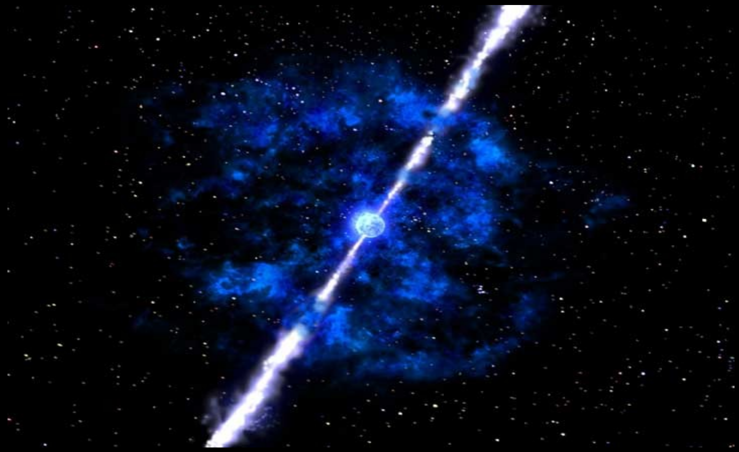
Gravitational Waves Counterparts of Gamma Ray Bursts with LIGO



Jordi Burguet-Castell
Nov 3 2011

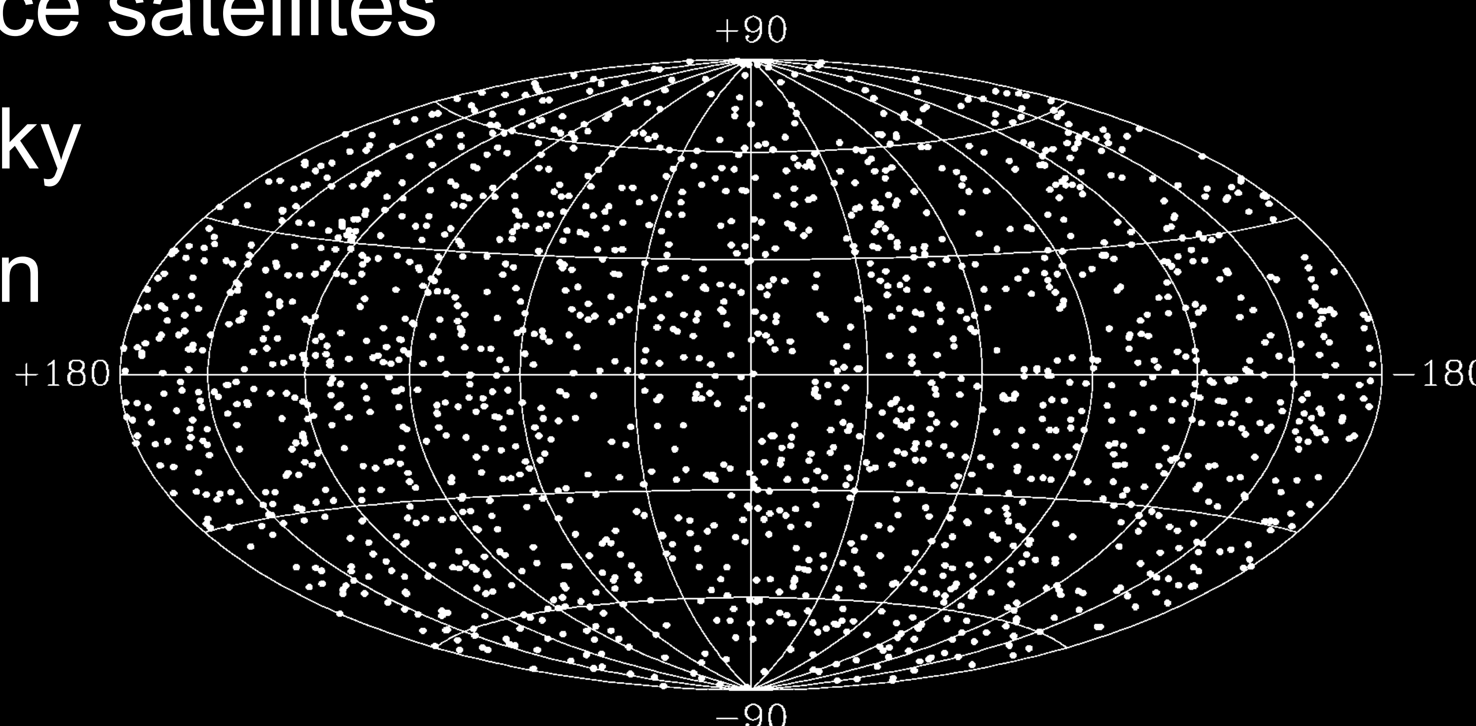
GWs Counterparts of GRBs with LIGO

- Physics of Gamma-Ray Bursts
- Physics of Gravitational Waves
- Interferometers for GWs Detection (LIGO)
- GWs Data Analysis – GRB-related signals
- Results and Conclusions

