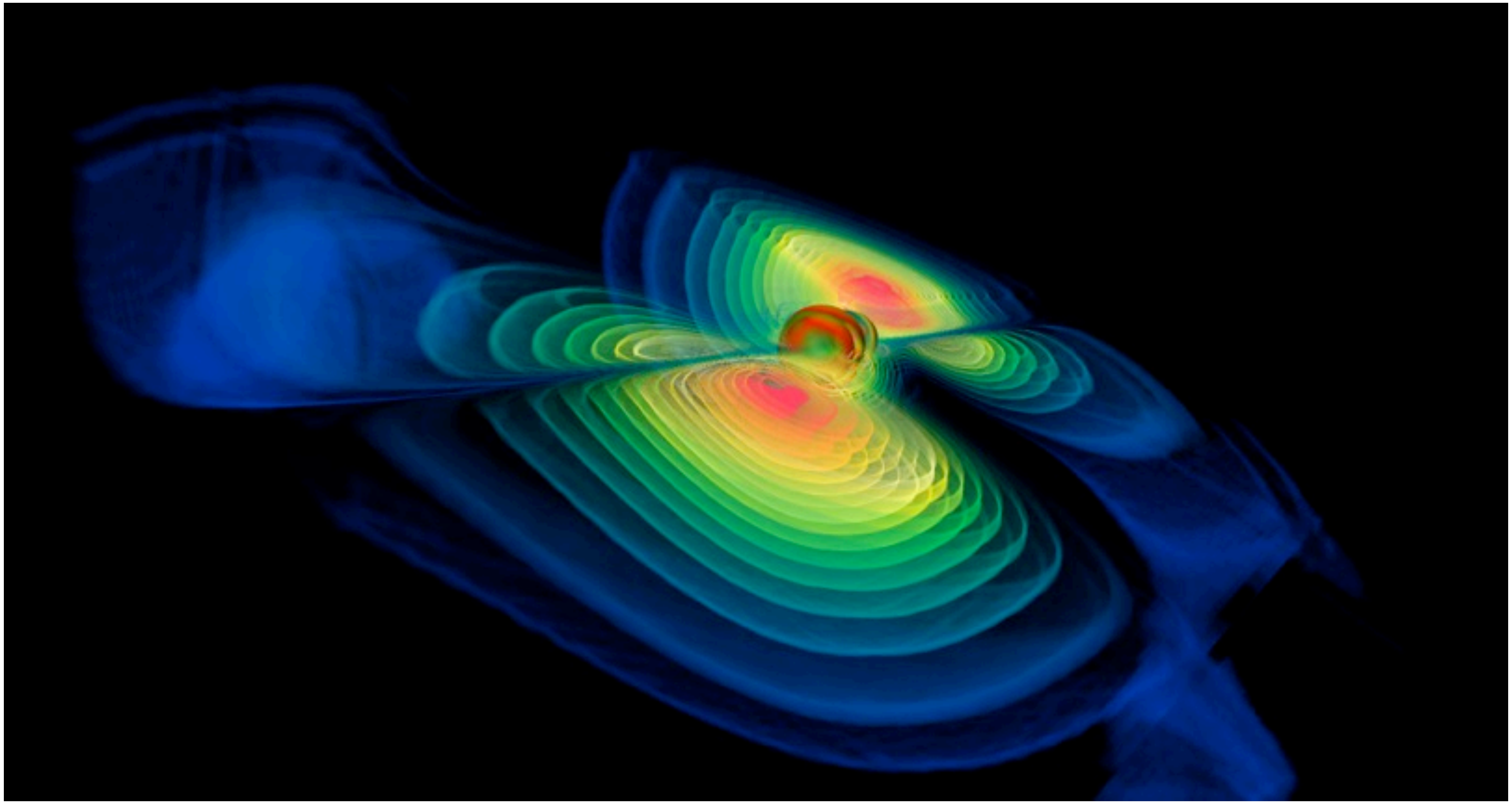
The Search for Gravitational Waves



Bruce Allen

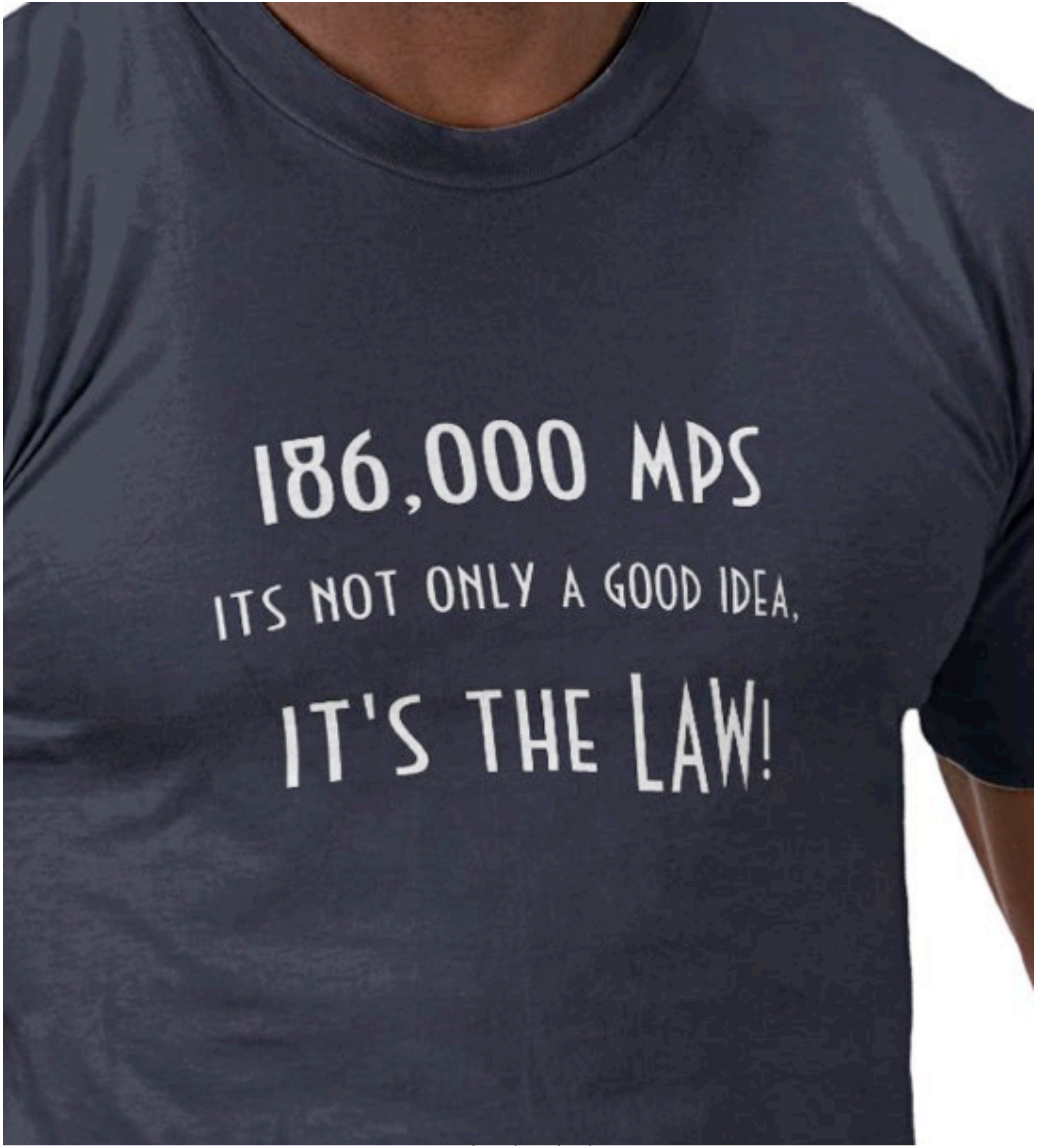
Max Planck Institute for Gravitational Physics
(Albert Einstein Institute)
Hannover, Germany

Outline

- What are gravitational waves (GWs)?
- How do GW detectors work?
- GW Sources and science
- Second-generation GW detectors: 2016-2020
- GWs and transient electromagnetic astronomy
- The future: 2020+

Gravitational waves


1904

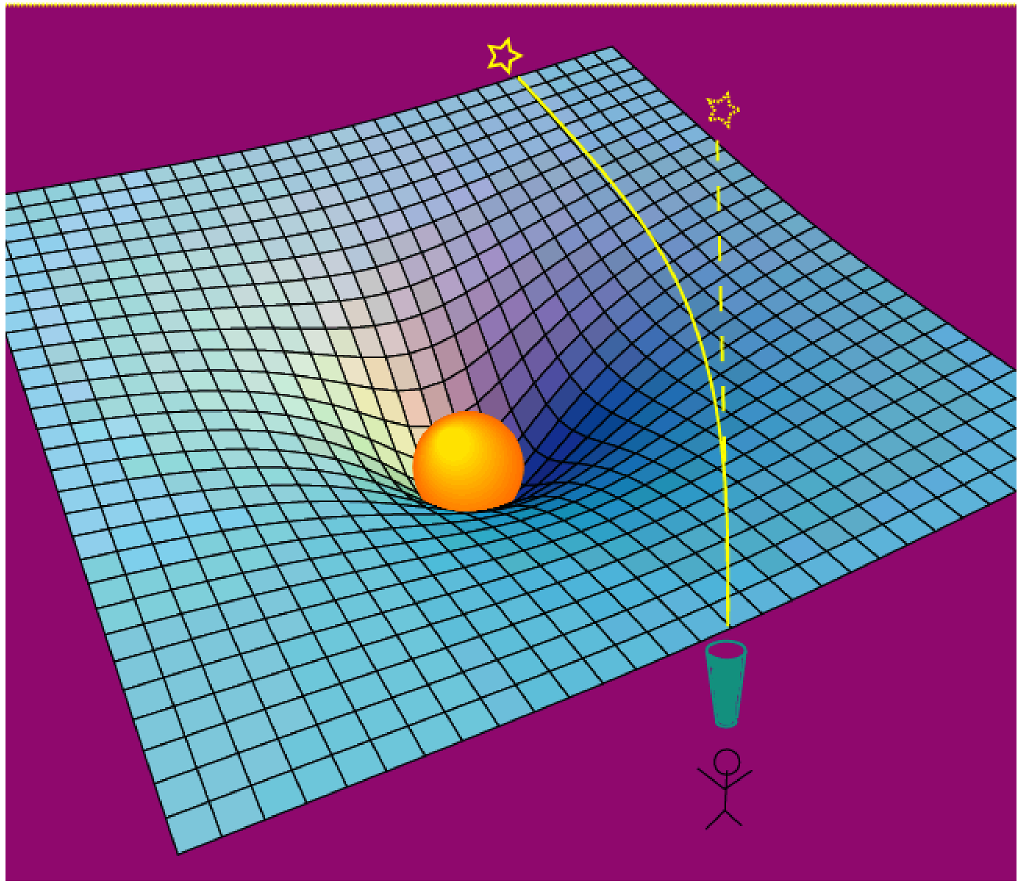

186,000 MPS
ITS NOT ONLY A GOOD IDEA,
IT'S THE LAW!

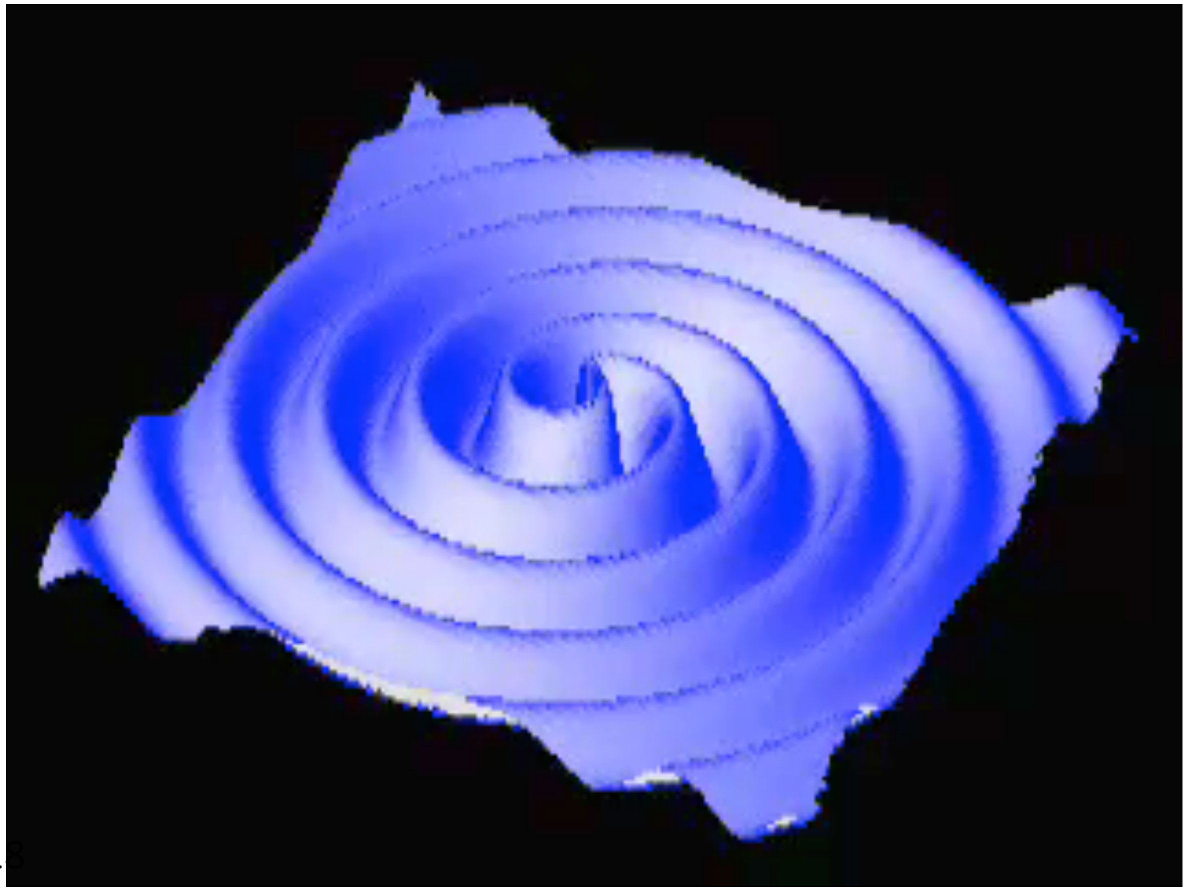
Gravitational Waves

- Predicted by general relativity, 1916-1918
- Consequence of 'nothing can go faster than light'
- Very weak: need compact stars with large accelerations

$$L = \frac{G}{5c^5} \left(\frac{d^3}{dt^3} Q_{ab}\right)\left(\frac{d^3}{dt^3} Q_{ab}\right)$$

- Einstein: undetectable





Prediction of Gravitational Waves: 1916

June 1916

Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen.

(It follows that the gravitational field propagates at the speed of light. In connection with these general solutions, we'll investigate gravitational waves and their sources.)

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

Sber Preuss. Akad. Wiss. 1916, I

Näherungsweise Integration der Feldgleichungen der Gravitation.

Von A. Einstein.

Bei der Behandlung der meisten speziellen (nicht prinzipiellen) Probleme auf dem Gebiete der Gravitationstheorie kann man sich damit begnügen, die $g_{\mu\nu}$ in erster Näherung zu berechnen. Dabei bedient man sich mit Vorteil der imaginären Zeitvariable $x_4 = it$ aus denselben Gründen wie in der speziellen Relativitätstheorie. Unter »erster Näherung« ist dabei verstanden, daß die durch die Gleichung

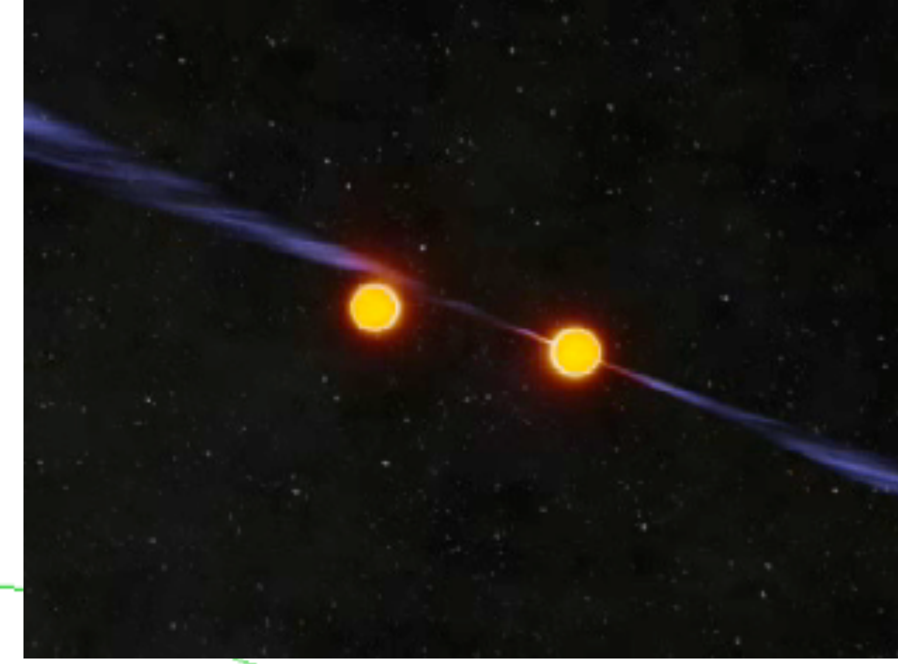
$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \qquad (1)$$

definierten Größen $\gamma_{\mu\nu}$, welche linearen orthogonalen Transformationen gegenüber Tensorcharakter besitzen, gegen 1 als kleine Größen behandelt werden können, deren Quadrate und Produkte gegen die ersten Potenzen vernachlässigt werden dürfen. Dabei ist $\delta_{\mu\nu} = 1$ bzw. $\delta_{\mu\nu} = 0$, je nachdem $\mu = \nu$ oder $\mu \neq \nu$.

Wir werden zeigen, daß diese $\gamma_{\mu\nu}$ in analoger Weise berechnet werden können wie die retardierten Potentiale der Elektrodynamik. Daraus folgt dann zunächst, daß sich die Gravitationsfelder mit Lichtgeschwindigkeit ausbreiten. Wir werden im Anschluß an diese allgemeine Lösung die Gravitationswellen und deren Entstehungsweise untersuchen. Es hat sich gezeigt, daß die von mir vorgeschlagene Wahl des Bezugssystems gemäß der Bedingung $g = |g_{\mu\nu}| = -1$ für die Berechnung der Felder in erster Näherung nicht vorteilhaft ist. Ich wurde hierauf aufmerksam durch eine briefliche Mitteilung des Astronomen de Sitter, der fand, daß man durch eine andere Wahl des Bezugssystems zu einem einfacheren Ausdruck des Gravitationsfeldes eines ruhenden Massenpunktes gelangen kann, als ich ihn früher gegeben hatte[1]. Ich stütze mich daher im folgenden auf die allgemein invarianten Feldgleichungen.

[1] Sitzungsber. XLVII, 1915, S. 833.

