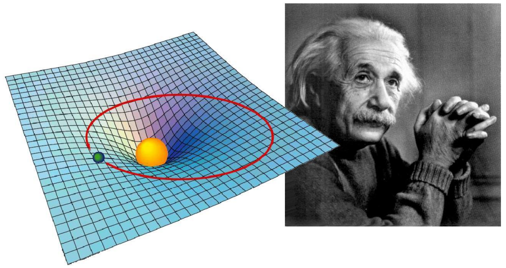
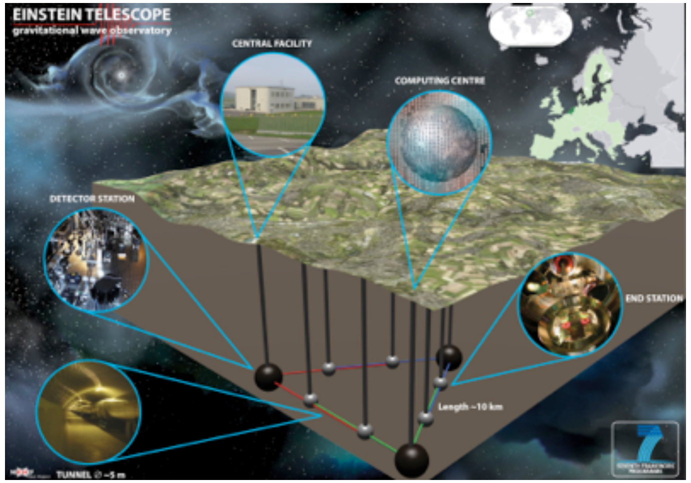
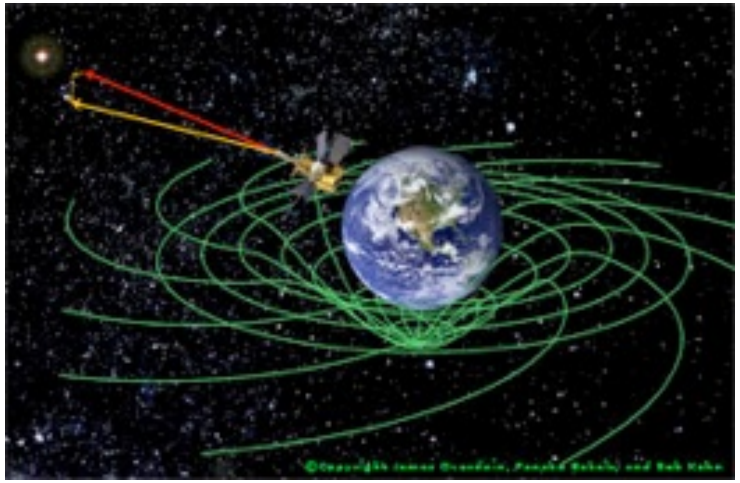
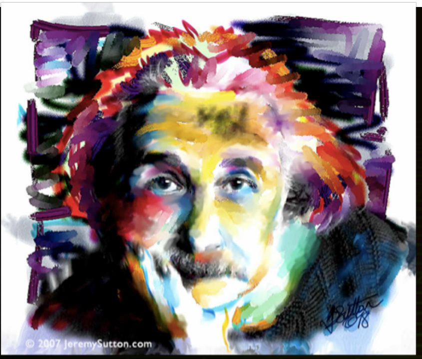


Experimental Gravitation
&
Relativistic Astrophysics

Kostas Kokkotas





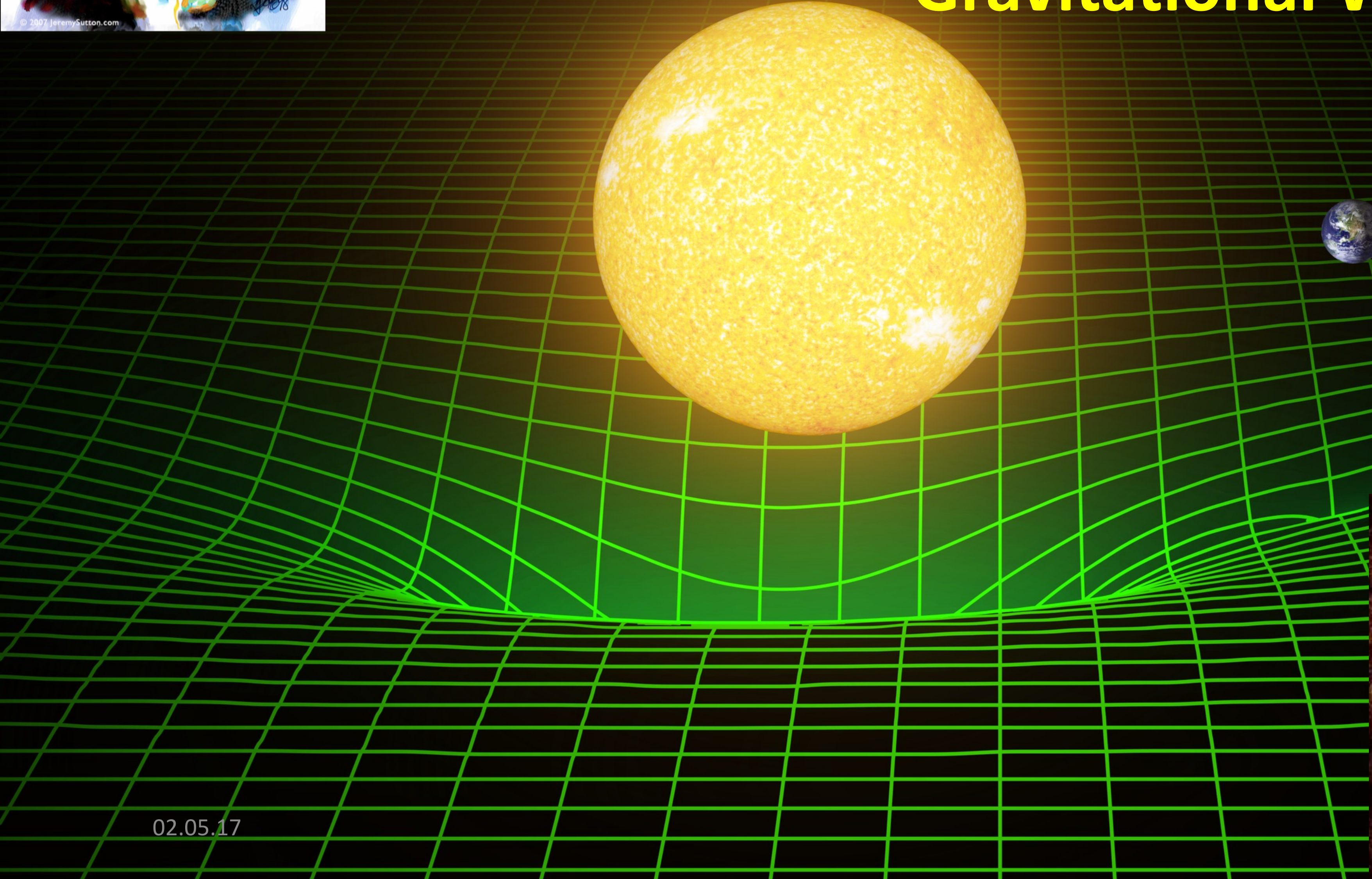


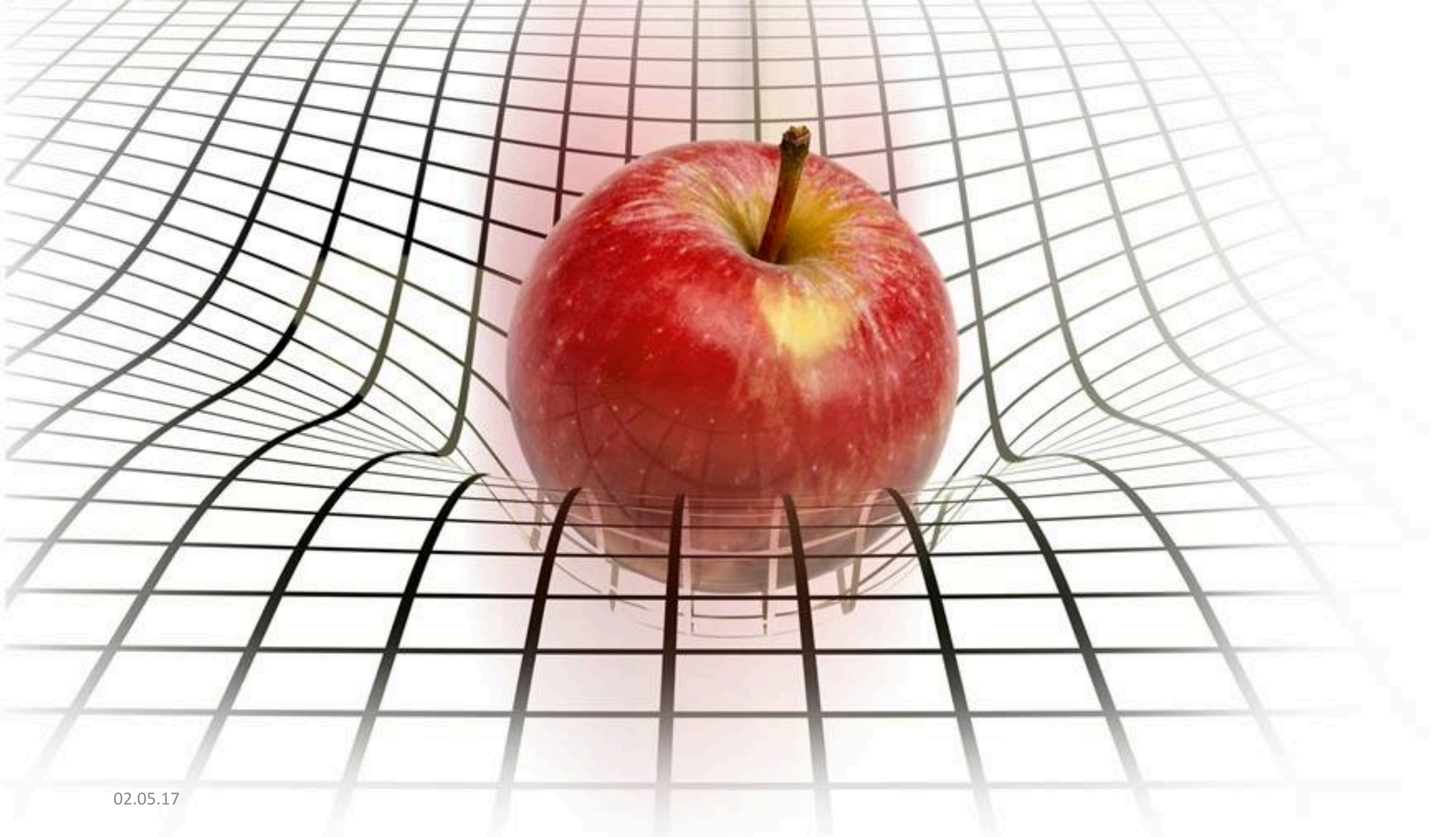
General Theory of Relativity

&

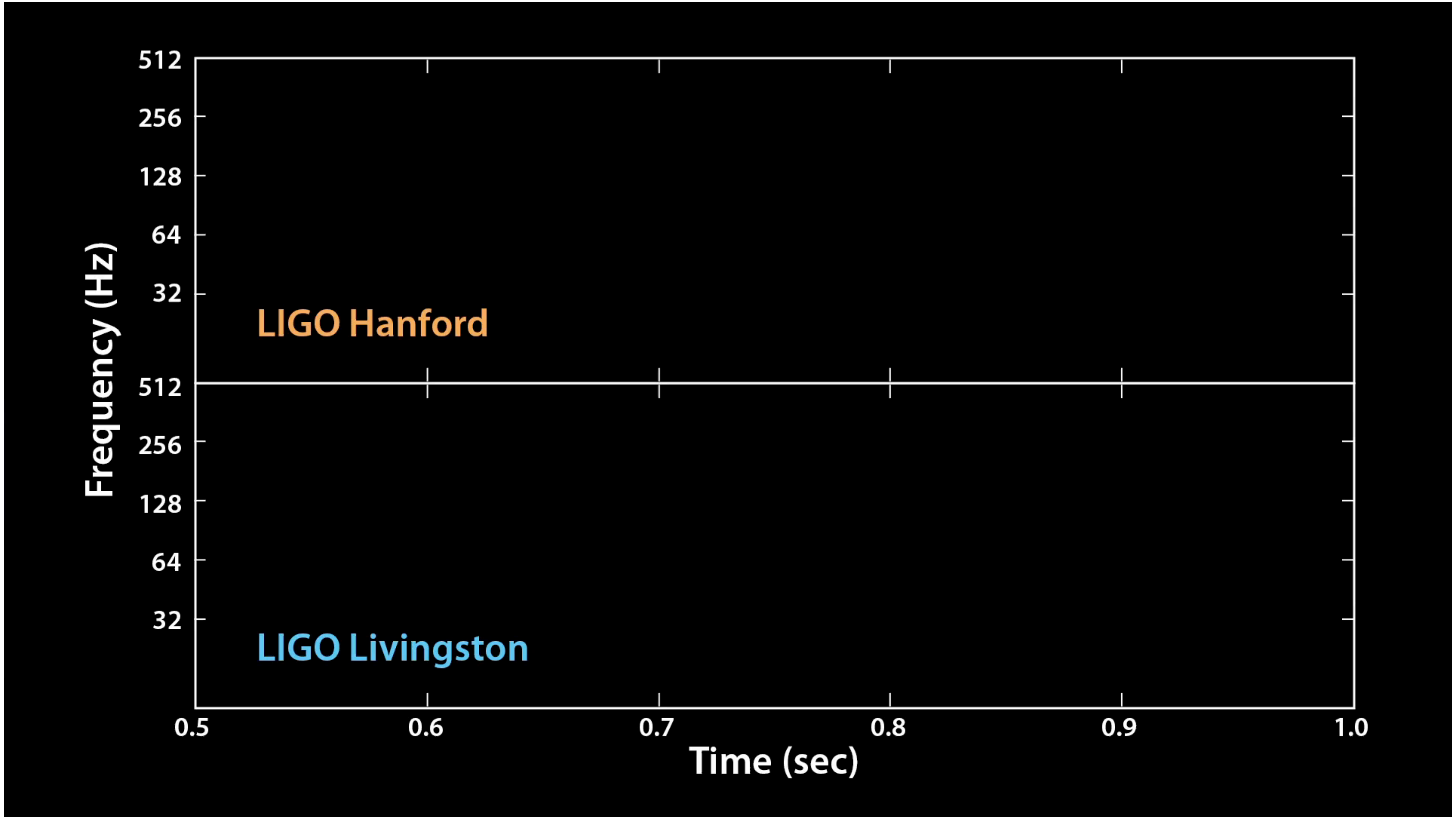
Gravitational Waves

KOSTAS KOKKOTAS





THE «SOUND» OF VACUUM



SPACE – TIME and GRAVITY

NEWTON

Absolute Space & Time

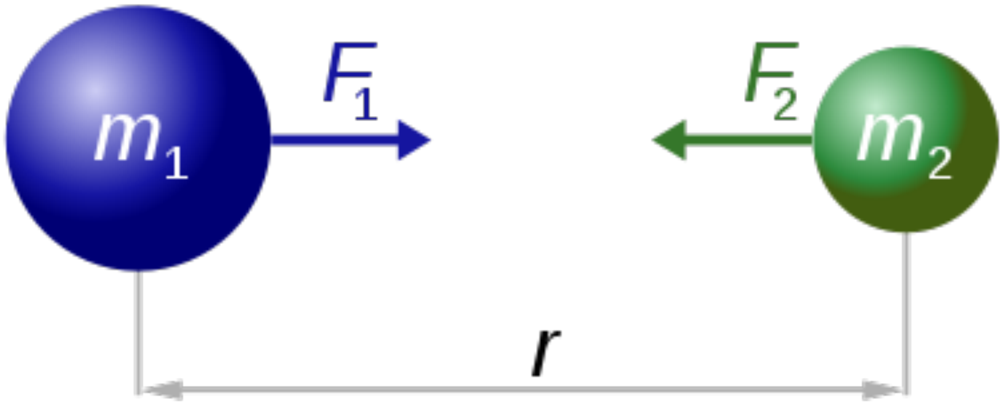
ARISTOTLE & DESCARTES

There is no space in the absence of matter

Ernst Mach -> Einstein

SPACE is defined as the distance between bodies

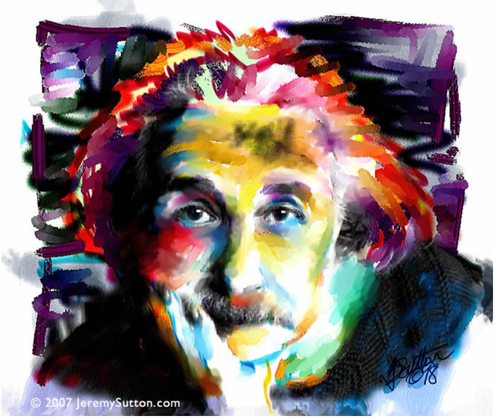
TIME as the interval between events



$$F_1 = F_2 = G\frac{m_1 \times m_2}{r^2}$$

$$\nabla^2 U \approx \rho$$

SPACE – TIME and GRAVITY



There is NO ABSOLUTE SPACE & TIME

SPECIAL THEORY 1905	The measurements **SPATIAL DISTANCES** and of **TIME INTERVALS** Are **velocity dependent!**
GENERAL THEORY 1915	The measurements **SPATIAL DISTANCES** and of **TIME INTERVALS** Depend on the **PRESENCE of MATTER!**

GENERAL THEORY OF RELATIVITY

matter tells spacetime how to curve

… and space tells matter how to move!

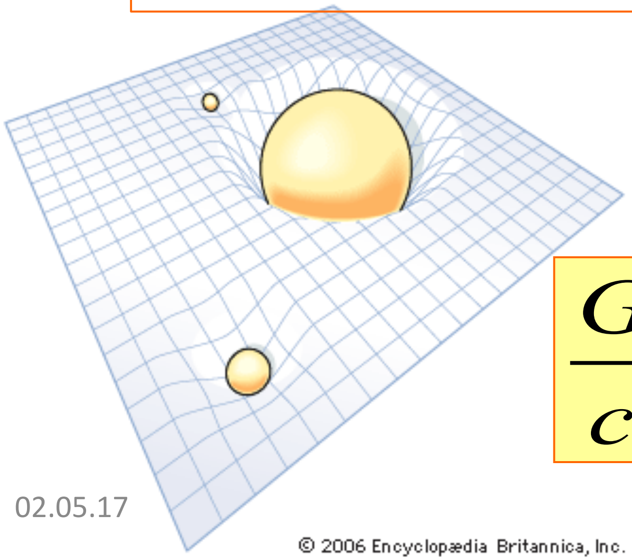
GEOMETRY

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

MATTER-ENERGY

There is no need of the notion of "gravitational force"

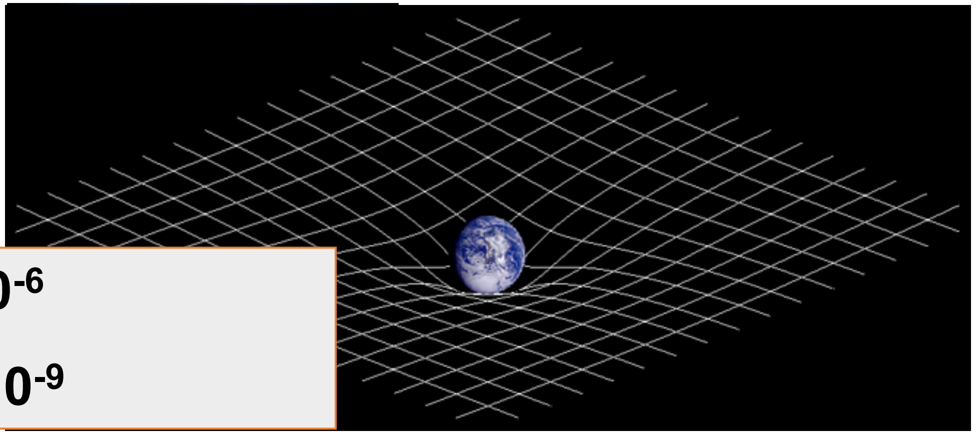
Gravitational field can be expressed via the spacetime curvature.



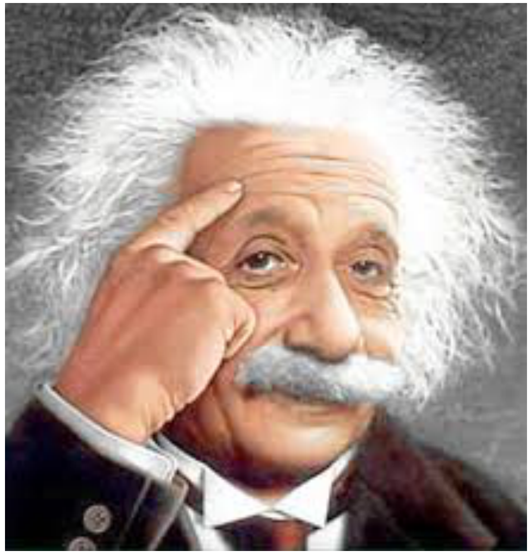
$$\frac{GM}{c^2 R} \sim 1$$

Sun~ 10^{-6}

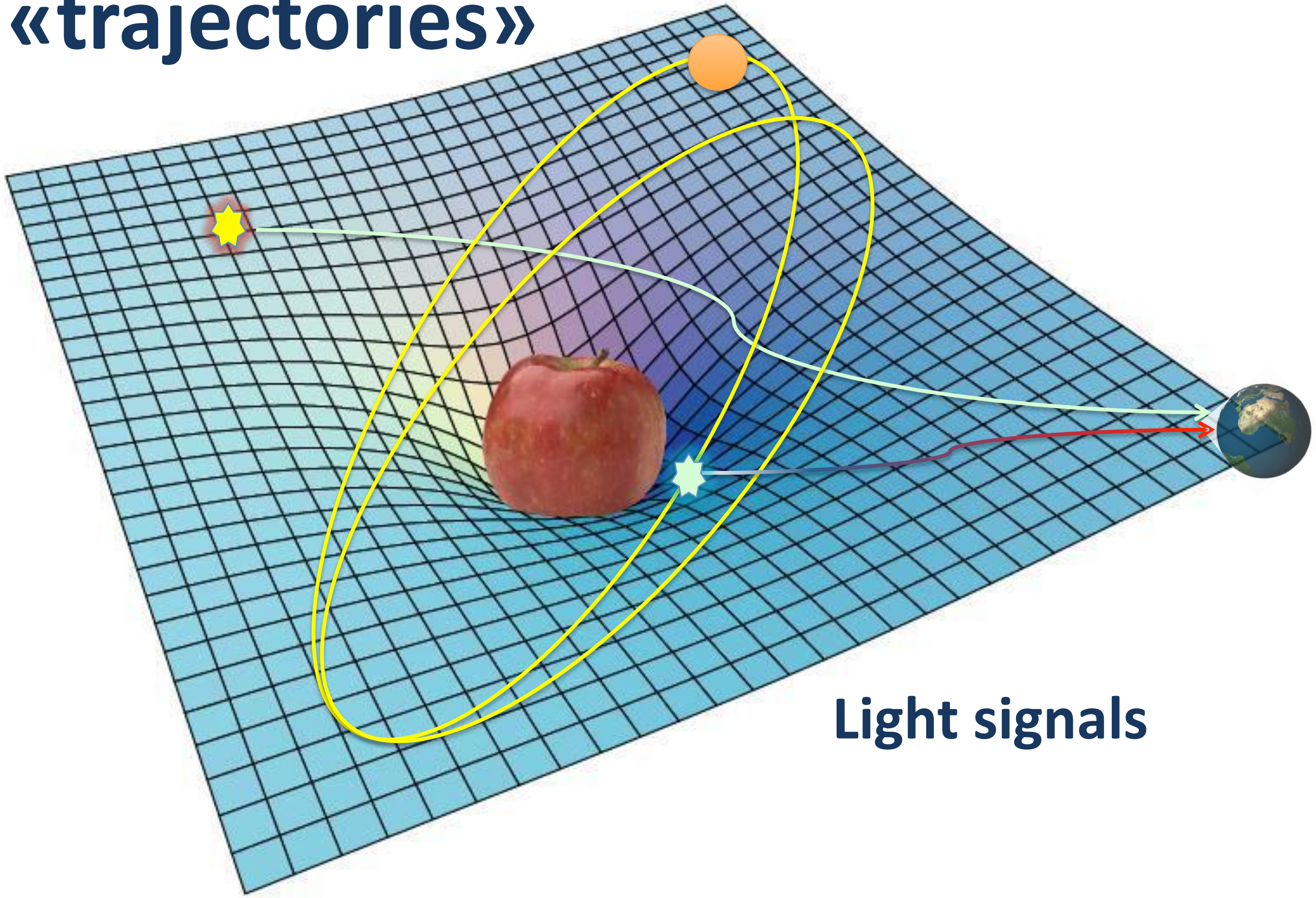
Earth~10^{-9}



HOW TO TEST IT?



«trajectories»



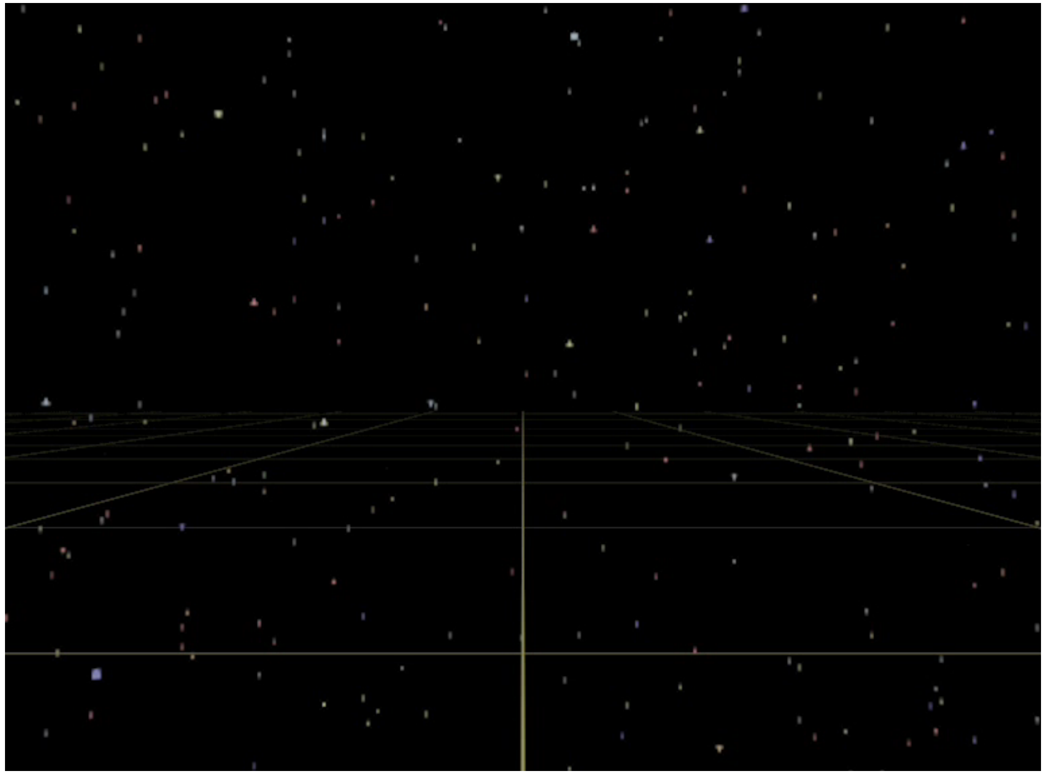
Light signals

GTR - RESOLVED

RESOLVED:

