Gravitational Wave Astronomy.
A multi-messenger approach

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LIGO Scientific Collaboration and the Virgo Collaboration
ERE, Granada 2010

Content

- Ground-based Interferometers:
  - initial and advanced
- Searches and astrophysics highlights
- Multi-messenger astrophysics
- Conclusions

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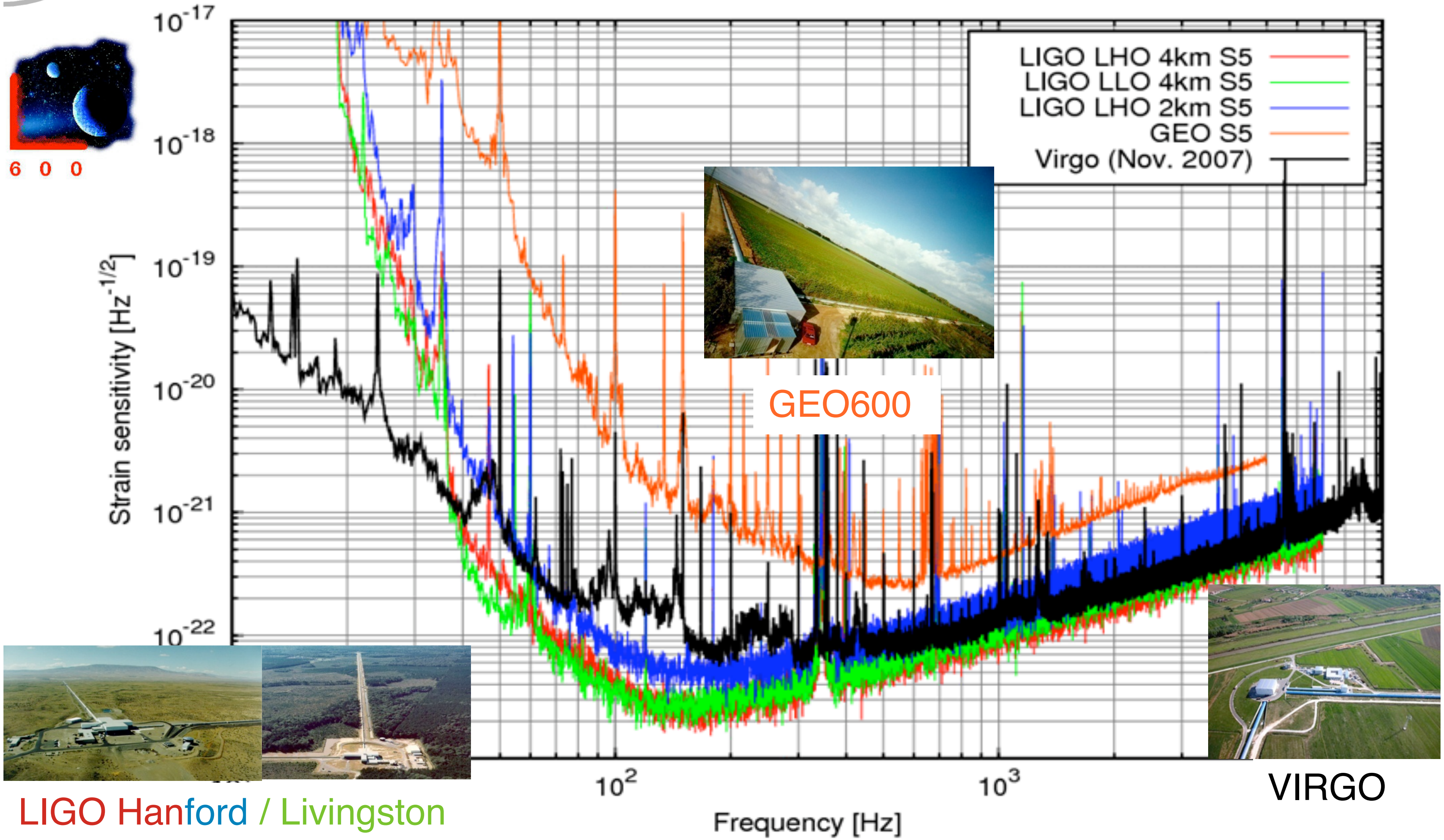
International network of GW detectors

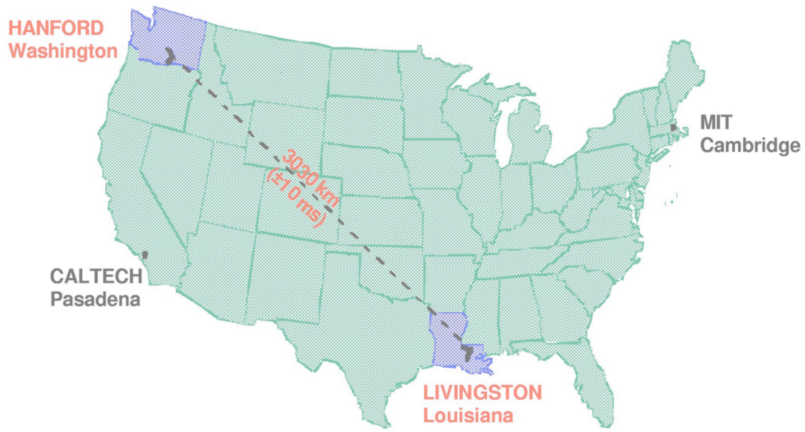
S5 Strain Sensitivities of LSC/Virgo 2005-2007

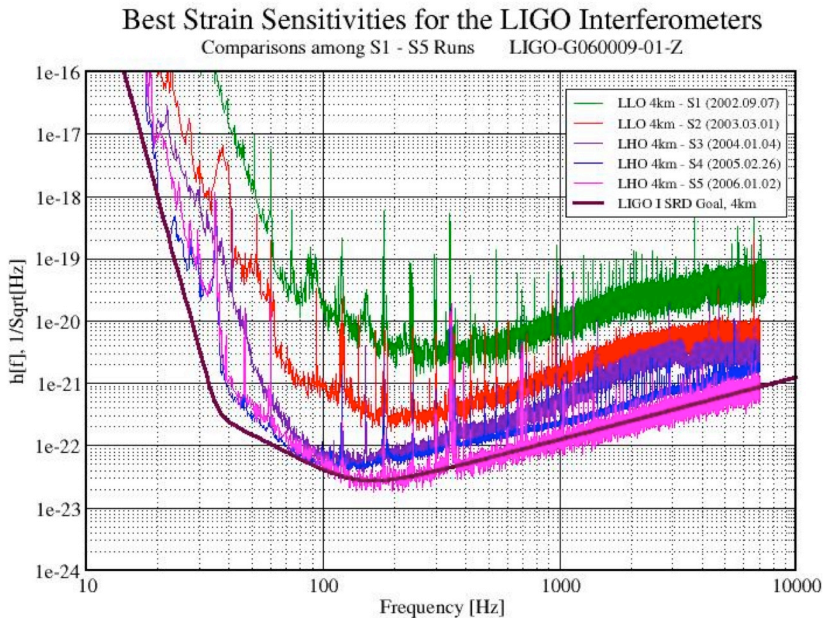
NS/NS inspiral (1.4 M_o) averaged range at SNR of 8

LIGO: 15 Mpc (4 km); 7 Mpc (2 km); VIRGO: 4 Mpc

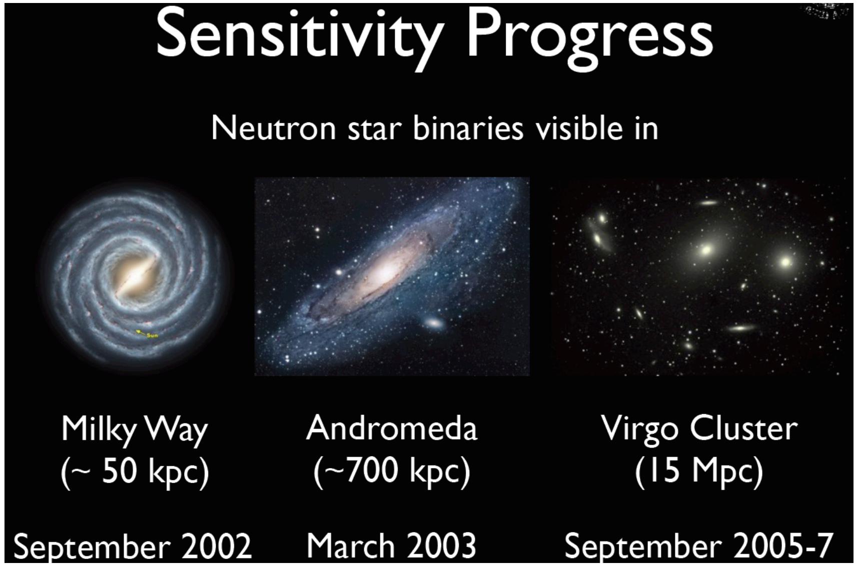


The LIGO Scientific Collaboration



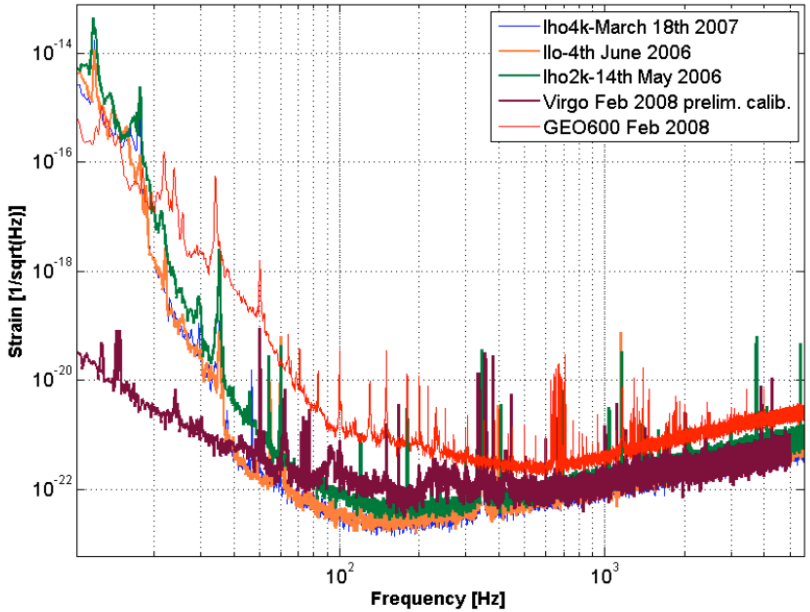


- The LSC is a large international collaboration seeking to detect gravitational waves, use them to explore the fundamental physics of gravity, <u>and develop gravitational wave observations as a tool of astronomical discovery</u>.
  - Almost 800 members from 12 countries
- The LSC has completed five science runs. All interferometers are at design sensitivity
- The fifth run took one year of triple coincident data
- No detection candidates seen
- LSC has set astrophysically interesting, meaningful constraints on:
  - Individual objects and events
  - Source populations (real or theorized)
  - Total energy density in GWs



GEO600

- LIGO runs in collaboration with the GEO600, the German-British interferometer
  - The GEO collaboration is part of the LSC
- GEO600 is a 600 m long interferometer in Hannover Germany
- Operated as one of the four LSC detectors and has been taking data since 2002.
- GEO600 will be the only GW interferometer in operation during the 2012 – 2015 time frame
  - The GEO600 detector much less sensitive than LIGO detectors; best sensitivity at high frequency



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Virgo

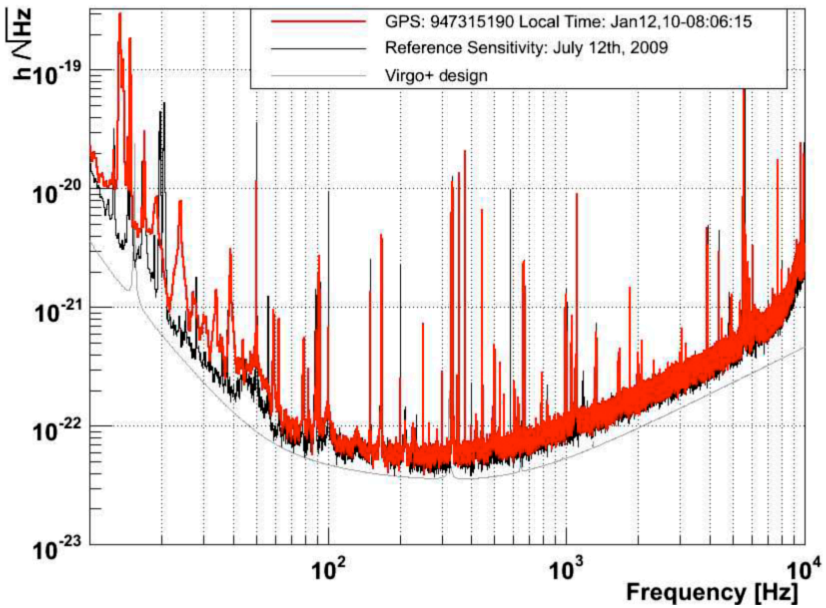
- Virgo is a 3 km long interferometer near Pisa, Italy
  - Configuration is very similar to LIGO; sensitivity close to LIGO interferometers

- Virgo started observations in May 2007

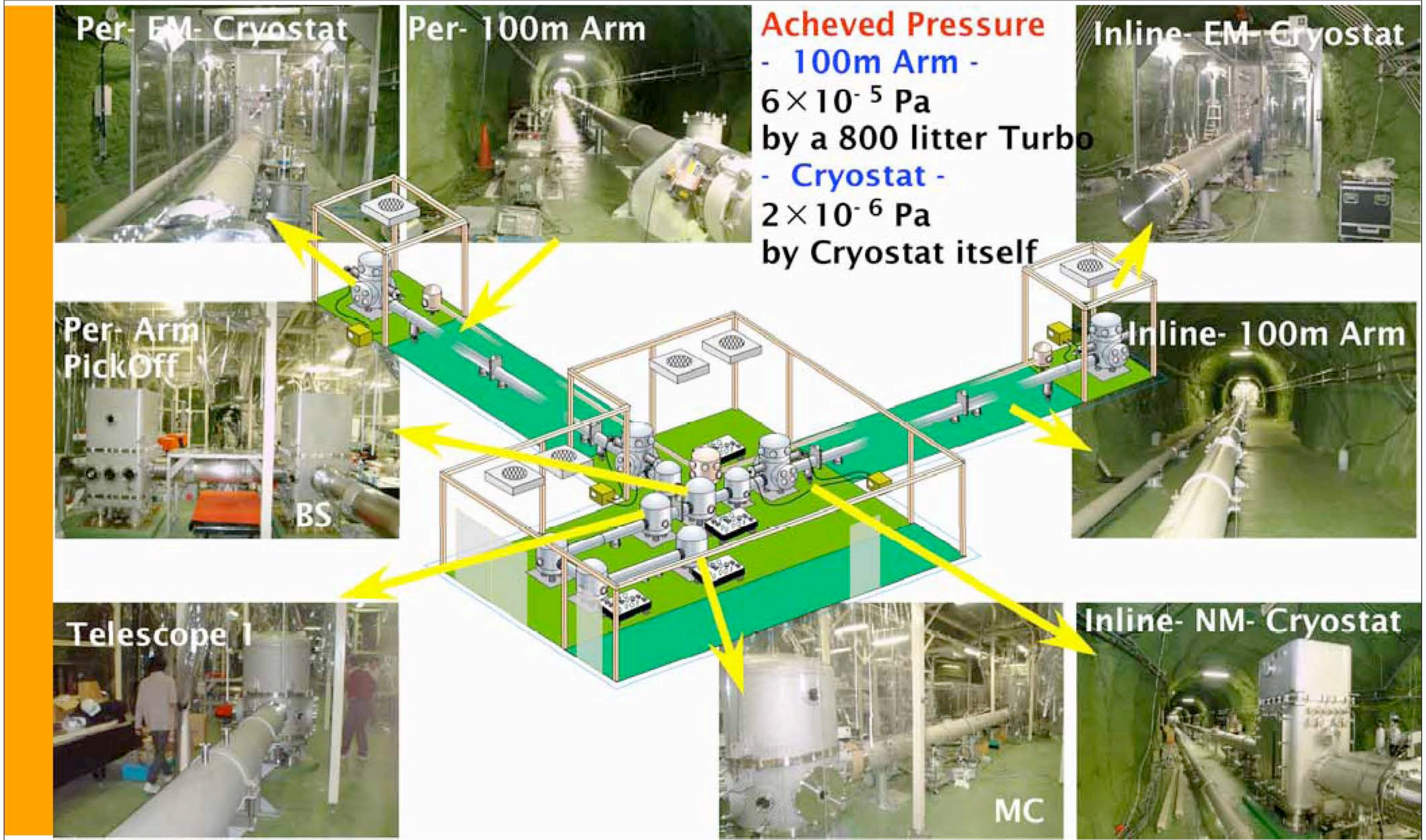
- The LSC and Virgo have a formal agreement to share and analyze data jointly
  - Virgo and LIGO are separate collaborations, but jointly ‘own’ L-V data.

