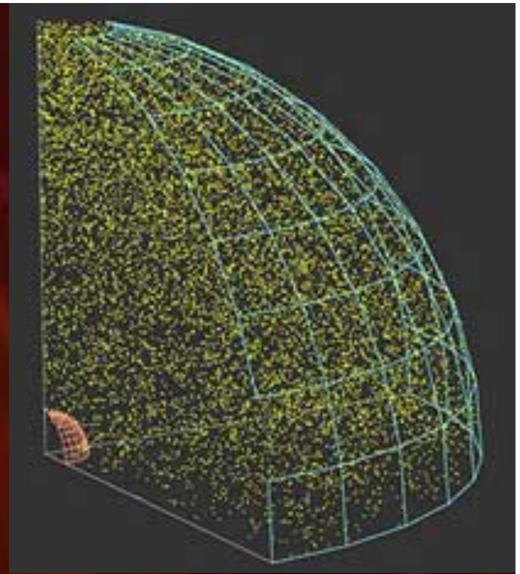
Gravitational Waves:
A new window into the cosmos



Alicia M. Sintes
Universitat de les Illes Balears

XL International Meeting on Fundamental Physics,
Benasque 2012

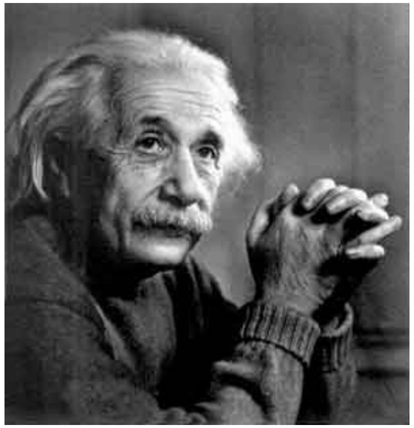
General Relativity: “a theorist’s Paradise, but an experimentalist’s Hell”

C. Misner, K. S. Thorne and J.A Wheeler, ***Gravitation*** p. 1131 (1973)

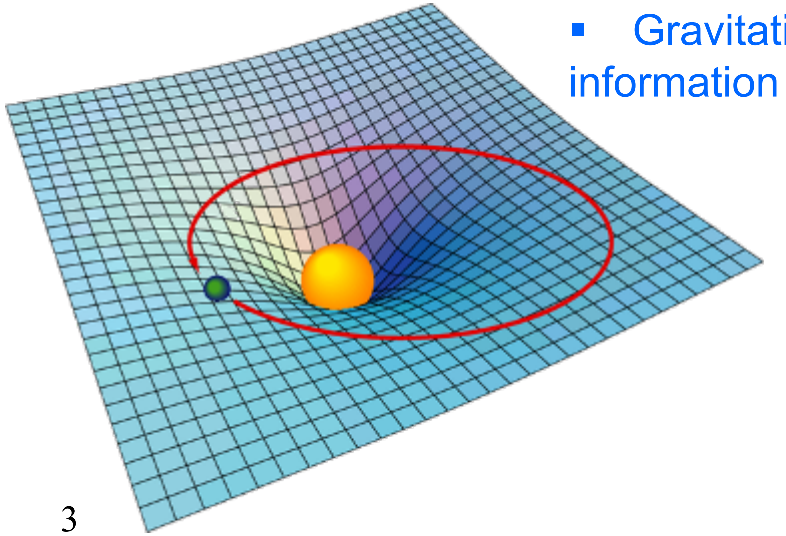
AIP Emilio Segrè Visual Archives

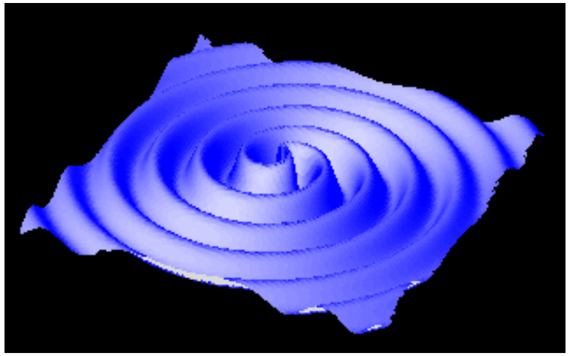
- Nothing exemplifies this statement like gravitational waves
- Convincing observational evidence for their existence not available until ~70 years after initial prediction (Binary Pulsar)
- After many years, direct detection still eludes us
- With luck, we may have a direct detection by the 100th anniversary of their prediction

Gravitational Waves



- According to Einstein's theory of general relativity, gravity is not a force but is related to the curvature of spacetime.
- Gravitational waves are "ripples in the fabric of space-time": perturbations of the space-time metric produced by rapid changes in shape and orientation of massive objects, or more precisely, produced by a time-changing mass quadrupole.
- They are produced by the acceleration of large amounts of matter and violent phenomena such as collisions of black holes, supernova explosions, in particular, had to arise in the most violent event occurred in the Universe: the first moments of the Big Bang
- Gravitational waves travel at the speed of light, carrying information about its origins.





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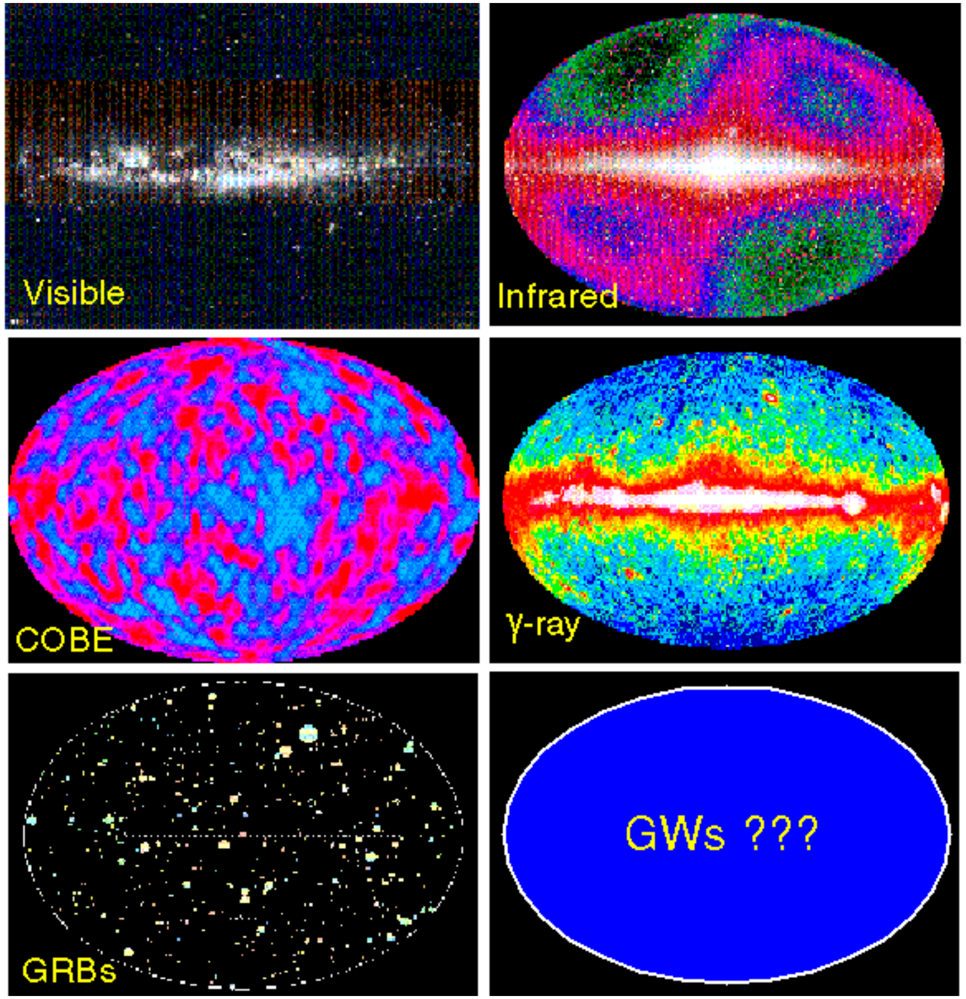
A new window on the Universe

The history of Astronomy:
new bands of the EM spectrum opened → major discoveries!

GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe



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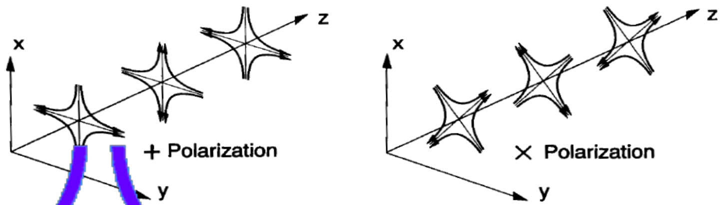
Gravitational wave properties

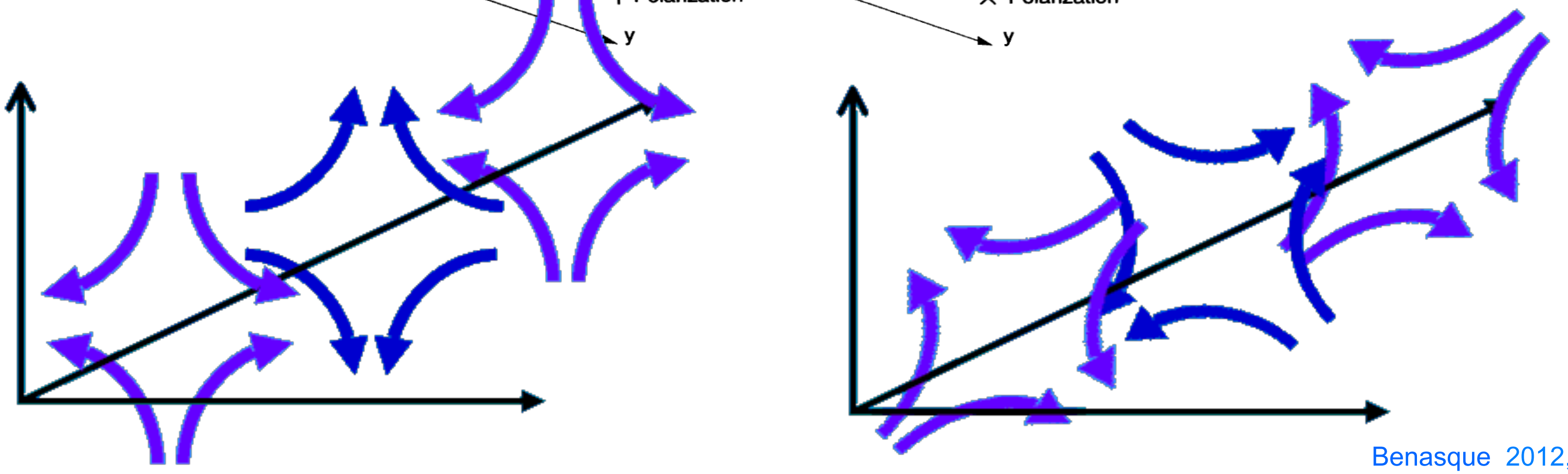
- Gravitational Waves will give a *non electromagnetic* view of the universe, and open a new spectrum for observation. This will be complementary information, as different from what we know as *hearing* is from *seeing*.

- The strength of a gravitational wave is given by the strain h(t) = change in length / length

- Detectors are sensitive to the amplitude instead of intensity:
  - → range is proportional to the sensitivity
  - → number of events to the sensitivity^3

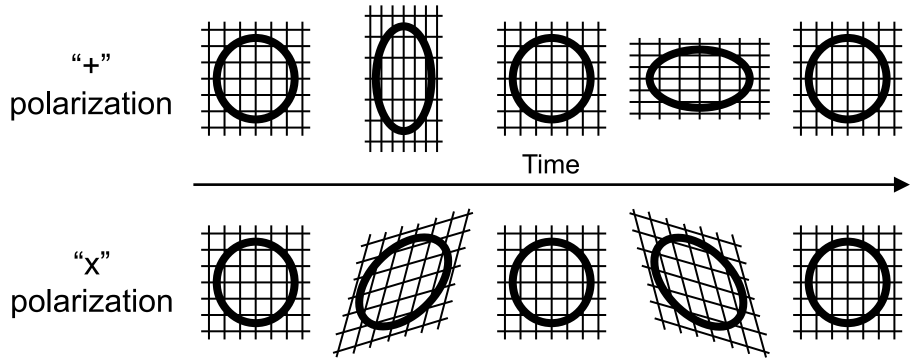
- Like light, Gravitational Waves interact with matter (but very weakly) and they have two polarizations "+" and "x"”





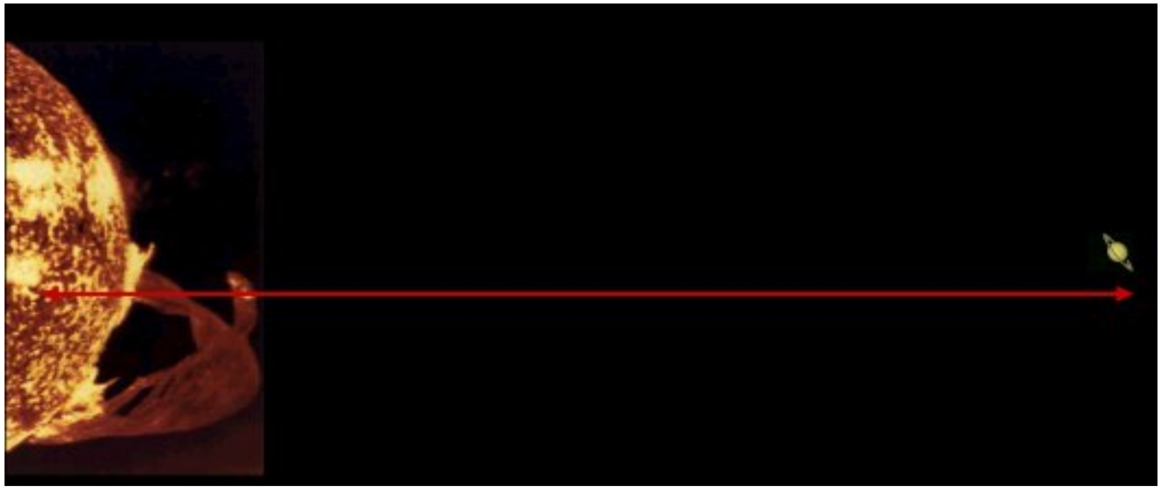
How Small is the Stretching and Squeezing?

- Compared to the ease with which electromagnetic signals are detected, the detection of gravitational radiation is technologically staggering.



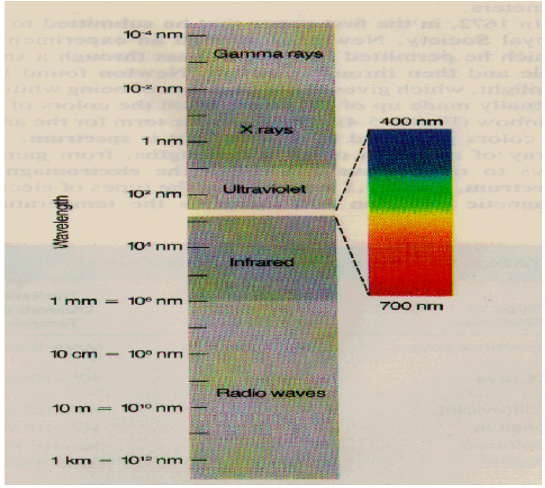
- The effect of a gravitational wave is to change the distance between freely falling test masses.

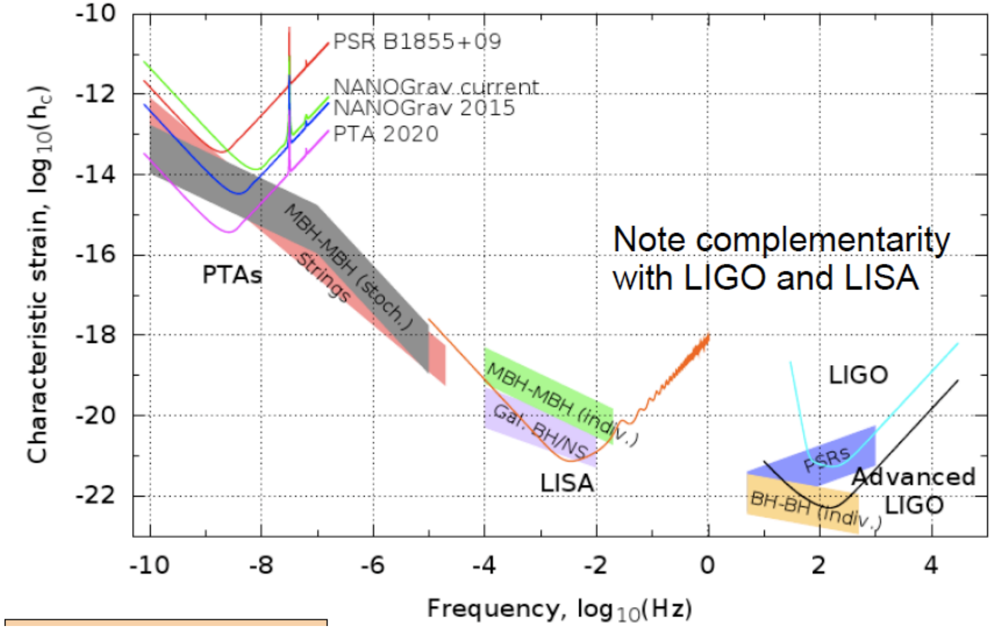
- The amount of stretching and squeezing of space which is predicted to occur near the Earth due to events such as the coalescence of a pair of neutron stars within about 100 million light-years from Earth is about one part in 10^{22}.



- Observing this fantastically tiny effect is equivalent to detecting the motion of Saturn if it were to move closer to the sun by the diameter of a single hydrogen atom!

Frequency range





Electromagnetic waves

- ~ 16 orders of magnitude. From ultra low radio wave frequency to gamma rays.

Gravitational waves could in principle exist at any frequency. However, very low frequency waves would be impossible to detect and there is no credible source for detectable waves of very high frequency.

- GWs that could be plausibly detected range from 10^{-9} Hz up to 10^{11} Hz.
- The frequency of the wave depends on the object's mass and its compactness:
  - Heavier objects emit at lower frequencies, (200 $M_\odot$ = 1 ms = 10^3 Hz).
  - More compact objects emit at higher frequencies

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Gravitational Wave Astronomy. A new field

Gravitational wave detectors will study sources characterised by extreme physical conditions: strong non-linear gravity and relativistic motions, very high densities, temperatures and magnetic fields.

Some of the key scientific questions to which answers will be sought:

fundamental physics:

- What are the properties of gravitational waves?
- 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?

astrophysics:

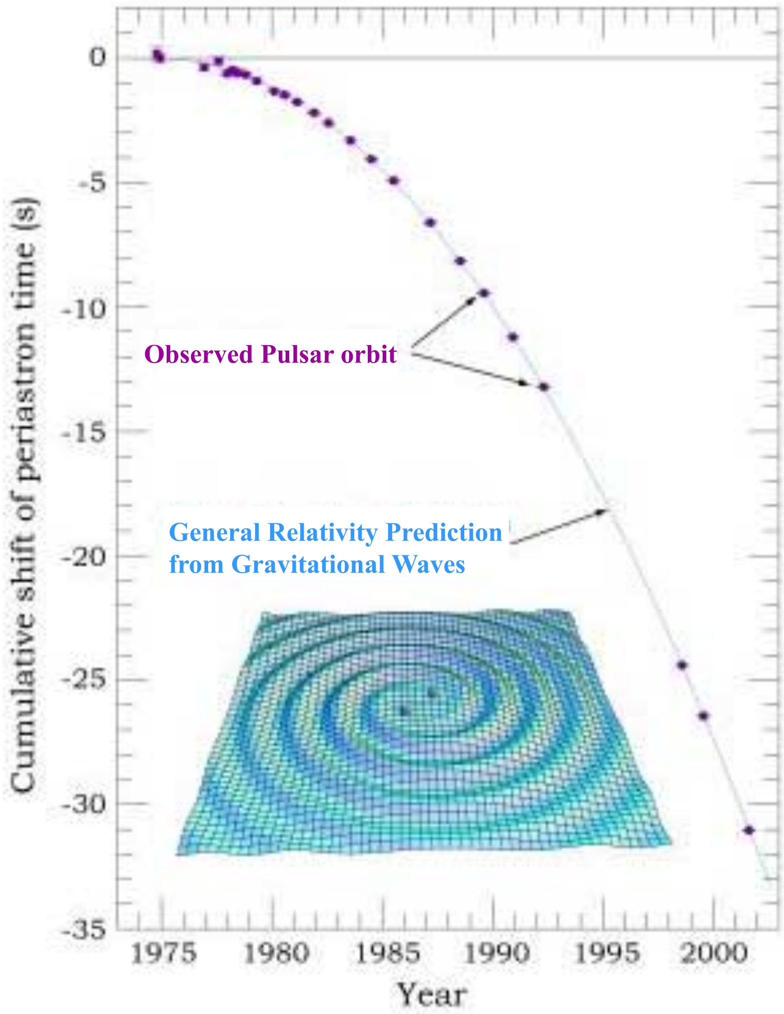
- How abundant are stellar-mass black holes?
- What is the mechanism that generates gamma-ray bursts?
- What are the conditions in the dense central cores of galactic nuclei dominated by massive black holes?
- Where and when do massive black holes form, and what role do they play in the formation of galaxies?
- What happens when a massive star collapses?
- How do compact binary stars form and evolve, and what has been their effect on star formation rates?

