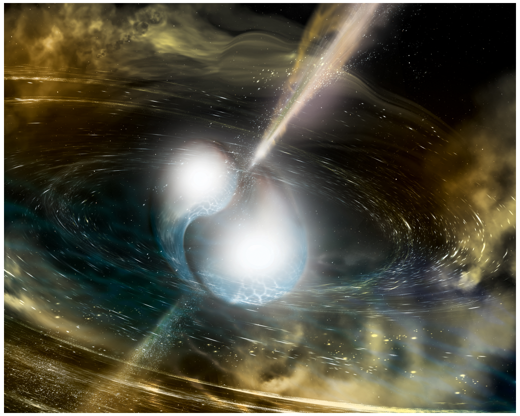


The direct detection of gravitational waves: Astrophysics, fundamental physics, and cosmology

Nikhef

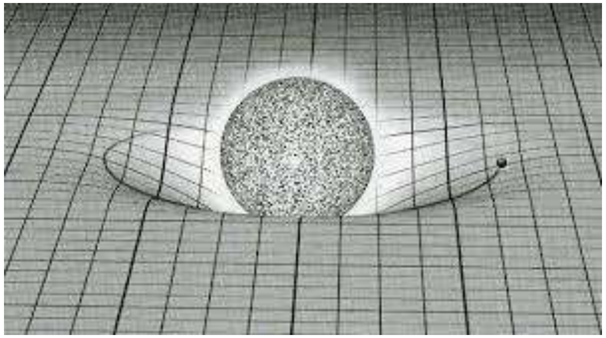
LIGO VIRGO

rijksuniversiteit groningen

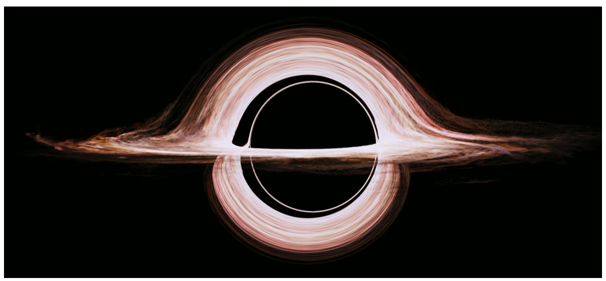
Chris Van Den Broeck

Solvay Workshop: SuGAR 2018, Brussels, 23-26 January 2018

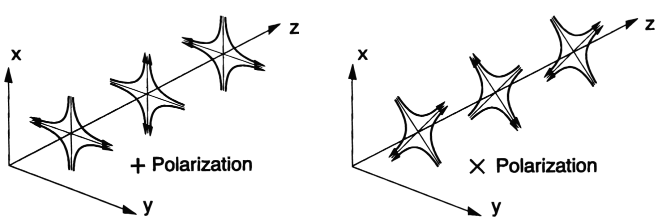
Gravitational waves



- 1915: Einstein's general relativity
  - Gravity as curvature of spacetime
  - "Matter tells spacetime how to curve, spacetime tells matter how to move

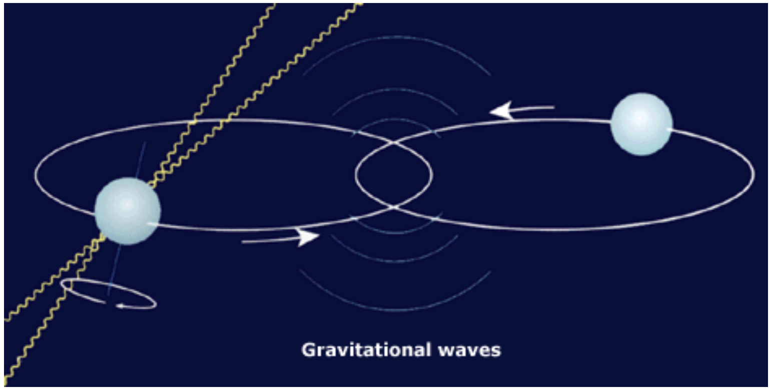


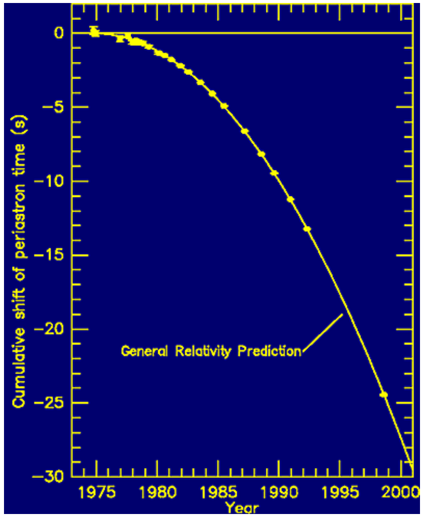
- Black holes
  - Completely collapsed stars
  - Region of spacetime from which nothing can escape



- 1916: Prediction of gravitational waves
  - Ripples in the curvature of spacetime
  - Can be viewed as traveling tidal field
- 2015: First direct detection
  - Nobel Prize in Physics 2017

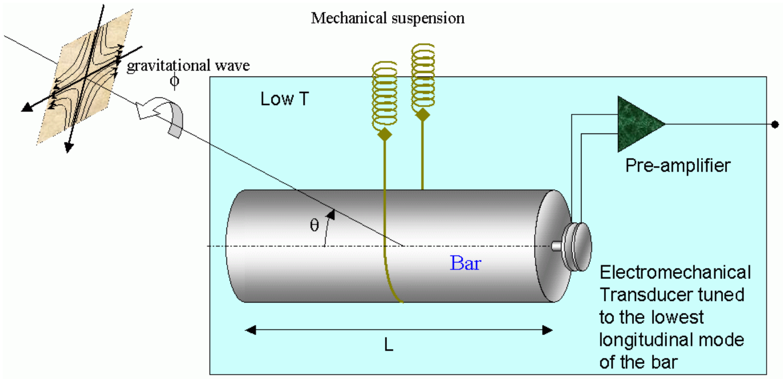
Indirect observations



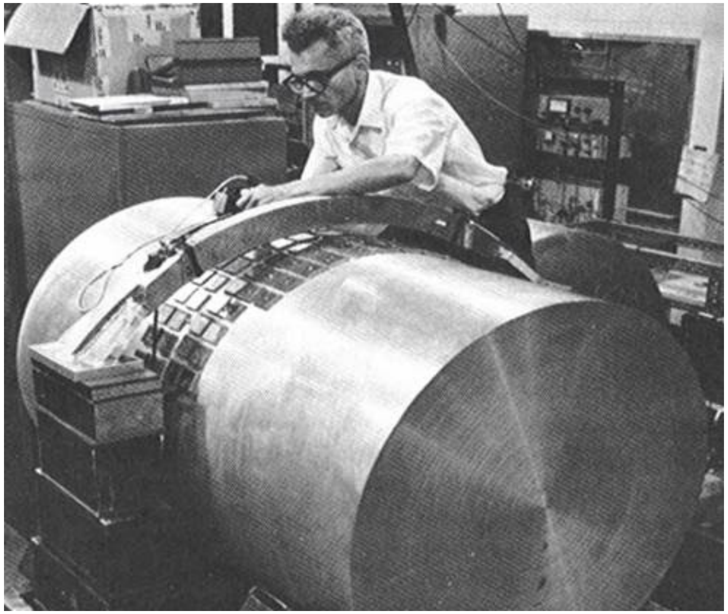


- 1974: Hulse and Taylor discover binary neutron star
- Observed over the course of decades
  - Slow orbital decay
  - Gravitational waves carrying away orbital energy
- Nobel Prize in Physics 1993

Can gravitational waves be observed directly?

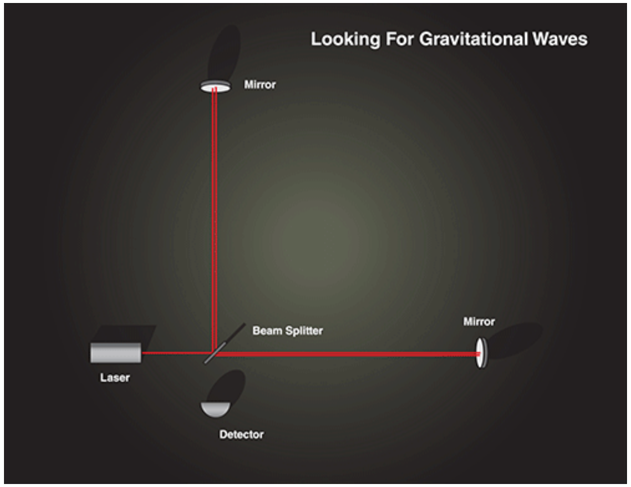


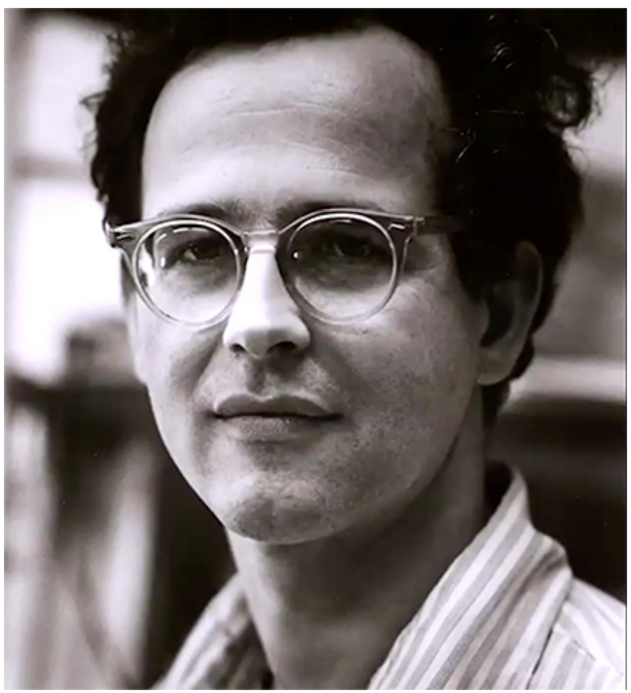
- 1960s: Joseph Weber constructs resonant bar detectors



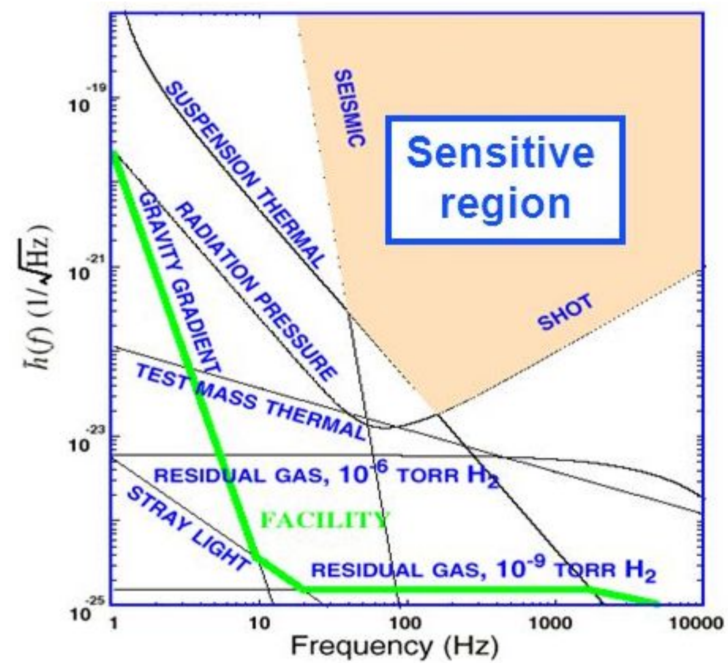
- Detection claims
  - Not reproducible by similar experiments in US, Europe, Japan
  - Theoretical problems, e.g. Milky Way should be losing energy at a noticeable rate