- Virgo along with the two LIGO interferometers comprise the GW network and enable GW source location
  - As well as detection confidence, ‘up time’, source parameter estimation from reconstructed waveform, and more sensitive searches

- Additional GW detectors would provide better sky coverage, better source localization
  - Large scale interferometers in planning stages in Australia and Japan



Construction of CLIO



Acheved Pressure
- 100m Arm -
6×10^{-5} Pa
by a 800 litter Turbo
- Cryostat -
2×10^{-6} Pa
by Cryostat itself

“Status of TAMA 300” N.Kanda & the TAMA collab. 19

LCGT is funded

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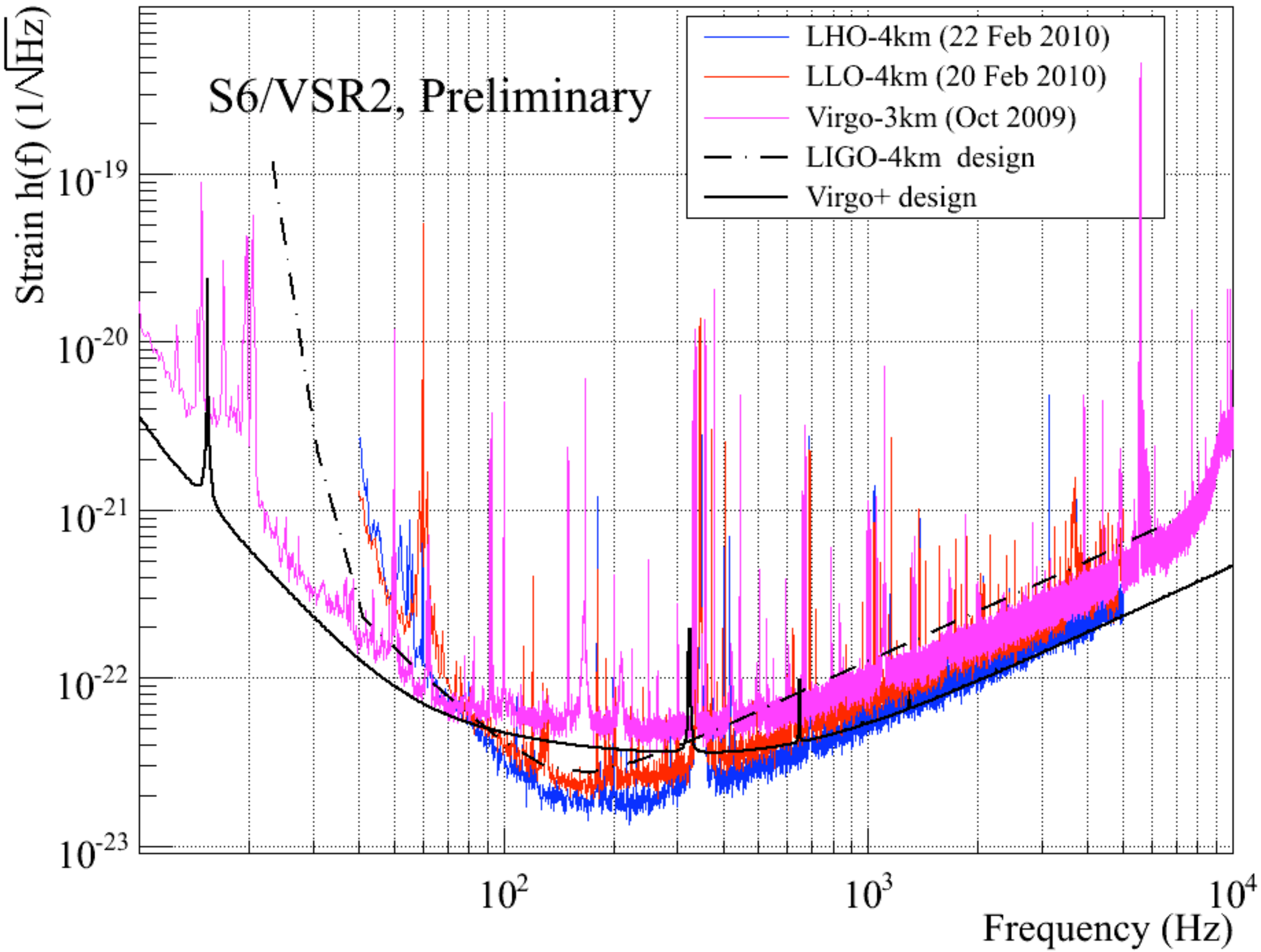
Detector Sensitivities



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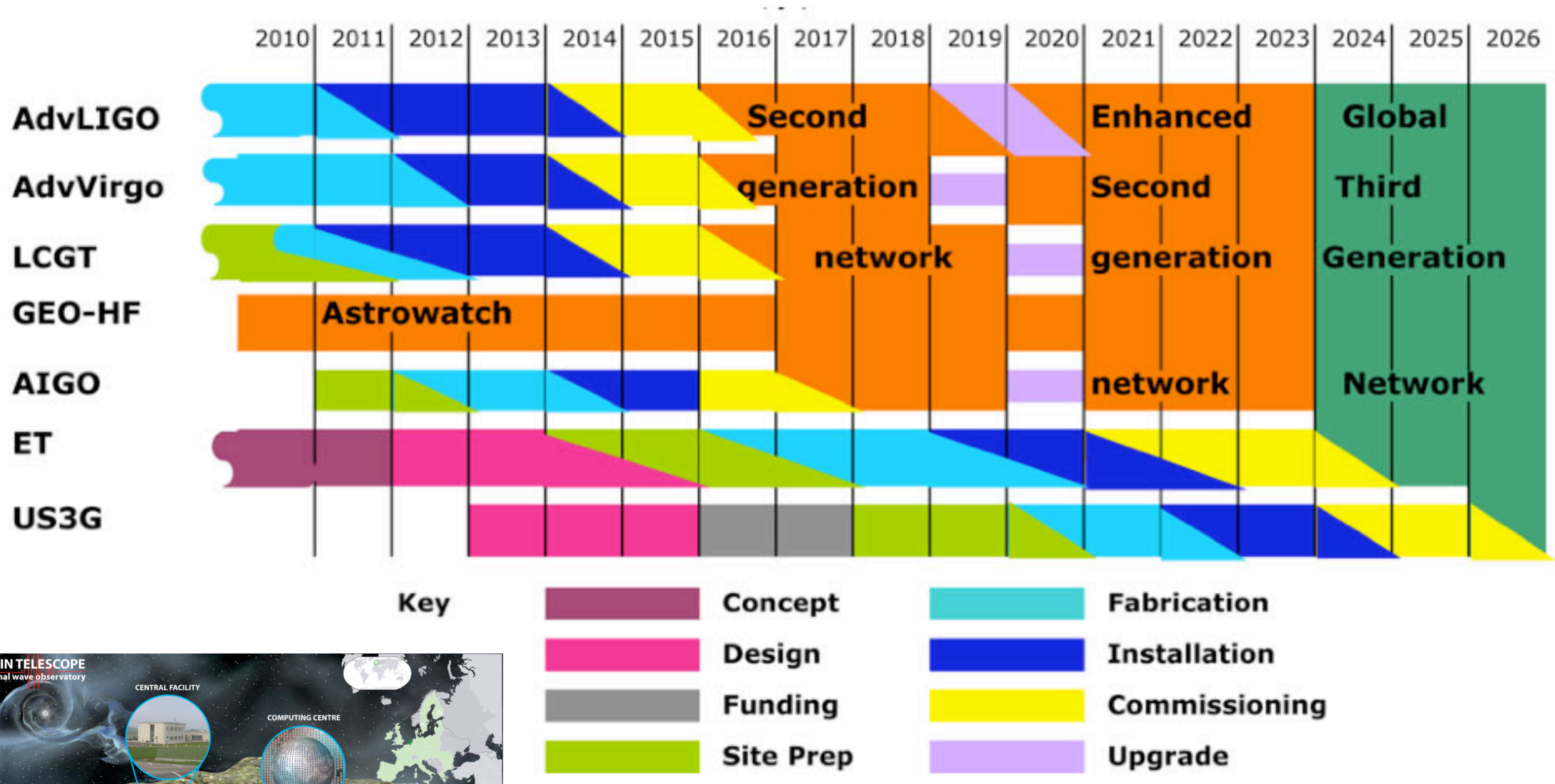
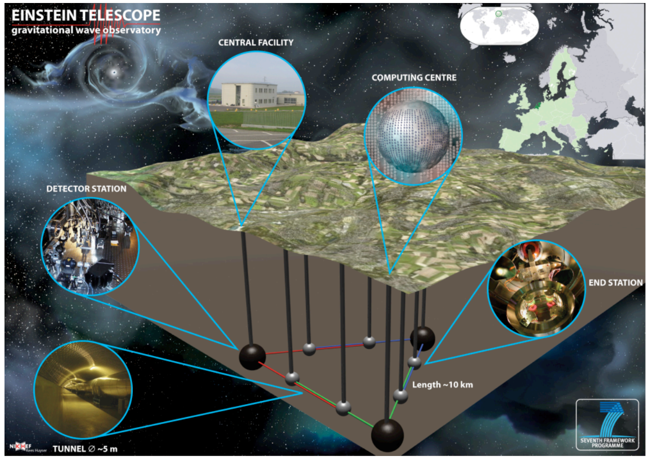
Advanced Detector Timeline





From GWIC Global Roadmap for the field of gravitational wave science

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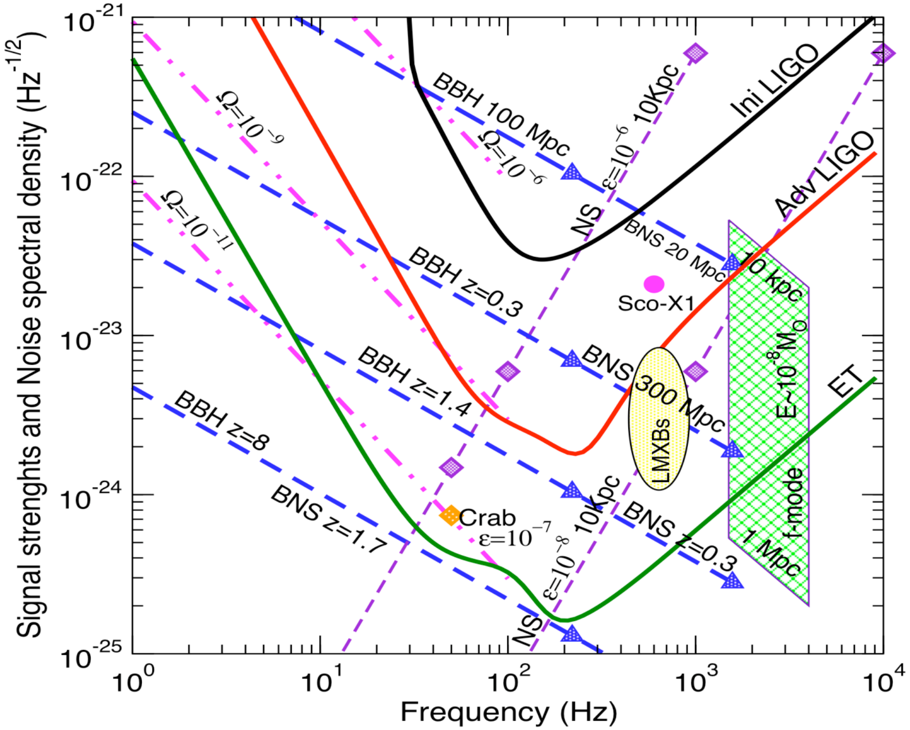
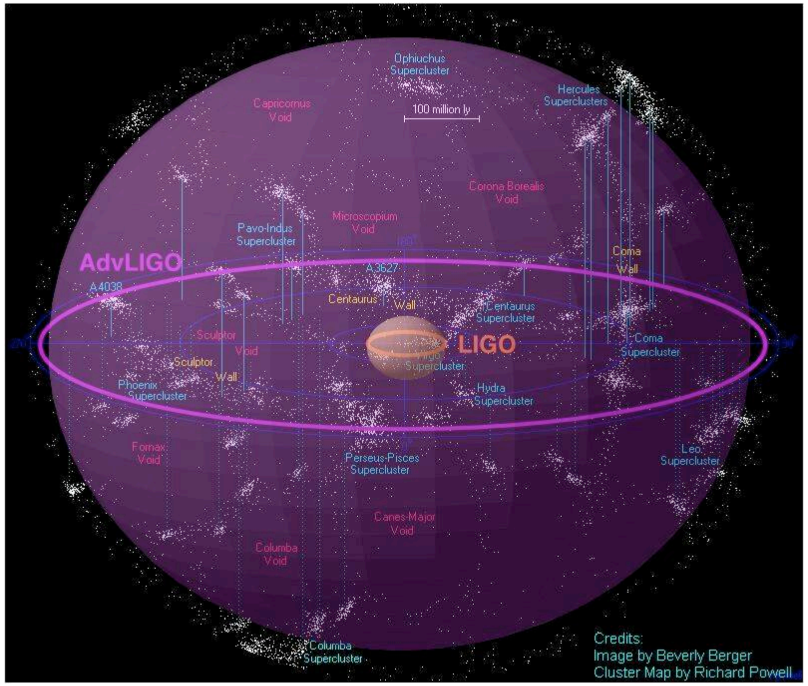
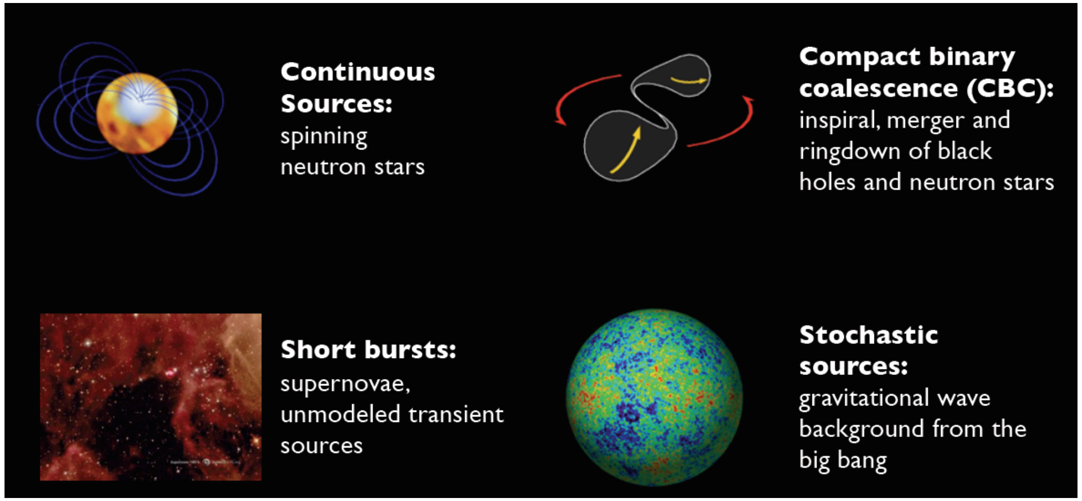
Sources for Ground Based Detectors

From Schutz & Sathyaprakash, Living Reviews in Relativity







Advanced LIGO reach (example):
h sensitivity will improve by 10, with improved bandwidth

NS-NS x10 better amplitude sensitivity

- ⇒ x1000 rate=(reach)^3
- ⇒ 1 day of Advanced LIGO
  - » 1 year of Initial LIGO !

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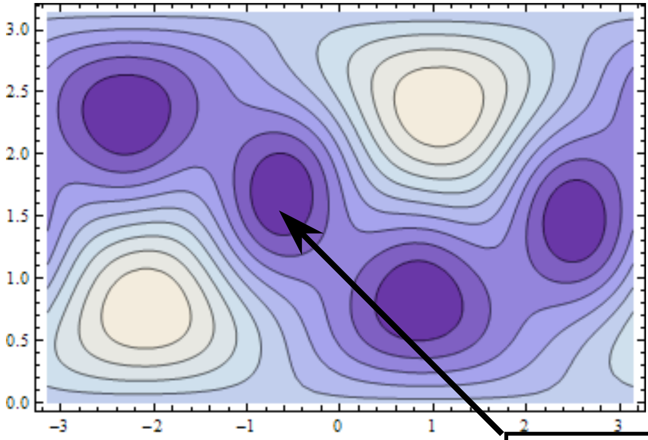
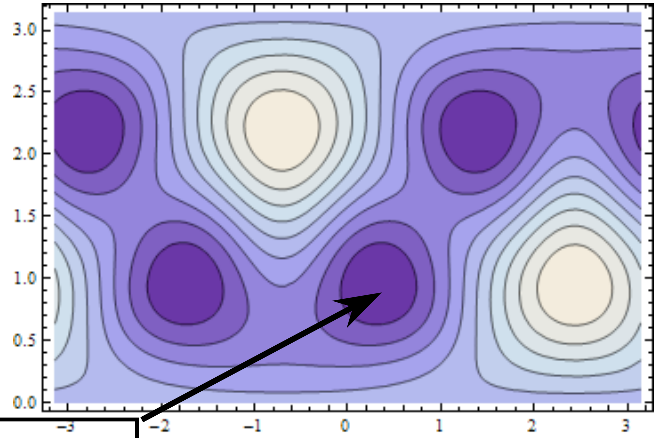
Benefits of a global network

- Improved sky coverage

LIGO Hanford

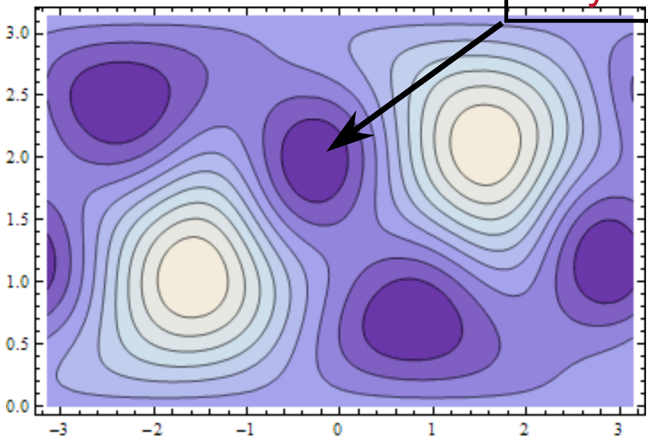


Virgo

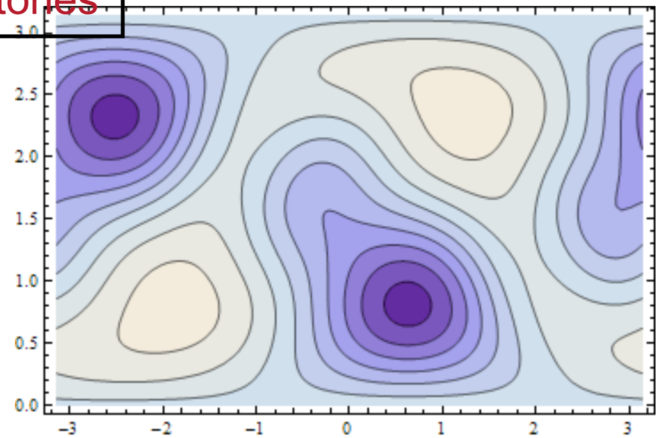


Nulls of the antenna pattern vary between observatories

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

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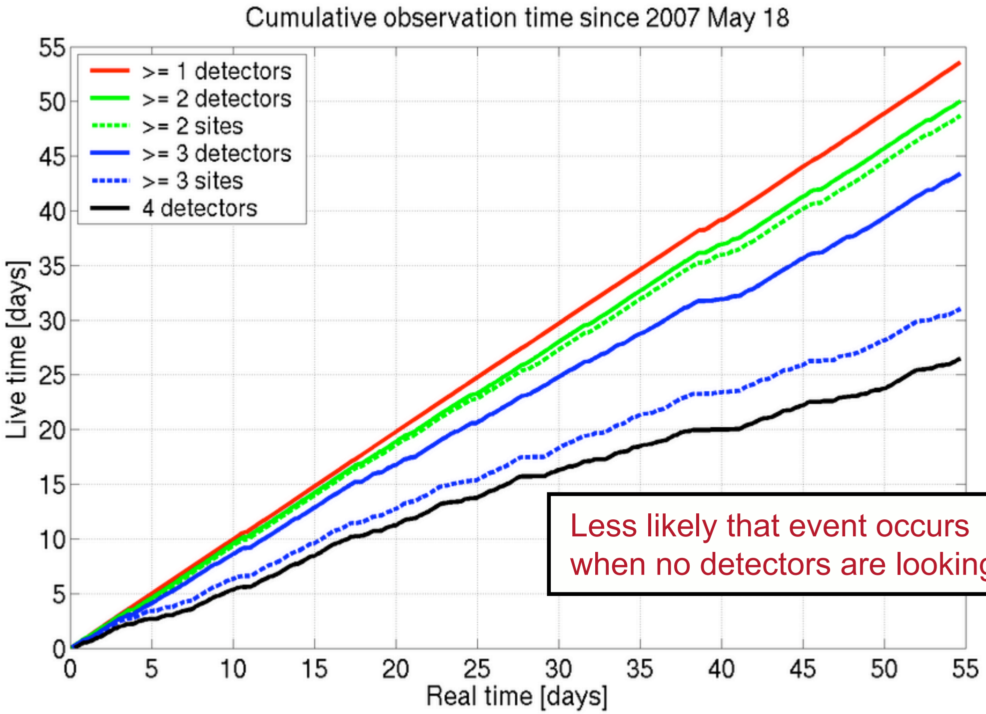
Benefits of a global network