Energy-loss by gravitational waves is seen: 1976



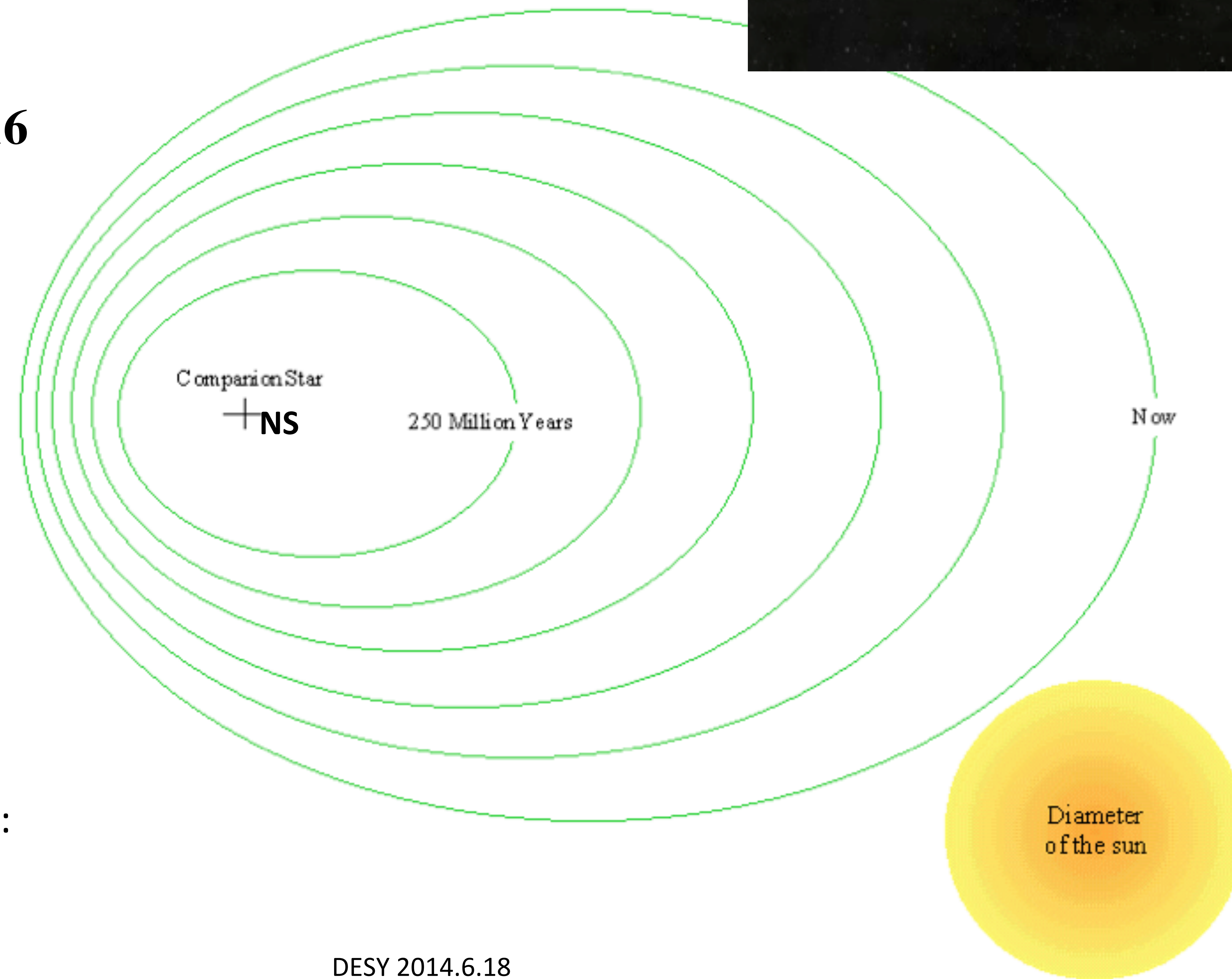
Hulse-Taylor binary pulsar PSR B1913+16

Pulsar: **17 Hz**
P_{orb} = **7.75 h**
$F_{orb} = 1/P_{orb}$ = **36 μHz**

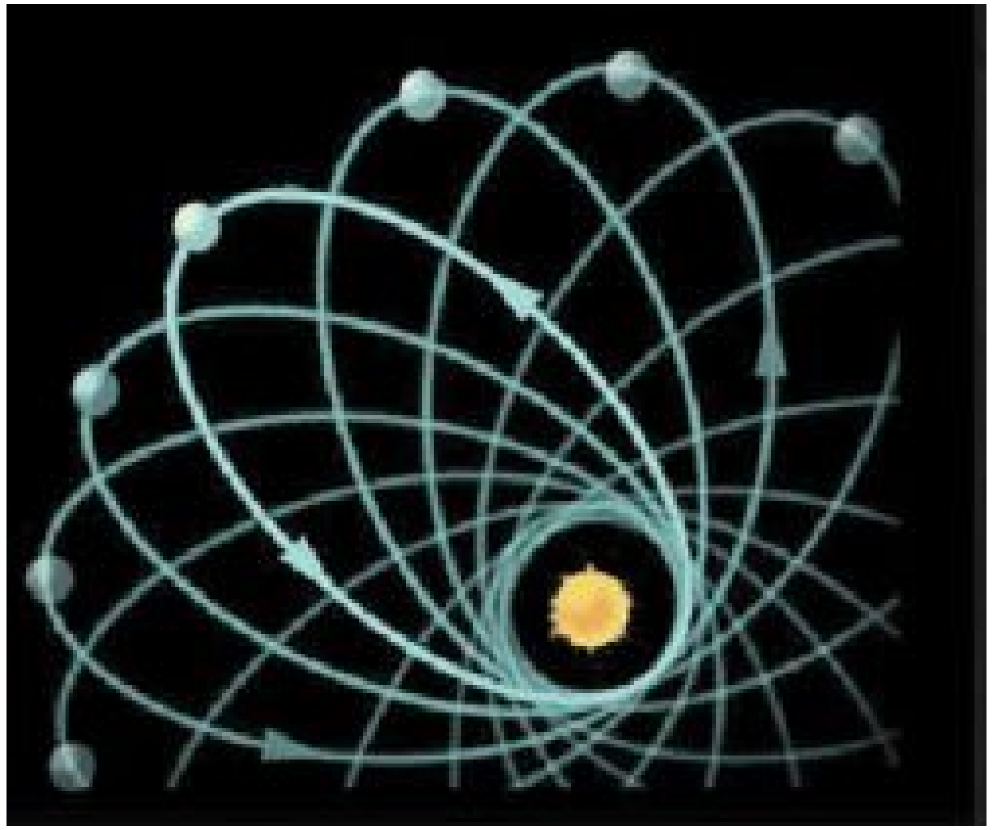
Semi-major axis: **2 Gm**
Eccentricity: **0.617**

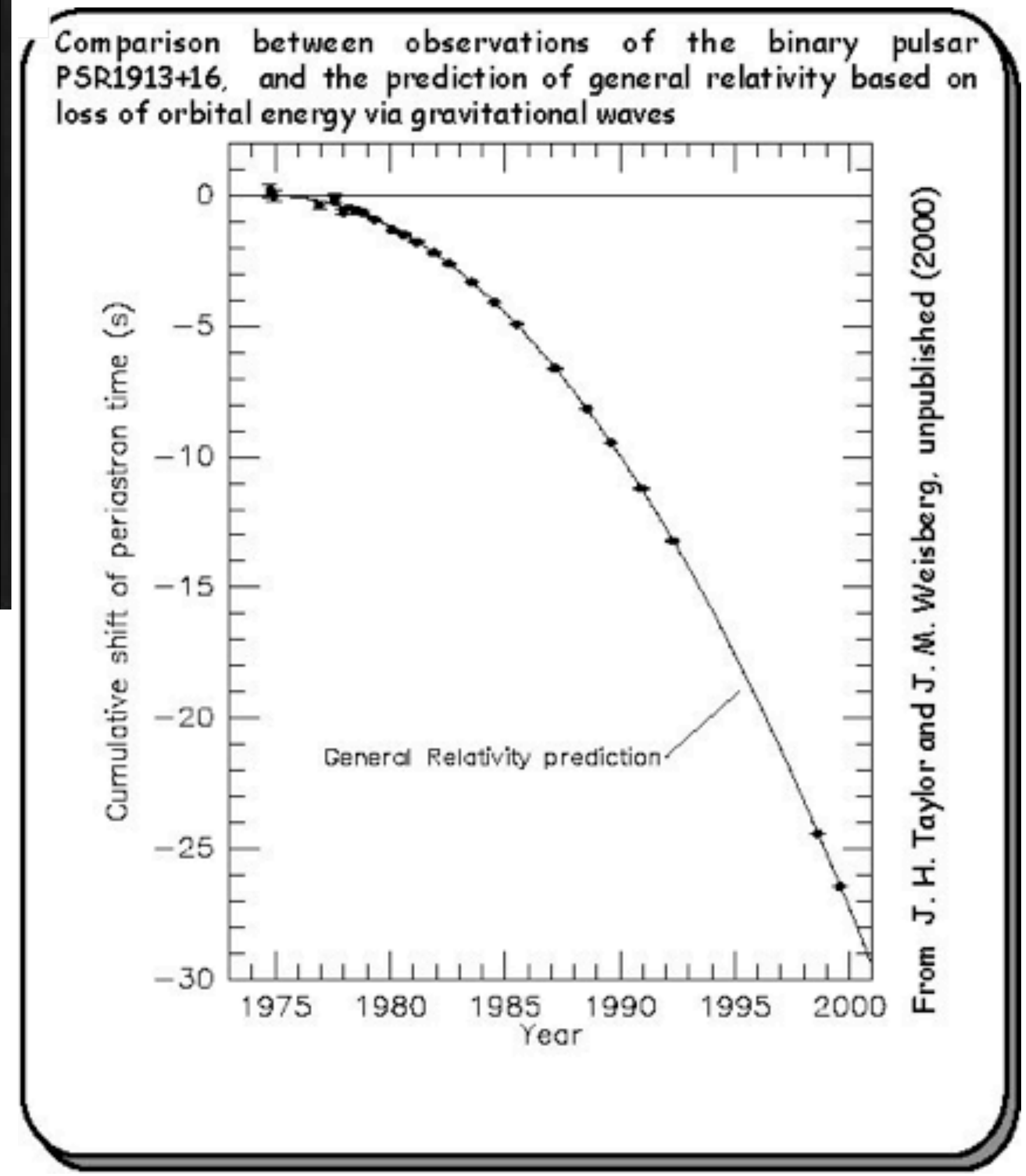
$F_{GW} = 2\ F_{orb}$ = **72 μHz**
Decay: 3mm/orbit
Detay time: 300 Myr

Decay time, circular orbit:
$\tau = 7.1\ \text{Myr}\ (P_{orb}/\text{hour})^{8/3}$



Energy-loss by gravitational waves is seen

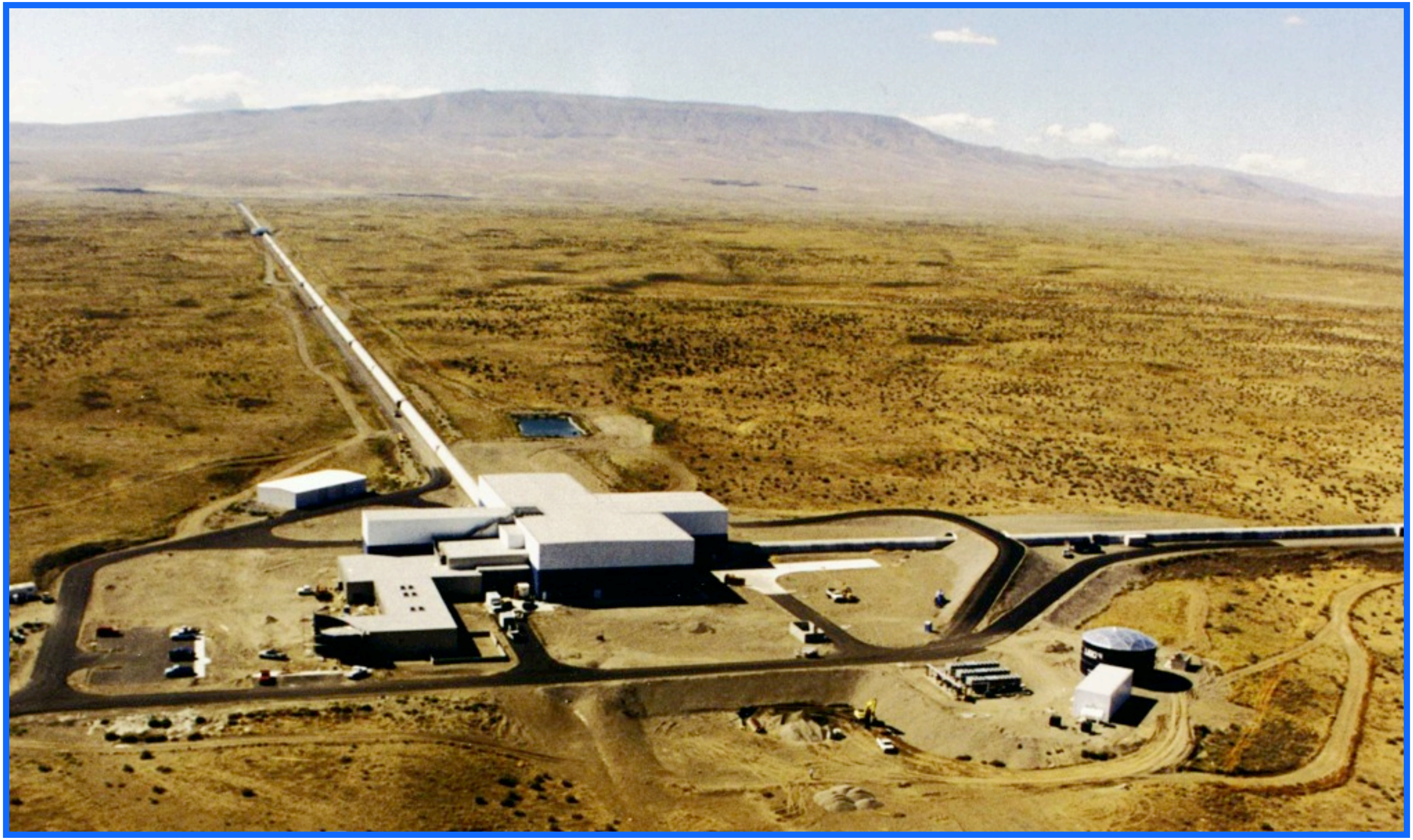




Significantly better tests come from the “double pulsar” PSR J0737-3039 which has a 2.4h period.

How to detect Gravitational Waves

LIGO (Hanford, WA, USA)

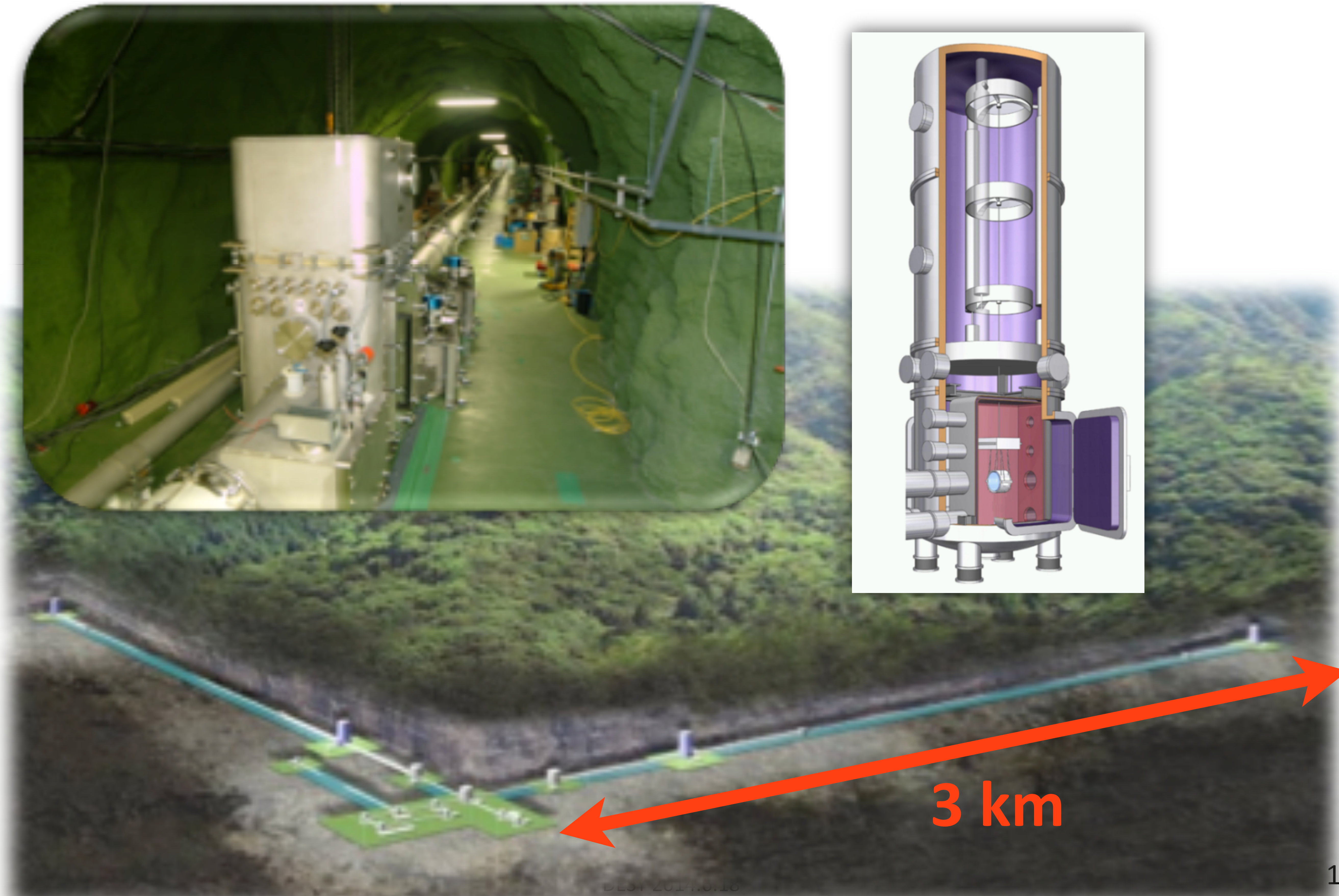


LIGO 4km (Livingston, Louisiana, USA)

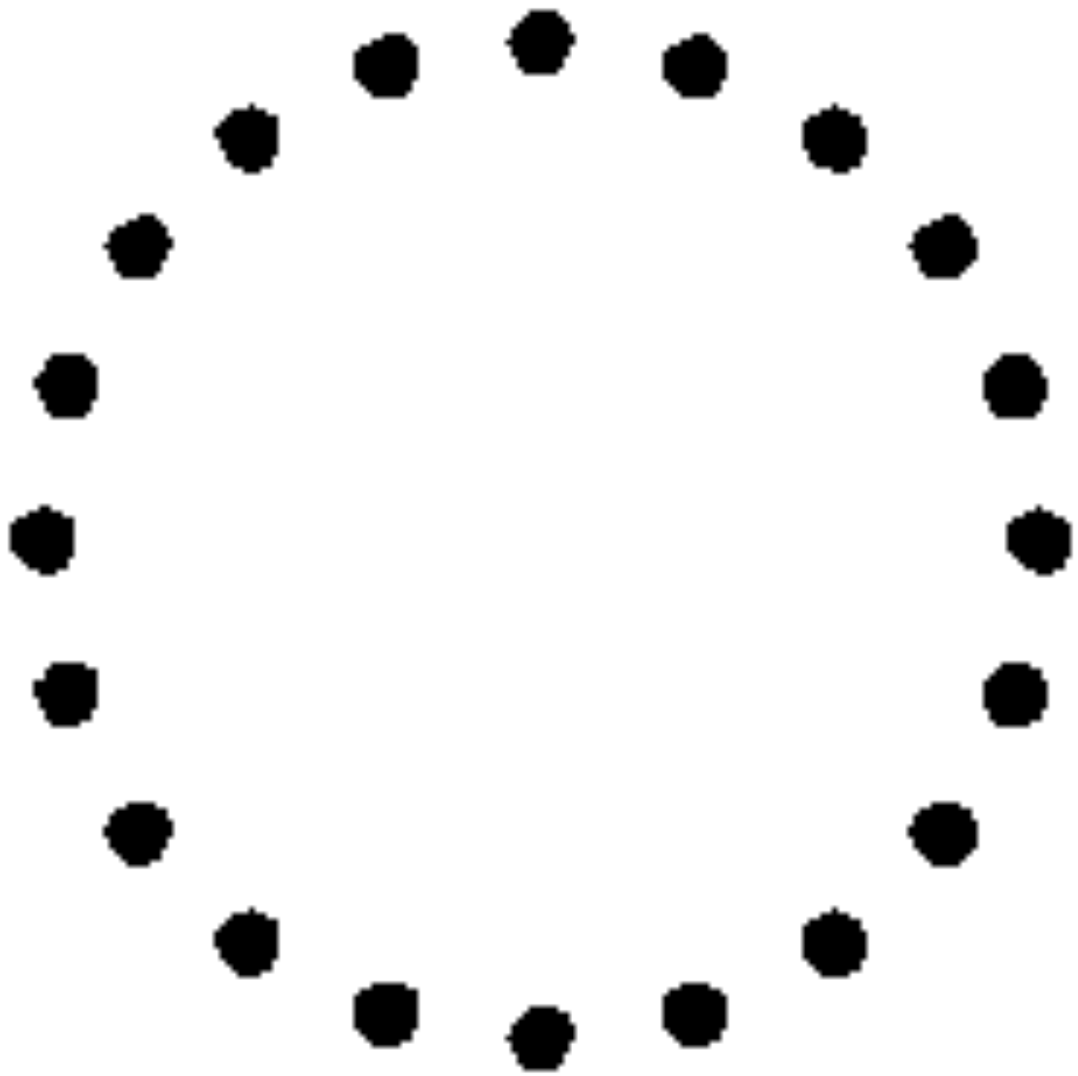
VIRGO (Cascina, Italy)

GEO (Ruthe, Gemany)

Japan Kamioka Gravitational wave detector (KaGra)
Large-scale Cryogenic Gravitational wave Telescope (LCGT)