Rainer Weiss and interferometers

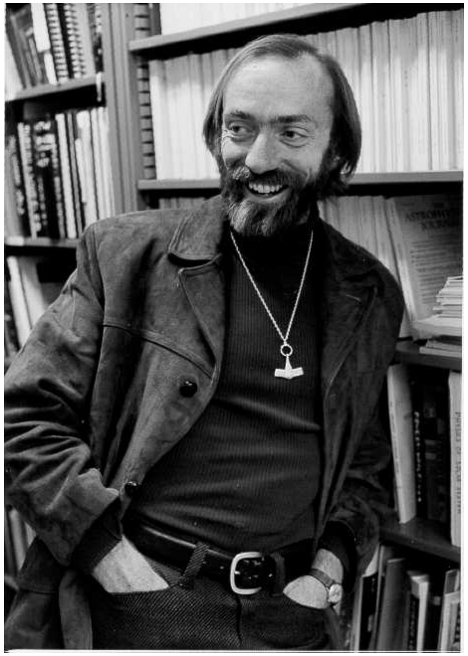




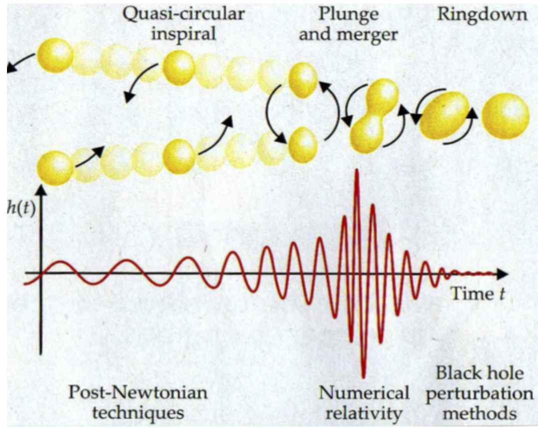
- Laser interferometer
  - Laser beam split in two
  - Both halves travel down “arms”
  - Reflected back
  - If no gravitational waves: destructive interference at the output
- Design study 1971
  - Need to control sources of noise, e.g.
    - Seismic
    - Thermal
    - Photon shot noise



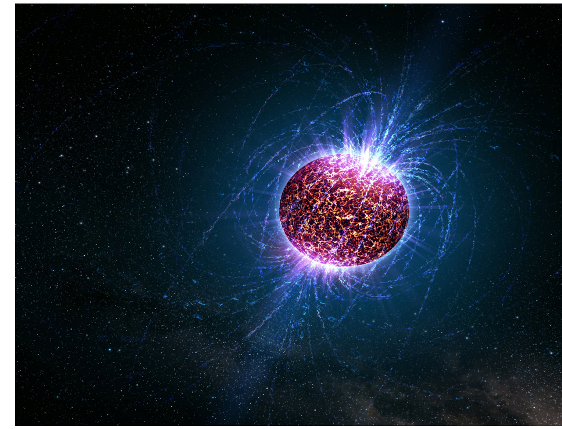
Kip Thorne: Detectable astrophysical sources?



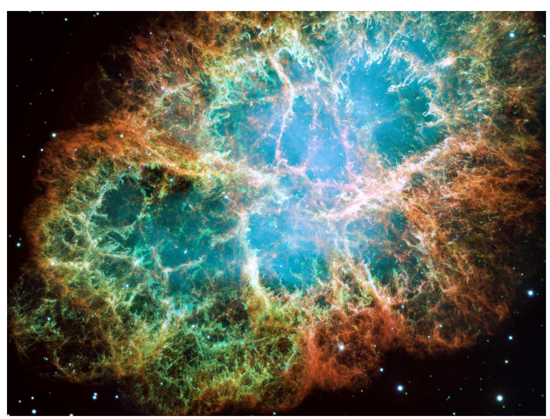
Merging neutron stars, black holes



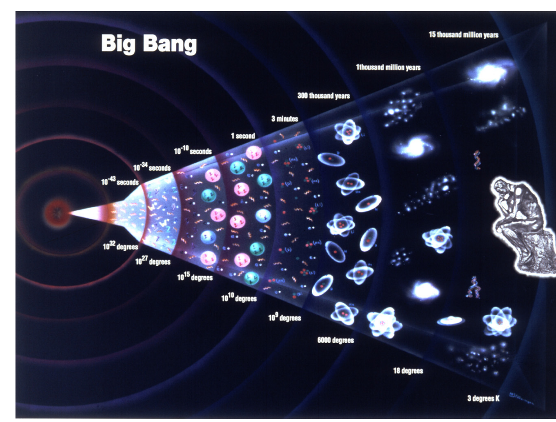
Fast-spinning neutron stars

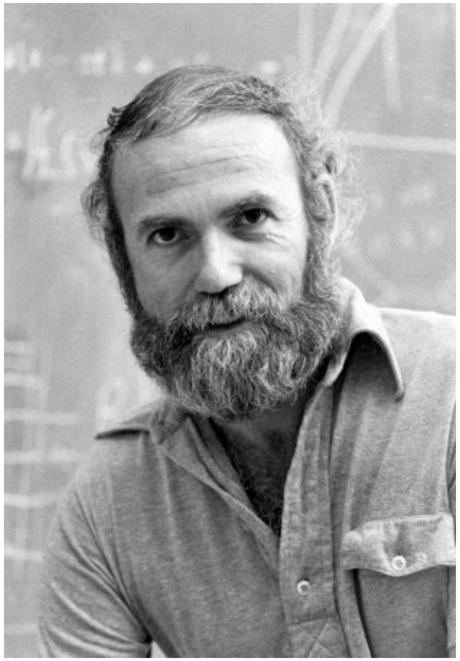


Supernovae



Primordial gravitational waves

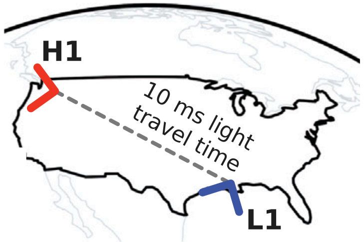




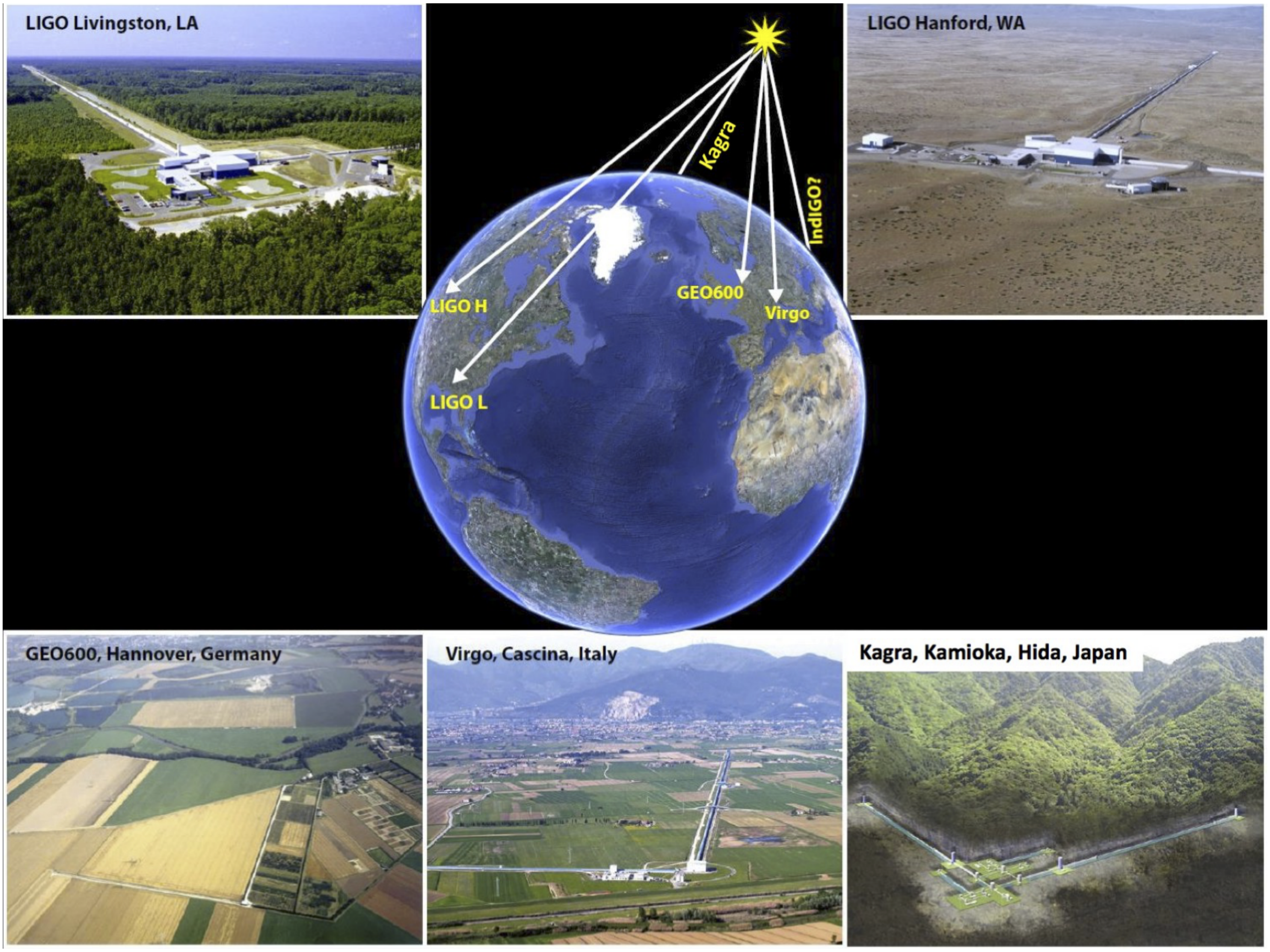
Barry Barish and LIGO

- 1994: Barish starts leading construction of **Laser Interferometer Gravitational-Wave Observatory (LIGO)**
  - Two interferometers in the US
  - Placed 3000 kilometers apart
  - 4 kilometer arms