- 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

Challenges & Payoffs

Many major challenges before we enter the era of gravitational wave astronomy

Building and installing advanced detector hardware

Commissioning detectors; achieving desired sensitivity

Understanding the detectors and the data they produce

Searching the data for gravitational wave signals

Using GW observations in astronomy, cosmology, relativity

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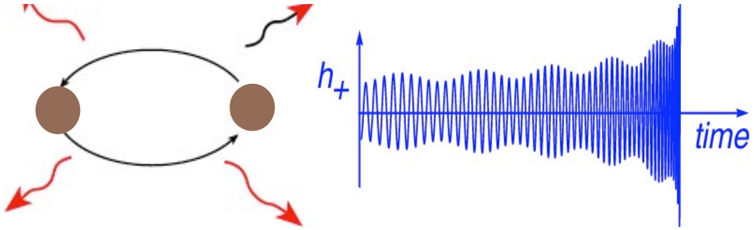
Neutron Star Binary Inspiral

NS-NS coalescence 'inspiral'
- Initial interferometers
  - Range: 20 Mpc
- Advanced interferometers
  - Range: 300Mpc

Signal shape very well known



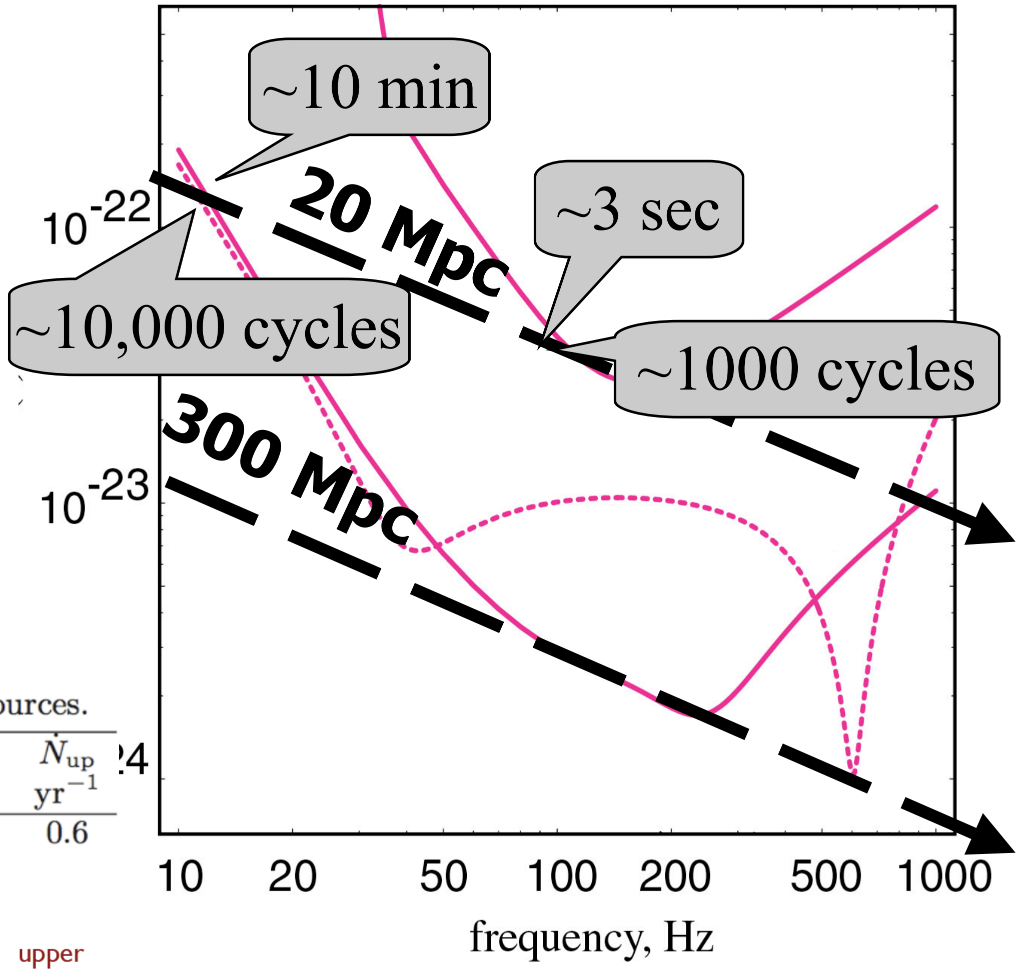


TABLE V: Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{\mathrm{low}}$ yr^{-1}	$\dot{N}_{\mathrm{re}}$ yr^{-1}	$\dot{N}_{\mathrm{pl}}$ yr^{-1}	$\dot{N}_{\mathrm{up}}$ 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	
		could be as low as...	most likely	could be as high as...	upper limit
	NS-NS	0.4	40	400	1000
	NS-BH	0.2	10	300	
Advanced	BH-BH	0.4	20	1000	

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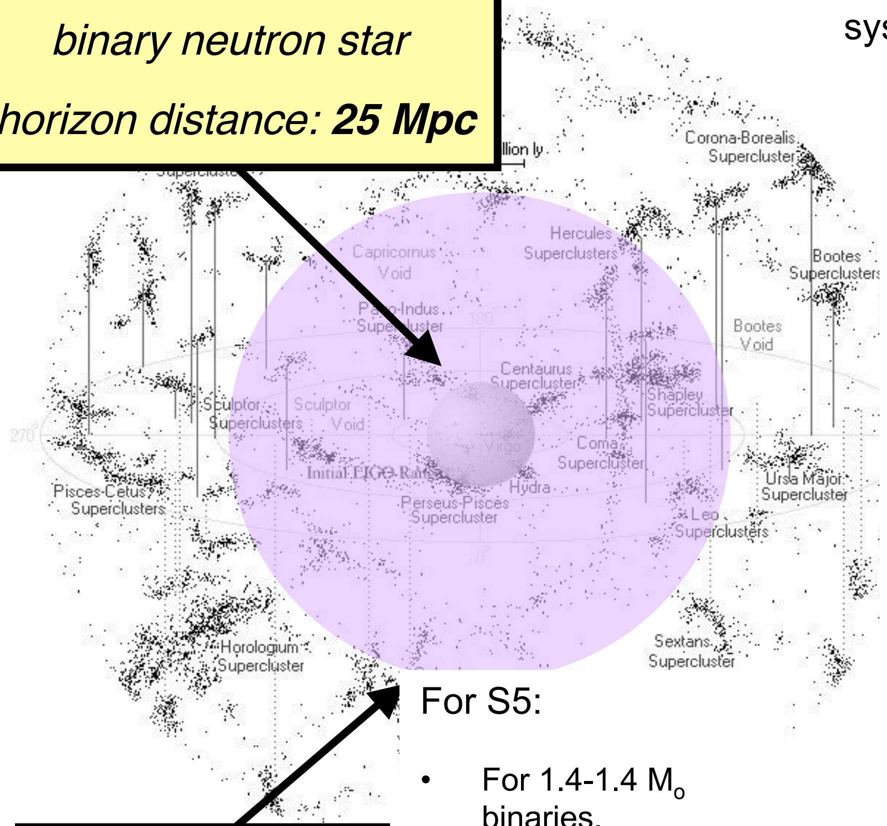
Searches for Coalescing Compact Binary Signals

binary neutron star

*horizon distance: **25 Mpc***



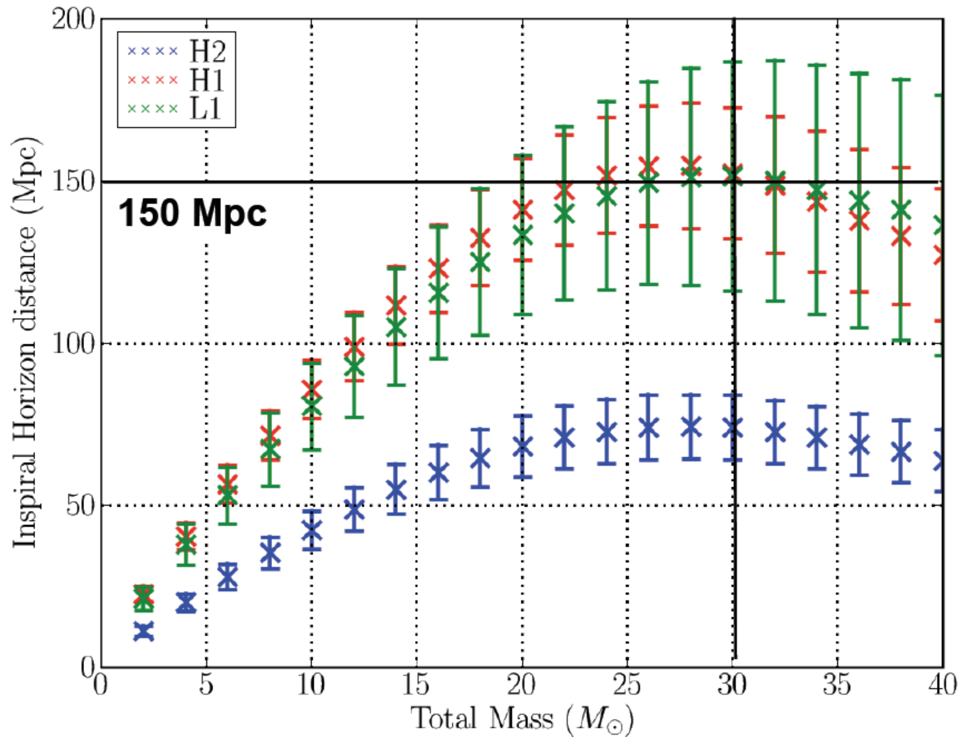
binary black hole

horizon distance

For S5:

- For 1.4-1.4 M_o binaries, ~ 200 MWEGs in range
- For 5-5 M_o binaries, ~ 1000 MWEGs in range

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

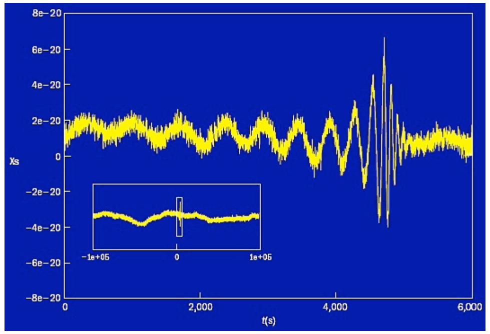


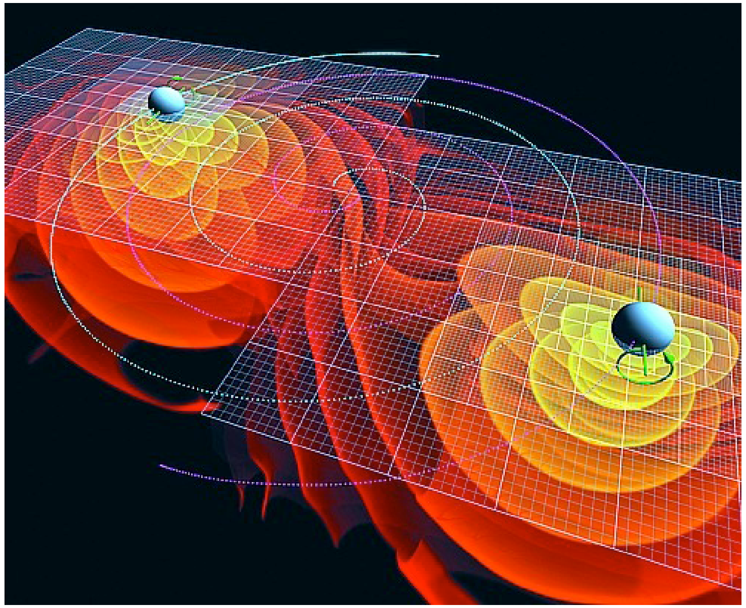
- No detection yet.
- Upper limits on rate are 1 to 2 orders of magnitude above optimistic astrophysical predictions,
- ~3 orders of magnitude above best estimates.

arXiv:0901:0302,
arXiv:0905:3710

Accurate modeling of black hole binaries

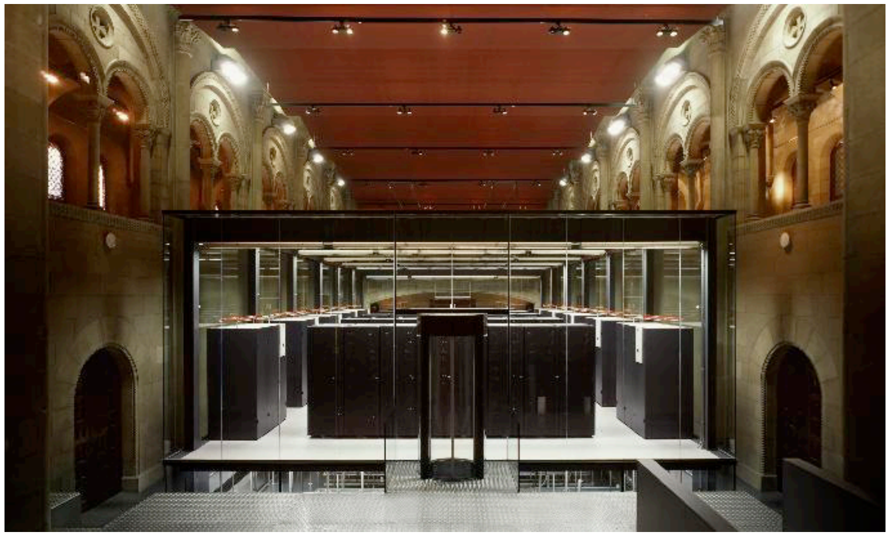
- Group members played a crucial role in developing numerical models of the coalescensce of relativistic binaries in GR,
  - leading to a wealth of astrophysical relevant information, (recoil velocities after merger, final spins, final mass)
  - as well as modeling their GW emission to construct waveforms





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

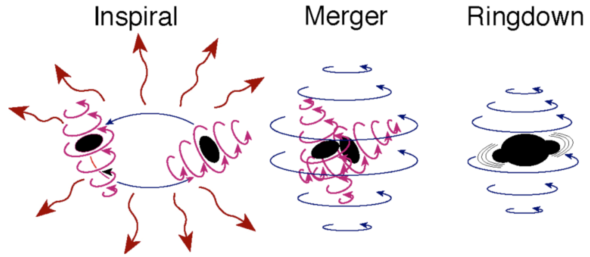
- We use several million CPU hours per year through allocations at BSC and CESGA in Spain, LRZ Munich, the Vienna Scientific Cluster, DEISA Extreme Computing Initiative, the TeraGrid (USA),…

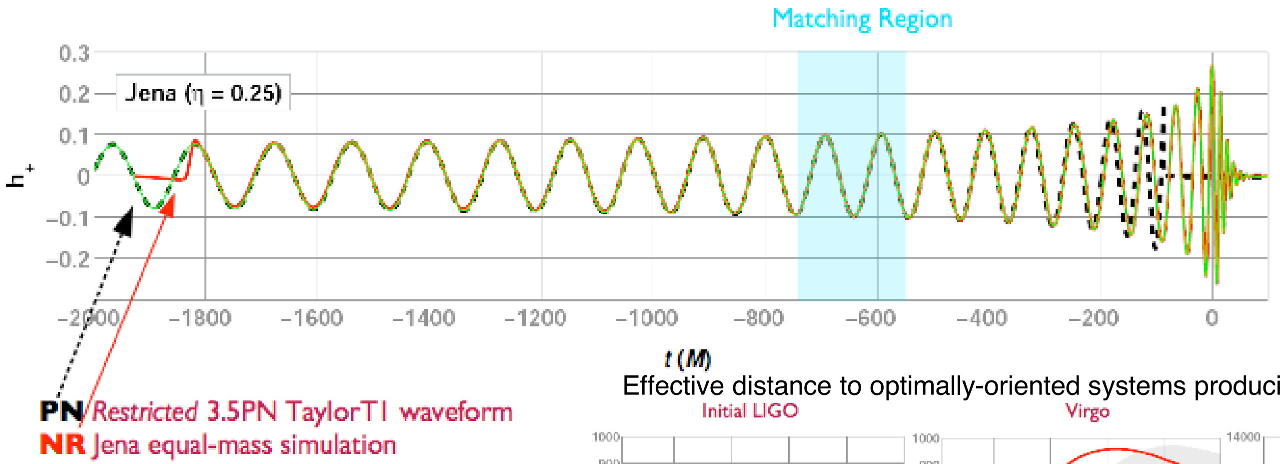


Construction of template banks

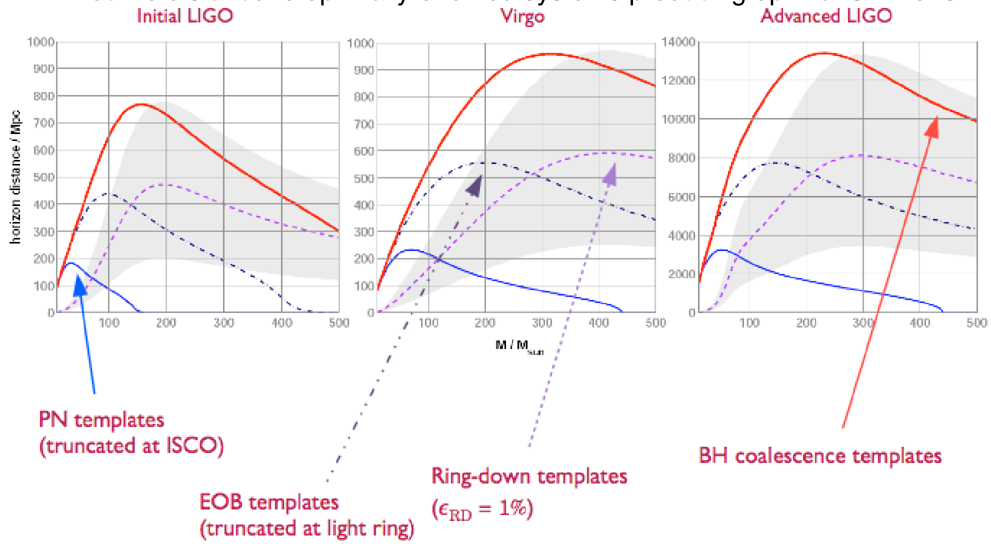
- Up to now, data analysis methods for coalescing binaries had to rely on post-Newtonian approximations, which break down before merger, and perturbative ringdown signals.

