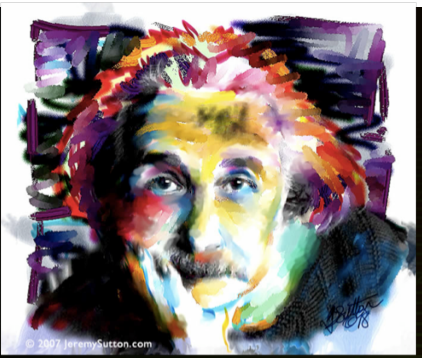
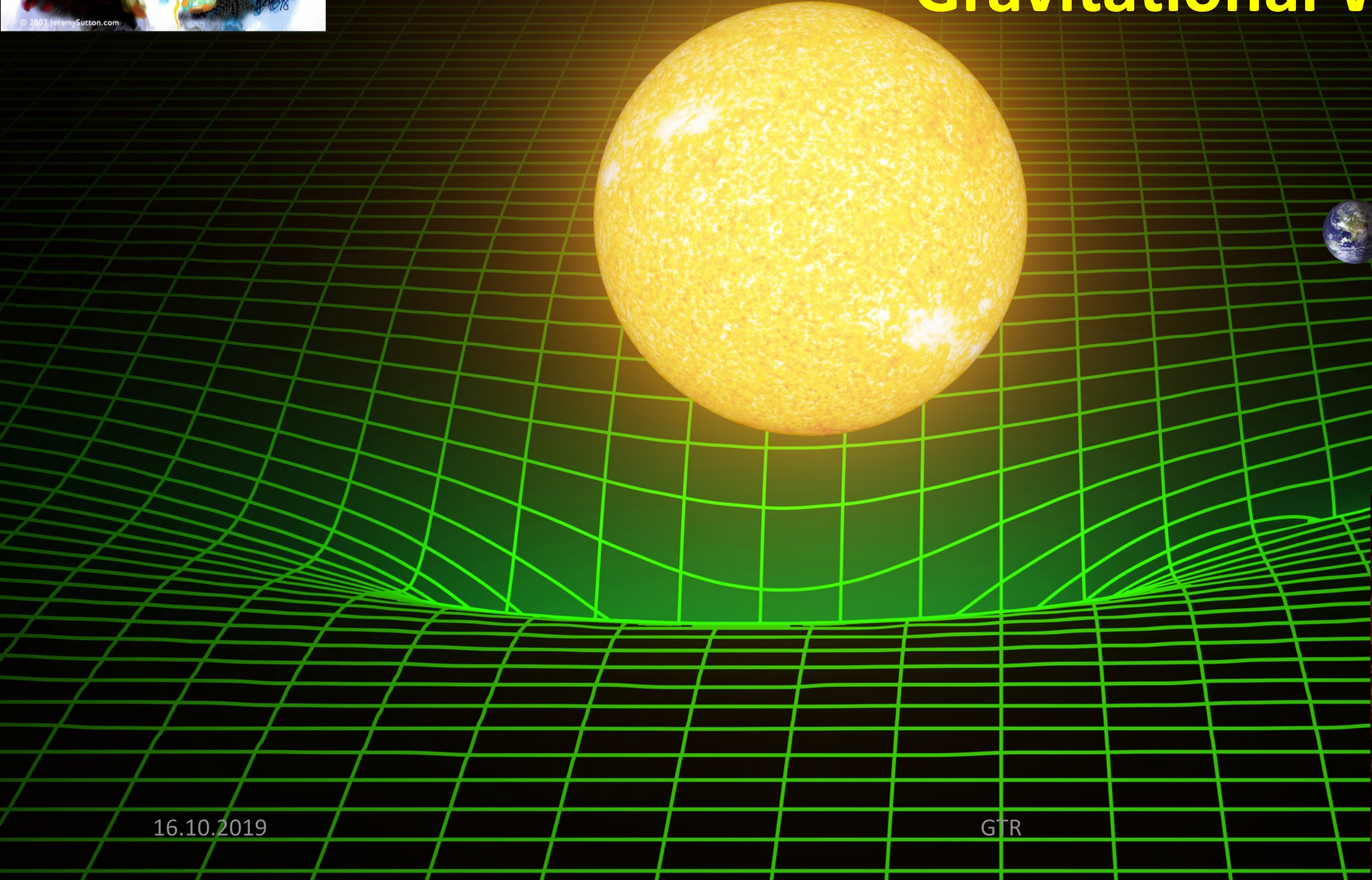


General Theory of Relativity
&
Gravitational Waves

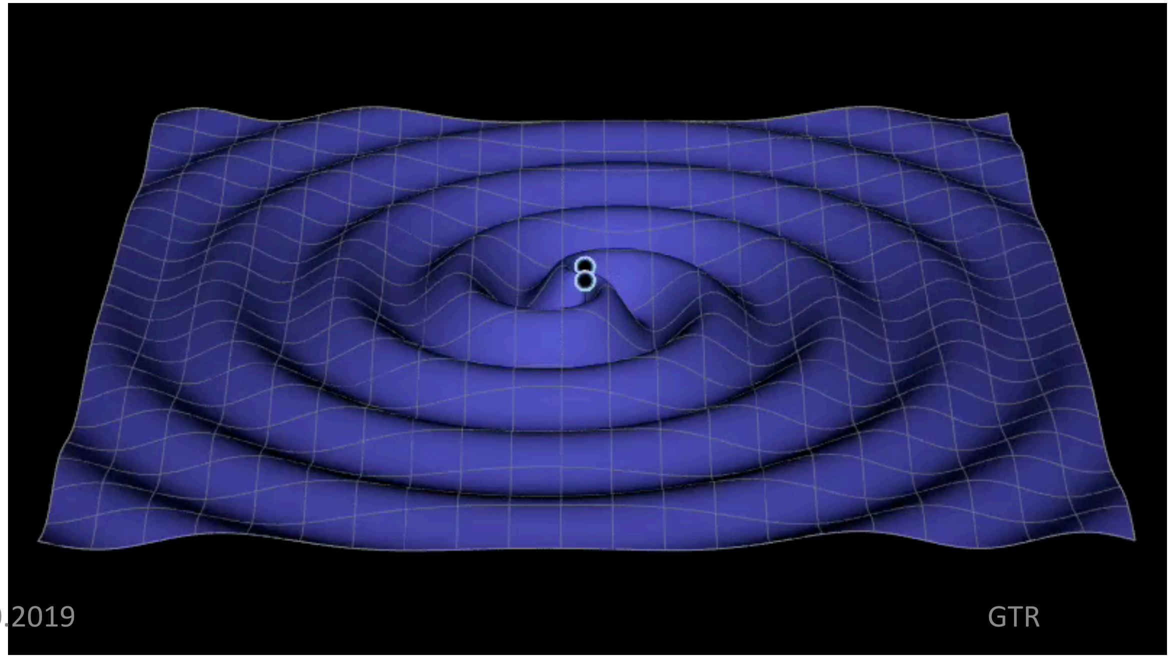
KOSTAS KOKKOTAS



WHAT ARE THE GRAVITATIONAL WAVES

- Ripples of Spacetime Curvature
- Ppropagate with the Speed of Light
- Interact WEAKLY with Matter
- Every Variation of the Gravitational Field Produces GWs

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

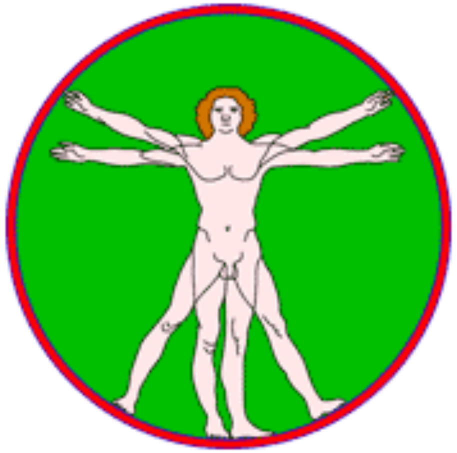


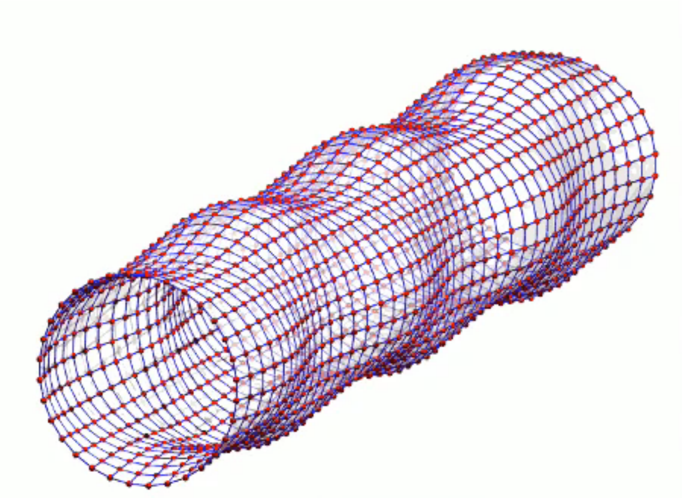
$$\left(\frac{1}{c^2}\frac{d^2}{dt^2} - \nabla^2\right) h^{\mu\nu} = \frac{4\pi G}{c^4} T^{\mu\nu}$$

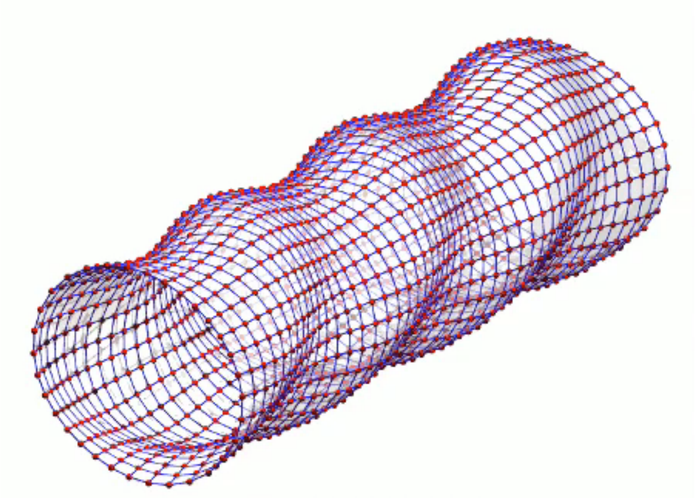
$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$

WHAT ARE GRAVITATIONAL WAVES

They produce **tidal deformations** on massive bodies.

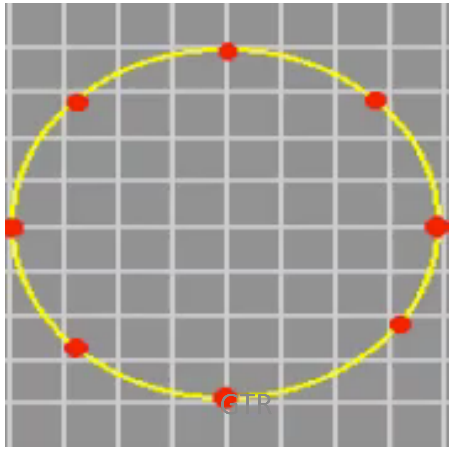


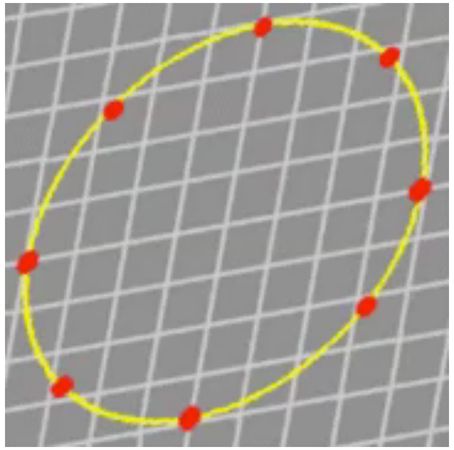




… and deform periodically the spacetime geometry

$$\Delta L \sim h \ * \ L$$





Gravitational vs Electromagnetic Waves

- **EM waves are radiated by individual particles, GWs are due to non-spherical bulk motion of matter.**
  - The information carried by EM waves is <u>stochastic</u> in natu <u>currents</u>.
- **The EM waves will have been scattered many tim matter and arrive at the Earth in pristine conditio**
  - Therefore, GWs can be used to probe regions of space that are opaque to EM waves.

Morale

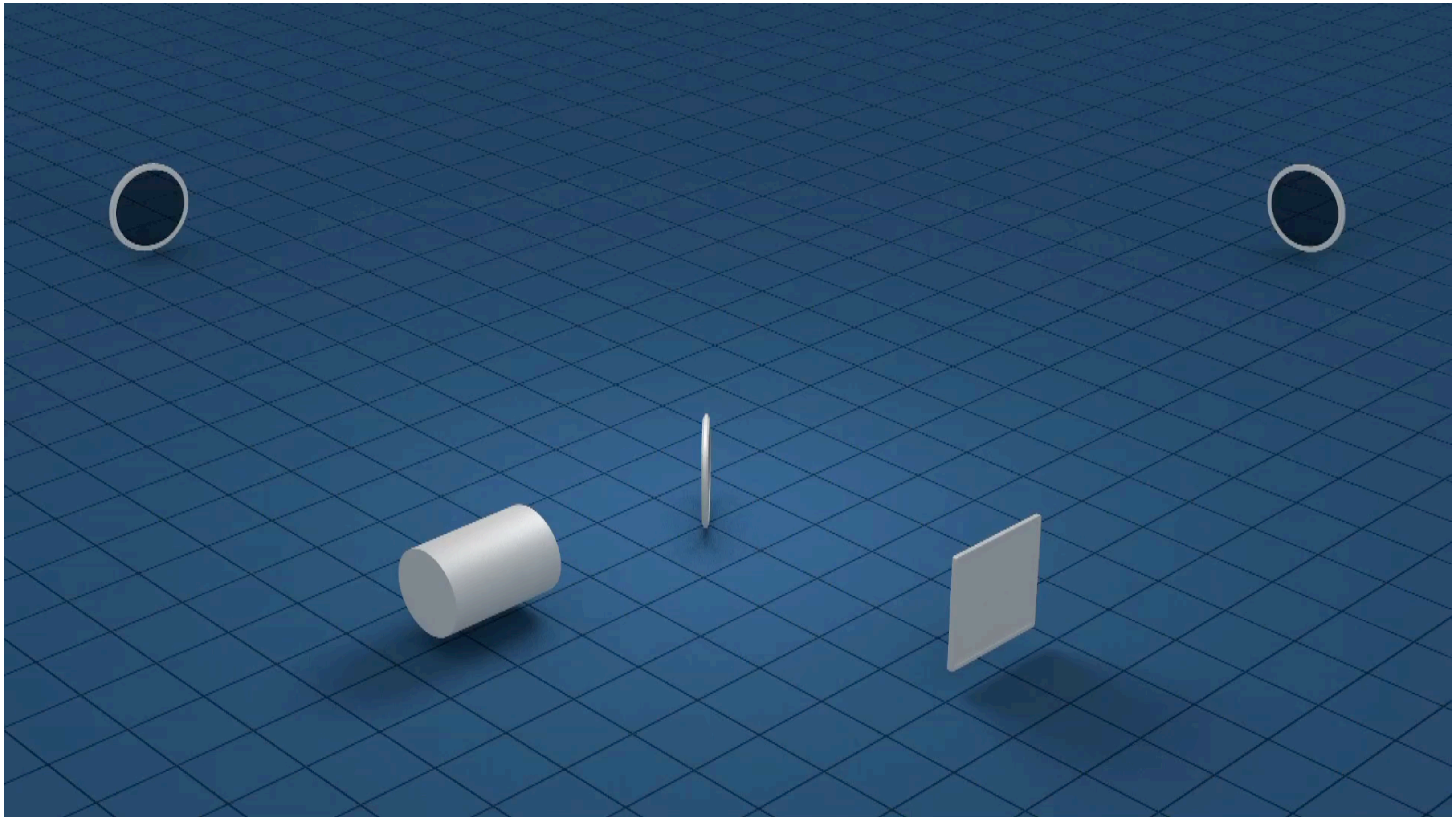
GWs carry information which would be difficult to get by other means.

- Standard astronomy is based on **deep imaging of small fields of view**, while **GW detectors cover virtually the entire sky**.
- **EM radiation has a wavelength smaller than the size of the emitter, while the wavelength of a GW is usually larger than the size of the source.**
  - Therefore, we cannot use GW data to create an image of the source.
  - ***<u>GW observations are more like audio</u>*** than **visual**
- **Neutrinos:** are more like EM waves than GW in most respects, except…
  - Propagate through most things like GW, so you can see dense centers
  - But neutron stars don't generate so many ν after first few minutes.

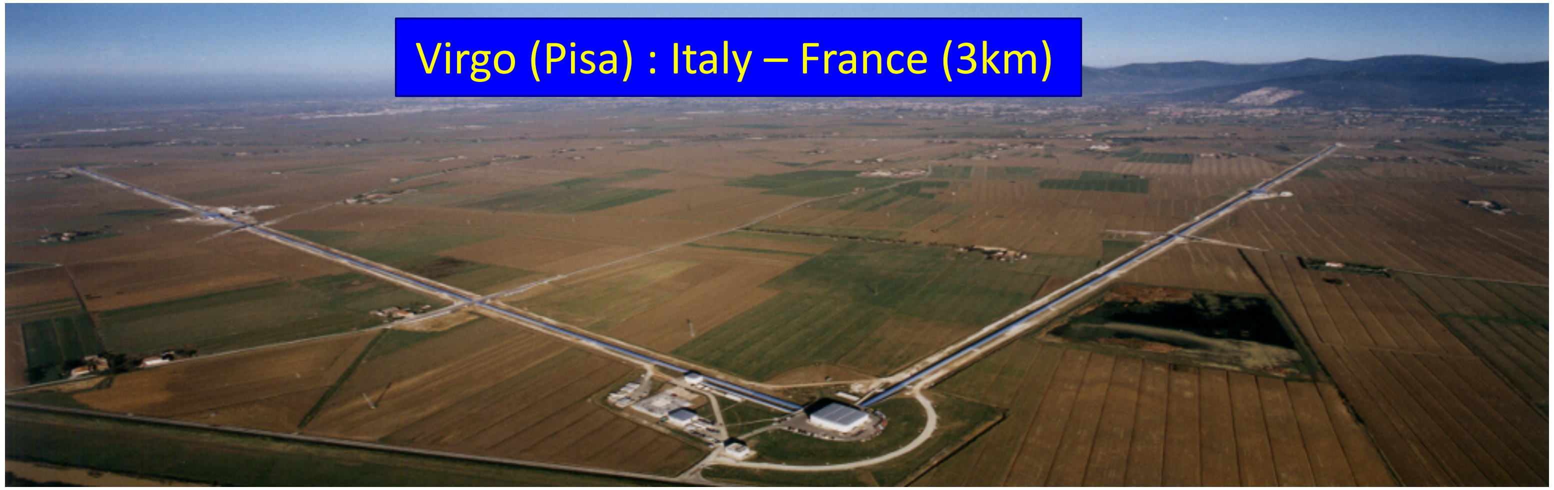
GRAVITATIONAL WAVE DETECTORS

Rainer Weiss

Roland Drever



THE FLAGSHIP DETECTORS



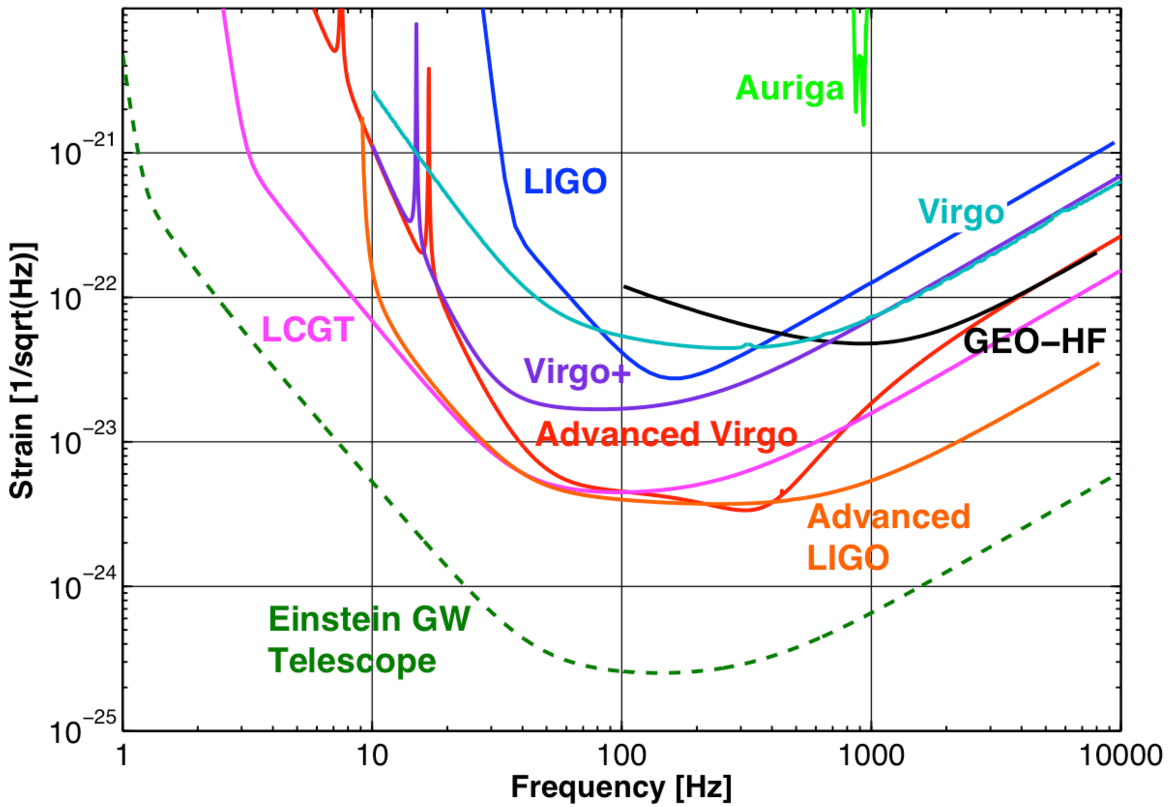
KAGRA:
Large-scale Cryogenic GW Telescope (Japan)

