Measuring Gravitational Waves Across the Frequency Spectrum

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Overview

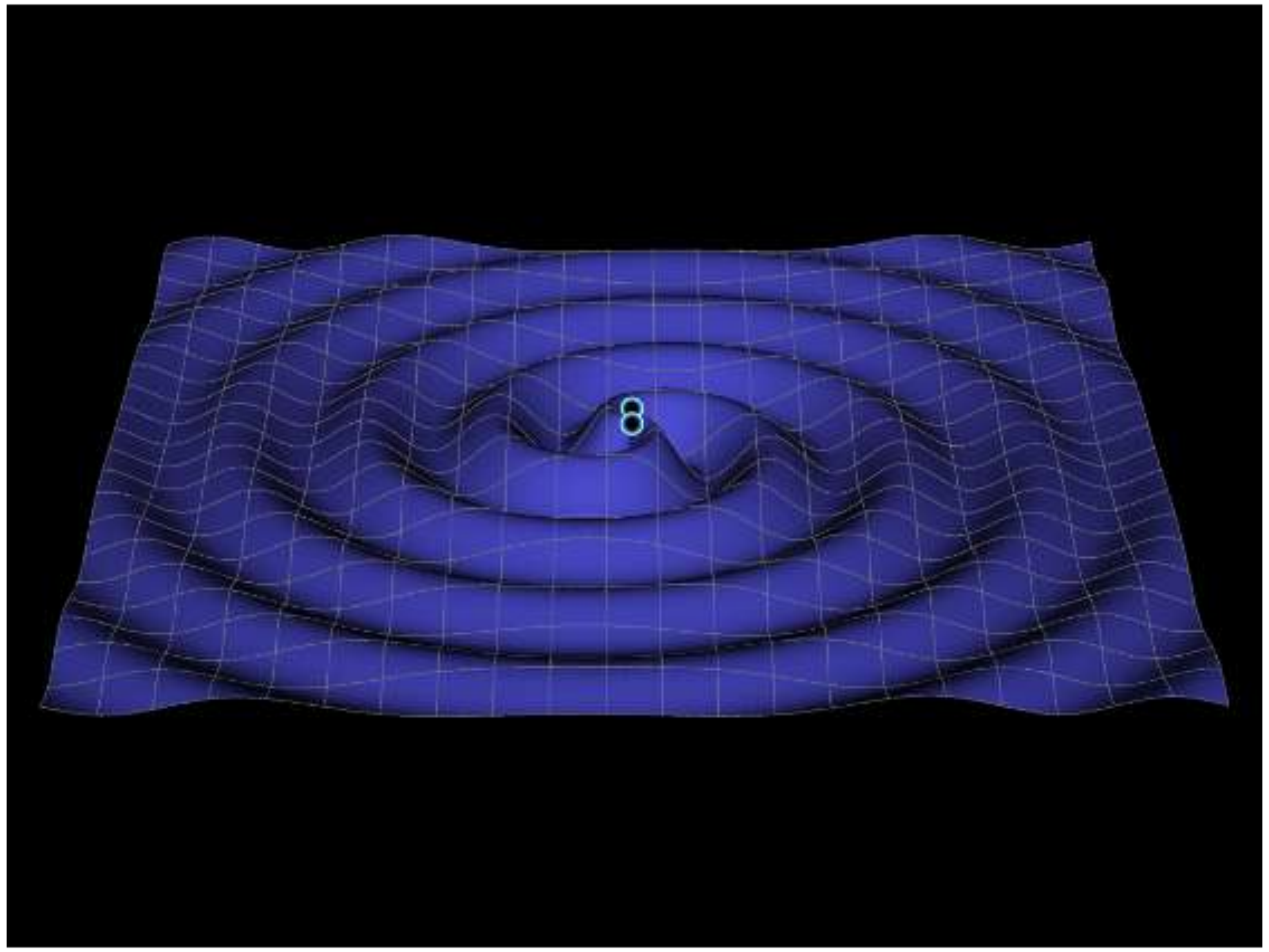
- Introduction to Gravitational Waves
- High Frequency GWs: Interferometry w/ LIGO/LISA
- Low Frequency GWs: More “Traditional” w/ PTAs and CMB

Prologue: Introduction to GWs

Gravitational Waves

Introduction

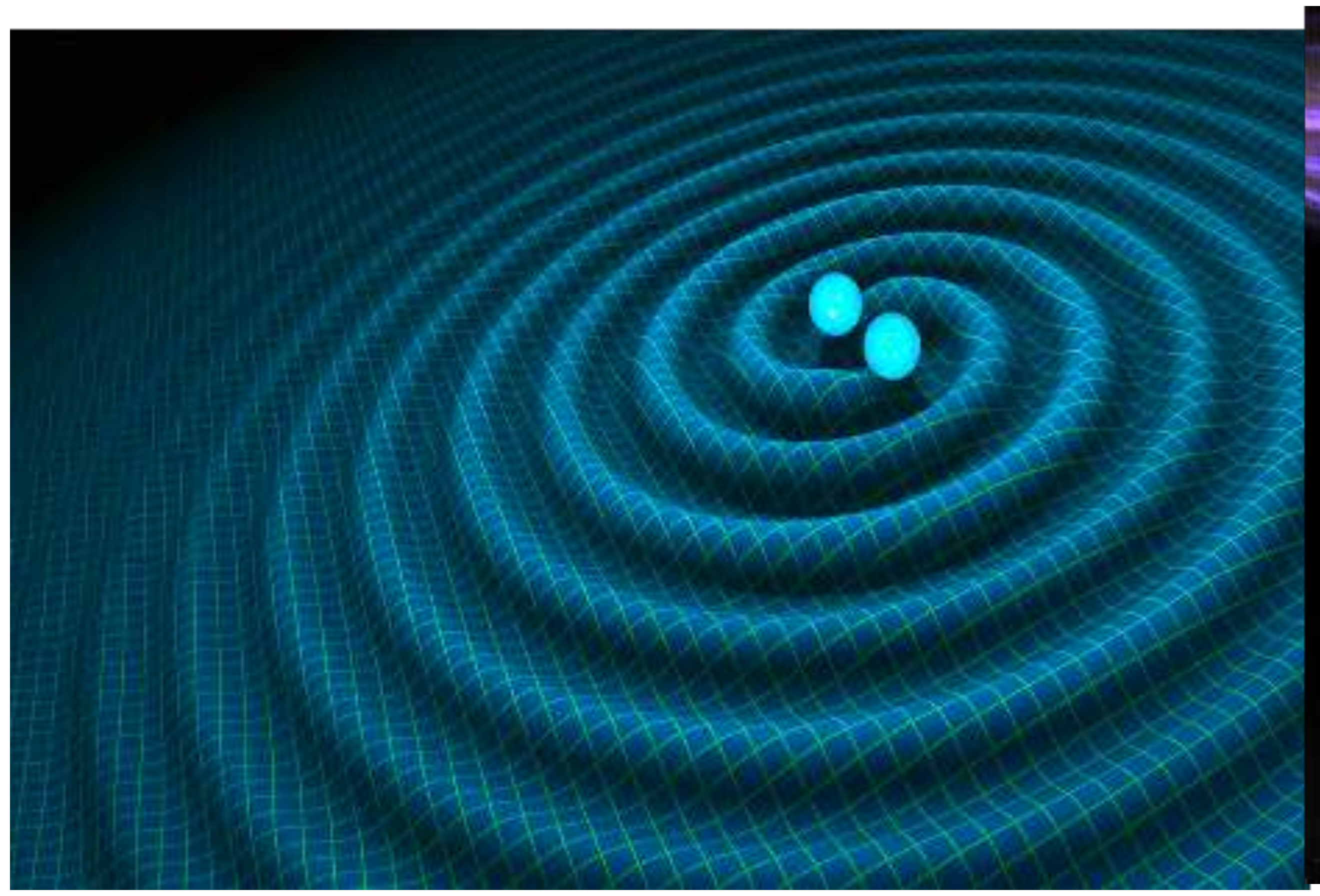
- GWs are perturbations in spacetime that propagate as waves
- Analogous to EM waves in many ways: speed c, propagate in vacuum, etc
- Predicted as a result of GR
- Only recently directly detected for the first time (2015)
- A new way to examine phenomena.



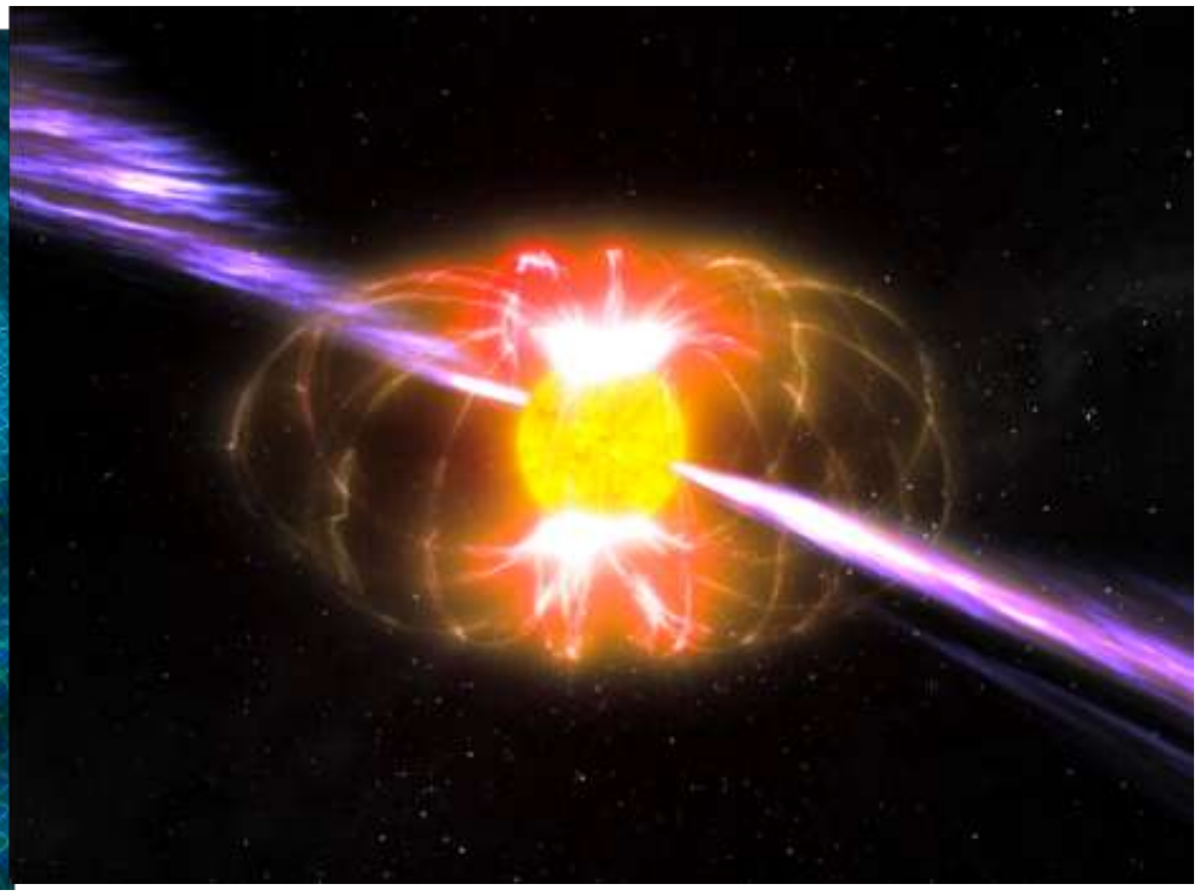
Gravitational Waves

Sources

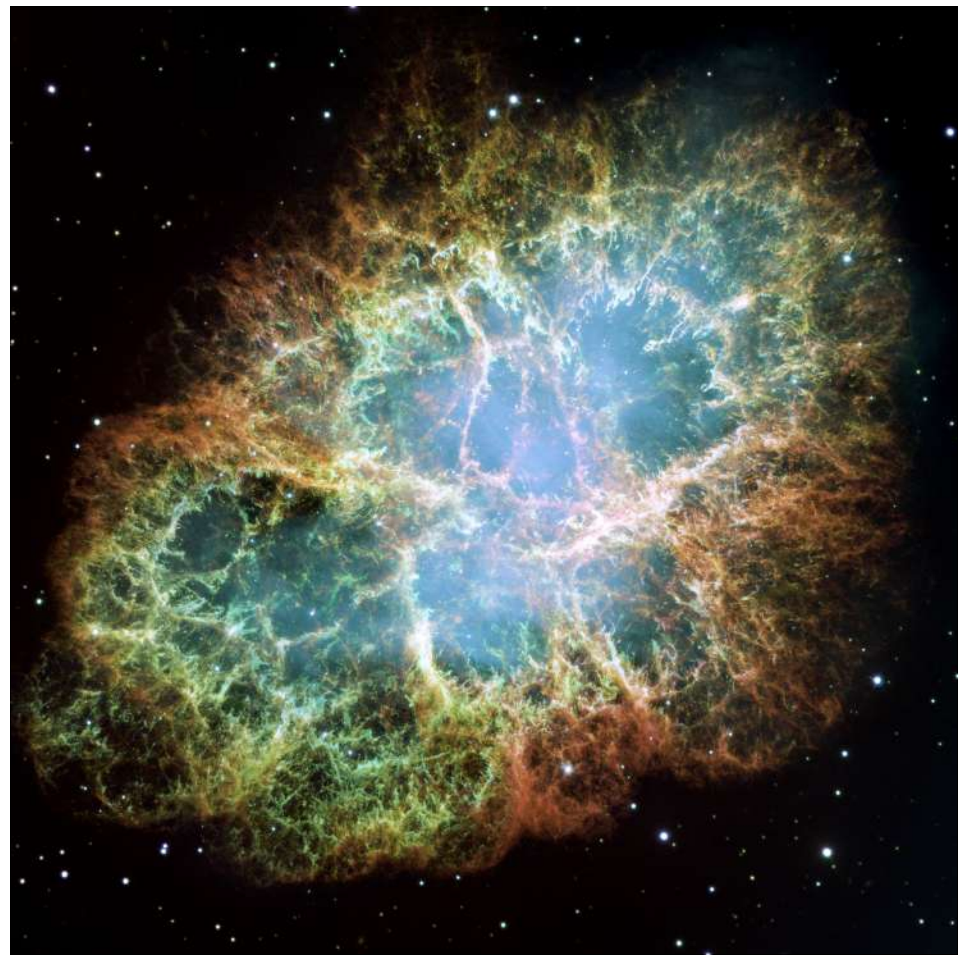
GWs are sourced by cataclysmic gravitational events.



