David Reitze, JGRG 22(2012)111404

"LIGO: Recent results, plans and prospects"

RESCEU SYMPOSIUM ON

GENERAL RELATIVITY AND GRAVITATION

JGRG 22

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LIGO: Recent Results, Plans, and Prospects

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RESCEU SYMPOSIUM ON GENERAL RELATIVITY AND GRAVITATION

LIGO-G1201178-v1

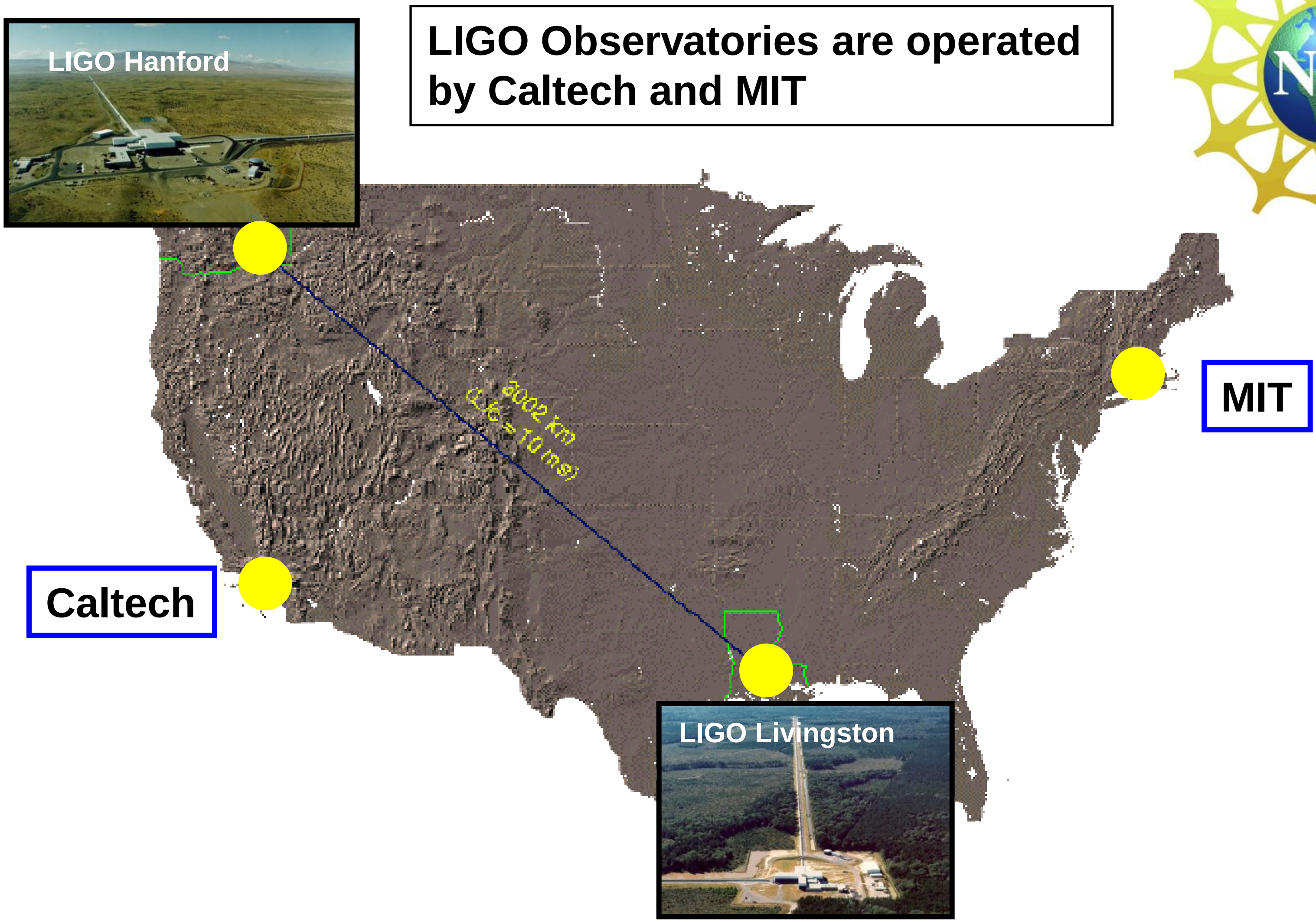
Image: "Gravitational Waves", http://www.chaoscope.org/gallery.htm

Topics

- Initial LIGO
- Selected Science Results from LIGO’s S5 and S6 Science Runs
- Advanced LIGO – Status and Progress
- The Global Gravitational Wave Network
- LIGO-India: Status and Prospects

LIGO Laboratory

LIGO Observatories are operated by Caltech and MIT

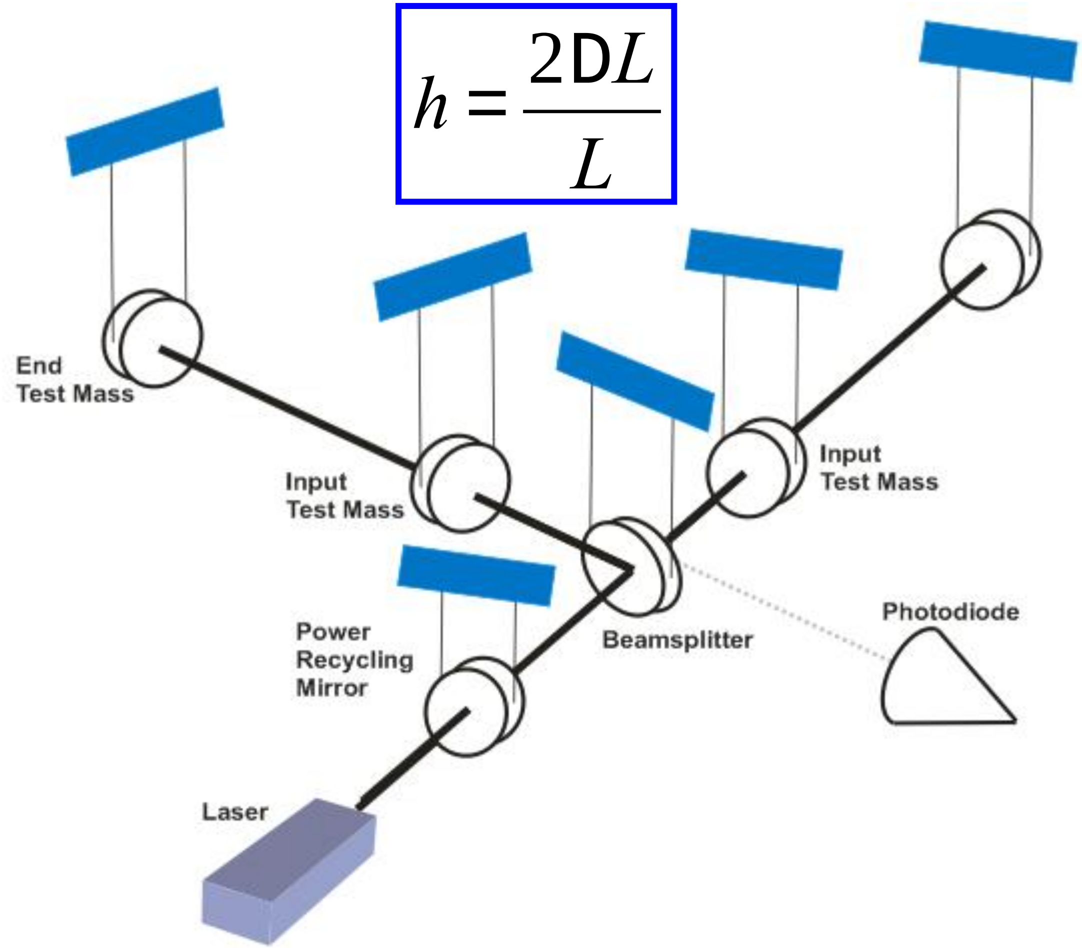


Initial LIGO Concept

- Power-recycled Michelson interferometer
- 4 km long Fabry-Perot arm cavites
- Passive seismic isolation
- 10 kg mirrors figured to $\lambda/1000$
- 10 W → 30 W pre-stabilized laser operating at 1064 nm

- Passing GWs modulate the time-of-flight of light between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - A coherent detector

$$h = \frac{2\Delta L}{L}$$



Initial LIGO Concept

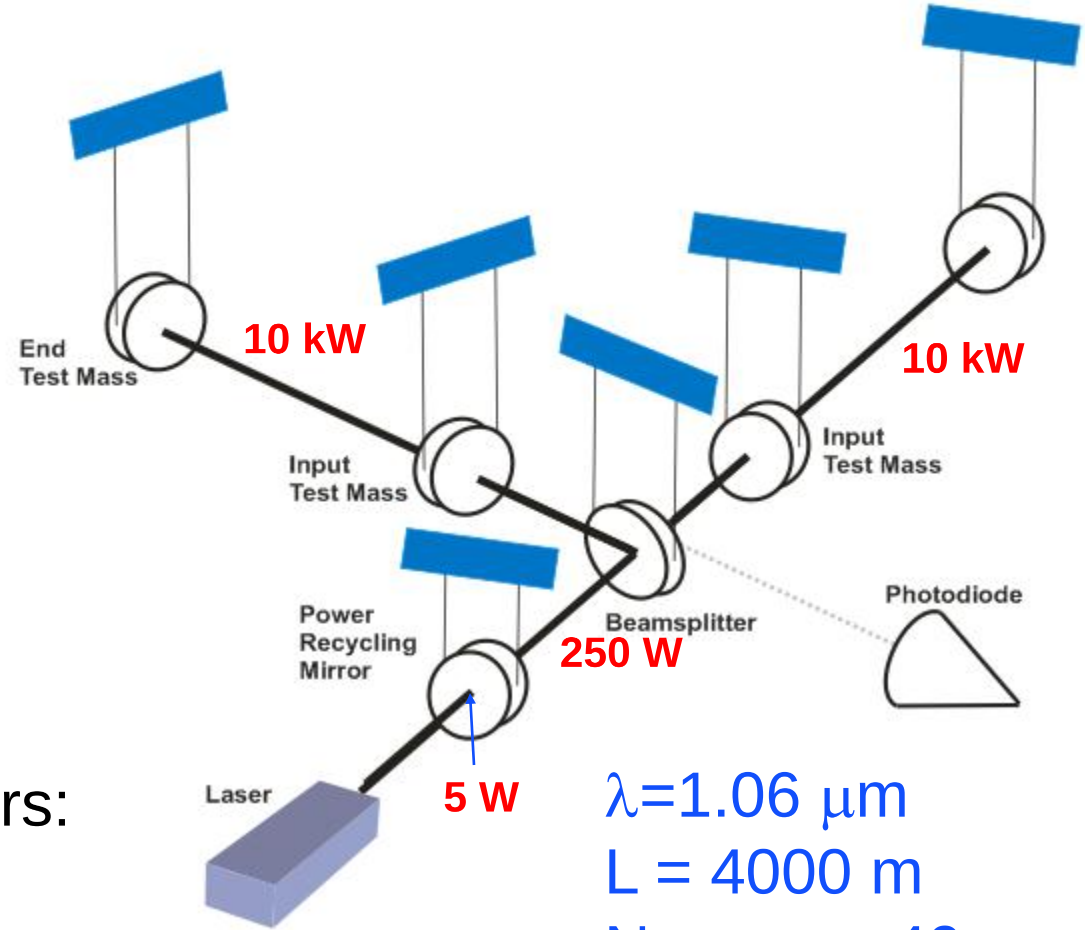
$$h \sim \frac{\lambda}{L}$$

$$\times \frac{1}{N_{roundtrip}}$$

$$\times \sqrt{\frac{1}{\dot{N}_{photon}\tau_{storage}}}$$

Putting in numbers:

***h* ~ 10^{-21}**



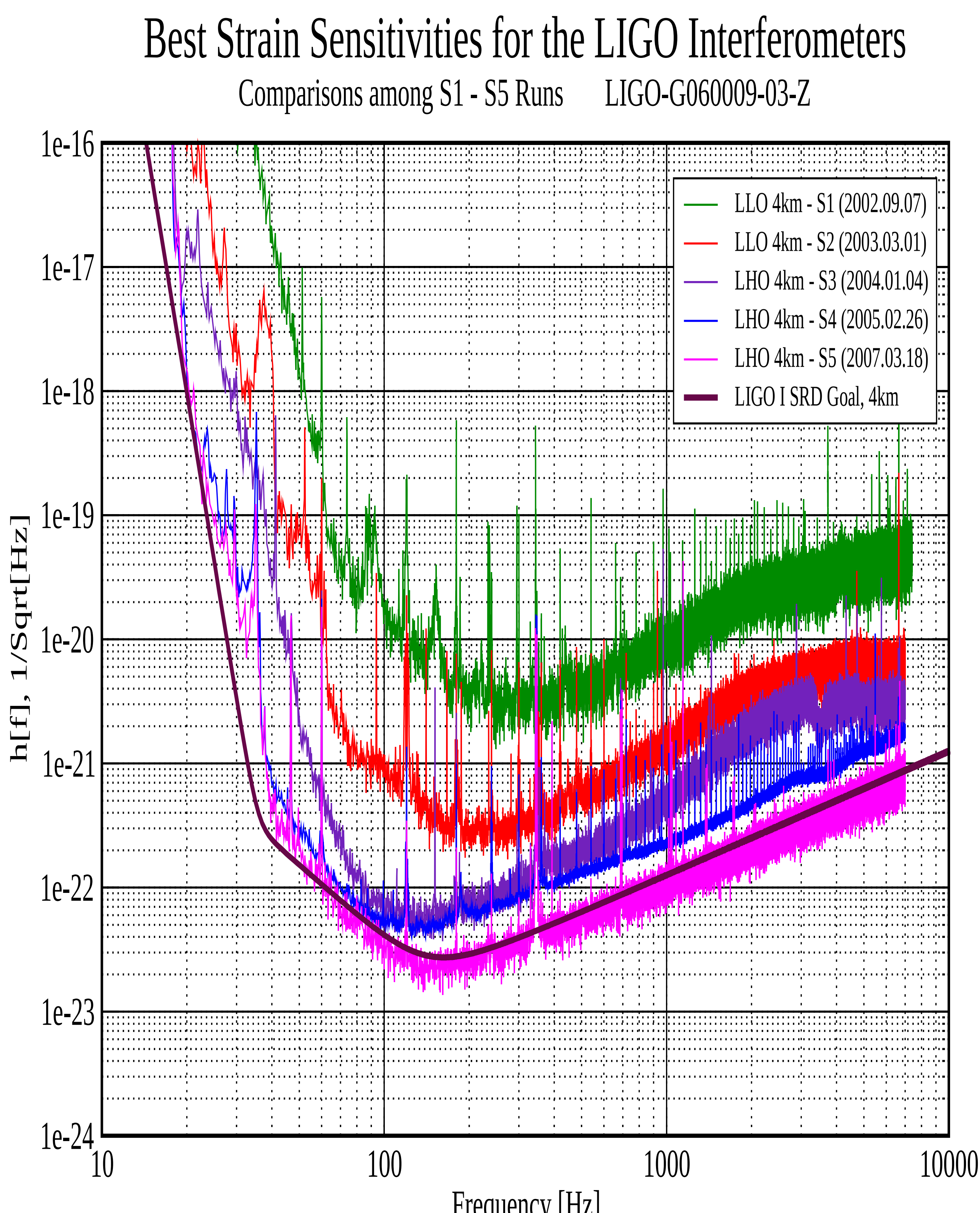
λ=1.06 μm

L = 4000 m

$N_{roundtrip}$ = 40

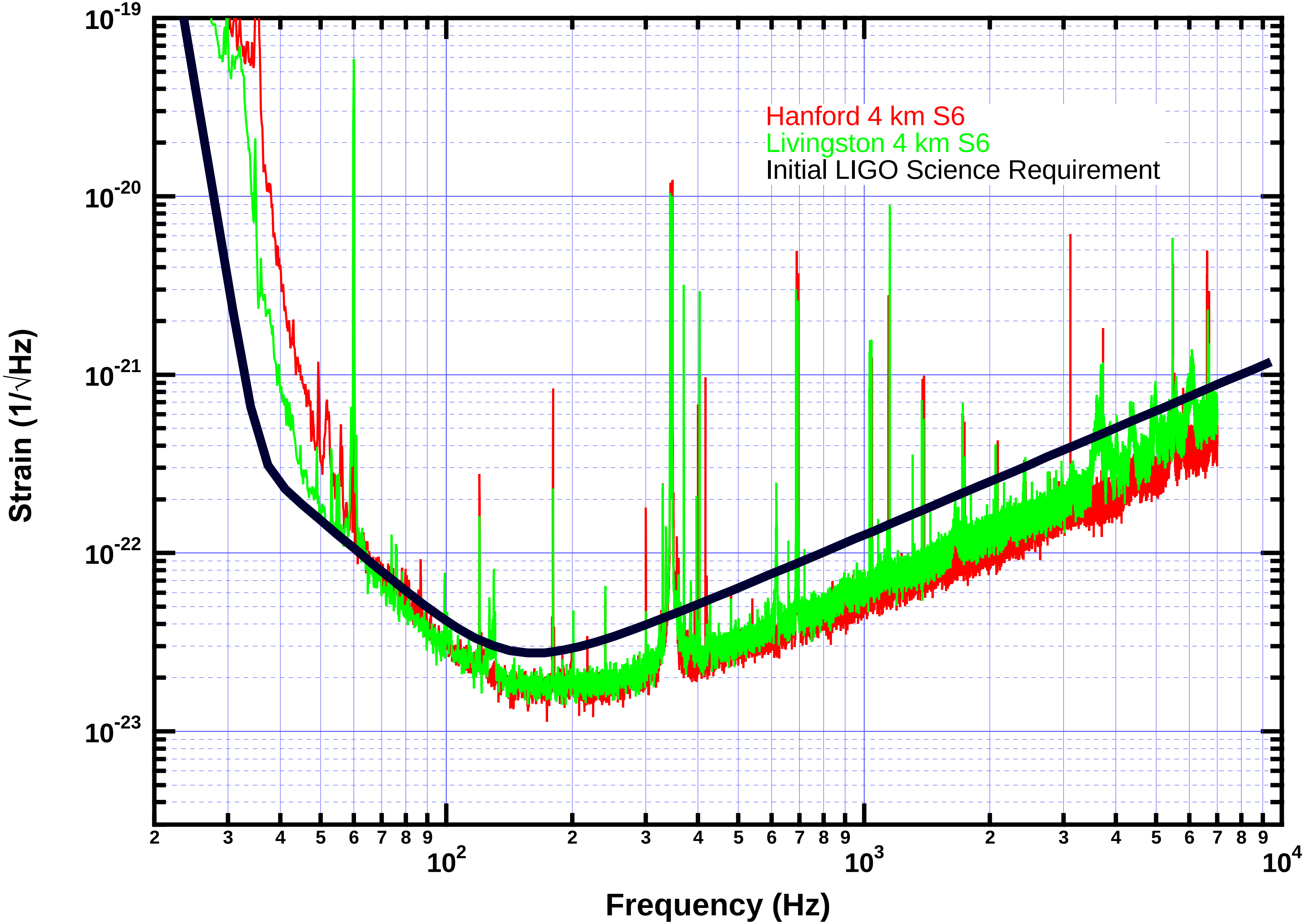
LIGO History

- **1989: LIGO Project proposed to NSF**
- 1992: LIGO Project funded by NSF
- 1995 – 1999: LIGO facilities construction at Hanford and Livingston
- 1998 – 2002: Installation/integration of initial LIGO interferometers
- 2002 - 2005: Interferometer commissioning interleaved with science runs (S1-S4)
- **Nov 4, 2005 – Sept 31, 2007: S5 science run**
  - » Design sensitivity reached; 15 Mpc range; > 1 year of triple coincidence data
- 2007 – 2009: Enhanced LIGO instrument upgrade
  - » Low cost upgrade, tests key Advanced LIGO technologies
- **April 2008: Advanced LIGO Construction begins**
- **July 7, 2009 – Oct 20, 2010: S6 science run**
  - » 18 Mpc range to merging binary neutron stars



Best Strain Sensitivities for the LIGO Interferometers
Comparisons among S1 - S5 Runs
LIGO-G060009-03-Z
h[f], 1/Sqrt[Hz]
1e-16
1e-17
1e-18
1e-19
1e-20
1e-21
1e-22
1e-23
1e-24
10
100
1000
10000
Frequency [Hz]
LLO 4km - S1 (2002.09.07)
LLO 4km - S2 (2003.03.01)
LHO 4km - S3 (2004.01.04)
LHO 4km - S4 (2005.02.26)
LHO 4km - S5 (2007.03.18)
LIGO I SRD Goal, 4km

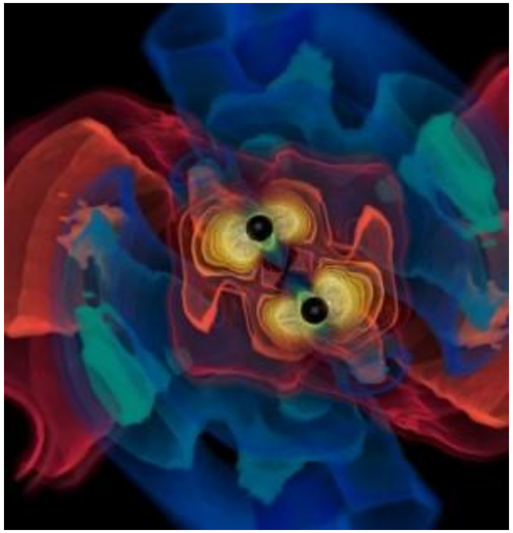
Best Strain Sensitivity: S6 Science Run



Recent LIGO/Virgo/GEO science results

All LSC/Virgo Observational Papers: https://www.lsc-group.phys.uwm.edu/ppcomm/Papers.html

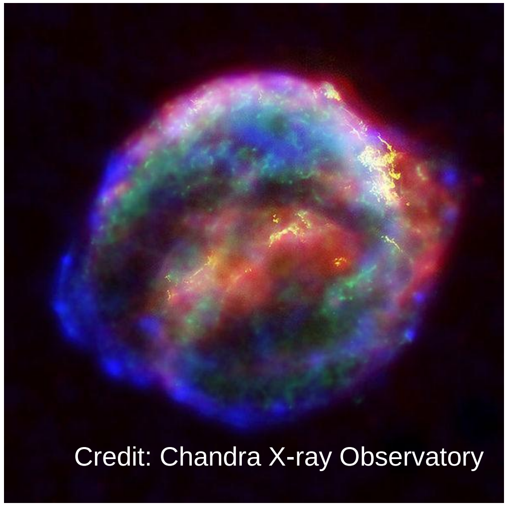
Astrophysical Sources of Gravitational Waves



Credit: AEI, CCT, LSU

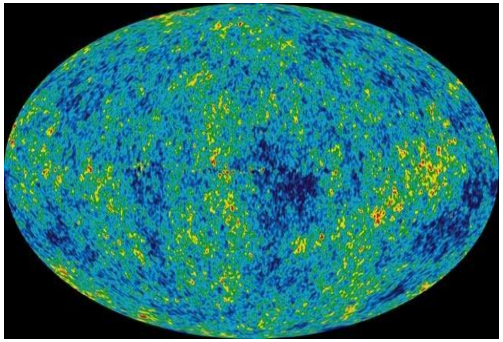
Coalescing Compact Binary Systems: *Neutron Star-NS, Black Hole-NS, BH-BH*

- Strong emitters, well-modeled,
- (effectively) transient



Asymmetric Core Collapse Supernovae

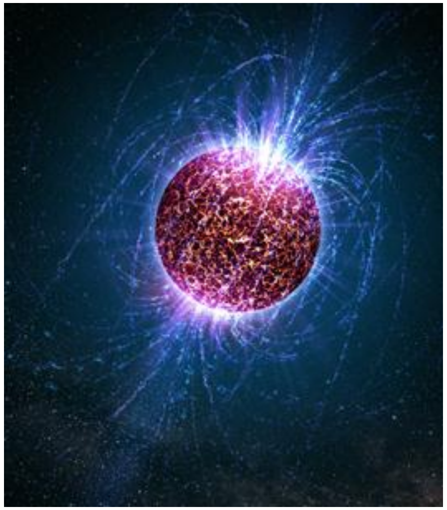
- Weak emitters, not well-modeled ('bursts'), transient
- Cosmic strings, soft gamma repeaters, pulsar glitches also in 'burst' class



NASA/WMAP Science Team

Cosmic Gravitational-wave Background

- Residue of the Big Bang, long duration
- Long duration, stochastic background

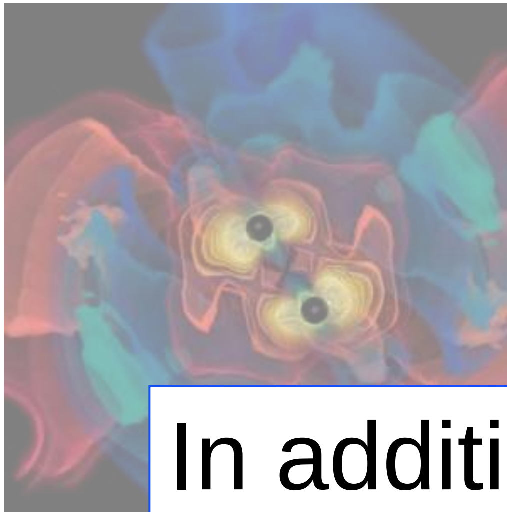


Casey Reed, Penn State

Spinning neutron stars

- (effectively) monotonic waveform
- Long duration

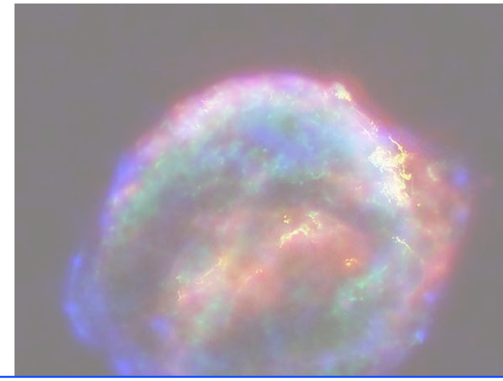
Astrophysical Sources of Gravitational Waves



Credit: AEI,

Coalescing Compact Binary Systems: Neutron Star-NS, Black Hole- BH BH-BH

- Strong emitters,



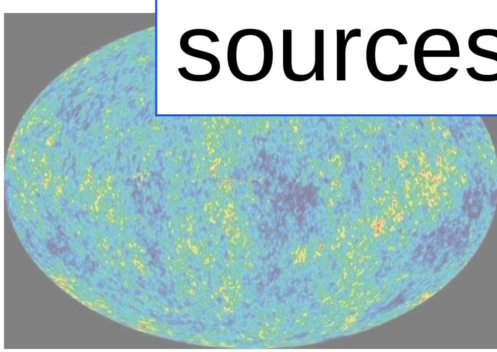
Asymmetric Core Collapse Supernovae

- Weak emitters, not well-modeled ('bursts'), transient

strings also

class

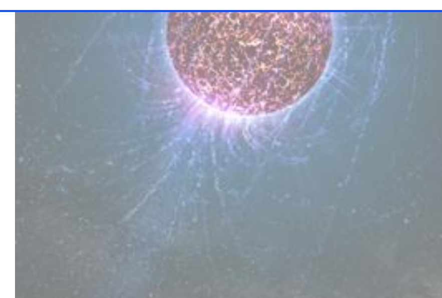
In addition to these known sources, there may be surprising sources of gravitational waves.



