

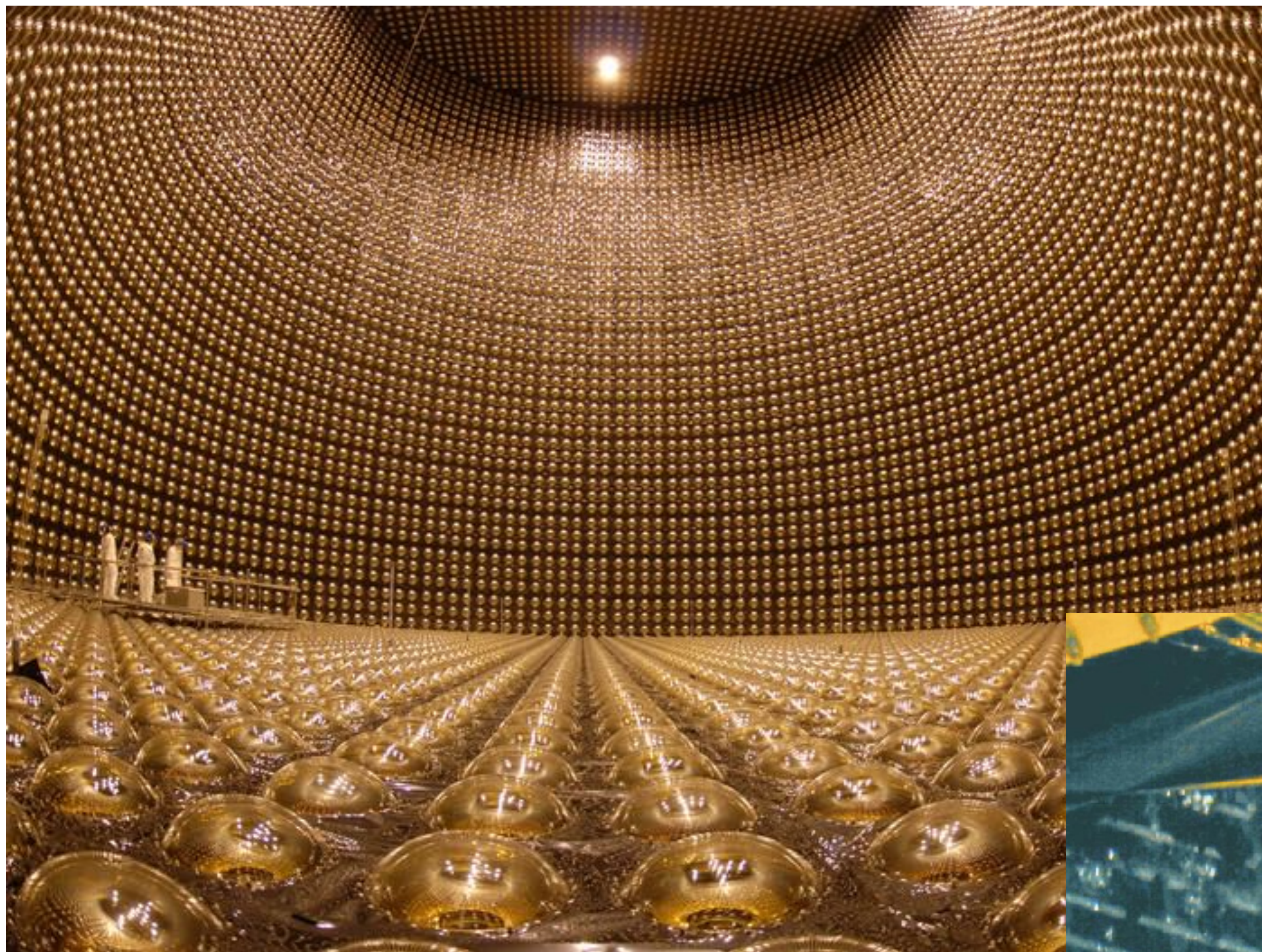
# Neutron star mergers and gravitational waves

## Lecture 1 Neutron stars

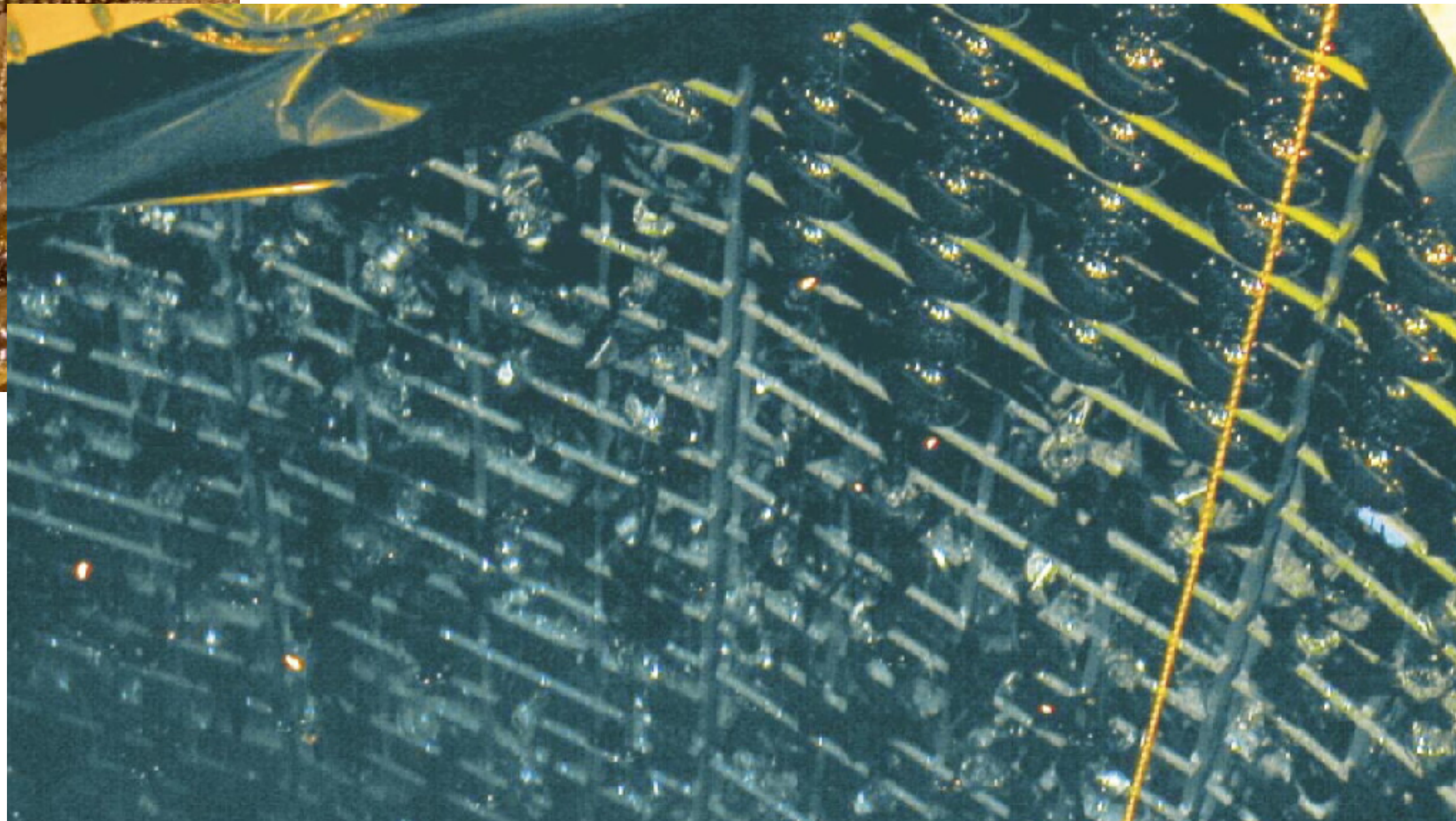
300 ft Green Bank Telescope

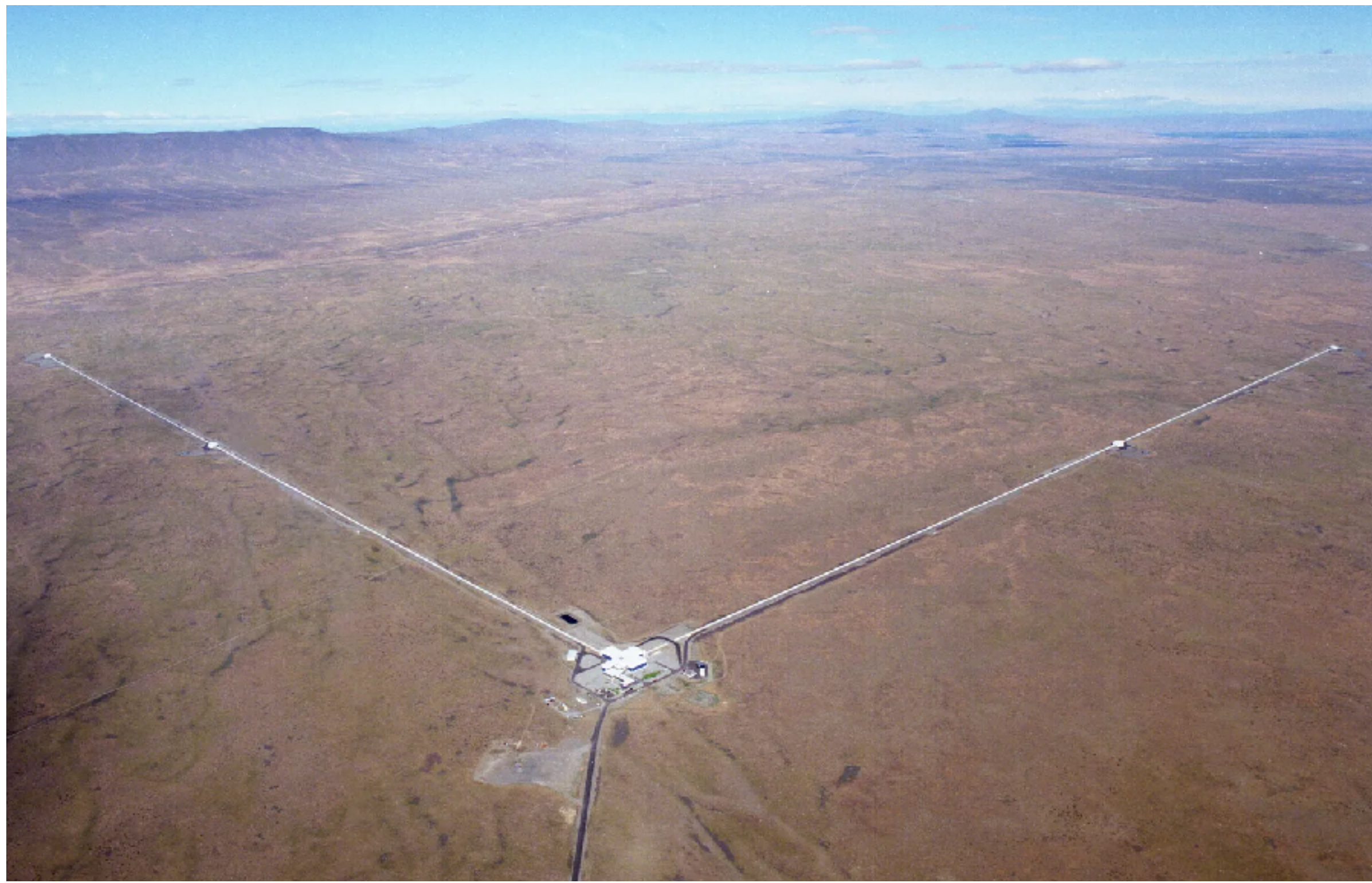


## Lecture 2 Supernovae



Super-Kamiokande neutrino detector  
“imploded” on 11/12/2001





LIGO Hanford

## Lecture 3 Neutron star mergers

A catastrophic vacuum failure at LIGO would be devastating. Its 4km vacuum tubes hold the second-largest ultra-high vacuum chambers in the world, operating at  $10^{-12}$  atmospheres. An implosion would instantly destroy the precision optics and shatter the facility.