- 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.





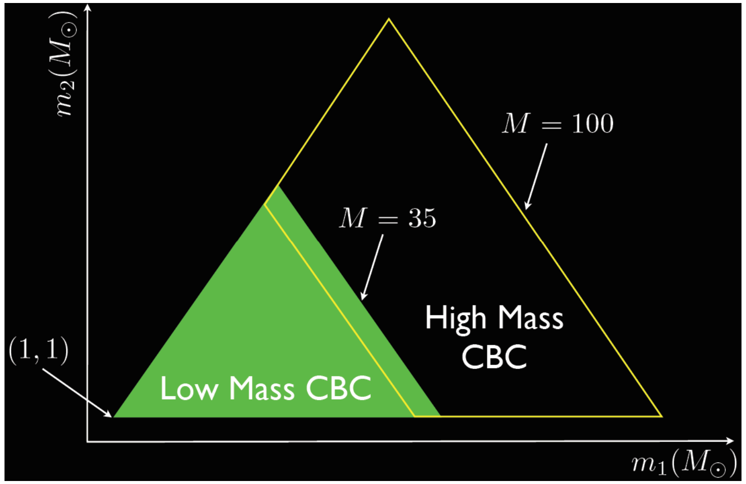
Effective distance to optimally-oriented systems producing optimal SNR of 8



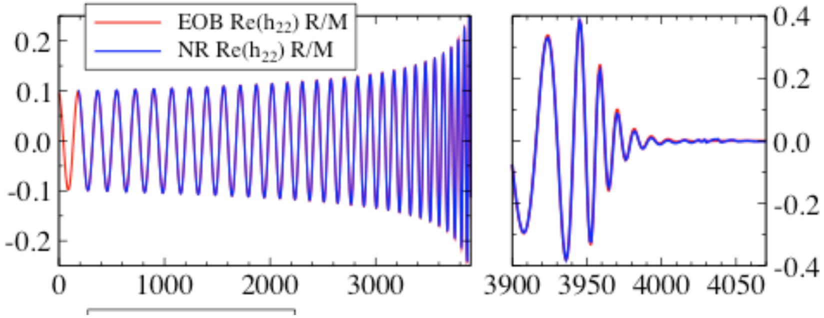
- First results show that numerical simulations in full GR will have significant implications on detection rates and the accuracy of parameter estimation.

- 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.

CBC searches



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

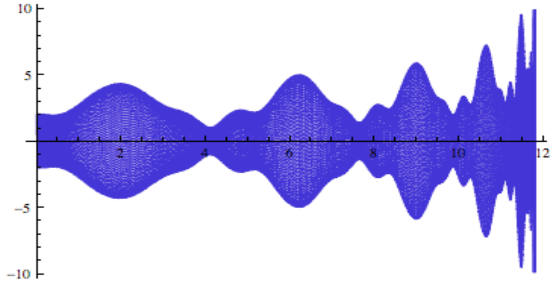


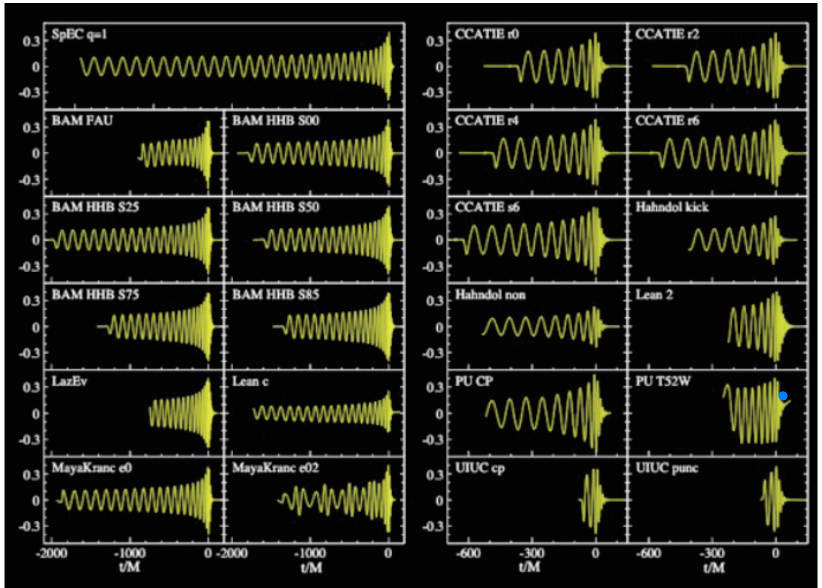
- Low mass search
  - Using non-spining and spining waveforms

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





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

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 on S5/VSR1 using these templates

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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…

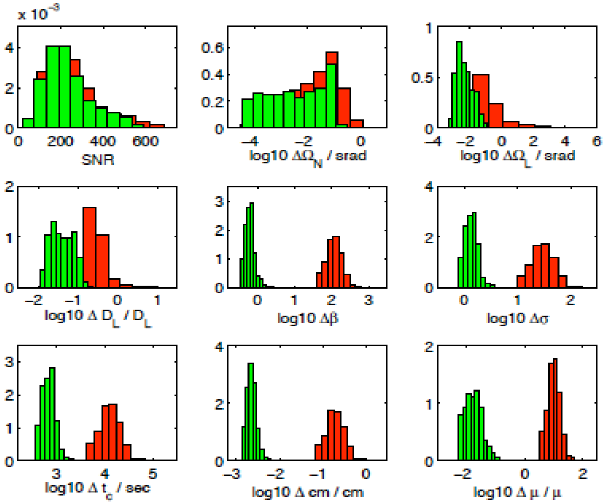
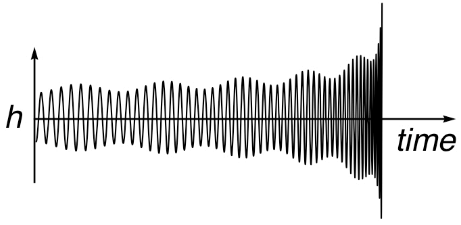
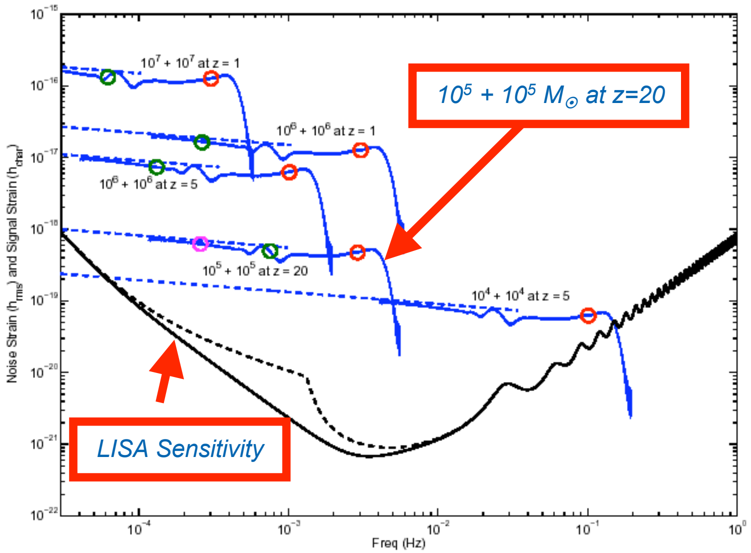


Figure 2. Probability distributions of SNR and measurement errors for the case $m_1 = 10^7 M_\odot$ and $m_2 = 10^6 M_\odot$ at $z = 1$. The clear grey (green) corresponds to the FWF and the dark grey (red) to the RWF.

Supermassive BH for LISA





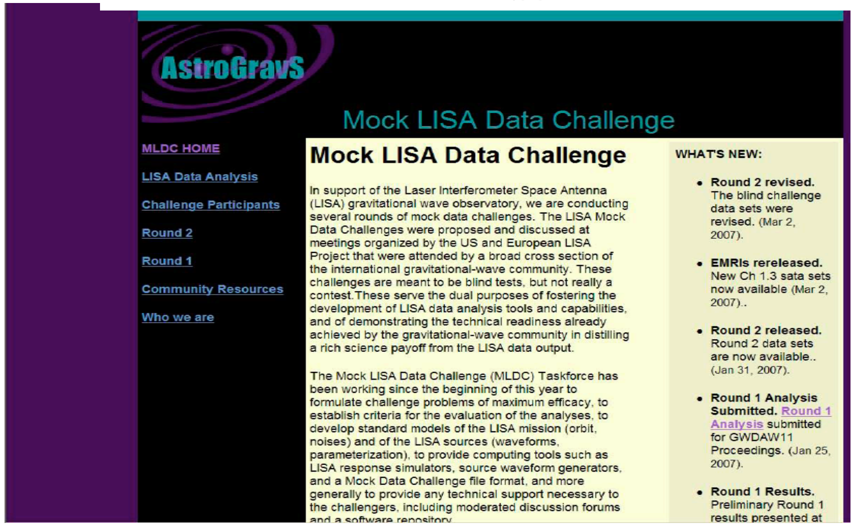
- Parameter estimation of supermassive black holes
  - Extract high precision black hole properties: Masses, spins to <0.1%, distances to ≤1% (z=1; an order of magnitude worse at z=20)
  - Early warnings
- Study astrophysical & cosmological implications:

  Measure the dark energy equation of state with LISA *along with the Hubble constant and other cosmological parameters*

- Gravitational wave standard sirens:
  - Observing them in the gravitational window provides direct measurement of the luminosity distance D_L. With the redshift z from EM observations, one can infer the dark energy equation of state parameter w. Assuming a spatially flat FLRW Universe with constant w,

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\left[\Omega_M(1+z')^3 + \Omega_{DE}(1+z')^{3(1+w)}\right]^{1/2}}, \qquad (1)$$

H_0 being the Hubble parameter, Ω_M and Ω_{DE} the dark matter and dark energy densities, respectively, all at the current epoch.



LISA Data analysis challenge:

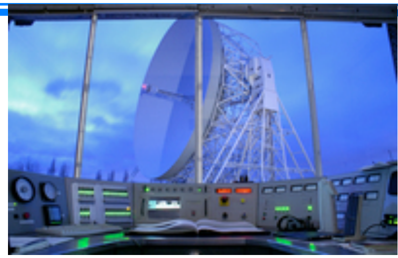
- Mock LISA Data Challenge: Friendly competition to develop tools and methods for LISA data analysis
- Development of delayed rejection schemes for efficient Markov-Chain Monte-Carlo sampling of multimodal distributions

tes

Search for periodic GW signals from known pulsars

- target signal: monochromatic signals emitted by pulsars
- most likely mechanism for production of detectable GW is small distortions of the NS shape away from axisymmetry
- search at GW frequency twice the pulsar rotation frequency

- 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
- S5 best limit: h_0=2.3E-26 at the sweet spot
- best ellipticity limit of 7E-8

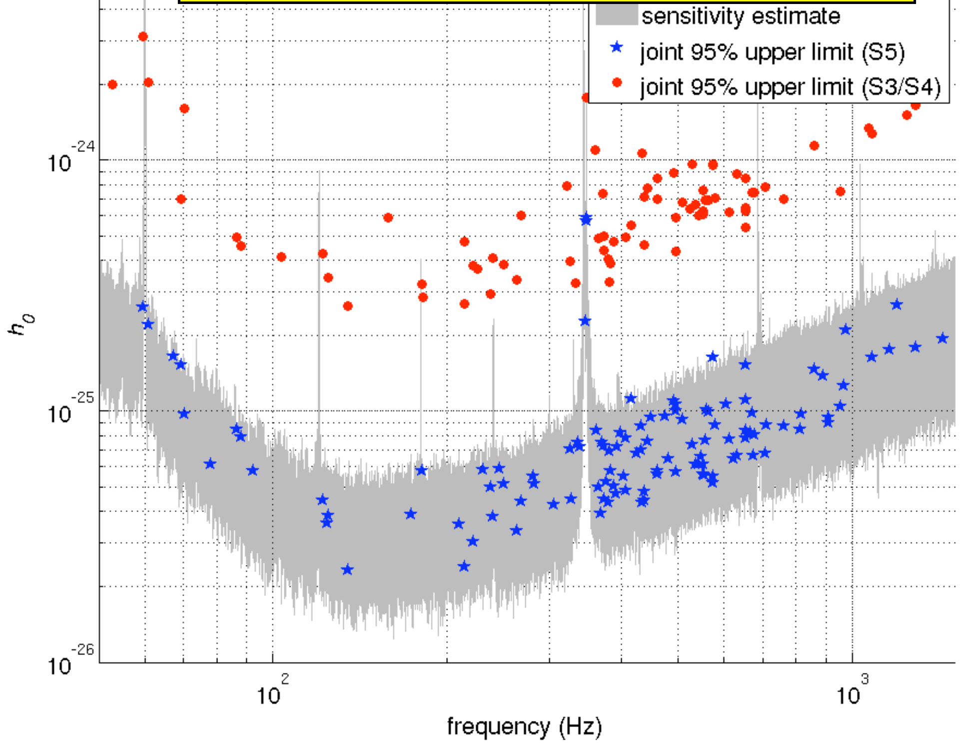


Jodrell Bank

Green Bank

Parkes Telescope

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



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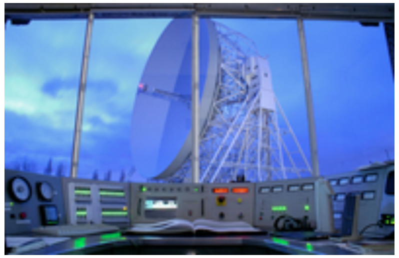
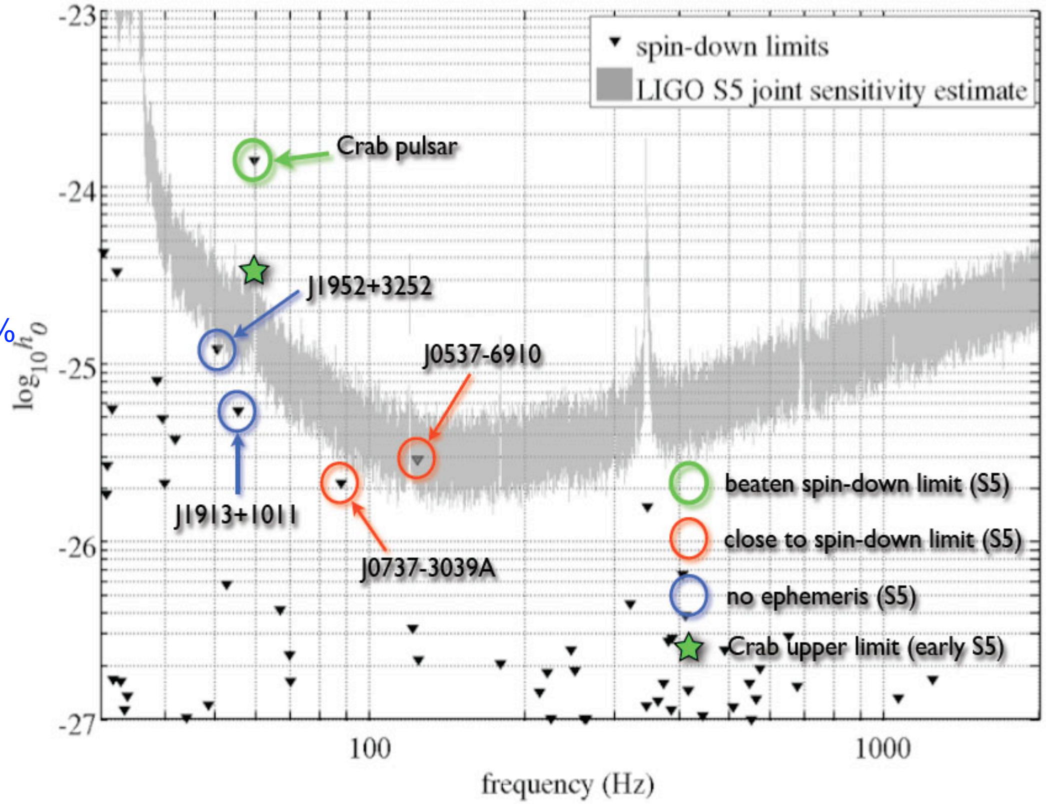
Crab pulsar: beating the spin-down limit

- CrabPulsar is a remnant of supernova observer in 1054
- Rotation rate observed (in radio) is slowing down due to electromagnetic braking, particle acceleration, ... , gravitational waves?
- Spin-down limit assumes all the pulsars rotational energy loss is radiated by gravitational wave, but we know some energy is emitted electromagnetically and is powering the expansion of the Crab nebula. This is poorly constrained and allows room for gravitational wave emission
- f_{GW} = 59.6 Hz
- Search method depends on data from Jodrell Bank Crab Pulsar monthly ephemeris to track the phase
- Using first nine months of LIGO S5 data, obtain 95% upper limit on strain amplitude of h_0=2.7E-25
  ➔ lower than classical spin-down limit by a factor of ~5
  (ApJ, 2008, 683, L45)
- Using entire S5 data gives UL which beats spin-down limit by ~7
  Abbott et al (LSC & Virgo) ApJ 713, 671 (2010)
- Spin down limit should also be achievable for Vela, but since f_{GW} = 22.38 Hz, requires Virgo's low-frequency sensitivity



Jodrell Bank

Credits:
X-ray: NASA/CXC/ASU/ J. Hester et al.;
Optical: NASA/HST/ASU/ J. Hester et al.