NASA/WMAP Science Team

- Residue of the Big Bang, long duration
- Stochastic, incoherent background

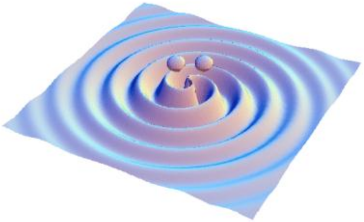
g neutron

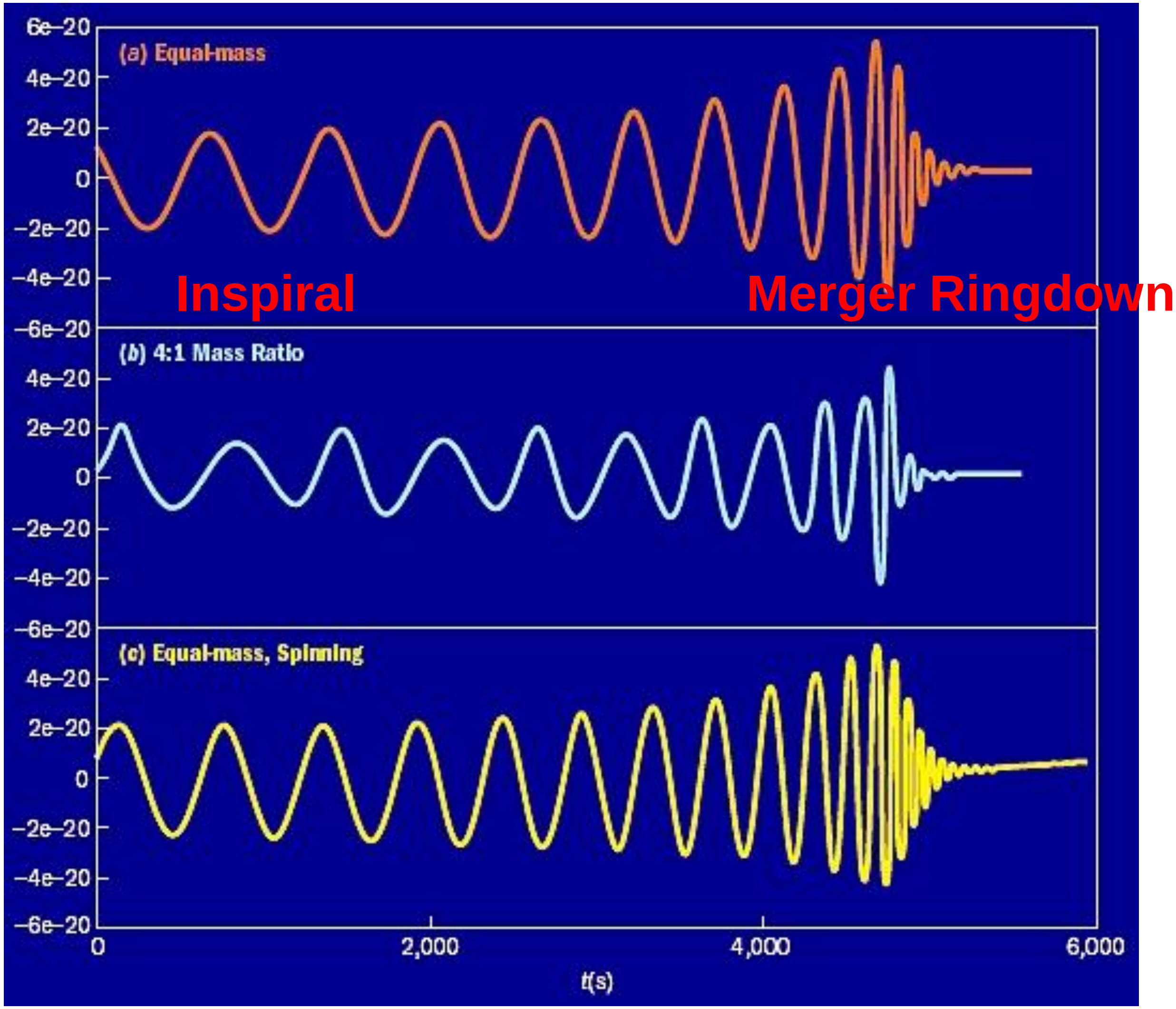


Casey Reed, Penn State

- (effectively) monotonic waveform
- Long duration

Compact binary inspiral, merger, ringdown





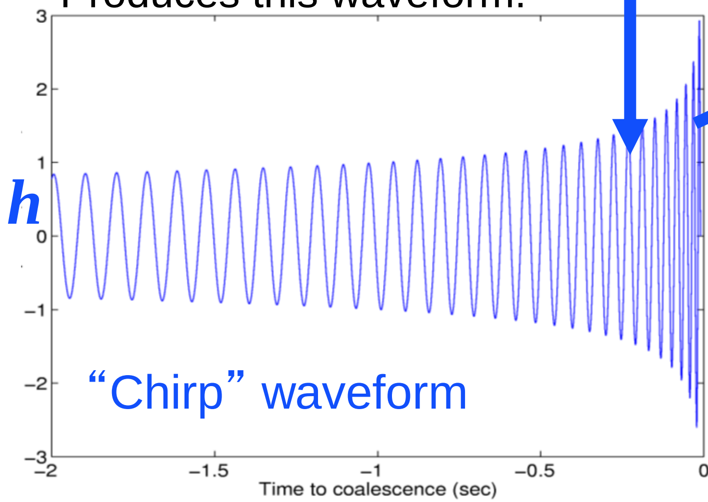
- There's a lot of physics and astrophysics in the waveforms!
- Waveform reconstruction (often buried in detector noise).

Searches for Binary Mergers

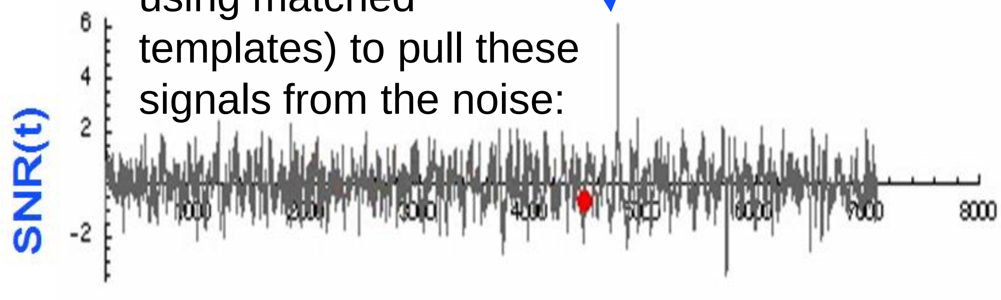
This source:

Buried in this noise stream:

Produces this waveform:

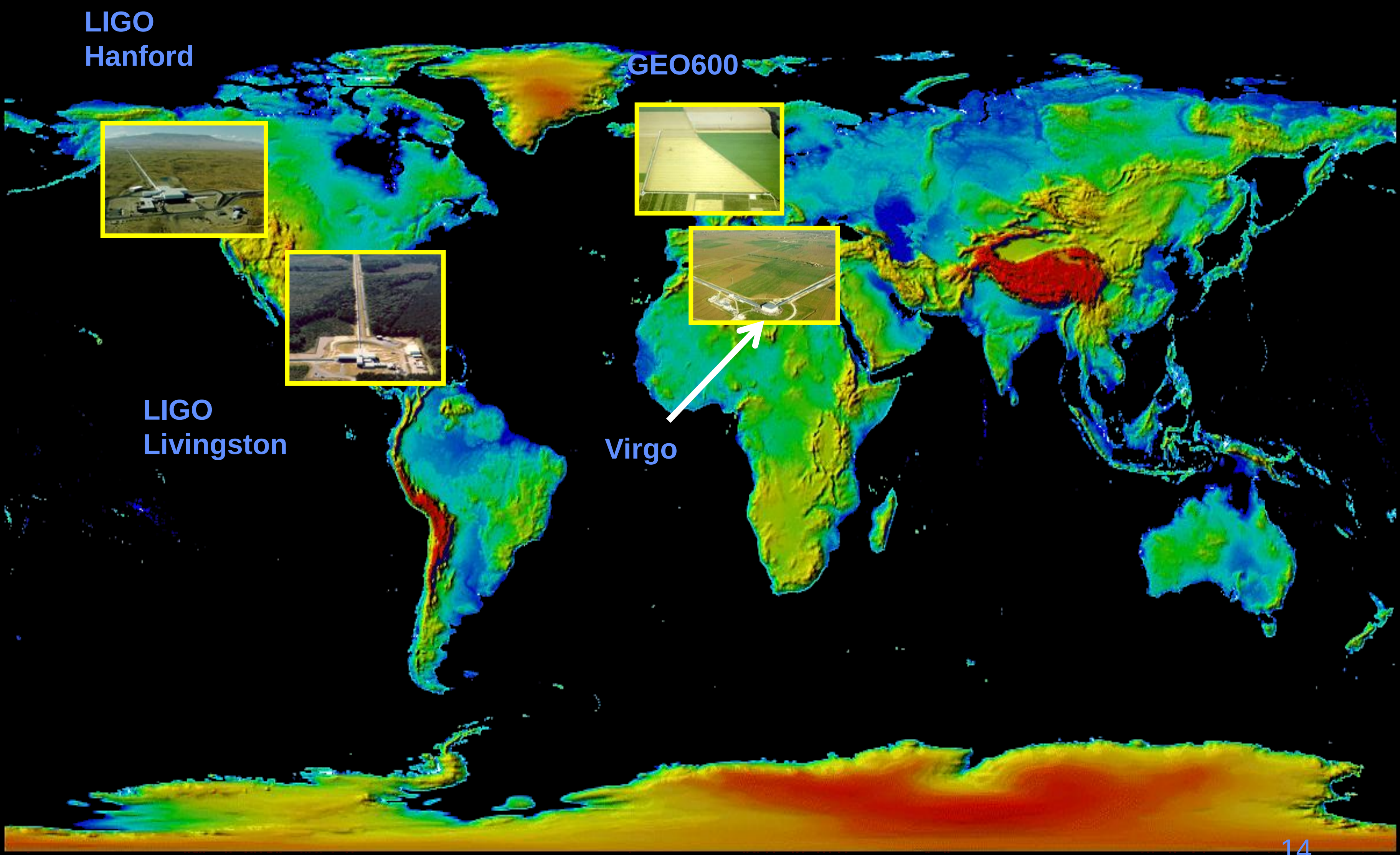


We use different methods (in this case optimal Wiener filtering using matched templates) to pull these signals from the noise:



The problem is that non-astrophysical sources also produces signals (false positives)

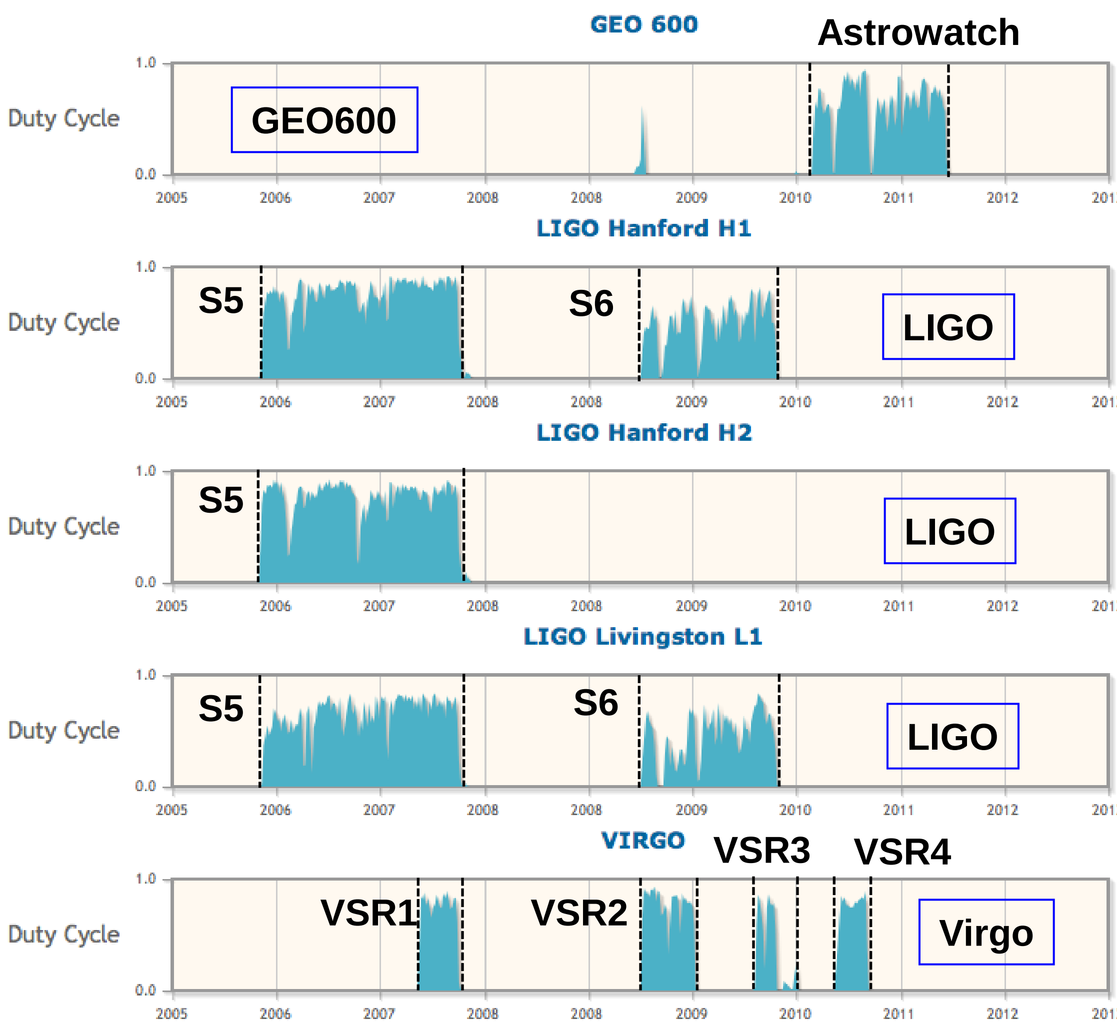
The Current GW Detector Network



Global gravitational-wave detector network

- GW science is *greatly* enhanced by having distribution of global interferometers. Advantages include:
  - Source localization
  - Enhanced Network Sky Coverage
  - Maximum Time Coverage - 'Always listening'
  - Detection confidence

- Since May 2007, LIGO, Virgo, and GEO600 has operated jointly as a global network



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 $M_\odot$

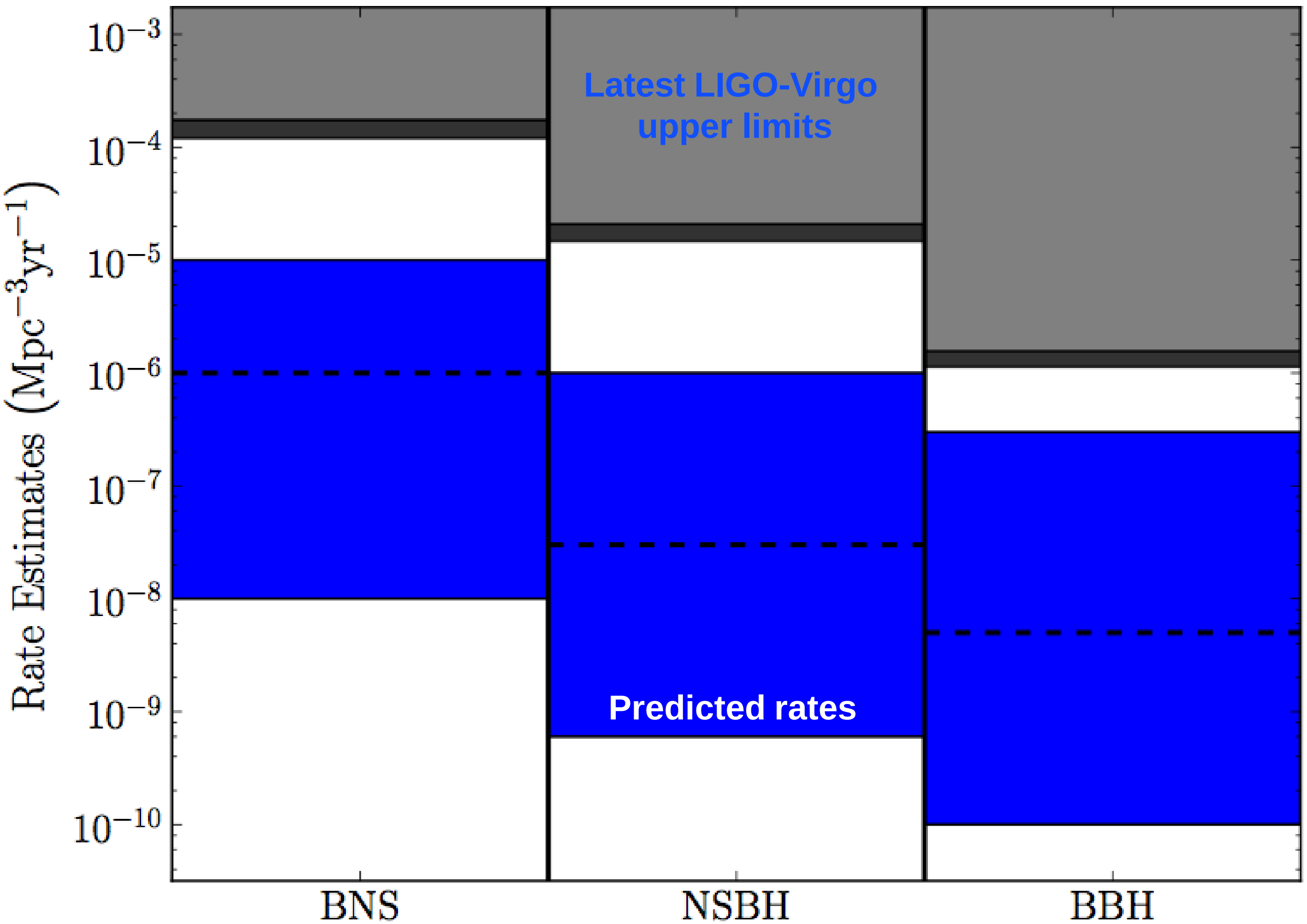
TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source	$\dot{N}_{\rm low}$ $\rm yr^{-1}$	$\dot{N}_{\rm re}$ $\rm yr^{-1}$	$\dot{N}_{\rm pl}$ $\rm yr^{-1}$	$\dot{N}_{\rm up}$ $\rm yr^{-1}$
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			$10^{-4\,d}$	$10^{-3\,e}$
[redacted]					

- **The error bar is large and important!**

Searching for Low Mass Compact Binary Coalescences

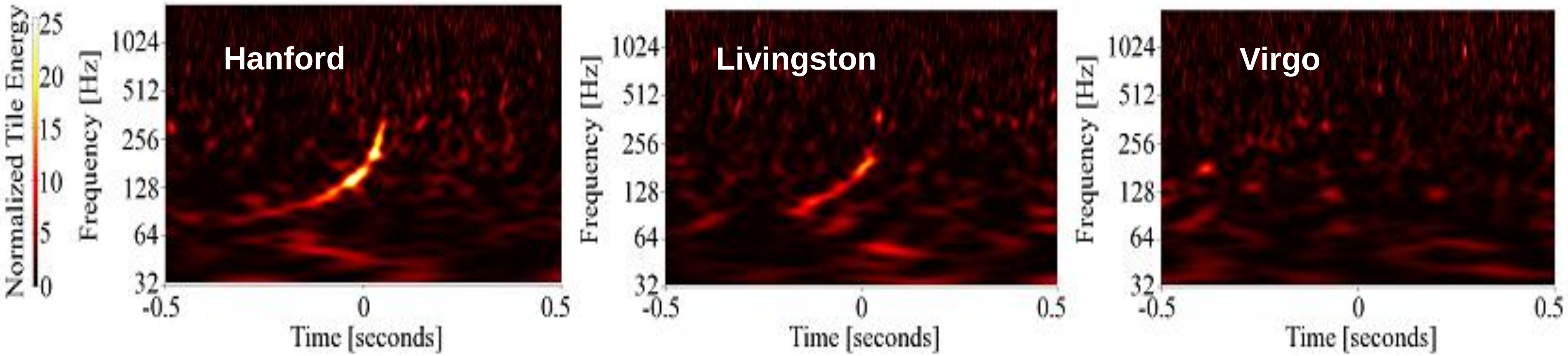
LIGO Scientific and Virgo Collaborations, "Search for Gravitational Waves from Low Mass Compact Binary Coalescence in LIGO's Sixth Science Run and Virgo's Science Runs 2 and 3", Phys. Rev D**85** (2012) 082002

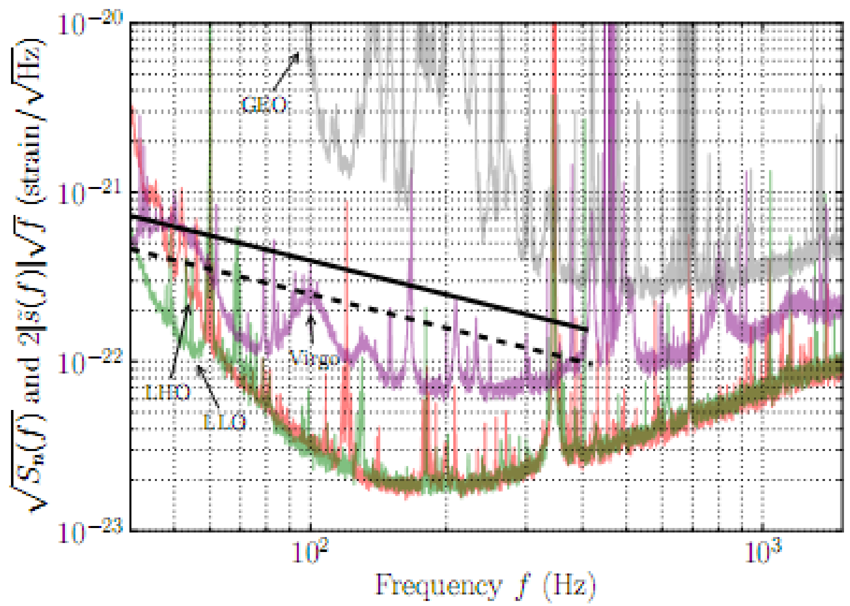


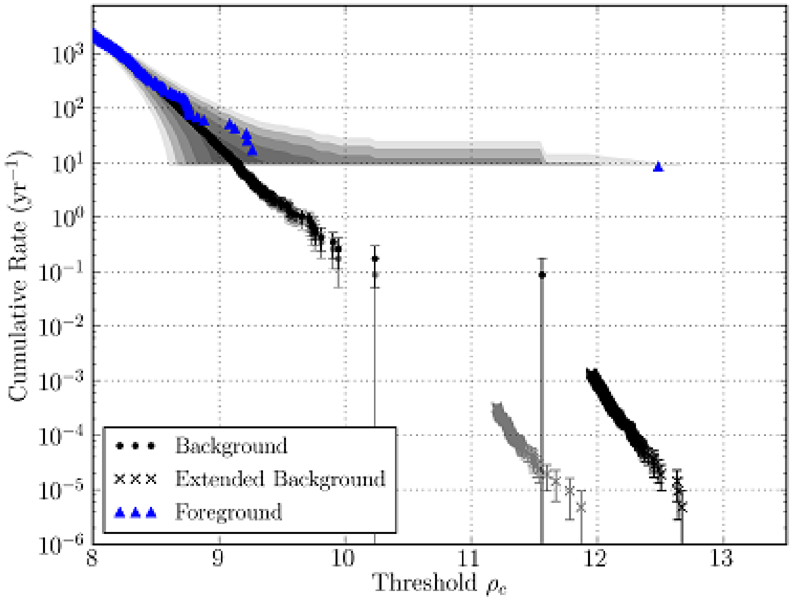
LIGO

‘Event’ GW100916 – A Blind Injection

http://www.ligo.org/science/GW100916/

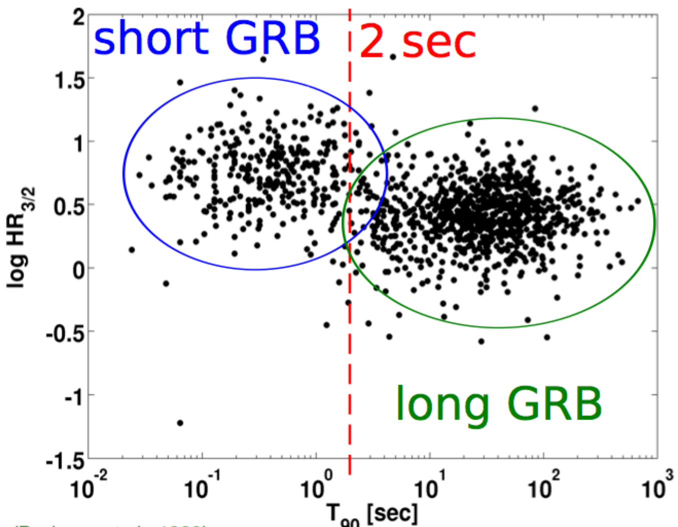




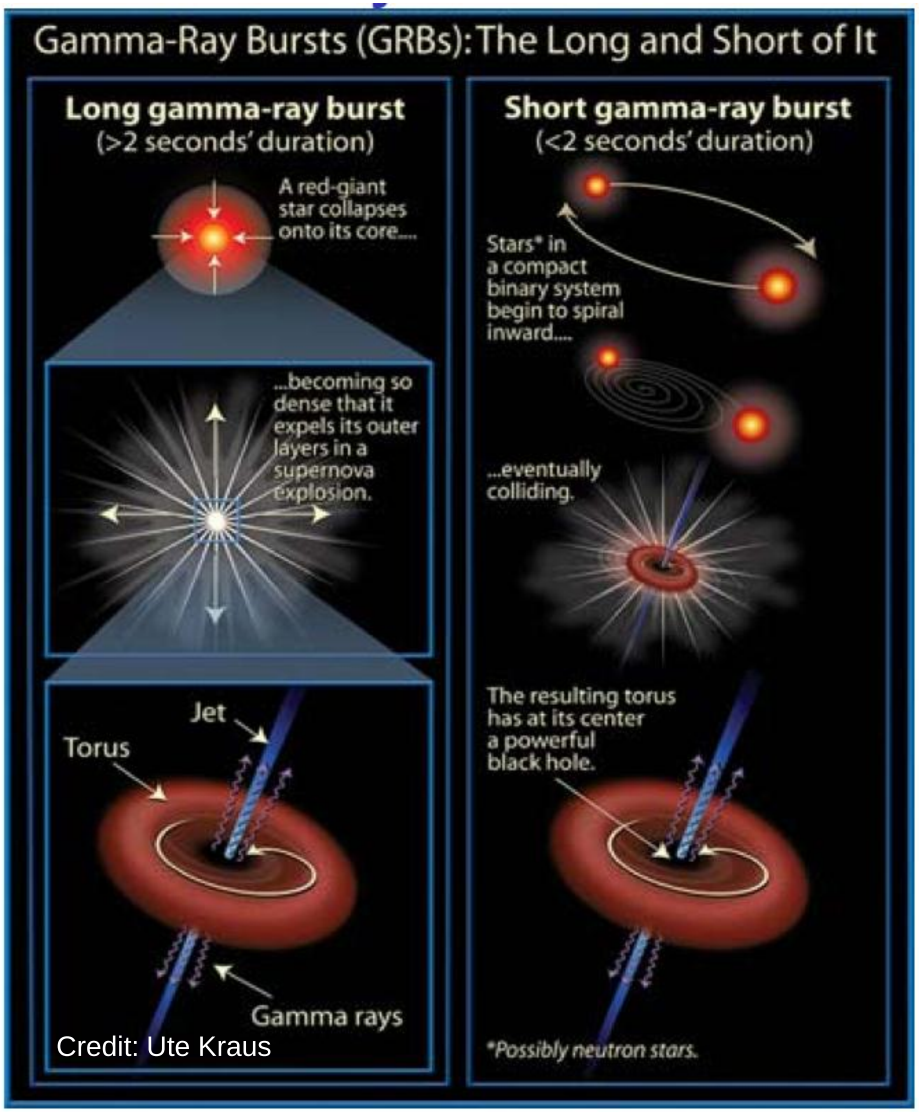


Triggered searches for gamma-ray bursts

- GRBs are good candidates for GW emission
- GRB progenitor models
  - » Long GRB → Core collapse SN of a massively spinning star
  - » Short GRB → coalescence of a neutron star and a compact object
    - – ≤ 15% from neutron star quakes
- Compact, relativistic, asymmetric!
  - » But measured red shifts → 10 Gpc