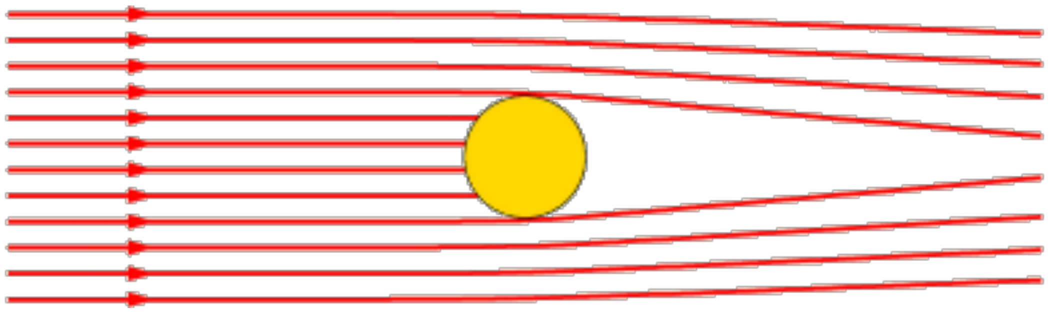
PERIHELION SHIFT OF PLANETS

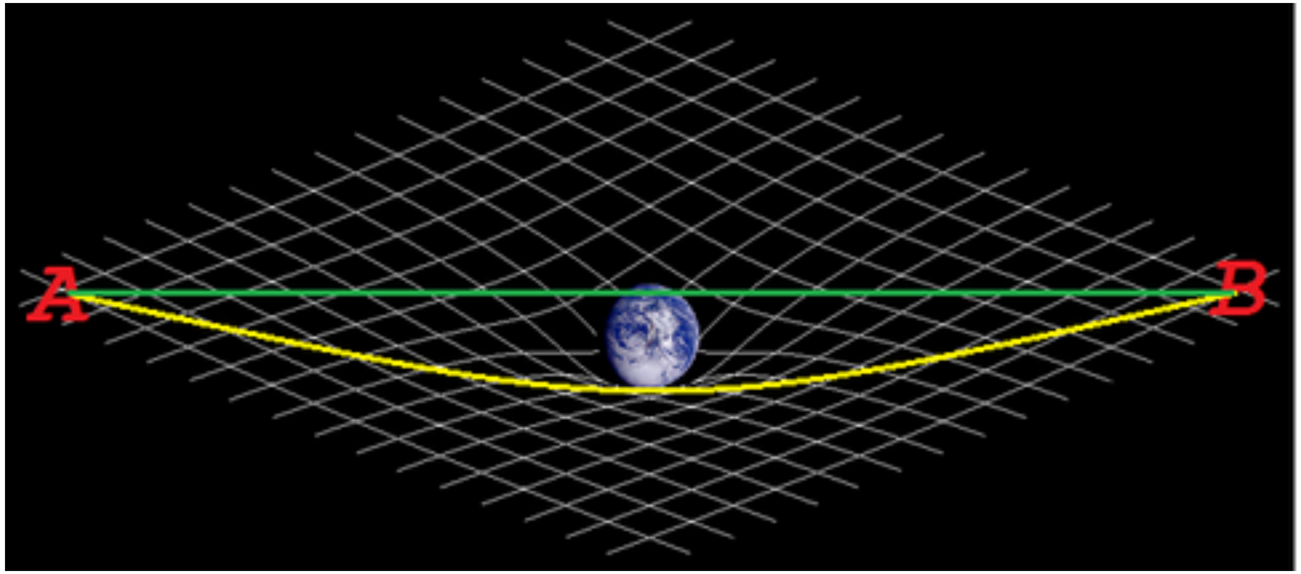
- **MERCURY:** 43.1” - 42.98”/CENTURY
- **VENUS:** 8.65” - 8.62” /CENTURY
- **EARTH:** 3.85” - 3.84”/CENTURY
- **PSR 1913+16 :** 4.2^0/YEAR



GTR - PREDICTED

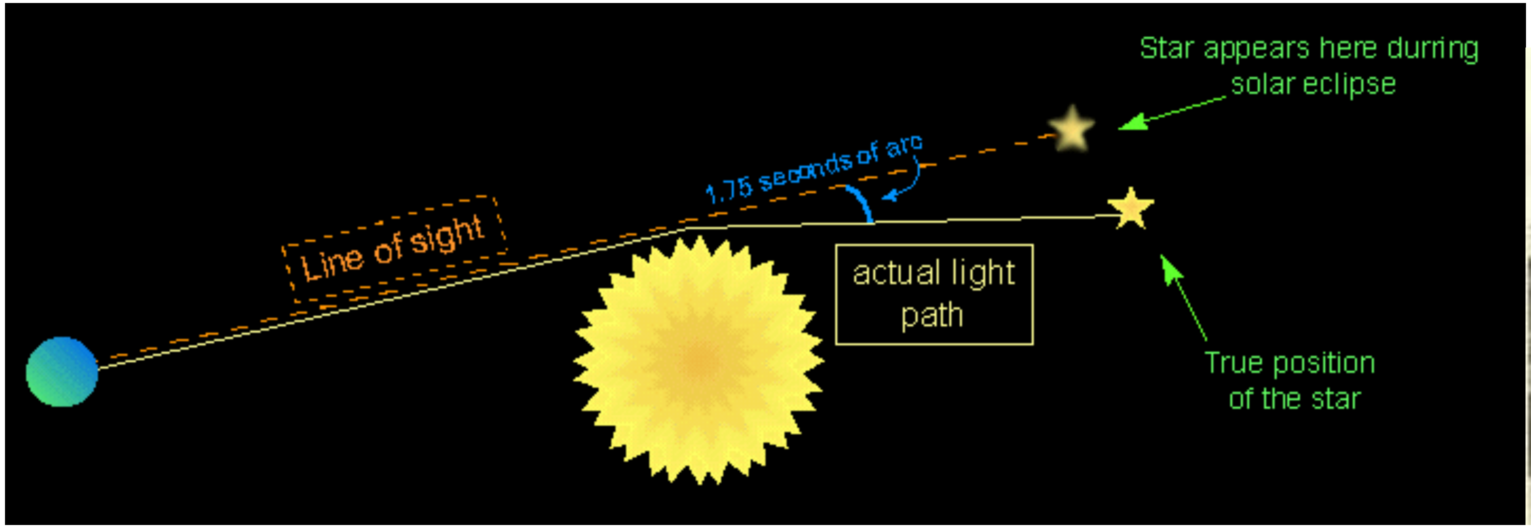
BENDING OF LIGHT





$$\delta\varphi \sim \frac{4GM}{c^2 r}$$

1919 : THE TRIUMPH



Edddington

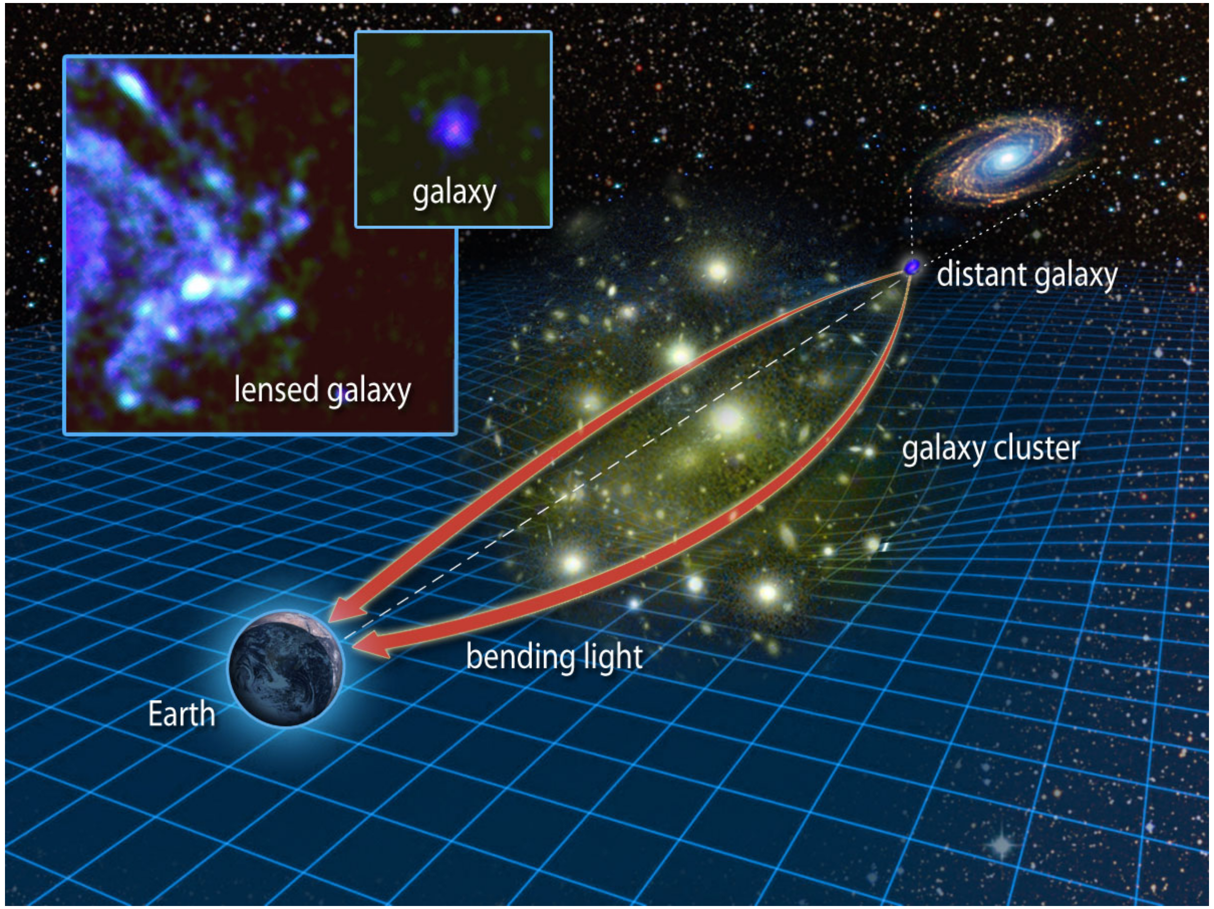
When a student asked Einstein:

what he would have done had the eclipse measurements not confirmed his theory

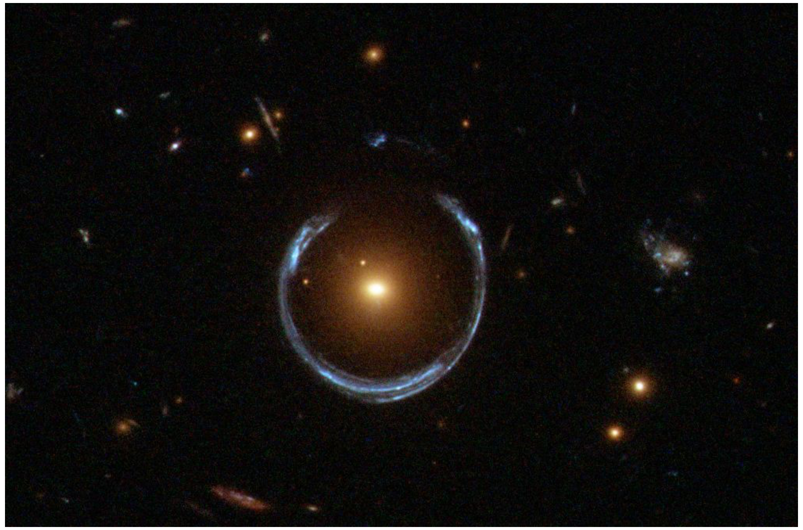
He replied:

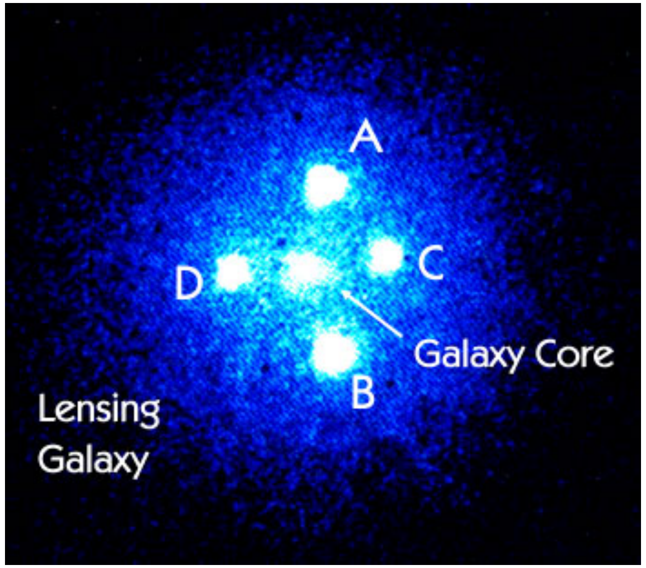
"In that case, I would have to feel sorry for God, because the theory is correct."

ASTROPHYSICS : GRAVITATIONAL LENSING



ESTIMATION OF DARK MATTER DISTRIBUTIONS





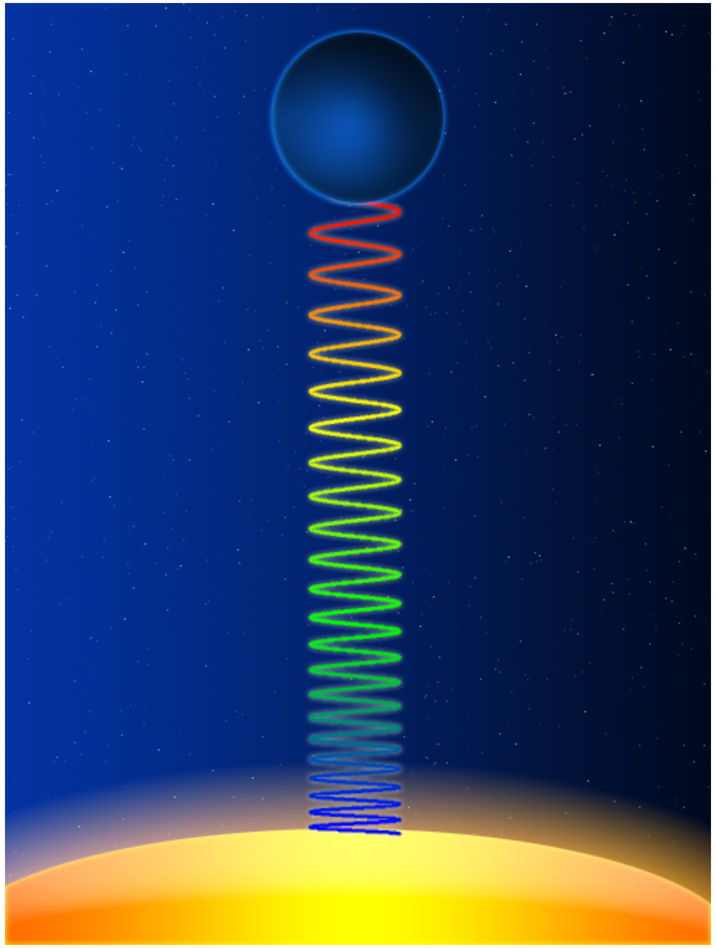
TIME & GRAVITY

GRAVITATIONAL REDSHIFT

$$\Delta t \sim \frac{G\,M}{c^2\,r}$$

Pound–Rebka Experiments 1959-65

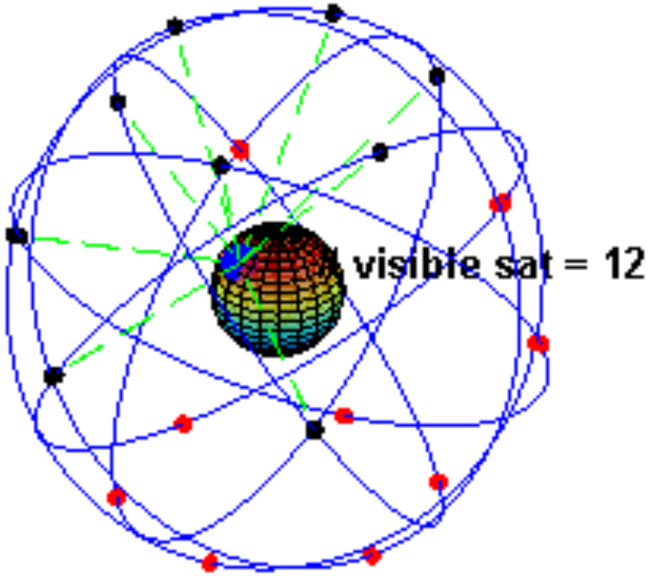
Basic instrument for measuring the strength of the gravitational field of astronomical objects



Global Positioning System

GPS & RELATIVITY

- **Satellite Orbit:** 20.000 km
- **Velocity:** 14.000 km/h



-7 µsec/day due to STR
+45 µsec/day due to GTR
+38 µsec/day due in total

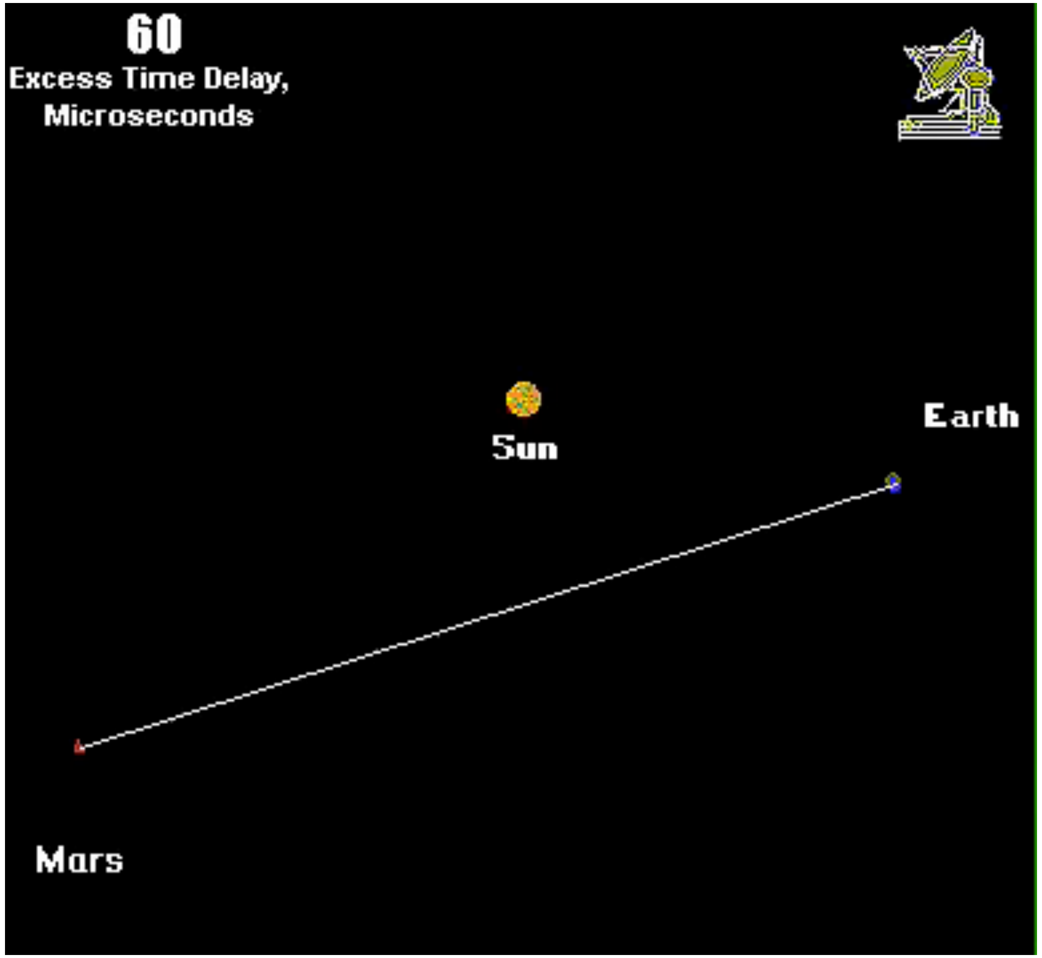
Error in position : **10 km/day**

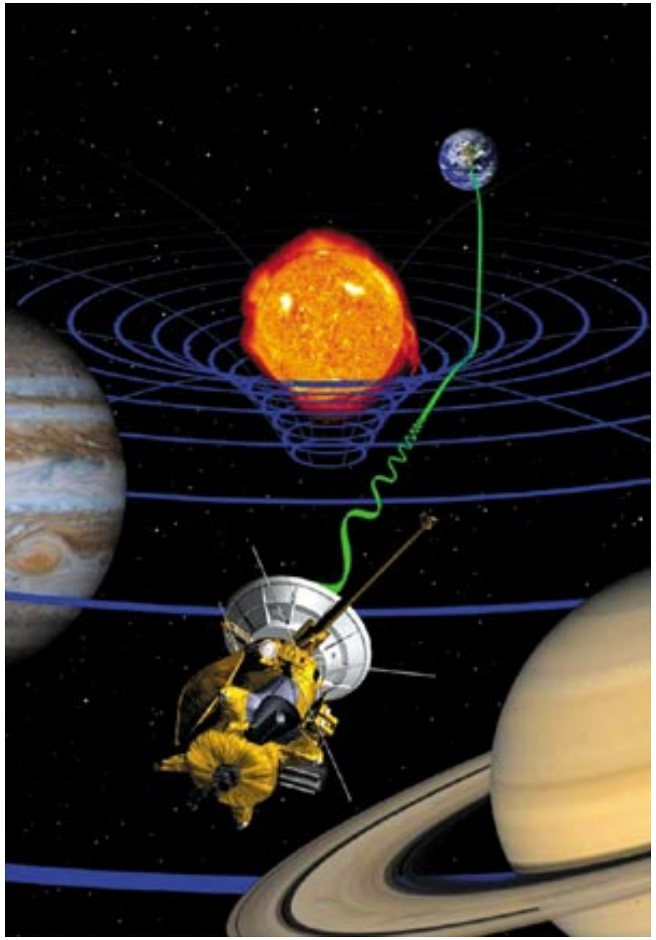
1960-70 & the Golden Decade

- **1957: Pirani**-Bondi+… demonstrate that gravitational waves carry energy
- **1960-** : Black Holes– (**Finkelstein**, Kruskal, **Wheeler**,…)
- **1963**: **1st** & **only** solution of Einstein equations describing rotating black holes (Roy Kerr)
- **1960-70** : Post-Newtonian Approximations (Chandrasekhar)
- **1963**: Peter & Mathews: gravitational radiation from binary systems
- **1965-…**: First Equations of State for Neutron Stars (not yet detected!)
- **1966-…:** Kip Thorne and collaborators engaged in the systematic study of gravitational wave sources
- **1967**: Detection of the 1st pulsar Jocelyn Bell Burnell & Antony Hewish
- **1960+: Zel'dovich** and collaborators «Relativistic Cosmology »

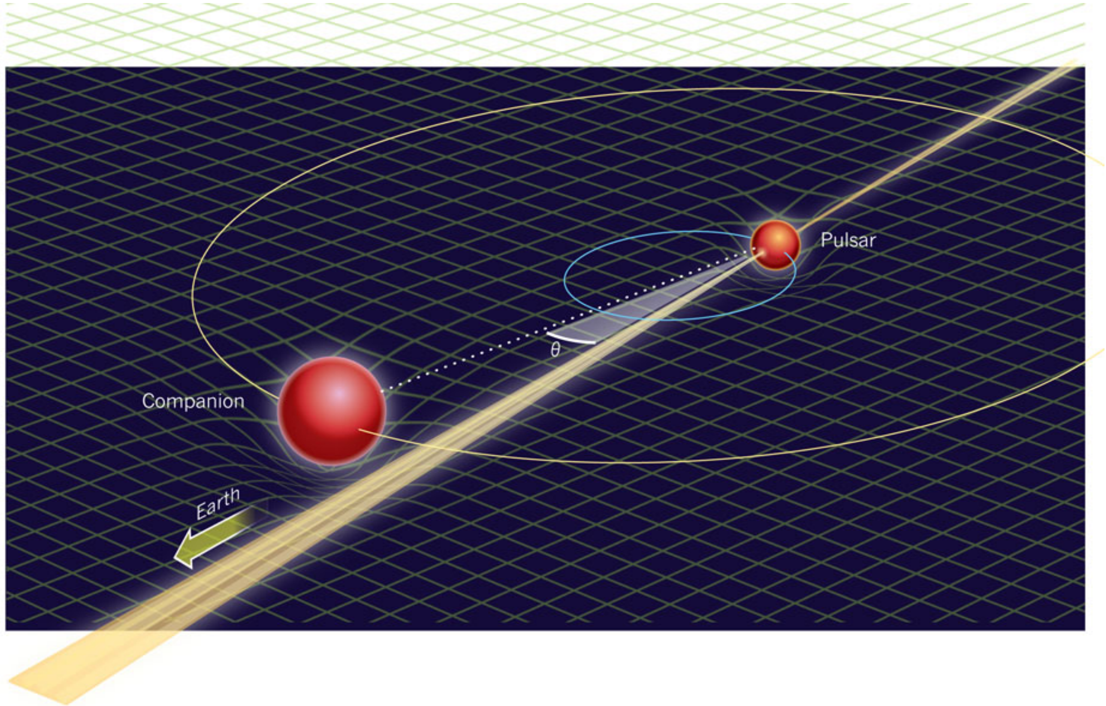
1970+ & Shapiro delay

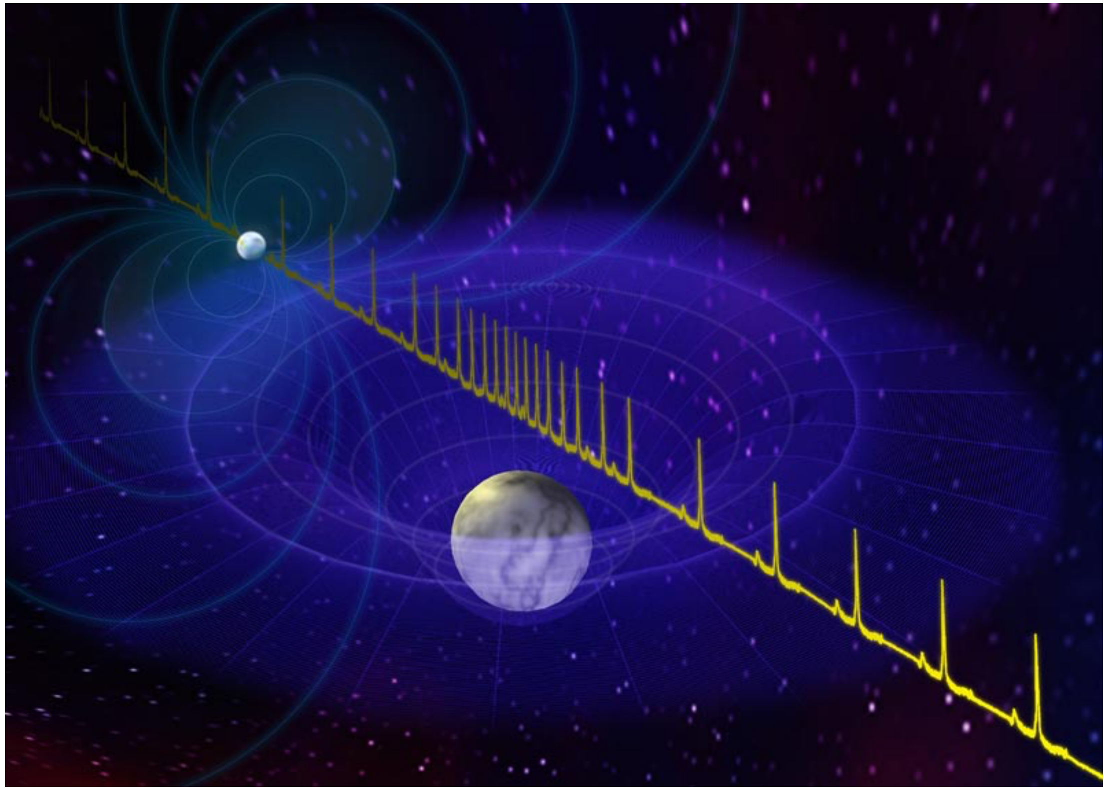
200 microseconds =0.0002 seconds





Shapiro delay: ASTROPHYSICS

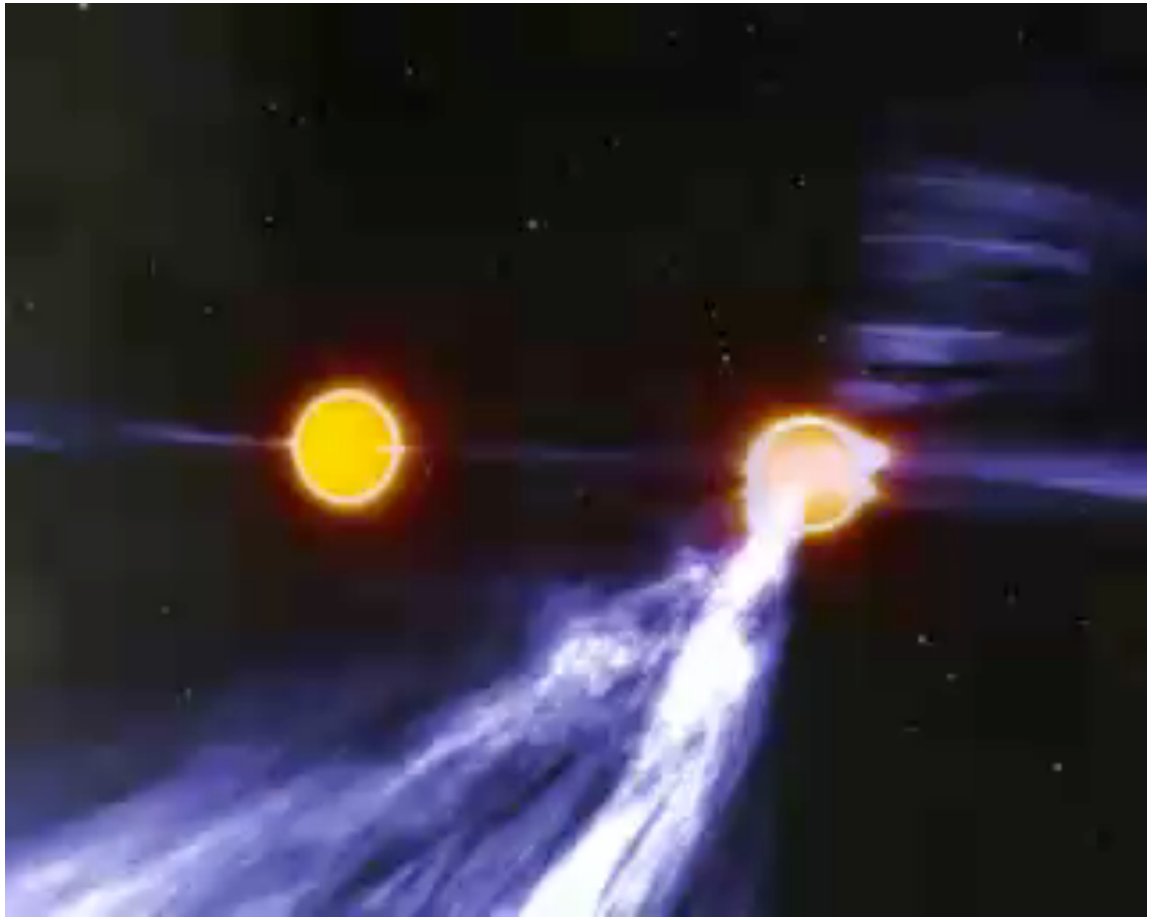




2010 – The 1st Neutron Star with 2M$_\odot$

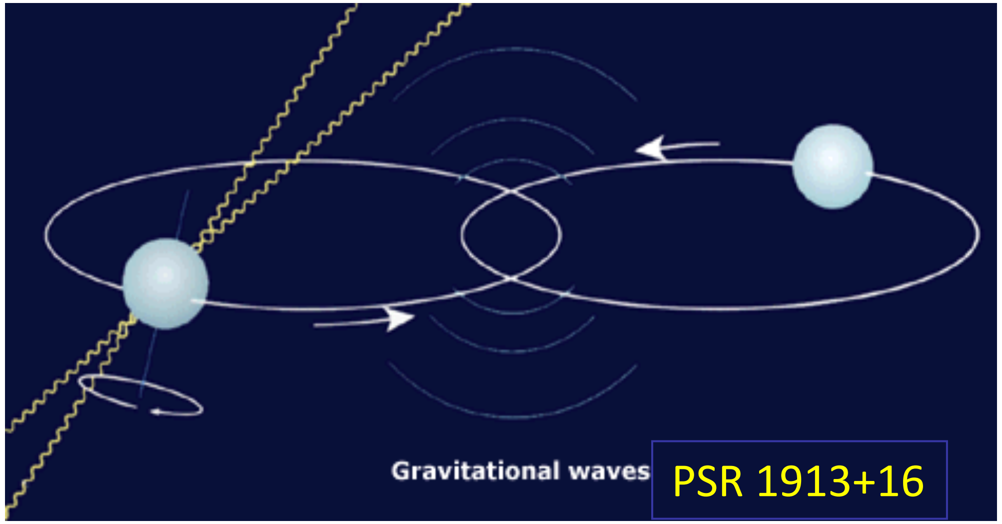
1973: BINARY PULSAR

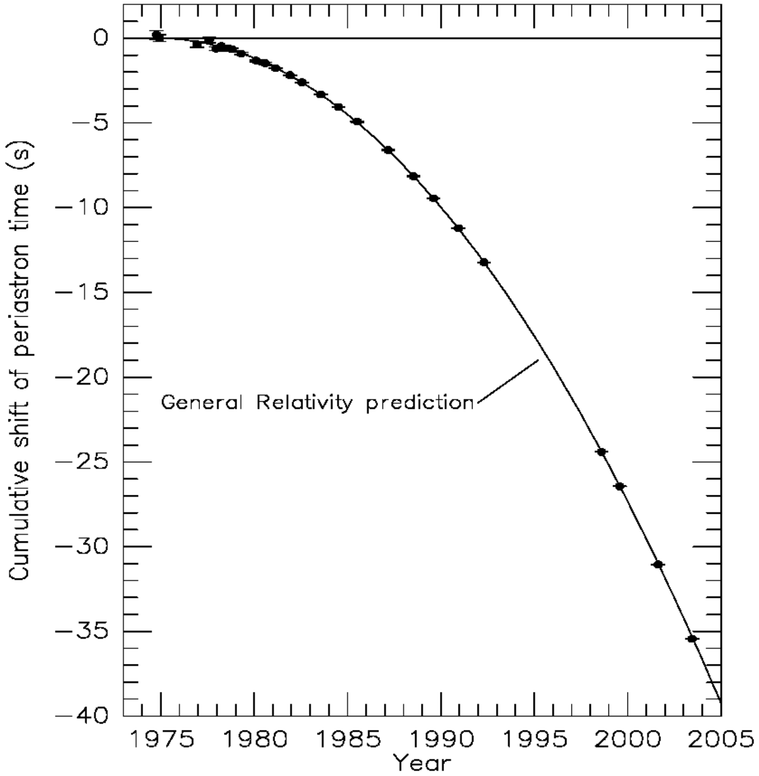
Binary Pulsar: PSR 1913+16



INDIRECT PROOF OF GRAVITATIONAL RADIATION EMISSION

GRAVITATIONAL WAVES: The CONFIRMATION





Hulse & Taylor

Nobel 1993

$$\frac{\dot{P}_{b,corrected}}{\dot{P}_{b,GR}} = 1.0013 \pm 0.0021$$

Was Einstein Right?

