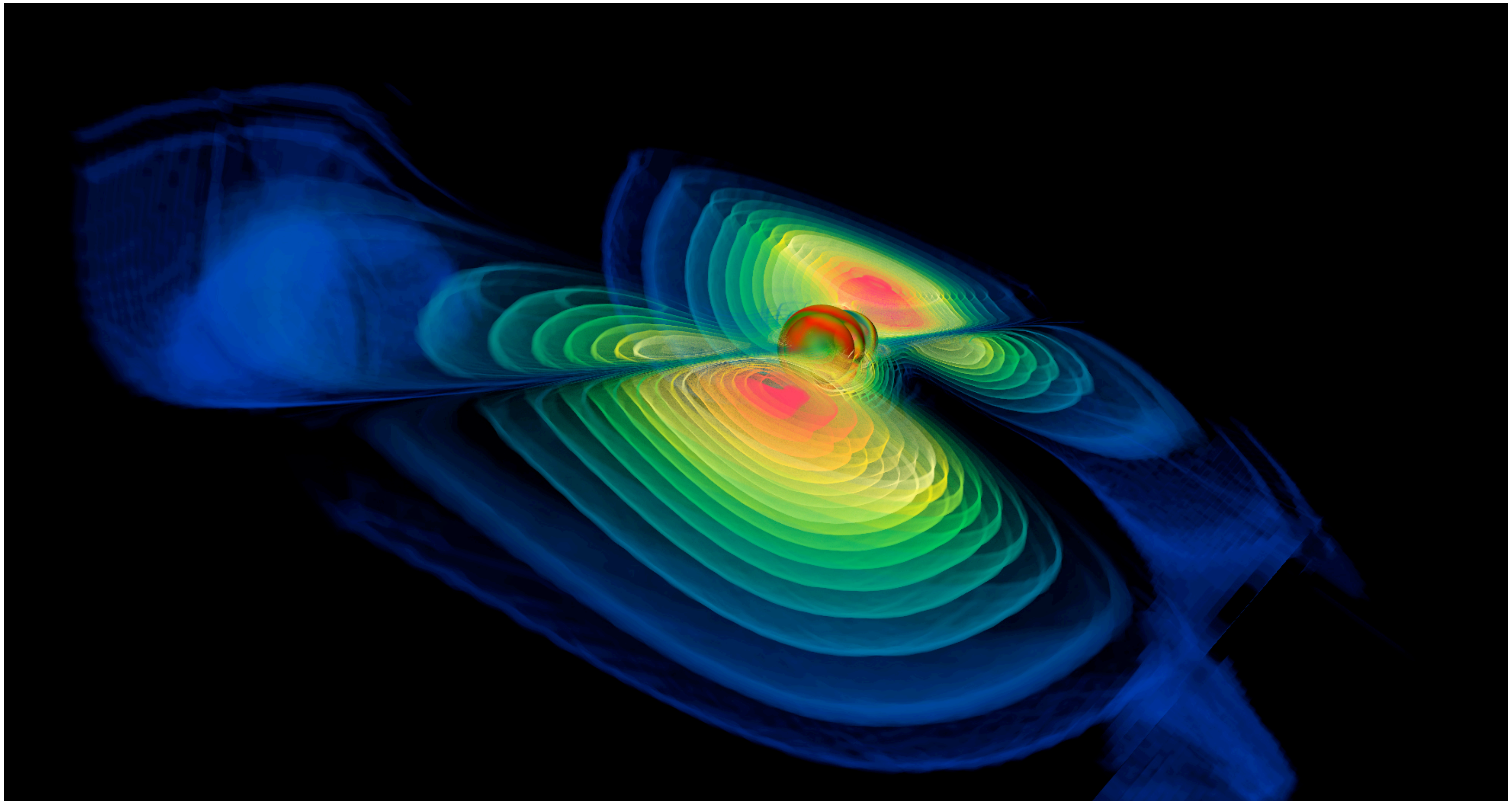
Ground-based gravitational wave detectors and their capabilities through 2020



Bruce Allen

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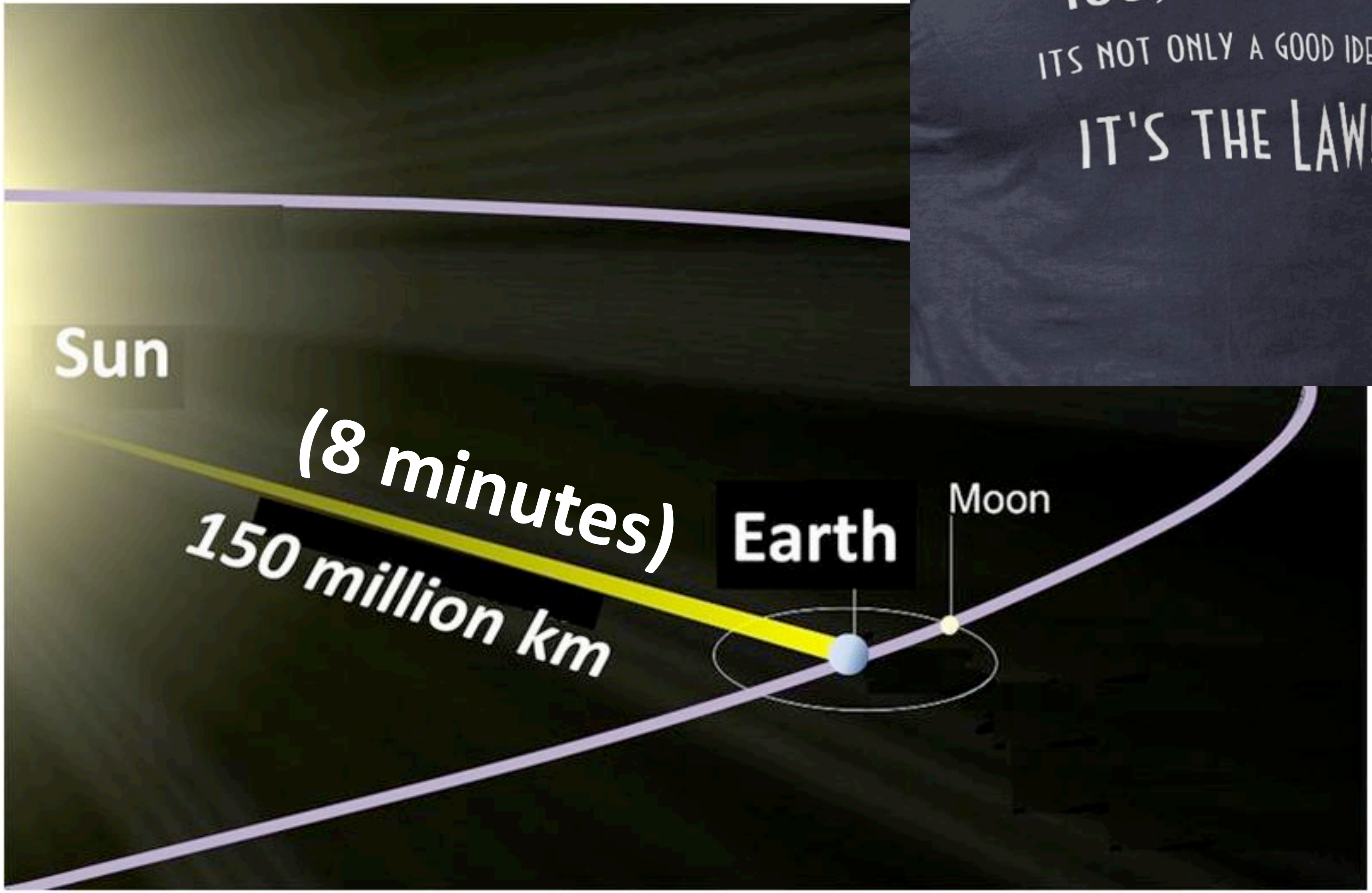
Hannover, Germany

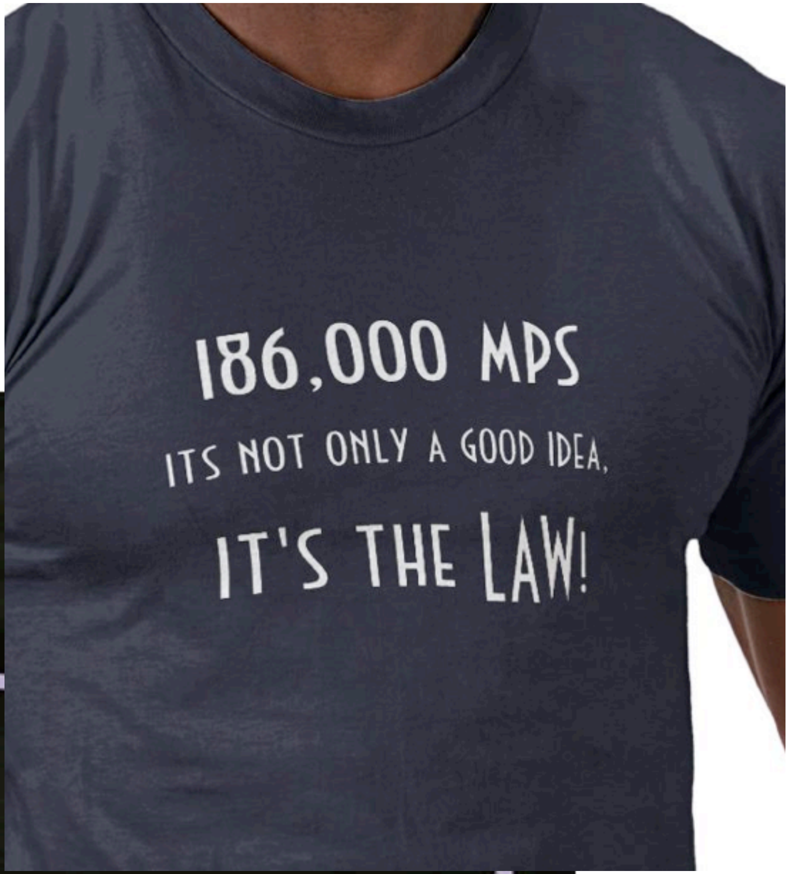
Bonn 5.2.2013

Outline

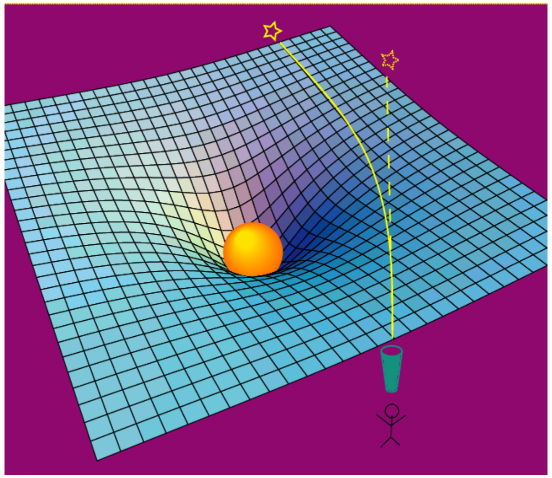
- Gravitational waves
- Brief history of **direct** detection attempts
- Modern “first generation” interferometric detectors
- Basic operating principle
- Sources, science, search methods
- Second generation interferometric detectors, and our expectations for the coming years
- The short GRB / binary inspiral connection
- Longer-term: ET, ~~space-based detectors~~
- ~~Pulsar Timing Arrays~~

Gravitational waves


Sun
(8 minutes)
150 million km
Earth
Moon


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

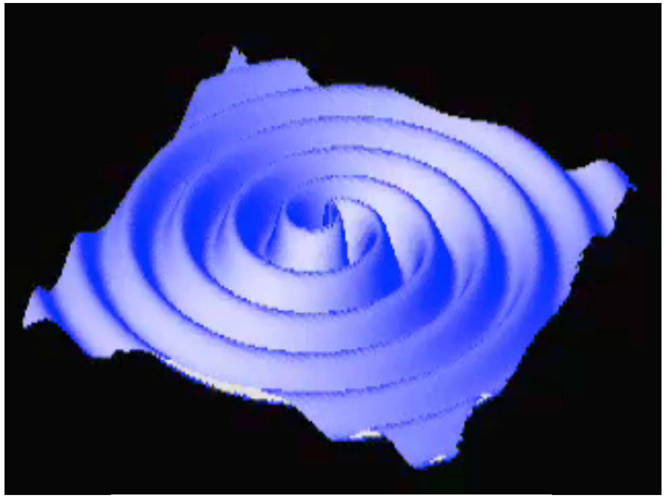
Gravitational Waves

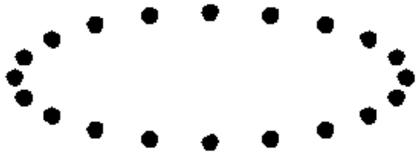


- Predicted by general relativity, Einstein, 1916
- Consequence of 'nothing can go faster than light'
- Very weak: need compact stars with large accelerations