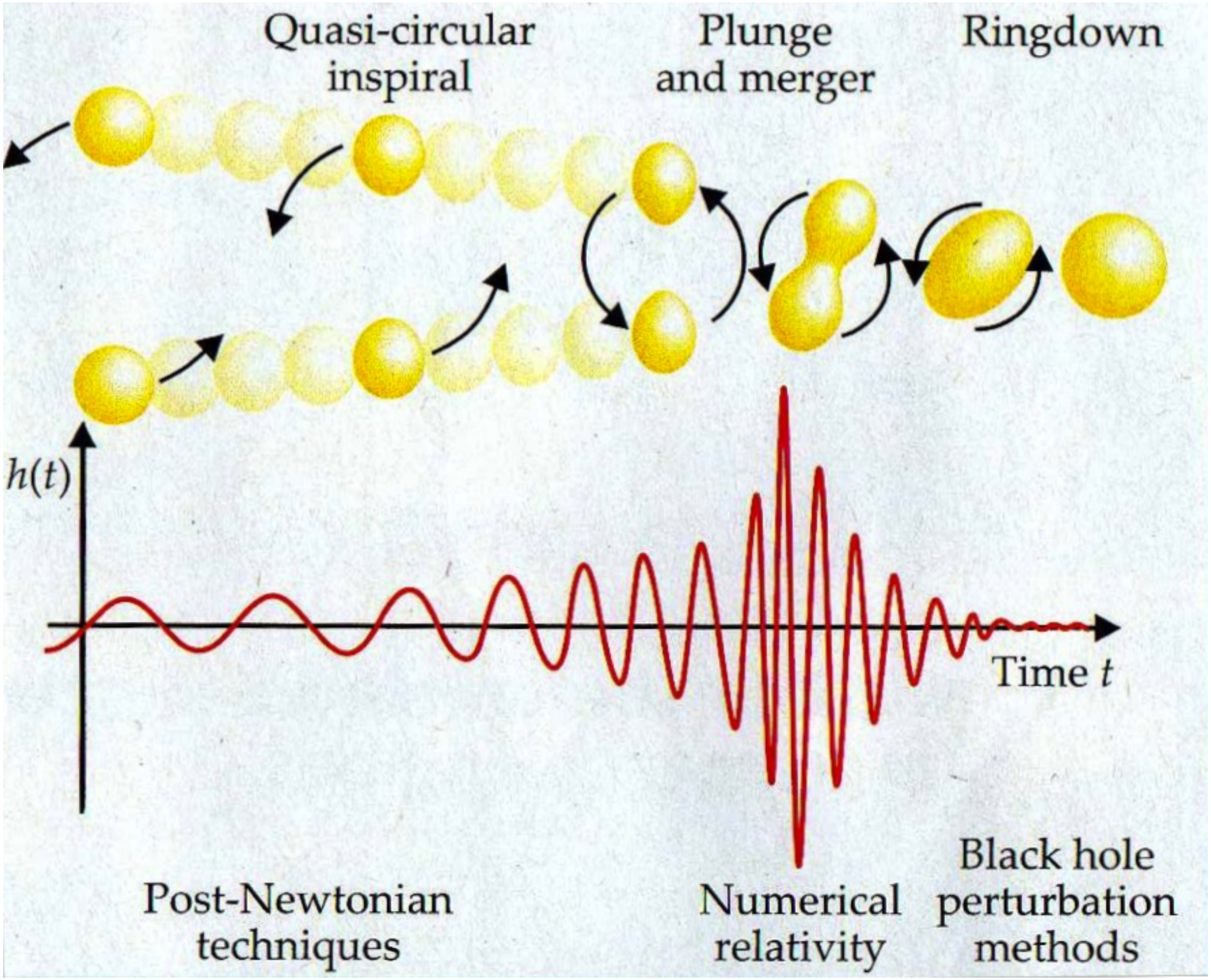
LIGO Hanford (Washington)



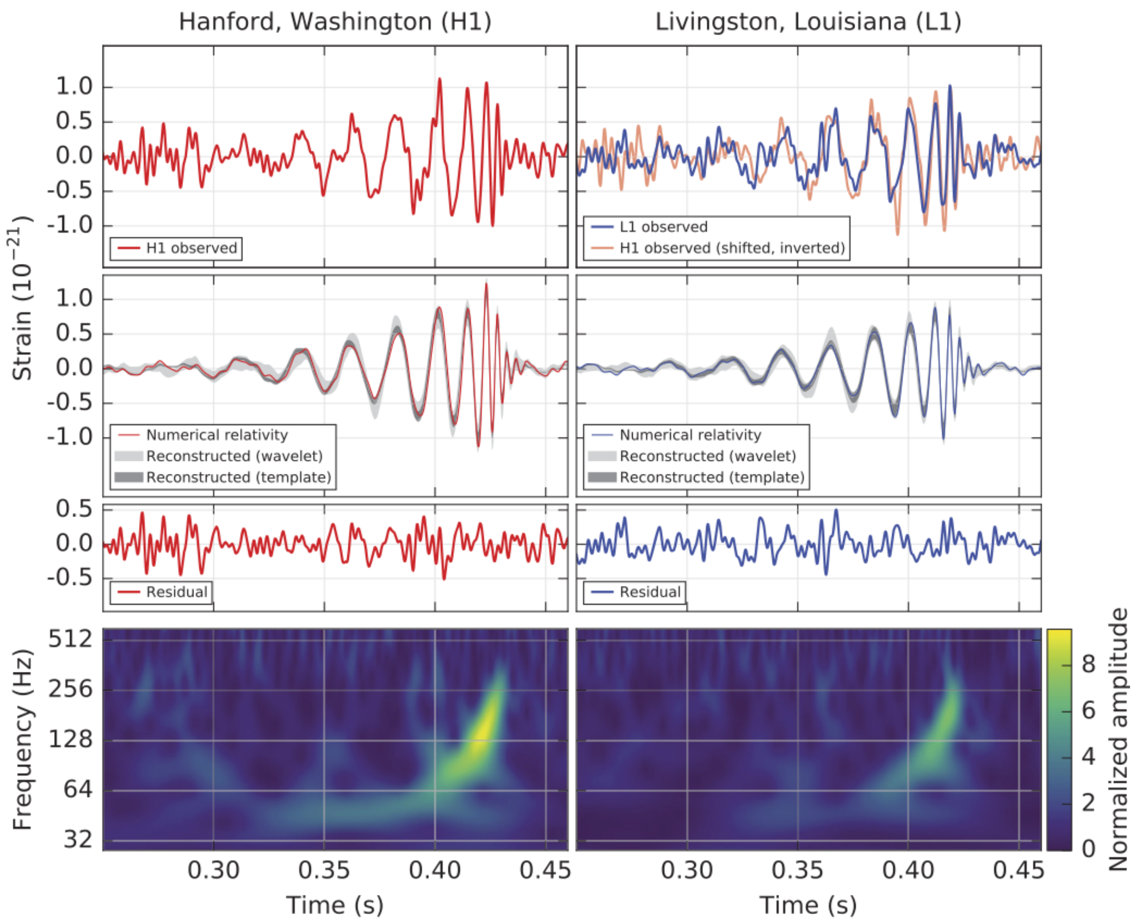
LIGO Livingston (Louisiana)


LIGO Livingston, LA
LIGO Hanford, WA
Kagra
IndIGO?
LIGO H
GEO600
Virgo
LIGO L
GEO600, Hannover, Germany
Virgo, Cascina, Italy
Kagra, Kamioka, Hida, Japan

The coalescence of binary neutron stars and black holes



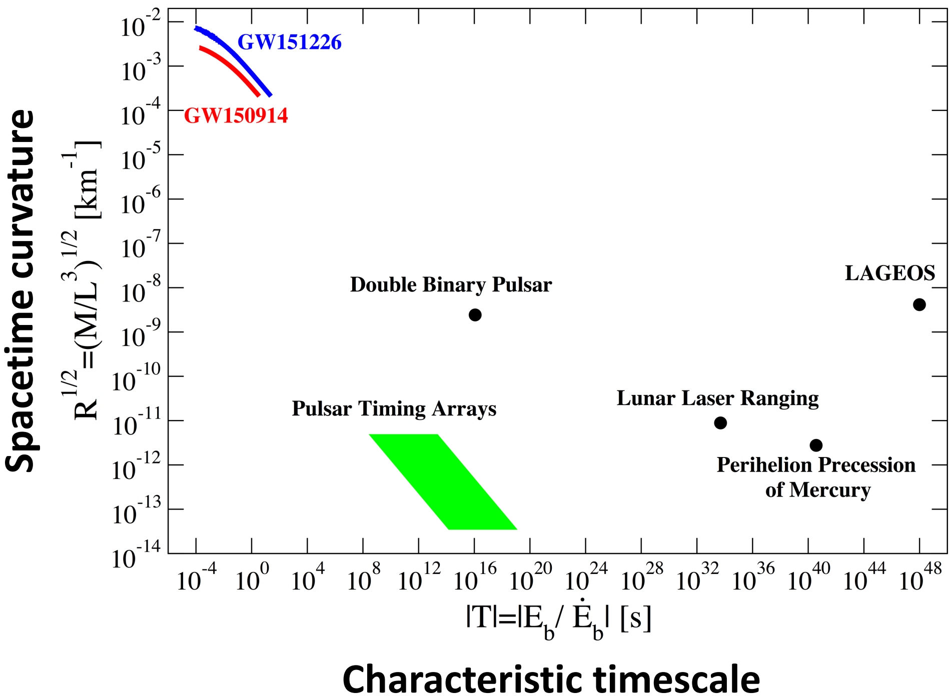
The first detection: GW150914



LIGO + Virgo, PRL **116**, 061102 (2016)

Five confirmed binary black hole detections so far:
GW150914, GW151226, GW170104, GW170608, GW170814

First access to the strong-field dynamics of spacetime



Yunes, Yagi, Pretorius, PRD **94**, 084002 (2016)

Before direct detection:

- Solar system tests
  - Weak-field
  - Dynamics of spacetime itself not being probed
- Radio observations of binary neutron stars
  - Relatively weak-field test of spacetime dynamics
- Cosmology
  - Dark matter and dark energy may signal GR breakdown

Direct detection from binary black hole mergers:

- Genuinely strong-field dynamics
- (Presumed) pure spacetime events

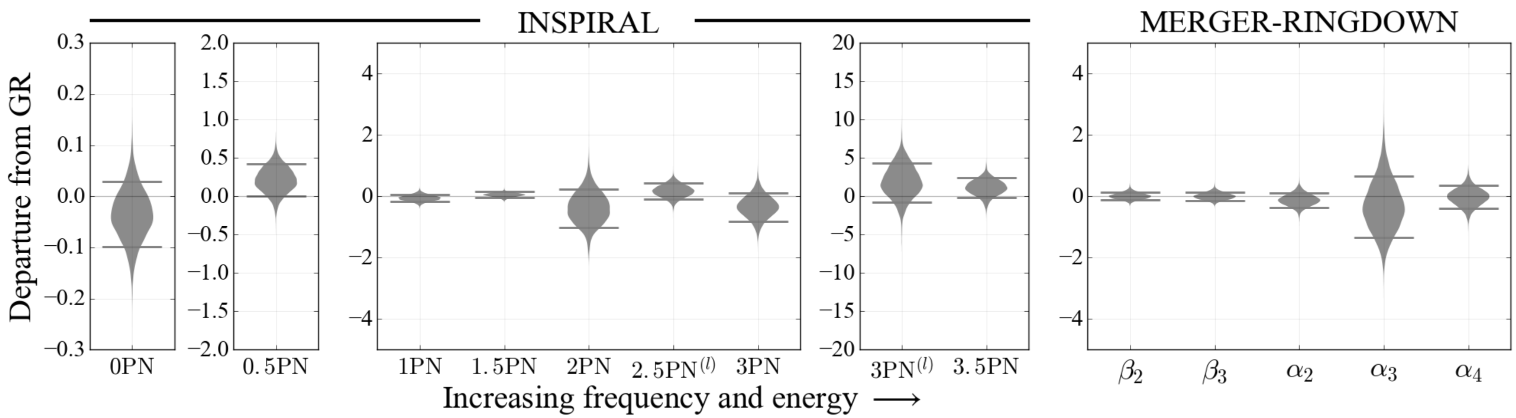
First access to the strong-field dynamics of spacetime