The "new potential" is the metric tensor

Flat Spacetime

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

«Even more» Curved

$$g_{\mu\nu} = \begin{pmatrix} -1 + 2U - 2\beta U^2 + \ldots & * & * & * \\ * & 1 - 2\gamma U & 0 & 0 \\ * & 0 & 1 - 2\gamma U & 0 \\ * & 0 & 0 & 1 - 2\gamma U \end{pmatrix}$$

Slightly Curved Spacetime

$$g_{\mu\nu} = \begin{pmatrix} -1 + 2U & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

Maximally curved

$$g_{\mu\nu} = \begin{pmatrix} * & * & * & * \\ & * & * & * \\ & & * & * \\ & & & * \end{pmatrix}$$

Was Einstein Right?

$$g_{00} = -1 + 2U - 2\beta U^2 + 2(\gamma + 1)\Phi_1 + 2[(3\gamma + 1 - 2\beta)\Phi_2 + \Phi_3 + 3\gamma\Phi_4] + O(c^{-5})$$

$$g_{0i} = -\frac{1}{2}(4\gamma + 3 + \ldots)U_i - \frac{1}{2}(1 + \ldots)W_i + O(c^{-5}),$$

$$g_{ij} = \delta_{ij}(1 + 2\gamma U) + O(c^{-4})$$

γ : How much space curvature g_{ij} is produced by unit rest mass ?

β : How much nonlinearity is there in the superposition law for gravity g_{00} ?

α1, α2, α3 : measure the extent of preferred frame effects

ζ1, ζ2, ζ3, ζ4 : measure the failure of conservation of energy, momentum and angular momentum.

GTR demands:

$\gamma = \beta = 1$

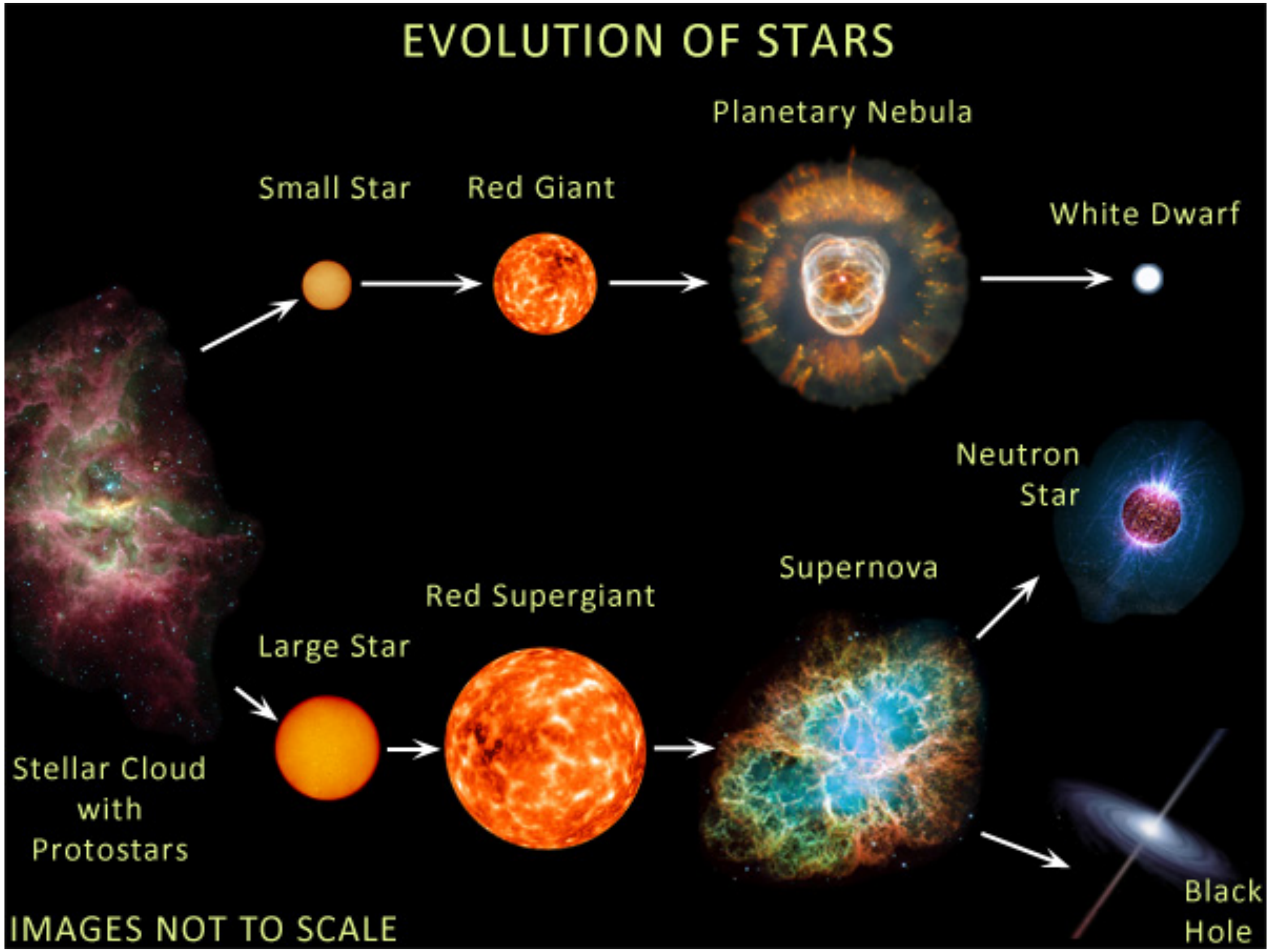
$\alpha_1 = \alpha_2 = \alpha_3 = \zeta_1 = \zeta_2 = \zeta_3 = \zeta_4 = \eta = 0$

Accuracy from Experimental Tests

Parameter	Bound	Effects	Experiments
$\gamma - 1$	2.3×10^{-5}	Time delay, Light deflection	Cassini tracking
$\beta - 1$	3×10^{-3}	Perihelion shift	Perihelion shift
$\beta - 1$	2.3×10^{-4}	Nordtvedt effect	Nordtvedt effect
ζ	0.001	Earth tides	Gravimeter data
α_1	10^{-4}	Orbit polarization	Lunar laser ranging
α_2	4×10^{-7}	Spin precession	Sun axis' alignment with ecliptic
α_3	2.2×10^{-20}	Self-acceleration	Pulsar spin-down statistics
ζ_1	0.02	-	Combined PPN bounds
ζ_2	4×10^{-5}	Binary pulsar acceleration	PSR 1913+16
ζ_3	10^{-8}	Newton's 3rd law	Lunar acceleration
ζ_4	0.006	-	Kreuzer experiment

Supernovae

LIFE CYCLE OF STARS



WHITE DWARFS

$$\frac{\mathrm{GM}}{c^2R} = 0.0002$$

NEUTRON STARS

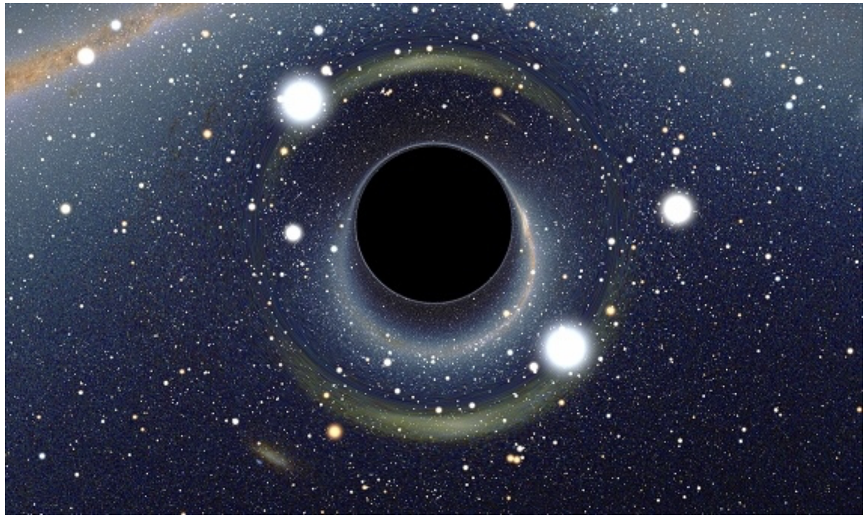
$$\frac{\mathrm{GM}}{c^2R} = 0.2$$

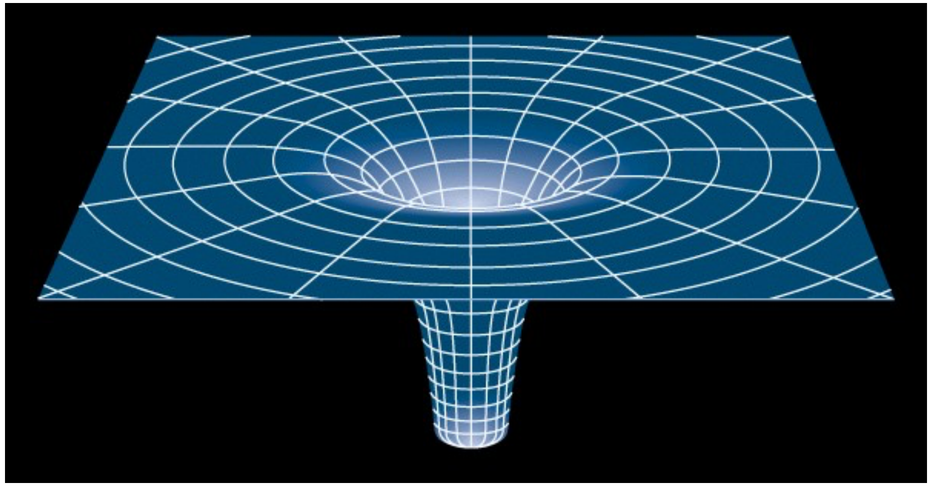
BLACK HOLES

$$\frac{\mathrm{GM}}{c^2R} = 0.5$$

COSMIC ABYSS... (BLACK HOLES)

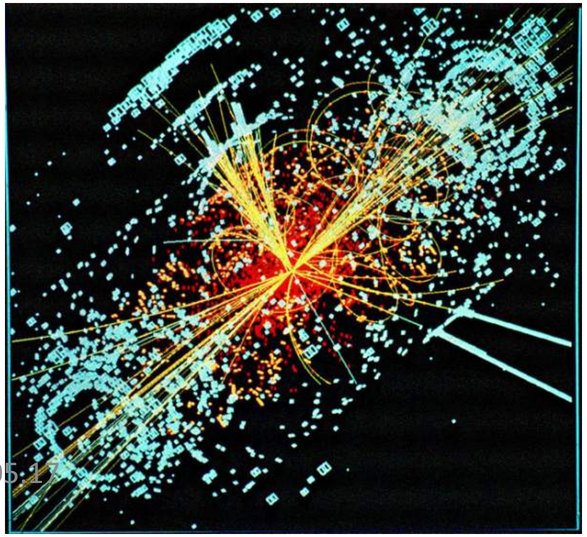
«INFNITE» SPACETIME DEFORMATION

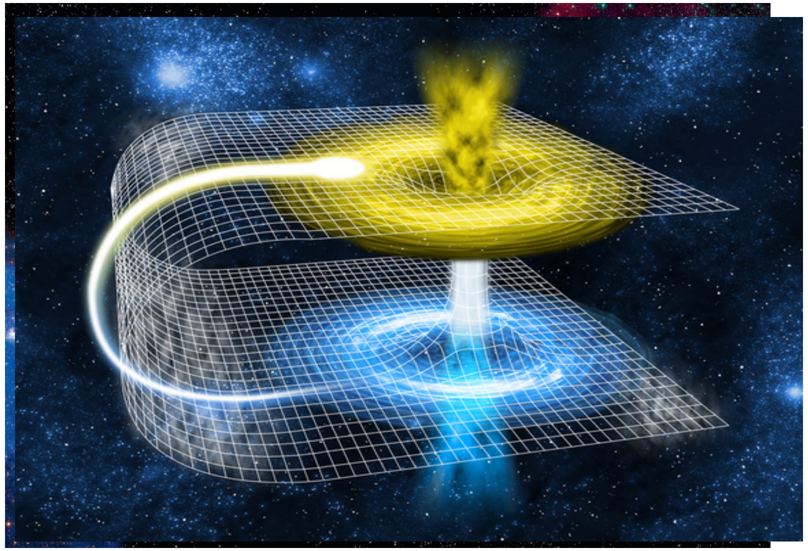




BLACK HOLES IN THE LAB

SCIENCE FICTION

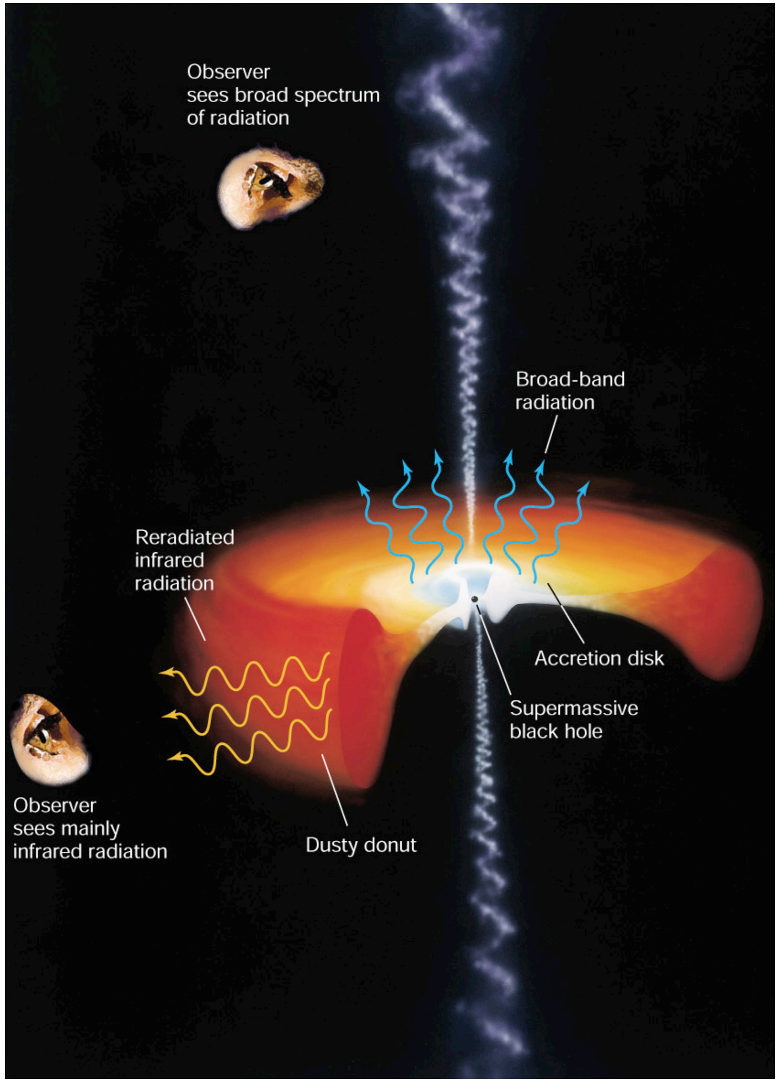




GALACTIC BLACK HOLES

MOST GALAXIES HOST A SUPER-MASSIVE BLACK HOLE IN THEIR CENTER

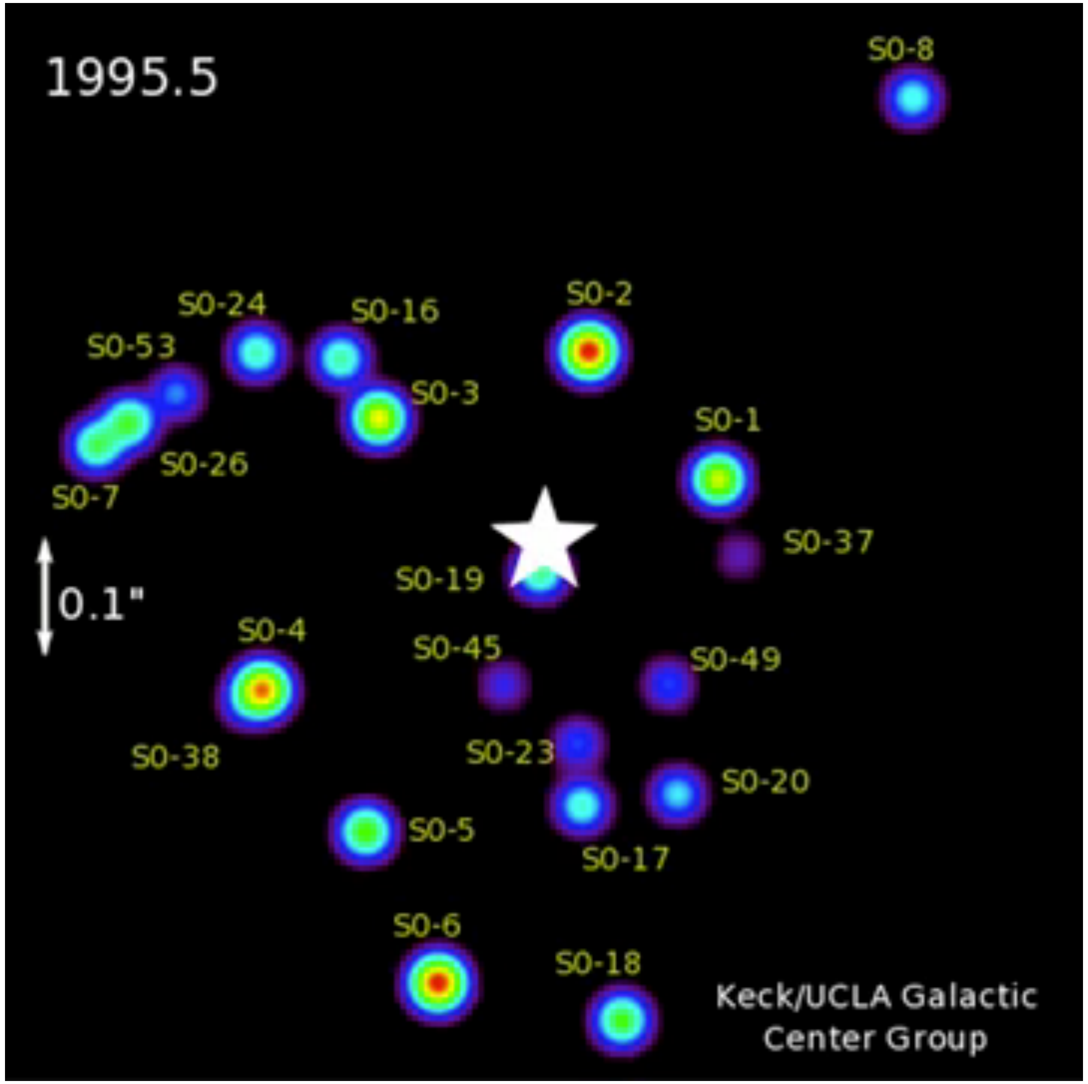
- **IN THE `60 : SUSPISIONS**
- **IN THE `70 : INDICATIONS**
- **IN THE `80 : PROOFS**



The BH in the CENTER of our GALAXY

MASS = 4.100.000$M_\odot$

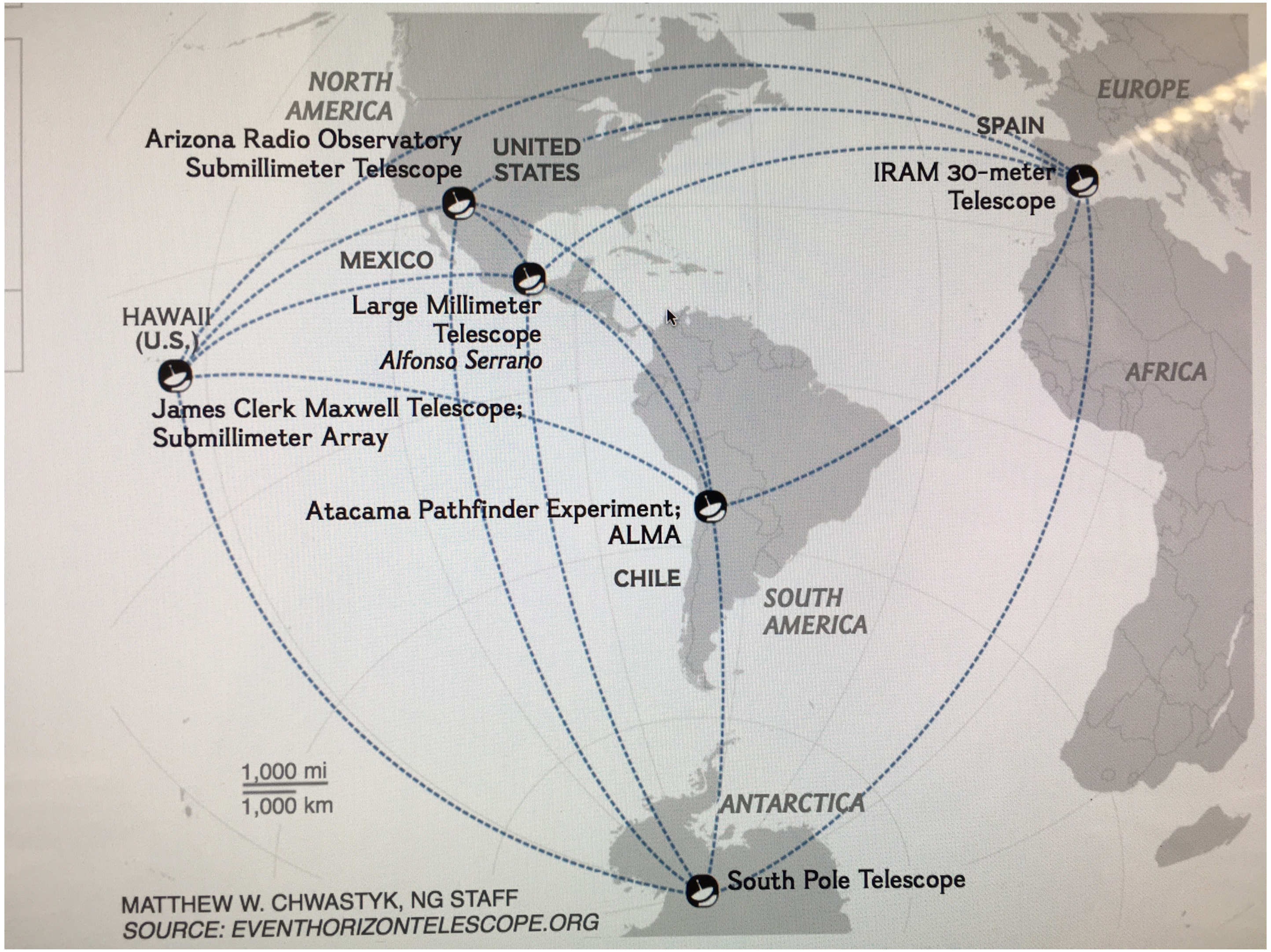
RANGE: $10^6 - 4\times10^{10}$ $M_\odot$



BHs in the Galaxy Centers : HORIZON

M87 (Virgo A)
$M = 4.1 \times 10^6 M_\odot$

M87 (Virgo A)
$M = 3.5\text{-}6.6 \times 10^9 M_\odot$



BHs in the Galaxy Centers

M87 (Virgo A)
$M = 4.1 \times 10^{6}\ M_{\odot}$

M87 (Virgo A)
$M = 3.5\text{-}6.6 \times 10^{9}\ M_{\odot}$

[Black Hole Hunters](http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=31)
http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=31

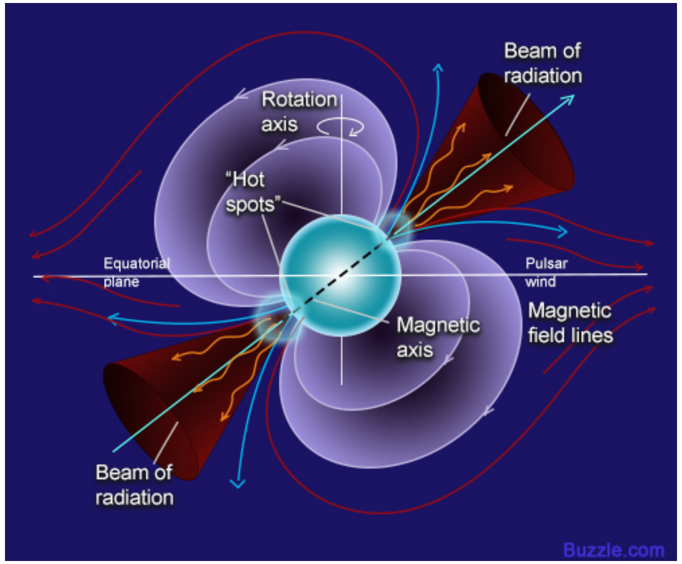
[Event Horizon Telescope ready to image black hole](http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=141)
http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=141

[Astronomers Might Have Just Captured the First Ever Photo of a Black Hole's Event Horizon](http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=148)
http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=148

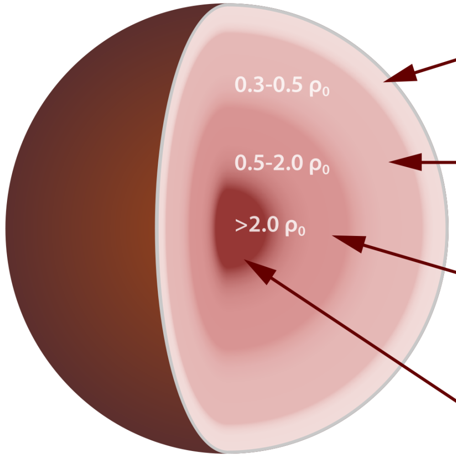
[Astronomers May Finally Have the First Picture of a Black Hole](http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=149)
http://www.tat.physik.uni-tuebingen.de/~tat/blog/index.php?controller=post&action=view&id_post=149

NEUTRON STARS

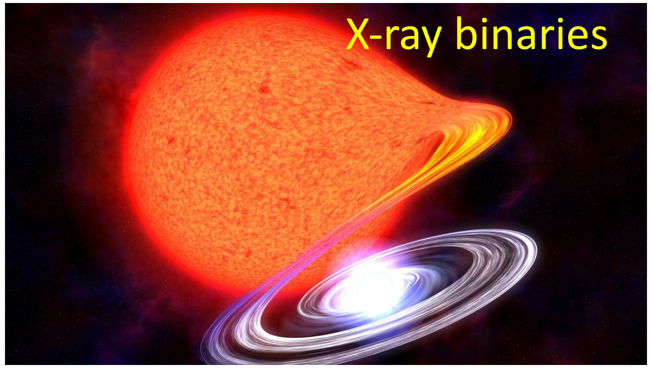
- They are the **most compact stars** known to exist in the universe.
- They have **densities equal to that of the early universe** and **gravity similar to that of a black hole.**
- Most extreme magnetic fields known in the universe up to **10^{16} G**.