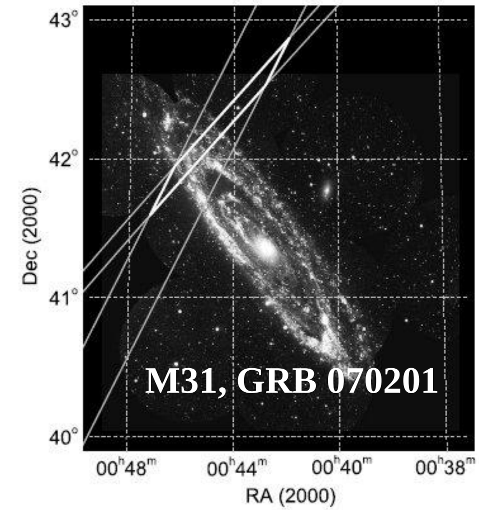
(Paciesas et al., 1999)

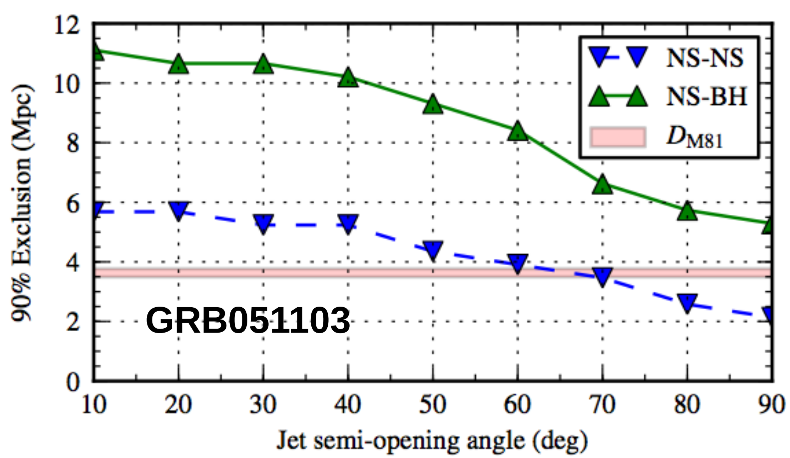


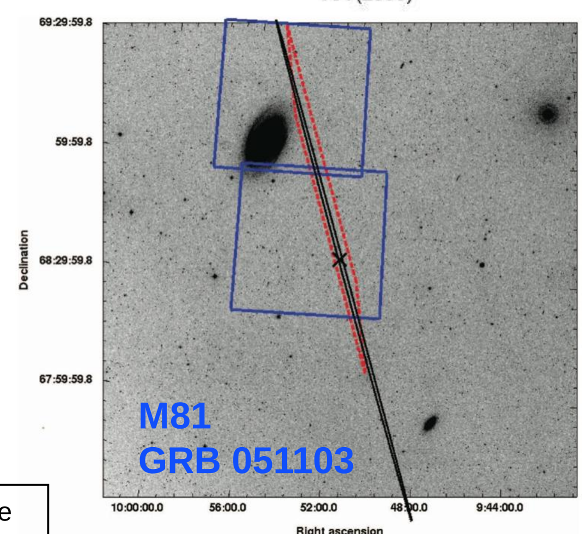
Credit: Ute Kraus

Searches for GWs from nearby GRB sources

- GRB050311, GRB070201: short GRBs with sky localizations that overlap nearby galaxies
  - GRB050311 overlap with M81 (3.6 Mpc)
  - GRB070201 overlap with M31 (770 kpc)
- Binary coalescence in M31 excluded at >99% confidence level
- BNS coalescence in M81 excluded at 98% confidence level







LIGO Scientific Collaboration, K. Hurley, "Implications for the Origin of GRB 070201 from LIGO Observations", Astrophys. J. **681** (2008) 1419

LIGO Scientific Collaboration, "Implications for the Origin of GRB 051103 from LIGO Observations", arXiv:1201.4413

Enabling multi-messenger astronomy with gravitational waves

- Many GWs sources are likely to radiate in the electromagnetic spectrum
- We want to see them via different observational methods simultaneously
- GW 'Aperture synthesis'
  - » Crude estimate of angular resolution

$$\theta_{GW} \sim \lambda_{GW} / d \sim \text{few degrees}$$

→ wide field telescopes
  + Image tiling
  + Galaxy weighting

→ Neutrino observatories

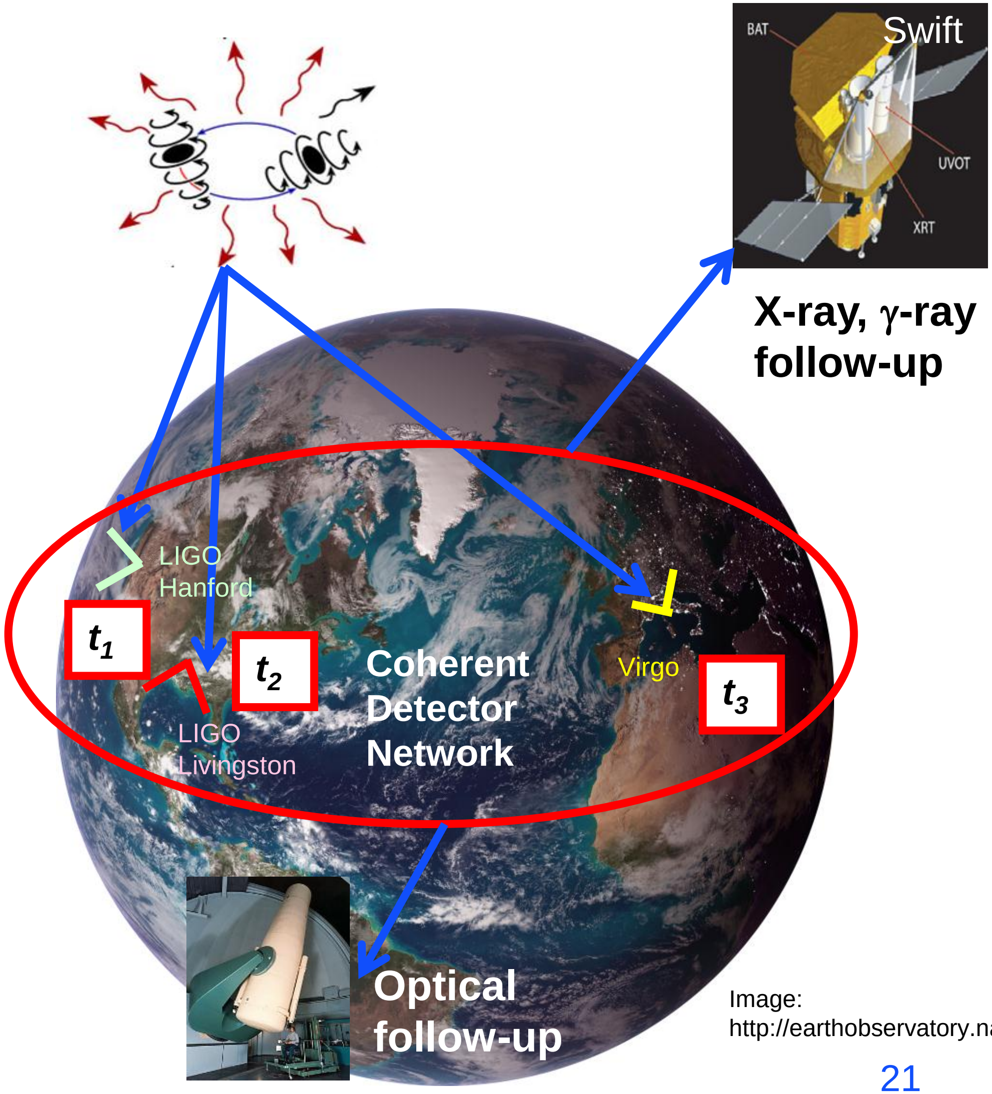
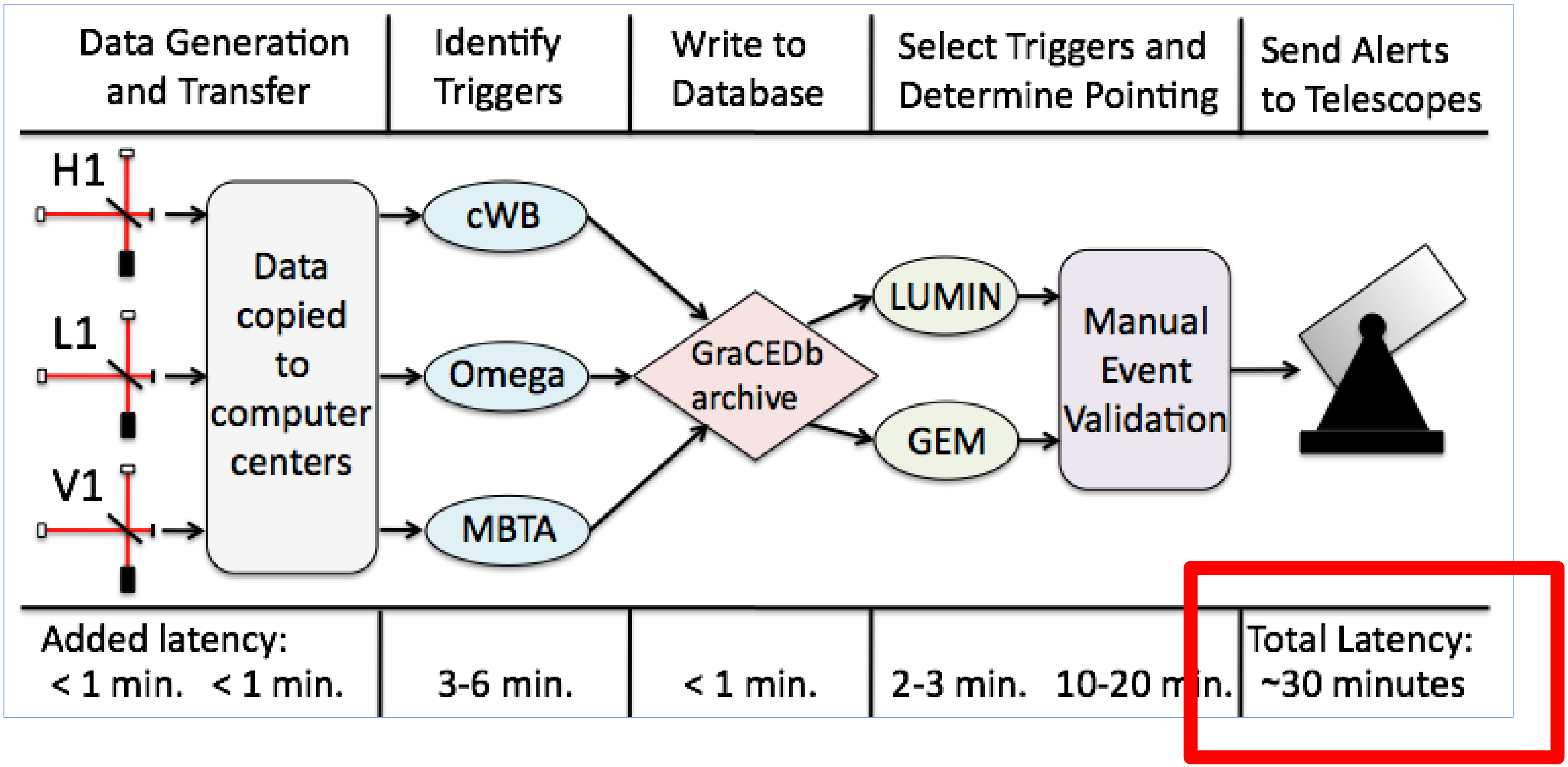
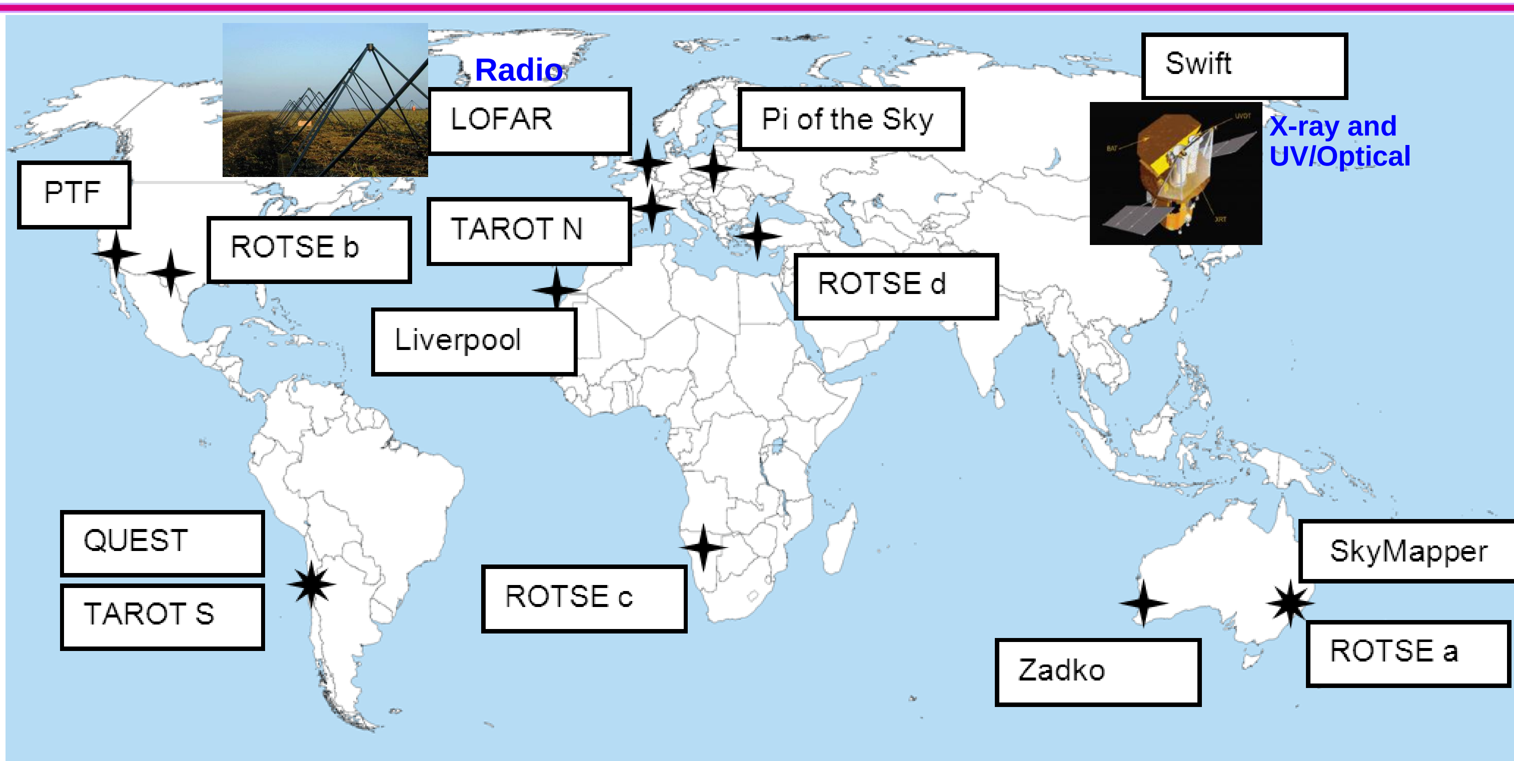


Image: http://earthobservatory.nasa.gov/

EM follow up of gravitational-wave triggers from S5, VSR1



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 S6/VSR2,3 followed up by at least one scope

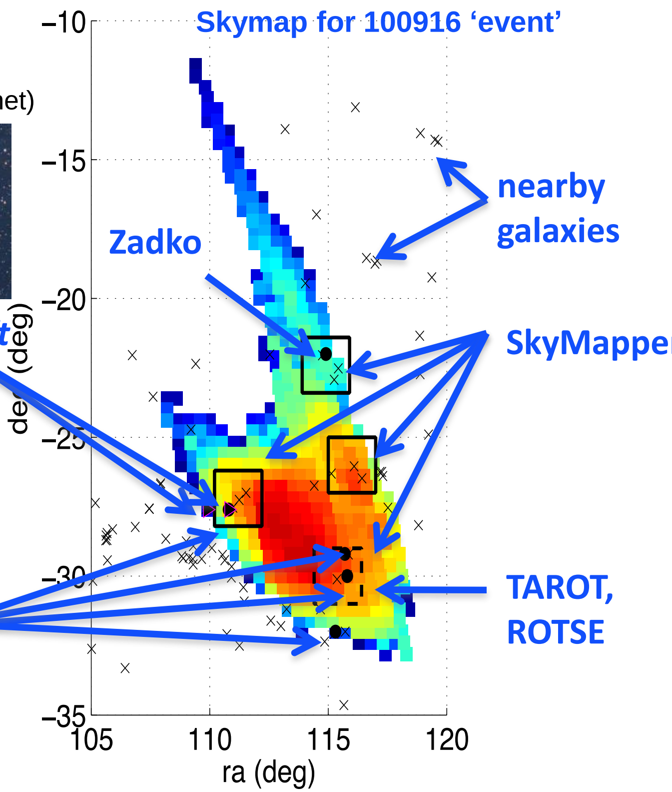
LIGO Scientific and Virgo Collaborations, "*Implementation and testing of the first prompt search for gravitational wave transients with electromagnetic counterparts*", A&A **539**, A124 (2012)

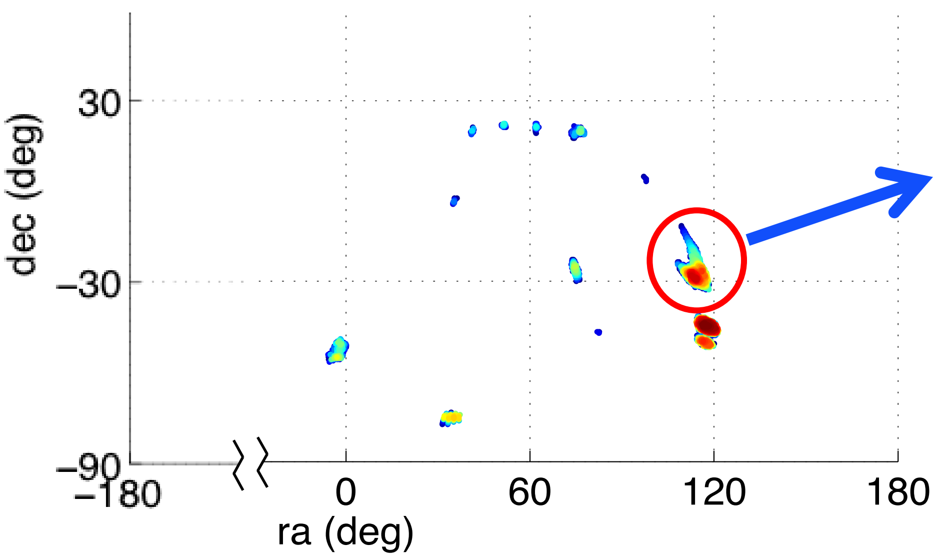
LIGO Scientific and Virgo Collaborations, "*First Low-Latency LIGO+Virgo Search for Binary Inspirals and their Electromagnetic Counterparts*", arXiv:1112.6005

Example: GW100916 Skymap

- LIGO-Virgo source localization ~ O(100 deg^2)
  - Disconnected regions
- Top probability pixels imaged by Swift and other ground-based optical telescopes
- Swift pixels maximized probability on NGC2380 and ESO492-010

NGC2380
(Credit: Las Cumbras Observatory www.lcogt.net)





LIGO Scientific and Virgo Collaborations, "*Swift Follow-Up Observations Of Candidate Gravitational-Wave Transient Events*" arXiv:1205.1124

Advanced LIGO

LIGO

CALTECH/MIT PROJECT

FOR A

LASER INTERFEROMETER

GRAVITATIONAL WAVE OBSERVATORY

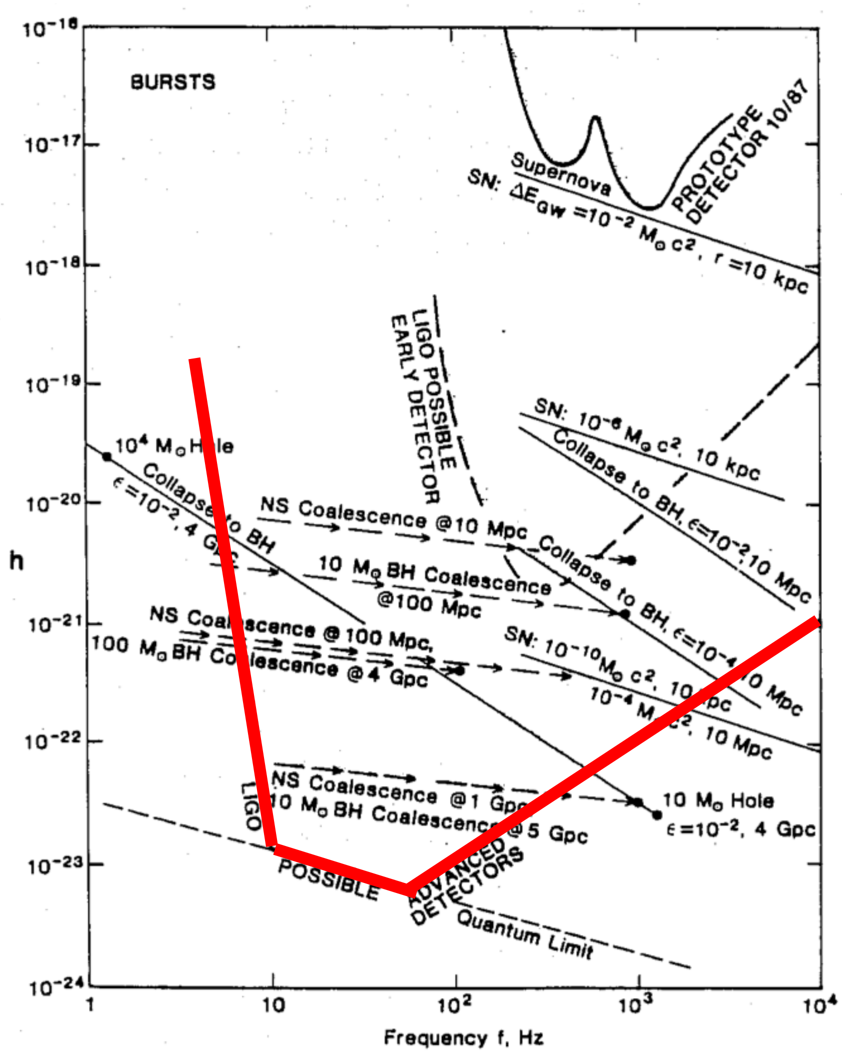
December 1987

LIGO-M870001-00-M

By comparing the source strengths and benchmark sensitivities in Figure II-2 and in the periodic and stochastic figures A-4b,c (Appendix A), one sees that *(i) There are nonnegligible possibilities for wave detection with the first detector in the LIGO. (ii) Detection is probable at the sensitivity level of the advanced detector. (iii) The first detection is most likely to occur, not in the initial detector in the LIGO but rather in a subsequent one, as the sensitivity and frequency are being pushed downward from the middle curve toward the bottom curve of Figure II-2.*

Rochus Vogt, Ron Drever, Kip Thorne, Rai Weiss 1987

LIGO



Rochus Vogt, Ron Drever, Kip Thorne, Rai Weiss 1987

Advanced LIGO

- Advanced LIGO – a complete upgrade of the LIGO interferometers
- Advanced LIGO is designed to increase the distance probed (‘reach’) by ~ 10X
  - » Leads to 1000X increase in volume → 1000X increase in event rate
- *<u>Expect 10s of detections per year at design sensitivity</u>*
  - » 1 aLIGO observational day = a few years of iLIGO