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

- Effect: differential acceleration in freely-falling test masses





Energy-loss from gravitational wave emission has been directly observed

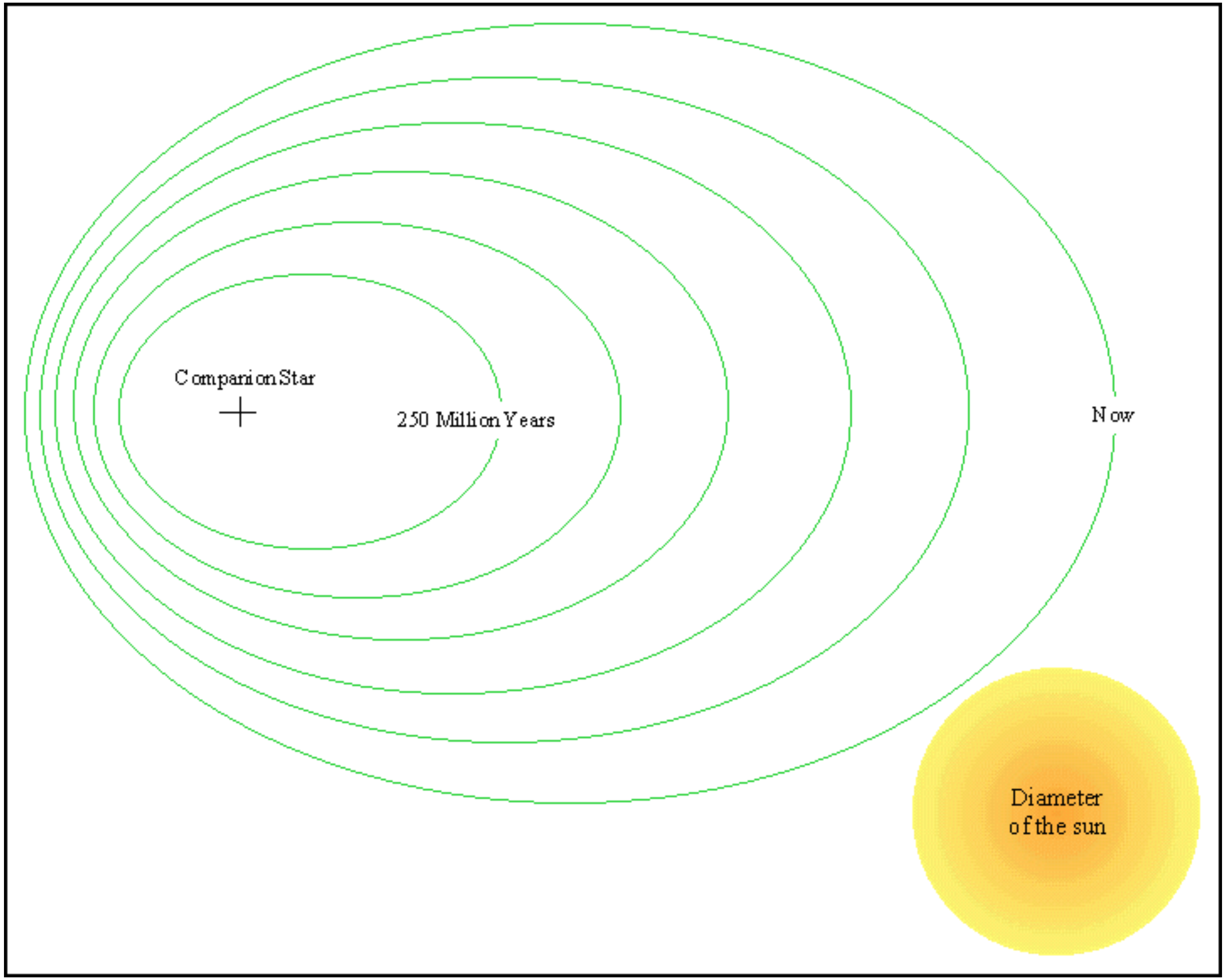
PSR B1913+16

(Hulse-Taylor binary)

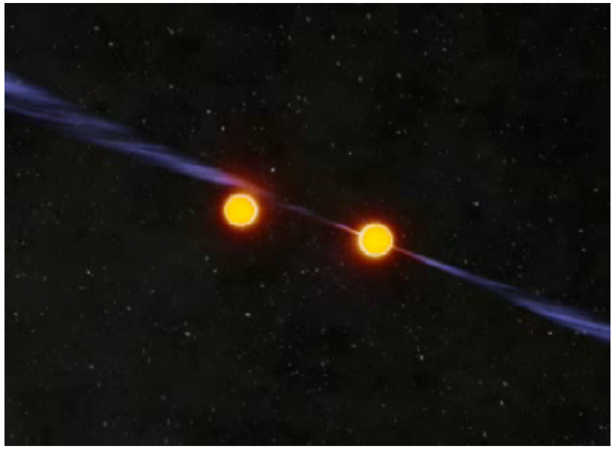
Pulsar: 17 Hz
Companion: NS
Orbital period: 7.75 h
Orbital frequency 36 µHz

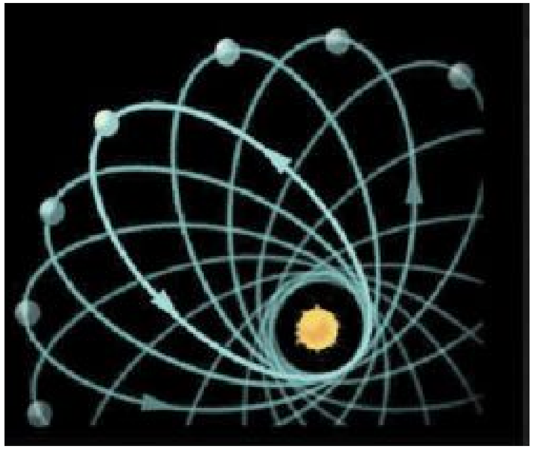
Semi-major axis: 2 Gm
Eccentricity: 0.617

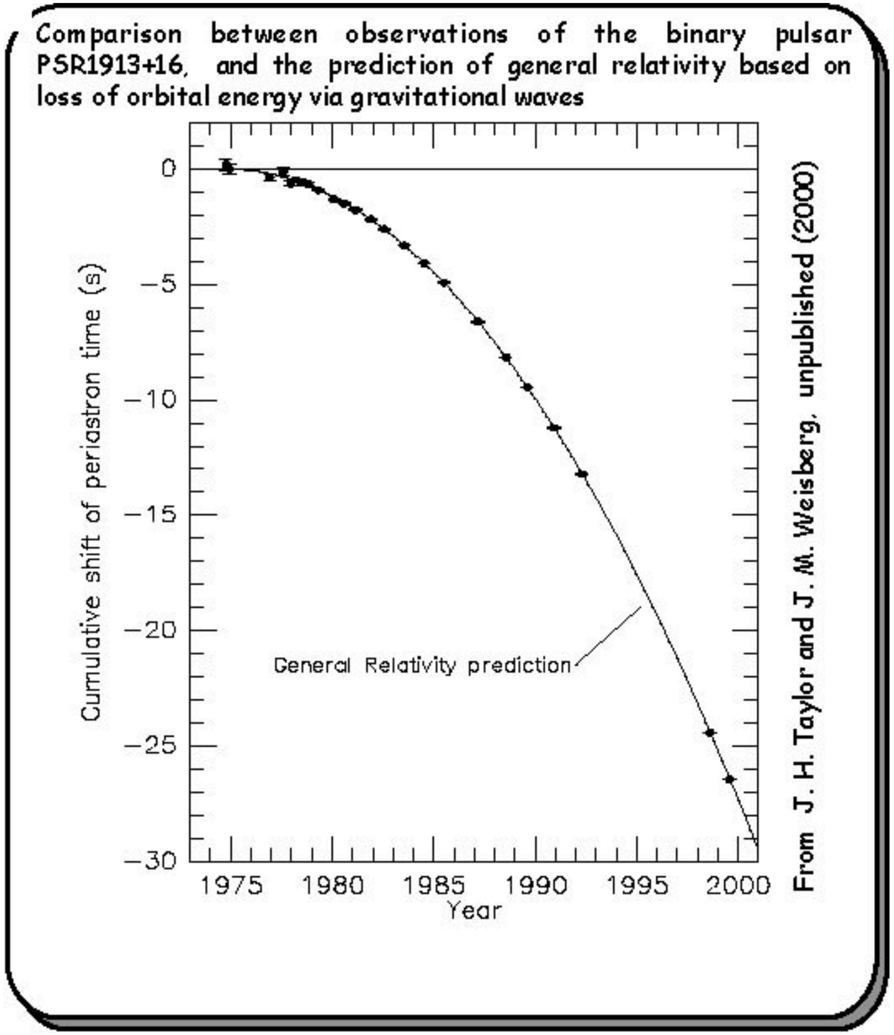
GW frequency 72 µHz GW
Decay: 3mm/orbit
Decay time: 300 M yr



Energy-loss from gravitational wave emission has been directly observed







Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves

From J. H. Taylor and J. M. Weisberg, unpublished (2000)

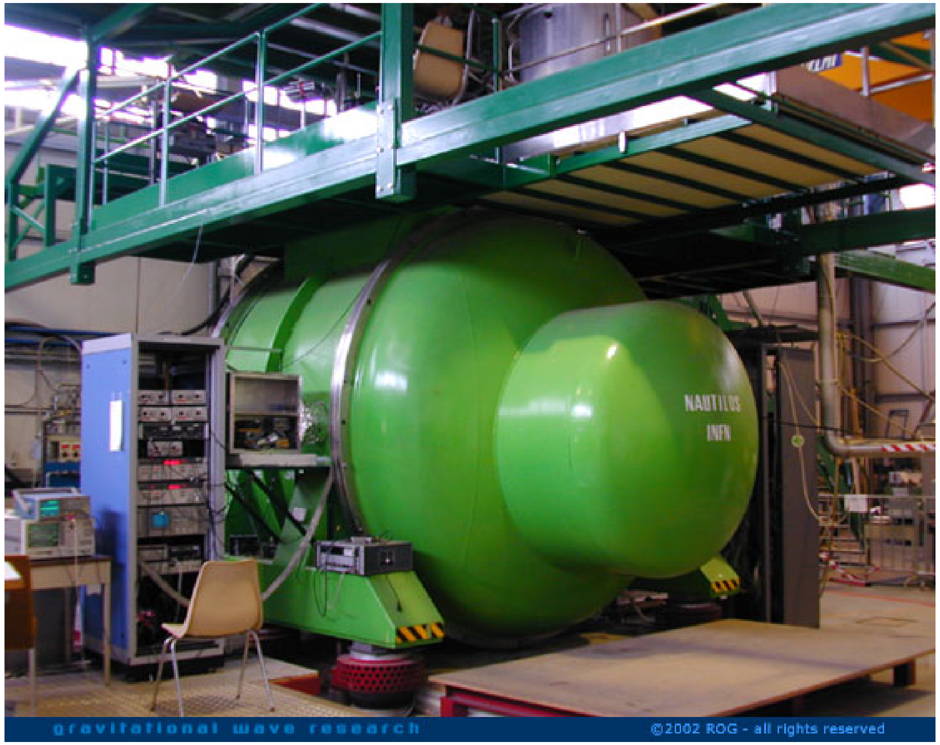
Note that significantly better tests come from the “double pulsar” PSR J0737-3039 which has a 2.4h period.

Brief history of DIRECT detection attempts

Bar / Resonant-Mass Detectors (narrowband: Δf=5Hz at f=900)

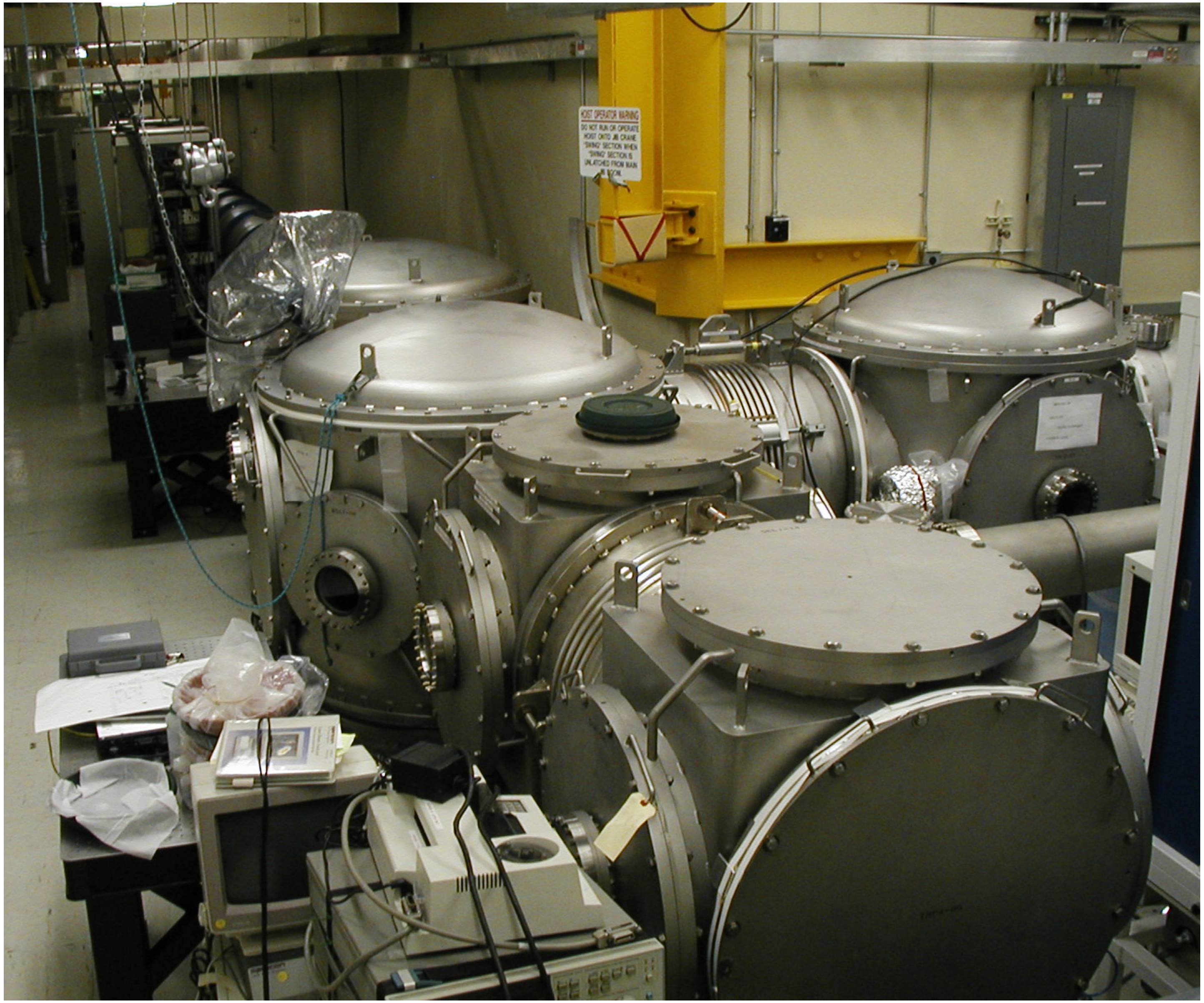
- 1918: Einstein, too weak to detect
- 1960s: Joseph Weber, U. Maryland
- 1970s: Second generation (cryogenic) bars at LSU, Stanford, Rome, Maryland, Germany