Mergers



Pulsars



Supernovae

Big Bang/Inflation

Gravitational Waves

Mathematics

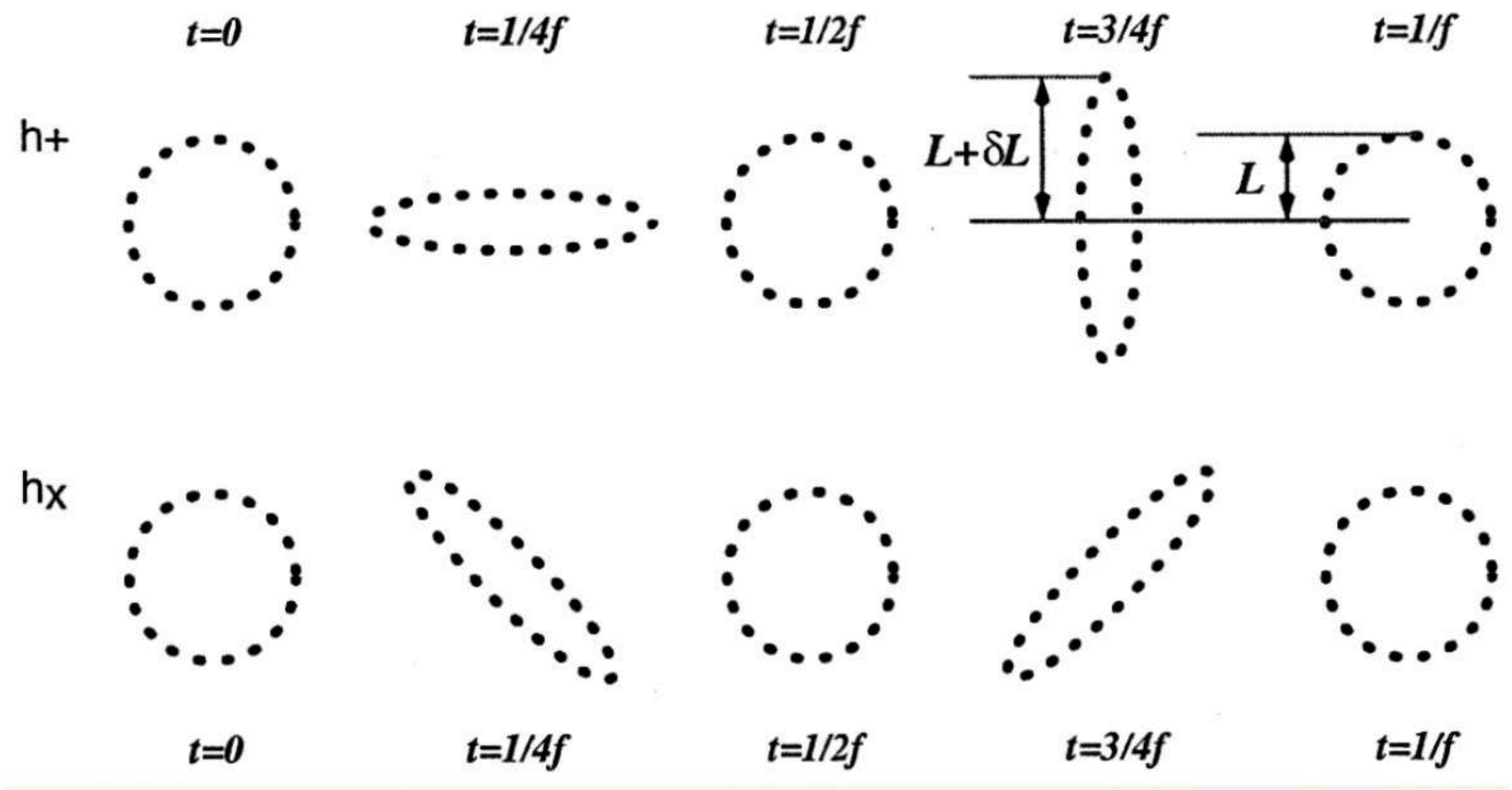
Spherical Harmonic Breakdown for BBH

$$h_+ - ih_\times = \frac{1}{D_L} \sum_{l=2}^{\infty} \sum_{m=-l}^{l} {}_{-2}Y^{lm}(\iota, \phi) A_{lm}(\overrightarrow{\lambda}) e^{i(\Psi_{lm}(\overrightarrow{\lambda}) + m\varphi)},$$

Two D.O.F (Polarizations)

No Monopole/Dipole!

Signal depends on source parameters! (In this case a BBH)



Gravitational Waves

Scale

Why aren't we torn apart by GW's?

By the time they reach us, these events are extremely small…

Most LIGO detections only see effects on length scales of 10^-19 m!

That is 1/1000th the width of a proton.

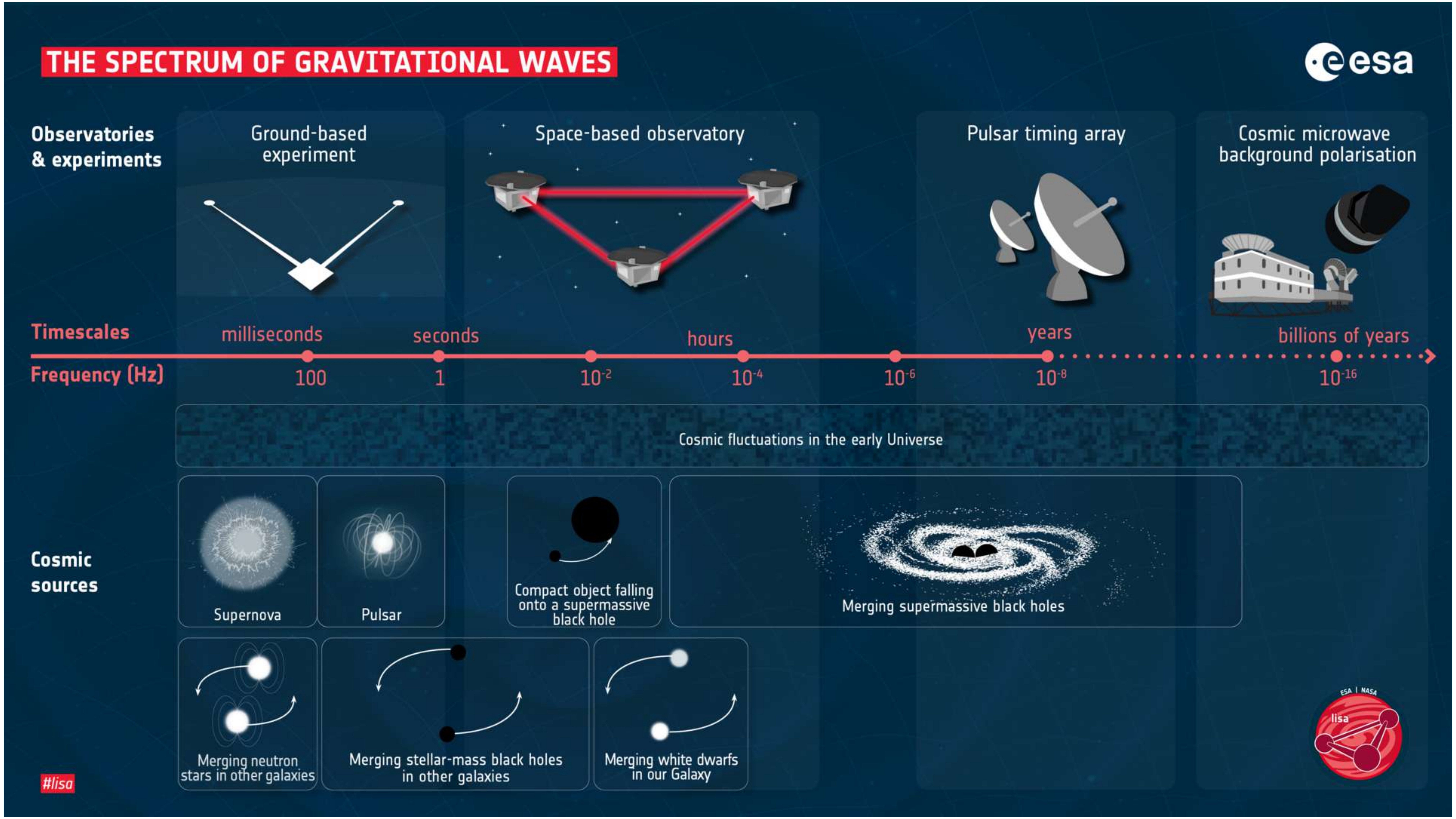
That is 1/1,000,000,000th (billionth) the width of an atom.

That is 1/10,000,000,000,000th (ten trillionth) the width of a fine hair.

This makes them incredibly difficult to detect.

Gravitational Waves

Spectra

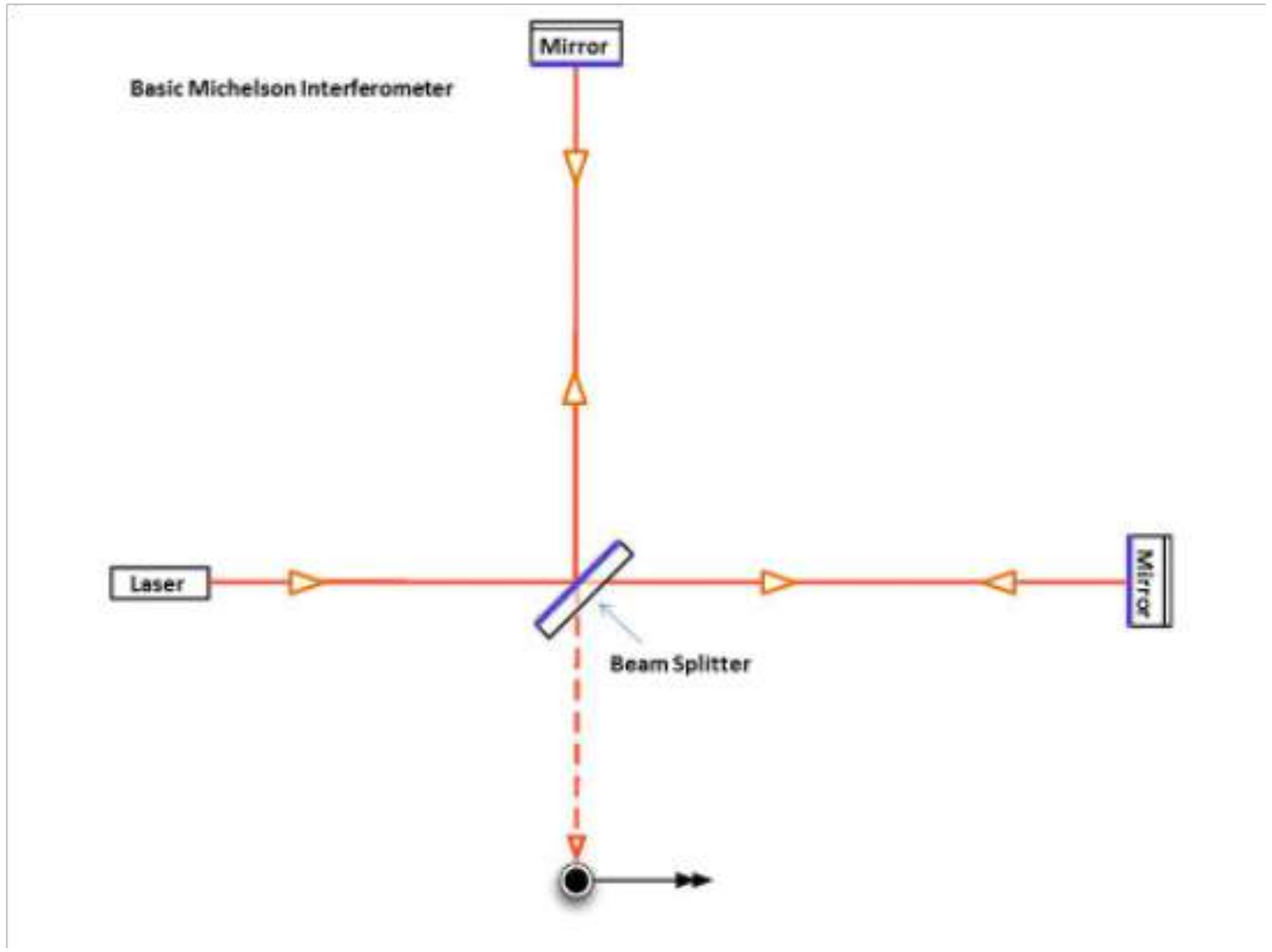


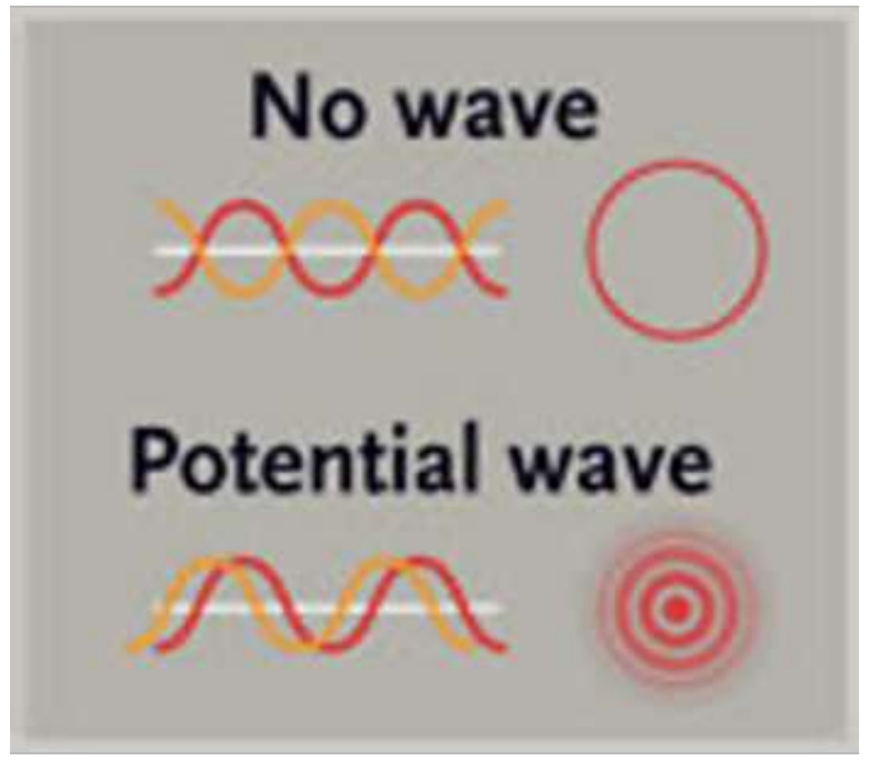
Part I: High Frequency Gravitational Waves (Interferometry)

