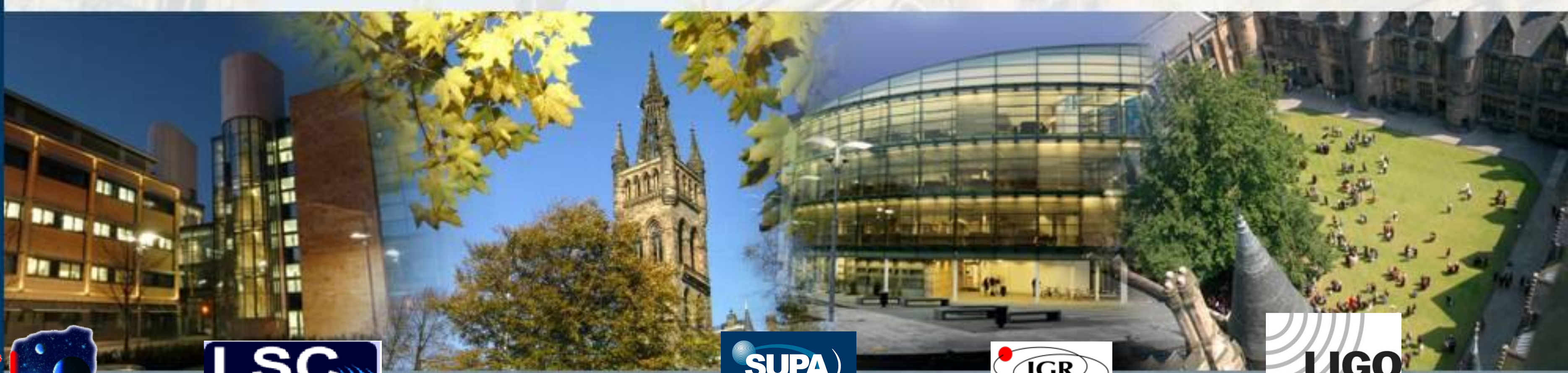
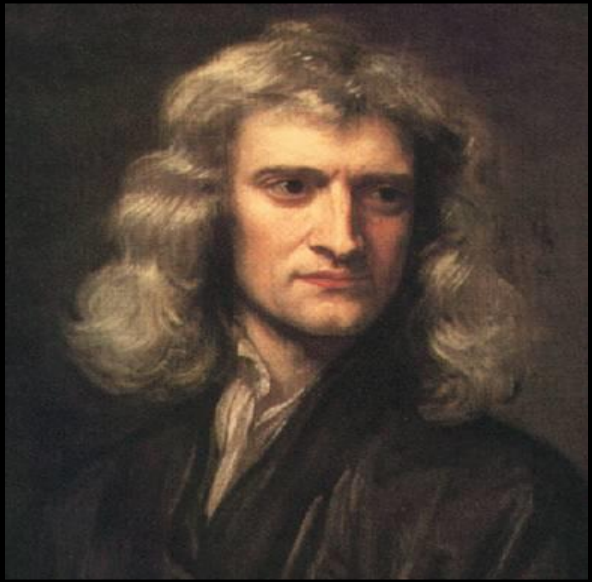
The Search for Gravitational Waves

Prof. Jim Hough
Institute for Gravitational Research
University of Glasgow

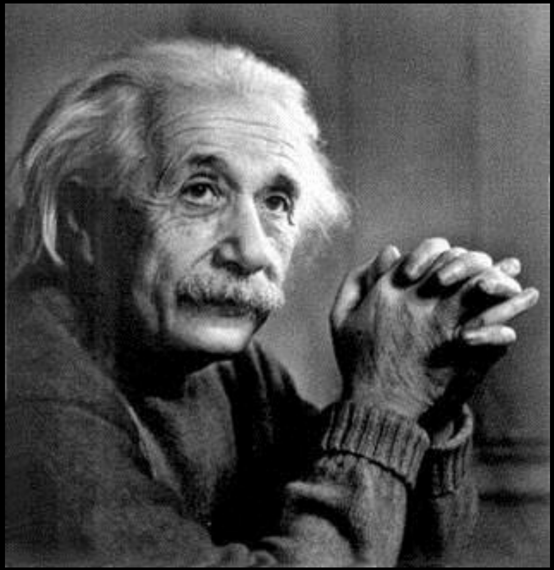


Gravitation



Newton's Theory

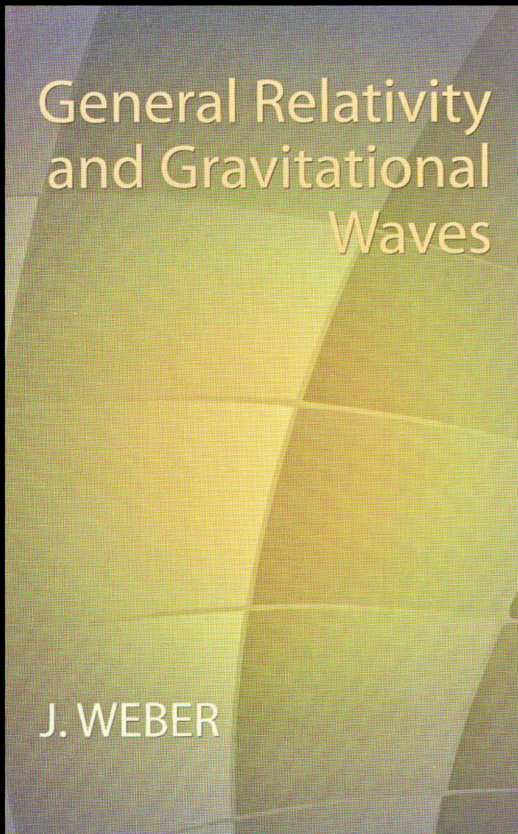
"instantaneous action at a distance"



Einstein's Theory

information cannot be carried faster than speed of light – there must be gravitational radiation

GW a prediction of General Relativity (1916)



GW 'rediscovered' by Joseph Weber

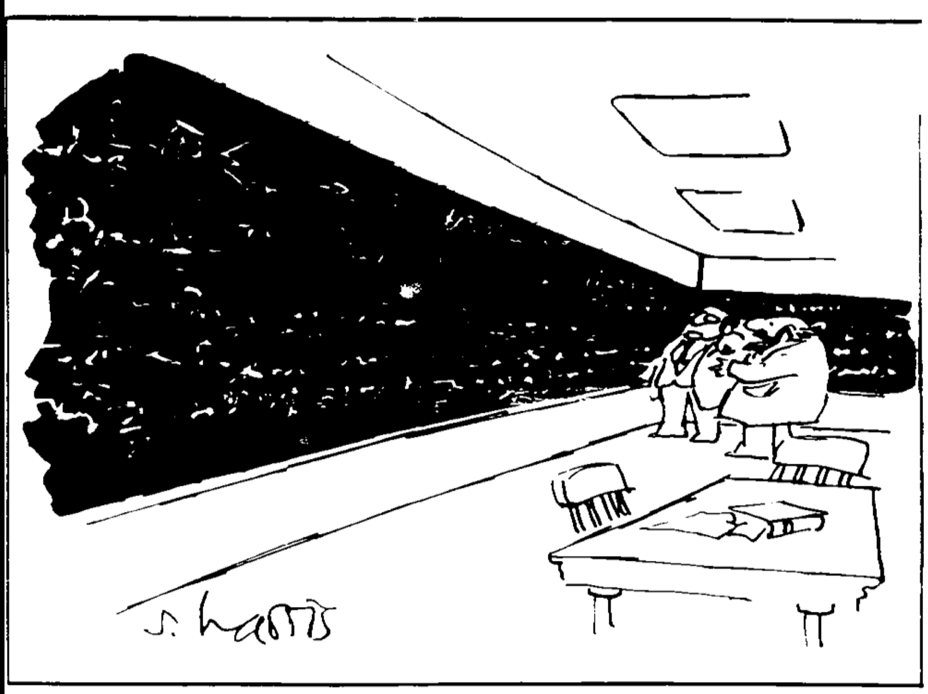
REVIEWS OF MODERN PHYSICS VOL. 29, # 3 JULY, 1957 509–515

Reality of the Cylindrical Gravitational Waves of Einstein and Rosen

JOSEPH WEBER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and University of Maryland, College Park, Maryland*
JOHN A. WHEELER, *Lorentz Institute, University of Leiden, Leiden, Netherlands, and Palmer Physical Laboratory, Princeton University, Princeton, New Jersey*

(1961)

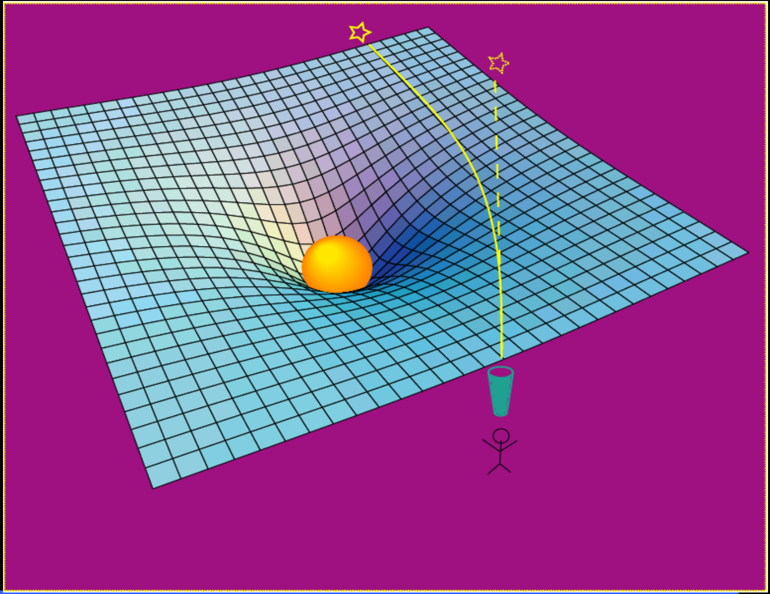
‘Gravitational Waves – the experimentalist’s view’



'But this is just a simplistic way of looking at the problem".

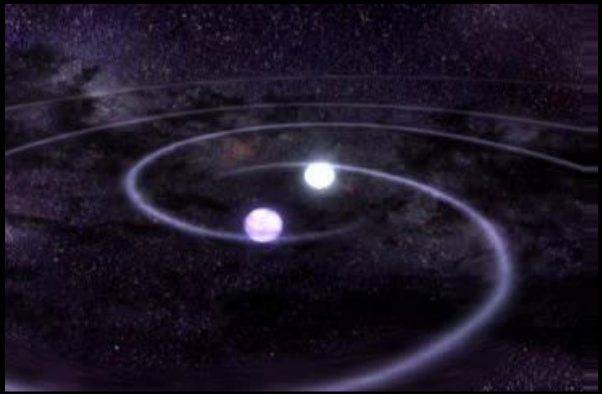
- **Gravitational waves**

  ‘ripples in the curvature of spacetime’ that carry information about changing gravitational fields – or fluctuating strains in space of amplitude *h* where: h ~ ΔL/L

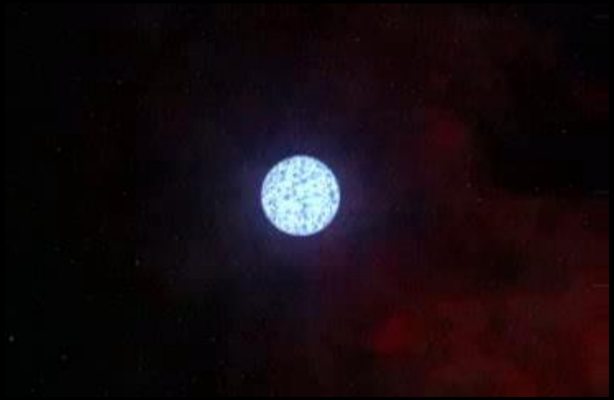


‘Gravitational Waves’- possible sources

- **Pulsed**
  Compact Binary Coalescences
  NS/NS; NS/BH; BH/BH
  Stellar Collapse (asymmetric) to NS or BH
- **Continuous Wave**
  Pulsars
  Low mass X-ray binaries (e.g. SCO X1)
  Modes and Instabilities of Neutron Stars
- **Stochastic**
  Inflation
  Cosmic Strings



Binary stars coalescing



Supernova

Science questions to be answered

Fundamental physics and GR

- *What are the properties of gravitational waves?*
- *Is general relativity the correct theory of gravity?*
- *Is general relativity still valid under strong-gravity conditions?*
- *Are Nature's black holes the black holes of general relativity?*
- *How does matter behave under extremes of density and pressure?*