UNIVERSITY OF MARYLAND

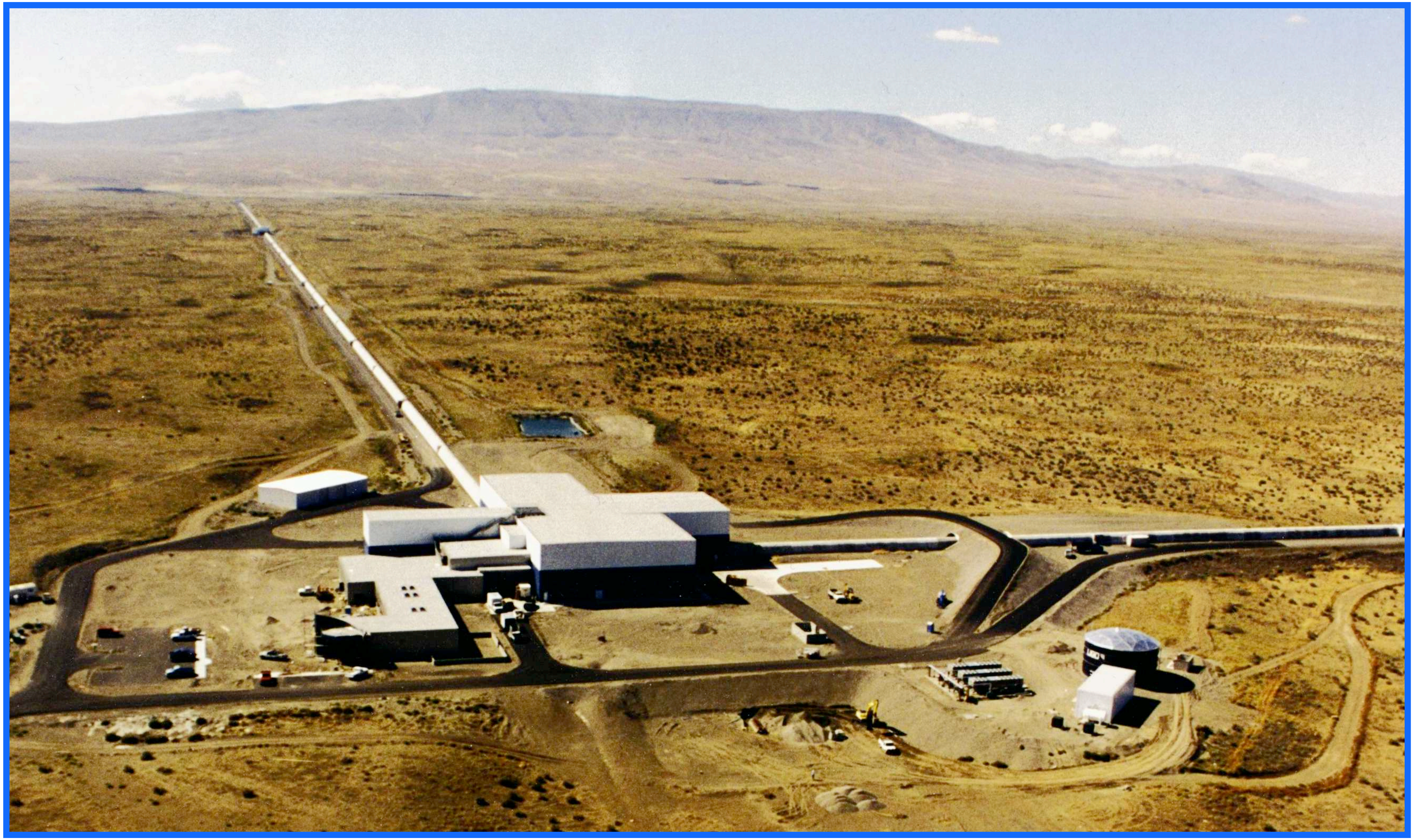


Suspended Interferometers

- 1970s-80s: zeroth generation of **broadband** laser interferometer detectors at MIT, Caltech, Glasgow, **MPI**, Hughes
- 1990s: Development LIGO (USA), VIRGO (France/Italy), GEO-600 (UK/Germany), TAMA-300 (Japan), Dulkyn (Russia)
- First generation detectors finished construction and began commissioning around 1999/2000



Modern "first generation" interferometric detectors (now being upgraded to "second generation")



LIGO 4km+2km (Hanford, Washington, USA)

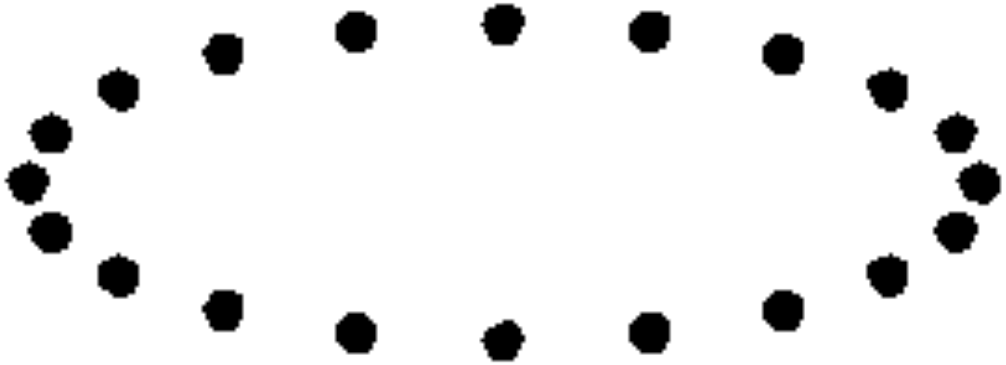
LIGO 4km (Livingston, Louisiana, USA)

VIRGO (Cascina, Italy)

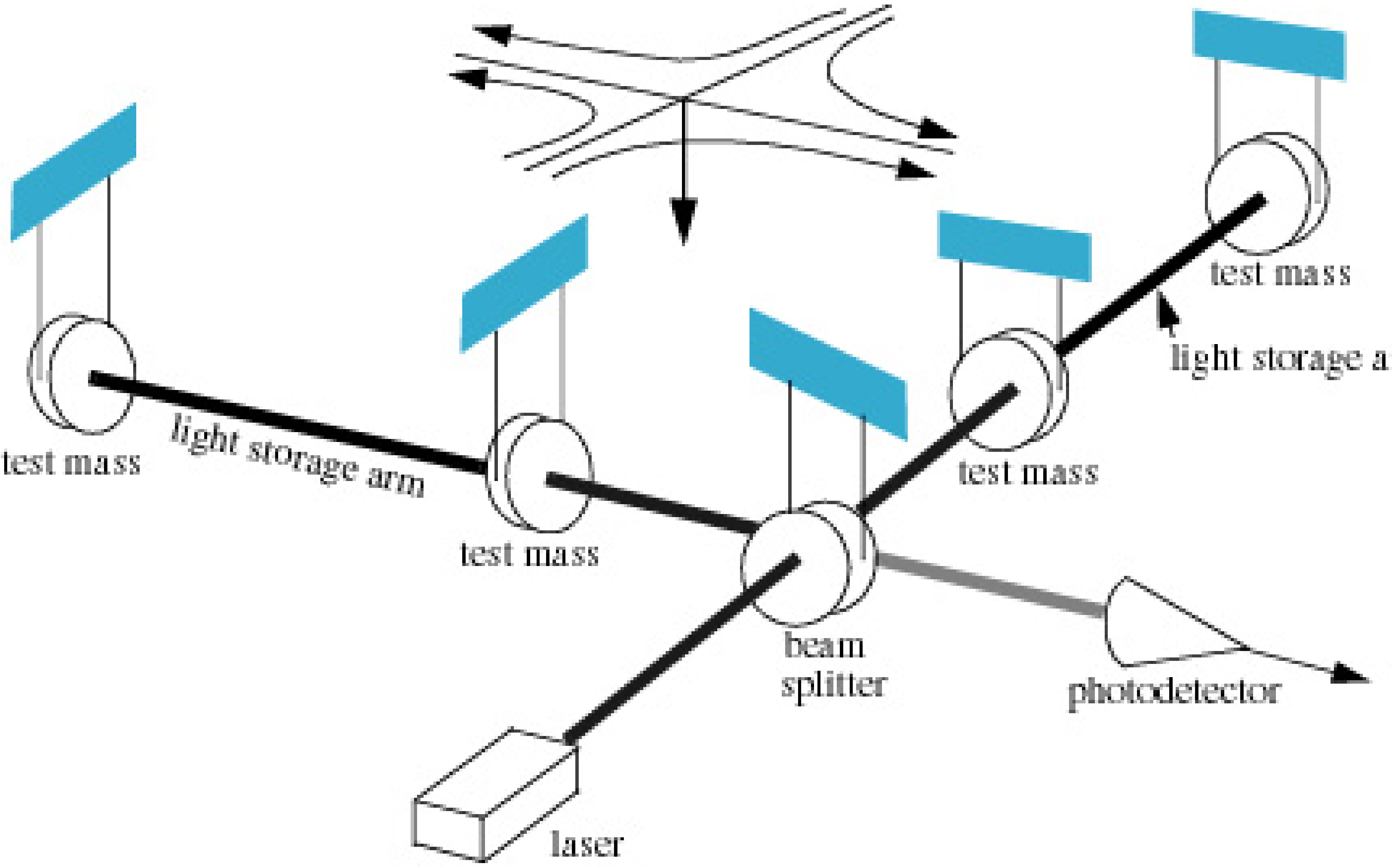
GEO: A UK/German Detector operated by AEI in Hannover

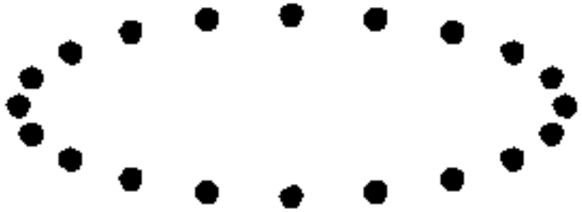
Basic operating principle

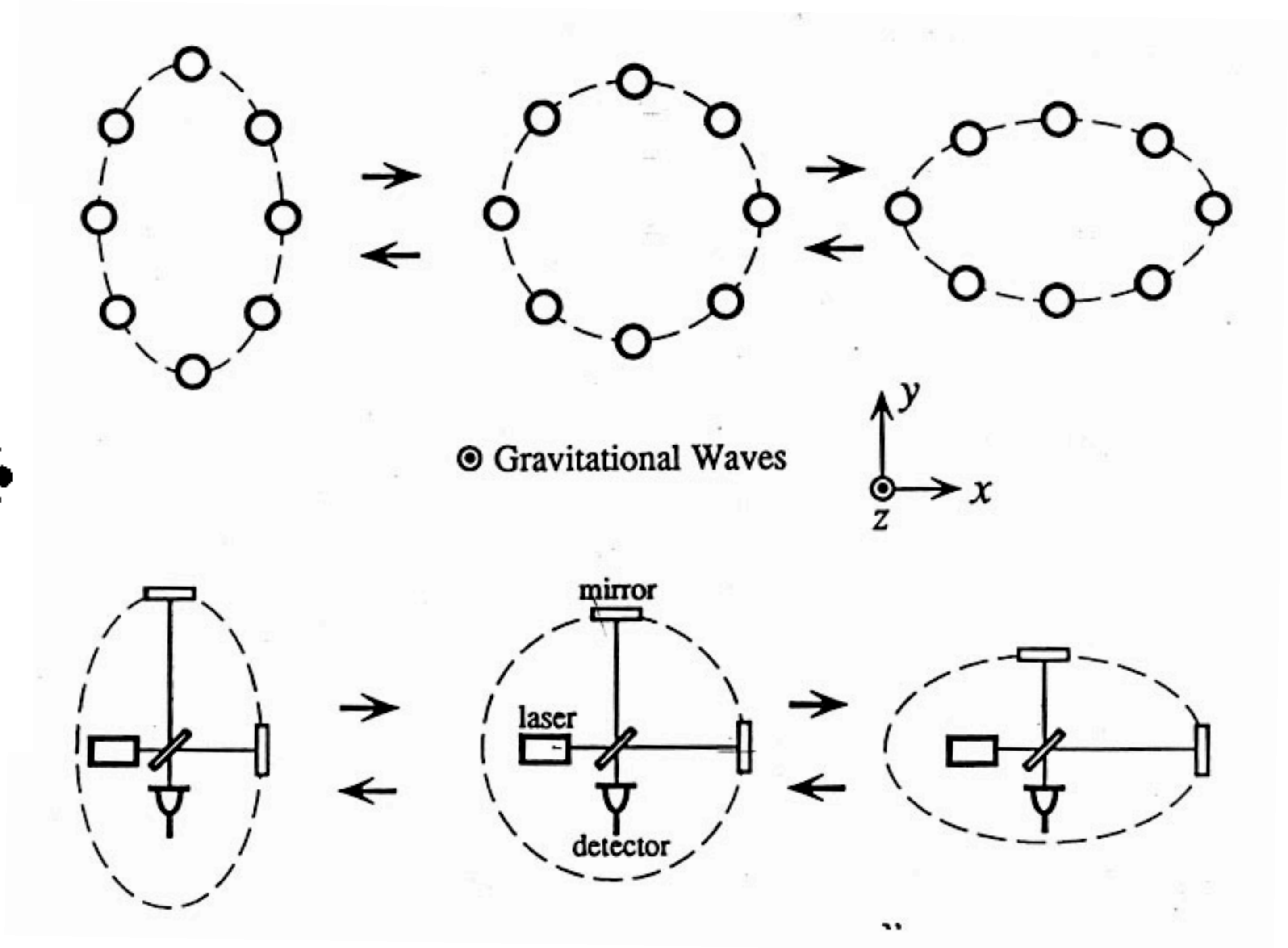
Effect of Gravitational Waves on Test Particles