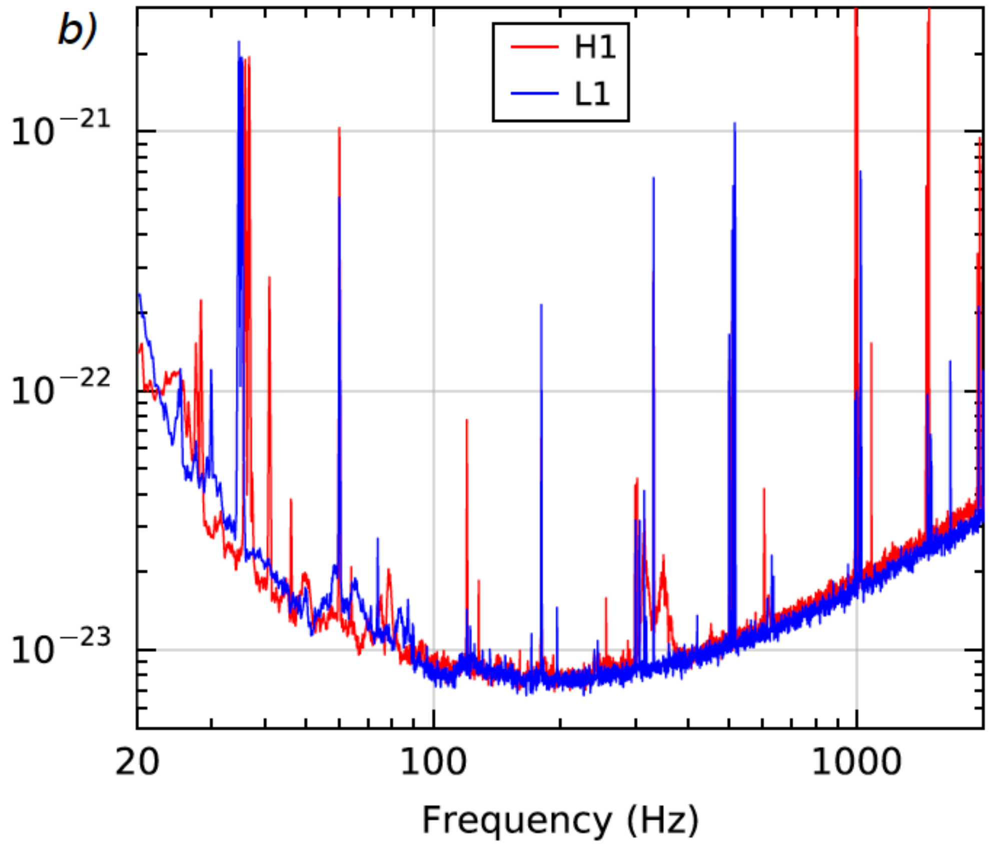
Maybe operational in 2019-20

- KAGRA consists of a modified Michelson interferometer with two 3-km long arms, located in the ground under Kamioka mine.
- The mirrors are cooled down to cryogenic temperature of -250 Celsius degree (20 Kelvin). Sapphire is chosen for the material of the mirror.

INDIGO (India-USA) : Similar to existing LIGOs

SENSITIVITY CURVES



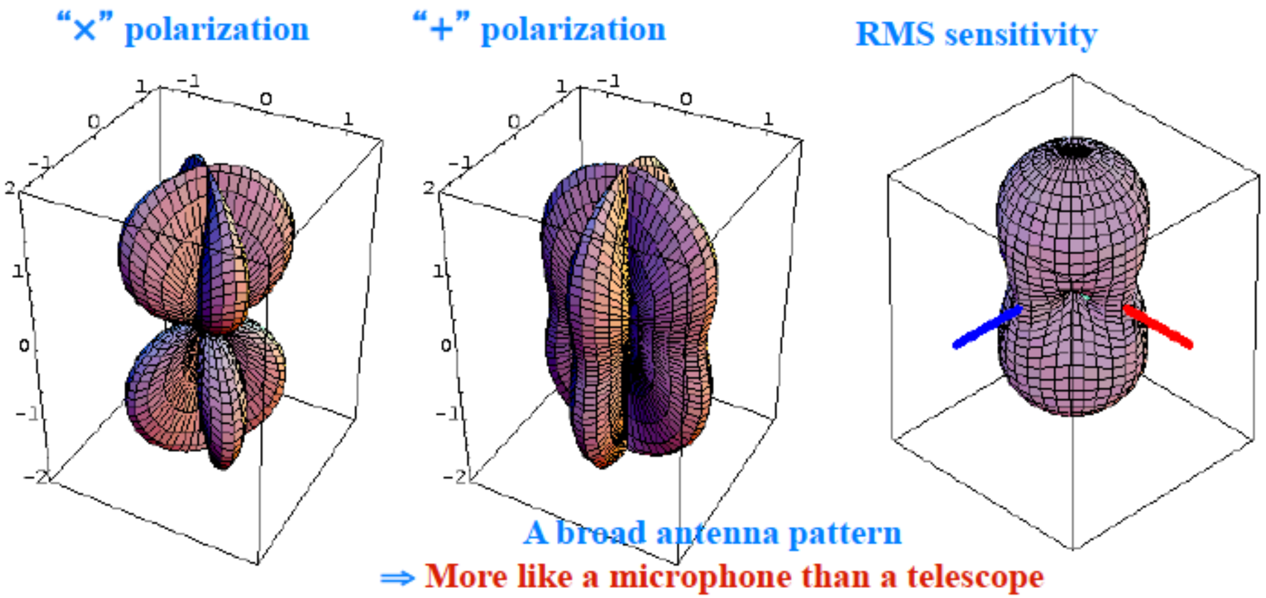


Antenna Pattern of a Laser Interferometer

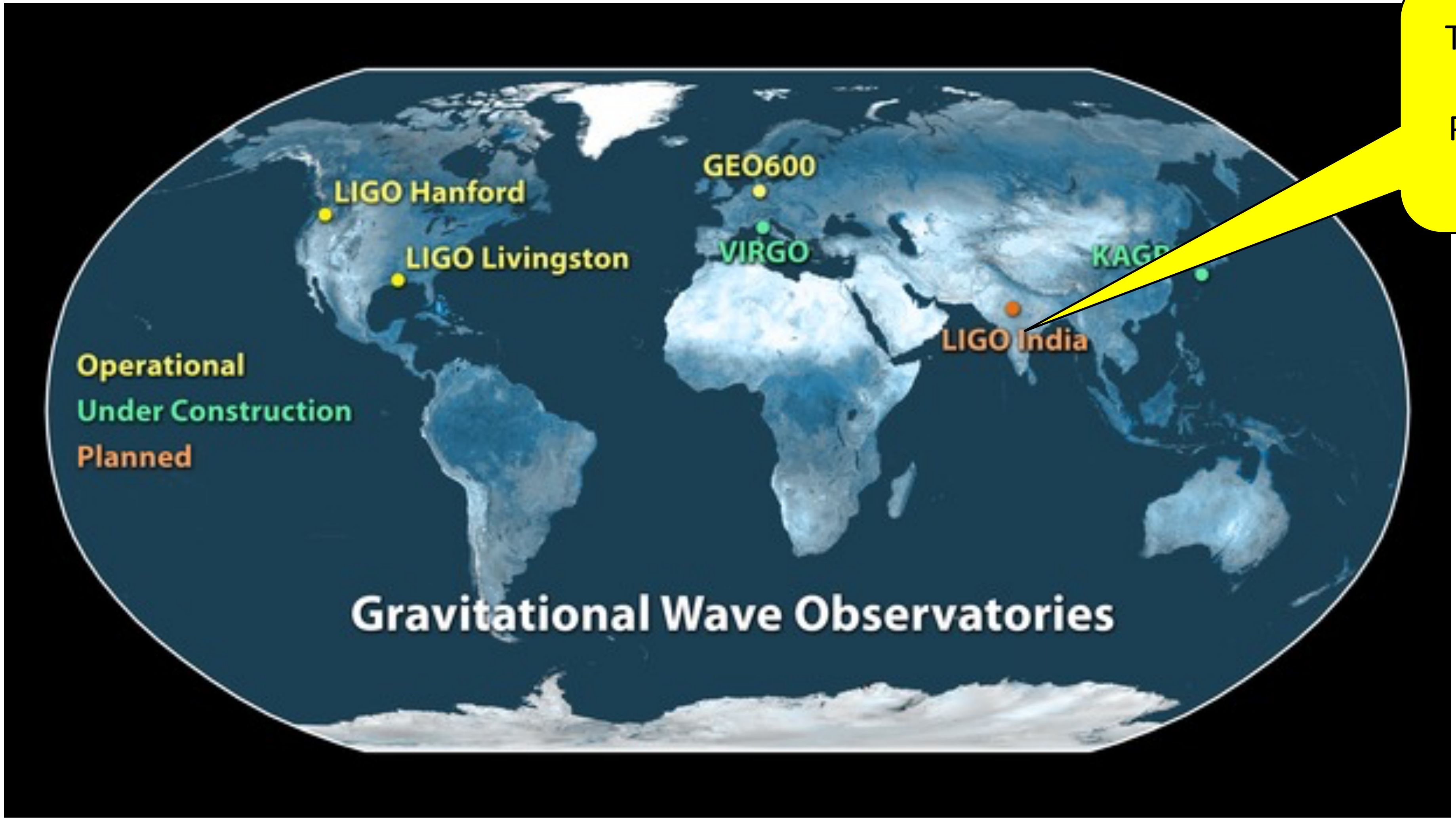
The strain **x(t)** measured by a detector is mainly dominated by noise **n(t)**, such that even in the presence of a signal **h(t)** we have

$$x(t) = n(t) + h(t) \quad \text{where } h(t) = F_{+}(t;\psi)h_{+}(t;\psi) + F_{\times}(t;\psi)h_{\times}(t;\psi)$$

F_+ and **F_x** are the strain antenna patterns. They depend on the orientation of the detector and source and on the polarization of the waves

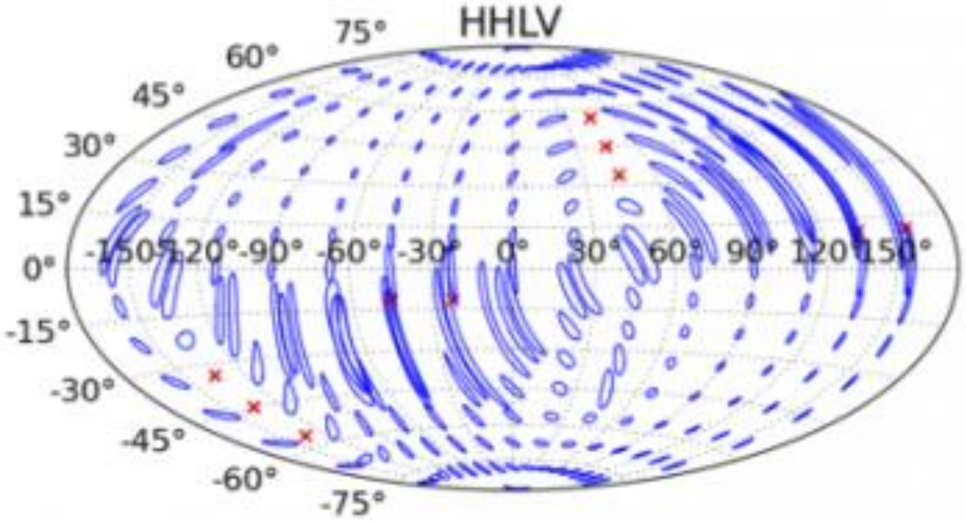


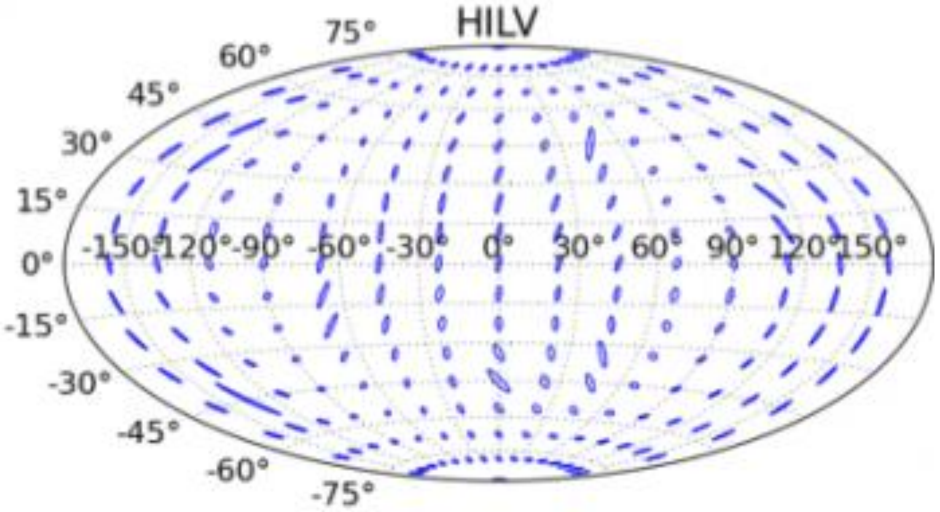
THE GLOBAL NETWORK



THE INDIAN GOV. APPROVED THE PROJECT ON THE **17.2.2016**

WHY SO MANY?





LIGO I
LIGO II
VIRGO

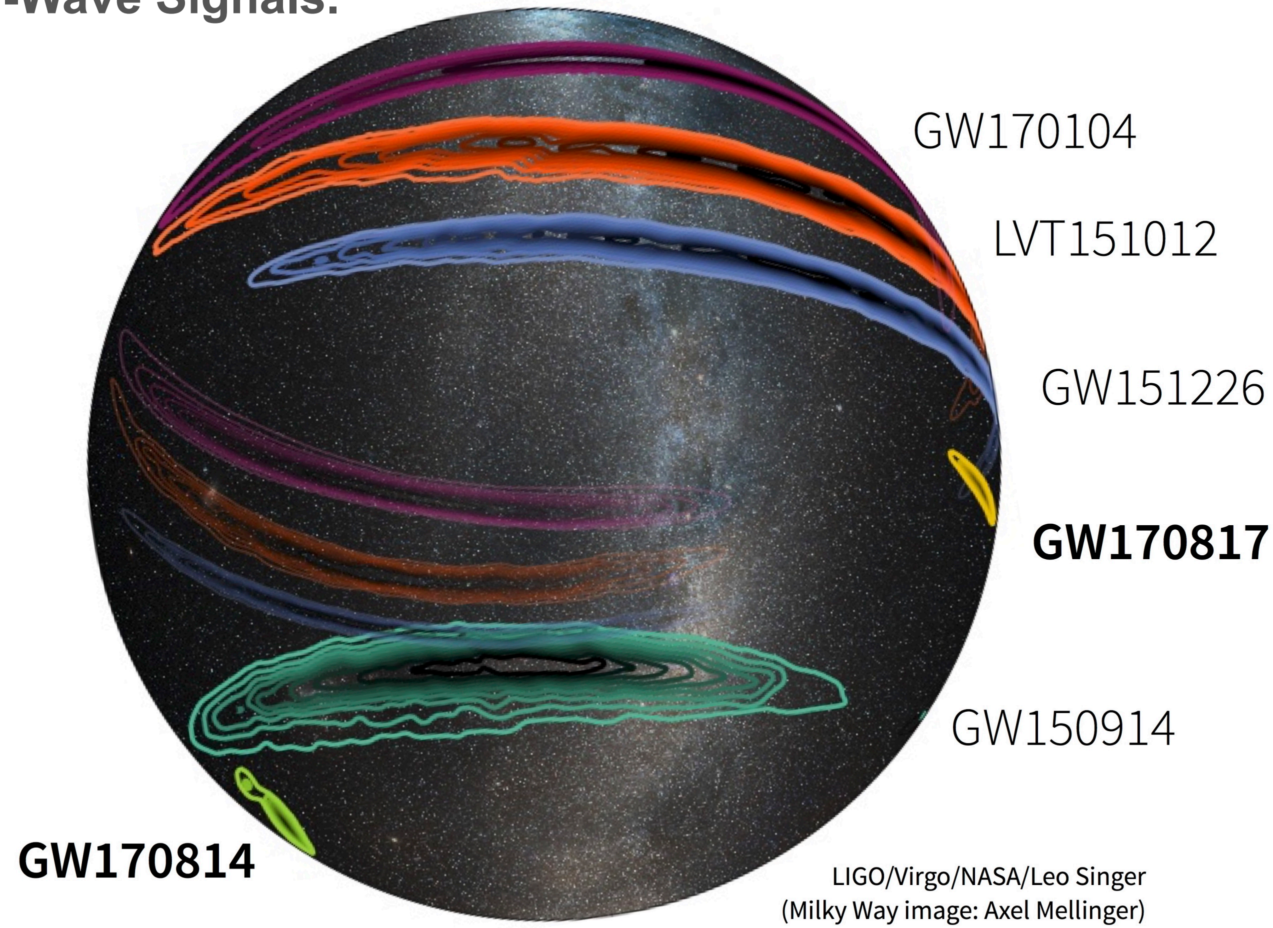
ERROR IN POSITIONING THE SOURCE

LIGO I
LIGO II
VIRGO
INDIGO

- ✓ **Confidently detect** & **locate** the sources of GWs
- ✓ **The detection delay** (~**10 milliseconds**) between LIGOs, Virgo, KAGRA, IntiGO will help pinpoint the sky location of the GW source.
- ✓ Sort out candidate GW **events that are caused by local sources**.

WHY SO MANY?

Virgo Helps Localize Gravitational-Wave Signals.



