Search for gravitational waves with LIGO and follow-up of candidate-events

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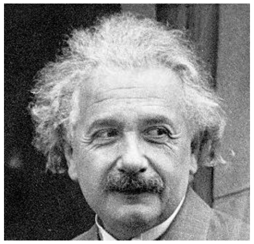
LIGO Scientific Collaboration

- *What are gravitational waves ?*
- *The LIGO experiment*
- *Search for Compact Binary Coalescences*
- *Detection checklist for candidate-events*
- *Towards gravitational-wave astronomy*

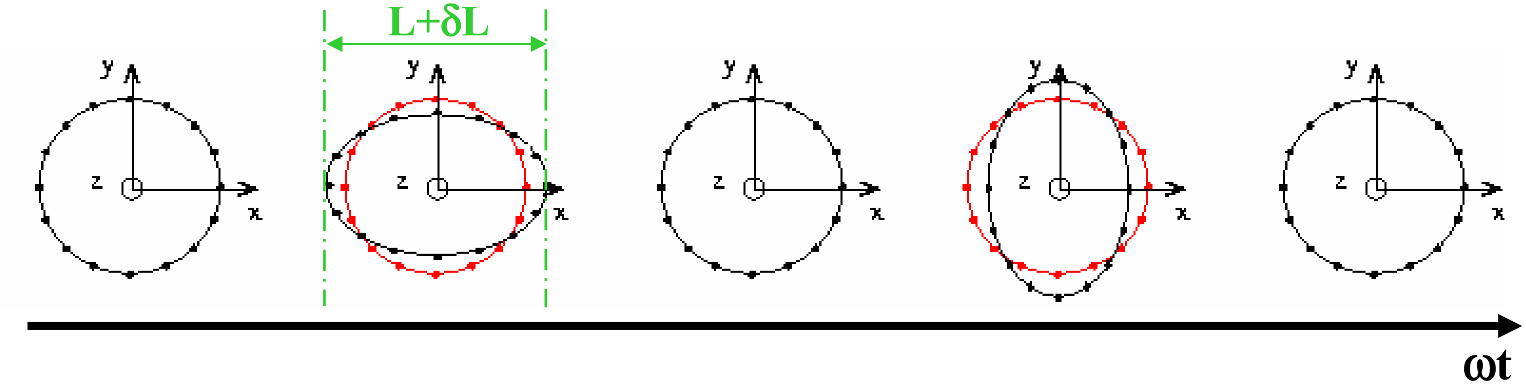
What are gravitational waves ?

Gravitational wave = propagating disturbance of the space-time



- **Predicted by Einstein's General Relativity**
- **Properties:** **- transverse plane waves**
  - travel at the speed of light
  - 2 polarization states
- **Modify distances between free falling masses**

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



- **Quadrupolar radiation: generated by asymmetric motions of matter**
- **Very weak amplitudes: requires compact, massive, relativistic objects**

Favored astrophysical objects: Neutron Stars, Black Holes, Supernovae, …

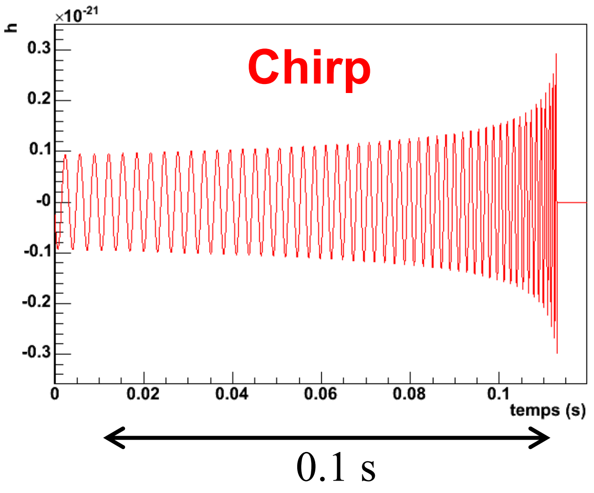
Sources of gravitational waves: Coalescences of compact binaries

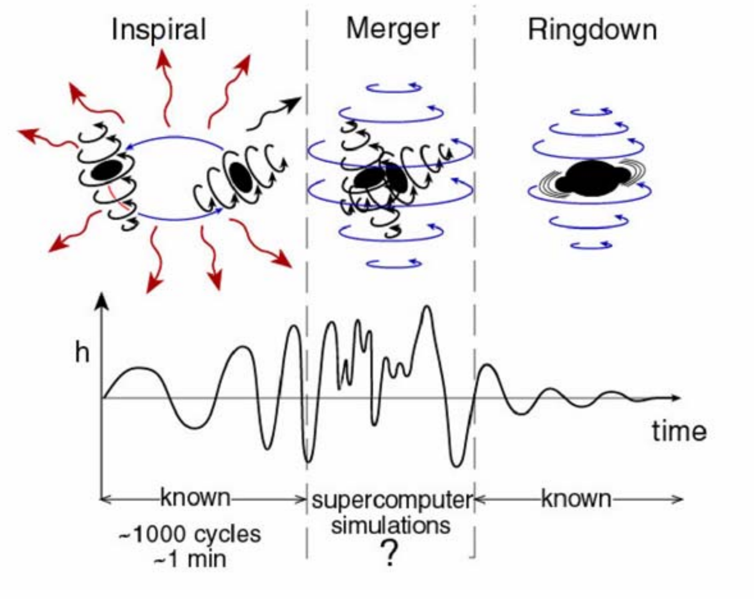
→ **Binary systems of 2 compact objects: Neutron stars, Black holes**

End of the life of the system = coalescence of the 2 stars

→ **During the inspiral phase, the waveform is known:**

(but depends on masses, and spins…)





Starting at low frequency, the signal can reach several hundred Hertz at the end of coalescence ⇒ enters in the band width of detectors such as LIGO/Virgo

LIGO Other sources of gravitational waves:

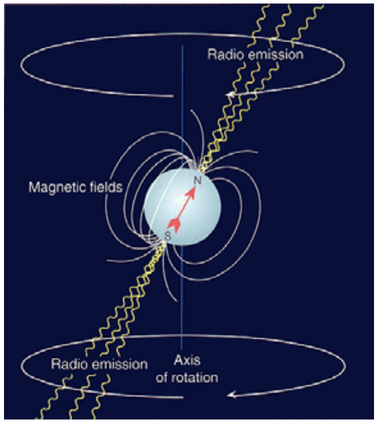
→ **Supernovae (gravitational collapse of massive stars):**

If asymmetrical collapse: produce GW

- Impulsive source: short signal duration (≤ 10 ms)

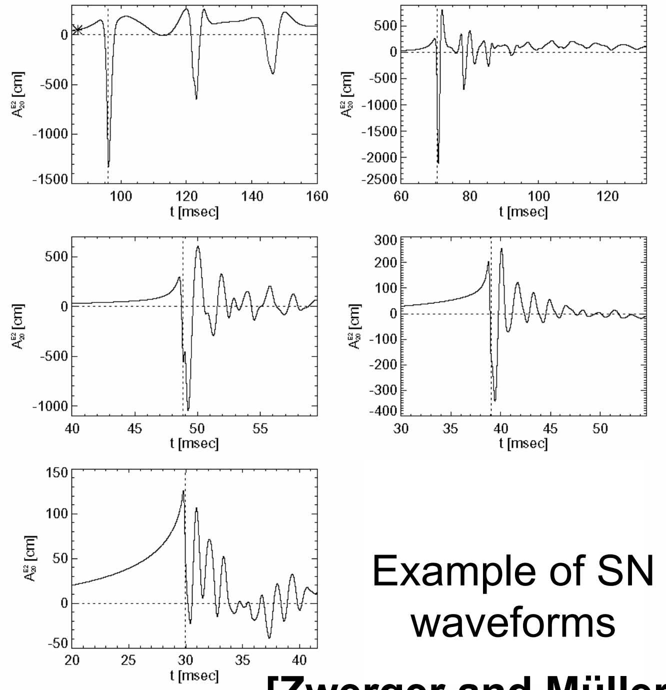
- Waveform and amplitude not very well known

→ **Pulsars (spinning rotating neutron star)**



Low amplitude but periodic source

⇒ Signal can be integrated over long durations



Example of SN waveforms

[Zwerger and Müller]

→ **Stochastic background of gravitational waves** (Big Bang gravitational echo)

Why detecting gravitational waves ?

- **Perform the first direct detection of gravitational waves**

- **Study the gravitational interaction**
  - Check gravitational wave properties (velocity, polarization)
  - GW radiated by Black Holes ⇒ test in strong fields the General Relativity

- **A new window to observe the Universe**
  - Coincidences with other messengers: photons, neutrinos
  - Observation of regions of the Universe opaque to electromagnetic waves

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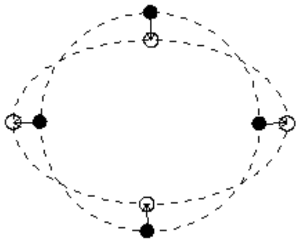
How to detect a gravitational wave ?

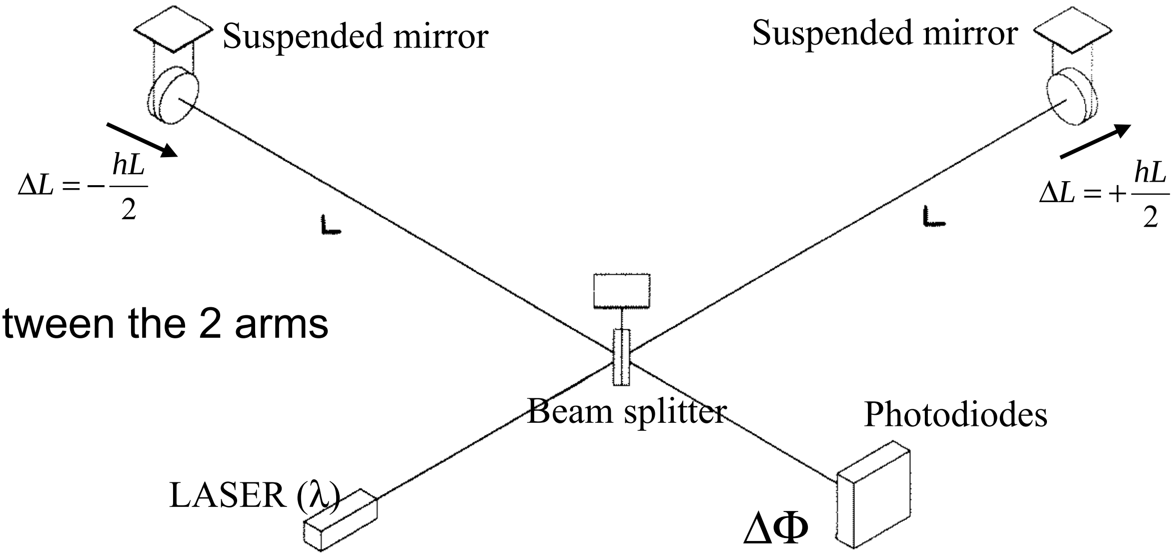
- Variation of the distance between free-falling masses



⇒ **Can be measured with a Michelson interferometer**

- suspended mirrors = free-falling masses
- gravitational wave ⇒ phase difference between the 2 reflected beams

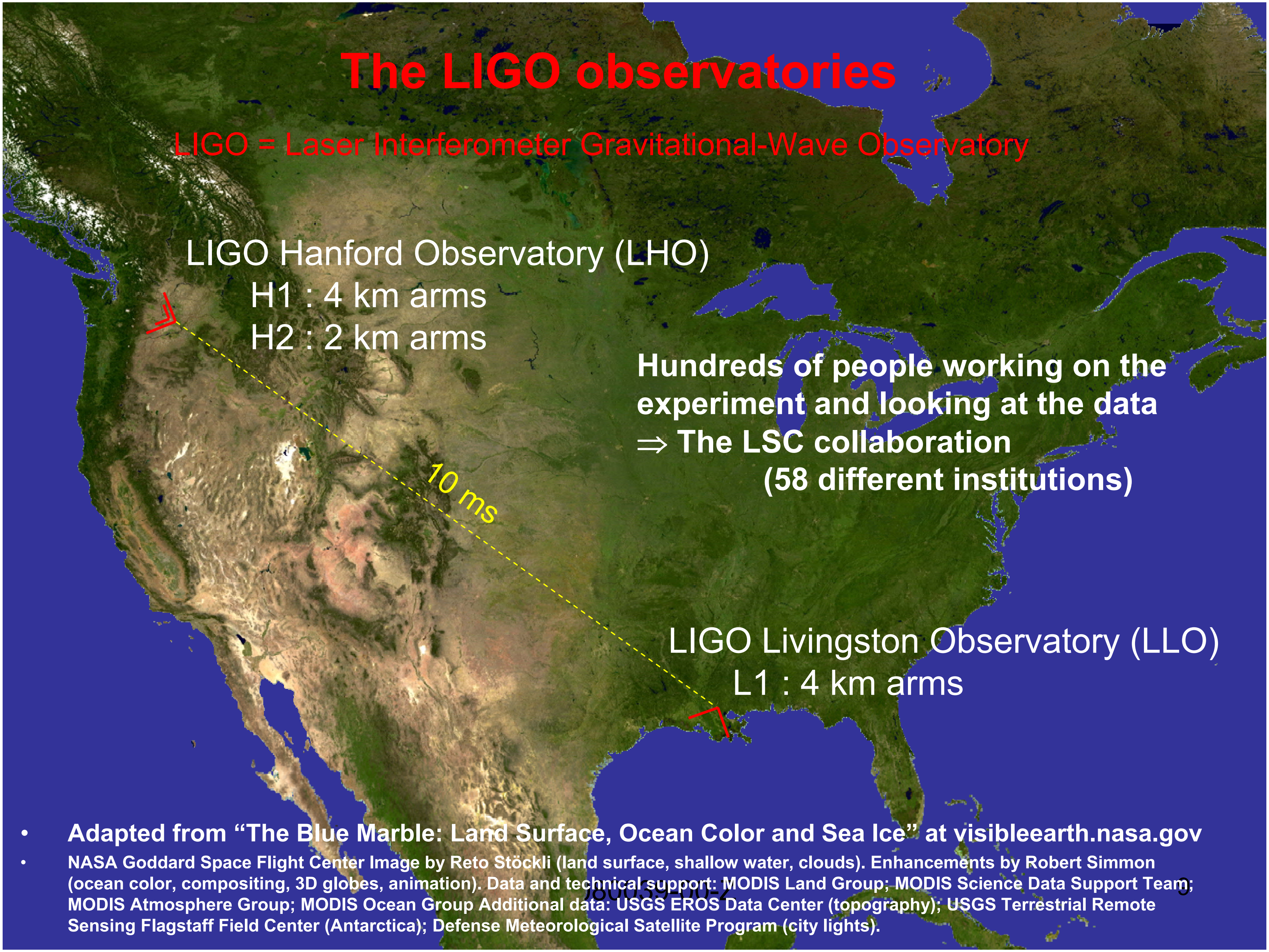
$$\Delta\Phi = \frac{4\pi}{\lambda} hL$$



h = ΔL/L
ΔL = length difference between the 2 arms
L = arm length

The LIGO observatories

LIGO = Laser Interferometer Gravitational-Wave Observatory



LIGO Hanford Observatory (LHO)
H1 : 4 km arms
H2 : 2 km arms

Hundreds of people working on the experiment and looking at the data
⇒ The LSC collaboration
(58 different institutions)

LIGO Livingston Observatory (LLO)
L1 : 4 km arms

- **Adapted from “The Blue Marble: Land Surface, Ocean Color and Sea Ice” at visibleearth.nasa.gov**
- **NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights).**

The LIGO observatories

LIGO Hanford:

4km / 2km share the same tubes

Visitors are welcome !

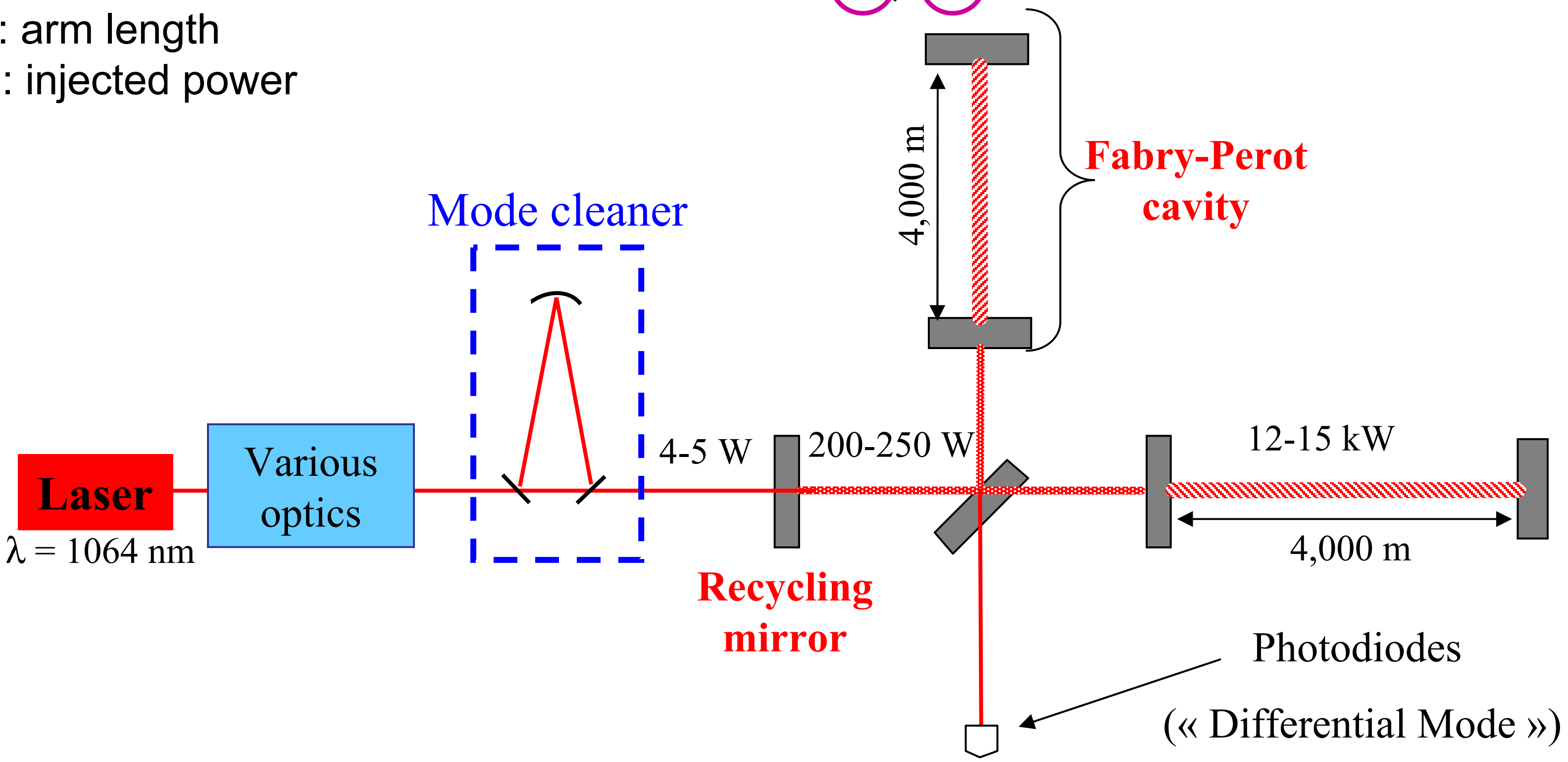
LIGO Livingston

The LIGO interferometers

Sensitivity of an interferometer limited by shot noise:

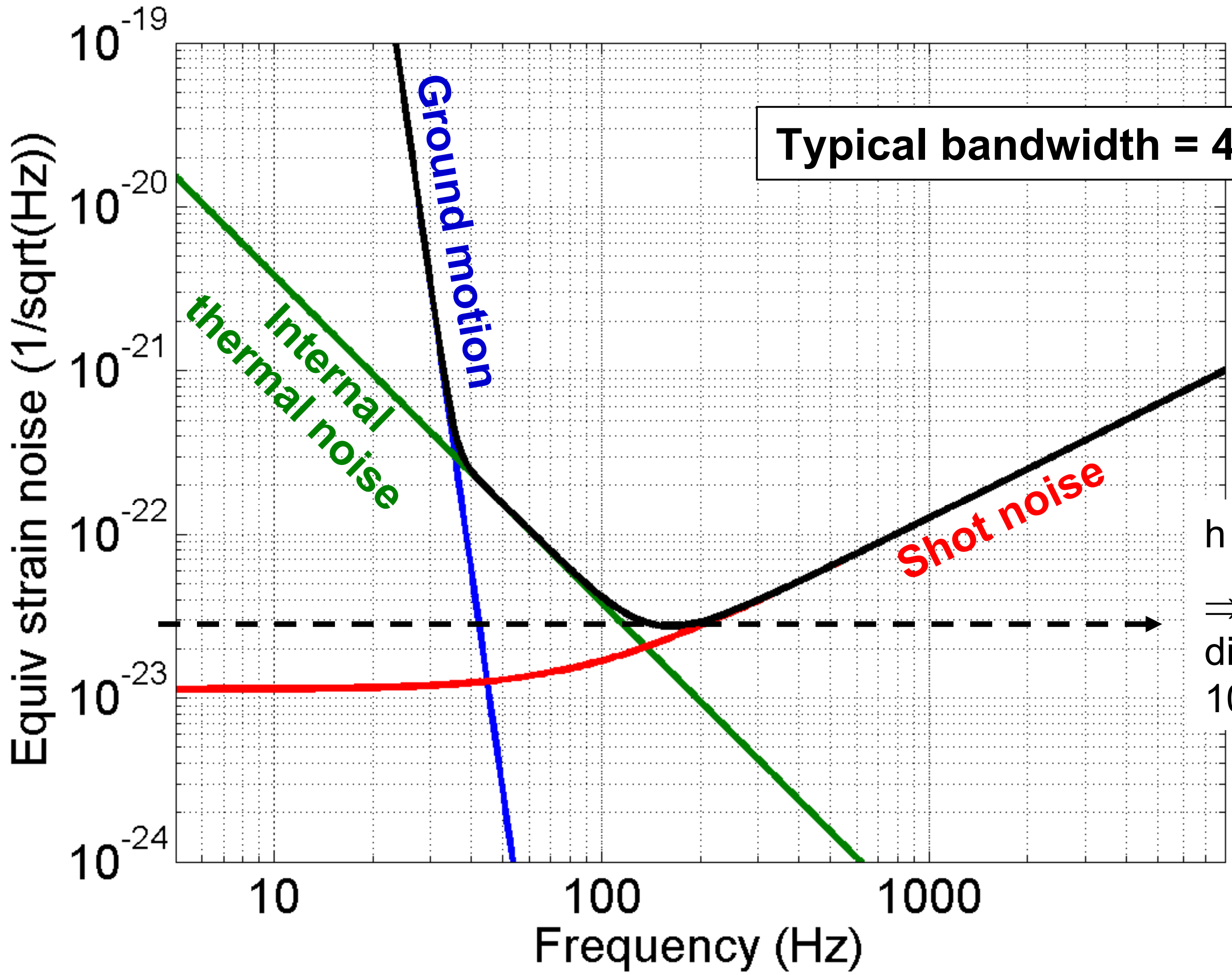
Smaller measurable displacement: $\tilde{h} \geq \frac{\lambda}{4\pi} \frac{1}{\bigcirc\!\!\!\!L} \sqrt{\frac{2\hbar\omega}{\bigcirc\!\!\!\!P}}$

L: arm length
P: injected power



- Fabry-Perot cavity: ~125 round trips ⇒ effective optical path = 500 km
- Recycling cavity: power x 50

Design sensitivity

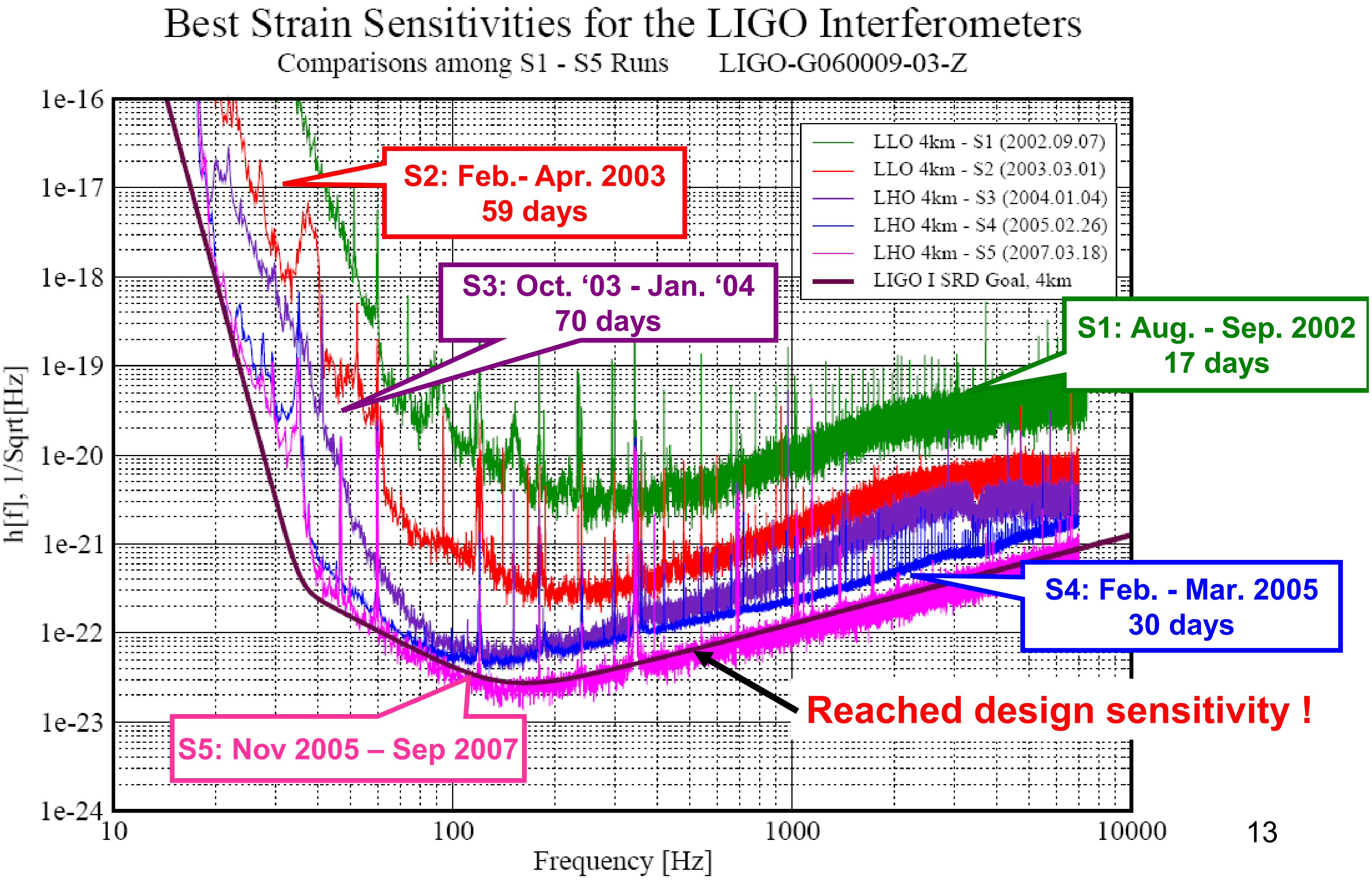


Typical bandwidth = 40-2,000 Hz

h ~ 2 x 10^{-23} /√Hz

⇒ measure displacements of 10^{-19} m

LIGO science runs & sensitivity improvements



S2: Feb.- Apr. 2003
59 days

S3: Oct. '03 - Jan. '04
70 days

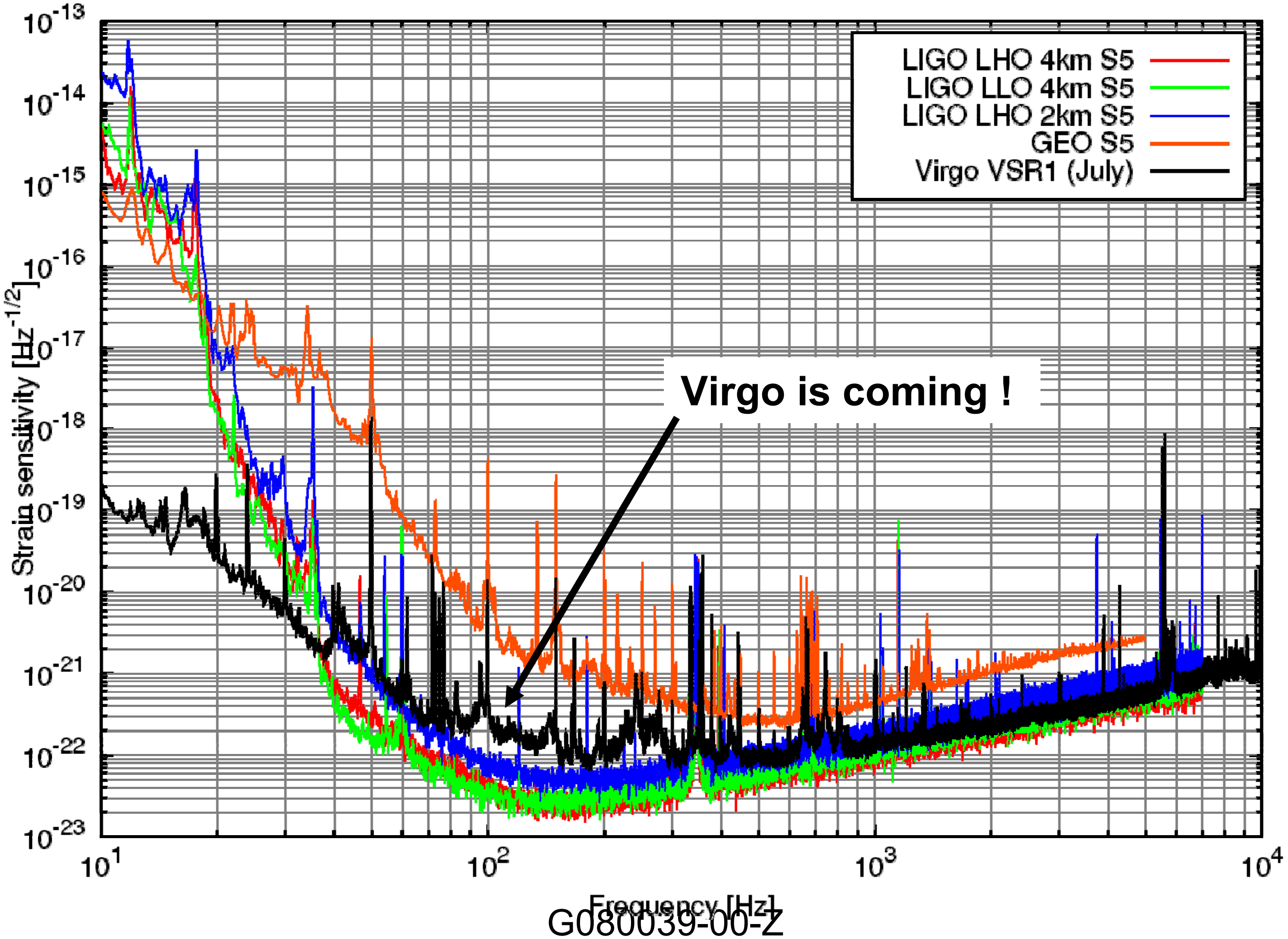
S1: Aug. - Sep. 2002
17 days

S4: Feb. - Mar. 2005
30 days

Reached design sensitivity !

S5: Nov 2005 – Sep 2007

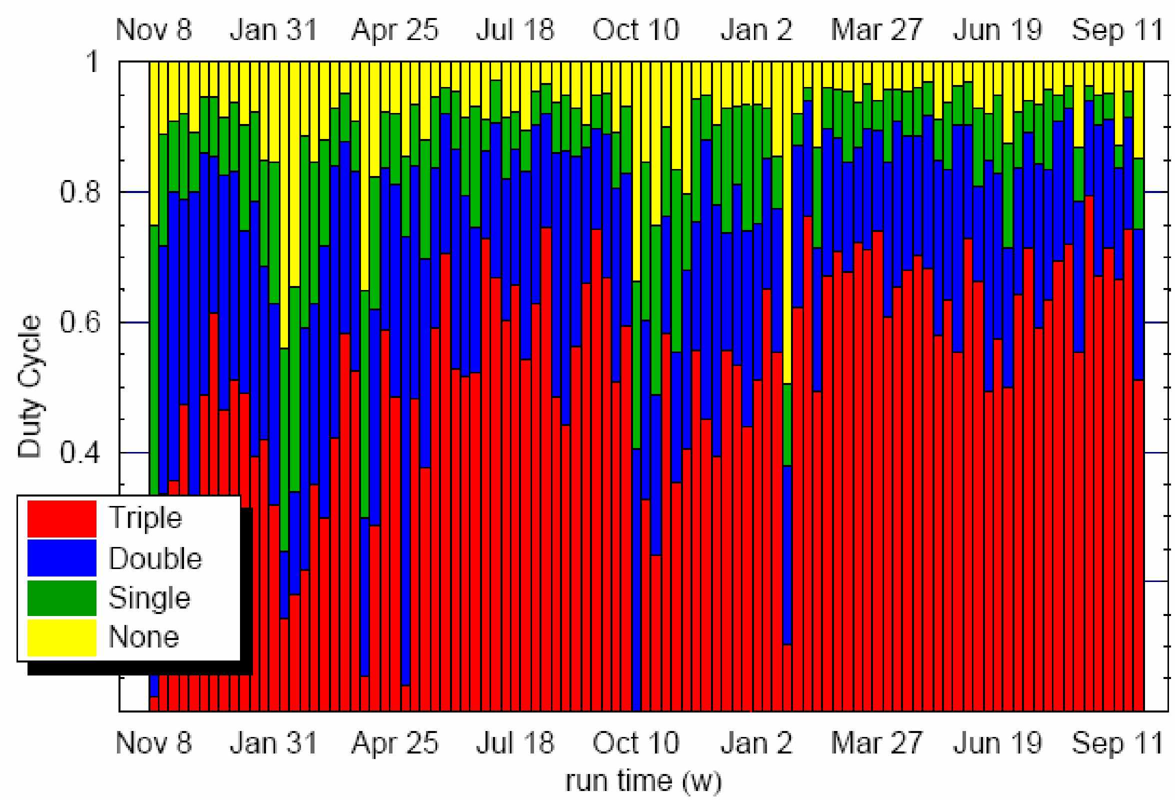
Current sensitivities of the large interferometers



Virgo is coming !

The S5 science run

- Started on Nov 2005 – Ended on Oct 2007
- Completion of one year of triple coincidence data between the 3 LIGO interferometers



S5 duty cycles:

- 52.8 % in triple coincidence
- 57.0 % in H1L1 coincidence
- Total for H1: 77.7 %
- Total for H2: 78.2 %
- Total for L1: 65.7 %

- H1H2L1V1: 11.3 %

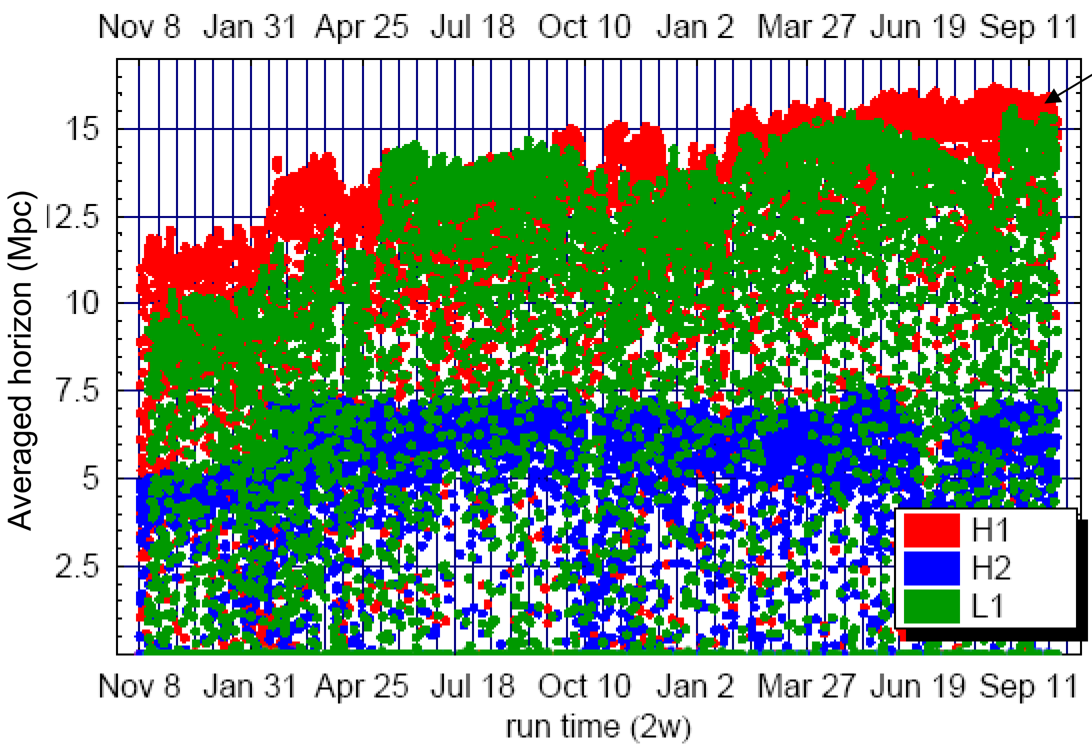
→ **at nominal sensitivity**

Horizon during S5

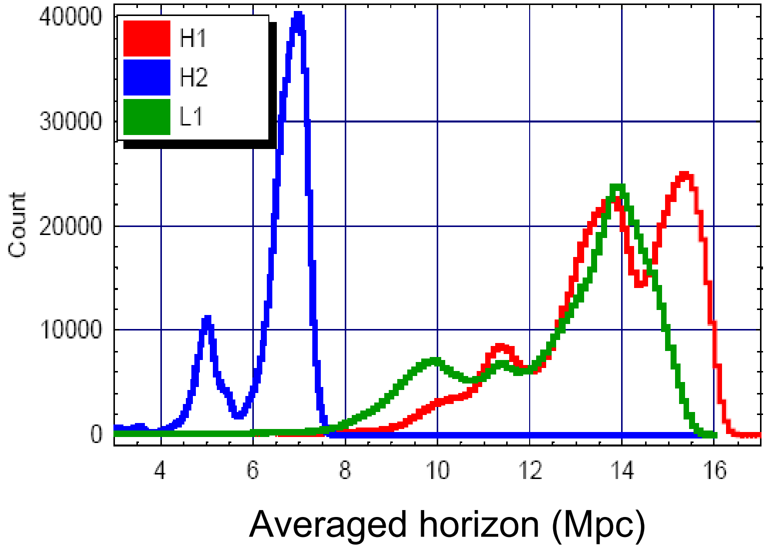
The sensitivity can be translated into distances surveyed.