# Gravitational Waves (GW)



- Gravitational waves are oscillations of space-time that change the distance between fixed objects.
- GW are an extraordinary prediction of General Relativity (Einstein's masterpiece).
- Hold out your hands ***and keep them very still.*** The distance between your hands can change if (1) either hand moves or (2) the space between your hands stretches or shrinks as a GW passes by.

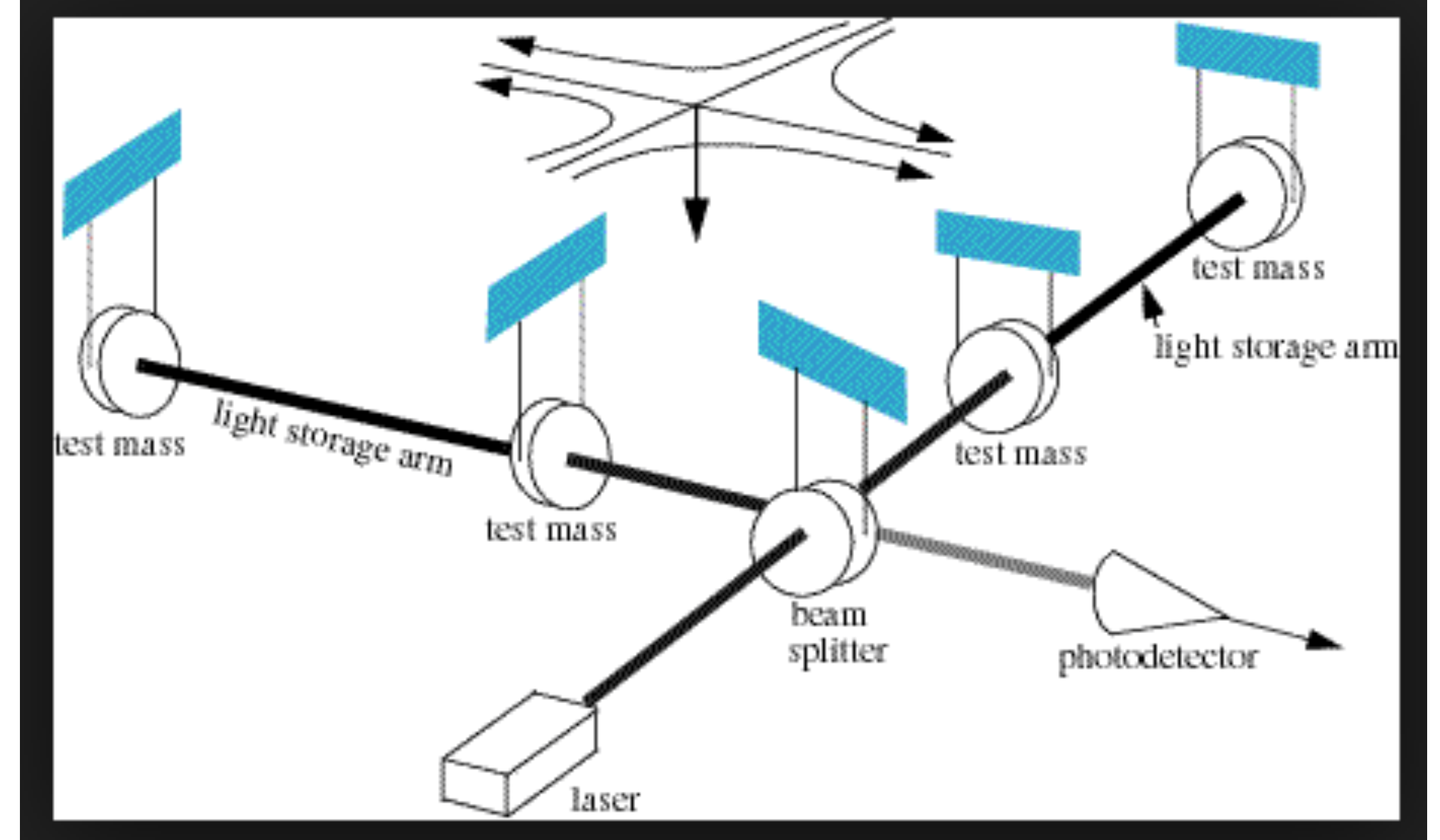


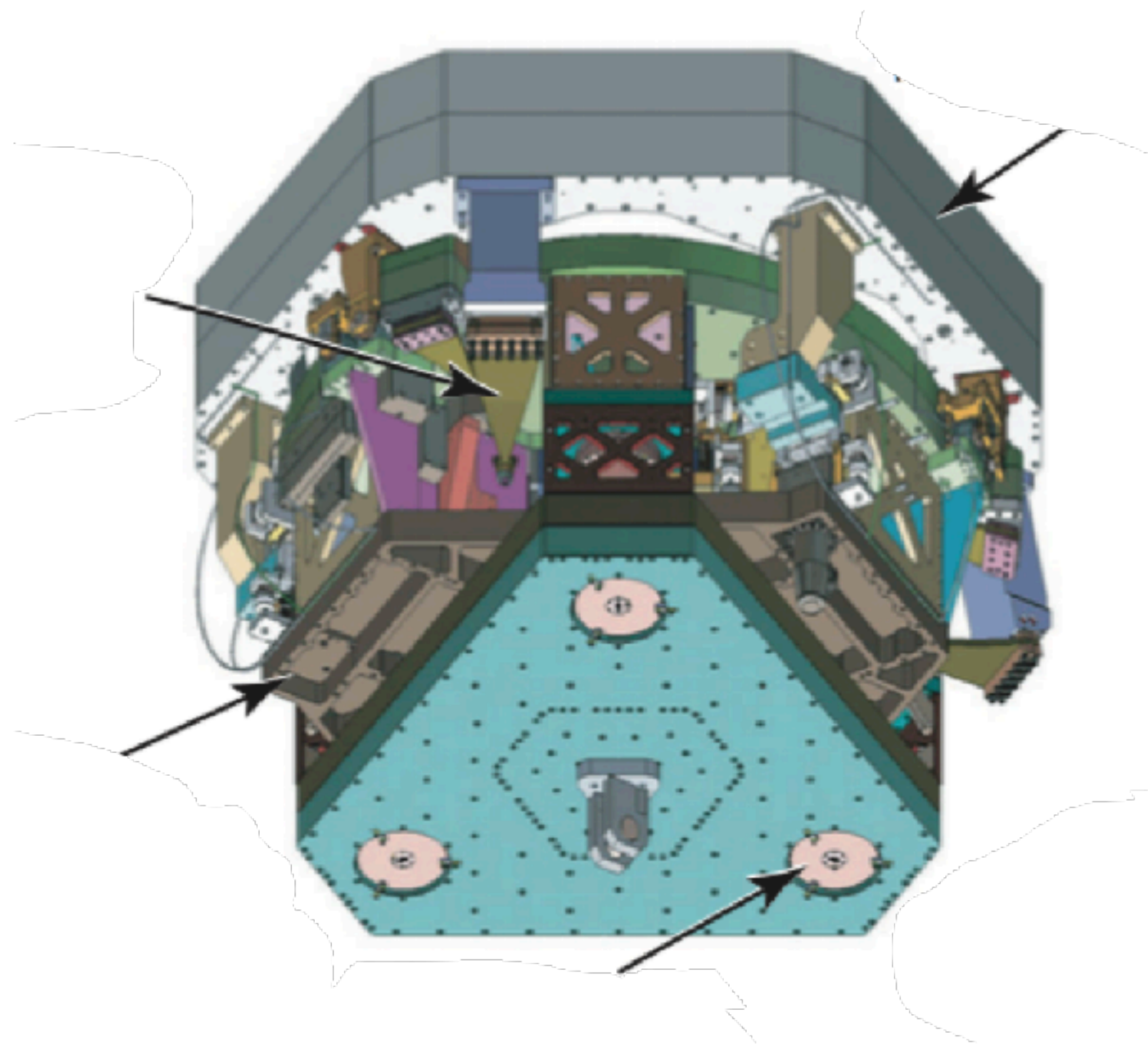


# L I G O

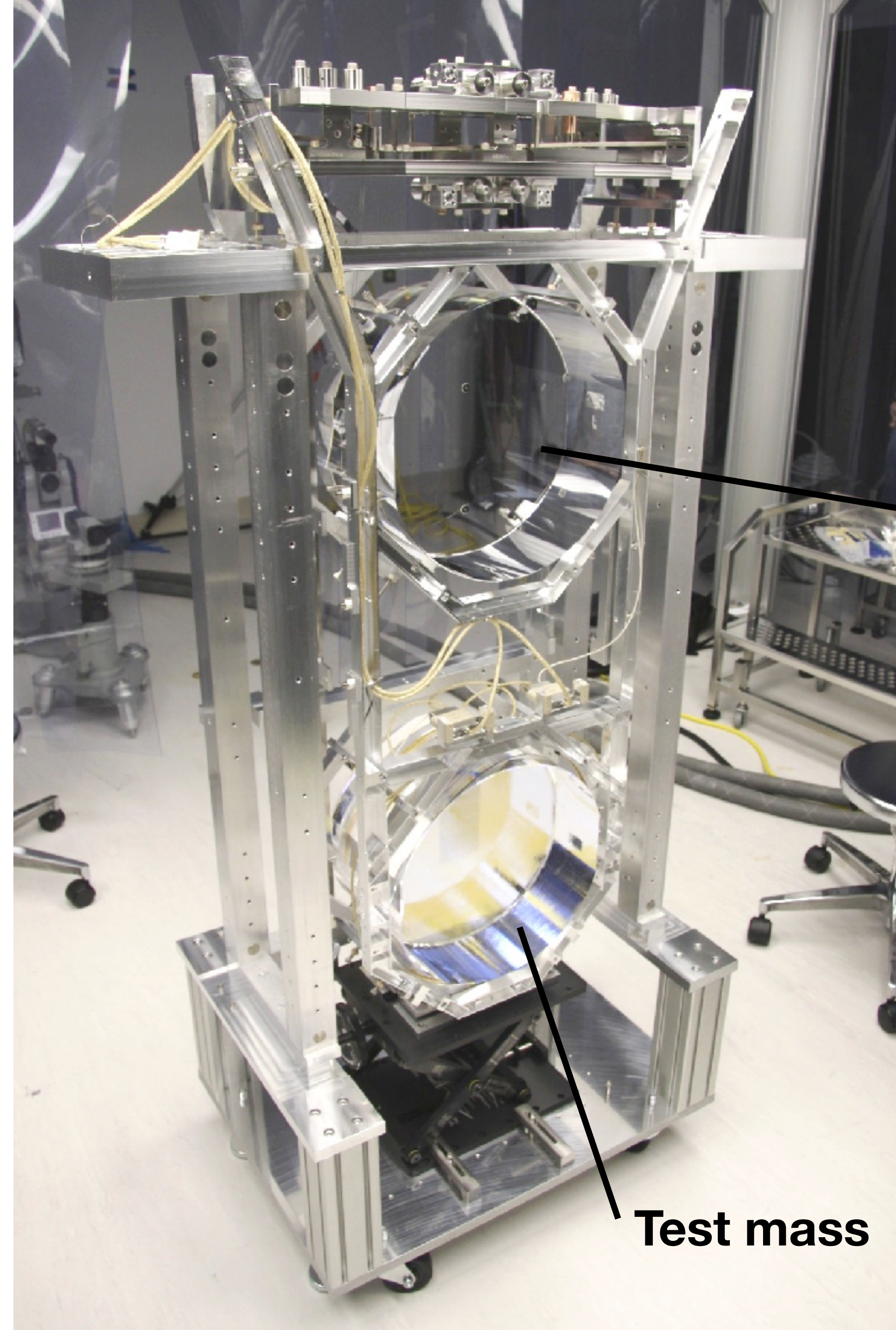
LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY

- LIGO consists of two 4km interferometers at Hanford Washington and Livingston Louisiana.
- Gravitational wave will shrink one 4km arm and stretch the other by 1/10 millionth the diameter of an atom.





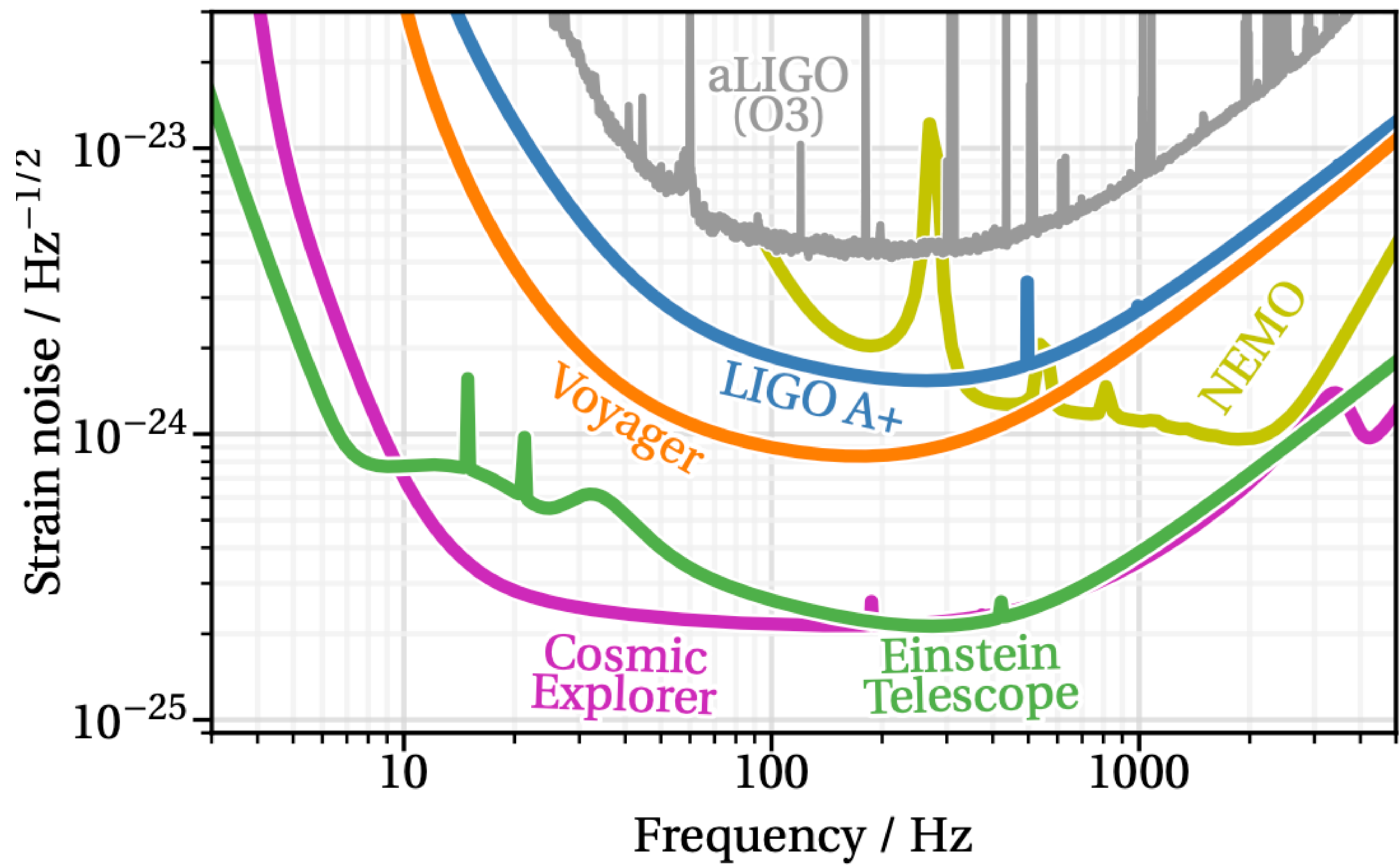
**Laser Interferometer Gravitational Wave Observatory (LIGO)** measures distance between test masses (high quality mirrors) hung in double pendulums from supports full of springs, seismometers and actuators (arrows). They act like very complicated noise canceling headphones to keep test mass still.



**Dummy mass**

**Test mass**





# Chirp mass

- Homework problem: Consider a binary system of two equal sized equal mass objects in a circular orbit. The density of each star must be.  