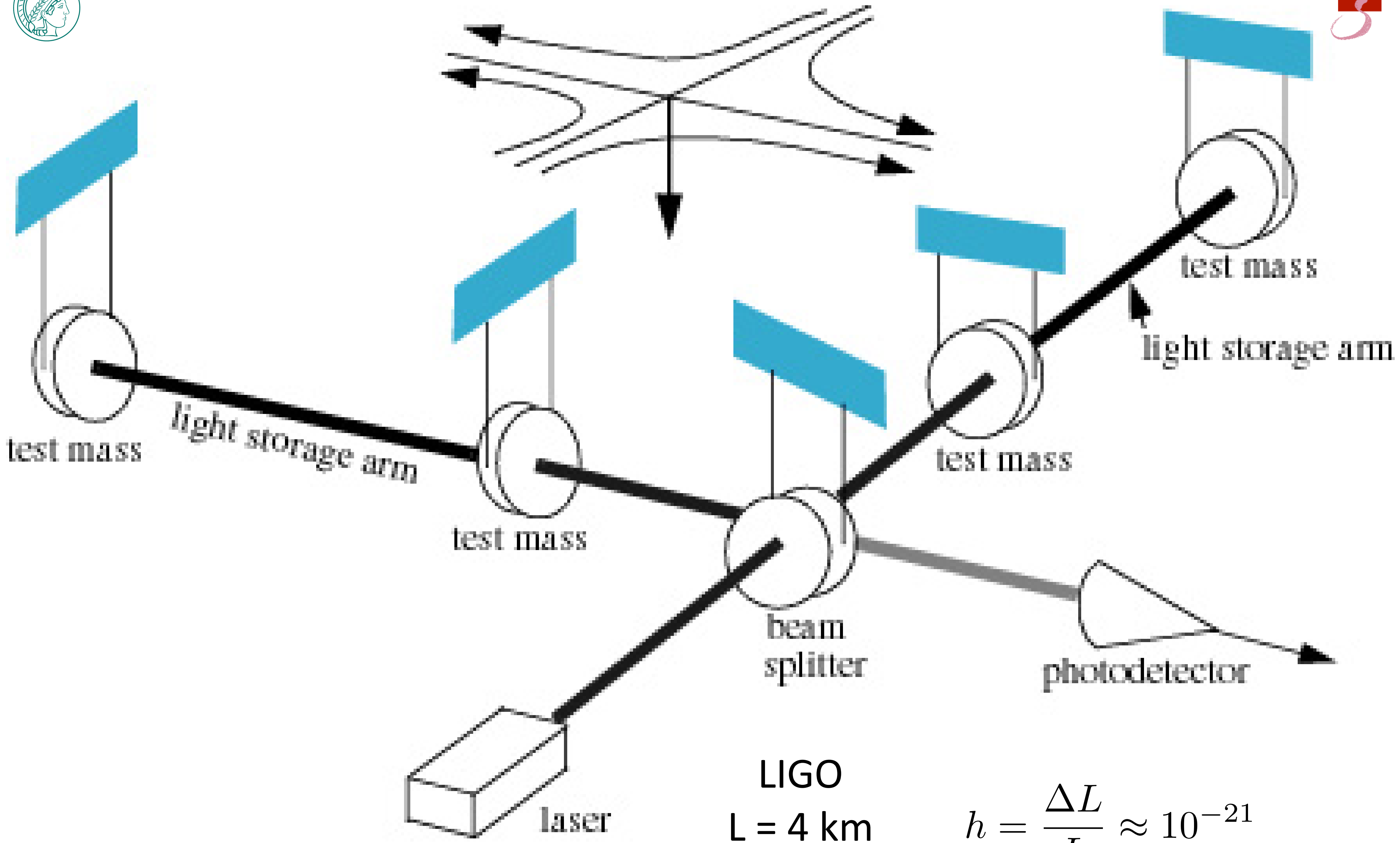


Motion GREATLY exaggerated!


test mass
light storage arm
test mass
test mass
light storage arm
test mass
beam splitter
photodetector
laser

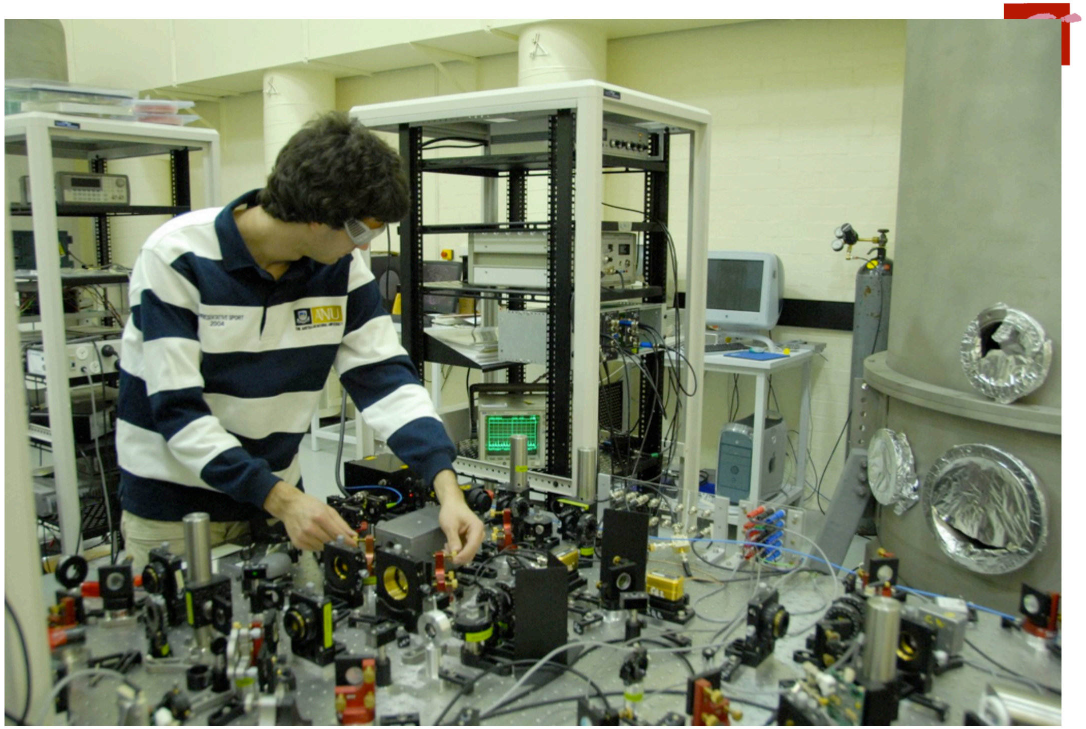



Gravitational Waves
y
x
z
mirror
laser
detector



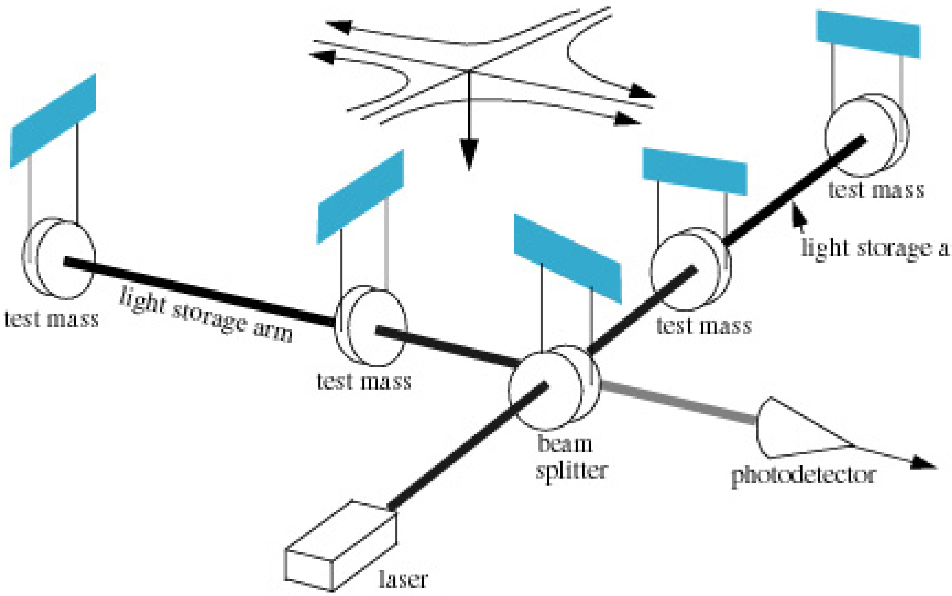
LIGO
L = 4 km
$\Delta L = 10^{-16}$ cm

$$h = \frac{\Delta L}{L} \approx 10^{-21}$$

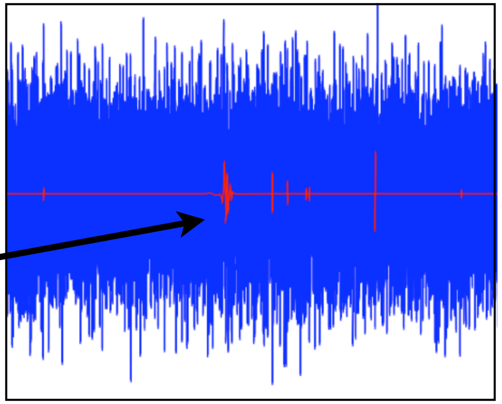


Copyright: LIGO lab, Caltech

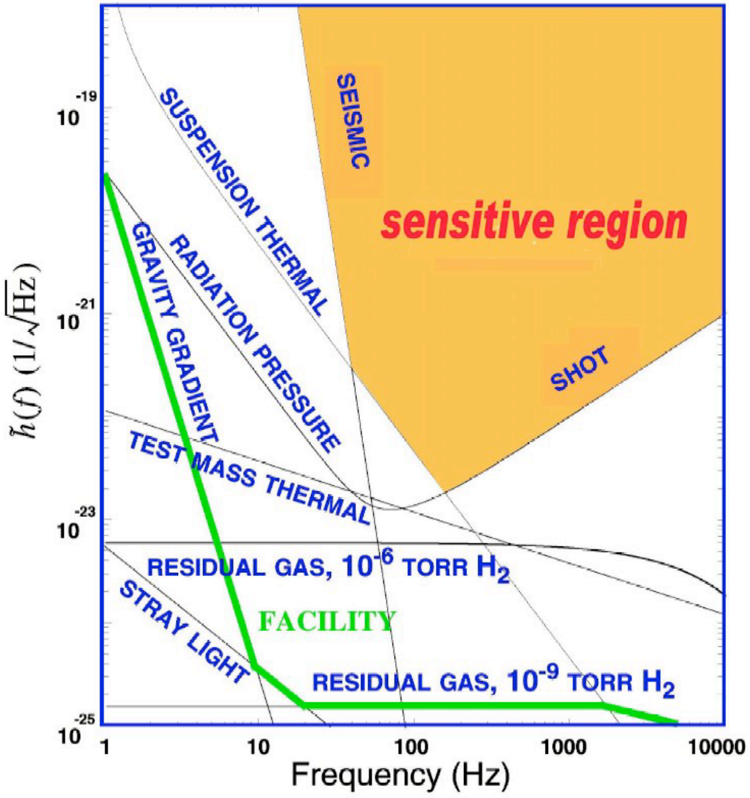
Interferometric Gravitational Wave Detectors

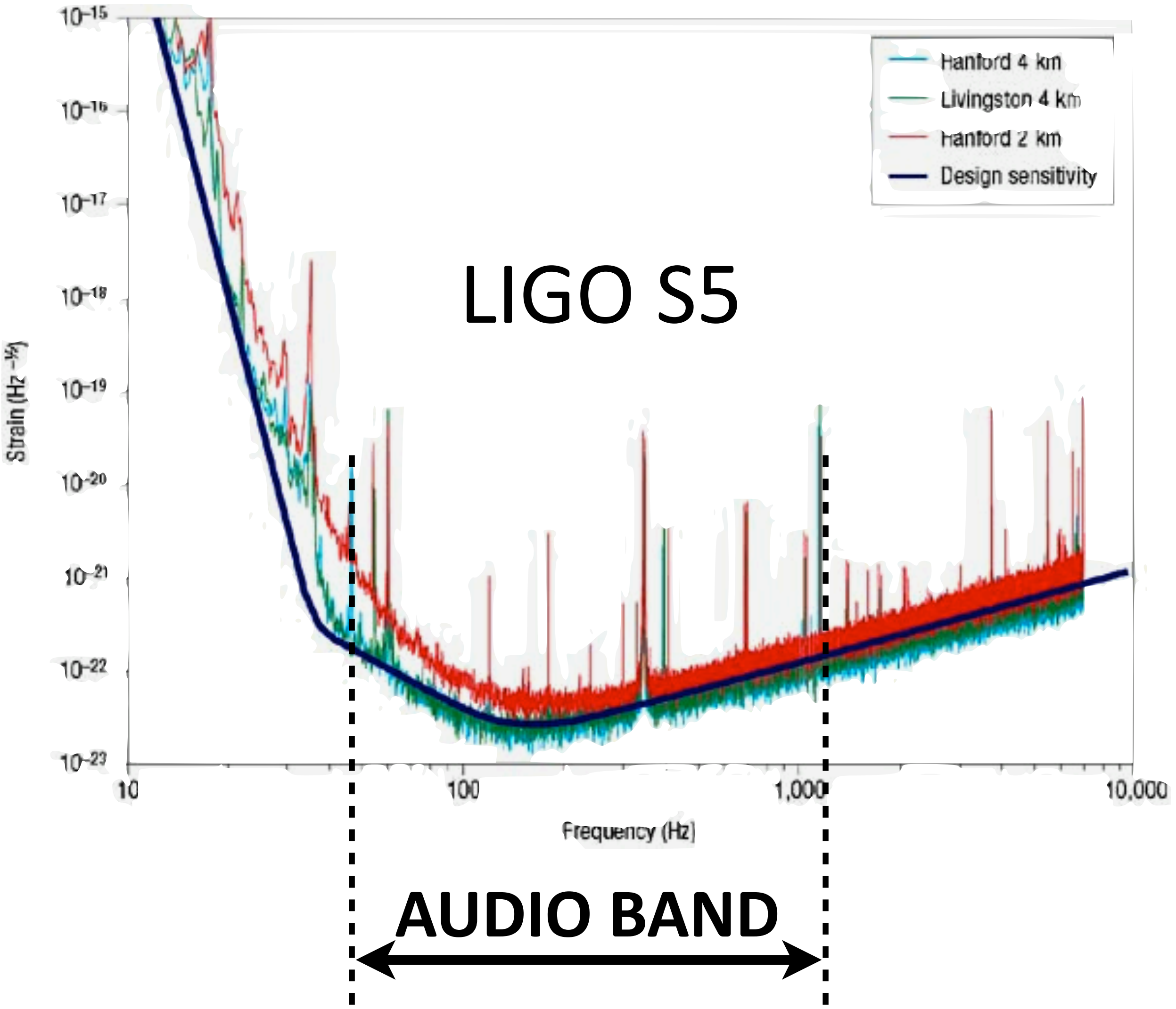


- Gravitational wave “changes distance between mirrors”
- Laser measures mirror positions: differential motion causes fringe shifts
- Detected via error signal in locked loop
- Search for weak signals in noise