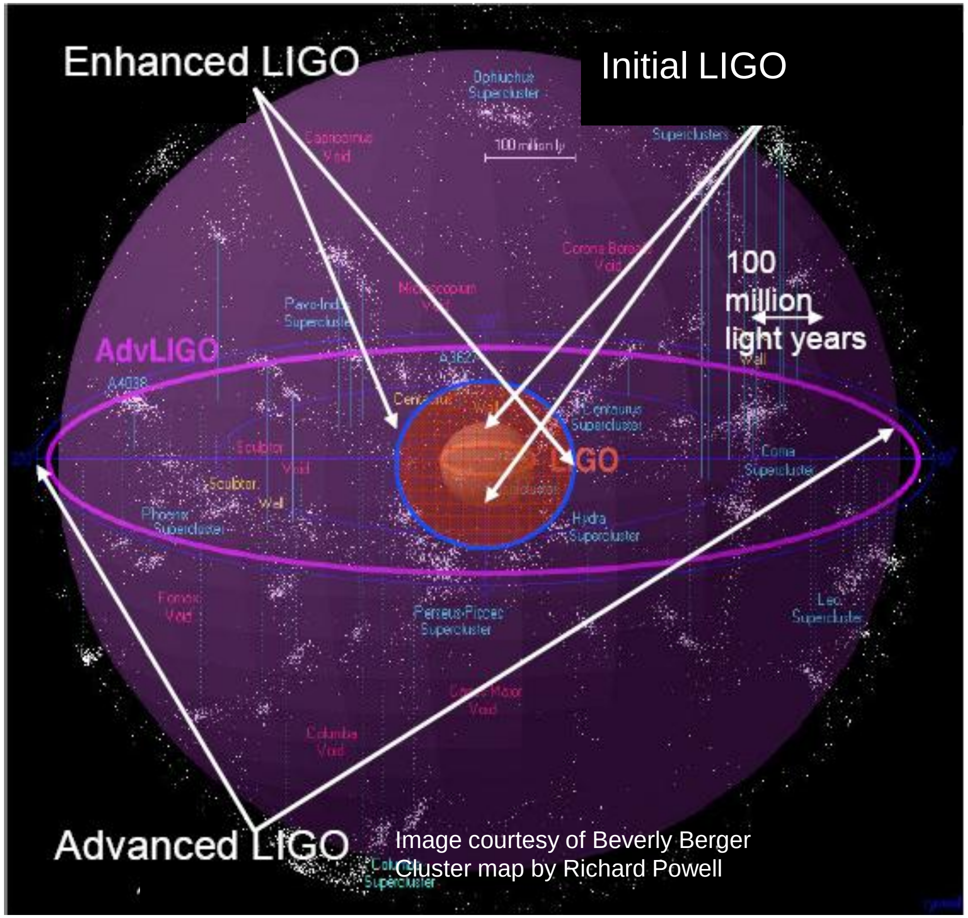


Image courtesy of Beverly Berger
Cluster map by Richard Powell

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
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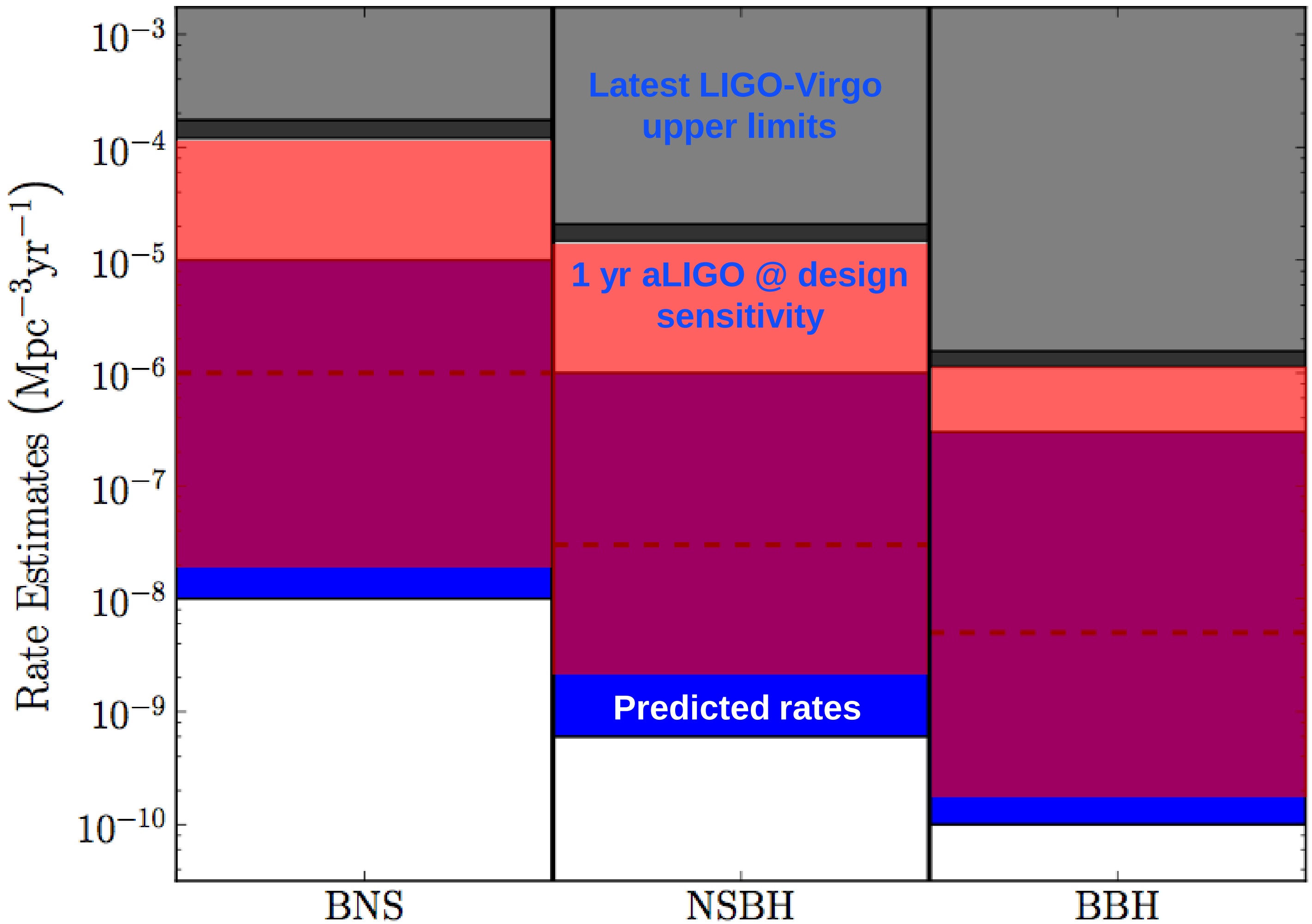
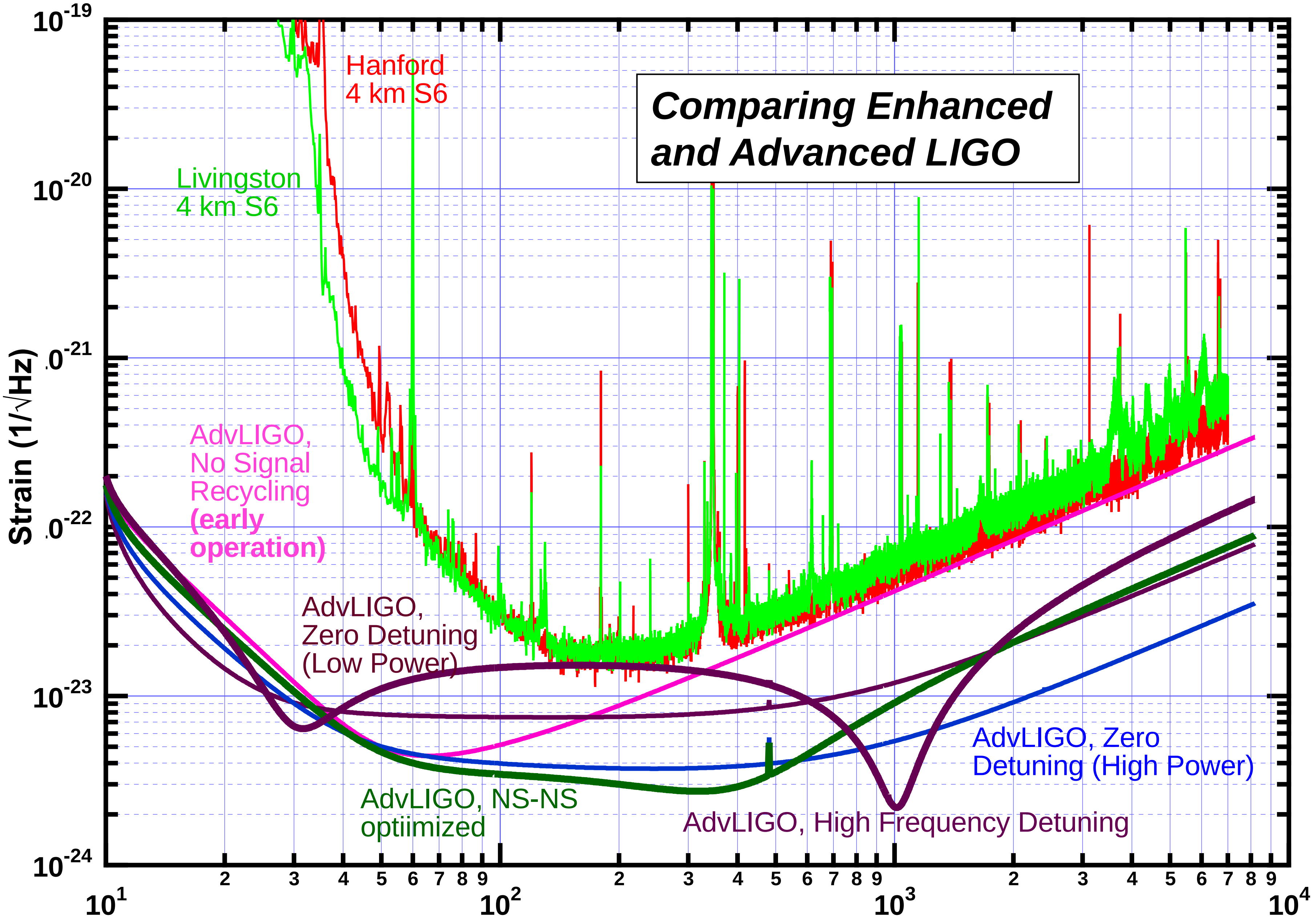
Initial LIGO	[redacted]				
Advanced LIGO	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
	BH-BH	0.4	20	1000	
	IMRI into IMBH			10^b	300^c
	IMBH-IMBH			0.1^d	1^e

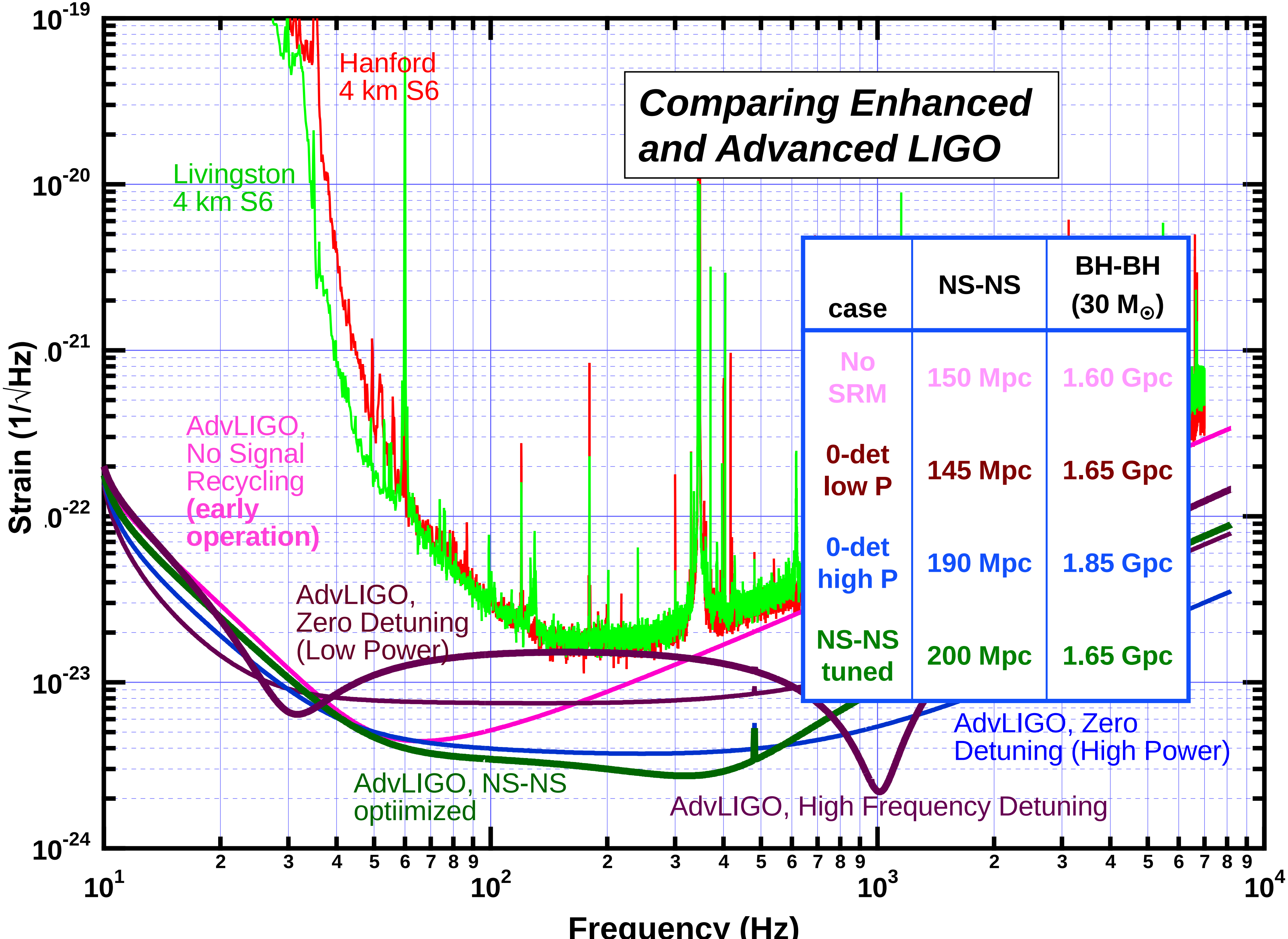
- **The error bar is large and important!**

Latest low mass CBC search results




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

Comparing Enhanced and Advanced LIGO

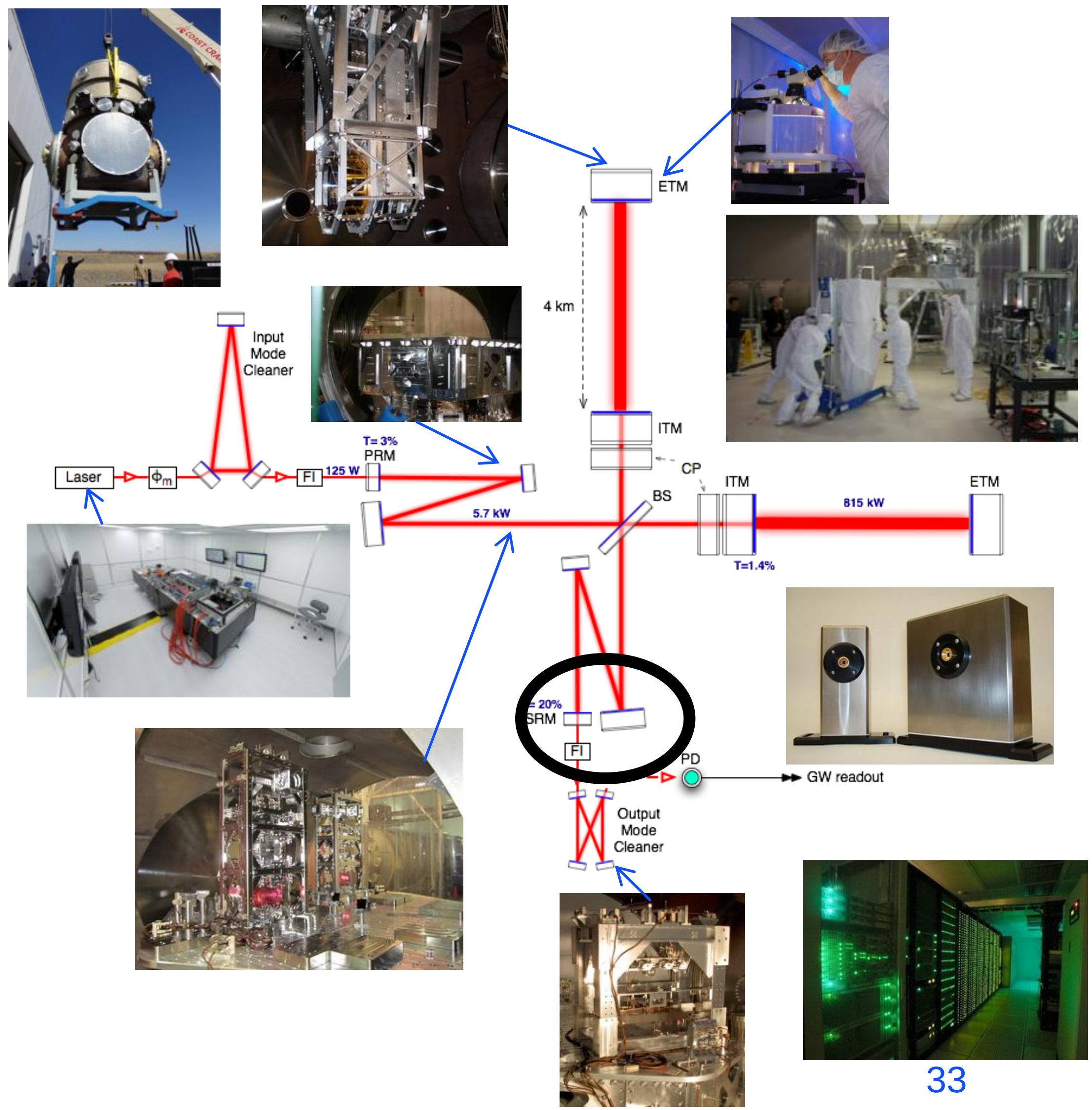


case	NS-NS	BH-BH (30 $M_\odot$)
No SRM	150 Mpc	1.60 Gpc
0-det low P	145 Mpc	1.65 Gpc
0-det high P	190 Mpc	1.85 Gpc
NS-NS tuned	200 Mpc	1.65 Gpc

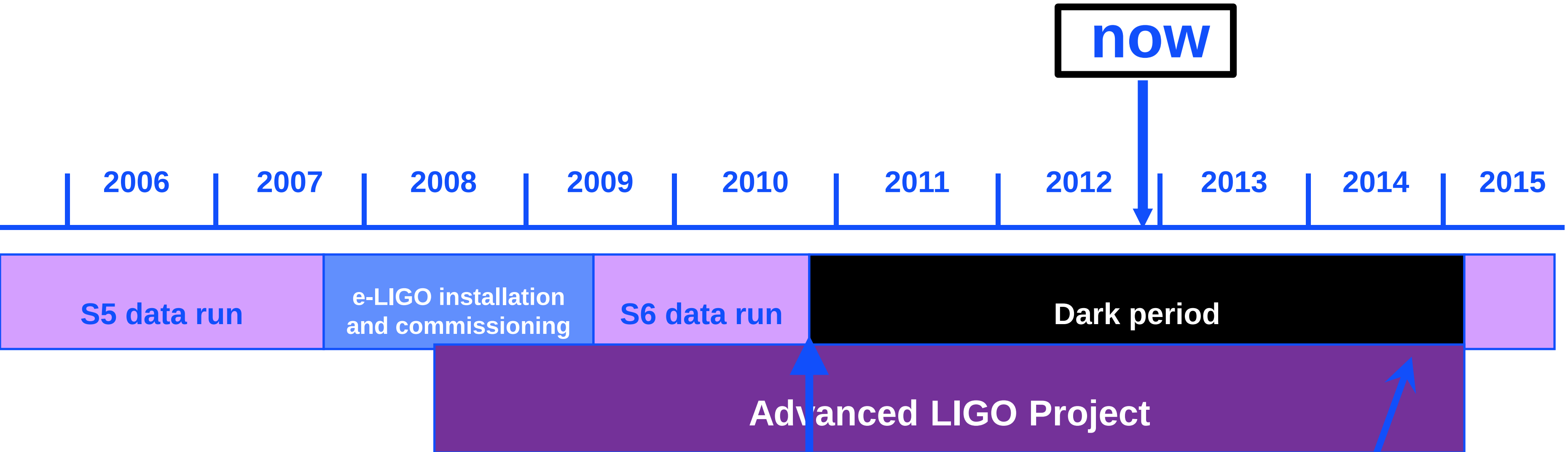
Advanced LIGO overview

What is Advanced?

Parameter	*Initial LIGO*	*Advanced LIGO*
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (stable recycling cavities)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	f_{low} ~ 50 Hz	f_{low} ~ 13 Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum



Advanced LIGO schedule



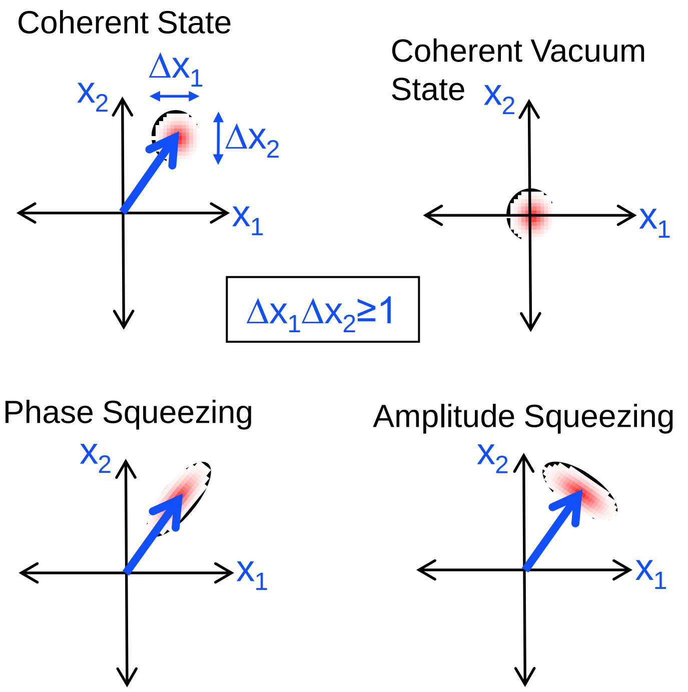
- Fabrication, subsystem assembly, and installation ~ 80% complete
- ***Interferometers operational in 2014***
- ***First science data expected in 2015***

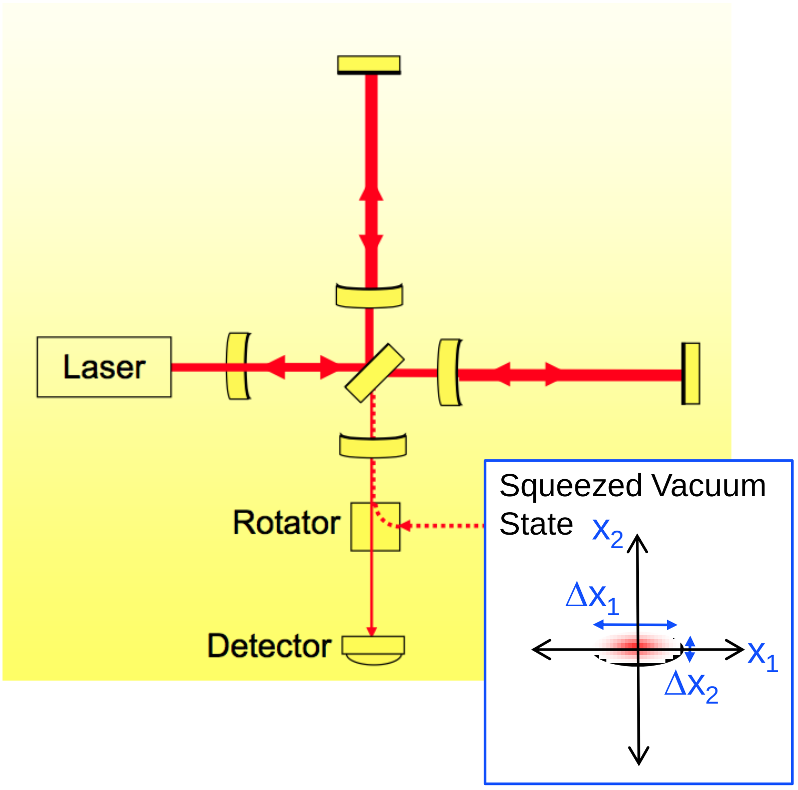
Adv LIGO Installation begins

Commissioning & initial data With Advanced LIGO

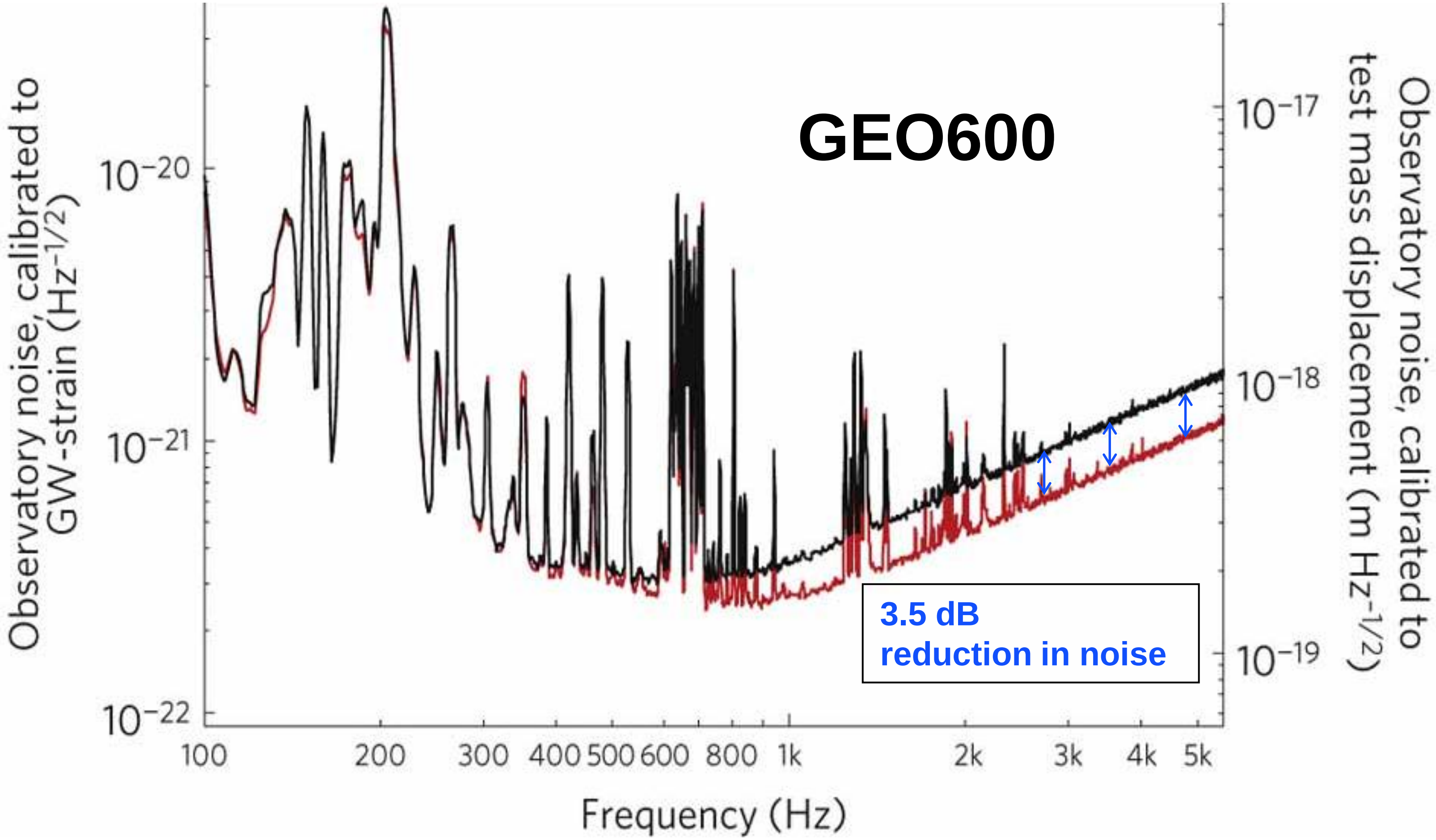
A Possible Upgrade: Squeezed Interferometry

Quantum Optics in service of Astrophysics!