 $\rho > 12\pi v^2/G = 6e10 \text{ g/cm}^3$  for  $f=2v=20\text{Hz}$   $\rightarrow$  LIGO only sensitive to NS and black holes.
- Chirp mass: As energy is lost to GW radiation objects spiral nearer increasing orbital frequency.

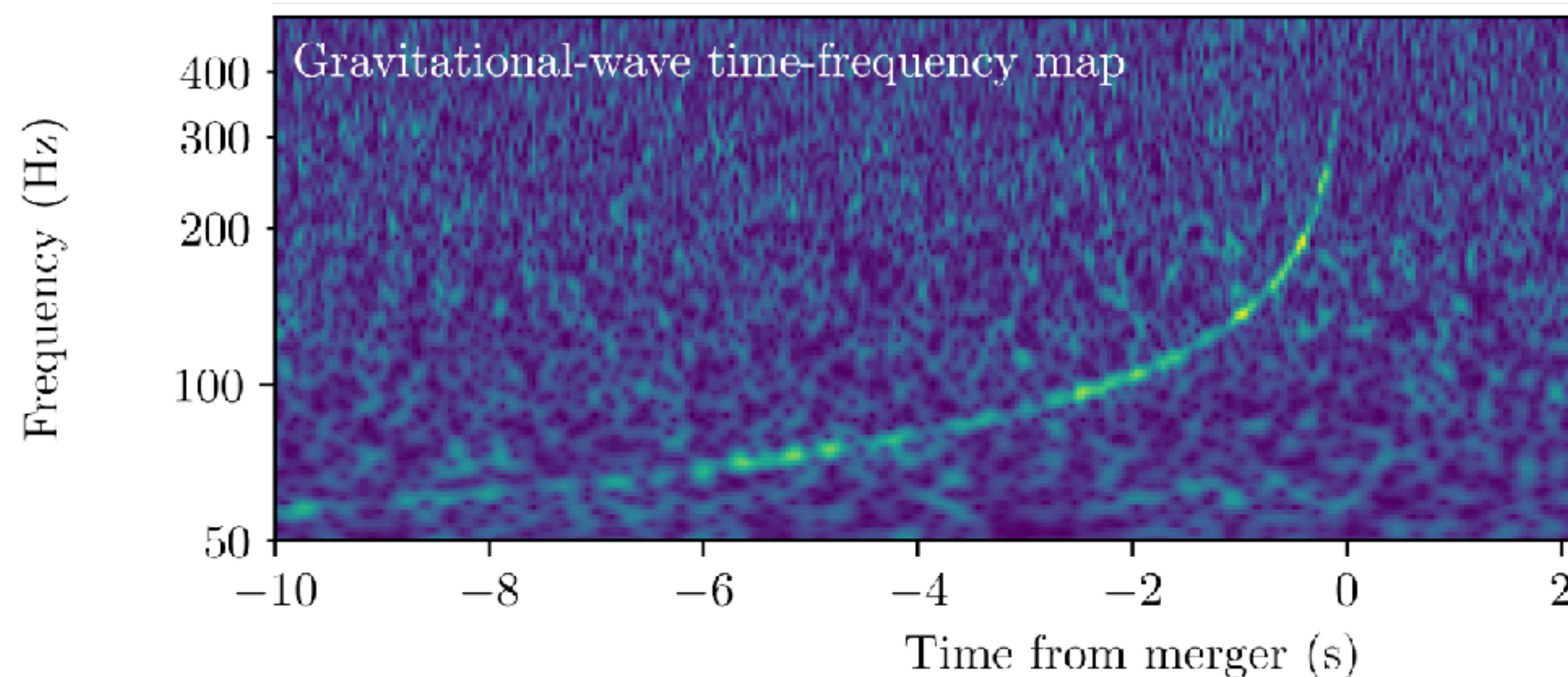
$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \quad \mathcal{M} = \frac{c^3}{G} \left( \frac{5}{96} \pi^{-8/3} f^{-11/3} \dot{f} \right)^{3/5}$$

# E+M vs GW Astronomy

	E+M	GW
Measure	Intensity $\sim 1/D^2$	Amplitude $\sim 1/D$
Spectrum	Composition and T	No lines
Density of source	No limits	Must be high
Mass of source	Not observed	Chirp mass $\sim f\text{-dot}$
Distance to source	Not observed	Luminosity distance: amplitude of signal $\sim M/D$

# Spectacular event GW170817

- On Aug. 17, 2017, the merger of two neutron stars observed with GW
- The Fermi and Integral spacecrafts independently detected a short gamma ray burst.
- Extensive follow up observed this event at X-ray, ultra-violet, visible, infrared, and radio wavelengths.