Indirect evidence of gravitational radiation: PSR 1913+16

J. Taylor R. Hulse

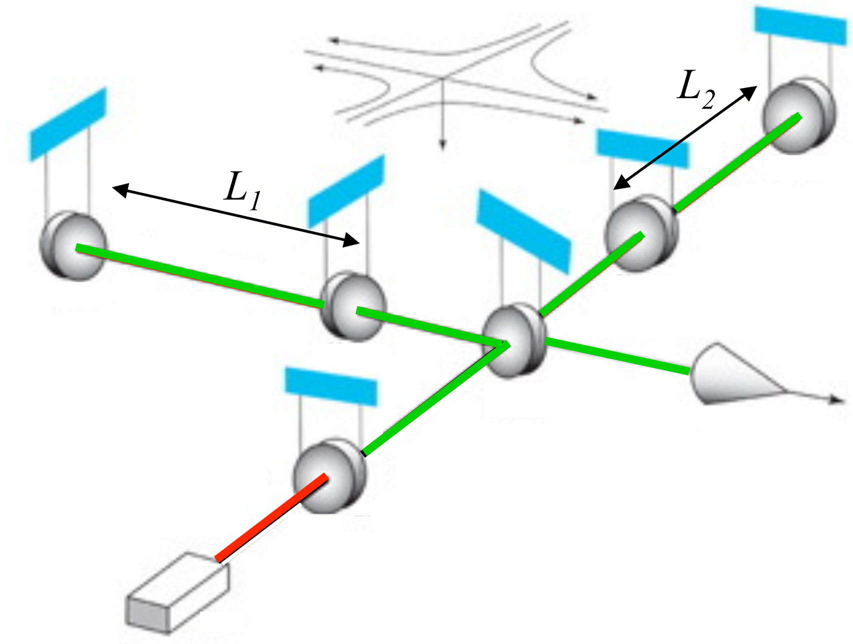
- The emission of gravitational waves by a pair of neutron stars orbiting each other has been observed by measuring a tiny systematic shrinkage of the orbit.
- For this seminal discovery Hulse and Taylor were awarded the Nobel Prize in 1993.
- However, this dramatic observation is referred to as an indirect confirmation of the existence of gravitational waves, since what we have observed is the effect of the waves on the binary orbit rather than the waves themselves.

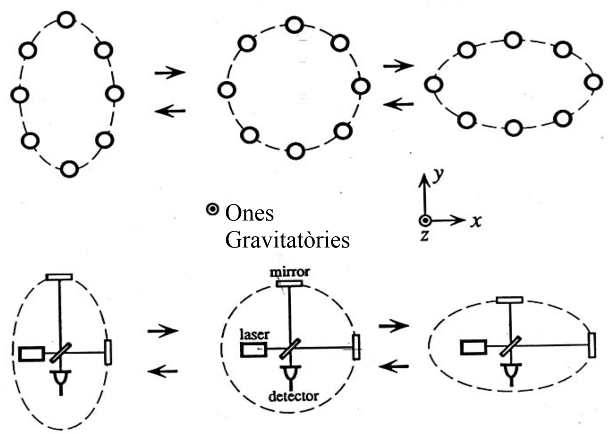
PSR 1913+16 orbit will continue to decay over the next ~300 million years, until coalescence. Gravitational wave emission will be strongest near the end.

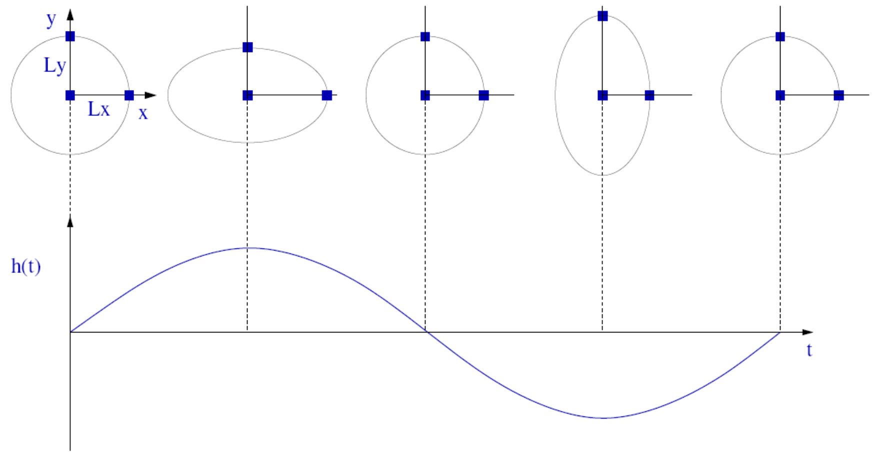


GW interferometer Layout

- Detecting a gravitational wave requires the construction of an L-shaped antenna approximately aligned with the polarization of the wave so that it is capable of detecting the squeezing of space along one arm of the antenna and the simultaneous stretching of space along the other arm.







- Laser light, which has a very accurately known wavelength, is the ruler that is used to measure the incredibly tiny squeezing and stretching that occurs.

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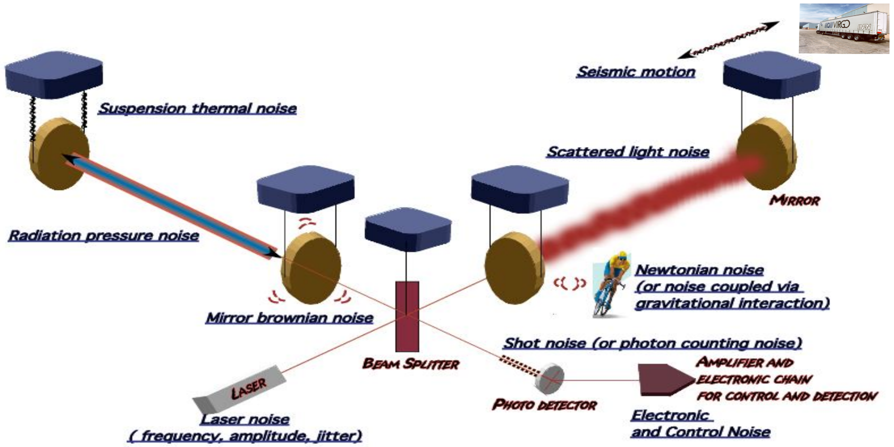
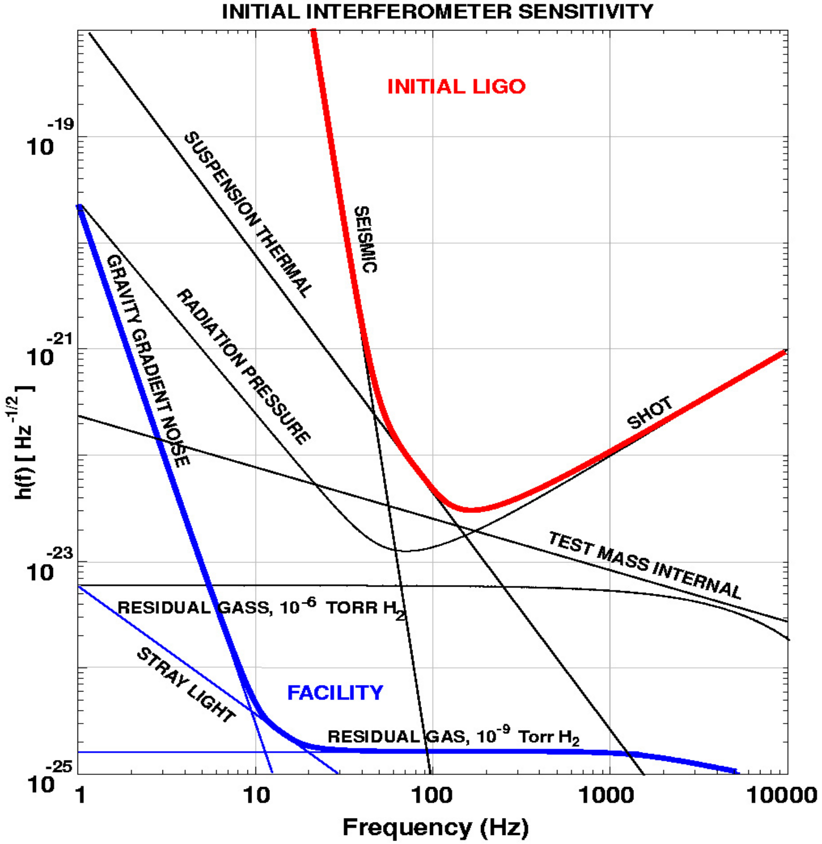
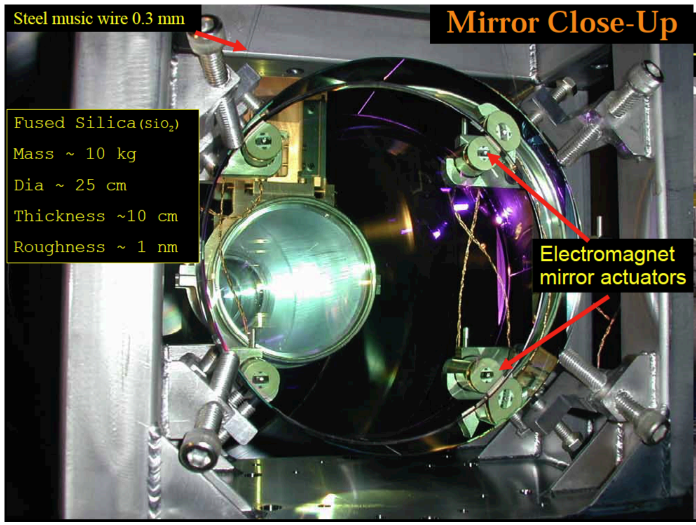
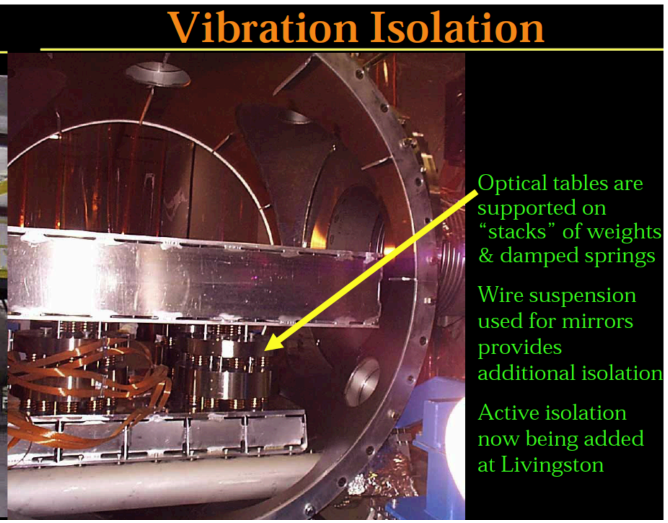
Fundamental Noise Sources





- Strain sensitivity $<3\times10^{-23}$ 1/Hz$^{1/2}$ at 200 Hz
- Displacement Noise
  - » Seismic motion, Thermal Noise, Radiation Pressure
- Sensing Noise
  - » Photon Shot Noise, Residual Gas
- Big challenge: reduce all other (non-fundamental, or technical) noise sources to insignificance





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International network of GW detectors

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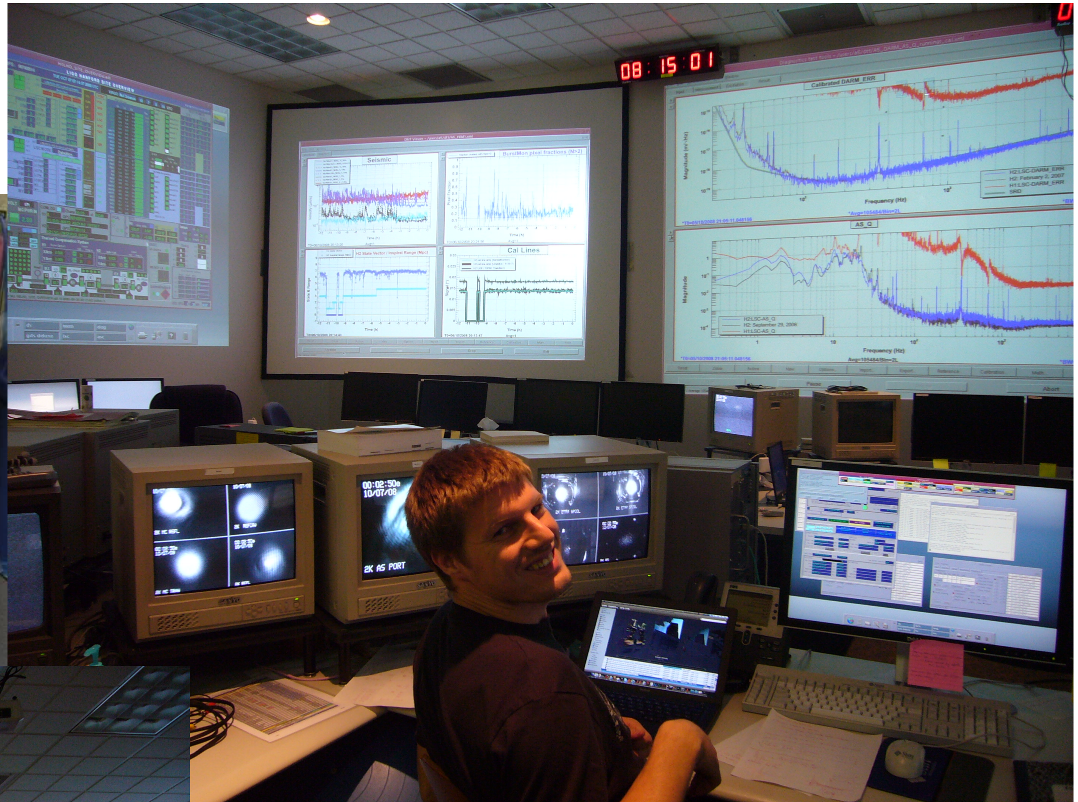

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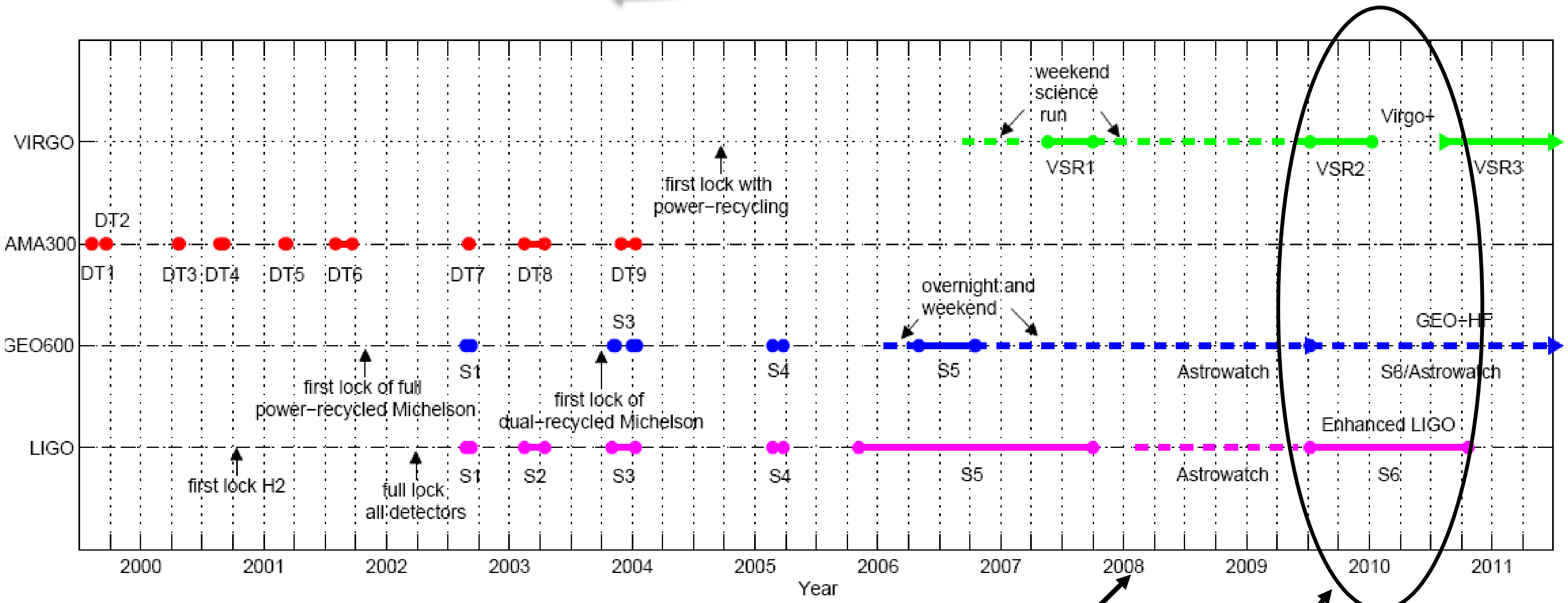
Timeline of GW searches to 2011