Maximal horizon = distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio ρ=8 (for a 1.4/1.4 solar mass system)

Averaged horizon = distance at which a binary system with averaged positions and orientations over all sky can be detected



Affected by microseism, wind, instruments,…



⇒ **H1 reached up to 16 Mpc at the end of the run**

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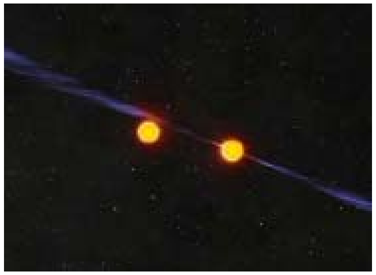
Search for Compact Binary Coalescences

- Known waveform: ⇒ use match filtering technique



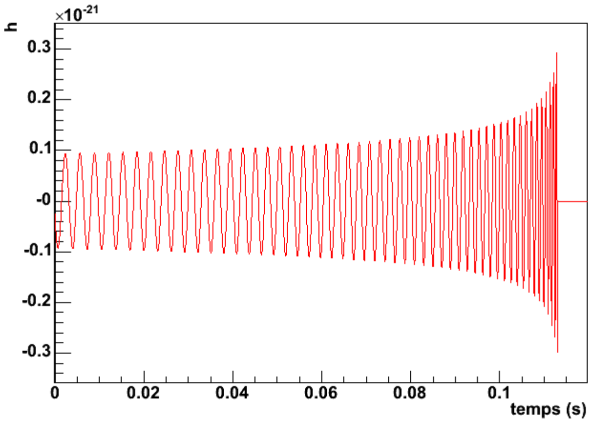
Data

Template

$$z(t) = 4\int_0^\infty \frac{\tilde{s}(f)\;\tilde{h}^*(f)}{S_n(f)}\, e^{2\pi i f t}\, df$$

Noise power spectral density

Chirp



- Calculated templates for inspiral phase ("chirp")

Waveform parameters:
distance, orientation, position,
$\mathbf{m_1}$, $\mathbf{m_2}$, t_0, ϕ (+ spin, ending cycles …)

Compact Binary Coalescences:
Overview of the search pipeline

3 interferometers = 3 data set

For each ifo: generate a **template bank**

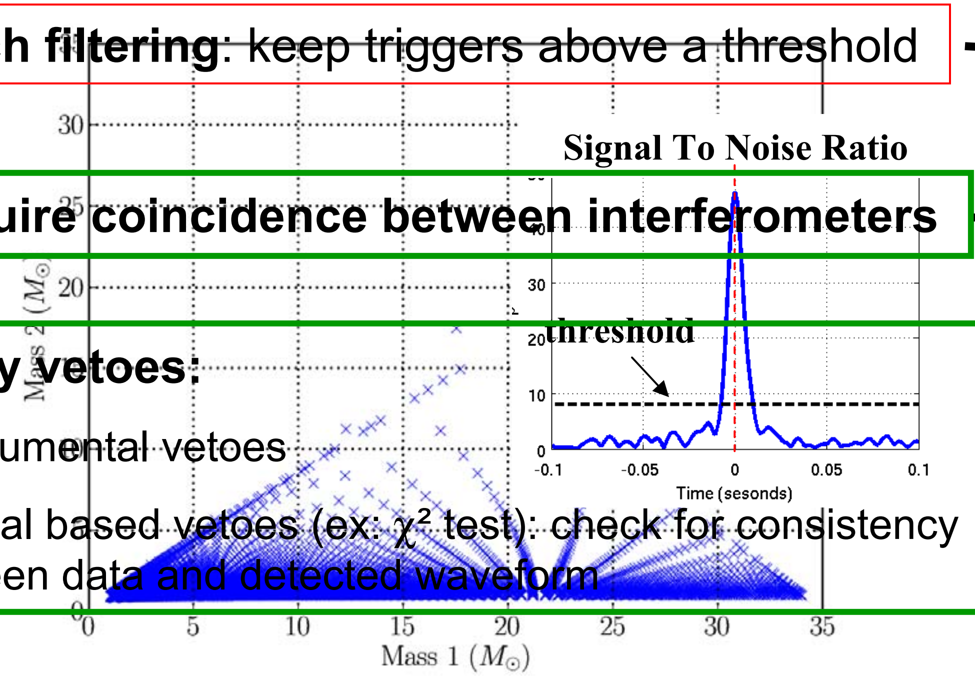
Match filtering: keep triggers above a threshold

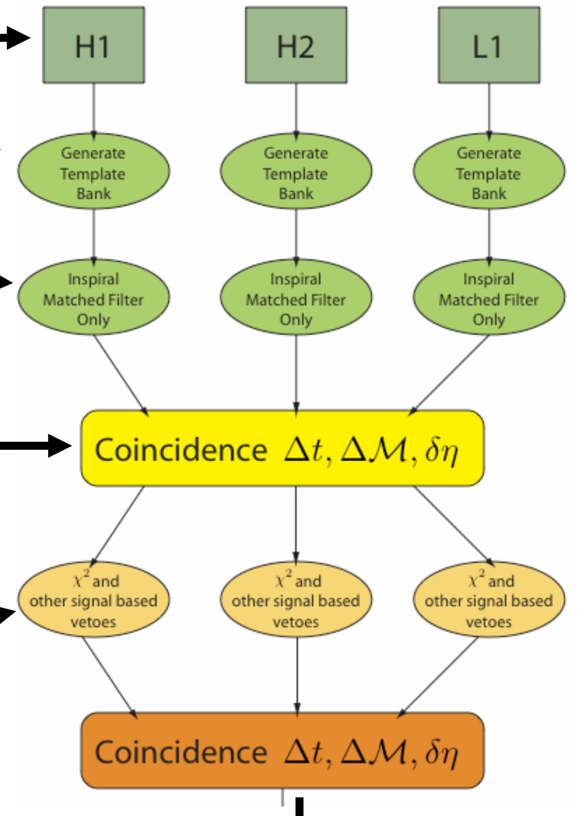
Require coincidence between interferometers

Apply vetoes:

- Instrumental vetoes

- Signal based vetoes (ex: χ^2 test): check for consistency between data and detected waveform





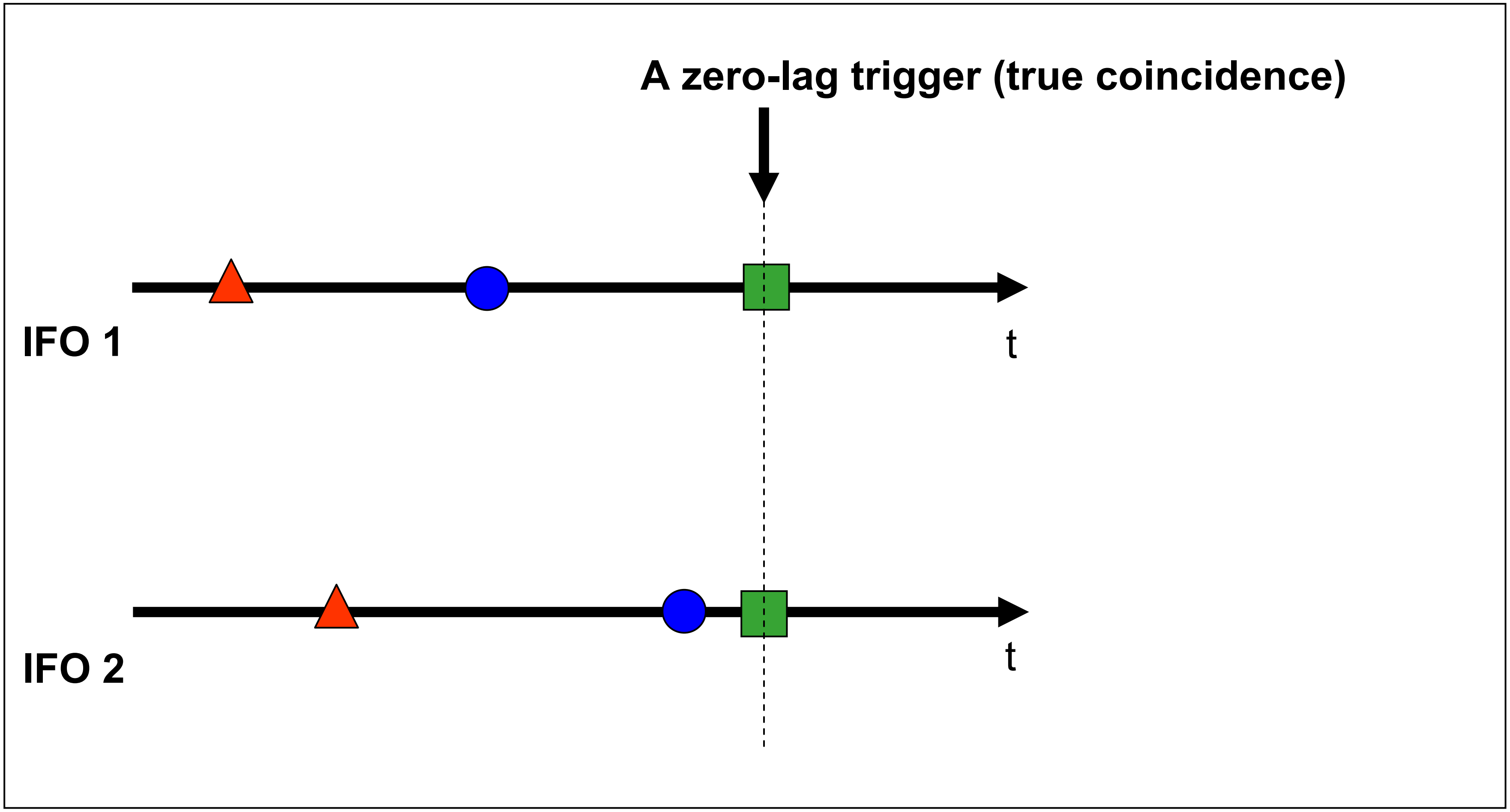
Surviving coincident triggers

$\Rightarrow$ need to distinguish gravitational waves from residual false alarms…

Compact Binary Coalescences:

Statistical significance of the candidates

→ **background estimated from time-slides triggers**



Compact Binary Coalescences:

Statistical significance of the candidates

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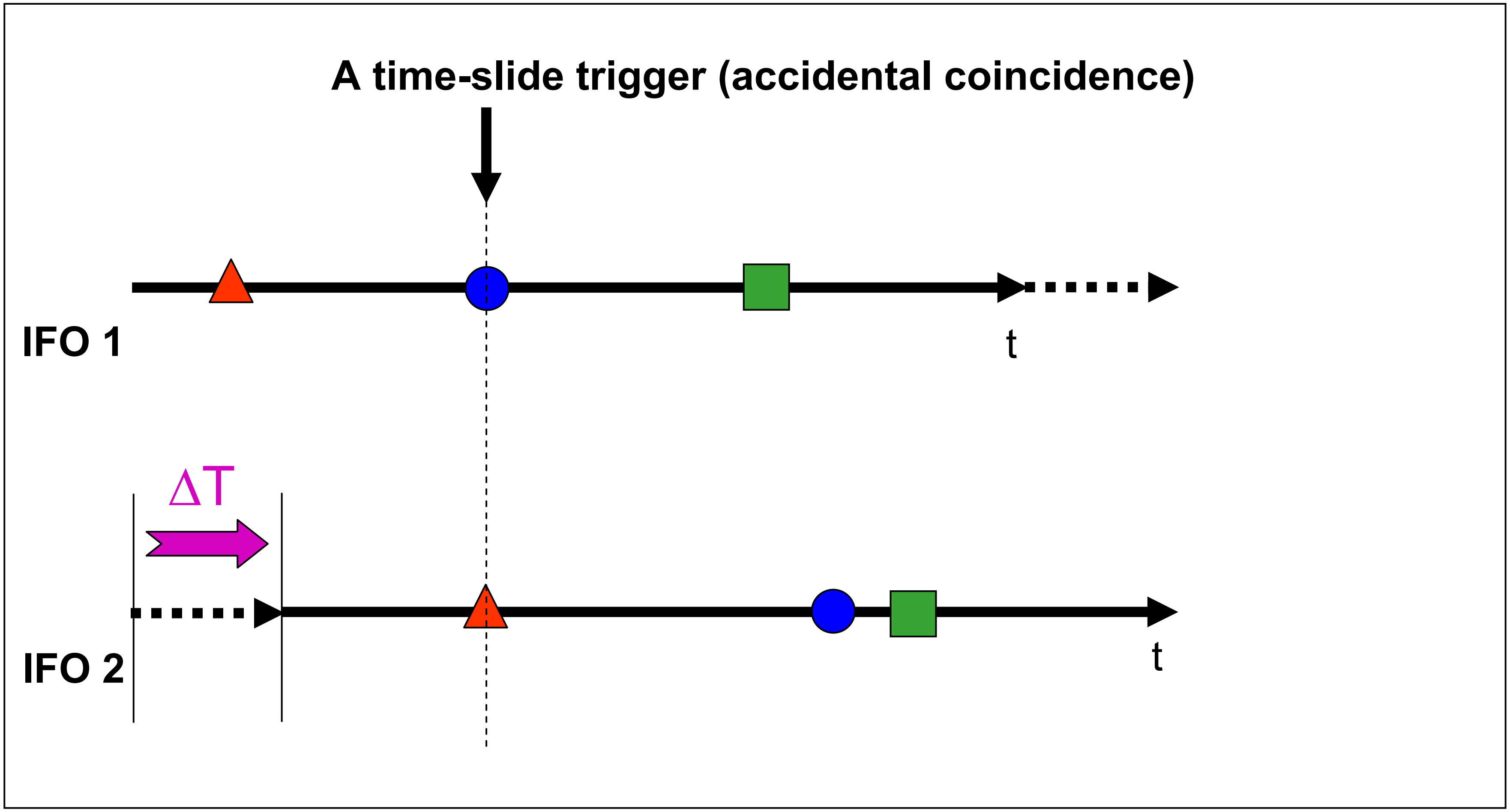


Compact Binary Coalescences:
Statistical significance of the candidates

→ **background estimated from time-slides triggers**

Ex: S4 Binary Neutron Star search [*arXiv:0704.3368*]

Total analyzed time = 576 hrs
(Feb 22 – March 24, 2005)

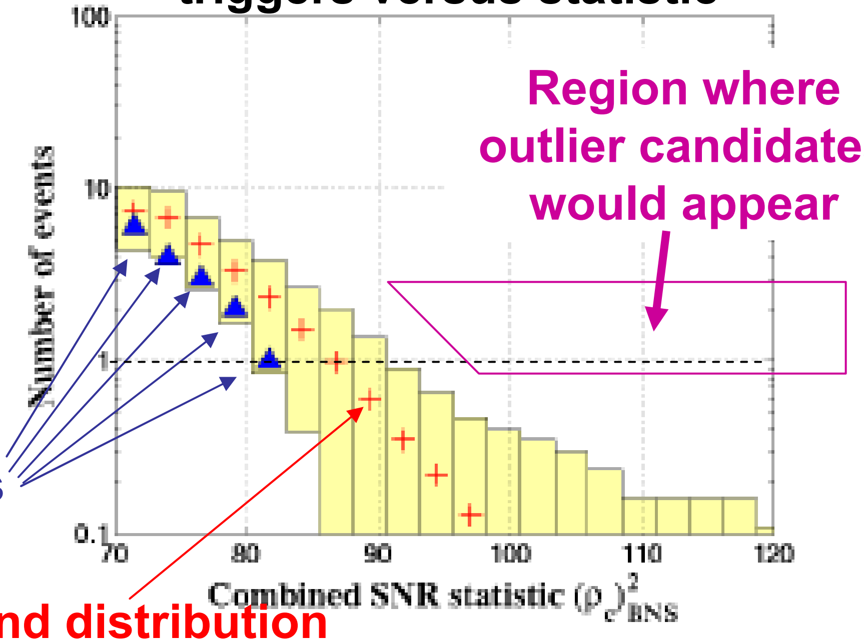
If candidates consistent with background:

⇒ detection is not likely

Else ?