Cosmology

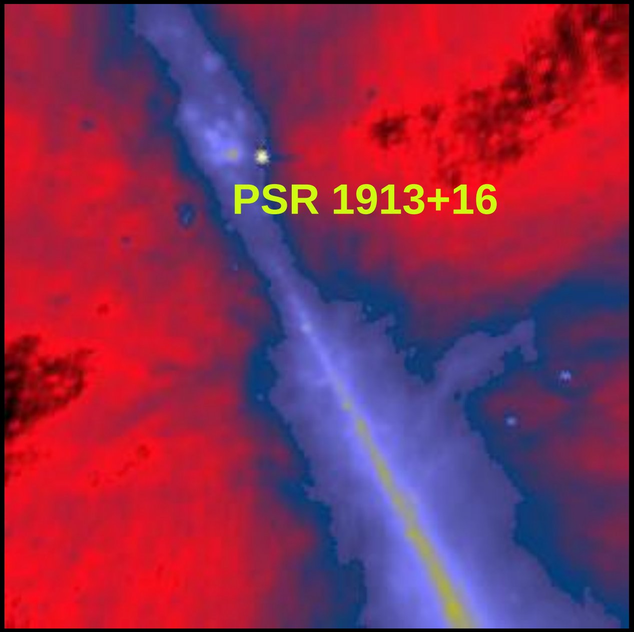
- *What is the history of the accelerating expansion of the Universe?*
- *Were there phase transitions in the early Universe?*

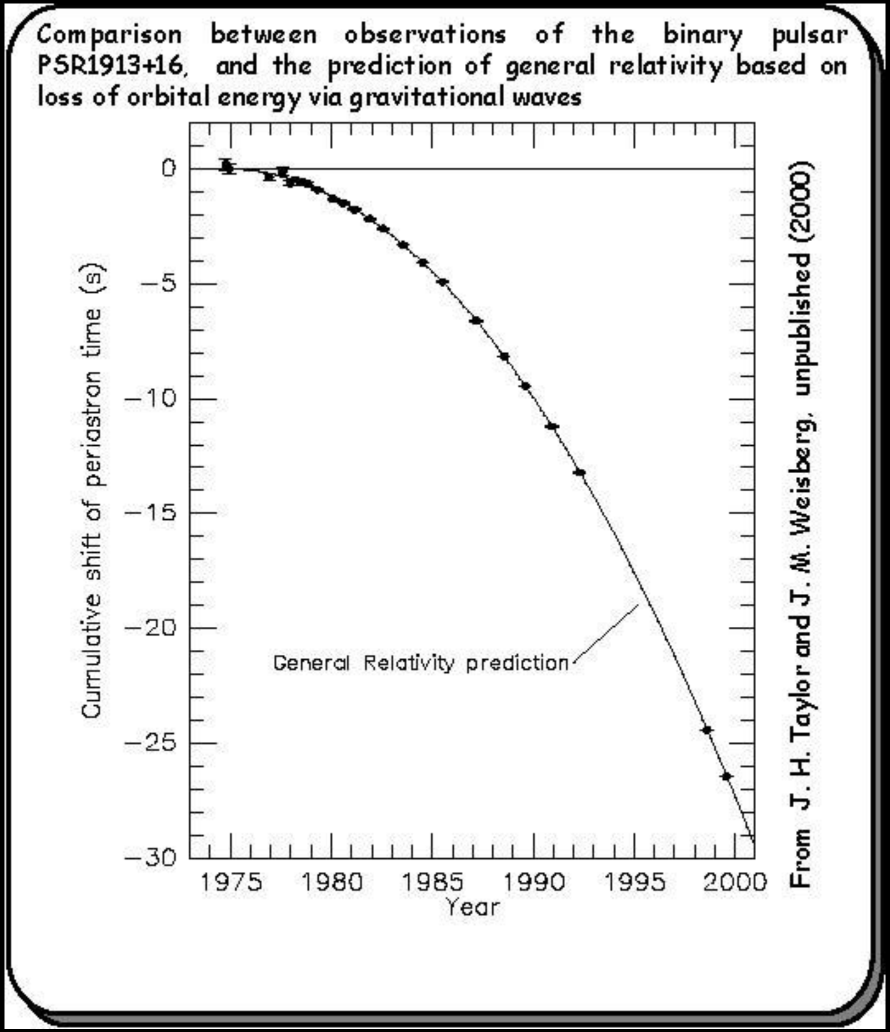
Astronomy and astrophysics

- *How abundant are stellar-mass black holes?*
- *What is the central engine behind gamma-ray bursts?*
- *Do intermediate mass black holes exist?*
- *Where and when do massive black holes form and how are they connected to the formation of galaxies?*
- *What happens when a massive star collapses?*
- *Do spinning neutron stars emit gravitational waves?*
- *What is the distribution of white dwarf and neutron star binaries in the galaxy?*
- *How massive can a neutron star be?*

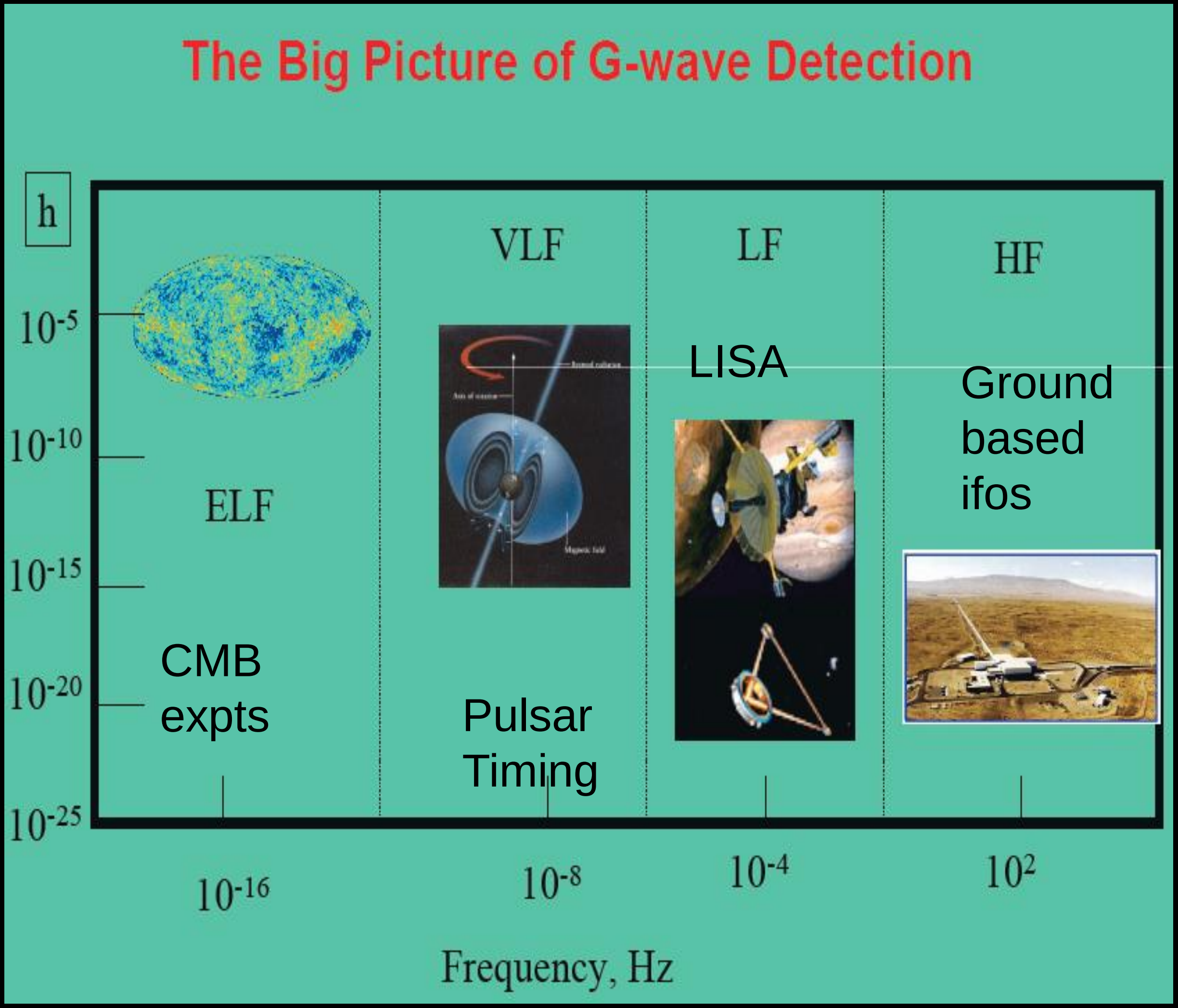
Evidence for gravitational waves

"Indirect"
detection
of gravitational waves





The Gravitational Wave Spectrum



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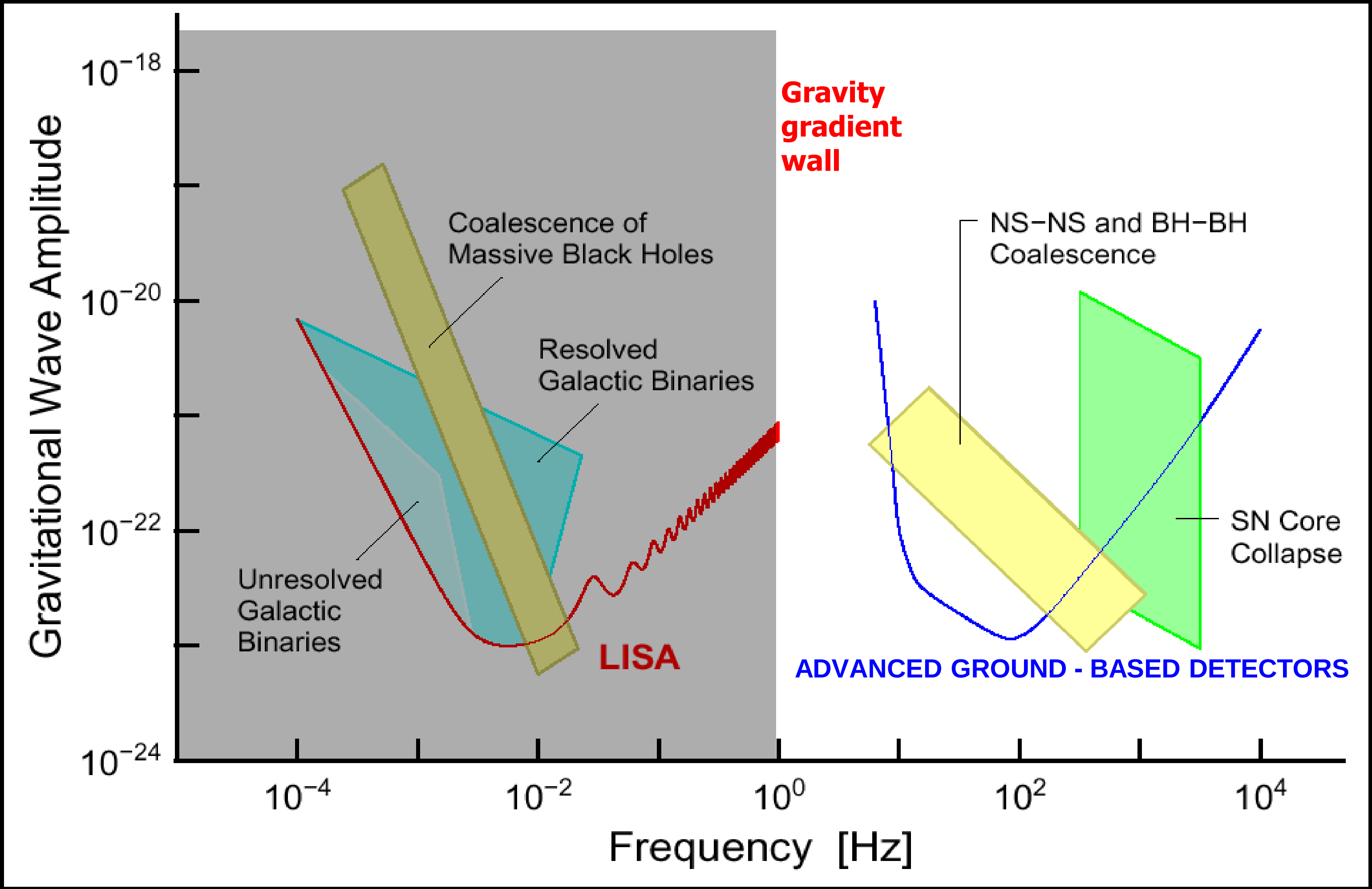
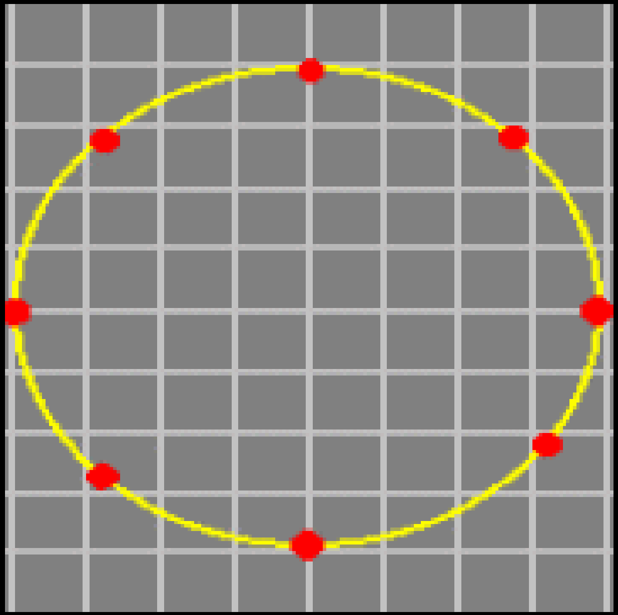
Sources – the gravitational wave spectrum