LIGO Interferometry

Introduction

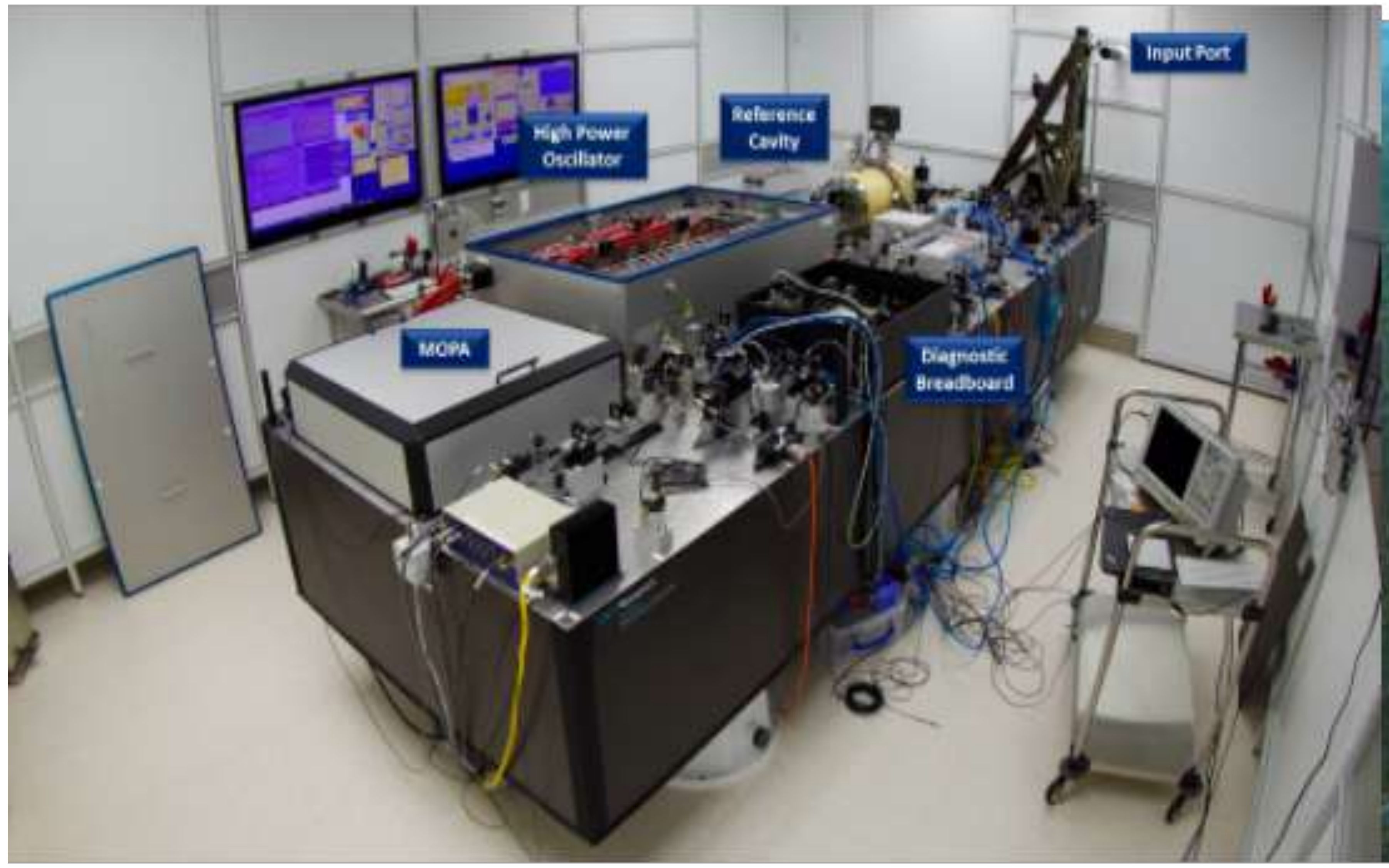
- High frequency gravitational waves detection uses interferometry
- GWs adjust Michelson Interferometer lengths to yield signals
- Allows for a “direct” waveform measurement
- Currently sensitive to GWs from BBH/BNS mergers, supernovae, pulsars (> 1 Hz)



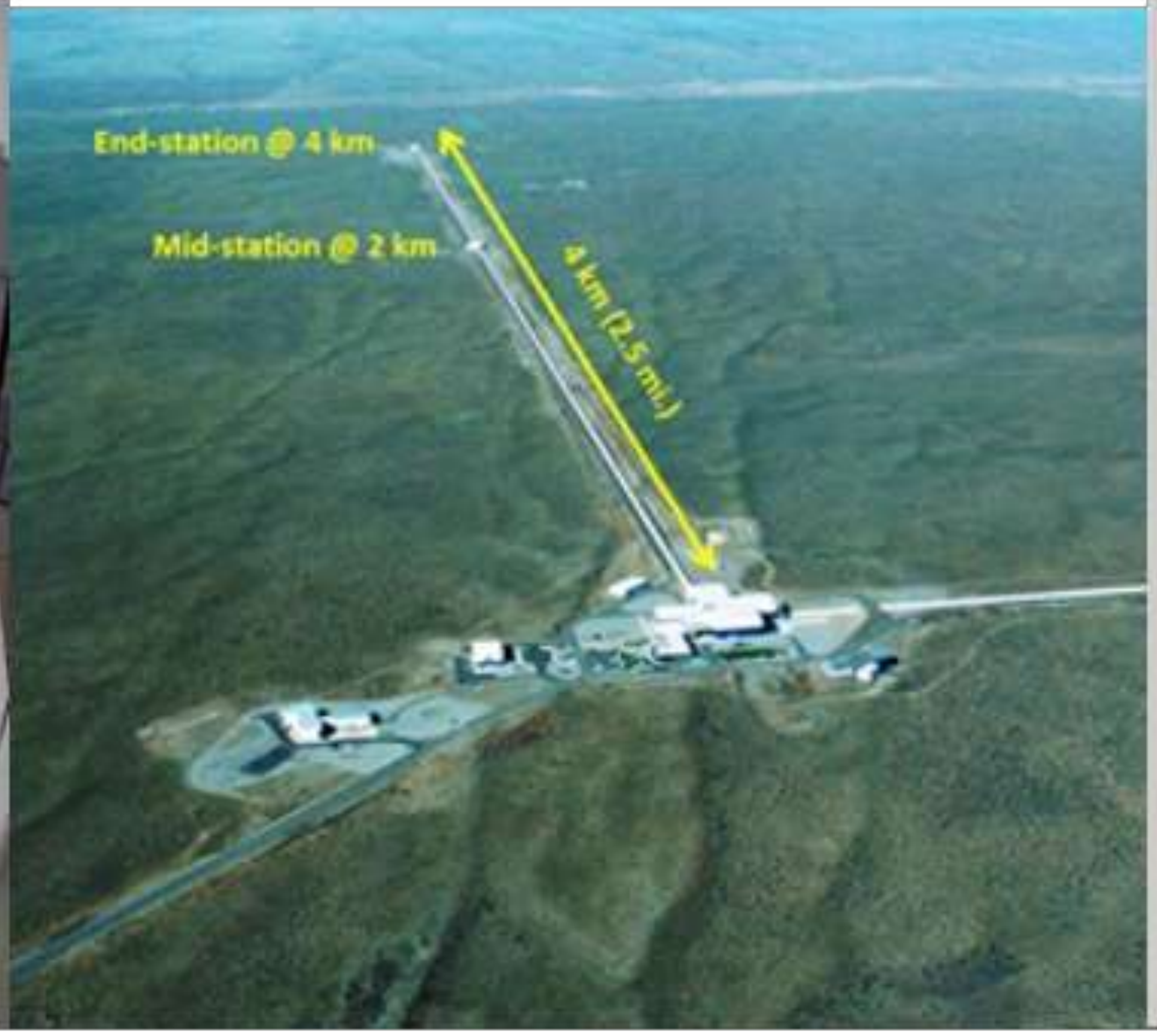


LIGO Interferometry

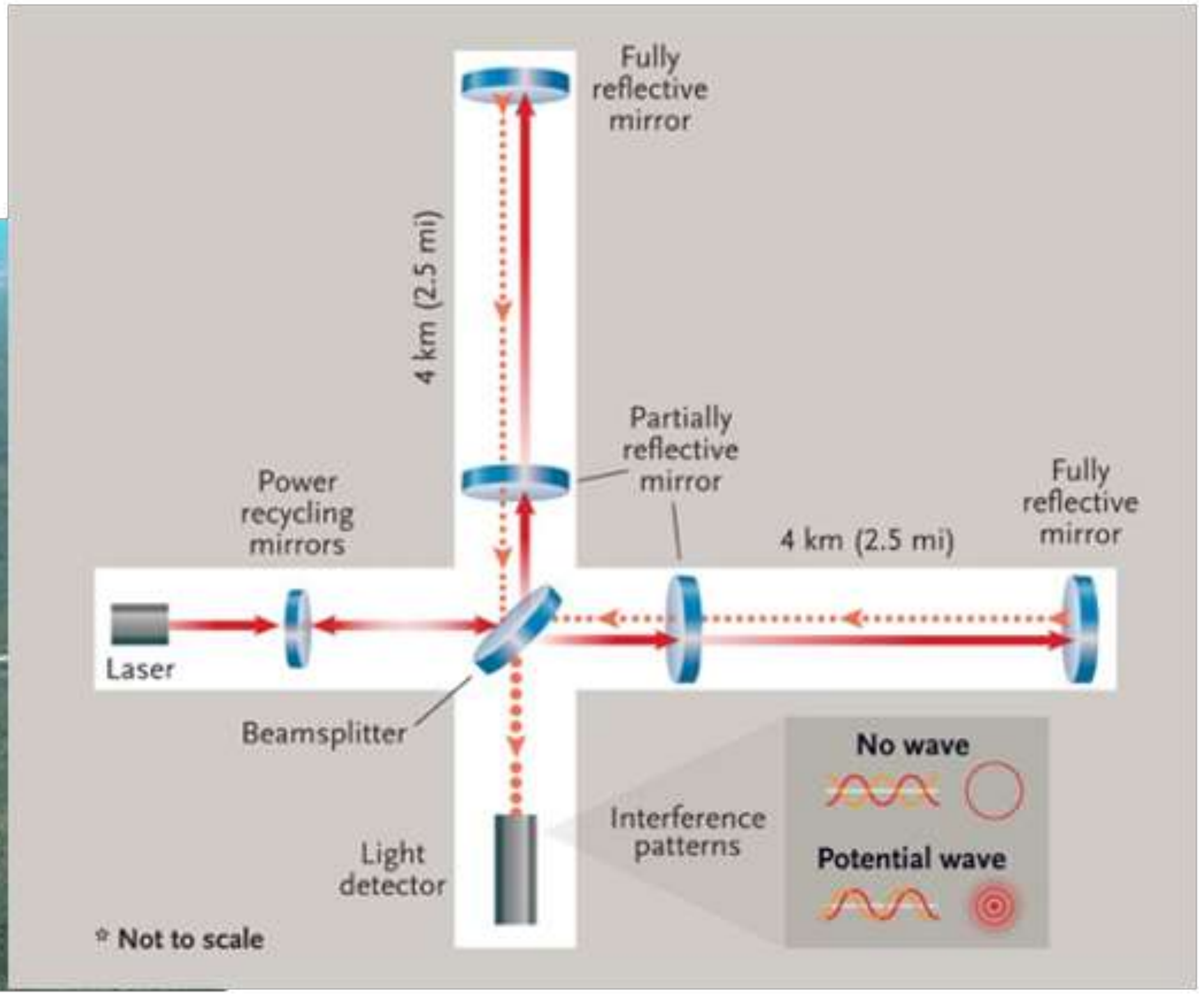
Immense Scale



40 W Laser



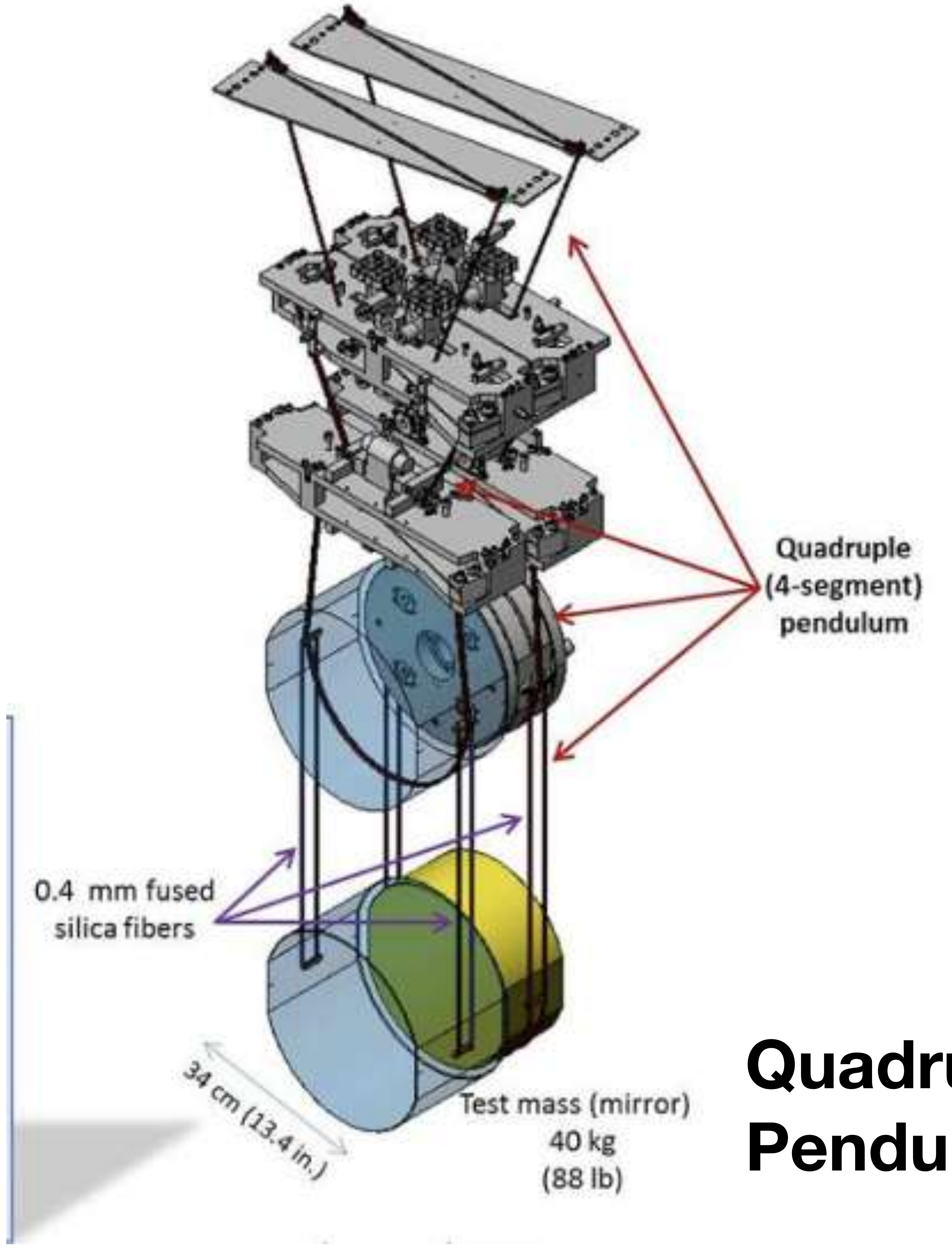
4 km long arms



Power recycling & reflection (eff. 1200 km, 740 kw)