The Challenge: Detector Noise Sources



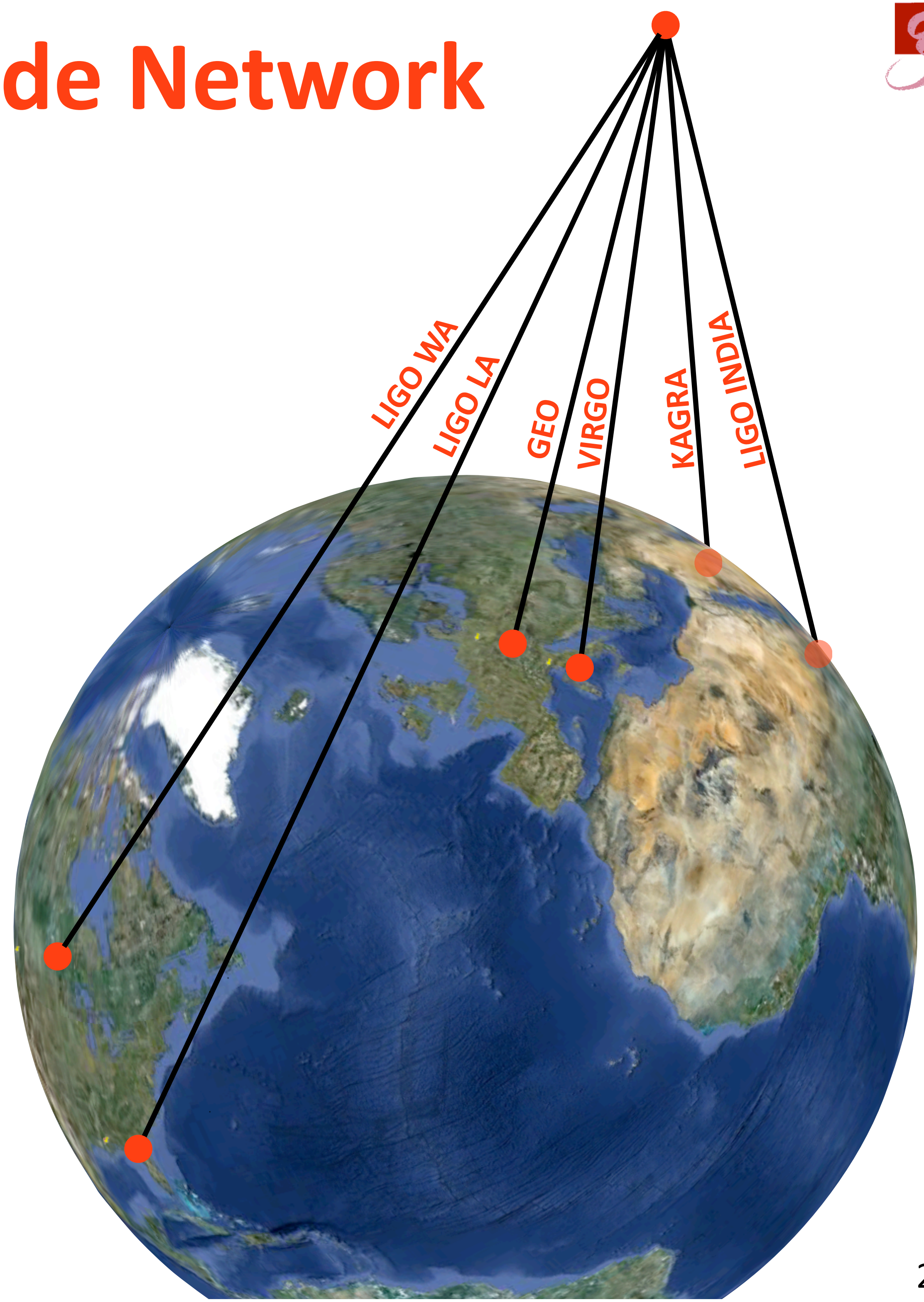


- Seismic: ocean waves, plate tectonics, cars, logging, mining,...
- Thermal: Brownian motion in suspensions, mirrors, mirror coatings
- Shot: photon counting noise

Sources, science, search methods

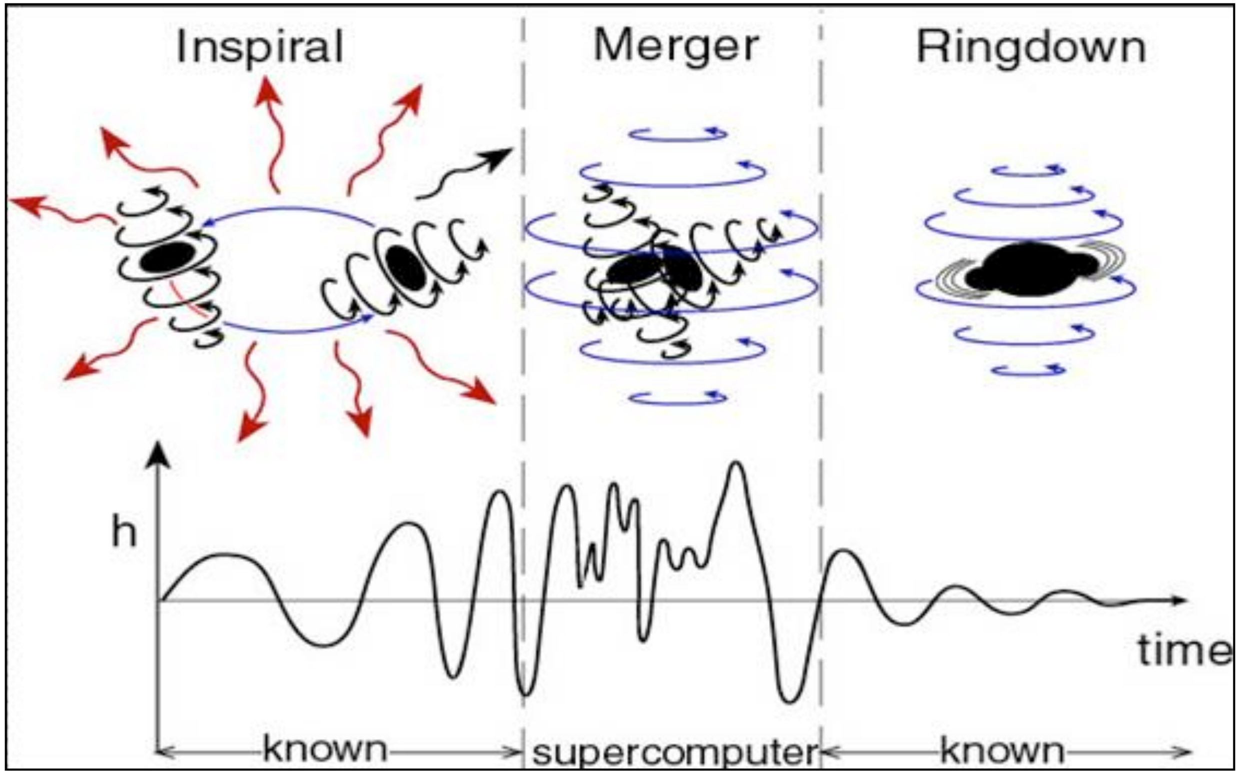
World Wide Network

- GW "Telescopes" do not point: need triangulation
- Signals are very weak, data dominated by detector noise of many types: share data to improved detection confidence & sensitivity
- All experiments (*apart from KAGRA*) have a joint data-sharing agreement.
- Improves detection efficiency, waveform and position reconstruction



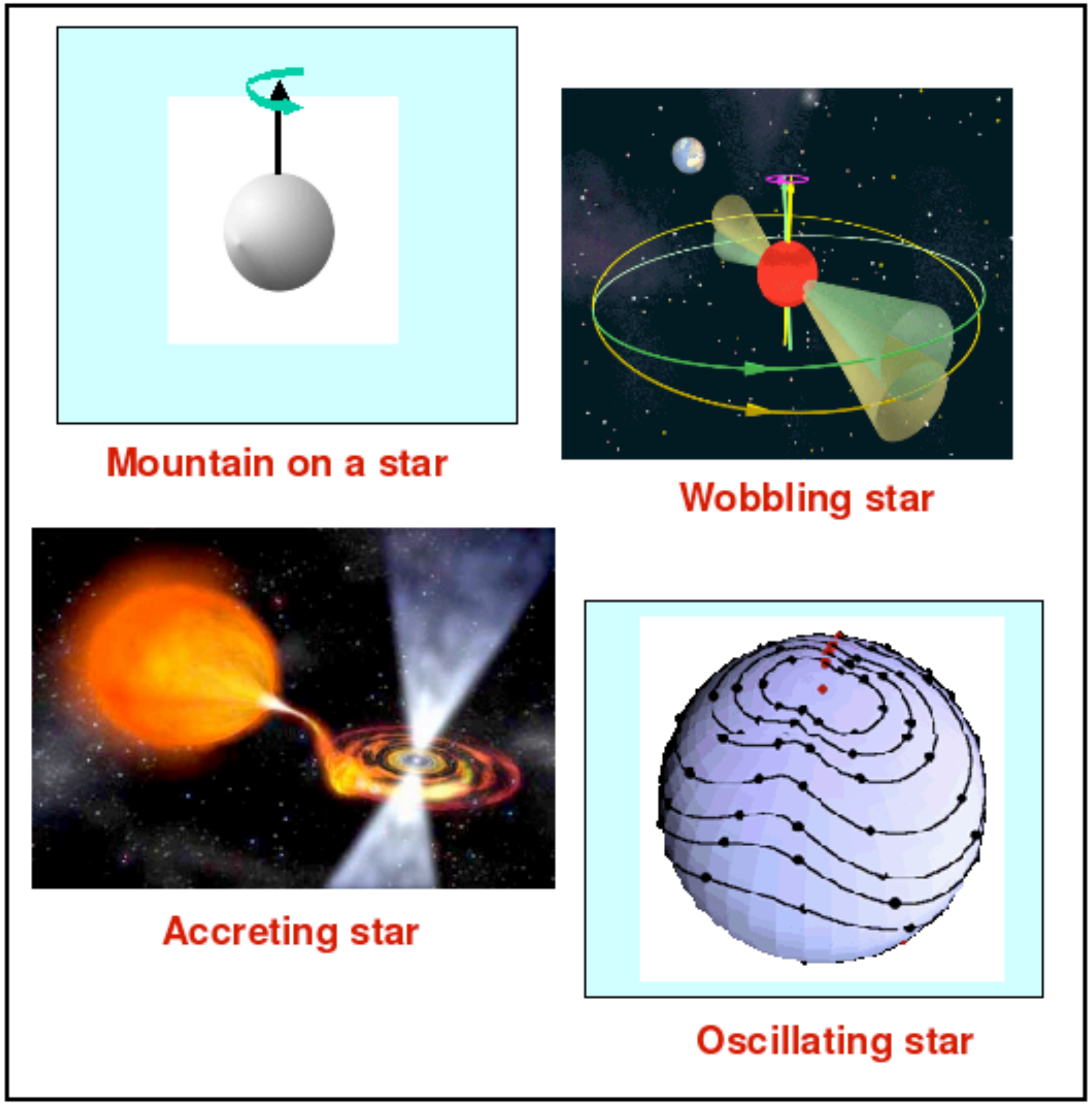
Sources and Science: Compact Binary Coalescence

- Signal produced when two compact objects (neutron stars = NS or black holes = BH) orbit, lose energy, come together and coalesce.
- Waveforms may be calculated precisely with a combination of analytic (post-Newtonian approximations, Effective One Body approximations) and numerical methods.
- Data analysis method: matched filtering with carefully picked template bank
- Benchmark source is inspiral of two NS, but rates very uncertain (by two orders of magnitude). Perhaps the origins of short gamma-ray bursts.
- Stringent test of dynamic strong-field gravity.
- Also useful for understanding stellar populations and evolution



Sources and Science: Continous Waves from Rapidly Spinning Neutron stars

- Continuous emission over time as stars spin down
- A very difficult data analysis problem (Einstein@Home + new methods)
- Neutron star structure: eccentricity, glitches, equation of state
- Population studies and stellar evolution
- Mechanisms at work in LMXBs (but better data-analysis methods needed)
- Prospects for detection are not encouraging. 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.