1989
LIGO Proposal submitted to NSF

1995
Construction started

1999
Inauguration



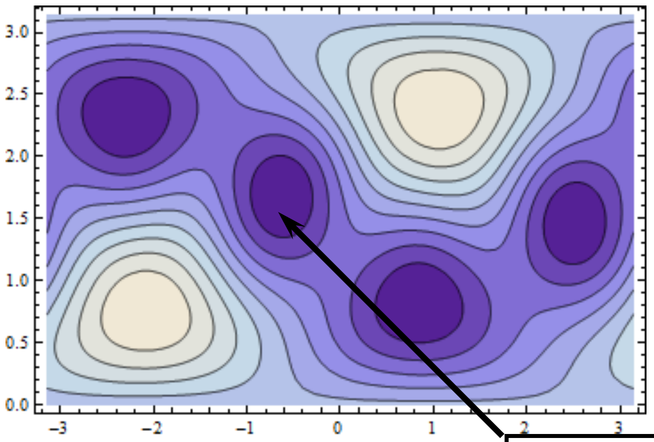
Advanced LIGO construction funded

Data analysis ongoing

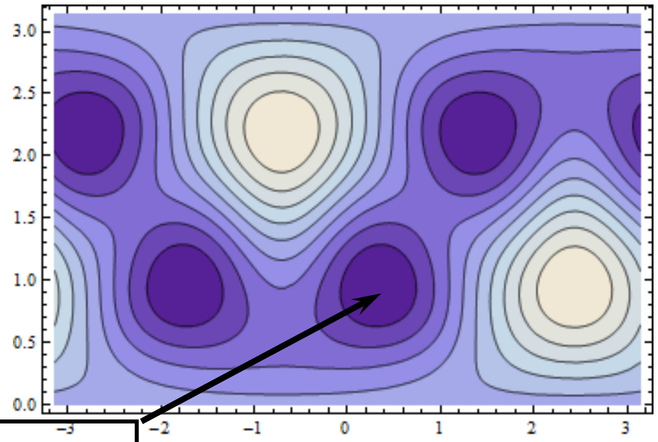
Benefits of a global network

- Improved sky coverage

LIGO Hanford

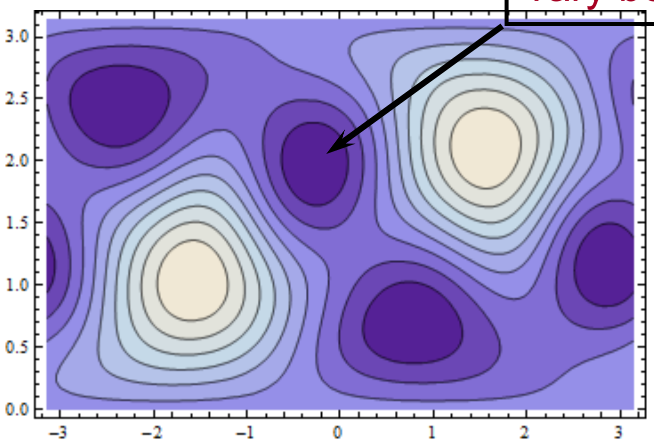


Virgo

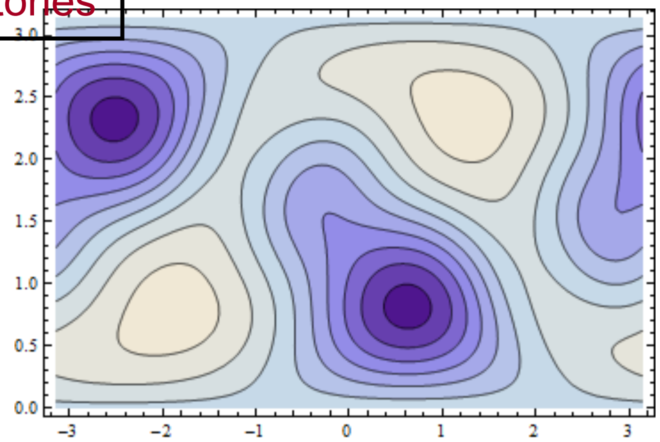


Nulls of the antenna pattern vary between observatories

LIGO Livingston



LIGO/Virgo

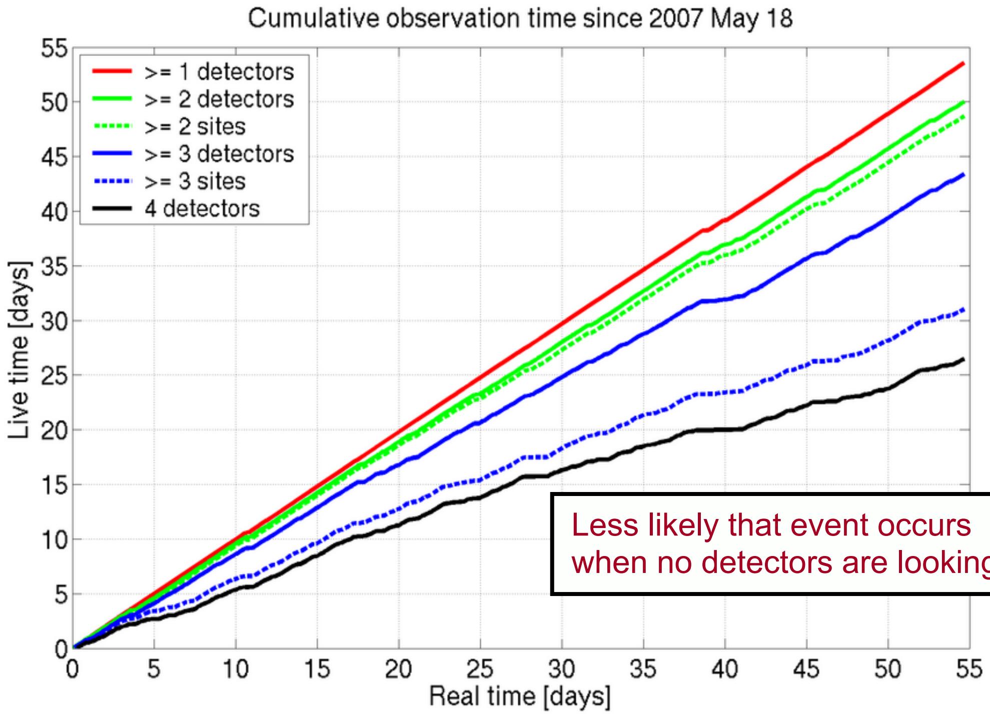


Average response to signals with random linear polarization in Earth fixed coordinates

Less likely that event occurs in a null of the detector network

Benefits of a global network

- Improved duty cycle



Less likely that event occurs when no detectors are looking

Cumulative observation time of the LIGO/Virgo network since 2007 May 18

- Increased signal to noise ratio
  - Coherently sum signals from multiple detectors
- Improved detection confidence
  - Multi-detector coincidence greatly reduces false rate
  - Coherent consistency tests can differentiate between gravitational-wave signals and instrumental anomalies
- Permits improved directional searches
  - Gamma ray burst progenitors
  - Supernovae
- Improved source reconstruction
  - "Inverse problem" requires **3** non-aligned detectors
  - Provides sky position and both polarizations of waveform
  - Permits comparison with theory
  - This is where the science is!
- Shared best practices
  - Learn from each other's approaches

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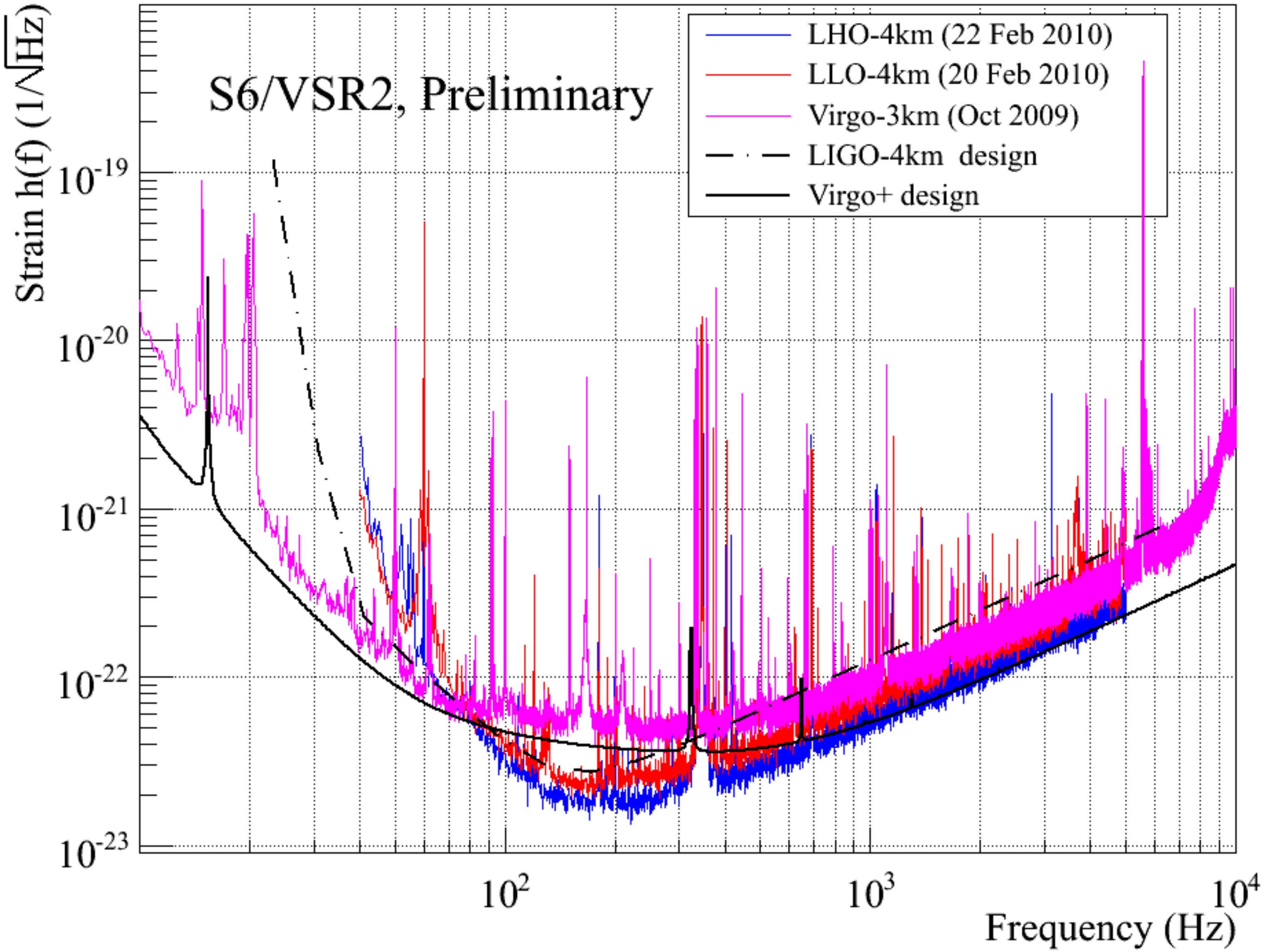
Detector Sensitivities



SCIENCE PAPERS BEING PUBLISHED

THE ASTROPHYSICAL JOURNAL, 715:1438–1452, 2010 June 1 doi:10.1088/0004-637X/715/2/1438
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SEARCH FOR GRAVITATIONAL-WAVE BURSTS ASSOCIATED WITH GAMMA-RAY BURSTS USING DATA FROM LIGO SCIENCE RUN 5 AND VIRGO SCIENCE RUN 1

PHYSICAL REVIEW D **82,** 102001 (2010)

Search for gravitational waves from compact binary coalescence in LIGO and Virgo data from S5 and VSR1

PHYSICAL REVIEW D **81,** 102001 (2010)

All-sky search for gravitational-wave bursts in the first joint LIGO-GEO-Virgo run

THE ASTROPHYSICAL JOURNAL, 715:1453–1461, 2010 June 1 doi:10.1088/0004-637X/715/2/1453
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SEARCH FOR GRAVITATIONAL-WAVE INSPIRAL SIGNALS ASSOCIATED WITH SHORT GAMMA-RAY BURSTS DURING LIGO'S FIFTH AND VIRGO'S FIRST SCIENCE RUN

Beating the spin-down limit on gravitational wave emission from the Vela pulsar

arXiv:1104.2712v2 [astro-ph.HE] 15 Apr 2011

nature

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

13

A Turning Point

- The era of the 1st generation ground-based interferometric detectors is ending…leaving a remarkably rich heritage
  - established the infrastructures
    - The same ones will be used for the next generation of LIGO, Virgo and GEO
    - New ones will be needed for KAGRA and for a detector in the Asia-Pacific region
  - basically reached the design sensitivities (and somewhere exceeded upon detector upgrades)
  - realized robust and reliable instruments
  - developed the paradigm for data analysis
  - established a network
  - started the multi-messenger approach
  - did real astrophysics
  - tested some technologies for 2_{nd} generation (and beyond)
  - a large (O(1000)) community grew around these projects and is now solidly established

- Such richness is being invested in a new generation of detectors that finally promises to detect gravitational waves and open a new window on the universe

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GW Observatories, now and in 2015

- The Enhanced LIGO detectors ended data taking in October 2010.
- During summer 2011, the Virgo and GEO-HF GW detectors took science data. (VSR4/S6e: Jun 3 - Sep 5)
  - exploit improved Virgo sensitivity at low frequency for pulsar search
  - coincident observations
- As of today, LIGO and VIRGO detectors have been decommissioned to install Advanced LIGO and Advanced Virgo
- GEO-HF to remain in astrowatch/commissioning
- Advanced LIGO construction will complete in 2014. Commissioning will commence, and first science runs in 2014-2015 at Hanford and Livingston.
- Advanced Virgo in Italy and KAGRA in Japan will also come on-line in the same time-scale.
- KAGRA will demonstrate 3rd generation techniques (underground operation, cryogenics). Observations to start in 2017
- The third Advanced LIGO detector will be installed not in Hanford but in India.

- The GW network will enable GW source location, increase detection confidence, ‘up time’, source parameter estimation from reconstructed waveform, and more sensitive searches.

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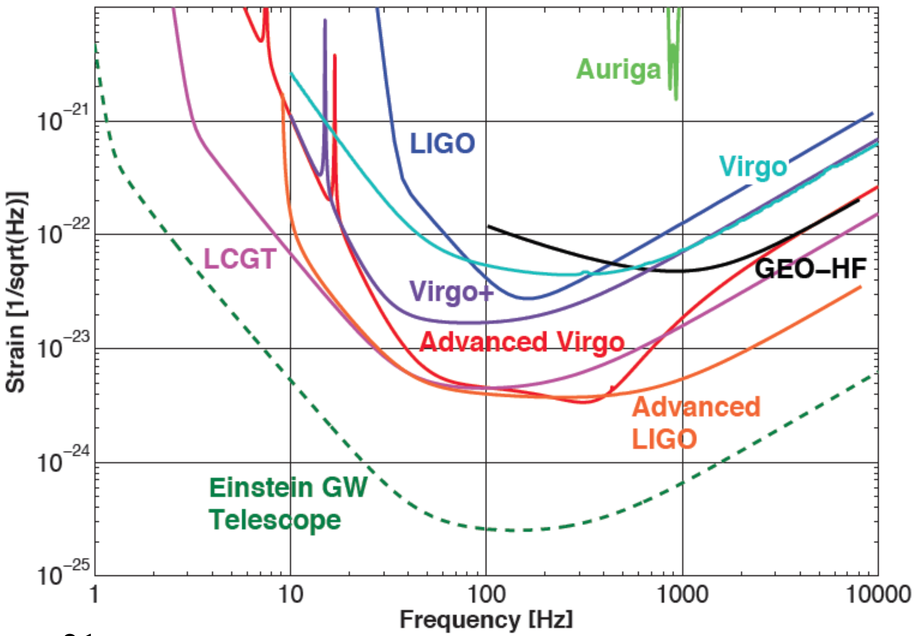
Einstein Telescope

- Einstein Telescope is a future third generation gravitational wave detector.
- ET is one of ASPERA's "Magnificent Seven" astroparticle physics large projects.
- It will be able to test GR in strong field condition and realize precision gravitational wave astronomy.
- The ET project just finished its conceptual design study phase, supported by the European Community FP7 with about 3M€ from May 2008 to July 2011.

Available at: http://www.et-gw.eu/etdsdocument

Expected ET Sensitivity



ET will observe radiation arising from:

- black hole collisions when the Universe was still in its infancy assembling the first galaxies
- neutron star collisions when star formation in the Universe was at its peak
- formation of black holes and neutron stars in supernovae and collapsars in the local neighbourhood
- stochastic backgrounds of cosmological and astrophysical origin

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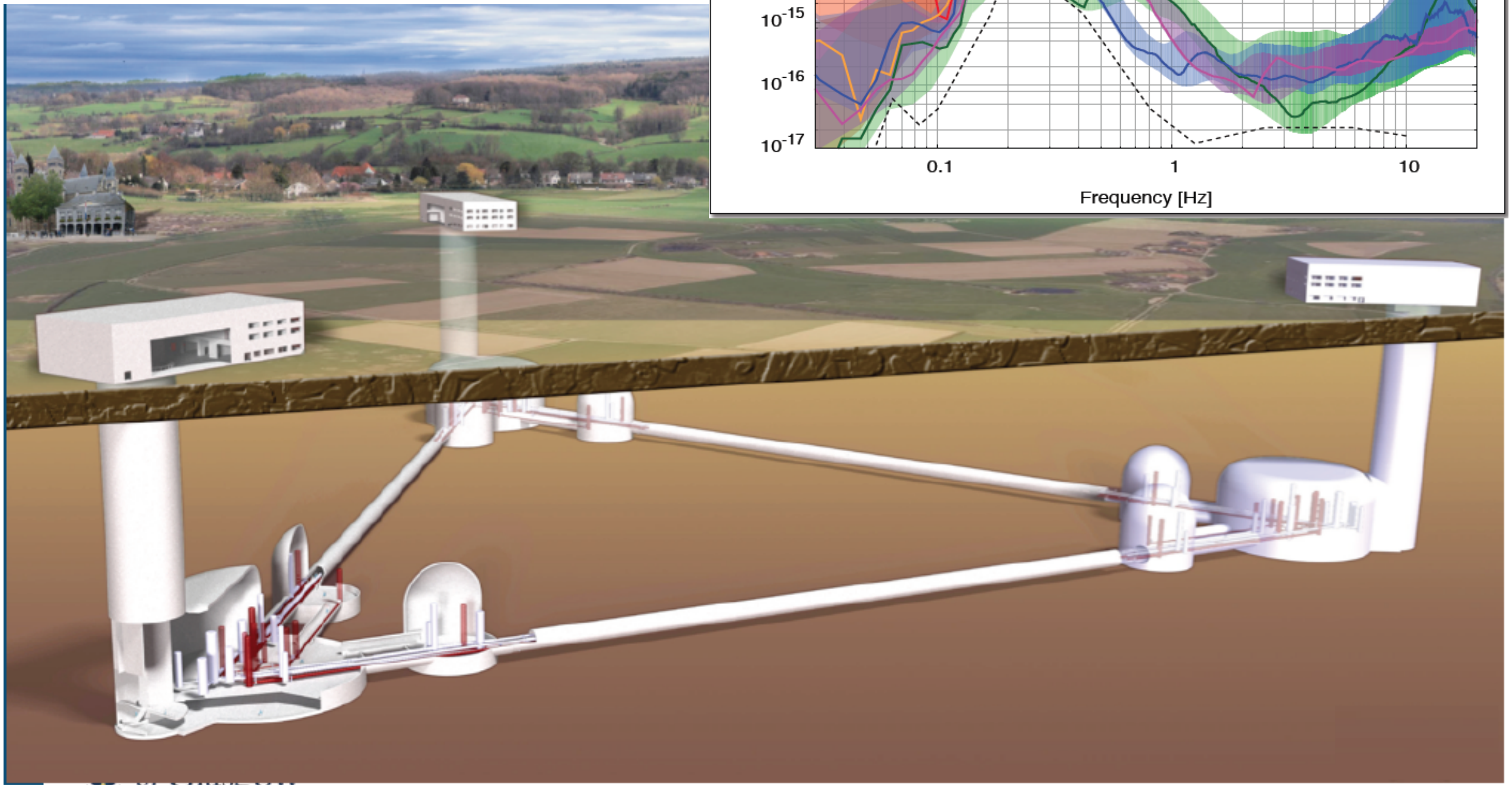
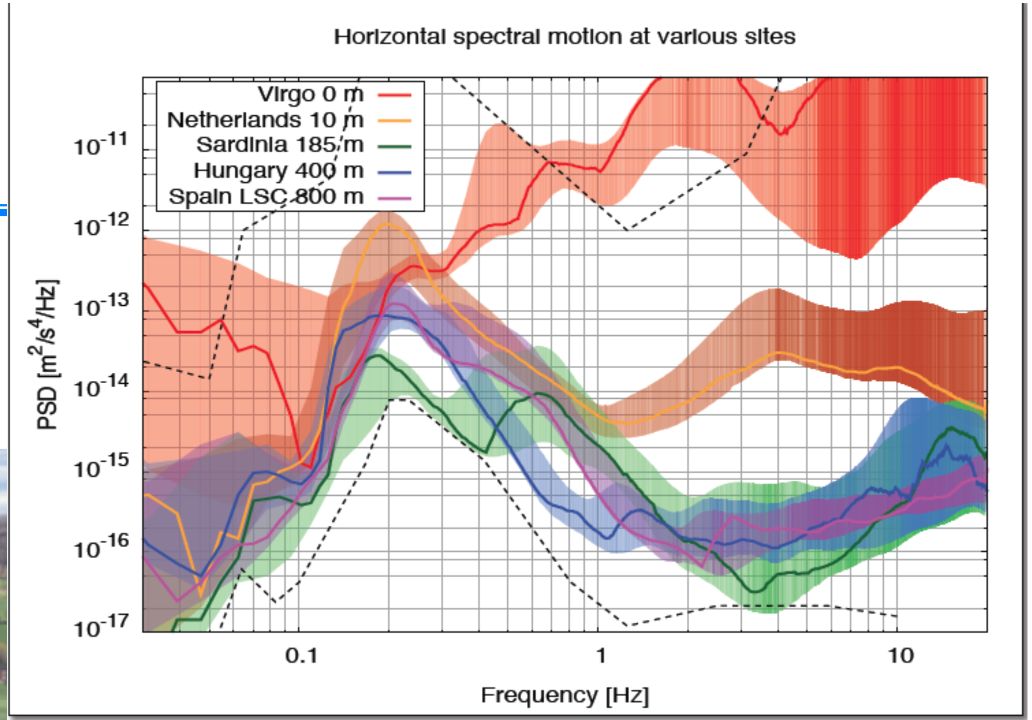
Artist's view of ET





