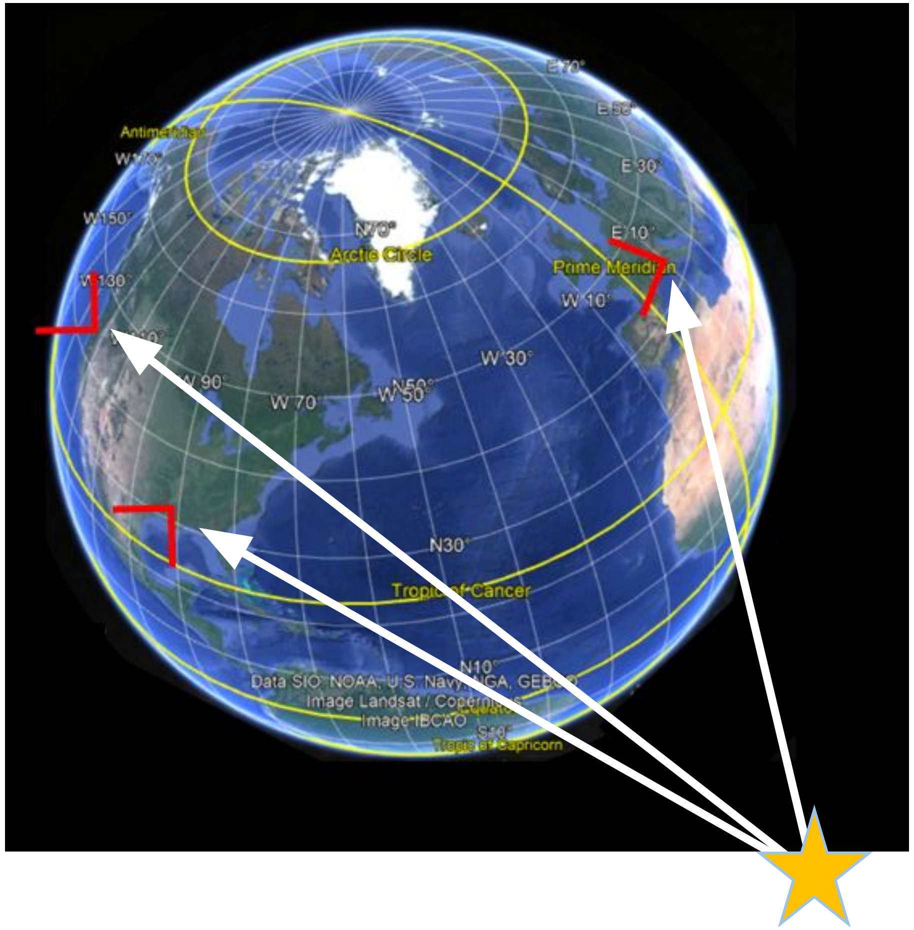
R. Abbott *et al* 2021 *ApJL* **915** L5



Multimessenger Astronomy - Electromagnetic Counterparts



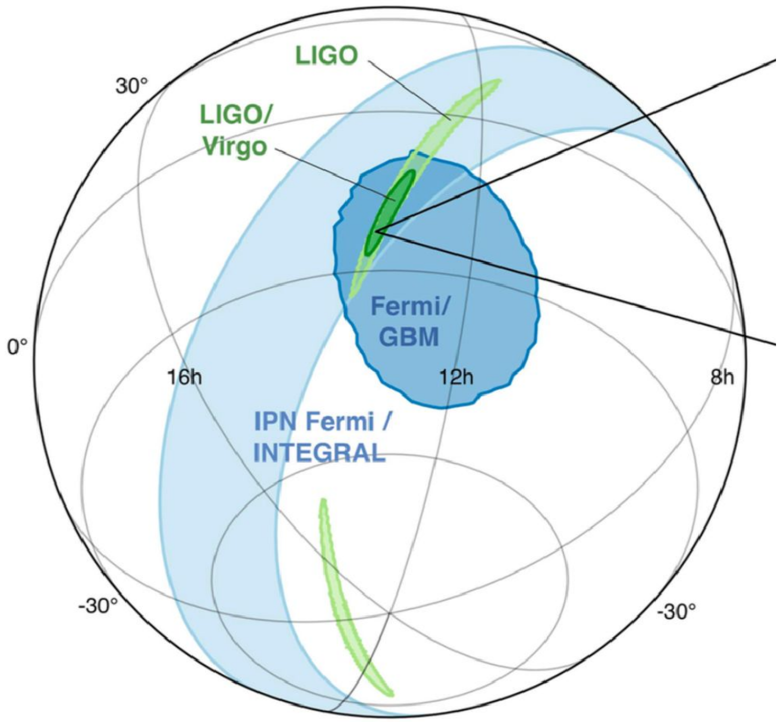
Localizing Gravitational-wave Events

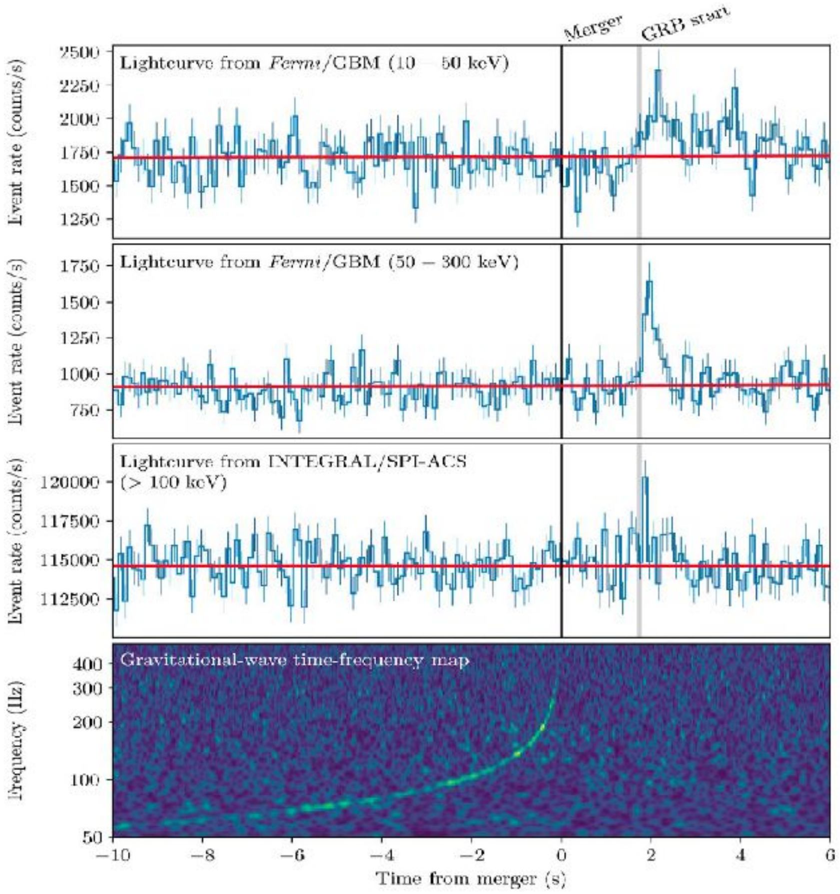


By measuring the arrival time of the gravitational-wave at each observatory, it's possible to identify its location on the sky

First Observed Multimessenger Gravitational-wave Event

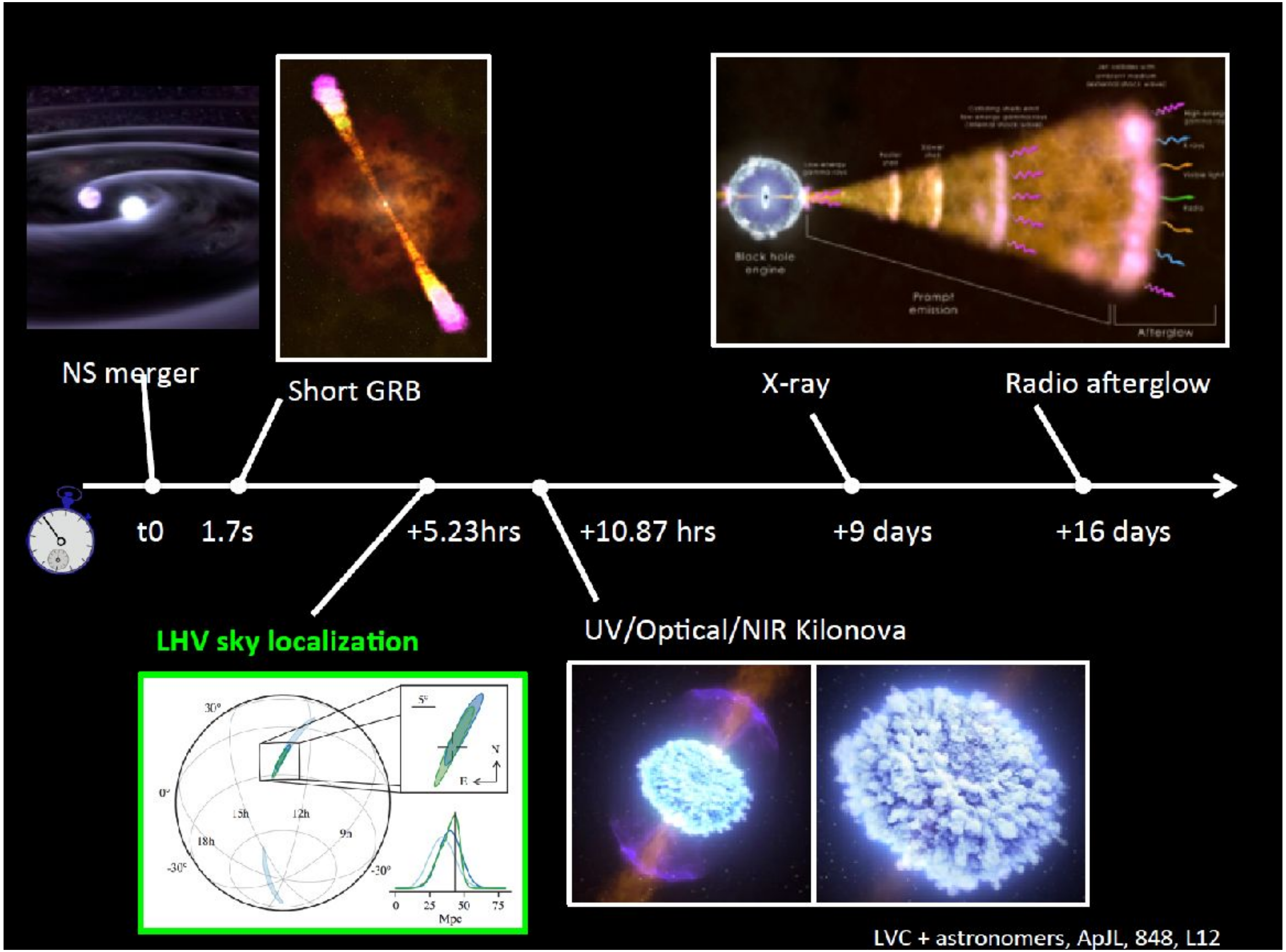
First BNS-GRB association ….