Good candidates are submitted to a detection checklist

Histogram of coincident triggers versus statistic



Region where outlier candidates would appear

candidates

Background distribution (time-slides)

- *What are gravitational waves ?*
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Overview of the detection checklist

Goal: Estimate confidence in our gravitational wave candidates

Legend: **- tests which are identical for both CBC and Burst groups (impulsive signal searches)**

- tests that involves methods specific to the search

- **Statistical significance of the candidate**
- **Status of the interferometers**
- **Check for environmental or instrumental causes**
- **Candidate appearance**
- **Check the consistency of the candidate estimated parameters**
- **Check for data integrity**
- **Check for detection robustness (ex: versus calibration uncertainties)**
- **Application of coherent network analysis pipelines**
- **Check for coincidence with searches external to our GW searches: other E/M or particle detectors…**

Two examples

- An inspiral gravitational-wave signal (hardware injection)

IFO	End Time (ms)	SNR	CHISQ	Chirp Mass	Eta	Mass 1	Mass 2	Eff Dist (Mpc)
L1	xxxxxxxxx.888	11.39	25.43	4.77	0.2026	8.92	3.51	69.48
H1	xxxxxxxxx.879	12.94	44.24	4.62	0.1284	13.43	2.39	62.44
H2	xxxxxxxxx.884	7.49	34.32	4.81	0.2074	8.74	3.63	48.92

- A false-alarm trigger (found with time slide)

IFO	End Time (ms)	SNR	CHISQ	Chirp Mass	Eta	Mass 1	Mass 2	Eff Dist (Mpc)
L1	xxxxxxxxx.896	20.89	278.34	13.22	0.1979	25.44	9.50	11.65
H1	xxxxxxxxx.898	5.61	69.38	10.38	0.1348	28.99	5.54	136.03
H2	xxxxxxxxx.899	6.24	24.79	15.23	0.25	17.5	17.5	94.44

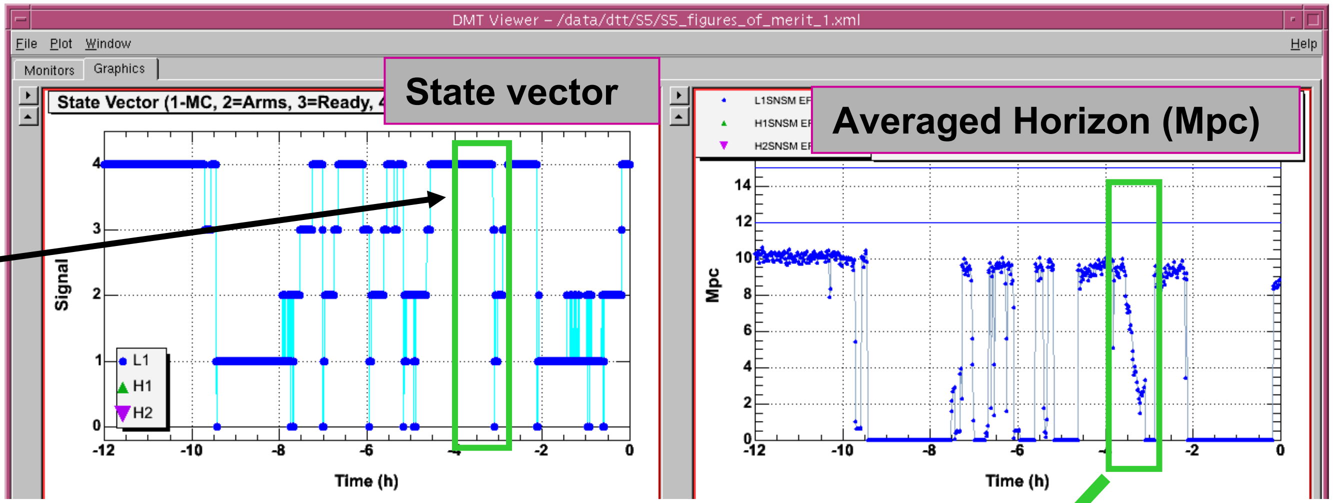
Both instances of candidates will be used to illustrate the tests of the detection checklist in the following slides…

Status of the interferometers (1/2)

Ex: Status of the L1 detector at the time of the background trigger

⇒ **Check figure of merits (state vector, inspiral averaged horizon, …)**

Figures of merit posted in the elog



State vector

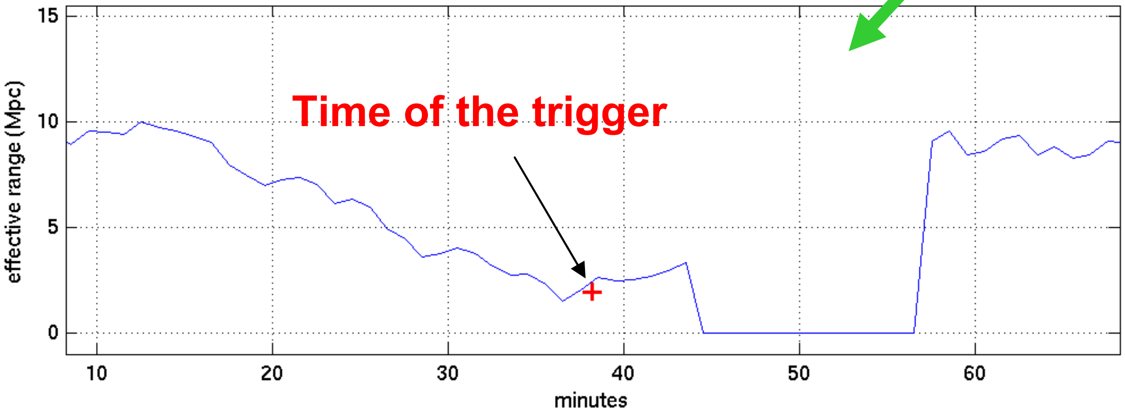
Averaged Horizon (Mpc)

State vector:

Flag indicating ifo in science mode (4 min before unlock)

Averaged horizon:
(for a 1.4/1.4 solar mass system)

Inspiral range (Mpc)



Time of the trigger

⇒ Candidate happens while L1 inspiral range is dropping

Status of the interferometers (2/2)

⇒ **Check list of data quality flags: "bad horizon"**

⇒ **Check comments posted by "scimon" and operator in the elog:**

> *"We had a slowly worsening noise spectrum over a period of about thirty minutes today […] The only hint of trouble was in the WFS; there was a lot of coherence between DARM and WFS1 pitch"*

⇒ The candidate is found during a very noisy time at Livingston, which indicates a misbehavior of the detector

⇒ No obvious instrumental cause was found at the time of the candidate (more investigations needed)

Environmental and instrumental causes (1/2)

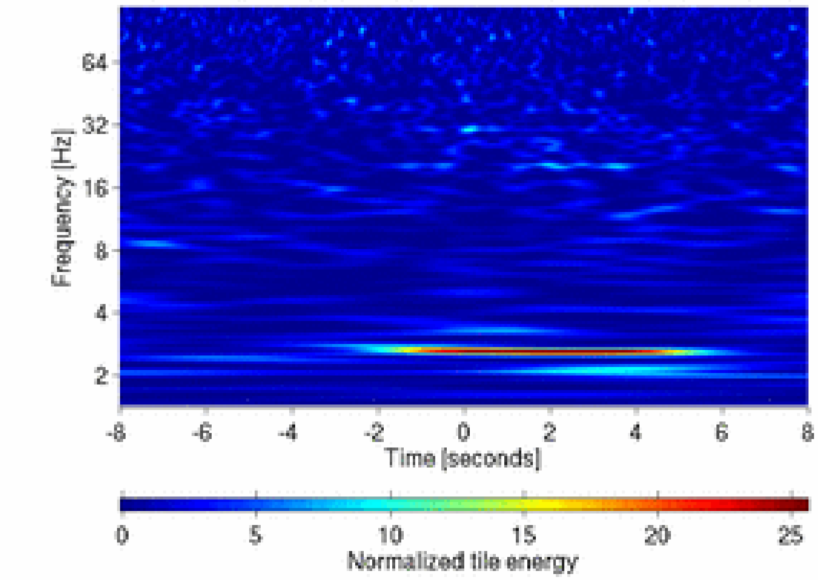
Ex: At time of the inspiral hardware injection

⇒ **Check band-limited RMS trends of seismometers**

⇒ **Check time-frequency maps of auxiliary channels**

Seismic transient at the Hanford Mid X station (close to H2 end mirror)

H0:PEM-MX_SEISY (seismometer)



How relevant is a transient found in an auxiliary channel, given its amplitude ?

- **Compare significance at candidate's time to background distribution (estimated by spectrograms at random times)**

- **Compare amplitude ratio Differential Mode channel / Auxiliary channel with measured transfer function (if available)**

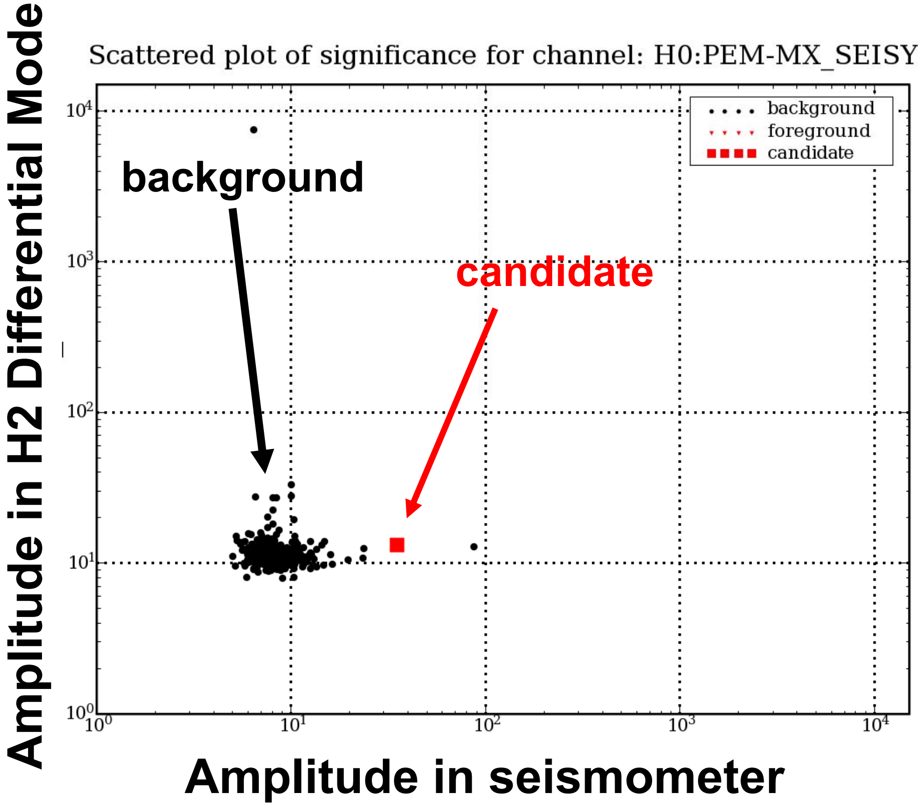
Environmental and instrumental causes (2/2)

Ex: At time of the inspiral hardware injection

⇒ **Check band-limited RMS trends of seismometers**

⇒ **Check time-frequency maps of auxiliary channels**

Seismic transient at the Hanford Mid X station (close to H2 end mirror)



At the time of the seismic transient, the significance in the differential mode channel is consistent with the background

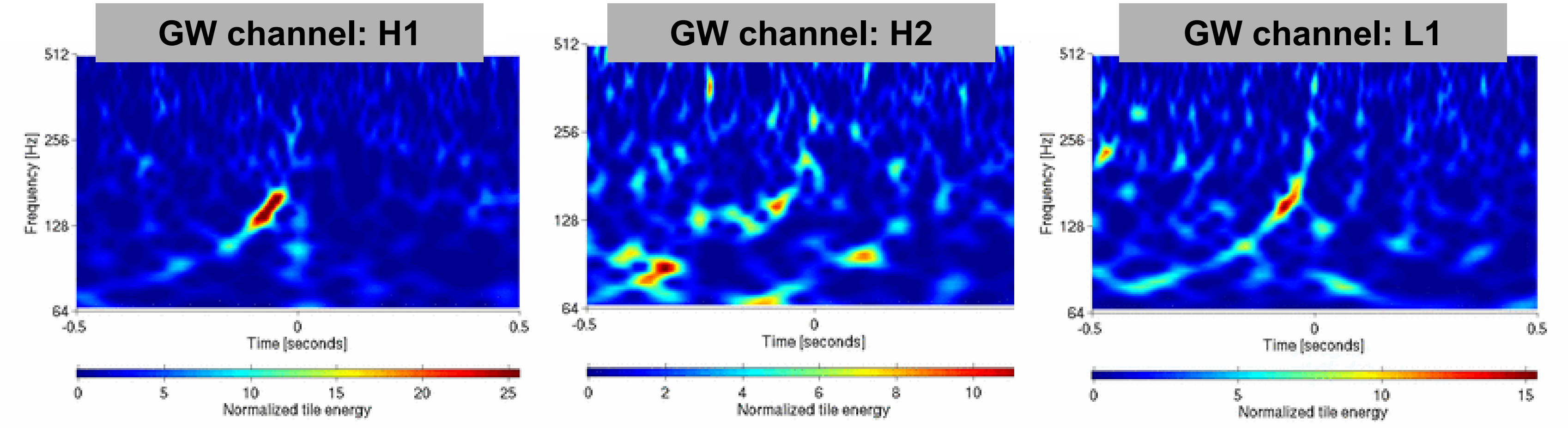
⇒ **There is no evidence of a seismic coupling to the Differential Mode channel**

⇒ **We can not determine if the candidate is due to this coincident seismic transient.**

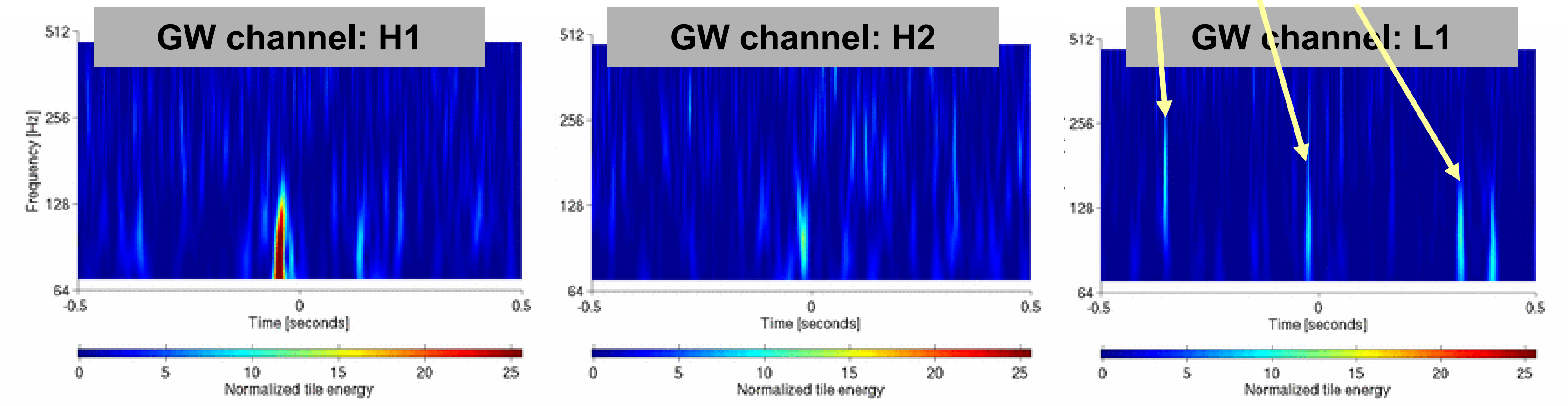
Candidate appearance (1/4)

⇒ **Check time series, and time-frequency spectrograms of the candidate**

Ex: Inspiral hardware injection → **Chirp visible in H1 and L1**



Ex: Background trigger (time slide) → **multiple transients at Livingston**

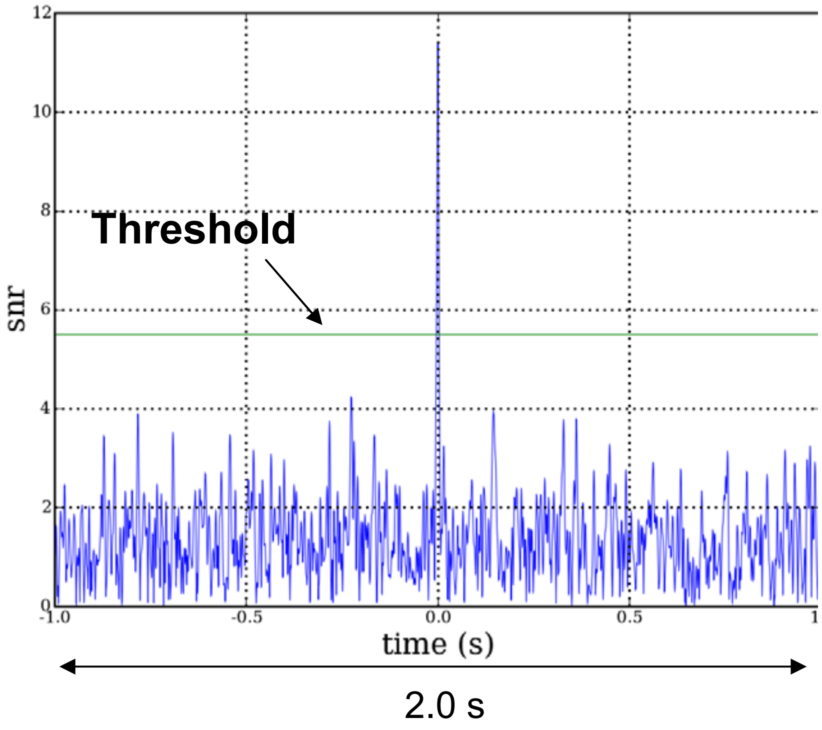


Candidate appearance (2/4)

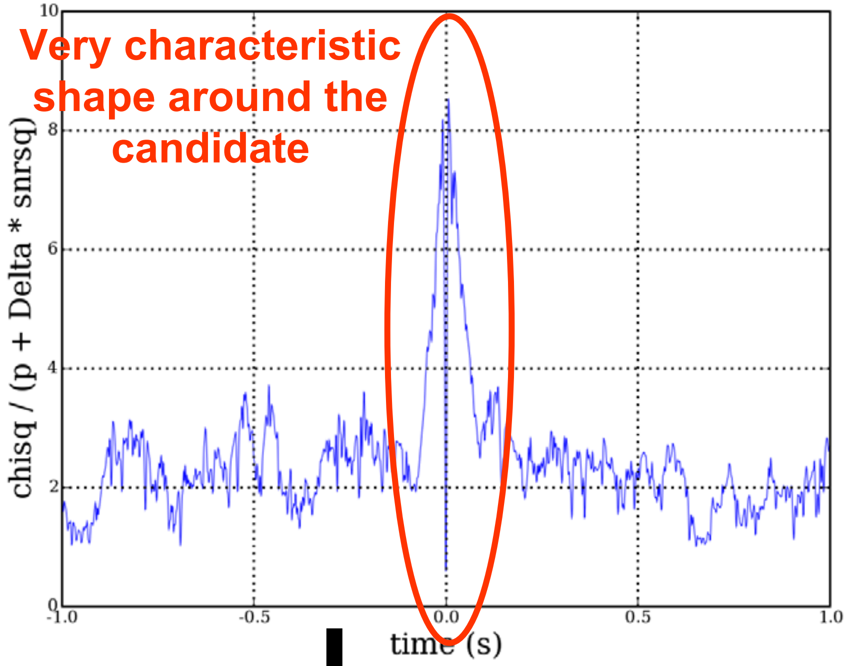
⇒ **Check SNR and CHISQ time series after match filtering the data**