LIGO Interferometry

Noise Reduction



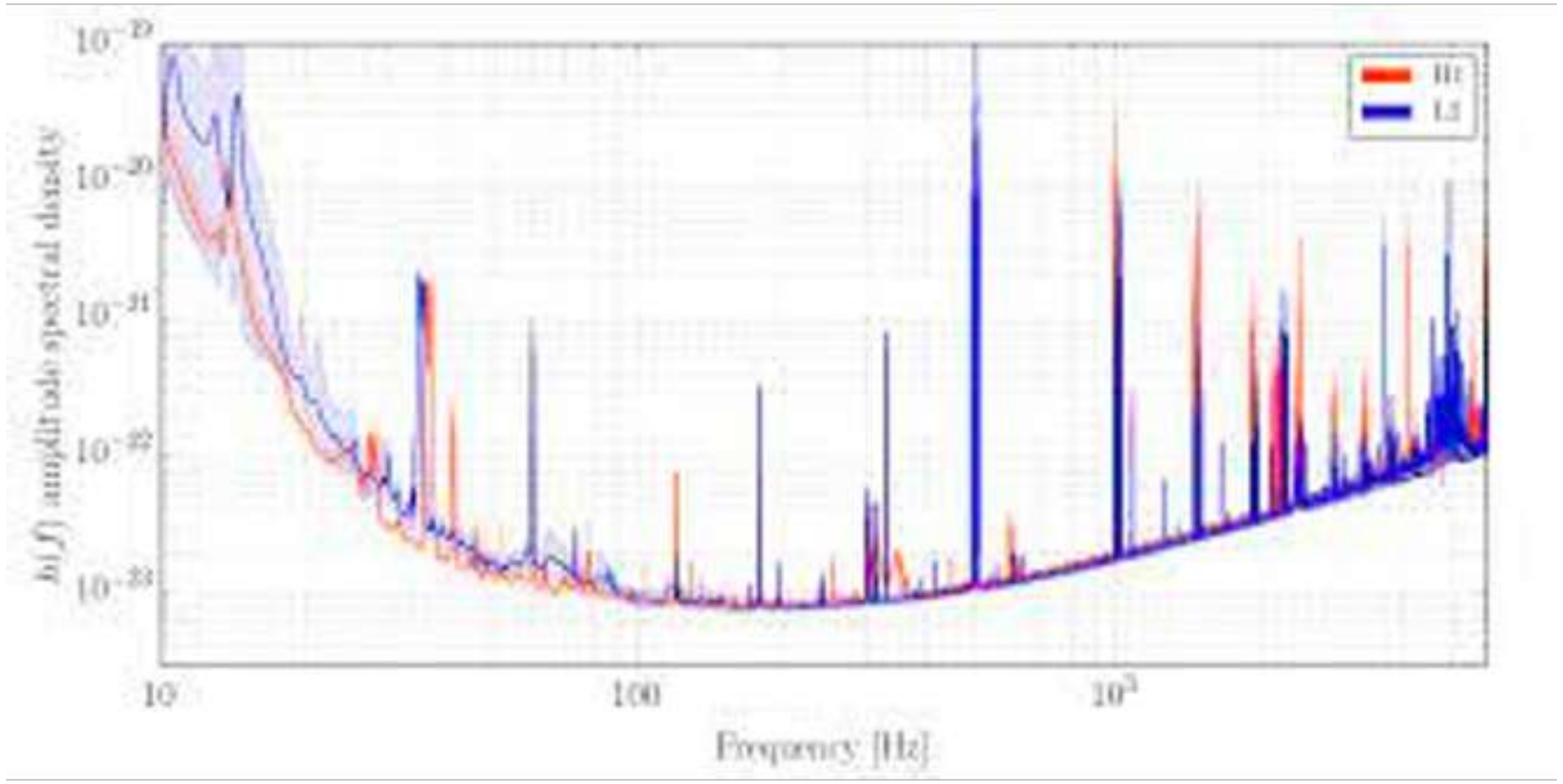
Quadruple Pendulum

Vacuum Chamber

Silica Mirrors

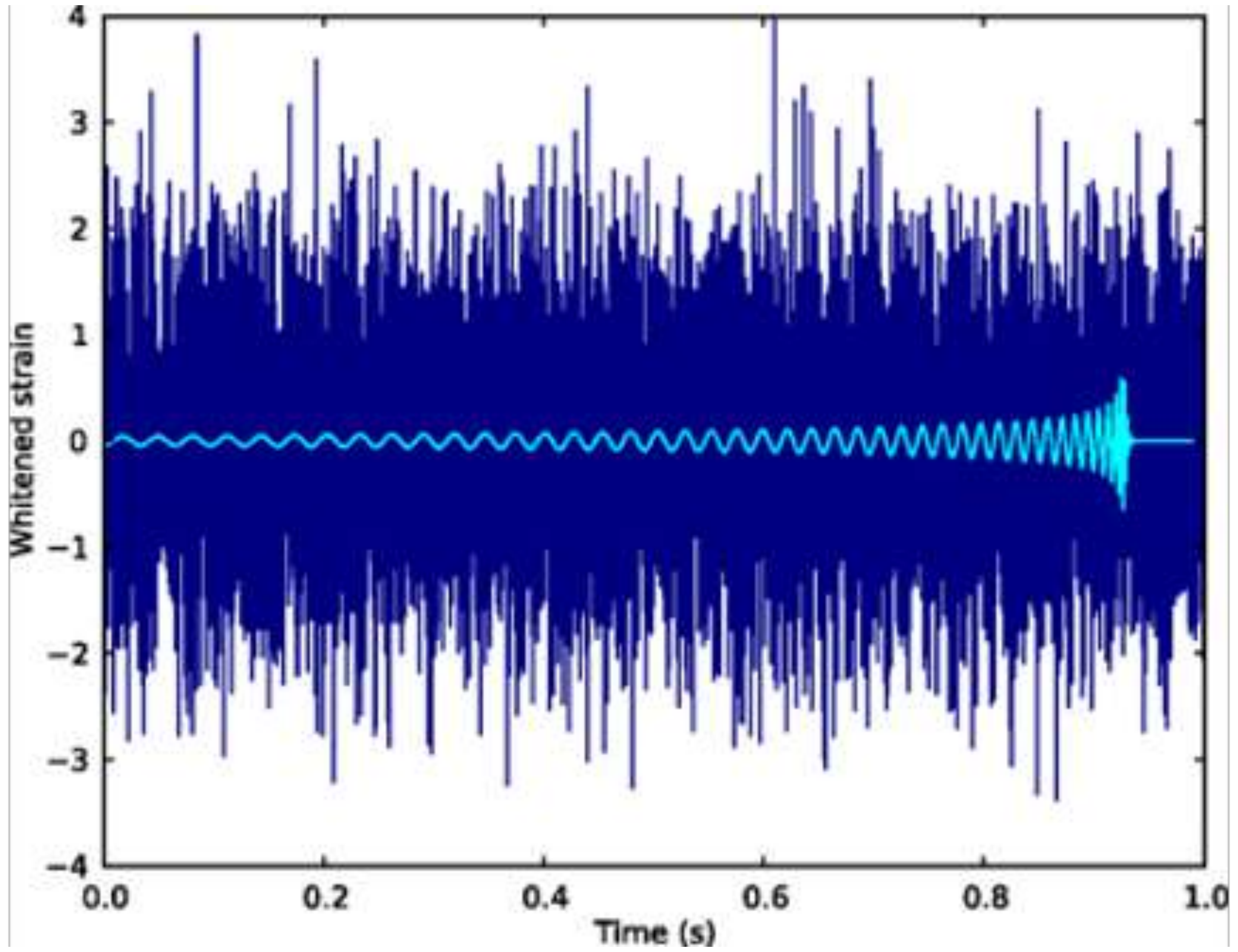
LIGO Interferometry

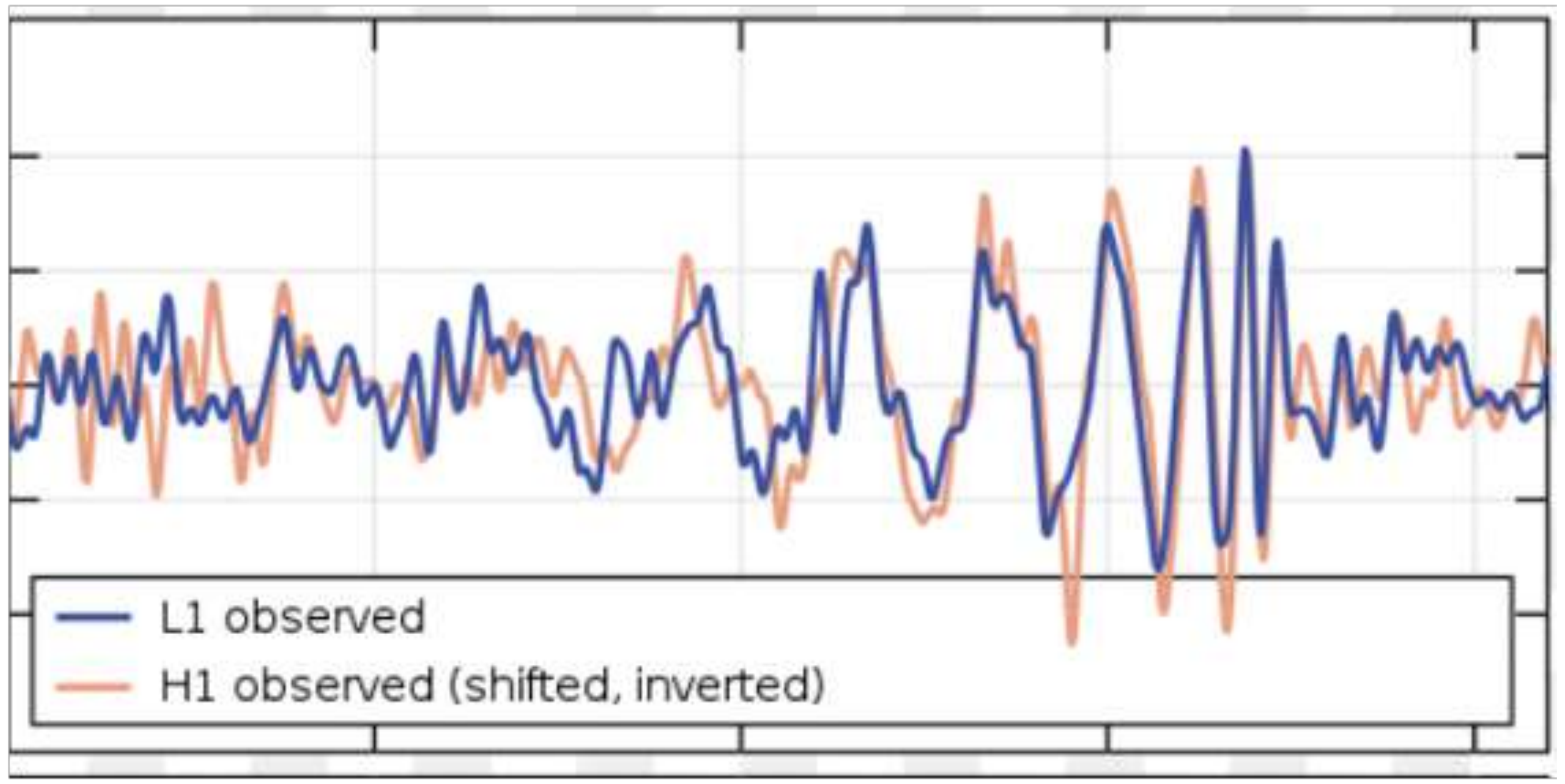
Statistical Methods



Frequency Domain

Match Filtering

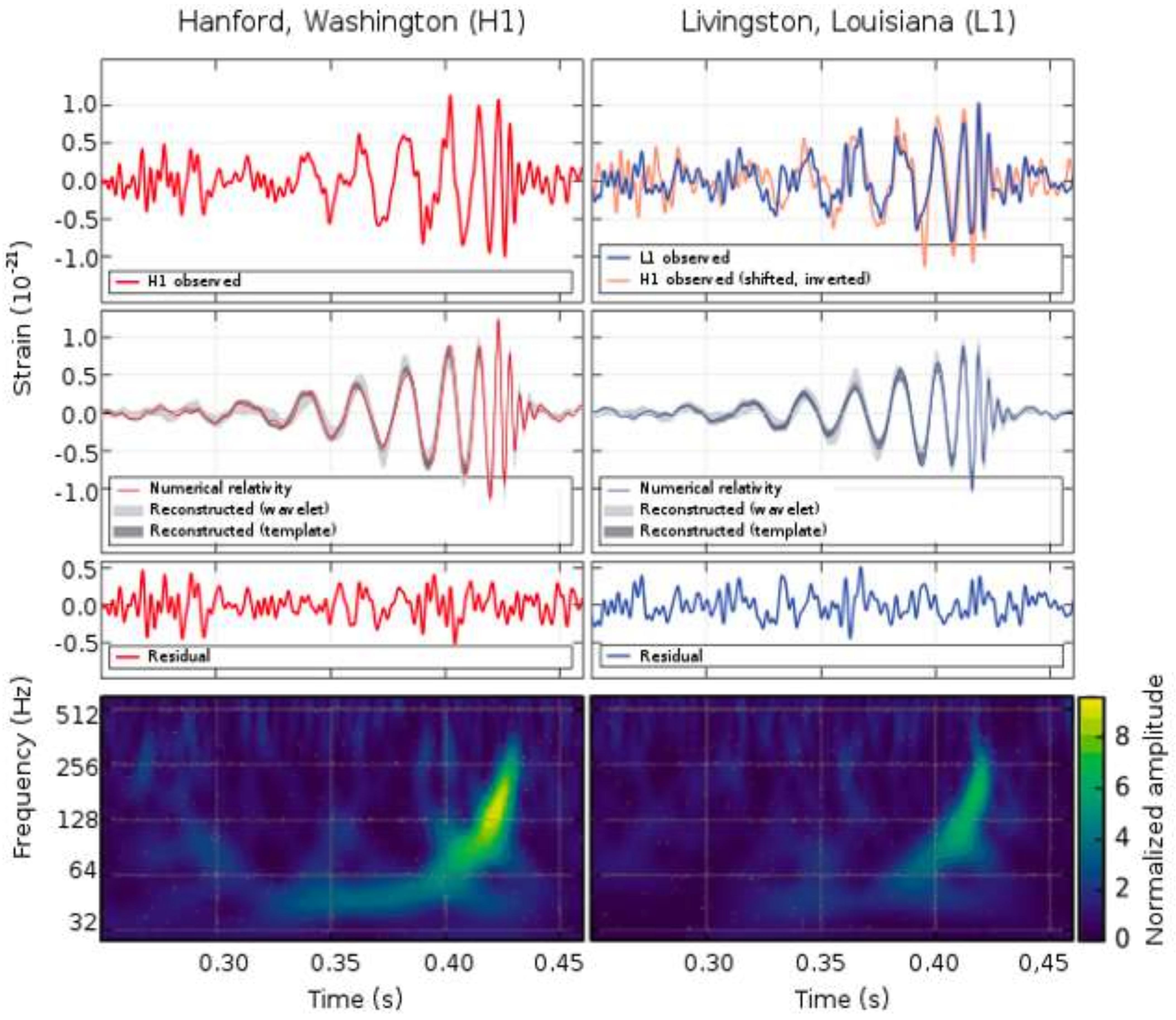




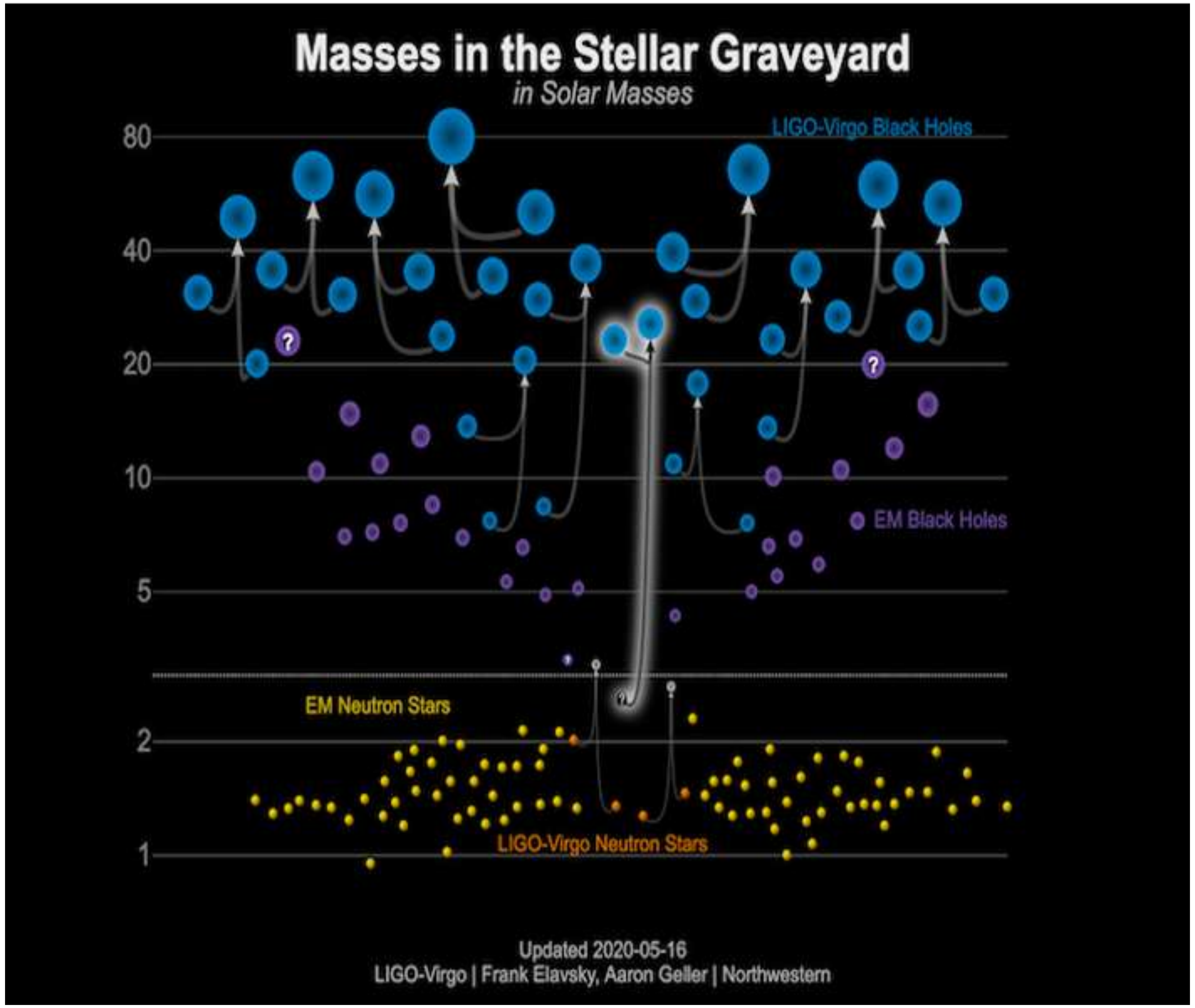
Multiple Detections

LIGO Interferometry

Success!



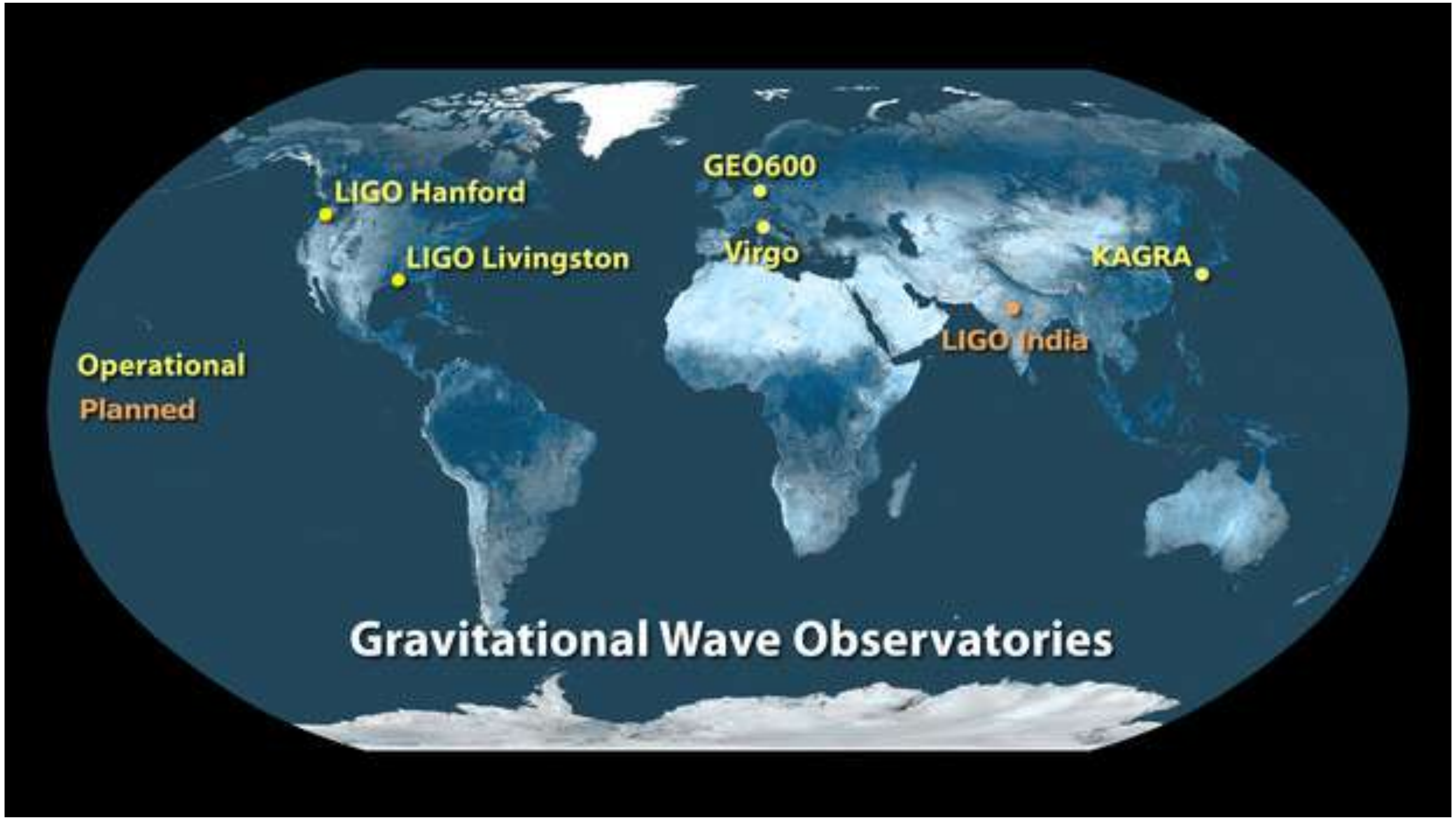
GW150914