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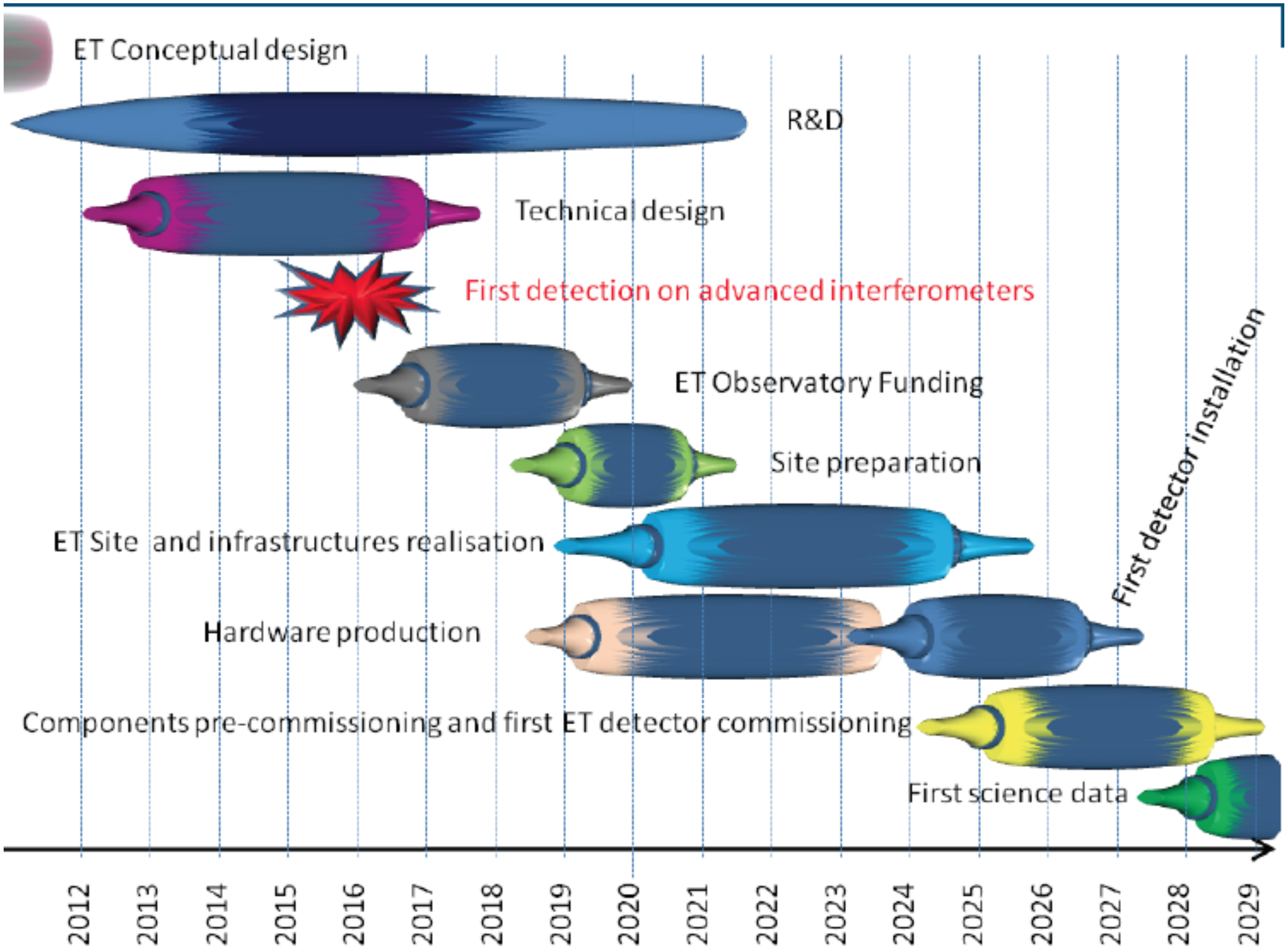
ET timeline



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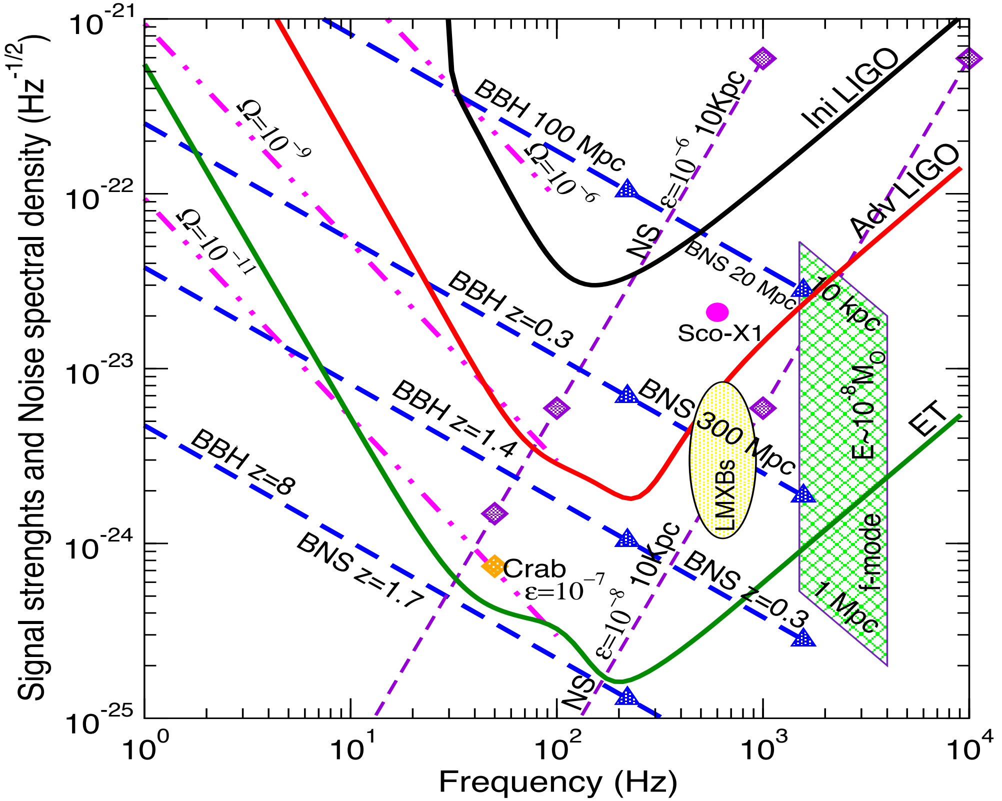
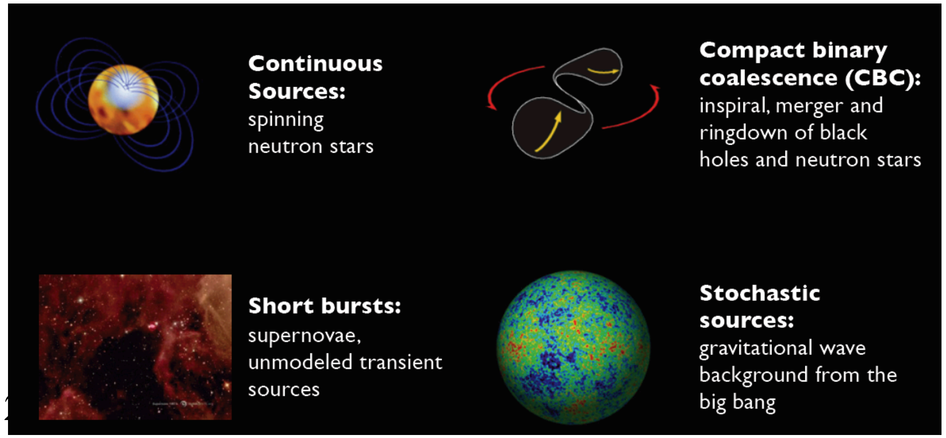
Sources for Ground Based Detectors

From Schutz & Sathyaprakash, Living Reviews in Relativity





Advanced LIGO (example):

Factor of 10 greater sensitivity than initial LIGO

Factor 4 lower start to sensitive frequency range

- ~10 Hz instead of ~40 Hz
- More massive astrophysical systems, greater reach, longer observation of inspirals

Intended to start gravitational-wave astronomy

NS-NS x10 better amplitude sensitivity

⇒ x1000 rate=(reach)^3

⇒ 1 day of Advanced LIGO

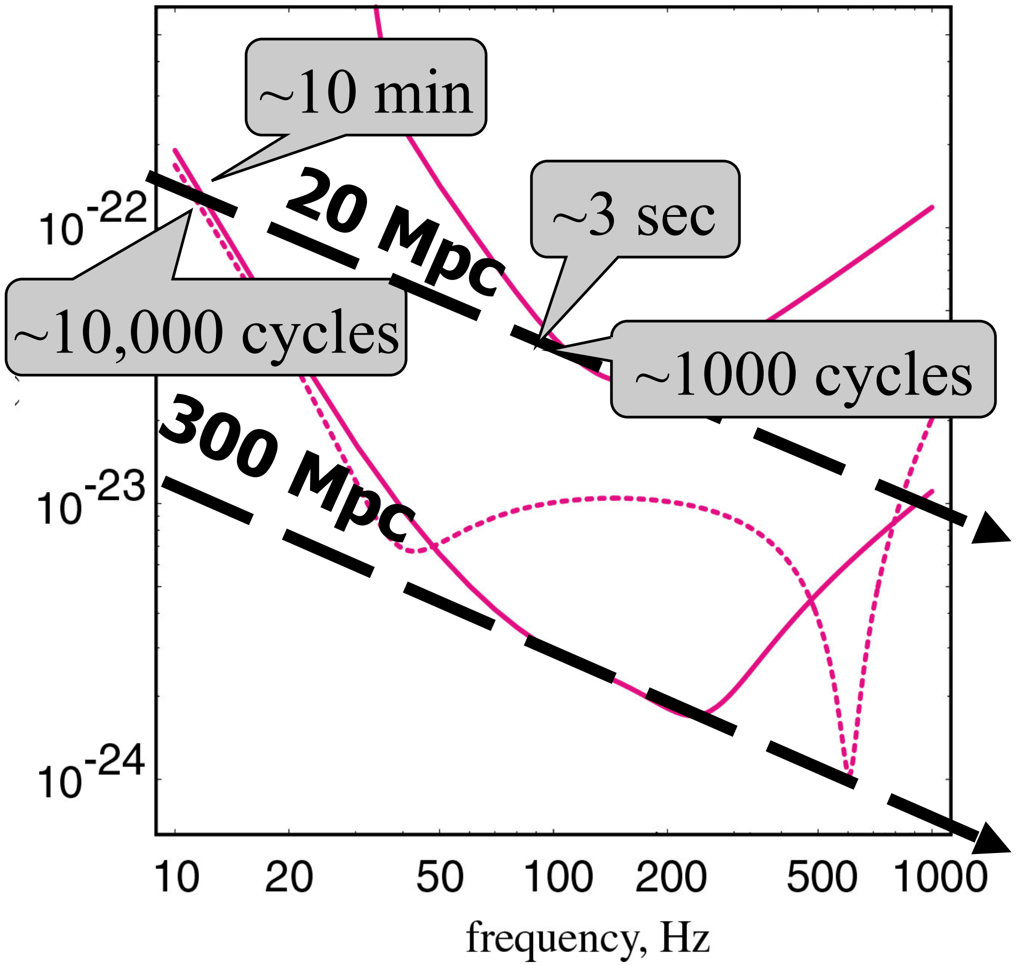
» 1 year of Initial LIGO !

- Frequent detections expected – exact rates to be determined, of course
  - Most likely rate for NS-NS inspirals observed: ~40/year

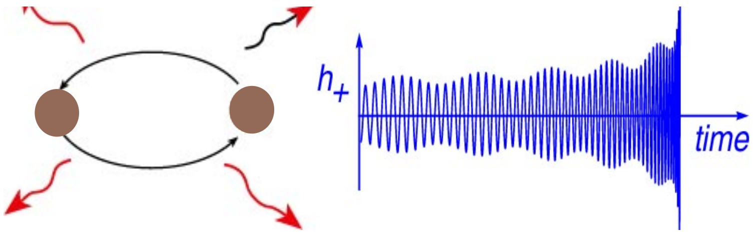
Neutron Star Binary Inspiral

NS-NS coalescence 'inspiral'

- Initial interferometers
  - Range: 20 Mpc
- Advanced interferometers
  - Range: 300Mpc



Signal shape very well known



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Matched filtering – A pattern matching technique

- Useful when the shape of the expected signal is known accurately
- Cross correlate the detector output with a copy of the expected signal
- In the absence of the expected signal the correlated output will be filtered noise with no particular time coherence
- In the presence of a sufficiently strong signal the correlated output will show a peak with time coherence

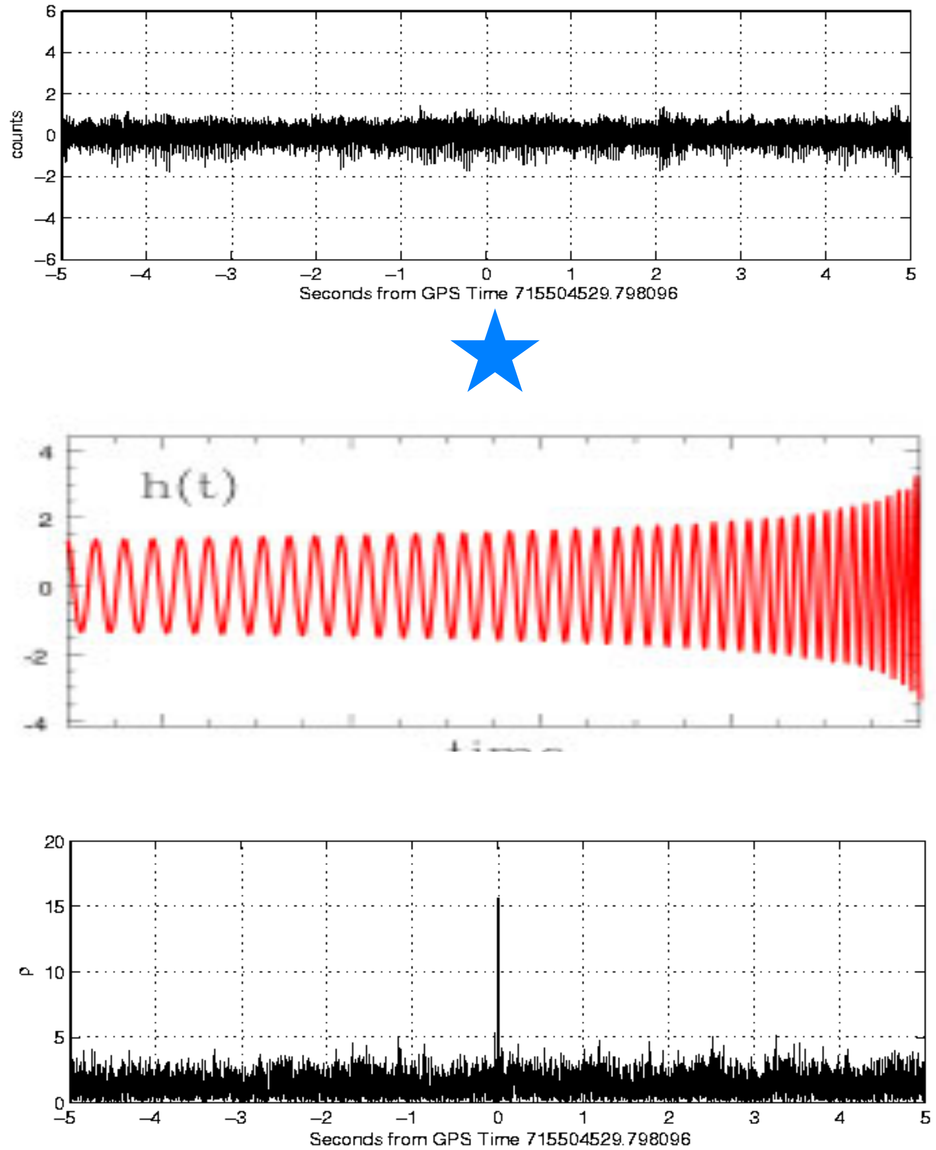
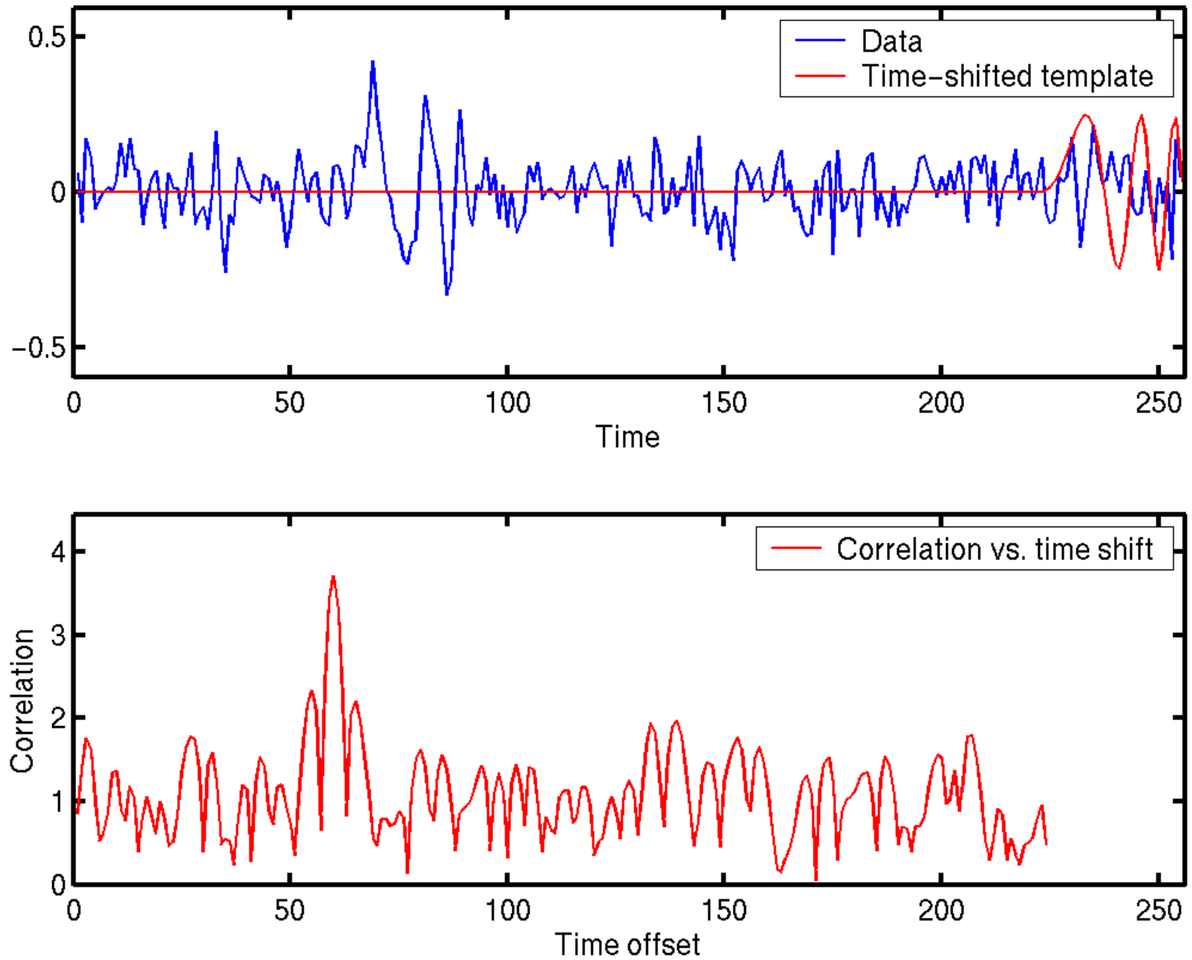


Illustration of “Matched Filtering”



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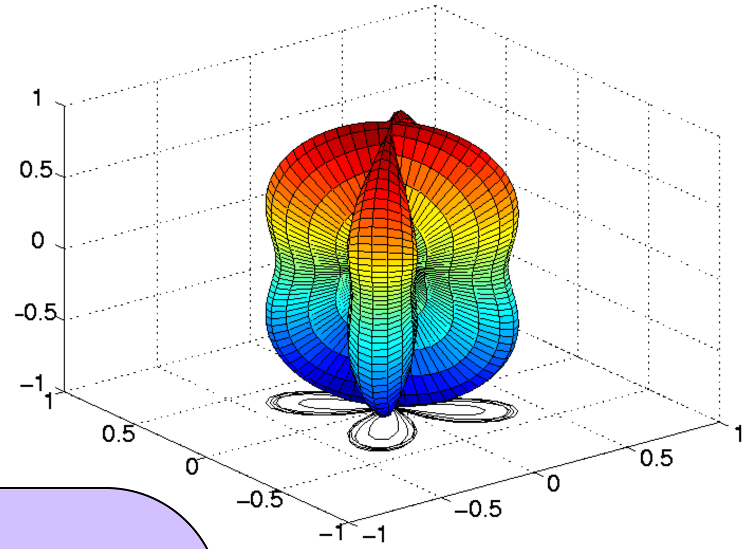
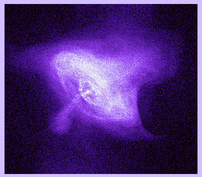
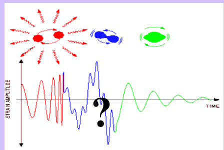
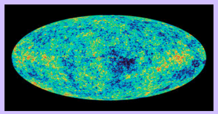
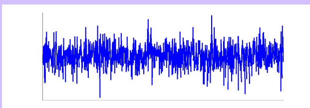
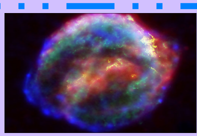
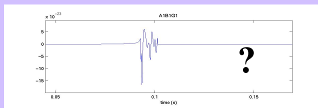
Why GW data analysis is challenging?