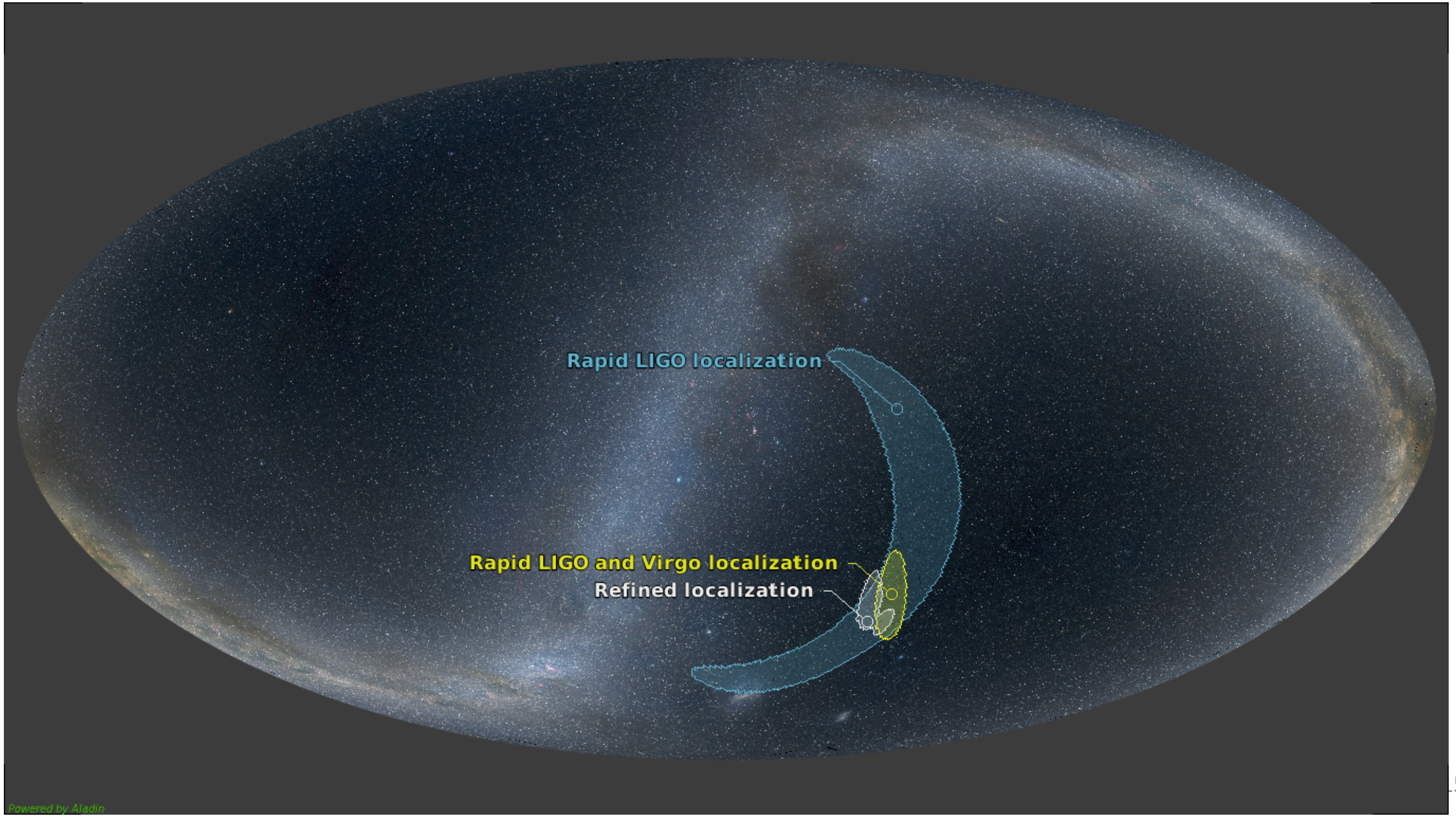
LIGO/Virgo/NASA/Leo Singer
(Milky Way image: Axel Mellinger)

Positioning the Source (GW20170814)

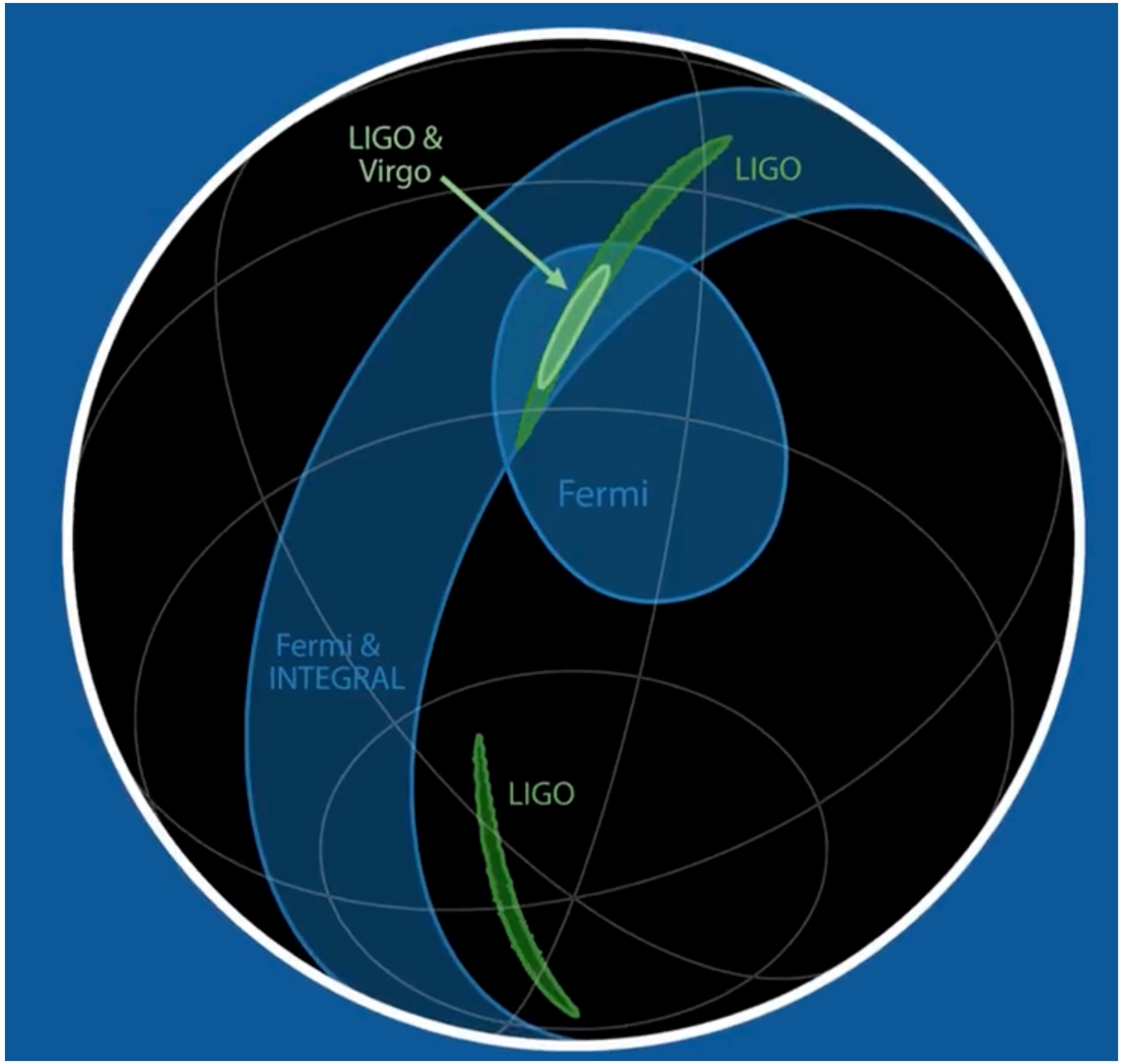
1160 deg²

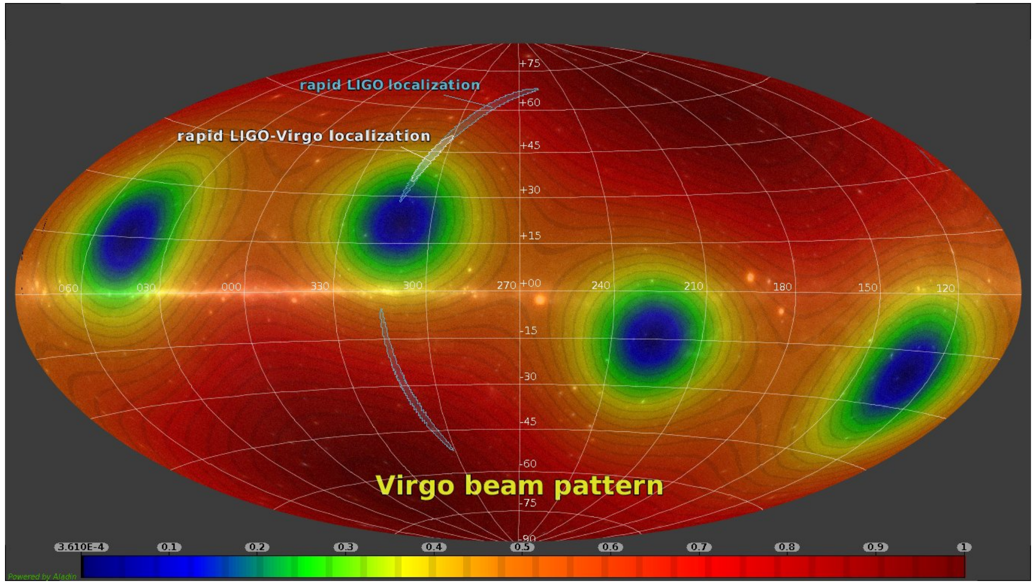
60 deg²

In the direction of Eridanus constellation

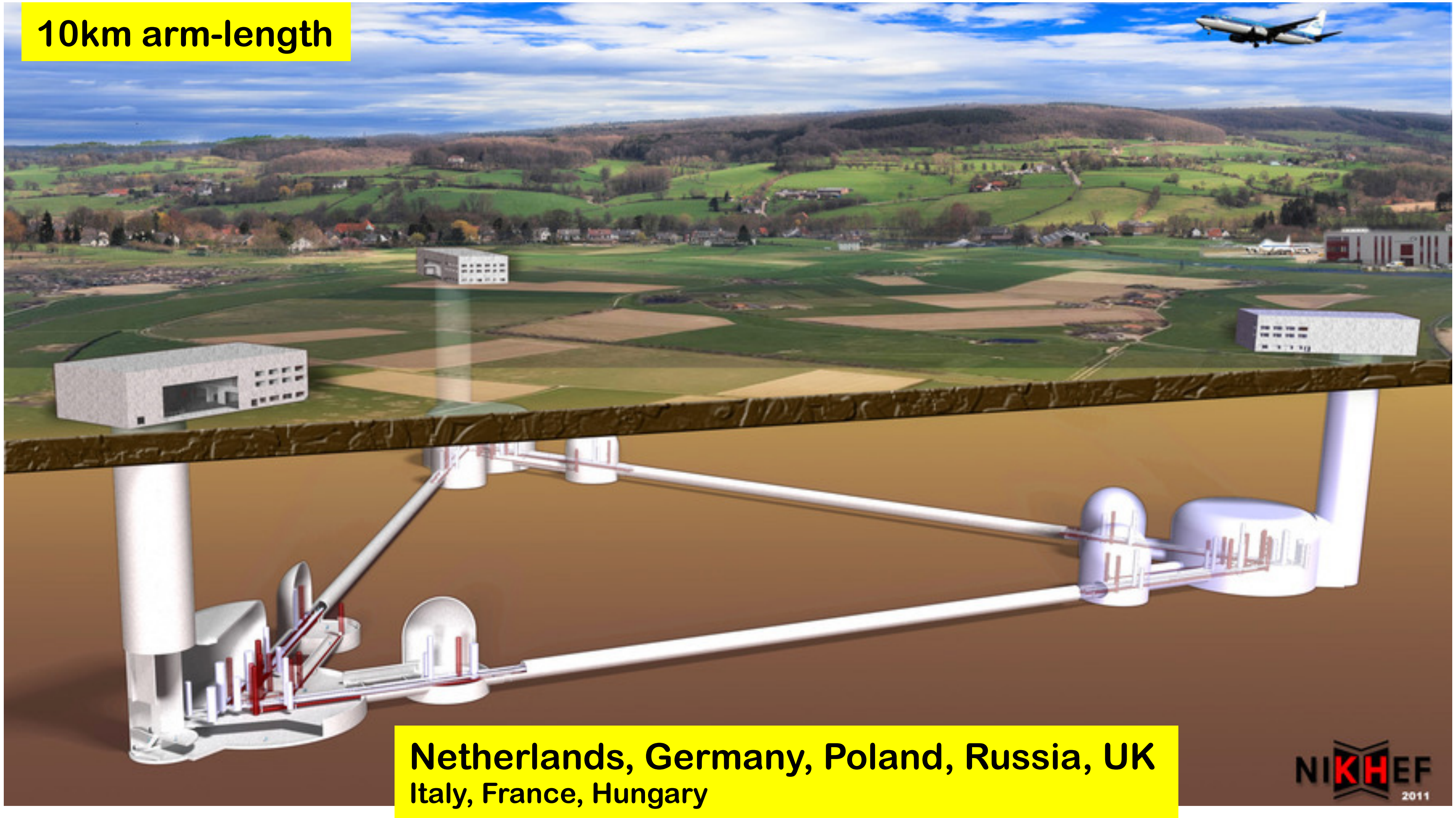


Neutron Star Mergers
Positioning the source



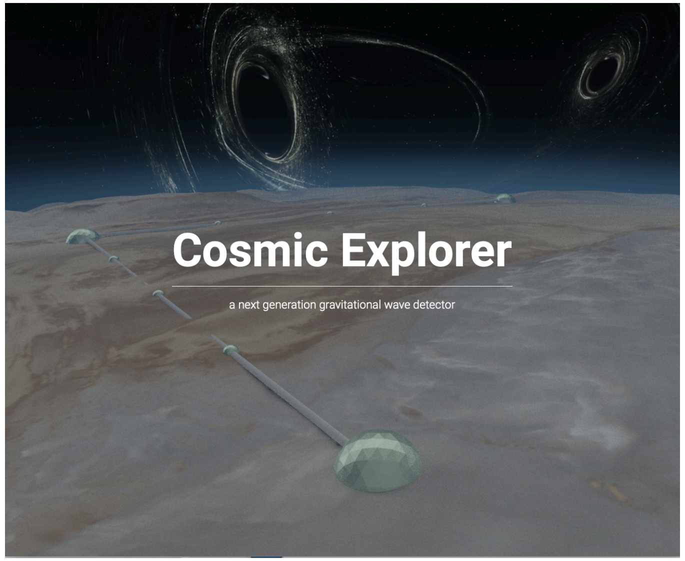


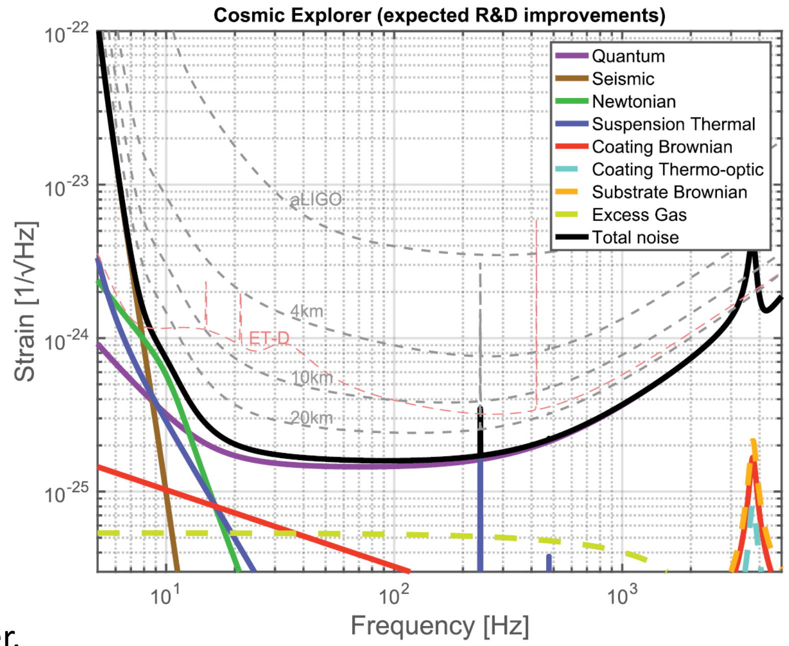
Einstein Telescope



Cosmic Explorer (2030+)

A **40 km long detector**, 10 times longer than Adv. LIGO, is well suited to detecting signals:
-- From **binary NS systems** and **core-collapse supernovae** up to **4 kHz in frequency**.
-- This length also provides sensitivity sufficient to detect **binary black holes from anywhere in the Universe (up to redshift of roughly 100).**



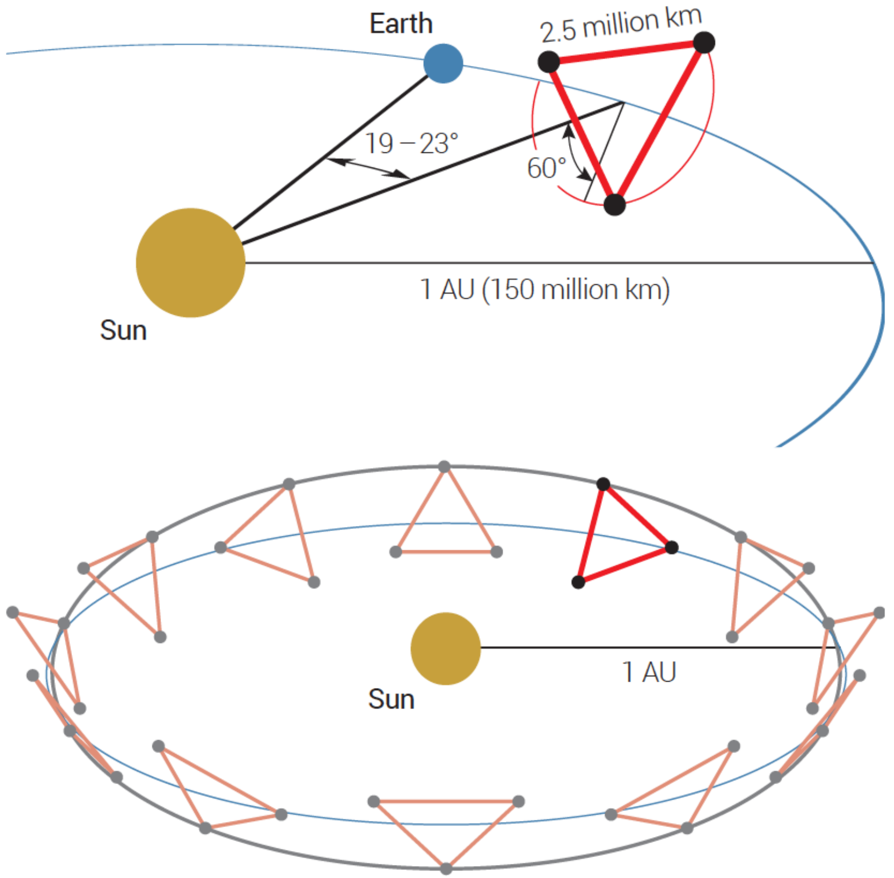


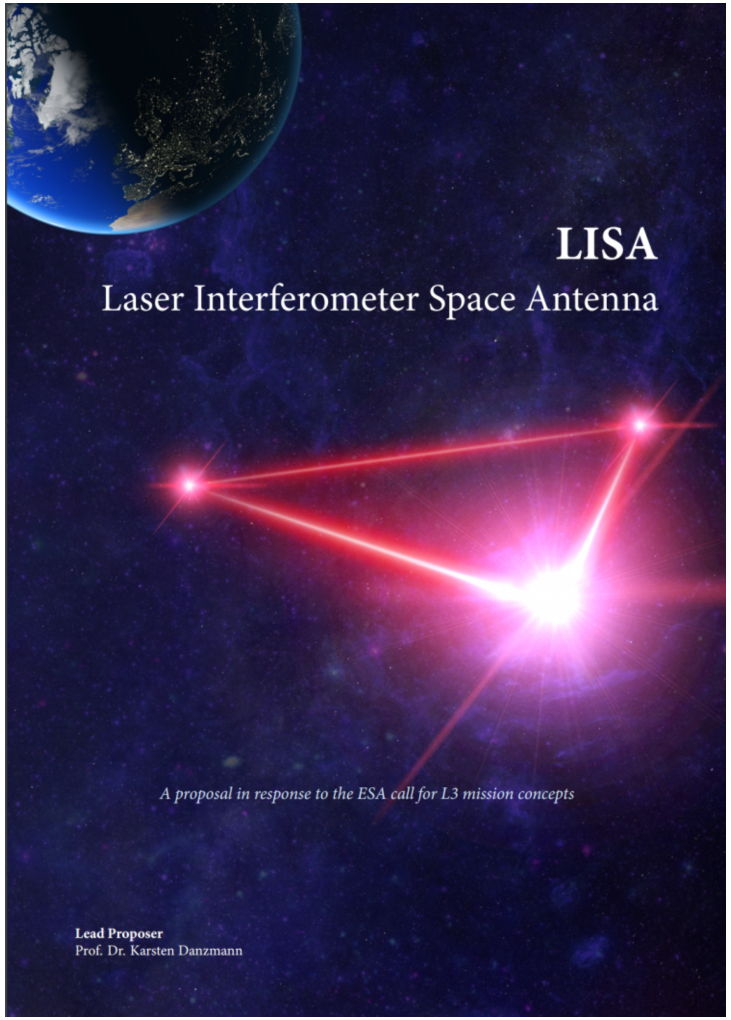
L-shaped geometry and houses a single interferometer.