- Inspiral-merger-ringdown process
  - Post-Newtonian description of inspiral phase

$$\Phi(v) = \left(\frac{v}{c}\right)^{-5} \left[\varphi_{0\mathrm{PN}} + \varphi_{0.5\mathrm{PN}}\left(\frac{v}{c}\right) + \varphi_{1\mathrm{PN}}\left(\frac{v}{c}\right)^2 + \ldots + \varphi_{2.5\mathrm{PN}^{(l)}} \log\left(\frac{v}{c}\right)\left(\frac{v}{c}\right)^5 + \ldots + \varphi_{3.5\mathrm{PN}}\left(\frac{v}{c}\right)^7\right]$$

  - Merger-ringdown governed by additional parameters β_n, α_n

- Place bounds on deviations in these parameters:



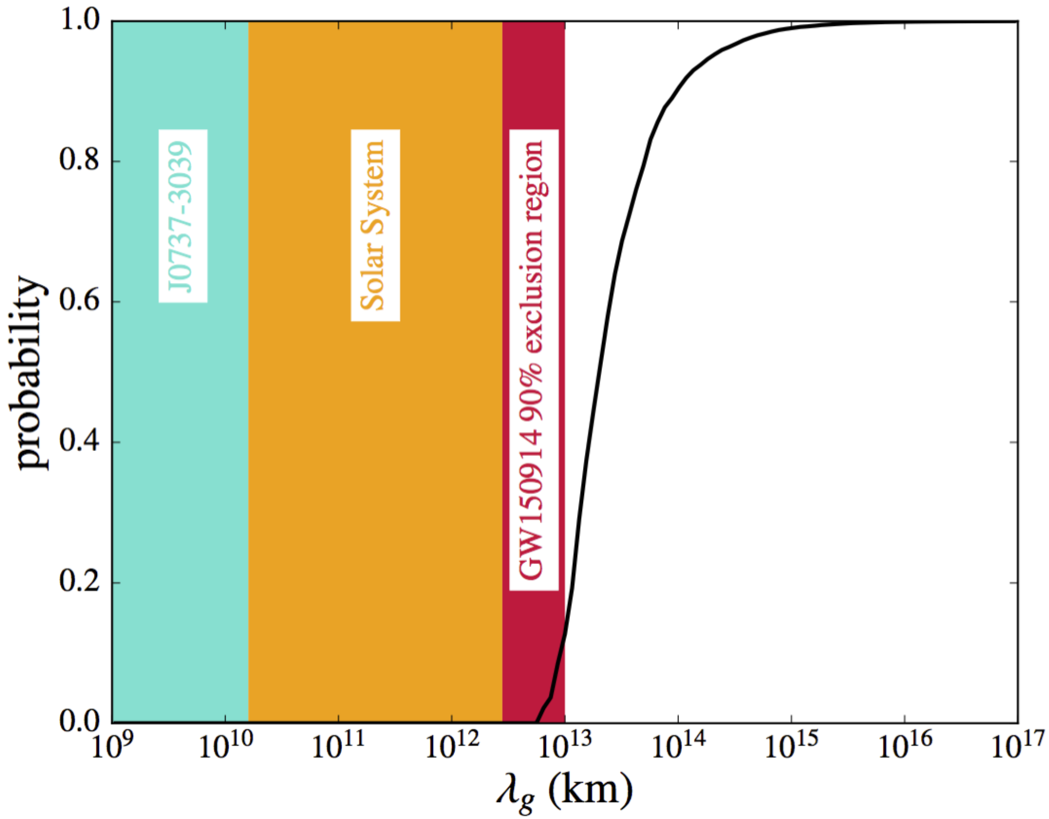
LIGO + Virgo, PRL **118**, 221101 (2017)

- Rich physics:
  Dynamical self-interaction of spacetime, spin-orbit and spin-spin interactions

How do gravitational waves propagate?

- Does the graviton have mass?

$$E^2 = p^2c^2 + m_g{}^2c^4$$



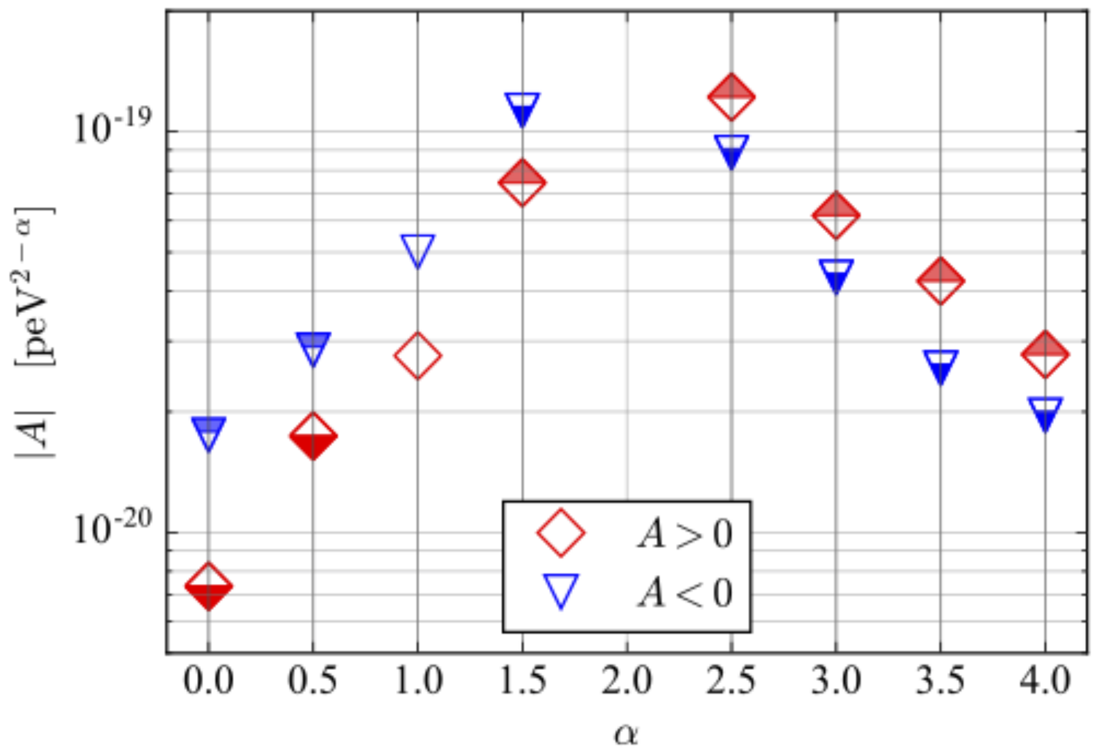
LIGO + Virgo, PRL **116**, 221101 (2017)

$$\mathbf{m_g < 10^{-22}\ eV/c^2}$$

How do gravitational waves propagate?

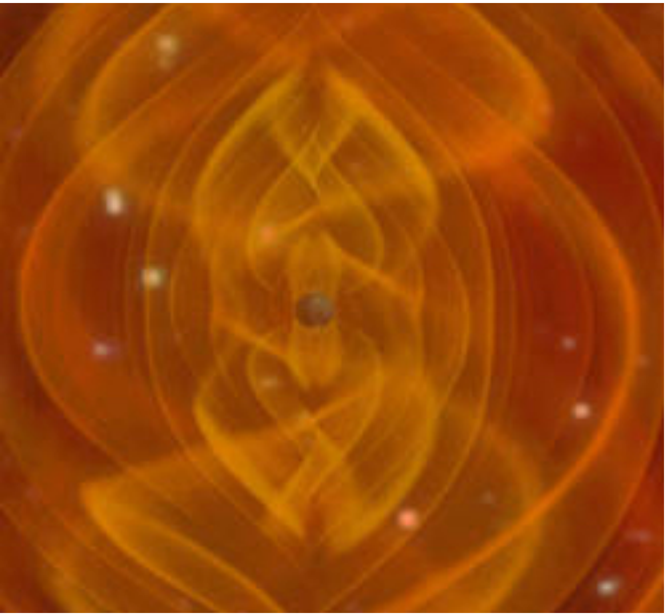
- Does local Lorentz invariance really hold?

$$E^2 = p^2c^2 + A\, p^\alpha c^\alpha$$



LIGO + Virgo, PRL **118**, 221101 (2017)

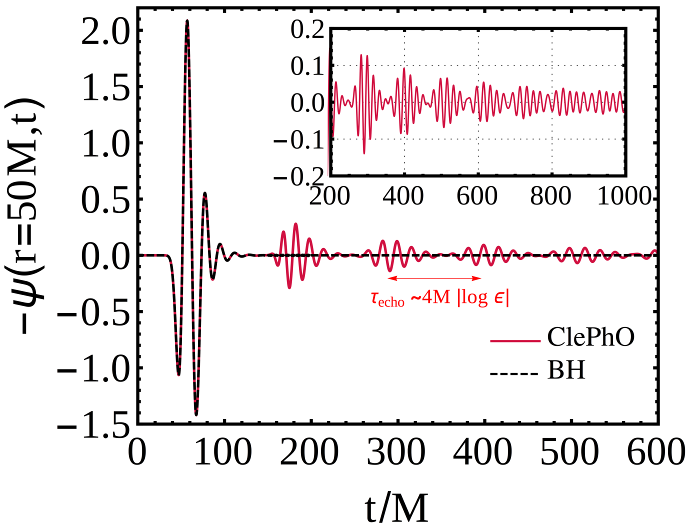
What is the true nature of black holes?