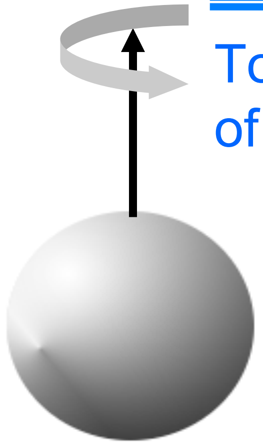
- All sky sensitivity
  - Quadrupolar antenna pattern
  - multiple detectors to determine direction to source
- Wide frequency band sensitivity
- Large data rates
  - Hundreds of instrumental and environmental channels
  - up to 10 MB per second from each detector
- Low event rates
- Large number of parameters and templates to search over



	Long duration		Short duration	
Matched filter	 	Crab pulsar (NASA, Chandra Observatory)		
Template-less methods	 	NASA, WMAP	 	NASA, HEASARC

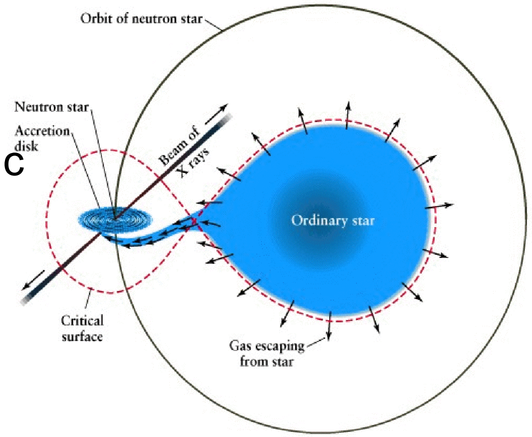
Sources and methods

Rapidly spinning neutron stars are a potential source of continuous GW



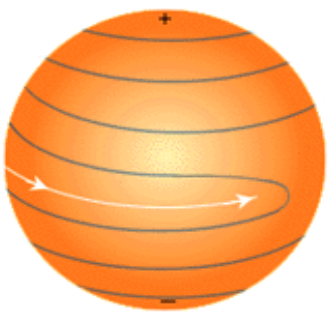
To emit CW they must have some degree of non axisymmetry:

- Deformation due to elastic stress or magnetic field;
- Free precession around rotation axis;
- Matter accretion from a companion star;

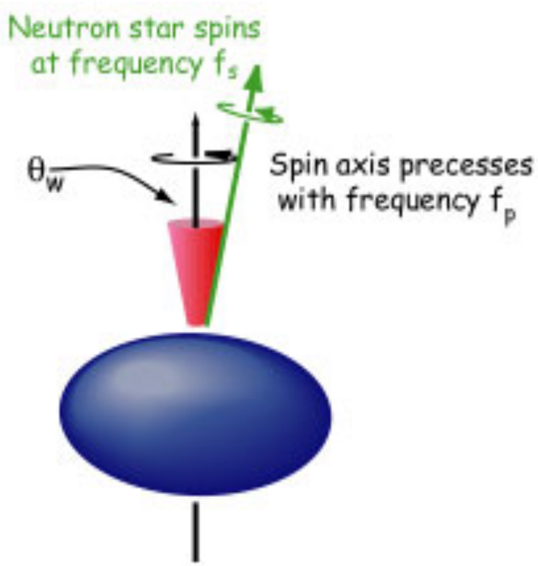


Bumpy Neutron Star

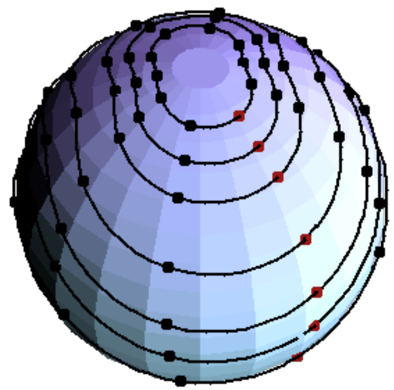
Low Mass X-Ray Binaries



Magnetic mountains



Wobbling Neutron Star



R-modes in accreting stars

- Gravitational waves from neutron stars could tell us about the equation of state of dense nuclear matter

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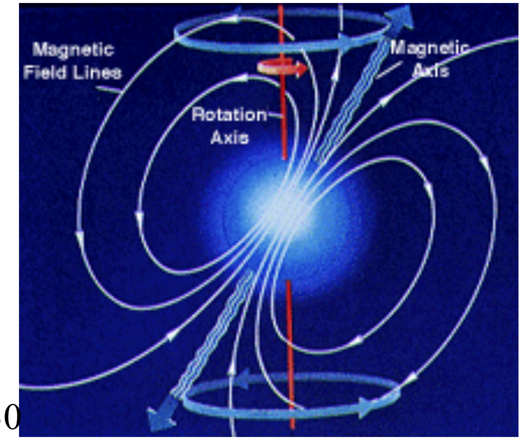
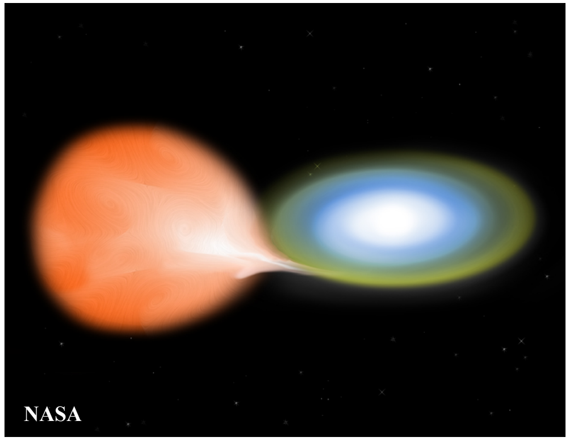
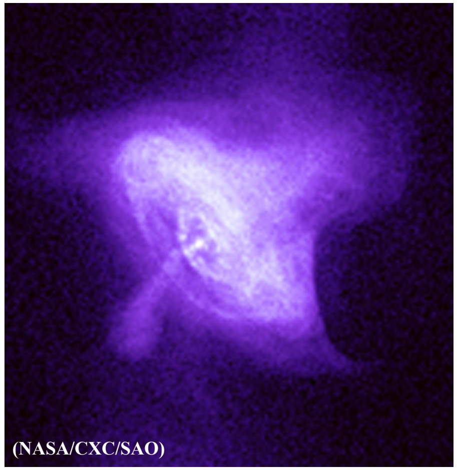
Exploring the galactic neutron star population with gravitational waves

- Our galaxy might contain ~10^9 NS, of which ~10^5 are expected to be active pulsars. Up to know ~2000 pulsars have been identified

- Different searches:
  - non-accreting known pulsars for which timing data is available;
  - non-accreting known stars without timing data;
  - unknown isolated stars;
  - accreting stars in known binary or stars in unknown binary systems.
- And for each of these we have to face a different data analysis challenge.
  - Most of the searches are computationally limited.
  - Directly constrained by astronomical observations.







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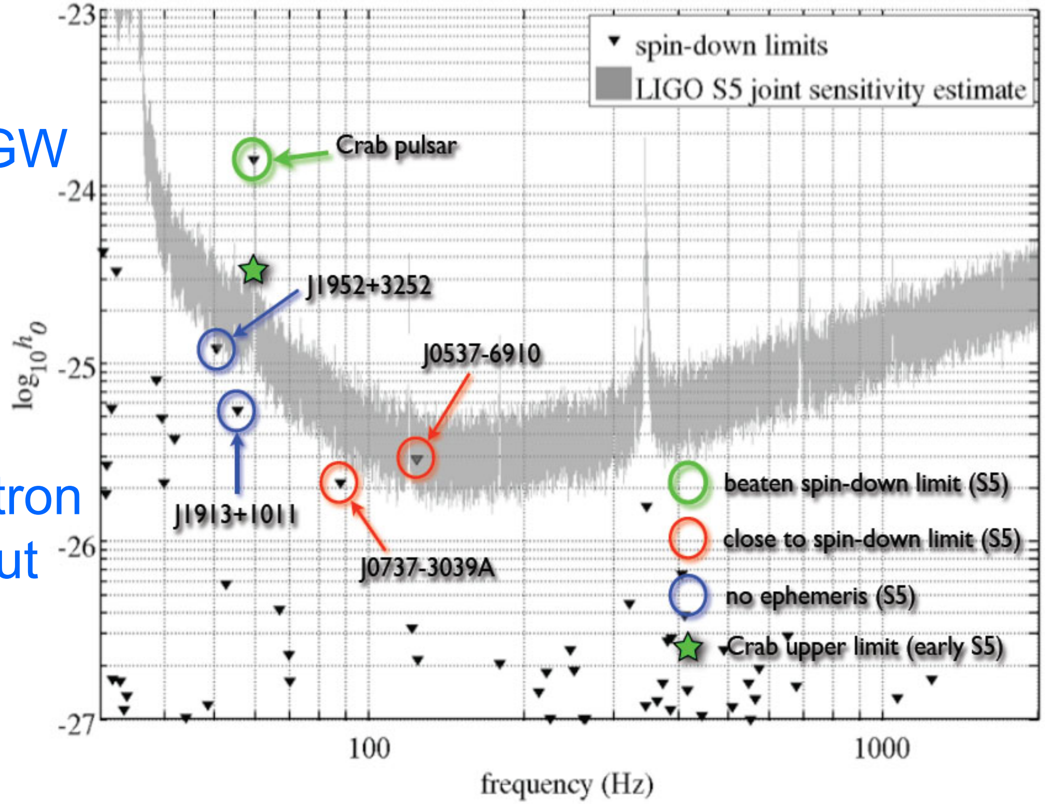
GW observations of neutron stars

- To date, LIGO and Virgo have not plausibly detected GW emissions from neutron stars (but analysis of existing data is ongoing).

- For 3 young neutron stars (Crab, Vela, Cassiopeia A), GW observations have placed more stringent limits than EM observations.

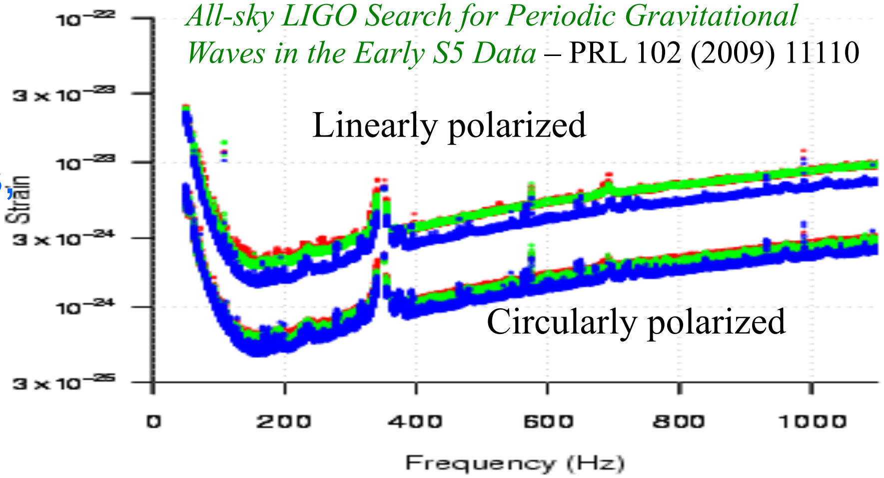
- Several broad-area searches have placed upper limits on GW fluxes from unknown neutron stars.

- Advanced detectors could plausibly detect Galactic neutron stars in the next five years (but no guarantees).

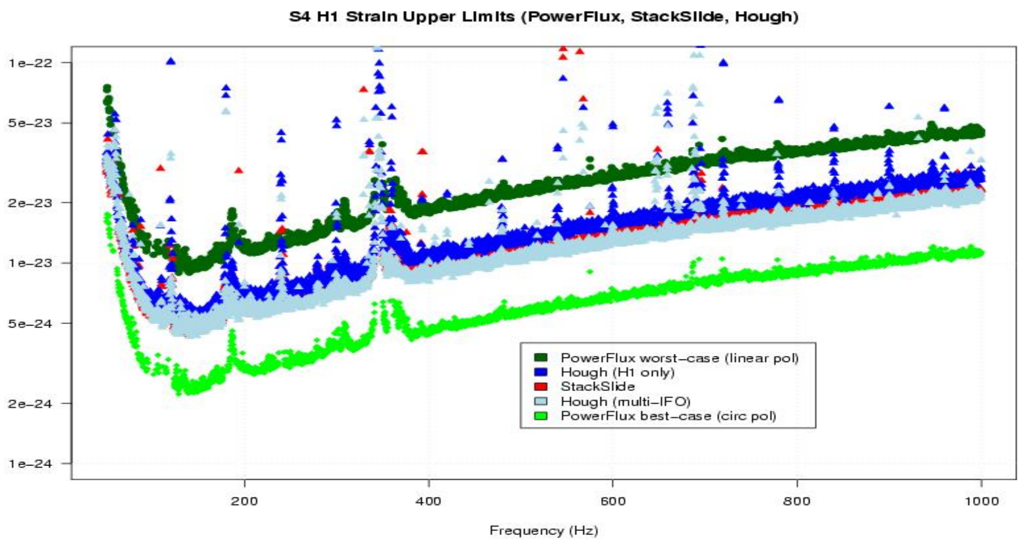


All sky surveys for isolated unknown NS

These are objects which have not been previously identified at all, and we must search over various possible sky positions, frequencies, and frequency derivatives. They are believed to constitute the overwhelming majority of neutron stars in the Galaxy.

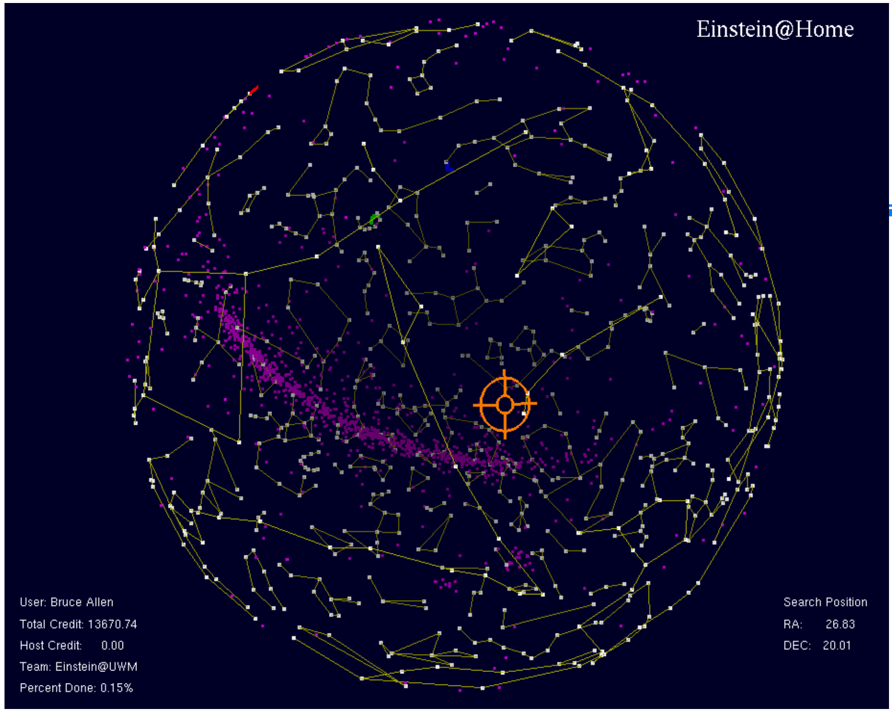


The parameter space for blind searches for weak signals from unknown isolated neutron stars is very large.

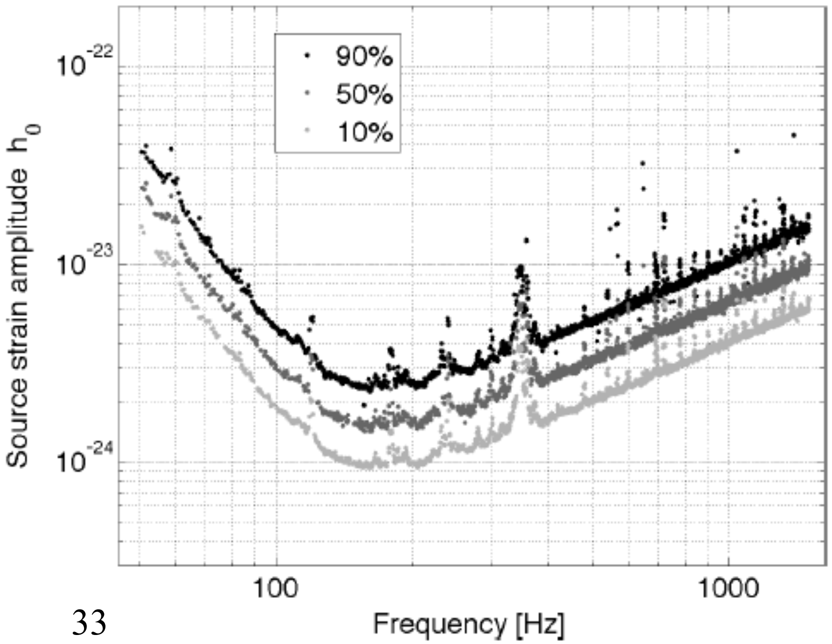


To probe full parameter space without restricting observation time, need to use semicoherent or incoherent methods. E.g., shift Fourier bins according to Doppler modulation & add power.