Many Other Events After!

LIGO Interferometry

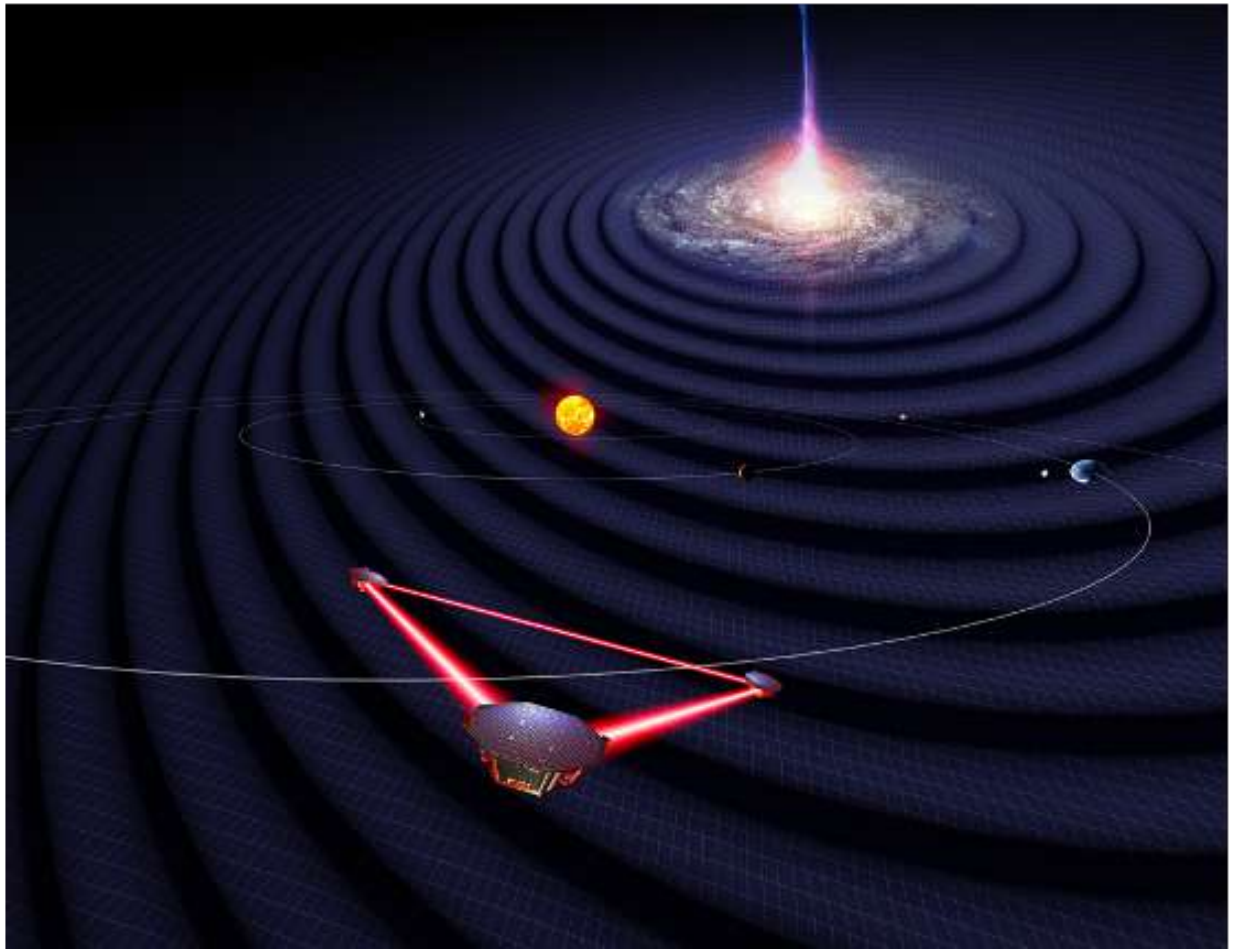
Current Generation Detectors



LISA Interferometry

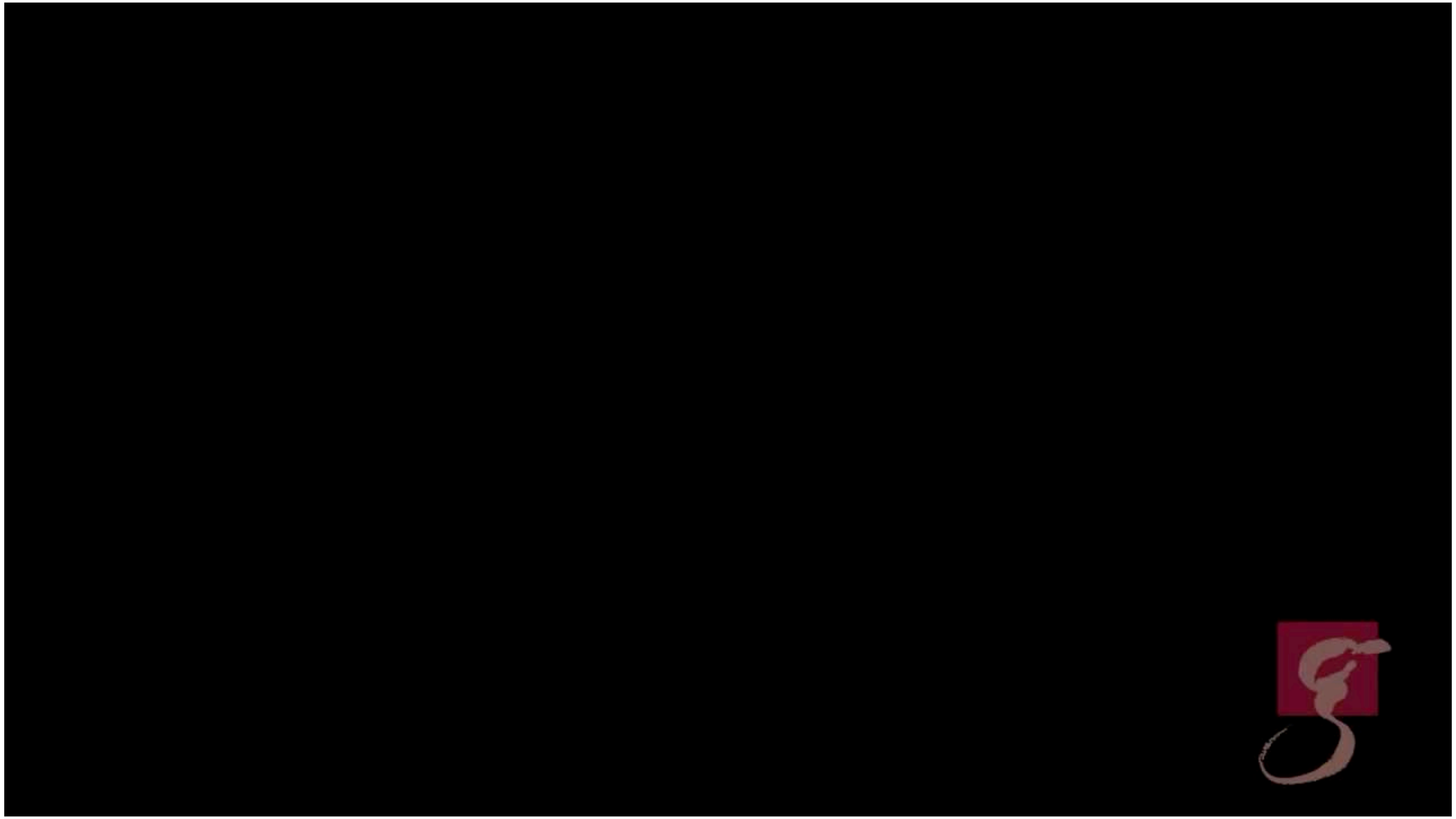
Space-Based Observatory

- Seismic activity limits detecting <1 Hz GWs w/ LIGO
- Can find mHz GWs w/ space based detector
- More event types: larger BBHs, white dwarf binaries, objects falling into SMBH
- “Pathfinder” proof of concept successful in 2017
- Fully funded, shooting for ~2030’s