Mountain on a star

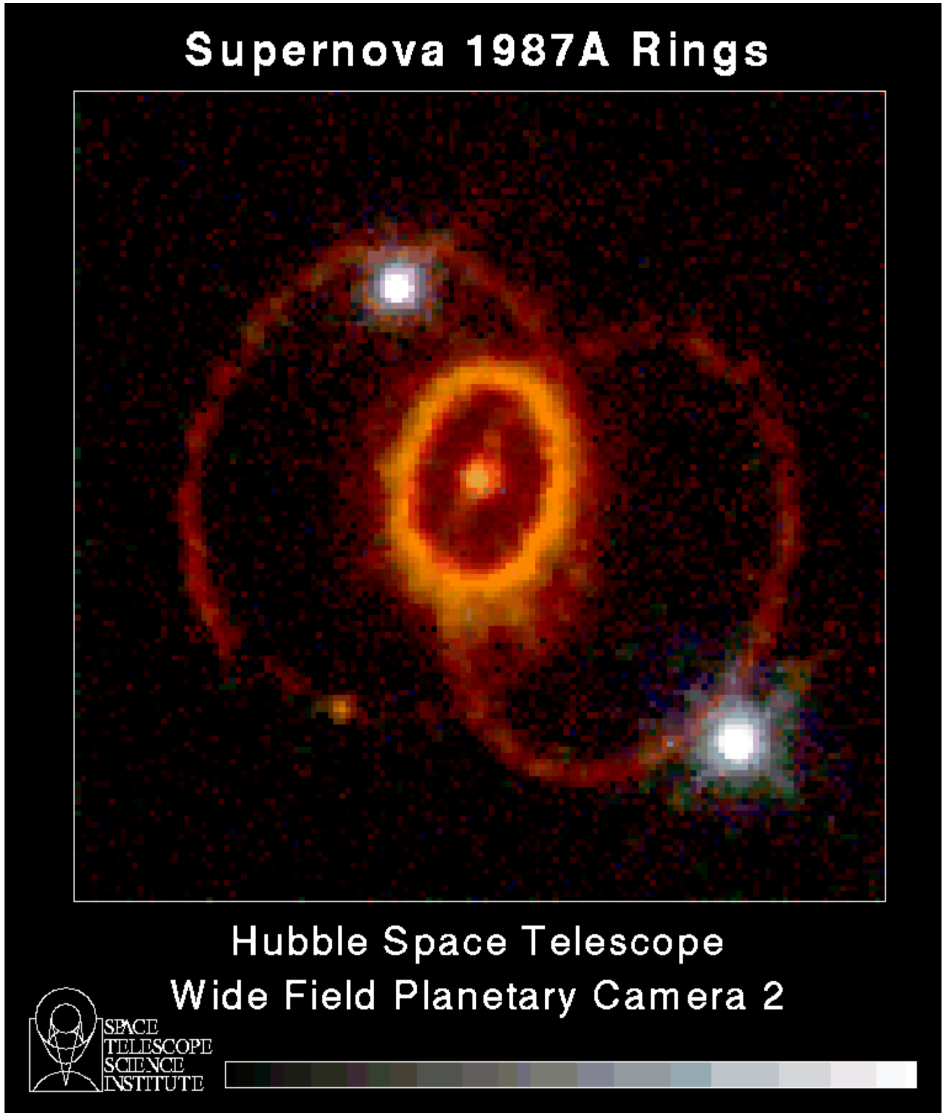
Wobbling star

Accreting star

Oscillating star

Sources and Science: Supernovae

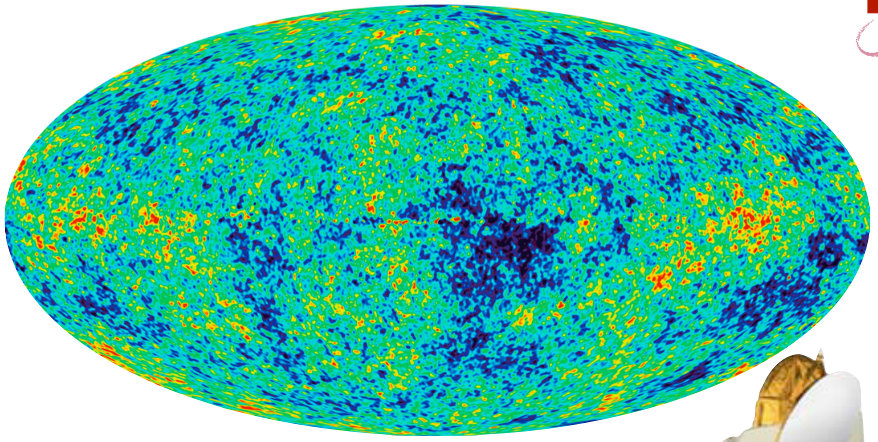
- Instruments only sensitive enough to detect SN within our Galaxy.
- Expected rates not encouraging, perhaps one SN every 50 to 100 years.
- Detection method for these and other “unmodeled” burst sources: look for blobs of energy in time-frequency wavelet plots
- Thomas Janka’s talk



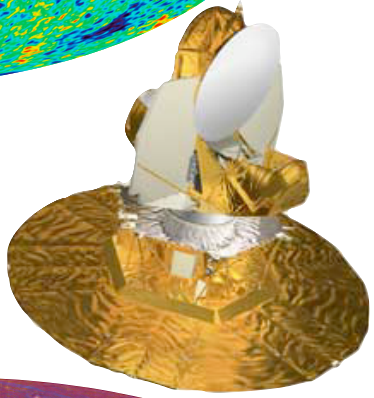
Sources and Science: Stochastic Background

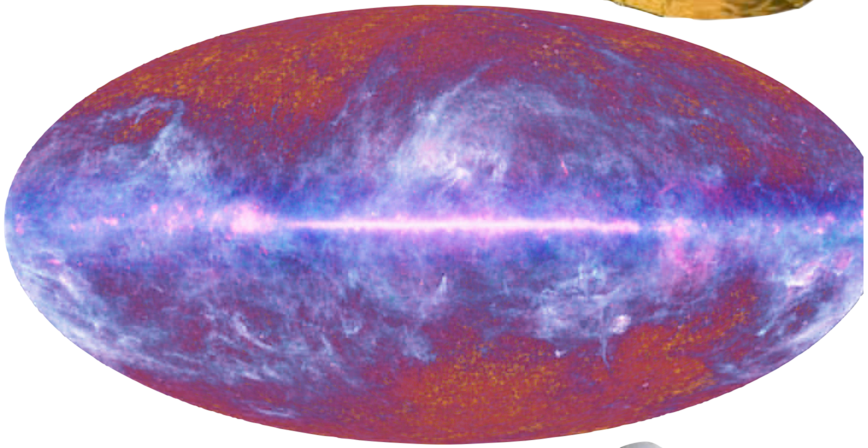
Perhaps get information about the very early universe

Penzias and Wilson 1965

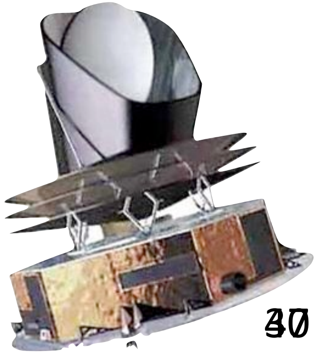


WMAP Satellite



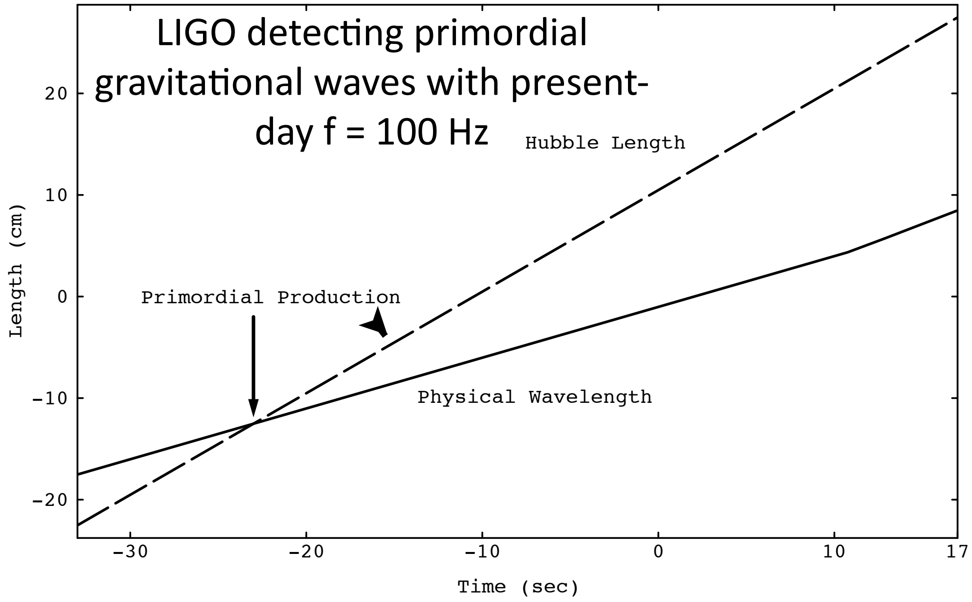


Planck Satellite

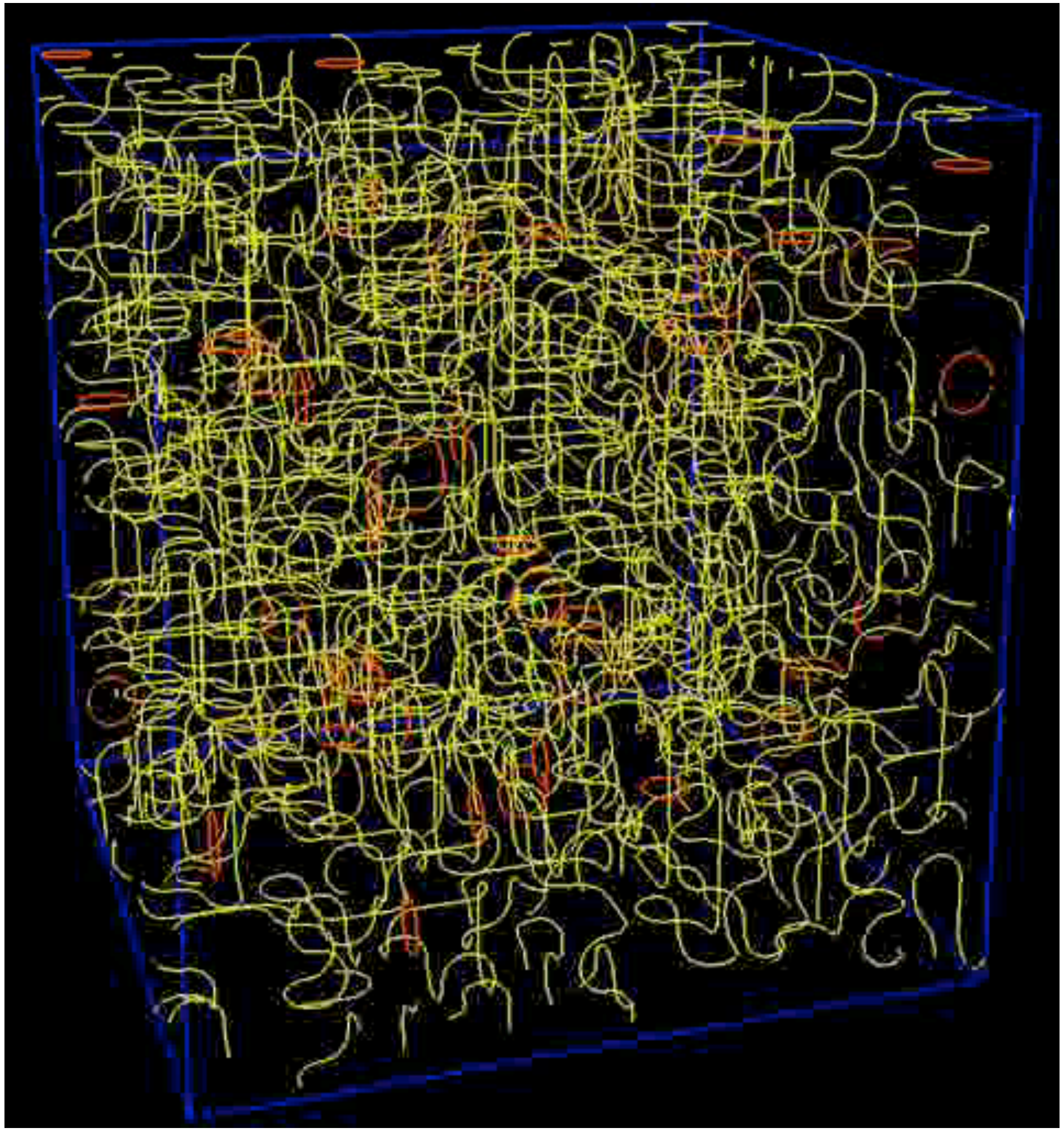


Sources and Science: Stochastic Background

- 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.



LIGO detecting primordial gravitational waves with present-day f = 100 Hz



Science Results To Date

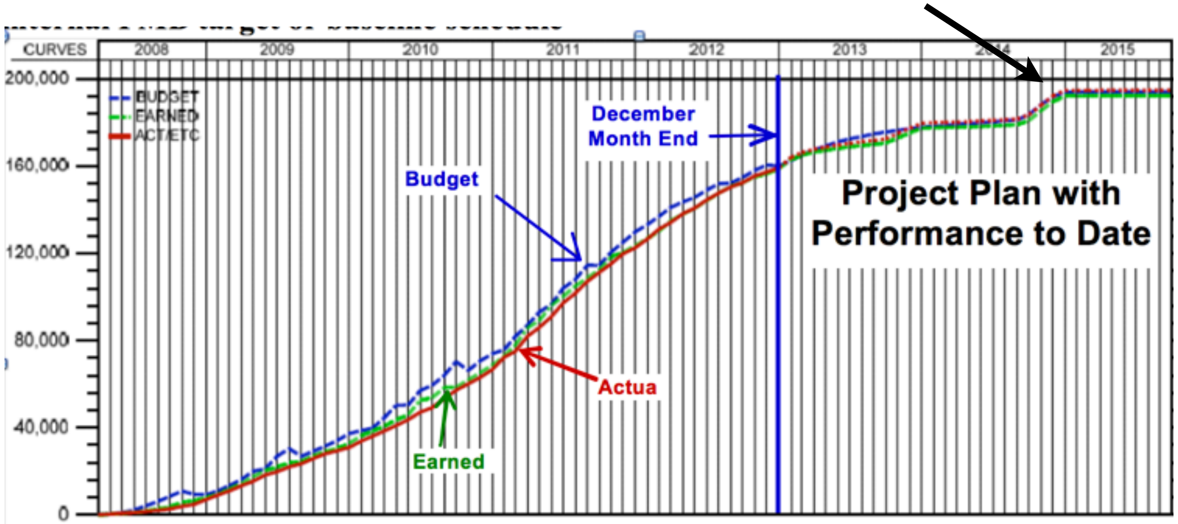
- No gravitational-wave detections so far[†]
- LIGO Scientific Collaboration: 76 scientific publications, 64 conference proceedings
- www.lsc-group.phys.uwm.edu/ppcomm/Papers.html

[†] BUT new data-analysis methods developed for gravitational-wave searches have discovered tens of new radio and gamma-ray pulsars in the past two years.