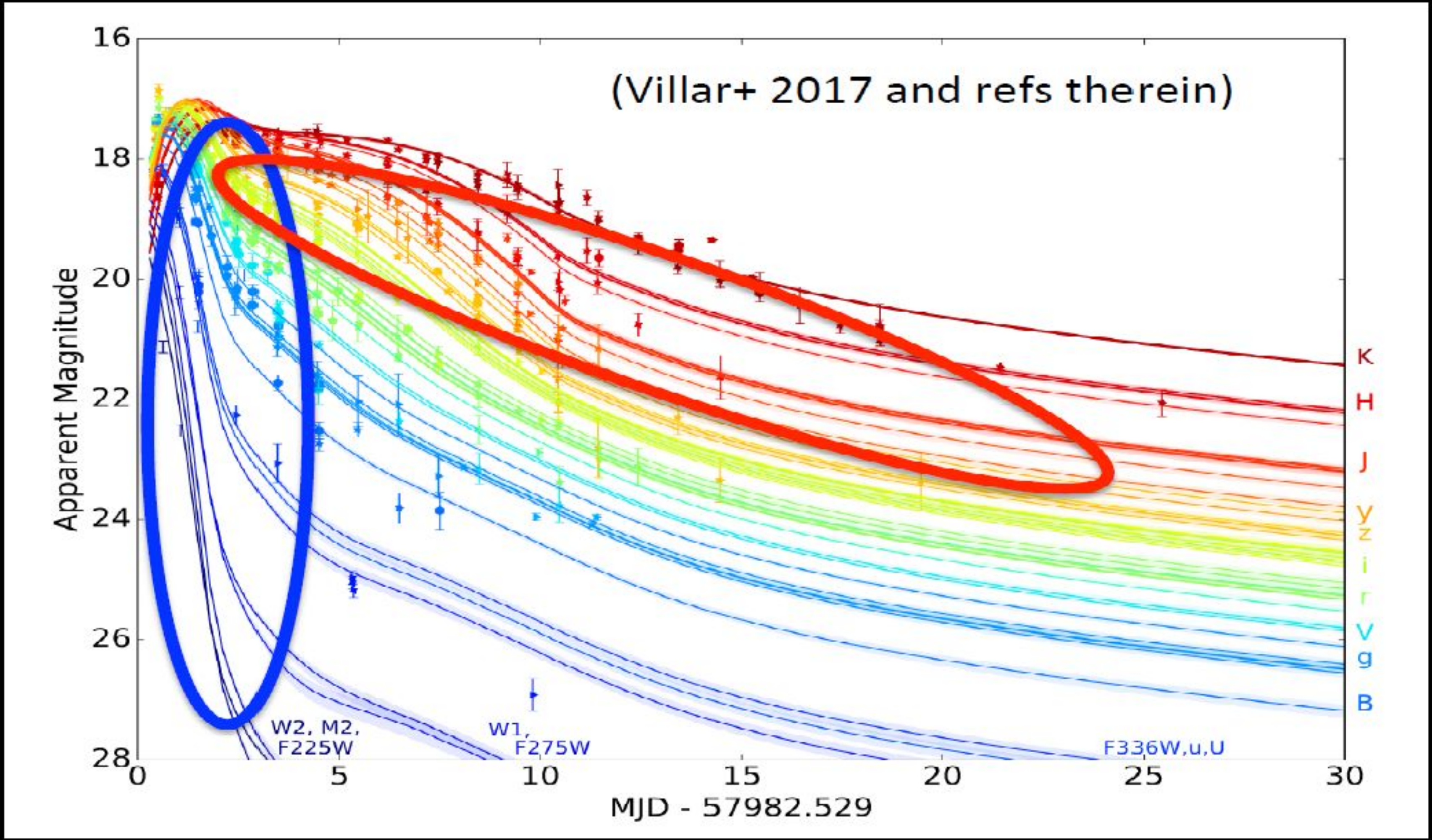


B. P. Abbott et al 2017 ApJL 848 L13

- GW170817
  - Binary neutron star (BNS) merger waves
- GW170817 & GRB 170817A
  - Fractional difference in speed of gravity and the speed of light is between -3×10^{-15} and 7×10^{-16}
- GW170817 & AT 2017gfo
  - Binary neutron star mergers produce kilonova explosions that generate heavy elements


NS merger
Short GRB
X-ray
Radio afterglow
t0
1.7s
+5.23hrs
+10.87 hrs
+9 days
+16 days
LHV sky localization
UV/Optical/NIR Kilonova
Black hole engine
Prompt emission
Afterglow
LVC + astronomers, ApJL, 848, L12

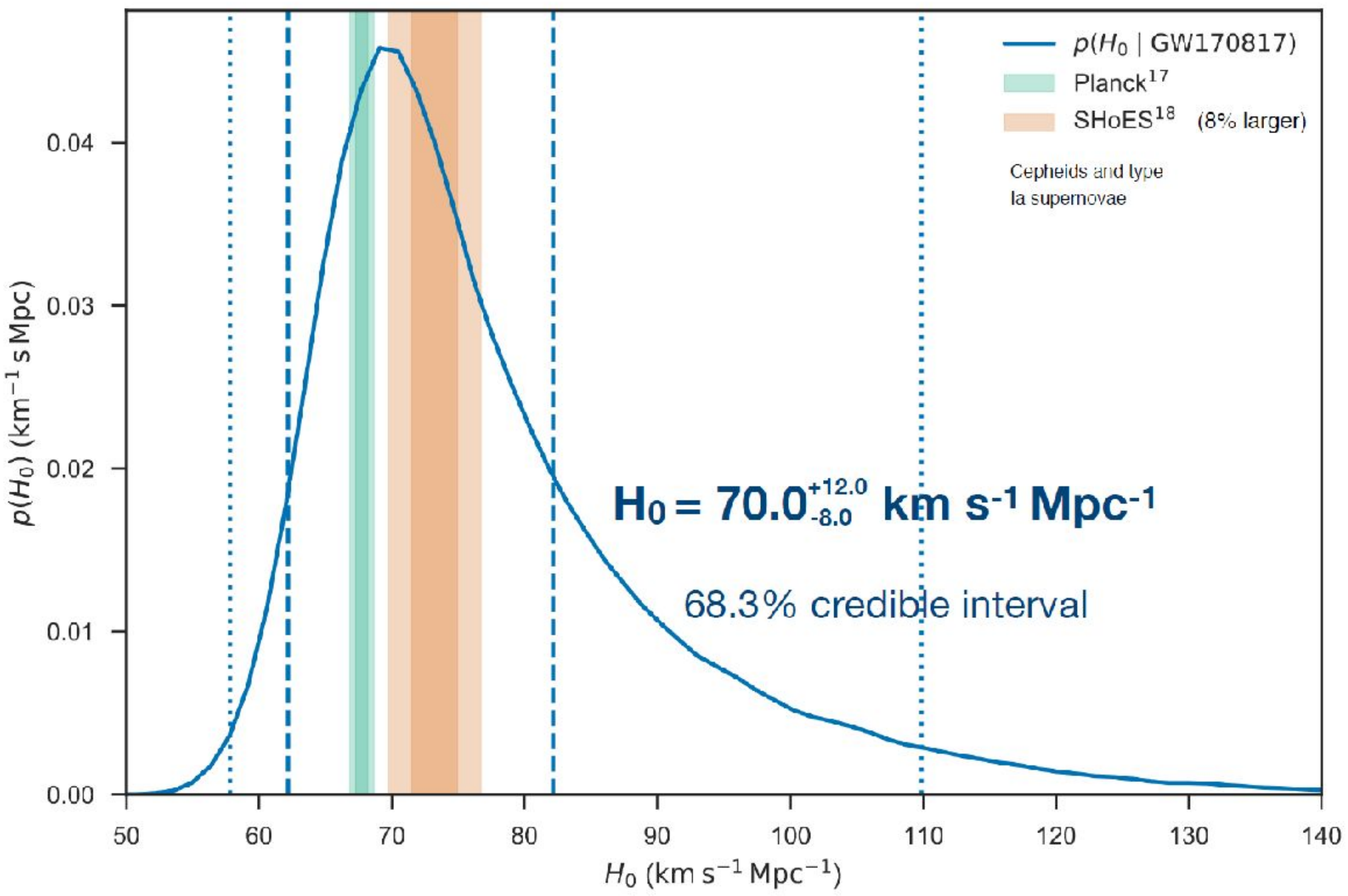
Light Curves



Extremely well characterized photometry of a Kilonova:

thermal emission by radiocative decay of heavy elements synthesized in multicomponent (2-3) ejecta!

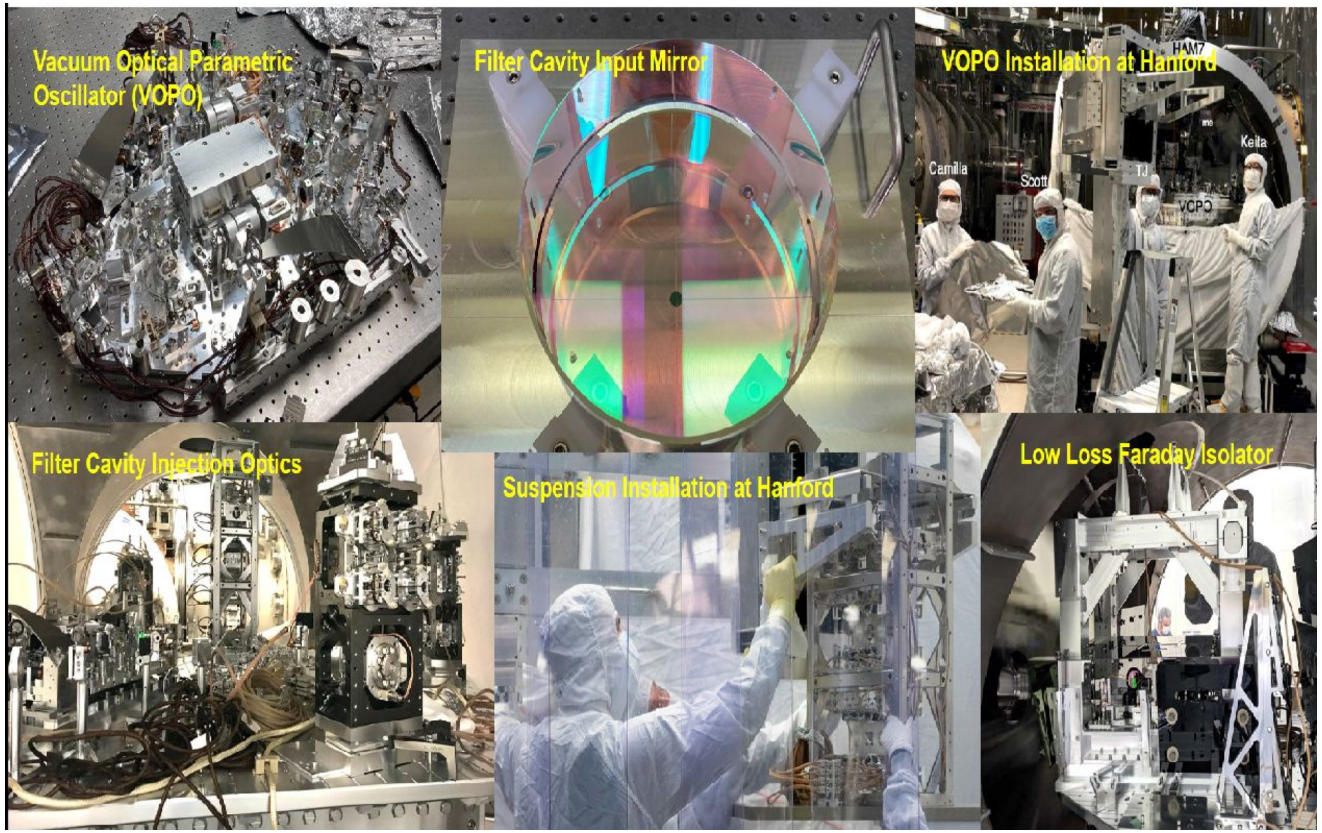
Hubble Constant – Expansion of the Universe