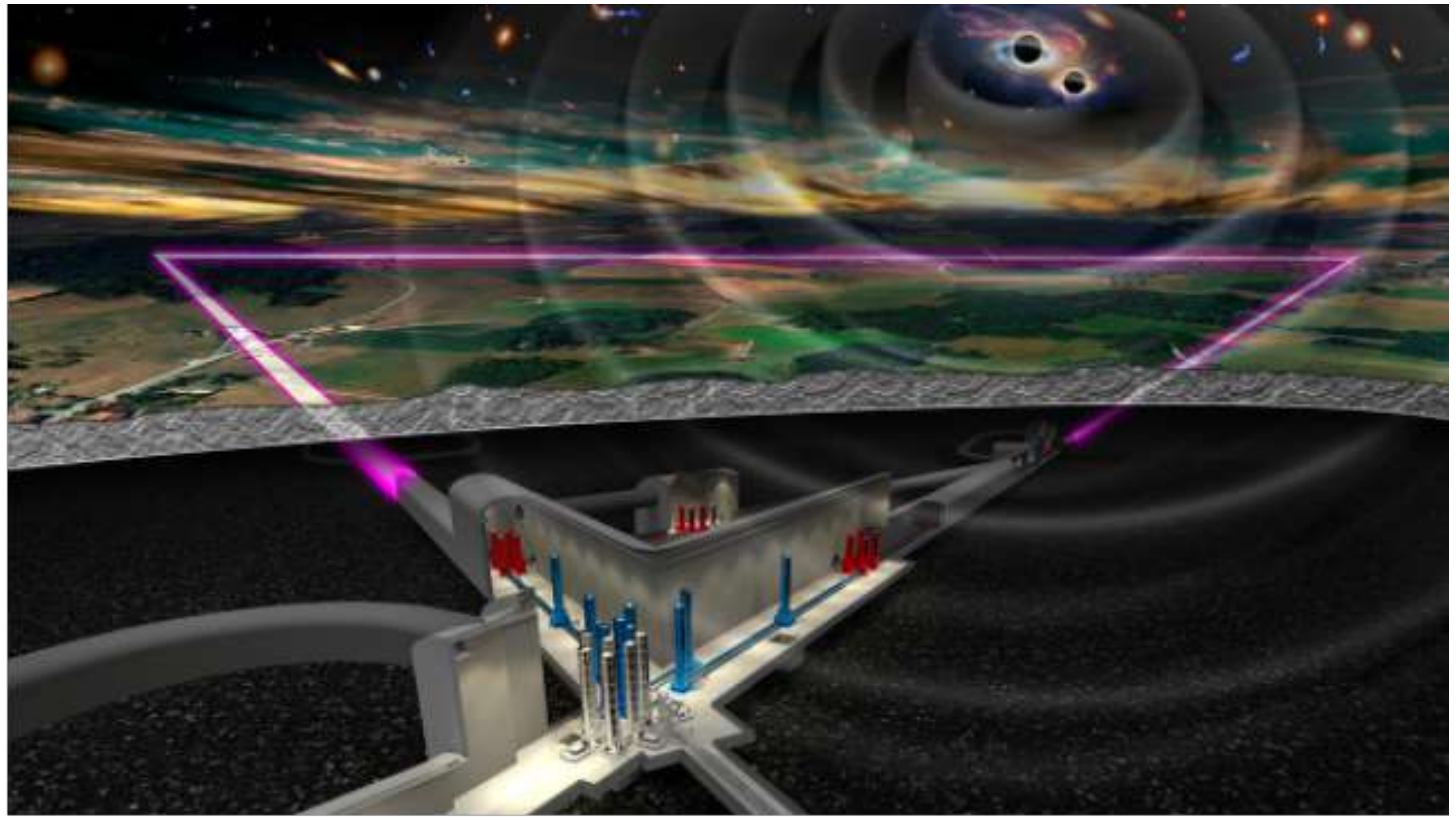
LISA Interferometry

Massive Scale



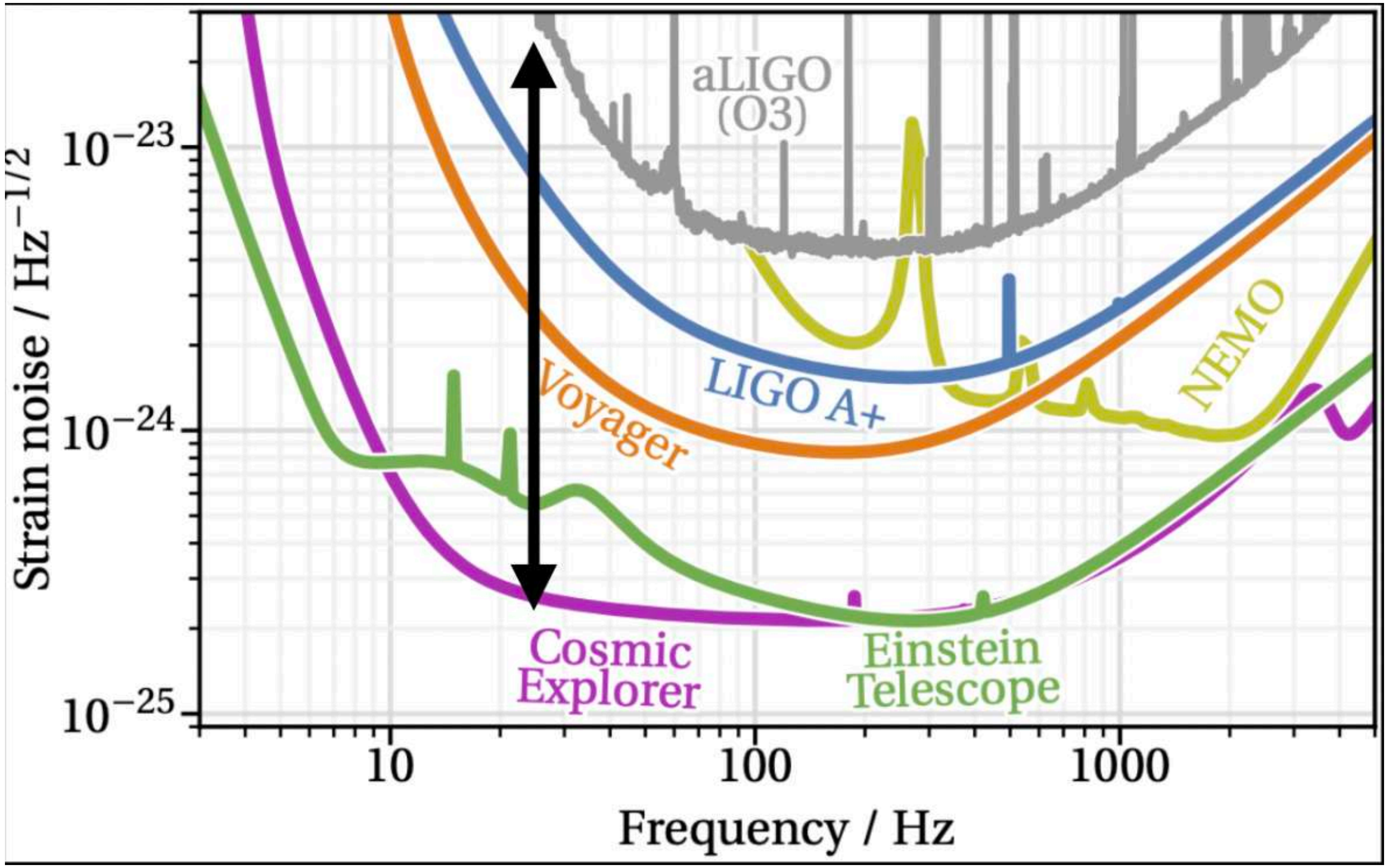
Next Generation Detectors

Cosmic Explorer (US): 40 km x 40 km



Einstein Telescope (EU)

Next Generation Detectors



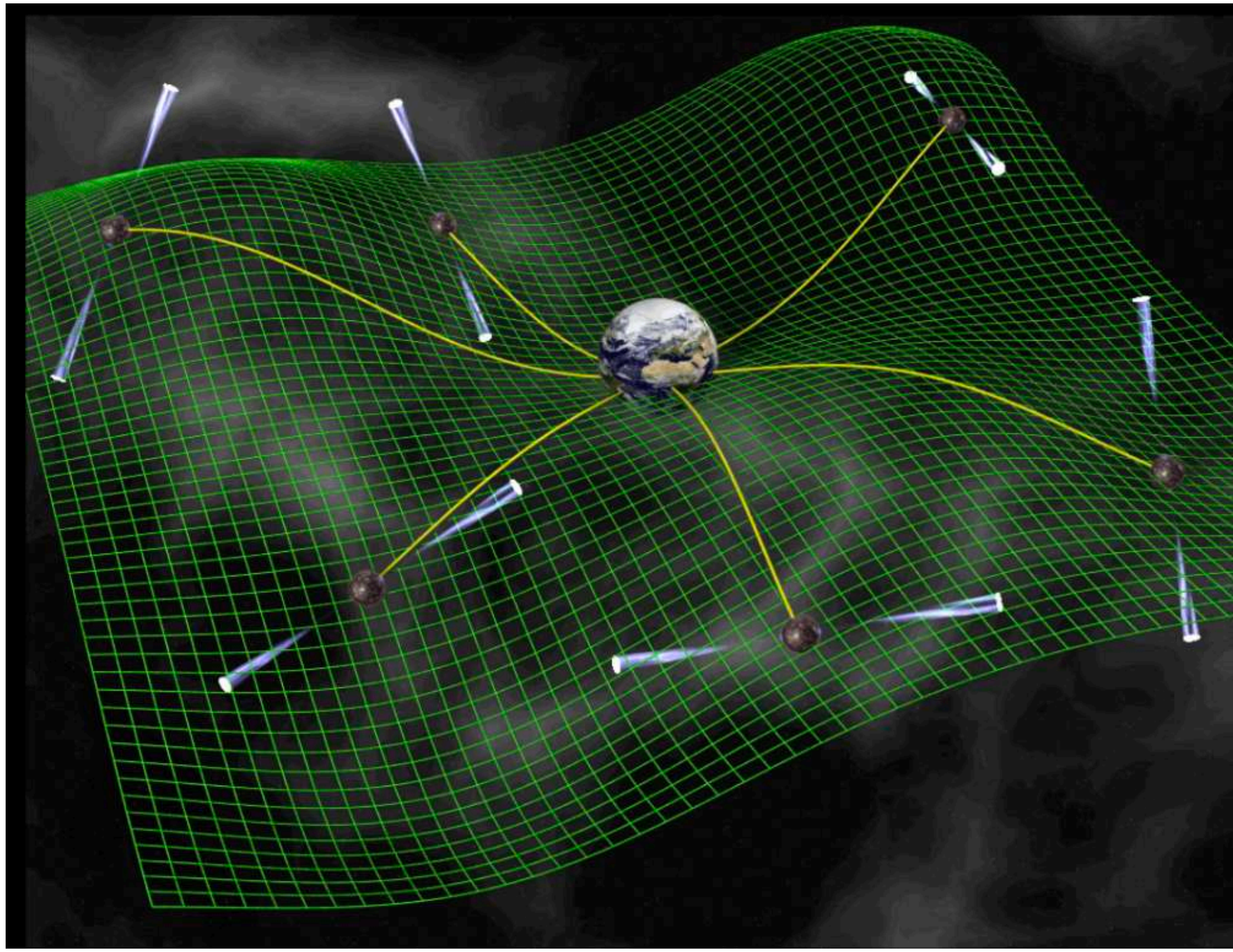
Sensitivities

Part II: Low Frequency Gravitational Waves (“Traditional” Astronomy)

Pulsar Timing Arrays

Introduction

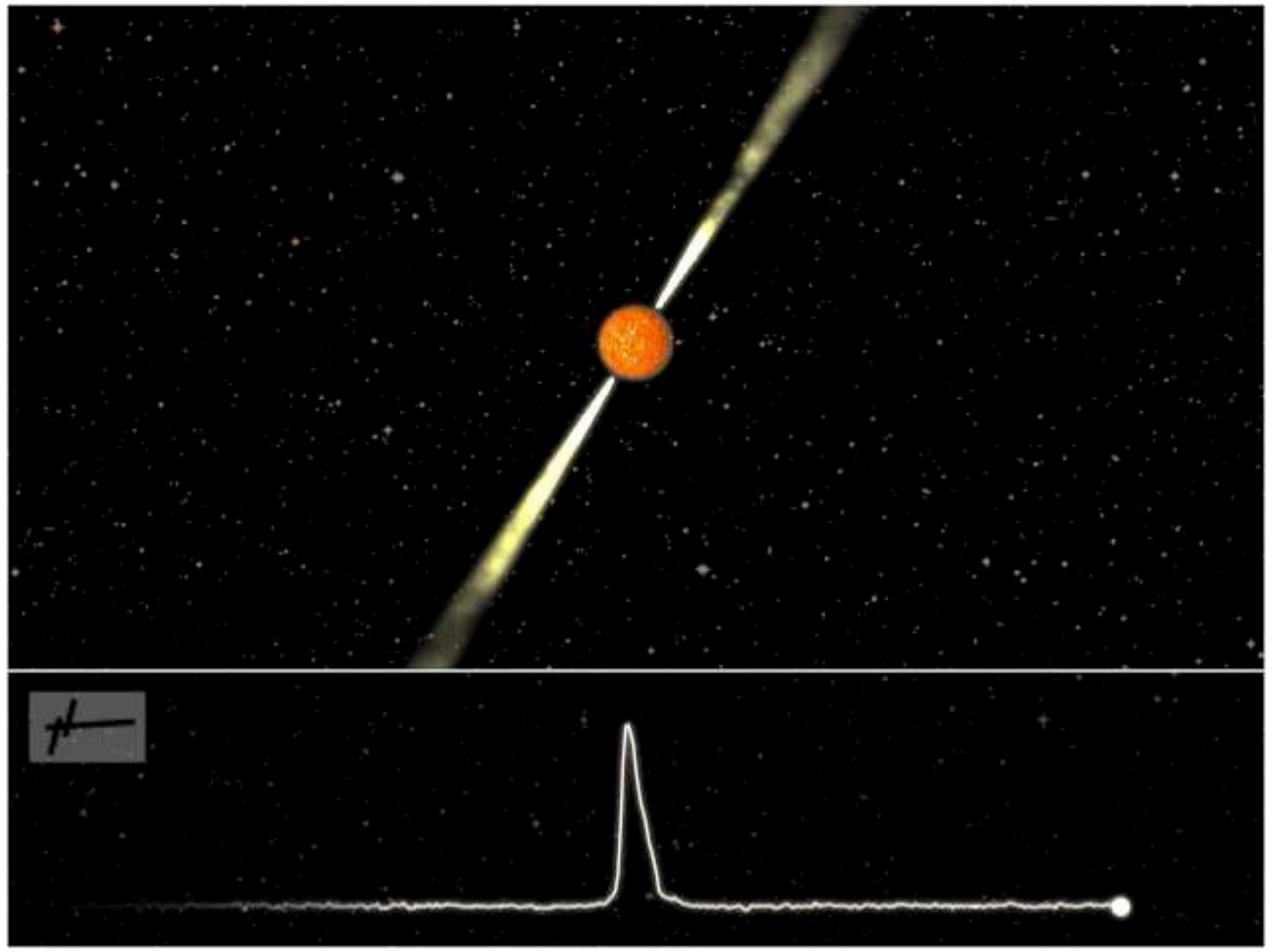
- GWs produced by SMBHBs have frequencies ~nHz scale
- Interferometers have no chance of detecting this
- GWs affect space -> slowly varying GWs affect the time astronomical signals reach us
- Need a very accurate clock for this -> pulsars