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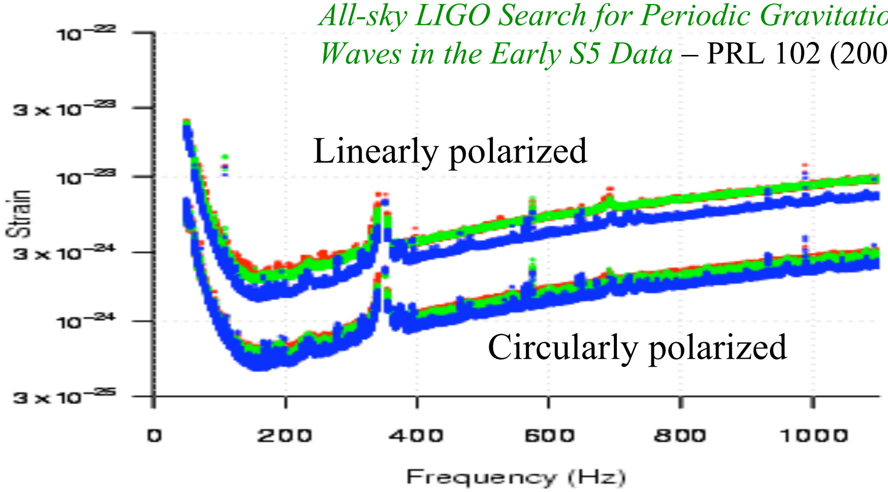
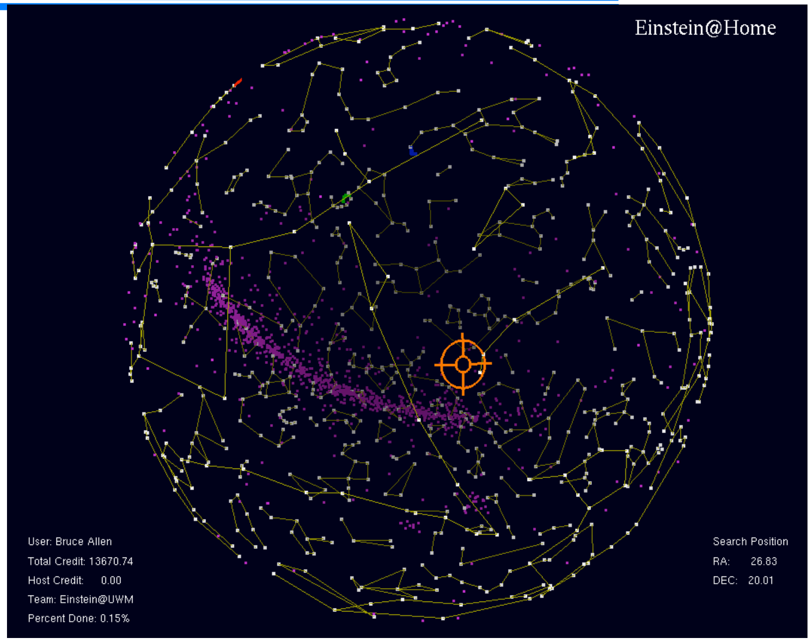
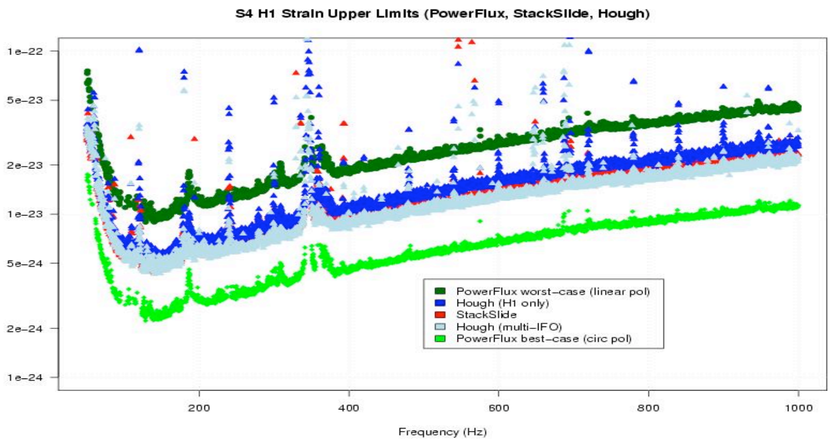
All sky surveys for isolated unknown NS

All-sky LIGO Search for Periodic Gravitational Waves in the Early S5 Data – PRL 102 (2009) 11110





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

- Einstein@home http://www.einsteinathome.org/
  - Increase computing resources by enlisting volunteers
  - Distributed using BOINC & run as screensaver

Cosmology Highlight

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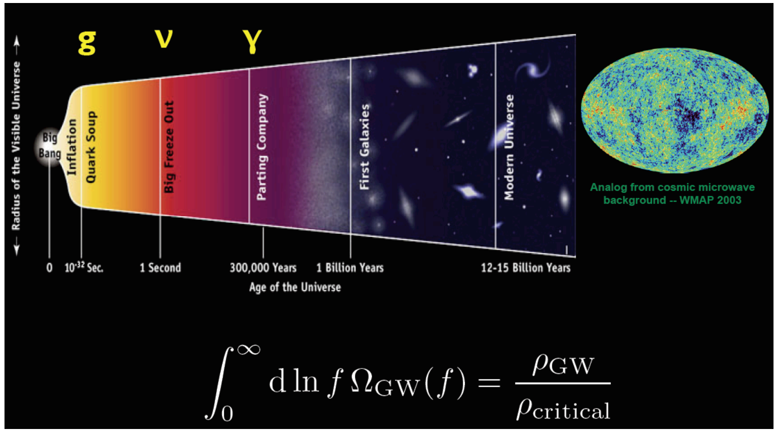
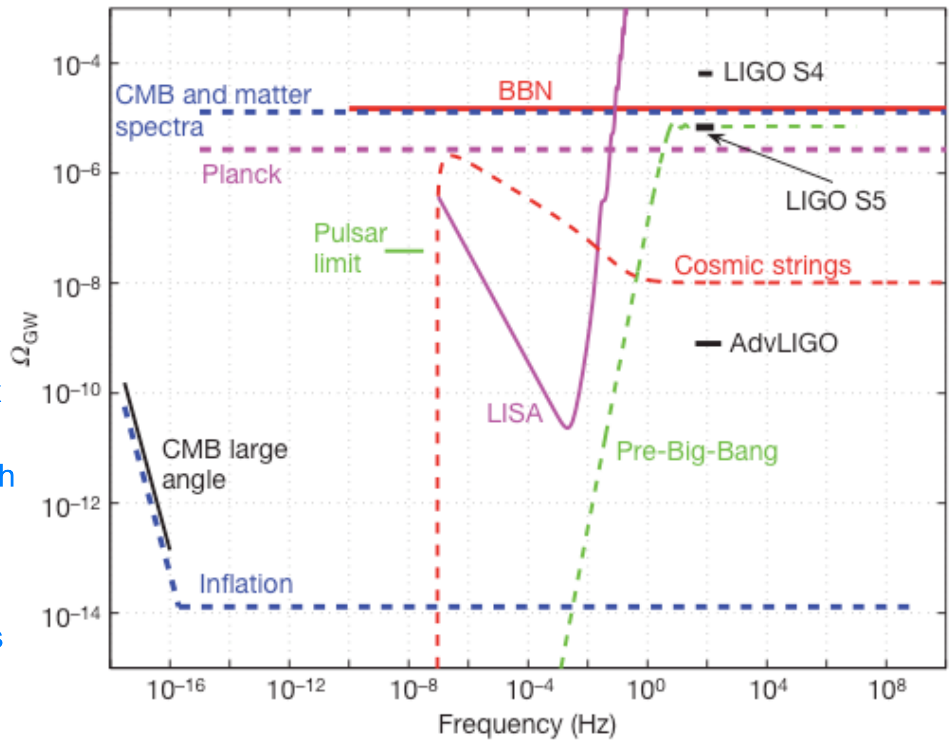
- A stochastic background of gravitational waves is expected to arise from a superposition of a large number of unresolved gravitational-wave sources of astrophysical and cosmological origin. Direct measurements of the amplitude of this background are of fundamental importance for understanding the evolution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

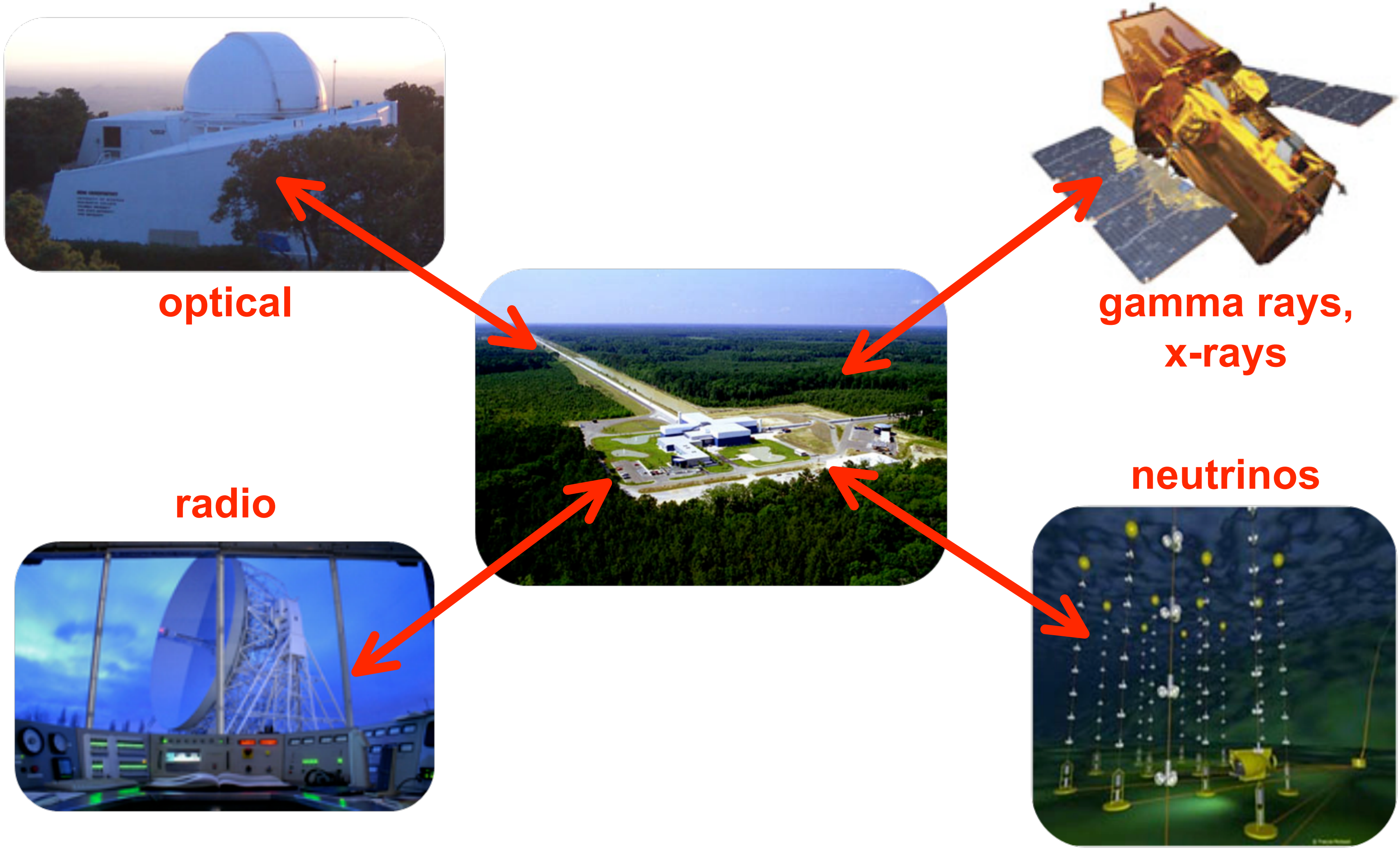


Comparison of different stochastic GW background measurements and models. *Abbott et al Nature* ***460 (2009).***



- 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.

LIGO-Virgo is fully engaged in multi-messenger astrophysics



Collaborations with EM/particle astrophysicists/astronomers

- Many gravitational wave sources will have wide-spectrum electromagnetic and neutrino counterpart emissions detectable by other means
- In the near term, additional “coincidence” tests enables confident detection of weaker GW signals
  - Greatly aids in reducing the false alarm probability
- In the future, GW observations will become a significant component of multi-messenger astronomy
  - Connecting different kinds of observations of the same astrophysical event or system
  - EM or particle signal may provide complementary information about the GW source
- Even for electromagnetically quiet GW emissions, reconstructed GW waveforms can be inverted to provide precise estimations of source parameters
- The LSC and Virgo have developed (or are developing) collaborations with many EM/astronomers and particle astrophysicists

Open Questions for Multimessenger Observations with Gravitational Wave Detectors?

1. **What is the speed of gravitational waves**, subluminal or superluminal ?
2. Does Einstein's theory of general relativity remain valid in the strong field regime?
3. Does gravity violate parity?
4. Is there a new length scale beyond which general relativity is modified?
5. Which alternative gravity theories can be excluded experimentally?
6. How often can an unidentified electromagnetic transient be explained by a gravitational wave emitter?
7. Is there a high redshiftpopulation of intermediate mass black holes?
8. Can gravitational waves help in explaining the origin of Ultra-Luminous X-ray binaries?
9. Can we search for new physics in the ultra-weak field regime?
10. Can a massive graviton serve as a cold-dark-matter candidate ?
11. What fraction of the cosmic source's energy is emitted in the form of gravitational waves?
12. **Can gravitational wave detectors provide an early warning to electromagnetic observers** to allow the detection of early light curves ?
13. Do gravitational measurements of distance agree with the concordance cosmology?
14. What is the mass spectrum and spin distribution of black holes ?
15. Are there extra gravitational wave polarizations?
16. Is there a significant non-axisymmetriccrust or core dynamics associated with SGRs?
17. **What is the precise origin of SGRs ?** (e.g., What is the mechanism for GW and EM emission and how are they correlated?)
18. Is there a fundamental difference between giant and common SGRs?
19. Do quark stars exist?
20. Can we exclude or confirm some of the SGR models?
21. What is the origin of pulsar glitches?
22. What is the composition and structure of neutron stars and their cores?
23. What is the tallest mountain that can be supported by neutron stars?
24. Can we use GW-EM observations to guide or EM+null GW results to distinguish the local extragalactic SGR contributions from the short GRB population?

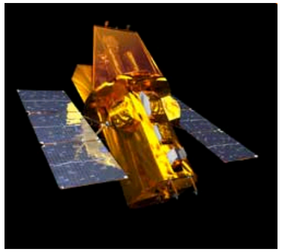
Open Questions for Multimessenger Observations with Gravitational Wave Detectors?

25. What is the nature of gravitational collapse?
26. What is the relationship between the supernova progenitor and remnant (e.g., final mass and spin)?
27. If the supernova remnant is not a black hole, how does it behave? (e.g., a transient hypermassiveremnant with unstable modes or collapse to a BH?)
28. **What happens in a core collapse supernova before the light and neutrinos escape?**
29. What is the delay in between neutrinos and gravitational waves in a core collapse supernovae?
30. What is the role of anisotropic neutrino emission in supernovae?
31. What is the mass of a neutrino?
32. Can we see core collapse supernovae in gravitational waves that are not visible in neutrinos?
33. Is there an electromagnetically hidden population of core collapse events?
34. How many dynamical scenarios are associated with core collapse supernovae? Can we distinguish between them?
35. Can pulsar birth kicks result in detectable gravitational waves?
36. What is the time delay between the electromagnetic brightening and the core collapse of a supernova?
37. What are the properties of the core collapse supernova progenitor?
38. What is the role of the rotation and magnetic fields in stellar core collapse?
39. What is the origin of long and short GRBs? What is the precise dynamics of each GRB engine?
40. Is there any longer-lasting central engine left over from the GRB explosion, and what's its nature?
41. **Are there electromagnetically hidden populations of GRBs?**
42. Does the hypothesized low luminosity GRB population exist?
43. Can we have direct inferences on the GRB jet parameters from gravitational waves?
44. Can we estimate properties of the nuclear equation state using short GRBs?
45. Can we relate the luminosity distribution of GRBs to beaming and the central engine mechanism?
46. What is the relationship between the parameters of a compact binary system and it's electromagnetic and neutrino emission?
47. **What GRB progenitor models can we confirm or reject?**
48. Are there other (sub)classes of GRBs? Do choked GRBs exist? What is the origin of choked GRBs? What is the cosmic population of choked GRBs?
49. What are the engines producing high energy neutrino and gravitational wave emission together?
50. What is the dynamics/energeticsof joint high energy neutrino and gravitational wave emitters?
51. What is the electromagnetic emission of binary neutron star coalescence?
52. What is the electromagnetic emission of a neutron star-black hole coalescence?
53. Is there any electromagnetic emission from binary black hole coalescence?
54. What is the nature of XRFs and their relationship to long GRBs?
55. **Is it possible to construct a competitive Hubble diagram based on gravitational wave standard sirens?**

… and dozens of other other exciting questions are waiting to be answered by the community!