Exploring the sensitivity of next generation gravitational wave detectors
B P Abbott et al 2017 CQG. 34 044001

Frequency-dependent responses in third generation gravitational-wave detectors
Essick, Vitale, Evans PRD **96**, 084004 (2017)
Theoretical physics implications of gravitational wave observation with future detectors
Chamberlain and Yunes PRD **96**, 084039 (2017)

LISA: THE SPACE DETECTOR
(January 2017)

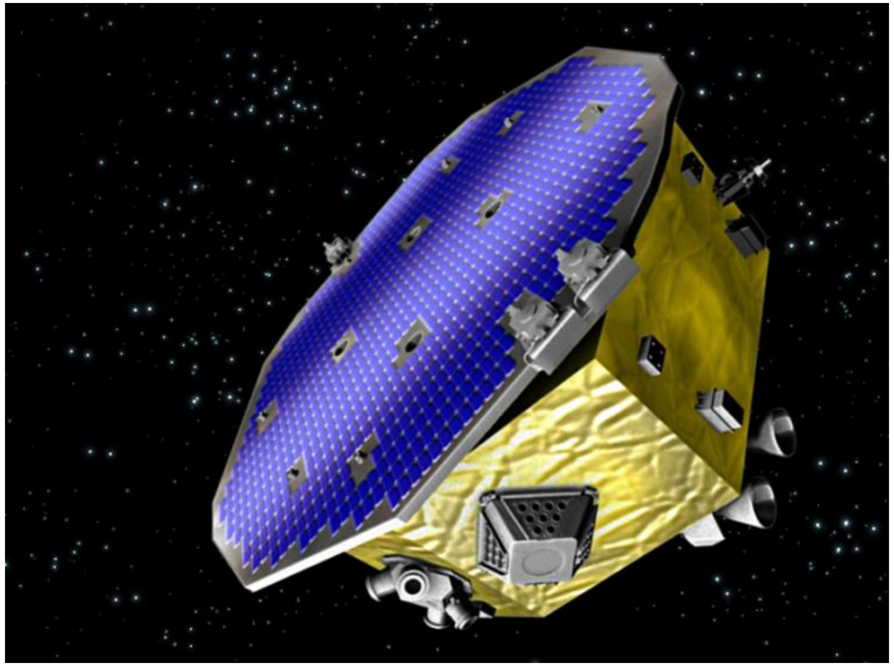




eLISA: Pathfinder

LISA Pathfinder is the precursor mission for all LISA-like missions.

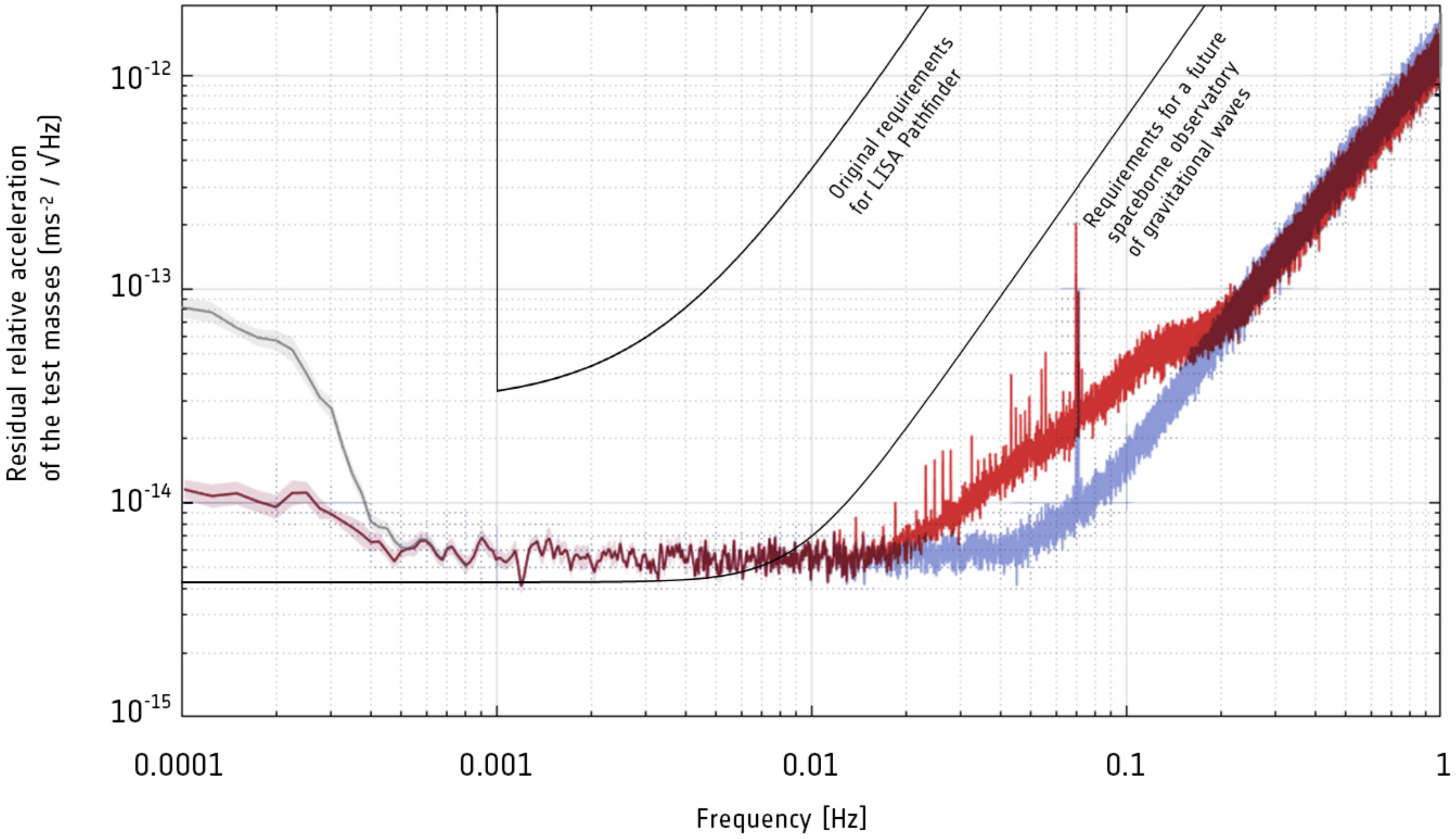
LPF was launched in December 2015.



LISA Pathfinder (LPF) placed two test masses in a nearly perfect gravitational free-fall, controlled and measured their relative motion with unprecedented accuracy.

LISA Pathfinder technologies are not only essential for eLISA, they also lie at the heart of any future space-based test of Einstein's General Relativity.

7th of June 2016 :
LISA pathfinder Exceeds expectations



This residual relative acceleration of the two test masses on LISA Pathfinder as a function of frequency.

GRAVITATIONAL WAVES: PRIMER

- Length Variation

$$\boxed{\frac{\Delta\ell}{\ell} = h}$$

- Amplitude

$$\boxed{h^{jk} \approx \frac{2}{r}\ddot{Q}^{jk} \approx \varepsilon \cdot \left(\frac{M}{r}\right) \cdot \left(\frac{M}{R}\right)}$$

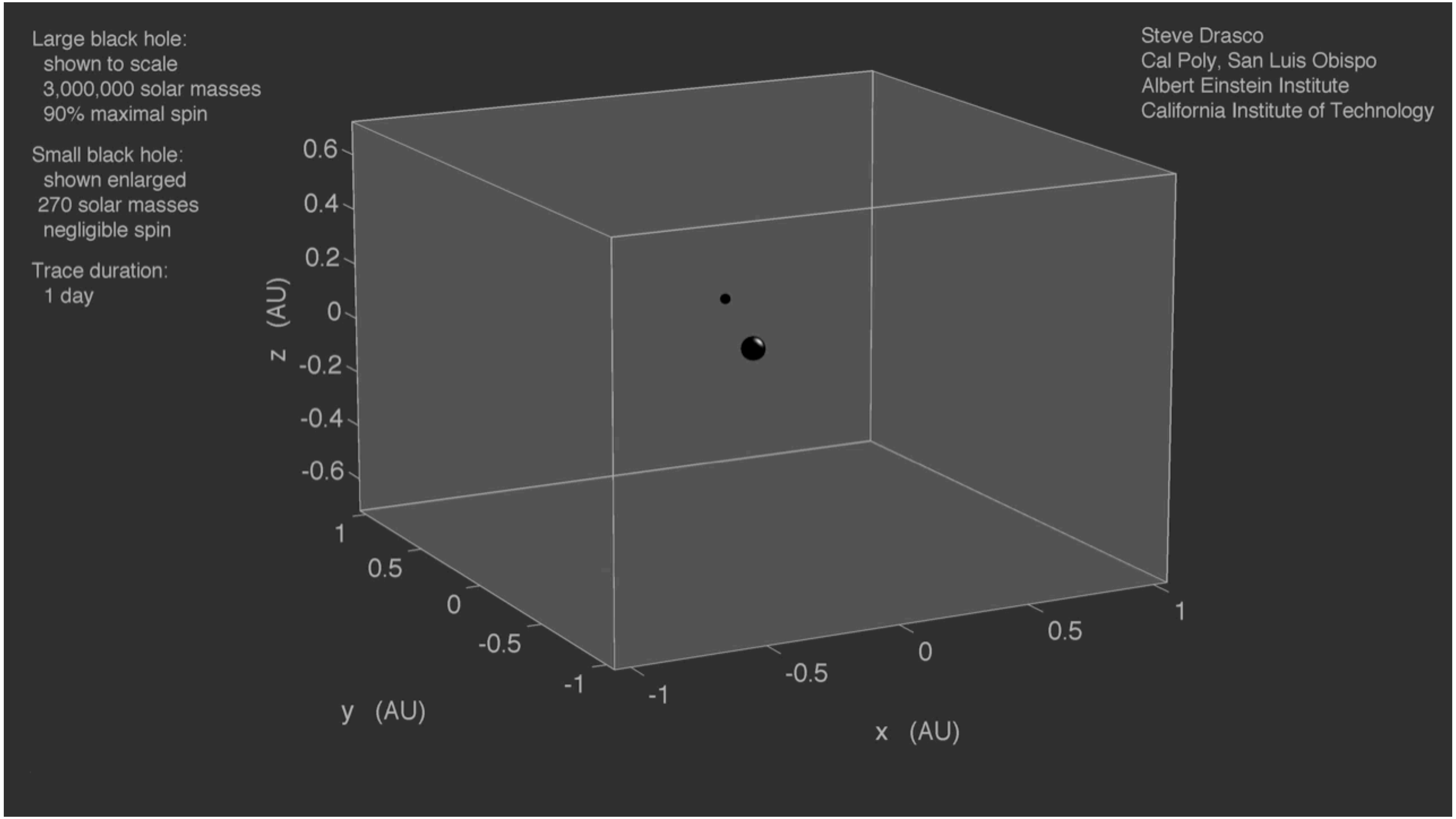
- Luminosity

$$\boxed{L_{GW} = -\frac{dE}{dt} = \frac{1}{5}\frac{G}{c^5}\sum_{ij}\left\langle \dddot{Q}_{ij}\dddot{Q}_{ij}\right\rangle \approx \left(\frac{M}{R}\right)^5}$$

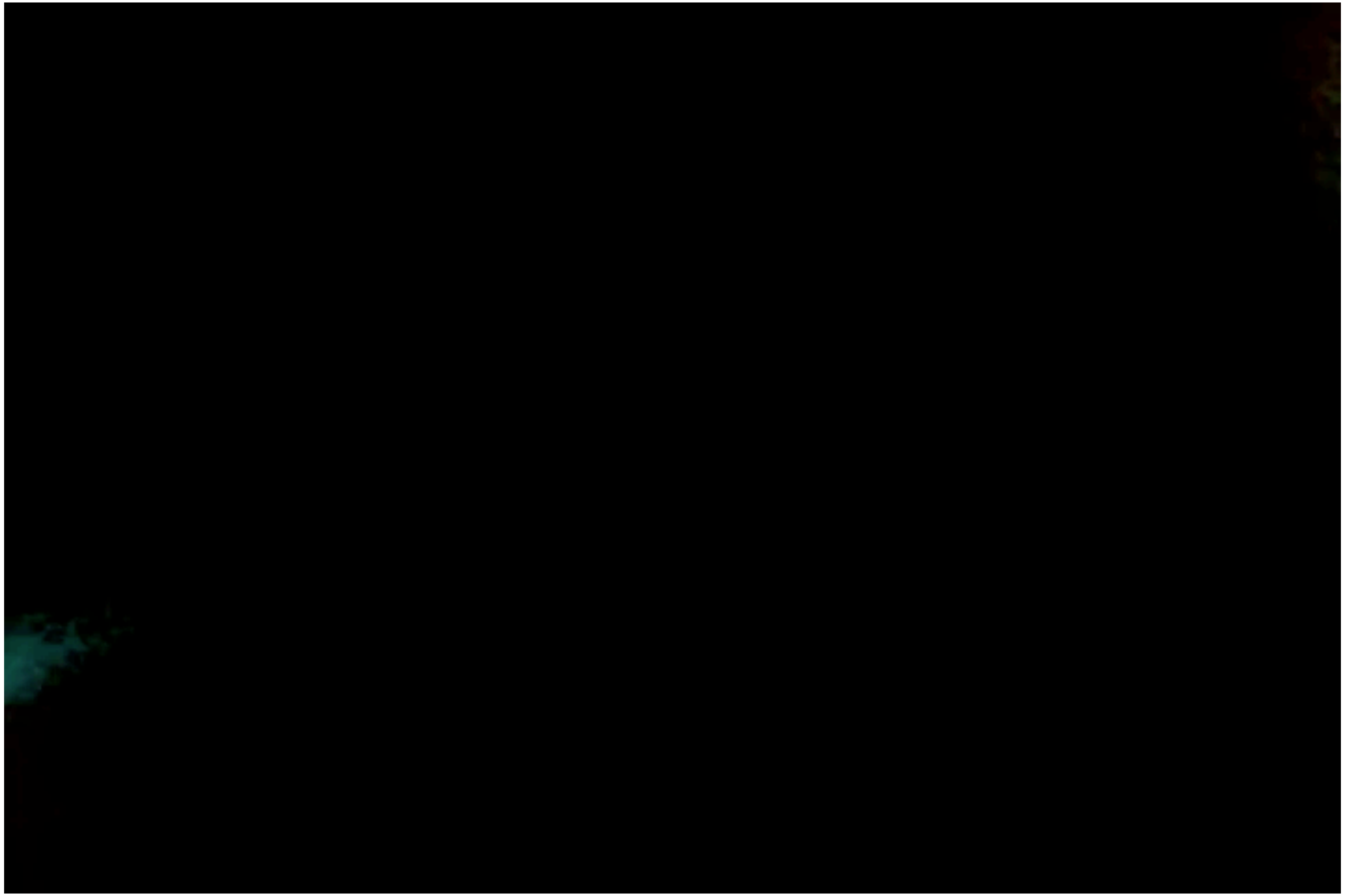
BLACK HOLES:	M/R=0.5
NEUTRON STARS:	M/R~0.2
WHITE DWRFS:	M/R~10^{-4}

COALESCING BINARY NEUTRON STARS

The «MUSIC» of BLACK HOLES



COLLIDING GALAXIES



COLLIDING GALAXIES

SIGNAL from BINARIES: PRIMER

$$M_c = \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}}$$ Chirp mass

$$h \approx \frac{1}{D} M_c^2$$ AMPLITUDE

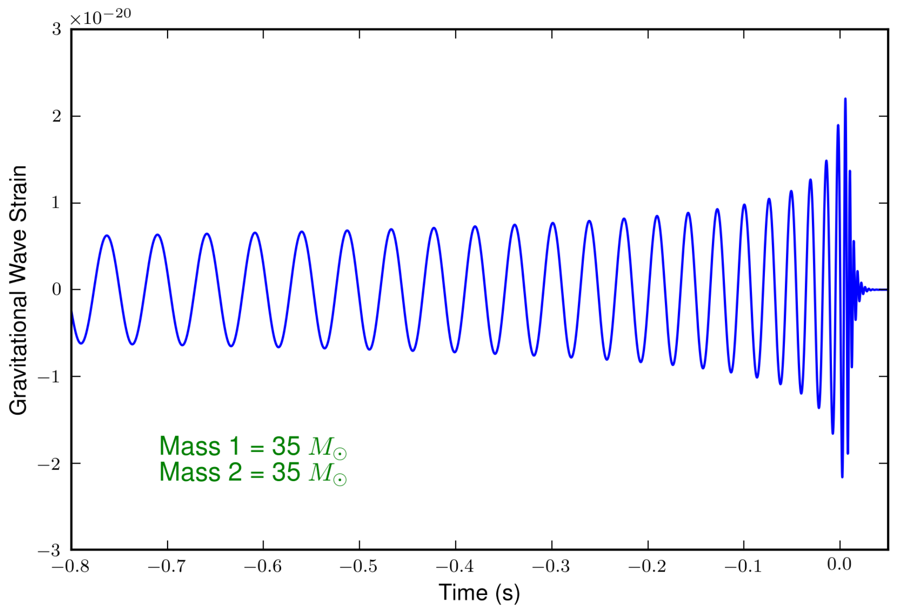
$$\dot{f} \approx f^{5/3} M_c^{-1/3}$$ Chirp

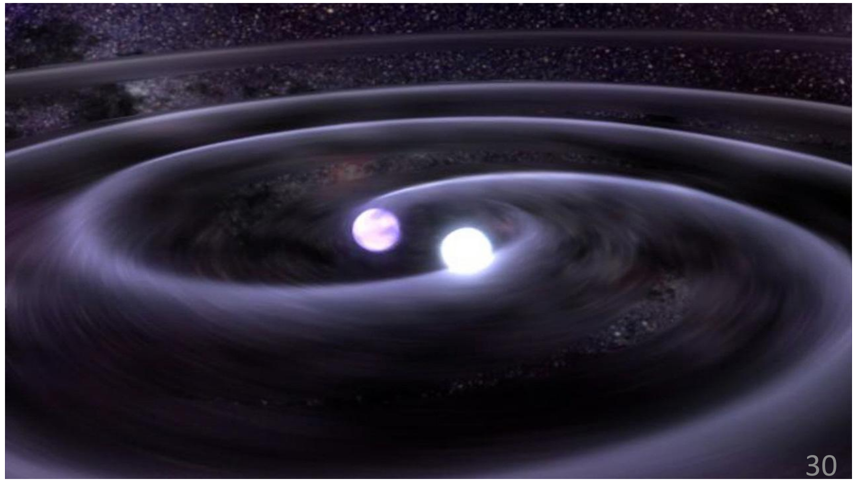
$$M_c \approx \left(f^{-11/3}\dot{f}\right)^{3/5} = f^{-11/5}\dot{f}^{3/5}$$ Chirp mass

$$D \approx \frac{1}{h}\left(\frac{\dot{f}}{f^3}\right) = \frac{1}{h} M_c^{5/3} (f)^{2/3}$$ DISTANCE

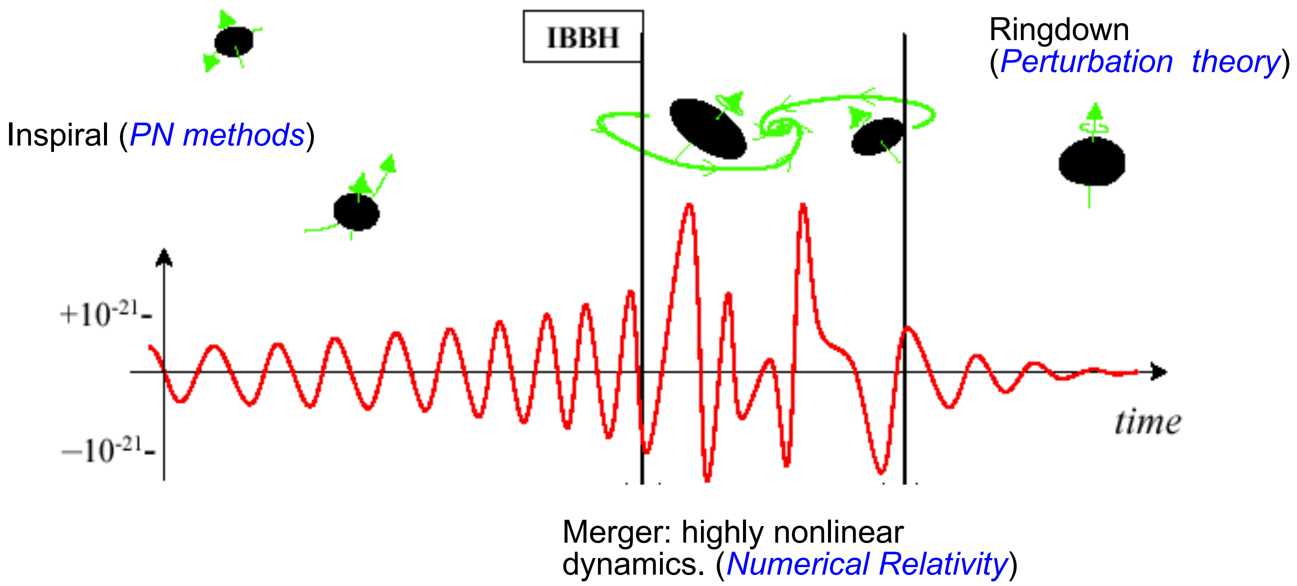
$$\mathrm{v} \approx f^{1/3} M^{1/3}$$ VELOCITY