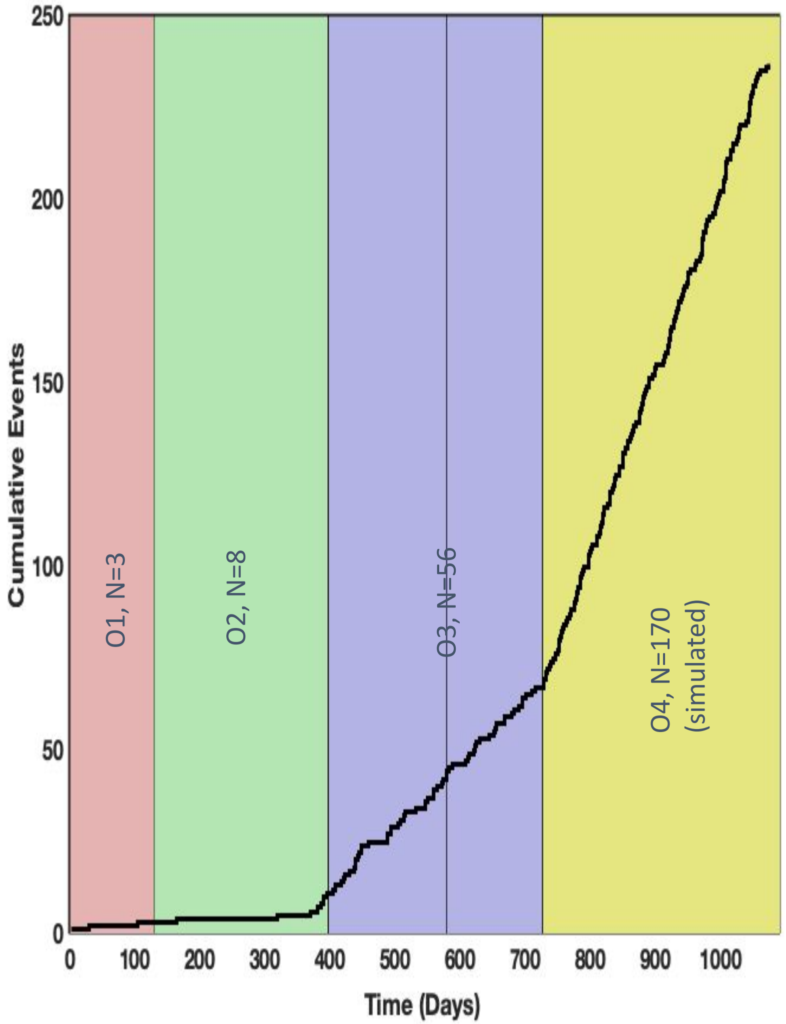


$$v_H = H_0 d$$

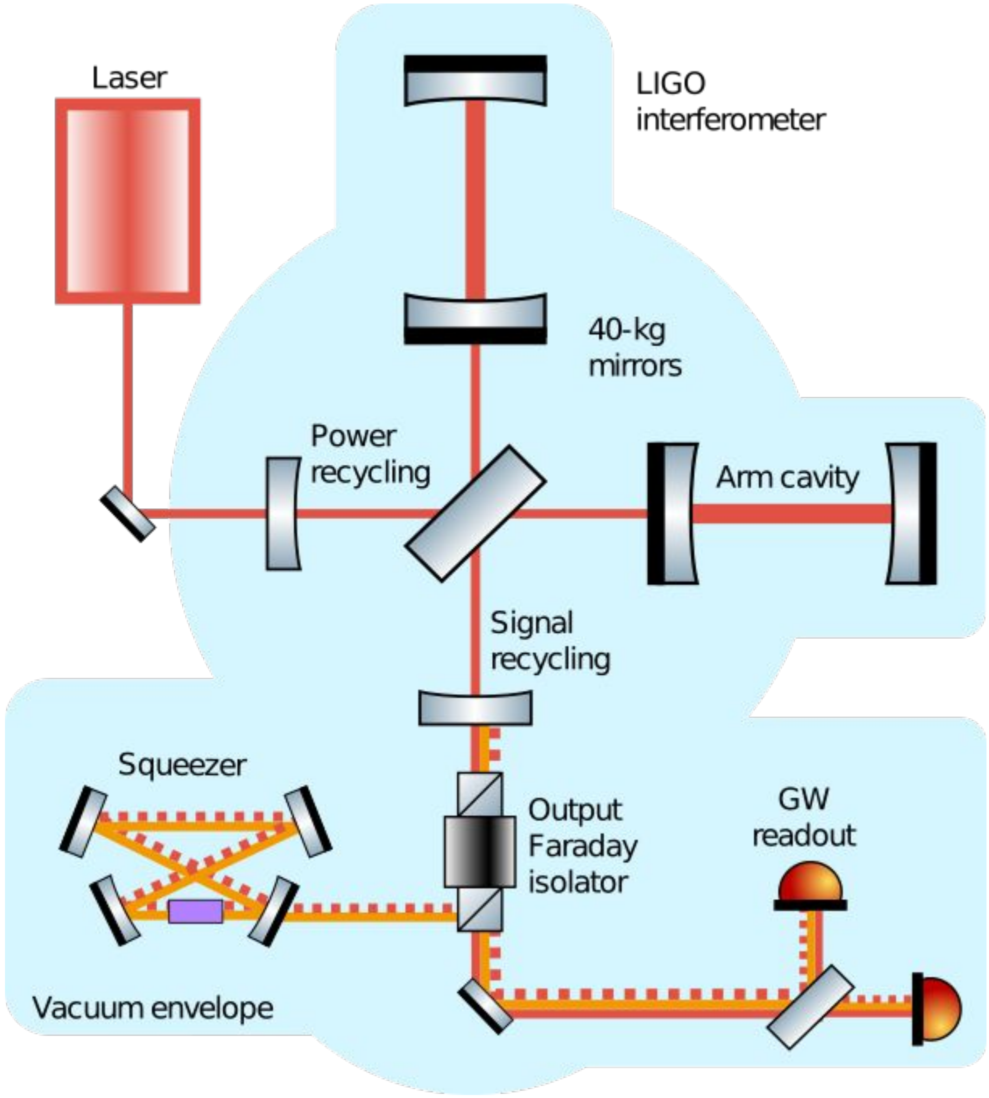
- v_D = local "Hubble flow" velocity of the source
- Optical identification of the host galaxy NGC 4993
- D = distance to the source

The Future: Improved Sensitivity and New Instruments

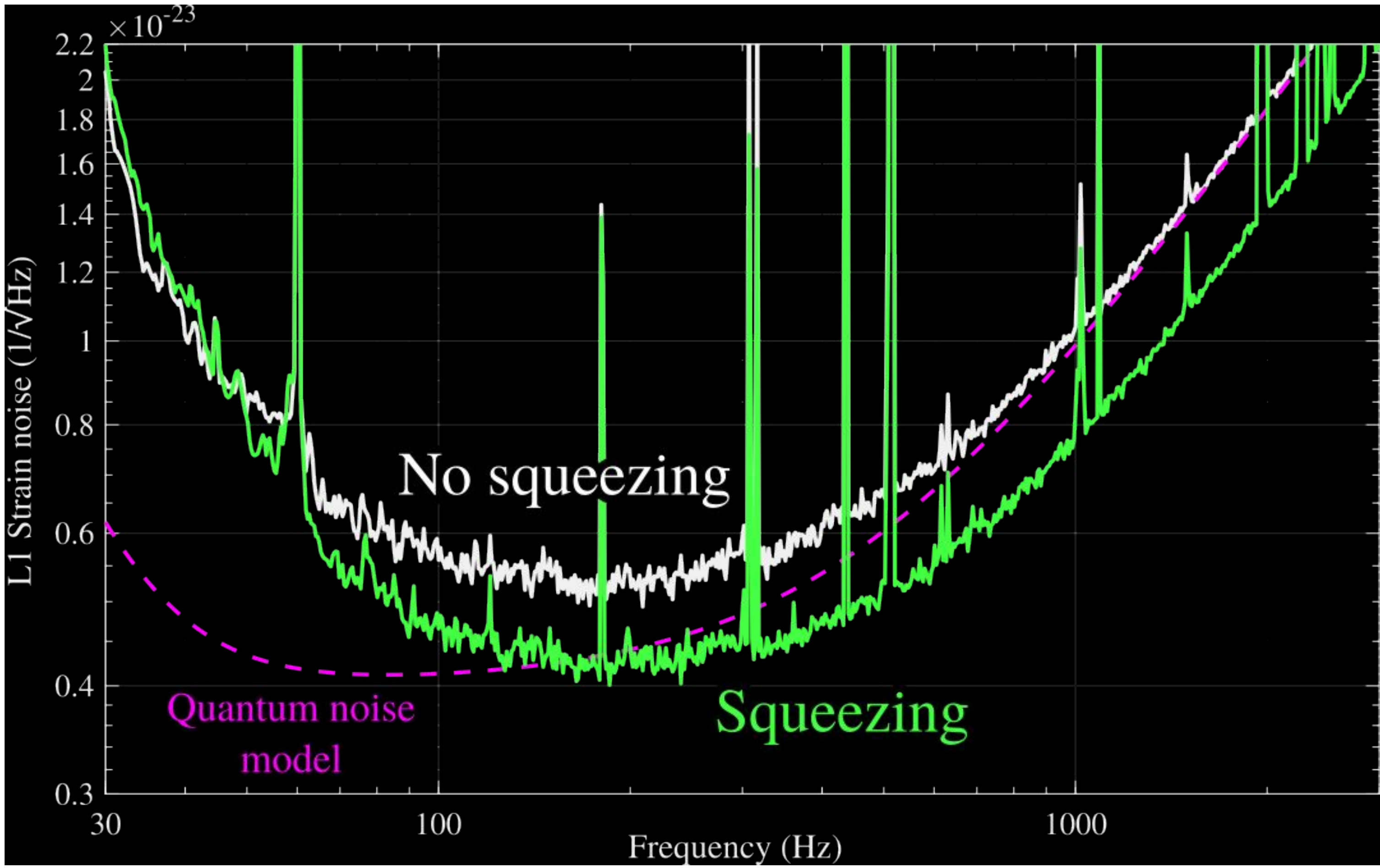




Squeezed light



Yu et al. (2020), *Nature* **583** 43

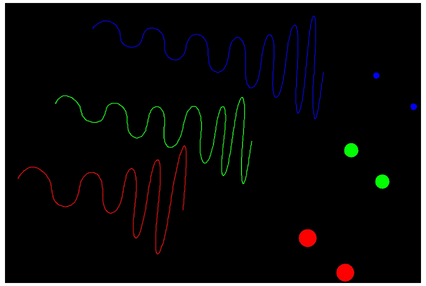


Tse et al. (2019), *PRL* **123** 231107

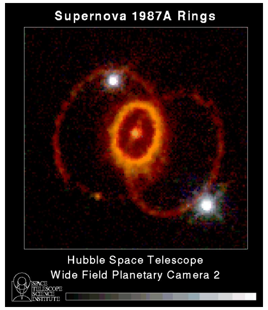
10dB squeezing in reference design requirement on interferometer…

Astrophysical Sources

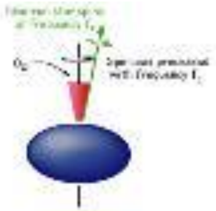
- Compact binary inspiral: *“chirps”*
  - NS-NS waveforms are well described
  - BH-BH need better waveforms
  - search technique: matched templates