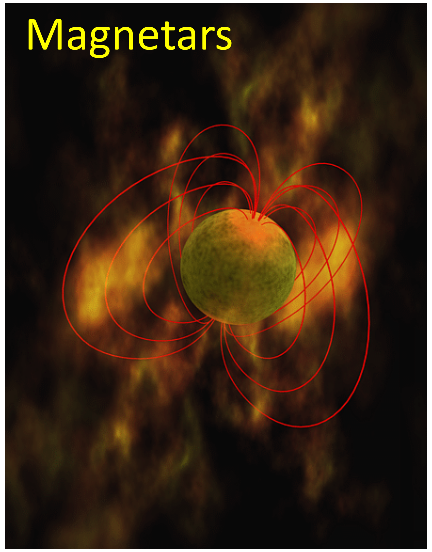


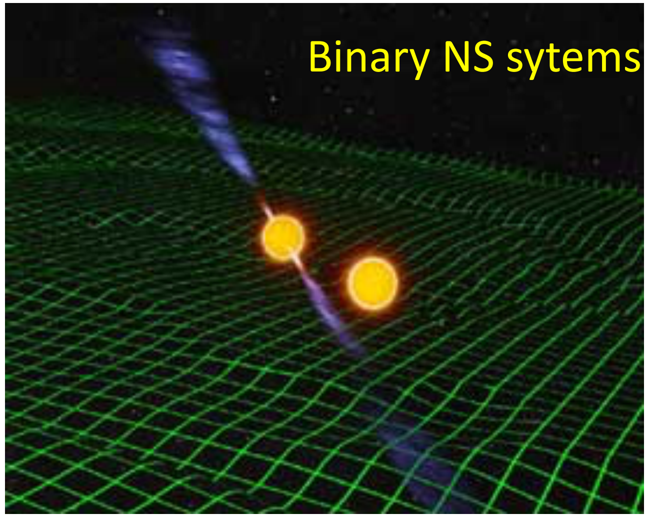
• **Conjectured**	**1931**
• **Discovered**	**1967**
• **Known**	**2500+**
• **Mass**	**1.2–2$M_{\odot}$**
• **Radius**	**8-14 km**
• **Density**	**10^{15}g/cm^3**
• **Spin**	**< 716 Hz**
• **In our Galaxy**	**~10^8**



THE MANY FACES of NEUTRON STARS







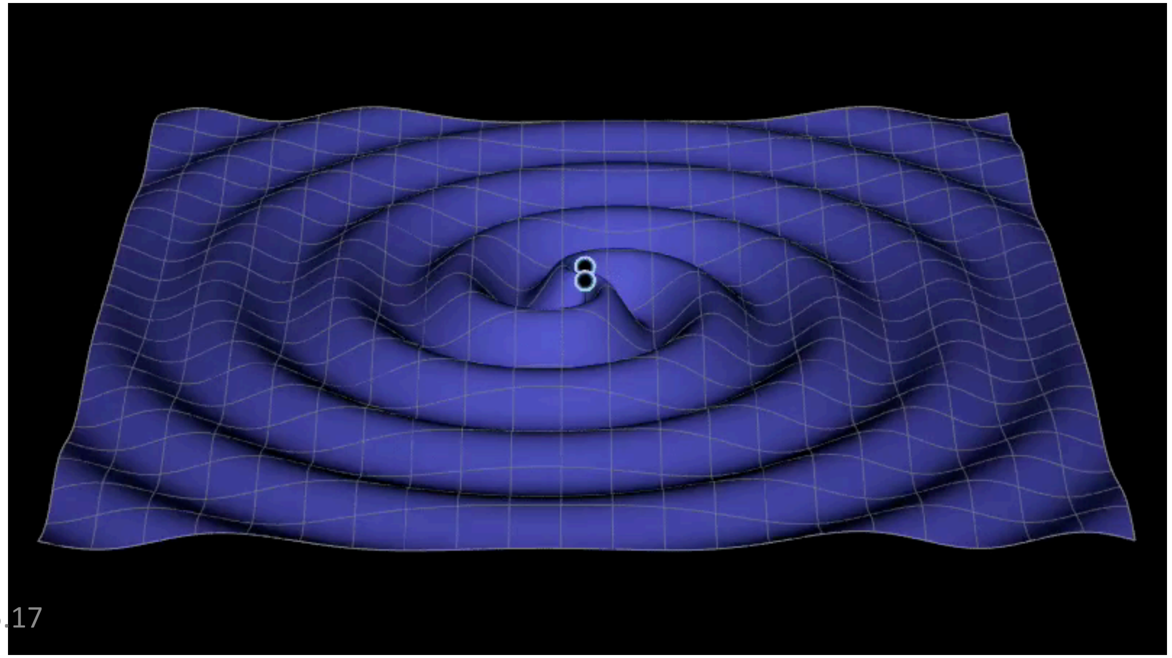
WHAT ARE THE GRAVITATIONAL WAVES

- RIPPLES OF SPACETIME CURVATURE
- PROPAGATE WITH THE SPEED OF LIGHT
- INTERACT WEAKLY WITH MATTER
- EVERY VARIATION OF THE GRAVITATIONAL FIELD PRODUCES GWs

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

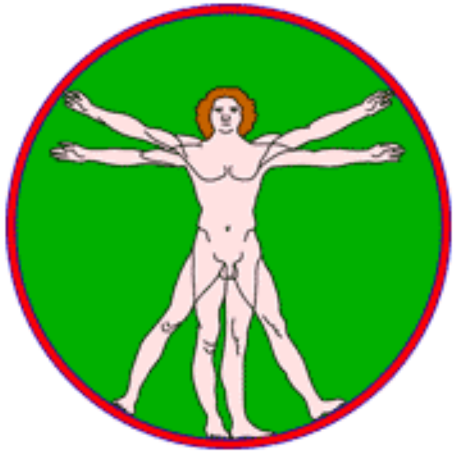
$$\left(\frac{1}{c^2} \frac{d^2}{dt^2} - \nabla^2 \right) h^{\mu\nu} = \frac{4\pi G}{c^4} T^{\mu\nu}$$

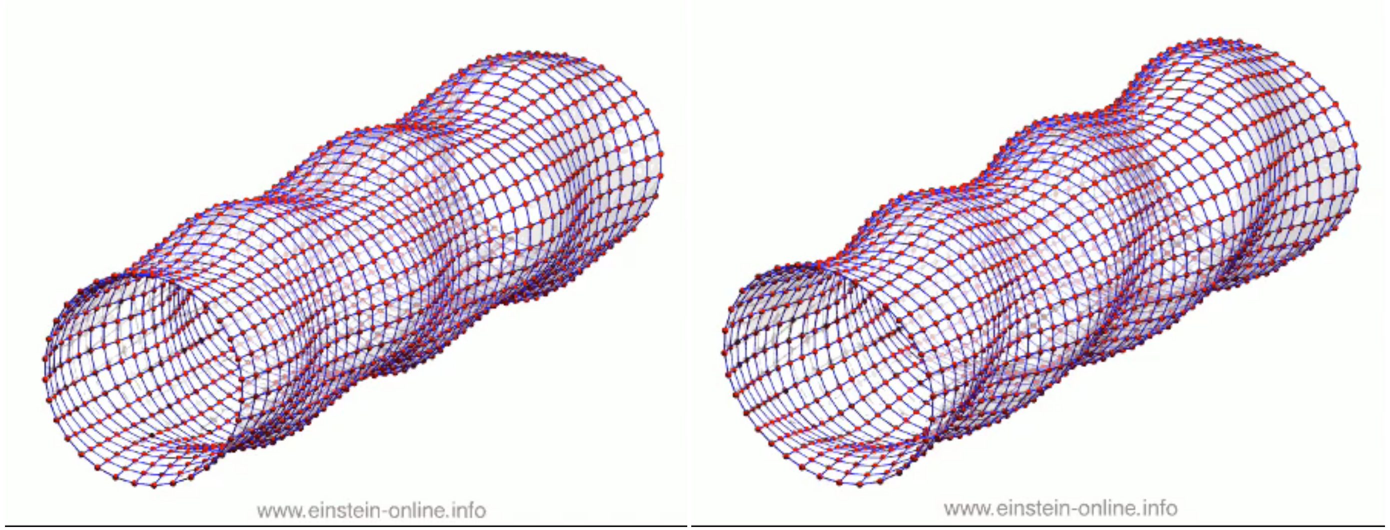
$$g^{\mu\nu} = \eta^{\mu\nu} + h^{\mu\nu}$$



WHAT ARE GRAVITATIONAL WAVES

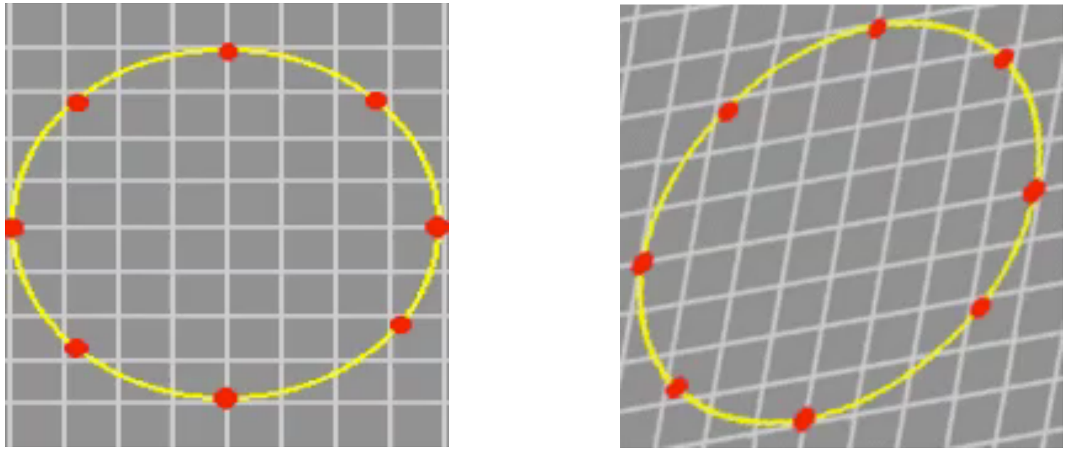
They produce <u>tidal deformations</u> on massive bodies.





… and deform periodically the spacetime geometry

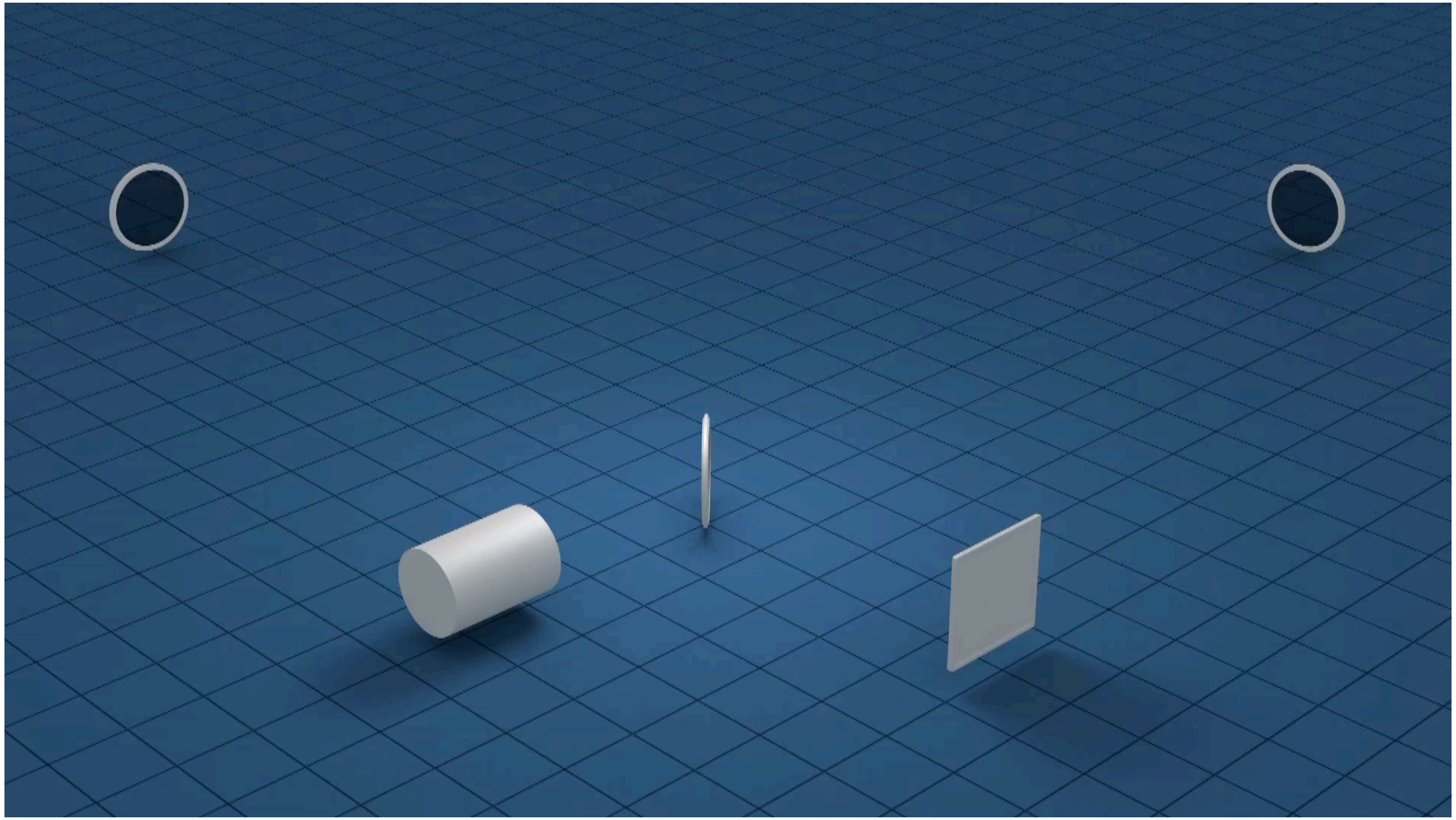
$$\Delta L \sim h \, * \, L$$



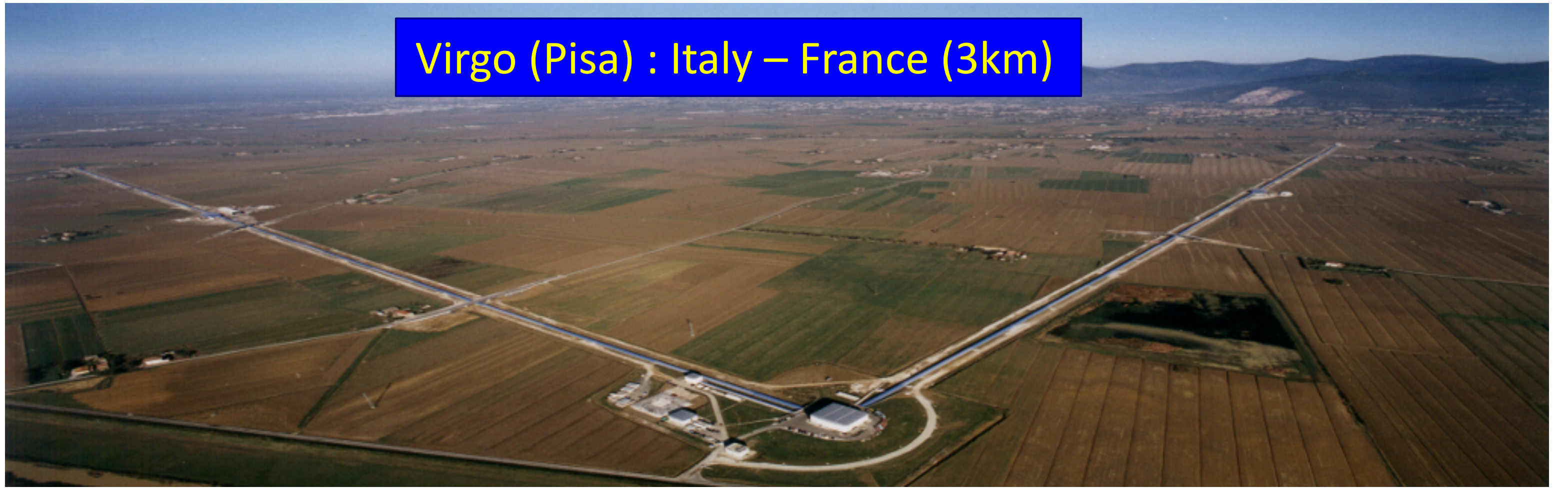
GRAVITATIONAL WAVE DETECTORS

Rainer Weiss

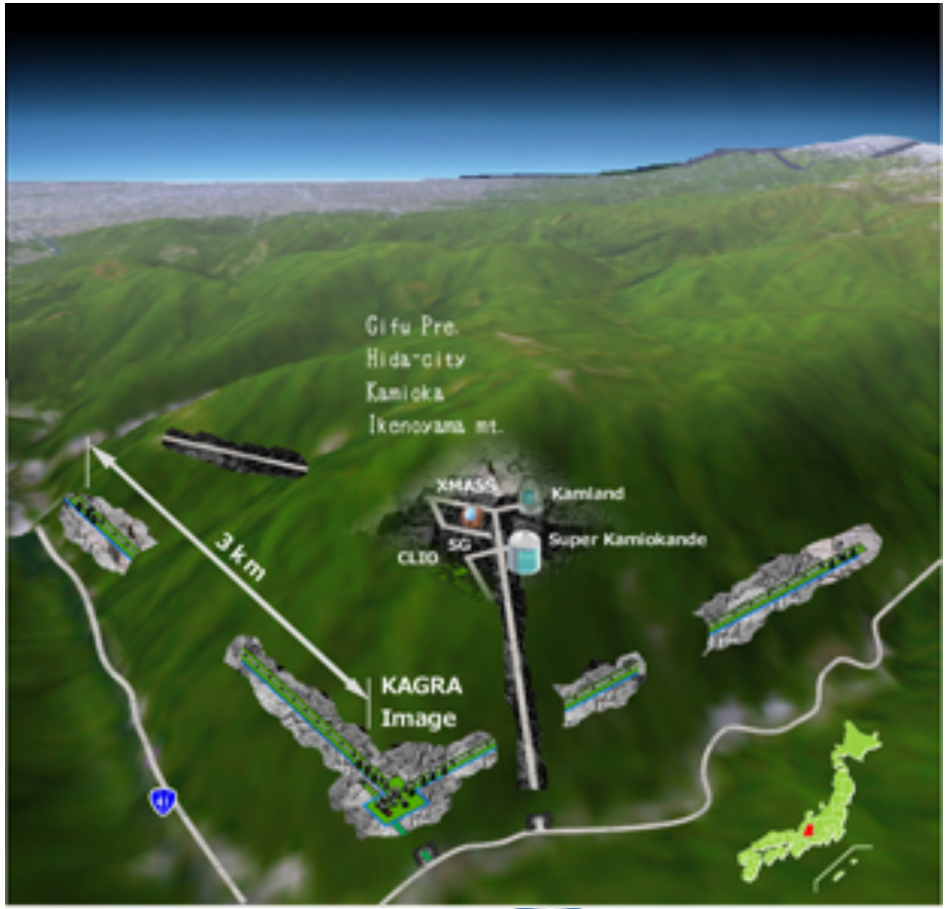
Roland Drever



THE FLAGSHIP DETECTORS



KAGRA
Large-scale Cryogenic Gravitational-wave Telescope



KAGRA

The construction has started in April 2012.

- KAGRA consists of a modified Michelson interferometer with two 3-km long arms, located in the ground under Kamioka mine.
- The goal sensitivity of KAGRA corresponds to observing the moment of coalescence of a binary pulsar beyond 200 Mpc, or detecting several GW events per year.
- The mirrors are cooled down to cryogenic temperature of -250 Celsius degree (20 Kelvin). Sapphire is chosen for the material of the mirror.

SENSITIVITY of the DETECTORS

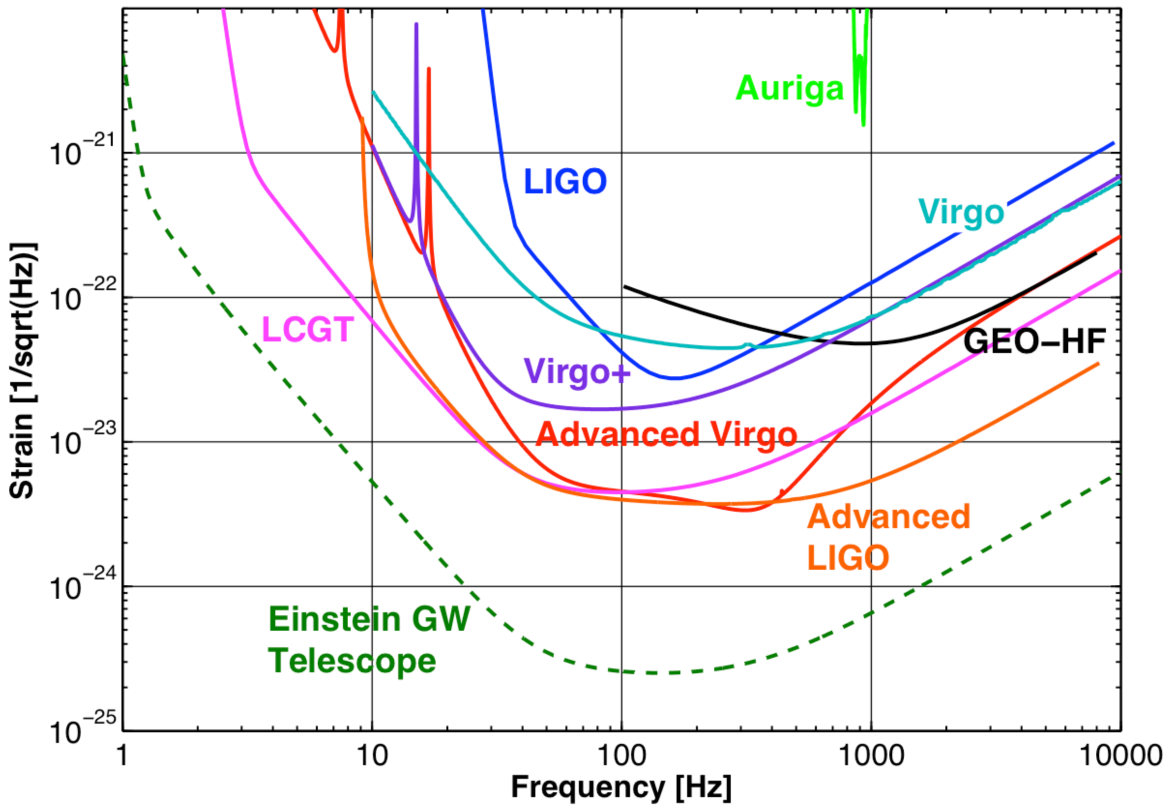
THE DISTANCE OF EARTH FROM THE GALACTIC CENTER IS:

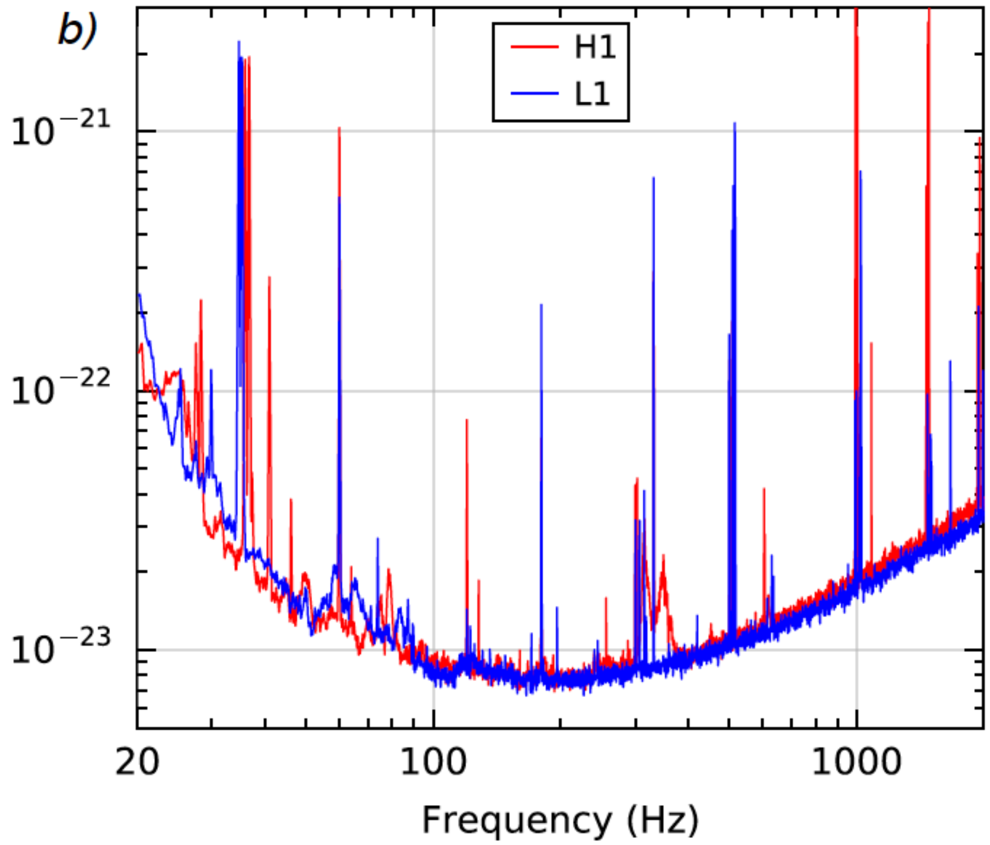
$L \sim 3 \times 10^{22}$ cm

$\Delta L = h \times L = 30$cm

THE DETECTORS CAN MEASURE VARIATIONS OF THE ORDER OF **30 cm**

SENSITIVITY CURVES



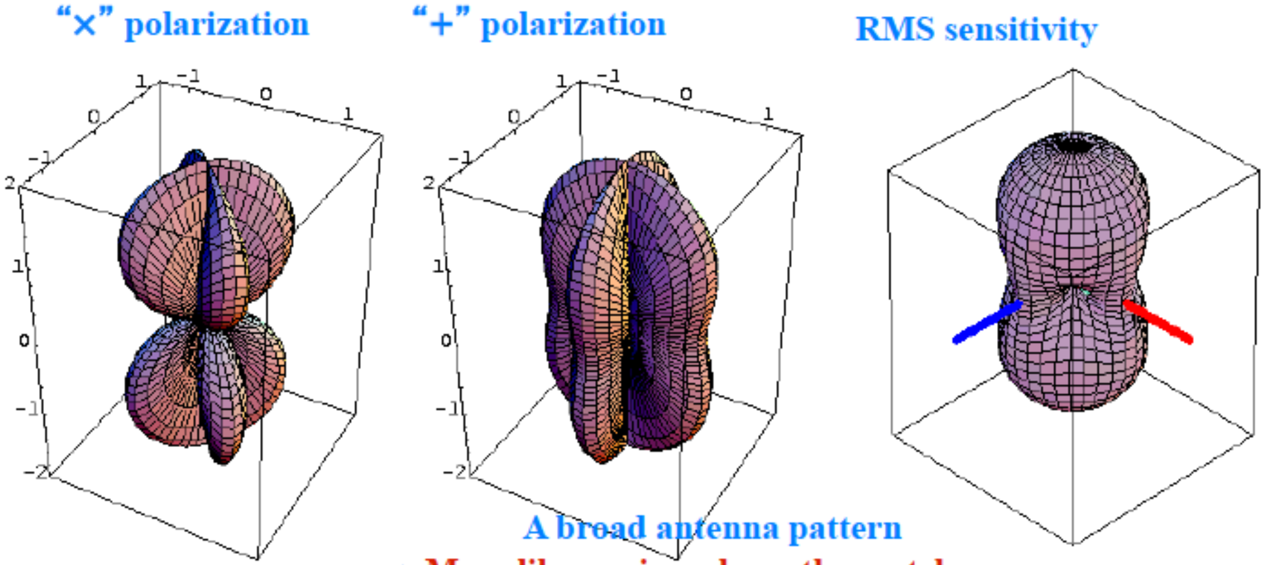


Antenna Pattern of a Laser Interferometer

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

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

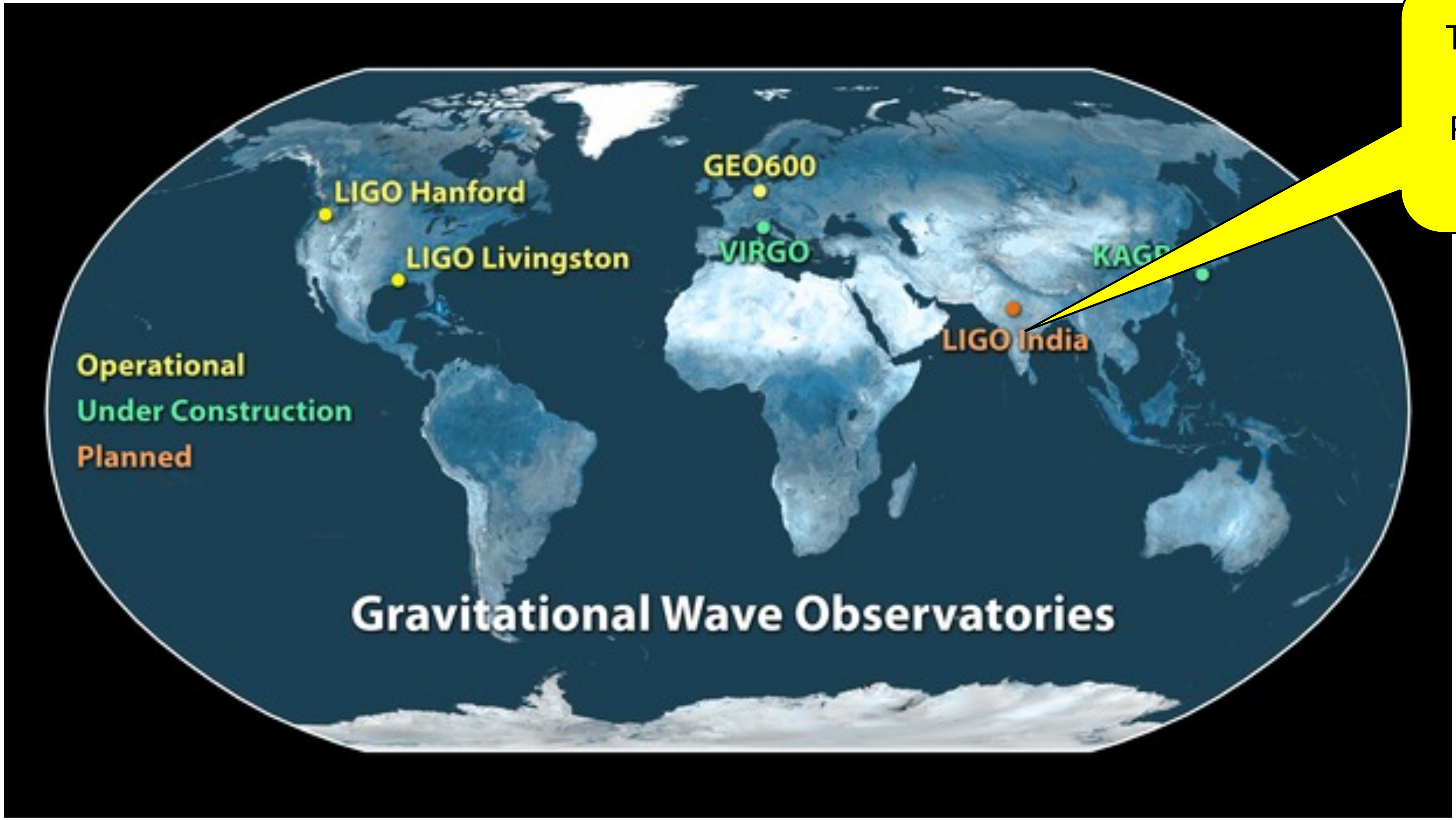
$\mathbf{F_+}$ and $\mathbf{F_x}$ are the strain antenna patterns. They depend on the orientation of the detector and source and on the polarization of the waves