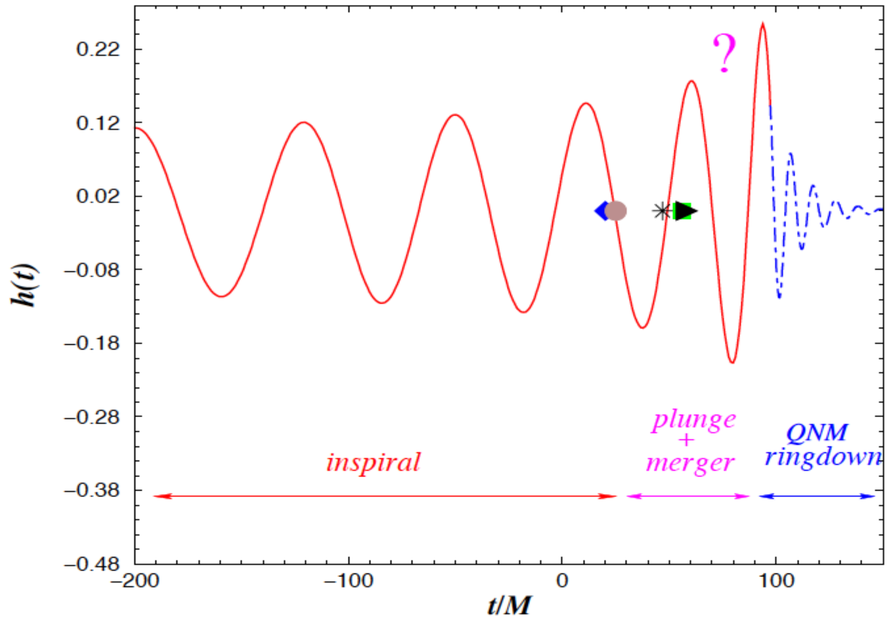
$$\eta = \frac{m_1 + m_2}{(m_1 + m_2)^2}$$





TEMPLATES for GWs from BBH coalescence





The black-hole «ringing» is its swan song

$$\omega \approx \frac{1}{M}(0.37 + 0.19a) \approx 12kHz\left(\frac{M_\odot}{M}\right)$$

$$\tau \approx M(1.48 + 2.09a) \approx 0.05ms\left(\frac{M}{M_\odot}\right)$$

THE INSPIRAL SIGNAL

Orbital phase at the 3.5PN approximation

$$\phi(t) = -\frac{1}{\nu}\Bigg\{\tau^{5/8} + \left(\frac{3715}{8064} + \frac{55}{96}\nu\right)\tau^{3/8} - \frac{3}{4}\pi\tau^{1/4}$$

$$+ \left(\frac{9275495}{14450688} + \frac{284875}{258048}\nu + \frac{1855}{2048}\nu^2\right)\tau^{1/8} + \left(-\frac{38645}{172032} - \frac{15}{2048}\nu\right)\pi\ln\left(\frac{\tau}{\tau_0}\right)$$

$$+ \left(\frac{831032450749357}{57682522275840} - \frac{53}{40}\pi^2 - \frac{107}{56}C + \frac{107}{448}\ln\left(\frac{\tau}{256}\right)\right.$$

$$+ \left[-\frac{123292747421}{4161798144} + \frac{2255}{2048}\pi^2 + \frac{385}{48}\lambda - \frac{55}{16}\theta\right]\nu + \frac{154565}{1835008}\nu^2$$

$$\left. -\frac{1179625}{1769472}\nu^3\right)\tau^{-1/8} + \left(\frac{188516689}{173408256} + \frac{140495}{114688}\nu - \frac{122659}{516096}\nu^2\right)\pi\tau^{-1/4}\Bigg\}$$

- T. Damour, G. Schaefer, L. Blanchet, C.M. Will
- B.R.Iyer, E. Poisson, P. Jaranowski,…

A catalog of 171 high-quality binary black-hole simulations for gravitational-wave astronomy [arXiv: 1304.6077]

Abdul H. Mroué,[1] Mark A. Scheel,[2] Béla Szilágyi,[2] Harald P. Pfeiffer,[1] Michael Boyle,[3] Daniel A. Hemberger,[3] Lawrence E. Kidder,[3] Geoffrey Lovelace,[4,2] Sergei Ossokine,[1,5] Nicholas W. Taylor,[2] Anıl Zenginoğlu,[2] Luisa T. Buchman,[2] Tony Chu,[1] Evan Foley,[4] Matthew Giesler,[4] Robert Owen,[6] and Saul A. Teukolsky[3]

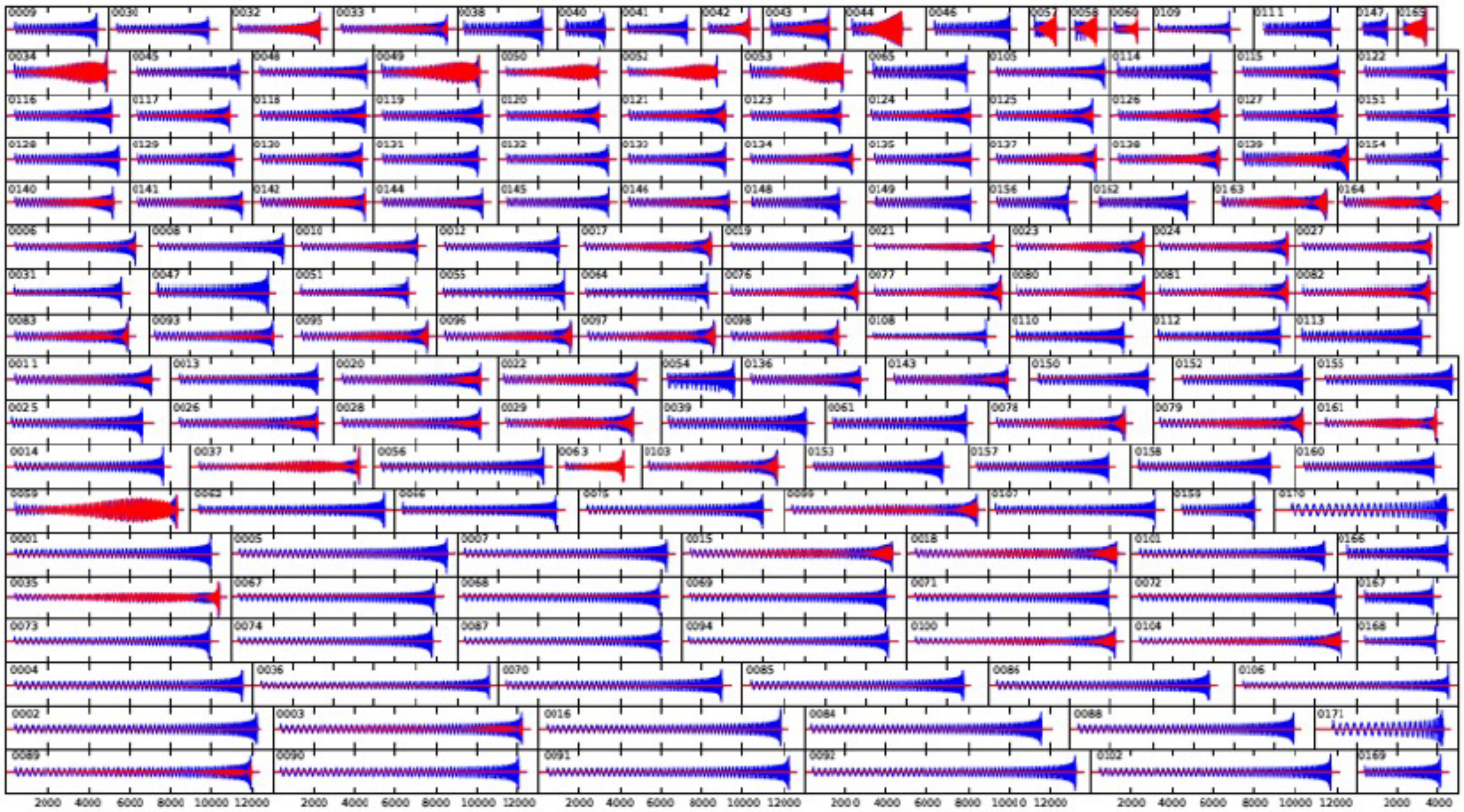
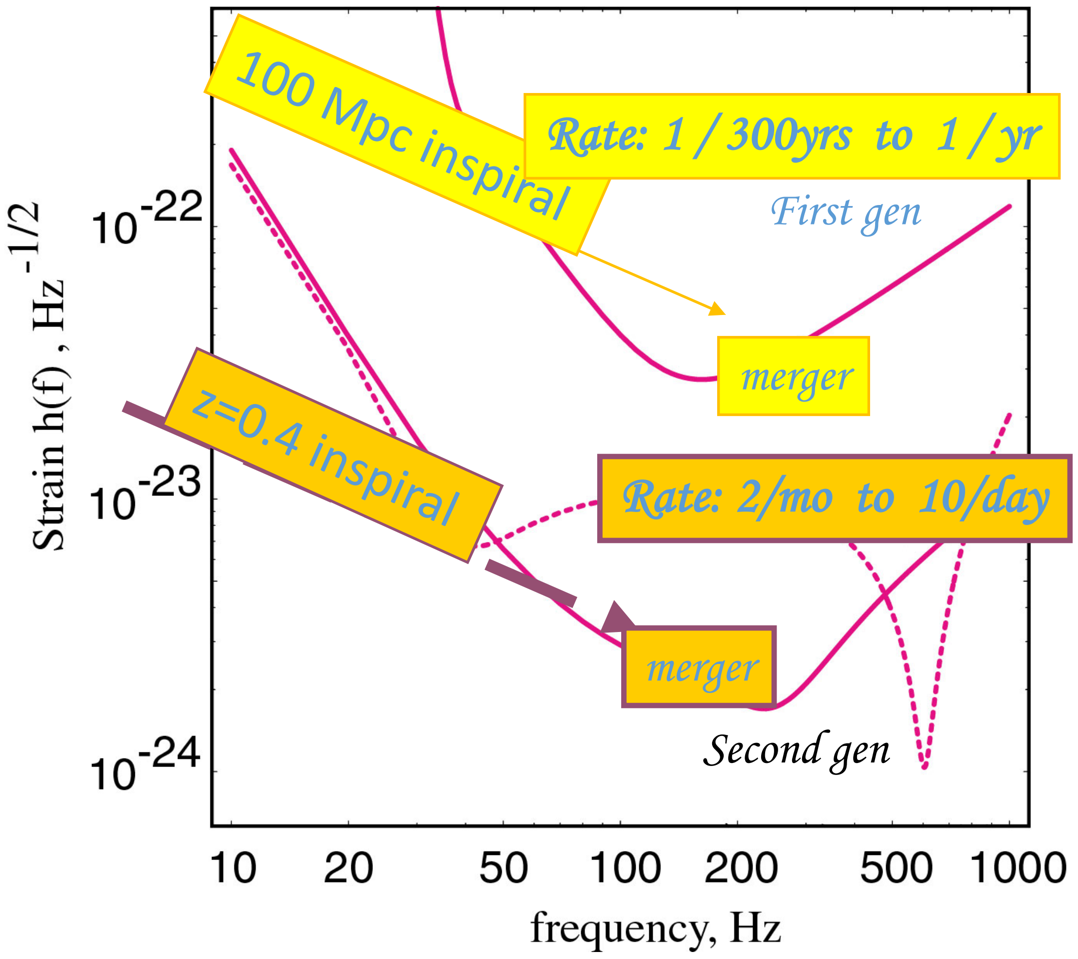


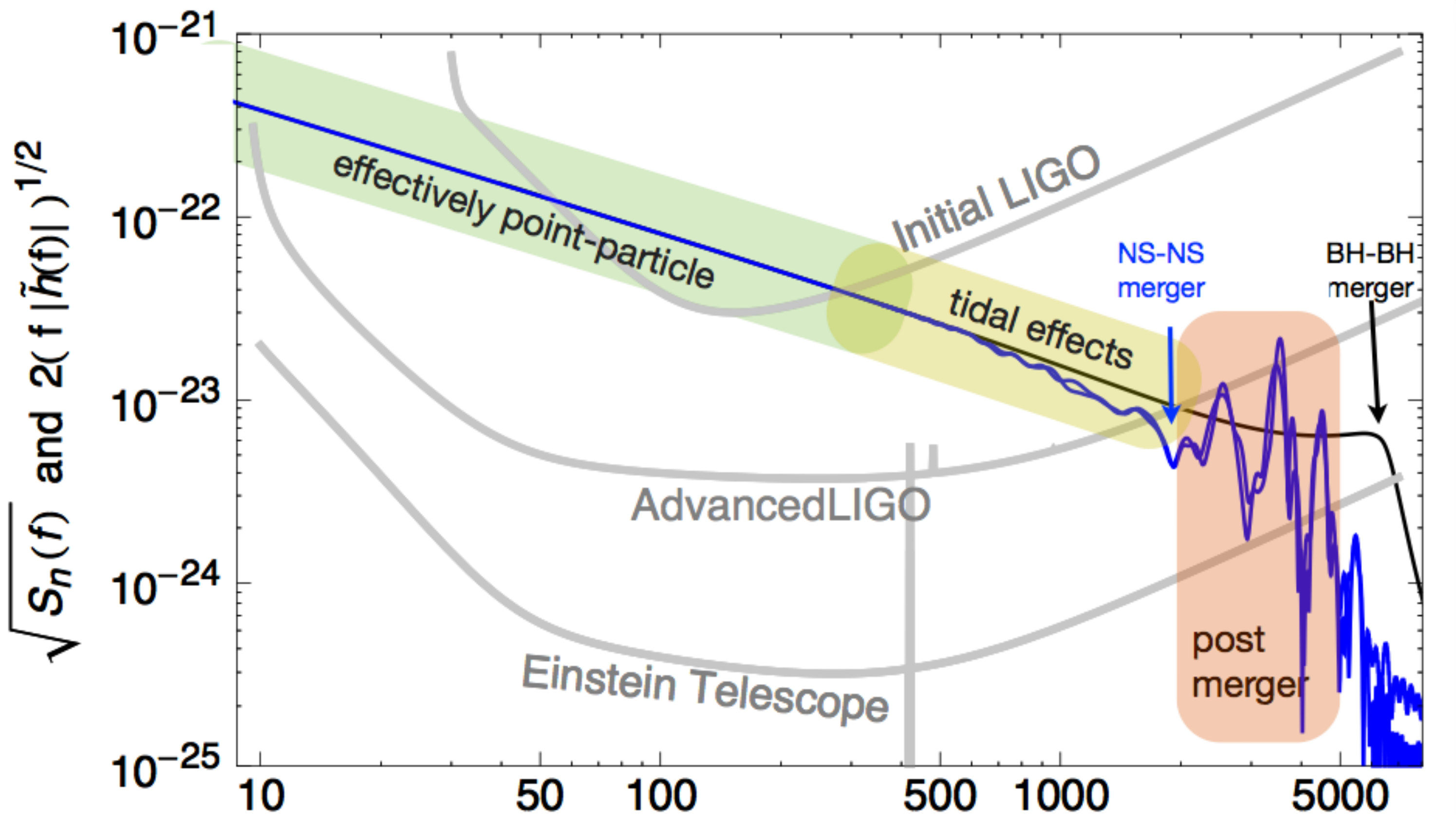
FIG. 3: Waveforms from all simulations in the catalog. Shown here are h_+ (blue) and h_x (red) in a sky direction parallel to the initial orbital plane of each simulation. All plots have the same horizontal scale, with each tick representing a time interval of $2000M$, where M is the total mass.

Possible First Source:
Binary Black Hole Coalescence

- $10M_\odot + 10\ M_\odot$ BH/BH binary
- Event rates based on population synthesis
- Mostly globular cluster binaries.
- Totally (EM) quiet!!



Binary Neutron Star Mergers
Tidal Interaction



100 Mpc

courtesy of Jocelyn Read

Tidal interactions affect the last part of the inspiral, modifying the orbital motion and the GW emission.

Prediction for the current Event Rate

@ Design Sensitivity

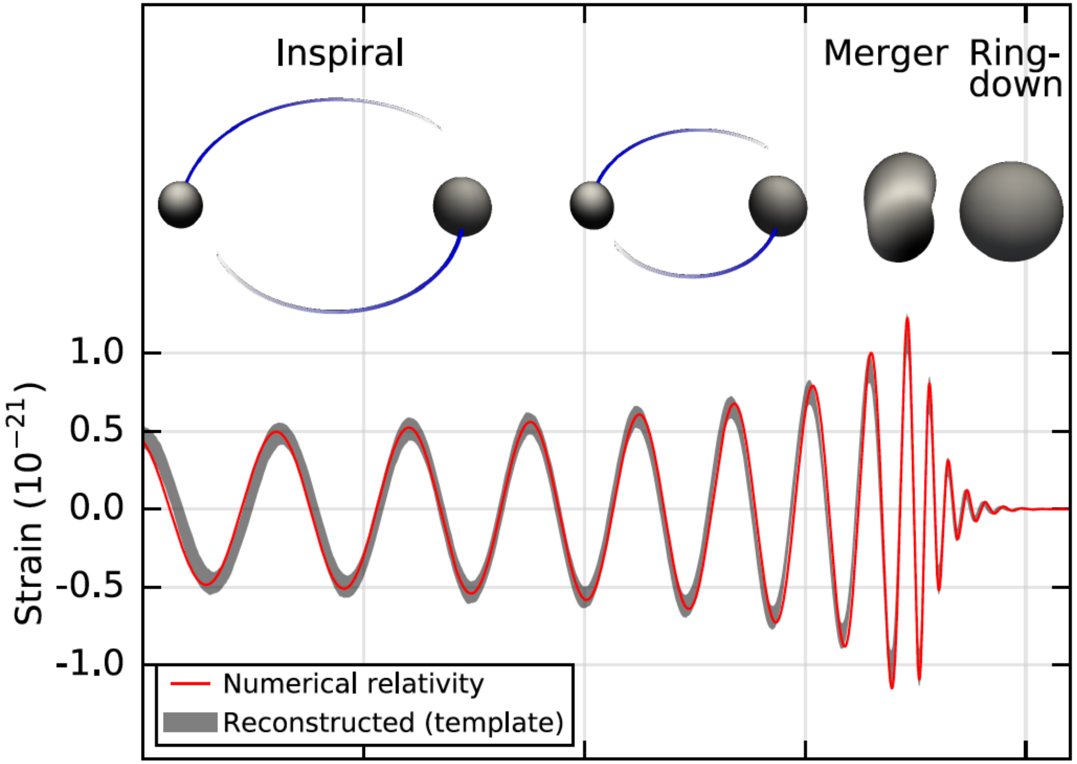
Abadie et al 2010; arXiv: 1003.2480

IFO	Source	$\dot{N}_{\rm low}$ $\rm yr^{-1}$	$\dot{N}_{\rm high}$ $\rm yr^{-1}$
Initial	NS-NS	2×10^{-4}	0.2
	NS-BH	7×10^{-5}	0.1
	BH-BH	2×10^{-4}	0.5
Advanced	NS-NS	0.4	400
	NS-BH	0.2	300
	BH-BH	0.4	1000

"Realistic" rates expected at ~ a few tens per year

From V. Kalogera

THE EVENT: 14/9/2015 (09:50:45 UT)



WHAT HAPPENED 1.3 BILLION YEARS AGO

Credits LIGO

WHAT DID THEY OBSERVE?