**LIGO**

# The advanced GW detector network: 2015-2025

Advanced LIGO  
Hanford  
2015



GEO600 (HF)  
2011



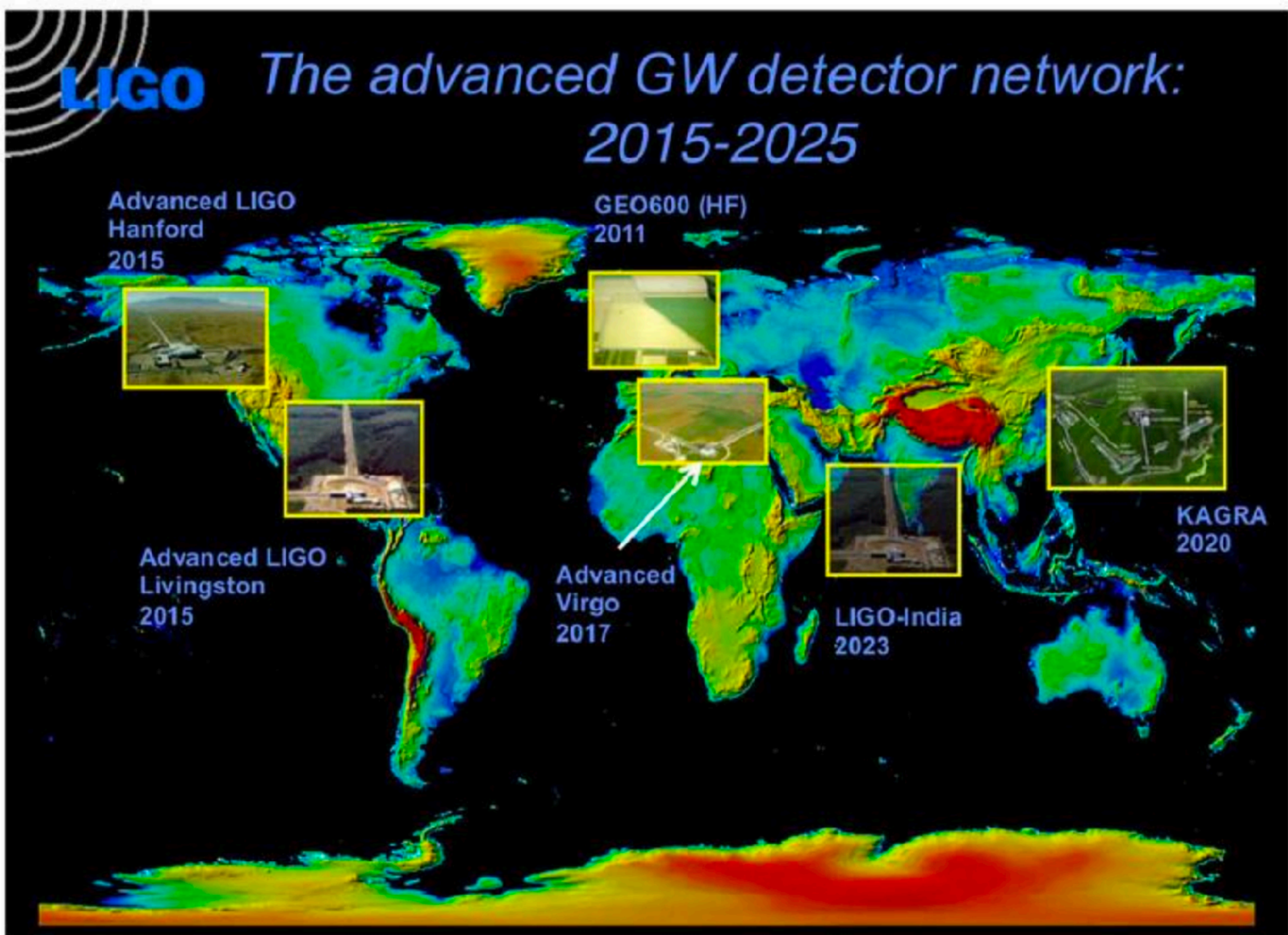
KAGRA  
2020

Advanced LIGO  
Livingston  
2015

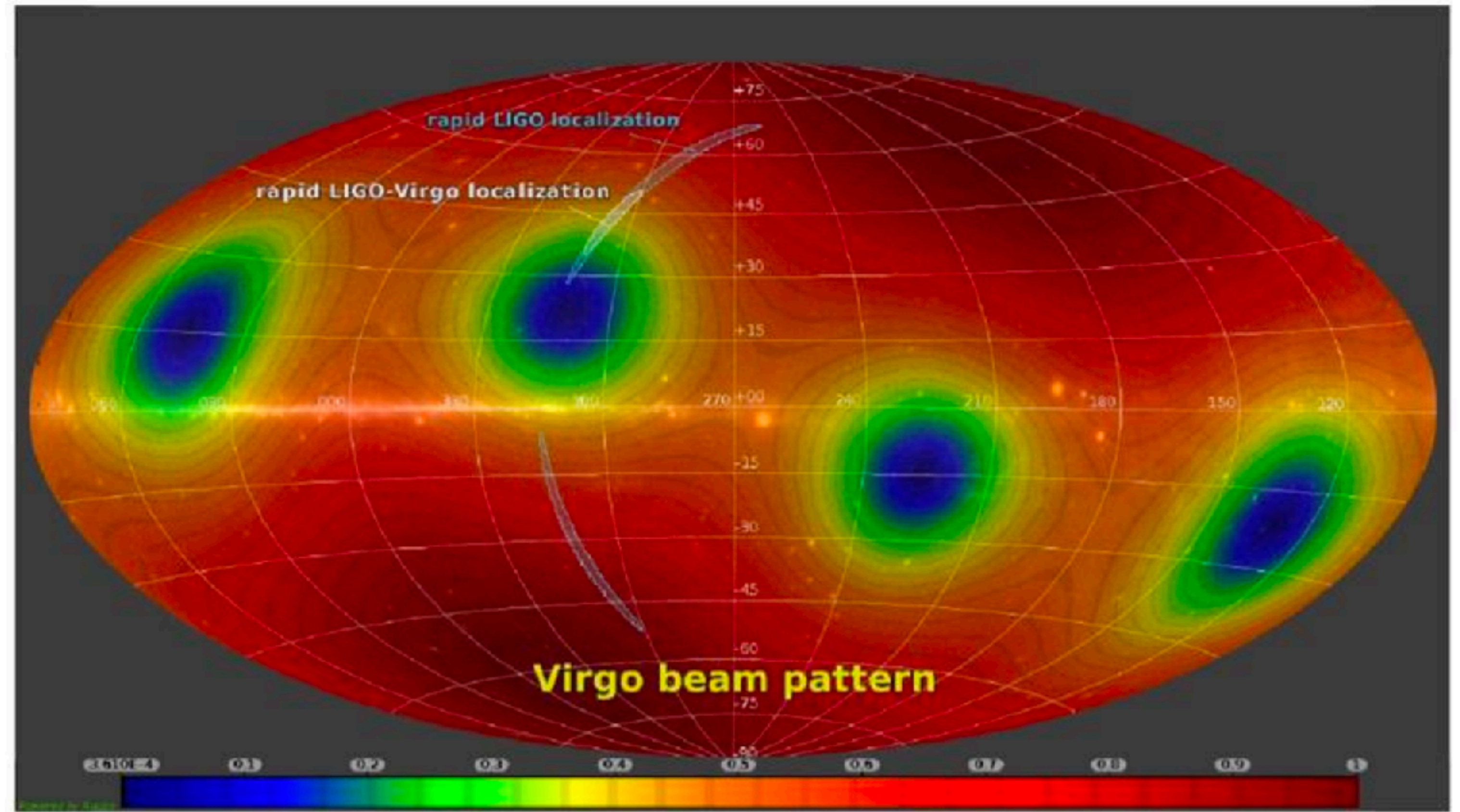
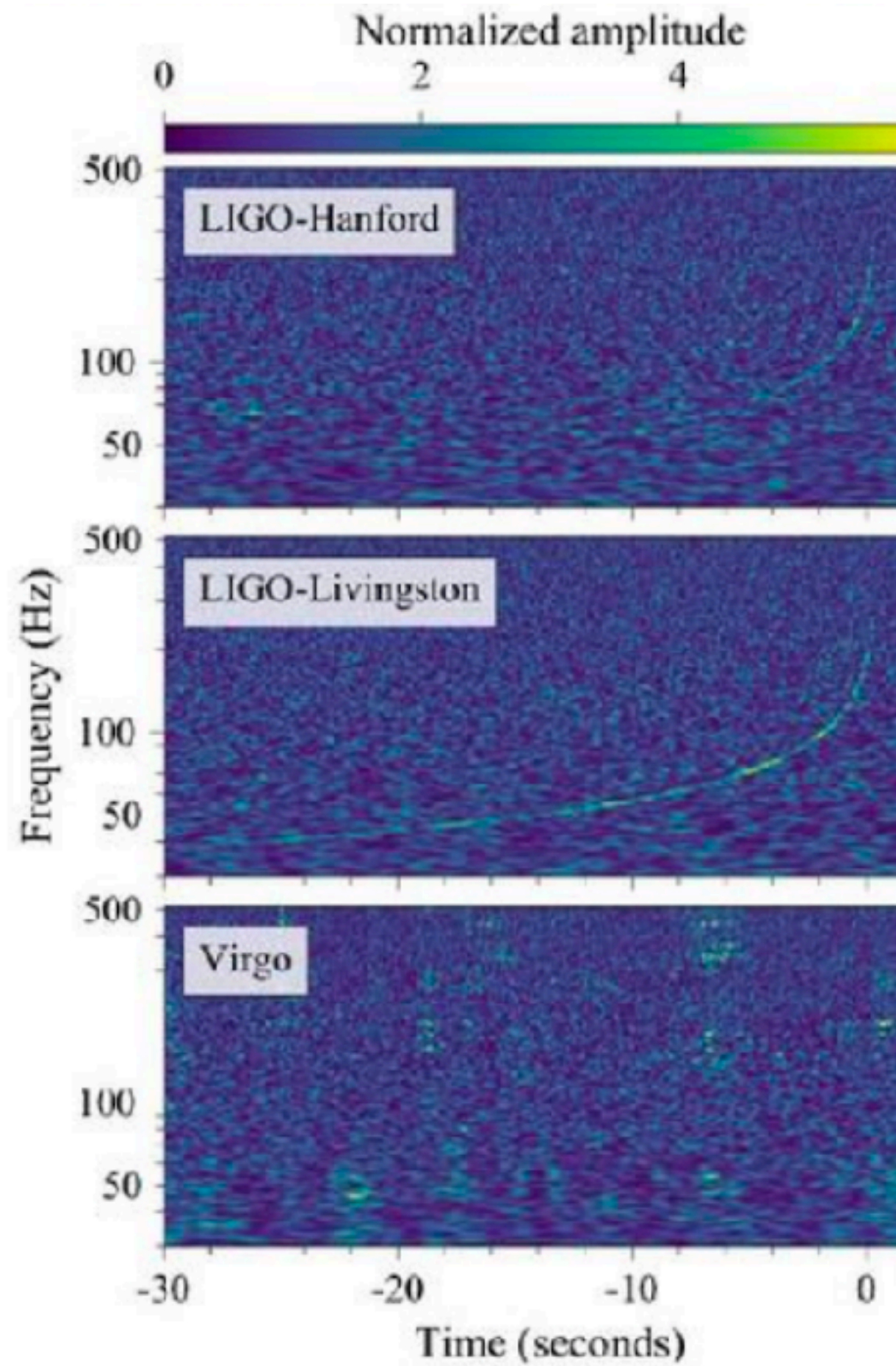
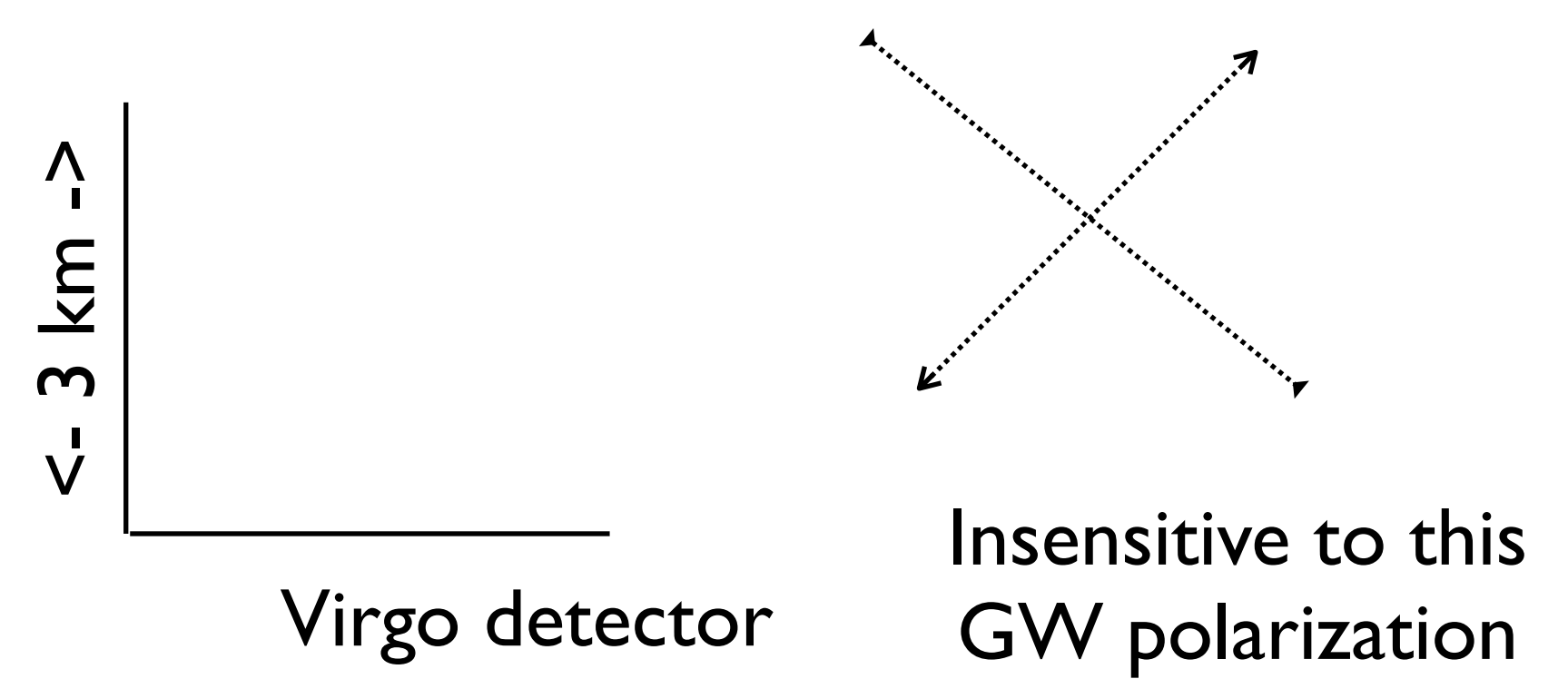
Advanced  
Virgo  
2017