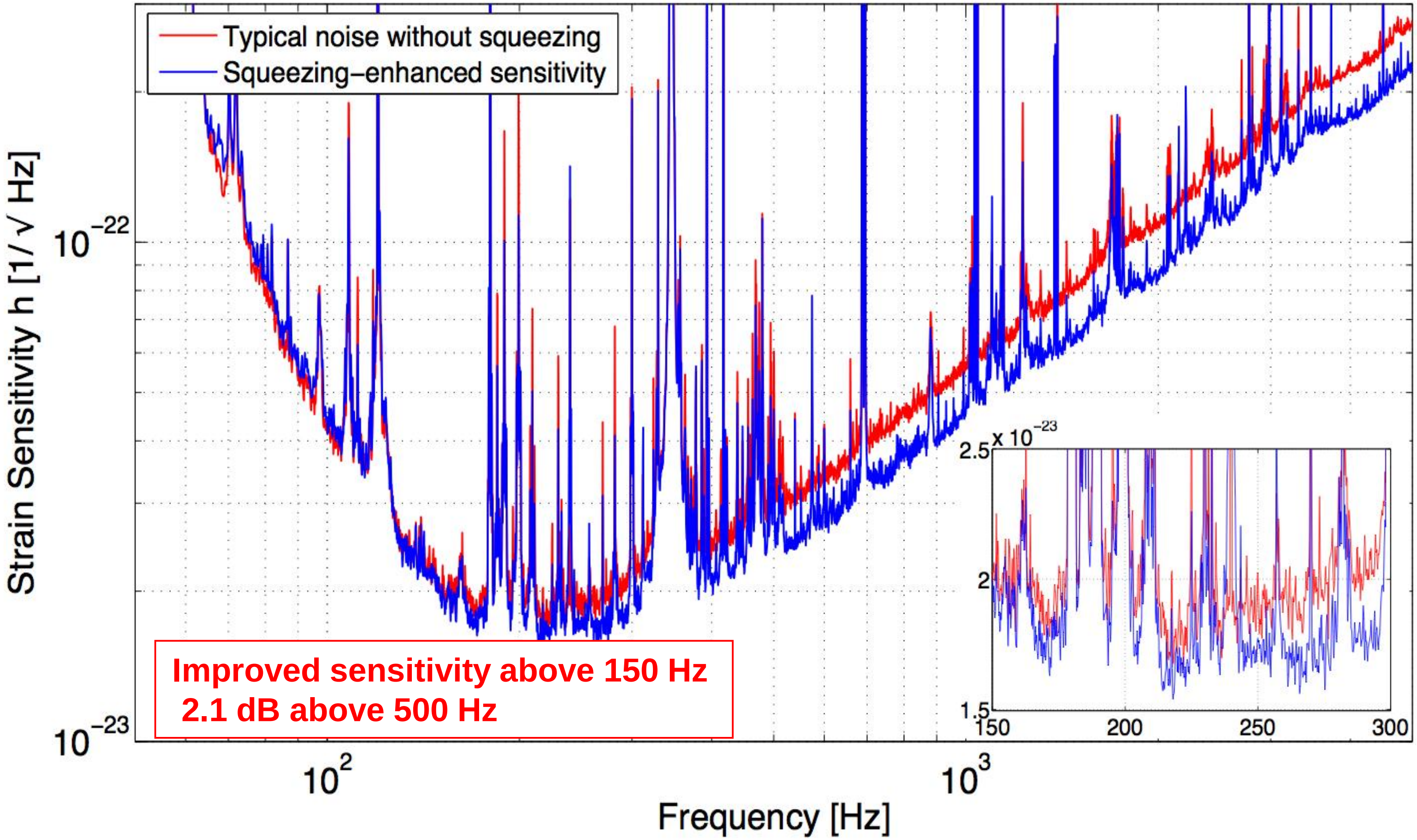
First Demonstration of Squeezed Interferometry in a Gravitational-wave Detector



LIGO Scientific Collaboration, "*A gravitational wave observatory operating beyond the quantum shot-noise* limit", Nature Physics **7**, 962–965 (2011)

Using Squeezed Light to Improve LIGO Sensitivity

LSC, "Enhancing the astrophysical reach of the LIGO gravitational wave detector by using squeezed states of light", in preparation



LIGO-India

- The idea in a nutshell–
- A direct partnership between LIGO Laboratory and India to build a LIGO interferometer on Indian soil

- Follows from earlier attempt to locate a LIGO detector in Australia

LIGO-India

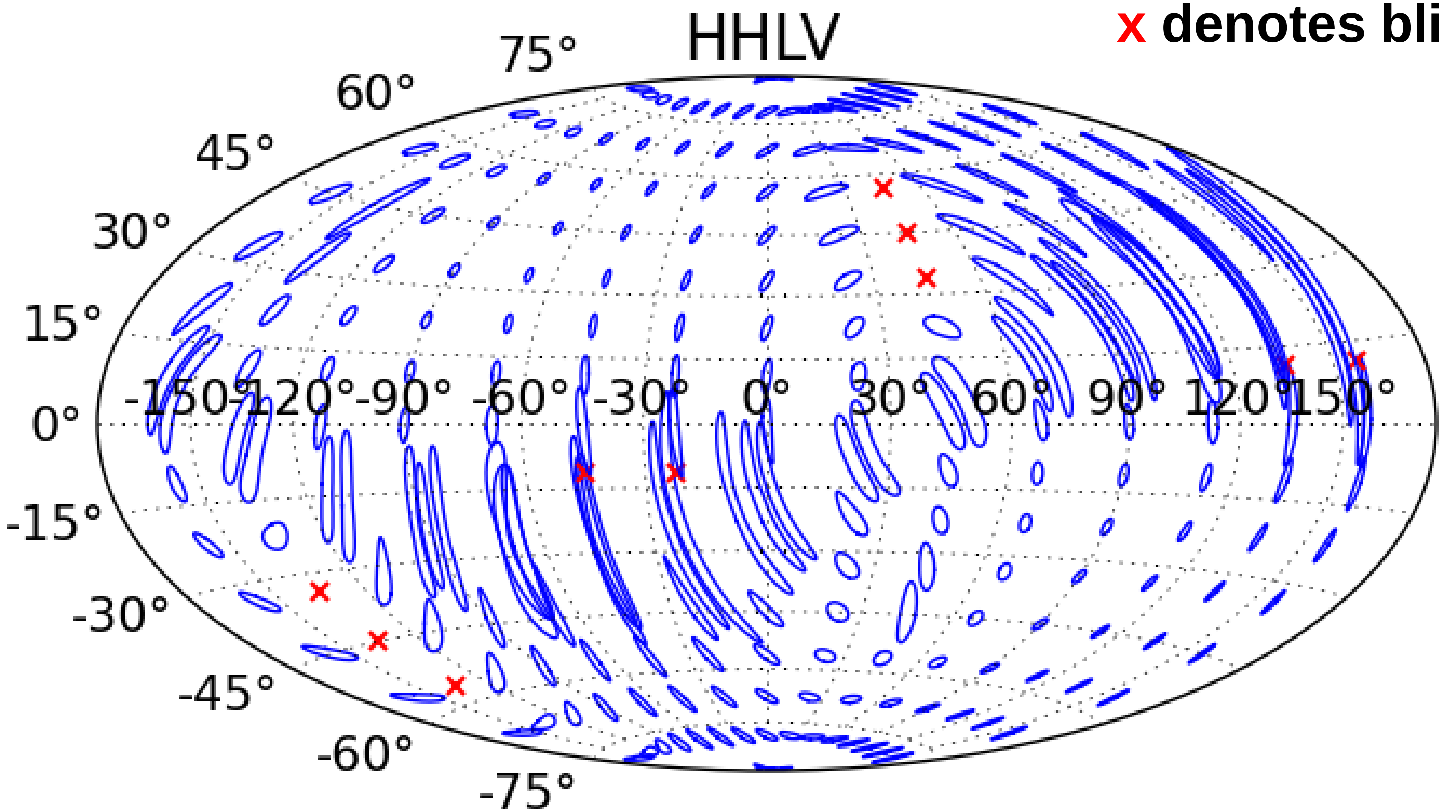
- LIGO Lab (with its UK, German and Australian partners) provides components for one Advanced LIGO interferometer (H2) from the Advanced LIGO project
- India provides the infrastructure (site, roads, building, vacuum system), "shipping & handling," staff for installation & commissioning, operating costs

- Indian Institutional Participants:
  - Inter-University Centre for Astronomy and Astrophysics (Astrophysics, Site Selection, Computing)
  - Raja Ramanna Centre for Advanced Technology (Detector Development)
  - Institute for Plasma Research (Facility and Vacuum construction, control systems)
  - + IndIGO Consortium (broader scientific community in India)

- Indian funding – LIGO-India is a Mega-science Project
  - Total request of ~ $230M to fund construction and operations
  - Funding status: approved by DAE/DST, referred to Cabinet of the Prime Minister of India for approval
- US funding – funding for aLIGO components through MREFC (no new costs)
  - Total contribution $140M (includes aLIGO components, designs, documentation)

Binary Neutron Star Merger Localization: Hanford-Livingston-Virgo

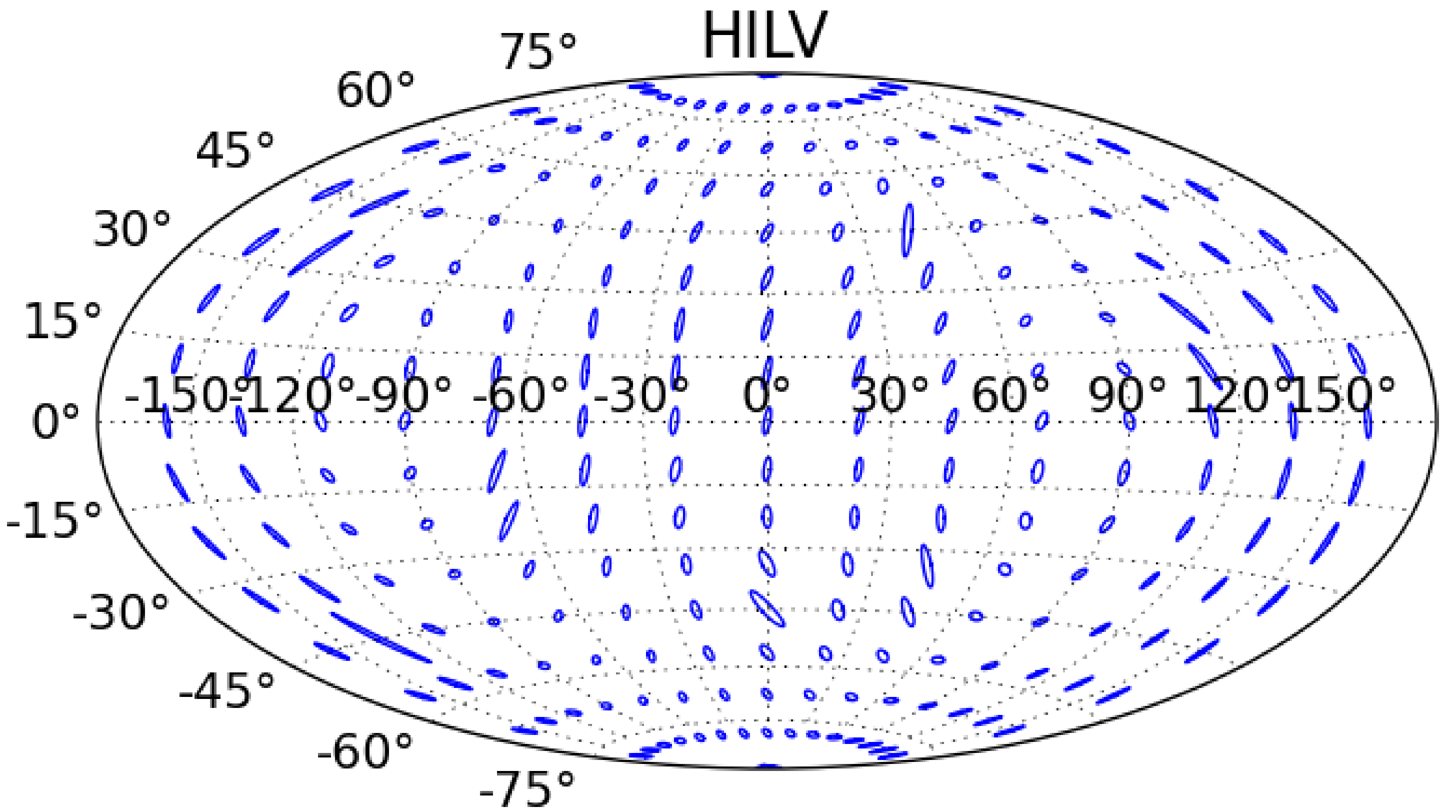
3 site network
x denotes blind spots



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

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

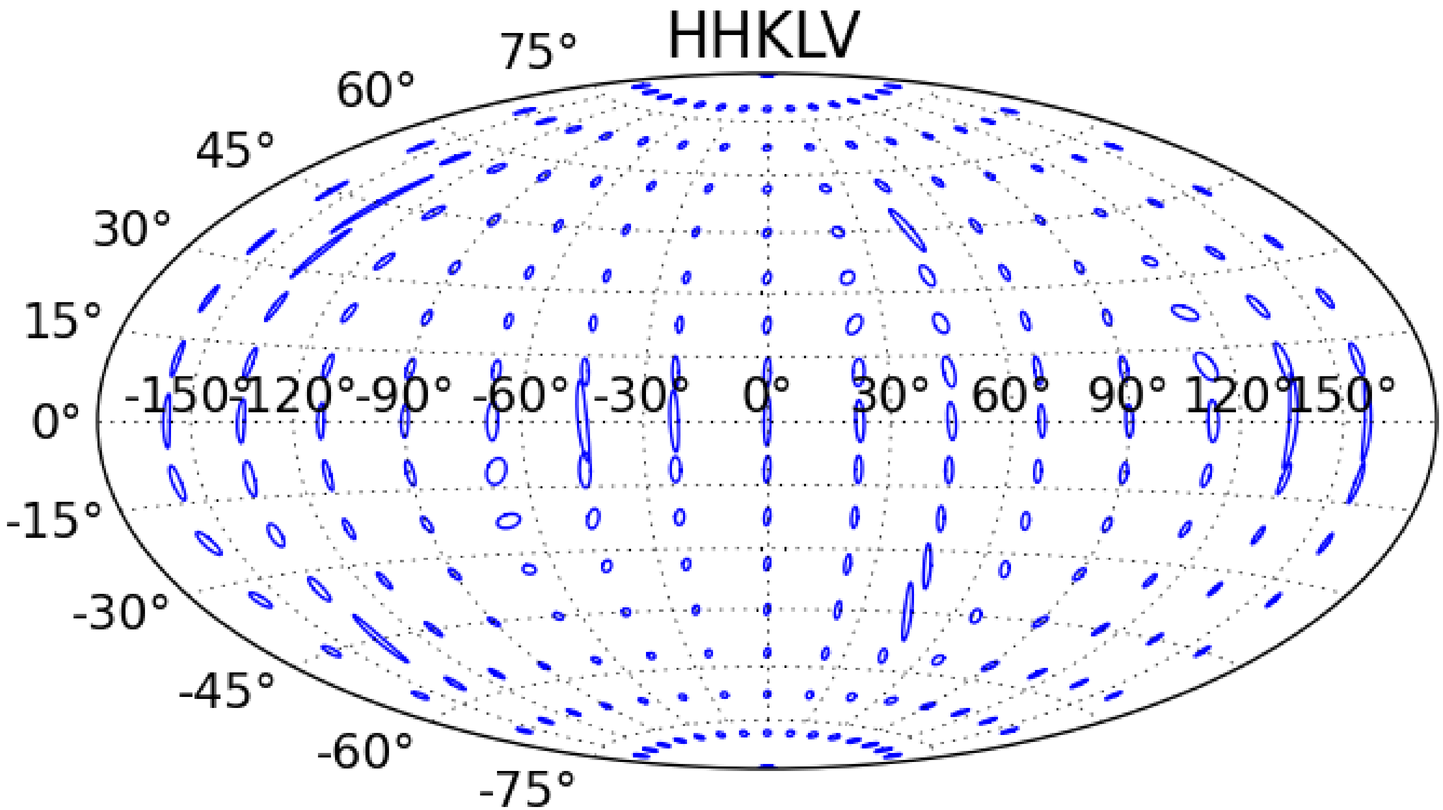
4 site network



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

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

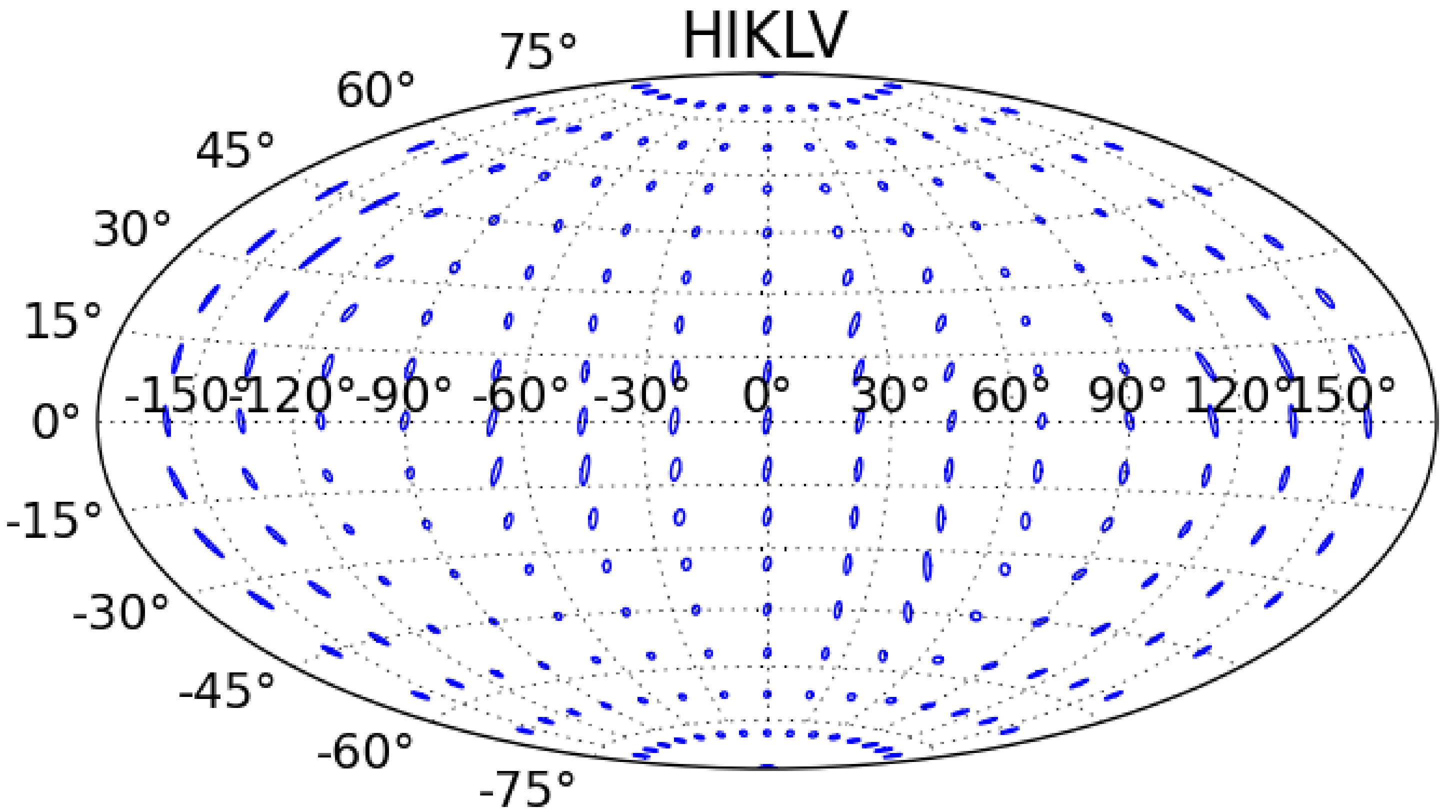
4 site network



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

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

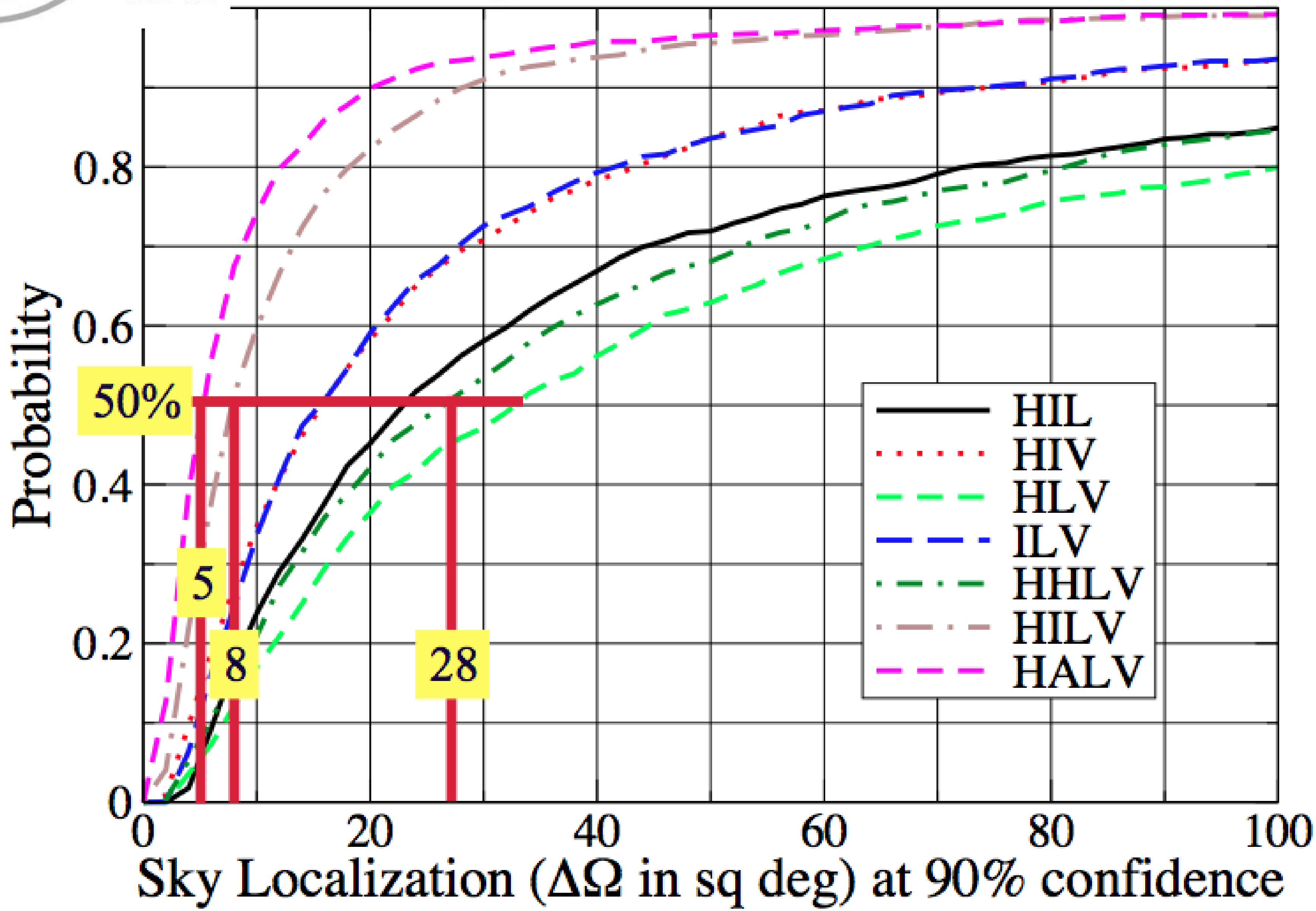
5 site network



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

Sky Localization

For Binary Neutron Star Coalesence

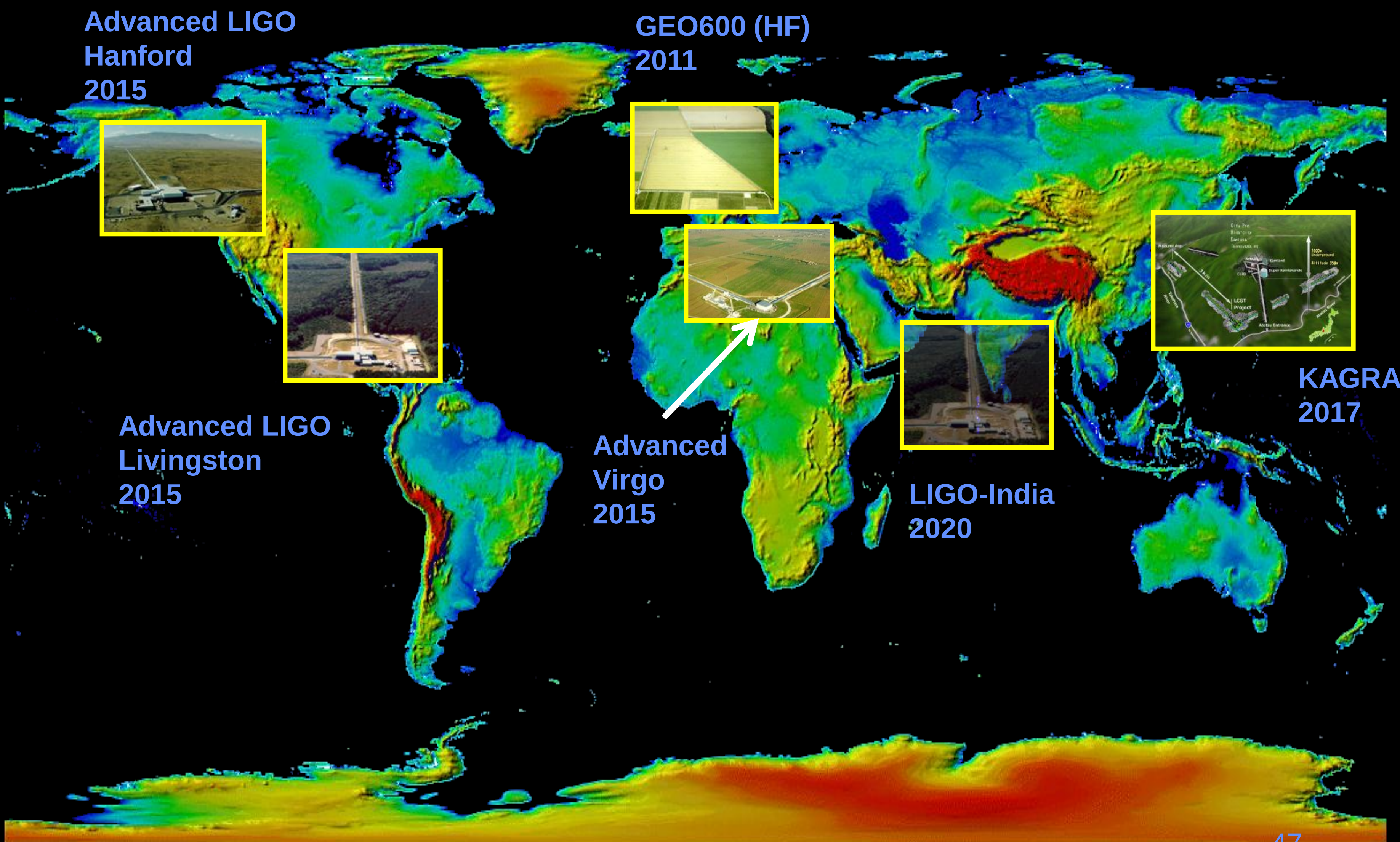


LIGO-India Status

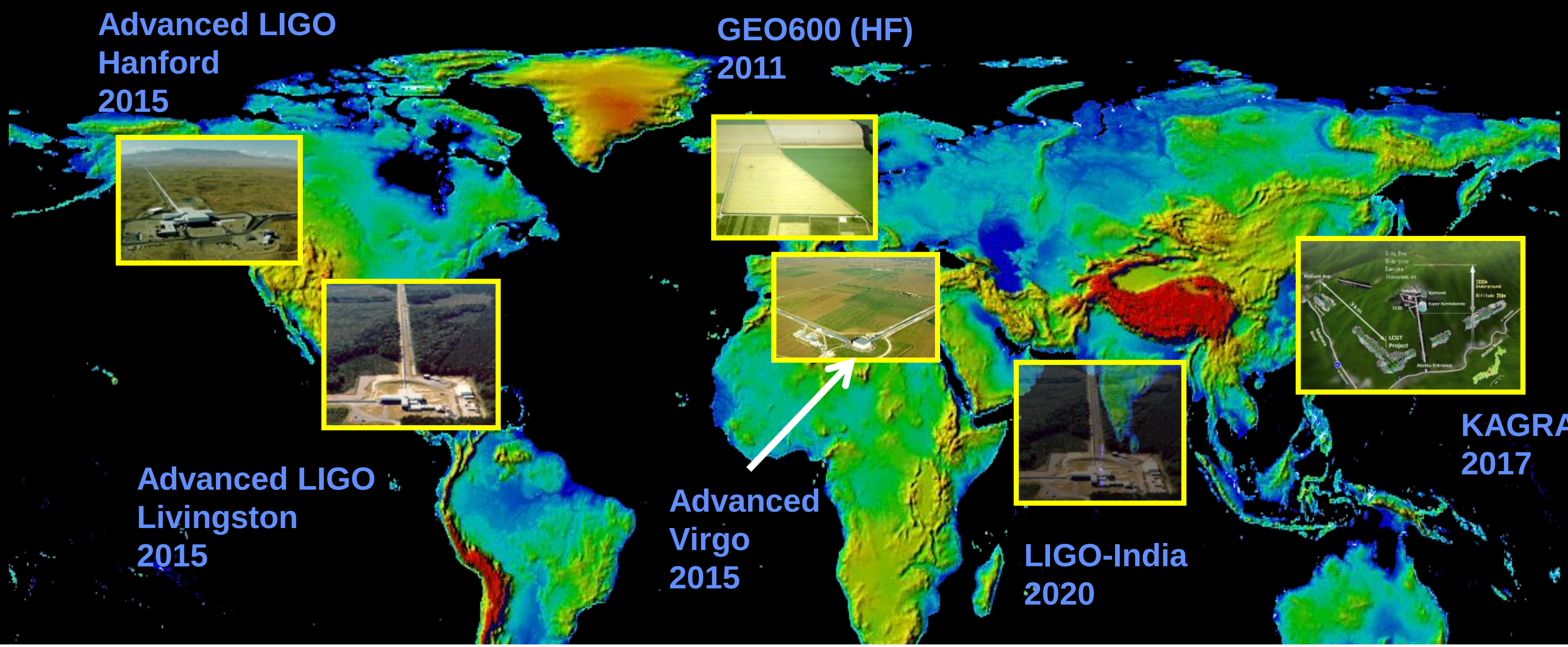
- Status in the US: -- the National Science Board has given permission to NSF, at its discretion, “to approve the proposed aLIGO Project in scope, enabling plans for the relocation of an advanced detector to India”
- Status in India – awaiting Cabinet approval and beginning of seed funding for facility design work
- Major activities in India are now focused on site evaluation/selection as well as development of a Tier 2 computing center @ IUCAA