Different techniques have been designed, each optimized for a different portion of parameter space



http://www.einsteinathome.org/



Einstein@home

- Einstein@Home, a volunteer distributed computing project, where host home or office computers automatically download "workunits" from the servers,carry out analyses when idle, and return results.
- Distributed using BOINC & run as a screensaver
- 270.00 active users, 2x10^6 computers, 300Tflops.
- Since 2009, E@H looks for signals in Arecibo (Parkes) data, using 30% of the search time. Found several new pulsars

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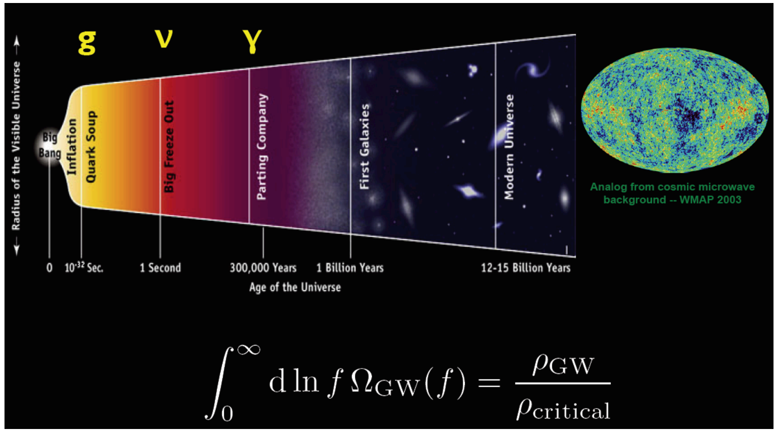
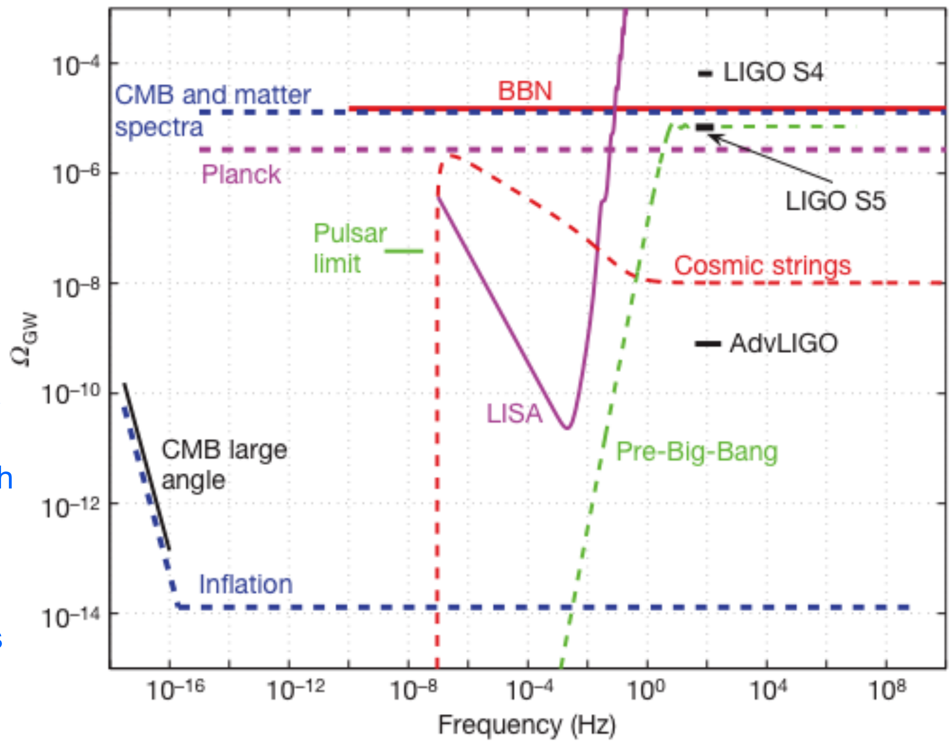
Cosmology Highlight

- A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved gravitational-wave sources of astrophysical and cosmological origin. Direct measurements of the amplitude of this background are of fundamental importance for understanding the evolution of the Universe when it was younger than one minute.



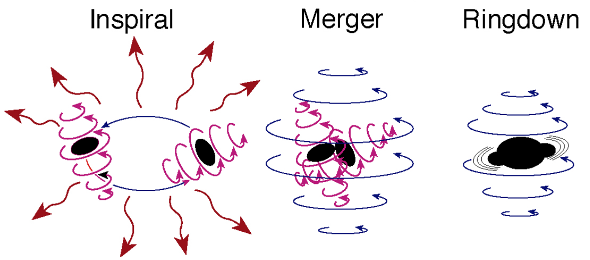
Comparison of different stochastic GW background measurements and models. *Abbott et al Nature **460 (2009)**.*

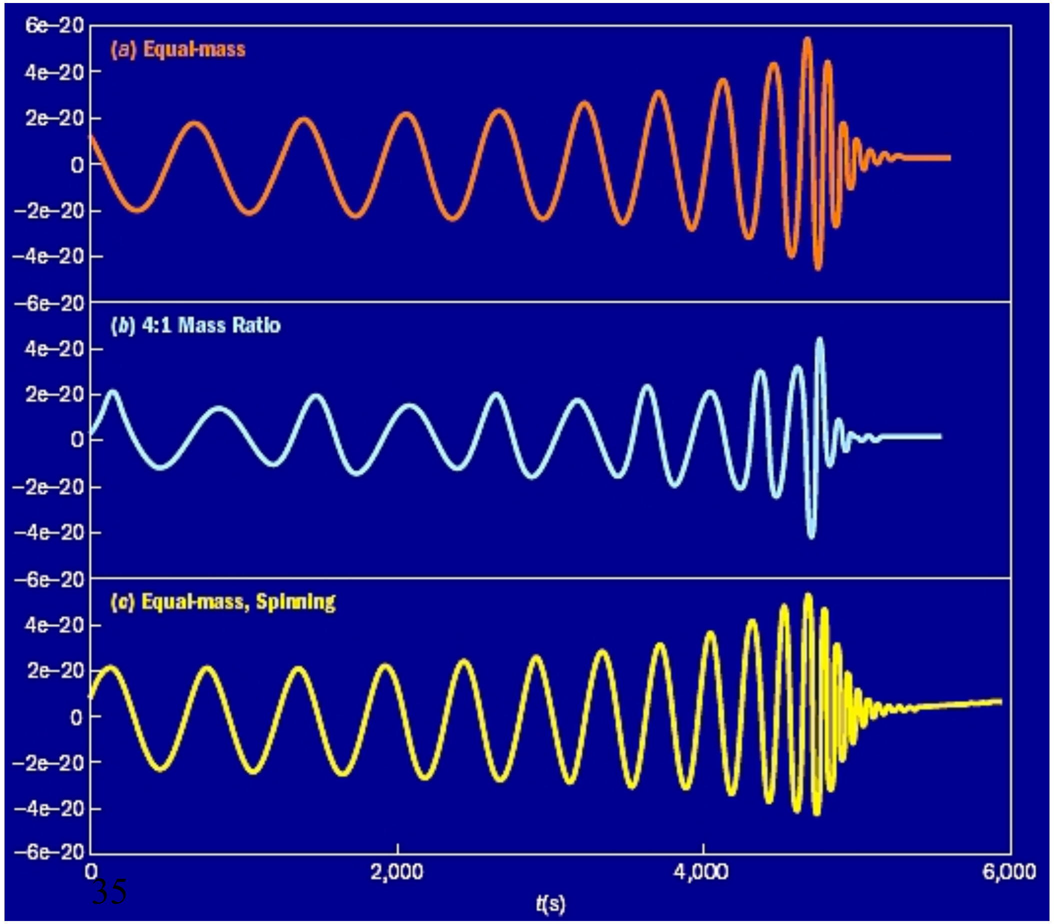


- LIGO S5 result constrains the energy density of the stochastic GW background of the Universe to be < 6.9 x 10^{-6} around 100 Hz, assuming a flat spectrum of GWs.
- The data rule out models of early Universe evolution with relatively large equation-of-state parameter, as well as cosmic (super)string models with relatively small string tension that are favoured in some string theory models.
- This search for the stochastic GW background improves on the indirect limits from Big Bang nucleosynthesis and cosmic microwave background at 100 Hz.

Compact binary inspiral, merger, ringdown

- Until not so long ago, data analysis methods for coalescing binaries had to rely on post-Newtonian approximations, which break down before merger, and perturbative ringdown signals.





By matching post-Newtonian and full-GR numerical relativity results, it is now feasible to construct "complete" waveforms describing the inspiral, merger and ringdown of compact binaries.

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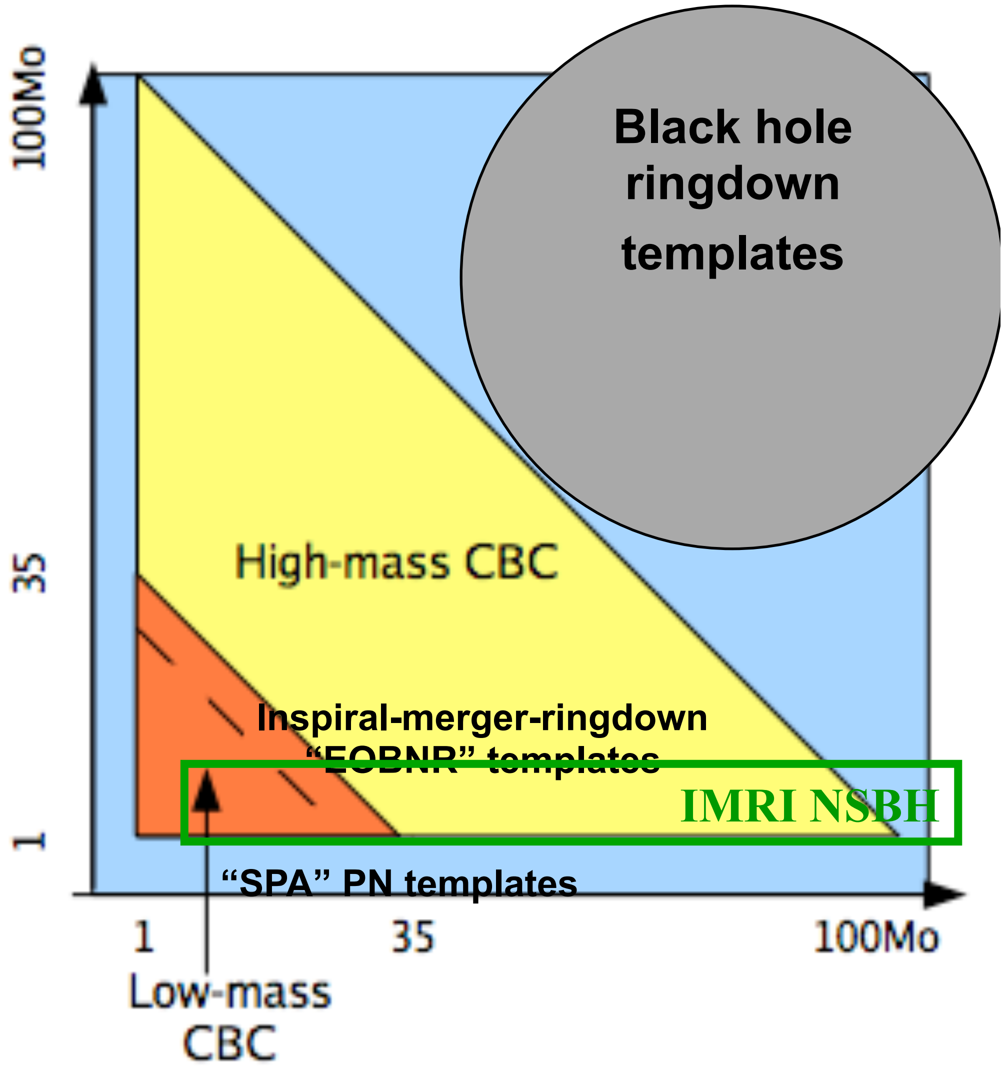
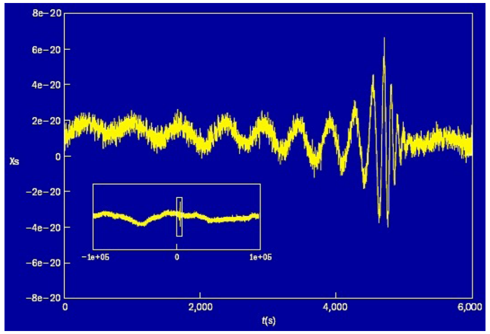
Mass space for template-based search

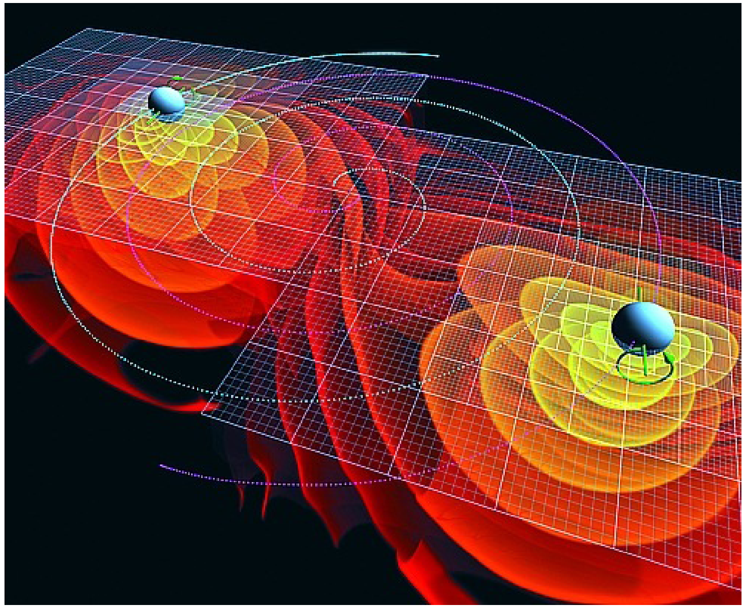
- The more massive the system, the lower the GW frequency at merger
- Binary neutron star (BNS) waveforms are in LIGO band during inspiral.
- Higher-mass Binary black hole (BBH) waveforms merge in-band
- Above ~100 M_{sun}, all LIGO can see is the merger and ringdown
- Spin will be important for the whole mass range in advanced detectors!



Accurate modeling of black hole binaries

- Group members played a crucial role in developing numerical models of the coalescensce of relativistic binaries in GR,
  - leading to a wealth of astrophysical relevant information, (recoil velocities after merger, final spins, final mass)
  - as well as modeling their GW emission to construct waveforms





- We are experts exploring the parameter space of binary BH coalescence with large scale numerical simulations.

- We use several million CPU hours per year through allocations at BSC and CESGA in Spain, LRZ Munich, the Vienna Scientific Cluster, DEISA Extreme Computing Initiative,PRACE, the TeraGrid (USA),…

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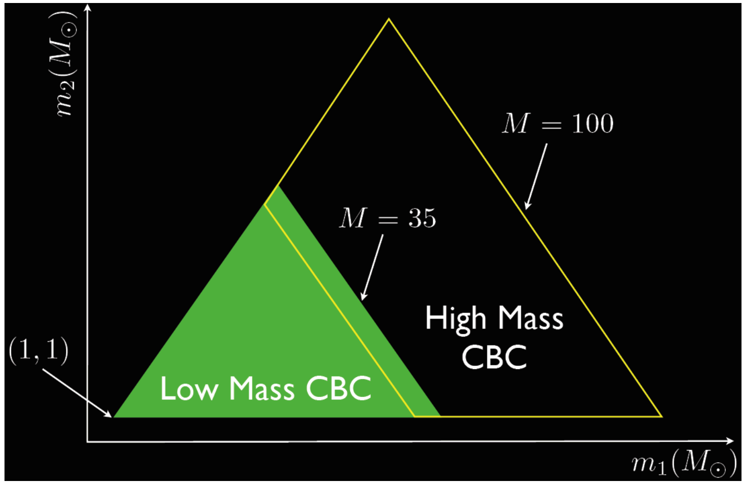
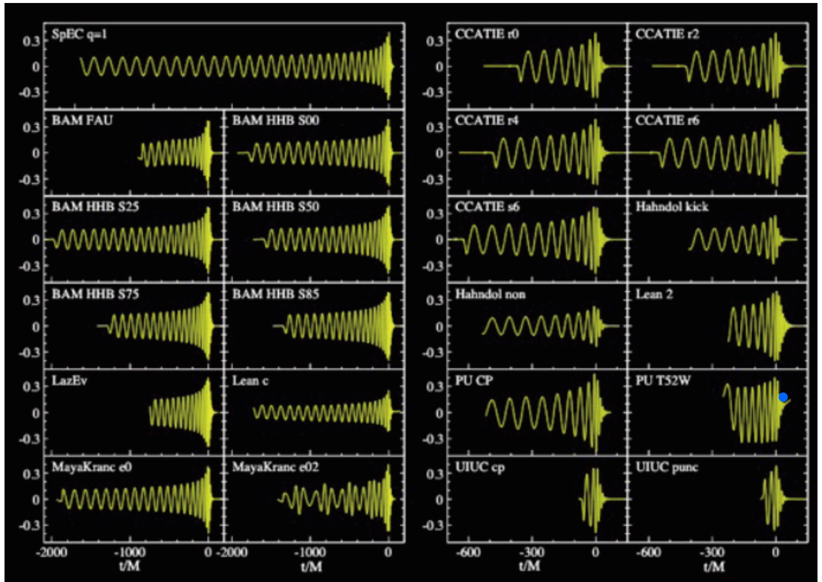
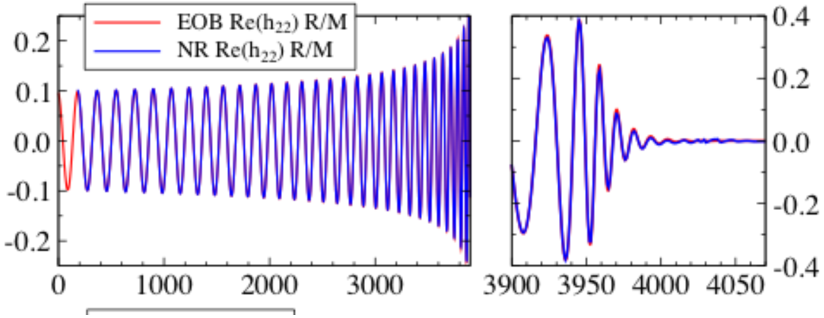
CBC searches





Aylott et. al. 2009 Class. Quantum Grav. 26 165008

We have several analytic families of waveform covering inspiral, merger, ringdown

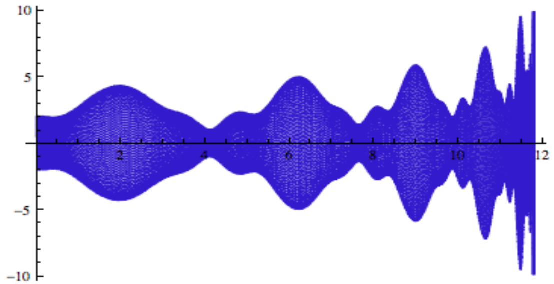


- Low mass search
  - Using non-spining and spining waveforms

Spin adds 6 extra dimensions to the parameter space, and precession of the orbital plane

First efforts focused on non-precessing waveforms

- Spins aligned with orbital angular momentum
- Analytic models of these waveforms are available

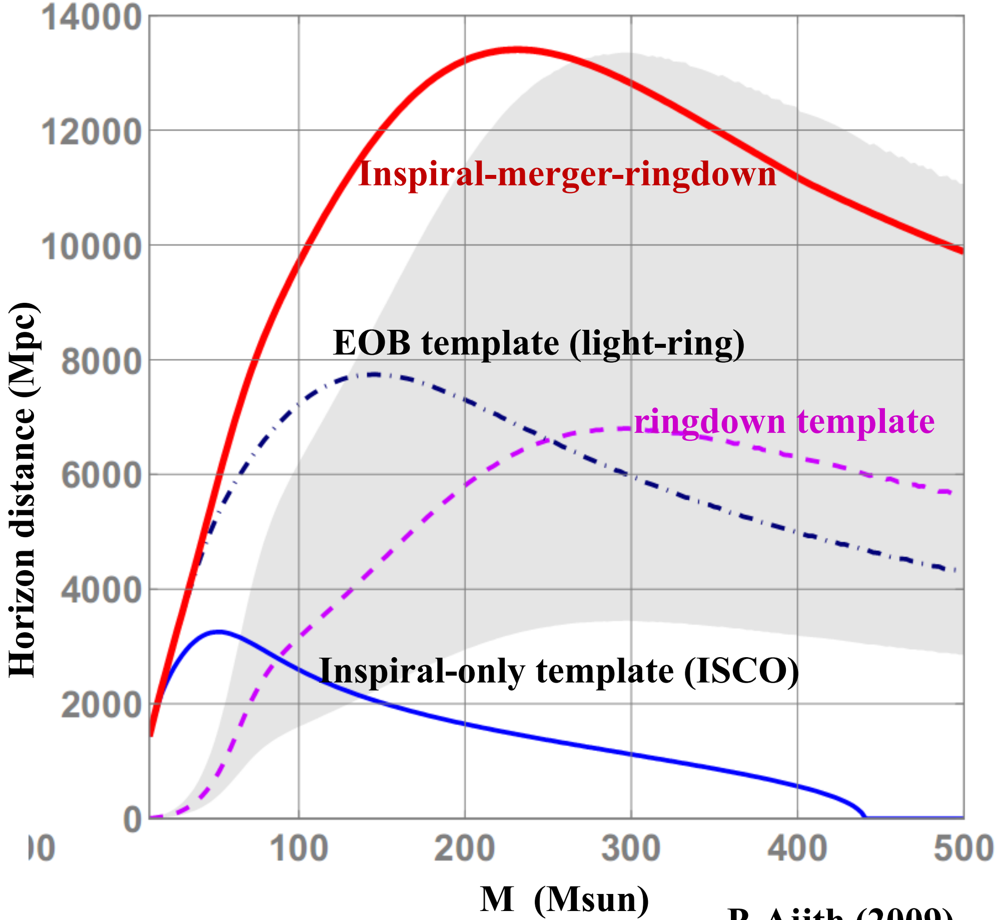


High mass search

- Major progress in numerical and analytical relativity has allowed us to use “complete” inspiral merger ringdown templates and extend search reach
- Search underway using these templates

Horizon distance & template banks for compact binary mergers

- Horizon distance: Distance in Mpc at which one Advanced LIGO detector can see an optimally-located, optimally oriented binary merger with an SNR=8, as a function of total mass.
  - Averaging over sky location and orientation degrades this by ~2.26.
- Important to use the right templates, including IMR, and spin effects!
- Results show that numerical simulations in full GR will have significant implications on detection rates and the accuracy of parameter estimation.
- To take full advantage of the increasing sensitivity of GW detectors:
  - need increasingly accurate source models and templates
  - need significant further advances in source modeling techniques.