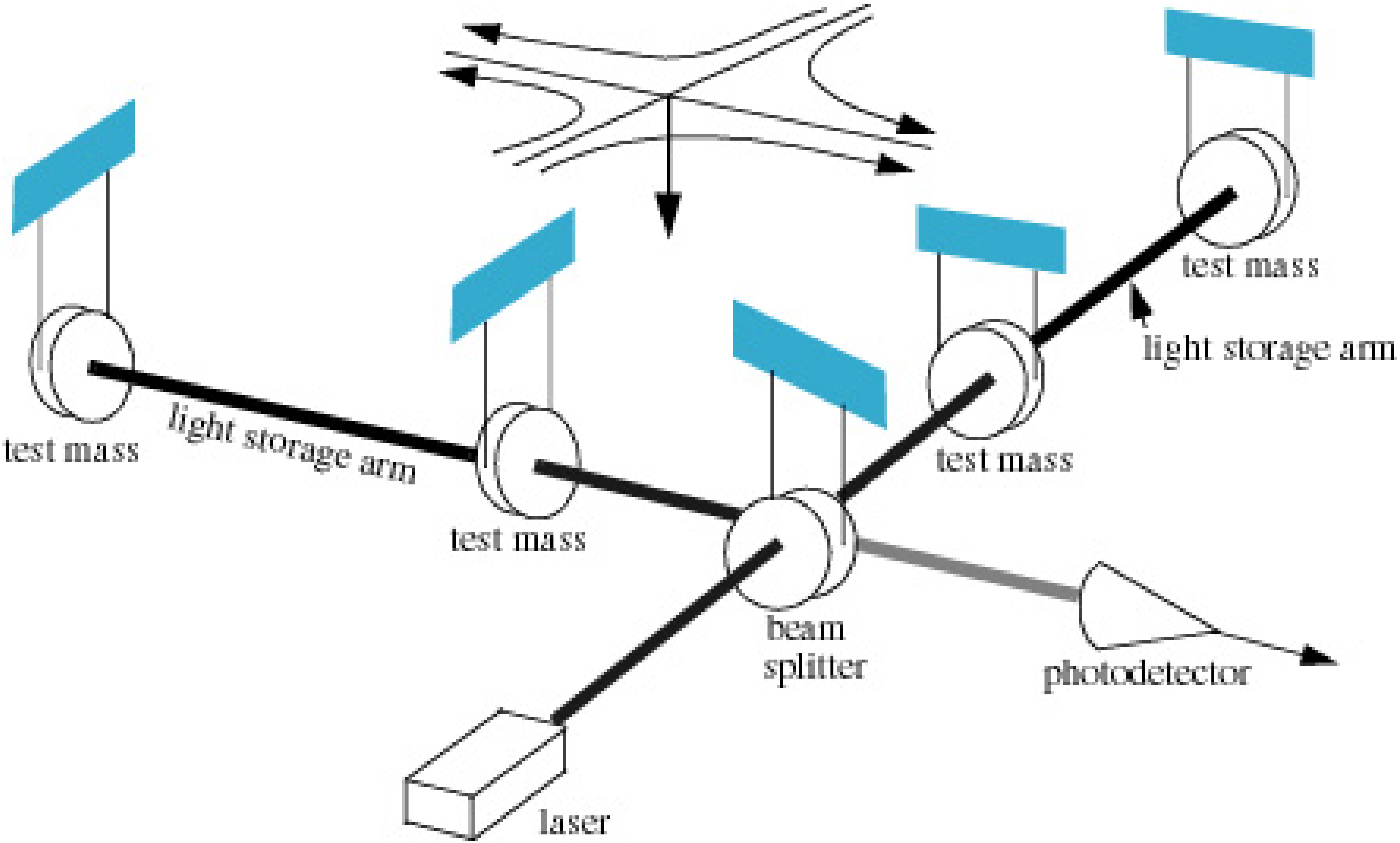


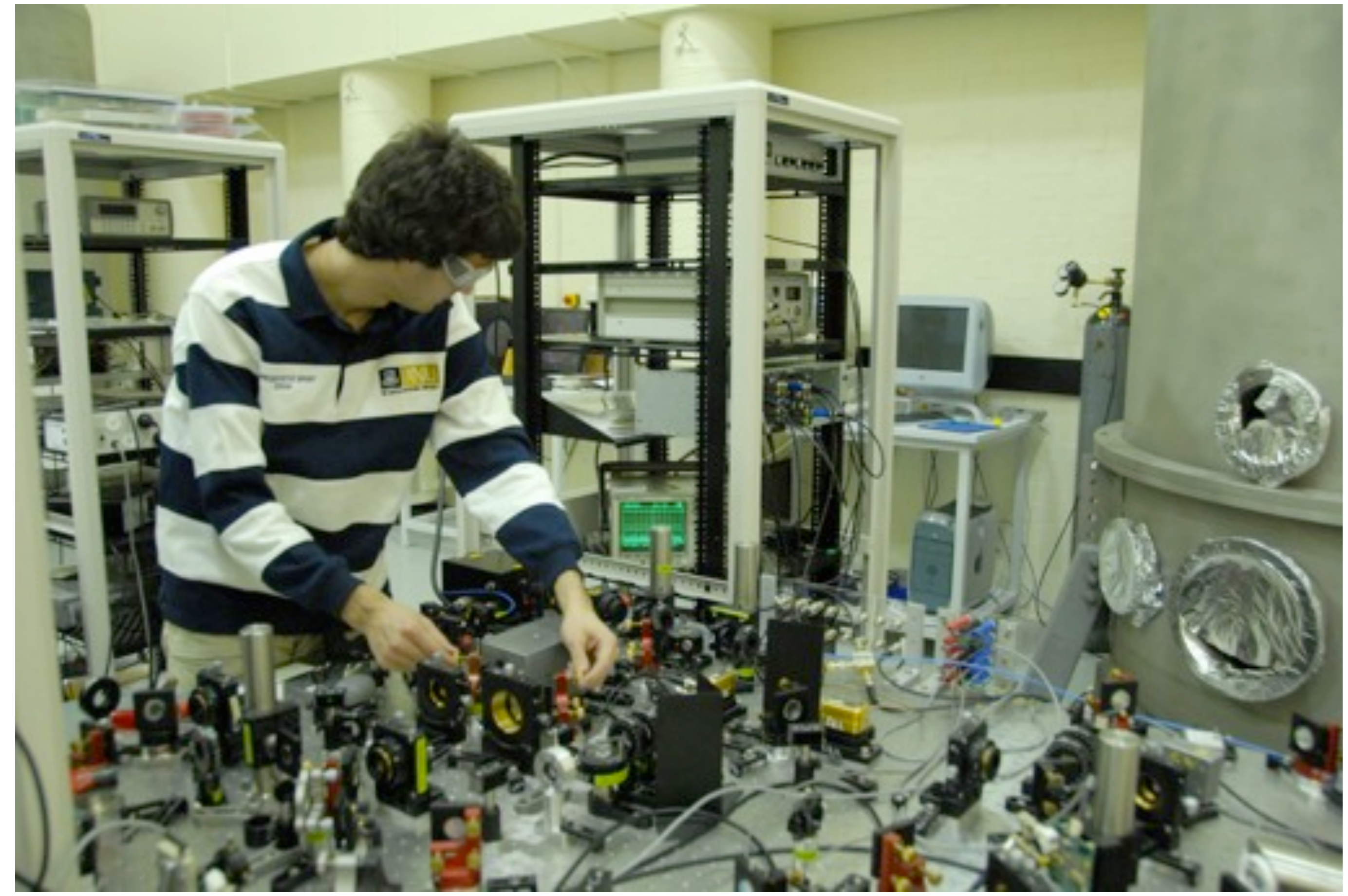
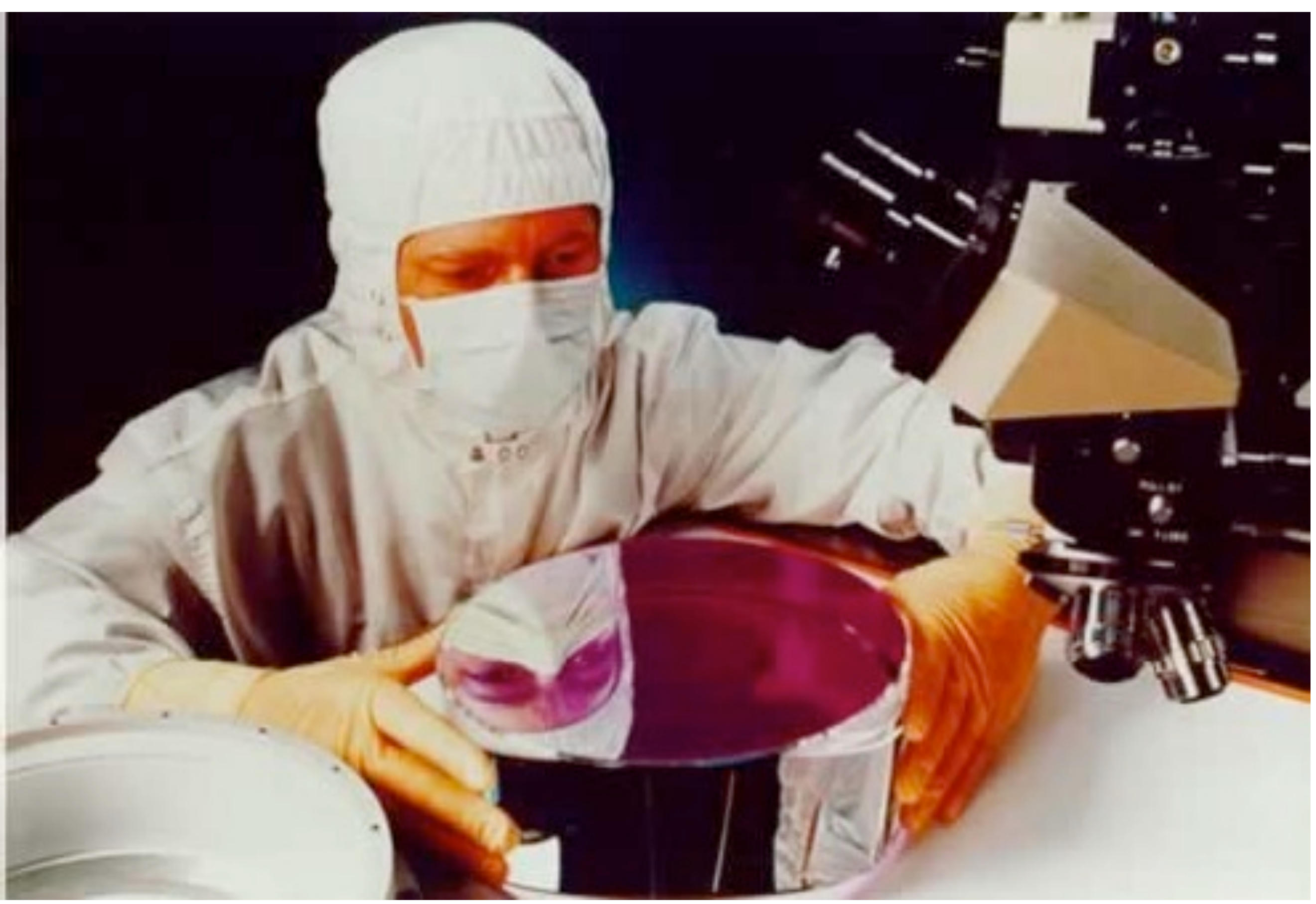
Effect of Gravitational Wave on Test Particles



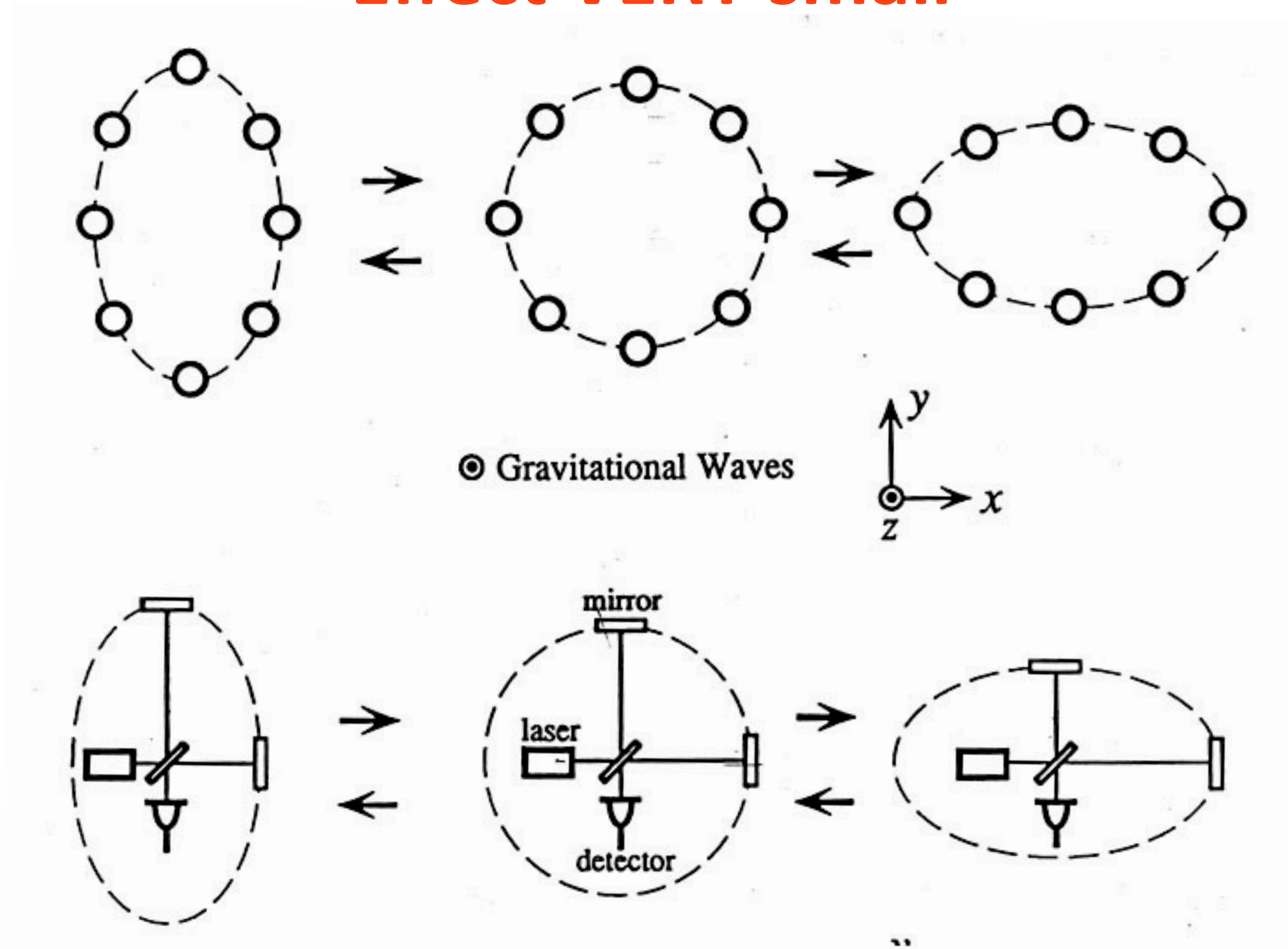
Motion GREATLY exaggerated!

Gravitational Wave Detector




Effect VERY small

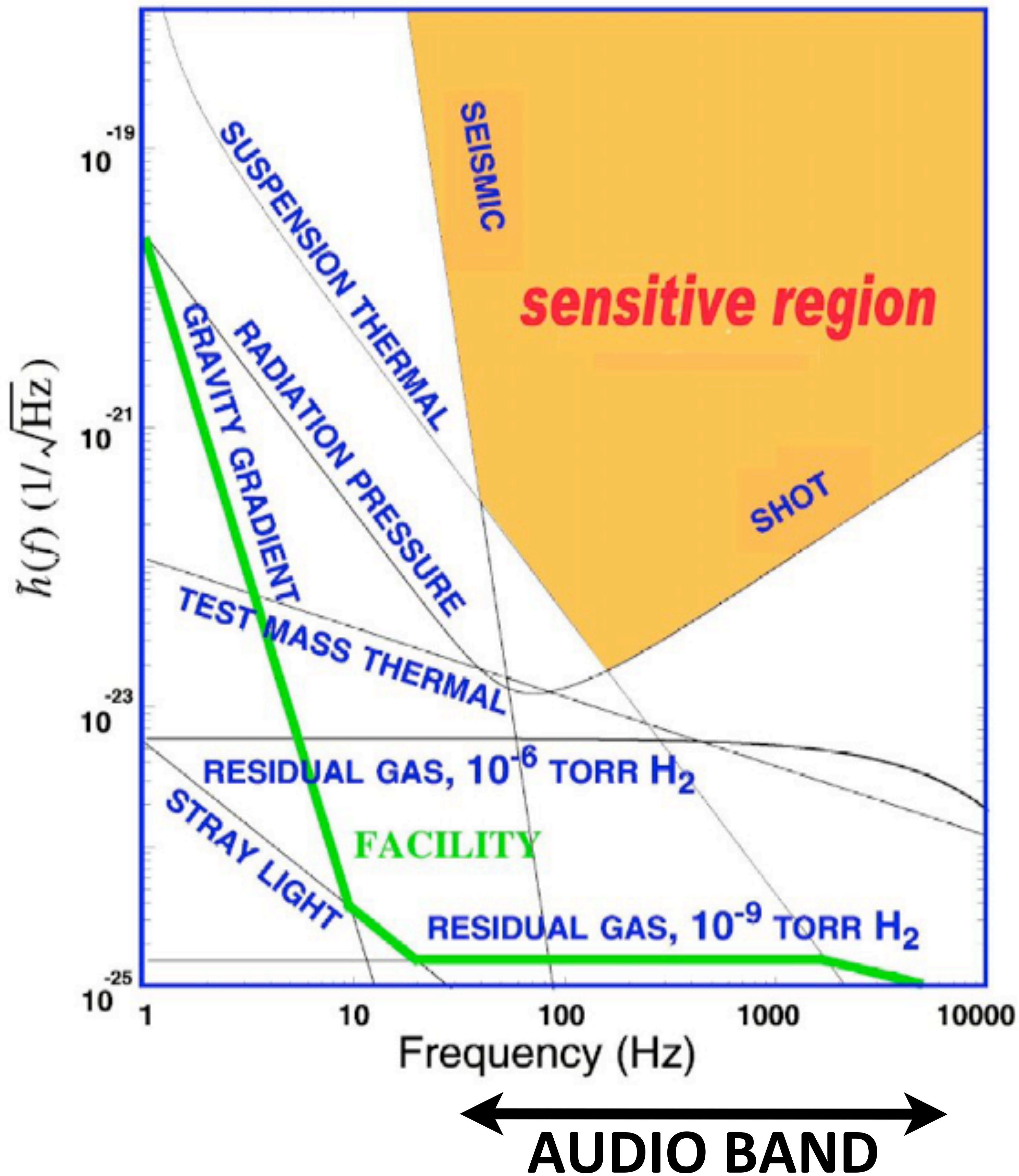


For LIGO, L = 4 km, and $\Delta L = 10^{-16}$ cm.

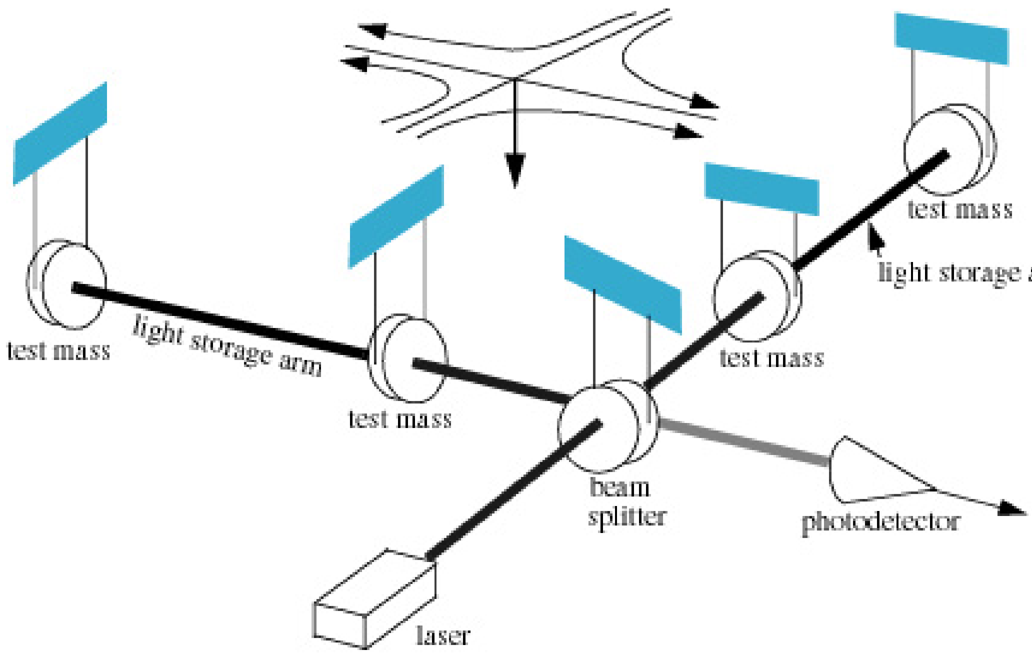
Dimensionless **strain h = $\Delta L/L \sim 10^{-21}$**