LIGO-India  
2023



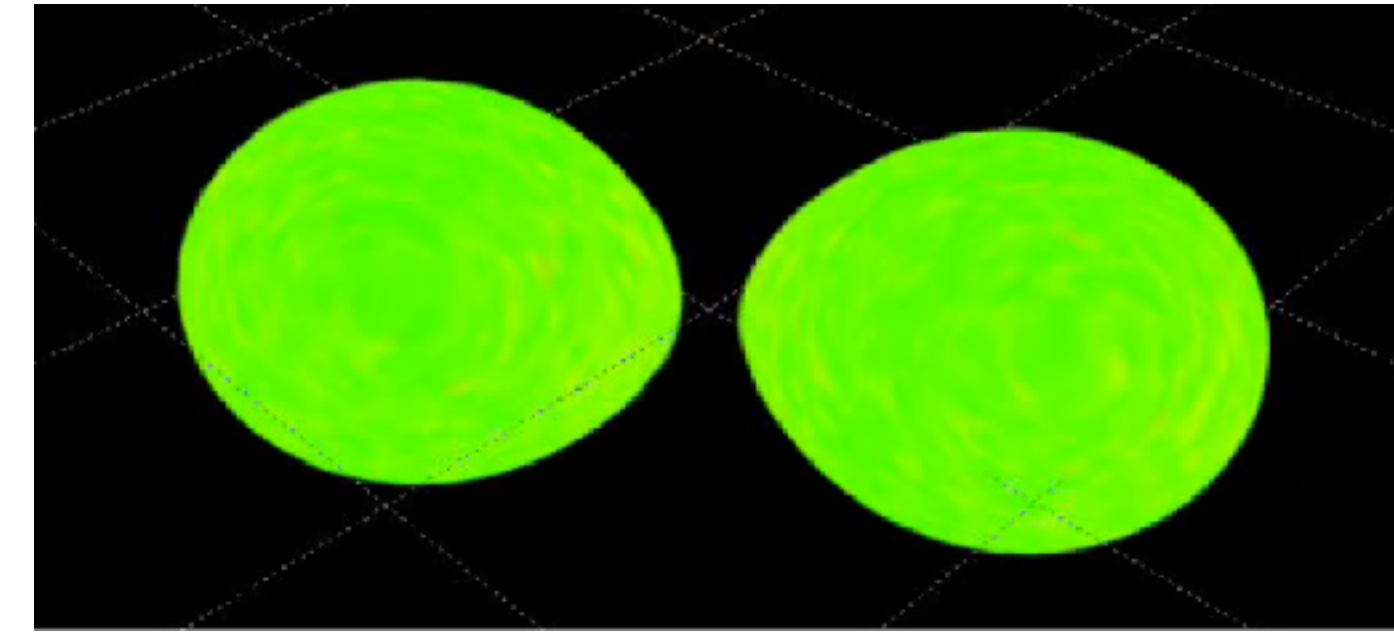
# GW170817 sky localization



- No clear signal in Virgo

# Merger GW170817: deformability of NS

- Gravitational tidal field distorts shapes of neutron stars just before merger.
- Dipole polarizability of an atom  $\sim R^3$ .

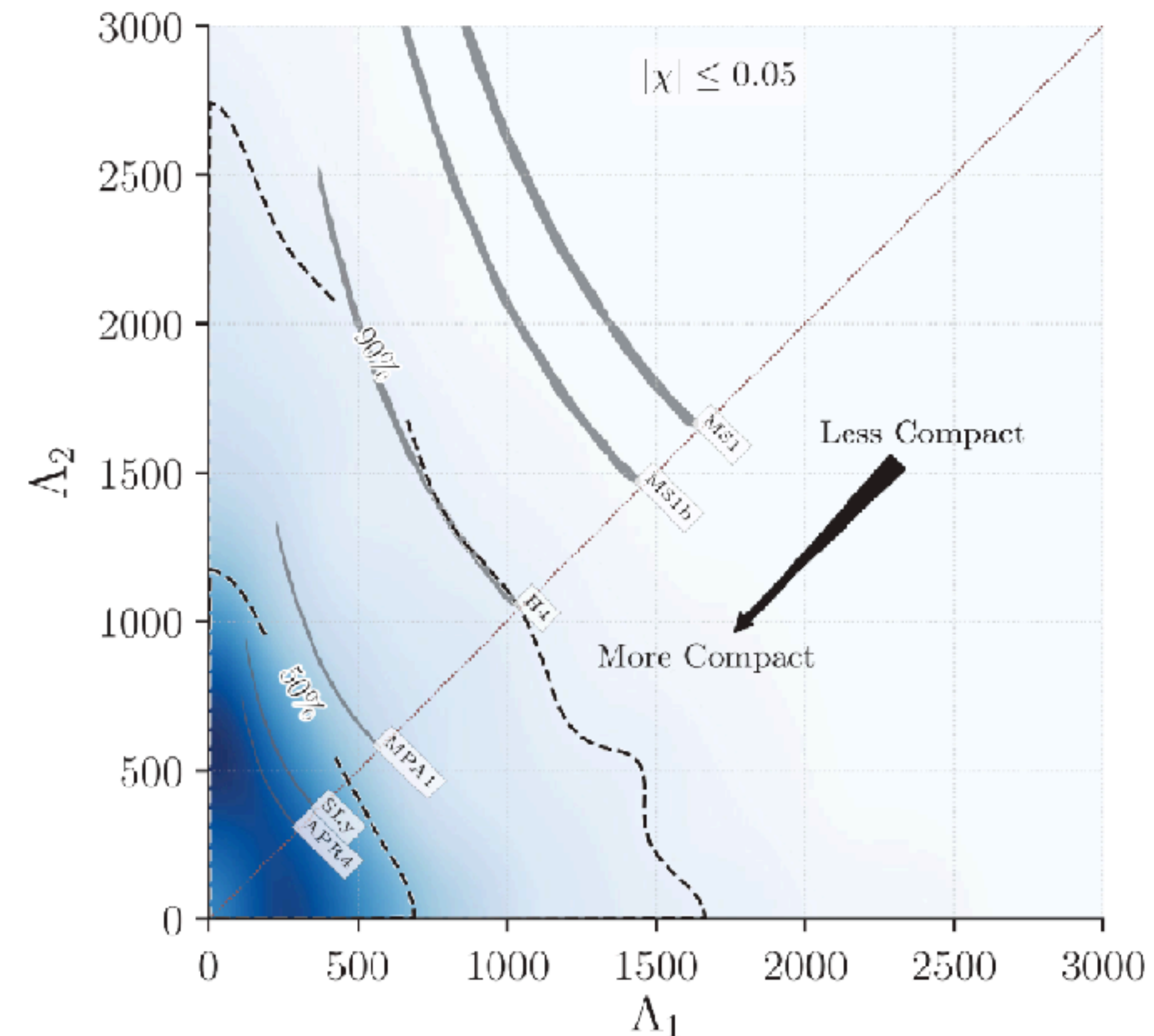


$$\kappa = \sum_f \frac{|\langle f | r Y_{10} | i \rangle|^2}{E_f - E_i} \propto R^3$$