Ringdown of newly formed black hole

- Not yet observed in detail
- Will enable indirect test of *no hair theorem*: *"Stationary, neutral black holes only characterized by mass and spin"*
- Requires further factor 3-4 improvement of detectors

Meidam *et al.*, PRD **90**, 064009 (2014)

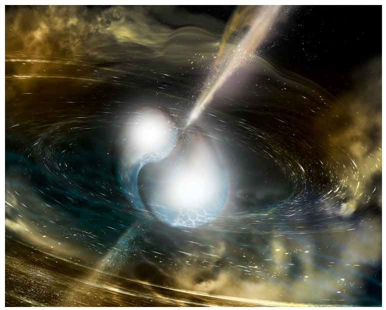


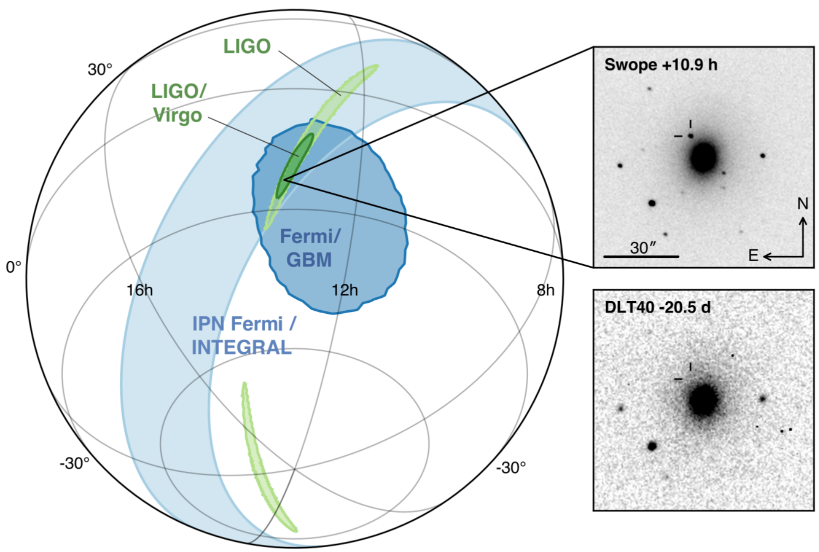
Gravitational wave echoes

- Alternatives to standard black holes, e.g. "firewalls" prompted by Hawking's information paradox
- Even after ringdown, black hole will continue to emit gravitational wave bursts: *echoes*
- Macroscopic signature of quantum gravity

Cardoso *et al.*, PRL **116**, 171101 (2016)
Cardoso *et al.*, PRD **94**, 084031 (2016)

2017: Advanced Virgo joins the network



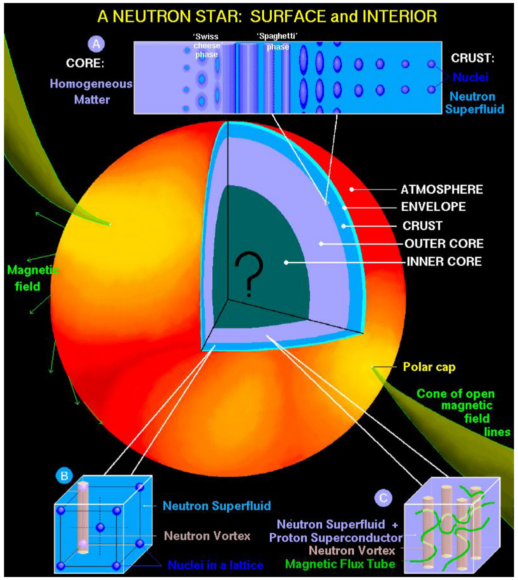


LIGO+Virgo, PRL **119**, 161101 (2017)

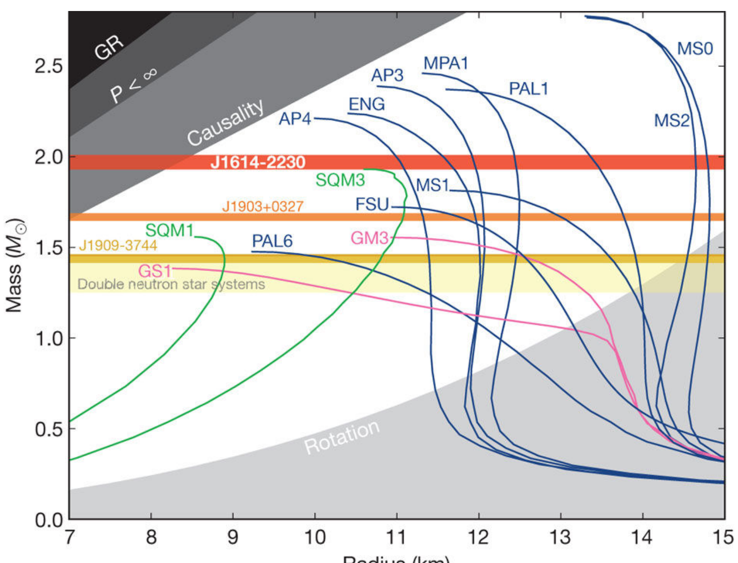
- 14 August 2017:
  First joint binary black hole detection by Advanced LIGO, Advanced Virgo

- 17 August 2017: First detection of binary neutron star merger
  - Gamma ray counterpart
    Origin of gamma ray bursts
  - Thanks to LIGO-Virgo triangulation: discovery of afterglow
    Origin of heavy elements
  - New cosmic distance markers
    Novel way of doing cosmology
  - Measurement of neutron star tides
    Structure of neutron stars
  - Speed of gravity = speed of light to 1 part in 10^{15}

Solving an astrophysical conundrum



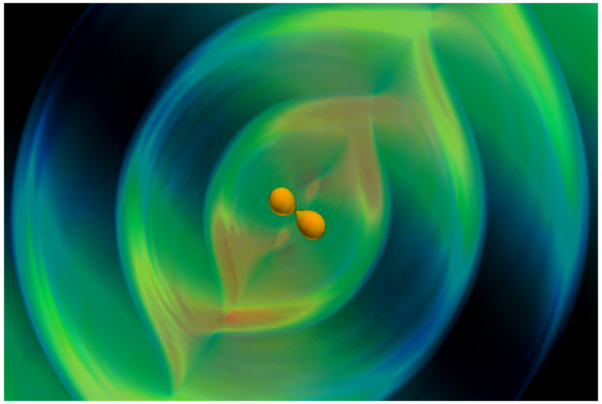
- Structure of neutron stars?
  - Structure of the crust?
  - Proton superconductivity
  - Neutron superfluidity
  - “Pinning” of fluid vortices to crust
  - Origin of magnetic fields?
  - More exotic objects?



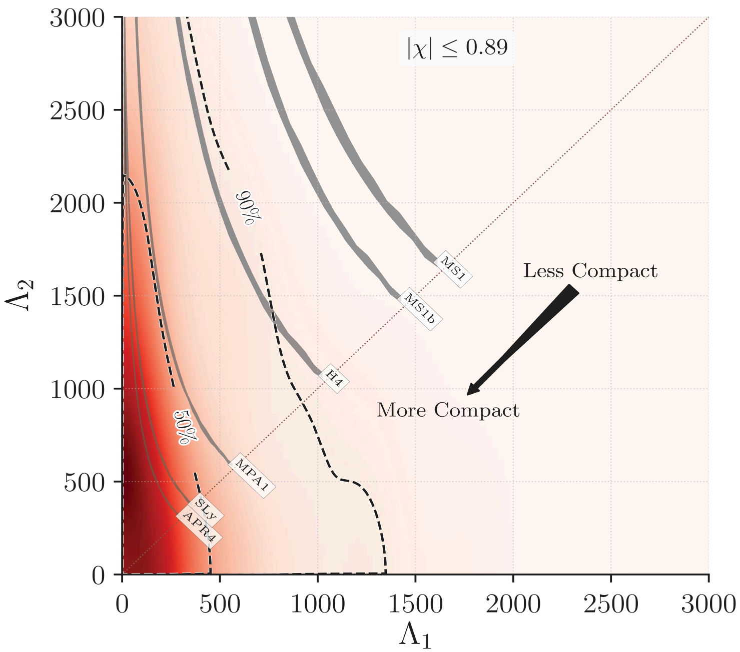
- Widely differing theoretical predictions for *equation of state*
  - Pressure as a function of density
  - Mass as a function of radius
  - *Tidal deformability as a function of mass*

Demorest *et al.*, Nature **467**, 1081 (2010)

Probing the structure of neutron stars

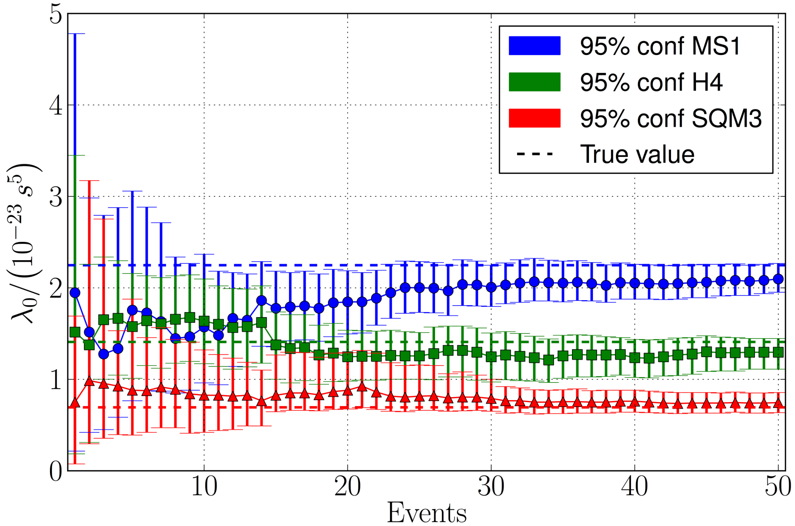


- Gravitational waves from inspiralling binary neutron stars:
  - When close, the stars induce tidal deformations in each other
  - These affect orbital motion
  - Tidal effects imprinted upon gravitational wave signal
  - *Tidal deformability maps directly to neutron star equation of state*
- Measurement of tidal deformations on GW170817
  - More compact neutron stars favored
  - “Soft” equation of state

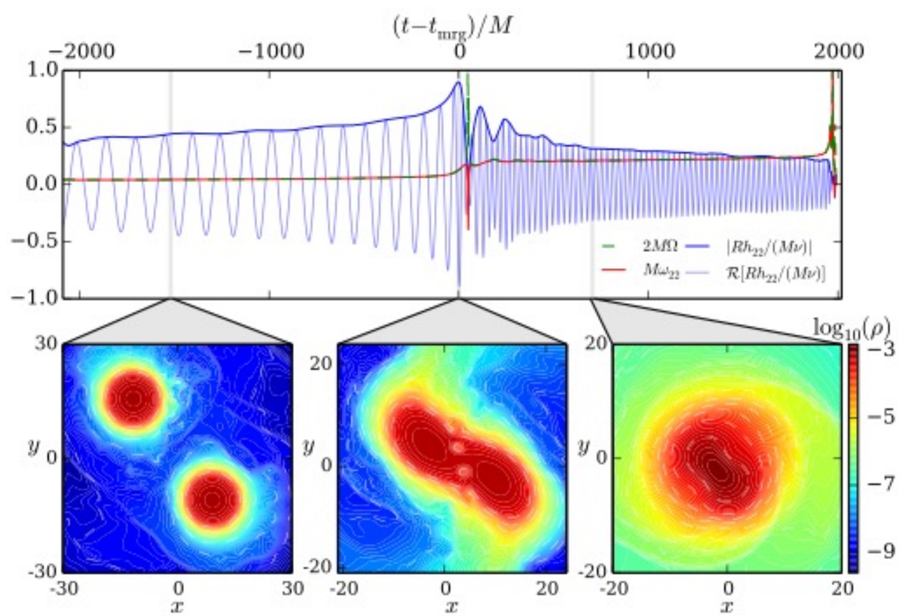


LIGO+Virgo, PRL **119**, 161101 (2017)

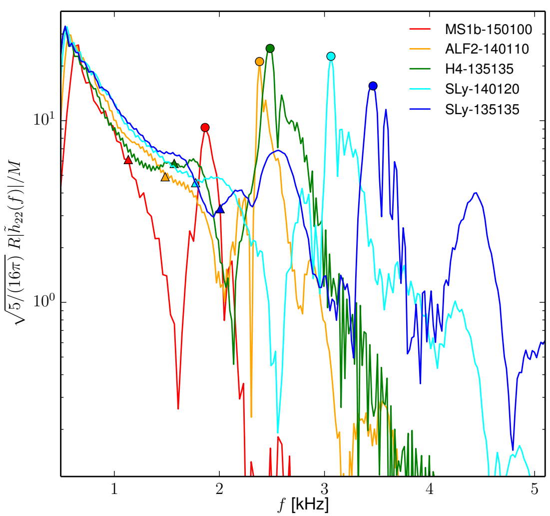
Probing the structure of neutron stars



Del Pozzo *et al.*, PRL **111**, 071101 (2013)