- ***Expect LIGO-India to begin operations in 2020 or 2021***

Summary: The advanced GW detector network



Summary: The advanced GW detector network



Memorandum of Understanding

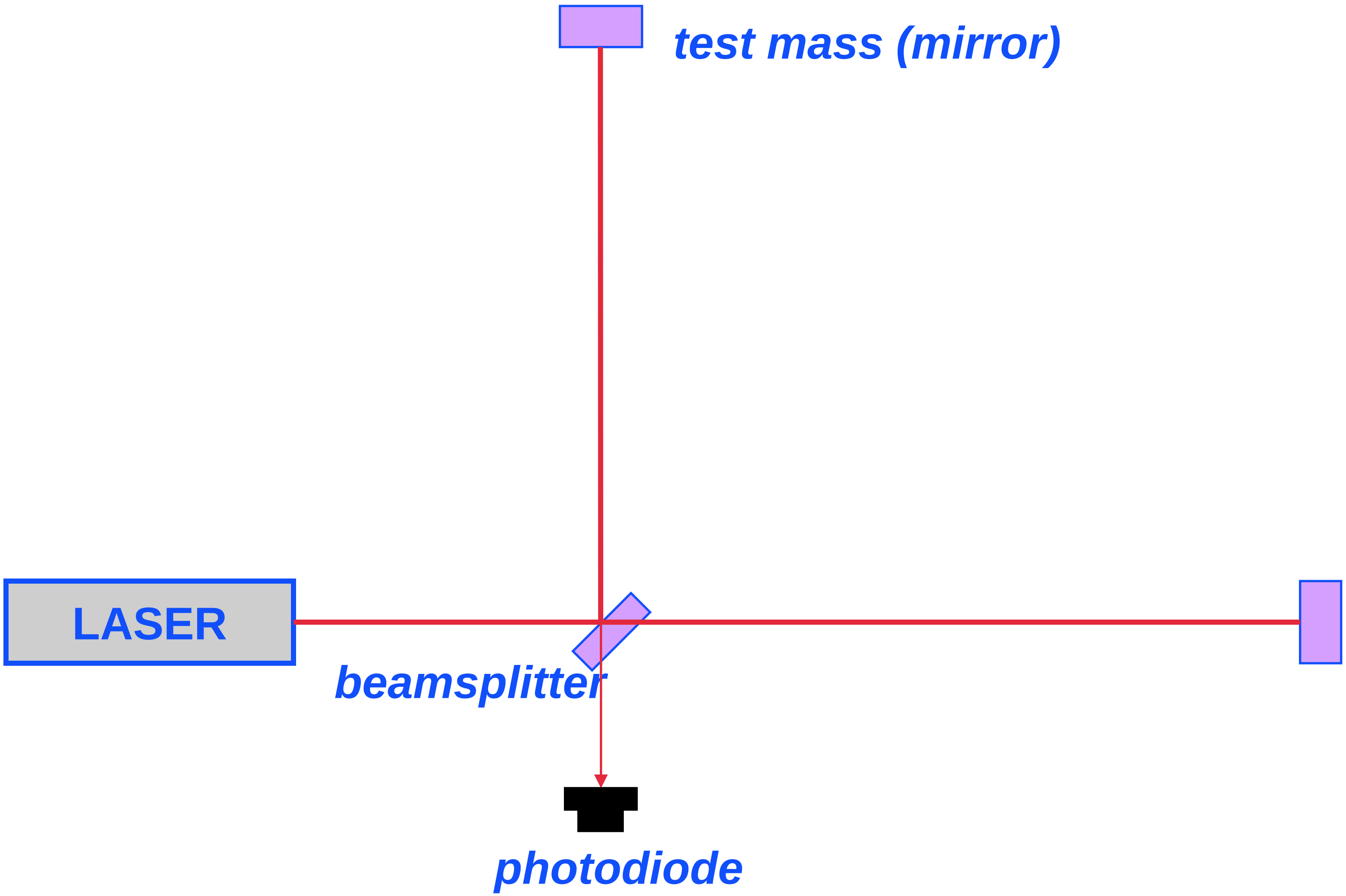
between

KAGRA, LIGO and Virgo Scientific Collaborations

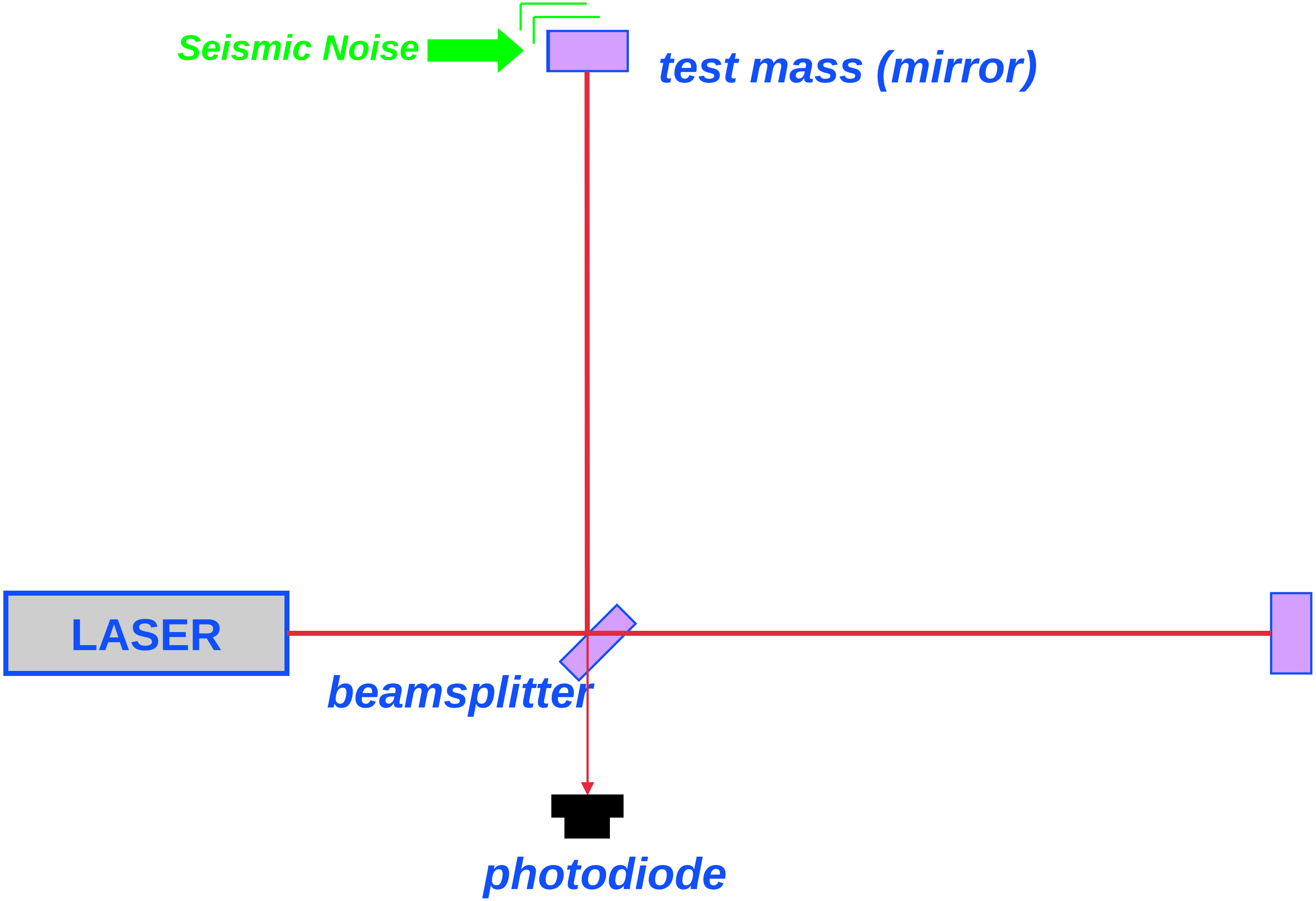
Conclusion

These are exciting times for gravitational wave physicists and astronomers!