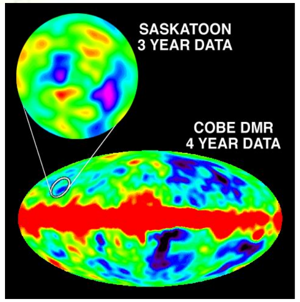
- Supernovae / GRBs: *“bursts”*
  - burst signals in coincidence with signals in electromagnetic radiation
  - prompt alarm (~ one hour) with neutrino detectors



- Pulsars in our galaxy: *“periodic”*
  - search for observed neutron stars (frequency, doppler shift)
  - all sky search (computing challenge)
  - r-modes



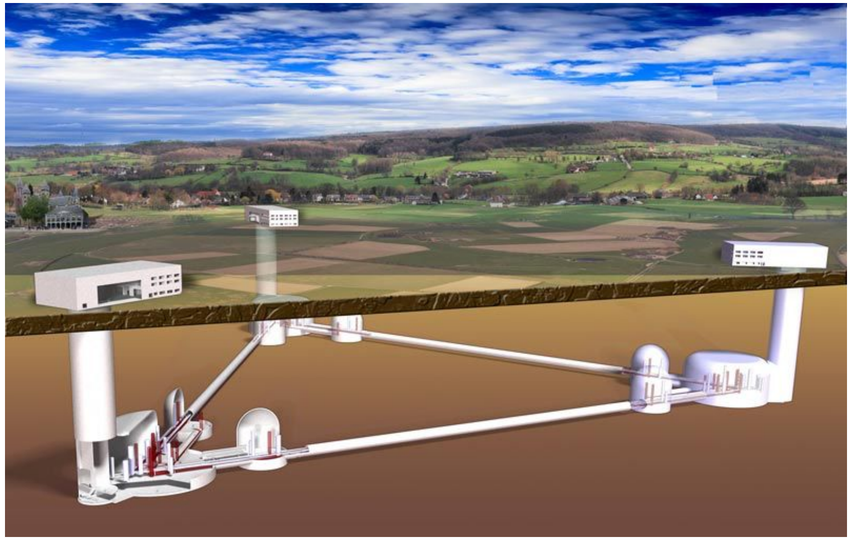
- Cosmological Signal *“stochastic background”*



Next Generation Detectors (2030s)   x10 aLIGO

Cosmic Explorer x10 Advanced LIGO

- Earths surface;
- 40 km arms + 20 km arms
- Low frequency configuration
- high frequency configuration

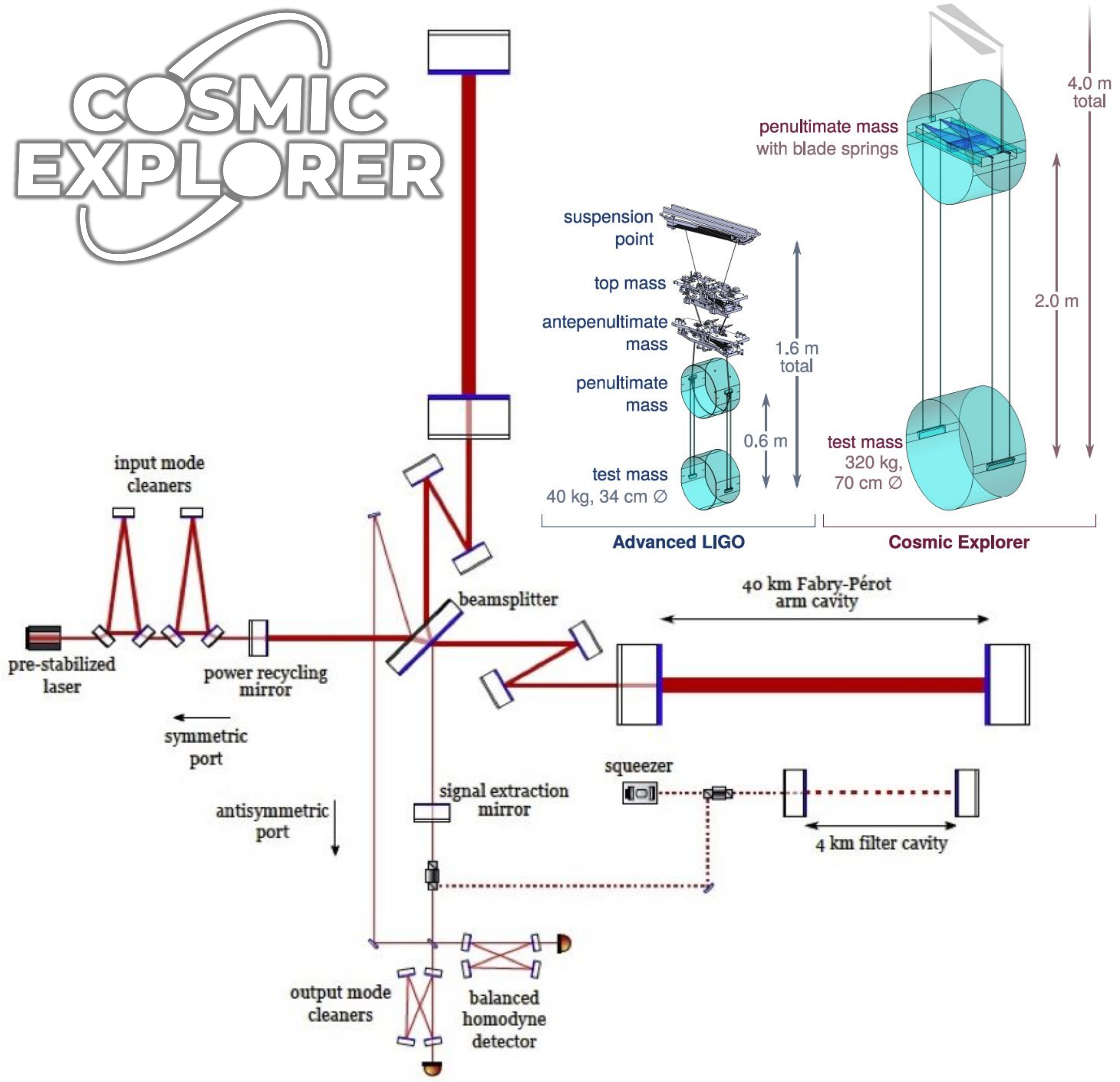


The Einstein Telescope

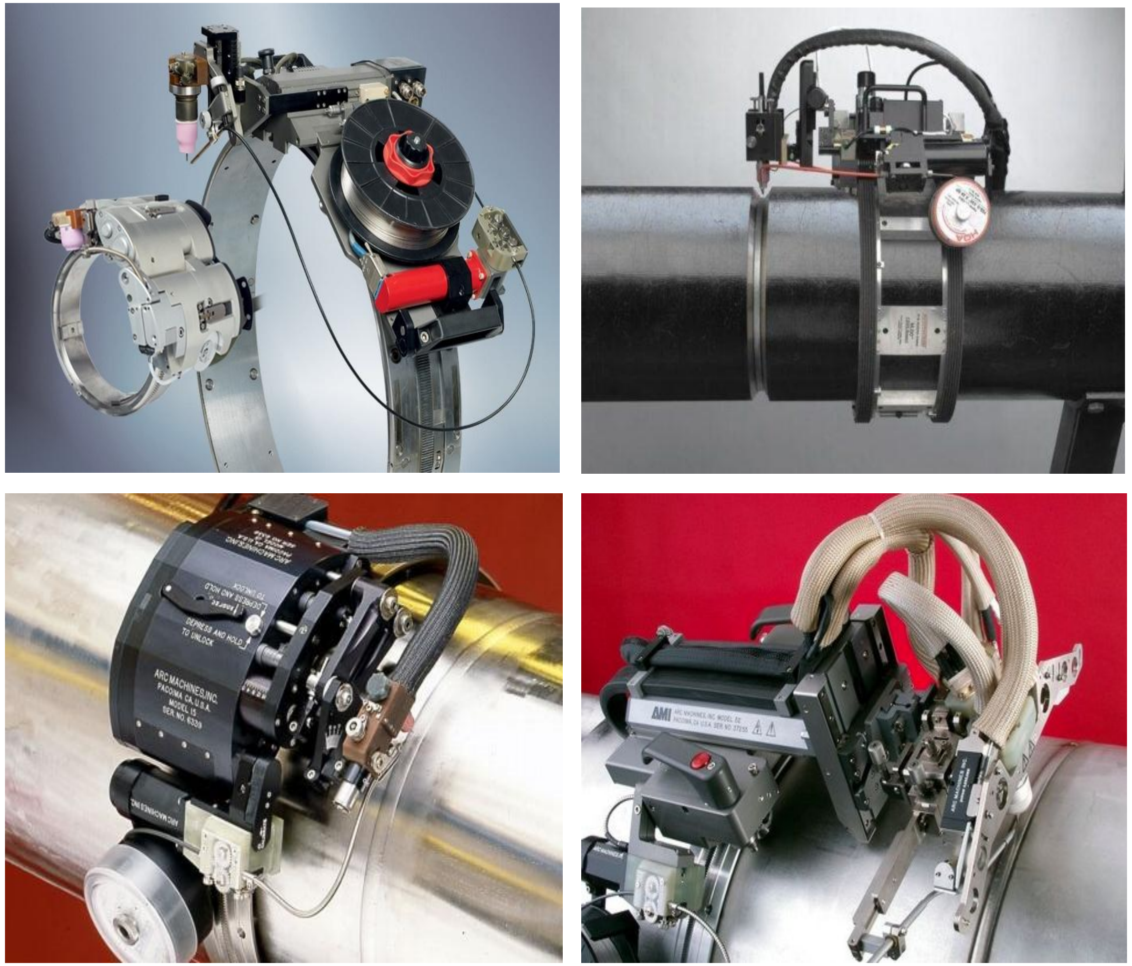
- Deep Underground
- Site Proposals: Sardinia; Holland 10 km arms
- Triangle (polarization)

CE Detector Concept

- The Cosmic Explorer instrument design is based on proven LIGO technology
- Development will be required to scale-up some technologies (e.g., larger mirrors, longer suspensions, …)
- Vacuum system is major cost driver, so R&D ongoing to find better and cheaper solutions