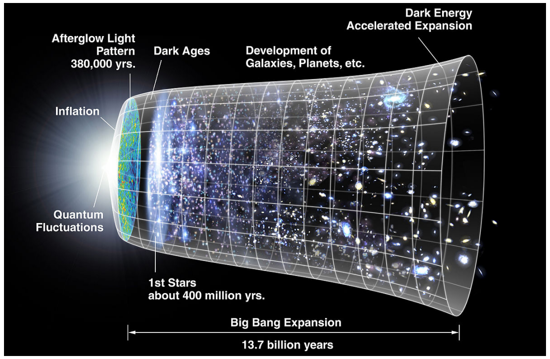


- More accurate determination of equation of state using tidal deformability after O(30) detection
- Post-merger signal?
  - Depends strongly on equation of state
    - “Soft”: prompt collapse to black hole
    - “Hard”: hypermassive neutron star
  - Characteristic frequencies in gravitational wave spectrum

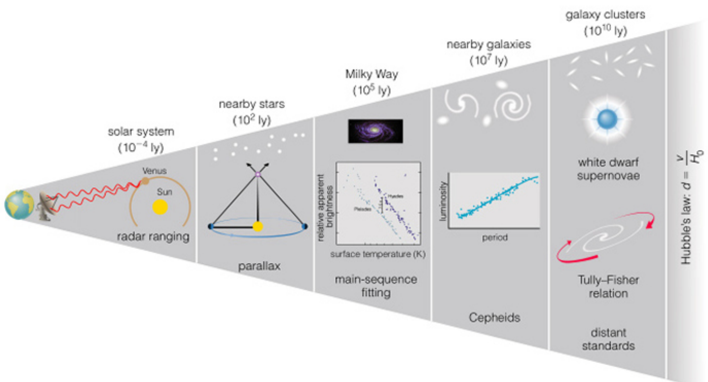


Bernuzzi *et al.*, PRL **115**, 091101 (2015)

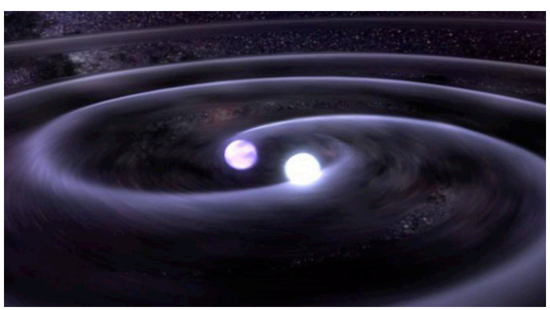
A new cosmic distance marker



- Mapping out the large-scale structure and evolution of spacetime by comparing:
  - Distance
  - Redshift

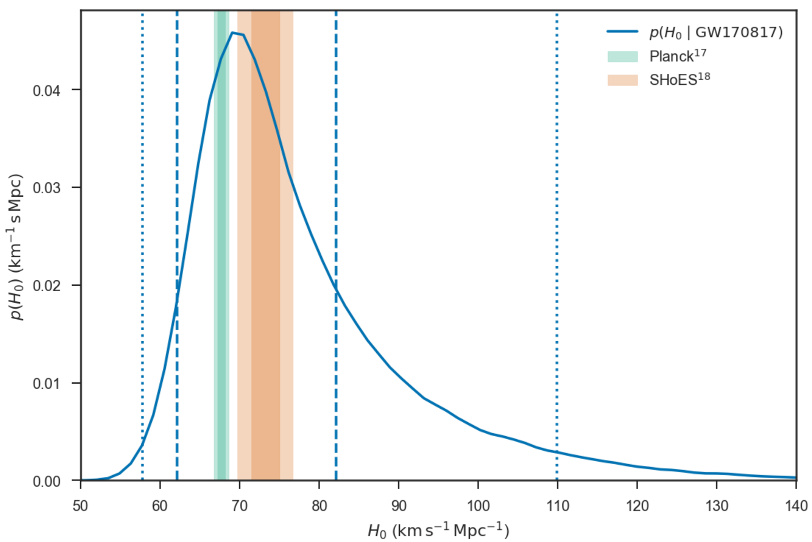


- Current measurements depend on *cosmic distance ladder*
  - Intrinsic brightness of e.g. supernovae determined by comparison with different, closer-by objects
  - Possibility of systematic errors at every “rung” of the ladder

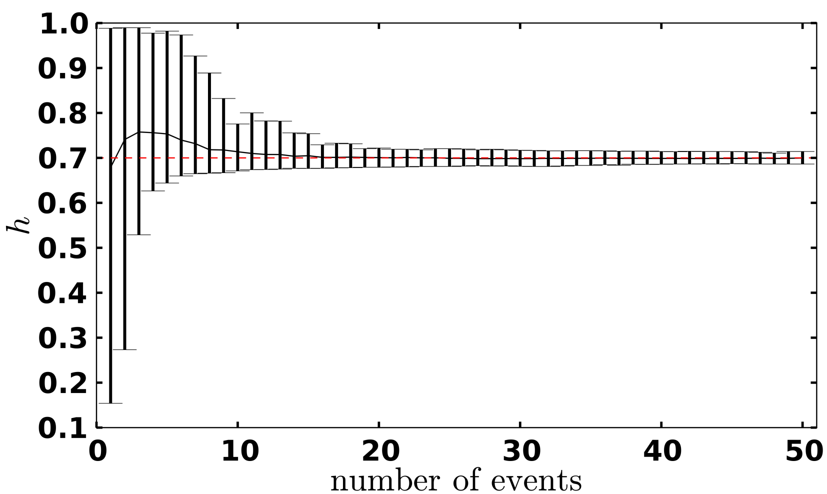


- Gravitational waves from binary mergers: *Distance can be measured directly from the gravitational wave signal!*

A new cosmic distance marker



LIGO+Virgo *et al.*, Nature **551**, 85 (2017)



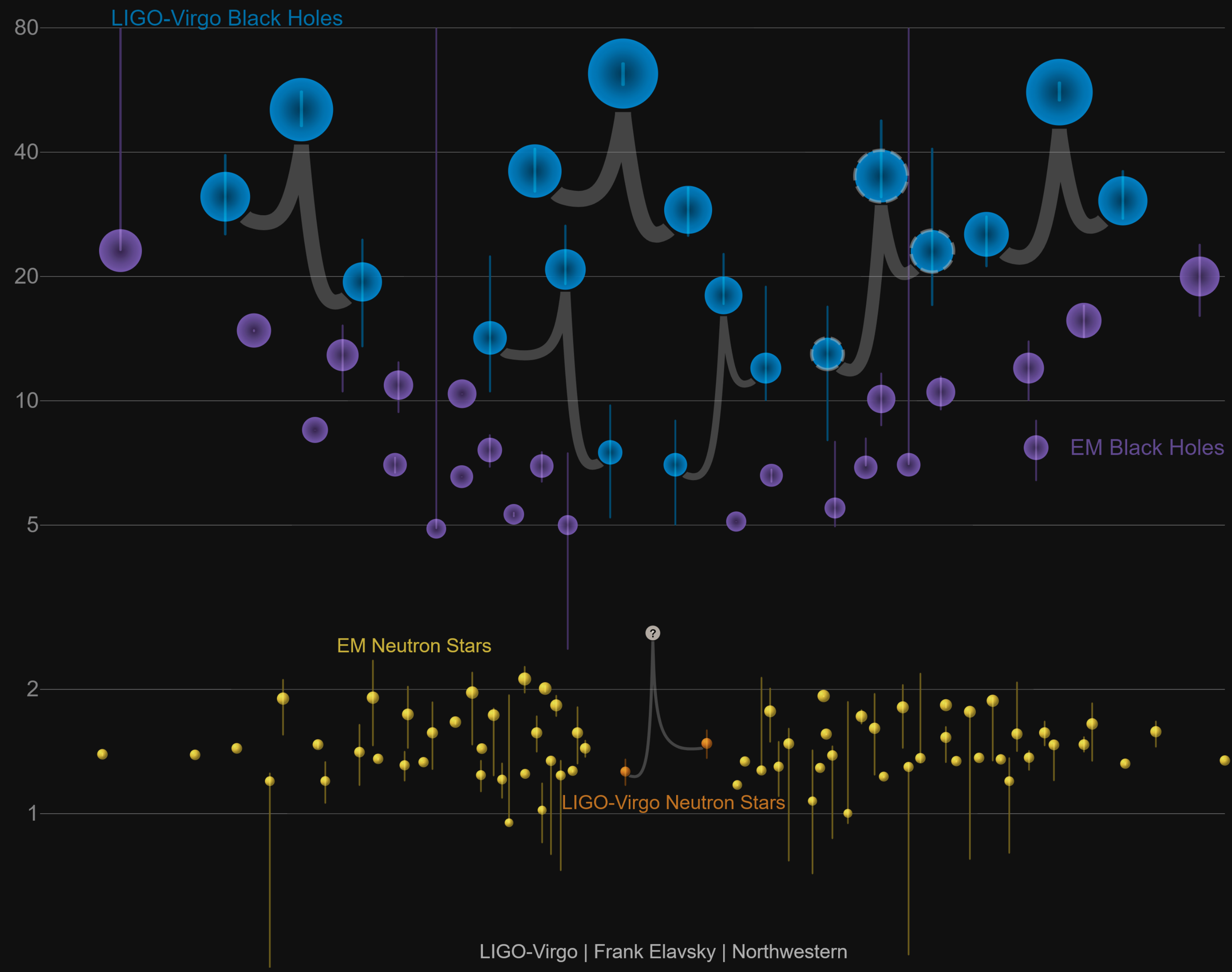
Del Pozzo, PRD **86**, 043011 (2012)

- Measurement of the local expansion of the Universe: The Hubble constant
  - Distance from GW signal
  - Redshift from EM counterpart (galaxy NGC 4993)

- One detection: limited accuracy
- Few tens of detections: O(1%) accuracy after few tens of detections

Masses in the Stellar Graveyard

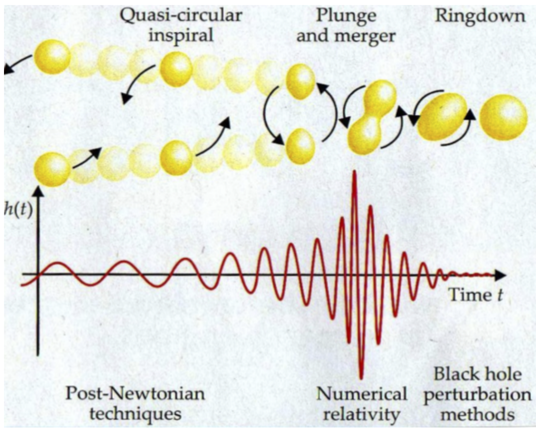
in Solar Masses



LIGO-Virgo | Frank Elavsky | Northwestern

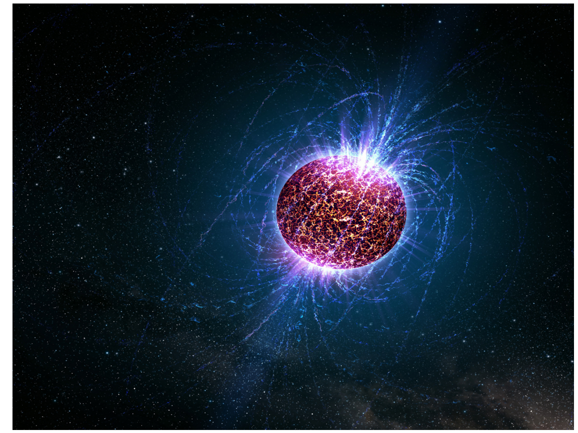
Multi-messenger astronomy

Merging neutron stars, black holes



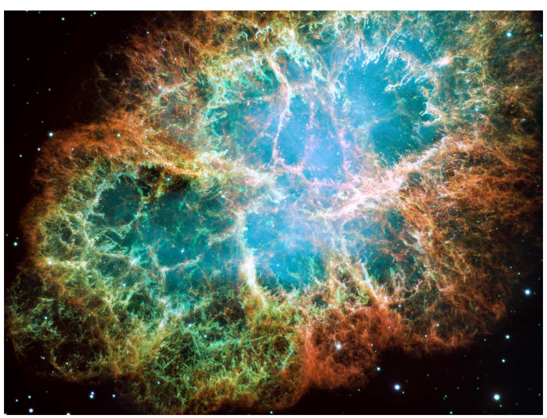
GW + EM (+ neutrinos?)