A broad antenna pattern

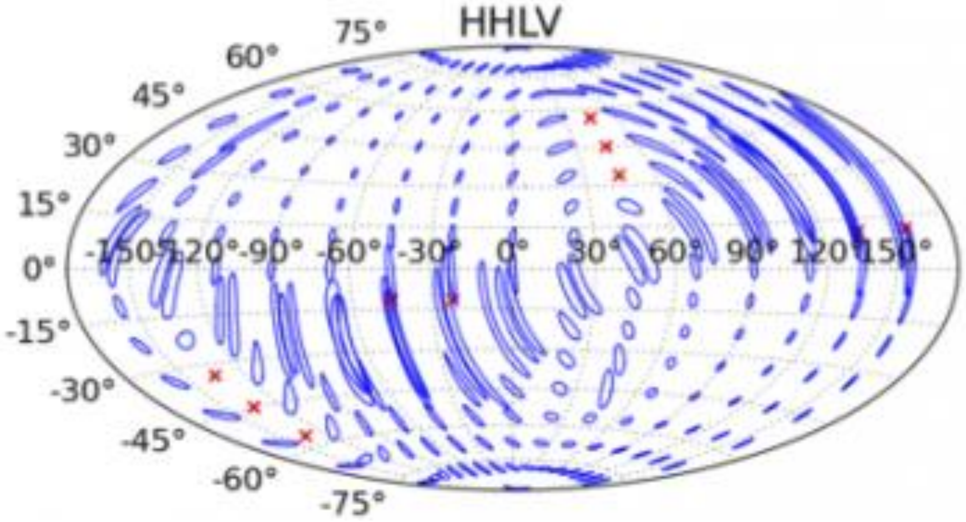
⇒ More like a microphone than a telescope

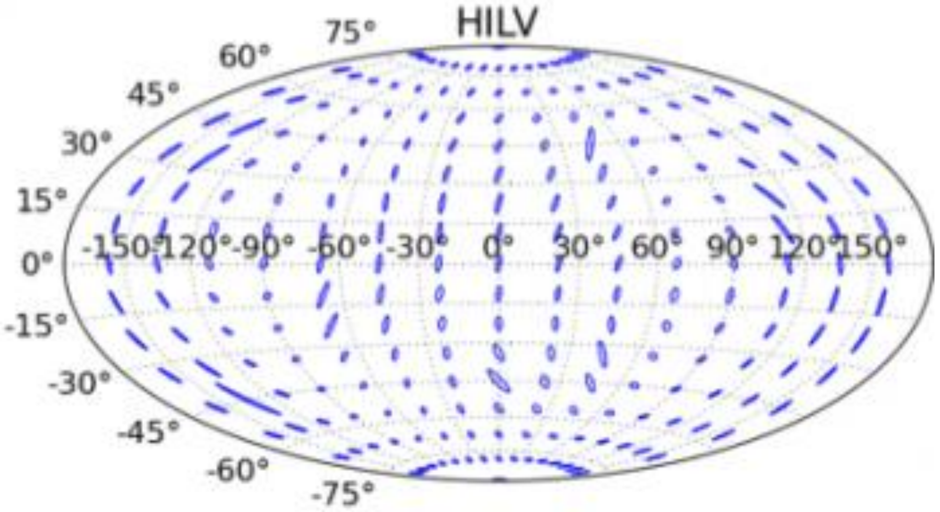
THE GLOBAL NETWORK



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

WHY SO MANY?





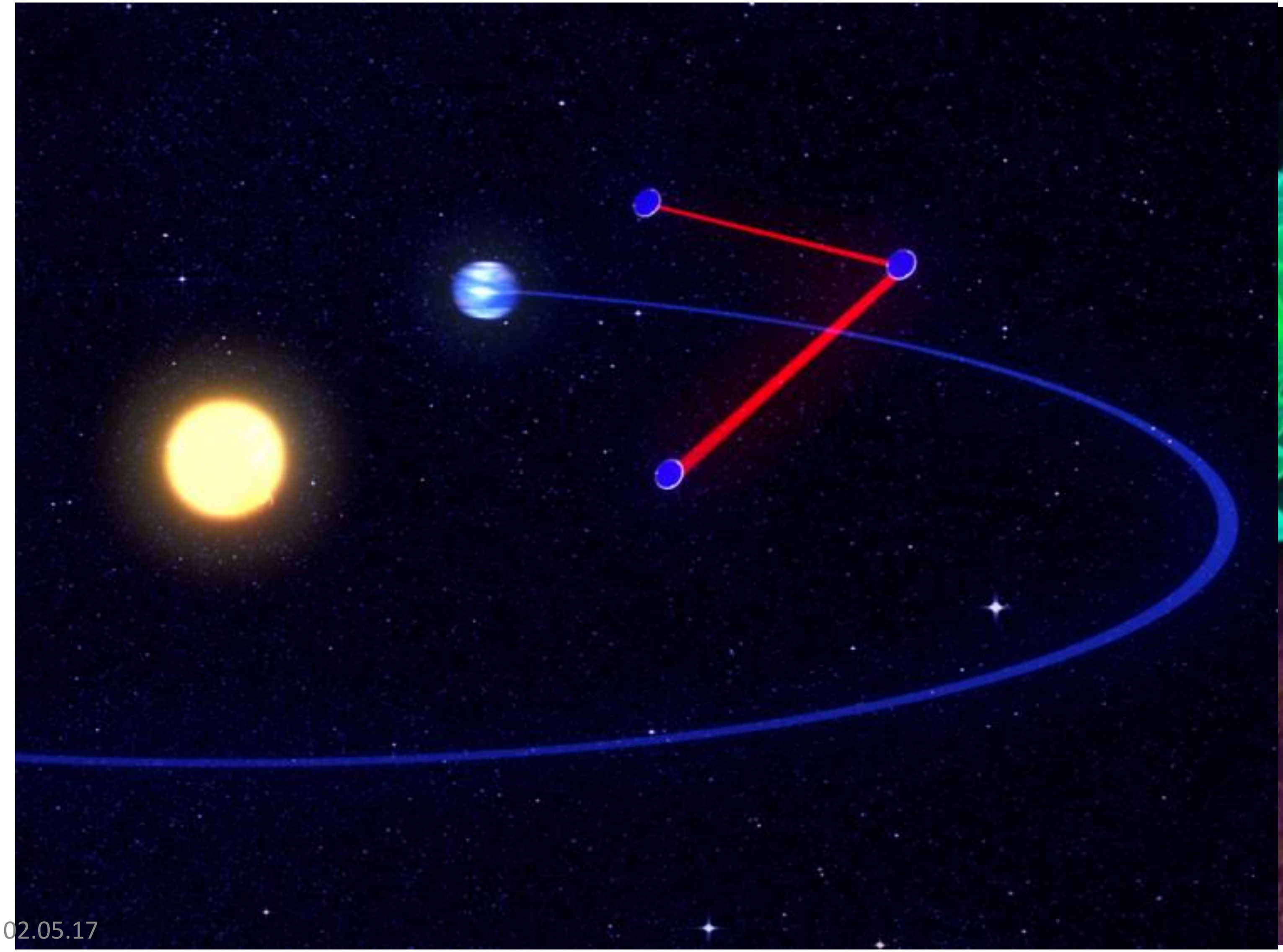
LIGO I
LIGO II
VIRGO

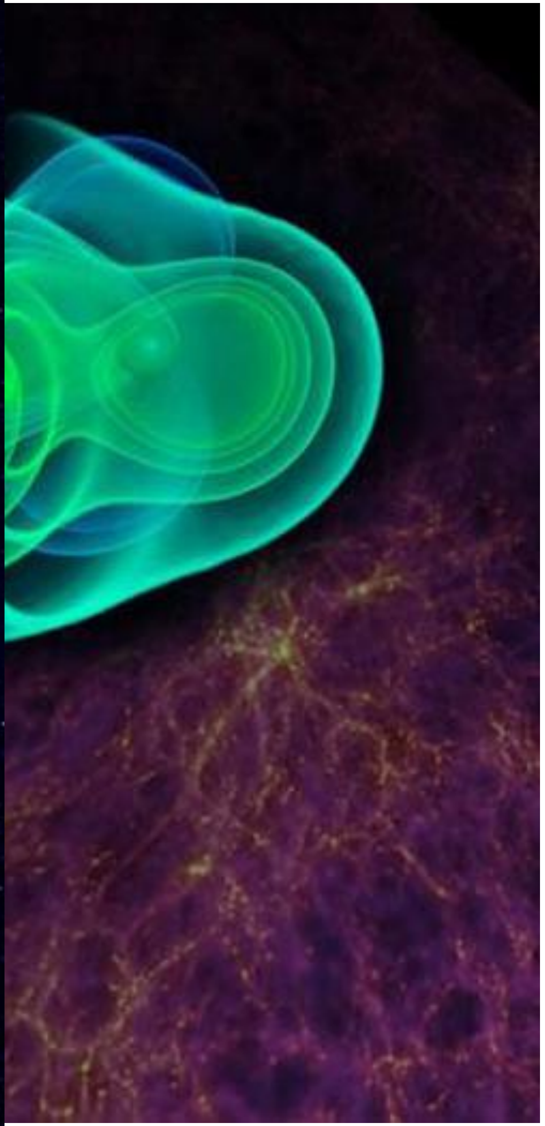
ERROR IN POSITIONING THE SOURCE

LIGO I
LIGO II
VIRGO
INDIGO

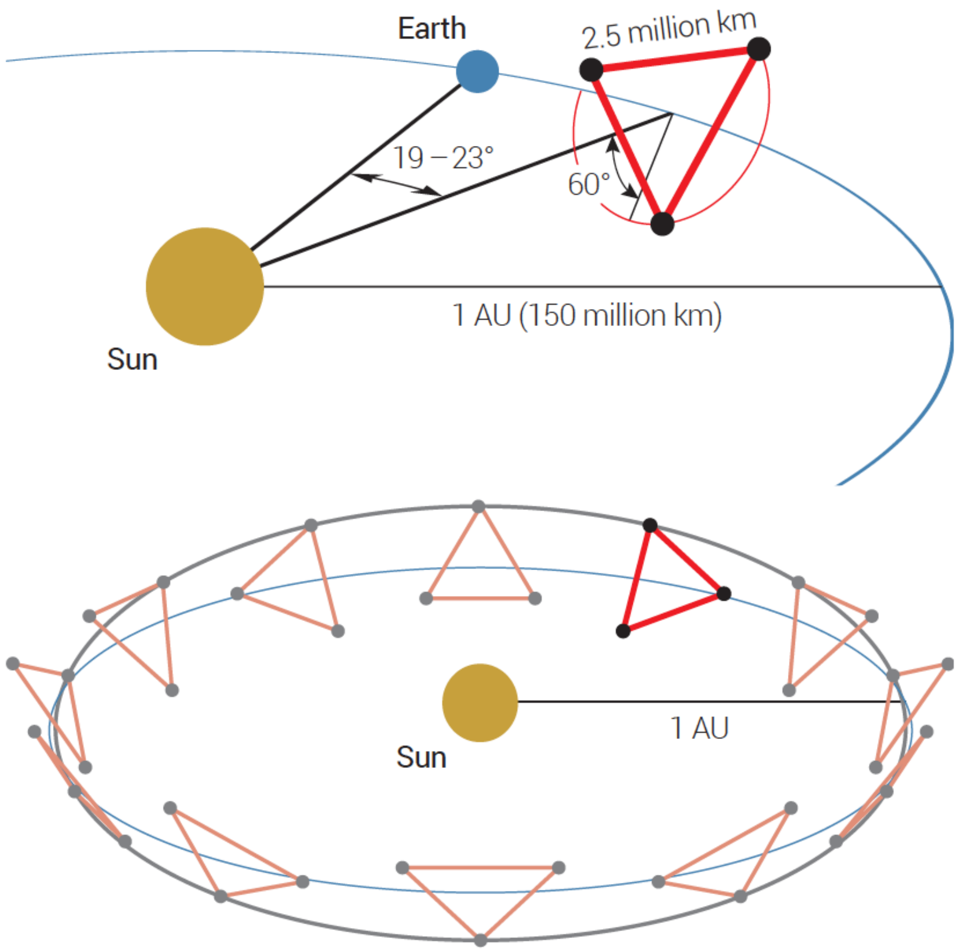
- ✓ **Confidently detect** & **locate** the sources of GWs
- ✓ **The detection delay** (~**10 milliseconds**) between LIGOs, Virgo, KAGRA, IntiGO will help pinpoint the sky location of the GW source.
- ✓ Sort out candidate GW **events that are caused by local sources**.

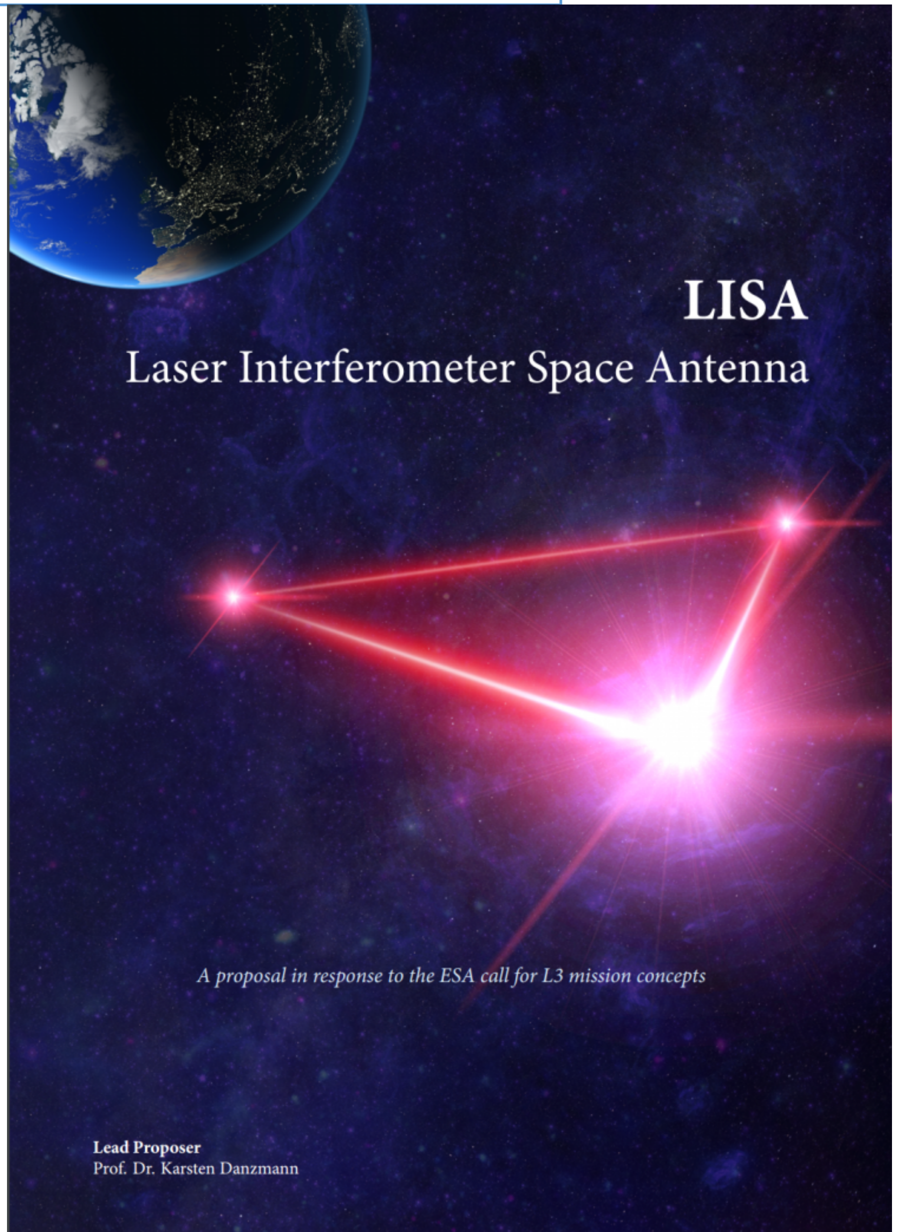
eLISA: THE SPACE DETECTOR



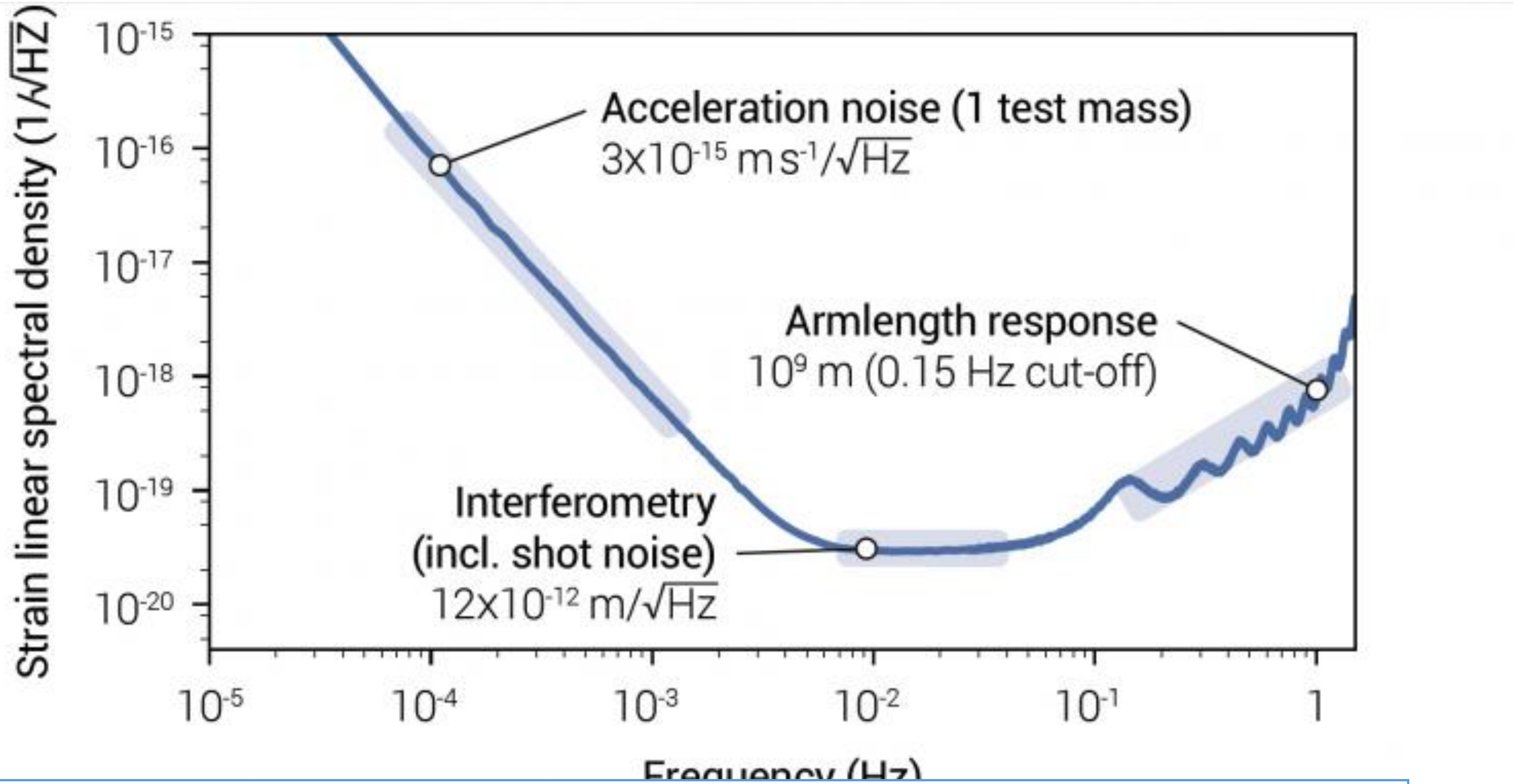


LISA (January 2017): Mission design





eLISA: Sensitivity

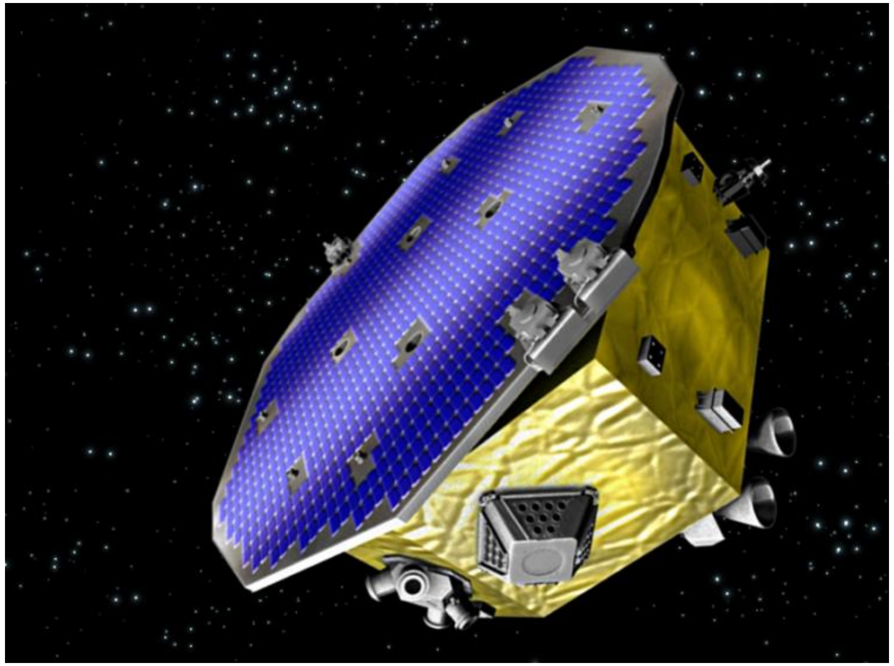


Time, sky and polarisation averaged eLISA sensitivity.
The noise spectrum (strain sensitivity) is plotted as a linear spectral density.

eLISA: Pathfinder

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

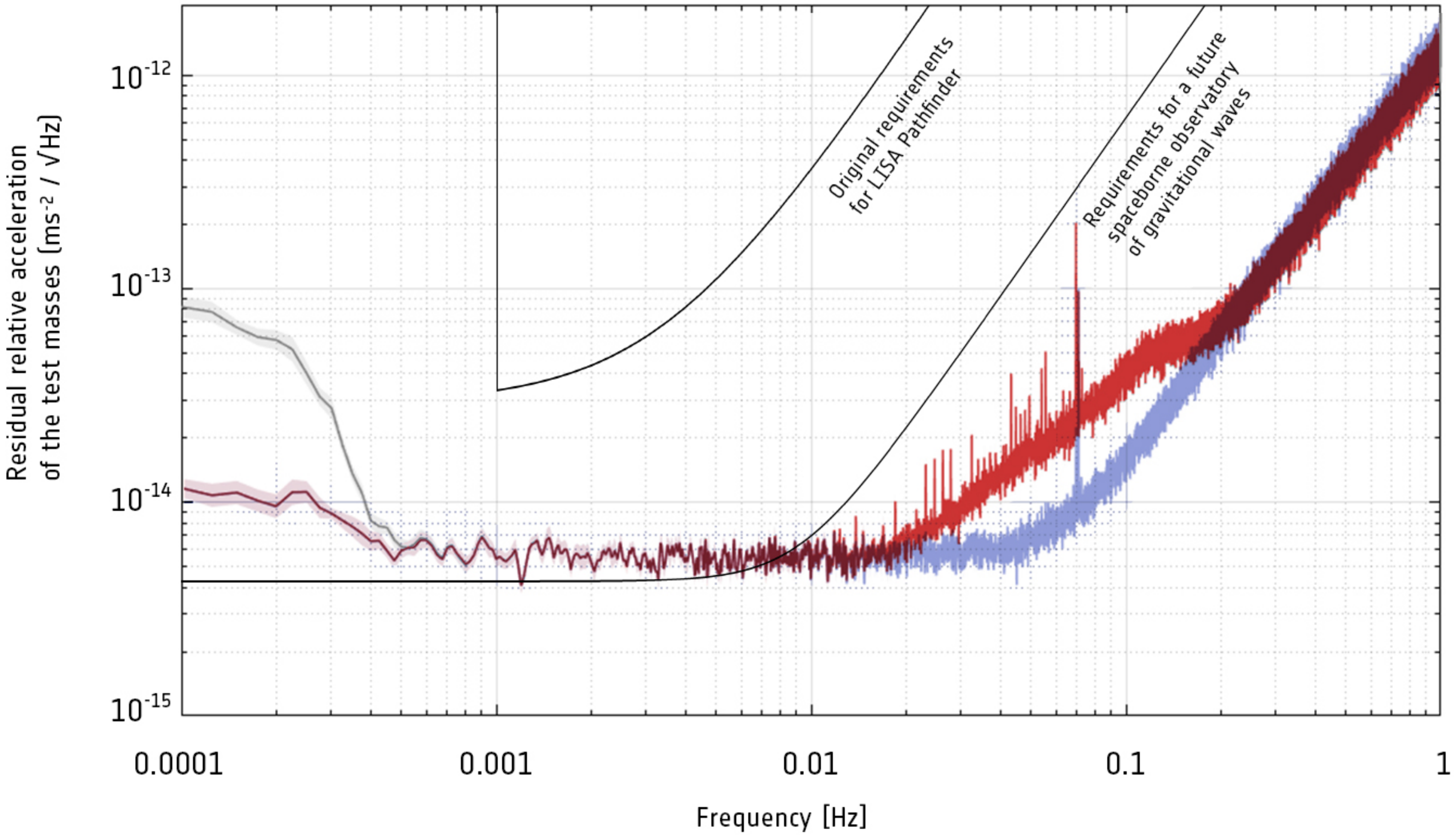
LPF was launched in December 2015.