Ex: Inspiral hardware injection, L1 trigger

SNR time series



χ^2 time series



Very characteristic shape around the candidate

check the consistency between triggered template and signal present in the data

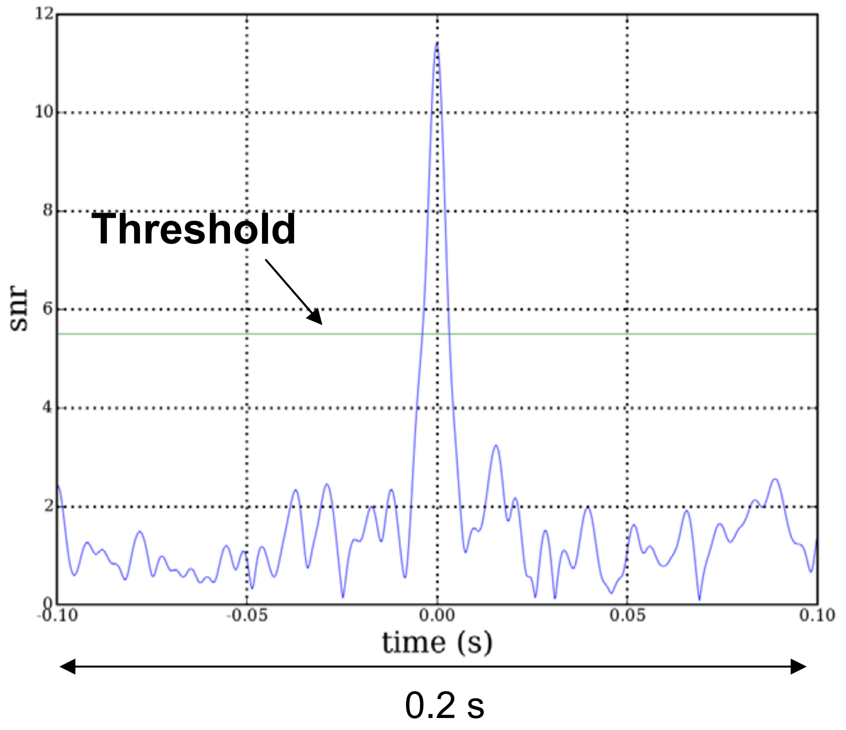
Candidate appearance (3/4)

⇒ **Check SNR and CHISQ time series after match filtering the data**

Ex: Inspiral hardware injection, L1 trigger

ZOOM

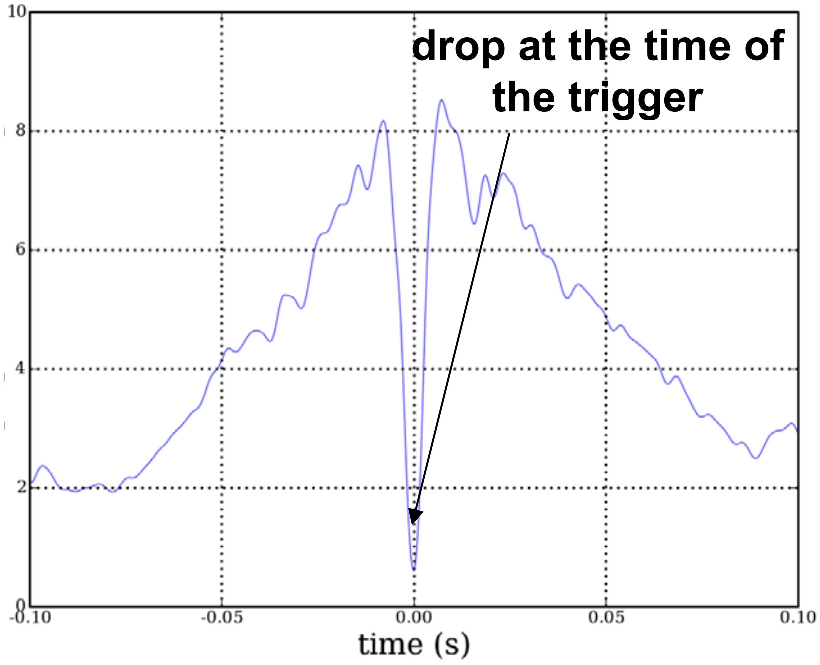
SNR time series



Threshold

0.2 s

χ^2 time series



drop at the time of the trigger

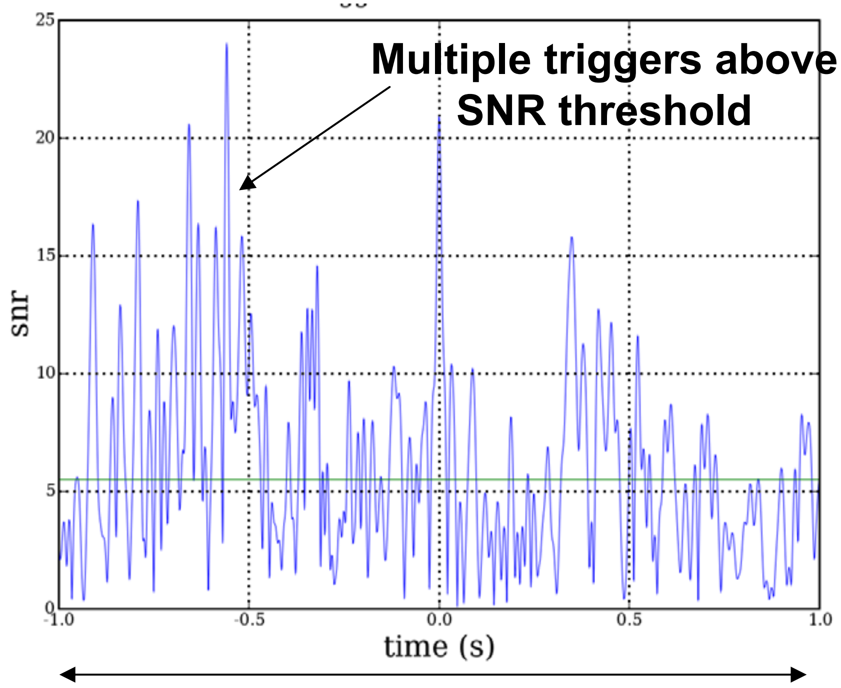
⇒ **The SNR and χ^2 time series appear to be consistent with a detection (this is an injection)**

Candidate appearance (4/4)

⇒ **Check SNR and CHISQ time series after match filtering the data**

Ex: Background trigger in L1

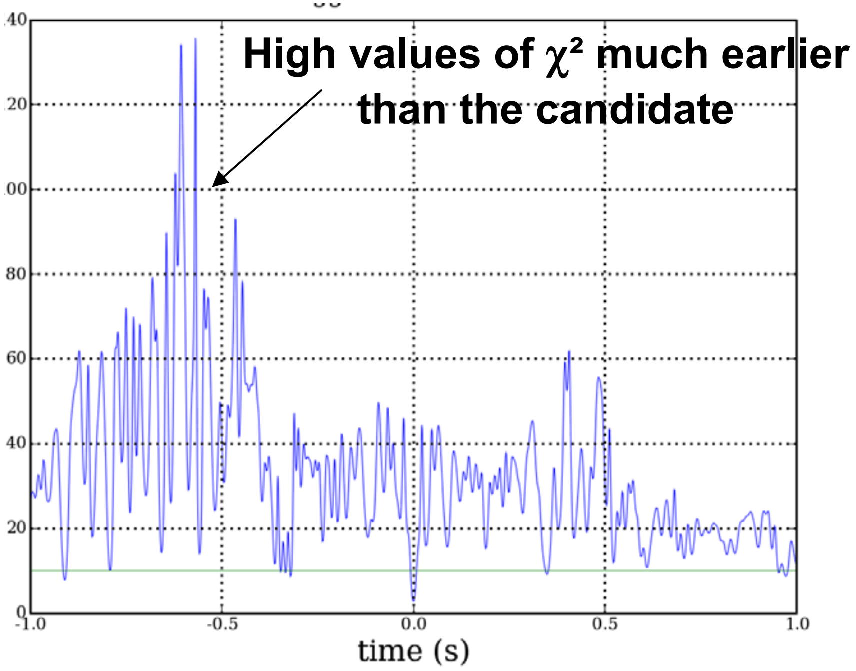
SNR time series



Multiple triggers above SNR threshold

2.0 s

χ^2 time series



High values of χ^2 much earlier than the candidate

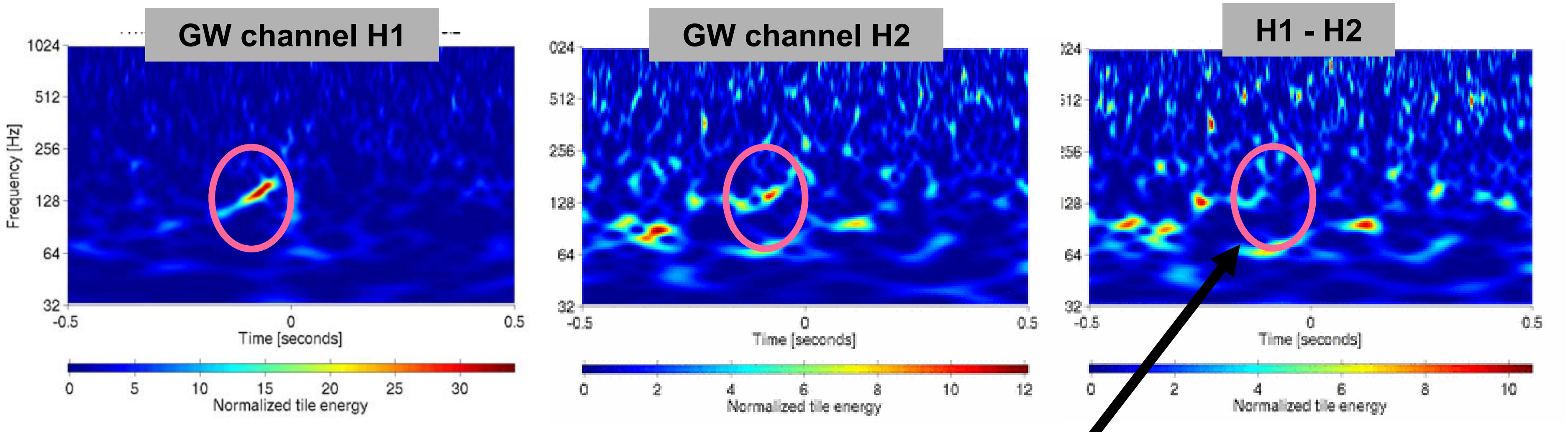
⇒ **Both time series show a very noisy period.**

⇒ **Thus this candidate cannot be defended**

H1/H2 correlation

Check for signal correlation between collocated interferometers

Ex: Inspiral hardware injection



The "chirp" pattern is removed in the coherent combination "H1 data - H2 data"

⇒ This indicates a correlated signal between the H1 and H2 interferometers

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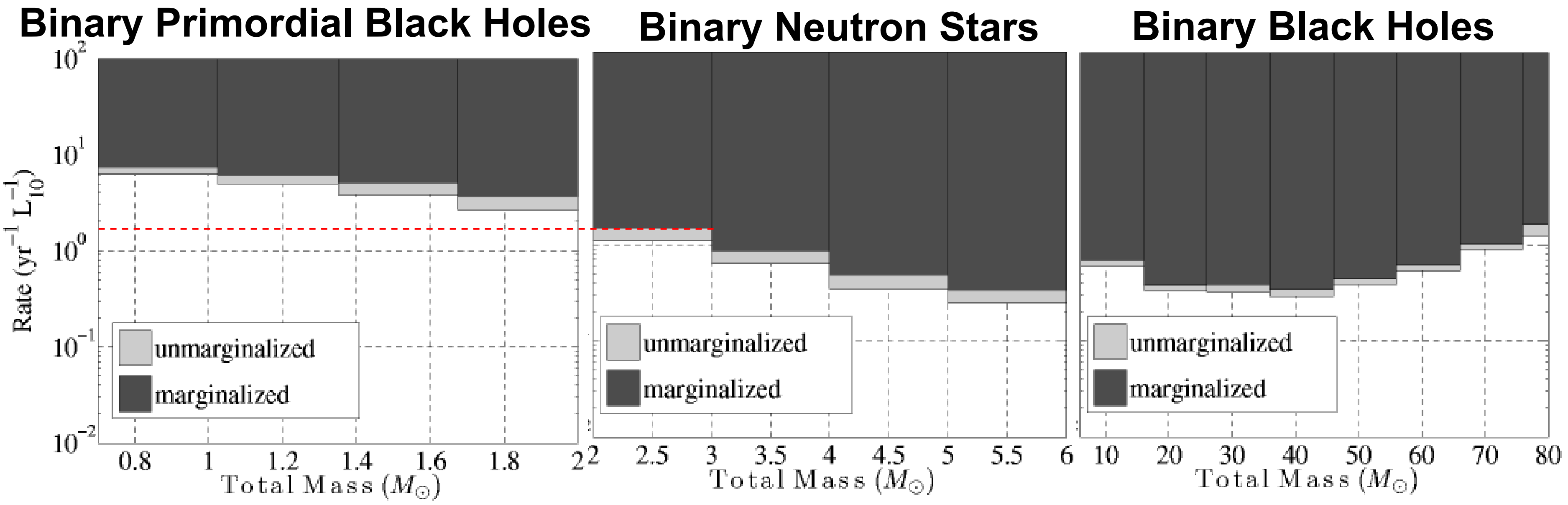
Compact Binary Coalescences:
Current results

- **S3/S4 runs:** ***[arXiv:0704.3368]***
  No GW signals identified
  Binary neutron star signals could be detected out to ~17 Mpc (optimal case)
  Binary black hole signals out to tens of Mpc
  ⇒ **Place limits on binary coalescence rate for certain population models**



Binary Primordial Black Holes **Binary Neutron Stars** **Binary Black Holes**

Theory prediction (1.4/1.4 M_*):

R ~ 10^{-5} – 1.7 10^{-4} yr^{-1} L_{10}^{-1}

- Rate/L_{10} vs. binary total mass
  $L_{10} = 10^{10}\ L_{\odot,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence

Compact Binary Coalescences:
S5 prospectives

Maximal horizon = distance at which an optimally oriented and located binary system can be seen with signal-to-noise ratio ρ=8

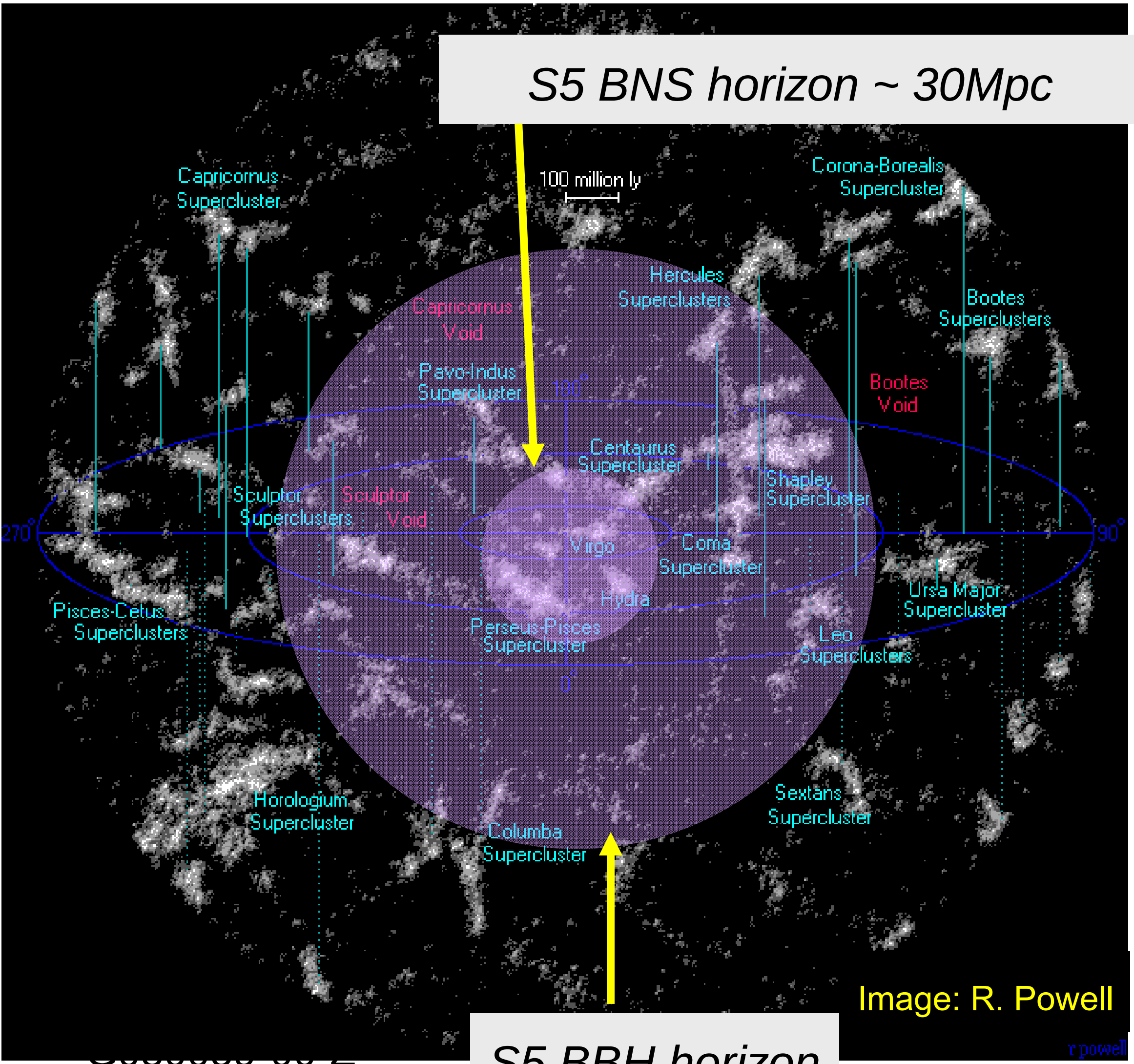
Expected rate for Binary Neutron Star:

~ 1/100 yrs

⇒ A detection is not granted in S5

(but wait for a few more slides…)

Our ability to detect gravitational waves will be tested with **blind injections**



S5 BNS horizon ~ 30Mpc

S5 BBH horizon

Image: R. Powell

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- *Towards gravitational-wave astronomy*

LSC-Virgo joint analysis

- **Cooperative agreement for data exchange and joint data analysis for last 5 months of S5**
- **Sharing of data started in May 2007:**

  ⇒ more than 4 months of coincidence between LIGO S5 and Virgo VSR1 runs

- **Benefits of a world wide network:**

  - Reduction of the false alarm rate by coincidence analysis
  - A better coverage of the sky
  - Improve the accuracy on parameter extraction

    ⇒ required for gravitational wave astronomy

  - Can help increasing the duty cycle

Advanced detectors (1/2)

- **Enhanced LIGO:**

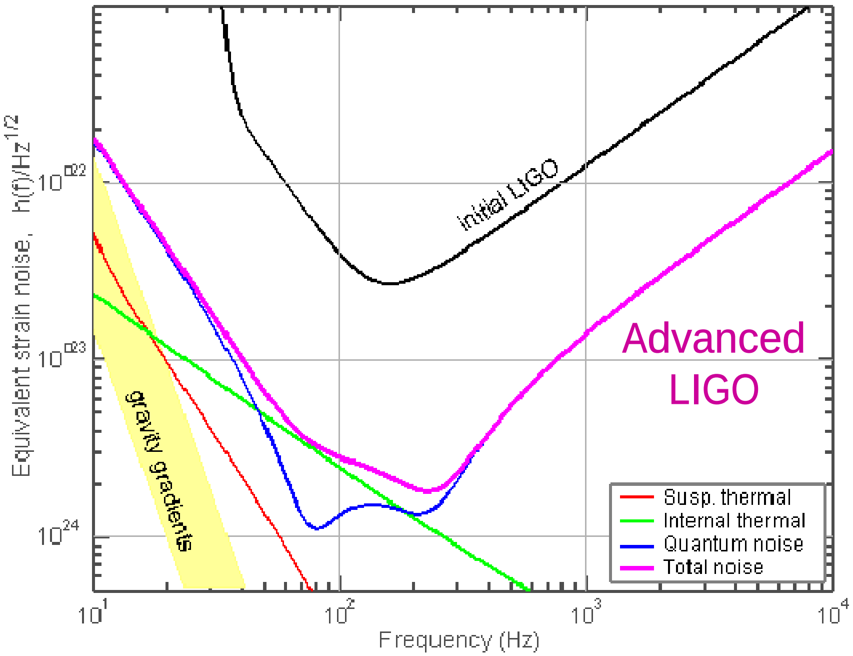
Started after S5: a series of fast upgrades
Goal: **a factor of ~2 sensitivity improvement**

Main upgrades:
- Increase laser power to 35 W
- DC readout scheme, photodetector in vacuum, suspended output mode cleaner

S6 run planned to begin in 2009, duration ~1.5 years

- **Advanced LIGO:**

A series of major improvements (starting ~2010)
- **Seismic noise**
  - Active isolation system
  - Mirrors suspended as 4th stage of quadruple pendulums
- **Thermal noise**
  - Suspension ➔ fused silica fibers
  - Mirror ➔ more massive; better coatings
- **Optical noise**
  - Laser power ➔ increase to ~200 W
  - Optimize itf response ➔ signal recycling



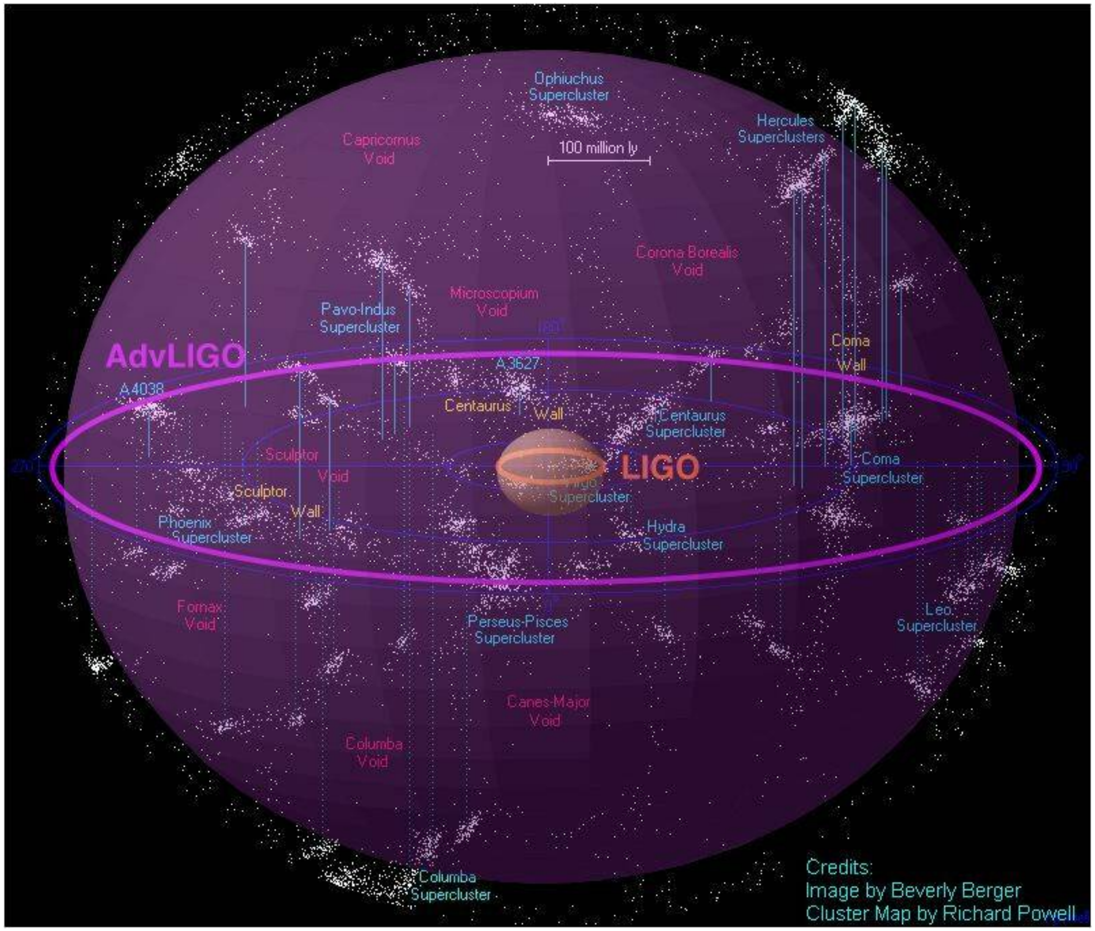
Factor of ~10 better than current LIGO ⇒ factor of ~1000 in volume !

Advanced detectors (2/2)

Neutron Star Binaries:

Maximal horizon > 300 Mpc

Most likely rate ~ 40/year !



Credits:
Image by Beverly Berger
Cluster Map by Richard Powell

The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

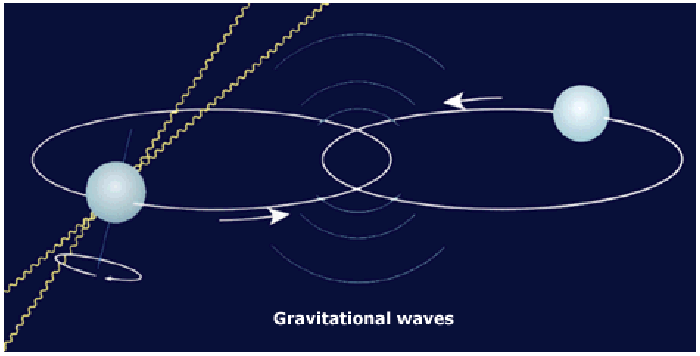
Summary

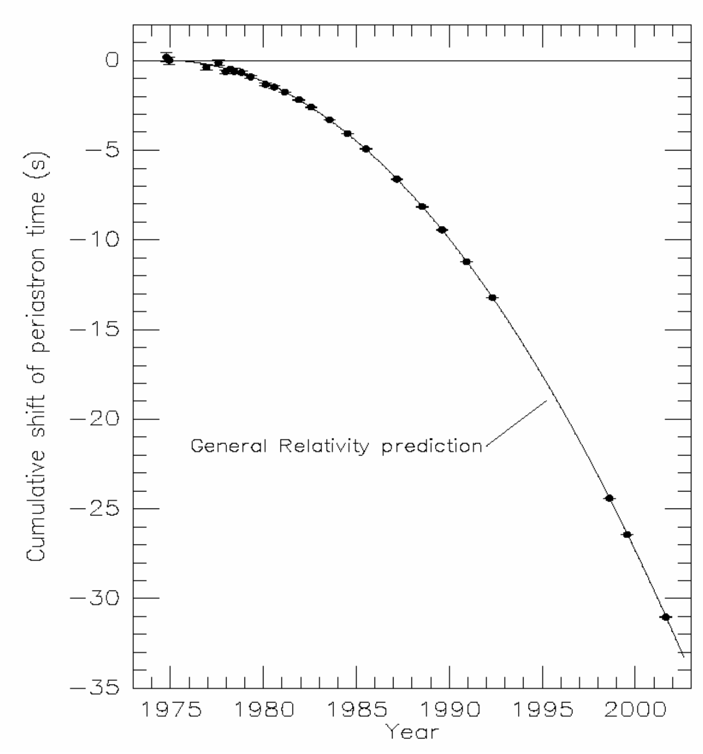
- **The LIGO detectors have reached their target sensitivities**
- **A long science run has been completed (1 year of data in triple coincidence)**
- **Analysis pipelines have been developed and tested**
- **A systematic checklist is developed to identify detections**
- **A world wide collaboration has started**
- **Gravitational-wave astronomy is starting !**

Spares

An evidence that gravitational waves exist…

- **Binary system 1913+16**: discovered in 1974 by Hulse and Taylor
  - 2 **neutron stars** of 1.4 solar masses
  - one of this star is a **radio pulsar**





⇒ Measurement of the orbital period decrease

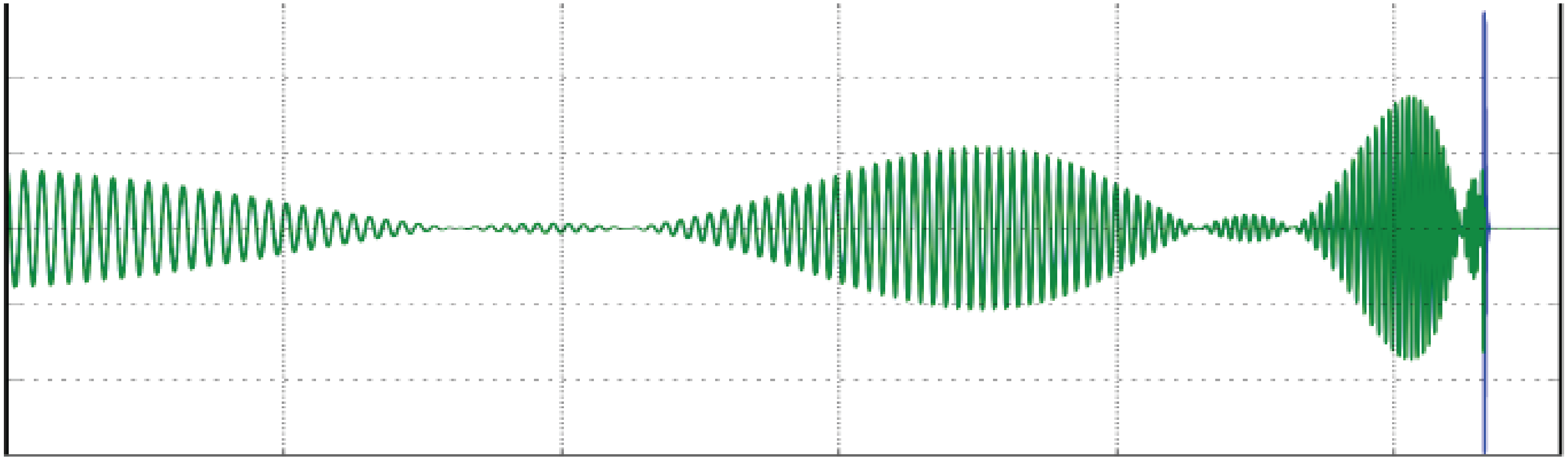
In agreement with an energy loss due to gravitational wave radiation

⇒ An indirect evidence for gravitational wave radiation !

Spin effect

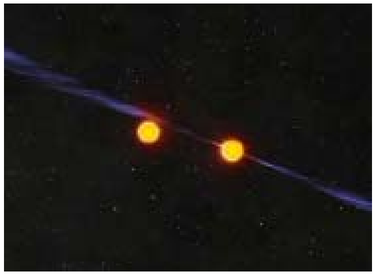
16.8 / 4.4 solar masses

|spin1| = 0.89 / |spin2| = 0.04



Search for Compact Binary Coalescences

- Known waveform: ⇒ use match filtering technique



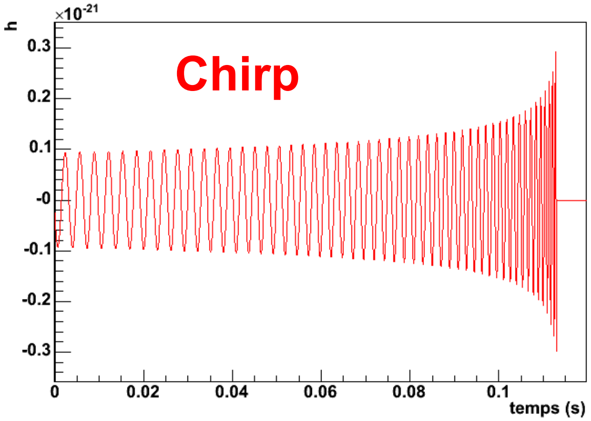
Data

Template

$$z(t) = 4\int_0^\infty \frac{\tilde{s}(f)\,\tilde{h}^*(f)}{S_n(f)}\,e^{2\pi i f t}\,df$$

Noise power spectral density

- Calculated templates for inspiral phase (“chirp”)



Waveform parameters:
distance, orientation, position,
m_1, m_2, t_0, ϕ (+ spin, ending cycles …)

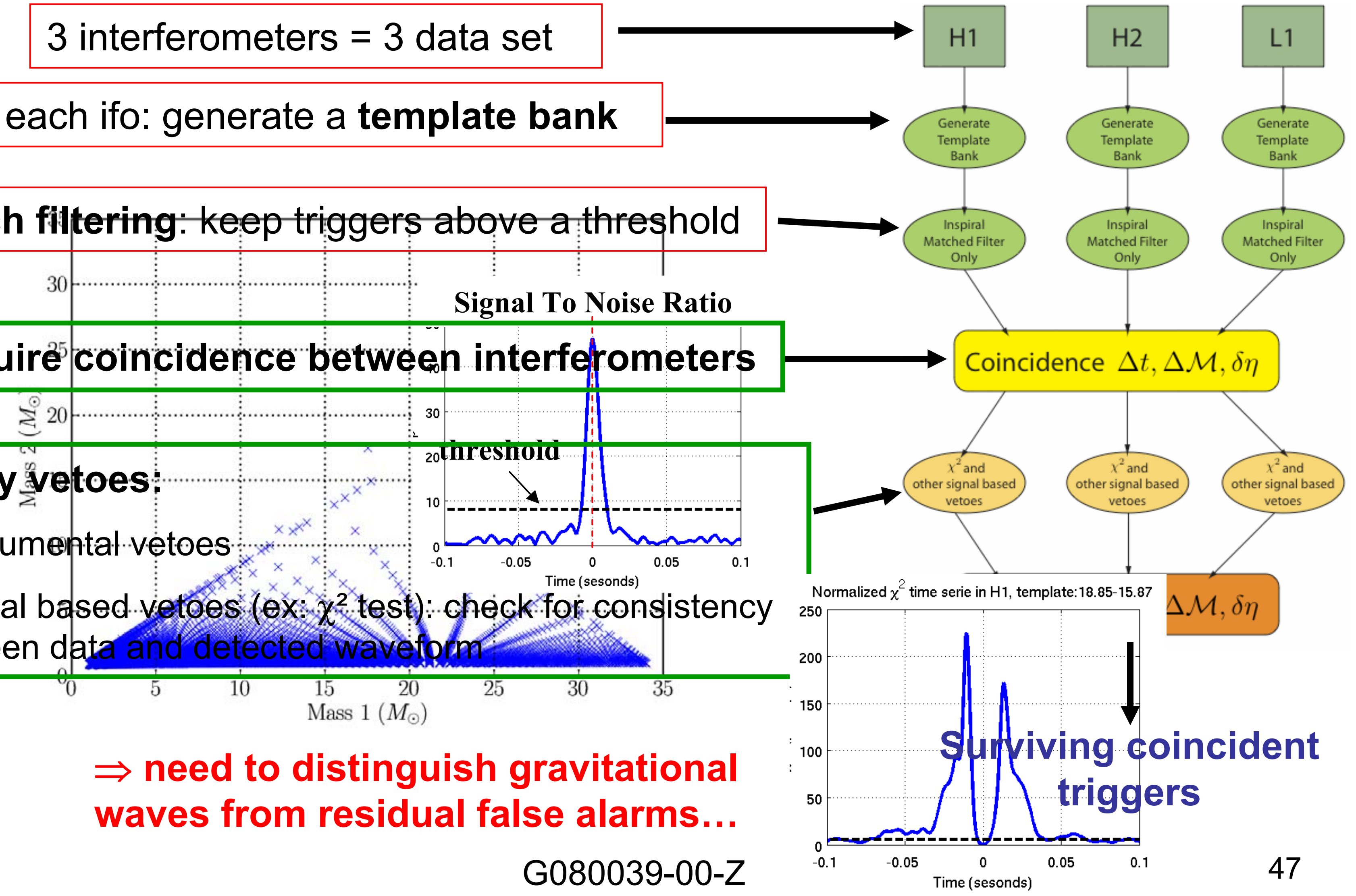
- Different template families used for different searches