M_1 : 36^{+5}_{-4} $M_\odot$

M_2 : 29^{+4}_{-4} $M_\odot$

S/N : **~24**

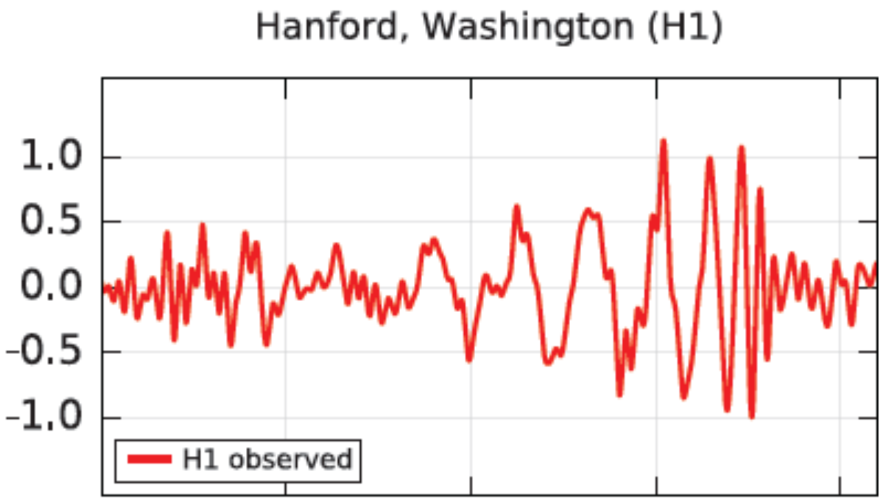
Spin : 0.67

Final Mass : 62^{+4}_{-4} $M_\odot$

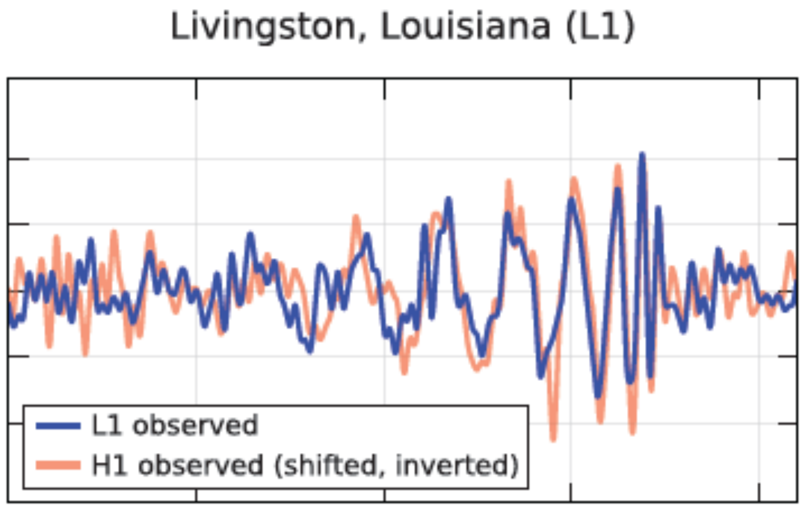
Distance : $410^{+160}_{-180}\ Mpc$

$\sim$**1.3 x 10^9 light years**

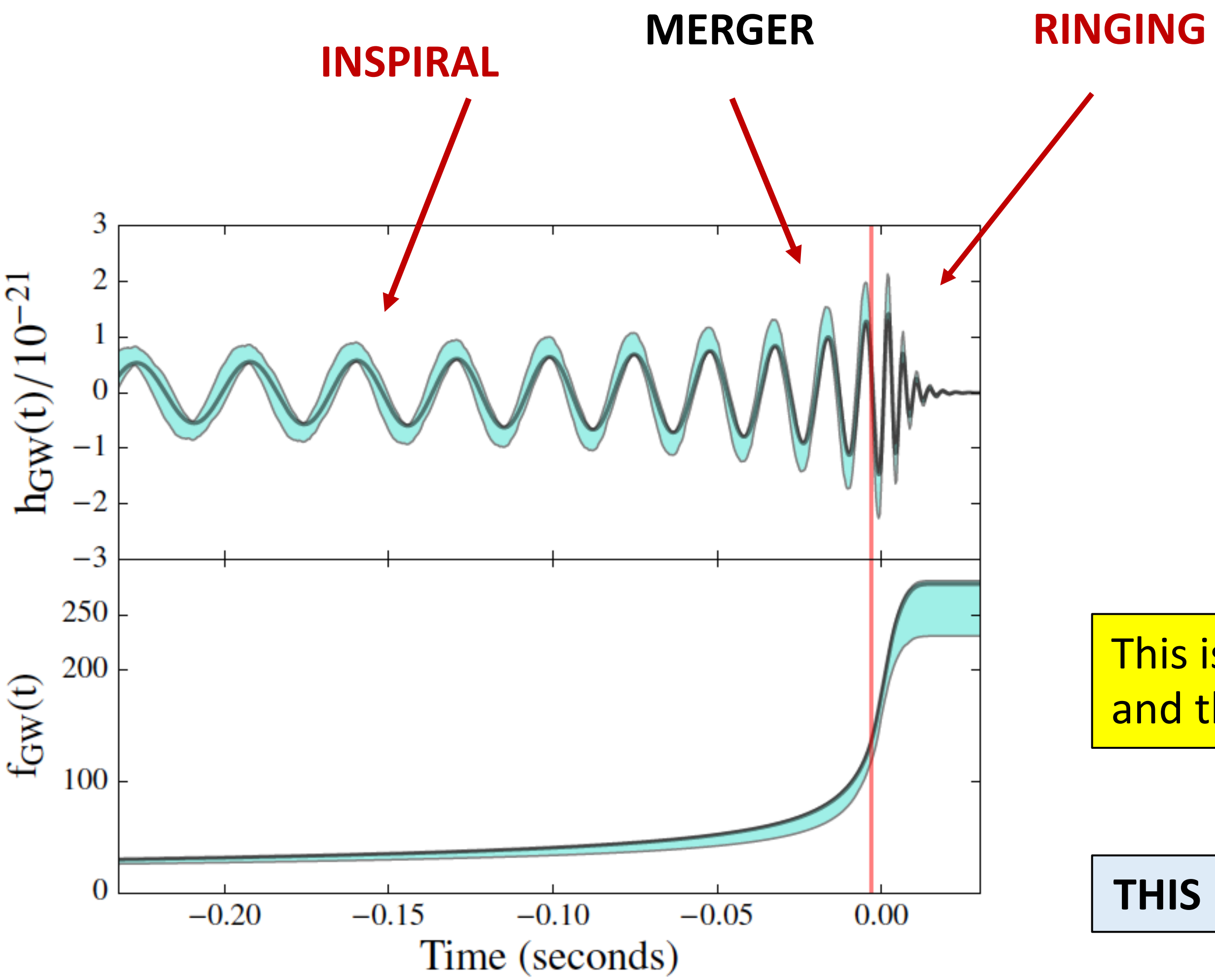
Redshift : z~$0.09^{+0.03}_{-0.04}$



GW150914



SIGNAL ANALYSIS



- $f_{GW} \sim 35\ Hz$
- $f_{GW} \sim 150\ Hz$
- 8 orbital rotations
- Duration ~0.23-0.25 sec
- $\frac{v}{c} \sim 0.5$

This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

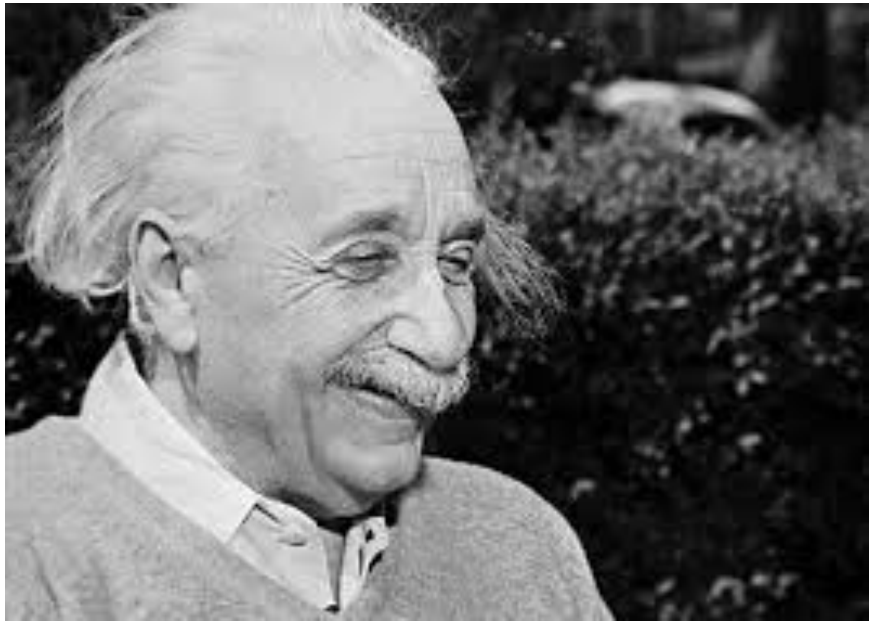
NOT ONLY!

THIS IS THE FIRST DIRECT DISCOVERY OF BLACK HOLES

FINDINGS

- **Quite good agreement with the event rate**
- **First detection of binary black-hole systems**
- **Larger than expected black-holes !**
- **------**
- Estimation of masses before and after merger
- Total energy emitted **~3 solar masses**
- Peak luminosity **3.6×10^{56} erg/sec**
    - **Equivalent to 200 solar masses/ sec**
    - **50 higher than the luminosity of the whole universe**
    - «Graviton mass» if exists should be smaller than: **$m_g < 1.2 \times 10^{-22}$ eV/c^2**
- The final “ringing” (quasi-normal mode) in agreement with the ringing of a Kerr black-hole.

FINDINGS



ALL FINDINGS ARE
IN GOOD AGREEMENT
WITH
GENERAL THEORY OF RELATIVITY

The NEXT SOURCE: Neutron Star Binaries

The 2nd most promising and exciting source: **NS-NS binaries**

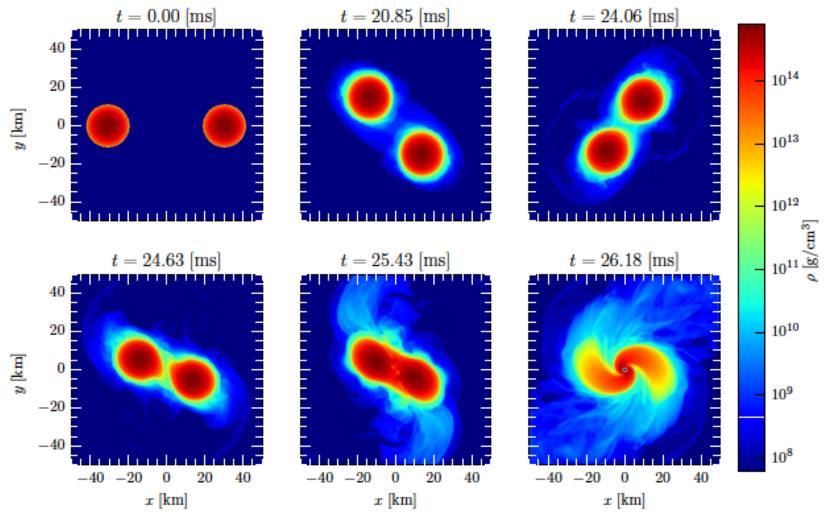
Binary Neutron Star Mergers

The typical scenario

I. After the merging the final body most probably will be a supramassive NS (2.5-3 $M_{\odot}$)

II. The body will be differentially rotating

III. This phase will last only a few tenths of msecs and can potentially provide information for the Equation of State.



Radice, Rezzolla, Galeazzi 2015

I. The “averaged” magnetic field will amplified due to MRI (up to 3-4 orders of magnitude)

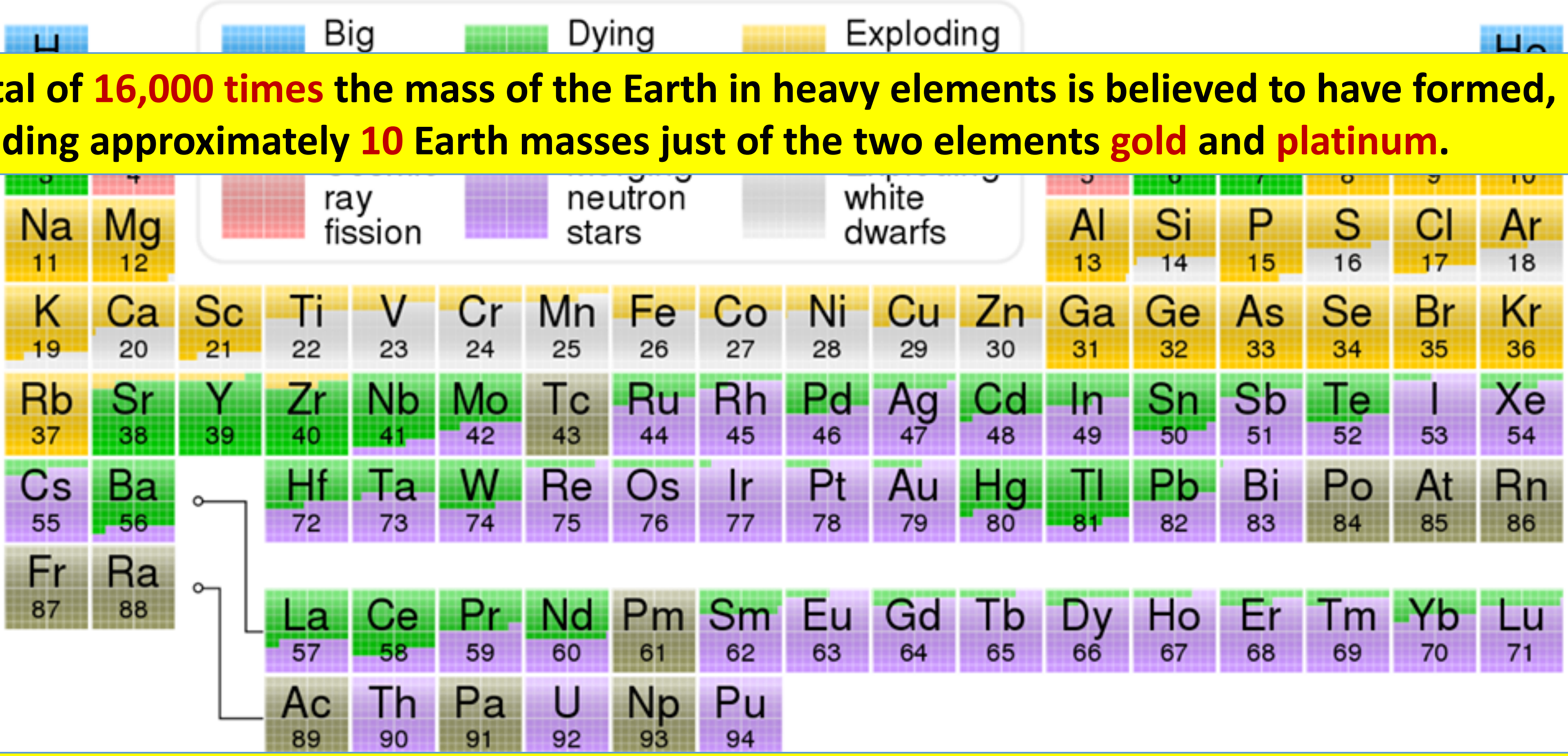
II. The strong magnetic field and the emission of GWs will drain rotational energy

Neutron Star Mergers
Sequence of Events

12:41:04 UTC	A **Gravitational Wave** from binary NS merger is detected
+2 sec	A **Short Gamma ray** burst is detected
	GW + EM from the same source provide compelling evidence that **GWs travel with the speed of light**
	The two events allow for the **measure of the expansion rate of the Universe**
	Kilonova: neutron star mergers responsible for the production of heavy elements in the universe.
+10 h **52** min	A new bright source of **optical light** is detected in a galaxy called NGC 4993 (constellation of Hydra)
+11 h **36** min	**Infrared emission** observed
+15 h	**Bright ultraviolet** emission detected
+9 days	**X-ray** emission detected
+16 days	**Radio** emission detected

Neutron Star Mergers

Alchemy or Heavy Element Production

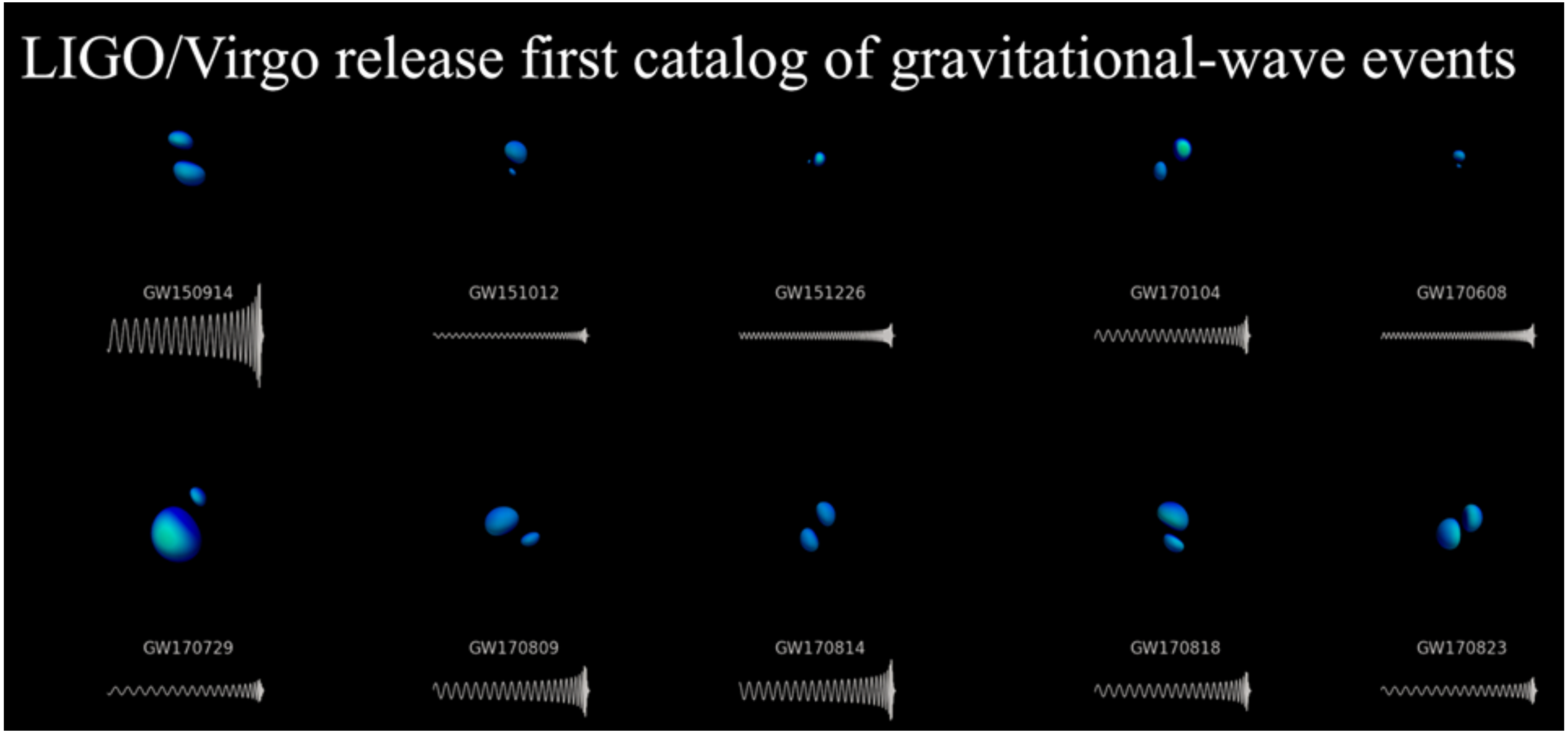


A total of 16,000 times the mass of the Earth in heavy elements is believed to have formed, including approximately 10 Earth masses just of the two elements gold and platinum.