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**

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

- **Amplitude**

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

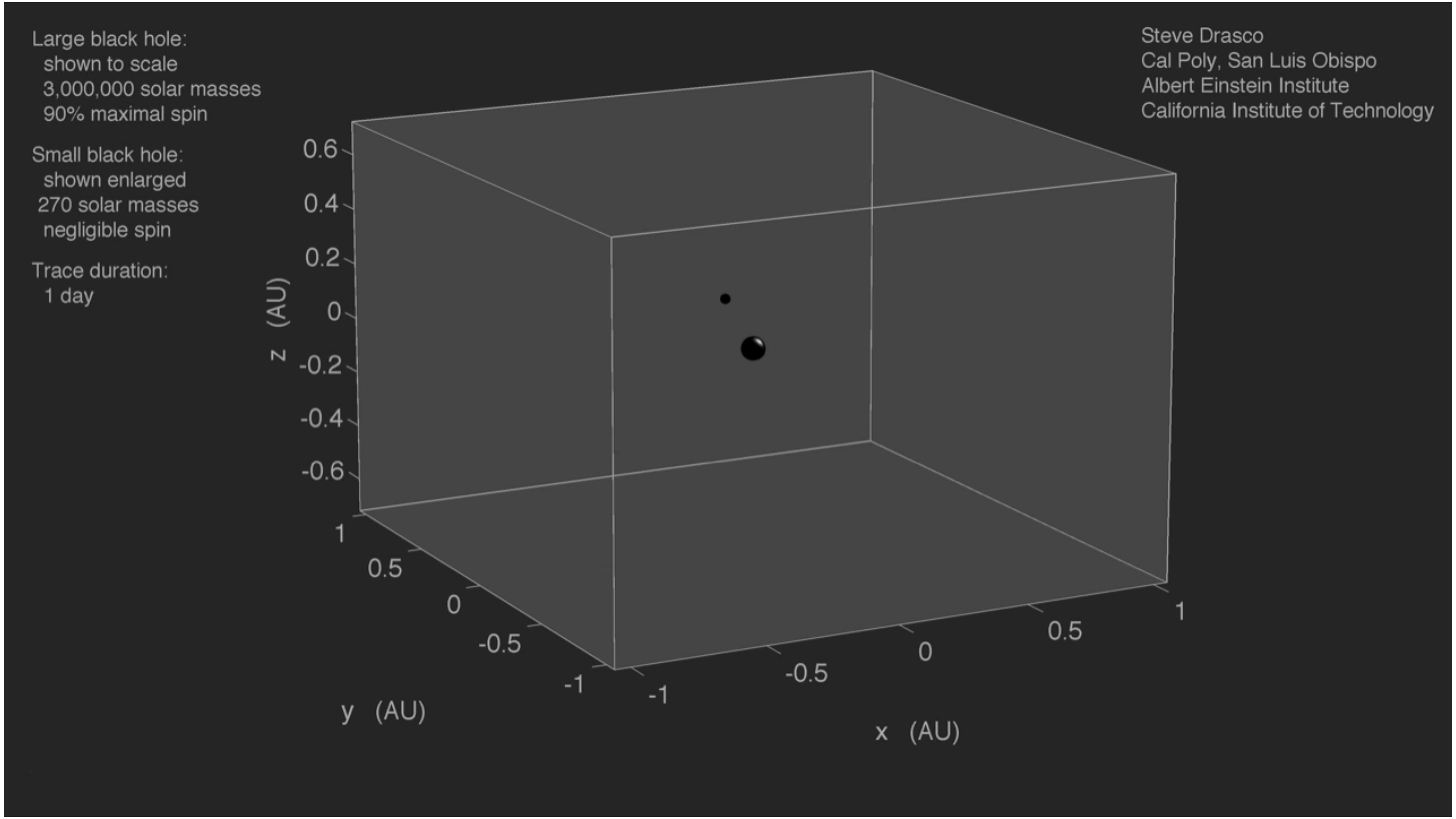
- **Luminosity**

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

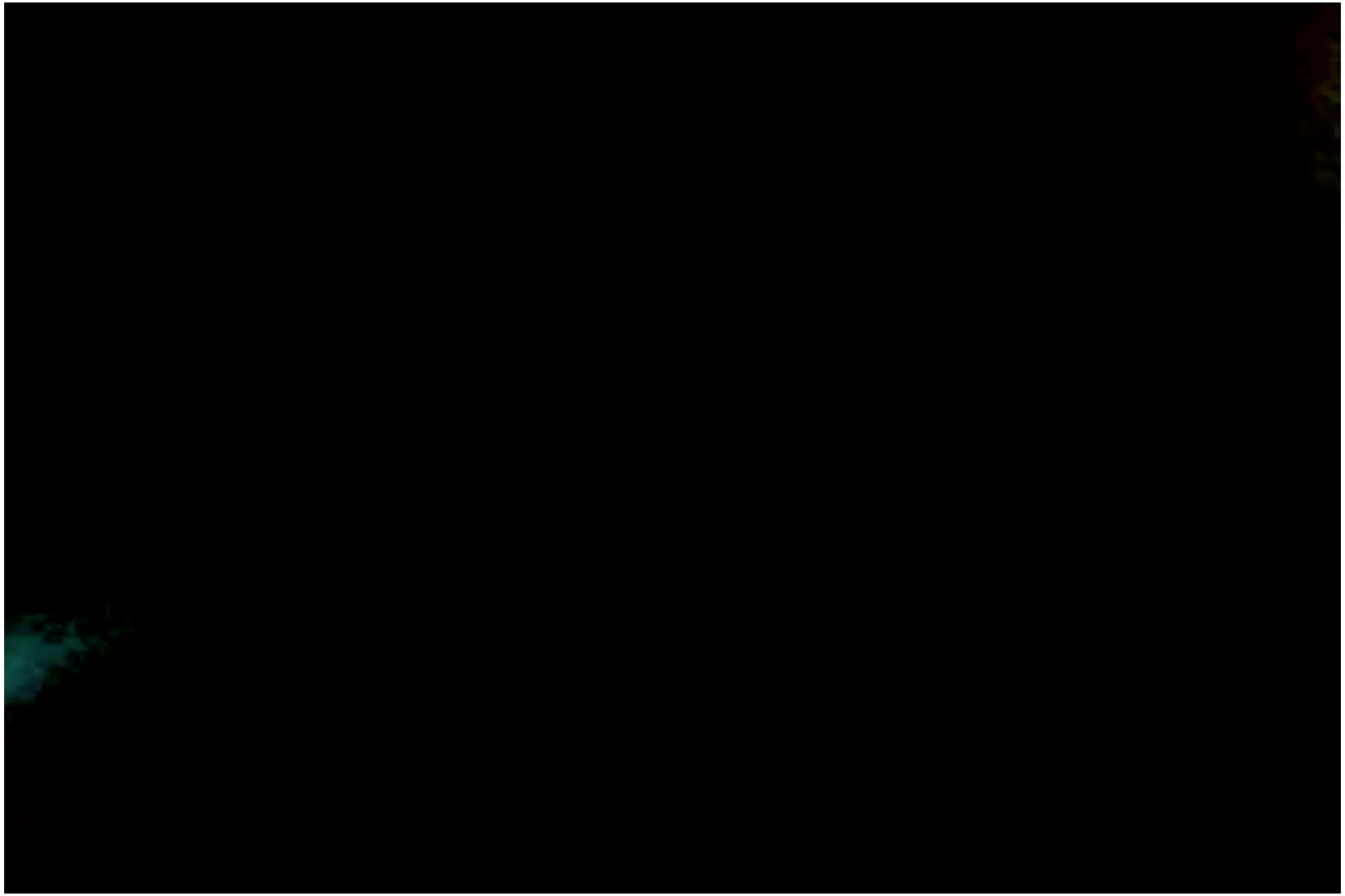
BLACK HOLES:	M/R=0.5
NEUTRON STARS:	M/R~0.2
WHITE DWRFS:	M/R~10^{-4}

COALESCING BINARY NEUTRON STARS

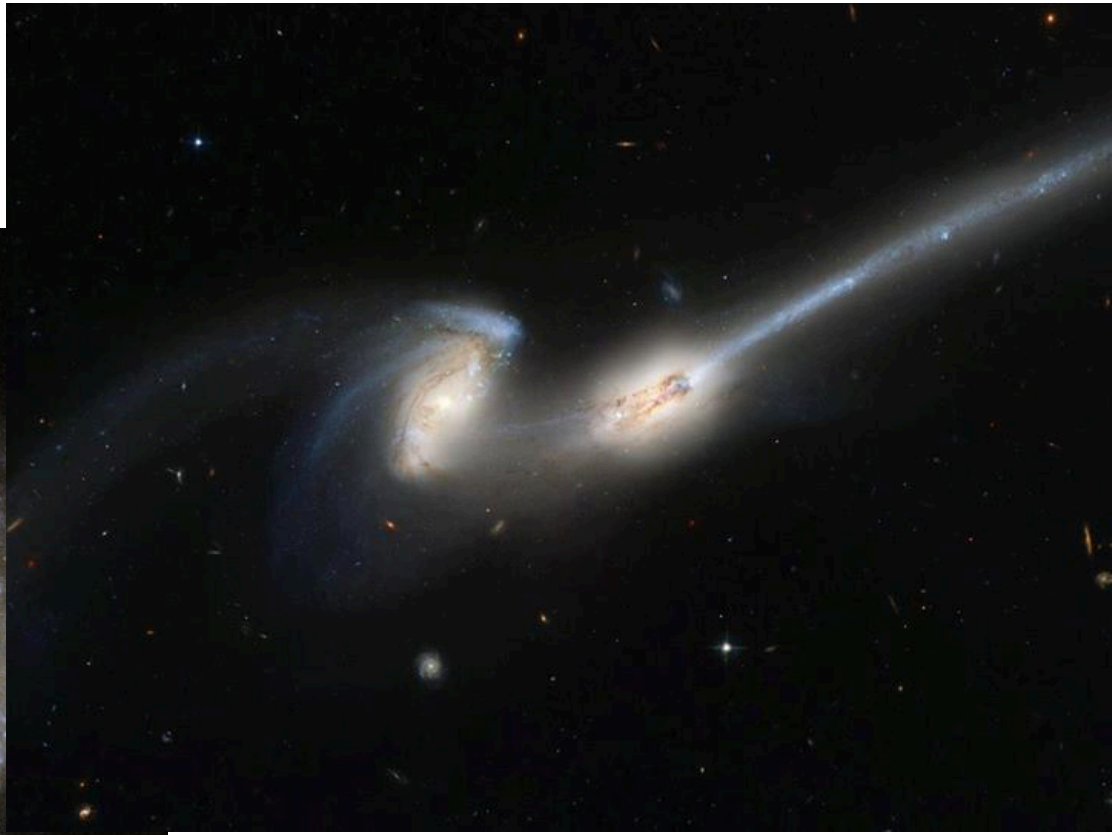
The «MUSIC» of BLACK HOLES



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

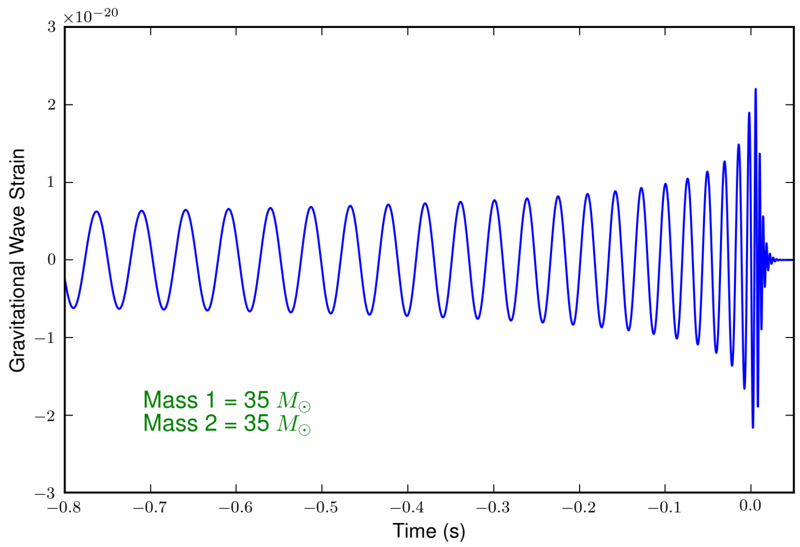
$$\dot{f} \approx f^{5/3} M_c^{-1/3}$$ Chirp

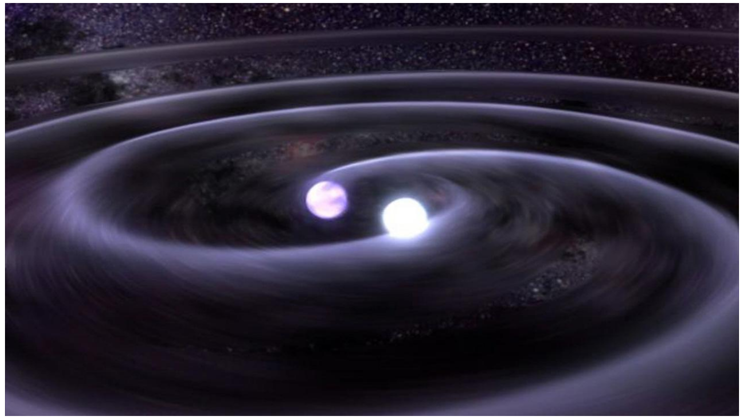
$$\boxed{M_c \approx \left(f^{-11/3}\dot{f}\right)^{3/5}}$$ Chirp mass

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

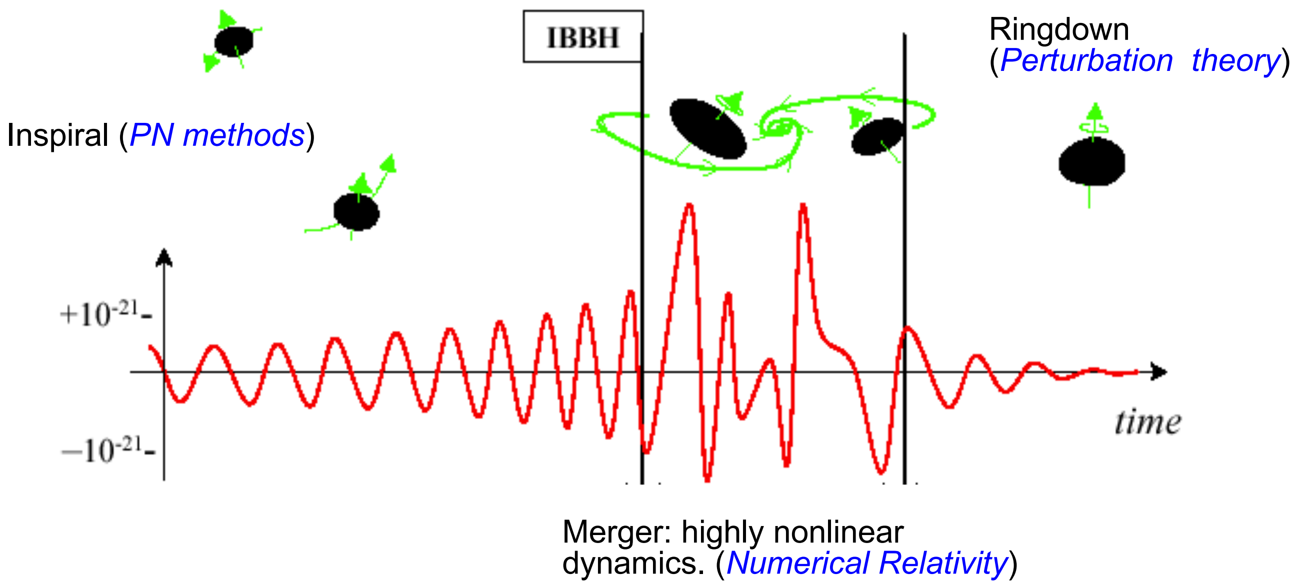
$$\mathrm{v} \approx f^{1/3} M^{1/3}$$ VELOCITY

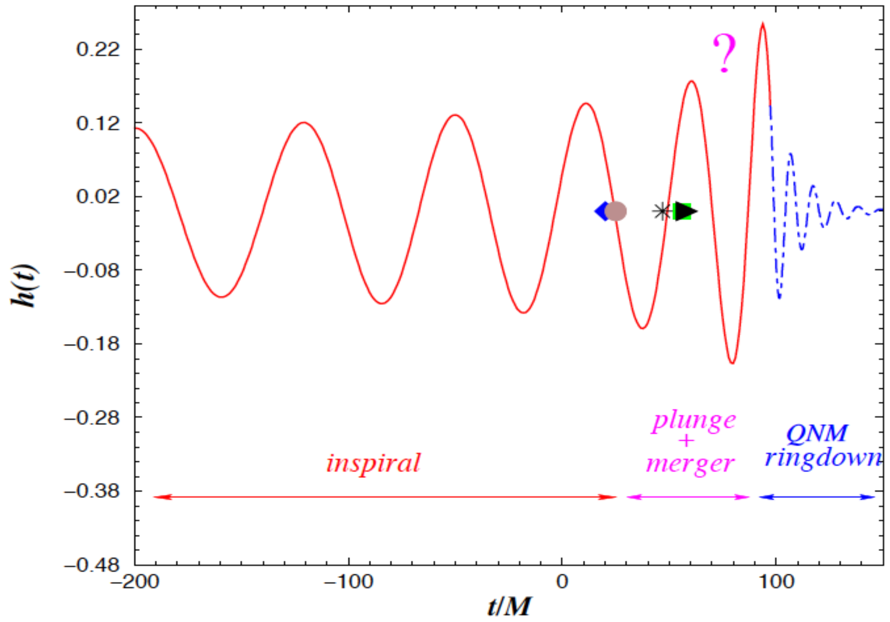
$$\eta = \frac{m_1 + m_2}{(m_1 + m_2)^2}$$





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

$$\phi(t) = -\frac{1}{\nu}\left\{\tau^{5/8} + \left(\frac{3715}{8064} + \frac{55}{96}\nu\right)\tau^{3/8} - \frac{3}{4}\pi\tau^{1/4}\right.$$
$$+ \left(\frac{9275495}{14450688} + \frac{284875}{258048}\nu + \frac{1855}{2048}\nu^2\right)\tau^{1/8} + \left(-\frac{38645}{172032} - \frac{15}{2048}\nu\right)\pi\ln\left(\frac{\tau}{\tau_0}\right)$$
$$+ \left(\frac{831032450749357}{57682522275840} - \frac{53}{40}\pi^2 - \frac{107}{56}C + \frac{107}{448}\ln\left(\frac{\tau}{256}\right)\right.$$
$$+ \left[-\frac{123292747421}{4161798144} + \frac{2255}{2048}\pi^2 + \frac{385}{48}\lambda - \frac{55}{16}\theta\right]\nu + \frac{154565}{1835008}\nu^2$$
$$\left.\left.-\frac{1179625}{1769472}\nu^3\right)\tau^{-1/8} + \left(\frac{188516689}{173408256} + \frac{140495}{114688}\nu - \frac{122659}{516096}\nu^2\right)\pi\tau^{-1/4}\right\}$$

- 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]

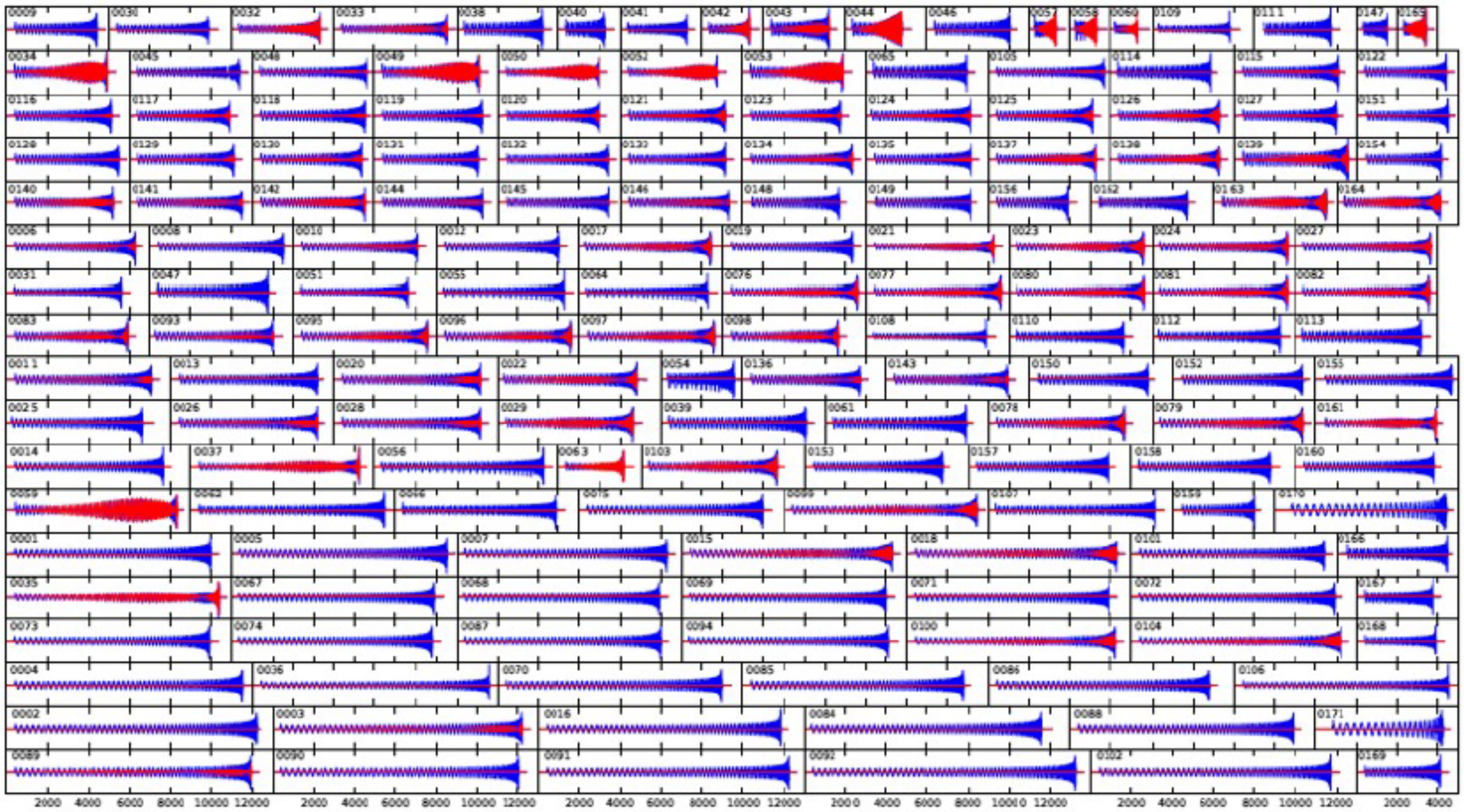
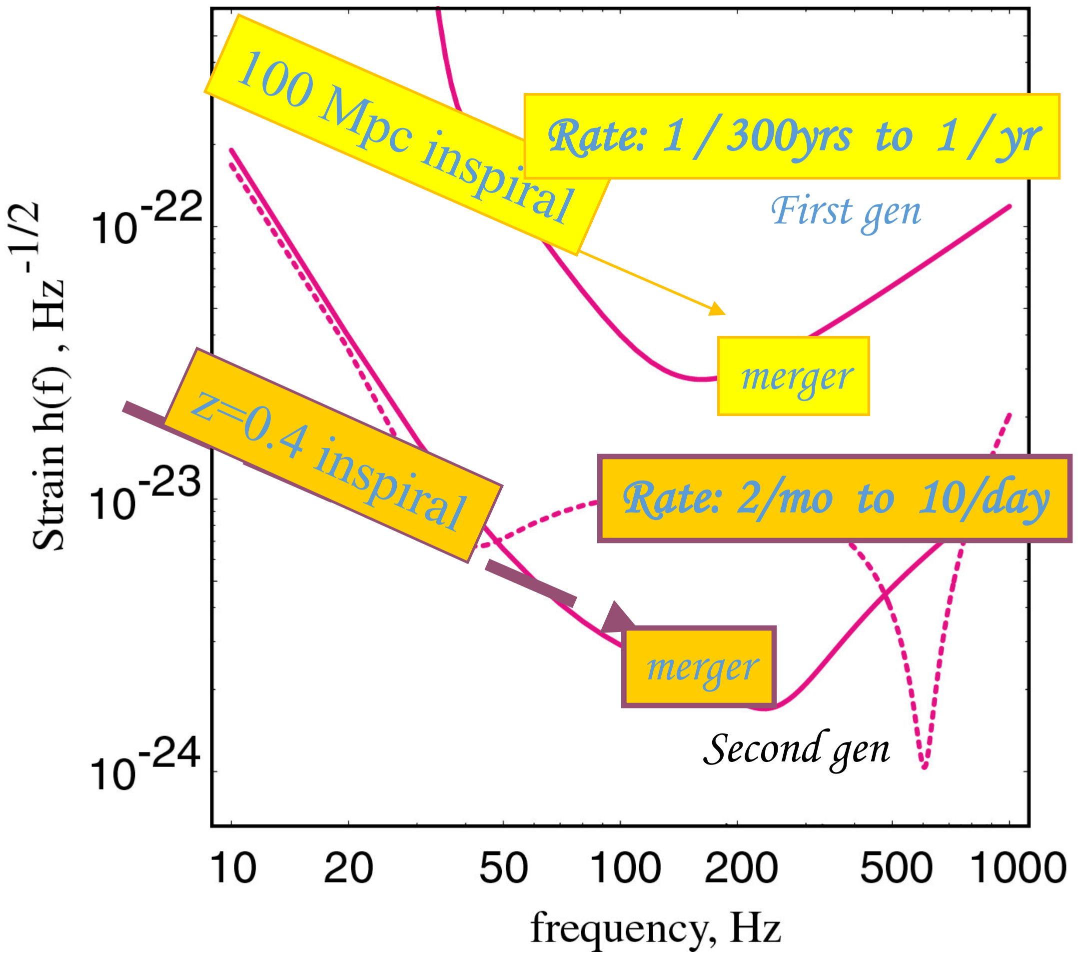


FIG. 3: Waveforms from all simulations in the catalog. Shown here are h_+ (blue) and $h_\times$ (red) in a sky direction parallel to the initial orbital plane of each simulation. All plots have the same horizontal scale, with each tick representing a time interval of $2000M$, where M is the total mass.

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!!