- Tidal deformability (or mass quadrupole polarizability) of a neutron star scales as  $R^5$ .

$$\Lambda \propto \sum_f \frac{|\langle f | r^2 Y_{20} | i \rangle|^2}{E_f - E_i} \propto R^5$$

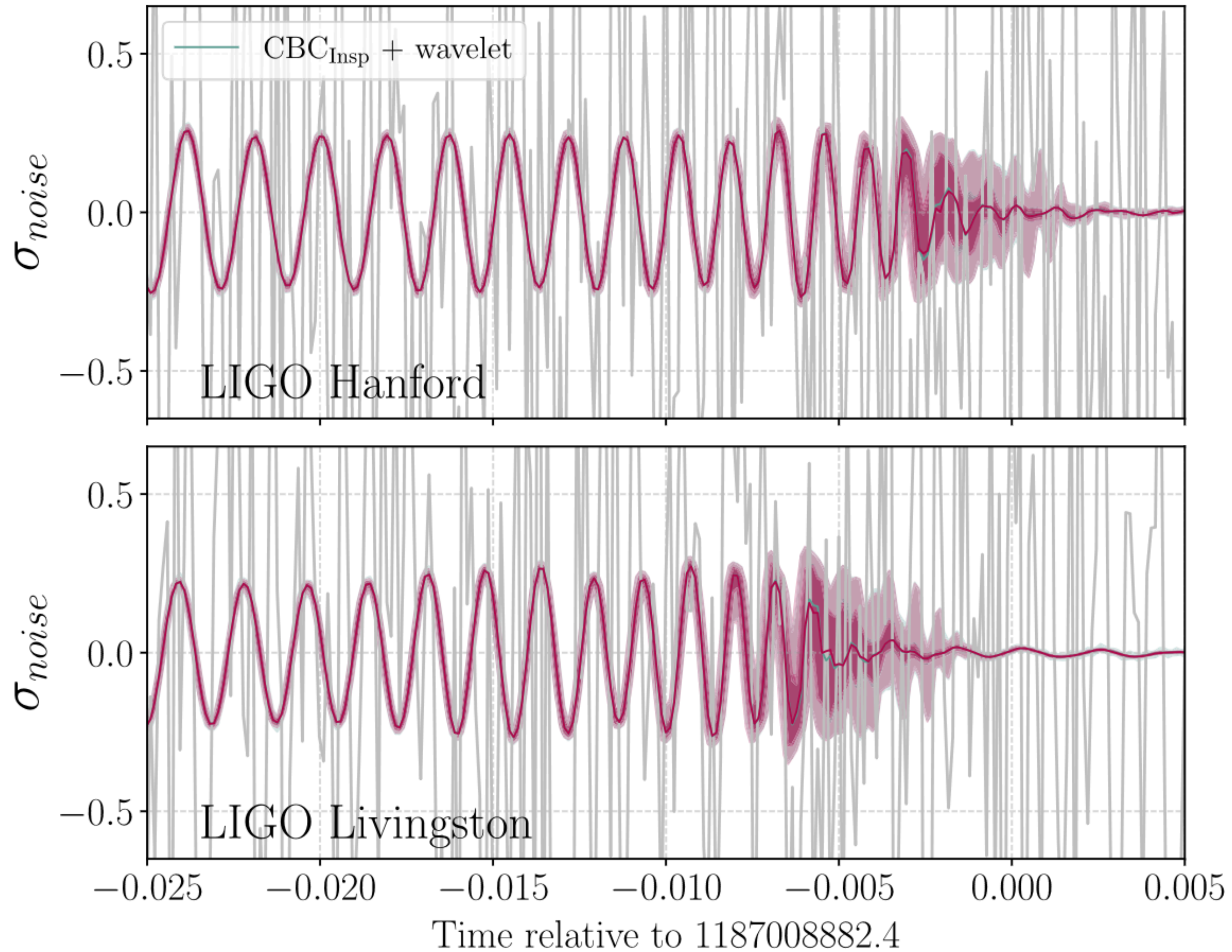
- GW170817 observations set upper limits on  $\Lambda_1$  and  $\Lambda_2$ .
- From  $R(M)$  can infer EOS.