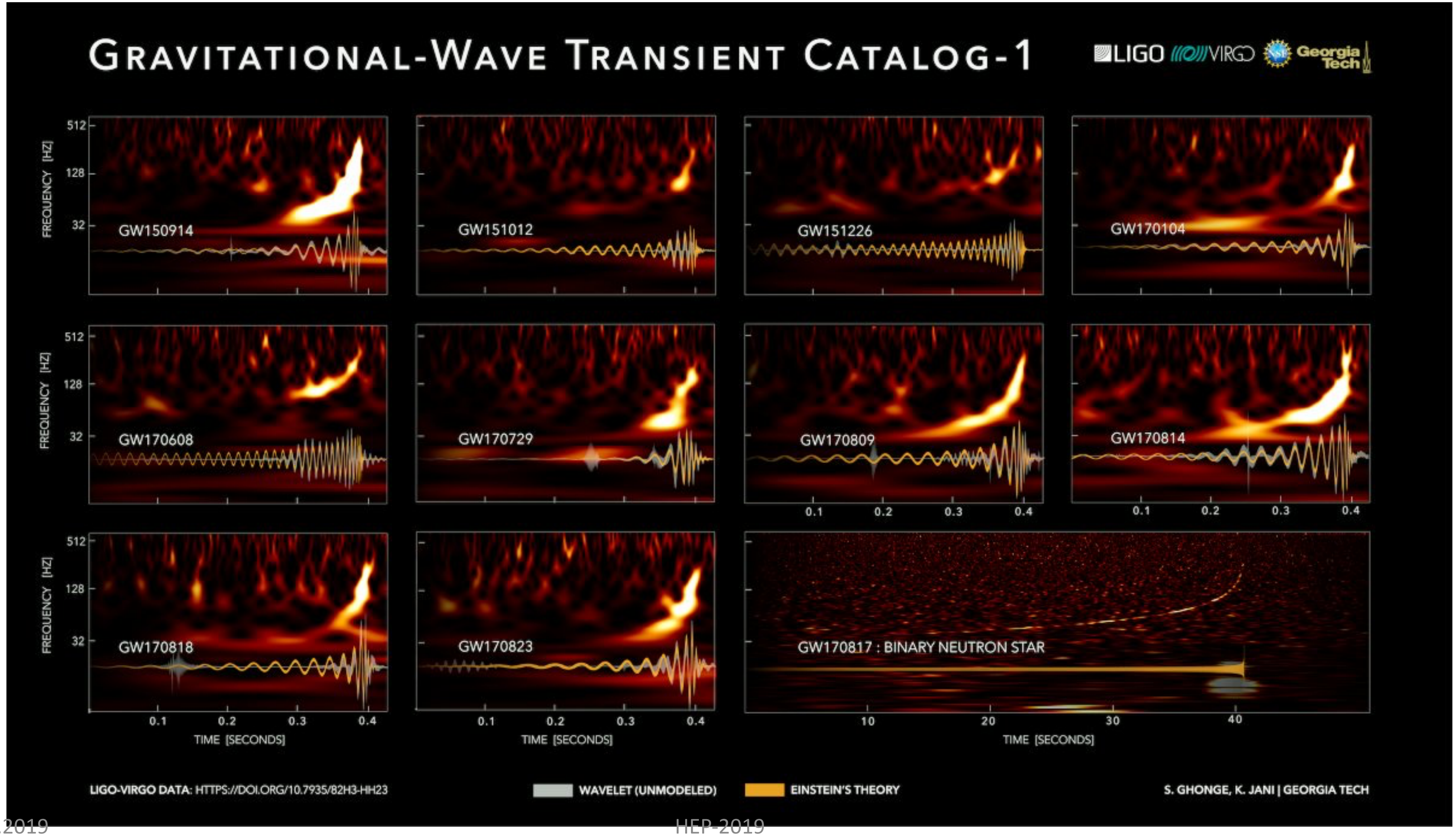
Light emitted after a neutron star collision showed signs of heavy elements present in the aftermath, confirming that certain elements (purple) are produced in such mergers

The Catalog of GW Events

O1 & O2 Runs

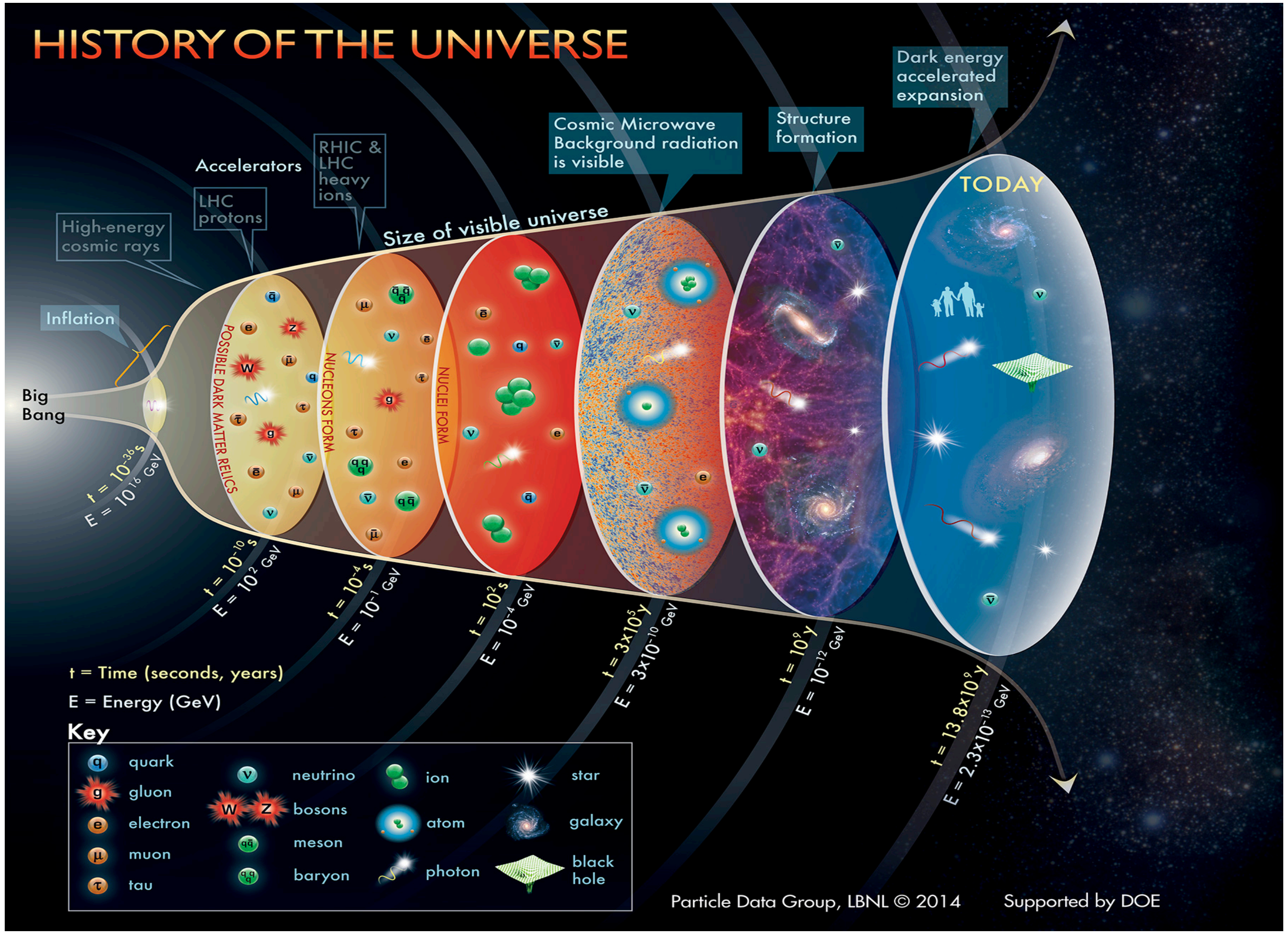


The Catalog of GW Events
1st & 2nd Run



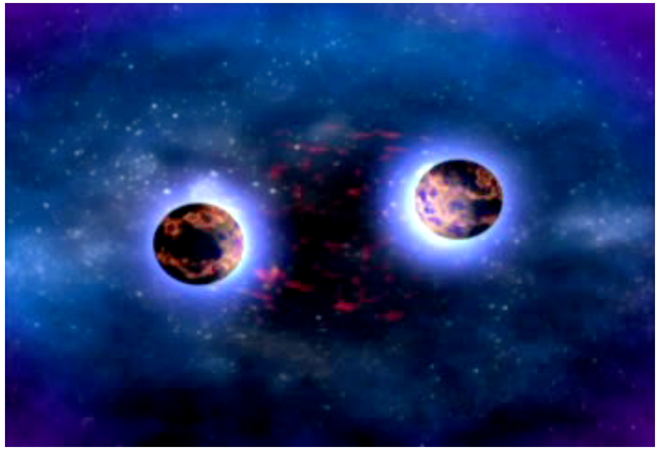
THE “STORY” OF THE UNIVERSE…

…WAS ALWAYS VIOLENT

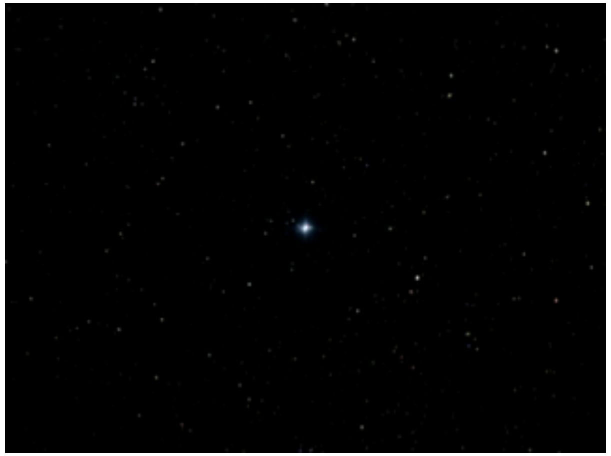


VIOLENT PHENOMENA ASSOCIATED WITH THE EMISSION OF GRAVITATIONAL WAVES

MAIN SOURCES for LIGO



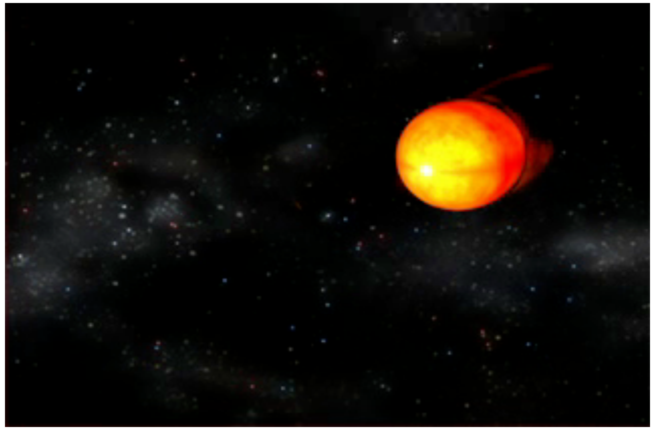
BH and NS Binaries



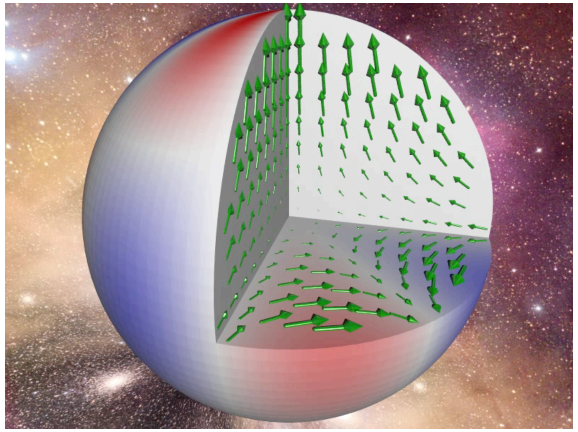
Supernovae, BH/NS formation

$$L_{GW} \sim \left(\frac{M}{R}\right)^5$$

$$h \sim \varepsilon \cdot \left(\frac{M}{r}\right) \cdot \left(\frac{M}{R}\right)$$



Spinning neutron stars in X-ray binaries

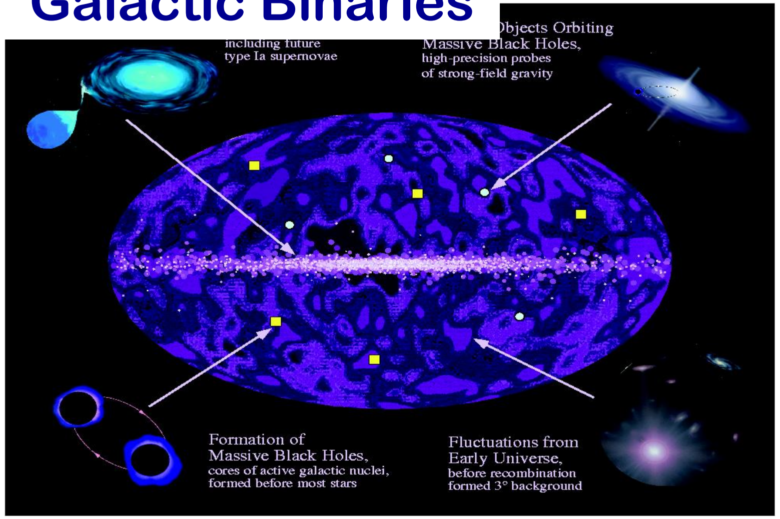


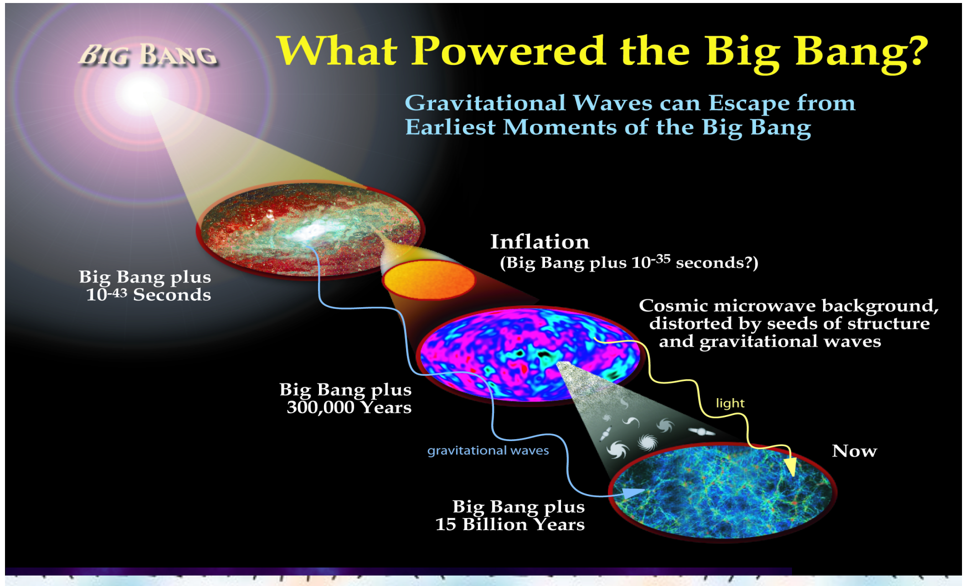
Neutron Stars:
Instabilities, Deformations

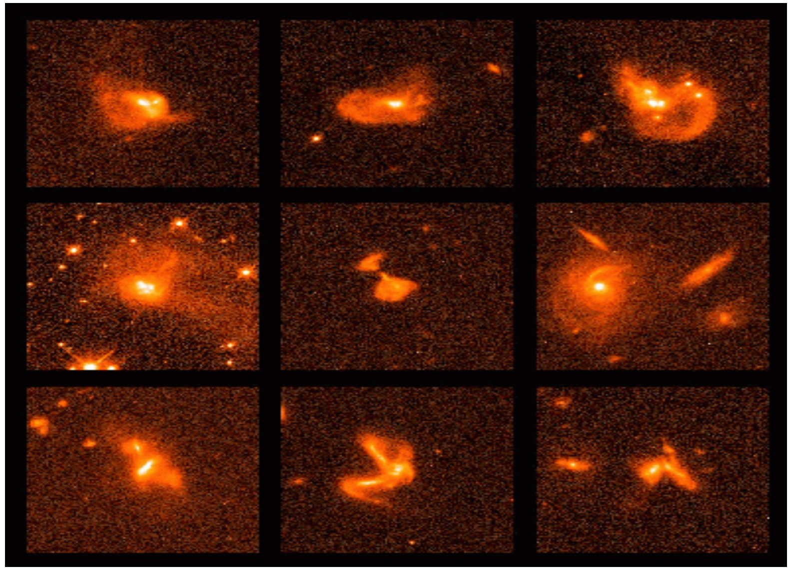
BLACK HOLES:	M/R=0.5
NEUTRON STARS:	M/R~0.2
WHITE DWRFS:	M/R~10^{-4}

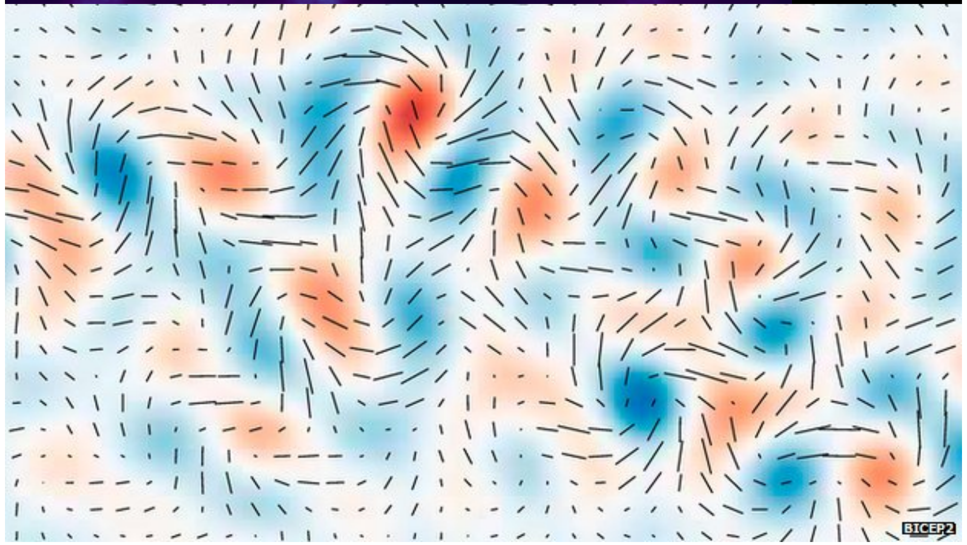
MAIN SOURCES for eLISA

Galactic Binaries



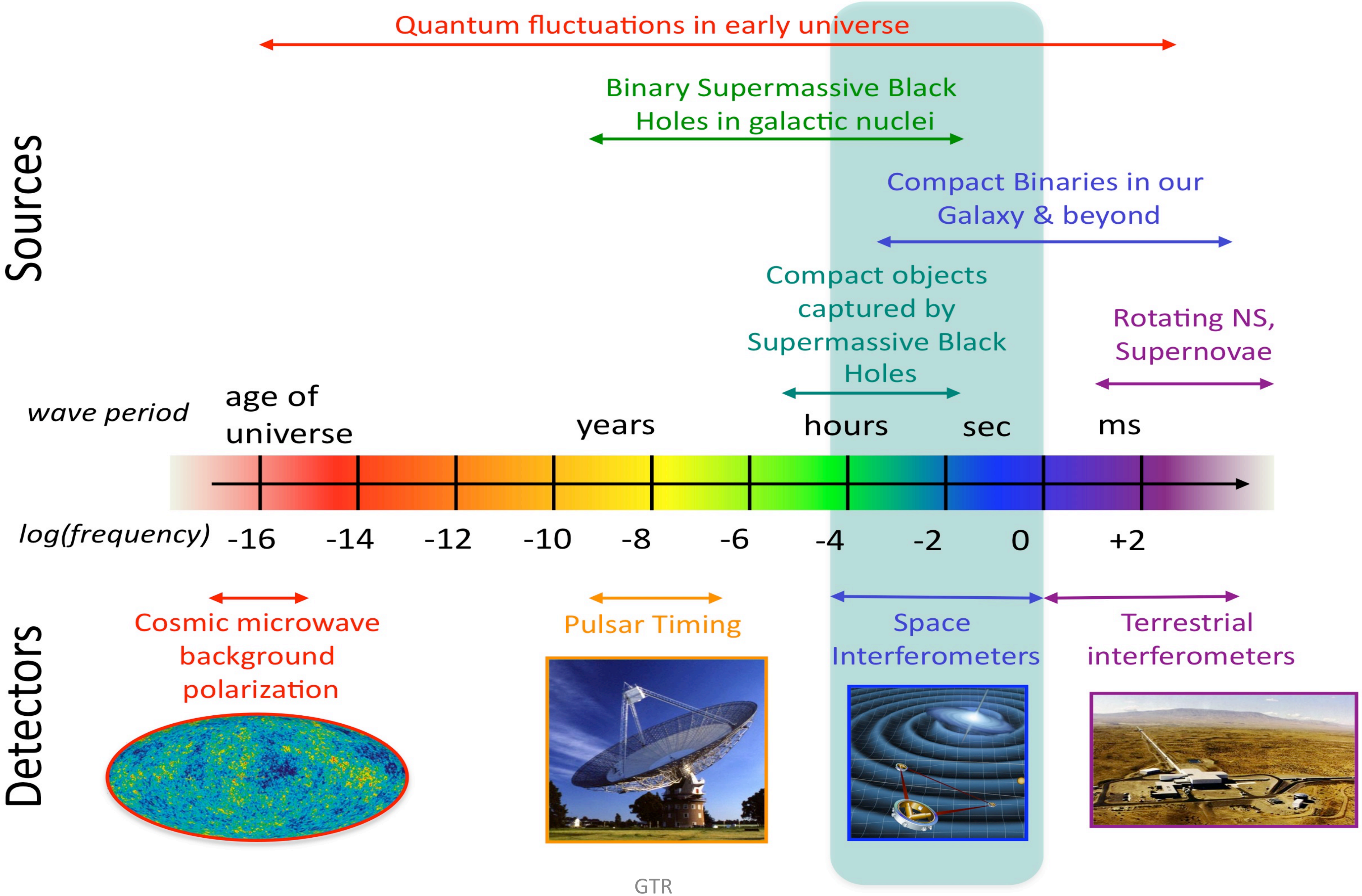






Galaxy mergers

The Gravitational Wave Spectrum



SCIENCE OBJECTIVES

Cosmology: Exploring black hole seeds

*The origin and evolution of BHs that seem to populate galactic cores is **one of the unsolved problems in modern cosmology**.*

Cosmography: Measuring the Universe with standard sirens

One of the most spectacular aspects of compact binary signals is that their amplitude is completely determined by GR, without the need for any complicated astrophysical modelling of their environments.