Multi-messenger Approaches

connecting different kinds of observations of the same astrophysical event or system



"ExtTrig" strategy:

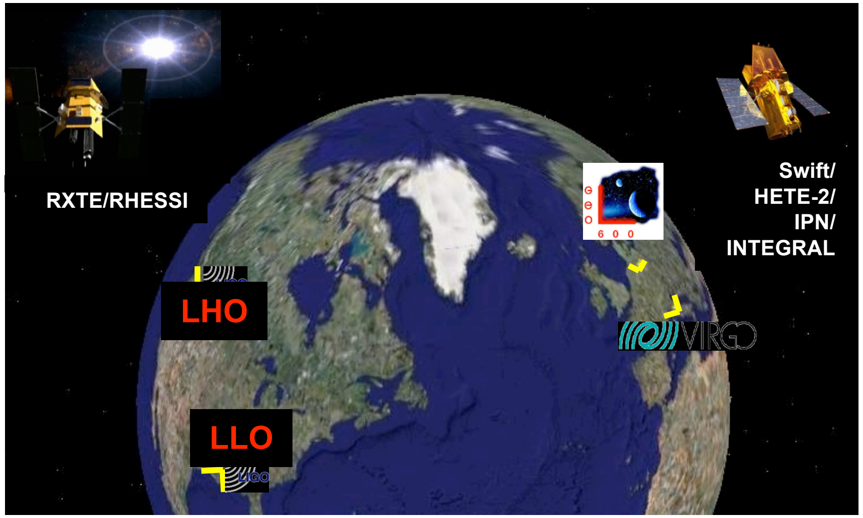
Telescopes, Satellites or other external entities → Flow of trigger information → **GW**

"LOOC UP" strategy:

Image courtesy ROTSE collaboration

GW → Flow of trigger information → **Telescopes, Satellites or other external entities**

Advantages of external triggers for GW searches



– Establish astrophysical observation based association between gravitational waves and electromagnetic or particle observations

- Gamma-ray transients (GRBs, SGRs)
- X-ray transients
- Optical transients
- Radio transients
- Neutrino events
- …

– Correlation in time (and direction) between a GW event candidate and the astrophysical trigger event should provide confident detection of GWs

– Better background rejection, higher sensitivity to GW signals

Information from External Observations

1. Trigger Time

   Search within an astrophysically motivated trigger time window

   ->higher detection probability at fixed false alarm probability

   ->better limits in absence of detection

2. Source Direction

   Search only the relevant portion of the sky or

   Veto candidates not consistent with expected Δt

3. Frequency Range

   Frequency-band specific analysis of data set (e.g. SGR QPOs)

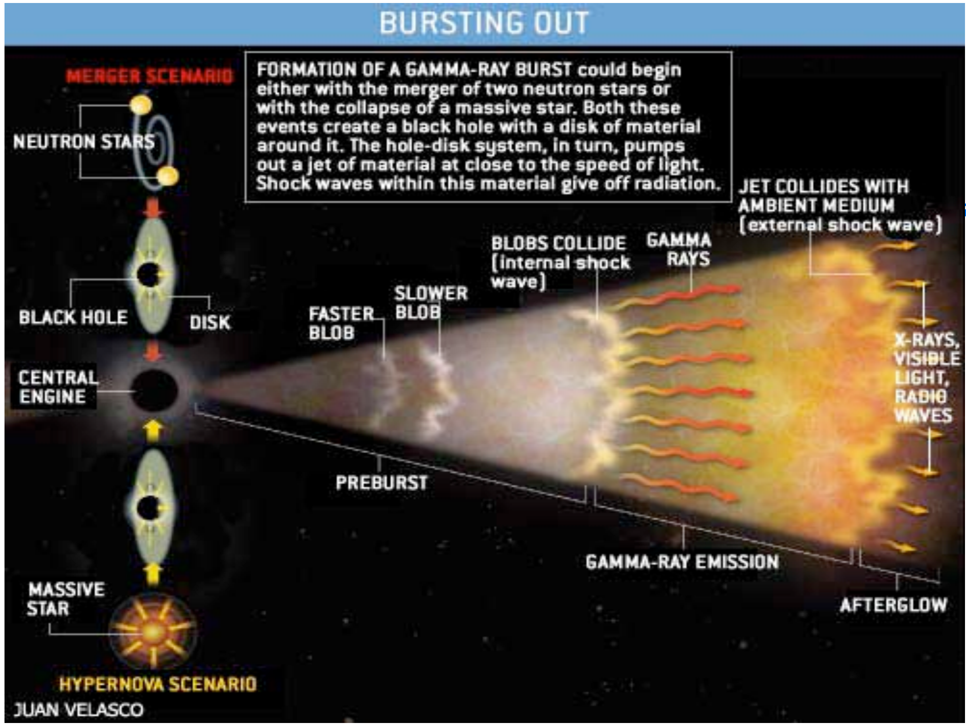
4. Progenitor Type

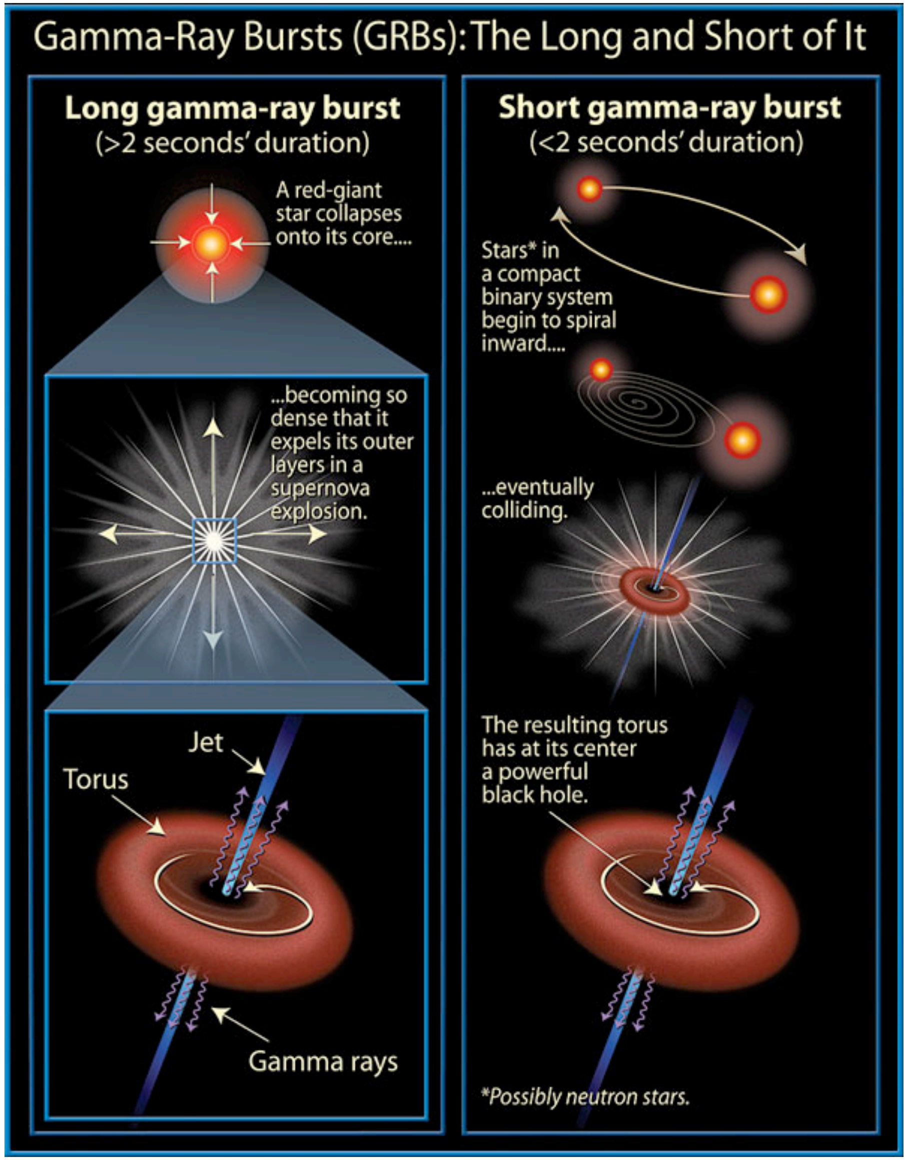
   Model dependent search can be performed, e.g.

   Search for burst (long GRBs, hypernovae)

   Search for CBC (short hard GRBs)

Gamma-ray bursts





GRBs are the result of catastrophic events

- Long GRB:
  - Core-collapse hypernovae
  - Modelling is complicated - GW emisssion is not well understood
  - Use "burst" detection methods (less sensitive, more robust)
- Short GRB:
  - Coalescense of NS-BH or NS-NS binaries
  - Inspiral due to GW emission, clean signal: post-newtonian expansions, numerical relativity
  - Use "matched filtering" (more sensitive, but only for precise waveform)

GRB triggers mostly from Swift; also from IPN, INTEGRAL, HETE-2.
GRB Coordinates Network (GCN): time, sky position, redshift.

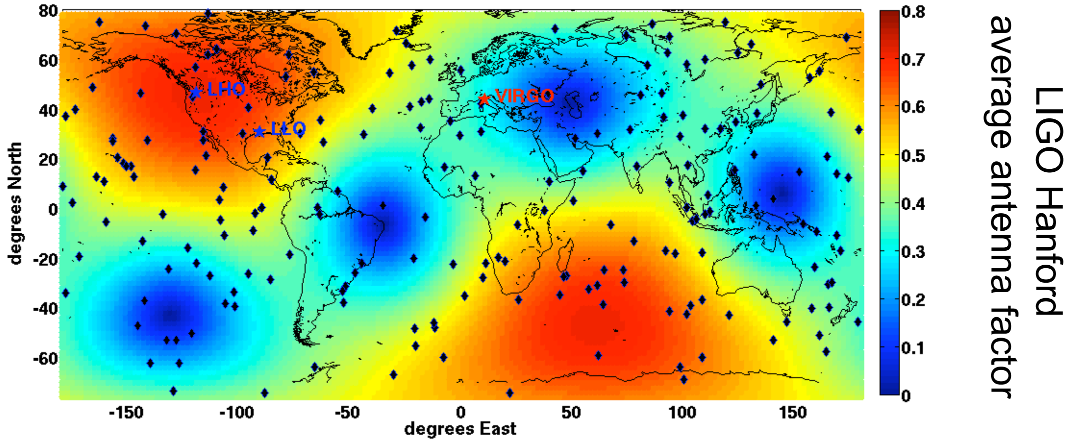
Astrophysical Event Triggered Searches

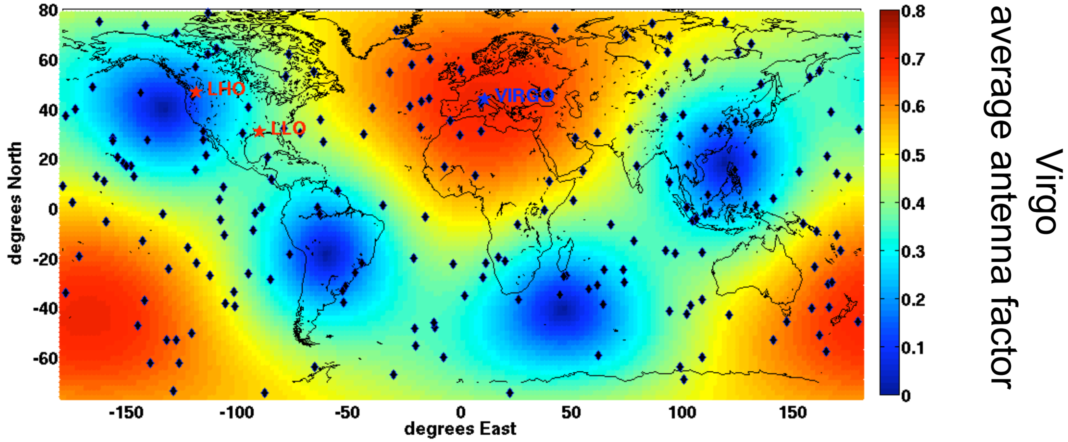
The GRB sample for the LIGO-VirgoS5/VSR1 run

- **212 GRB triggers** from Nov. 4, 2005 to Oct. 1, 2007
  - ~70% **with double-IFO coincidence LIGO data**
  - ~45% **with triple-IFO coincidence LIGO data**
  - ~15% **short-duration GRBs**
  - ~25% **with redshift**
- **during S6/VSR2 run, GRB triggers will be mostly from Fermi+Swift**

  ➔ factor of ~3 increase in trigger rate

GRB triggers were mostly from Swift; some were from IPN3, INTEGRAL, HETE-2





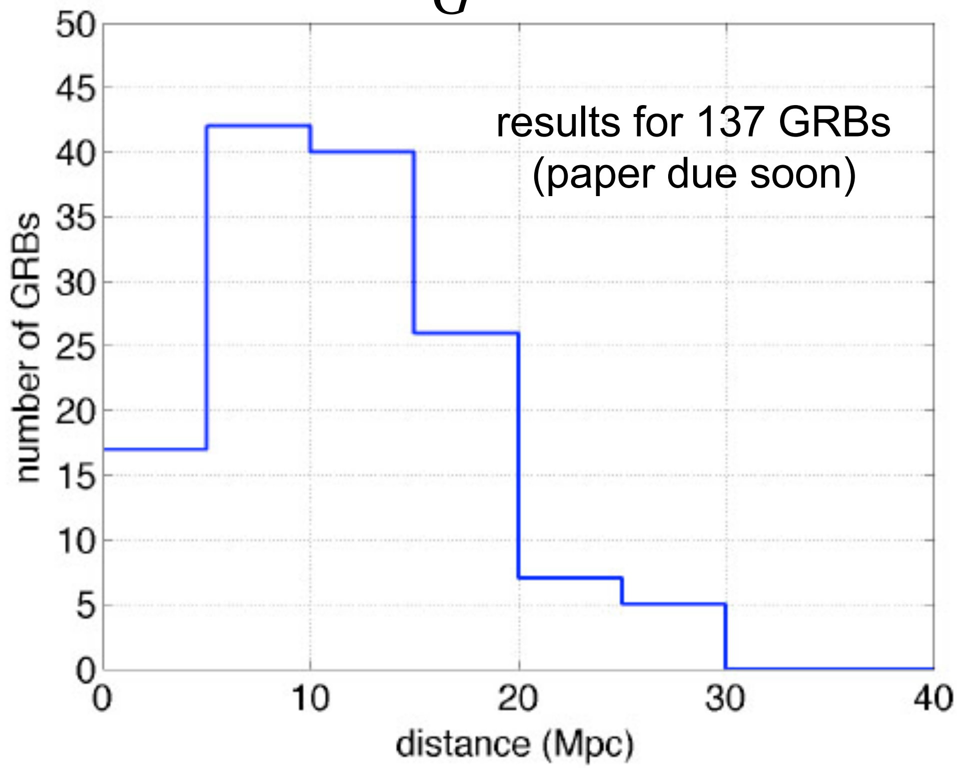
Search for gravitational-wave burst (GWB) counterparts to GRBs (S5/VSR1 run)

- used to search for GW counterpart to both long and short GRBs
- burst search is model-independent
- targets GW signals less than ~few seconds
- fully coherent search which cross-correlates data streams from different interferometers
- set 90% upper limits on strain for each GRB
- assuming energy emitted in GW

$$E_{\mathrm{GW}} = 0.01\, M_{\mathrm{sun}},\ f_0 = 150\ \mathrm{Hz}$$

$$\boxed{\Rightarrow D \sim 15 \left(\frac{E_{\mathrm{GW}}}{0.01\, M_{\mathrm{sun}}} \right)^{1/2} \mathrm{Mpc}}$$

$$E_{\mathrm{GW}} \approx \frac{\pi^2 c^3}{G} D^2 f_0^2 h_{\mathrm{rss}}^2$$



$$V \propto D_{\mathrm{reach}}^3 \propto h_{\mathrm{IFO}}^{-1/3}$$

for Advanced LIGO-Virgo
D ~ 150 Mpc

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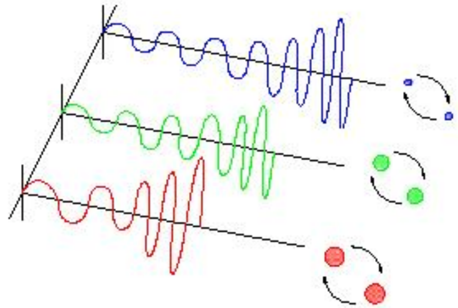
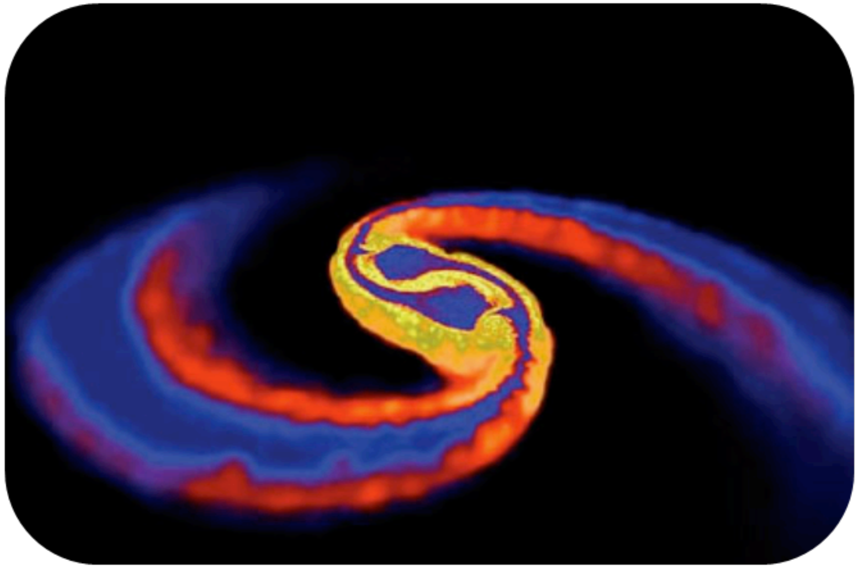
Search for GW inspiral signals from GRBs

- used to search for GW counterpart to short GRBs
  - there is evidence that short GRBs are nearer
- search makes use of inspiral templates
- target GW inspiral signals from coalescing masses in the range $1\ M_\odot < m_1 < 3\ M_\odot$, $1\ M_\odot < m_2 < 40\ M_\odot$
- during S5 run, inspiral search range for NS merger event was ~15 Mpc (SNR=8)
- **for S5 run, 21 short GRBs have been analyzed; no candidate events found**
- **set lower limit on distance for each GRB**





NS-NS merger simulation
Price and Rosswog

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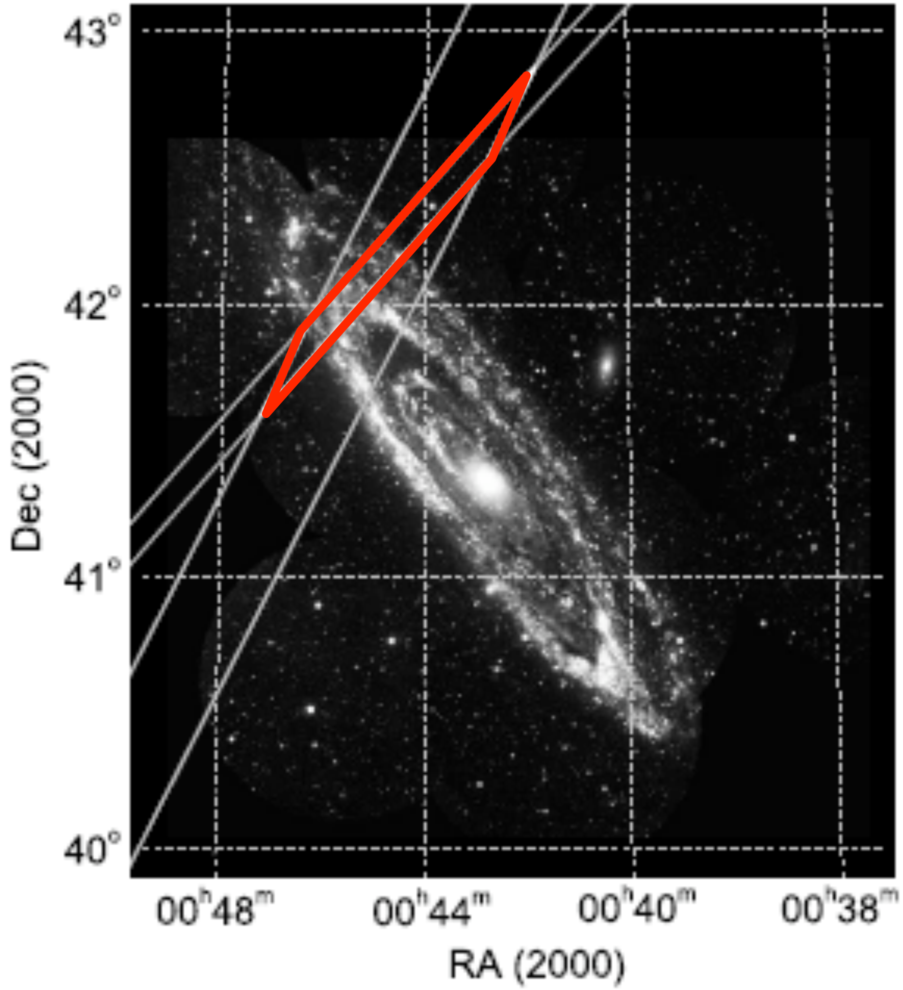
GRB 070201: In M31 or beyond? GRB or soft gamma repeater (SGR)?