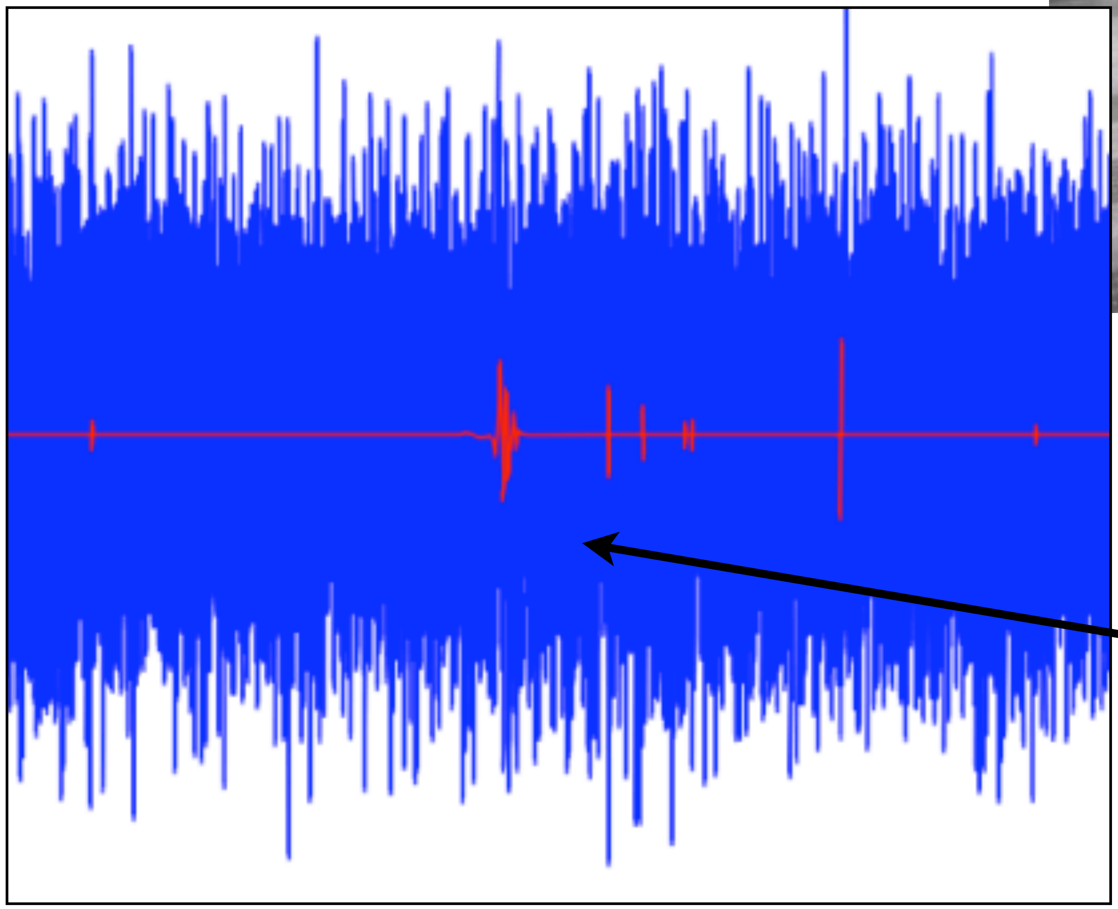
Challenge: Detector Noise

- **Seismic**: ocean waves, plate tectonics, cars, logging, mining,...
- **Thermal**: Brownian motion in suspensions, mirrors, mirror coatings
- **Shot**: photon counting noise



Signals Hidden in Noise

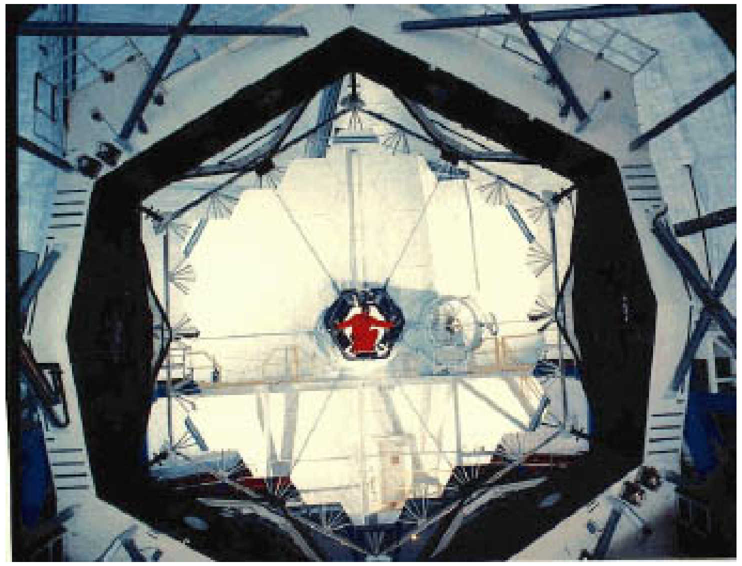
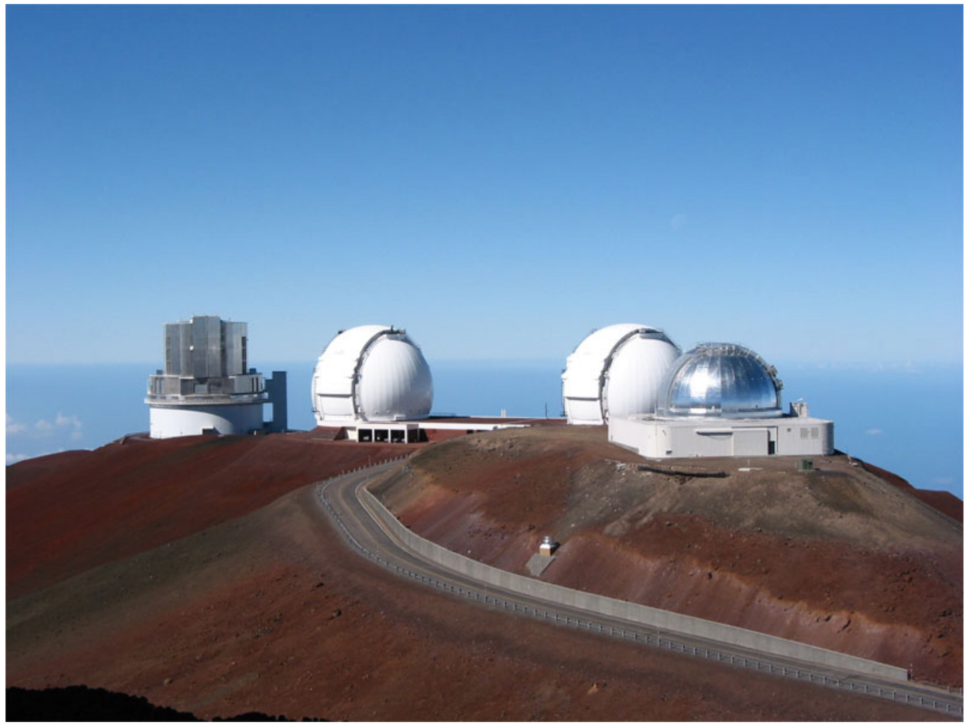




A typical signal (red) is hidden in the detector noise (blue)

Sources, science, search methods

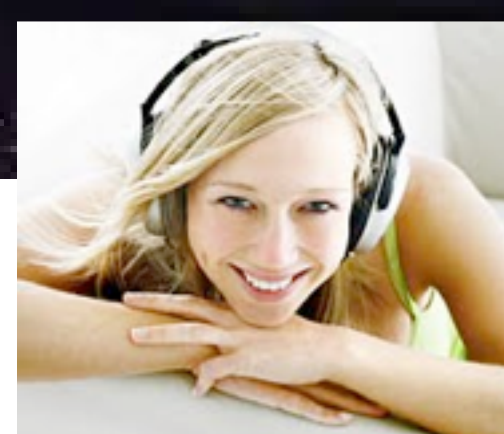



"It doesn't matter how beautiful your theory is, it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong."
Richard P. Feynman

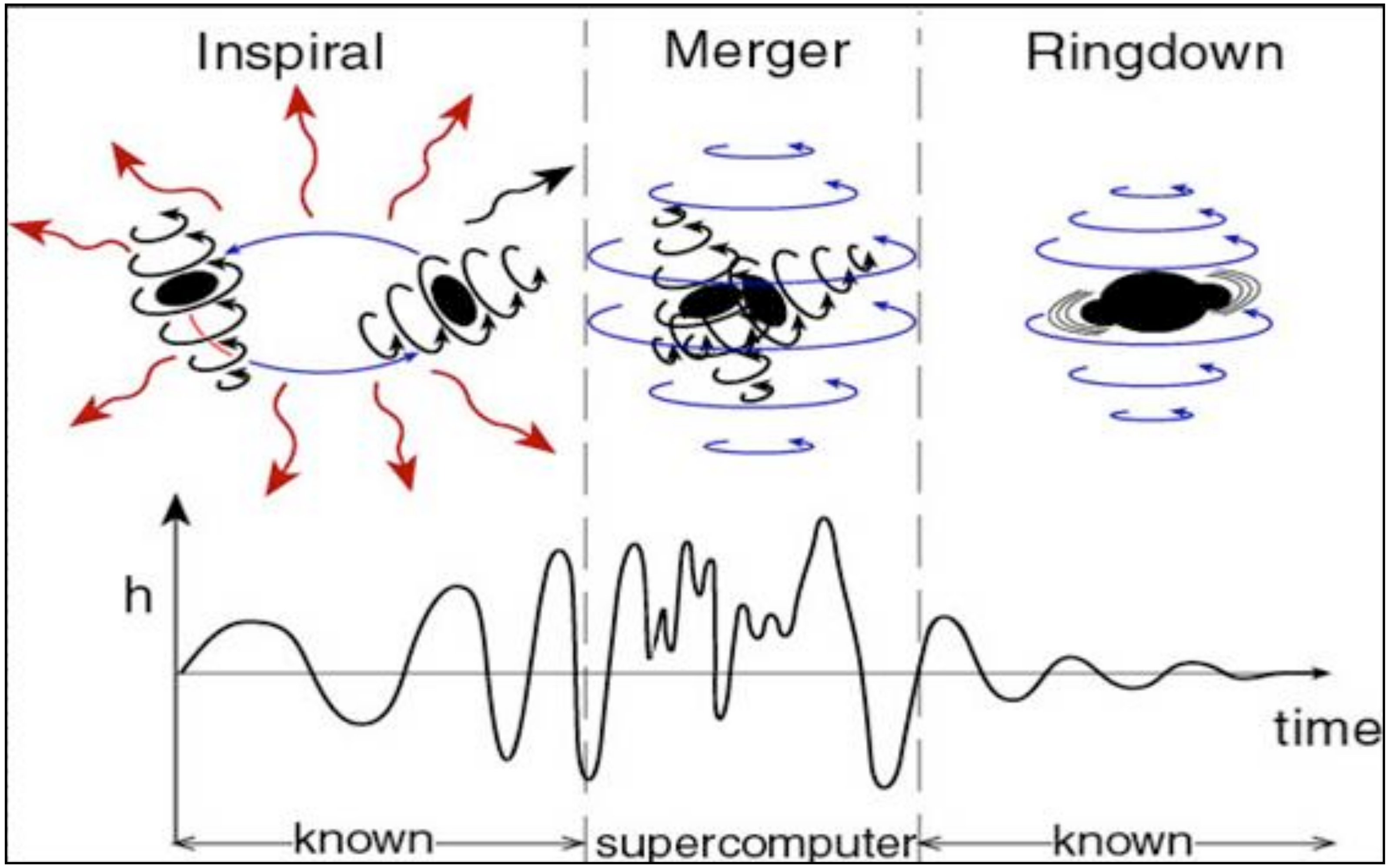
How would Gravitational Waves from Compact Binary Coalescence Sound?

- In 14 Gpc (entire Universe): every five minutes
- Initial LIGO (sees 20 Mpc): one per hundred years
- Advanced LIGO (sees 200 Mpc): ~tens per year



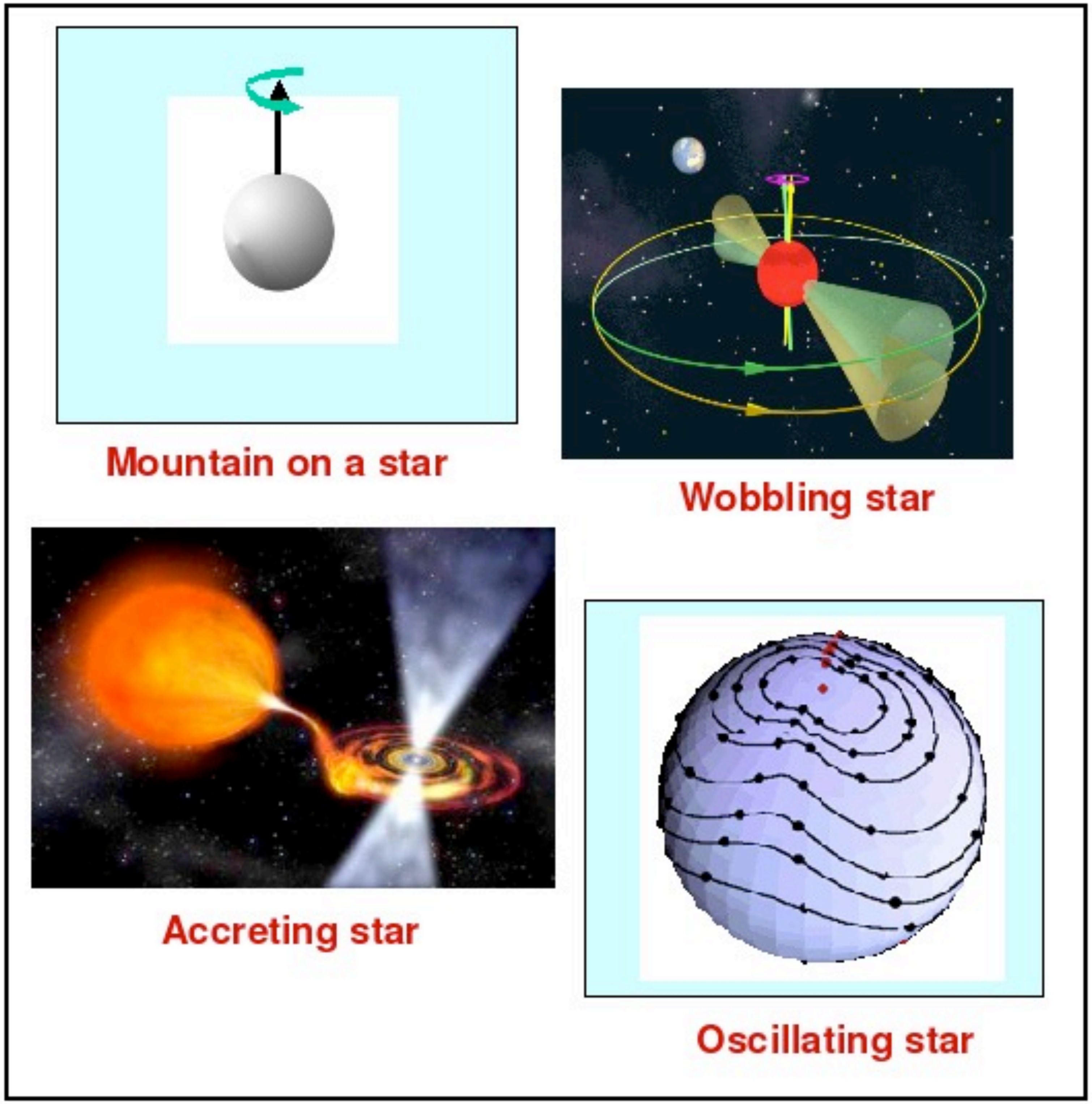
Compact Binary Coalescence

- Gravitational waves from NS/NS, NS/BH, BH/BH
- Data analysis method: matched filtering with carefully picked template bank
- Stringent test of dynamic strong-field gravity.
- Observation of inspiral rate will "calibrate' stellar populations and evolution models
- Likely source of electro-magnetic (EM) counterparts!



Continous Waves from Rapidly Spinning Neutron stars

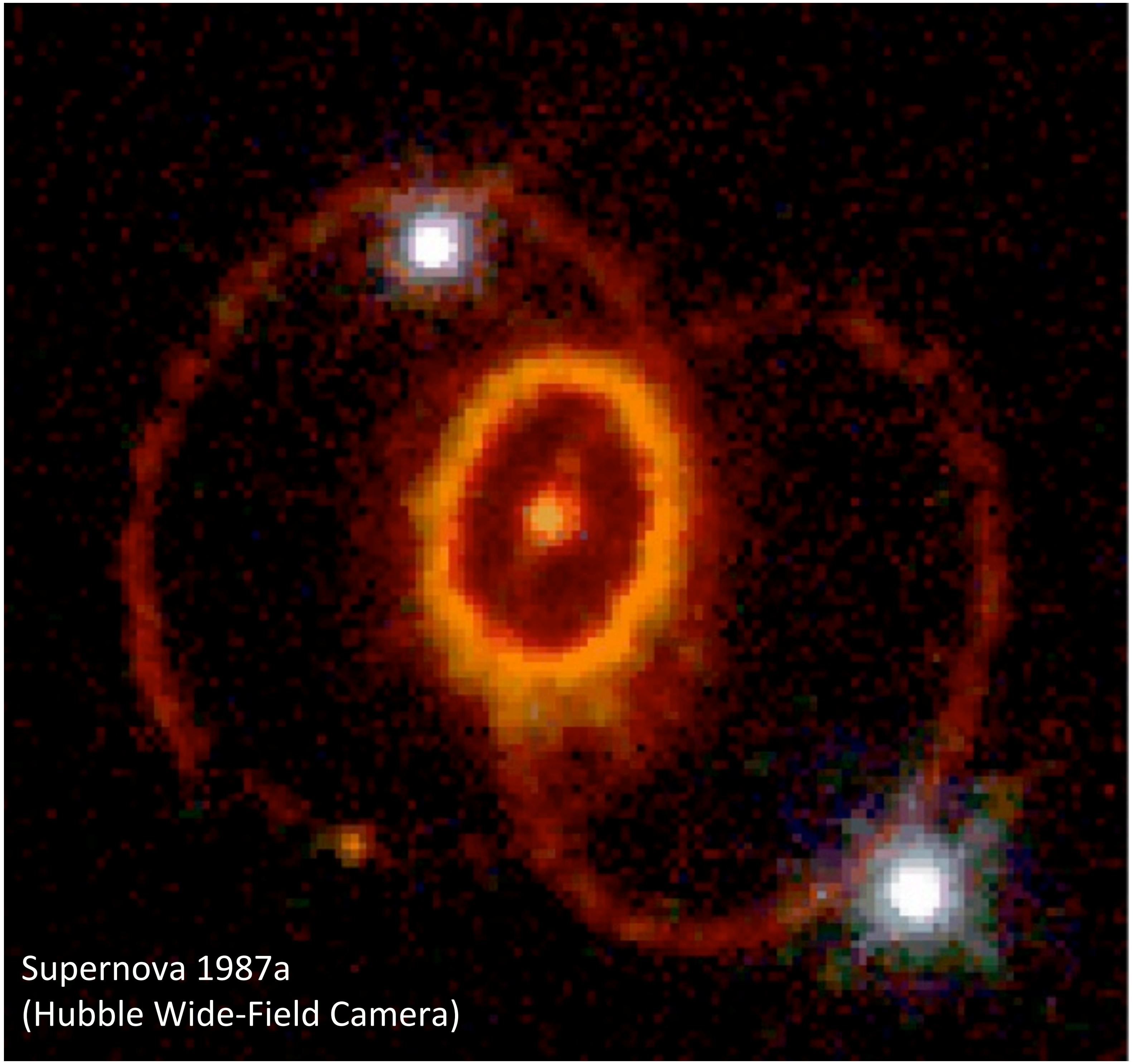
- Continuous emission over time as stars spin down
- Existing LIGO results (*Search for gravitational waves from 116 known pulsars*, ApJ 713, 2010, p671) shows h < 2.3 x 10^{-26} for J1603-7202 (recycled pulsar in binary) and ellipticity ε < 7 x 10^{-8} for J2124-3358 (isolated x-ray pulsar).
  Crab pular: GW energy-loss is less than < 2% of EM energy-loss.
- Blind search is a very difficult data analysis problem (Einstein@Home + new methods)
- Neutron star structure: eccentricity, glitches, equation of state, mechanisms at work in LMXBs



Sources and Science: bursts

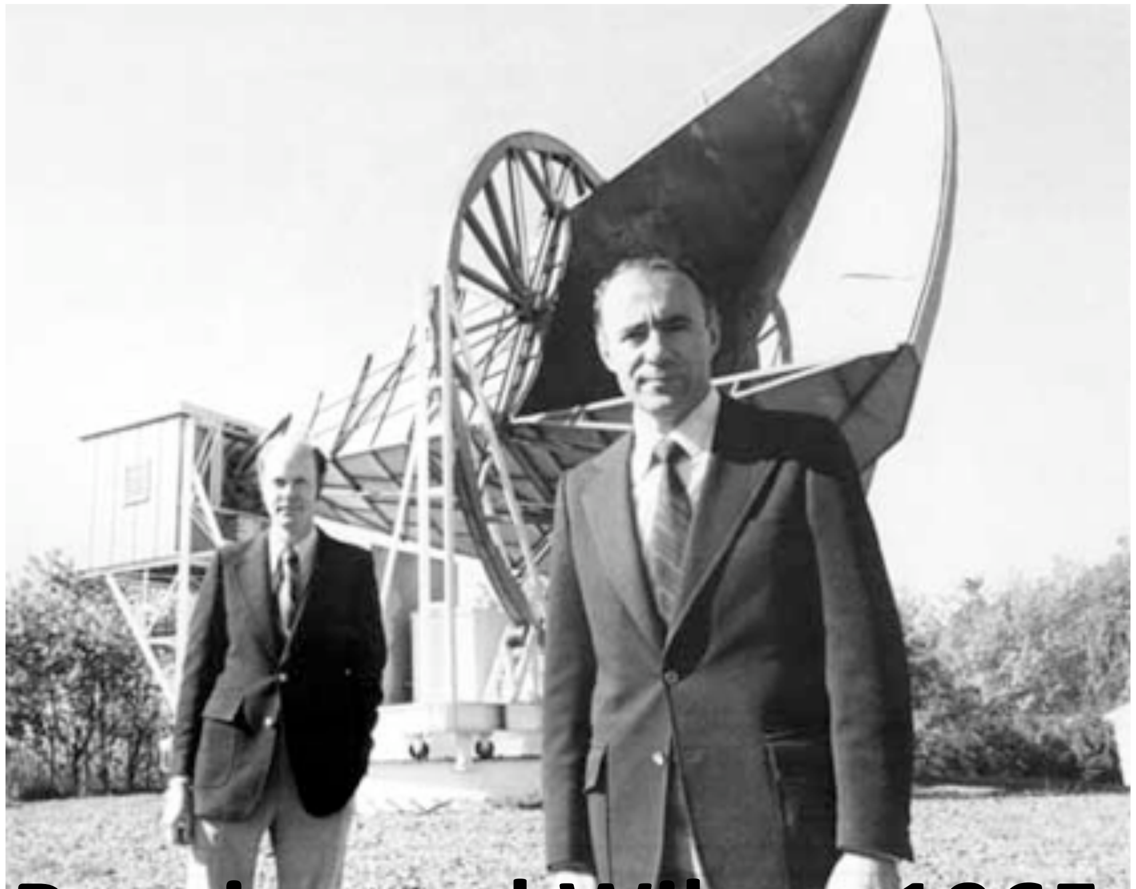
Duration < 1 sec

- Merger of NS/NS and NS/BH binaries
- Collapse of NS to BH
- Galactic core-collapse supernovae (one per 50-100 years)
- NS collapse to BH
- Star-quakes associated with magnetar flares or pulsar glitches
- “Exotic souces”, ie cosmic string cusps