Vacuum Hardware at CERN



Examples of mechanized welding machines

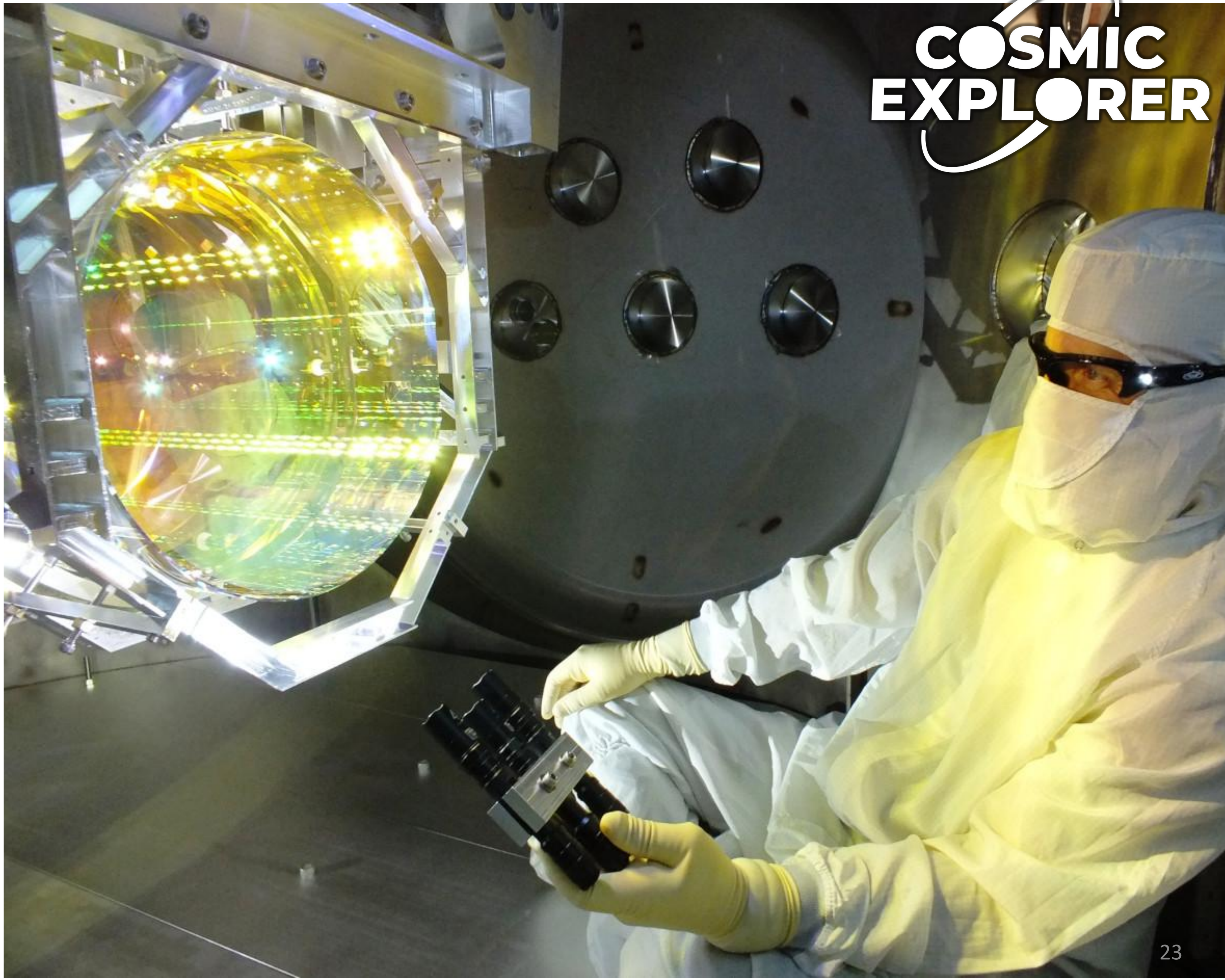
304L Pre-prototype available for UHV tests

Large Test Masses

320 kg ultra-pure glass:
Reduce thermodynamic fluctuations and heat-induced deformation

Research into fabrication techniques & metrology

Metal-oxide thin-film coatings:
Turn test mass into a mirror with reflectivity >99.995%

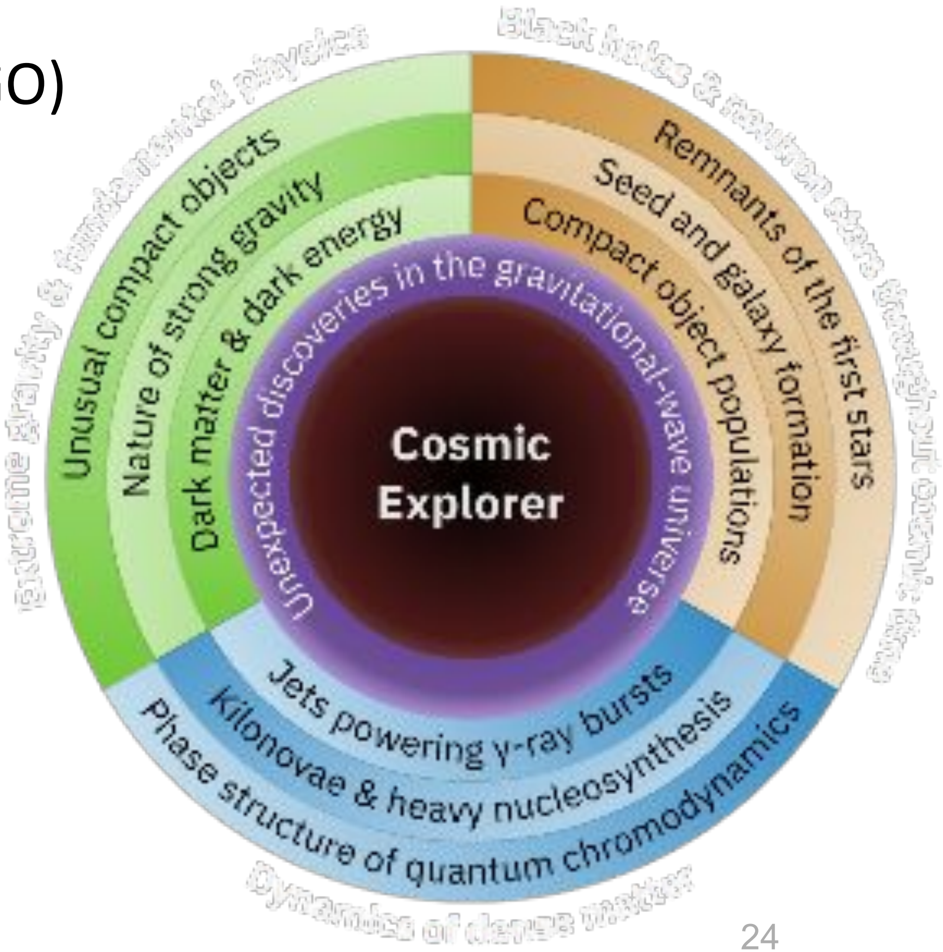


COSMIC EXPLORER

Cosmic Explorer and

- **Next-Generation Gravitational-Wave Observatory**
  - 40 km and 20 km L-shaped surface observatories
  - 10x sensitivity of today's observatories (Advanced LIGO)
  - Global network together with European Einstein Telescope

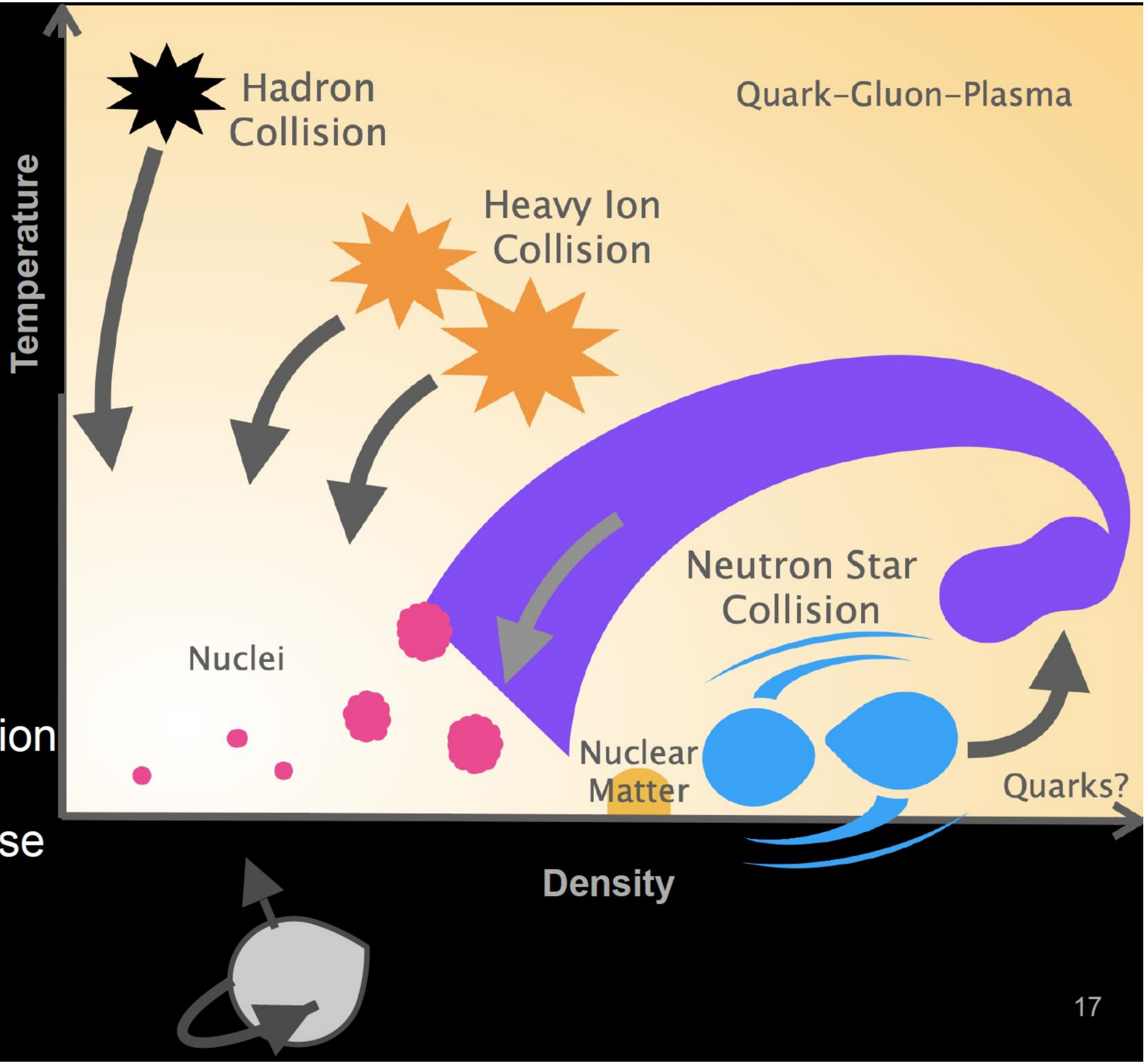
- **Enables access to**
  - Stellar to intermediate mass mergers throughout Cosmic Time
  - Dynamics of Dense Matter
  - Extreme Gravity



Dynamics of Dense Matter

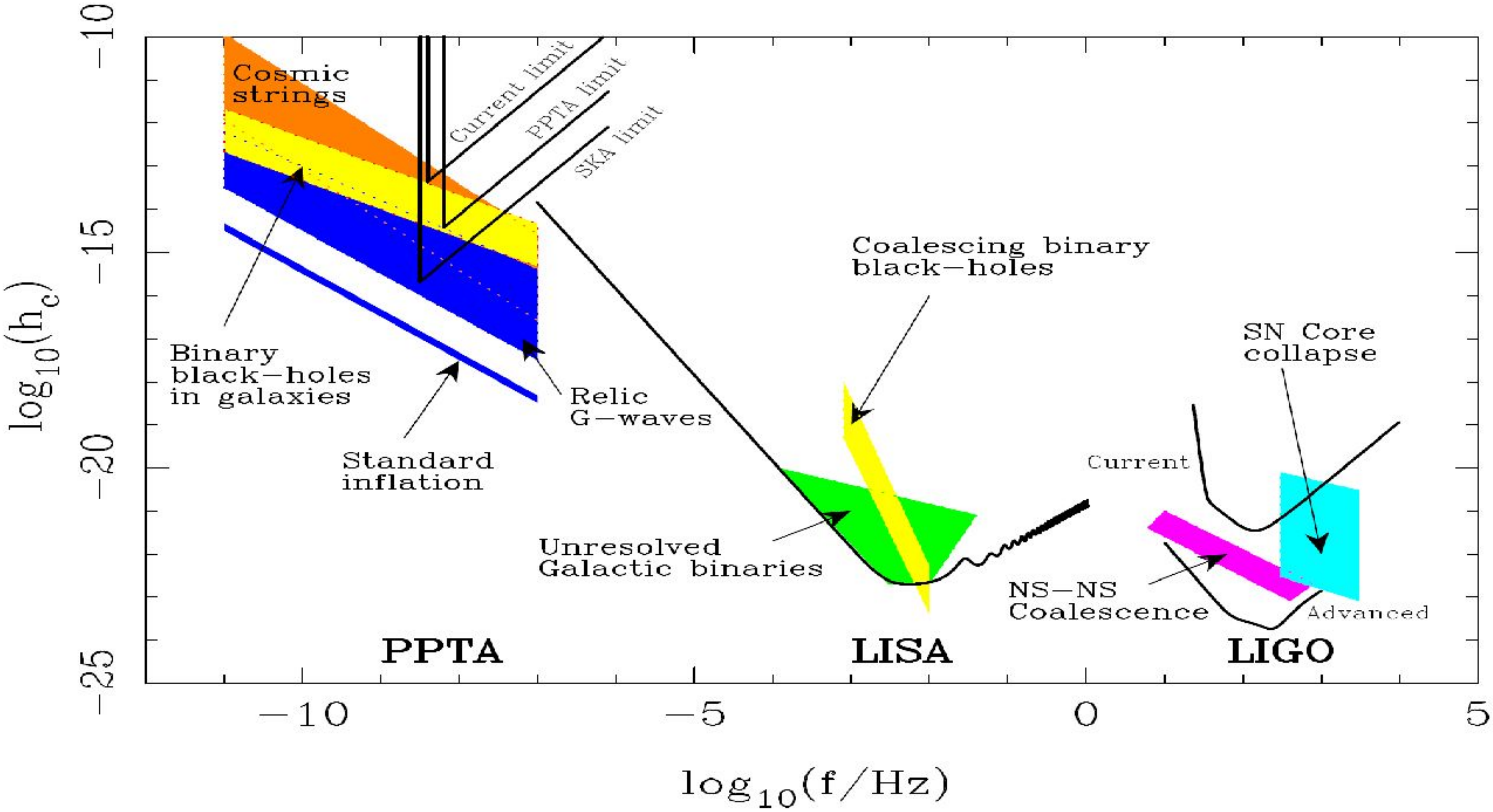
How does matter behave under the most extreme conditions in the universe?