Second-generation instruments and our expectations through 2020

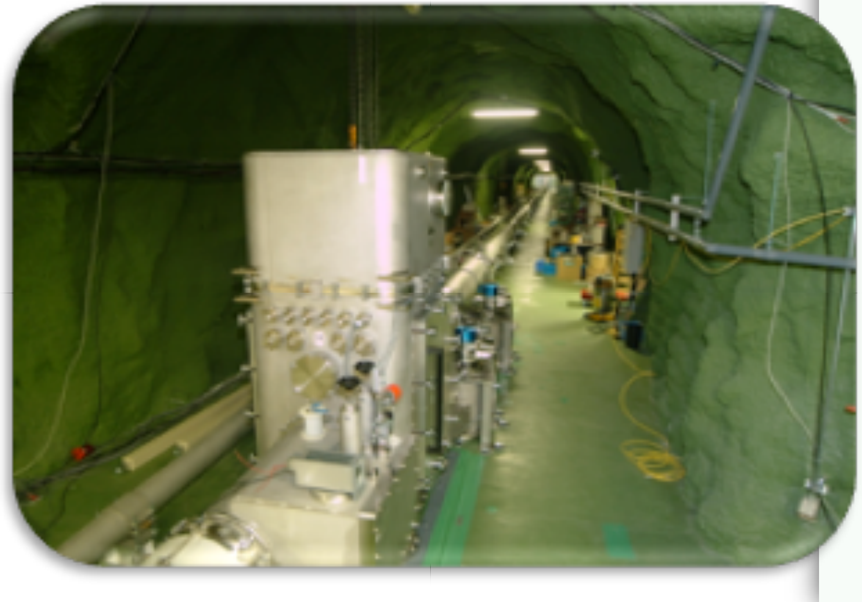
Second-Generation Instruments

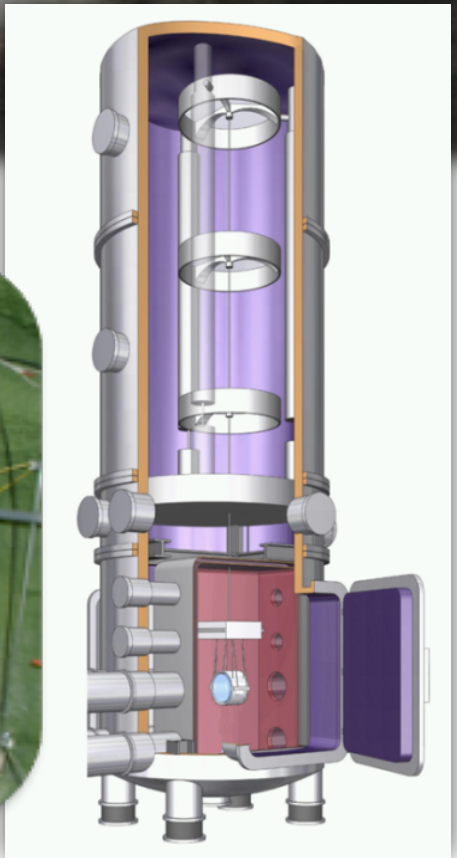
- October 2010: the LIGO detectors were **decomissioned**
- Installation of advanced detectors (aLIGO, graph below) is 82% complete (earned value) or 67% (installation/integration). In-kind contributions from UK (supensions) & Germany (high-power lasers)
- Advanced VIRGO upgrade in progress.
- GEO-600 undergoing an incremental upgrade (GEO-HF) with higher-power lasers and squeezed light to provide high frequency sensitivity comparable to other instruments.
- These advanced (second-generation) detectors should start serious data collection around 2015.



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

- Construction funded summer 2010, 10 billion yen
- Under mountain at Kamioka mine (reduces seismic noise by factor of 100) at the site of the Kamiodanka neutrino detector
- Cryogenically cooled optics and suspensions)
- Ground-breaking January 2012; tunneling work currently underway

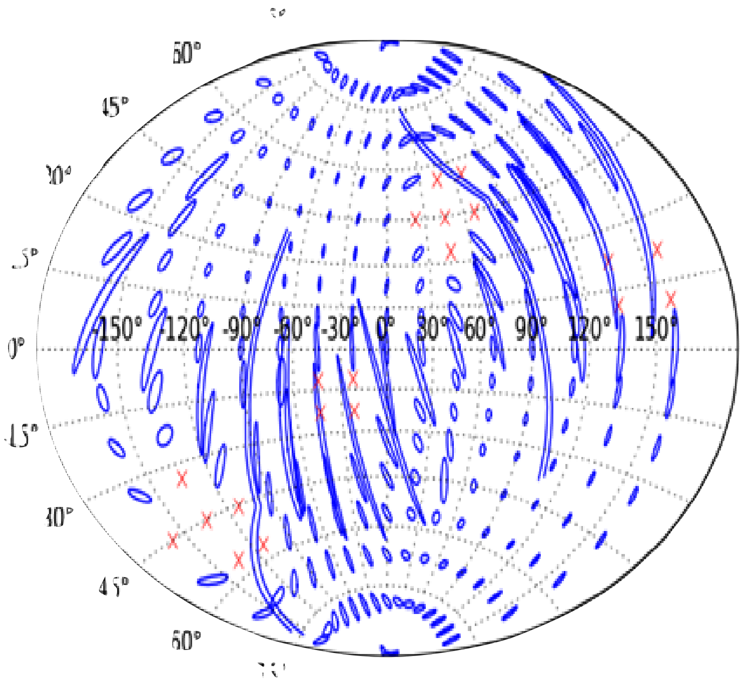


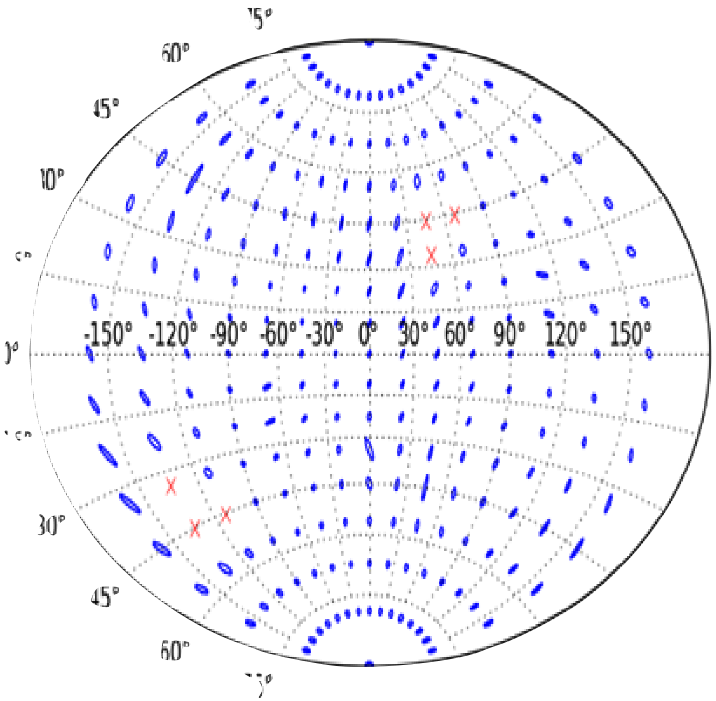


LIGO-India

- India is moving ahead with a plan to build a second-generation interferometer using components originally built for a 3rd LIGO detector in the USA. Instead of having two LIGO detectors in a single vacuum system in Hanford, Washington, USA, locate one of those instruments in India
- US contribution: one detector
  Indian contribution: vacuum system, roads, operating costs
- In August 2012, the US National Science Board "... authorizes the NSF Deputy Director at her discretion to approve the proposed Advanced LIGO Project change in scope, enabling plans for the relocation of an advanced detector to India."
- Third location of similar sensitivity is needed for triangulation. This would significantly increase pointing accuracy, number of sources visible.
- **BUT** LIGO India too late to participate in the first detections

2012 - 2013
Site survey and acquisition; insfrastructure preparation
2014 - 2017
Fabrication of spiral welded tubes and UHV components
2016
Start of interferometer assembly
2016 - 2018
Integration, tests and validation
2018 - 2019
Detector operation and tuning to design sensitivity
2019 -
Science runs and operation; GW astronomy

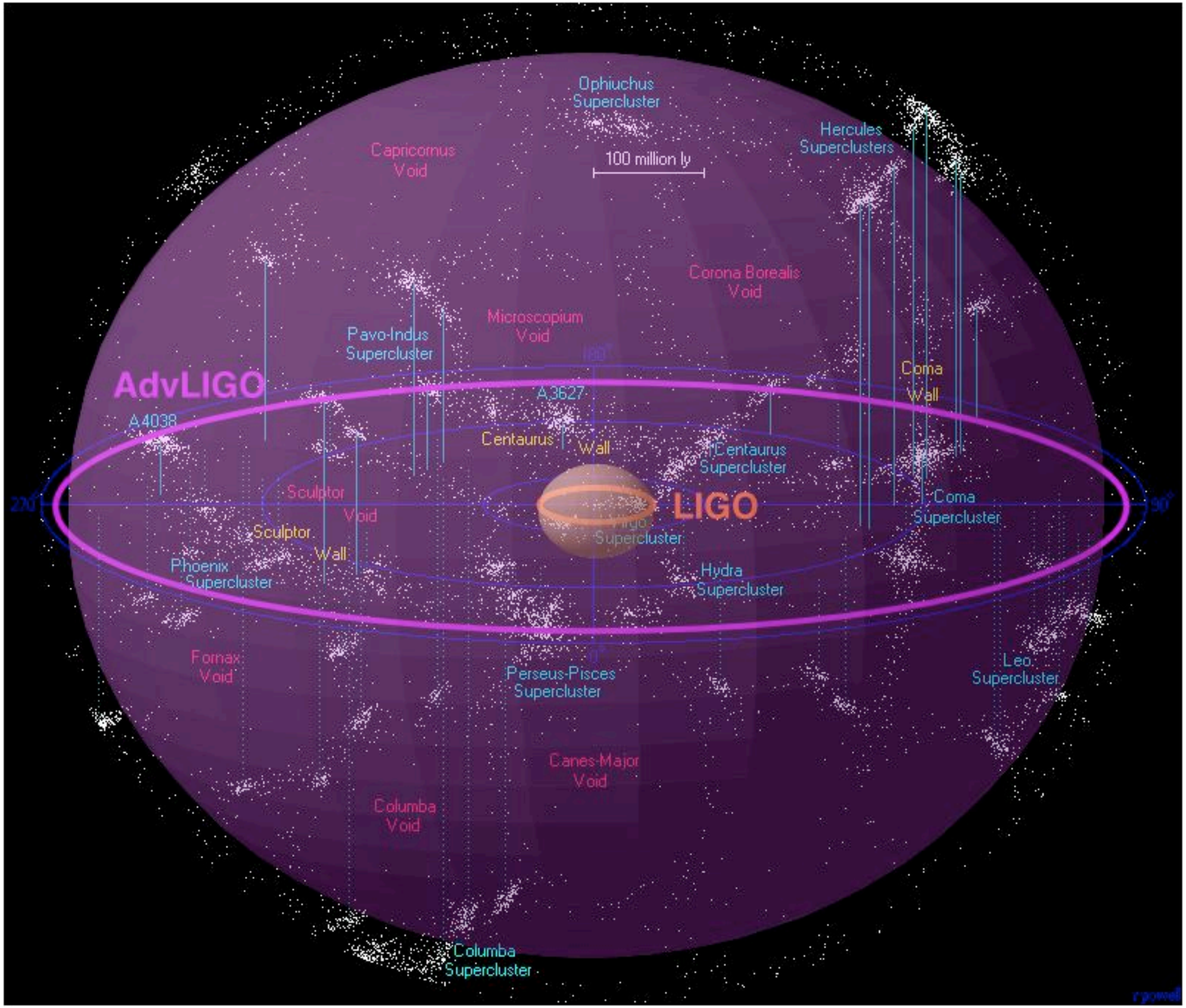




Advanced Detectors

	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

Advanced Detector Reach



Expected First Detection

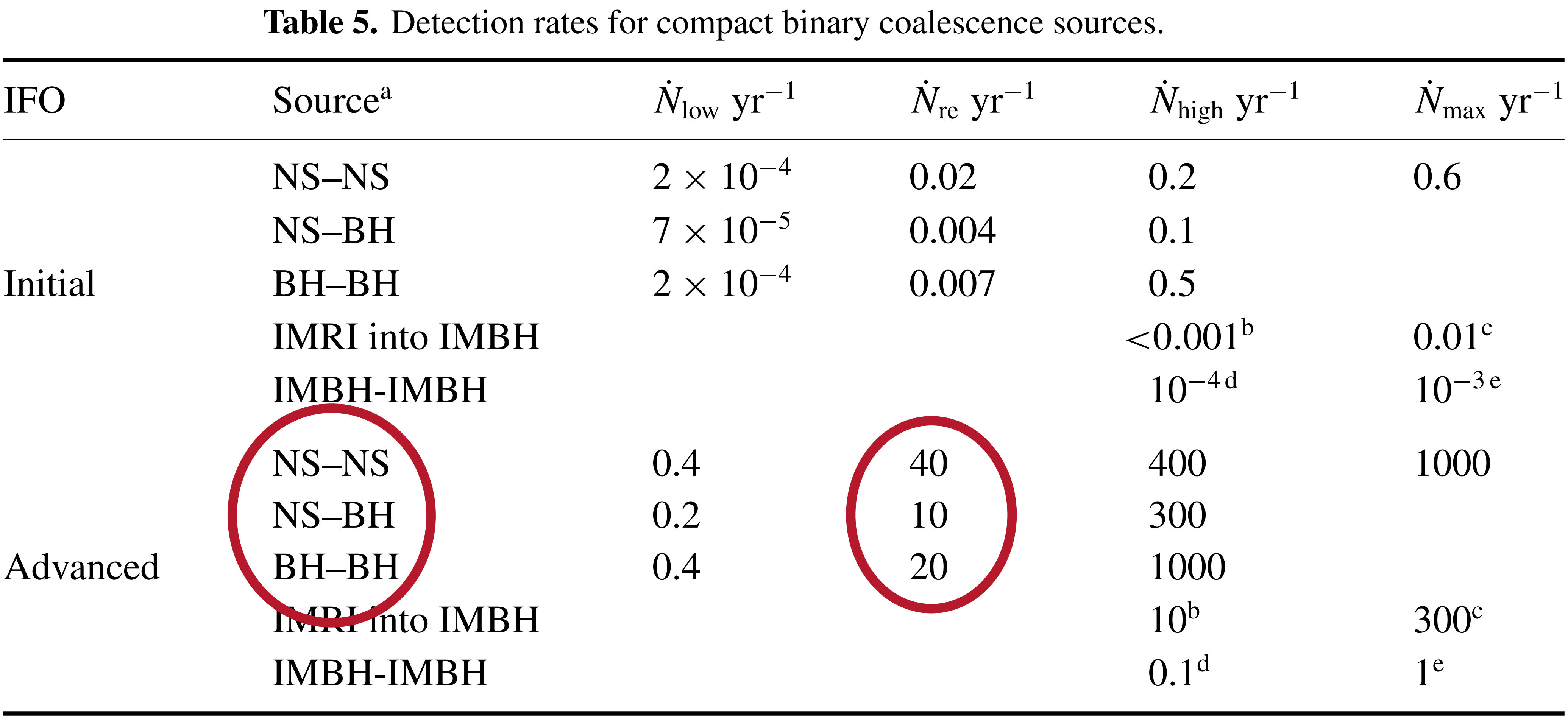


Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm high}$ yr^{-1}	$\dot{N}_{\rm max}$ yr^{-1}
Initial	NS–NS	2×10^{-4}	0.02	0.2	0.6
	NS–BH	7×10^{-5}	0.004	0.1	
	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]
Advanced	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
	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)