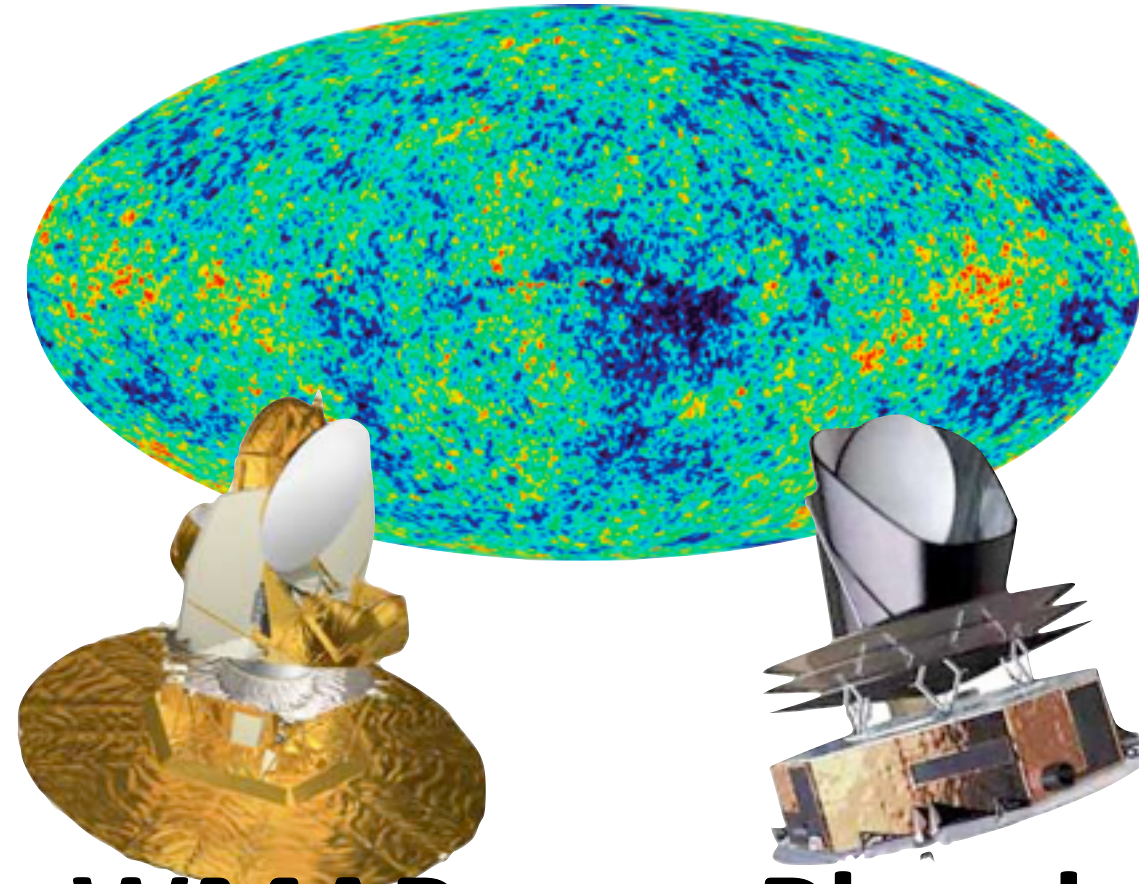


Supernova 1987a
(Hubble Wide-Field Camera)

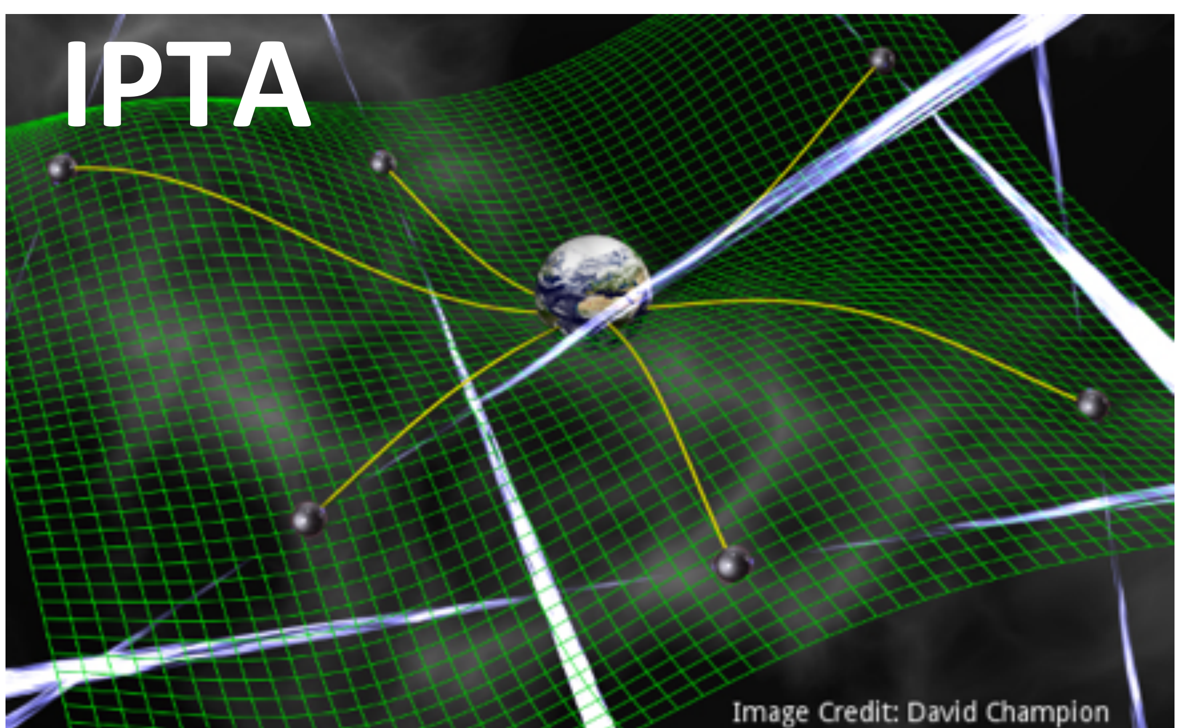
Gravitational Wave Stochastic Background



Penzias and Wilson 1965



WMAP Planck



Science Results To Date

- No gravitational-wave detections so far†
- LIGO Scientific Collaboration, 91 scientific publications, 65 conference proceedings:

`www.lsc-group.phys.uwm.edu/ppcomm/Papers.html`

**†However improved data-analysis methods developed for gravitational-wave searches have discovered more than fifty new radio and gamma-ray pulsars in the past three years:
Allen et al., ApJ 773, 91 (2013); Knispel et al., ApJ, 774, 93 (2013), Pletsch et al. Science 338 (6112), 1314 (2012), ApJ Lett. 755 (1), L20 (2012); ApJ 744 (2), 105 (2012); ApJ Lett. 779 (1), L11 (2013); Knispel et al., ApJ Lett 732 (1), L1 (2011); Science 329 (5997), 1305 (2010).**

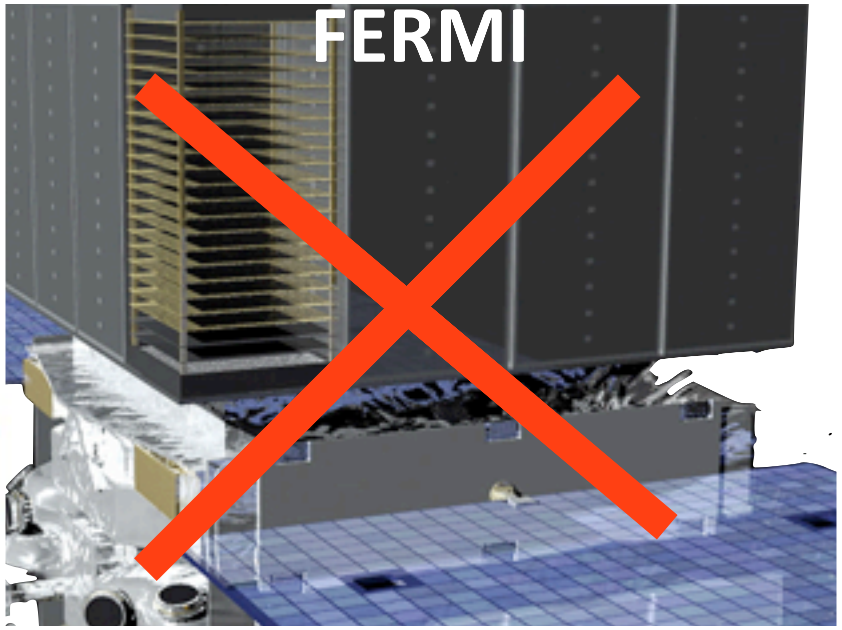
They also play an important role in the Kepler Satellite discovery of new exoplanets: Seader et al., ApJS 206, 25 (2013)

What’s coming: present - 2020

One Gravitational Wave Telescope can't "Point"

CHANDRA

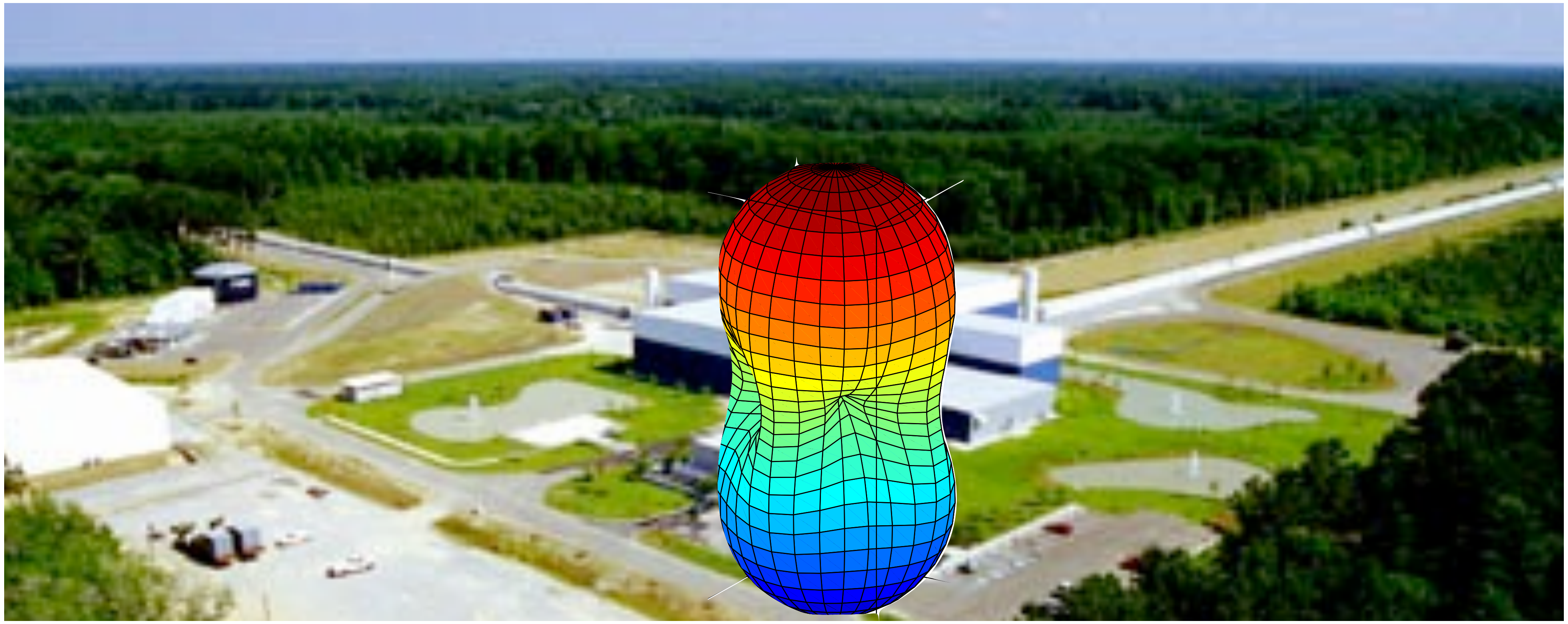
FOV 0.5 deg, PSF 0.5 arcsec



FOV 1/5 of sky PSF 0.8 degree @ 1 GeV

2 arcmin FOV @ 1.4 GHz

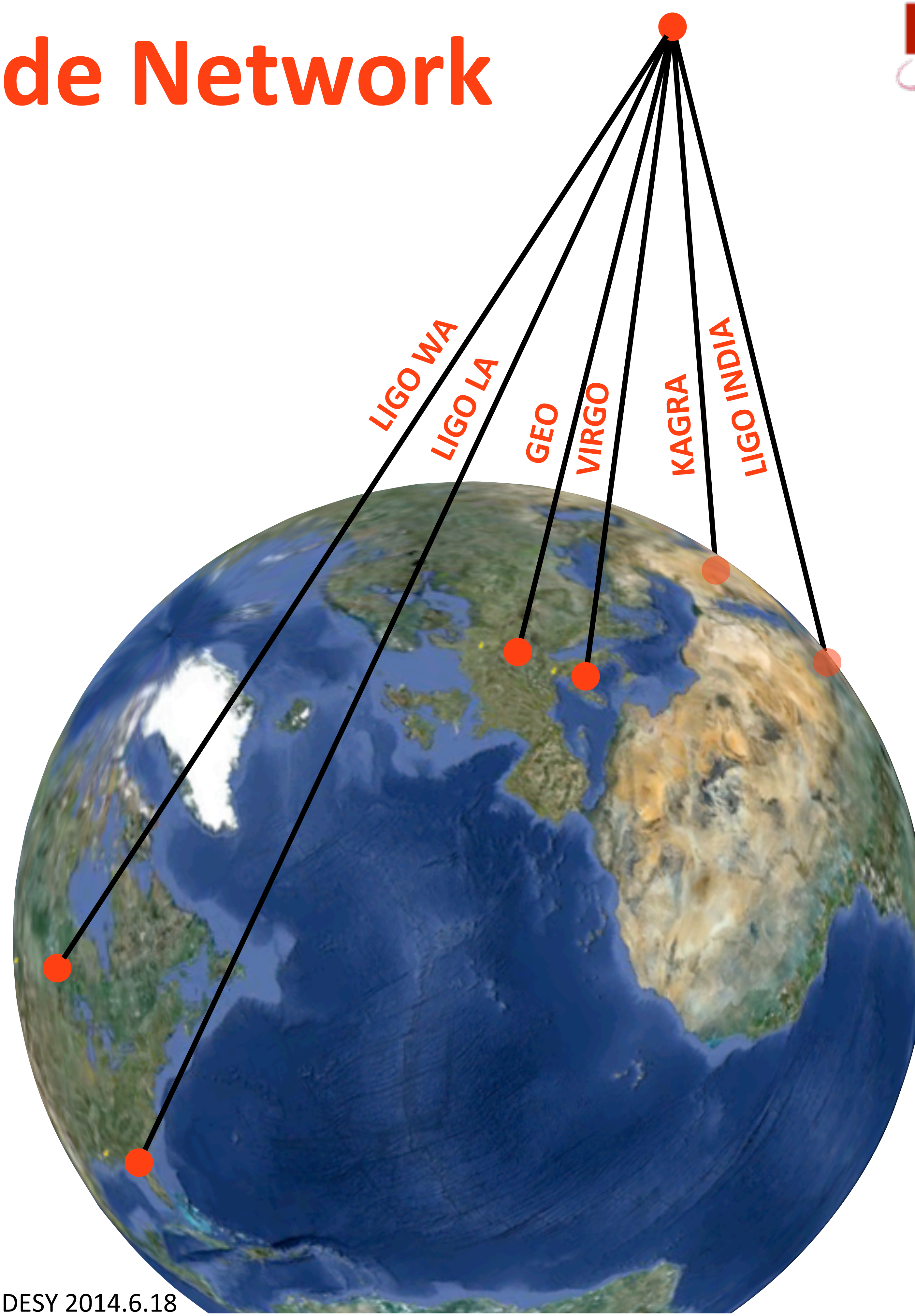
"Antenna pattern" or point-spread function for an interferometric detector covers the entire sky!



FOV entire sky! PSF entire sky!

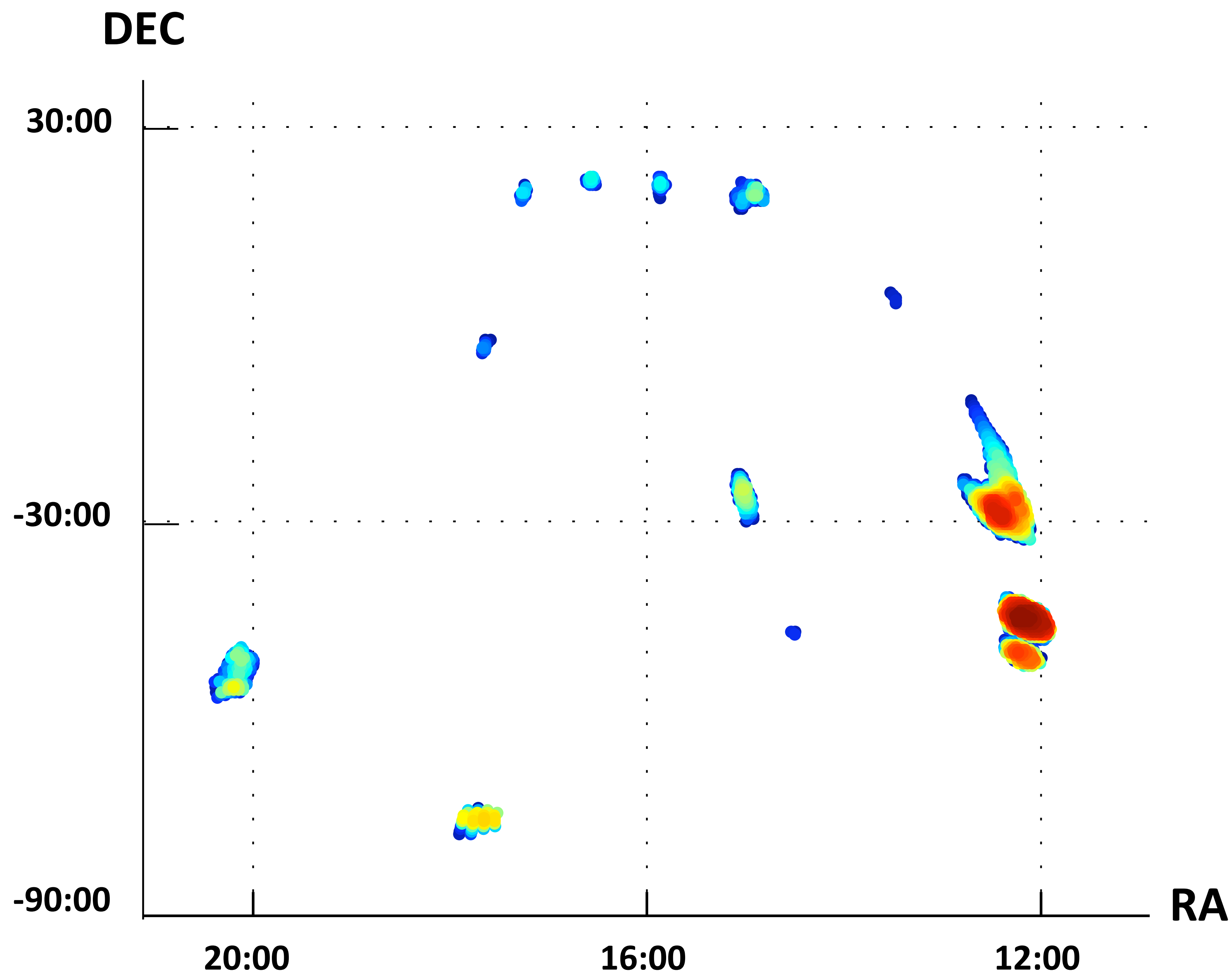
World Wide Network

- Use arrival-time delay of signals to find source location in the sky
- Increase detection confidence, waveform reconstruction
- All experiments (*apart from KAGRA*) have a joint data-sharing agreement.
- Angular error:
  $\Delta\theta \approx c\, \Delta t/R_{earth}$ radians
  Timing error $\Delta t \approx 0.3$ ms
  $\Rightarrow \Delta\theta \approx$ few degrees



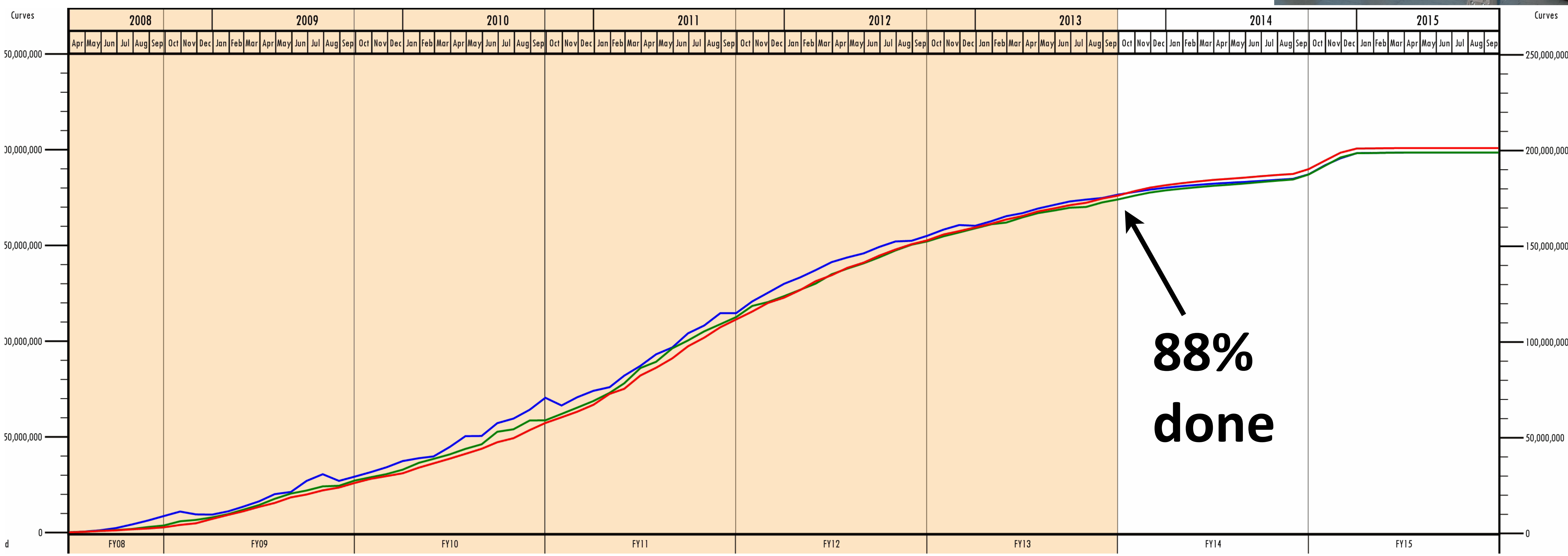
“Point-spread function” messy!