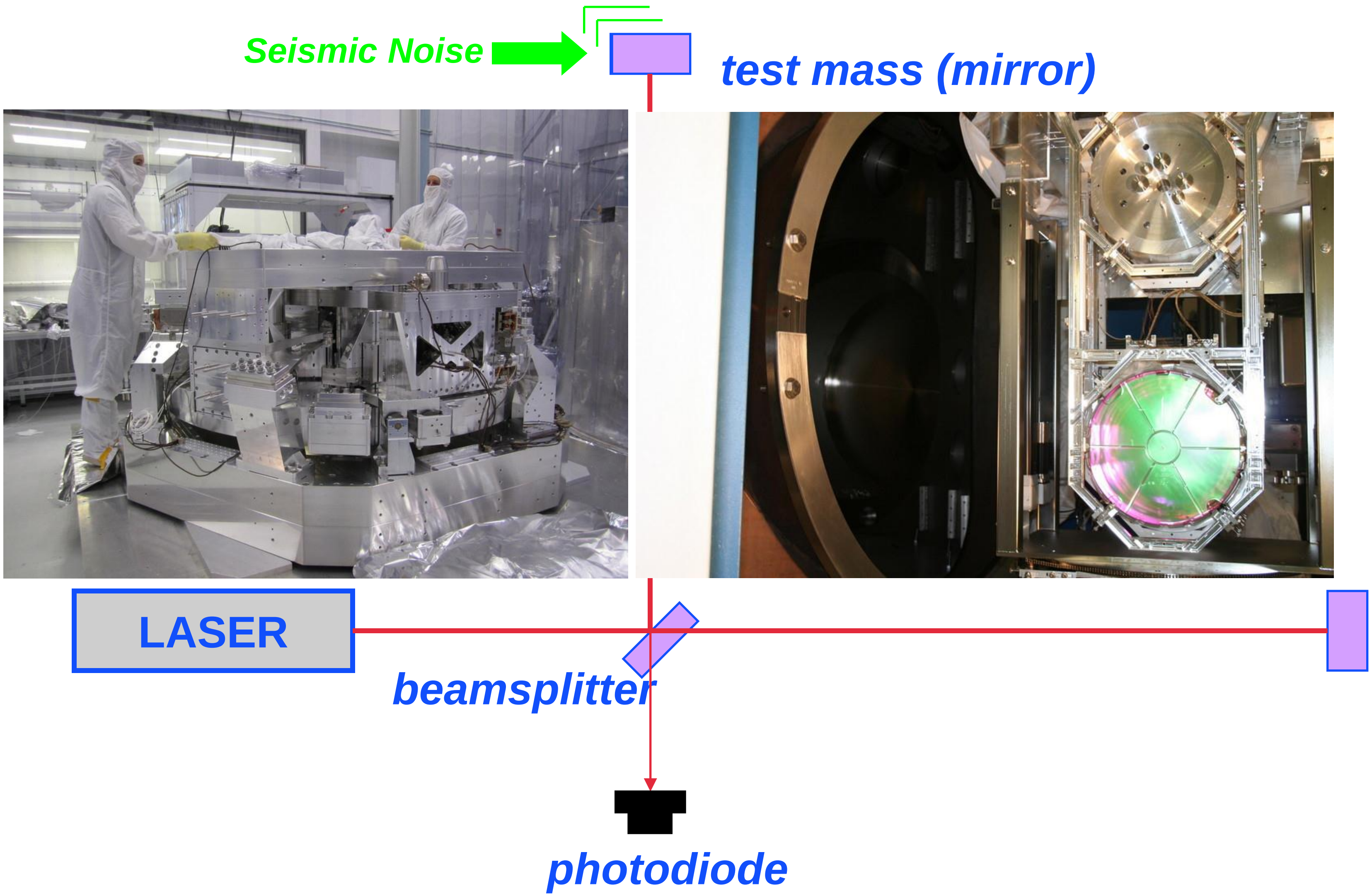
Reducing the interferometer noises



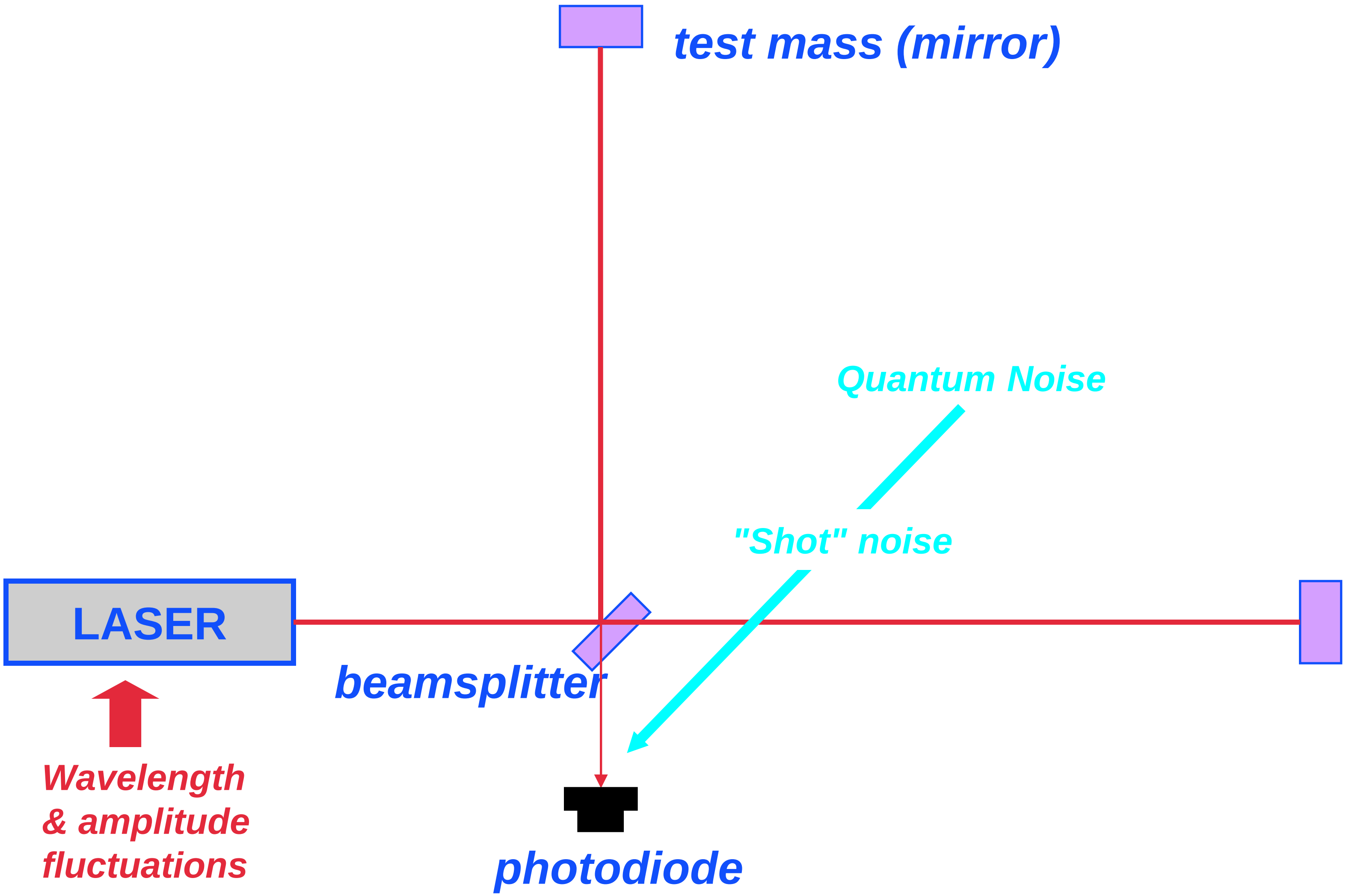
Reducing the interferometer noises



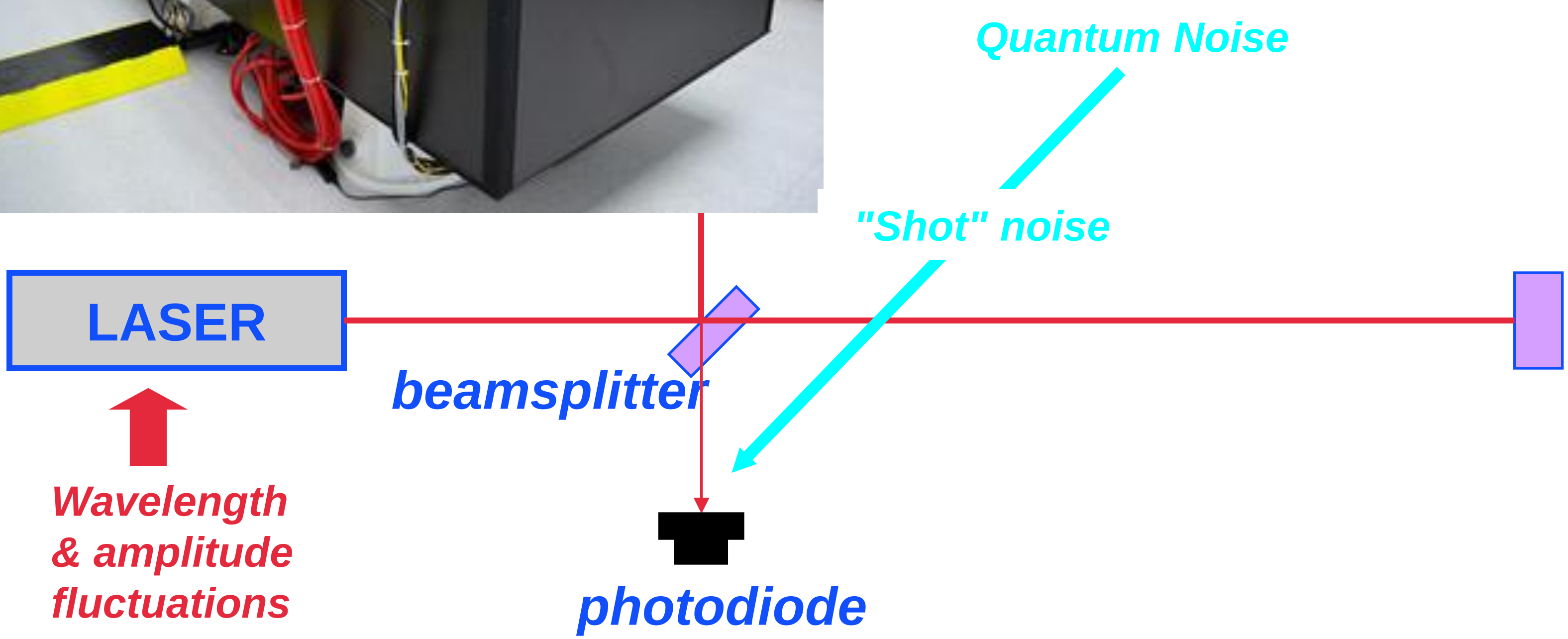
Reducing the interferometer noises



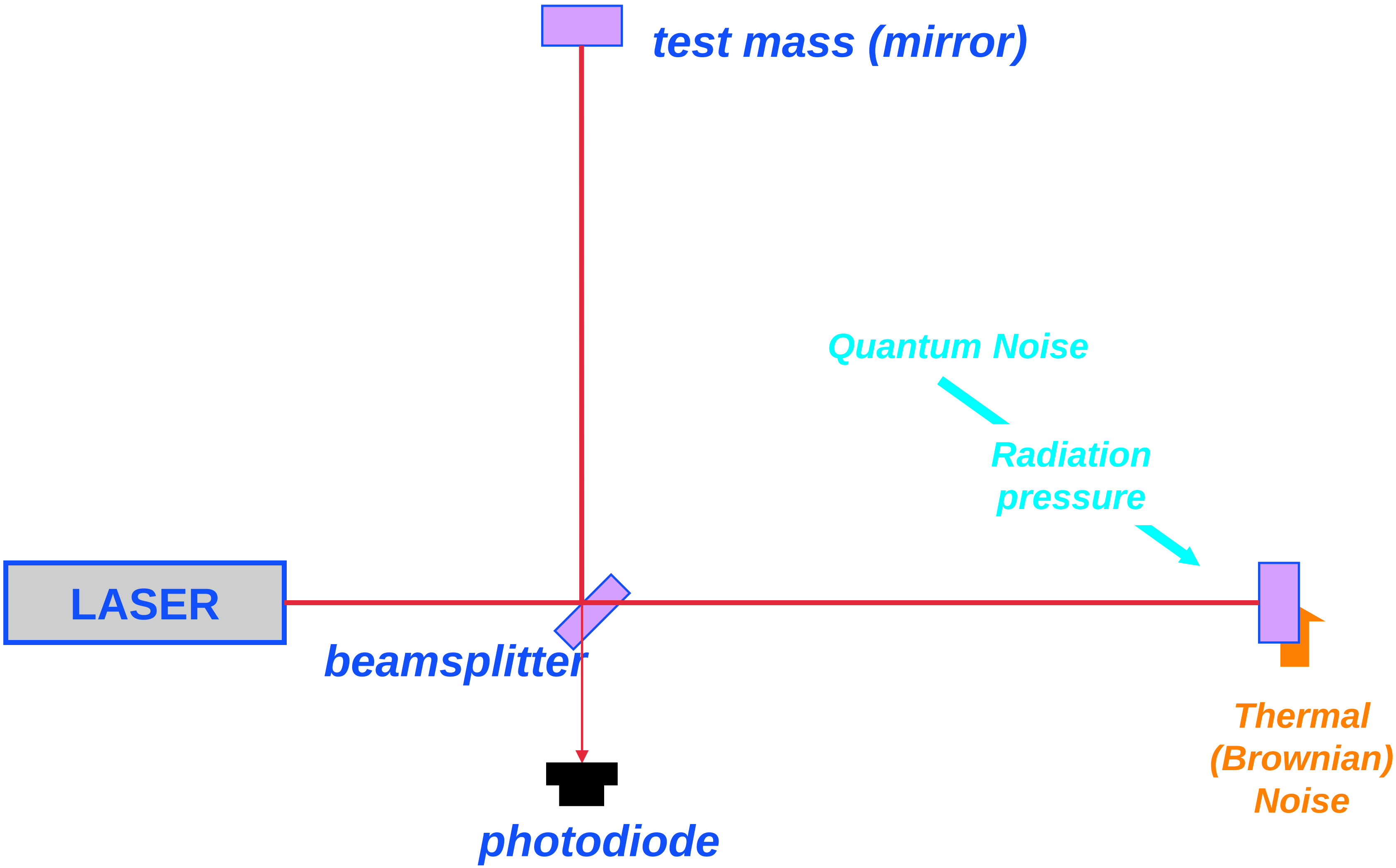
Reducing the interferometer noises



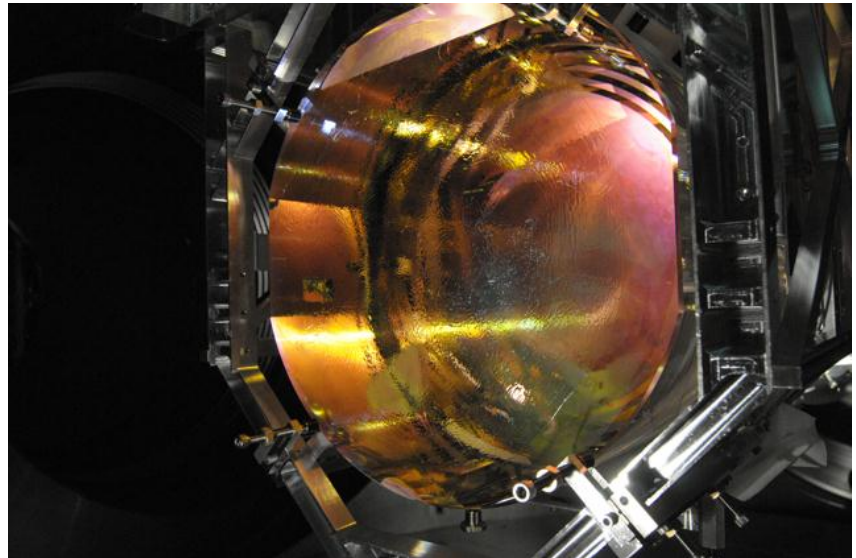
Reducing the interferometer noises

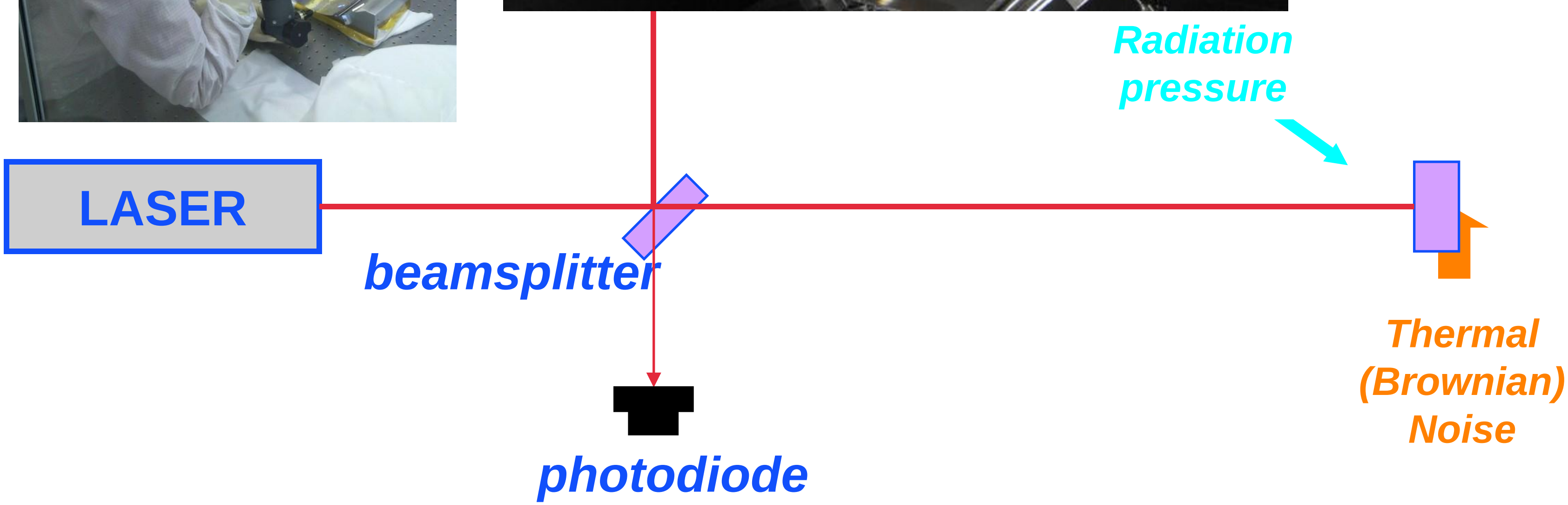


Reducing the interferometer noises

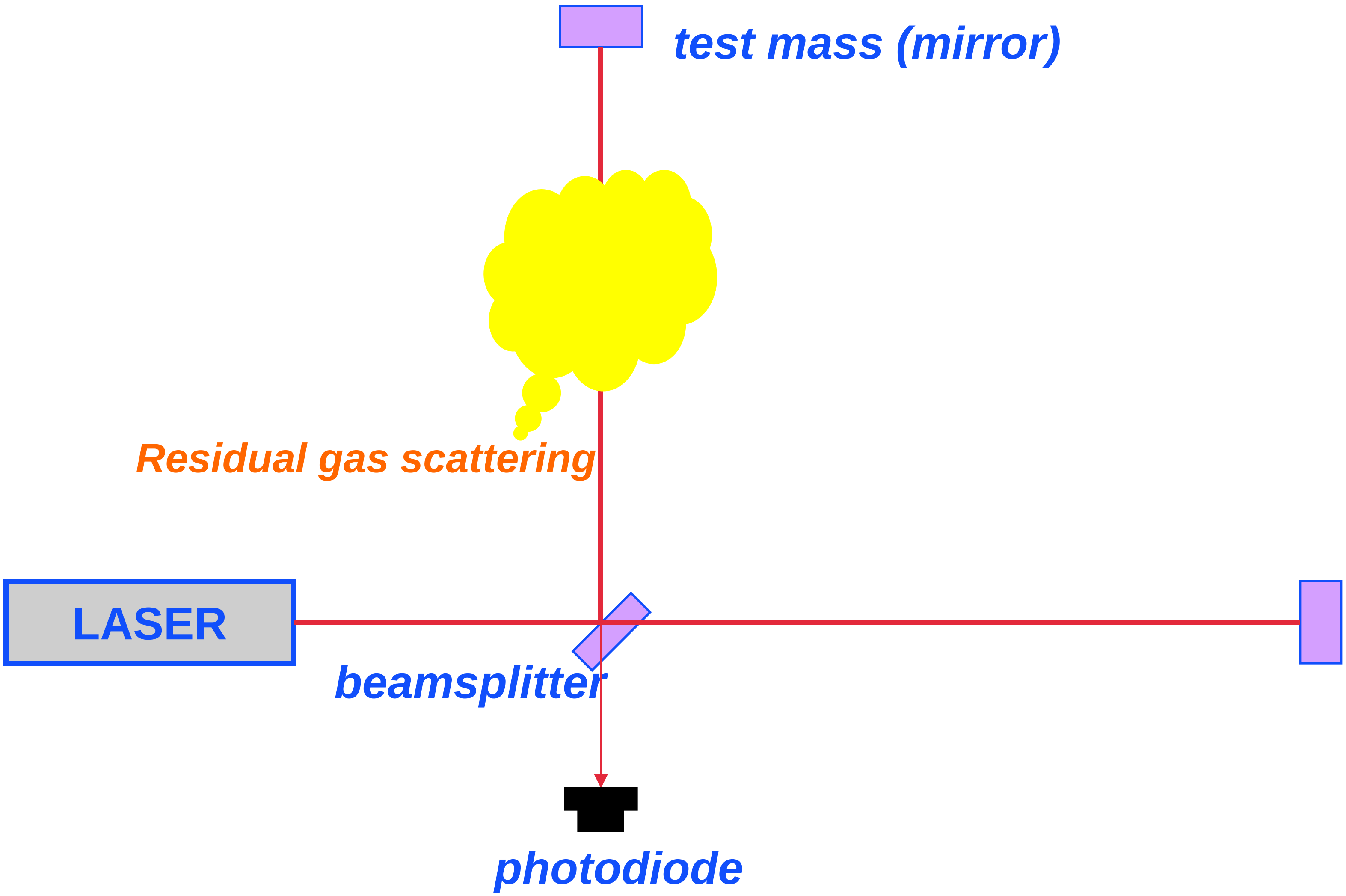


Reducing the interferometer noises

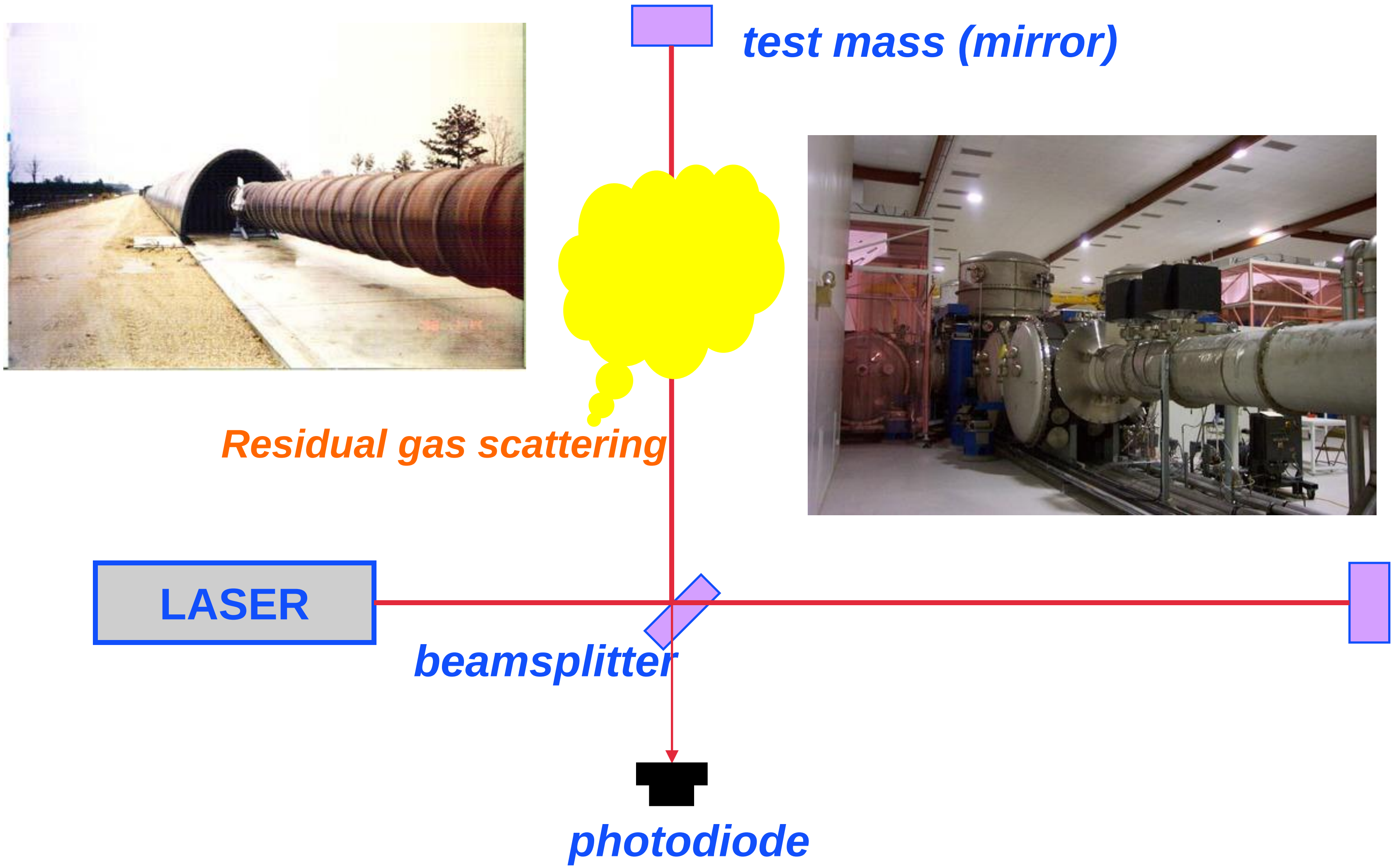




Reducing the interferometer noises



Reducing the interferometer noises

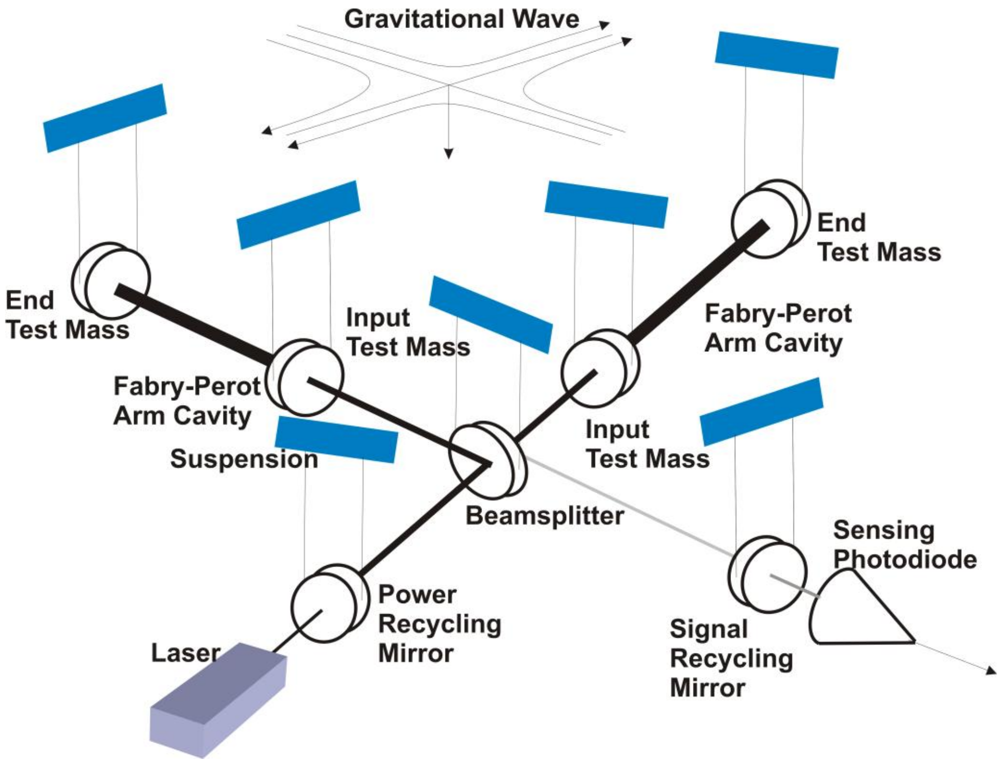


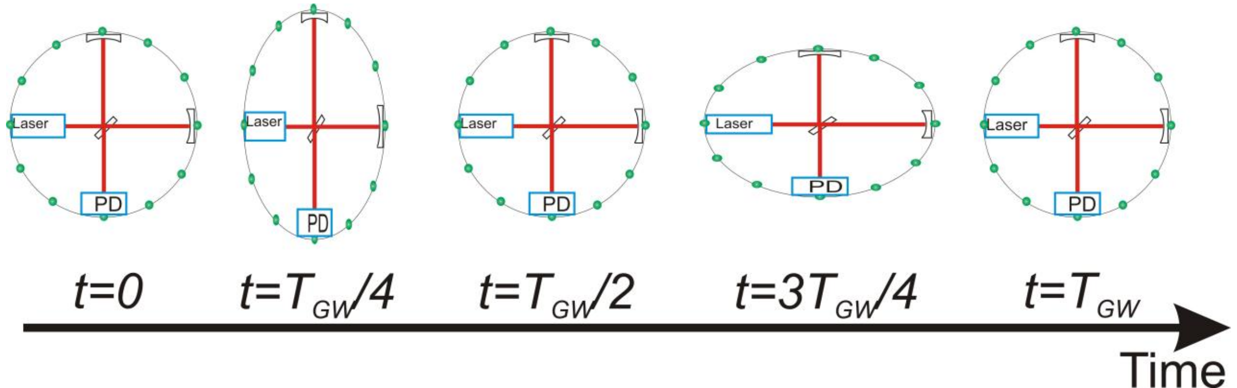
LIGO

First Generation Interferometers

Gravitational-wave interferometers

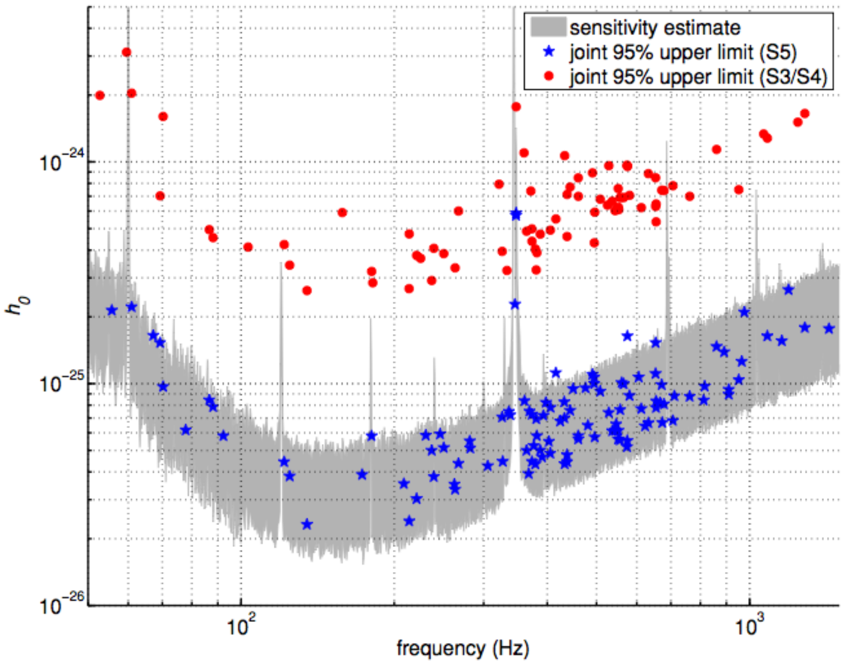
- Enhanced Michelson interferometers
  - » LIGO, Virgo, and GEO600 use variations
- Passing GWs modulate the distance between the end test mass and the beam splitter
- The interferometer acts as a transducer, turning GWs into photocurrent
  - » A coherent detector





Searches for GWs from known pulsars

- Continuous gravitational-wave emission due to asymmetry rotation axis
  - » elastic deformations of the solid crust or core
  - » Distortion an extremely strong misaligned magnetic field
  - » Weak emitters
- Spin-down limit: $h_{\rm sd} = \left(\frac{5}{2}\frac{GI_{zz}|\dot{\nu}|}{c^3 r^2 \nu}\right)^{1/2}$
- Crab pulsar (using LIGO data):
  - » $h_0 < h_{sd}/7$, $E_{GW} < 0.02E_{total}$
- Vela pulsar (using Virgo data):
  - » $h_0 < 0.66h_{sd}$, $E_{GW} < 0.45E_{total}$
- S5 search of 116 pulsars
  - Lowest upper-limit h_0: 2.3×10^{-26} (PSR J1603-7202)
  - Lowest upper-limit ellipticity: 7×10^{-8} (PSR J2124-3358)



LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Crab pulsar*", Astrophys. J. Lett. **683** (2008) 45

LIGO Scientific and Virgo Collaborations, "*First search for gravitational waves from the youngest known neutron star*", Astrophys. J. **722** (2010) 1504

LIGO Scientific and Virgo Collaborations, "*Beating the spin-down limit on gravitational wave emission from the Vela pulsar,*" Astrophys. J. **737** (2011) 93

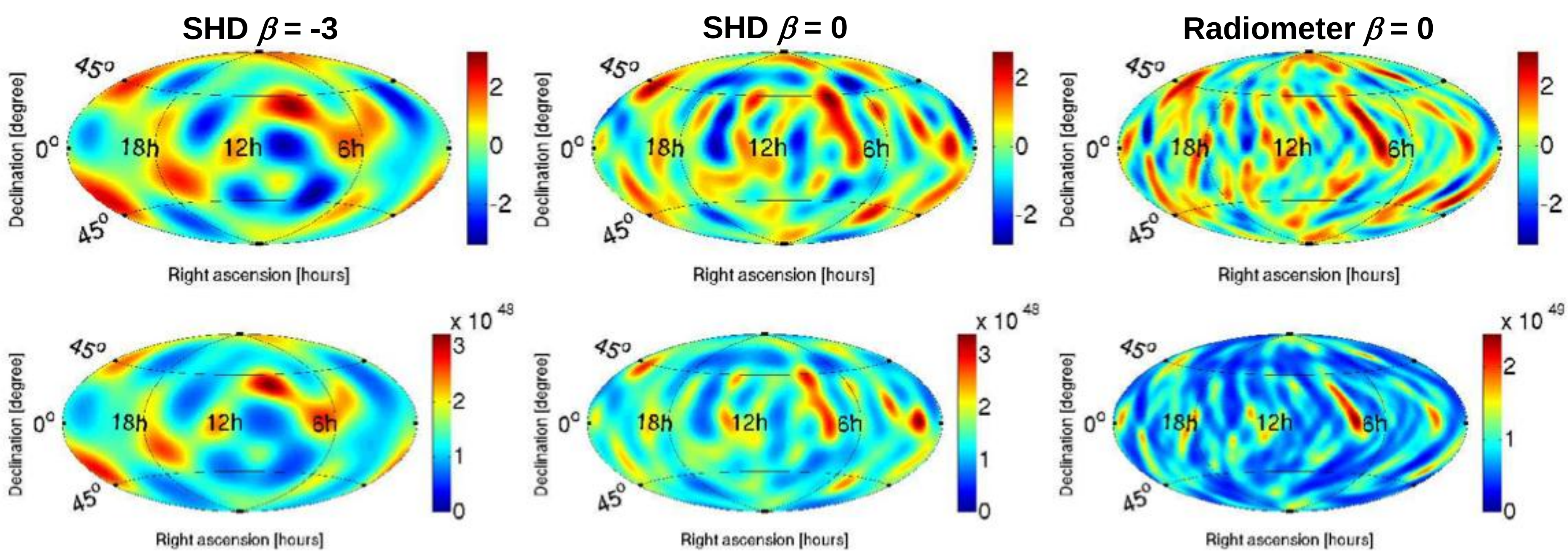
LIGO Scientific and Virgo Collaborations, "*Searches For Gravitational Waves From Known Pulsars With Science Run 5 LIGO Data*", Astrophys. J. **713** (2010) 671

Searches for stochastic gravitational waves

- Stochastic sources - primordial GWs or ensemble of incoherent point-like or extended emitters
- LIGO/Virgo S5 isotropic stochastic GW upper limit: $\Omega_0 < 6.9 \times 10^{-6}$
  - » Beats inferred upper limit from BBN: $\Omega_0^{BBN} < 1.1 \times 10^{-5}$
- LIGO/Virgo S5 directional search for point-like/extended emitters
  - » New: spherical harmonic decomposition for arbitrary angular distributions

LIGO Scientific and Virgo Collaborations, "*An upper limit on the stochastic gravitational-wave background of cosmological origin*", Nature, **460**: 990 (2009).

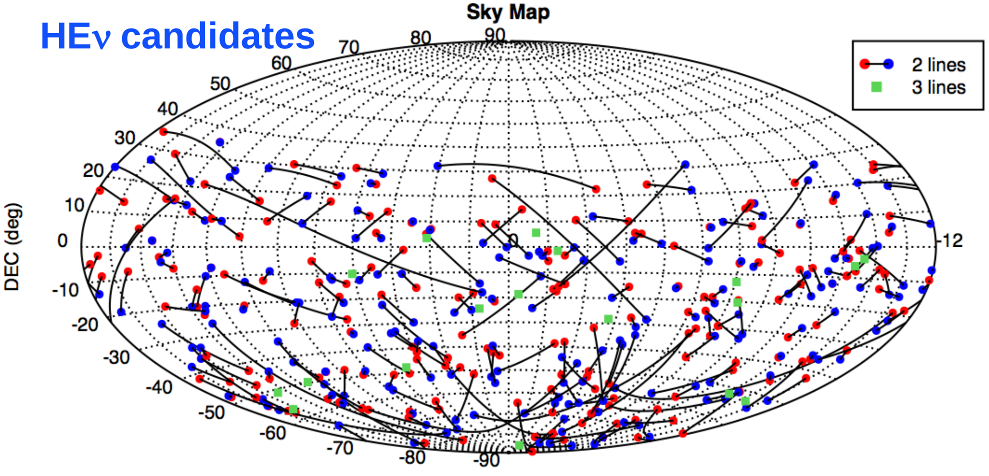
LIGO Scientific and Virgo Collaborations, "*Directional Limits on Persistent Gravitational Waves Using LIGO S5 Science Data*", Phys. Rev. Lett. **107** (2011) 271102

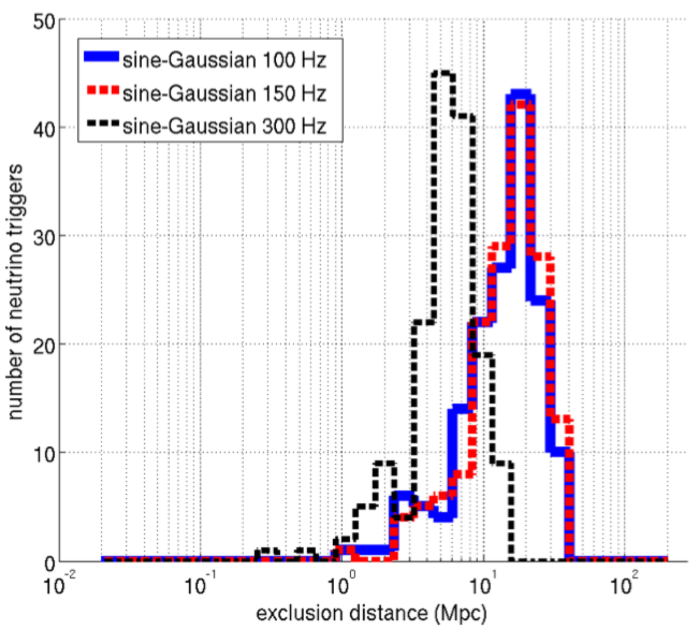


Joint GW-high energy neutrino searches with ANTARES

- Several plausible astrophysical joint GW-HEν emission sources
  - » Conventional: soft gamma repeaters, GRBs, choked GRBs
  - » More exotic: cosmic strings
- Both GWs and HEνs are very weakly interacting → information preserving, traveling unimpeded for cosmological distances
- Co-analysis with ANTARES Neutrino Telescope
  - » undersea, 40 km off southern coast of France
  - » 3D array of PMTs → ν position reconstruction
- 154 HEν triggers followed up with X-pipeline
  - » No candidates → exclusion distance

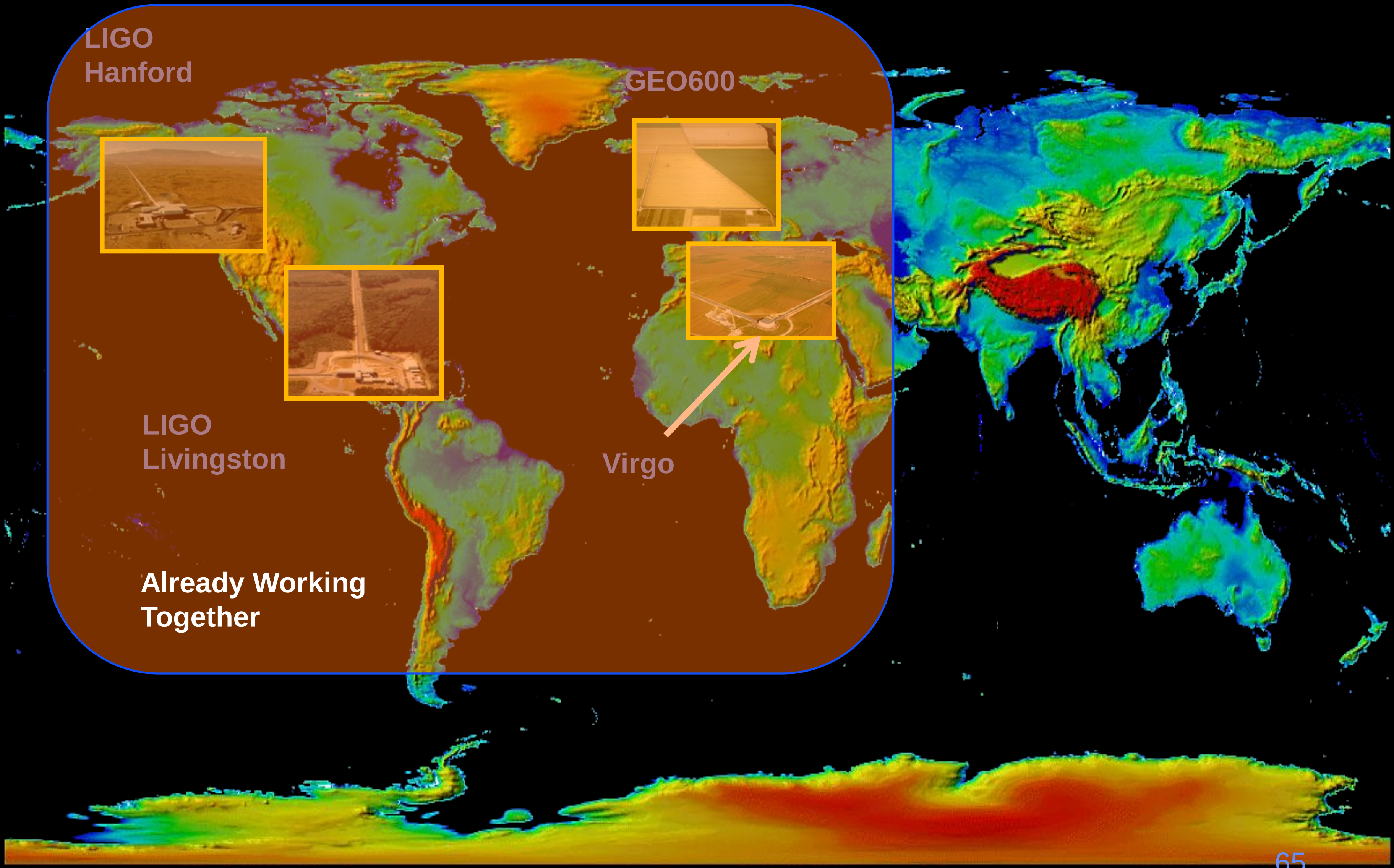
HEν candidates



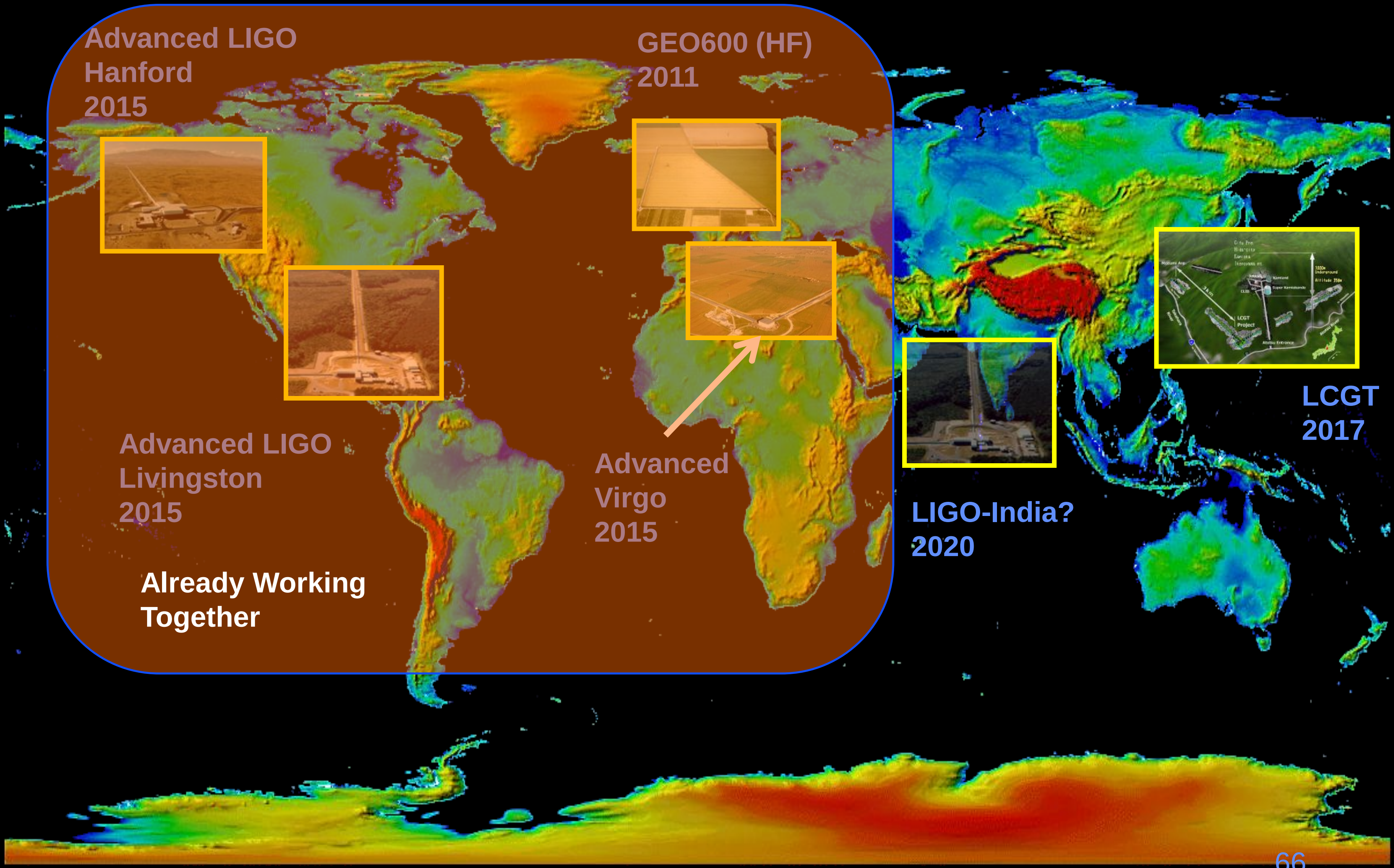


ANTARES, LIGO, AND Virgo Collaborations, "A first search for coincident gravitational waves and high energy neutrinos using LIGO, Virgo and ANTARES data from 2007", arXiv:1205.3018