- Neutron star structure, composition
- New phases of dense matter
- Chemical evolution of the universe
- Gamma-ray bursts and jets

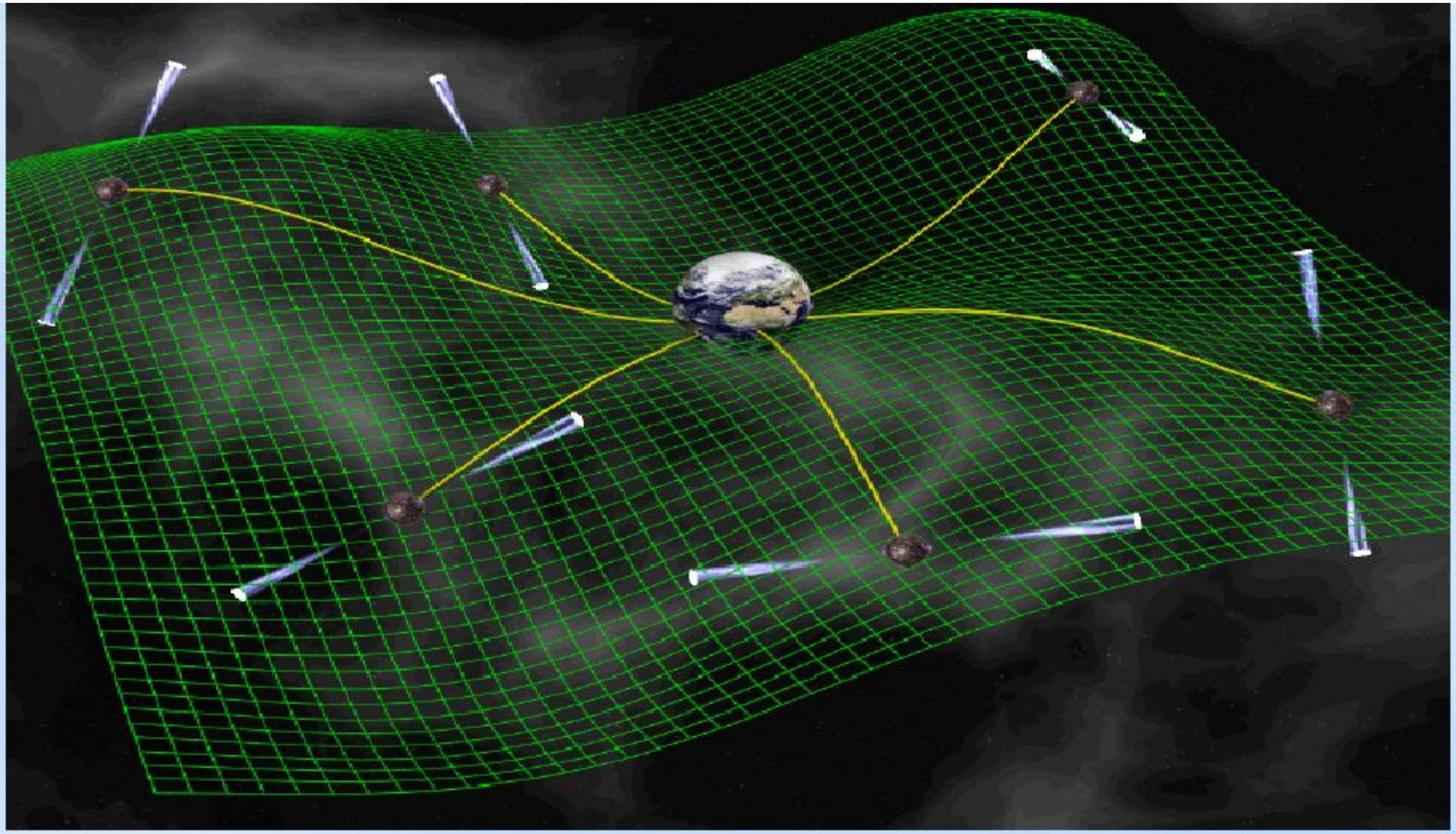


Slide: P Landry, Figure: P Landry, J Read

Gravitational Wave Frequency Coverage



Pulsar Timing Arrays

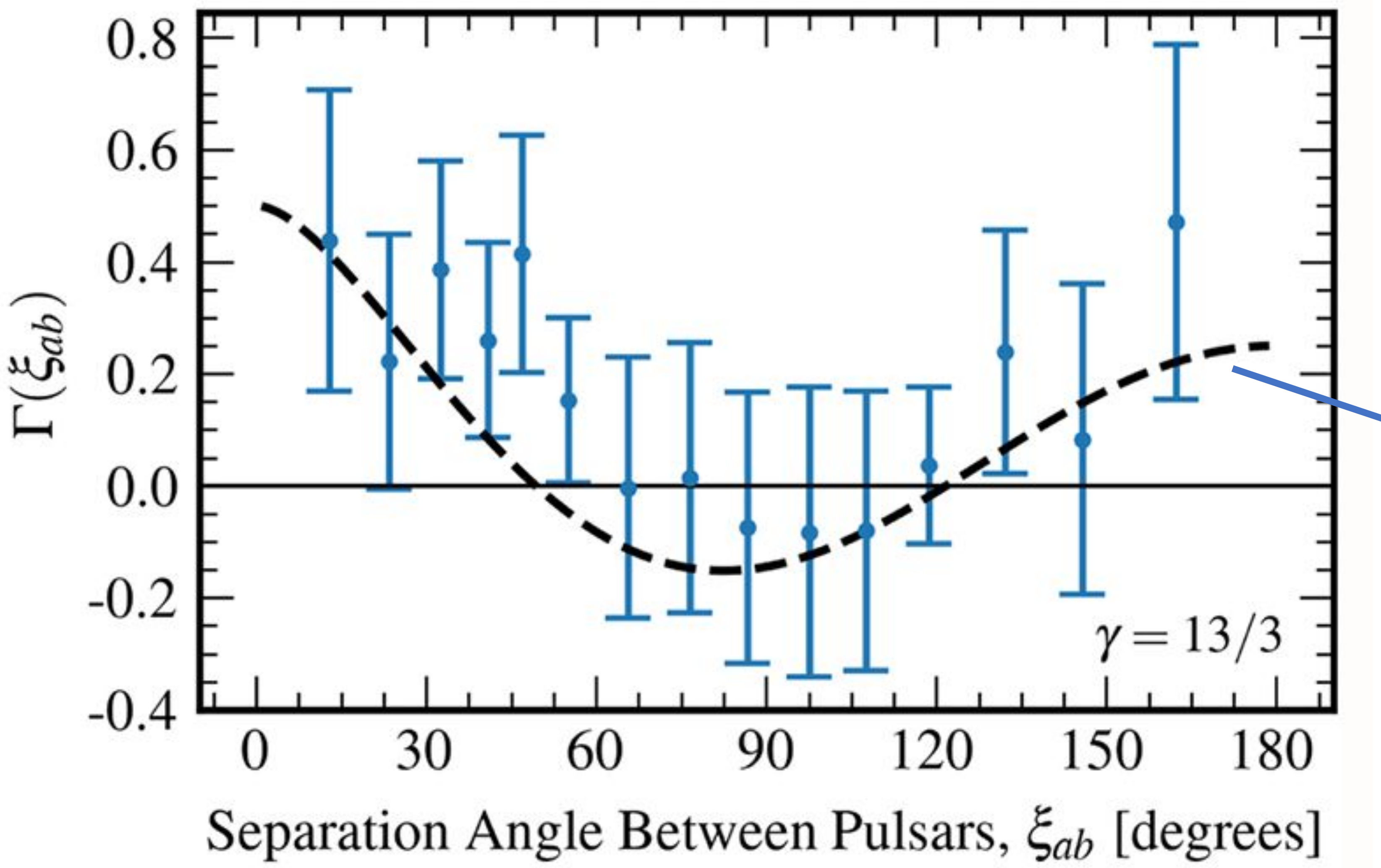


Distant pulsars send regular radio pulses – highly accurate clocks.
A passing gravitational wave would change the arrival time of the pulse.

Numerous collaborations around the world. Interesting upper limits and likely detections in the near future.