Fast-spinning neutron stars



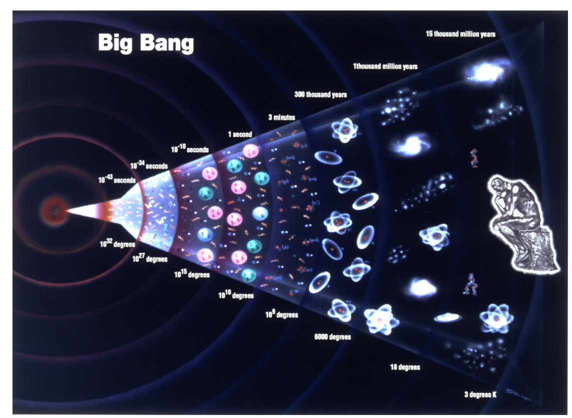
GW + EM

Supernovae



GW + EM + neutrinos

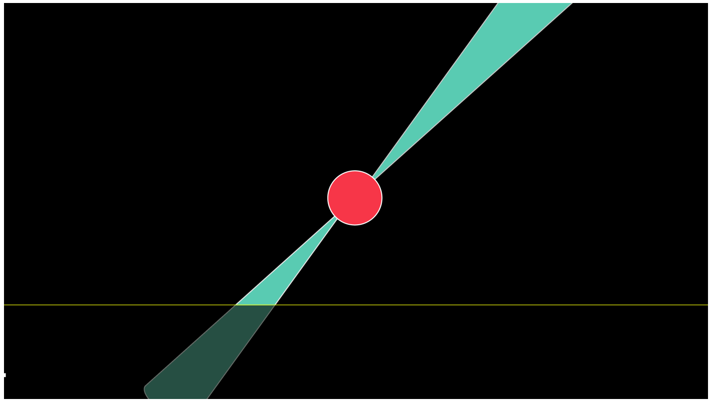
Primordial gravitational waves

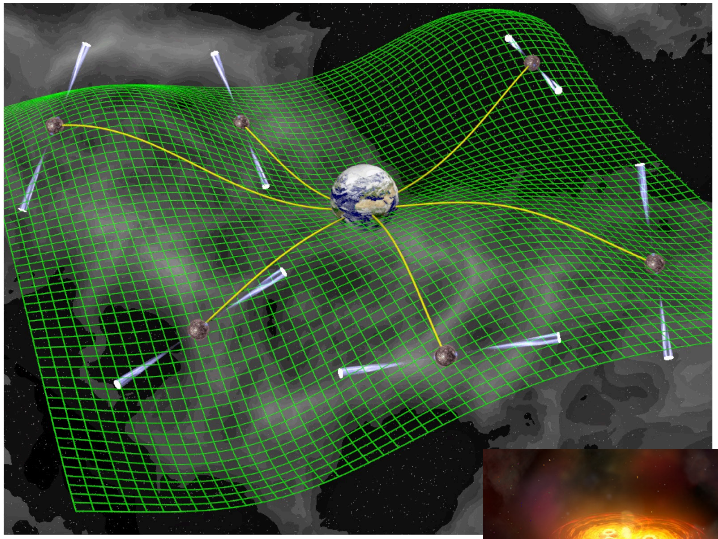


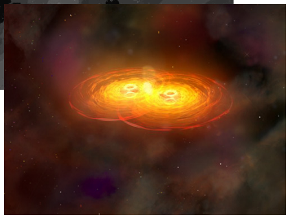
GW + CMB

Into the future

Pulsar timing arrays: Milky way sized detectors

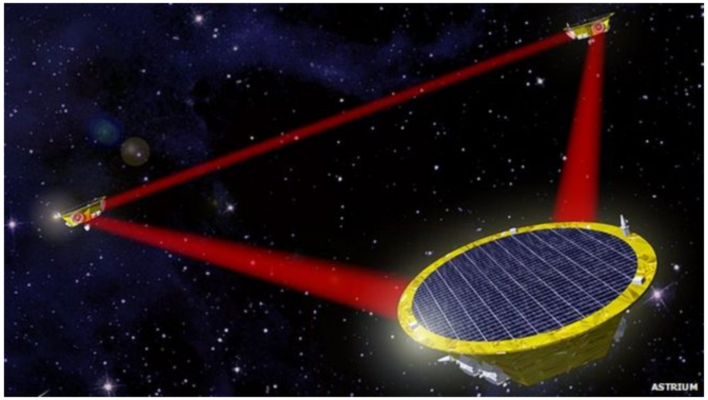




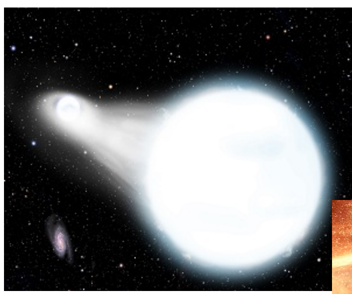


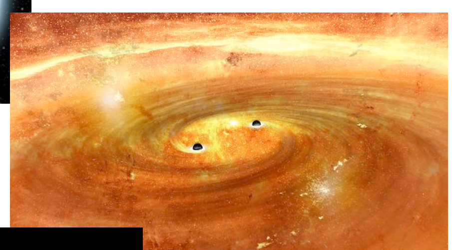
- Radio astronomers monitor *pulsars*:
  - Neutron stars as lighthouses
  - High-accuracy measurement of periods
- A passing gravitational wave affects pulse rate
- Large number of pulsars together form a gravitational wave detector
  - Sensitive to ultra-low frequenties: $10^{-9} – 10^{-6}$ Hz
- Observation of supermassive binary black holes long before merger
  - First detection in the next decade?

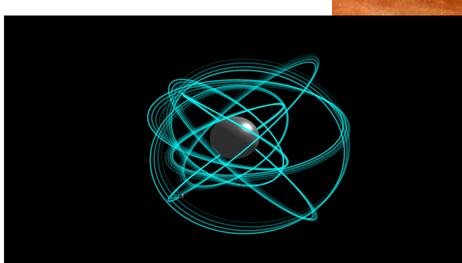
The Laser Interferometer Space Antenna (LISA)



- Three probes in orbit around the Sun, exchanging laser beams
  - Triangle, O(10^6) km sides
  - Sensitive to low frequencies: 10^{-5} – 10^{-1} Hz
  - Approved by ESA for launch in 2034

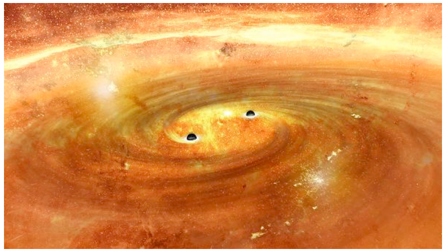


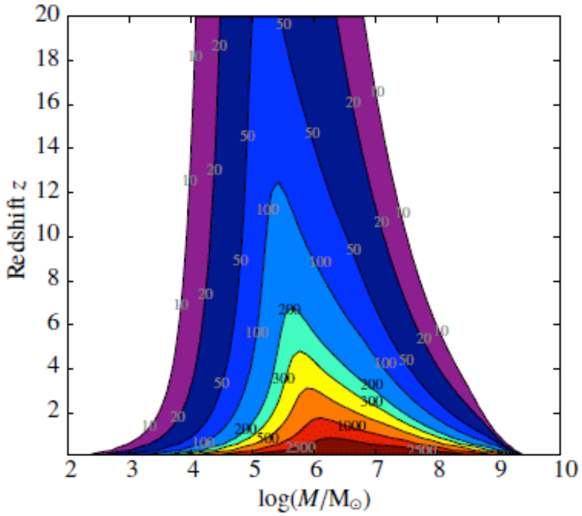


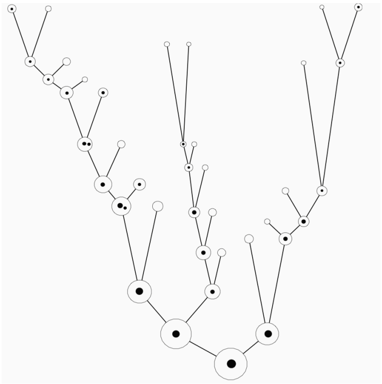


- Different sources:
  - Binary white dwarfs in Milky Way
  - Mergers of supermassive binary black holes
  - Smaller objects in complex orbits around supermassive black hole

The Laser Interferometer Space Antenna (LISA)

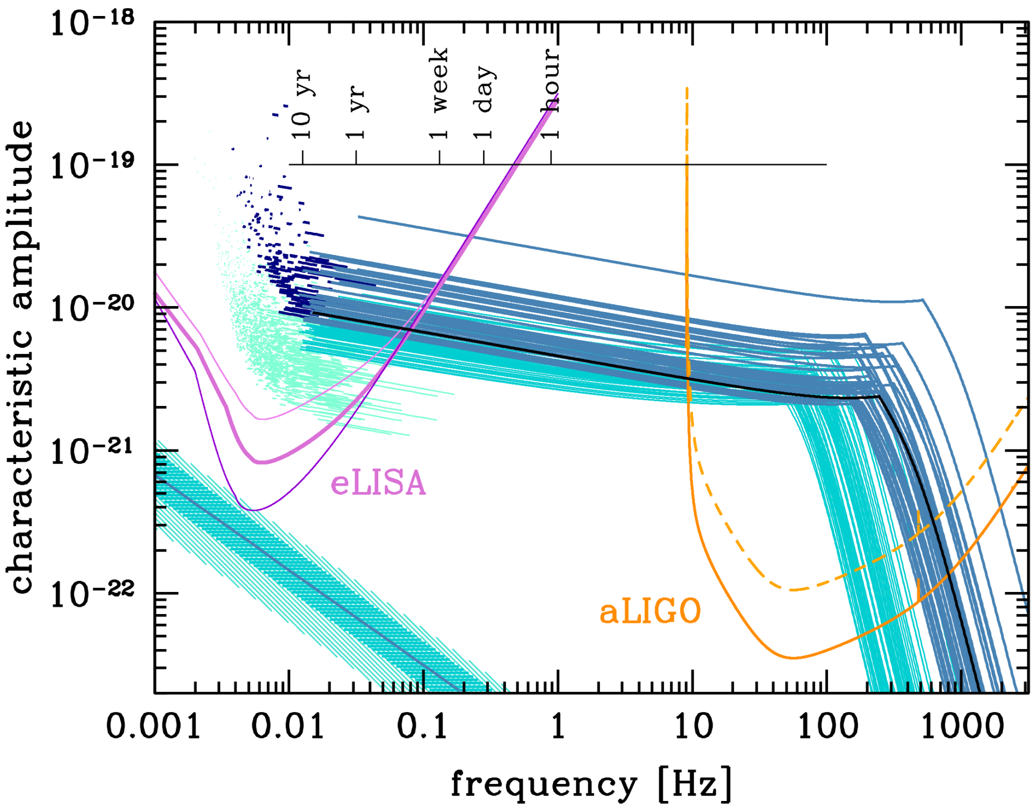






- Most galaxies are believed to harbor a supermassive black hole (10^6 – 10^9 Solar masses)
- LISA will see binary mergers throughout the Universe
- How did supermassive black holes come about?
  - Formed almost immediately in early Universe?
  - Instead started with light black holes, growth through successive mergers?