Pulsar Timing Arrays

Pulsars

- Pulsars: rotating neutron stars with a characteristic “pulse”
- Pulse from magnetic radiation misaligned w/ rotation (“lighthouse affect”)
- ms period pulsars are highly accurate
- Observed in gamma/radio rays primarily
- Low frequency GWs affect the highly precise period in a detectable manner



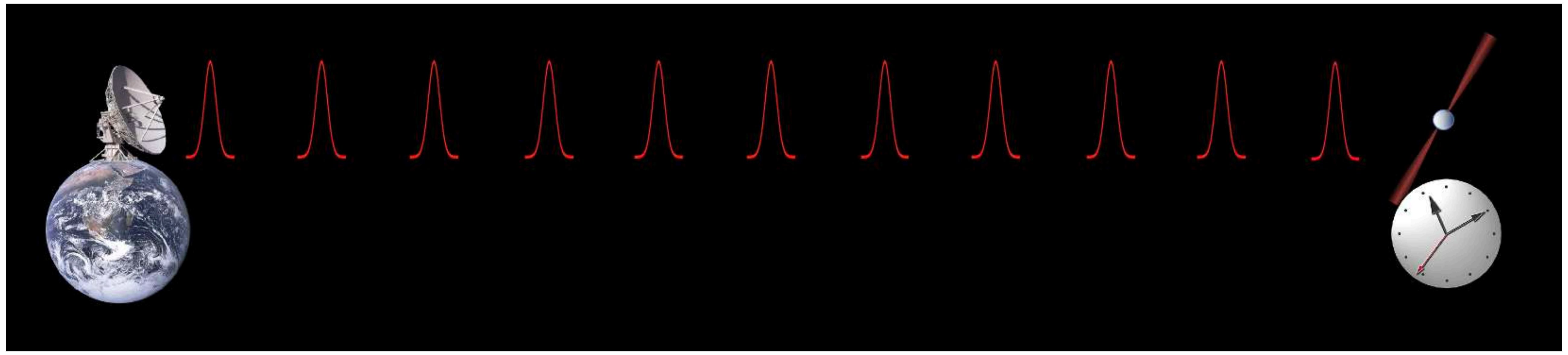
Pulsar Timing Arrays

Pulsar Timing Models

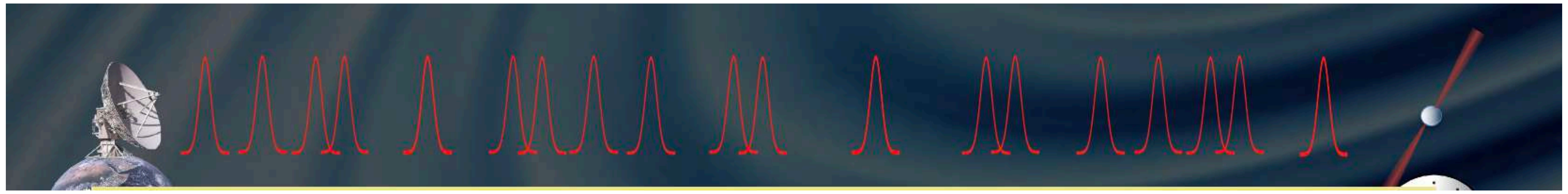
$$t_{emit} = t_{arriv} - \Delta t_{GW} - \Delta t_{other}$$

Arrival Time vs Emitted Time

- Because of the consistent period, we have an model of the expected arrival times given the original arrival time.
- Can calculate the difference between the expected arrival time (after accounting for other effects) and the measured arrival time
- This should give evidence of GW timing changes.



Timing Model (no GWs)

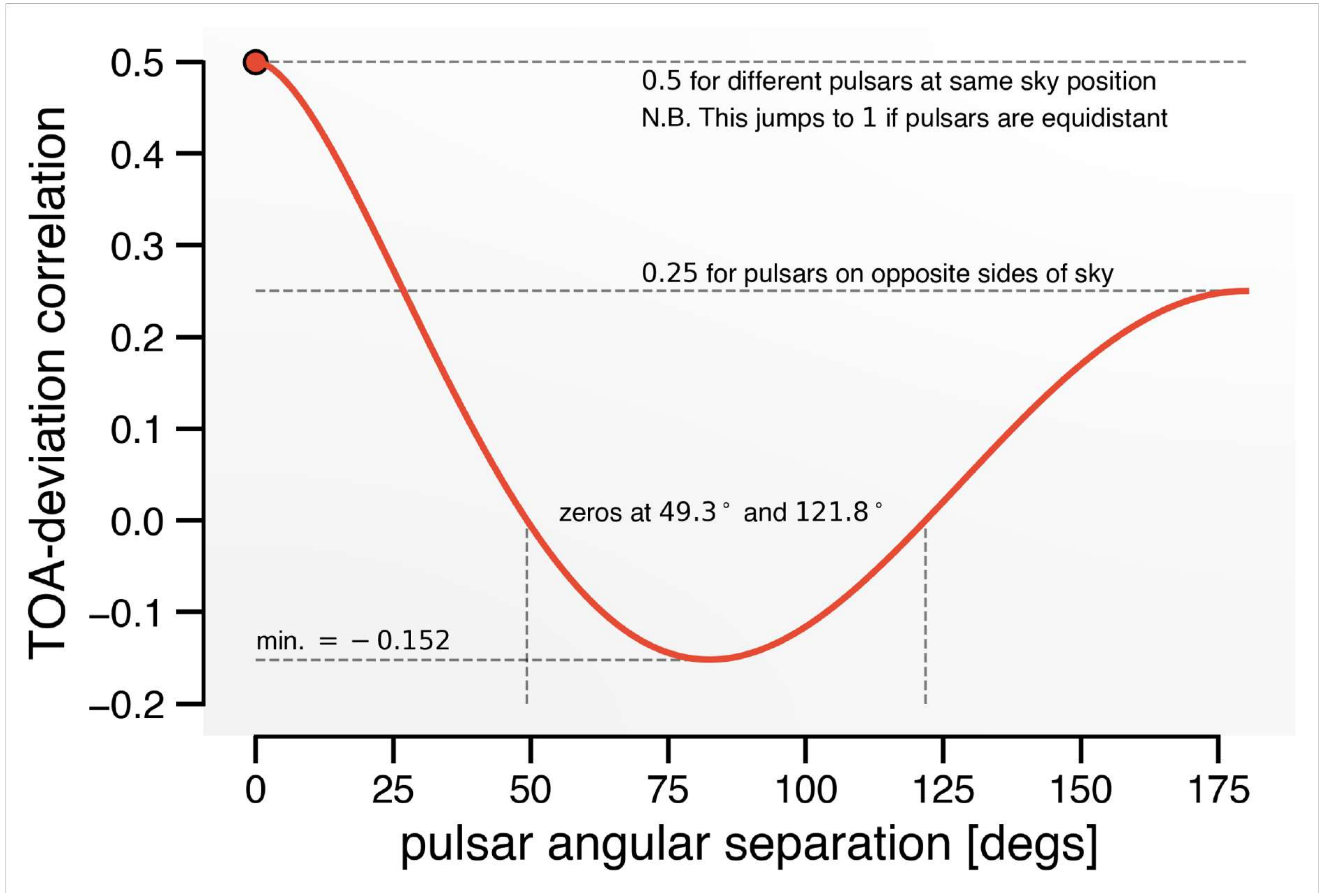


Signal

Pulsar Timing Arrays

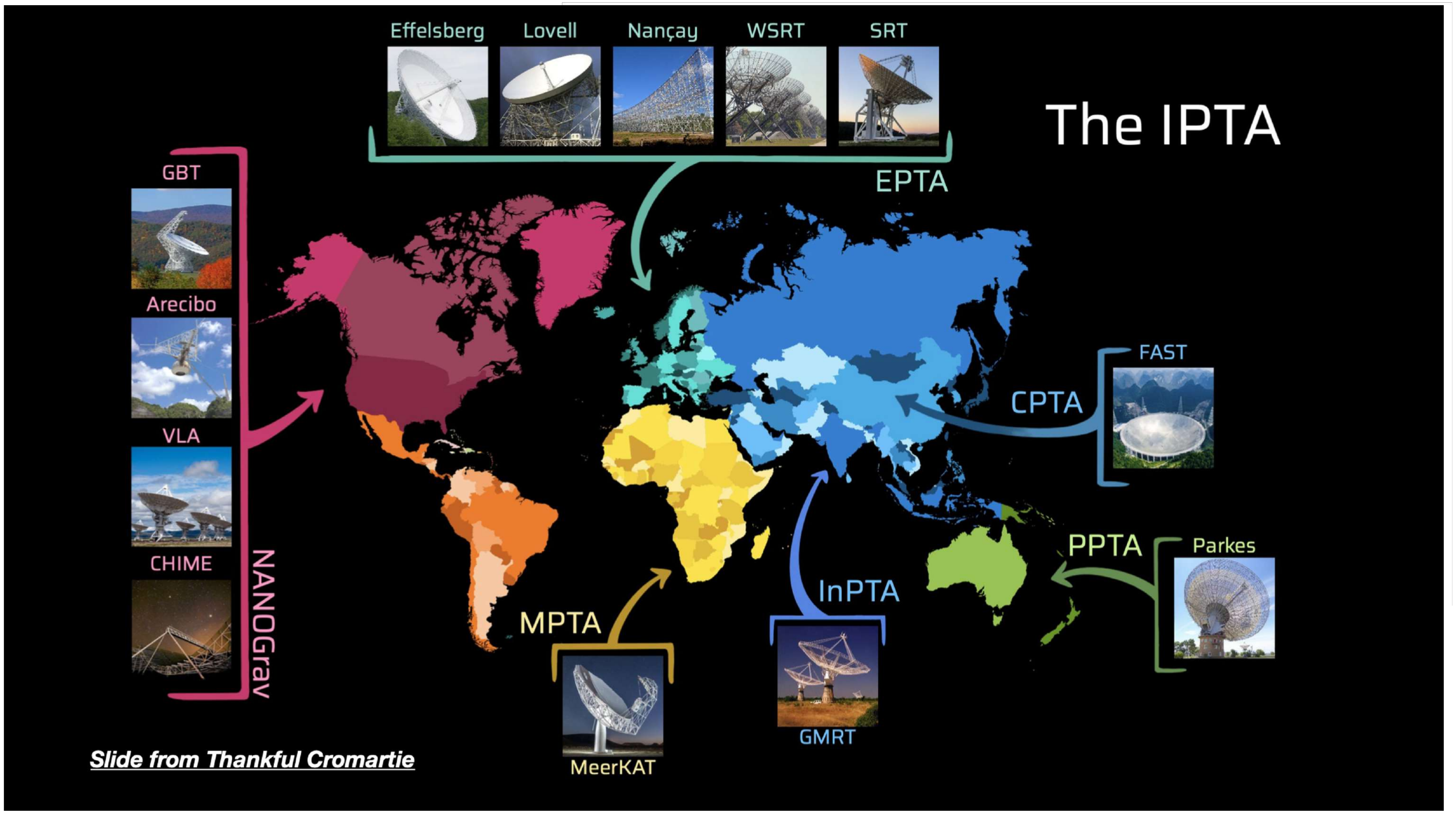
Stochastic GWs

- Not enough information from a single pulsar or single GW
- Look for correlations between pulsars to look for evidence of GWs produced stochastically
- Can derive the “Hellings-Down” curve between separation and timing deviation