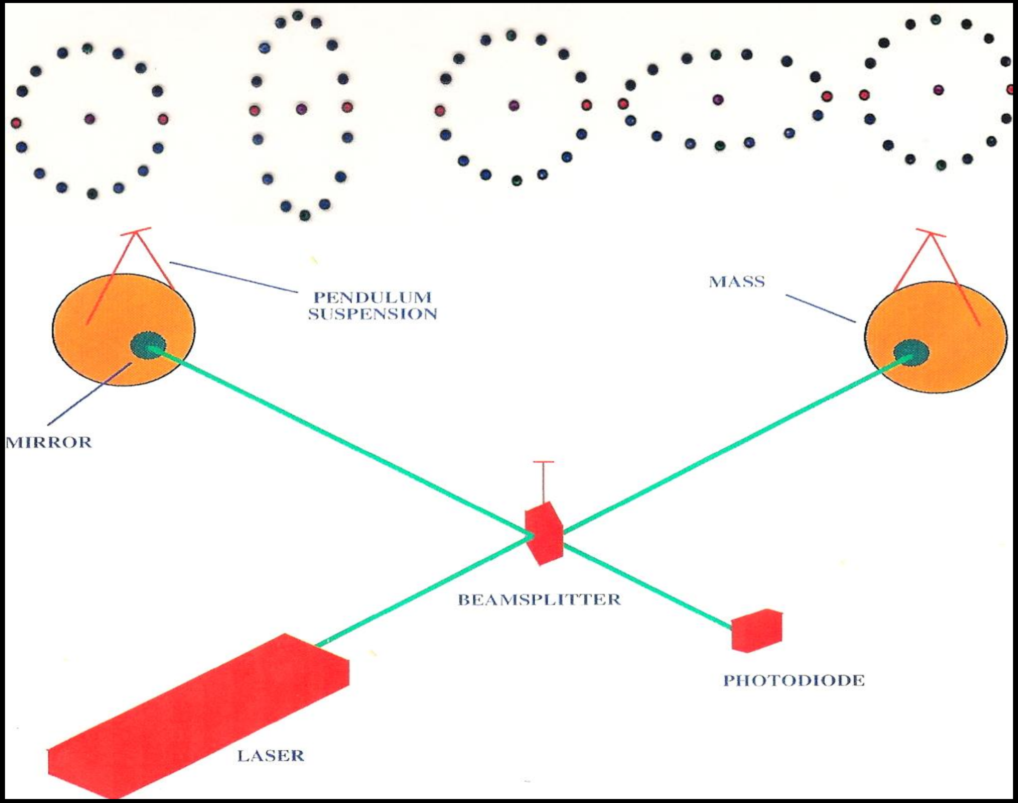


The Effect of Gravitational Waves



Detection of Gravitational Waves

Consider the effect of a wave on a ring of particles :



One cycle

Michelson Interferometer

Gravitational waves have very weak effect: Expect movements of less than 10^{-18} m over 4km

Principal limitations to sensitivity ground based detectors

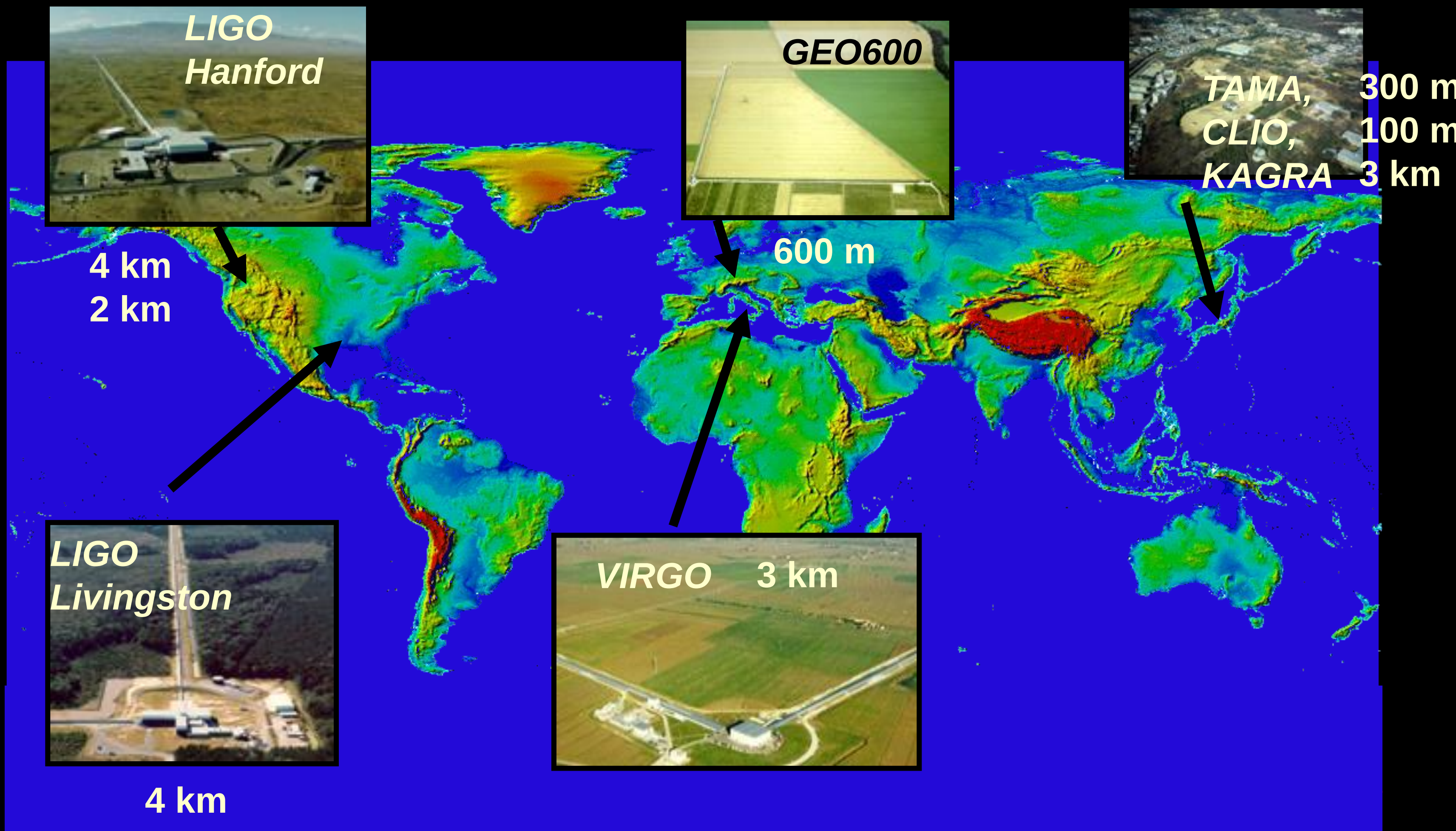
- Photon shot noise (improves with increasing laser power) and
  radiation pressure (becomes worse with increasing laser power)

  There is an optimum light power which gives the same limitation expected by application of the Heisenberg Uncertainty Principle - the 'Standard Quantum limit'

- Seismic noise (relatively easy to isolate against – use suspended test masses)
- Gravitational gradient noise, – particularly important at frequencies below ~10 Hz
- Thermal noise – (Brownian/thermo-elastically induced motion of test masses and suspensions) – need materials of ultra-low mechanical loss

All point to long arm lengths being desirable and projects were planned and built in the US (LIGO), Europe (Virgo and GEO 600) and Japan (TAMA 300)

Worldwide Network of Interferometers

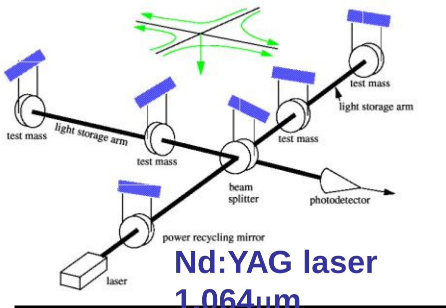


Initial LIGO detectors

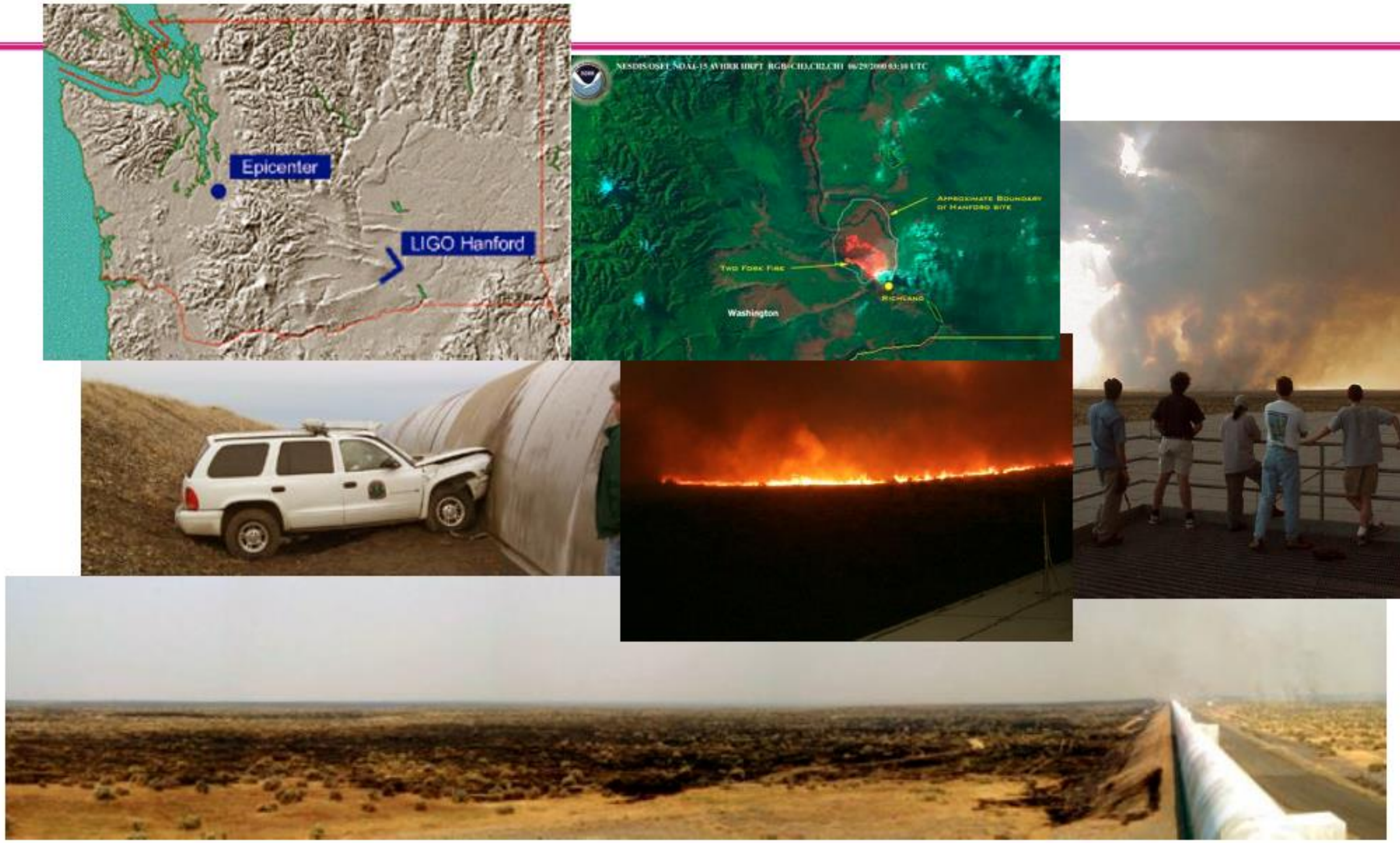
LIGO project (USA)

- 2 detectors of 4km arm length + 1 detector of 2km arm length
- Washington State and Louisiana

Each detector is based on a 'Fabry-Perot – Michelson'