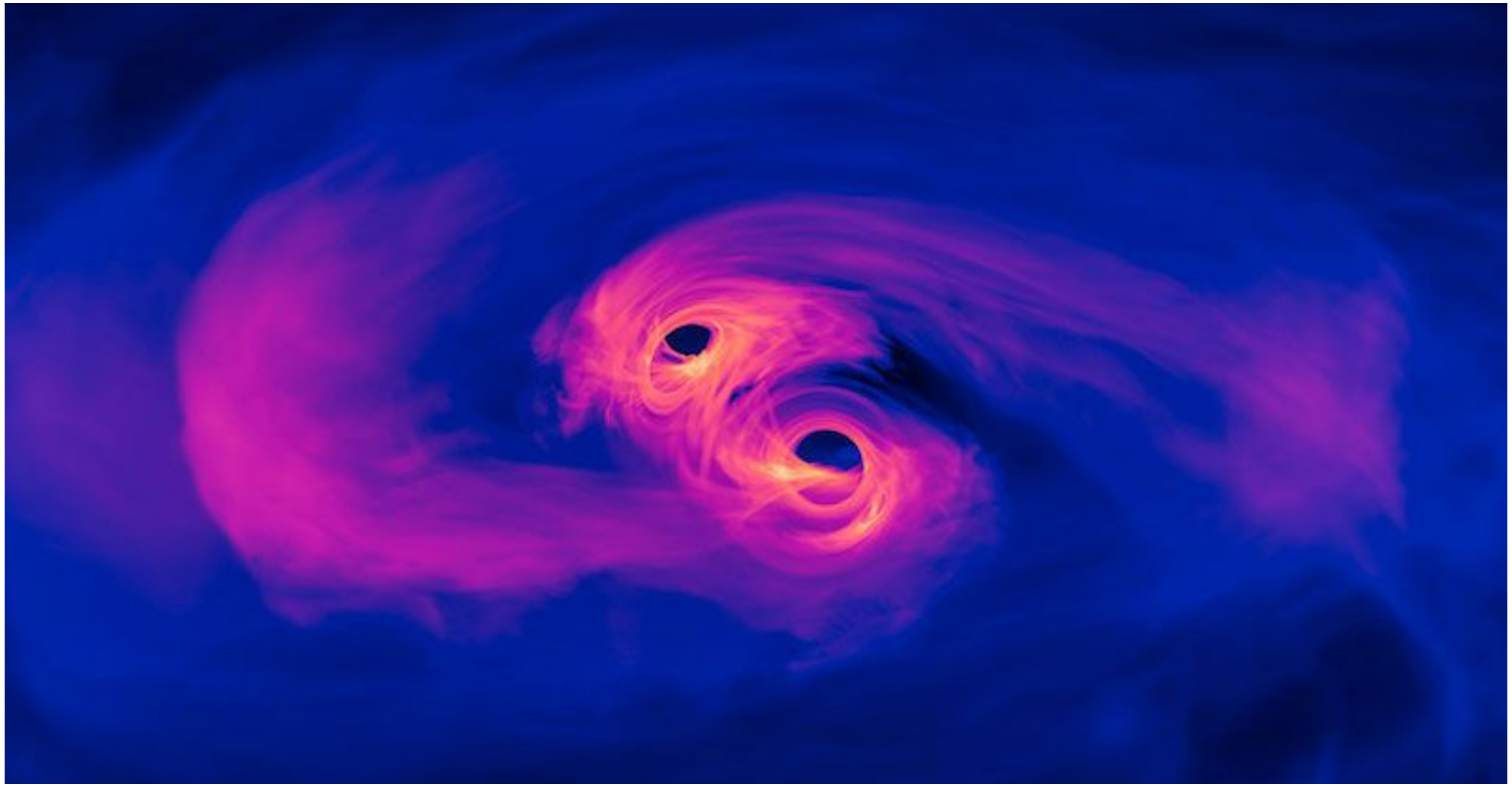
arXiv:1211.4590

Pulsar Timing Array – Angle Between Pulsars



Hellings-Downs Curve (Expected Correlation for Gravitational Waves)

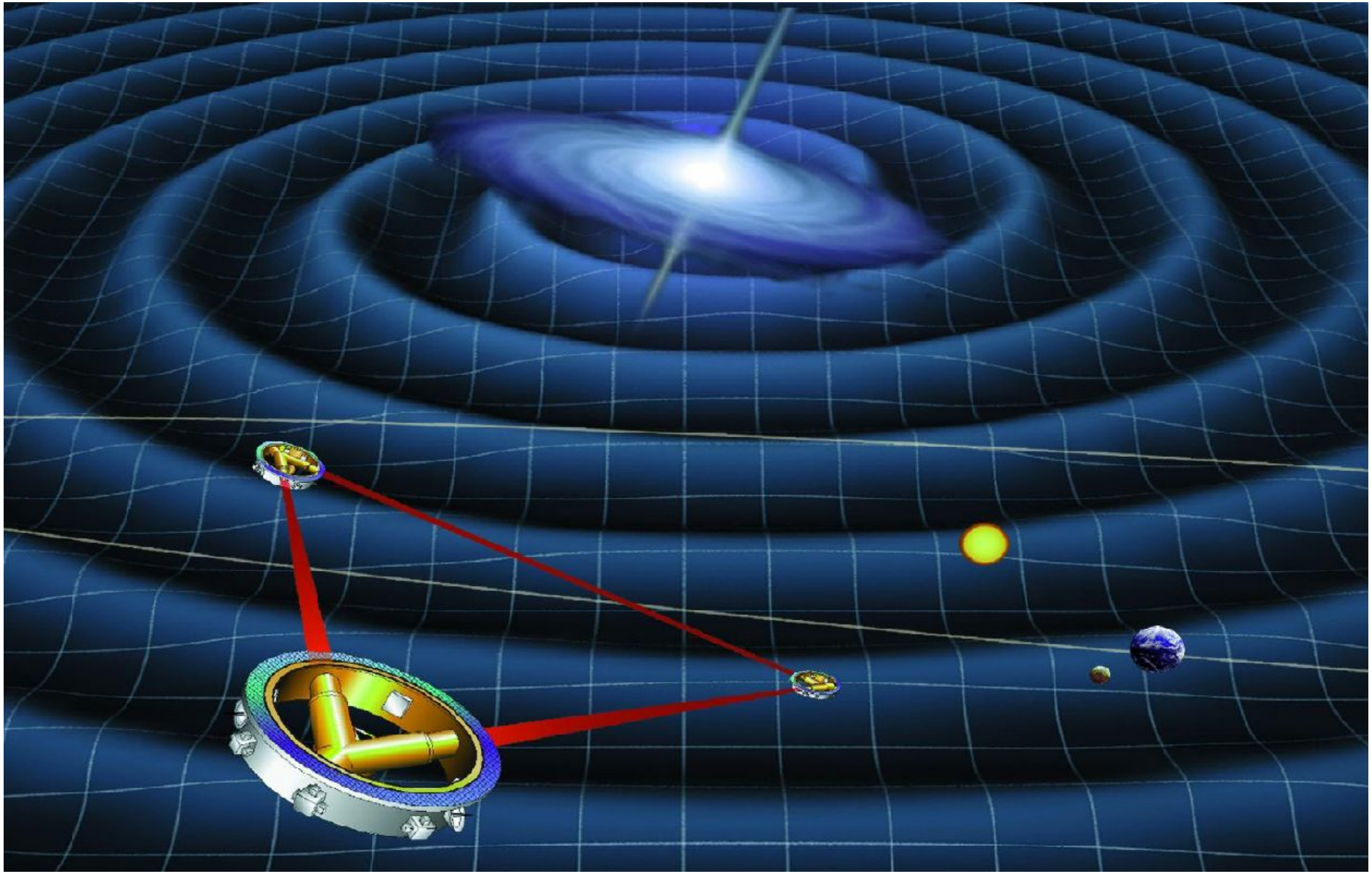
Pulsar Timing Array – Sources of Signals



Pairs of supermassive black holes (as depicted in this computer simulation) are considered a likely explanation of the observed gravitational-wave background signal.

Other possibilities include primordial signals from inflation, dark matter, or cosmic defects known as cosmic walls and strings.