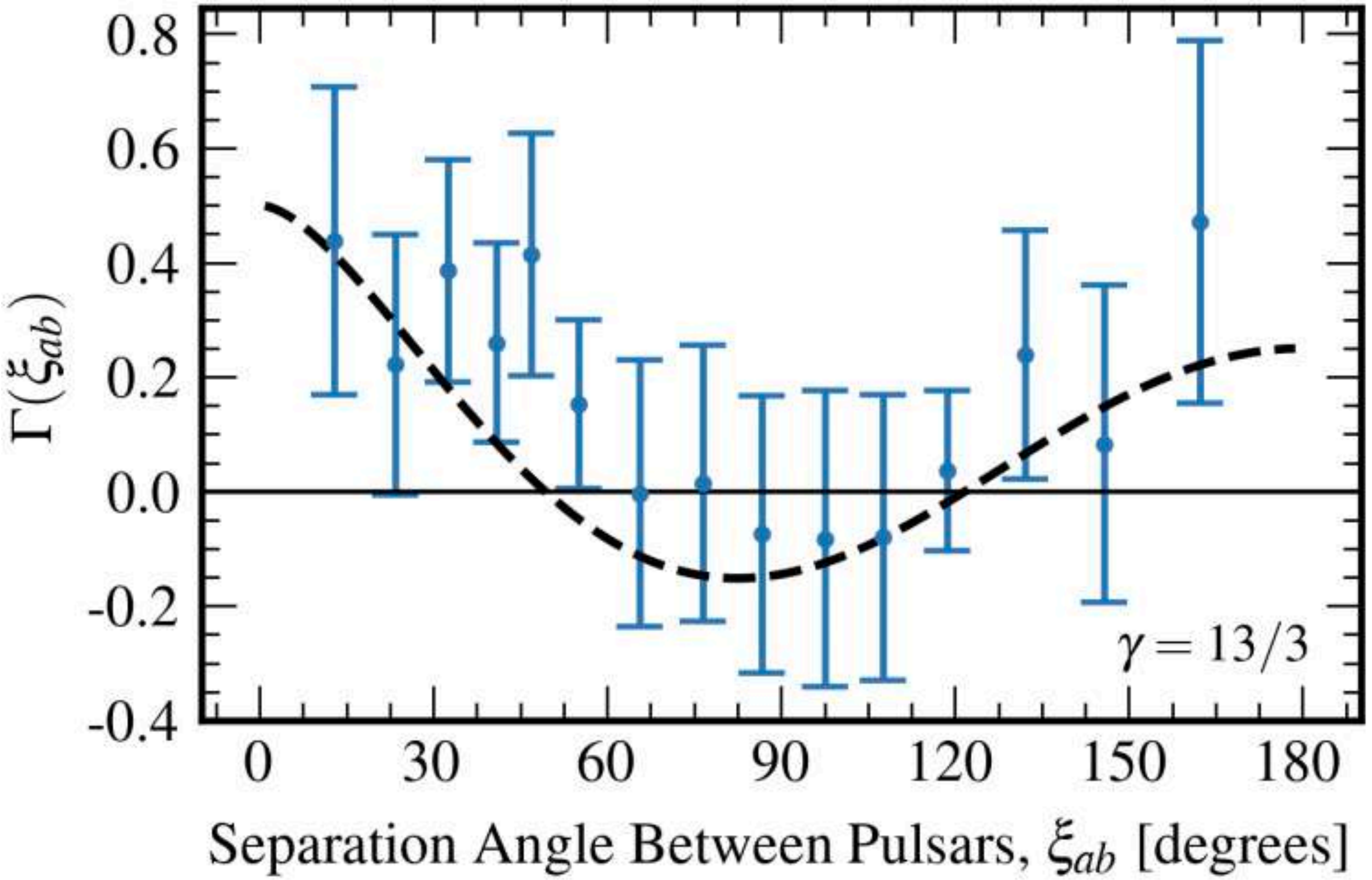
Pulsar Timing Arrays

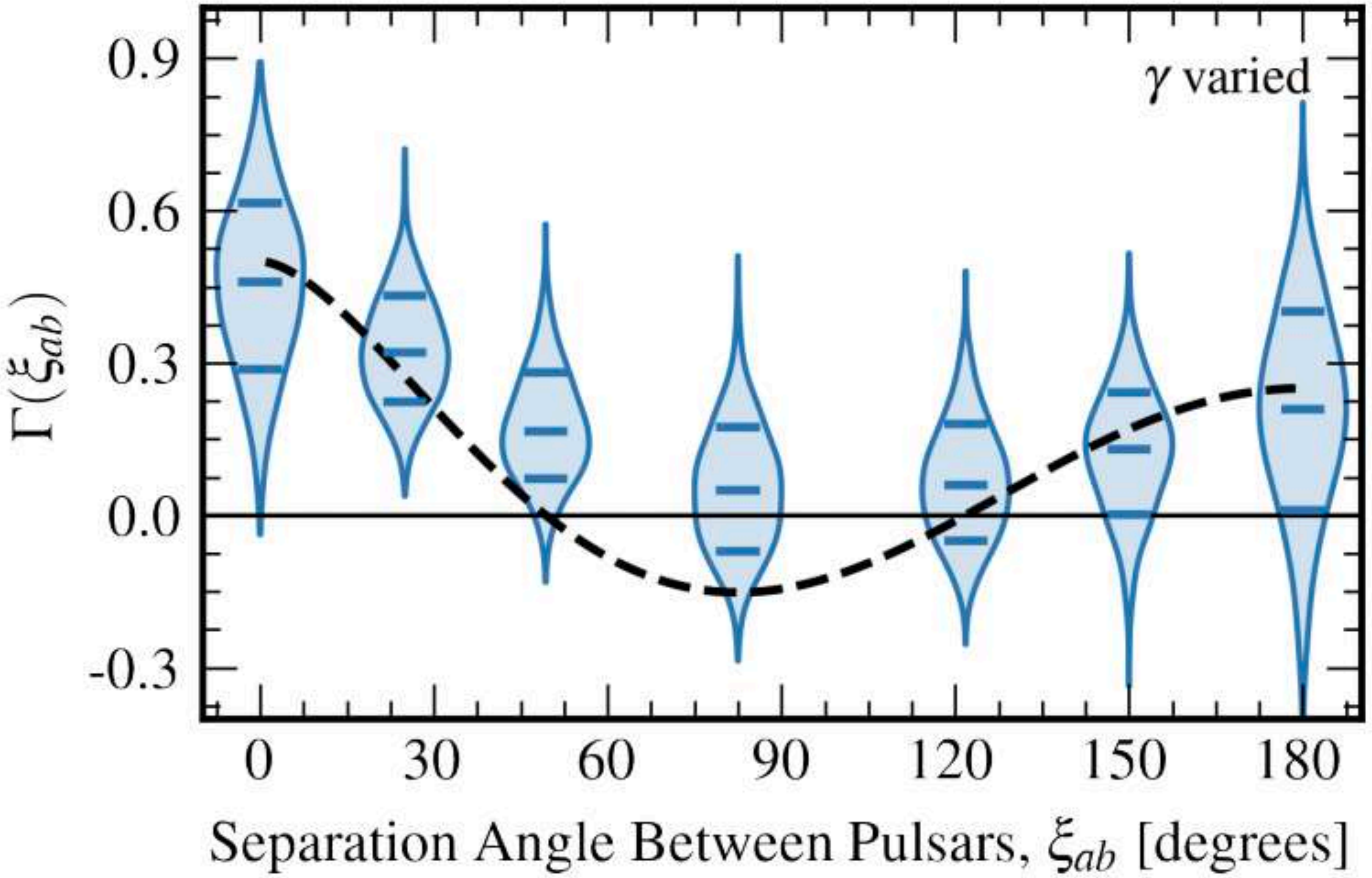
Telescope Network



Pulsar Timing Arrays

Success!

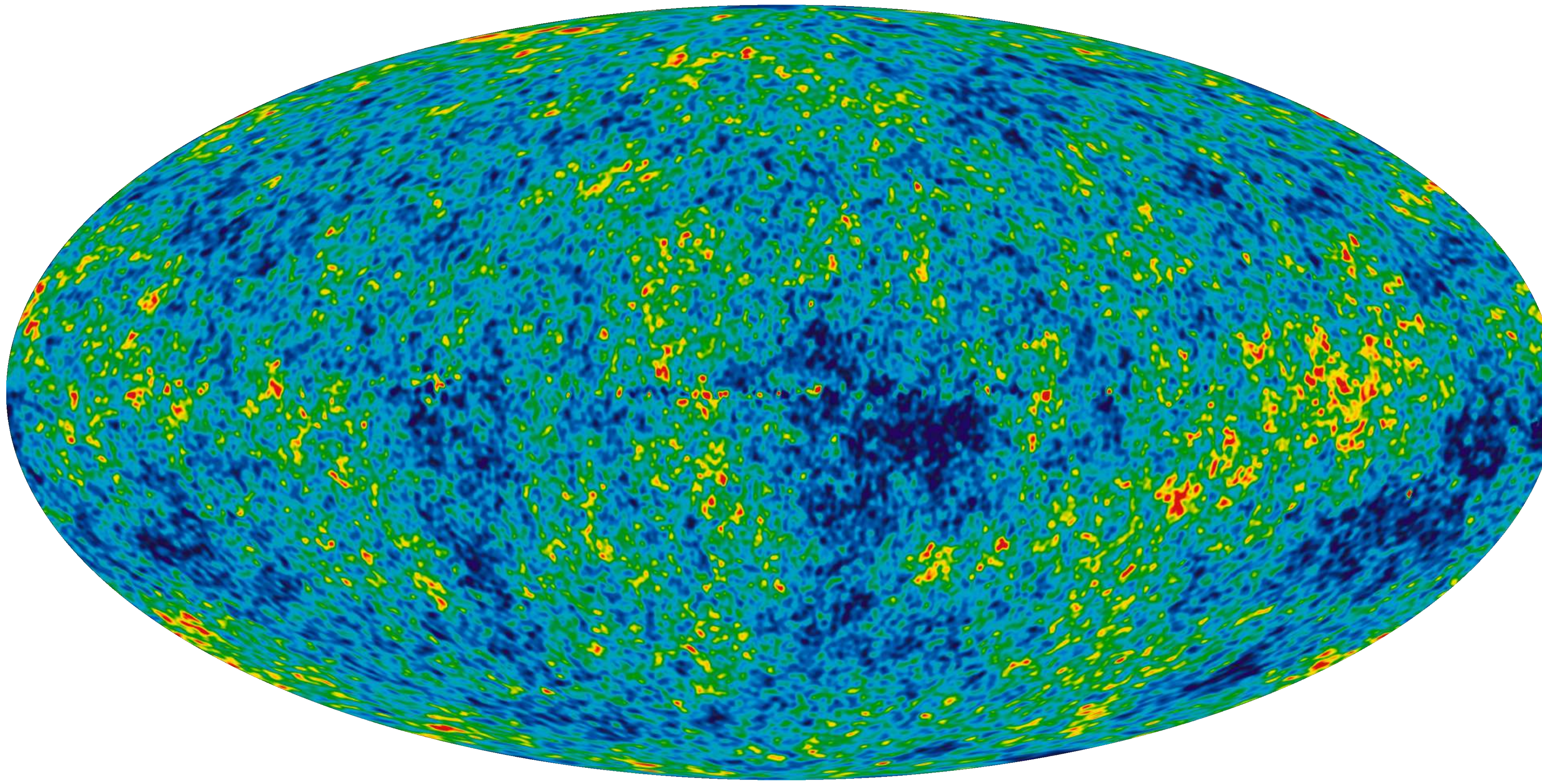




CMB Polarization

Primordial Gravitational Waves

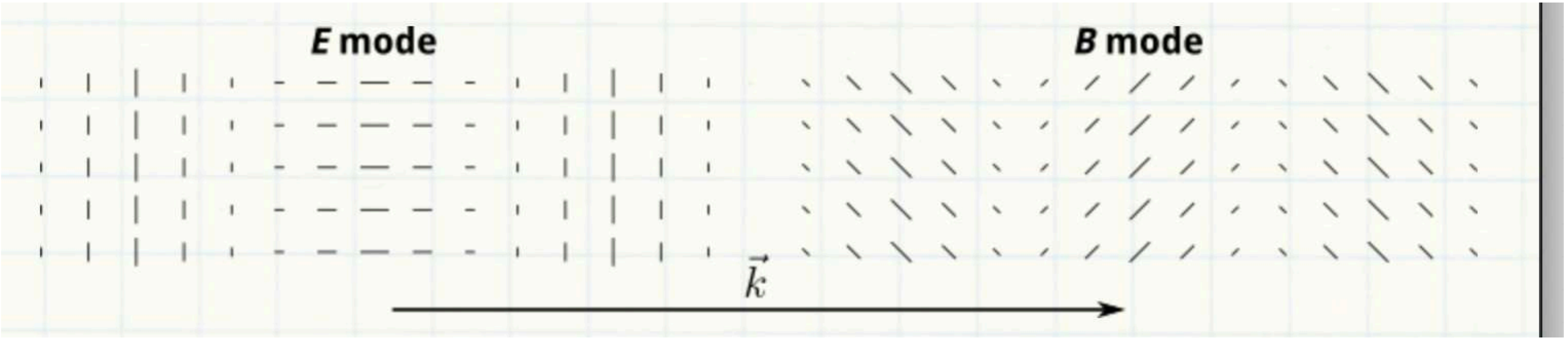
- Predict GW background from primordial universe -> inflation
- Some have timescales at age of universe
- Only way to detect these through CMB polarization
- Early GW's should leave a unique "imprint" on the polarization, deviation from isotropies



CMB Polarization

Polarization

- Polarization of CMB can be broken-down into E and B modes
- Not electric/magnetic field, called such because they are mathematically analogous
- Early universe density changes dominate anisotropies but only affect E modes
- B mode polarization = “smoking gun” of GWs



CMB Polarization

No Evidence Yet :(

Caltech

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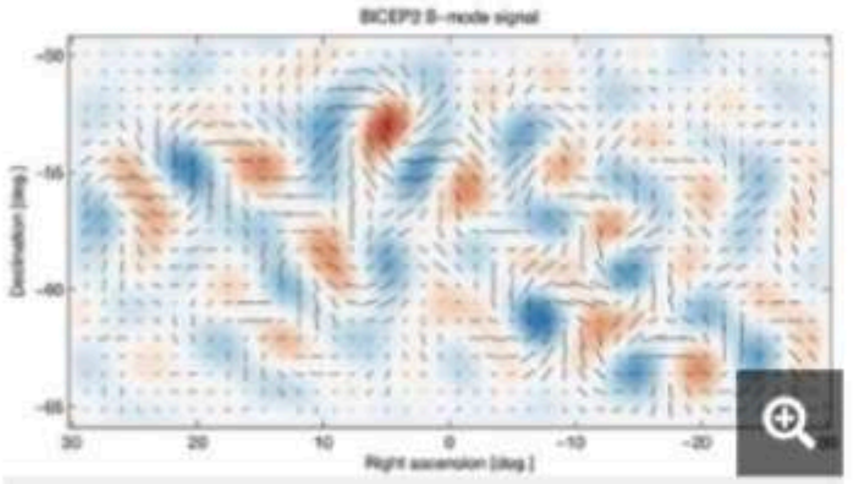
BICEP2 Discovers First Direct Evidence of Inflation and Primordial Gravitational Waves

March 17, 2014

Astronomers announced today that they have acquired the first direct evidence that gravitational waves rippled through our infant universe during an explosive period of growth called inflation. This is the strongest confirmation yet of cosmic inflation theories, which say the universe expanded by 100 trillion trillion times in less than the blink of an eye.



Gravitational waves from inflation generate a faint but distinctive twisting pattern in the polarization of the CMB, known as a "curl" or B-mode pattern. Shown here is the actual B-mode pattern

We thought in 2014...

nature

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Published: 30 January 2015

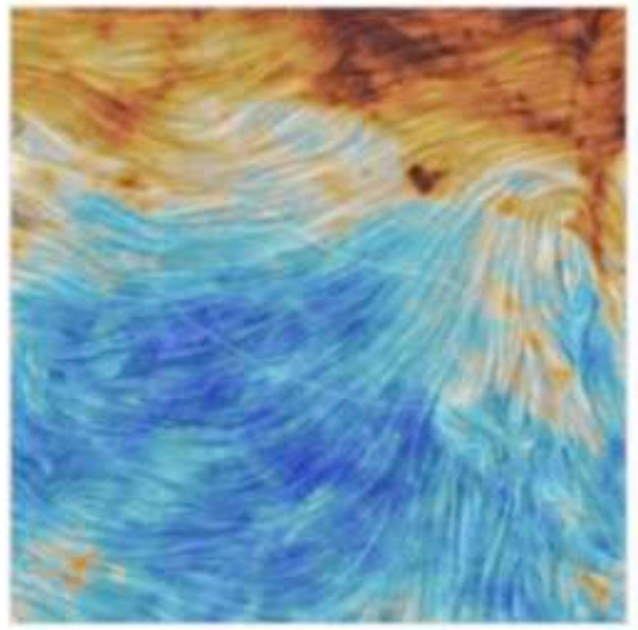
Gravitational waves discovery now officially dead

Ron Cowen

Nature (2015) | Cite this article

1546 Accesses | 4 Citations | 681 Altmetric | Metrics

Combined data from South Pole experiment BICEP2 and Planck probe point to Galactic dust as confounding signal.



but no.

Summary

- GW Physics is a burgeoning field still in its infancy in a lot of ways, with several collaborations across the frequency spectrum: LIGO/LISA, PTA collaborations, CMB collaborations, etc.
- In the > 1 Hz range, we can directly measure gravitational wave signals using ground-based interferometry, signals from 1-100 solar mass BBH’s and BNS’s.
- In the mHz range, we expect to use space-based interferometry to detect signals larger BBH’s and merging white dwarves.
- In the nHz range, PTA analyses have successfully detected a stochastic gravitational wave background likely from merging SMBHBs.
- We hope to find an imprint of primordial GW’s (timescales of the universe’s age) in the B-modes of the CMB polarization.


THE SPECTRUM OF GRAVITATIONAL WAVES
esa
Observatories & experiments
Ground-based experiment
Space-based observatory
Pulsar timing array
Cosmic microwave background polarisation
Timescales
milliseconds
seconds
hours
years
billions of years
Frequency (Hz)
100
1
10-2
10-4
10-6
10-8
10-16
Cosmic fluctuations in the early Universe
Cosmic sources
Supernova
Pulsar
Compact object falling onto a supermassive black hole
Merging supermassive black holes
Merging neutron stars in other galaxies
Merging stellar-mass black holes in other galaxies
Merging white dwarfs in our Galaxy
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