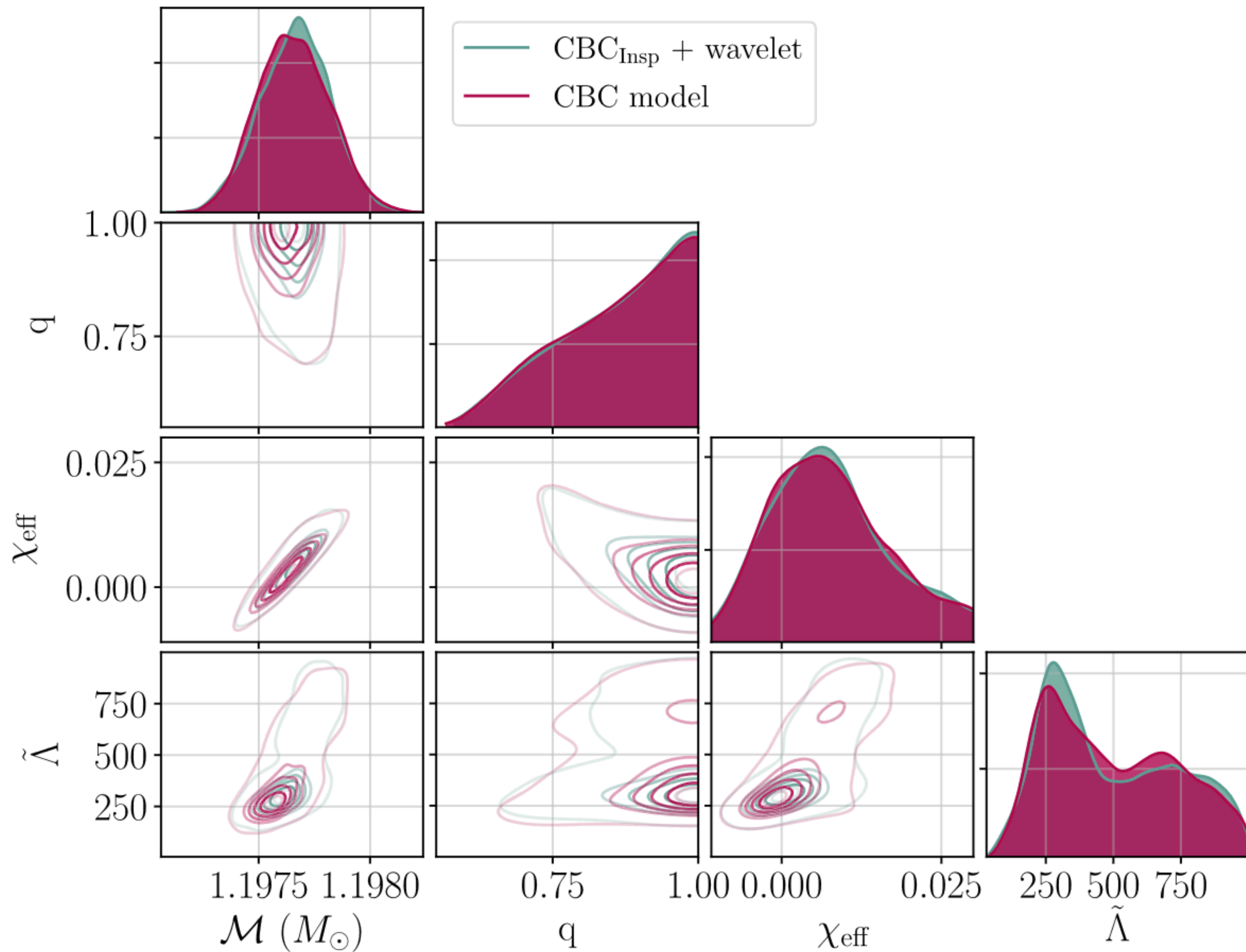
# Static and dynamical polarizabilities

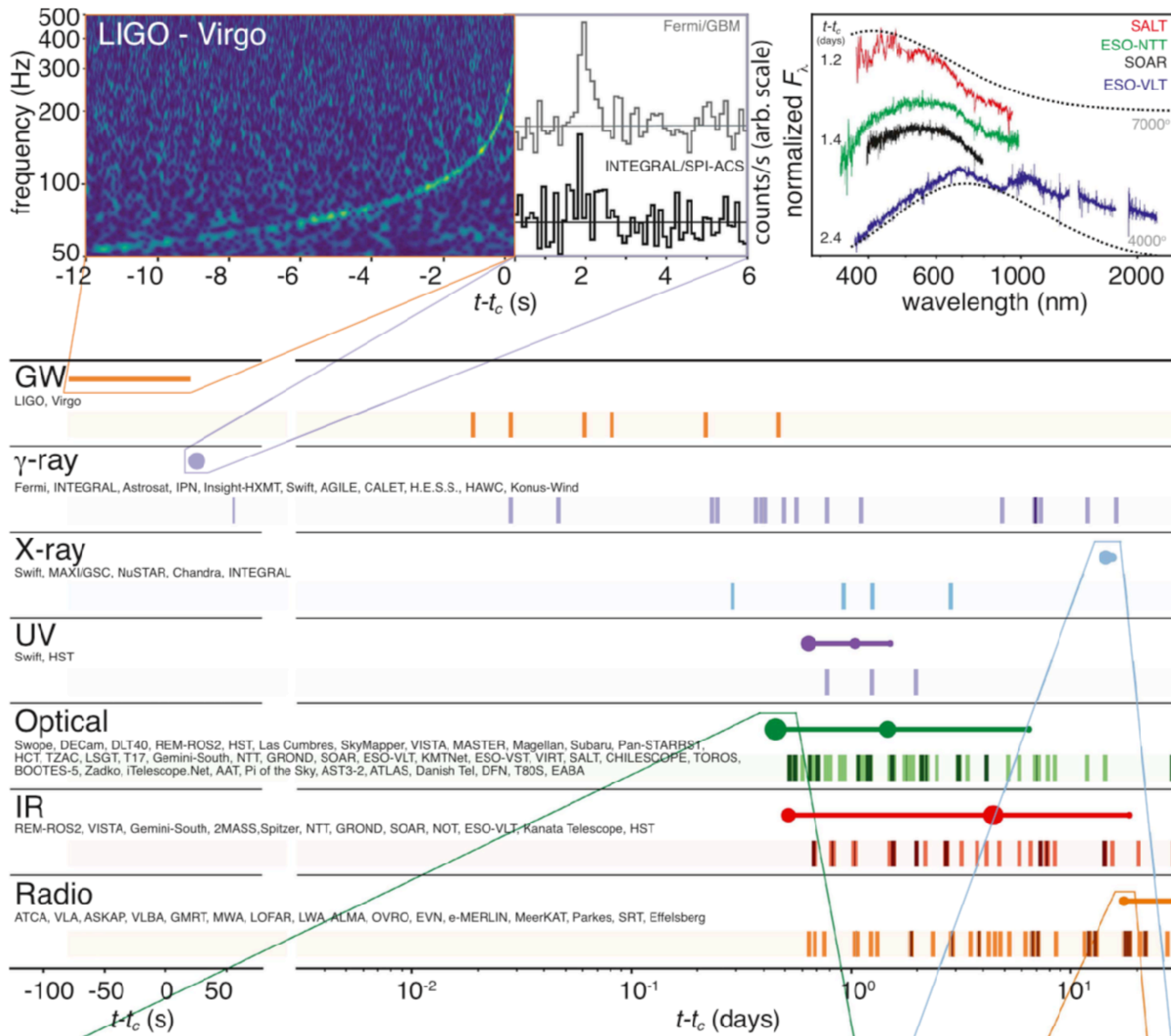
- Nuclear response to static electric field described by static dipole polarizability. Response to time dependent field  $\longrightarrow$  dynamical polarizability.
- NS response to static tidal field  $\longrightarrow$  described by gravitational deformability. Also can calculate dynamical tides.
- Important excitation modes: low energy pygmy resonance for neutron rich nuclei. For NS quadrupole f-mode important for deformability. Frequency of mode somewhat greater than merger frequency limits dynamical tides.

# Waveforms



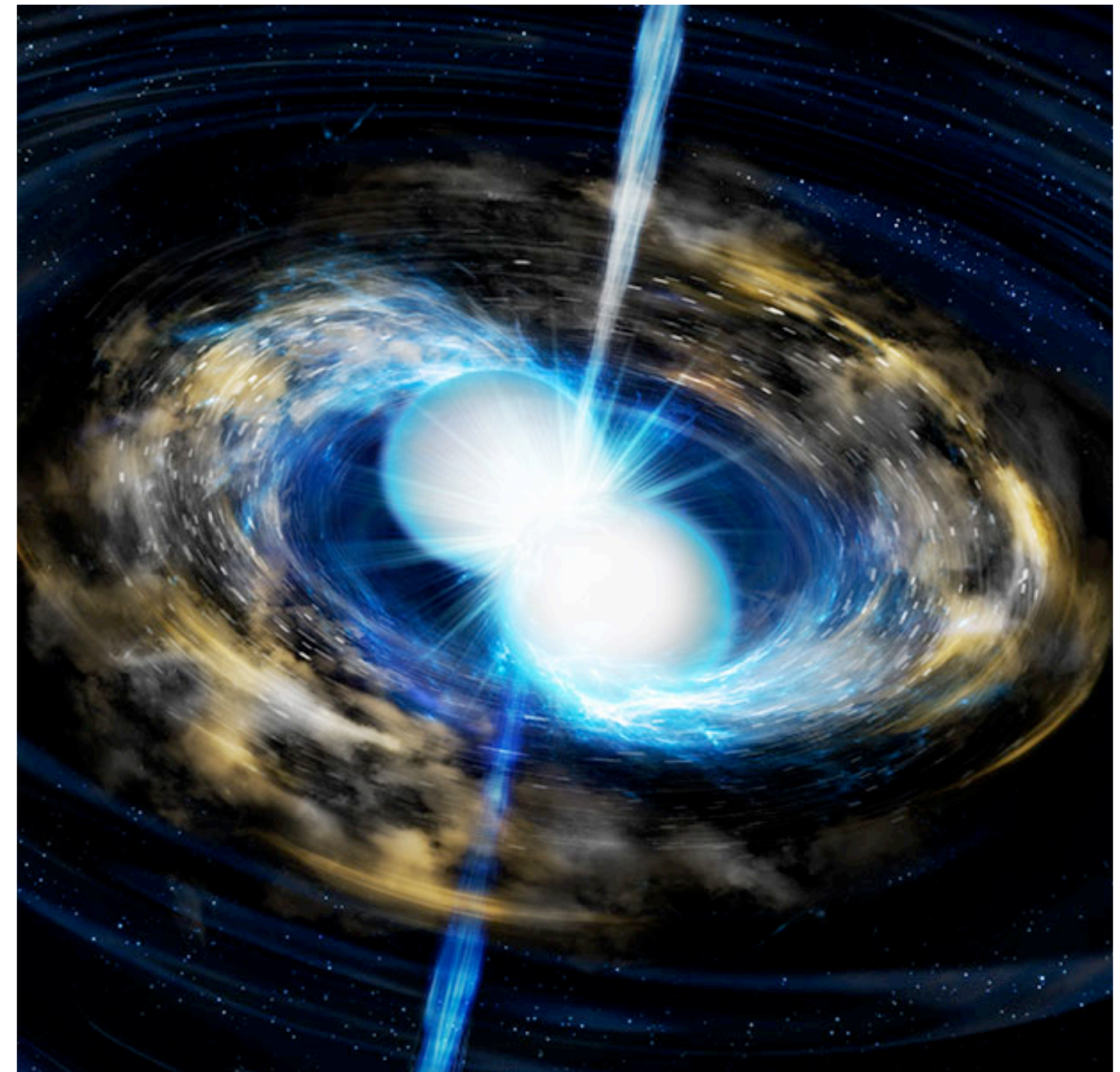
# Extracted parameters





# Kilonova: Merger of two NS

- Two neutron stars collided and ejected very neutron rich radioactive material. Radioactive decay powered kilonova seen with optical telescopes.
- Very red color suggests large optical opacity from lanthanides made in r-process nucleosynthesis.



Artist's conception of a neutron star merger and the resulting kilonova. (Credit: Tohoku University)

# Neutrons for the r-process

- Compress material to high density. Electron capture makes it n rich. Next, eject material without resetting  $Y_e$  with neutrinos. Dynamical ejecta could leave merger too quickly for neutrinos to destroy n.
- Or change neutrino flavors. If mostly anti- $\nu_e$  and little  $\nu_e$  then wind can make n. Example, n rich material may be ejected into lower density disk around remnant. This originally n rich disk will then leptonize and radiate more anti-neutrinos. Note, proto-NS is deleptonizing and radiating more neutrinos. Disk evaporation may be n rich.

# High speed of sound

- Large maximum NS mass  $\rightarrow$   $P$  is high at high densities.
- GW170817 set upper limit on deformability of NS  $\rightarrow$   $P$  is not too large near  $2\rho_0$ .
- $P$  rises rapidly with density. Speed of sound  $C_s^2 = dP/d\rho$  is large  $> (1/3)c^2$ .
- Expect  $C_s^2 = 1/3$  as  $\rho \rightarrow$  infinity in QCD. Not there yet.

# Why is sound speed high?

- Massless fermions or bosons  $C_s^2 = 1/3$
- Massive vector exchange  $C_s^2 \rightarrow 1$
- Perturbative QCD  $\rightarrow 1/3$  from below as  $\rho \rightarrow \text{infinity}$
- Dense matter in NS is strongly interacting system probably beyond Chiral EFT and not yet asymptotically free quarks and gluons.
- Is it strongly interacting quarks or strongly interacting hadrons?

# Diversity of neutron star mergers

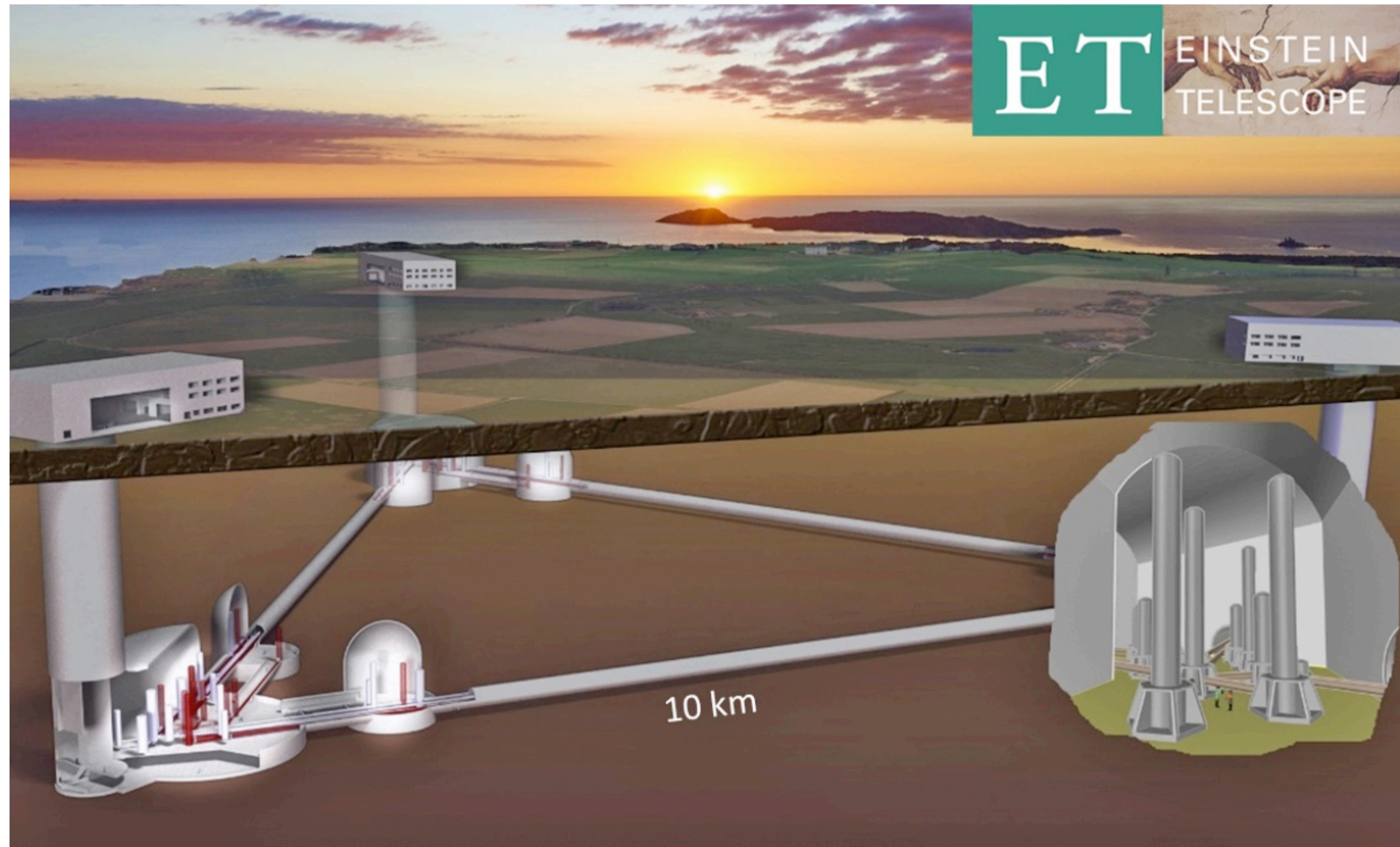
- GW170817 had chirp mass  $1.198M_{\text{sun}}$  for equal mass stars this implies  $M_1=M_2=1.38M_{\text{sun}}$ . Total mass  $=2.76 M_{\text{sun}}$ . This is above TOV mass so system very likely collapsed to black hole.
- Merger with a larger total mass will likely collapse sooner and eject less material producing a dimmer kilonova. In the limit  $M_1=M_2=2M_{\text{sun}}$  the system may undergo prompt collapse to BH with little E+M radiation.
- Mergers with smaller total mass will have remnants that live longer, ejecting more material and may have a brighter kilonova.
- In the limit  $M_1+M_2 < M_{\text{TOV}} + \sim 0.15M_{\text{sun}}$  (GW radiation) A stable massive NS could be produced! This would likely be a ms Magnetar and have a very large luminosity.