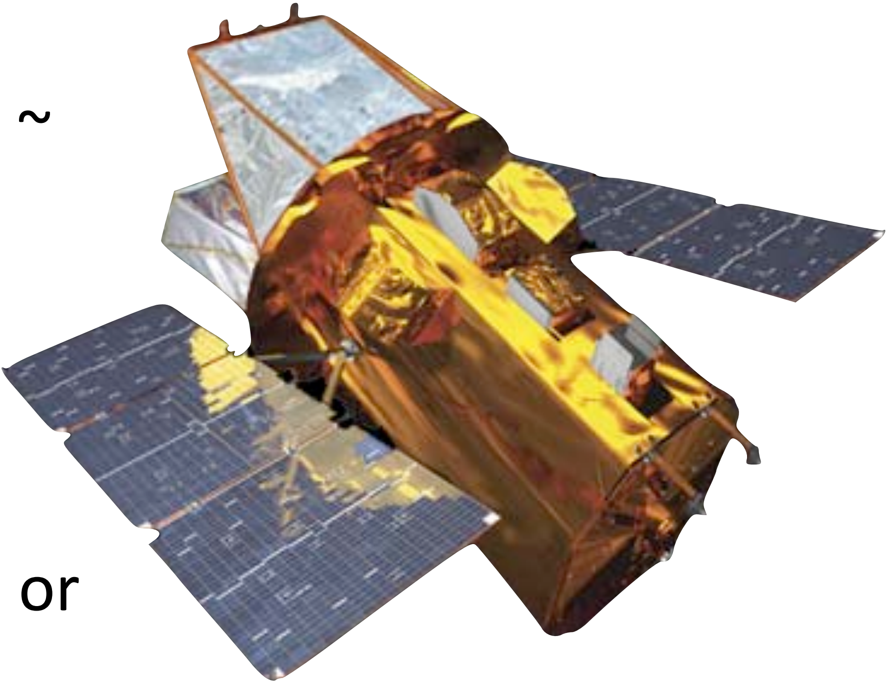
Expected rates: one event per week!

The short GRB / binary inspiral connection

Combining Electromagnetic, Neutrino and Gravitational-Wave Observations

- Possible “triggers” include long and short GRBs, magnetar flares (SGRs and AXPs), radio pulsar glitches, high and low energy neutrinos events, radio transients ...
- Reducing the volume of “search space” with external 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). NB: GW error boxes are tens 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.

Gamma Ray Bursts



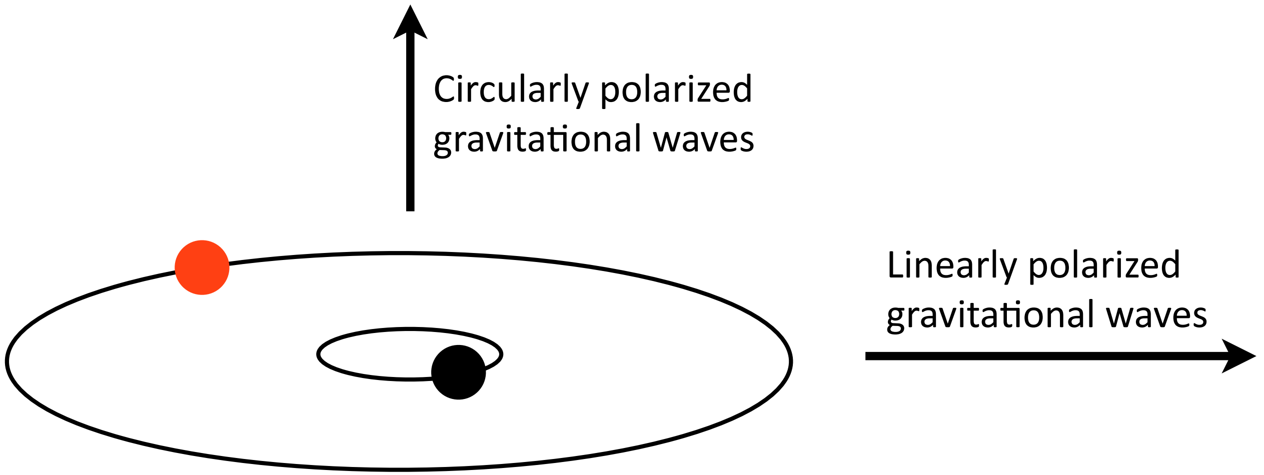
- Oberved for more than 25 years, rate ~ 1/day. Instruments include BATSE, BeppoSAX, HETE-2, SWIFT
- Long GRBs: core collapse of very massive stars
- Short GRBs: likely the result of NS/NS or NS/BH coalesence (Nakar, Phys. Rept. 442: 166-236, 2007). Numerical work (Rezzolla et al. Astrophys. J. 732, L6, 2011) has shown that NS merger produces jet-like structures which could power short GRBs.

Short GRBs and Gravitational Waves in Initial LIGO

- Negative searches for coincidence with inspiral and burst events in LIGO S5 data (137 short GRBs)
- Negative searches for coincidence with inspiral and burst events LIGO/VIRGO S6 data (154 short GRBs)
- The results are **not** surprising. The GRBs come from events at cosmological ~Gpc distances. Even the closest of these is too distant to observe with initial detectors.

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)
- With reasonable assumptions, should observe ~1 coincident GW-GRB event from a NS/BH system every three years (Metzger & Berger, ApJ., 746, 48, 2012)

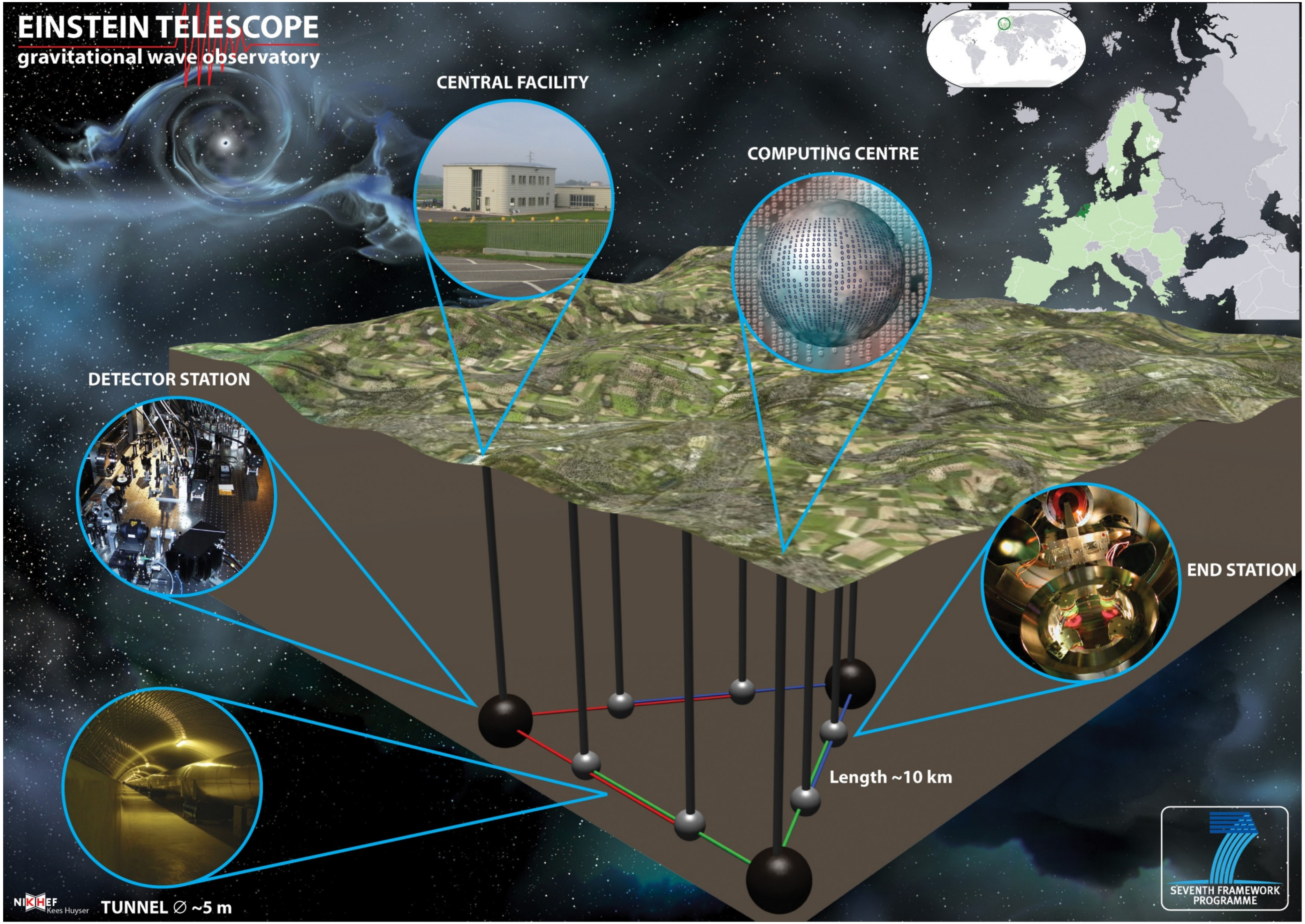


Longer Term

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

Einstein Telescope

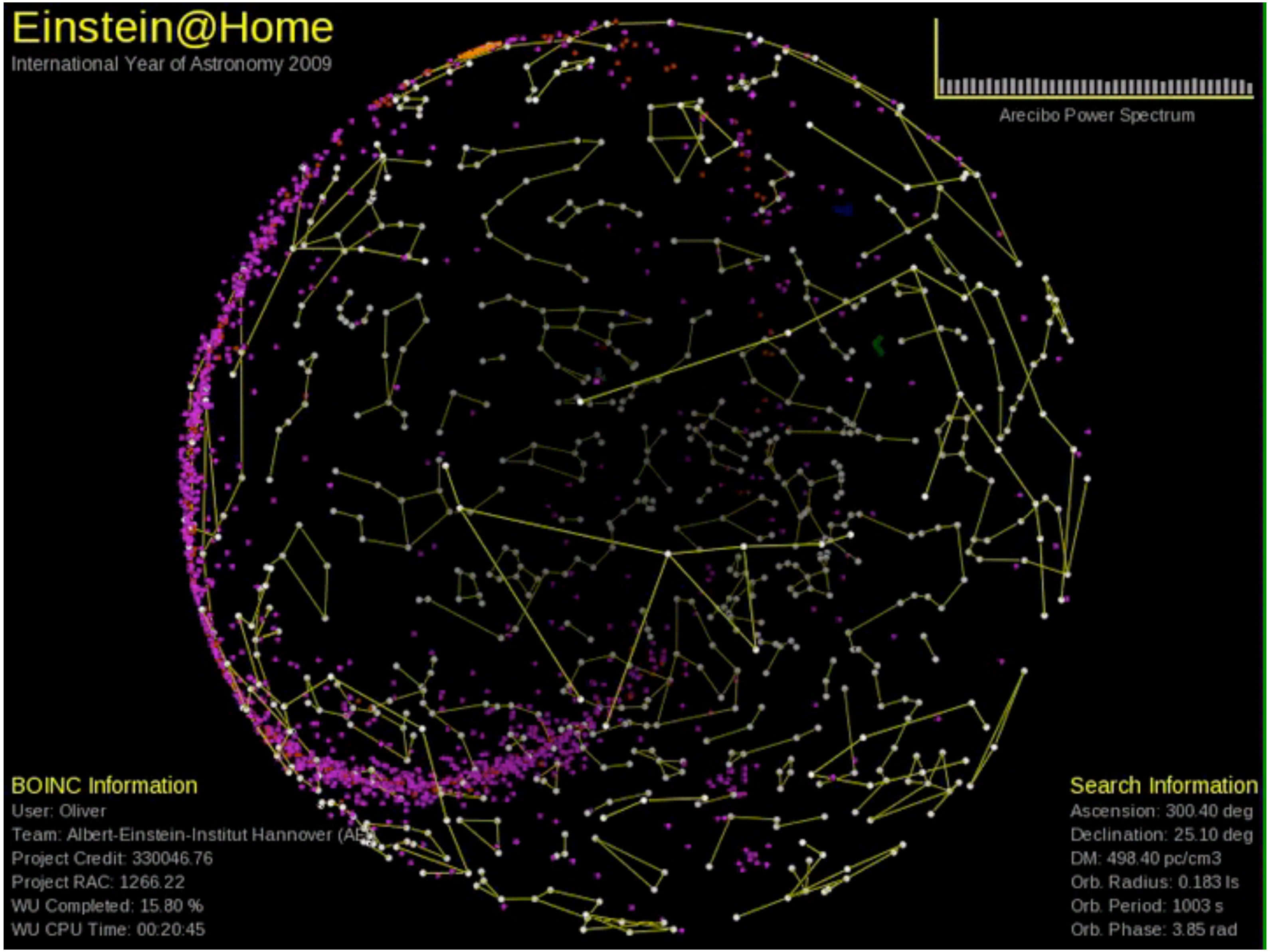


Conclusion

- Gravitational wave detectors are in operation. They have not made detections yet, but can already do interesting science.
- In 3 to 4 years, the LIGO-VIRGO-GEO network should make its first detections.
- Most likely sources: compact binary coalescence. These are also an interesting target for potential simultaneous gamma-ray burst observations
- On the 15 year time-scale, the planned European Einstein Telescope will be sensitive enough to observe **all** NS/NS binary inspirals out to redshift z=2!

THANK YOU!

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



Einstein@Home

International Year of Astronomy 2009

BOINC Information

User: Oliver

Team: Albert-Einstein-Institut Hannover (AE

Project Credit: 330046.76

Project RAC: 1266.22

WU Completed: 15.80 %

WU CPU Time: 00:20:45

Search Information

Ascension: 300.40 deg

Declination: 25.10 deg

DM: 498.40 pc/cm3

Orb. Radius: 0.183 ls

Orb. Period: 1003 s

Orb. Phase: 3.85 rad