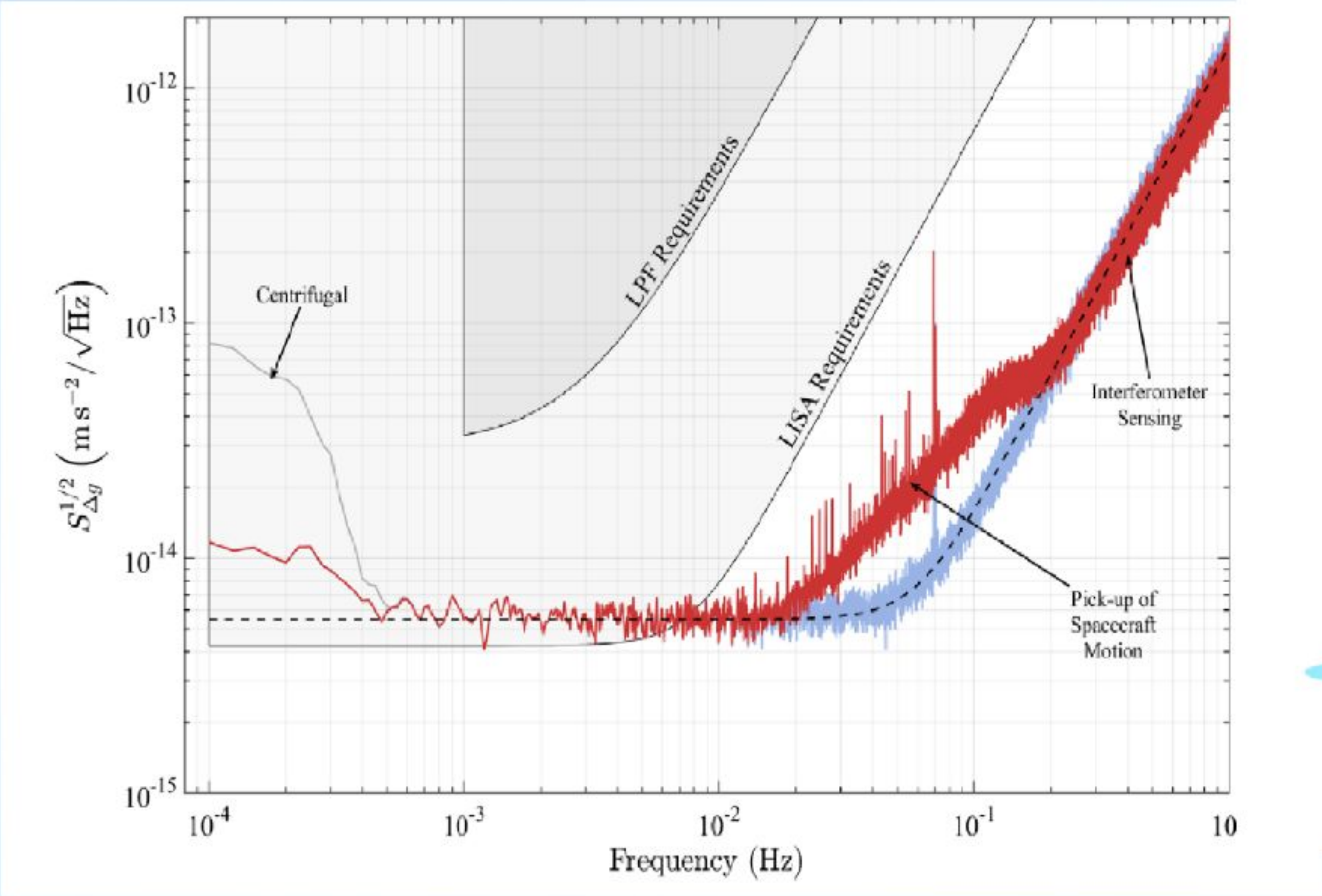
LISA: Laser Interferometer Space Array

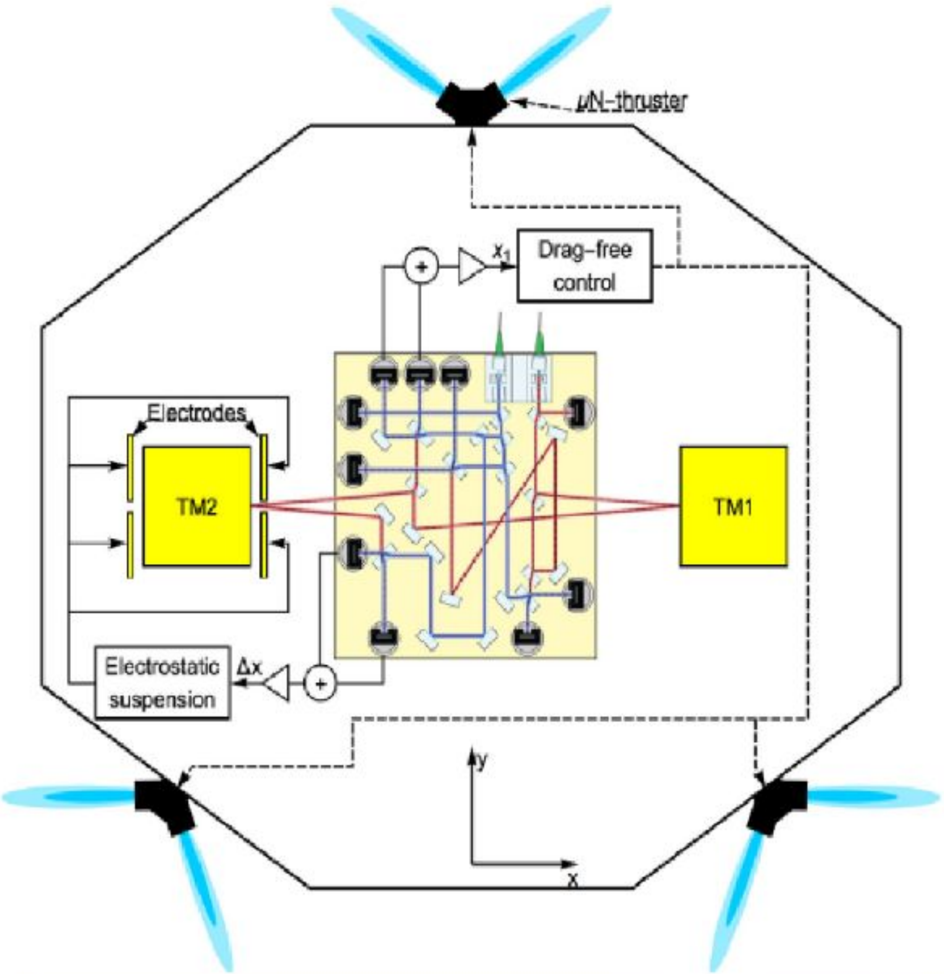


Three Interferometers

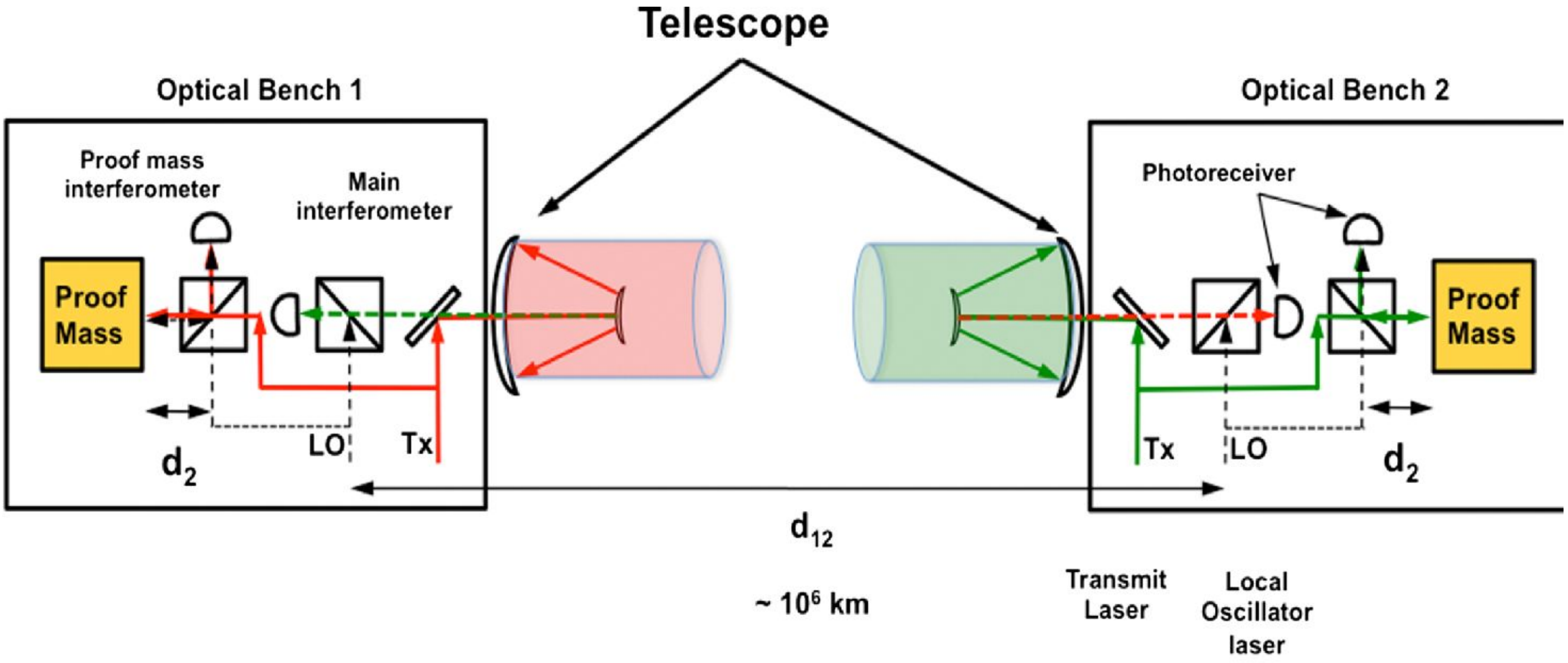
$2.5\ 10^6$ km arms

LISA Pathfinder – Technology Demonstration



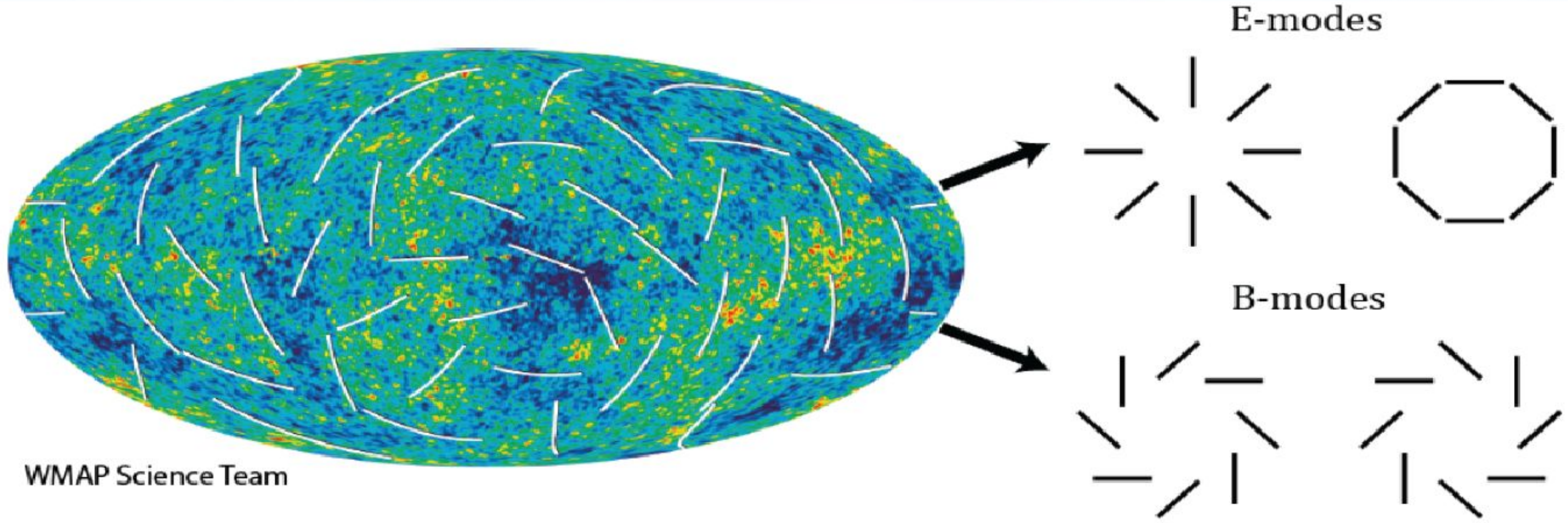


LISA Proof Masses, Optical Bench, Interferometry and Telescope



Total distance = $d_1 + d_{12} + d_2$

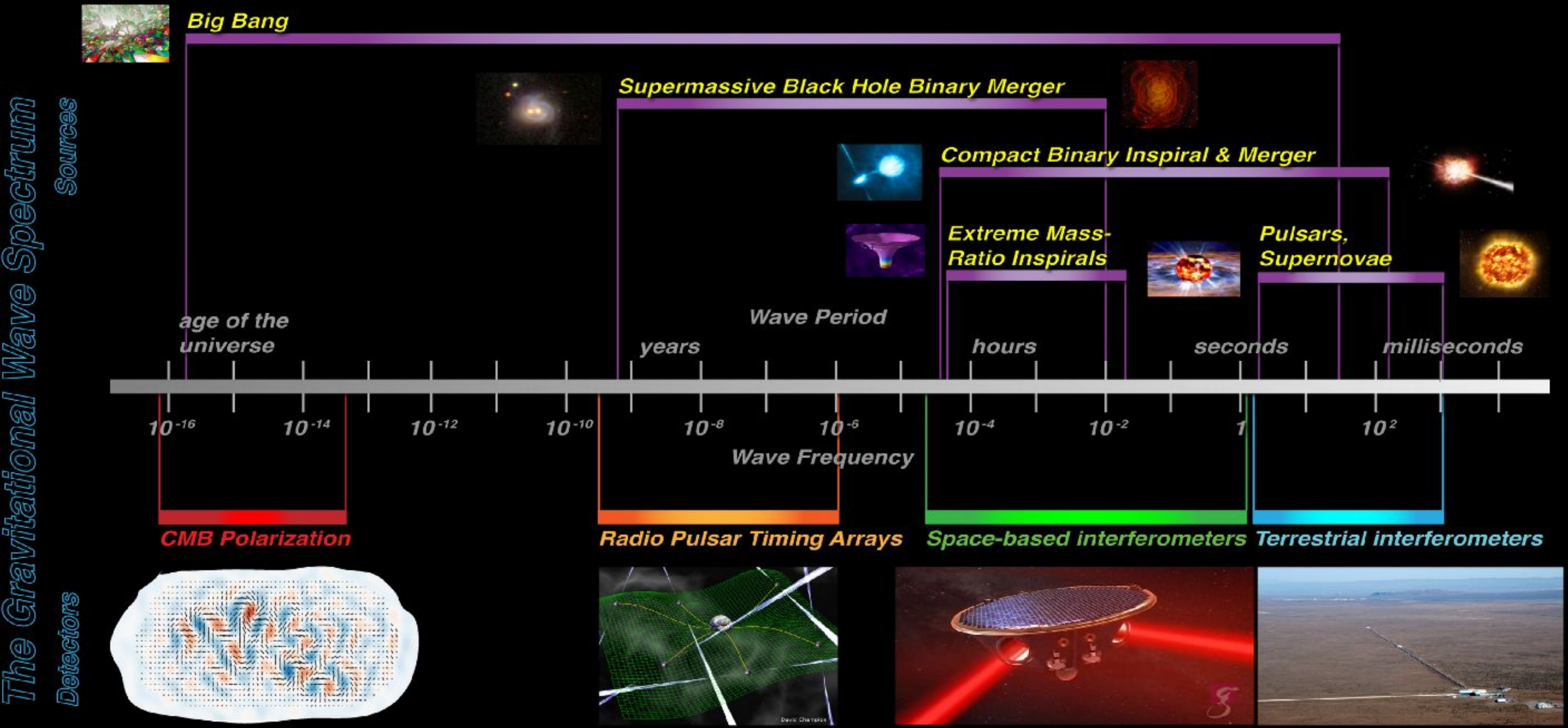
Polarization Maps for CMB Experiments



The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence-free odd-parity B-modes.

Gravitational waves in the early universe imparts a "curl" on CMB polarization. 67
arXiv:1407.2584

Exploring the Universe with Gravitational Waves



Stan was my Long-time Colleague and Friend
He Made Many of our Lives and Careers Much Richer