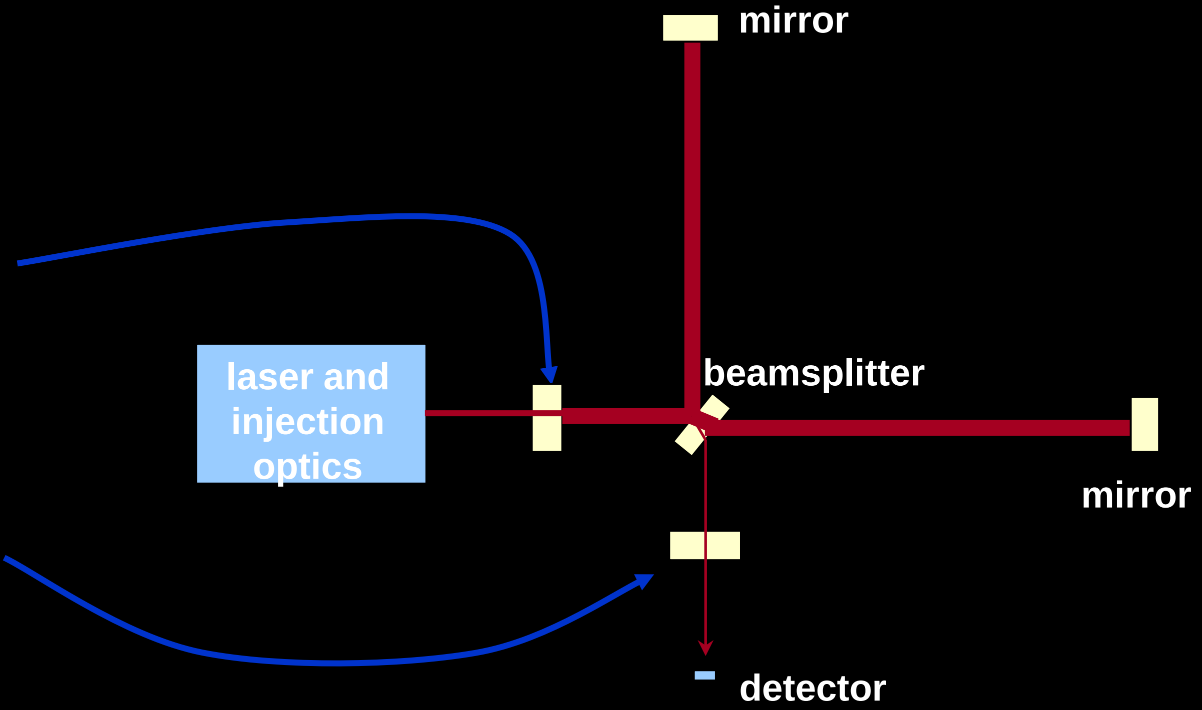
It's never as easy as it looks…



GEO 600

Unique GEO Technology 1 - Advanced Interferometry

- One of the fundamental limits to interferometer sensitivity is photon shot noise
- Power recycling effectively increases the laser power
- Signal recycling – a GEO invention – trades bandwidth for improved sensitivity



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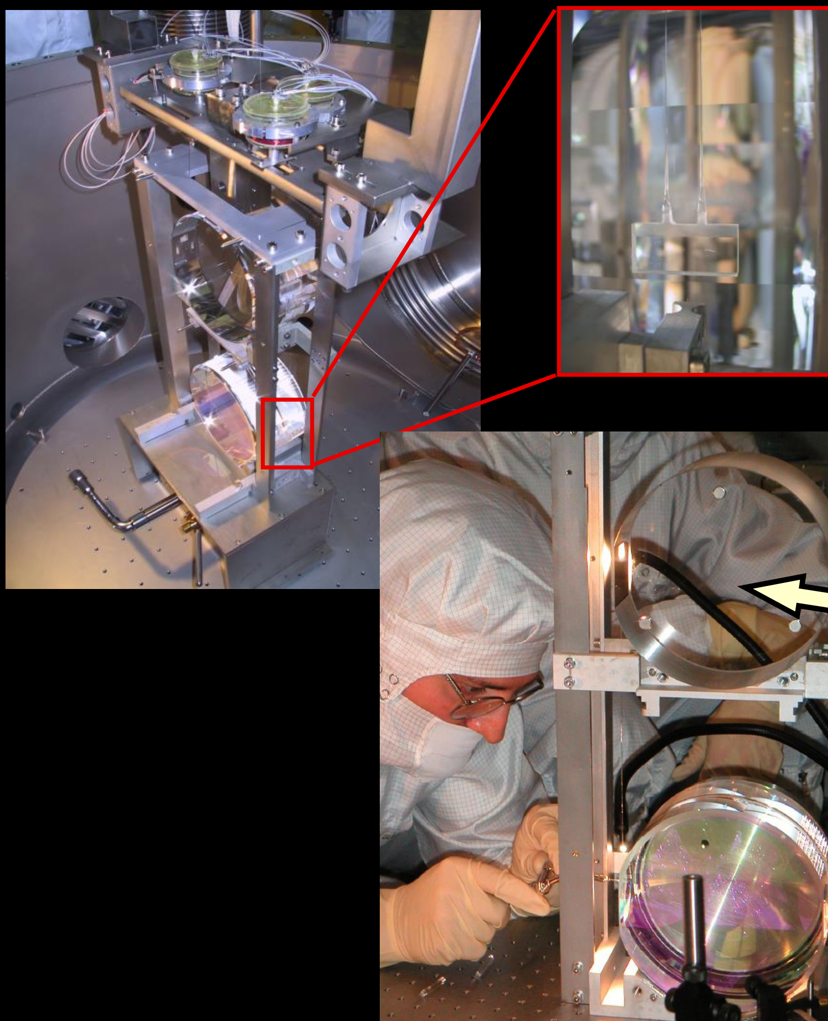
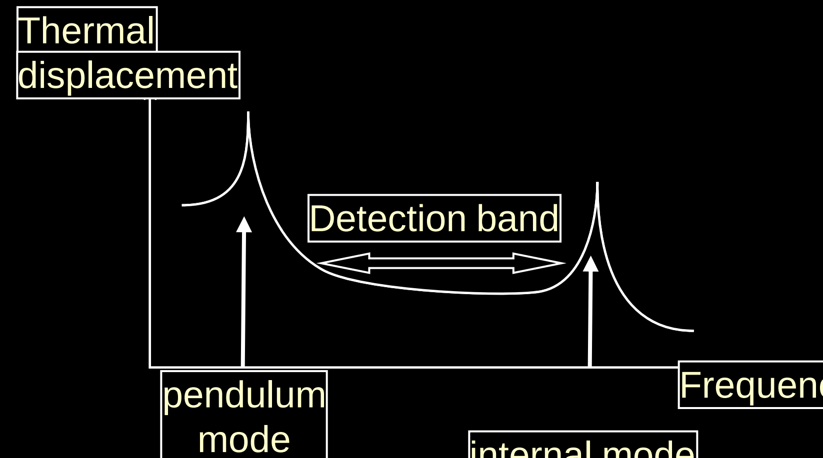
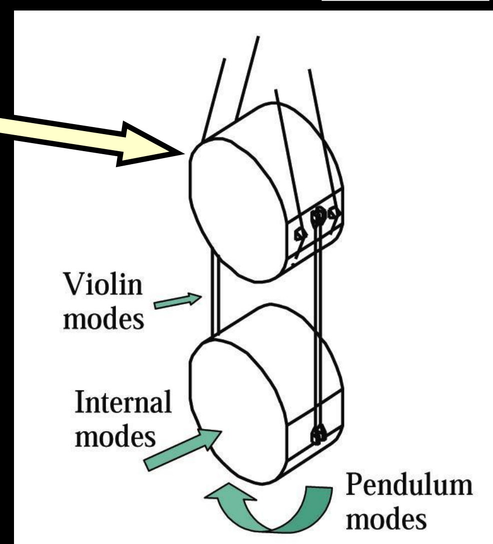
Unique GEO Technology 2 - Monolithic Silica Suspension



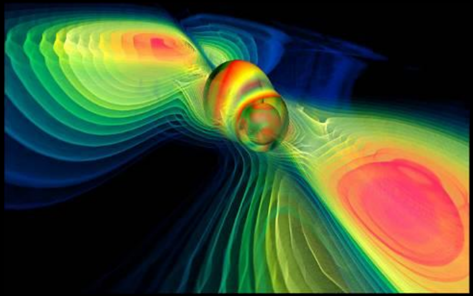


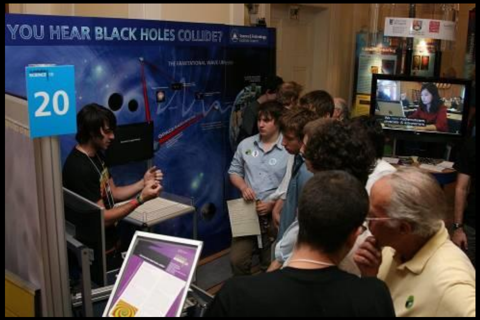


Ultra-low mechanical loss suspension at the heart of the interferometer

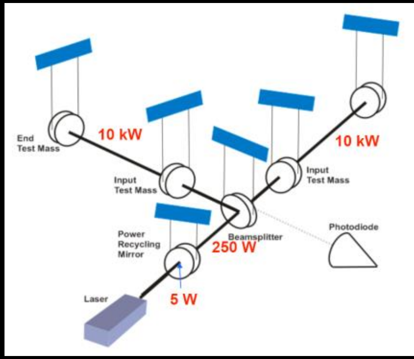
GEO 600 LSC SUPA IGR LIGO

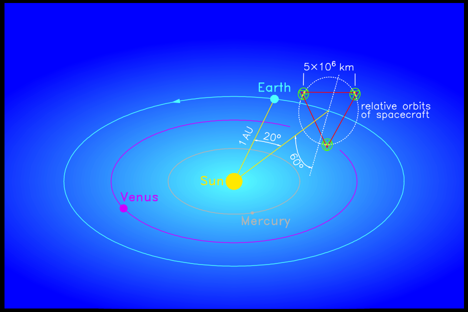
Real Progress in field over last few years



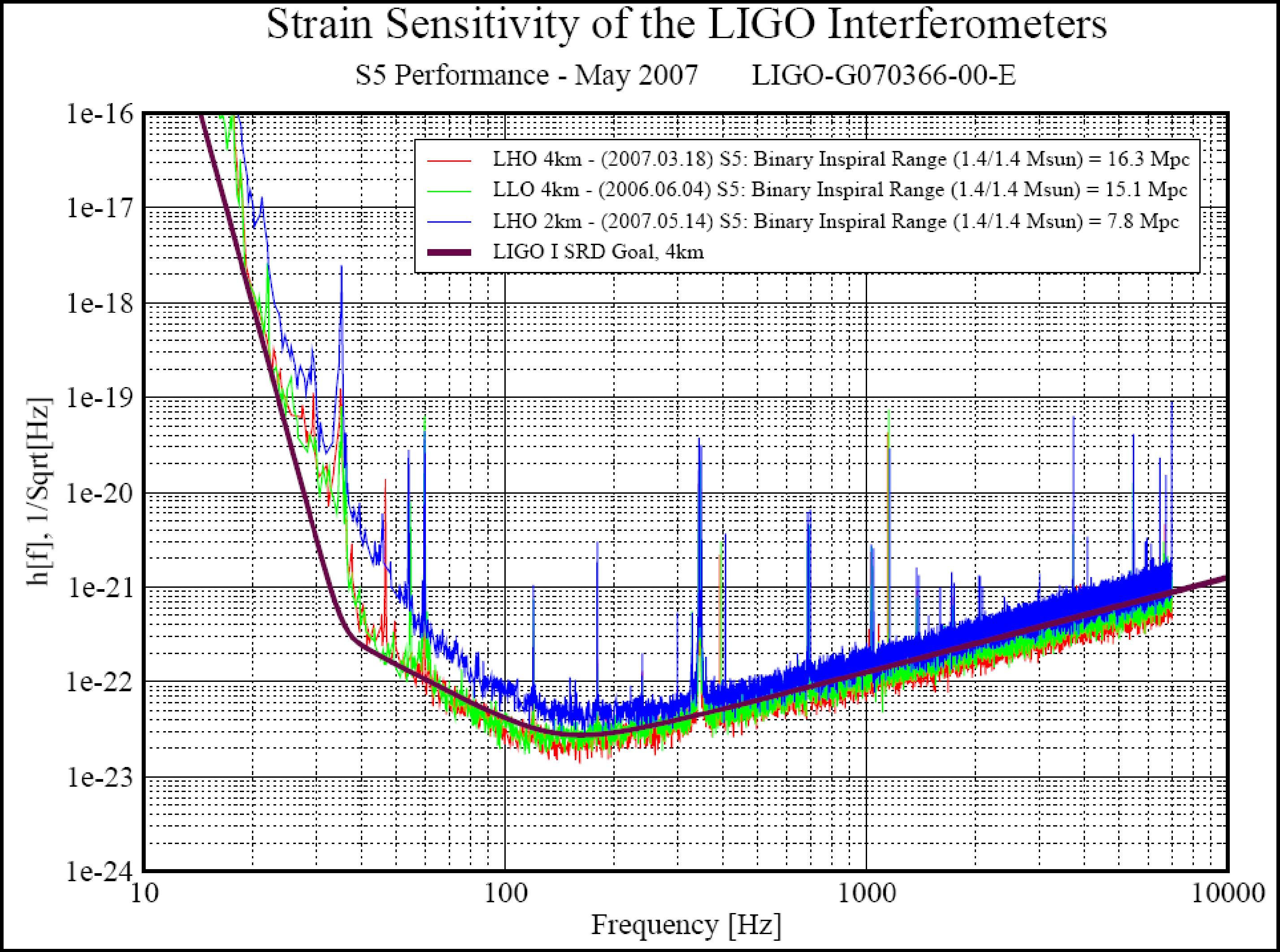


- Operation of six ground based interferometers (in addition to three cryogenic bar detectors)
- Waveform Predictions from Numerical Relativity
- Significant advances in Space Borne Detectors – Pathfinder for LISA due to launch in 2015
- Pulsar Timing coming to the fore
- Importance of Multi-messenger Astronomy