Example: S3-S4 searches

- **Binary Neutron Stars: “physical templates”** (2nd order restricted post-Newtonian, stationary-phase approximation)

- **Binary Black Holes: “phenomenological templates”** (BCV)

Compact Binary Inspirals: Overview of the search pipeline



3 interferometers = 3 data set

For each ifo: generate a **template bank**

Match filtering: keep triggers above a threshold

Require coincidence between interferometers

Apply vetoes:

- Instrumental vetoes
- Signal based vetoes (ex: χ^2 test): check for consistency between data and detected waveform

Surviving coincident triggers

⇒ need to distinguish gravitational waves from residual false alarms…

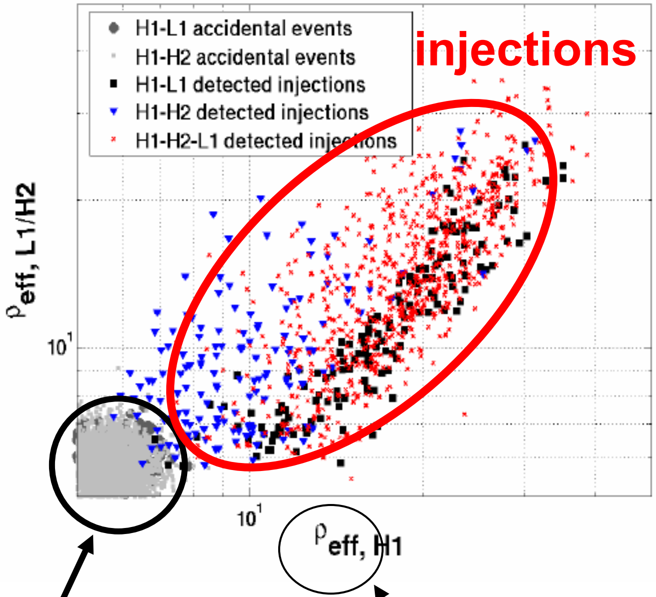
Compact Binary Inspirals: Identifying a possible gravitational wave (1/2)

- **First step**: estimate the false alarm probability

  ⇒ **compare candidate to expected background**

→ **background estimated by applying time-slides before coincidence**

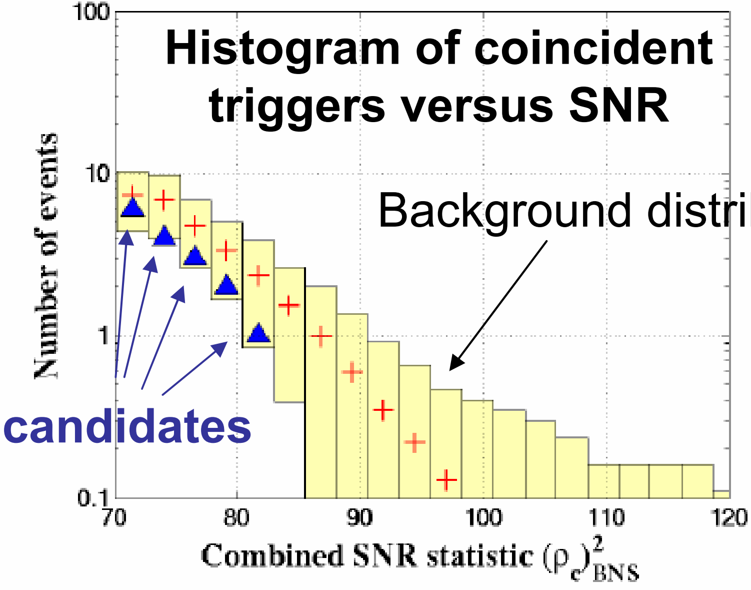
Ex: S4 Binary Neutron Star search [*Preprint arXiv:0704.3368*]



injections

background

Effective signal to noise ratio



Histogram of coincident triggers versus SNR

Background distribution

candidates

If candidates consistent with background ⇒ no detection

Else ?

Periodic signals from Radio/X-ray pulsars (1/2)

- **Targeted searches:**

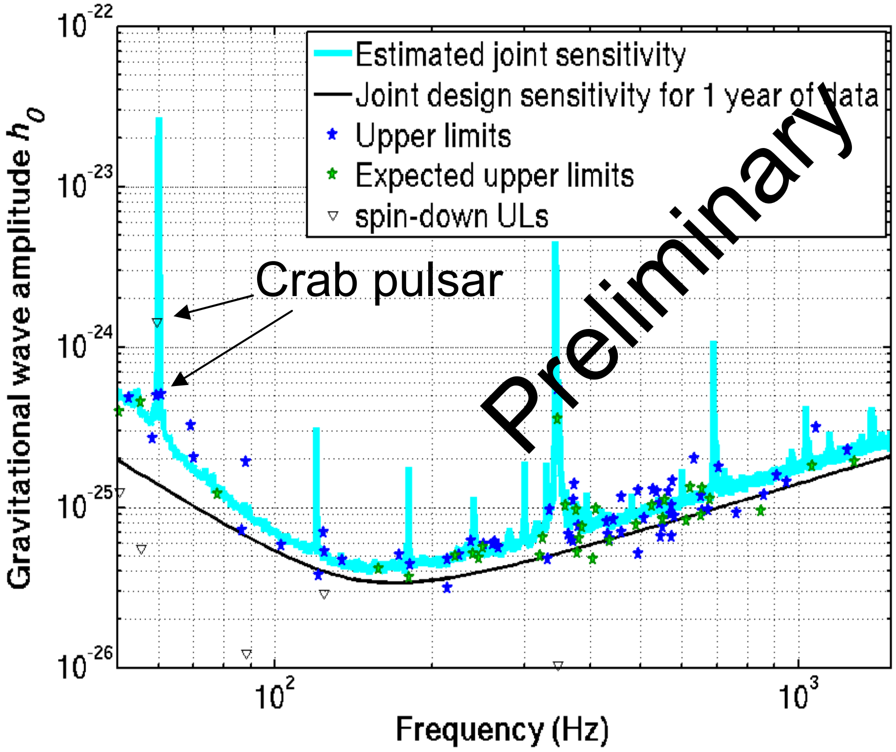
→ for **97 known (radio and x-ray) systems**: isolated pulsars, binary systems, pulsars in globular clusters…

→ place **upper limits** on gravitational wave amplitude and equatorial ellipticities

ε limits as low as ~10^{-7}

Crab pulsar: LIGO limit on GW emission is now **below** upper limit inferred from spindown rate

upper limits from first ~13 months of S5



G

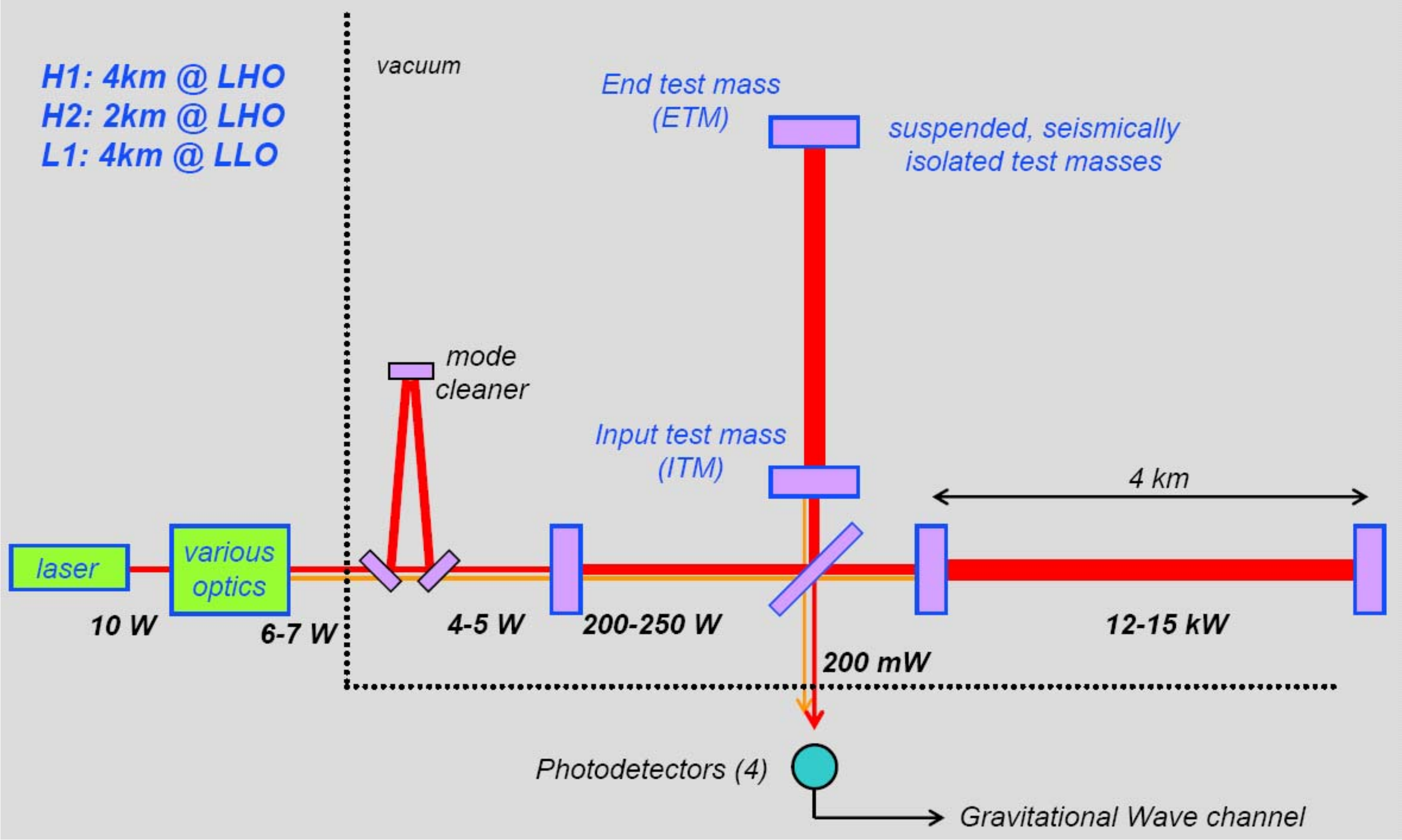
LIGO

Australian Consortium
 for Interferometric
 Gravitational Astronomy
The Univ. of Adelaide
Andrews University
The Australian National Univ.
The University of Birmingham
California Inst. of Technology
Cardiff University
Carleton College
Charles Stuart Univ.
Columbia University
Embry Riddle Aeronautical Univ.
Eötvös Loránd University
University of Florida
German/British Collaboration for
 the Detection of Gravitational Wav
University of Glasgow
Goddard Space Flight Center
Leibniz Universität Hannover
Hobart & William Smith Colleges
Inst. of Applied Physics of the Russian
Academy of Sciences
Polish Academy of Sciences
India Inter-University Centre
 for Astronomy and Astrophysic
Louisiana State University
Louisiana Tech University
Loyola University New Orleans
University of Maryland
Max Planck Inst. for Gravitati
 Physics

LSC

- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical
 Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento,
 and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

The LIGO interferometers

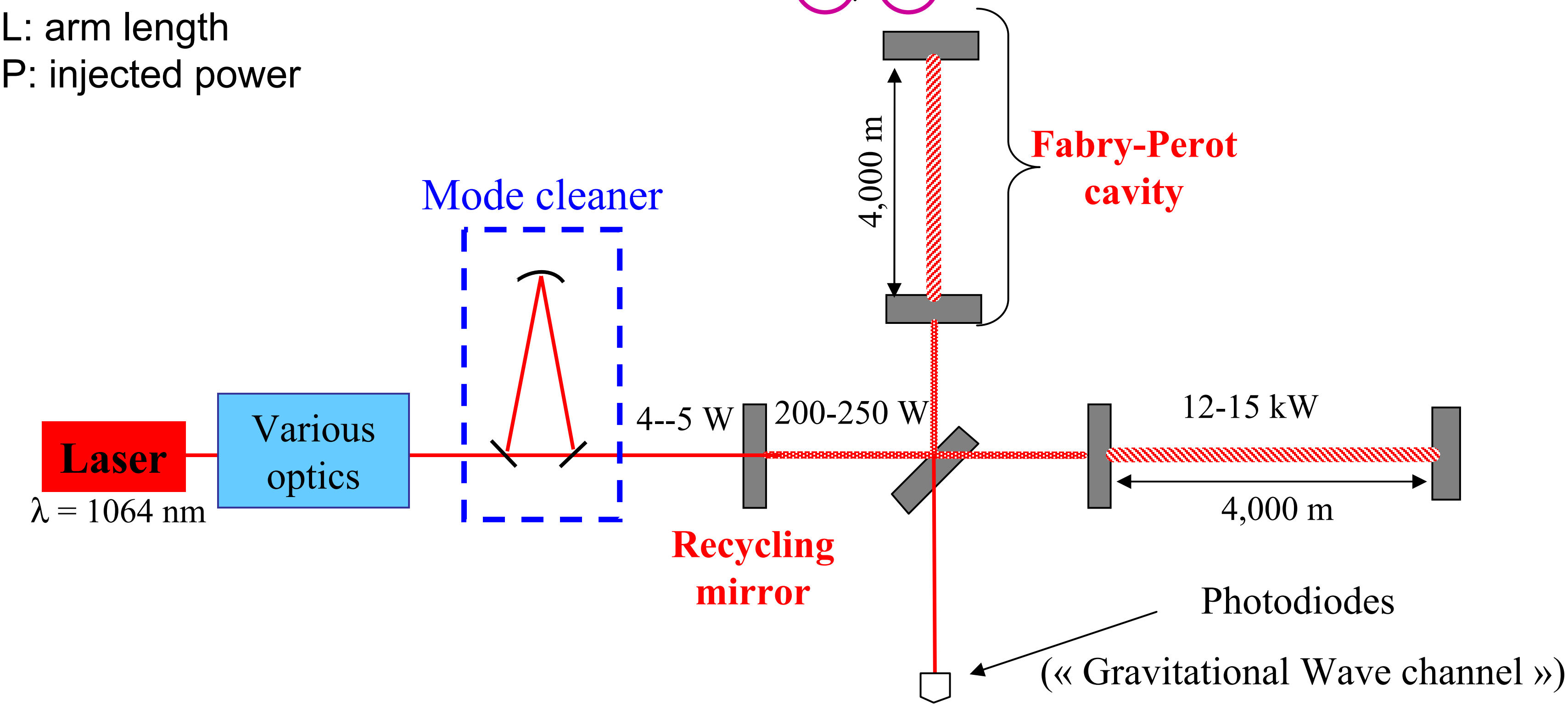


The LIGO interferometers

Sensitivity of an interferometer limited by shot noise:

Smaller measurable displacement: $\tilde{h} \geq \frac{\lambda}{4\pi}\frac{1}{L}\sqrt{\frac{2\hbar\omega}{P}}$

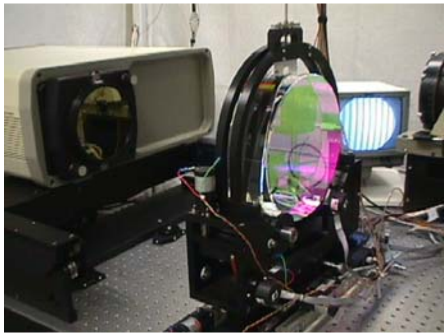
L: arm length
P: injected power



- Fabry-Perot cavity: ~125 round trips ⇒ effective optical path = 500 km
- Recycling cavity: power x 50

Fundamental noises

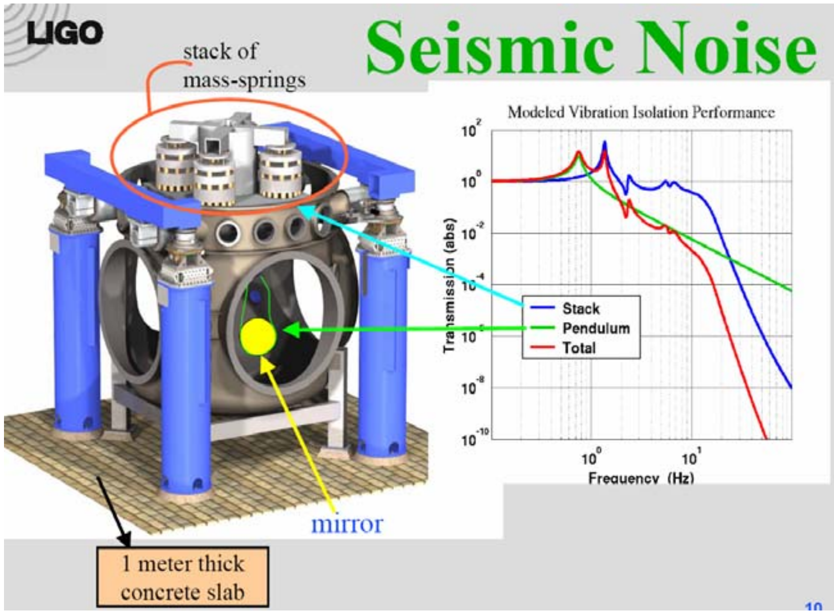
- **Thermal noise:** affecting mirrors and suspensions



- high-purity fused silica
- largest mirrors are 25 cm diameter, 10 cm thick, 10.7 kg
- surfaces polished to ~1 nm rms
- low scattering loss (<50 ppm)