Prediction for the current Event Rate

@ Design Sensitivity

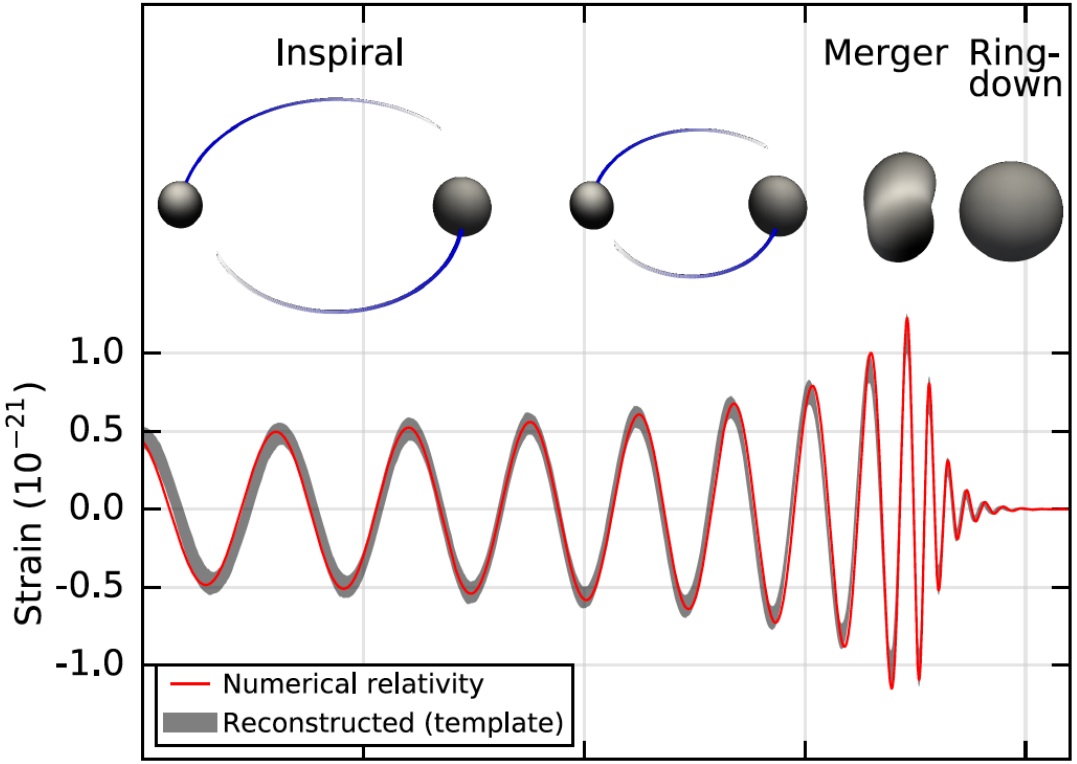
Abadie et al 2010; arXiv: 1003.2480

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

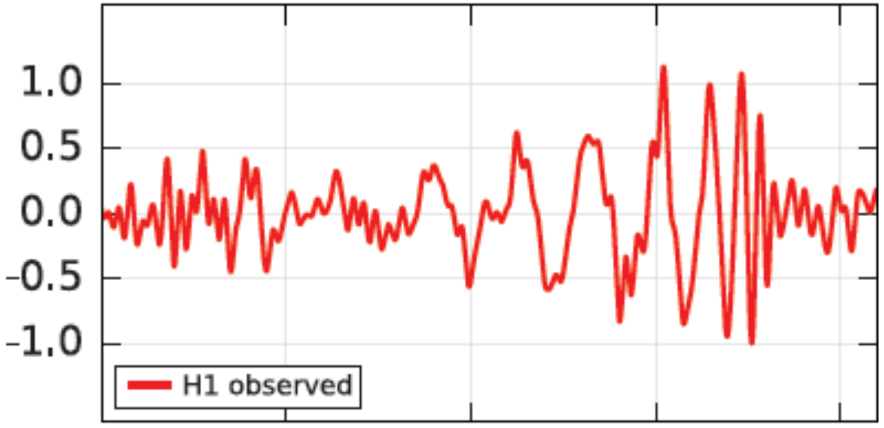
Final Mass : 62^{+4}_{-4} $M_\odot$

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

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

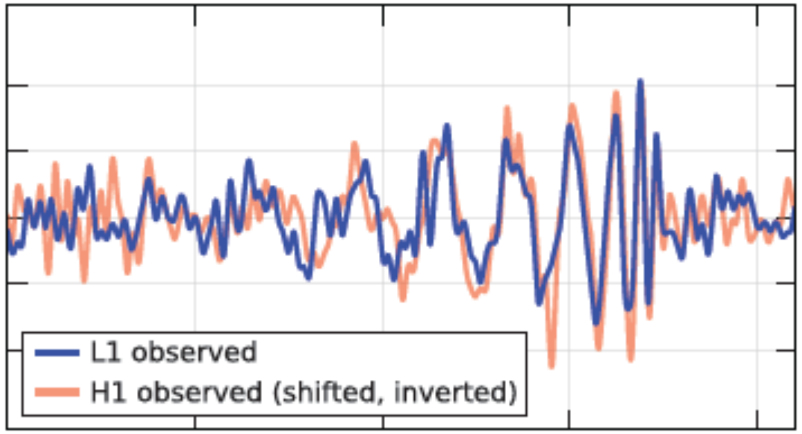
Redshift : **z~**$0.09^{+0.03}_{-0.04}$

Hanford, Washington (H1)

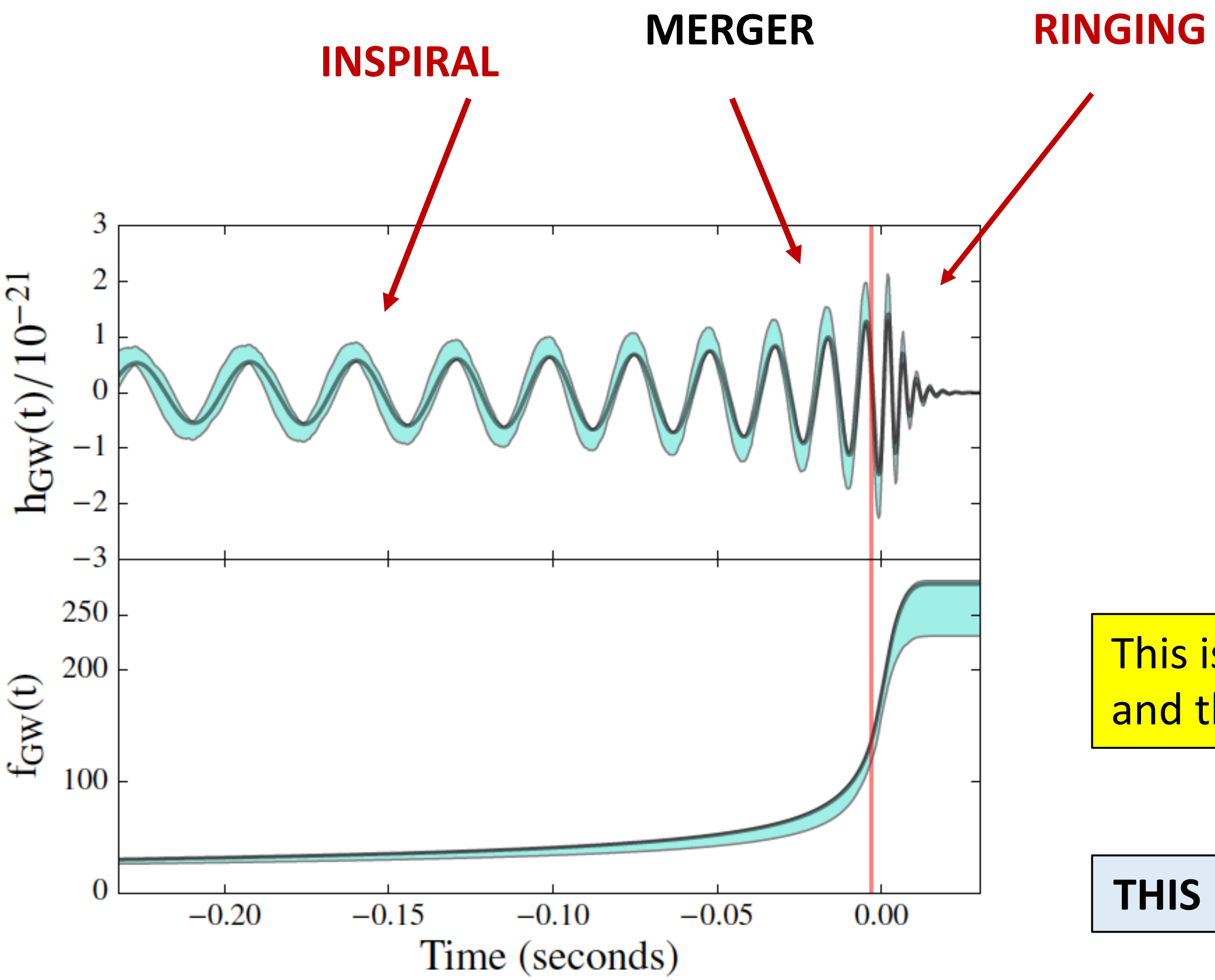


GW150914

Livingston, Louisiana (L1)



SIGNAL ANALYSIS



- f_{GW}~35 Hz
- f_{GW}~150 Hz
- 8 περιφορές
- 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.

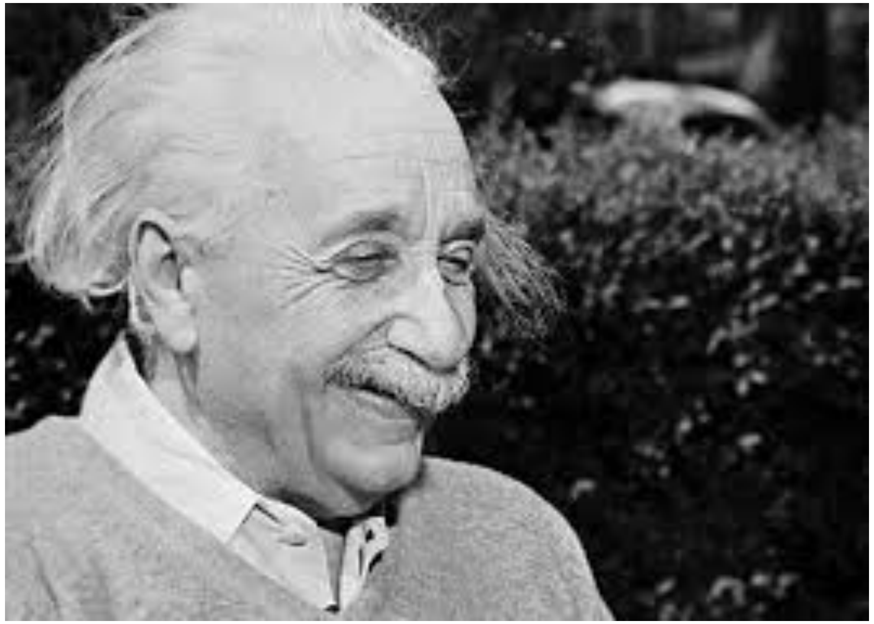
NOT ONLY!

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.

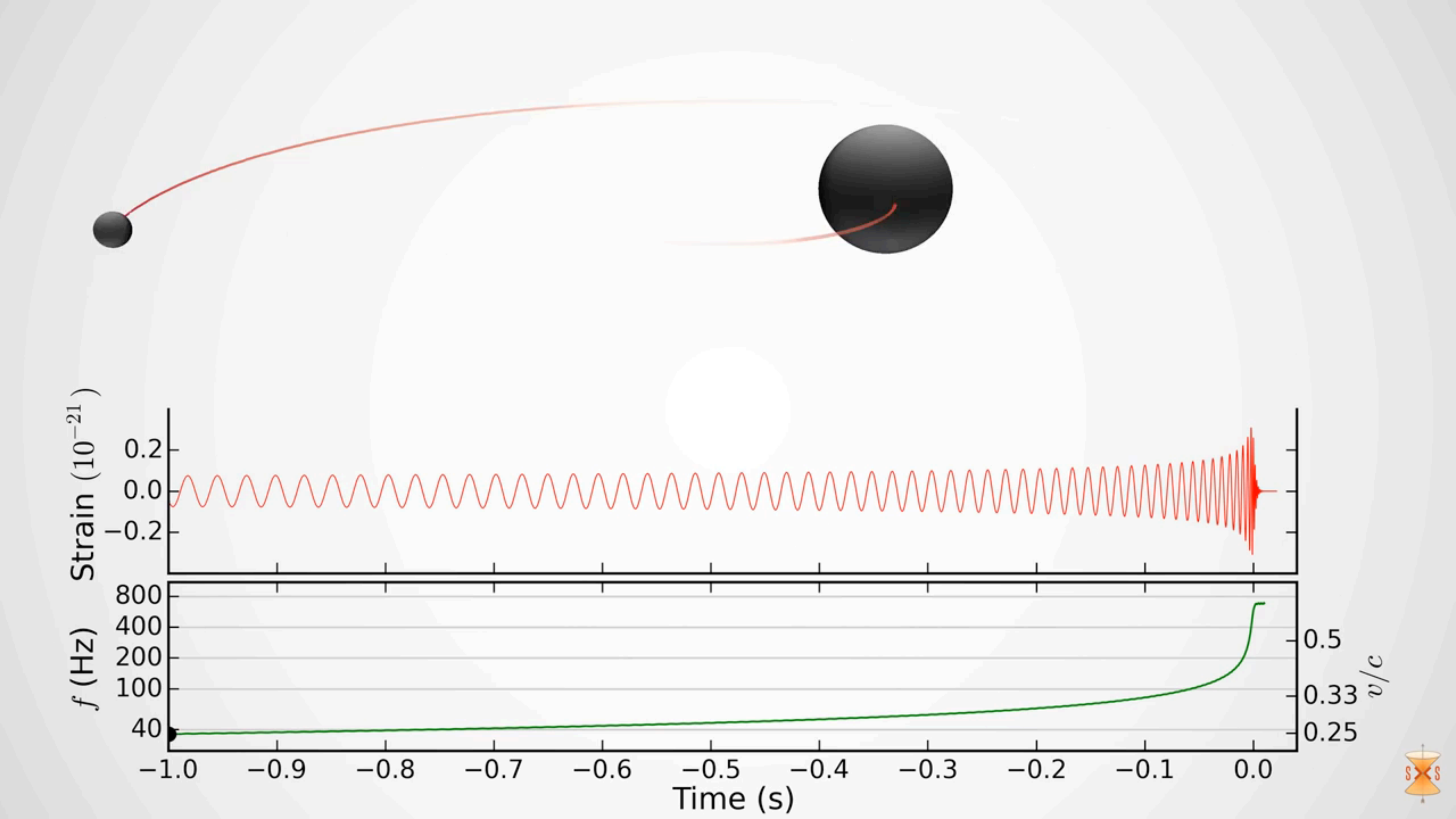
FINDINGS



ALL FINDINGS ARE
IN GOOD AGREEMENT
WITH
GENERAL THEORY OF RELATIVITY

100 days later,
it happened again

26.12.2015 – Boxing day



Strain (10^{-21})
0.2
0.0
−0.2
f (Hz)
800
400
200
100
40
v/c
0.5
0.33
0.25
−1.0
−0.9
−0.8
−0.7
−0.6
−0.5
−0.4
−0.3
−0.2
−0.1
0.0
Time (s)

WHAT DID THEY OBSERVE?

GW151226

M_1 : $14.2^{+8.3}_{-3.7}$ $M_\odot$

M_2 : $7.5^{+2.3}_{-2.3}$ $M_\odot$

S/N : ~13

Spin : 0.74

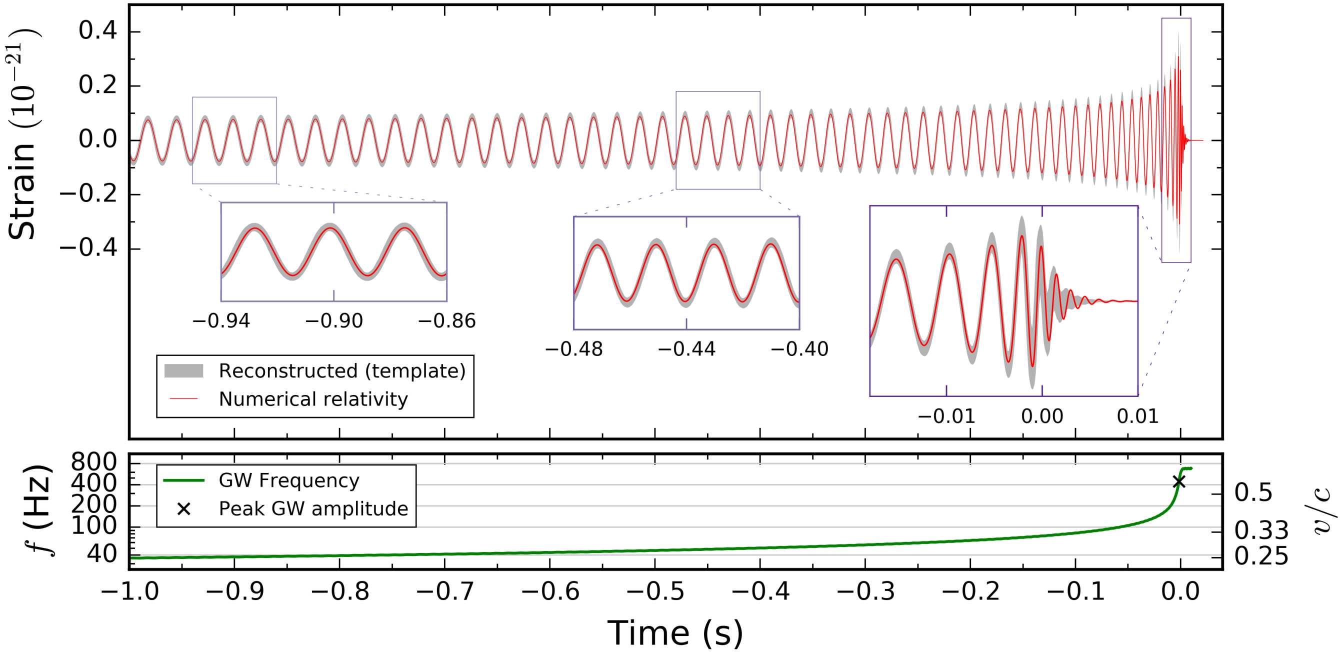
Final Mass : 20.8^{+4}_{-4} $M_\odot$

Distance : 440^{+180}_{-190} Mpc

$\sim$1.4 x 10^9 light years

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

Radiated GW energy : $\sim 1.0^{+0.1}_{-0.2}$ $M_\odot c^2$



Waveforms from the 3 events

The 3rd event

LVT151012

M_1 : 23^{+18}_{-6} $M_\odot$

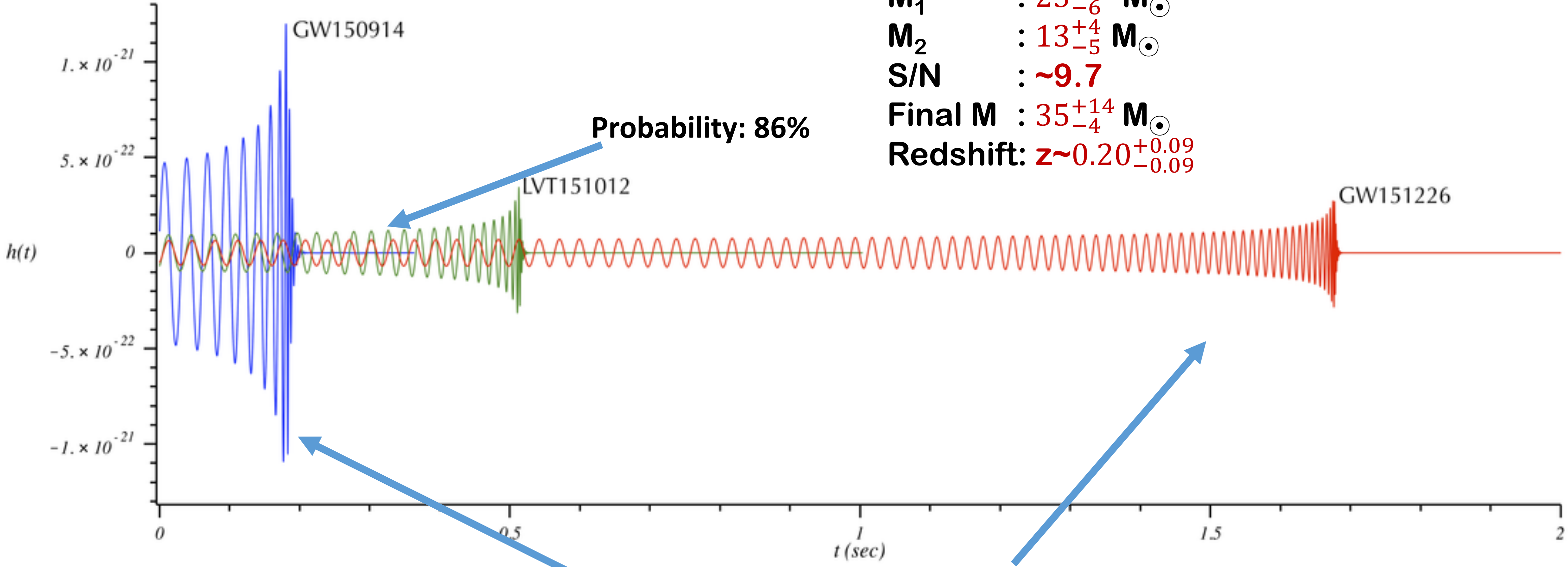
M_2 : 13^{+4}_{-5} $M_\odot$

S/N : **~9.7**

Final M : 35^{+14}_{-4} $M_\odot$

Redshift: $z\sim 0.20^{+0.09}_{-0.09}$

Probability: 86%



Probability: 99.9999%

LIGO Timeline

APRIL 2017 UPDATE ON LIGO'S SECOND OBSERVING RUN

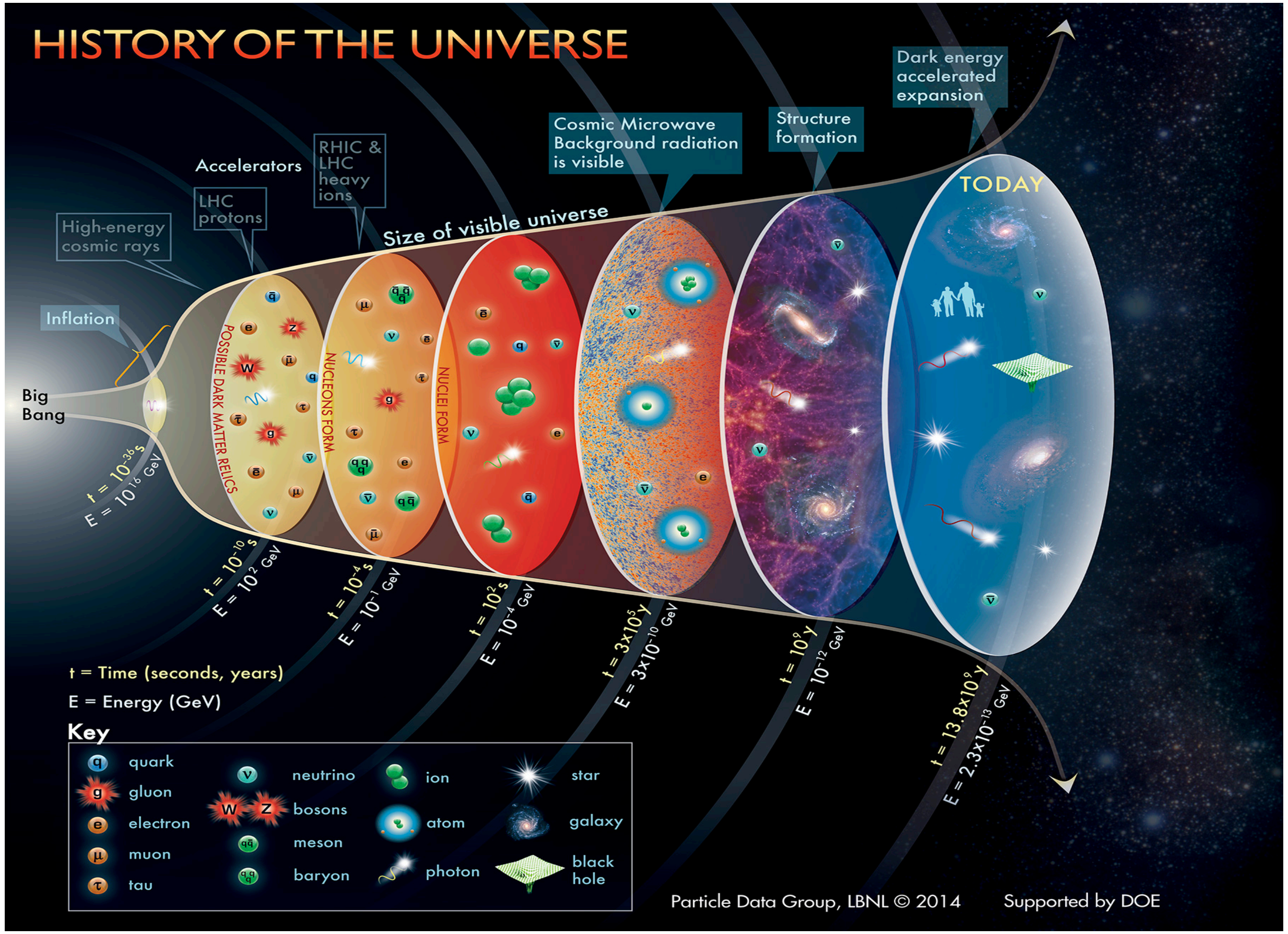
6 April 2017 -- The second Advanced LIGO run began on **November 30, 2016** and is currently in progress. As of March 23 approximately 48 days of Hanford-Livingston coincident science data have been collected, with a scheduled break between December 22, 2016 and January 4, 2017.

The average reach of the LIGO network for binary merger events has been around
70 Mpc for **1.4+1.4 Msun**,
300 Mpc for **10+10 Msun** and
700 Mpc for **30+30 Msun mergers**,
with relative variations in time of the order of 10%.

As of March 23, 6 triggers, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic follow up.
A thorough investigation of the data and offline analysis are in progress; results will be shared when available.

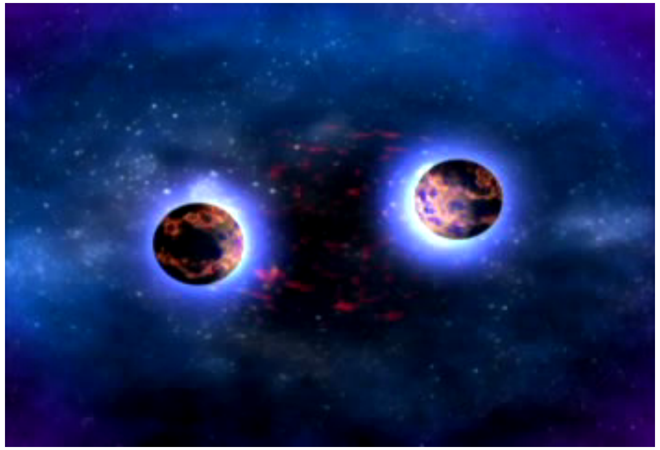
THE “STORY” OF THE UNIVERSE…

…WAS ALWAYS VIOLENT

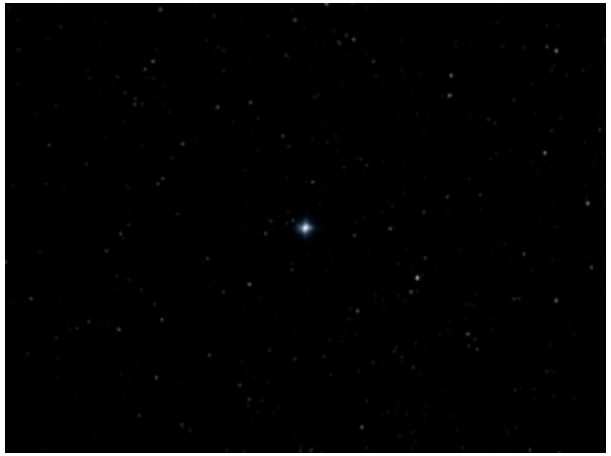


VIOLENT PHENOMENA ASSOCIATED WITH THE EMISSION OF GRAVITATIONAL WAVES

MAIN SOURCES for LIGO



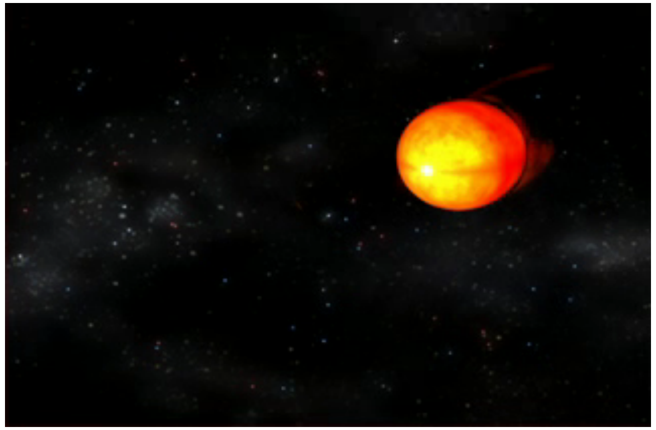
BH and NS Binaries



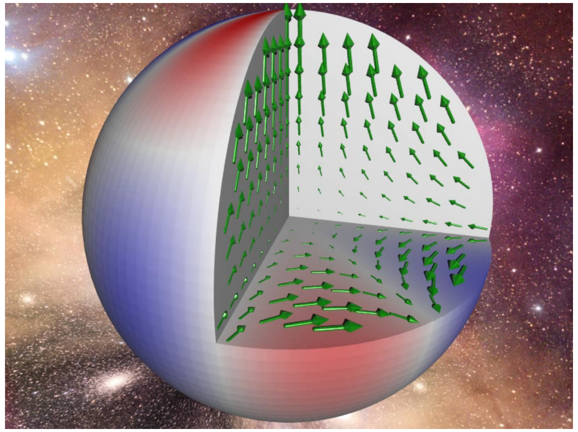
Supernovae, BH/NS formation

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

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



Spinning neutron stars in X-ray binaries

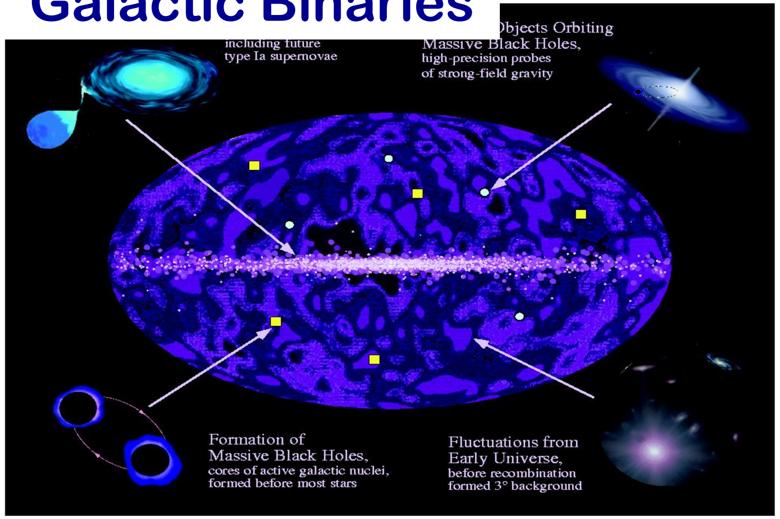


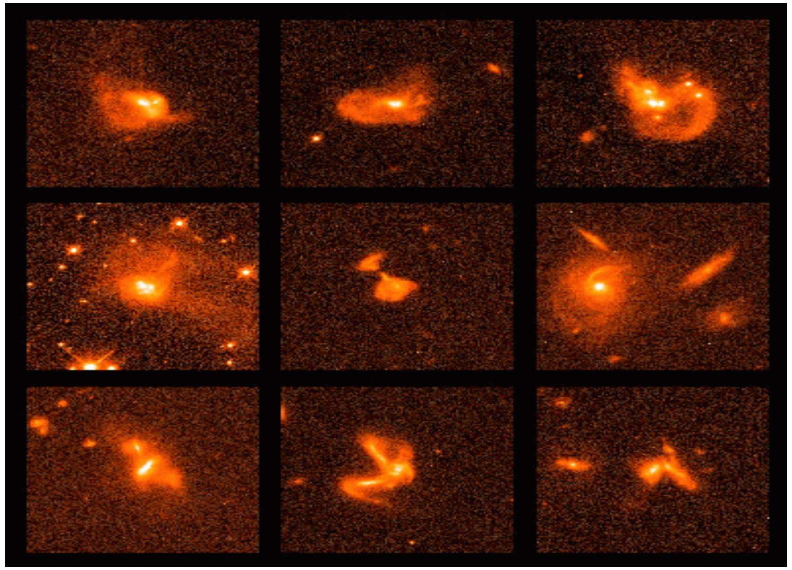
Neutron Stars:
Instabilities, Deformations