- Triangulation time delays can be uncertain by one or two cycles
- Detectors not sensitive to the same combination of polarizations
- Uncertainty regions are not ellipses, but probability regions



Status in USA and Europe

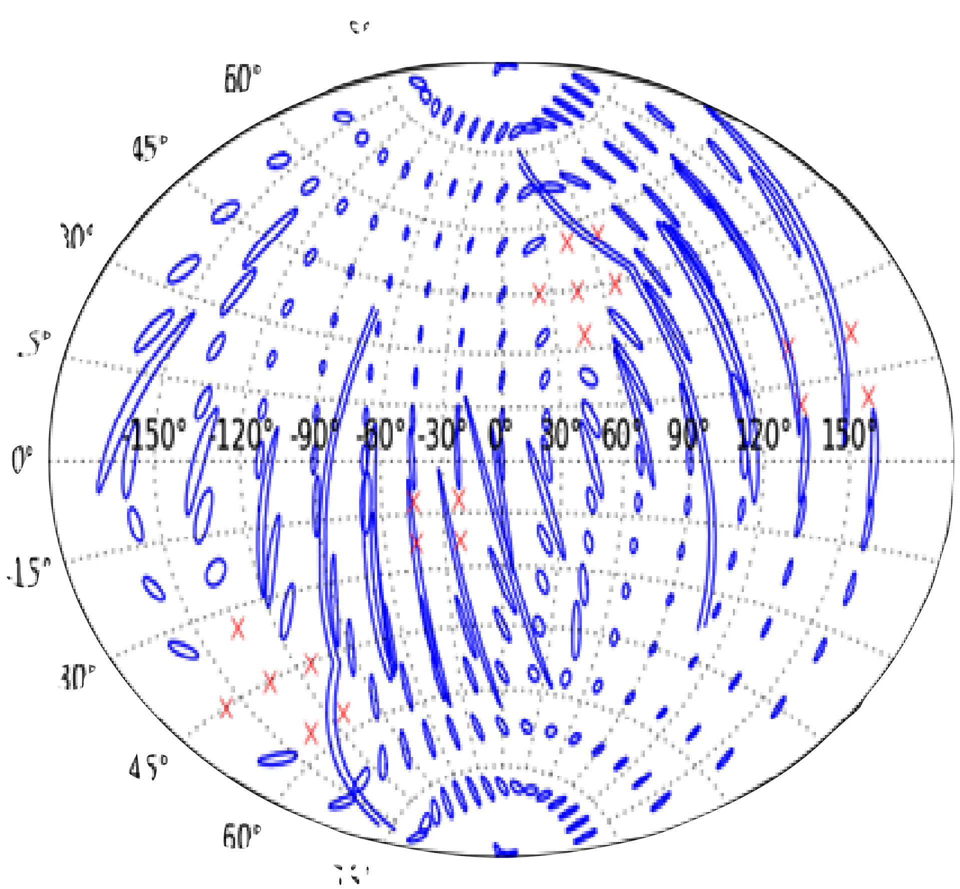
- 2010: the initial LIGO detectors were **decomissioned**
- Advanced LIGO (aLIGO) construction finishing
- Breaking news: Last week the LIGO Livingston Interferometer LOCKED FOR TWO HOURS
- GEO and VIRGO upgrades in progress
- aLIGO Data collection will start in 2015

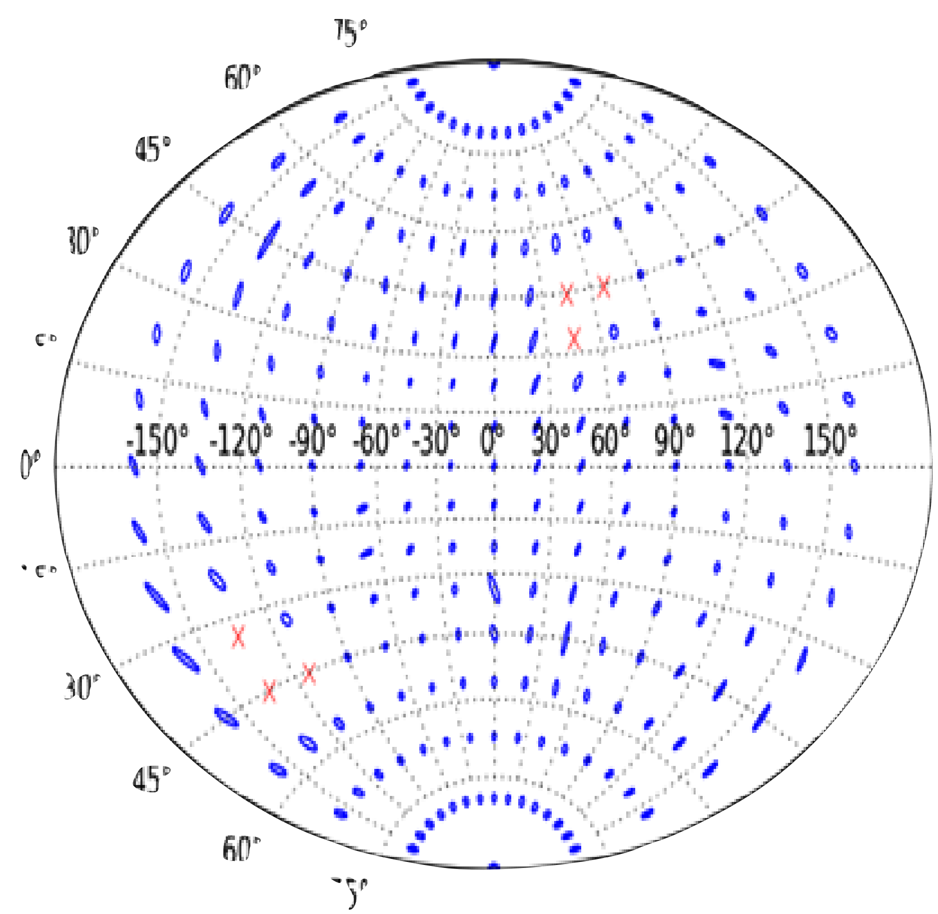


LIGO-India

- US contributes detector
- India contributes the site and the vacuum system
- Location will significantly increase pointing accuracy

LIGO INDIA SCHEDULE
2012-13: Site survey and acquisition; insfrastructure preparation
2014-17: Fabrication of spiral welded tubes and UHV components
2016-18: Detector assembly, integration, tests and validation
2018-19: Detector operation and tuning to design sensitivity
2019 and onwards: Science runs and operation; GW astronomy





Expected First Detection

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{re}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{high}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{max}}\ \mathrm{yr}^{-1}$
	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
Initial	BH–BH	2×10^{-4}	0.007	0.5	
	IMRI into IMBH			<0.001[b]	0.01[c]
	IMBH-IMBH			10^{-4}[d]	10^{-3}[e]
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	
	IMRI into IMBH			10[b]	300[c]
	IMBH-IMBH			0.1[d]	1[e]

J Abadie et al, Class. Quantum Grav. 27 173001 (2010)

Expected rates: one event per week!

Expected First Detection

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200
2022+ (India)	(per year)	105	80	200	130	0.4 – 400

Expectations, including uncertainties from both NS-NS inspiral rate, and rate of commissioning and improvement of instruments, from LSC, arXiv:1304.0670

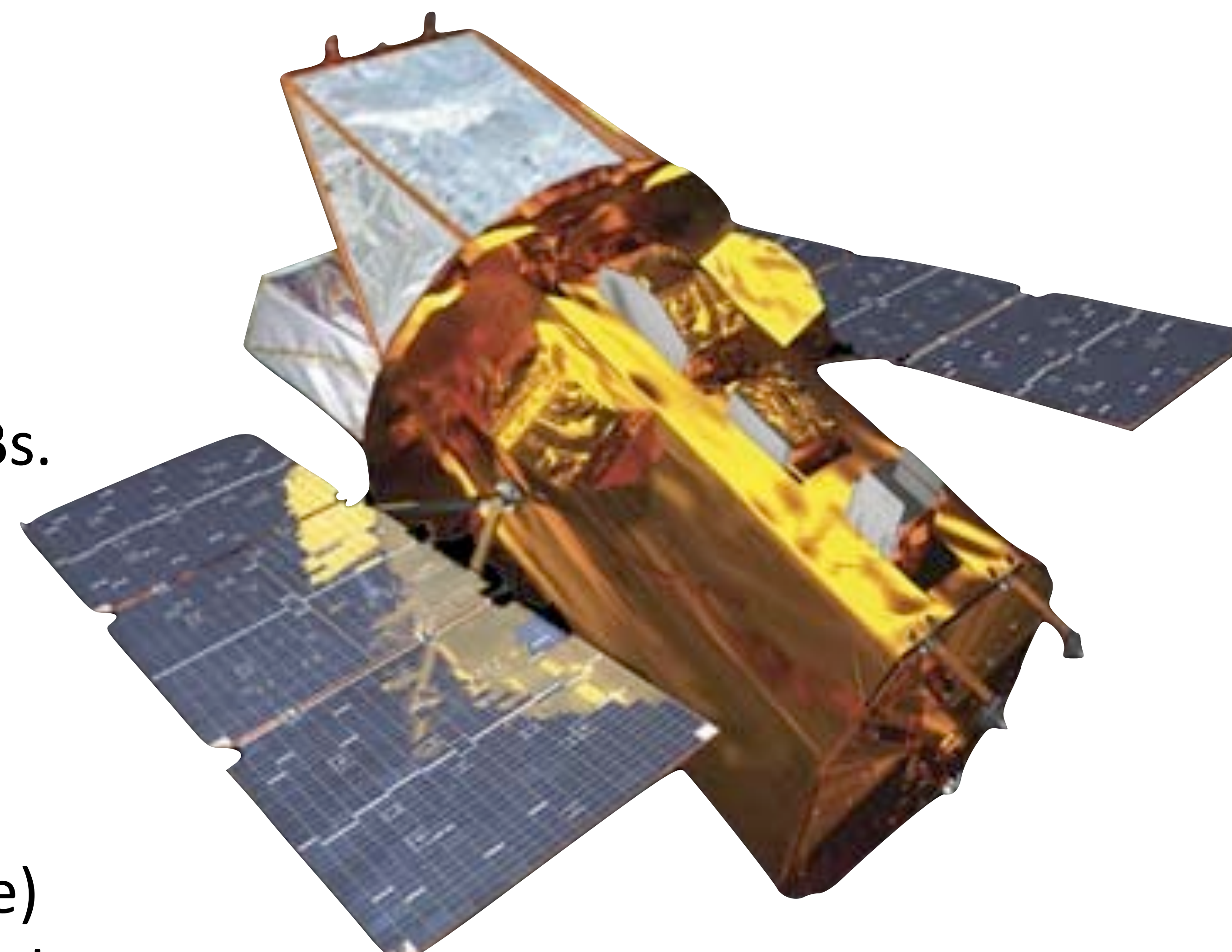
Gravitational Waves
and
Transient Astronomy

Combining Electromagnetic, Neutrino and Gravitational-Wave Observations

- "Triggers": long and short GRBs, magnetar flares (SGRs and AXPs), radio pulsar glitches, high and low energy neutrinos events, radio transients ...
- Reducing the size of "search space" with these triggers increases the strain sensitivity of a GW search by ~2 compared with an all-sky / all-time search. Makes sense since GW detector "sees the whole sky".
- Pointing EM instruments on GW triggers would be useful to "dig into the GW noise", for follow-up studies, and to increase confidence (full light curve for SN or GRB).
  But: GW error boxes are tens to hundreds of square degrees.
- **Politics**: before the first few published GW detections, the LIGO Scientific Collaboration will not openly distribute events or data. Interested astronomy partners can collaborate via a simple "boilerplate" MOU.

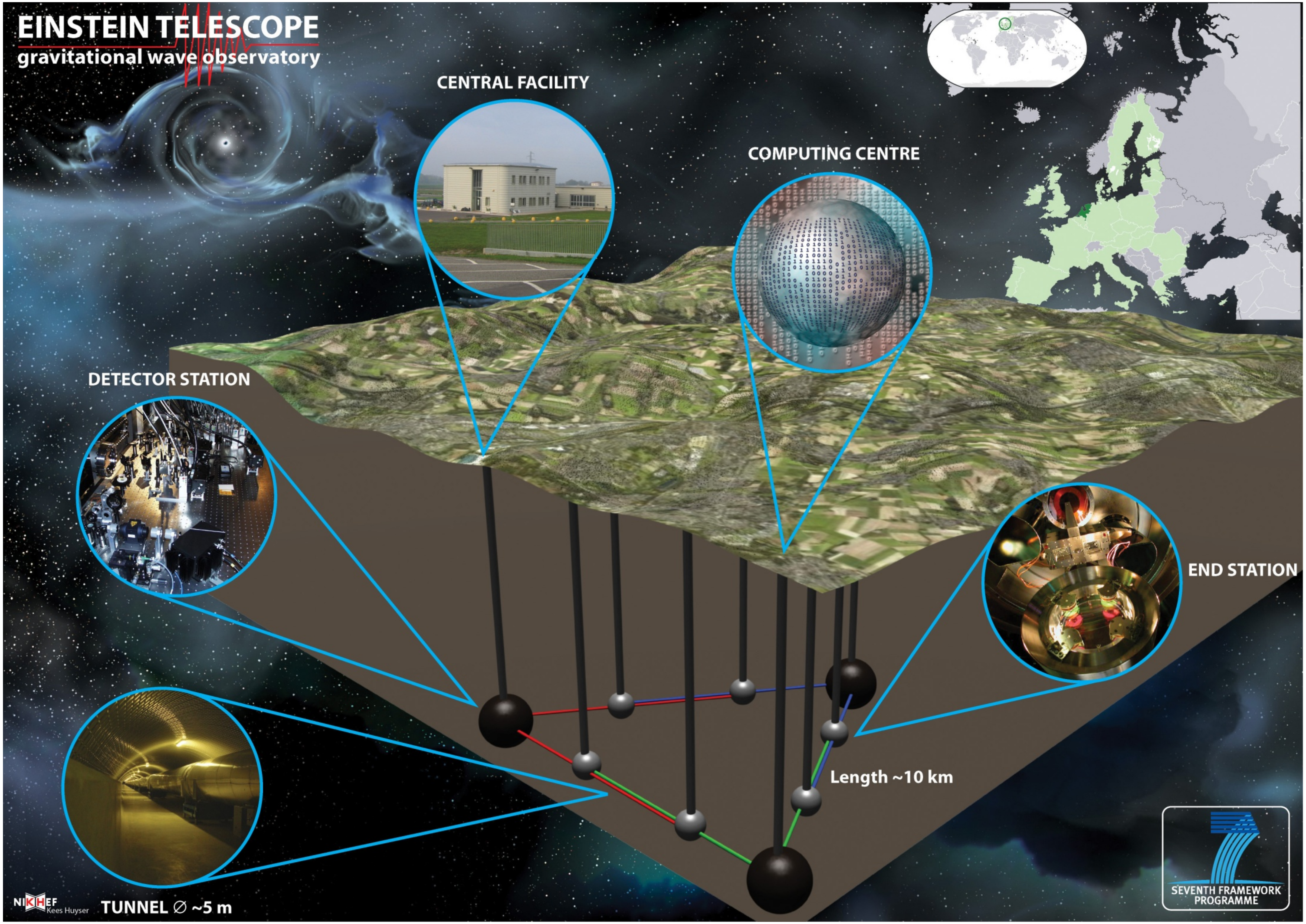
Short Gamma Ray Bursts

- Short GRBs probably result from NS/NS or NS/BH coalesence (Nakar, Phys. Rept. 442: 166-236, 2007).
- Numerical work (Rezzolla et al. Astrophys. J. 732, L6, 2011) has shown that NS merger produces jet-like structures which could power short GRBs.
- With reasonable assumptions, might observe ~1 coincident GW-GRB event from a NS/BH system every three years (Metzger & Berger, ApJ., 746, 48, 2012)
- Optical counterparts (few day time-scale) might also be possible (Nissanke, Kasliwal et al., ApJ, 767, 124 (2013))



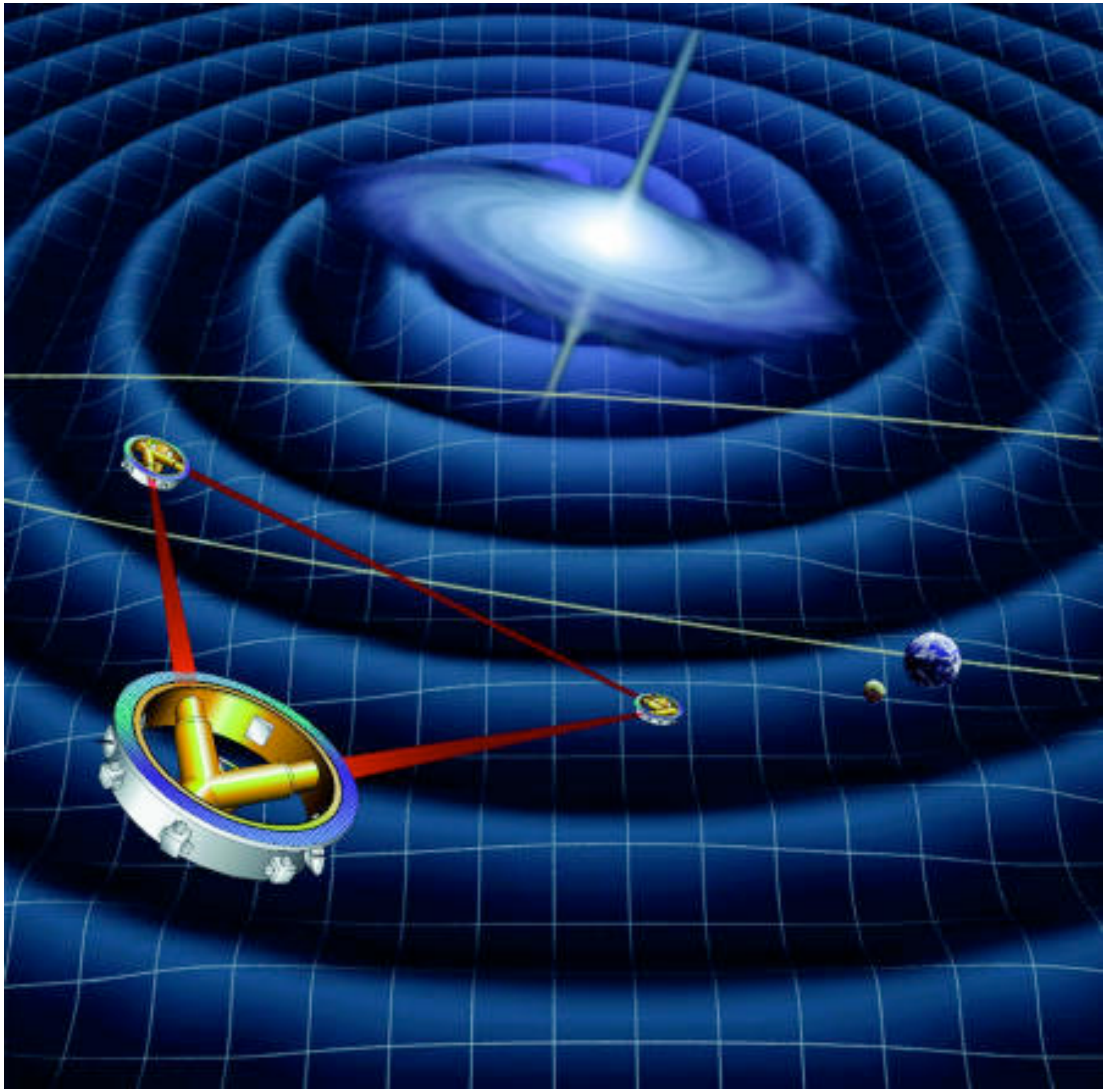
The Future:
2025 -2035

Einstein Telescope



Laser Interferometer Space Antenna (LISA)