- **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)



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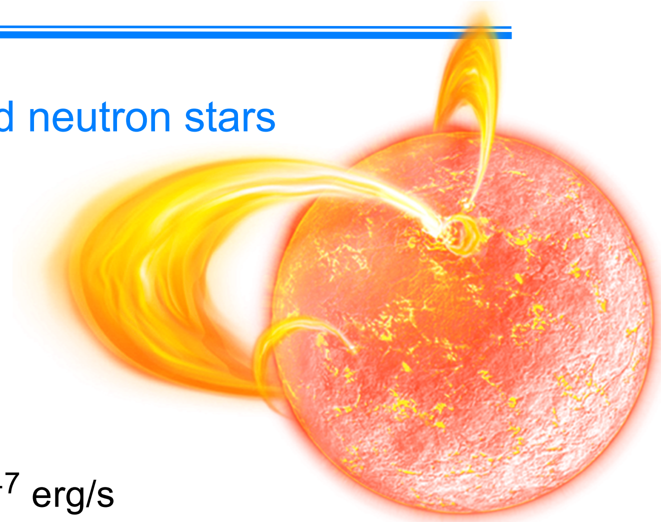
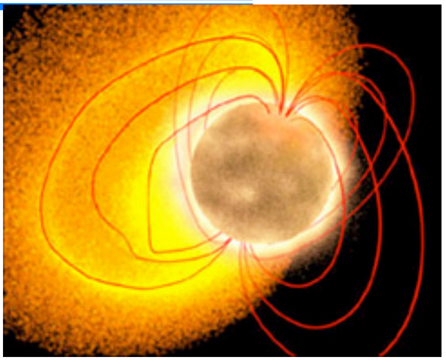
Soft Gamma Repeater (SGR) Flares



- SGRs are believed to be magnetars: highly magnetized neutron stars
  - Neutron stars with magnetic field ~10^{15} G interacting with crust
  - Anomalous X-ray pulsars (AXPs) are essentially the same thing
- Emit short-X & gamma-ray-bursts at irregular intervals
- Occasionally emit flares of soft gamma rays
  - Ordinary flares $E_{EM} \sim 10^{42}$ erg, peak EM luminosity ~ 10^{47} erg/s
  - Some SGRs have produced a ***giant flare*** with energy ~10^{46} erg in GWs
  - Could account for up to 15% of short GRBs
- May induce catastrophic non-radial motion in stellar matter
- Thought to be associated with cracking of the crust
  - Probably excite vibrational modes of the neutron star
  - Quasiperiodic oscillations seen in X-ray emission after giant flares
- Some vibrational modes couple to gravitational waves !
- Galactic SGRs are plausible sources of GWs
  - Can probe what is going on with the star

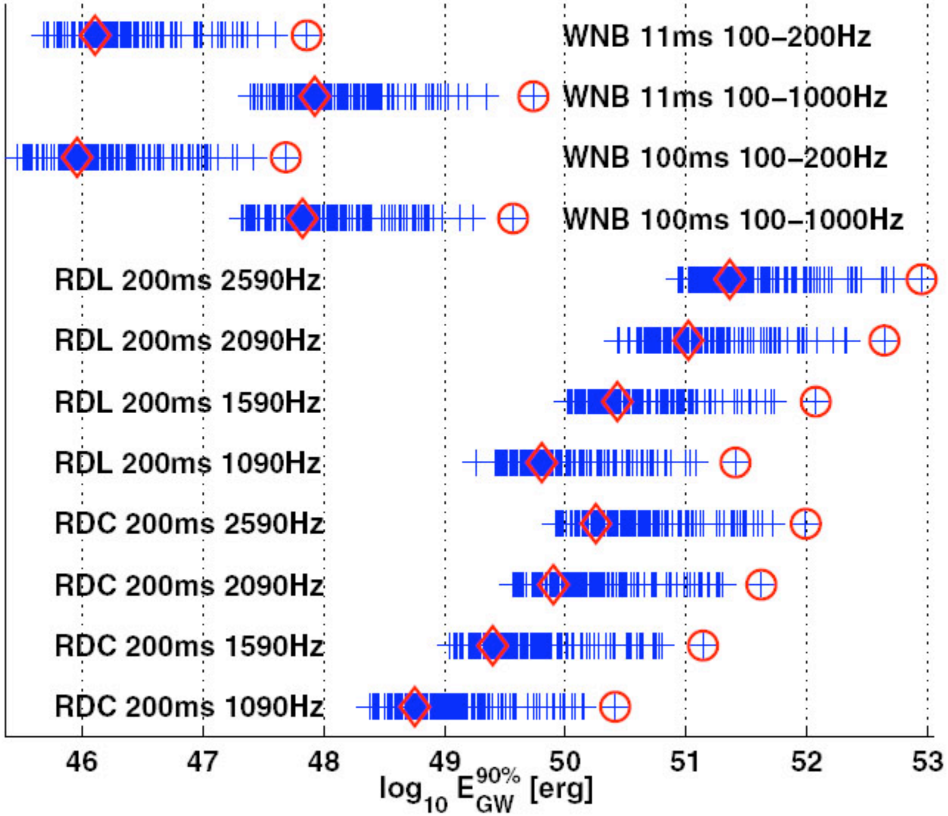
Search for GW bursts coincident with soft gamma repeater (SGR) bursts

Robert Mallozzi (UAH, MSFC)



- SGRs thought to be highly magnetized neutron stars (~1E+15 G)
- most observed SGRs are Galactic
- SGR bursts from crustal deformations and catastrophic cracking may be accompanied by GW burst emission

90% UL on energy of GW emission coincident with 215 SGR bursts (PRL, 2008, 101, 211102)



- search for excess power from GW burst relies on SGR lightcurves from Interplanetary Network (IPN3), including Swift, Konus-Wind, etc.
- 191 bursts from SGR 1806-20 and SGR 1900+14 have been analyzed for coincident GW emission using LIGO
- some of the upper limits set on GW energy emission already explore some SGR models

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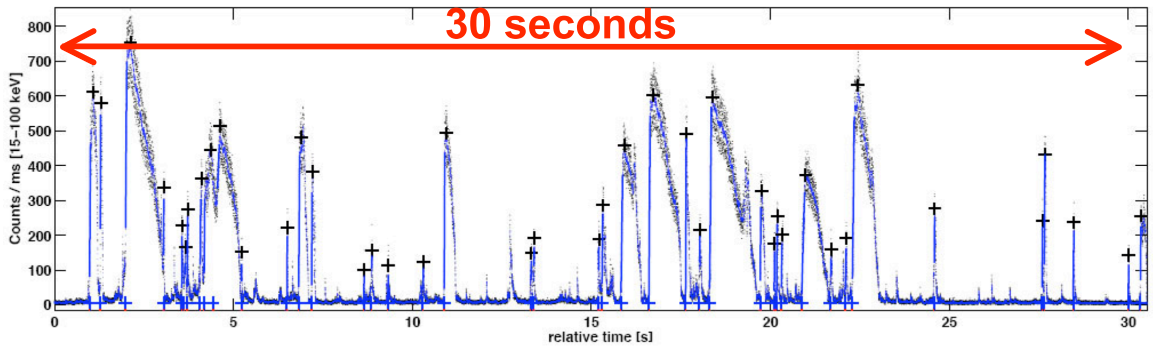
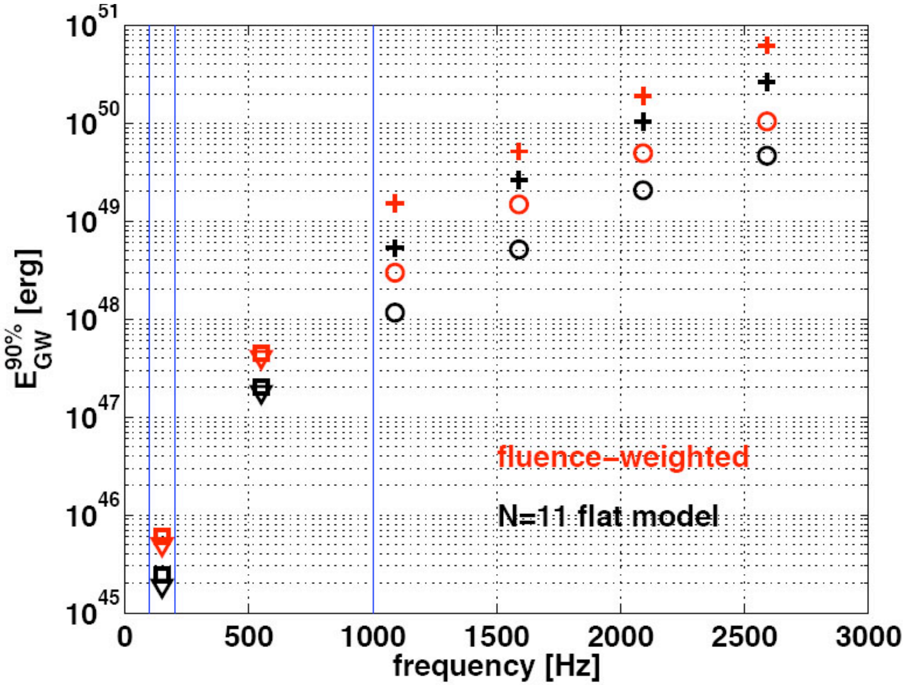
Search for GW burst emission from an SGR storm (SGR 1900+14)

SGR 1900+14 lightcurve (Mar 29, 2006) from Swift-BAT telescope



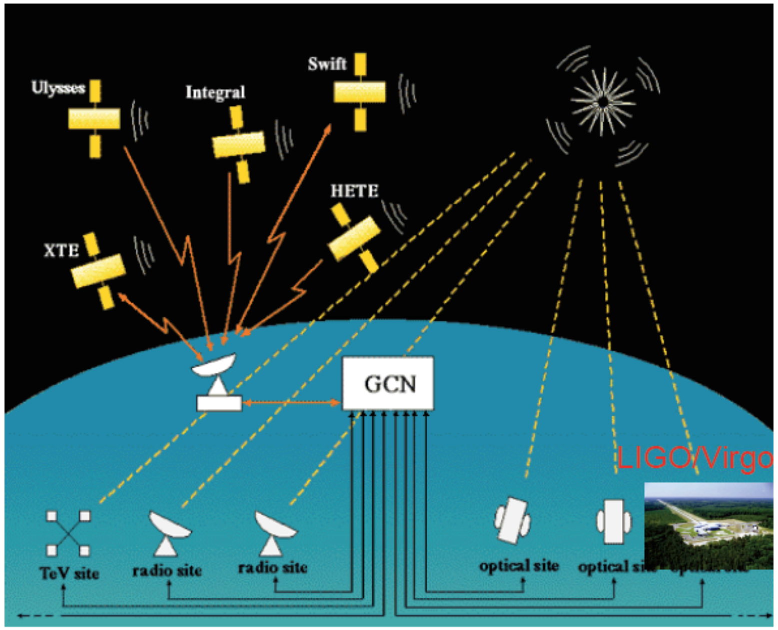
- assume GW signal accompanies each storm episode
- "stacking" power from different storm episodes leads to increased GW search sensitivity
  ➔ requires precise timing from SGR lightcurve for start time of each storm episode
- resulting upper limits on GW energy emission ~order of magnitude lower than non-stacked analysis (arXiv:0905.0005)



Current focus: S6-VSR2

- LIGO-Virgo started S6-VSR2 data taking run in mid 2009.
- Big goal for data analysts: online / low latency searches

- GRB & SGR - triggered burst searches:
  - Automatically run, triggered by GCN notice / SNEWS alert
  - Expect GRB trigger rate of ~1 per day (high-confidence GRBs)
  - Plan to have analysis results within a few hours of GRB trigger
  - Availability of results within ~hours means we can contribute in timely manner to discussion of interesting GRBs
  - For interesting GRBs, disseminate results to science community within ~week
    - Currently: ~1 day latency from receipt of event trigger to final results for Swift GRBs
    - Handling of Fermi GRBs, SNEWS alerts being implemented

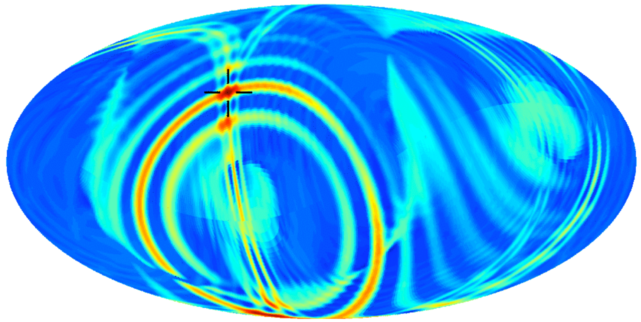


http://gcn.gsfc.nasa.gov/

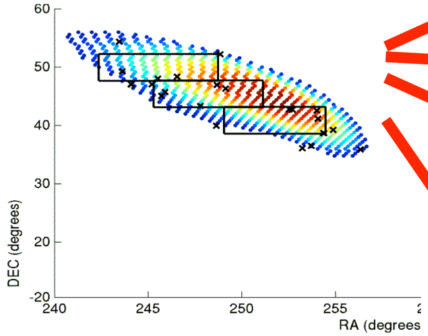
LOOC UP : Locating and Observing Optical Counterparts to Unmodeled Pulses in GW

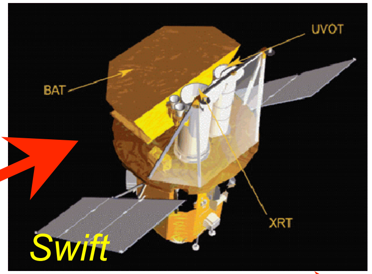
GW detectors are nearly “all-sky” sensitive while X-ray/optical telescopes are not…

LoocUp concept:



- Analyze GW data promptly to identify possible event candidates and reconstruct their apparent sky positions; alert telescopes via automated interface
- Look promptly for relatively short-lived flash / afterglow
  - Have been observed for some GRBs, supernovae
  - We’d be looking for a fairly significant (i.e. Bright) optical signal
  - Try to capture an EM transient that would otherwise have been missed!
  - Expect initial latency of ~30-60 minutes from GW trigger to imaging
- Follow up a fairly large number of low-threshold triggers
  - A few per week, or maybe up to one per day
- Be ready to call on more telescopes if we catch an exceptional event candidate
  - First attempts underway
- In detection era, (GW) multi-messenger astronomy will become even more interesting…





Other telescopes…

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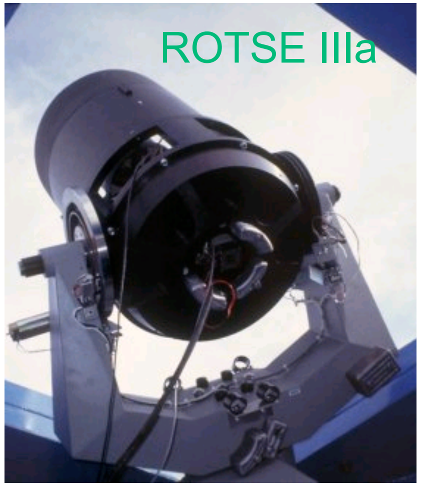
Wide Field Optical Follow-ups

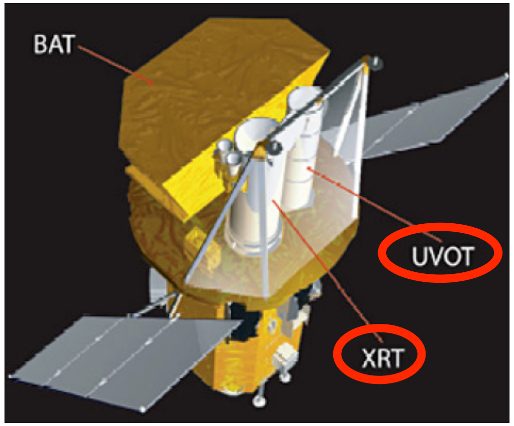
- Partners: :
  - ROTSE, TAROT, SkyMapper, QUEST, Palomar Transient Factory, Pi in the Sky, LONEOS
- Science case:
  - Such scopes are designed to find *transients in large error boxes*
  - Automated pointing
  - Software is appropriate: trigger acceptance, transient classification software, etc.
- Primary astronomical sources:
  - GRB afterglows, galactic SNe, macronovae
- *Low latency analysis* (5 min – 1 hour)
- Plans for S6/VSR2:
  - GW data points telescopes (~ once per week)
  - Presence/absence of transient provides additional coincidence test
  - First exercised in December 2009
    - 8 triggers passed, 4 followed up

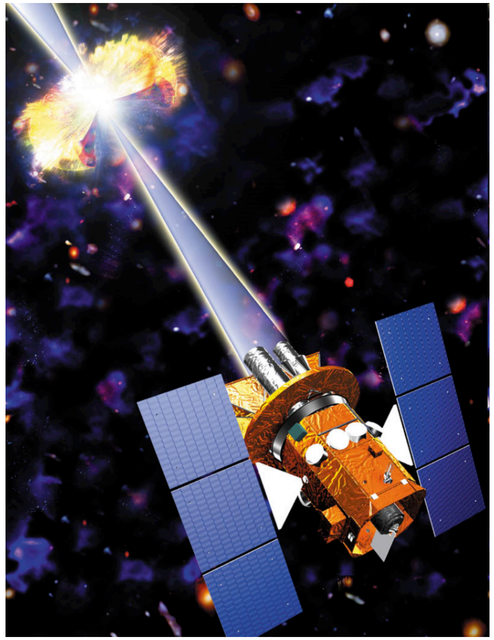
Name	FOV (Deg)	Aperture (m)	Locations
ROTSE III	1.85×1.85	0.45	Siding Spring Obs, Australia McDonald Obs, USA Mt. Gamsberg, Namibia National Obs of Turkey
TAROT	1.85×1.85	0.25	La Silla Obs, Chile Calern Obs, France
SkyMapper	2.4×2.4	1.3	Siding Spring Obs, Australia
QUEST	4.5×3.5	2.2	La Silla Obs, Chile
PTF	3.4×2.3	1.2	Palomar Obs, USA
Pi of the Sky (prototype)	20×20	0.07 (effective)	Las Campanas Obs, Chile
Pi of the Sky (final)	20×20 or 40×40	0.28 or 0.14 (effective)	La Palma & Tenerife?