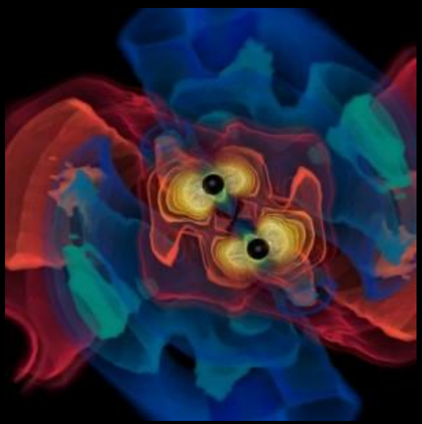


Current Status 1 -LIGO reached design sensitivity



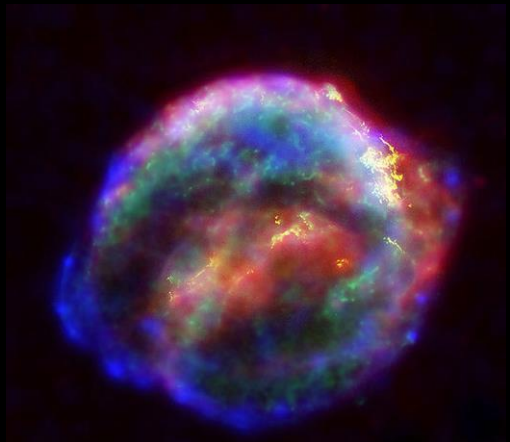
Current status 2

- Initial Science Runs Complete (LIGO, Virgo, GEO 600, TAMA)
- Upper Limits set on a range of sources (no detections as yet)


Credit: AEI, CCT, LSU

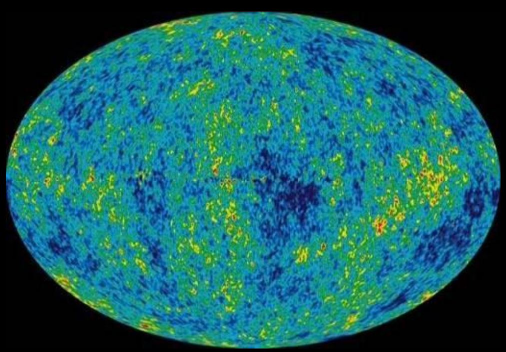
Coalescing Binary Systems

- Neutron stars, low mass black holes, and NS/BS systems


Credit: Chandra X-ray Observatory

Bursts'

- galactic asymmetric core collapse supernovae
- cosmic strings
- ???


NASA/WMAP Science Team

Cosmic GW background

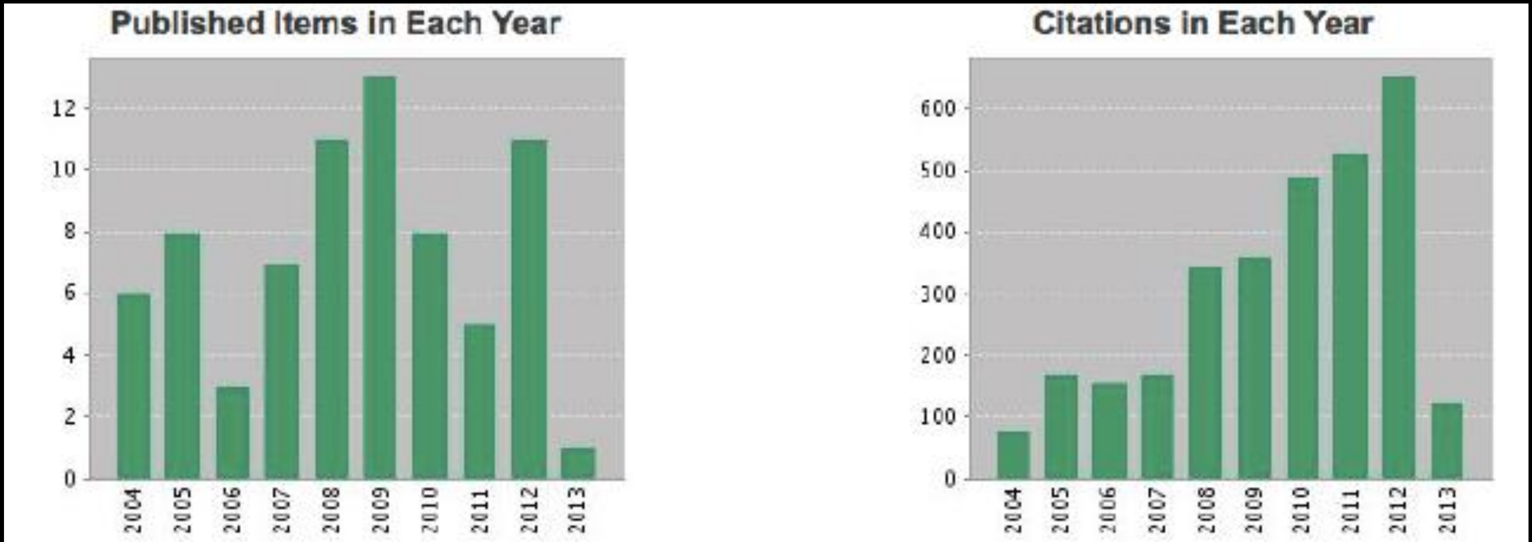
- stochastic, incoherent background
- unlikely to detect, but can bound in the 10-10000 Hz range


Casey Reed, Penn State

Continuous Sources

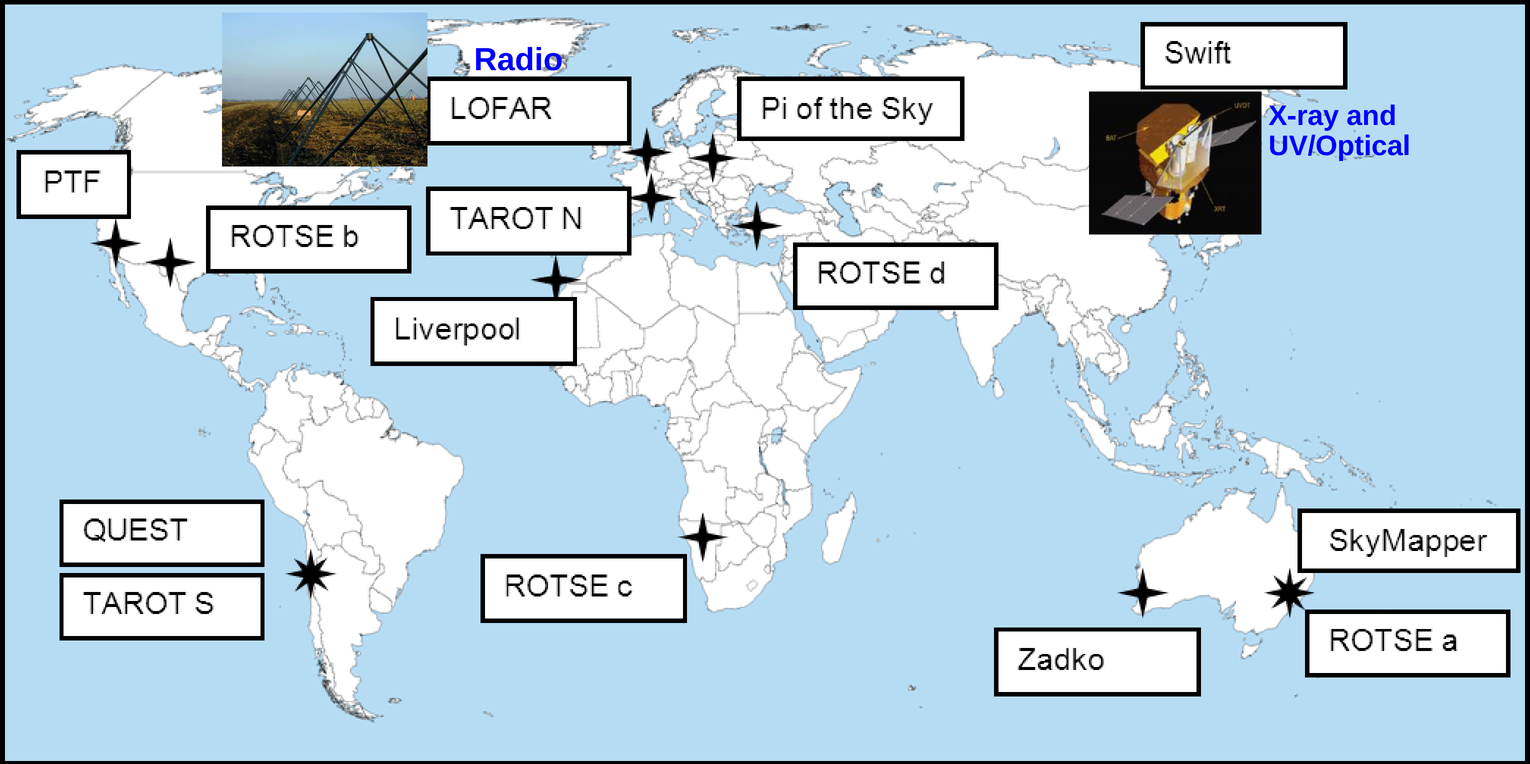
- Spinning neutron stars
- probe crustal deformations, 'quarki-ness'

LSC Output



Published Items in Each Year
0
2
4
6
8
10
12
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
Citations in Each Year
0
100
200
300
400
500
600
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013

Observing Partners During 2009-2010



- Mostly (but not all) robotic wide-field optical telescopes
  - Many of them used for following up GRBs and/or hunting for supernovae
- Nine event candidates in latest LIGO/Virgo data runs, 3 followed up by at least one scope

Current status 3

- 2nd generation
  - Advanced LIGO under construction (x10 to 15 improved sensitivity, operational ~2014)
  - Advanced Virgo under construction, operation on same timescale
  - GEO upgraded to use ‘squeezed light’ to reduce photon noise and operating to maintain ‘astrowatch’ while LIGO and Virgo being upgraded

For Comparison:

- Neutron Star Binaries:
  - Initial LIGO (S5): ~15 Mpc → rate ~1/50yr
  - Adv LIGO: ~ 200 Mpc → rate ~ 40/year
- Black Hole Binaries (Less Certain):
  - Initial LIGO (S5): ~100 Mpc → rate ~1/100yr
  - Adv LIGO: ~ 1 Gpc → rate ~ 20/year

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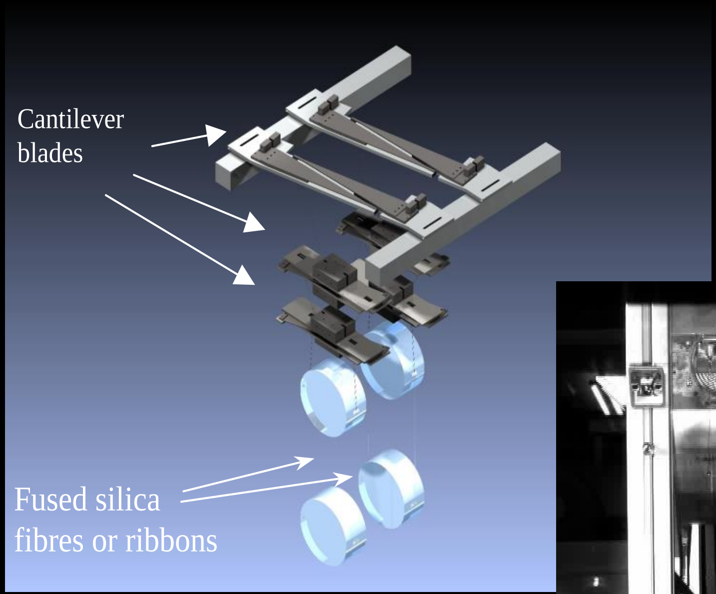
Advanced LIGO - major GEO involvement

Achieve x10 to x15 sensitivity improvement:

GEO technology being applied to LIGO

- silica suspensions
- more sophisticated interferometry
- more powerful lasers from colleagues in Hannover