- Third ESA “large” mission: L3, launch 2036
- 3 spacecraft, ~Gm arms
- Band: 0.1 - 100 mHz
- Detect inspiral signals from thousands of binaries (NS, BH, WD) in our galaxy
- LISA Pathfinder technology demonstrator will launch in July 2015

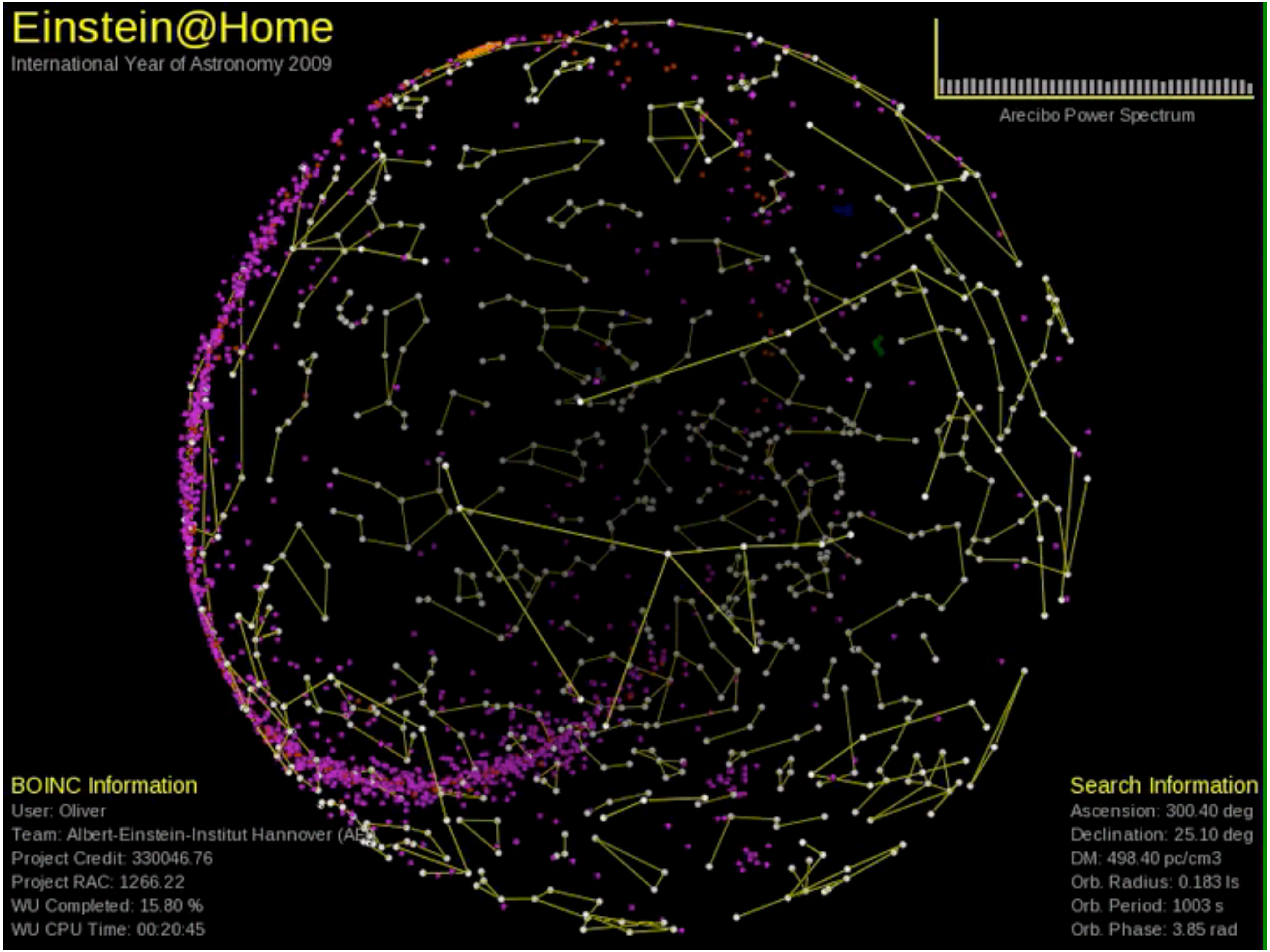


Conclusions

- By the end of the decade, the LIGO-VIRGO-GEO network should make its first GW detections, arXiv: 1304.0670
- Most likely GW sources: compact binary coalescence of NS and/or BH systems. Also interesting target for potential simultaneous gamma-ray burst observations and optical follow-up
- GW pointing precision: tens to hundreds of square degrees
- Longer term prediction: X-ray astronomy went from first cosmic detections to the Chandra telescope in 40 years. GW astronomy will proceed at a similar rate after first detections.

THANK YOU!

To help us to find gravitational waves, please sign up your home and office computers to Einstein@Home

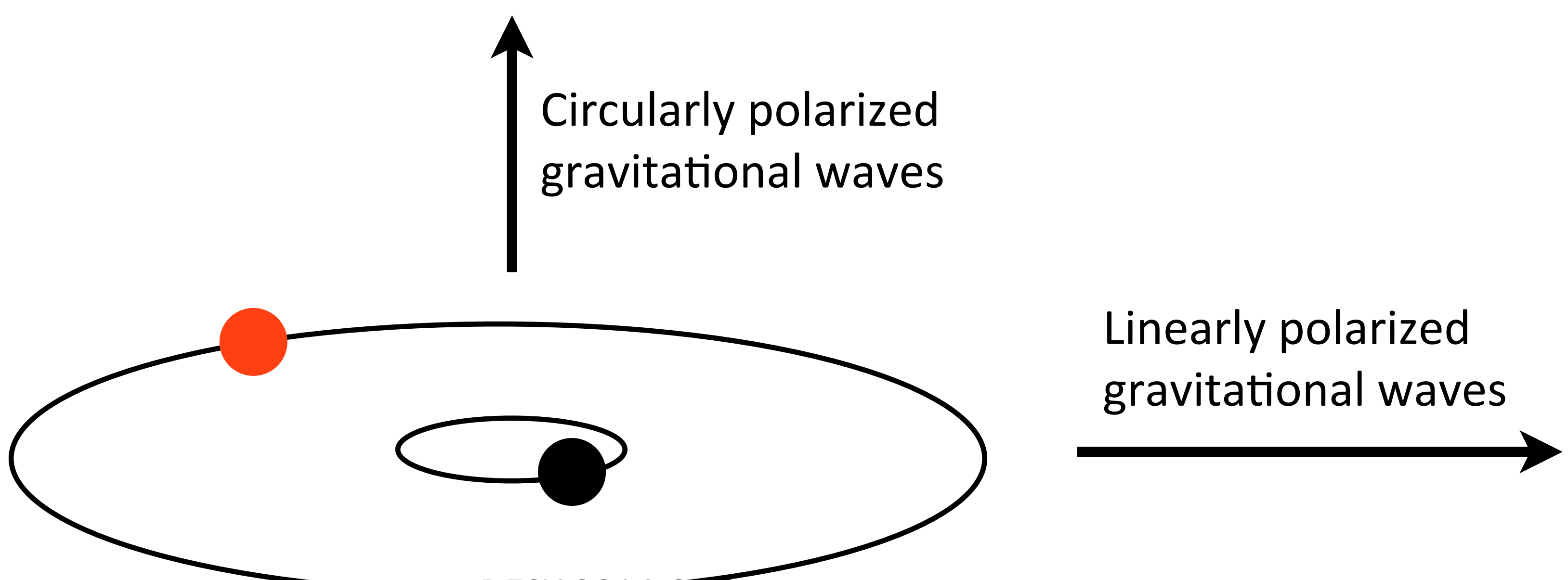


Advanced Detectors

	Initial LIGO	Advanced LIGO	Advanced VIRGO	KaGra/LCGT	GEO-HF	LIGO -India
Length	2 x 4 km + 1 x 2 km	2 x 4 km + ~~1 x 4 km~~	3 km	3 km	0.6 km	1 x 4 km (from Ad LIGO)
Suspensions	Steel wires	Silica fibers	Silica fibers	Sapphire @ 16K	Silica fibers	Copy of Advanced LIGO
Laser power	10 W	180 W	200W	100 W	30W -> 180W	
Circulating power	30 kW	830 kW		300 kW	30kW	
Mirror masses	11 kg	40 kg	40 kg	30kg Sapphire @ 20K	10 kg	
Seismic isolation system	Passive	Active servo	Active servo	Passive under mountain	Passive	
Topology	Power recycled Fabry-Perot	+ Tunable signal recycling	+ Tunable signal recycling	Fabry-Perot + signal recyling	+ Tunable signal recycled Michelson	
Squeezed light	No	Perhaps	Perhaps	Perhaps	Yes	
NS/NS Inspiral reach	20 Mpc	200 Mpc	“comparable”	180 Mpc	NA: this is a high frequency detector	
Extended data collection	11.05-10.07	2014-	2014-	2017	2010- (incremental)	2019

Short GRBs and Gravitational Waves in Advanced LIGO

- Complicated to estimate the probability of observing a coincident short GRB / binary inspiral with aLIGO
  - Typical short GRBs are at comological (Gpc) distances, so low number statistics at low redshift.
  - The gamma ray jet is probably orthogonal to the orbital plane of the inspiral. Inspirals with such orientations are observable to larger distances than "edge-on" inspirals, since circularly polarized gravitational waves are more likely to have good "overlap" with the detector antenna pattern
  - NS-BH inspirals are observable to greater distances than NS-NS inspirals, but rates less certain.
  - We don't know the GRB opening angles (probably in the range 10-30 degrees)
-



LSC Science Runs: Analyzing Detector Noise

The LIGO, VIRGO and GEO Instruments have collected and analyzed more than a year of triple-coincident data. Science runs:

S1 - 17 days, 2002

S2 - 62 days, 2003

S3 - 70 days, 2003-2004

S4 - 30 days, 2005

S5 - 694 days, 2005-2007

S6 - 468 days, 2009-2010

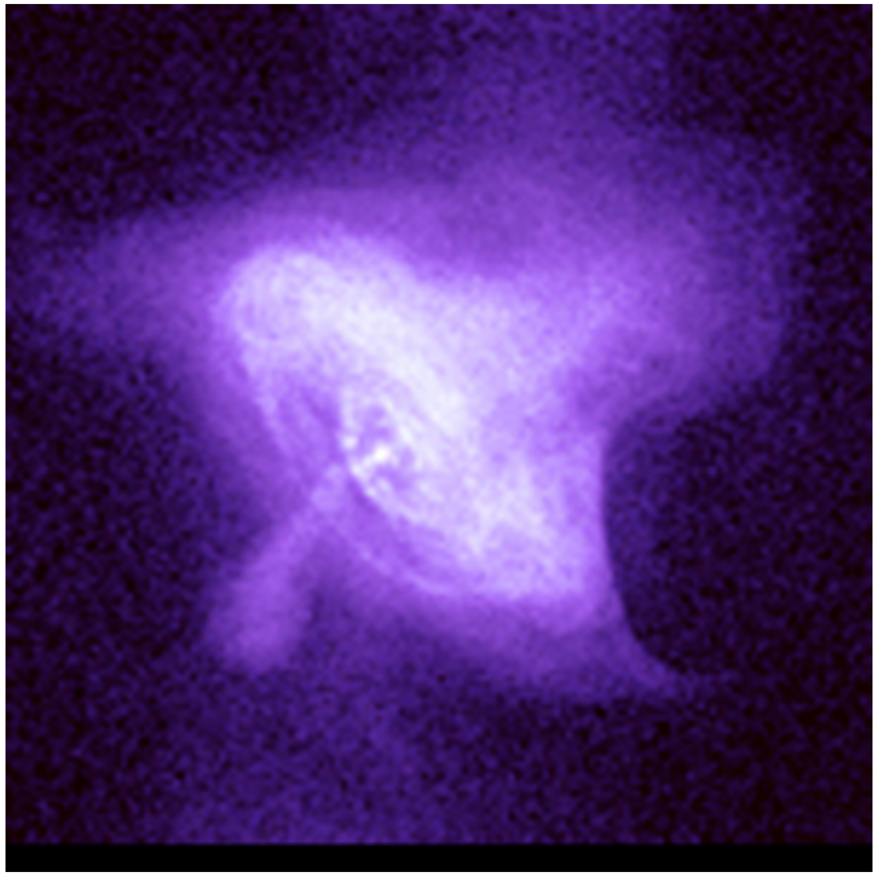
So far, the LIGO Scientific Collaboration has **published about 50 scientific journal papers**, and **detected exactly 0 signals**. Nevertheless some interesting results.

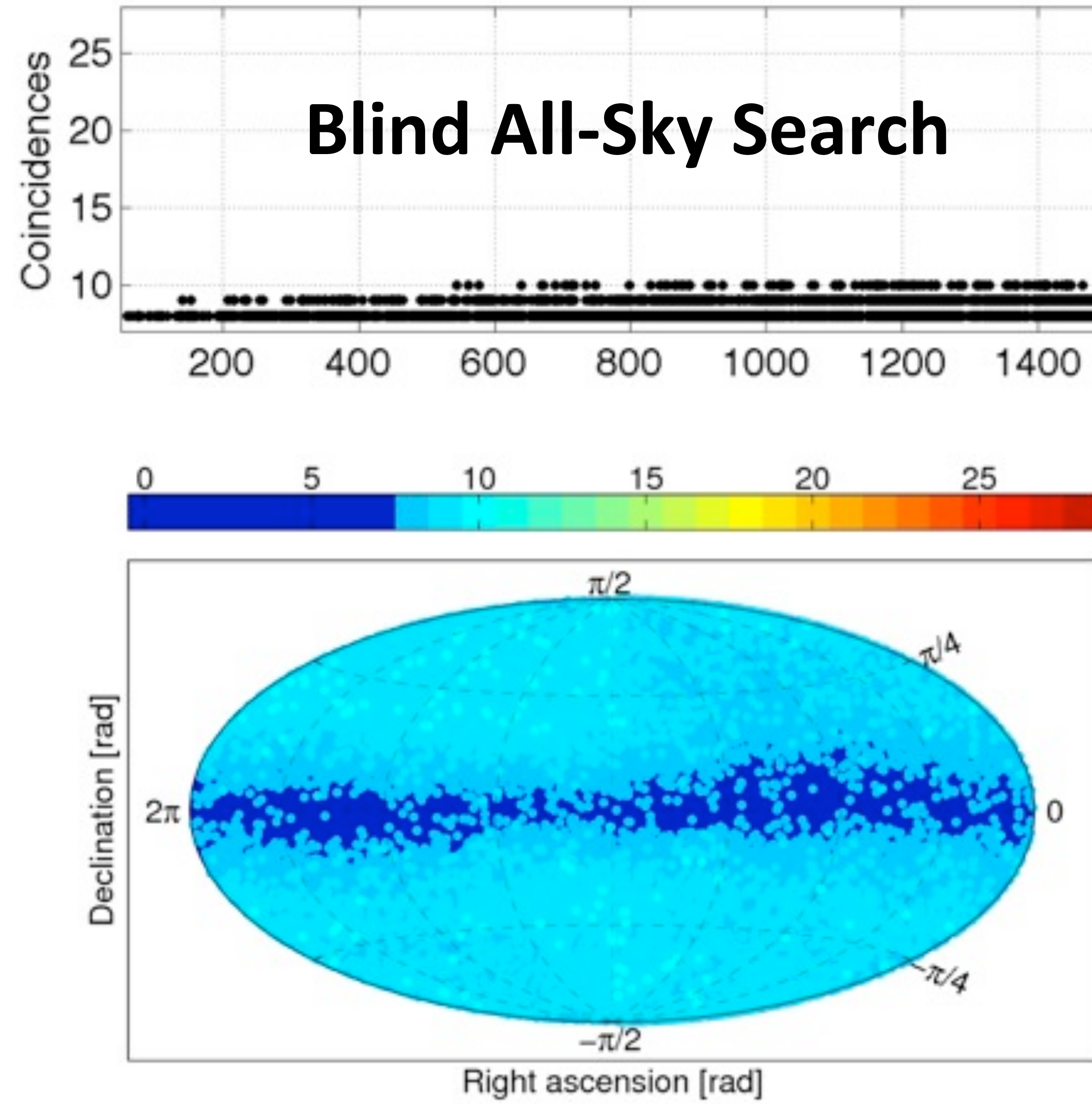
Analyzing Detector Noise

Stochastic Background (**Nature 460, 2009, p990**) correlating LIGO L1/H1 gives a limit $\Omega_{gw} < 6.9 \times 10^{-6}$ for 40 - 170Hz.

Beats the best existing limit ($\Omega_{gw} < 1.1 \times 10^{-5}$ from Big Bang Nucleosynthesis).

Analyzing Detector Noise





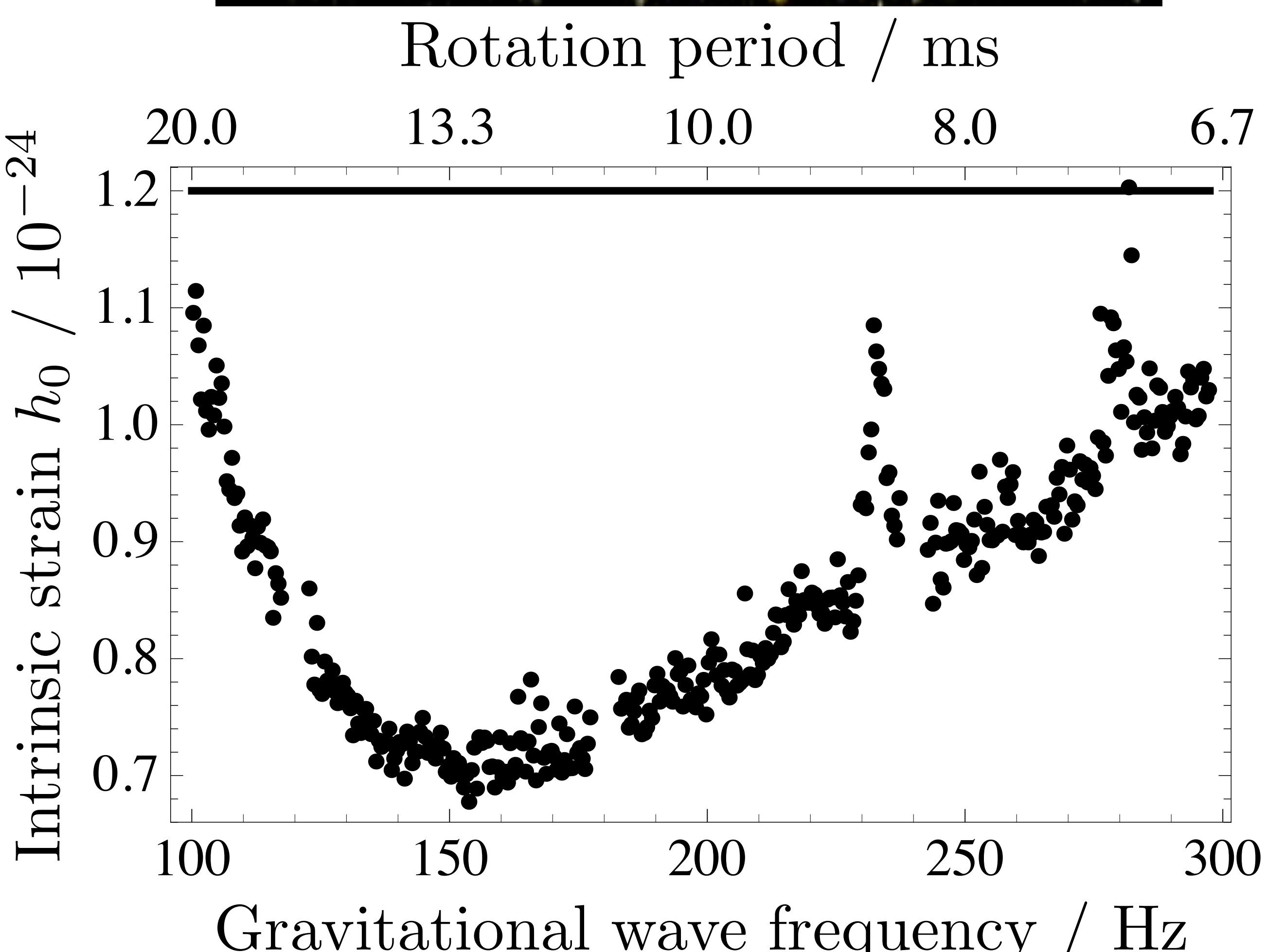
- Crab Pulsar (**Ap J. Lett 683, 2009, L45**) less than 4-6% of the energy-loss from spin-down is going into gravitational waves.
- Search for gravitational waves from 116 known pulsars (**Astrophys. J. 713, 2010, p671**) shows < 2.3 x 10^{-26} for J1603-7202 and ε < 7 x 10^{-8} for J2124-3358. **Crab pular**: GW energy-loss is less than < 2% of EM energy-loss.