The Current GW Detector Network

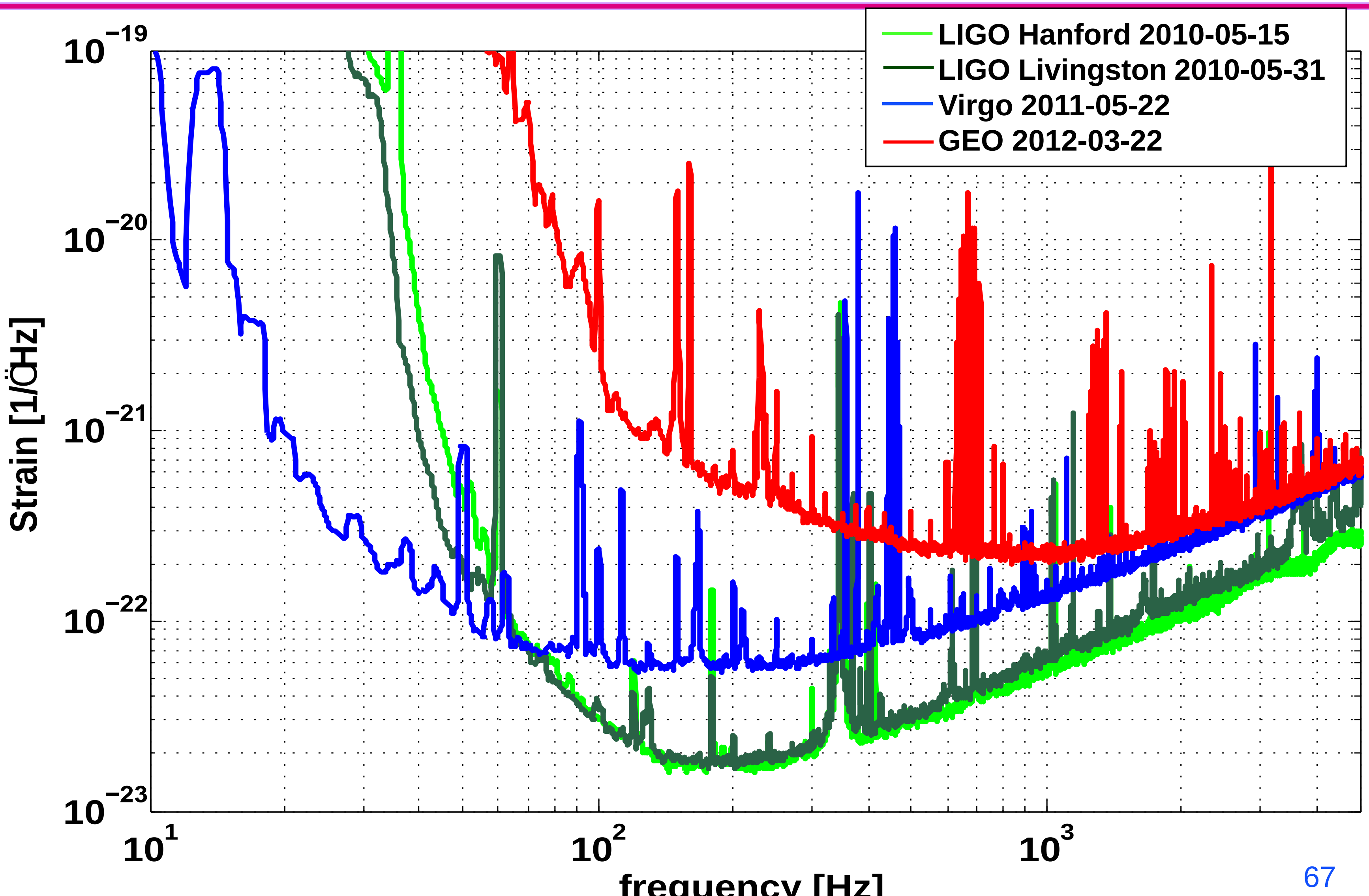


The Advanced GW Detector Network



LIGO

LIGO Scientific Collaboration, "*LIGO: The Laser Interferometer Gravitational-Wave Observatory*", Rep. Prog. Phys. **72** (2009) 076901
H. Grote (for the LSC), "*The Upgrade of GEO600*", Class. Quantum Grav. **27**, 084003 (2010)
T. Accadia, et al., "*Virgo: a laser interferometer to detect gravitational waves*", J. Instrumentation **7**, P03012 (2012)



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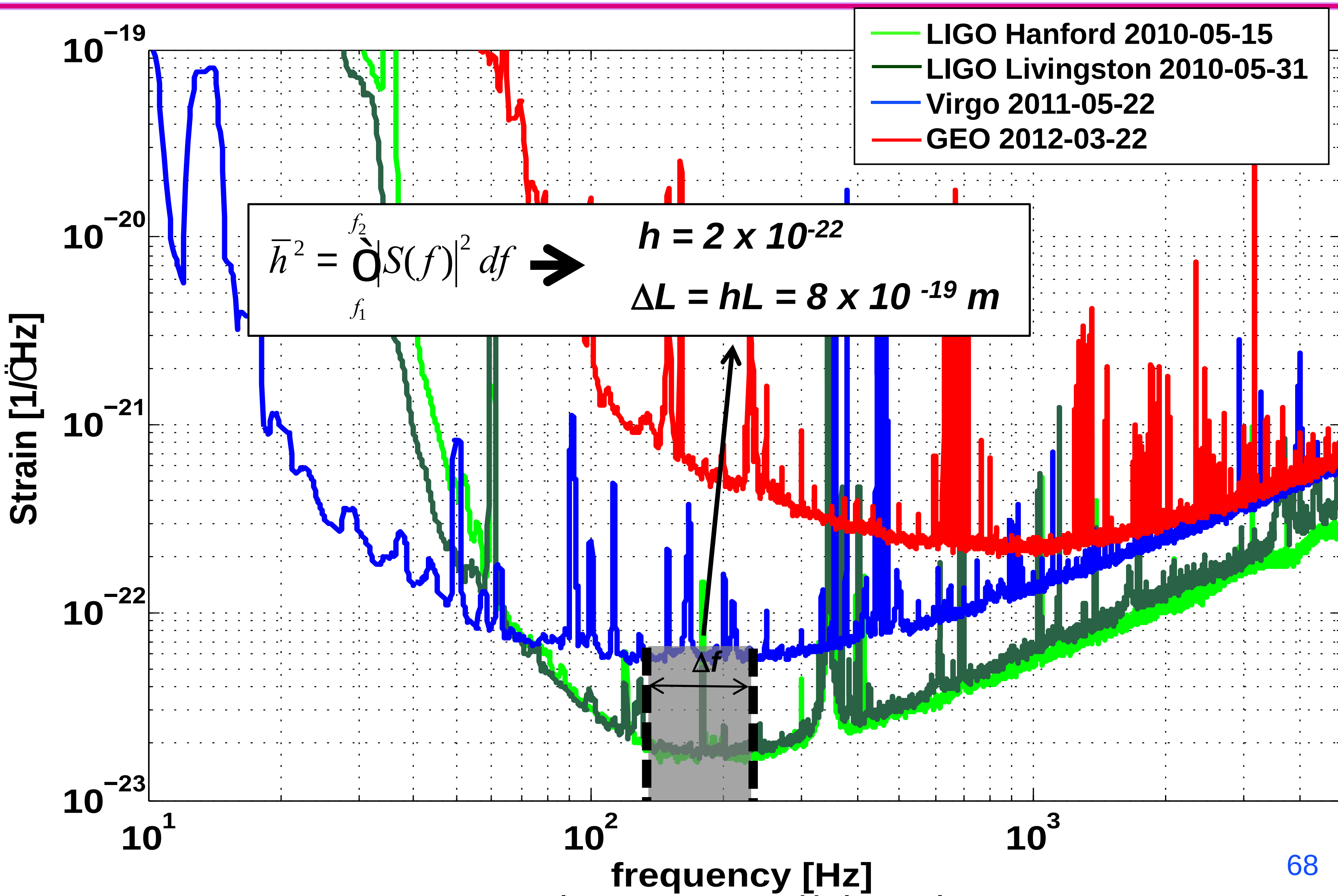
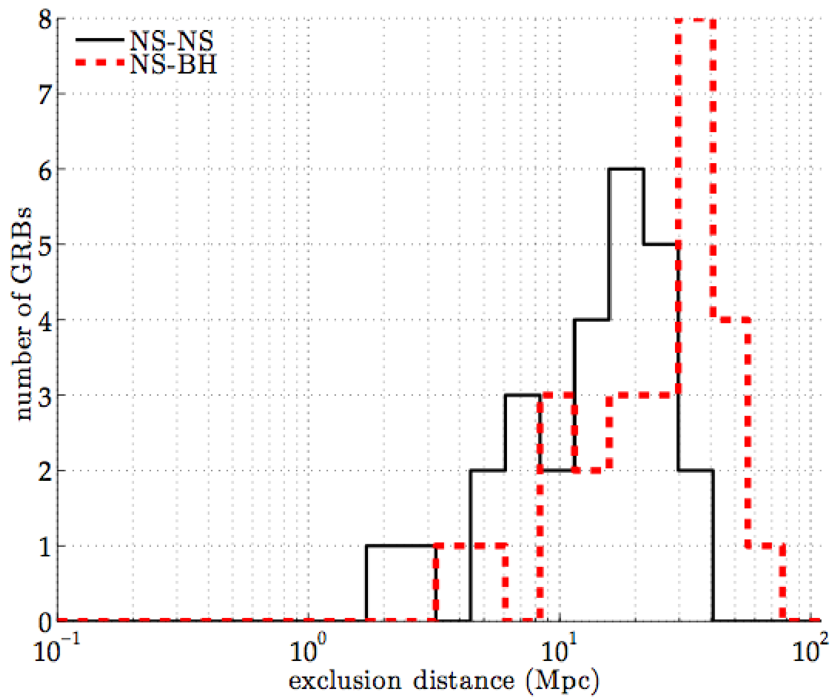


Triggered searches for gamma-ray bursts

- Data from LIGO S6 and Virgo VSR 2,3
- Modeled search for NS-NS, NS-BH coalescences
  - » TaylorF2 3.5 PN order templates, [2, 40) $M_\odot$ total mass range
- Unmodeled search for GW bursts
  - » Coherent network analysis (‘X-pipeline’); time-frequency clustering
- 404 GRBs from Swift, Fermi, MAXI, SuperAGILE, INTEGRAL
- Require 2 detectors in science mode → 154 GRB triggers analyzed
  - » 10% with redshift; well beyond LIGO/Virgo range

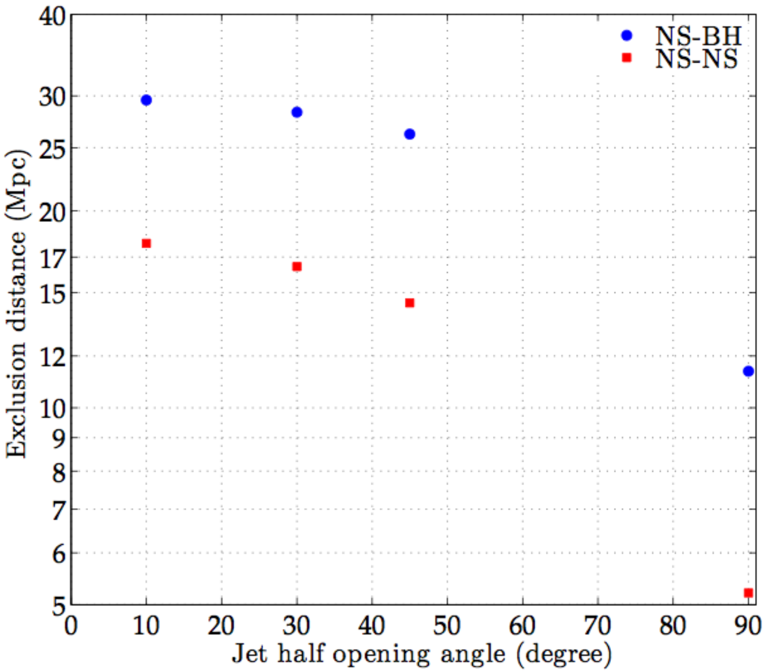
Binary system coalescence



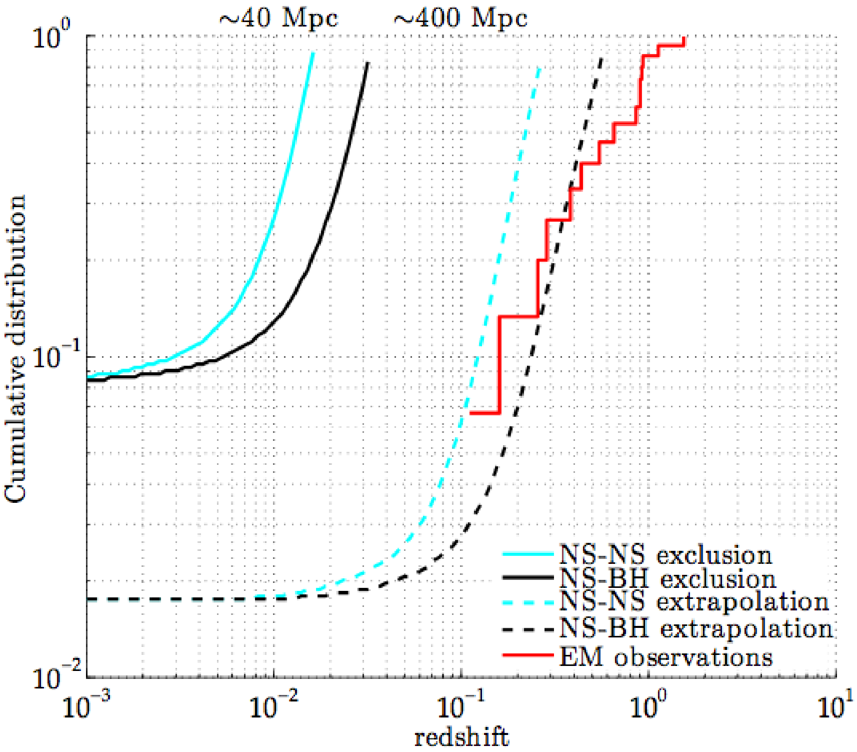
LIGO Scientific and Virgo Collaborations, Briggs, et al., “Search For Gravitational Waves Associated With Gamma-Ray Bursts During Ligo Science Run 6 And Virgo Science Runs 2 And 3”, arXiv:1205.2216

Exclusion distance

Exclusion Distance vs. Jet Angle



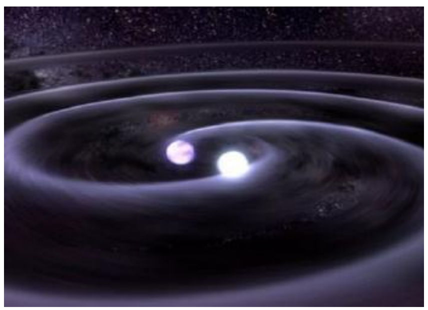
Cumulative Redshift Distribution

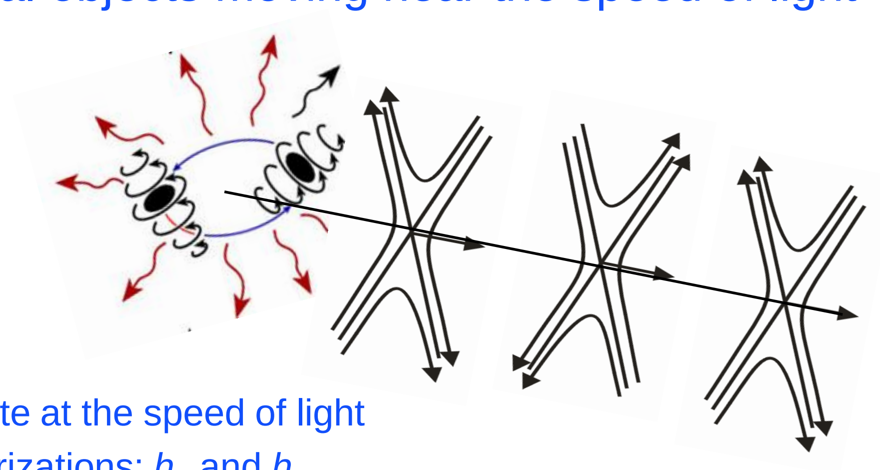


LIGO Scientific and Virgo Collaborations, Briggs, et al., "Search For Gravitational Waves Associated With Gamma-Ray Bursts During Ligo Science Run 6 And Virgo Science Runs 2 And 3", arXiv:1205.2216

Gravitational waves

- Gravitational waves are propagating solutions to the Einstein Field Equations in GR (‘ripples’ in space-time)
  - » Emissions from rapidly accelerating mass distributions
- Practically, need astrophysical objects moving near the speed of light





  - » According to GR, GWs propagate at the speed of light
  - » Quadrapolar radiation; two polarizations: h_+ and h_x
- Physically, gravitational waves are *strains*:

$$h = \frac{\Delta L(f)}{L}$$

- Sense of scale: strain from a binary neutron star pair
  - » M = 1.4 M⊙, $r = 10^{23}$ m (15 Mpc, Virgo), R = 20 km, f_{orb} = 400 Hz

$$h \approx \frac{4\pi^2 G M R^2 f_{orb}^2}{c^4 r} \quad \Rightarrow \quad h \sim 10^{-21}$$

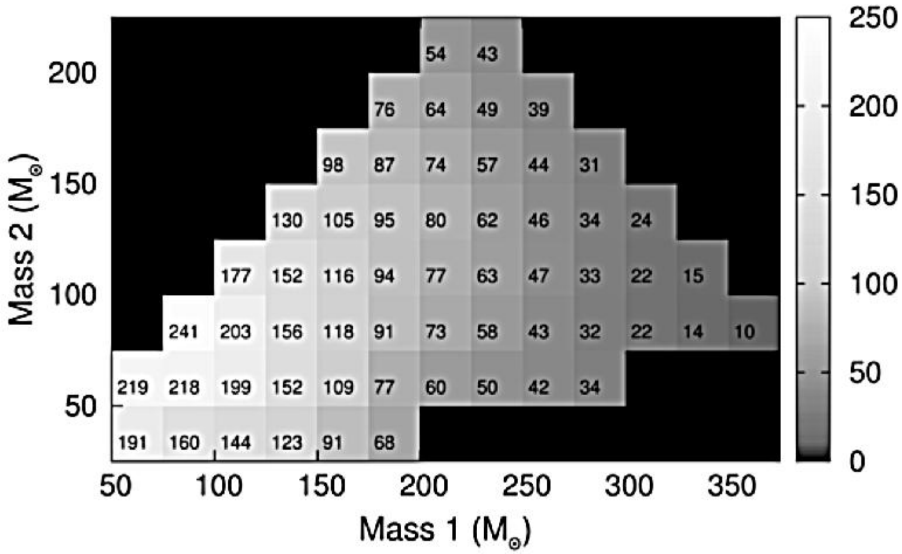
LIGO

Initial LIGO

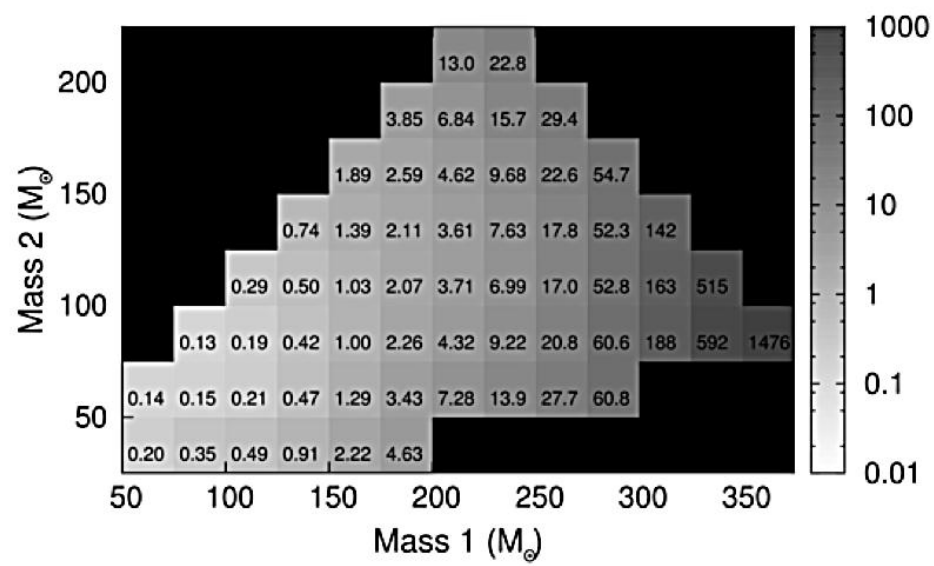
Searching for High Mass Compact Binary Coalescences

- IMBH formation proposed to complete BH mass hierarchy…
  - » Via stellar collision in globular clusters, stalled supernovae of early pop III stars, progressive accumulation into higher mass
- …but their existence is uncertain
  - » Stellar winds suppression of runaway accumulation, merger recoil ejection of BH from GC
- Candidates exist: ultraluminous x-ray sources M82 X-1, NGC 1313 X-2
- S5/VSR1 search using constrained unmodelled waveform (Coherent WaveBurst algorithm)

Effective Range (Mpc) for H1H2L1V1



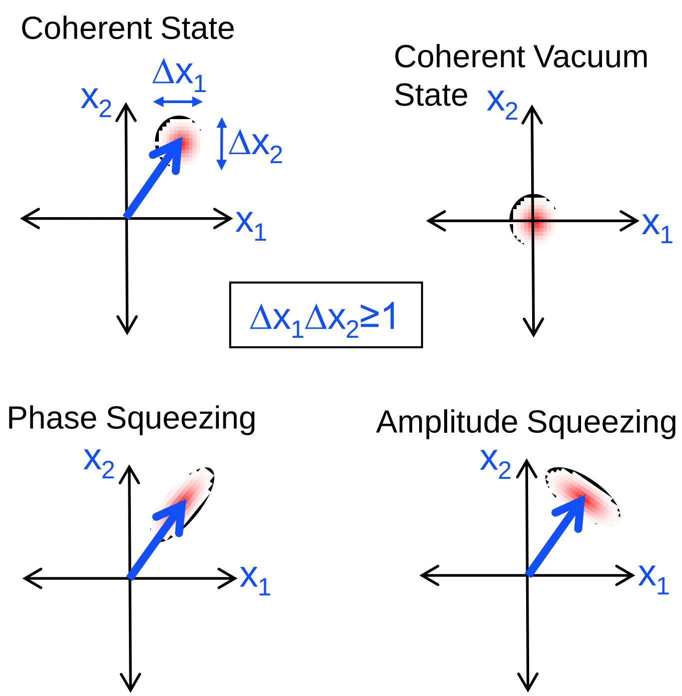
Rate Density Upper Limit (Mpc^{-3} Myr^{-1})

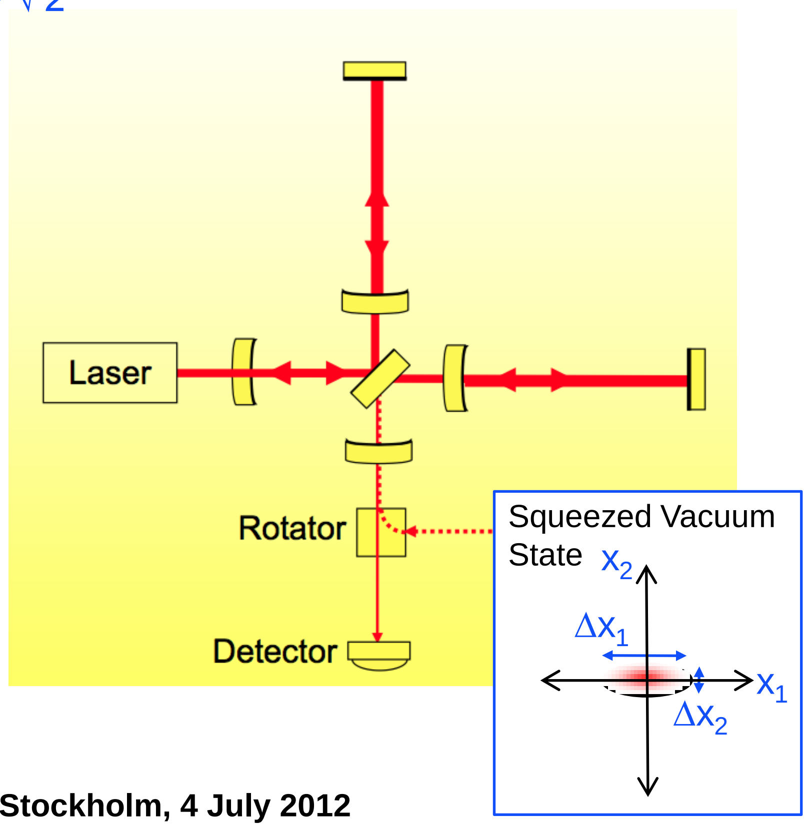


LIGO Scientific and Virgo Collaborations, "*Search for gravitational waves from intermediate mass binary black holes*", Phys. Rev. D**85**, 102004 (2012)

Squeezed Interferometry

- Shot noise and radiation pressure come from statistical fluctuations ultimately arising from the Heisenberg uncertainty principle
  - » These fluctuations exist in the vacuum state. They enter the interferometer at the output port.
- A noise reduction in one quadrature can be achieved at the expense of the other quadrature → ‘squeezed light’
  - » 3 dB injected squeezed vacuum reduces noise by √ 2
  - » Possible to achieve 10 dB





Advanced LIGO schedule