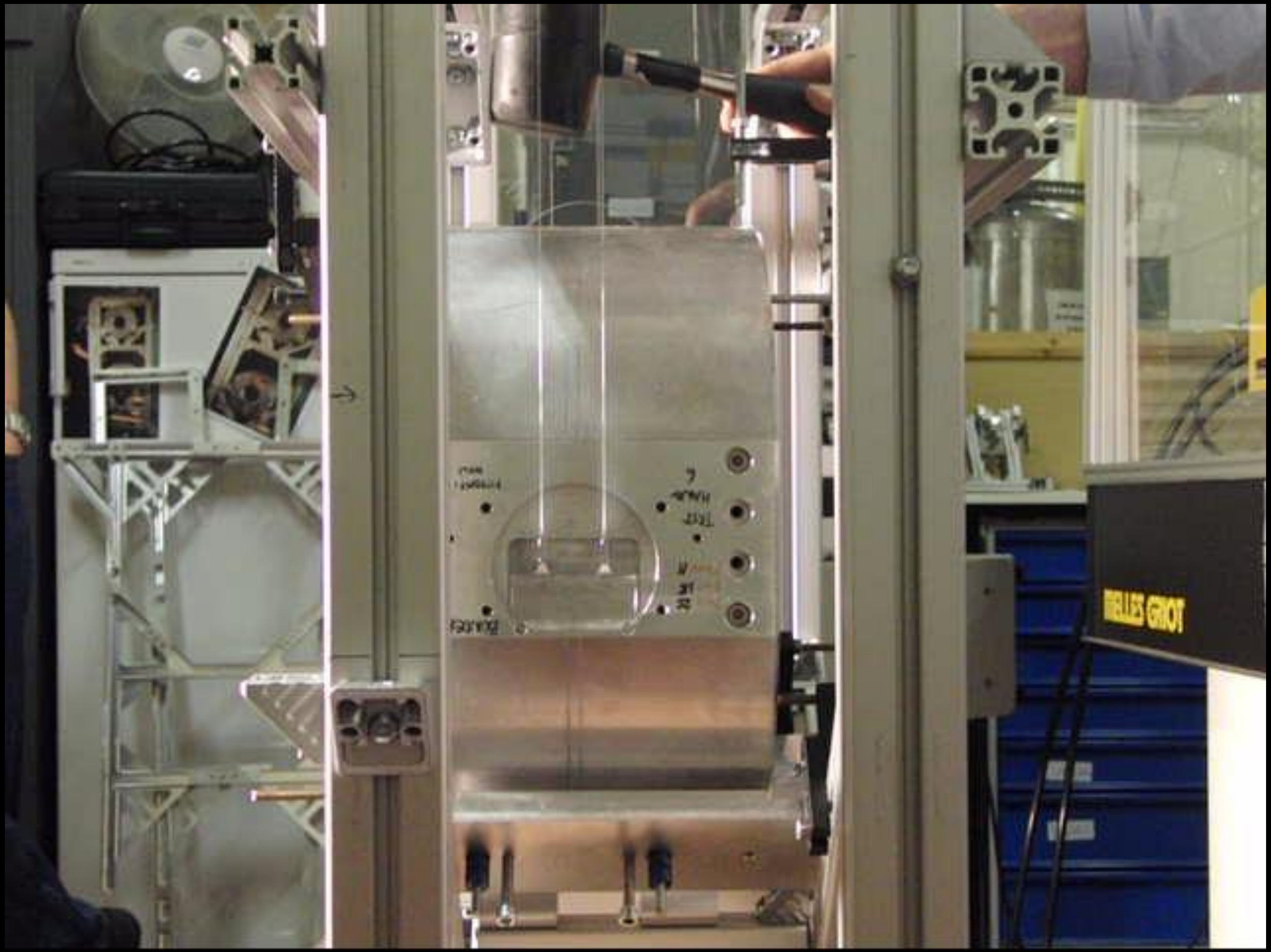


Plus active isolation, high power optics and other input from US groups

RAL, University of Birmingham and University of Glasgow play essential roles in this work

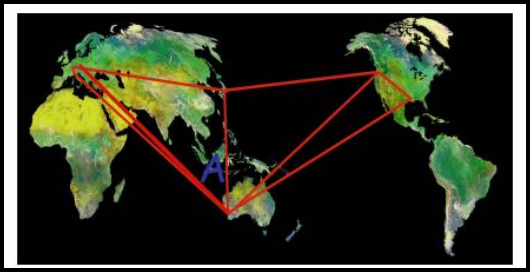
GEO 600 LSC SUPA IGR LIGO

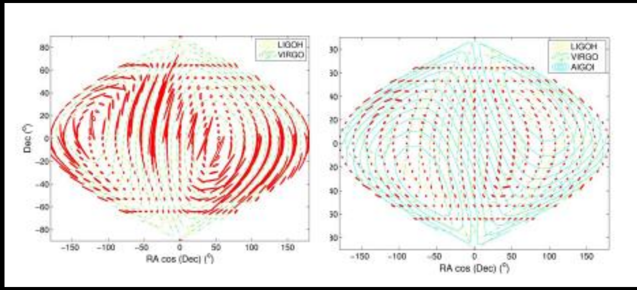
Suspension testing



But Further

Need a network of detectors for good source location and improve overall sensitivity





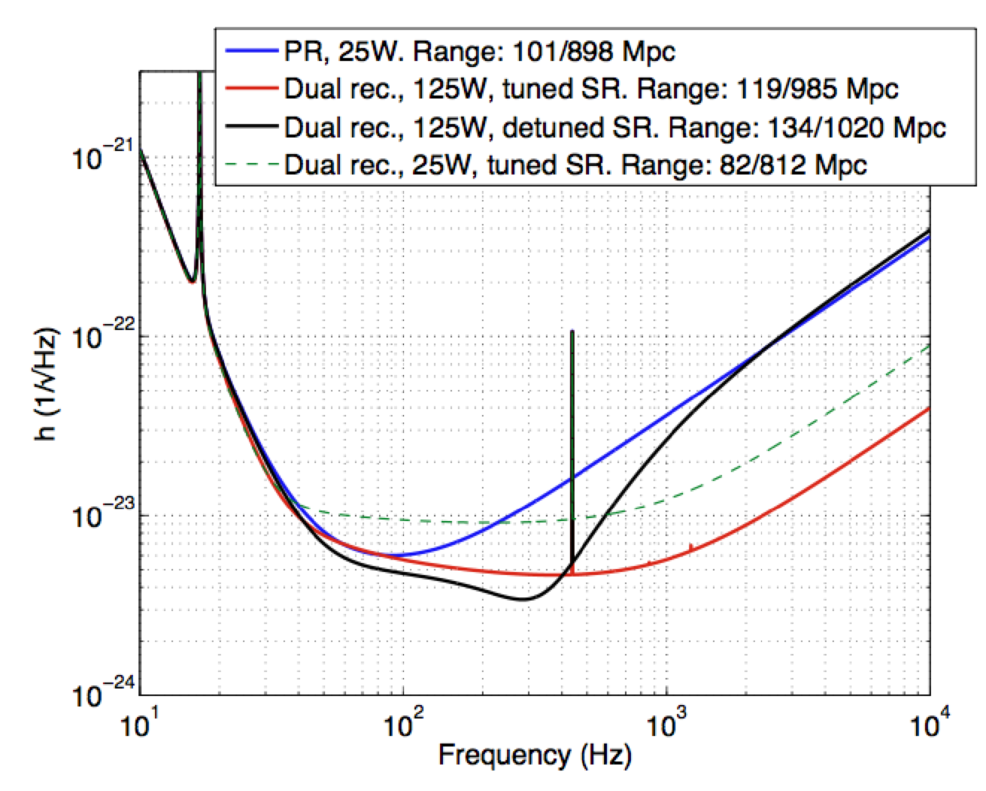
Second Generation Network

Advanced LIGO/Advanced Virgo/Geo-HF/KAGRA/LIGO India

- KAGRA under construction (initial phase) (cryo, underground interferometer in Kamioka mine)
- LIGO India plans progressing

Advanced Virgo

- Design sensitivity goal:
  - NS/NS merger: 134 Mpc
  - BH/BH merger: 1020 Mpc
- Low and high power operational modes
- Currently being installed at the Virgo Observatory in Cascina
- Science operations scheduled to begin in 2015
  - Full power dual-recycled operation in 2017



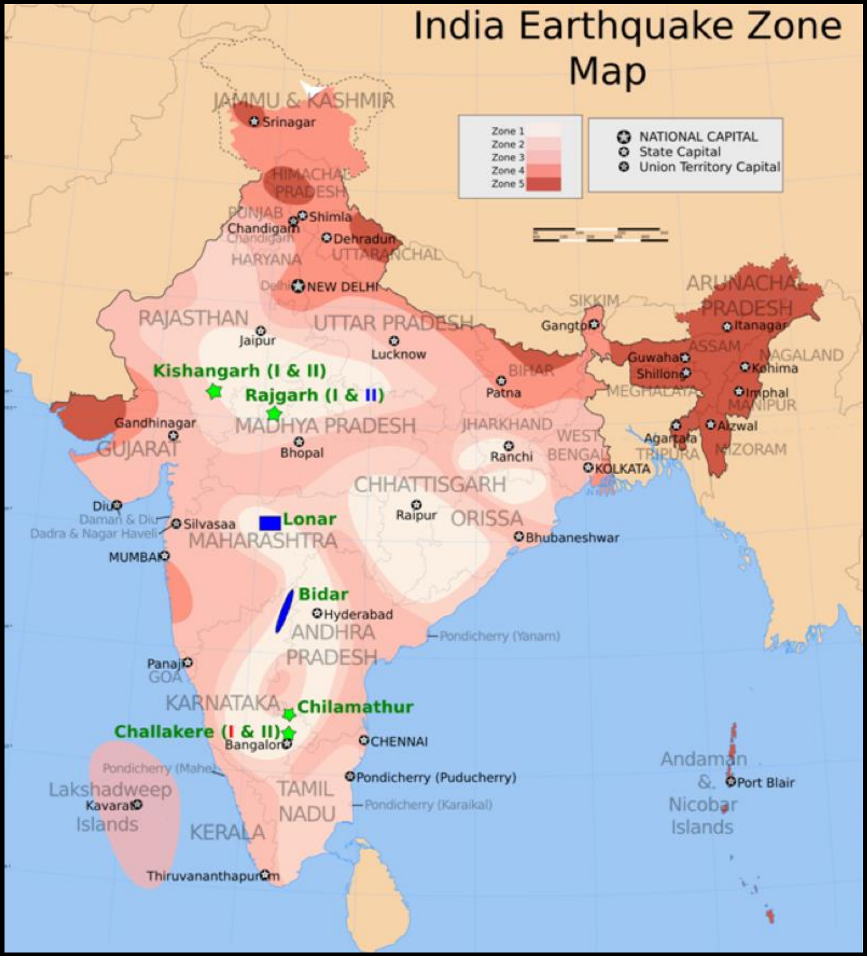
Advanced Virgo Reference Design: https://tds.ego-gw.it/itf/tds/file.php?callFile=VIR-0128A-12.pdf

KAGRA

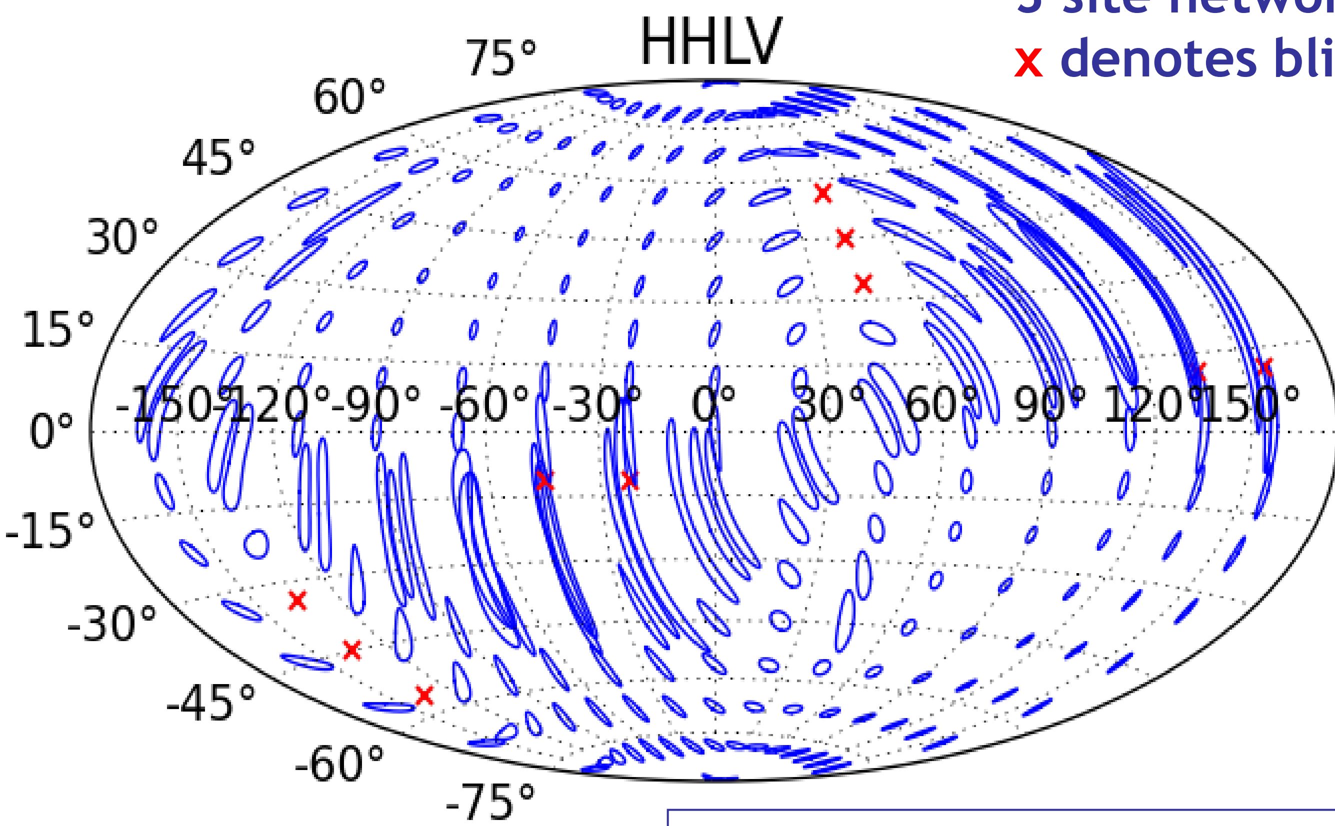
- New Japanese interferometer
- Innovative design features
  - Located underground in the Kamioka mine → Better immunity to seismic motion
  - Incorporates sapphire cryogenic test masses → Lower thermal noise
- Design sensitivity: 270 Mpc for NS/NS mergers
- Funding in 2010; tunnel construction begun in March 2012
- Planned high sensitivity science operations in 2018