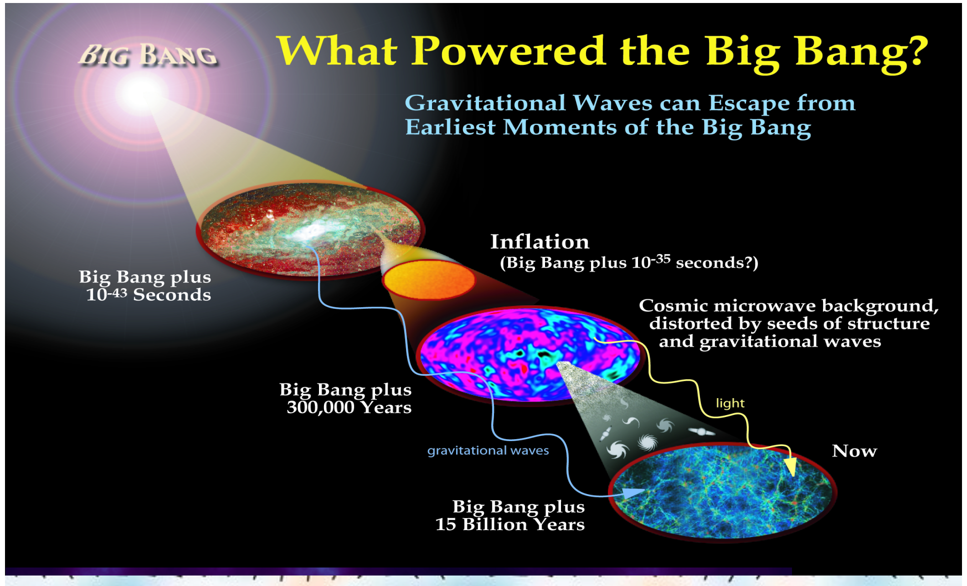
BLACK HOLES:	M/R=0.5
NEUTRON STARS:	M/R~0.2
WHITE DWRFS:	$M/R \sim 10^{-4}$

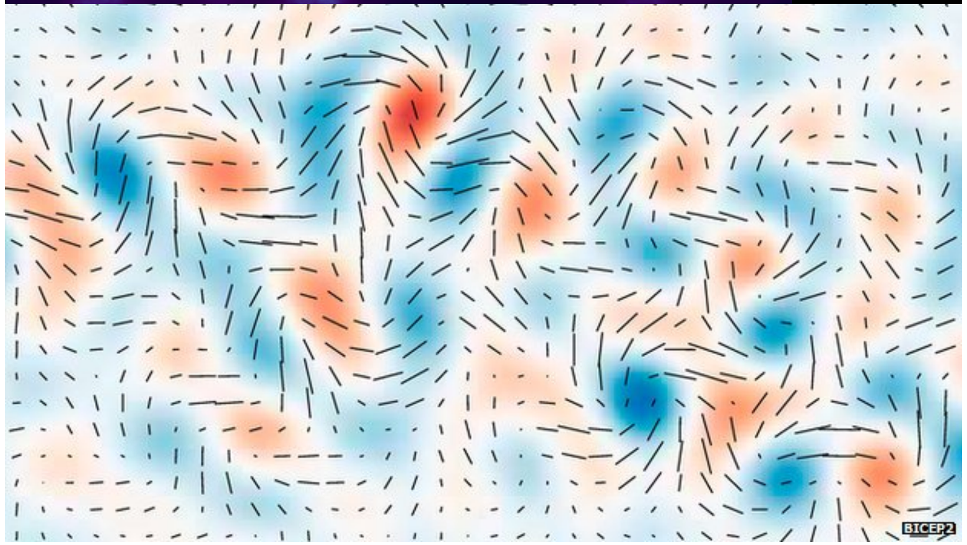
MAIN SOURCES for eLISA

Galactic Binaries



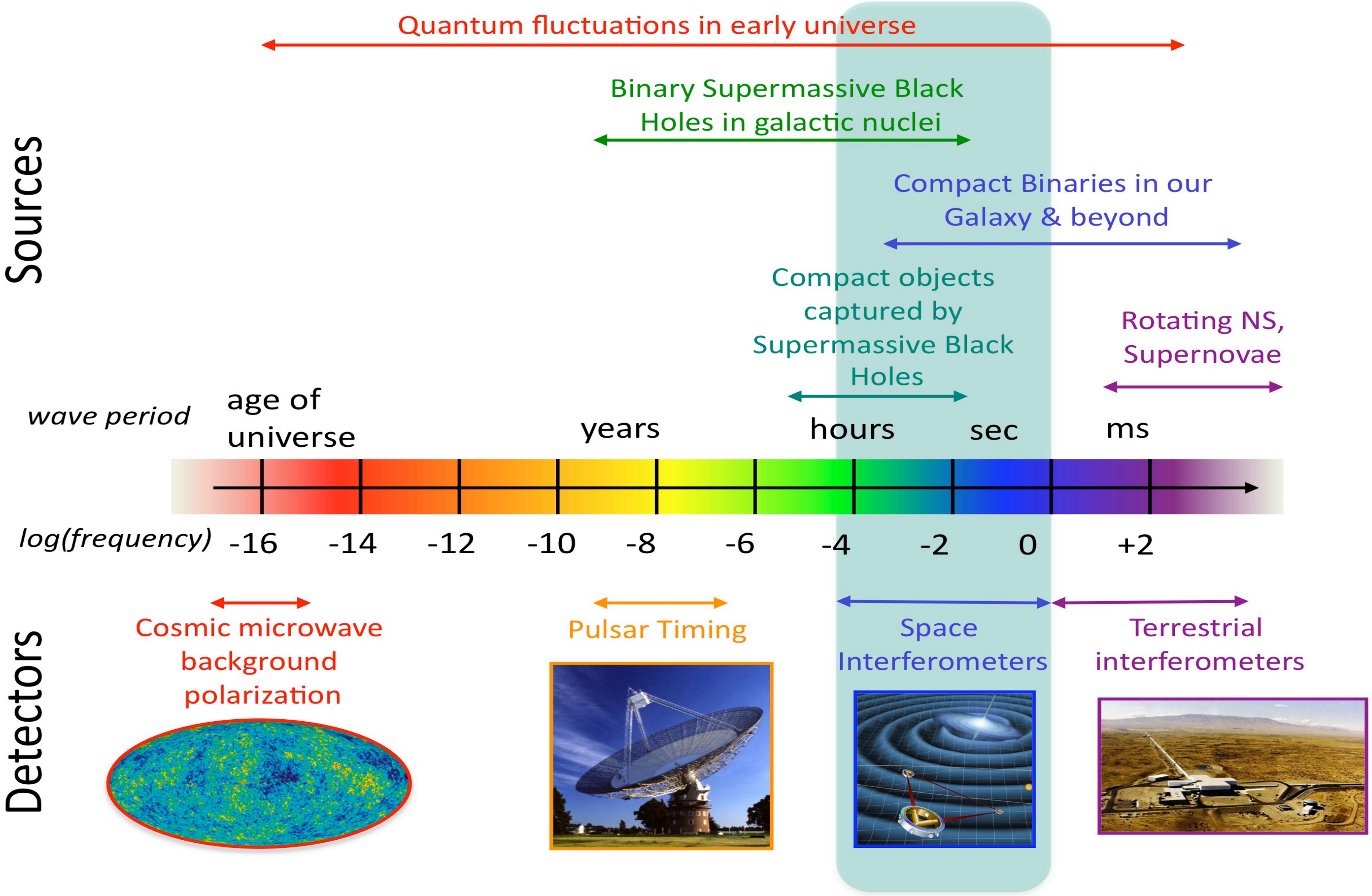






Galaxy mergers

The Gravitational Wave Spectrum



The NEXT SOURCE: Neutron Star Binaries

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

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

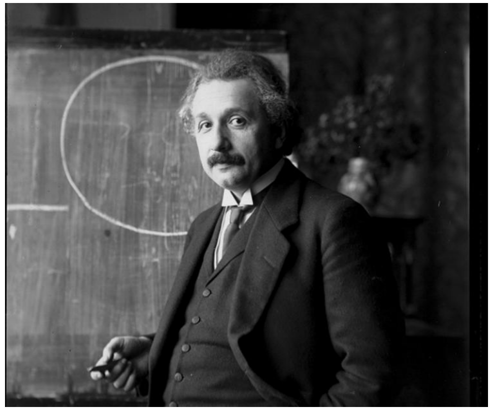
Neutron star cores are laboratories of extreme conditions of density, gravity and magnetic fields. The structure and composition of NS cores have largely remained unresolved even half-century after pulsars were first discovered. Their cores could be host to unknown physics and might be composed of quark-gluon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

CONFRONTING GR with OBSERVATIONS

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

- Does gravity travel at the speed of light?
- Does the graviton have mass?
- How does gravitational information propagate: Are there more than two transverse modes of propagation?
- 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?
- **Are astrophysical black holes described by the Kerr metric, as predicted by GR?**

eLISA : The Laws of Nature



Confronting General Relativity with experimental measurements of gravity is one of the most important objectives of fundamental physics.

eLISA will map the spacetime around astrophysical BHs, yielding a battery of precision tests of GR in an entirely new regime.
These have the potential to uncover hints about the nature of quantum gravity, as well as enabling measurements of properties of the universe on the largest scales.

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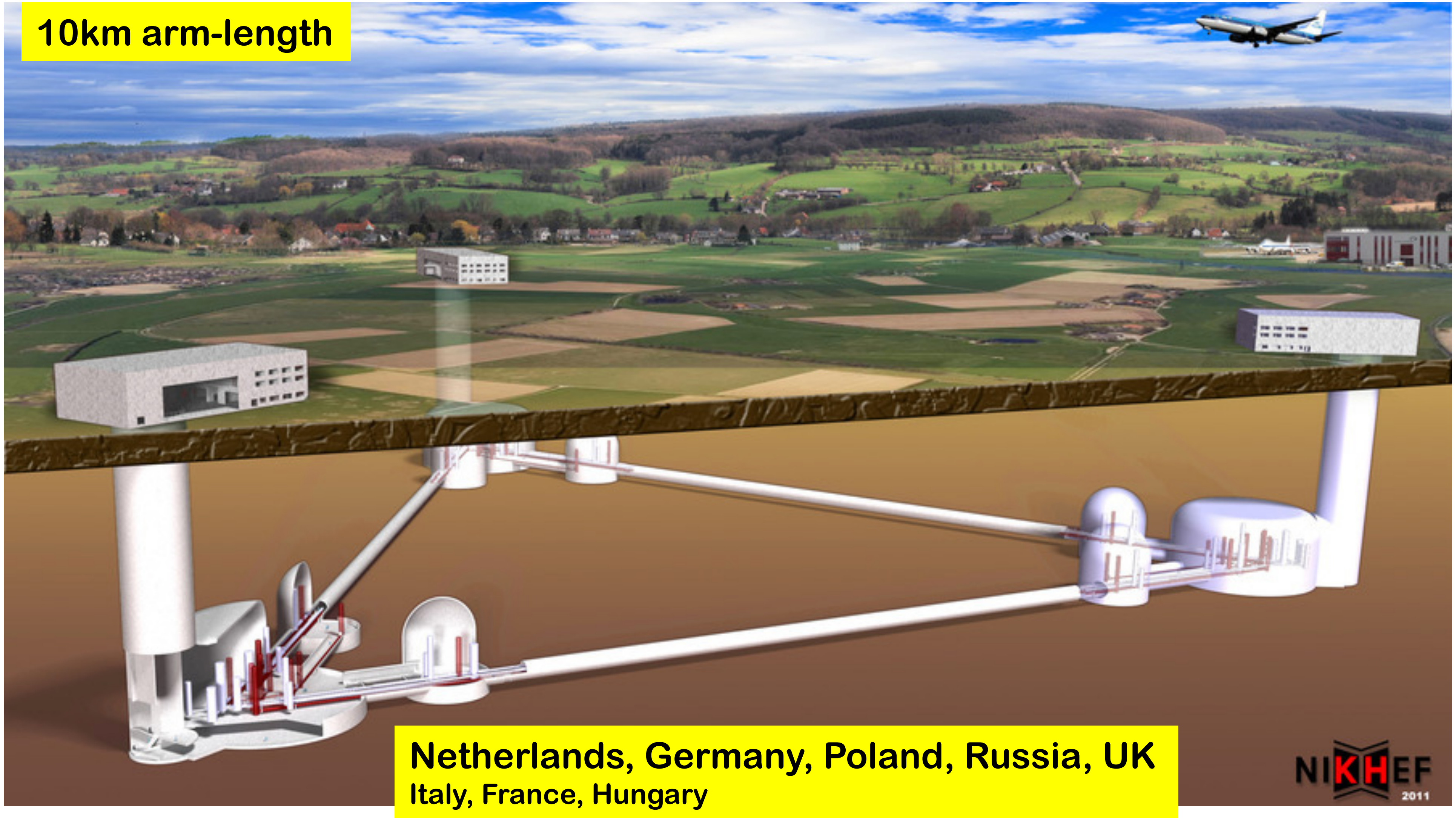
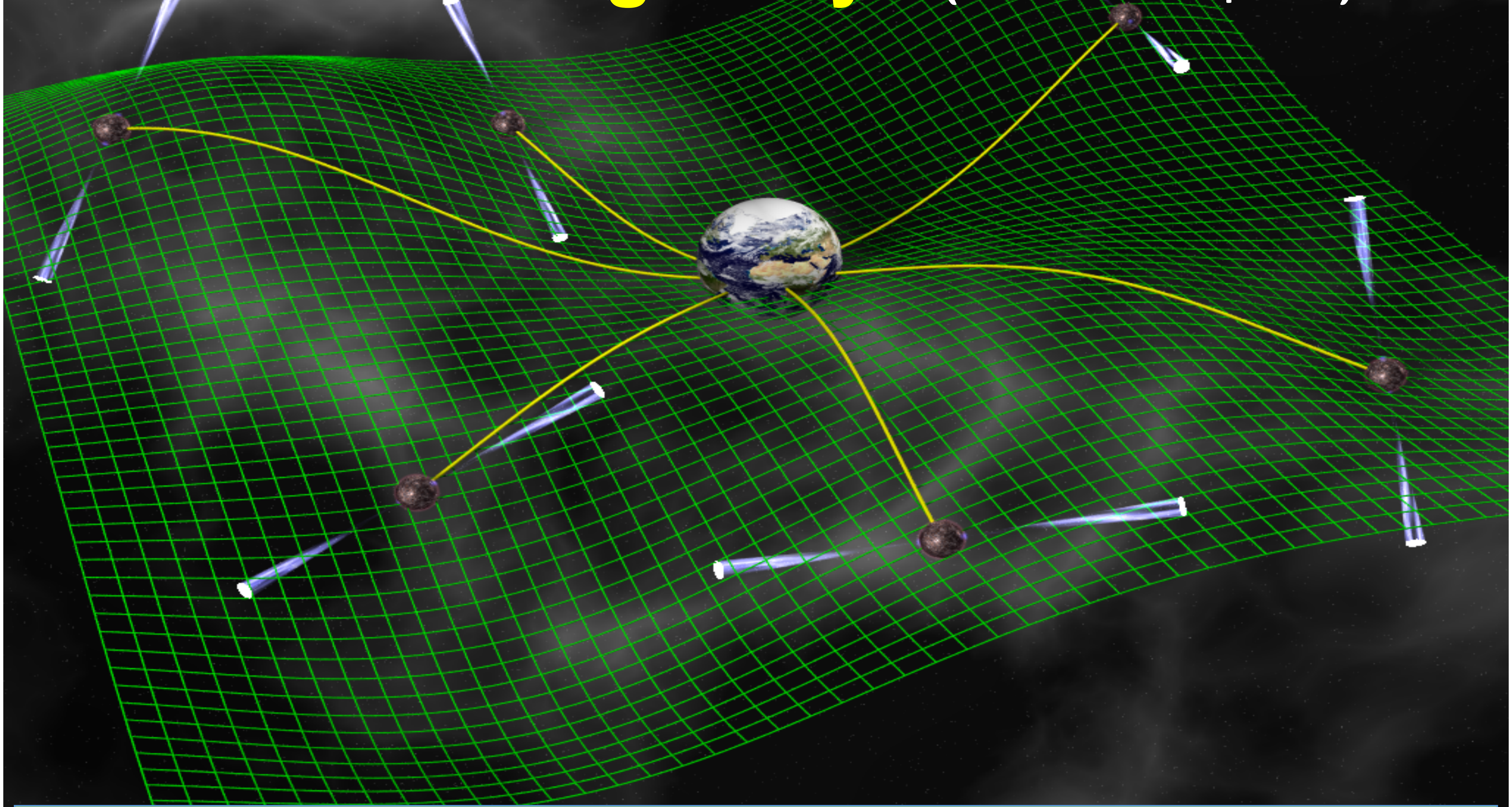
Einstein Telescope



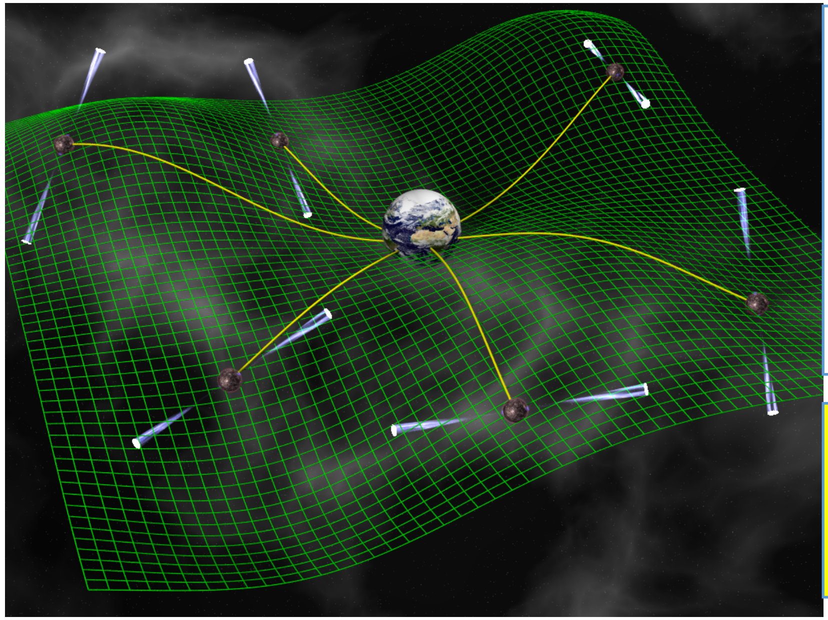
Pulsar Timing Arrays (10-1000 μHz)



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



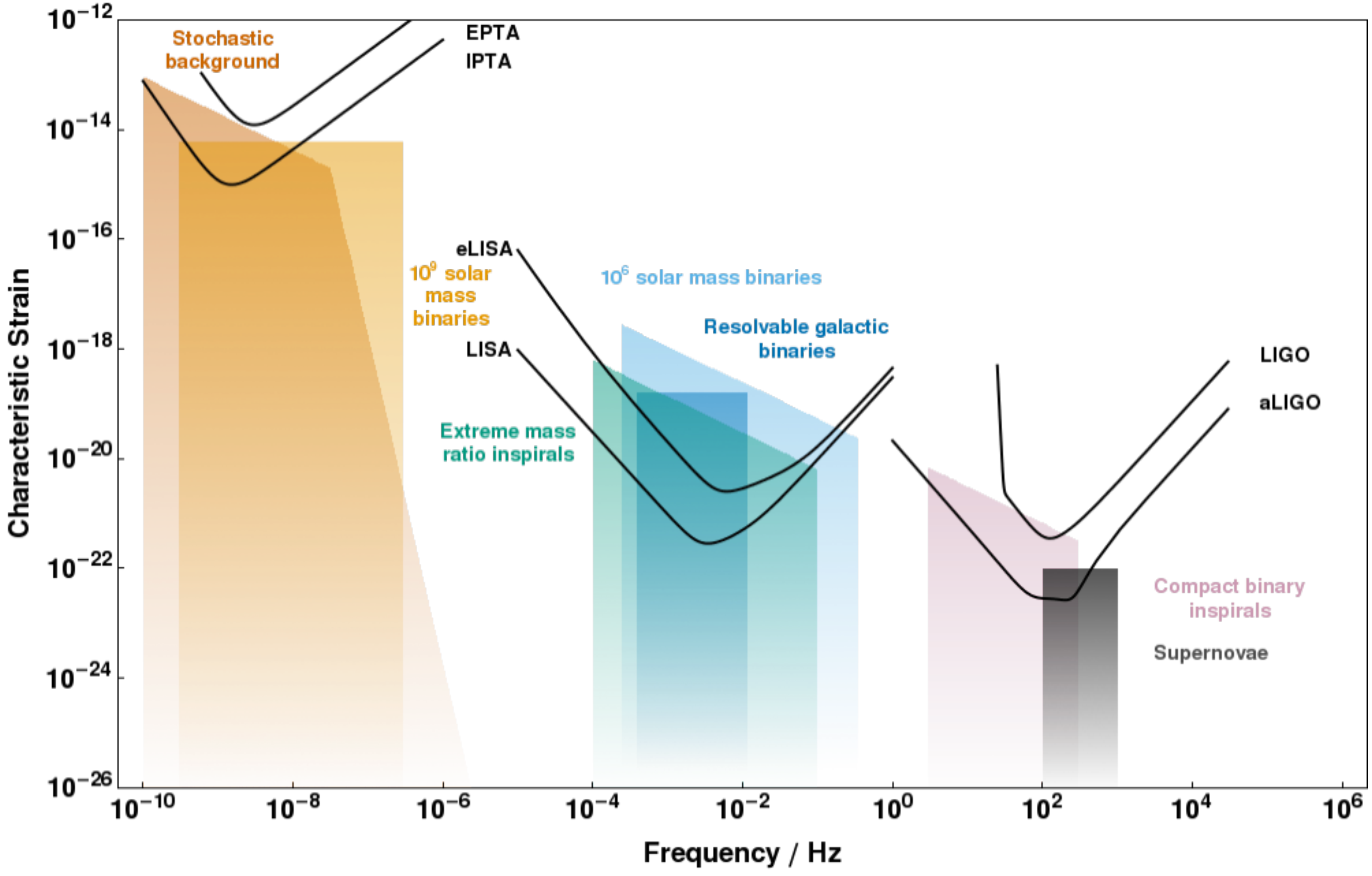
A different approach to detecting GWs is used by pulsar timing arrays, such as the

- 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



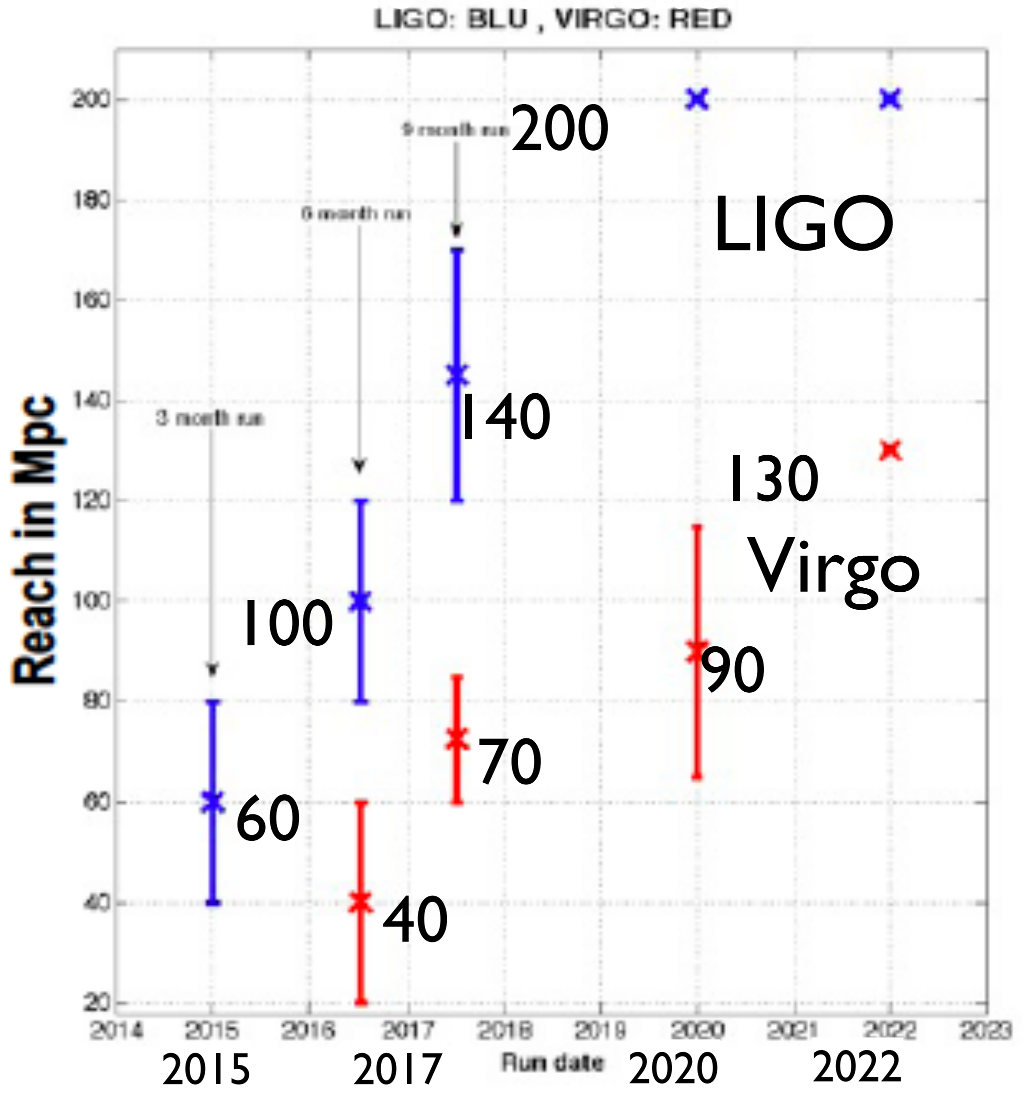
LIGO: PLAN

Second generation interferometers to begin science operations:

- Advanced LIGO (2 interferometers) – 2015
- Advanced Virgo (1 interferometer) – 2016

Approximate run schedule:

- **Advanced LIGO:**
  ~ 3 month run in 2015,
  ~ 6 month run in 2016-17
  ~ 9 month run in 2017-18
- **Advanced Virgo:**
  ~ 6 month run in 2016-17
  ~ 9 month run in 2017-18
- *Modification of run schedules is likely as we learn more about the instruments*

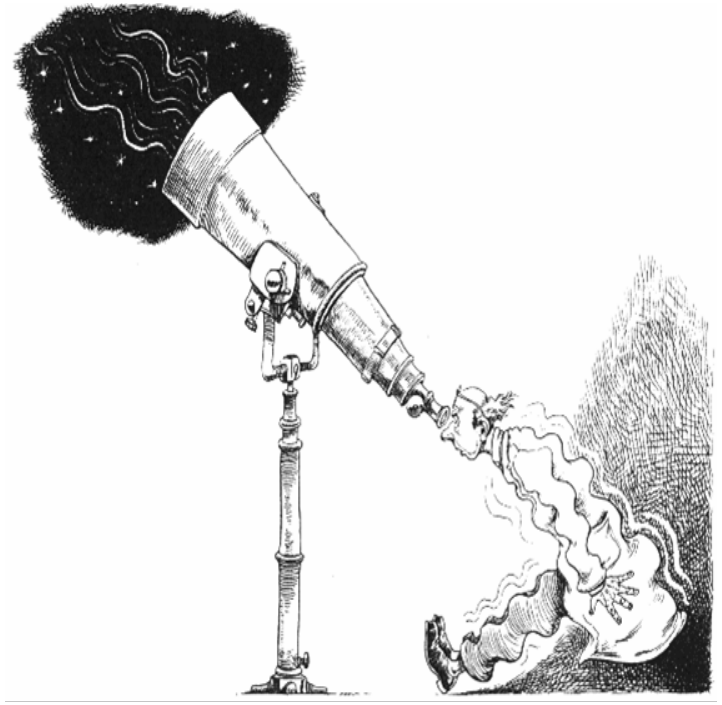


From V. Kalogera

BLACK-HOLE COLLISIONS WERE EXPECTED
– BUT 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

List of Lectures

1. Introduction to GR (3? lectures)

2. Gravitational Collapse to Black Holes & Neutron Stars

3. Post-Newtonian Approximation

4. Testing the Equivalence Principle

5. Gravitational Wave: Sources & Detectors

6. Black Holes
   - Thermodynamics
   - Extra-dimensions
   - Jets

7. Gravitational Lensing

8. Numerical Relativity

9. The Double Pulsar System, as a laboratory for gravity

10. Neutron Stars
    - Astrophysics
    - Dynamics
    - Equations of State
    - Magnetic Fields

11. Measuring the Whirling of Spacetime

Project Titles

- Gravitational collapse
- Quark stars
- Active Galactic Nuclei and Jets
- Gravitational Lensing
- Cosmology
- GPS and relativity

- **Gravitational Waves**
  - …sources
  - …theory e.g. in ATG
  - …detection techniques
  - LISA etc
  - BICEP2
  - Pulsar Timing Arrays
- A project of your choice