P. Ajith (2009)

Interface NR - DA - AR

Generate "complete" BBH waveforms,

e.g., hybrid waveforms, constructed by matching PN and NR

Propose analytical template families which are very close to the "complete" BBH waveforms.
Explicitly parametrized in terms of the physical parameters of the system

Parameter estimation using the "complete" BBH waveforms

Inject numerical and/or hybrid waveforms into LIGO/VIRGO data.

Test of search pipelines

The Numerical INJection Analysis (NINJA) Project

- Collaboration between simulators and searchers
  - Simulate a population of binary black hole signals from contributed waveforms
  - Testing GW search sensitivity to BH waveforms
  - Both detection and parameter estimation
  - Make use of real detector data
  - www.ninja-project.org

The NR-AR Project

- Collaboration between numerical and analytical relativity
  - Produce accurate NR waveforms covering large fraction of parameter space, including BBH with generic spins
  - Develop and calibrate analytical families of templates: Phenom, EOB, PN- Phenom…

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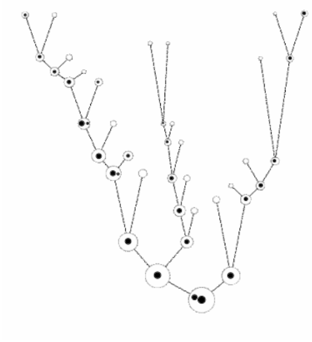
Astrophysical science with binary mergers

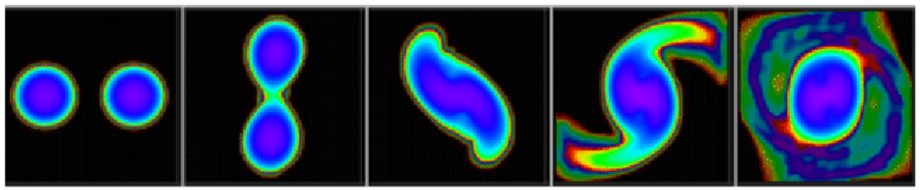
- Merger rates as function of mass, mass ratio, spin
  - Establish existence of black hole binaries
  - Neutron star mass distribution
  - Black hole number, mass, spin and location distribution
  - Search for intermediate-mass black holes
- Inform / constrain astrophysical source distribution
  - Extract population synthesis model parameters.
  - Binary formation and evolution history
  - Explore hierarchical merger scenarios

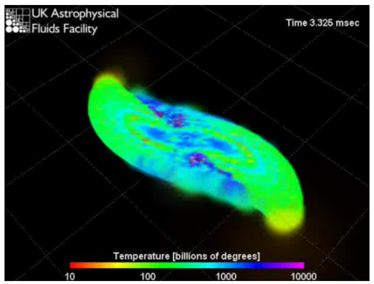


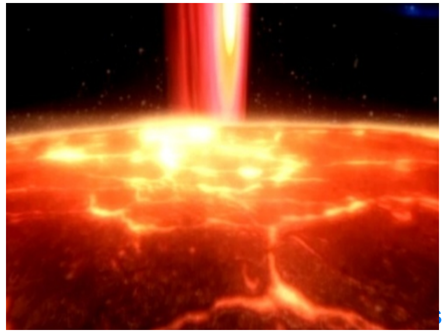
ciera.northwestern.edu/rasio

- Study matter effects in waveform: tidal disruption, NS EOS.

• Neutron star – neutron star (Centrella et al.)



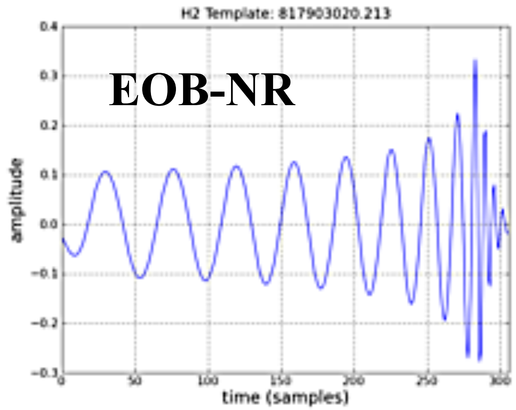




Testing GR

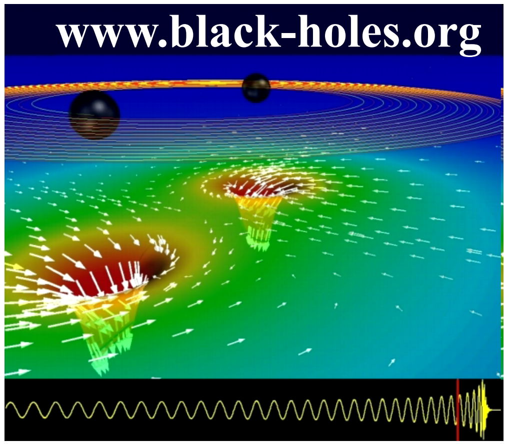
- Test post-Newtonian expansion of inspiral phase.

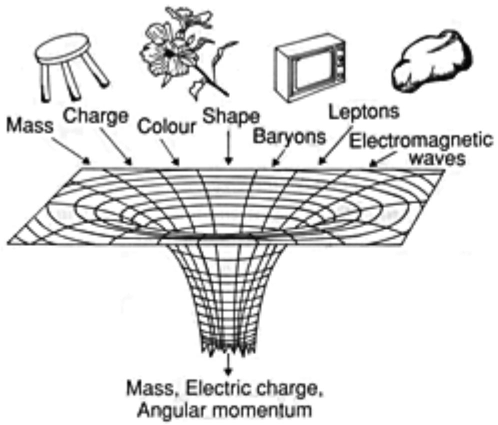
$$\Psi(f) \equiv 2\pi f t_0 + \varphi_0 + \frac{3}{128\eta v^5}\left(1 + \sum_{k=2}^{7} v^k \psi_k\right).$$



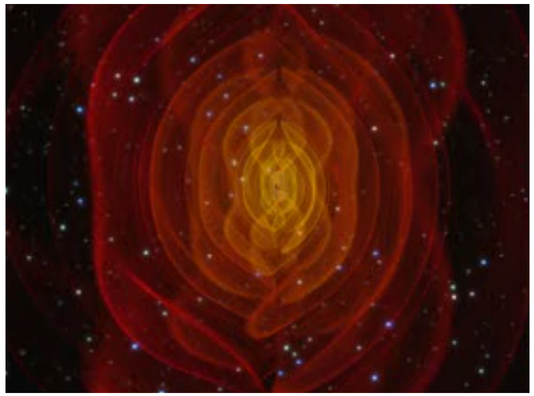
- Test NumRel waveform prediction for merger phase.

- Test association of inspiral and ringdown phases: BH perturbation theory, no-hair theorem.





nonlocal.com/hbar/blackholes.html



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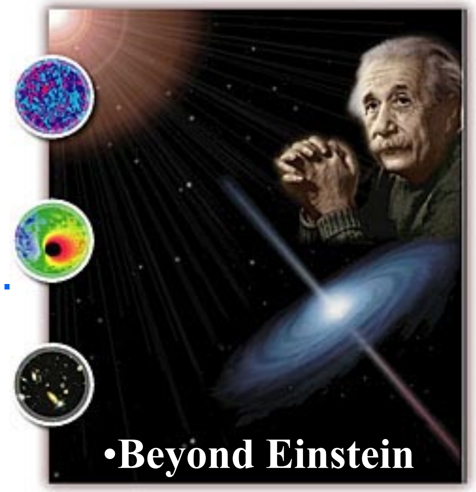
Testing beyond-GR



- Constrain beyond-GR parameters (Will, 2006)
- Directly measure speed of gravitational waves, constrain (or measure) the mass of the graviton.
- Constrain (or measure) longitudinal or other polarizations.
- Constrain (or measure) parity-violating effects in wave generation/propagation (Yunes et al, 2010).
- Constrain "parameterized post-Einsteinian framework" (Yunes & Pretorius, 2009)
- Test specifically for scalar-tensor and other alternative-gravity theories

- If there are surprises, it will affect our ability to detect!
  – The "chicken and egg problem" - Be prepared

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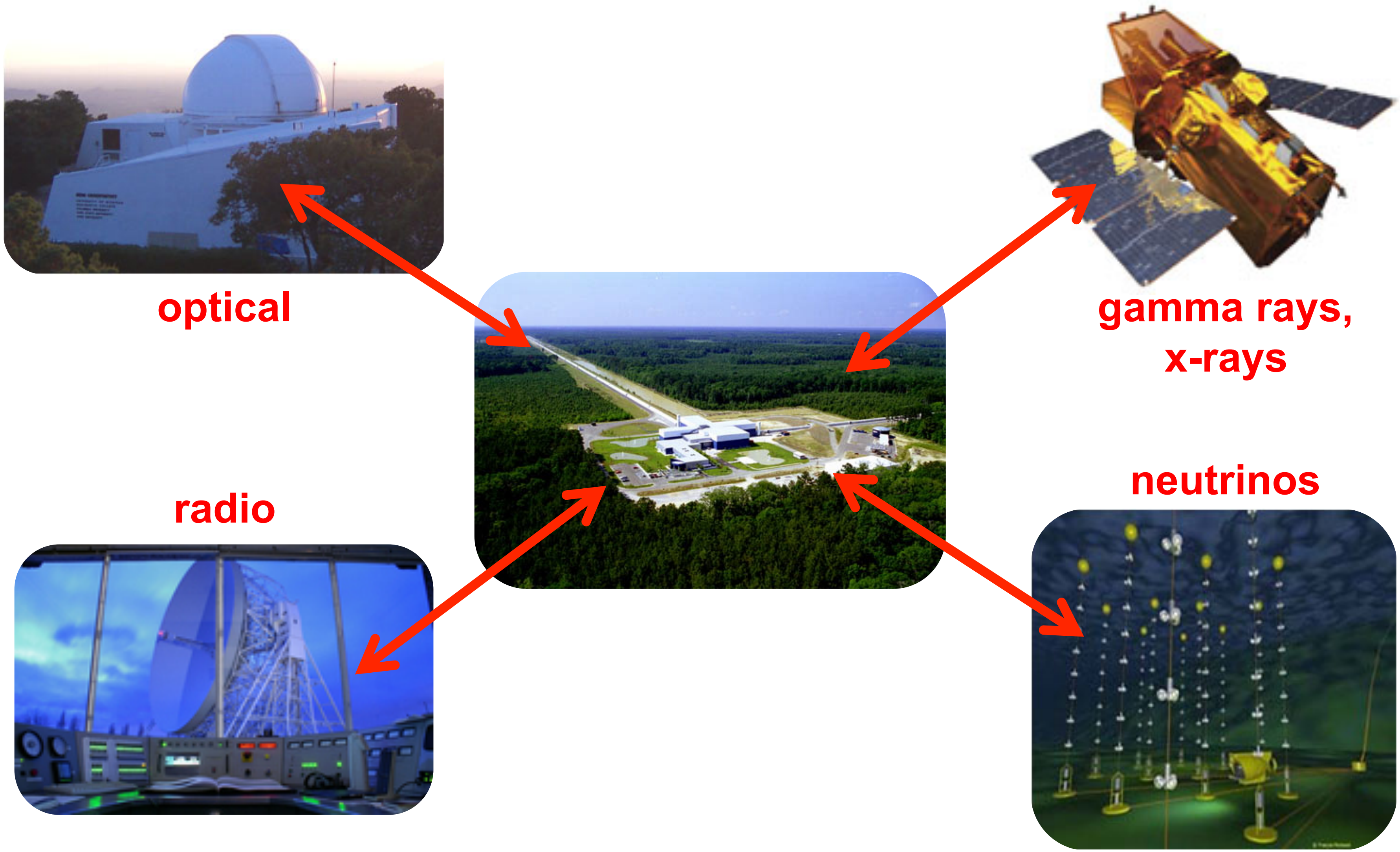
LIGO-Virgo is fully engaged in multi-messenger astrophysics



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GW and EM Multi-messenger Astronomy

Gravitational Waves:

- Bulk motion dynamics
- Binary parameters
- Direct probe of central engine
- Progenitor mass
- GW energetics
- Luminosity distance

Light Curve & Spectrum:

- Precise sky location
- Host galaxy
- Gas environment
- Progenitor star
- EM energetics
- Red shift

more complete picture of progenitor physics

•Short-hard GRBs:

- **Confirm (or rule out) merger progenitor**
- **Study progenitor systems, including orientation and beaming**
- **Relate GW and EM energy release**
- **Relate merger parameters to hosts (metallicity, SFR, …)**

Combining these observations will also

- increase detection confidence,
- allow a measurement of the local Hubble constant, a(z), dark energy EoS

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The flow of information

- EM triggers ⇒ GW detector analysis
  - From, eg, space-based X-ray and gamma ray telescopes
  - Knowing precise time and sky location of event reduces noise contamination in GW detector network; searches can go deeper
- GW detections ⇒ Pointing EM telescopes
  - To catch prompt emission, must point quickly
  - requires development of low-latency GW detection and sky localization pipelines, protocols to pass info, telescope scanning strategies and coordination

- GW detections + all-sky telescopes
  - Eg, neutrino detectors, optical transient surveys, wide-field radio transient surveys
  - Can be done offline, using data “in the can” – “data mining”
- Prototypes for all of these paths have been developed; they need to be flawless and ready in 2015!

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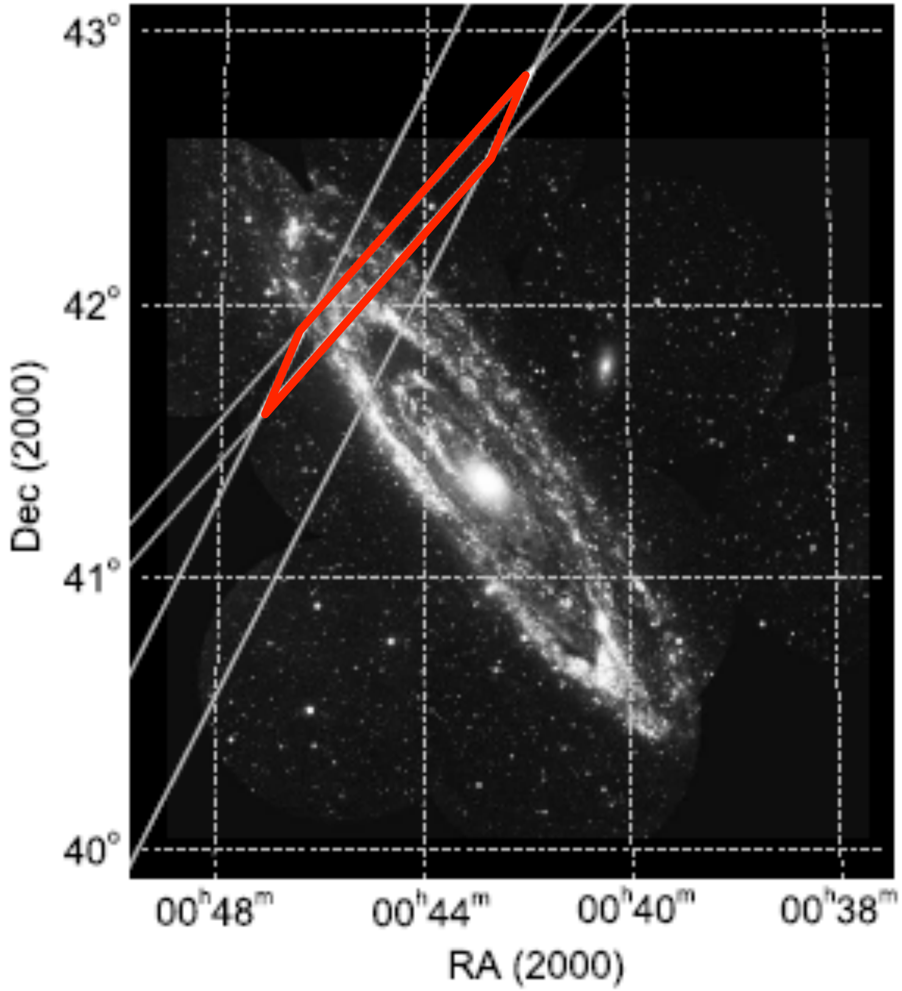
GRB 070201: In M31 or beyond? GRB or soft gamma repeater (SGR)?