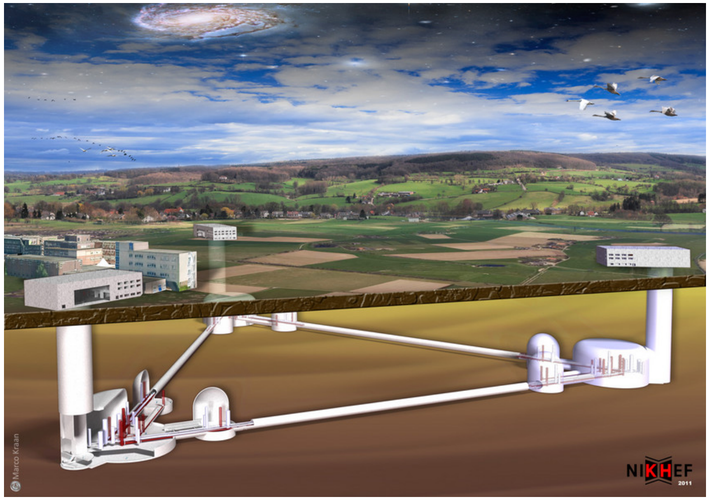
The Laser Interferometer Space Antenna (LISA)

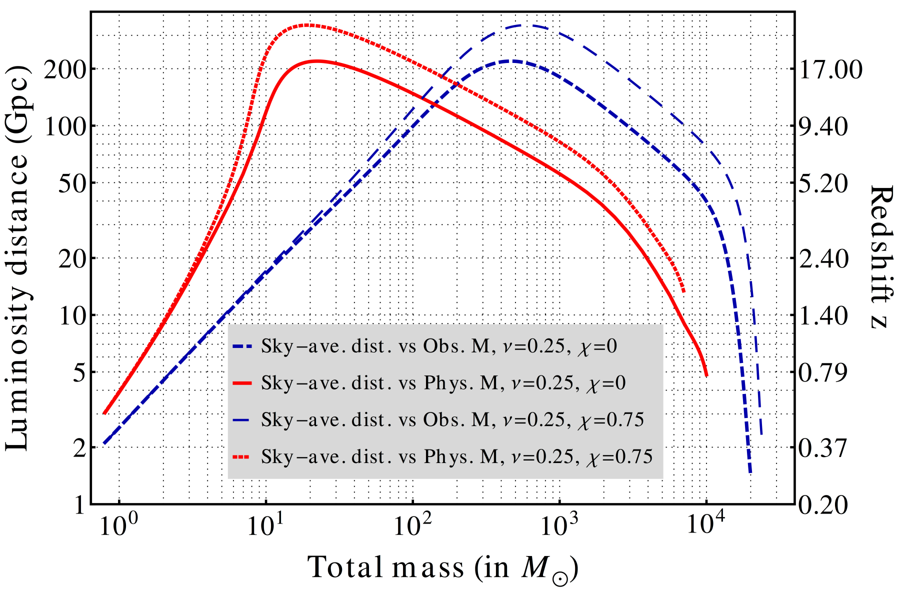


Sesana, J. Phys. Conf. Ser. **840**, 012018 (2017)

- Joint observations of LISA and ground-based detectors:
  - Binary black holes first visible in LISA
  - Weeks later also in detectors on the ground

Einstein Telescope

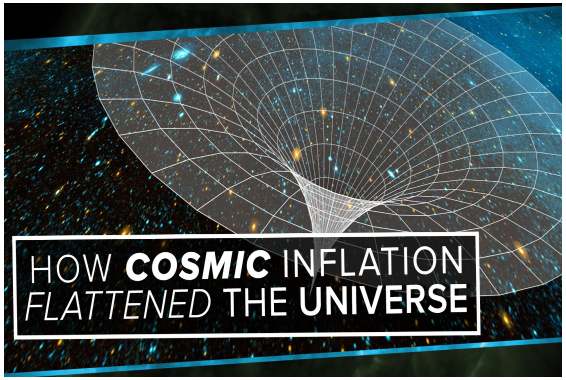




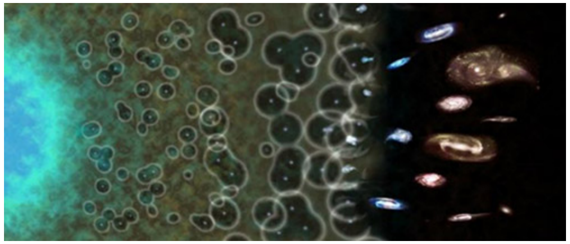
Sathyaprakash *et al.*, CQG **29**, 124013 (2012)

- EU-funded design study 2011
  - Triangular, sides of 10 km
  - Underground
  - Superior noise suppression
  - More sensitive optics
  - Six interferometers:
    - High frequencies(high laser power)
    - Low frequencies (cryogenic)
- Factor 10 improvement in sensitivity over Advanced LIGO/Virgo
- Merging black holes, neutron stars in the entire visible Universe
  - 100,000 sources per year!
    - How did stellar mass binary black holes arise?
    - Detailed probe of neutron star interiors
    - Cosmology
- Site studies e.g. in Southern Limburg

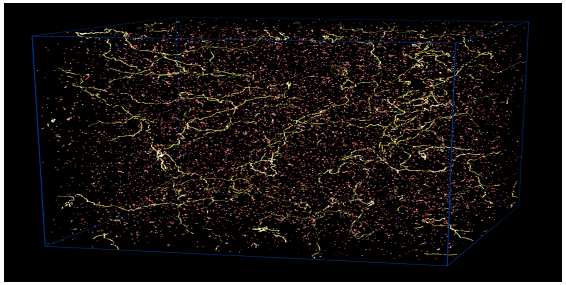
Primordial gravitational waves?



- Cosmic inflation:
  Exponential expansion of spacetime
  - Amplification of vacuum fluctuations
    - Study CMB polarization
  - What kind of field was the “inflaton”?
    - Gravitational wave background?



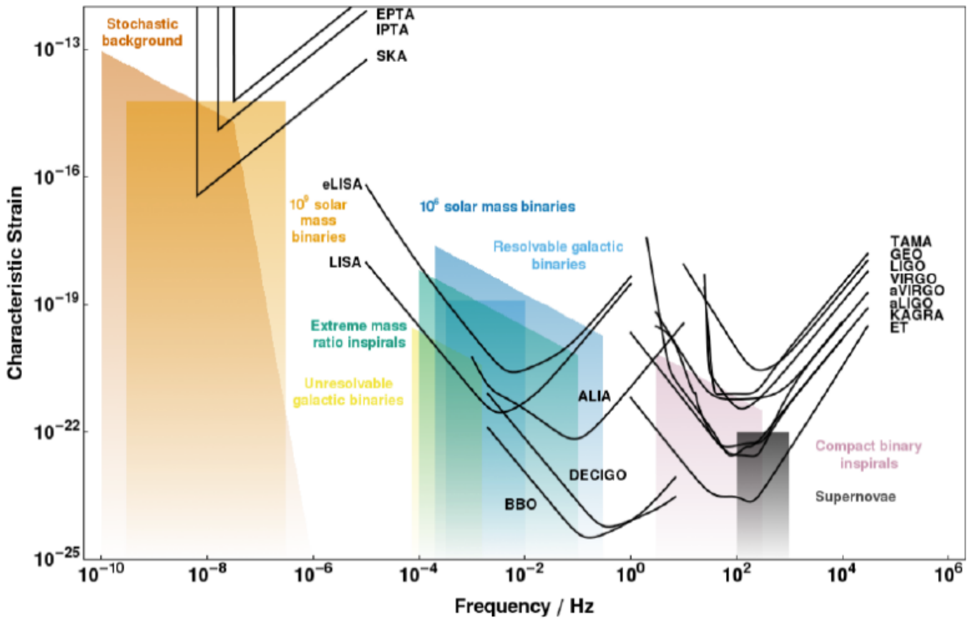
- Phase transitions in the early Universe
  - Forces of nature splitting off



- Cosmic strings?
  - Fundamental (string theory)
  - Topological defects, quantum field theory

- Black holes from the Big Bang itself?
  - Einstein Telescope will be able to see mergers of binary black holes *before* the formation of the first stars

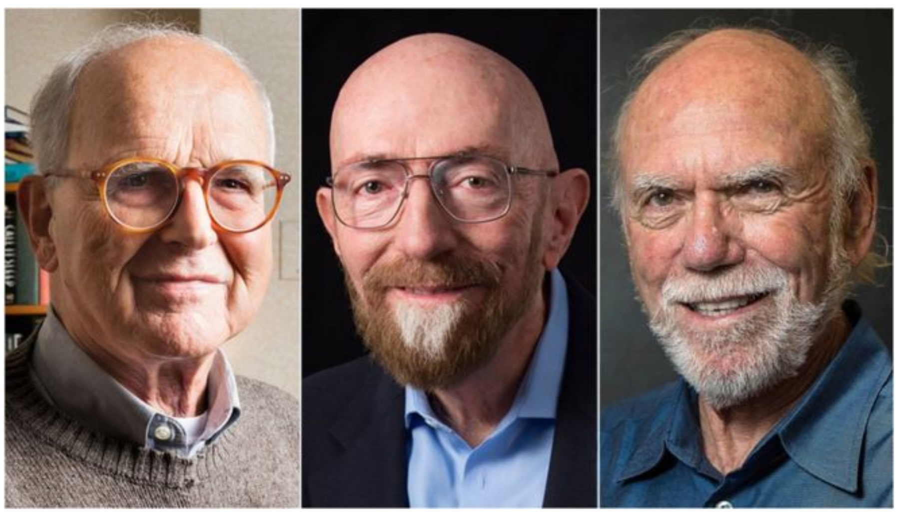
Into the future



Pulsar Timing, LISA, Einstein Telescope:

- Spectrum ranging $10^{-9} – 10^{4}$ Hz
- Most extreme events in the Universe
- Primordial gravitational waves from immediately after Big Bang?

New field at the intersection of fundamental physics, astrophysics, cosmology



Rainer Weiss Kip Thorne Barry Barish

Nobel Prize in Physics 2017

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