NASA Swift satellite

- Primary astronomical sources: short hard GRBs, galactic SNe
  - High risk/high reward: definitively identify binary mergers as progenitors of short hard GRBs
- Target of Opportunity (ToO) observations using Swift XRT and UVOT to search for X-ray, UV afterglows
- *Low latency analysis* – sky-localized GW triggers passed to Swift with 5-15 minute latency
  - Sky localization typically 5 deg x 5 deg
  - Enhanced pointing precision using galaxy targeting (catalog: Kopparapu et al. 2008, ApJ **675**, 1459)
- First exercised in December 2009
  - 1 trigger passed to Swift, false alarm rate of ~ 1/day
  - Swift observed beginning 12 hours later
- Resumed when Virgo interferometer came back on line in August





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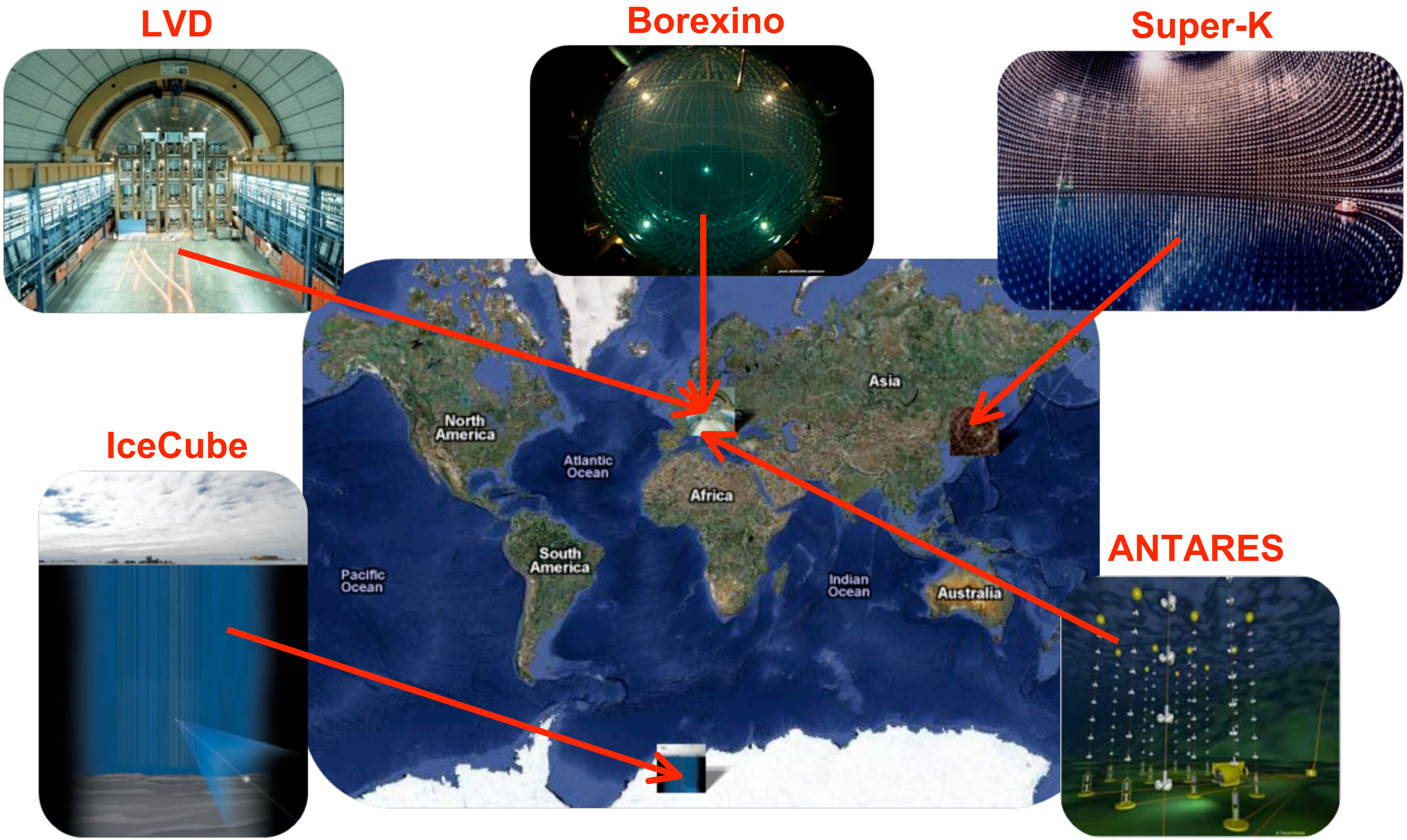
Gravitational waves and neutrinos
(nascent collaborations)



Supernova early warning system (SNEWS)

http://snews.bnl.gov

- Alert system which would send out notification of high-confidence SN to astronomical community a few minutes after detection of neutrino burst by multiple detectors

- LIGO-Virgo is signed up to get these alerts in the control rooms

- There is a proposed joint GW-neutrino search which will complement the existing infrastructure and procedures which are in place in the event of a SNEWS alert

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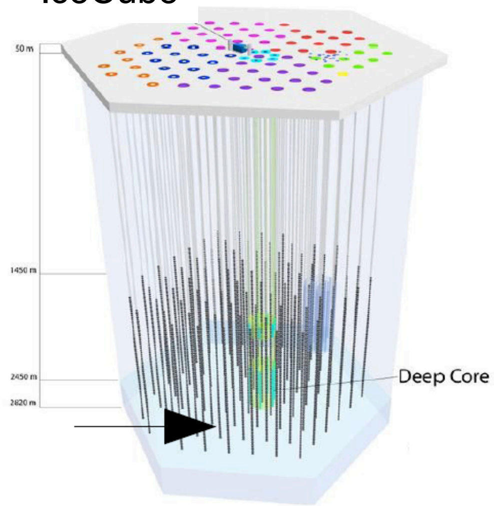
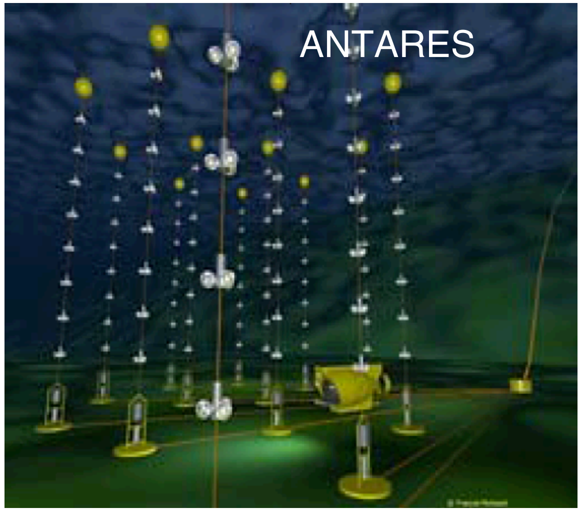
High Energy Neutrinos: ANTARES and IceCube

- Motivation: high energy neutrinos are 'clean' messengers of high energy catastrophic astrophysical events
  - 10s GeV < E_ν < 100 TeV
  - Weakly interacting; travel cosmological distances
- Possible sources of correlated GW+HEνs
  - GRBs (short, failed), SGRs, micro-quasars
    - All have plausible scenarios for Heν production
- HE-ν collaborators
  - ANTARES – 12 string PMT array at 2500 m depth in the Mediterranean Sea
  - IceCube – ~ 1 km^3 59 string PMT array located at the South Pole station
  - Directional search: < 2 deg x 2 deg angular resolution
- *Offline analysis* - search for coincident sky positions in a conservative time window
  - Background rates for satellites improve GW-EM coincidence:
    - $FAP_{GW} \times FAP_{EM} \ll FAP_{GW}$
- Data sharing agreements in place
  - Beginning searches of S5/VSR1 data

IceCube





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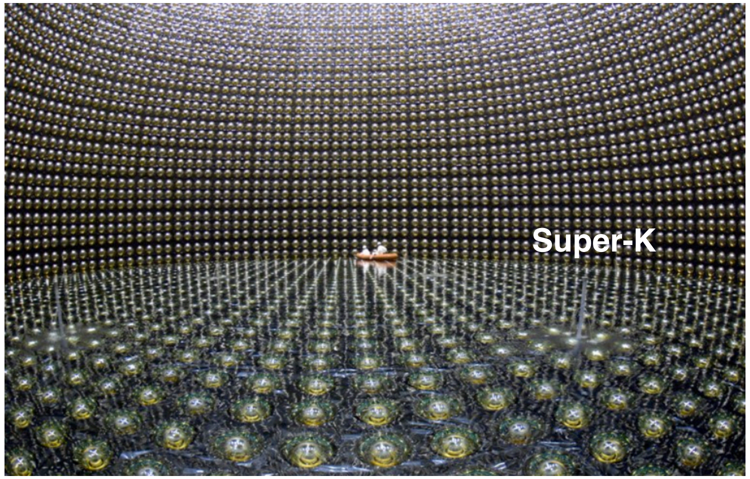
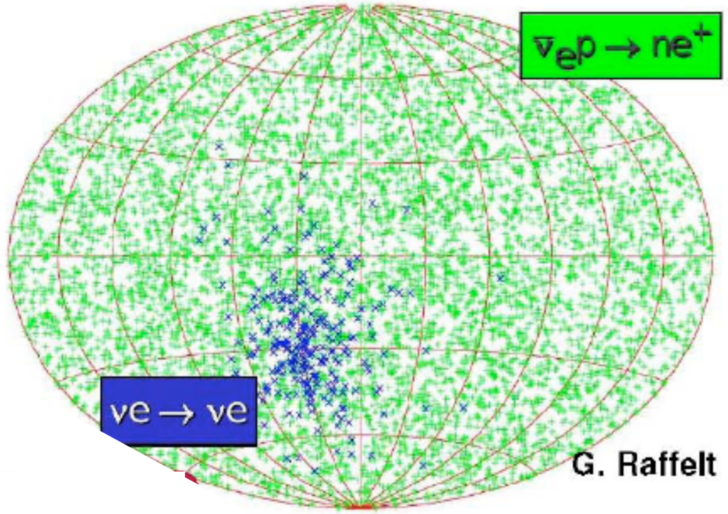
Low Energy Neutrinos: Super-K, LVD, Borexino

- Low energy neutrinos are 'clean' messengers of physics of SNe core collapse
  - E_ν ~ 10s MeV
  - Several mechanisms for GW production from SNe;
- For SNe, LIGO probes Milky Way galaxy
  - Small time delays (< 1 s) between GW and ν signals
  - Super-K: expect 8000 νs from SNe located 8.5 kpc
- Discussing collaboration with several LE-ν projects/collaborators
  - Super-K
  - LVD
  - Borexino
- *Offline analysis* - search for coincident triggers with correlated sky positions in a narrow time window
  - Directional search; 4 deg x 4 deg resolution for Super-K; worse for LVD and Borexino





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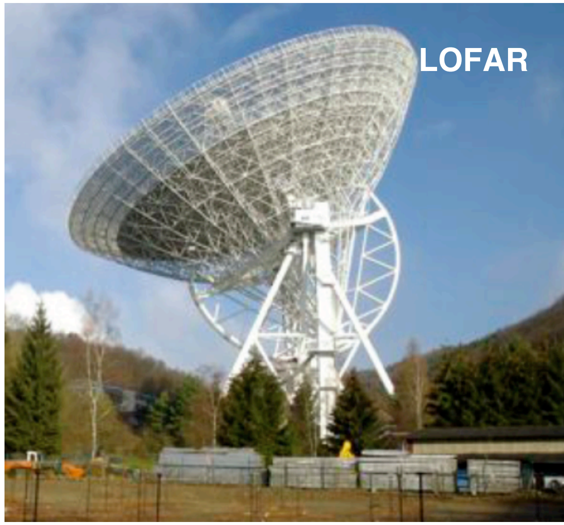
Joint GW-radio searches

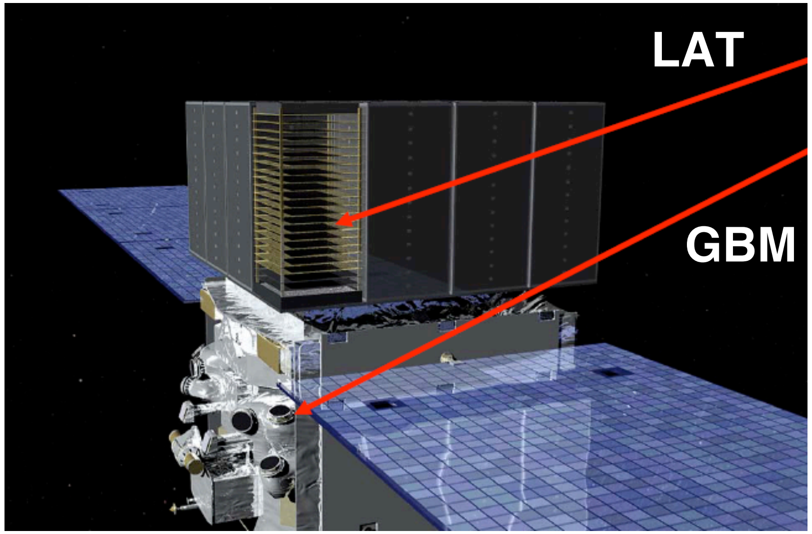
- Plausible sources of joint GW-radio emissions include:
  - BNS mergers (magnatar component, plasma excitation)
  - GRB radio afterglows (< minutes)
  - Pulsar glitches
  - Unidentified transients
- *Offline analysis*
  - Possibility for low latency search; rapid radio follow-up
- Potential partners:

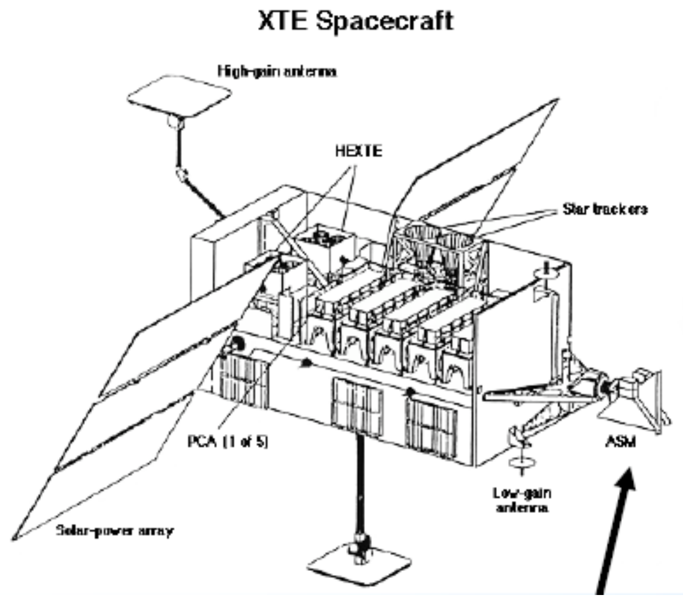


Instrument	Band	Type	Field of View	Slew Time
LOFAR	40-240 MHz	Array	30° beam(s)	Software
ETA	29-47 MHz	Array	Two 30° beams	Software
NRAO Green Bank	300MHz-50 GHz	Dish	0.027 sq. deg. (at 1 GHz)	18°/minute
ARECIBO	312 MHz - 10.2 GHz (ALFA: 1.225 - 1.525 GHz)	Dish	15 arcmin @ 312 MHz 0.5 arcmin @ 10.2 GHz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

NASA Photon Missions

- Similar in spirit to Swift ToO
- However, missions will search for excess power below mission transient thresholds
  - Background rates for satellites improve GW-EM coincidence:
    - $FAR_{GW} \times FAR_{EM} << FAR_{GW}$
- Target sources:
  - GRBs, SGRs, SNe
- Partners (All have wide-field instrumentation):
  - Swift: BAT
  - RXTE: ASM (through 2010)
  - Fermi: GBM, LAT
- *<u>Offline analysis</u>* - search for coincident sky positions in a conservative time window





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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
- Enhanced detectors are currently taking the best data ever
- Advanced detector era is just around the corner
- Significant experimental, astrophysical, theoretical, numerical challenges remain. These must be solved to ensure we extract the best physics and astrophysics from our detectors

- LIGO and Virgo are fully engaged in multi-messenger astrophysics. They are pursuing many modes of multi-messenger astronomy:
  - GW searches triggered by astrophysical events, e.g. GRBs, SGR flares, supernovae,...
  - Joint searches with neutrinos, radio telescopes
  - Electromagnetic follow-up observations of GW event triggers
- These multi-messenger analyses continue to be pursued during the current S6/VSR2 run

- These activities and the nascent collaborations serve as a strong foundation for analyses of future, more sensitive data as an era of regular GW detections is anticipated with advanced LIGO-Virgo.