- **EM Observations - GRB 070201**
  Described as an *"intense short hard GRB"* (GCN 6088)
- **detected by Konus-Wind, INTEGRAL, Swift, MESSENGER**
  - Duration ~0.15 seconds, followed by a weaker, softer pulse with duration ~0.08 seconds
  - R.A. = 11.089 deg,
    Dec = 42.308 deg,
    error = 0.325 sq. Deg
  - **E_{iso} ~ 10^{45} ergs if at M31 distance** (more similar to SGR energy than GRB energy)

- short GRB whose position error box overlapped with spiral arms of Andromeda galaxy (M31, ~770 kpc)
- occurred during LIGO S5 run; two Hanford interferometers were in science mode

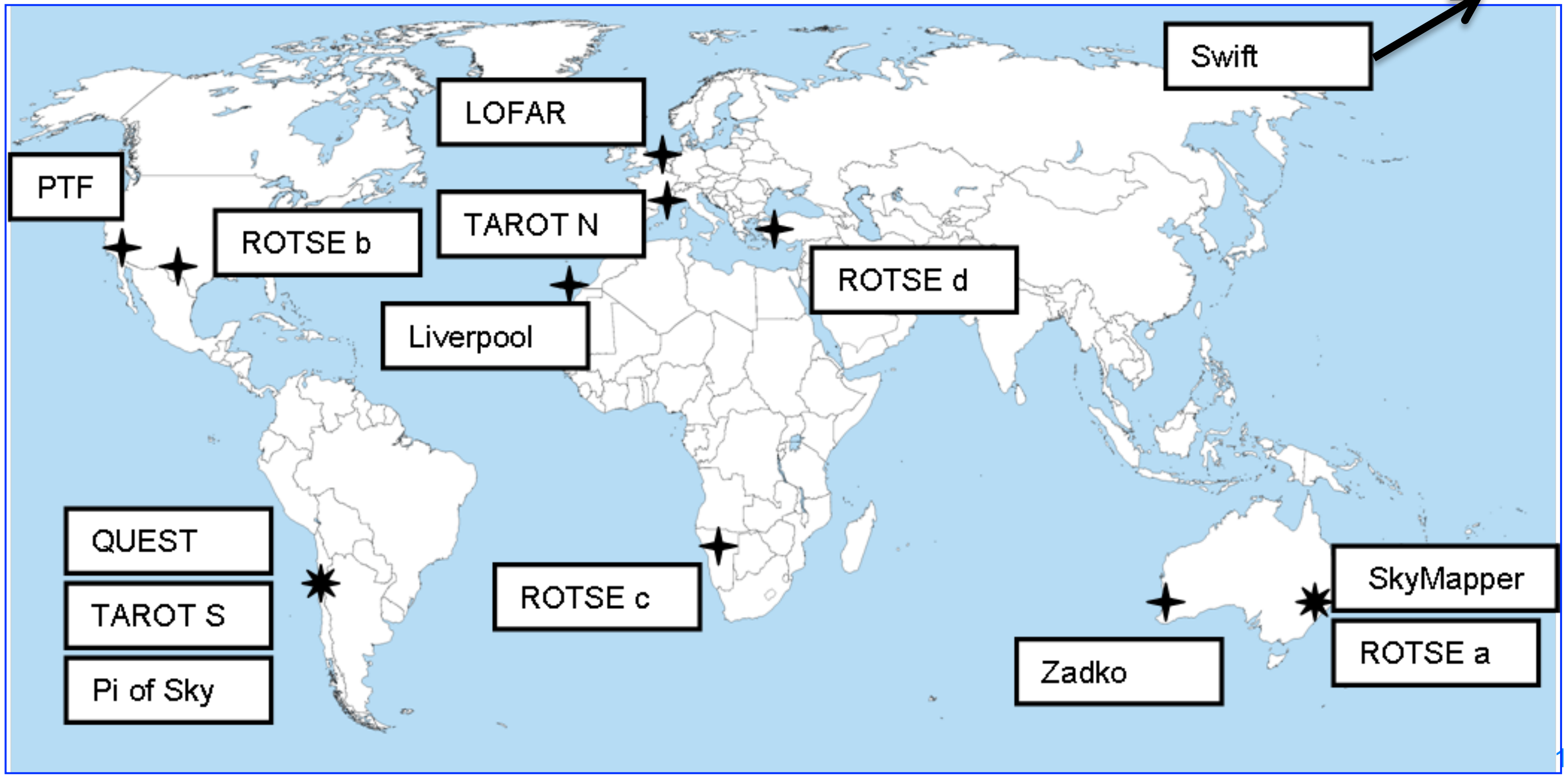
- inspiral search analysis excludes binary merger event at M31 with >99% confidence; larger distances also excluded with high confidence
- burst search analysis gives upper limits on GW energy released; these limits do not exclude a model of a soft gamma repeater in M31 (ApJ, 2008, 681, 1419)

(arXiv:0712.1502)



Telescope Network

- LIGO and Virgo partnered with rapid-pointing telescopes for observation run in summer and fall of 2010.
- Total of 14 triggers sent out (FAR < ¼ d), 8 followed up.
- Image analysis in progress, participation by LIGO and Virgo scientists.
- Also Swift (one event) and LOFAR radio array (commissioning during run).



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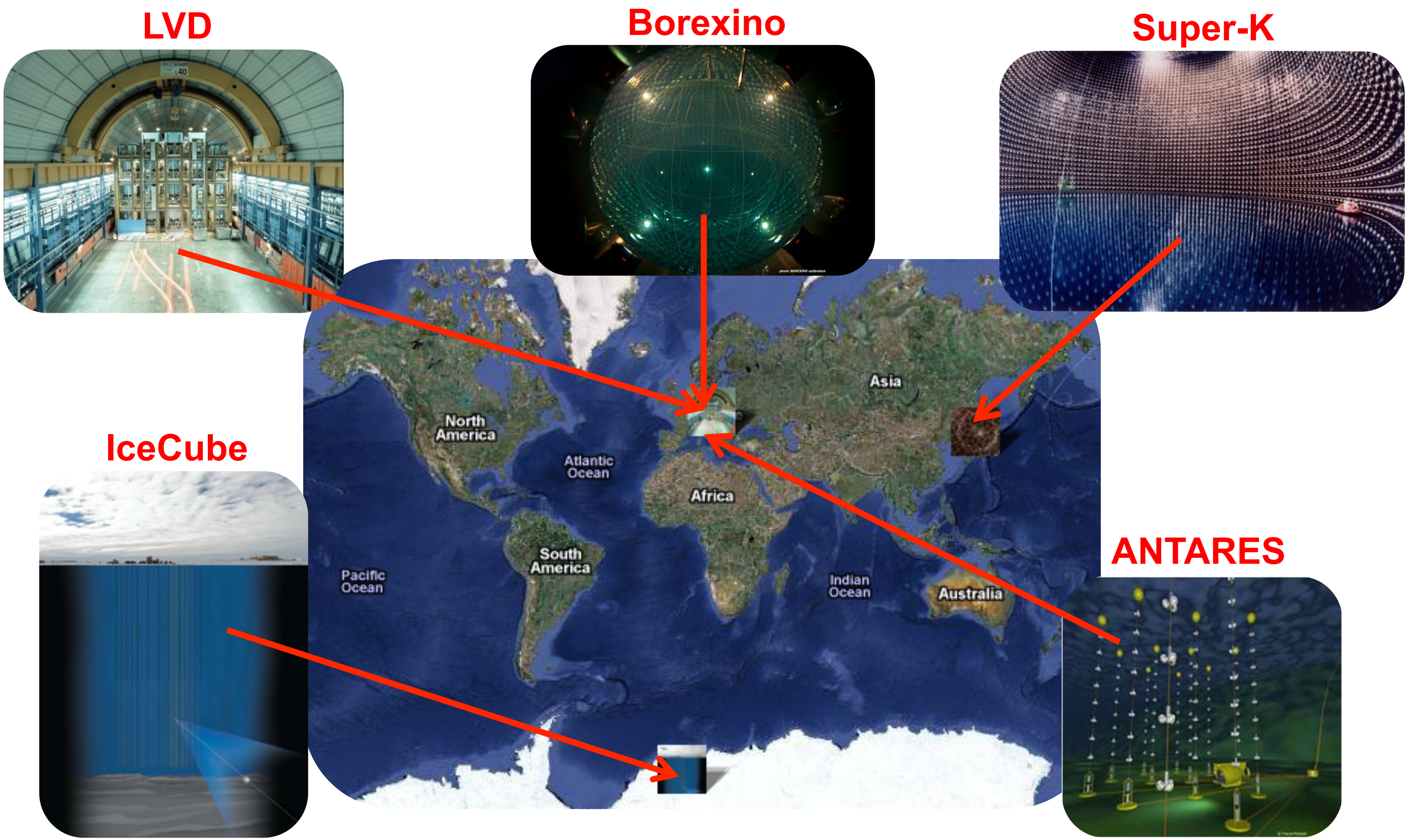
Gravitational waves and neutrinos
(nascent collaborations)



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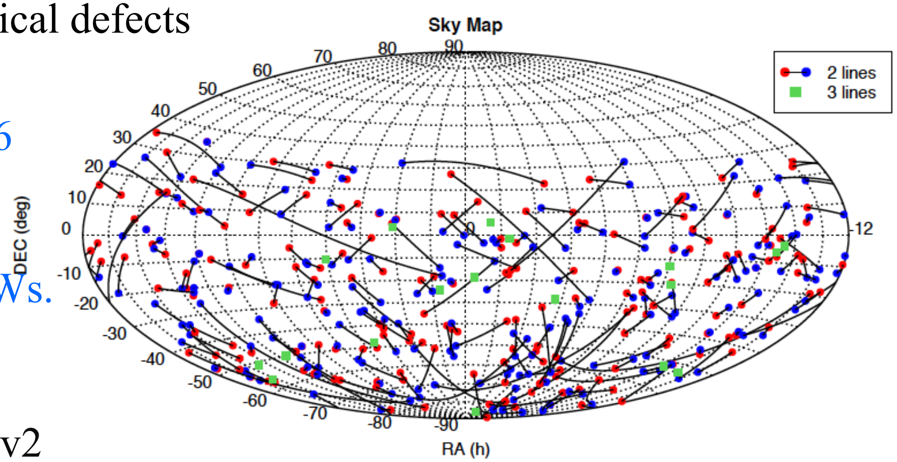
A First Search for coincident GWs and HENs using LIGO, Virgo and ANTARES data from 2007

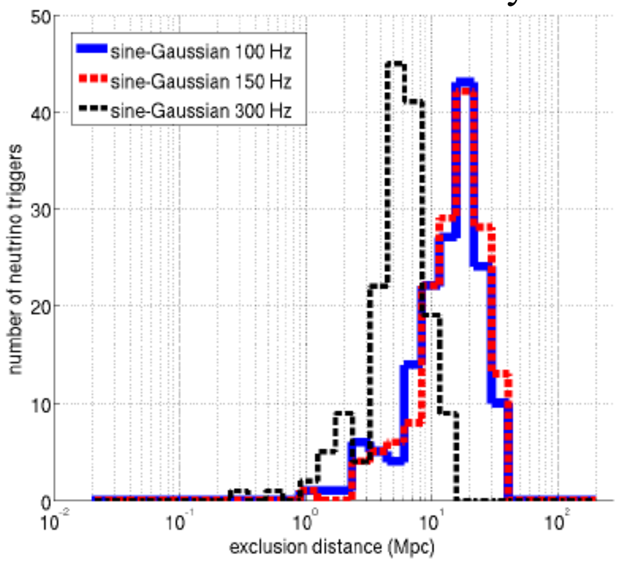
Several known astrophysical sources are expected to produce both GWs and HENs:
- Plausible galactic sources of joint emission are Soft Gamma Repeaters (SGRs)
- One of the most interesting extragalactic sources are gamma-ray bursts (GRBs)
- Other sources include: cosmic strings and topological defects

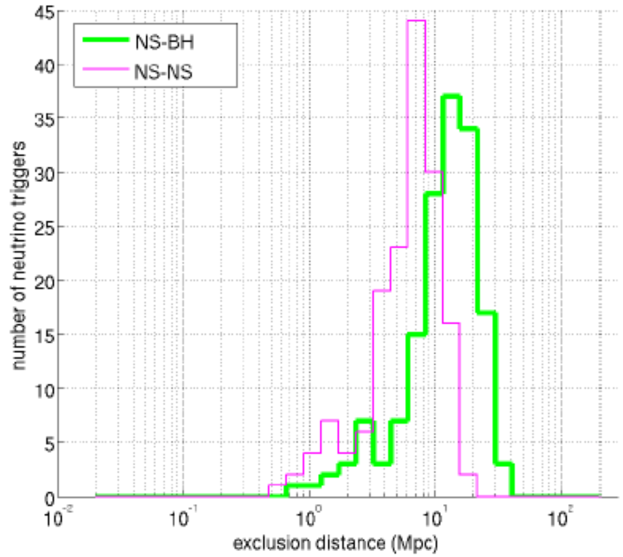


ANTARES (operating with 5 active lines) selected 216 potential neutrino events. LIGO-Virgo exploited the knowledge of the time and possible directions of the neutrino event to improve the search sensitivity for GWs.

No coincidences were found.

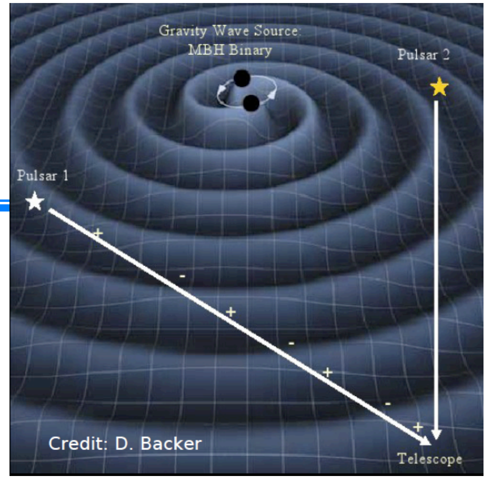
17 May 2012 arXiv:1205.3018v2



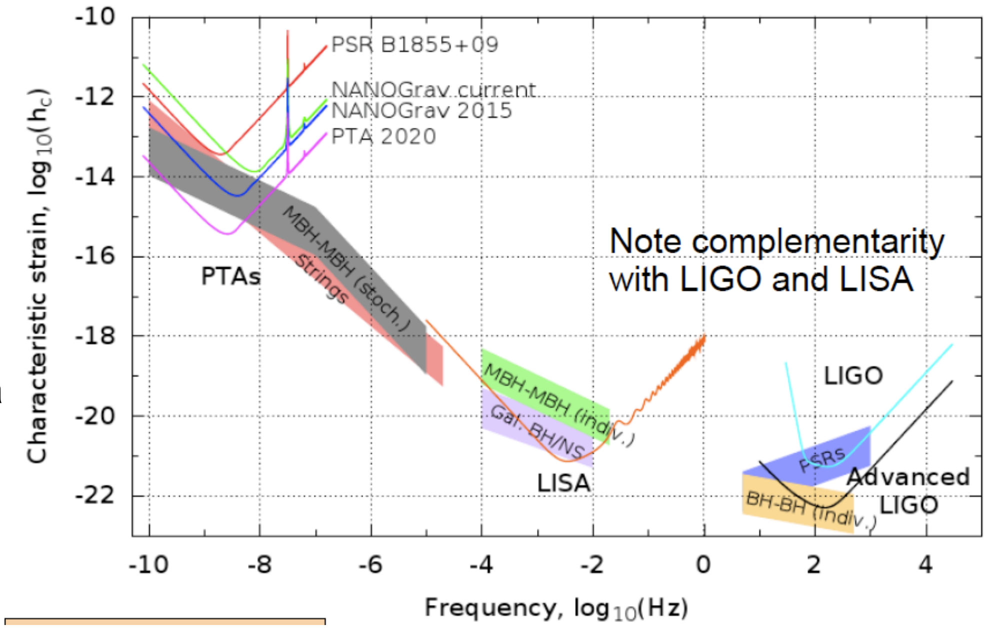


That means that if any any of the neutrino candidates came from the astrophysical sources considered, they must have been too far away for the gravitational waves to be detectable.

Pulsar timing array



- A pulsar timing array is a set of millisecond pulsars that can be used to detect and analyze gravitational waves in the frequency range of 10^{-9} to 10^{-6} Hz .
- The expected astrophysical sources are massive black hole binaries in the centers of merging galaxies, where tens of millions of solar masses are in orbit with a period between months and a few years.
- Globally there are three active pulsar timing array projects.
  - The Parkes Pulsar Timing Array (64m) collecting data since March 2005.
  - The European Pulsar Timing Array uses data from the largest telescopes in Europe:
    - Effelsberg (100 m)
    - Westerbork (96 m)
    - Nancay (92 m)
    - Lovell (76 m)
    - Sardinia (64 m)
  - The Nort Amenrican Nanohertz Gravitational Wave Observatory uses data collected by the Arecibo and Green Bank Radio telescopes.
- These three projects have begun collaborating under the title of the International Pulsar Timing Array project.



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Summary

- It is an exciting time to be searching for gravitational waves

  No detections so far...

  ...but the data allow us to start probing regions of the parameter space that are astrophysically and cosmologically relevant

- LIGO and Virgo are fully engaged in multi-messenger astrophysics.
- These activities and the nascent collaborations serve as a strong foundation for analyses of future, more sensitive data.

- Advanced detector era is just around the corner

- Future observatories, such as ET or US3G, will be able to realize precision gravitational wave astronomy.

- Significant experimental, astrophysical, theoretical, numerical challenges remain.
- These must be solved to ensure we extract the best physics and astrophysics from our detectors

LISA Status…

- LISA was strongly endorsed in the Astro2010 decadal survey
  - Ready to proceed after LPF and CV selection,
  - Start LISA in 2016 to enabled launch in 2025.
- Cosmic Vision L-Mission down-select currently underway in Europe
  - including LISA, IXO (International X-ray Observatory), & Laplace (mission to Jovian moons)
- However, on April 2011, NASA announced that it would likely be unable to continue its LISA, or any other L-Mission, partnership with the European Space Agency, due to funding limitations.

➢ ESA decided to re-scope the three L missions
  - ✧ ESA-only mission (later contributions by partner agencies not excluded, only ‘enhancement’, no strategic component)
  - ✧ 850 M€ cost to ESA
  - ✧ additional member state contribution
    - always hardware, never money
    - however: ~ 150 M€ - 200 M€ potential ‘money equivalent’
  - ✧ Decision on L-mission in April 2012

The new gravitational wave mission at ESA NGO/eLISA

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Classic LISA: optimize science/$ in definitive mission
New LISA: design best mission that fits cost cap

Mass is money — launch systems are a major cost!

mass = bus + payload + propellant

payload → smaller telescopes, mother–daughter

propellant → orbit x mass → shorter arms, lunar assist; nonlinear!

Time is money — shorter mission

Risk is money — less redundancy

A current baseline design within the cost cap:

Interferometry:	two arms only, mother–daughters
Launch:	possibly two Soyuz rockets with lunar assist(s)
Orbits:	1×10^6 km arms, 10° behind Earth, drifting to 25° after 5 years
Displacement noise:	3×10^{-15} m/s^2/Hz$^{1/2}$ (LISA DRS)—no trade studies on payload
Position noise:	1×10^{-12} m/Hz$^{1/2}$ shot + 6.2×10^{-12} m/Hz$^{1/2}$ other optical (LISA 2-W laser and 40-cm telescope, shorter armlength)
Possible trade:	100 m/s → additional 1×10^6 km armlength

http://elisa-ngo.org/

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Ranges of expected binary merger rates

Table 4. Compact binary coalescence rates per Mpc^3 per Myr[a].

Source	R_{low}	R_{re}	R_{high}	R_{max}
NS–NS ($\mathrm{Mpc}^{-3}\,\mathrm{Myr}^{-1}$)	0.01 [1]	1 [1]	10 [1]	50 [16]
NS–BH ($\mathrm{Mpc}^{-3}\,\mathrm{Myr}^{-1}$)	6×10^{-4} [18]	0.03 [18]	1 [18]	
BH–BH ($\mathrm{Mpc}^{-3}\,\mathrm{Myr}^{-1}$)	1×10^{-4} [14]	0.005 [14]	0.3 [14]	

[a] See footnotes in table 2 for details on the sources of the values in this table.

Table 5. Detection rates for compact binary coalescence sources.

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

1.4/1.4, 445 Mpc
1.4/10., 927 Mpc
10./10., 2190 Mpc

LVC, Class. Quantum Grav. 27 (2010) 173001

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Joint GW-radio searches

- Plausible sources of joint GW-radio emissions include:
  - BNS mergers (magnatar component, plasma excitation)
  - GRB radio afterglows (< minutes)
  - Pulsar glitches
  - Unidentified transients
- *Offline analysis*
  - Possibility for low latency search; rapid radio follow-up
- Potential partners:

Instrument	Band	Type	Field of View	Slew Time
LOFAR	40-240 MHz	Array	30° beam(s)	Software
ETA	29-47 MHz	Array	Two 30° beams	Software
NRAO Green Bank	300MHz-50 GHz	Dish	0.027 sq. deg. (at 1 GHz)	18°/minute
ARECIBO	312 MHz - 10.2 GHz (ALFA: 1.225 - 1.525 GHz)	Dish	15 arcmin @ 312 MHz 0.5 arcmin @ 10.2 GHz (ALFA: 10 arcmin @ 3.5 arcmin resolution (7 beams))	< 16 min

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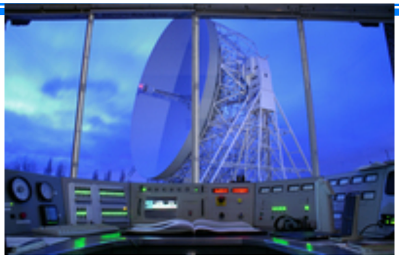
Search for periodic GW signals from known pulsars



Jodrell Bank

Green Bank

Parkes Telescope

- search method makes use of a signal template for each pulsar
  ➔ requires updated ephemeris data to model phase evolution of pulsar signal
  ➔ requires collaboration with radio pulsar astronomers

- Highlights:
  - Crab pulsar: $h_0 < 1.9 \times 10^{-25}$ GWs <2% of spindown energy
  - Vela pulsar: $h_0 < 2.1 \times 10^{-24}$ GWs <35% of spindown energy
  - J0537−6910: $h_0 < 5 \times 10^{-26}$ At spindown limit
  - J1603−7202: $h_0 < 2.3 \times 10^{-26}$ Lowest h_0 limit
  - J2124−3358: $\varepsilon < 7.0 \times 10^{-8}$ Lowest ε limit

116 known pulsars 95% upper limits
Abbott et al (LSC & Virgo) ApJ 713, 671 (2010)