# **(Im)patiently waiting for next neutron star merger**

We have not seen another (with E+M counterpart) in ~10 years

# Next generation gravitational wave observatories

- The Einstein Telescope is proposed GW detector to be built at Dutch-Belgian-German border or in Sardinia.
- Cosmic explorer is proposed US detector with 40 km arms.
- 10 times more sensitive, 1000 x detection rate, of existing LIGO and VIRGO.
- They could accurately measure deformability of neutron stars. Only depends on GR and EOS.



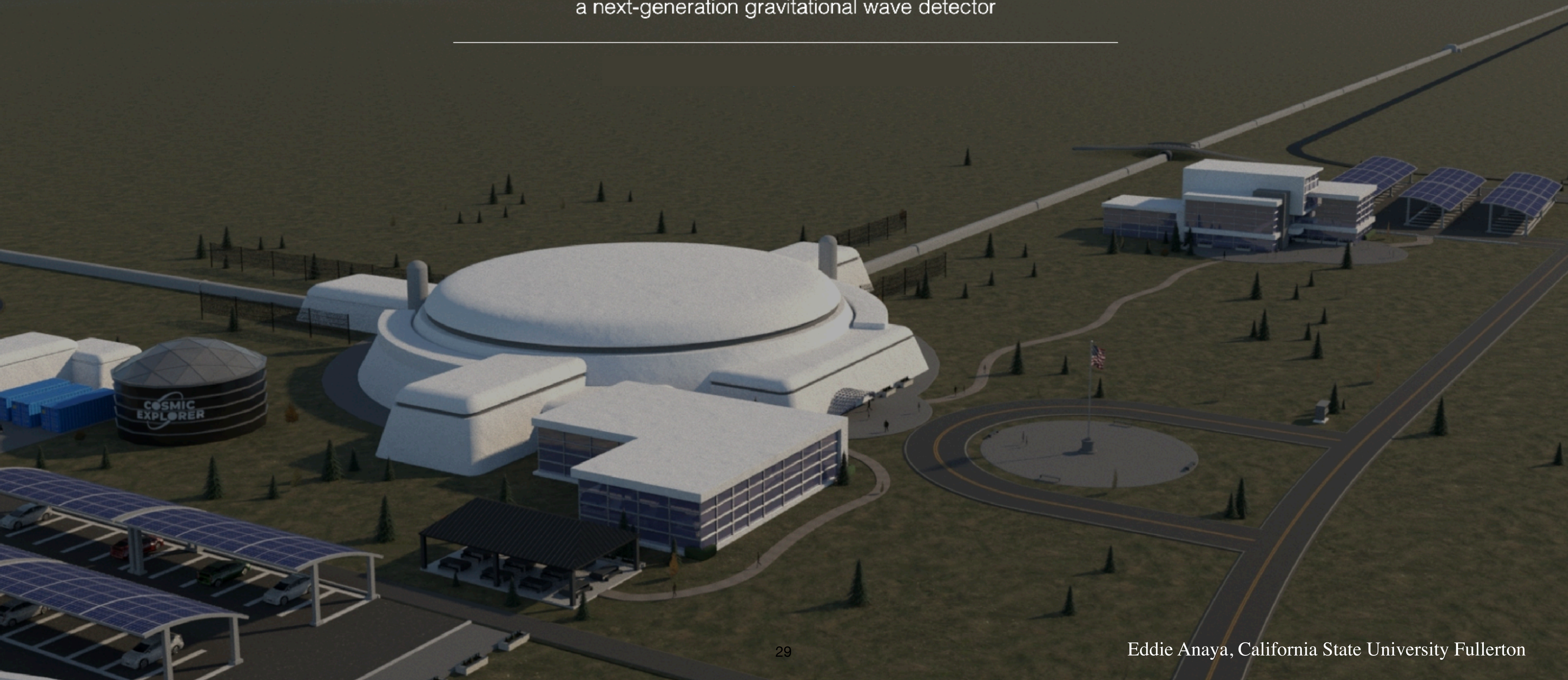
# Gravitational Deformability

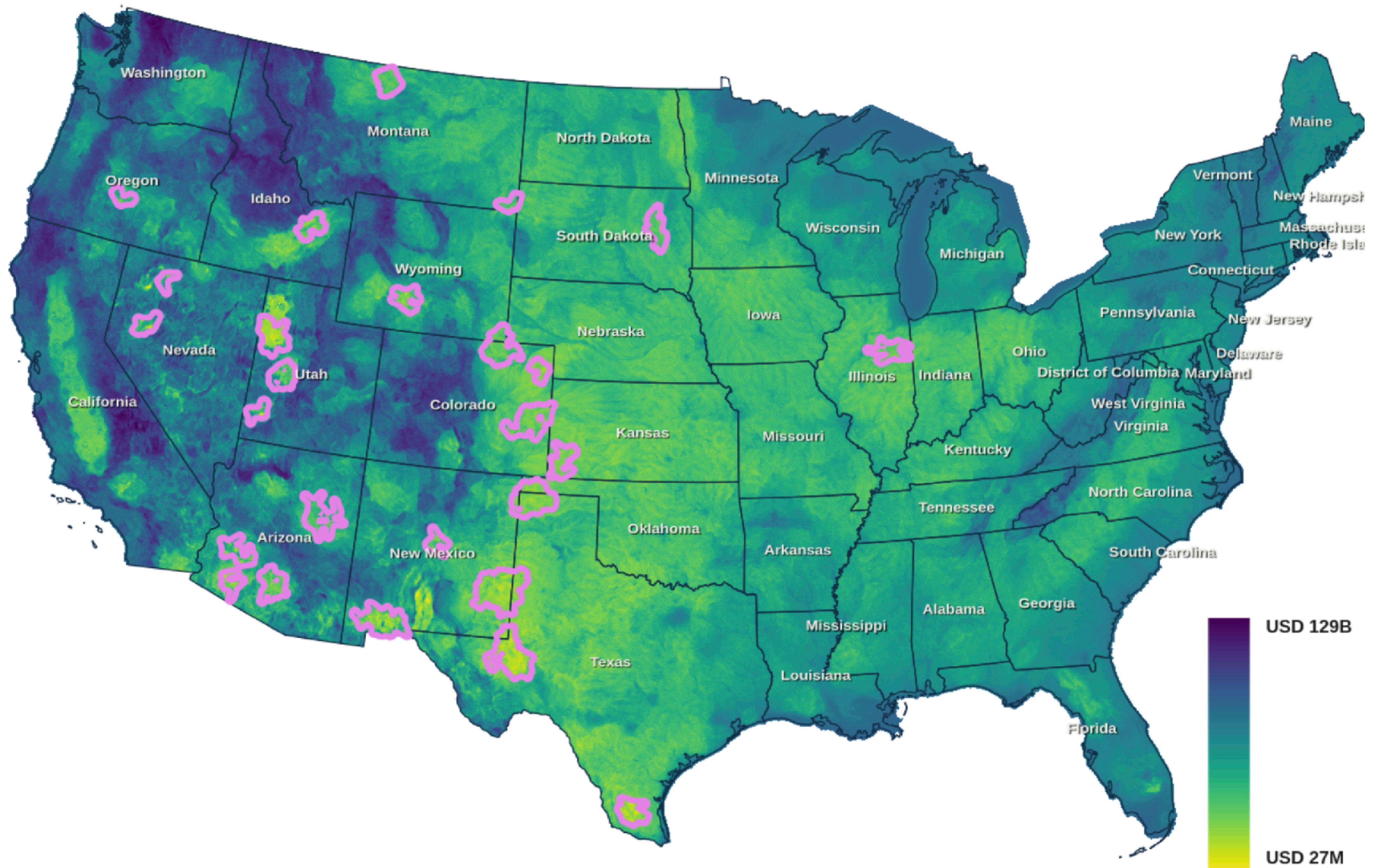
- Theory: depends only on GR and EOS.
- Observation: systematic errors from model wave forms, machine calibration ... can be controlled.
- Next generation detectors Cosmic Explorer, Einstein Telescope with 10 times sensitivity can accurately measure deformabilities. Very exciting.

# Cosmic Explorer

a next-generation gravitational wave detector

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# Network of next generation detectors

- Needed to locate sources on sky for E+M follow up.
- Current thinking: 40 km Cosmic Explorer in US, roughly comparable Einstein Telescope in Europe (could be two 15 km detectors), and 4 km LIGO India

# Some open NS merger questions

- What is the NS deformability and how does it depend on mass. What is equation of state of dense matter.
- How long does merger remnant survive before collapse to black hole?
- How bright is Kilonova? What is nucleosynthesis yield? How do these grow with decreasing system mass?
- How diverse are NS mergers? What is mass distribution?
- Is a millisecond Magnetar produced? Is it stable?
- Can we detect GW from post merger? Is there evidence of a phase transition at high density?