LIGO-India

- For the past year, the LIGO Laboratory and the IndIGO consortium have been advancing a project to locate an Advanced LIGO interferometer in India
- Strong science driver → greatly improved sky localization of gravitational-wave events w.r.t. baseline Advanced LIGO
- The project in a nutshell: a direct partnership between LIGO Laboratory, Indian Laboratories, and IndIGO to build a LIGO interferometer in India



Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo



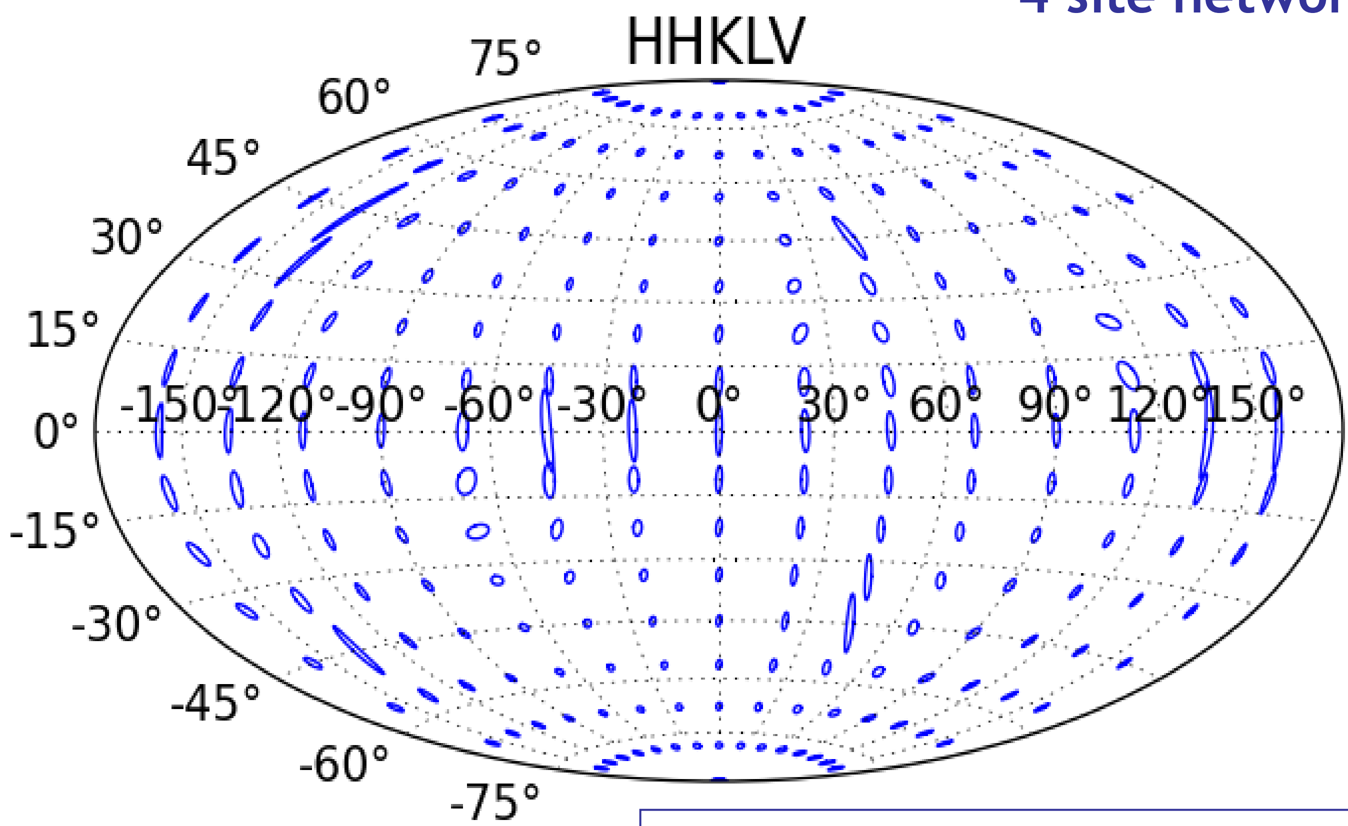
3 site network

x denotes blind spots

S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-KAGRA

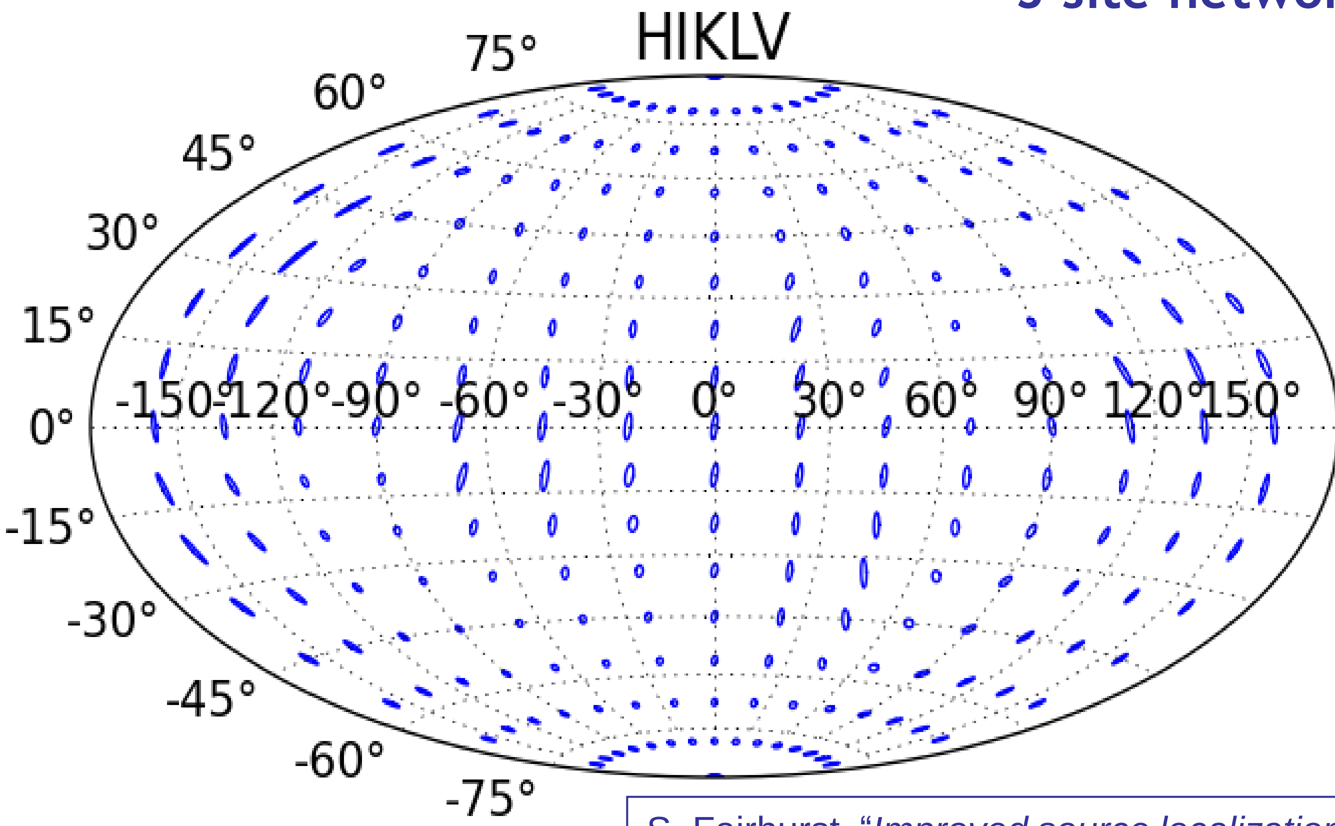
4 site network



S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo-India-KAGRA

5 site network

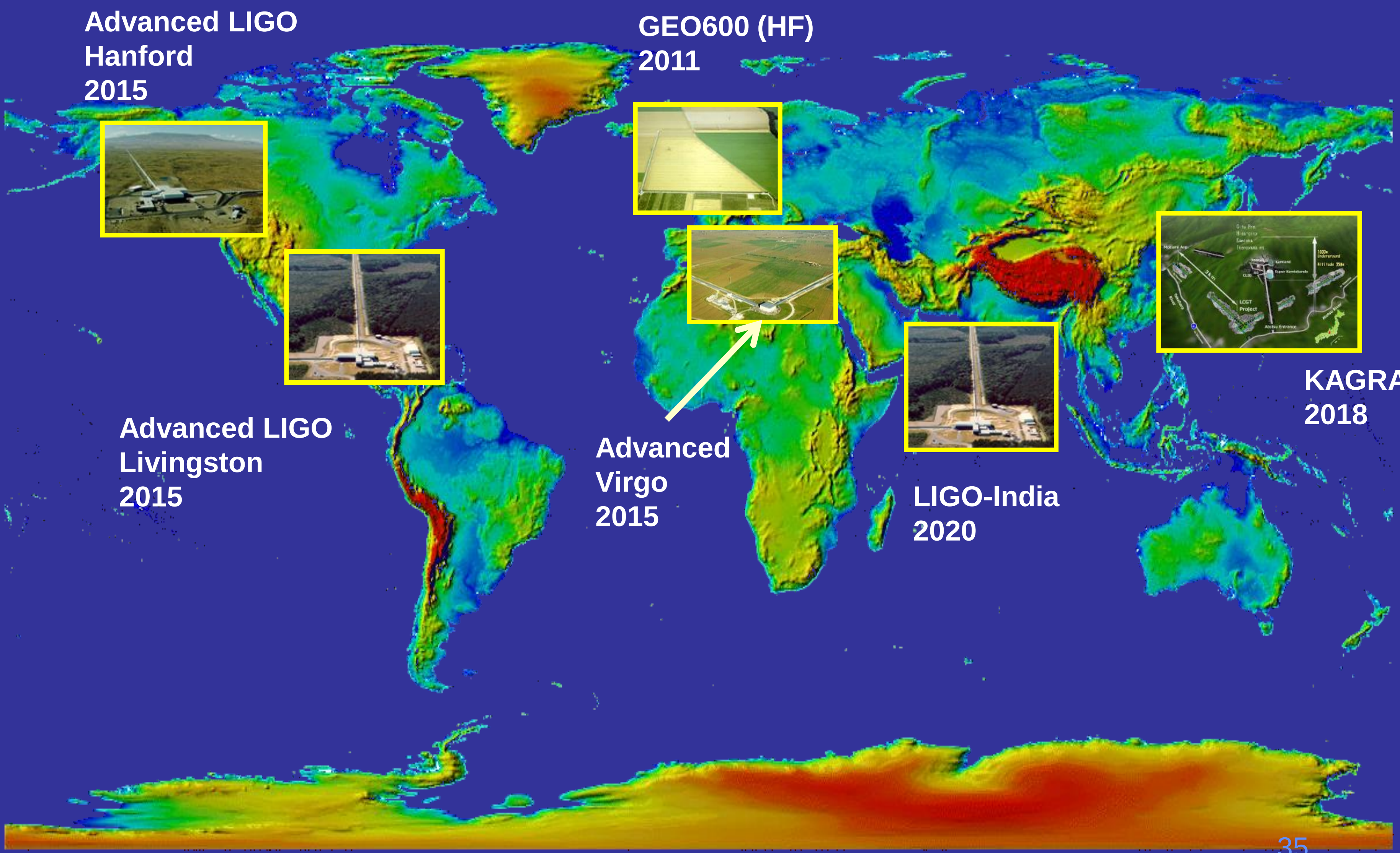


S. Fairhurst, "*Improved source localization with LIGO India*", arXiv:1205.6611v1

Status of LIGO-India

- Excellent progress in moving forward on the Indian and US sides!
- India
  - LIGO-India identified as a 'Mega-Science Project' in the XIIth Plan Commission Report
    - Referred to Cabinet of the Government of India for funding
  - Inter-University Centre for Astronomy and Astrophysics (IUCAA), Raja Ramanna Centre for Advanced Technology (RRCAT), and Institute for Plasma Research (IPR) taking on leading roles in India
  - Site selection/characterization has begun
- USA
  - LIGO Laboratory is holding off installation of second Advanced LIGO interferometer at Hanford for use in India
    - Development of plans
  - Positive reviews of LIGO-India National Science Foundation; process for final approval by the National Science Board has begun
  - LIGO-India featured as one of three major cooperative large scale science project at the US State Department Second Indo-US Joint Commission Meeting on Science and Technology Cooperation
- Expect formal project approval on both sides later this year
- LIGO-India will be operating early in the next decade

The advanced GW detector network



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Plans

What does the LSC plan to do?