- **Acoustic noise / index fluctuations**

Vacuum equipment



Seismic Noise

stack of mass-springs

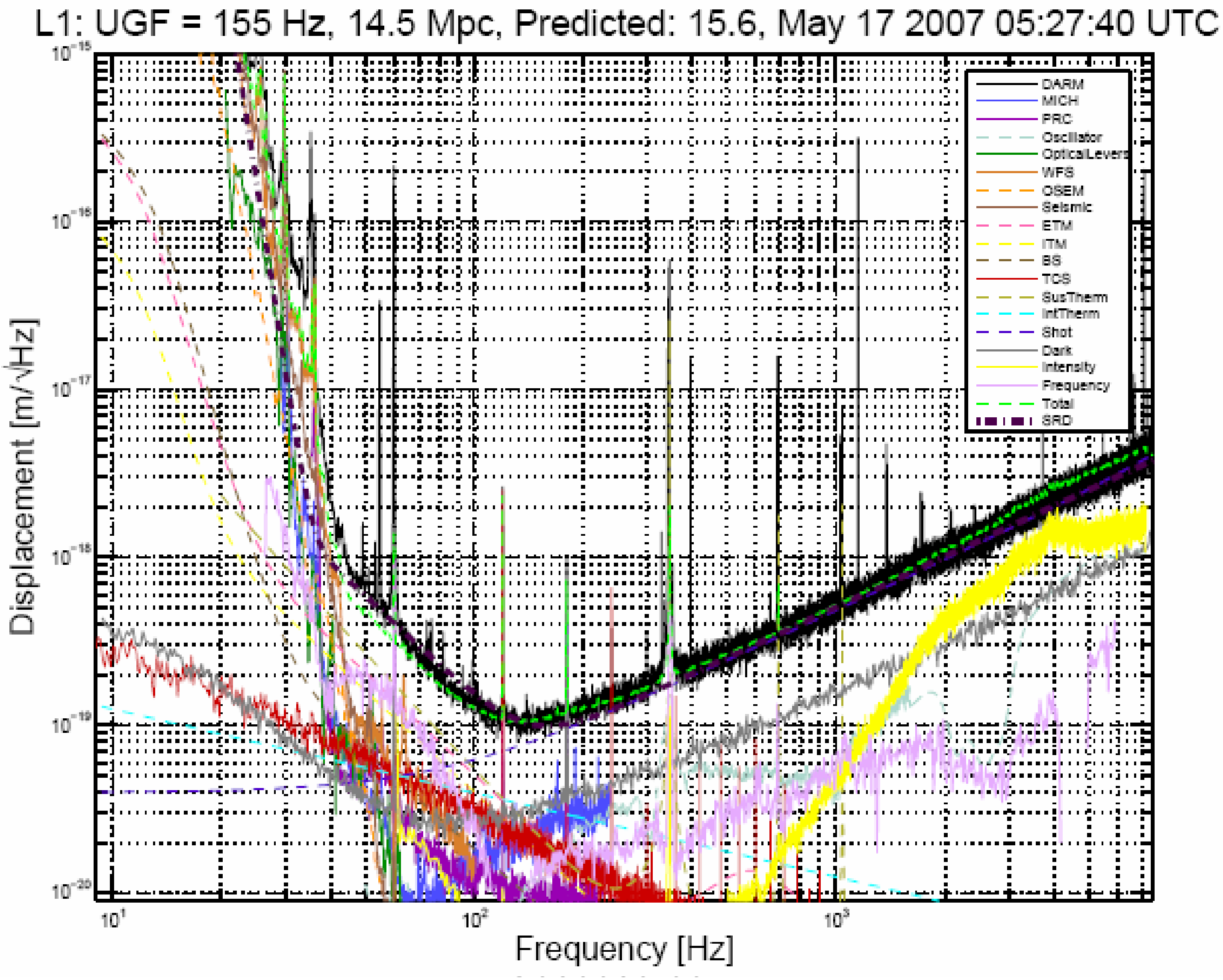
mirror

1 meter thick concrete slab

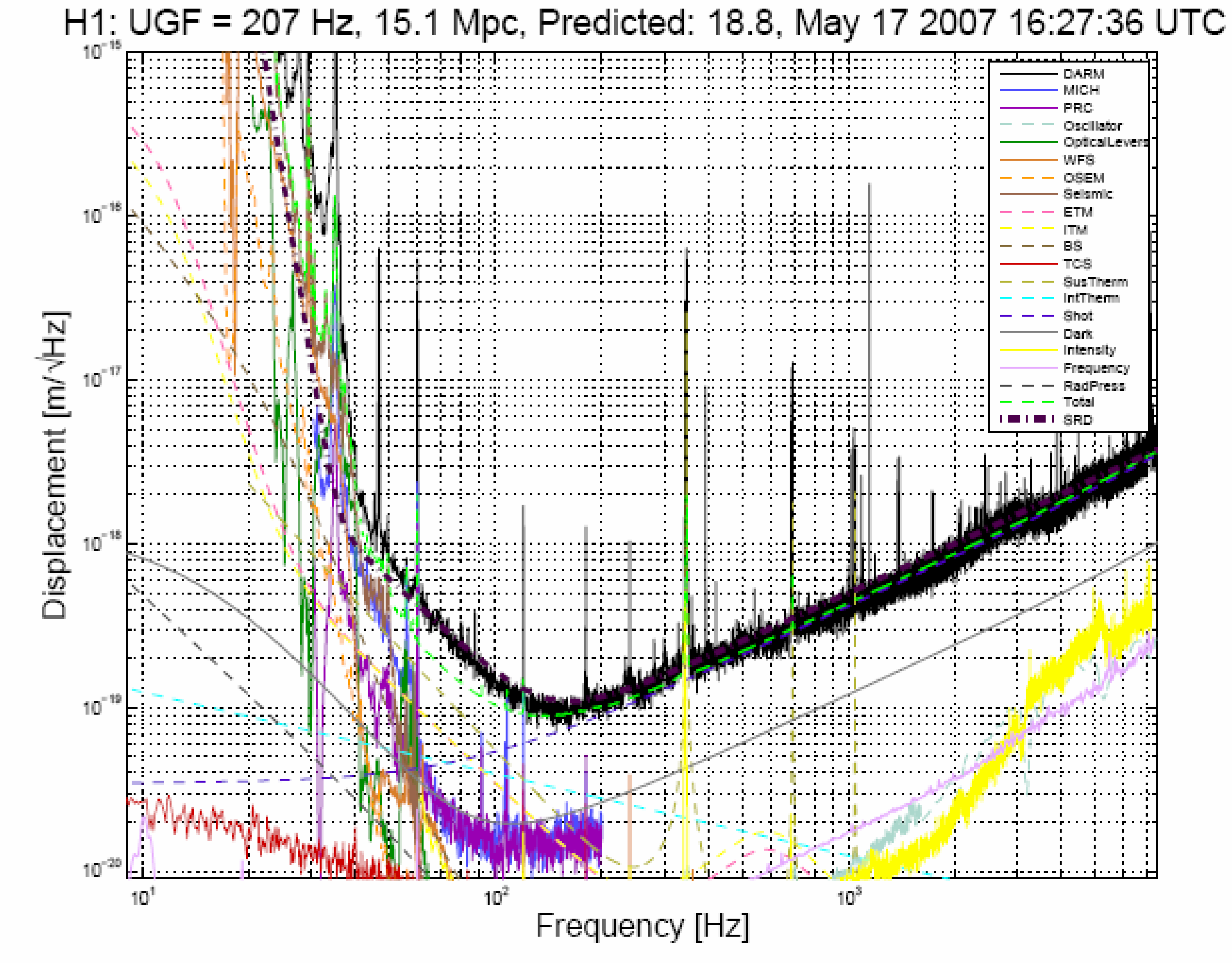
- **Seismic noise**

- Hydraulic external pre-isolator
- Stacks
- Pendulum

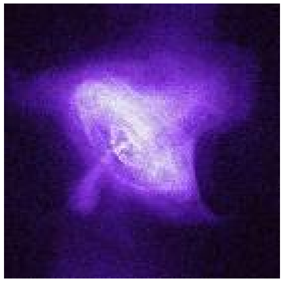
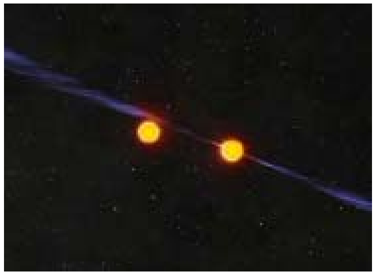
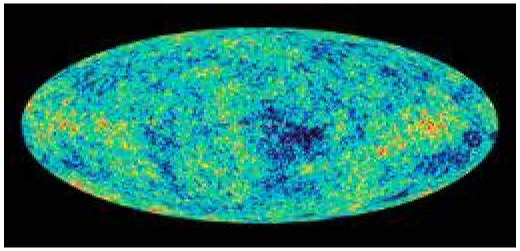
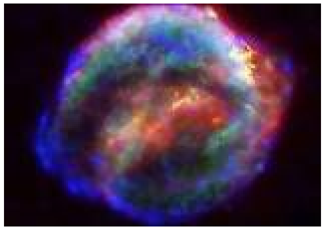
Livingston noise budget



Hanford (4 km) noise budget



Sources and methods

	Long duration	Short duration
Matched filter	 Pulsars	 Compact Binary Inspirals
Template-less methods	 Stochastic Background	 Bursts

Burst searches

- **Motivations:** minimal assumptions, open to unexpected/unknown waveforms

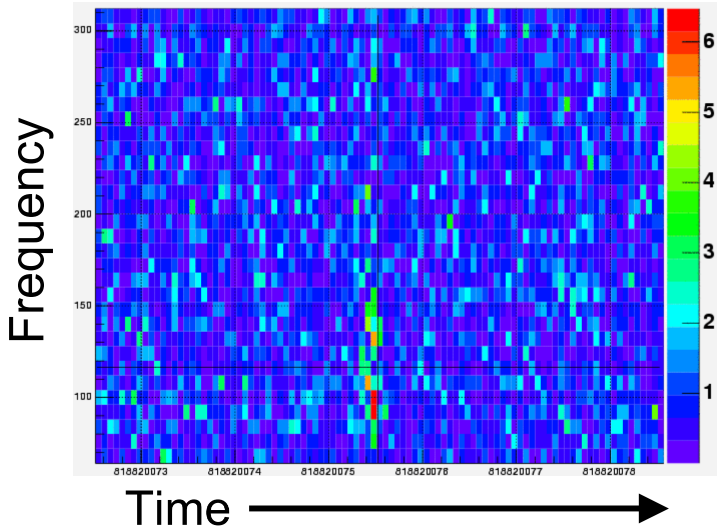
- **Methods:**

- Excess Power:

Decompose data stream into
time-frequency pixels

⇒ Look for hot pixels or clusters of pixels

- Calculate cross-correlation between interferometer data streams



- **S4 general all-sky burst search** *[Preprint arXiv:0704.0943]*

Searched 15.53 days of triple-coincidence data (H1+H2+L1)
for short (<1 sec) signals with frequency content in range 64-1600 Hz

No event candidates observed

⇒ Upper limit on rate of detectable events

- **S5:** analysis on going …

Periodic signals from Radio/X-ray pulsars

- **Targeted searches:**

→ for **97 known (radio and x-ray) systems**: isolated pulsars, binary systems, pulsars in globular clusters…

→ place **upper limits** on gravitational wave amplitude and equatorial ellipticities

ε limits as low as $\sim 10^{-7}$

Crab pulsar: LIGO limit of GW emission is now **below** upper limit inferred from spindown rate

- **All-sky, unbiased searches:**

→ Search for a sine wave, modulated by Earth's motion,
and possibly spinning down: easy, but computationally expensive!

http://www.einsteinathome.org/

Einstein@Home

~175,000 users

~75 Tflops on average

LSC-Virgo joint data analysis

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- **Sharing of data started in May 2007:**

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  - Can help increasing the duty cycle

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Starting after S5 (~now): a series of fast upgrades
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Requires new thermal compensatio

- DC readout scheme
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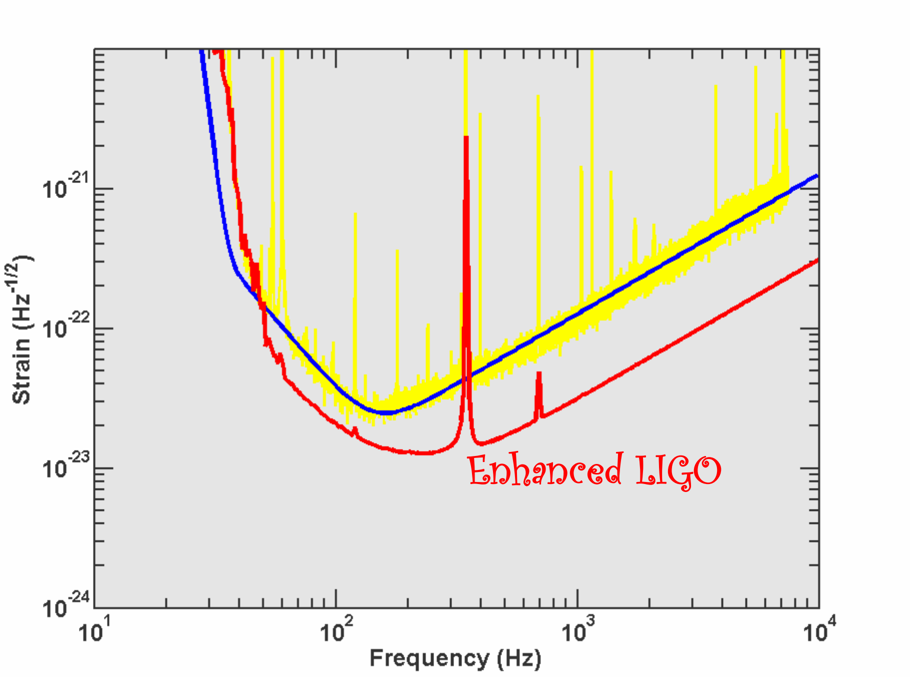
Output mode cleaner



S6 run planned to begin in 2009, duration ~1.5 years
Virgo improvements and joint running planned on same time scale

Advanced LIGO (1/2)

A series of major improvements after the S6 run (starting ~2010):

- **Seismic noise**

  Active isolation system
  Mirrors suspended as fourth stage of quadruple pendulums

- **Thermal noise**

  Suspension ➔ fused silica fibers
  Test mass ➔ more massive; better coatings

- **Optical noise**

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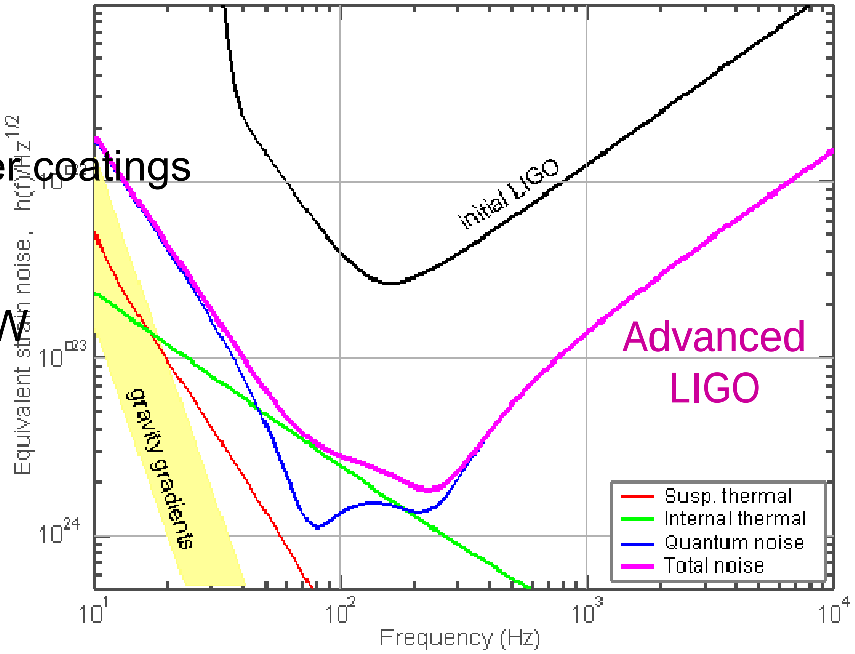


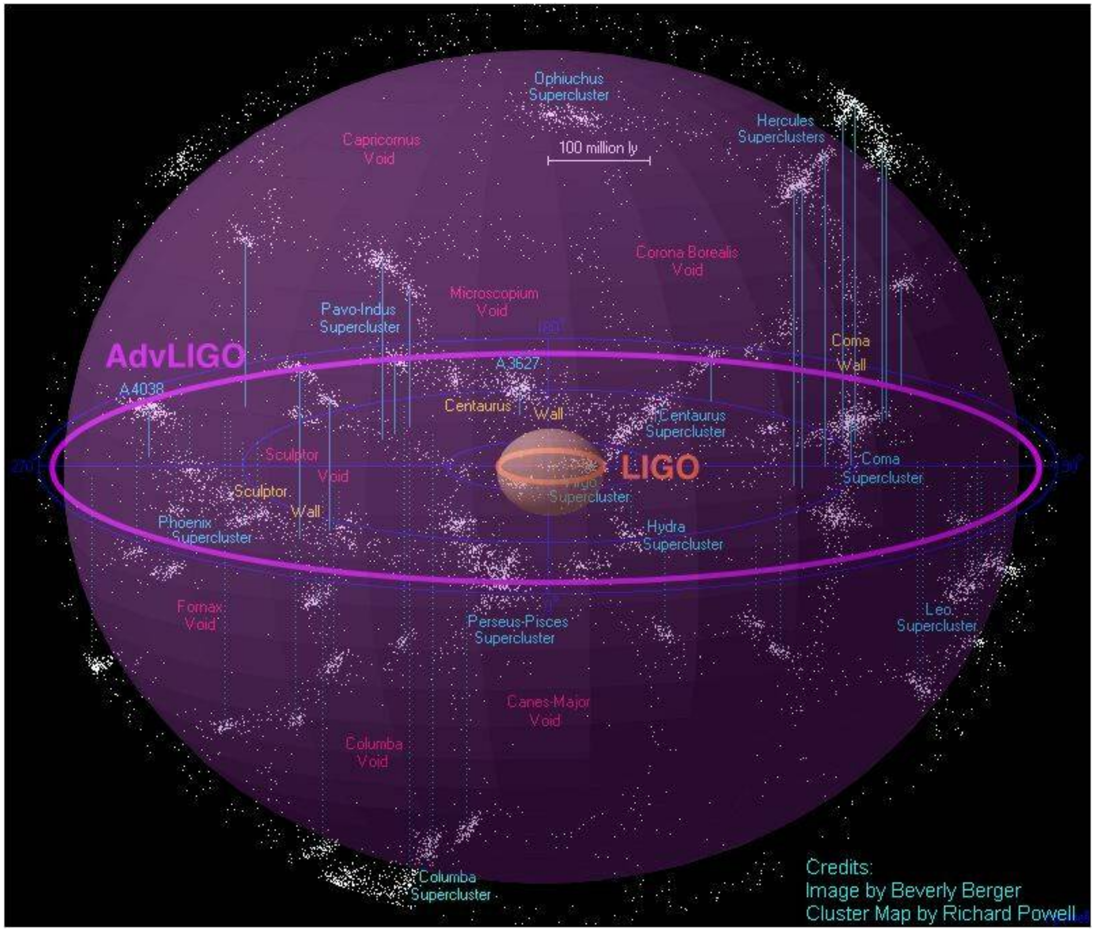
Factor of ~10 better than current LIGO ⇒ factor of ~1000 in volume !

Advanced LIGO (2/2)

Neutron Star Binaries:

Maximal horizon > 300 Mpc

Most likely rate ~ 40/year !



Credits:
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Cluster Map by Richard Powell

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