Phys. Rev. D80, 042003 (2009)

Final result: no statistically significant candidate

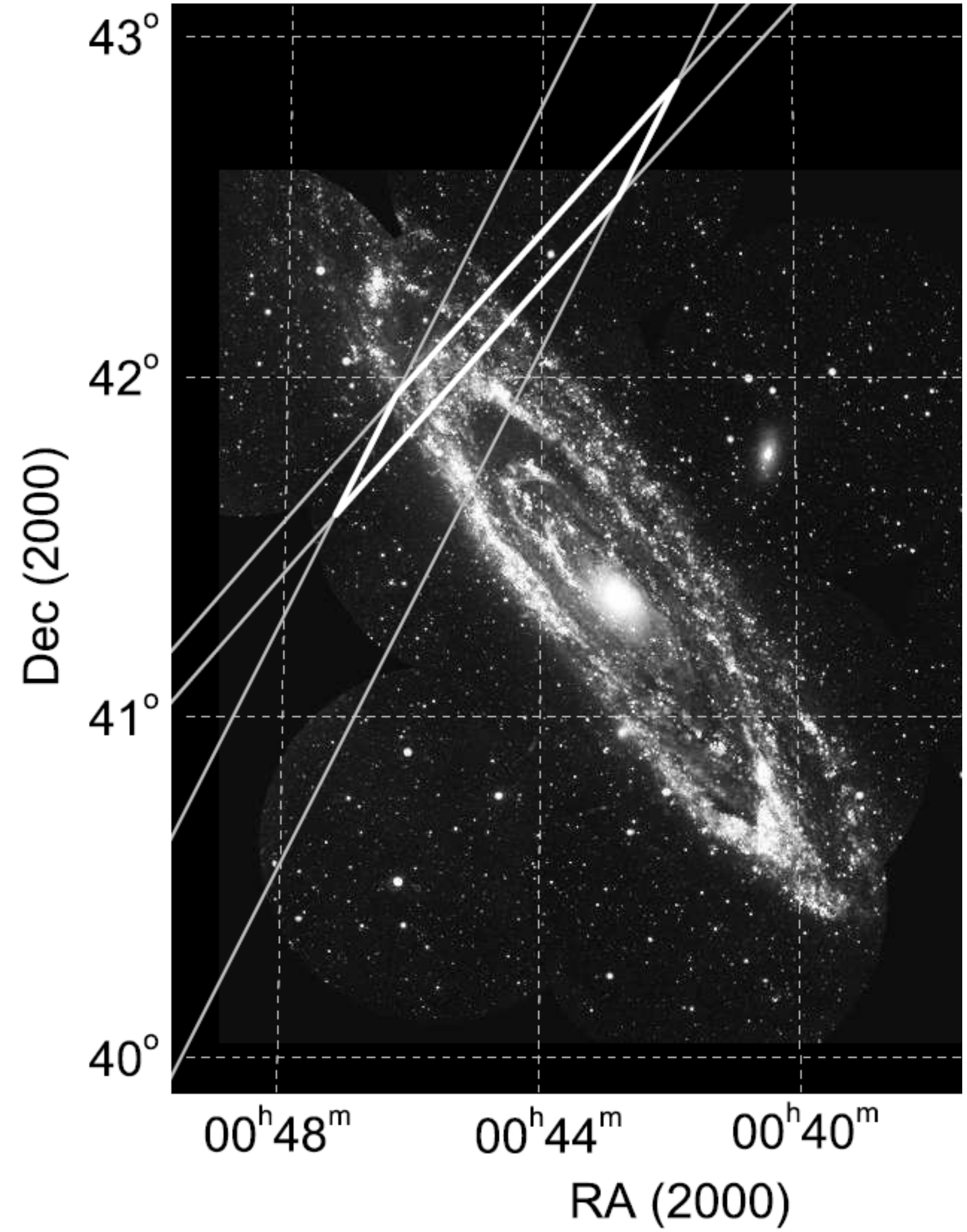
Search for GWs from the youngest neutron star

- A directed search for continuous gravitational waves from the brightest radio source in the sky, the supernova remenant Casseopeia A (Cass A) which contains the youngest-known neutron star (born 1681 ± 19).
- Beats "inferred" spin-down limit
- **J. Abadie et al., ApJ 722 (2010) 1504.**



Analyzing Detector Noise

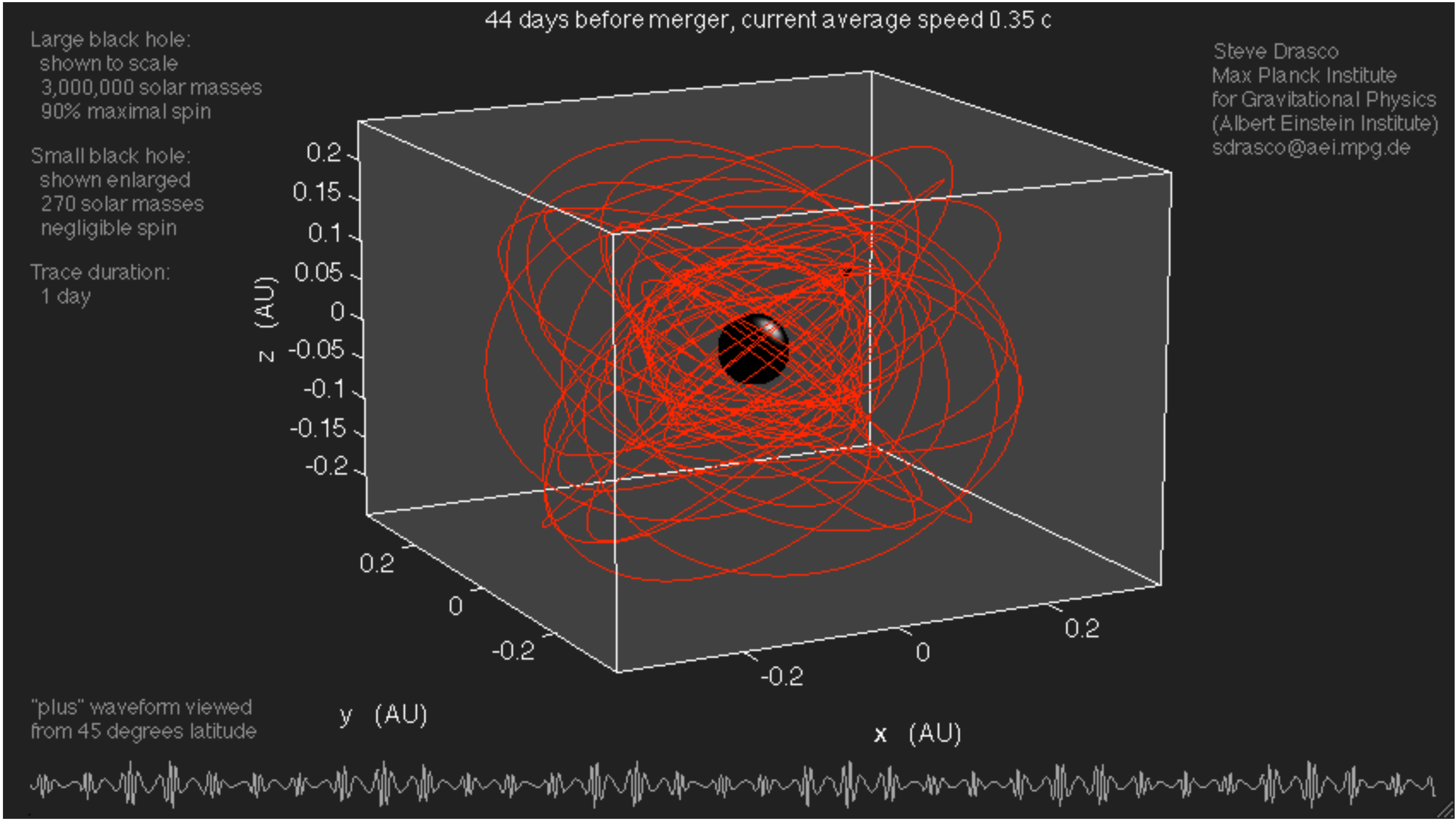
- **GRB 070201** (short, hard gamma-ray burst) **was NOT a binary inspiral in M31 (ApJ 681, 2008, p1419)**.
  Most likely an SGR giant flare in M31.



Inter-Planetary Network
3-sigma error region from Mazets et al., ApJ 680, 2008, p545

15 Year Future: Einstein Telescope (ET)

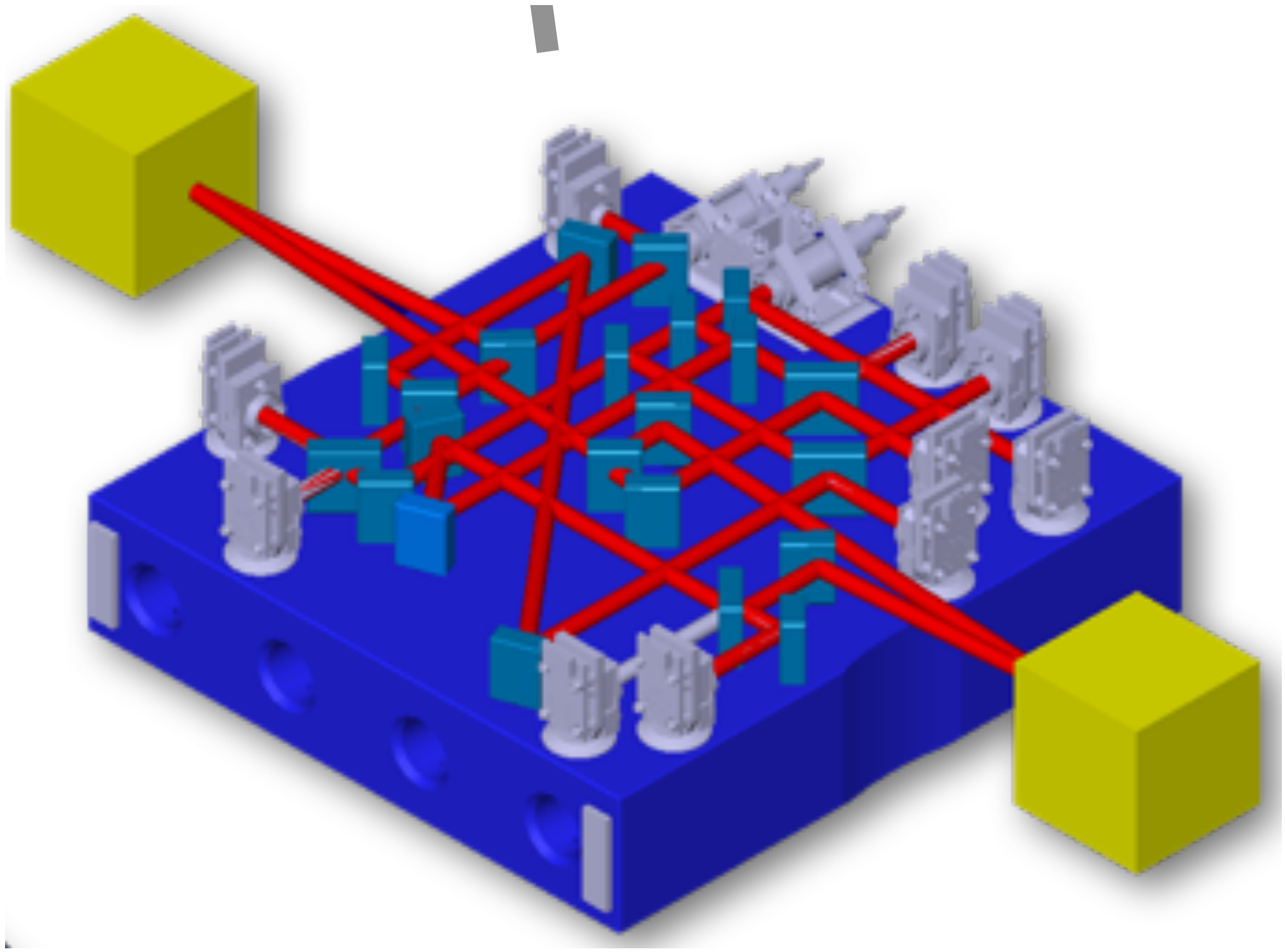
- European project, in a design study phase, 3rd generation
- Additional order-of-magnitude sensitivity beyond Advanced LIGO/VIRGO/LGCT/GEO-HF
- Triangular configuration: underground and/or under-mountain
- Sensitive from 1 Hz to few kHz
- Will see all NS/NS coalescences to z=2, BH/BH to z=8 (10^6 per year, one every 30 seconds).
  - High-precision cosmography
  - Mass spectrum of compact stars
  - Accurate determination of the equation of state of neutron stars

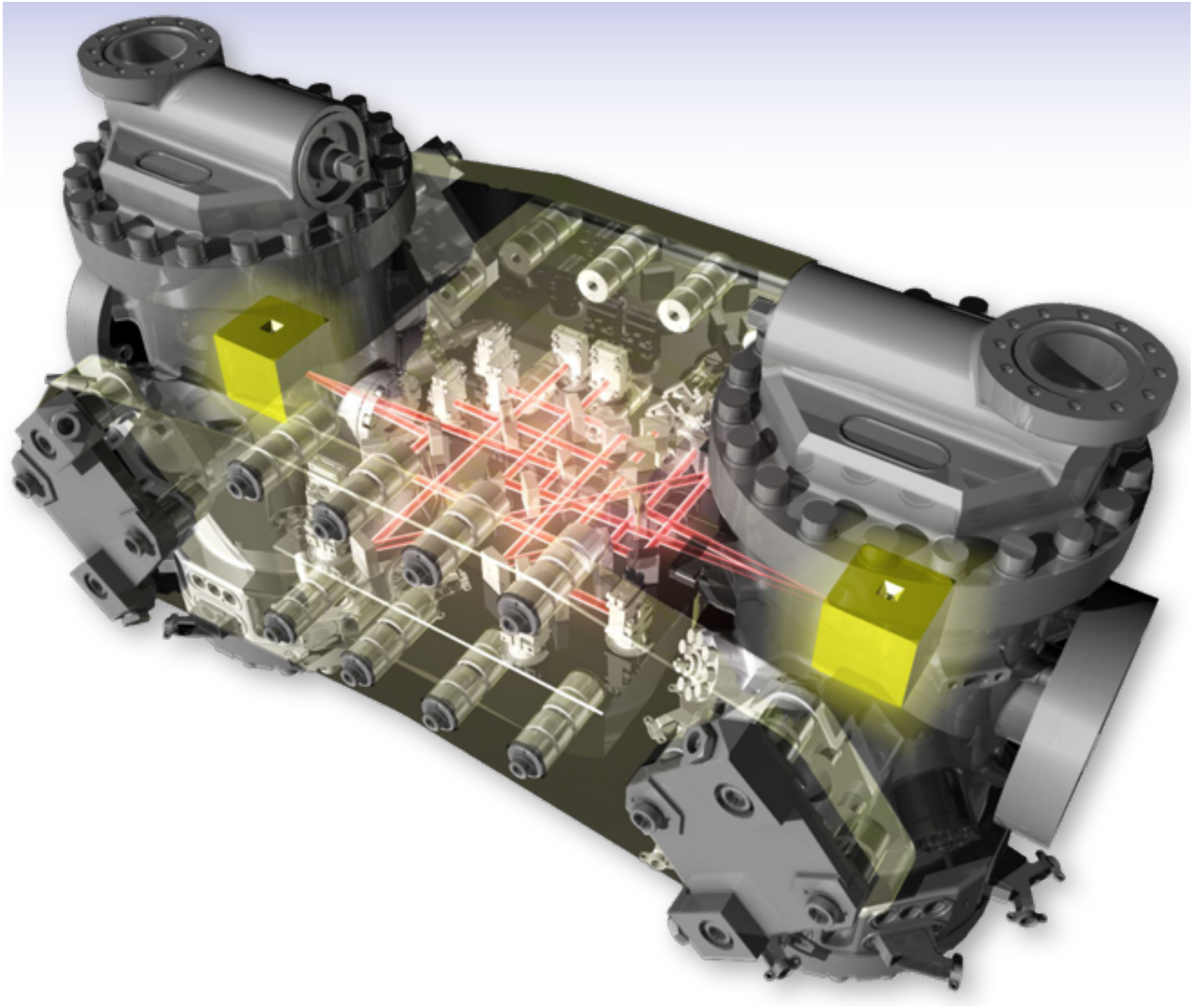


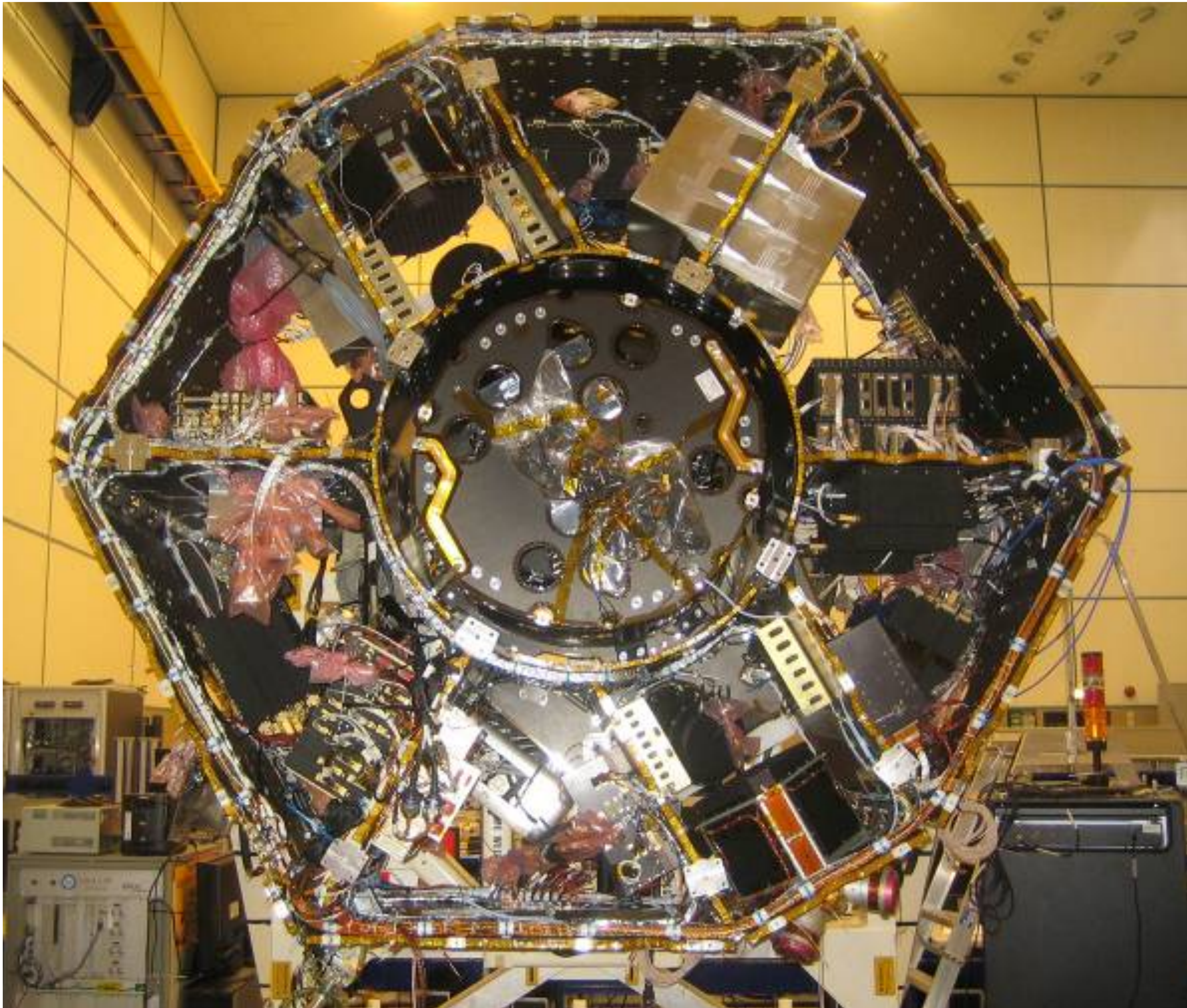
Movie: Steve Drasco, AEI

LISA Pathfinder

- Validate technology: measure relative acceleration of two freely-falling test masses enclosed in a drag-free satellite.
- Planned launch 2014








IABG

Sources and Science: Stochastic Background

- The motivation: get "a picture" of the very early universe t ~ 10^{-22} s after the big bang
- Prospects for detection in current- and next-generation instruments is unlikely:
  - Cosmological background from inflation is too small to detect by 5 to 6 orders of magnitude
  - Cosmological background from exotic early universe models (stringy inflation) might be observable if all the parameters are favorable
  - A "foreground" from unresolved binary systems is right at the edge of obervability.