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	% BNS Localized within 5 deg^2	20 deg^2
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	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 70	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Including:

- Make sure DQ is good (2015+)
- Promptly analyze the data (2015+)
- Find GWs (2016?)
- Promptly publish results
- Prepare trigger release
- Follow up GWs (2016+?)
- Prepare data release

And be ready with 3rd gen!

GEO 600 LSC SUPA IGR LIGO

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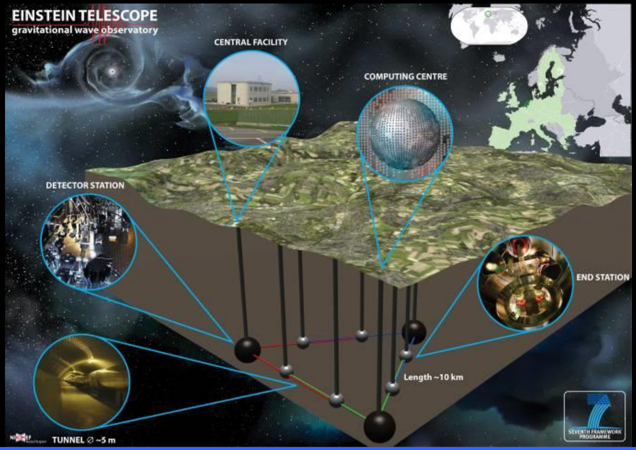
The Next Generation

Third Generation Network –

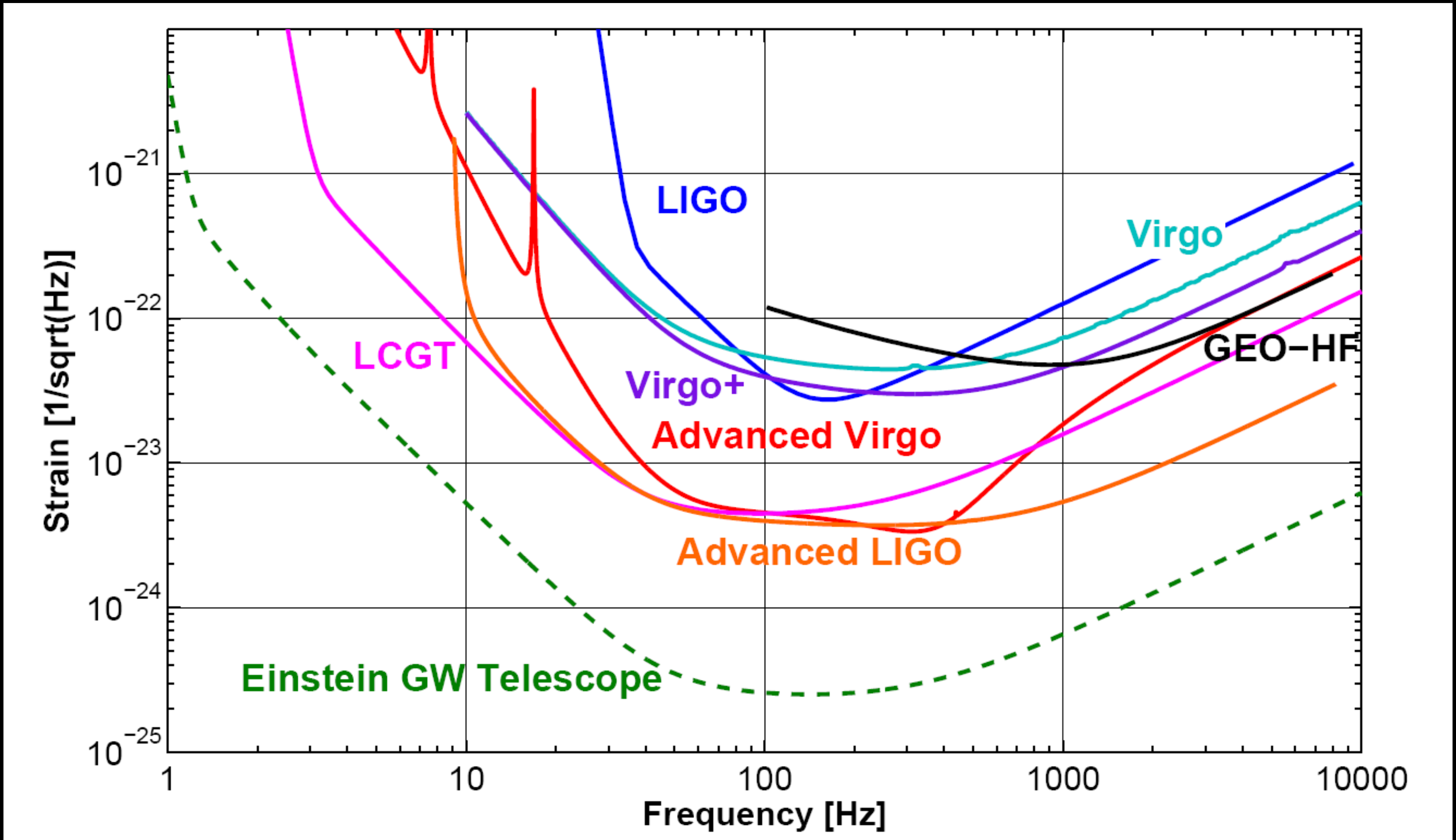
- *Upgrades to aLIGO and aVirgo to further improve sensitivity*
- *Third-generation underground facilities aimed at having excellent sensitivity from ~1 Hz to ~10^4 Hz.*

For LIGO a range of designs – both room temperature and cryogenic are being considered for the future

In Europe, a three year-long design study for a third-generation gravitational wave facility, the Einstein Telescope (ET), has been carried out with funding from the European Union. Goal: 100 times better sensitivity than first generation instruments.



The current and planned GW network



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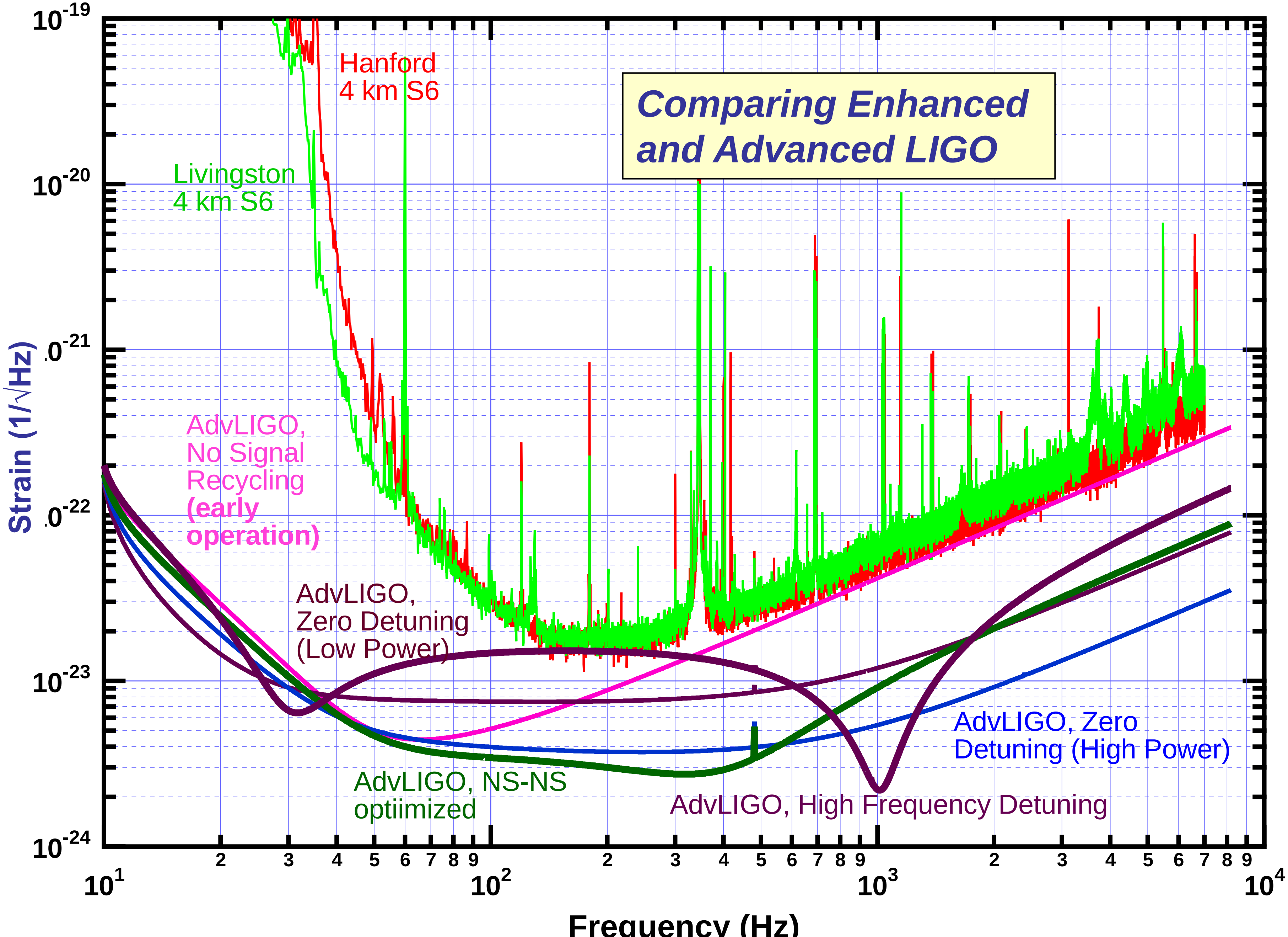
Summary

- First generation gravitational wave detectors – LIGO,Virgo and GEO 600 – have demonstrated sustained high sensitivity operation over the last decade.
- No detections as yet but interesting upper limits to radiation from a range of sources
- Demonstration of the possibility of multi-messenger astronomy involving GW, EM and neutrino detectors.
- Second generation now under construction – aLIGO, aVirgo and KAGRA – with operations planned for 2015 and beyond

Thank-you

- **Thanks to Dave Reitze LIGO) Harmut Grote (GEO600), Masaki Ando (KAGRA), Jerome Degallaix (Virgo), Sathyaprakash (GEO600), Peter Shawhan (LIGO), Erik Katsavounidis (LIGO), Steve Fairhurst (GEO600) and many other colleagues in the field for the material for this talk!**


Comparing Enhanced and Advanced LIGO
Hanford 4 km S6
Livingston 4 km S6
AdvLIGO, No Signal Recycling (early operation)
AdvLIGO, Zero Detuning (Low Power)
AdvLIGO, Zero Detuning (High Power)
AdvLIGO, NS-NS optiimized
AdvLIGO, High Frequency Detuning
Strain (1/√Hz)
Frequency (Hz)
10^-19
10^-20
10^-21
10^-22
10^-23
10^-24
10^1
10^2
10^3
10^4

Expected detection rates for compact binary mergers

LIGO Scientific and Virgo Collaborations,"Predictions for the Rates of Compact Binary Coalescences Observable by Ground-based Gravitational-wave Detectors" Class. Quantum Grav. **27** (2010) 173001

- Binary coalescences rates
  - neutron star (NS) = 1.4 $M_\odot$, Black Hole (BH) = 10 $M_\odot$

TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source	$\dot{N}_{\rm low}$ yr^{-1}	$\dot{N}_{\rm re}$ yr^{-1}	$\dot{N}_{\rm pl}$ yr^{-1}	$\dot{N}_{\rm up}$ yr^{-1}
Initial LIGO	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			$10^{-4\,d}$	$10^{-3\,e}$
Adv'ed LIGO	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

- The error bar is large and important!