Fundamental physics: Testing gravity with black holes

*Nearly a hundred years after its formulation, GR continues to be the preferred theory of gravity. **However, the theory is yet to be tested in strong gravitational fields that occur in the vicinity of BH horizons**. Gravitational wave observations of compact binaries could facilitate many such tests*

SCIENCE OBJECTIVES

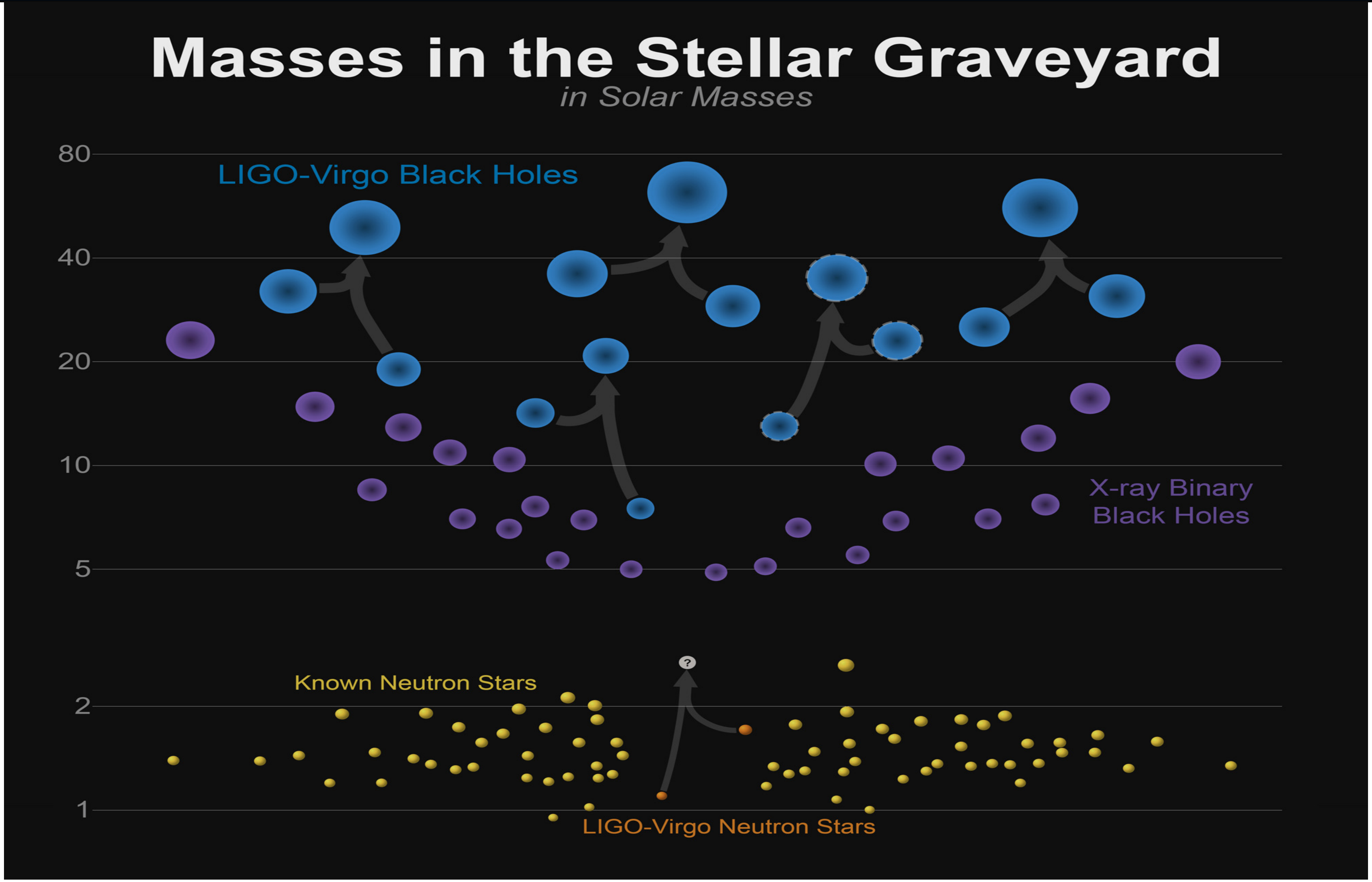
Astrophysics: Catching supernovae in their act

*It is expected that the gravitational collapse and the ensuing explosion can be fully understood **only by studying the deep interiors of the proto-neutron star that forms in the process**, which is inaccessible to electromagnetic observations.*
Modelling SNe involves inputs from almost all branches of physics and current simulations of the process are far from complete.

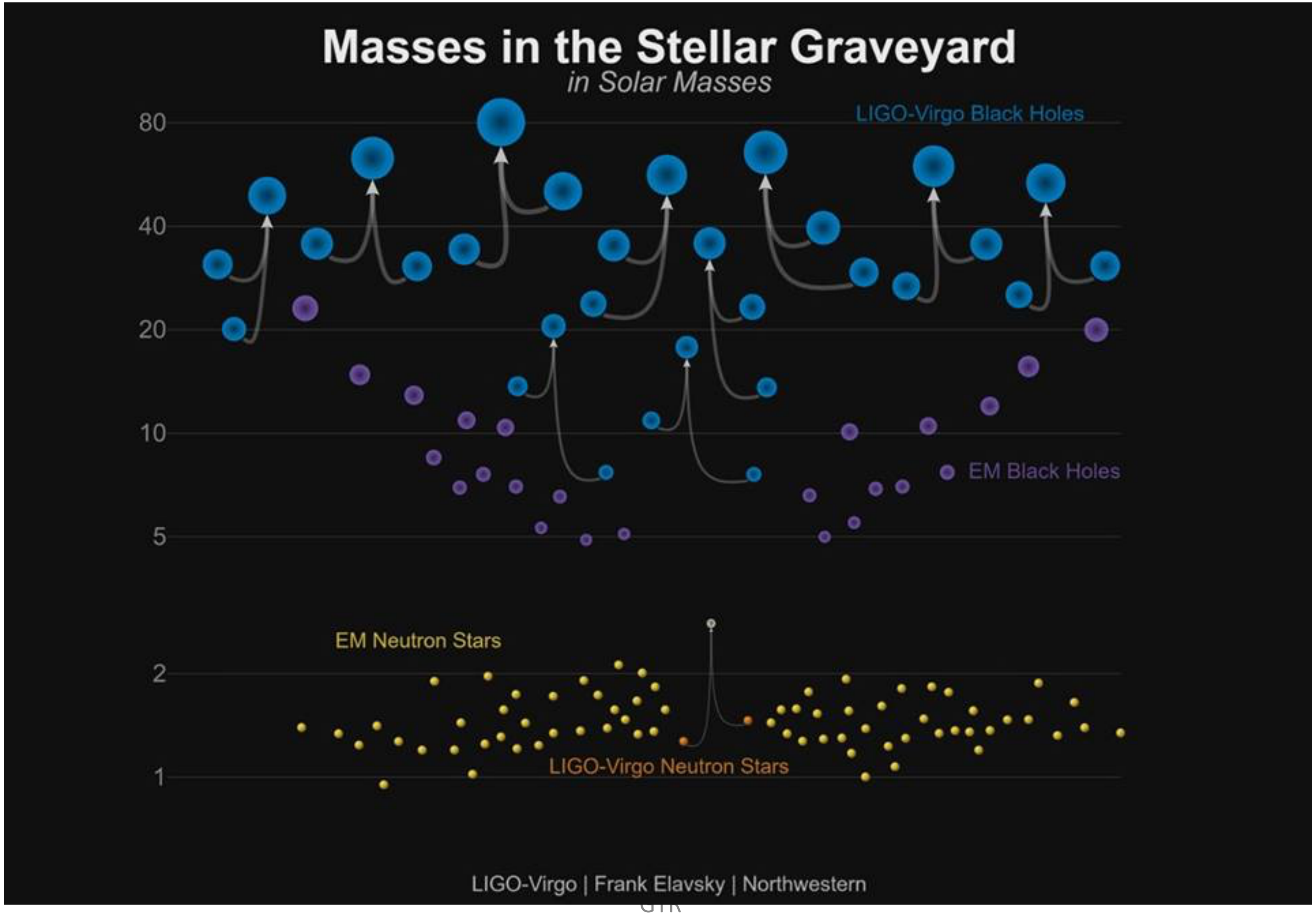
Nuclear Physics: Probing neutron star cores

Neutron star cores are laboratories of extreme conditions of density, gravity and magnetic fields. The structure and composition of NS cores have largely remained unresolved even half-century after pulsars were first discovered. Their cores could be host to unknown physics and might be composed of quark-gluon plasma, hyperons or other exotica.

Some Interesting Astrophysics



Some Interesting Astrophysics
1^{st} & 2^{nd} Run

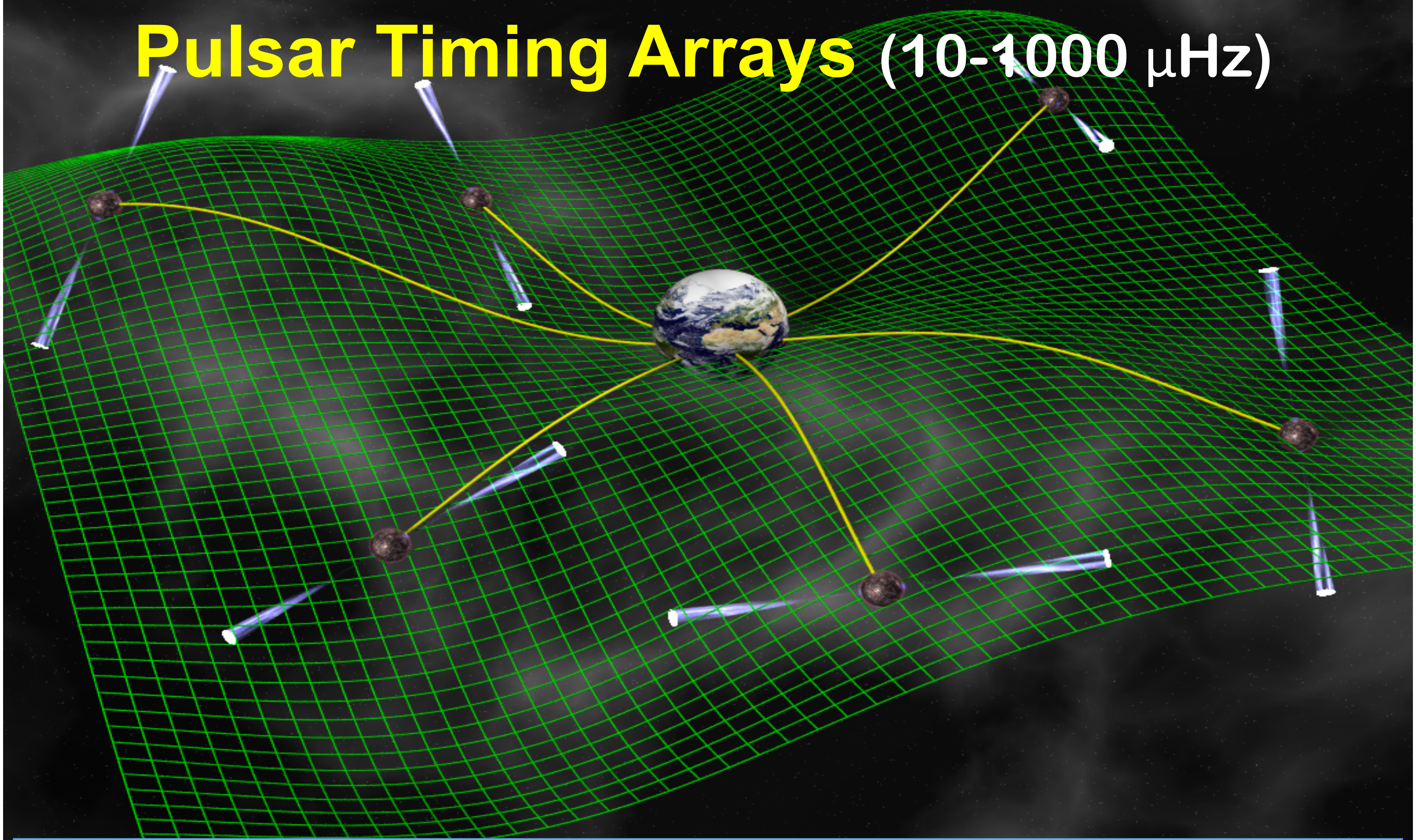


Confronting GR with Observations

The nature of gravity in the strong-field limit is so far largely unconstrained, leaving open several outstanding questions.

QUESTION	ANSWER
Does gravity travel at the speed of light? ➢ Does the graviton have mass?	YES NO
How does gravitational information propagate: Are there more than two transverse modes of propagation (polarization)	Most probably NOT
Does gravity couple to other dynamical fields, e.g., massless or massive scalars?	?
What is the structure of spacetime just outside astrophysical black holes?	?
Do their spacetimes contain horizons?	Maybe
Are astrophysical black holes described by the Kerr metric, as predicted by GR?	Most probably YES

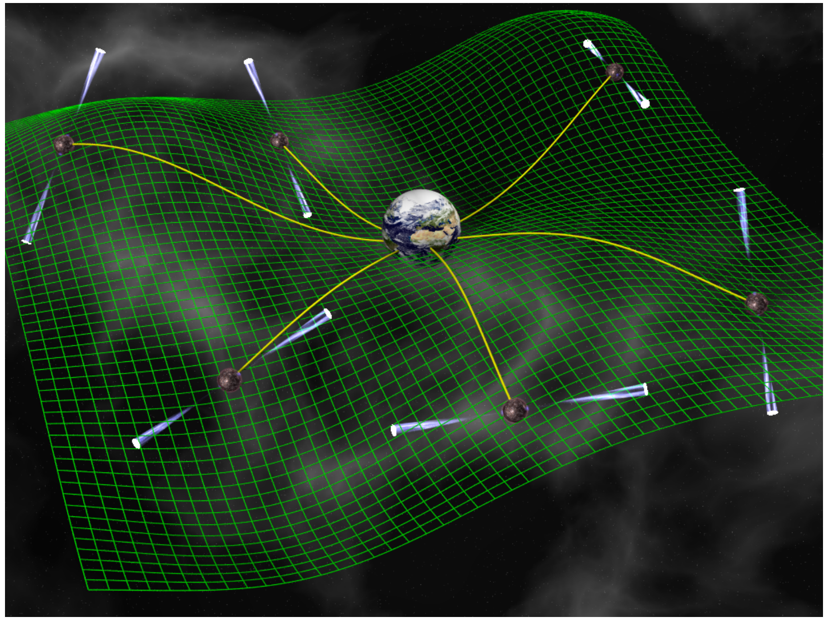
Pulsar Timing Arrays (10-1000 μHz)



Available pulsar data have already placed limit of about **$h<10^{-13}$** on the amplitude of such low-frequency GWs

Pulsar Timing Arrays

10-1000 μHz



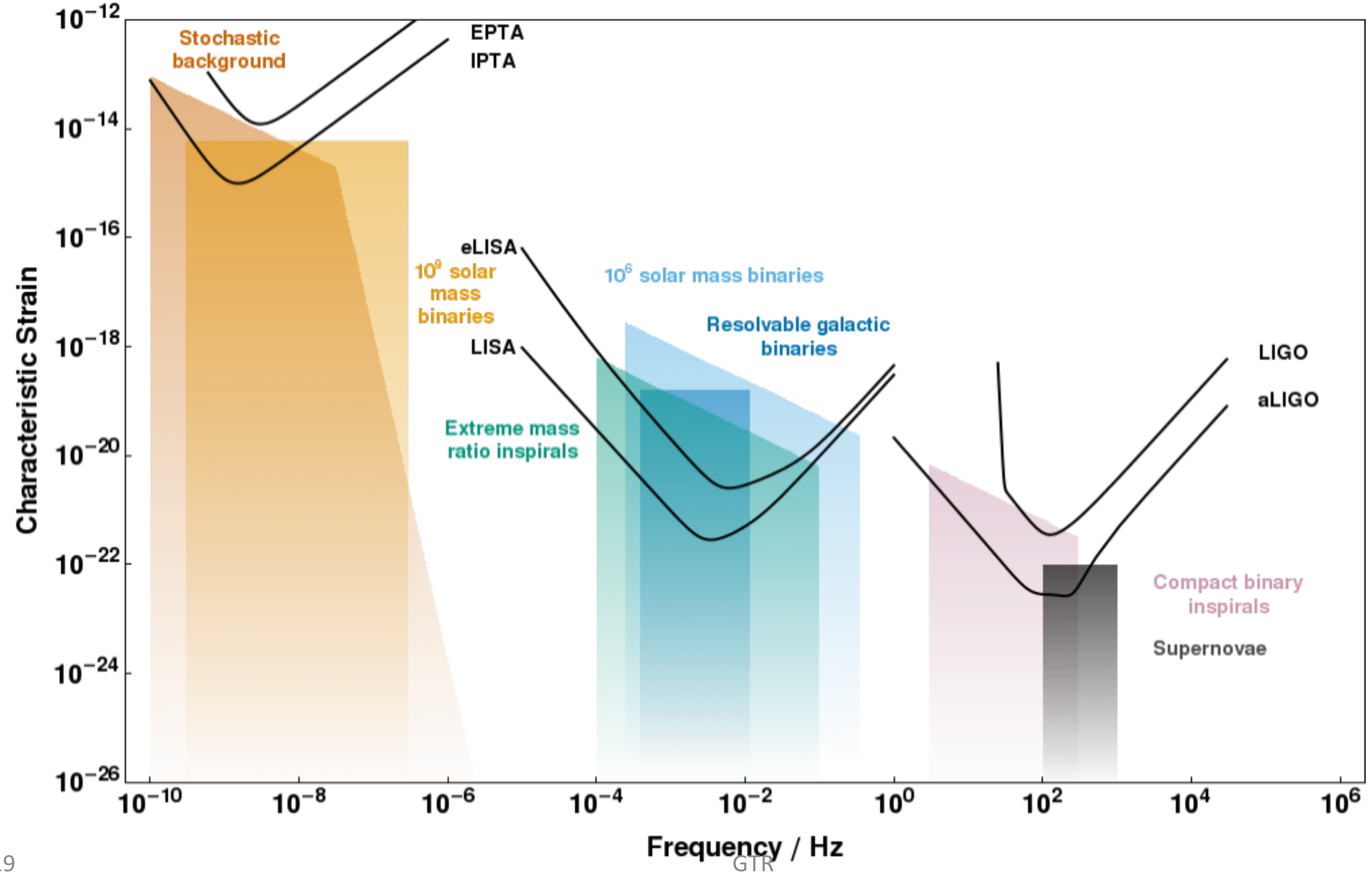
A different approach to detecting GWs is used by pulsar timing arrays, such as the

- European Pulsar Timing Array (EPTA)
- North American Nanohertz Observatory for GW (NANOGrav)
- Parkes Pulsar Timing Array (PPTA)

Available pulsar data have already placed limit of about **$h<10^{-13}$** on the amplitude of such low-frequency GWs

- These projects propose to detect GWs by looking at the effect these waves have on the incoming signals from an array of 20–50 well-known millisecond pulsars.
- As a GW passing through the Earth contracts space in one direction and expands space in another, the times of arrival of pulsar signals from those directions are shifted correspondingly.
- By studying a fixed set of pulsars across the sky, these arrays should be able to detect gravitational waves in the nanohertz range.
- Such signals are expected to be emitted by pairs of merging supermassive black holes.

THE GRAVITATIONAL WAVE SPECTRUM

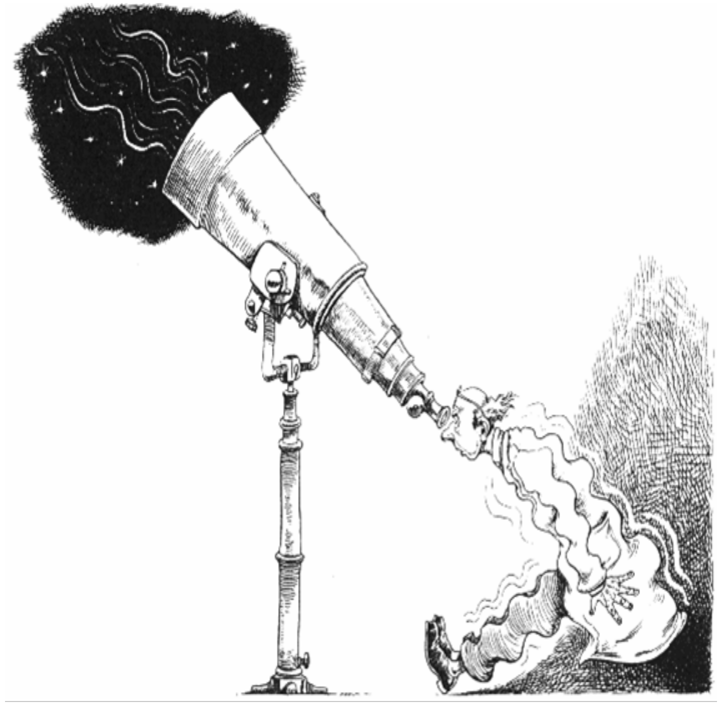


BLACK-HOLE & NEUTRON STAR COLLISIONS WERE EXPECTED

IS THERE ANYTHING ELSE OUT THERE?

THE DETECTION OF GRAVITATIONAL WAVES OPENED A NEW WINDOW IN TO THE UNIVERSE

IT’S UP TO US TO “LISTEN” ITS SECRETS



THANK YOU