Physics of GRBs

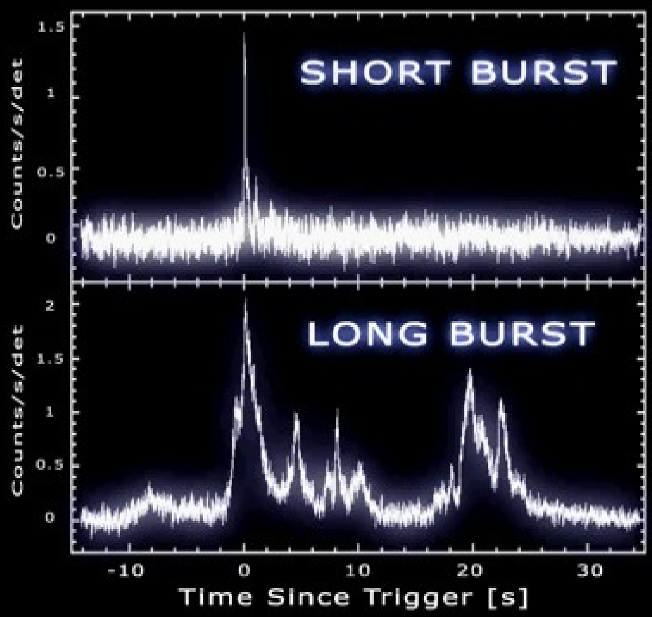
Physics of GRBs

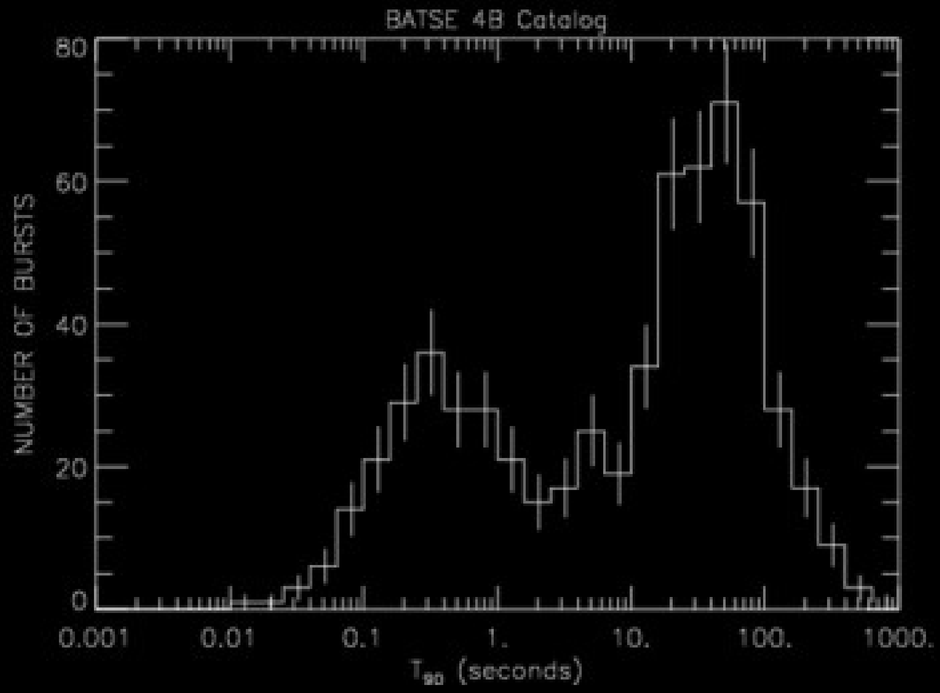
- Bursts of γ-rays - *Most powerful* explosions in the sky
- Discovered in the 60's by nuclear bomb surveillance satellites
- Uniform sky distribution



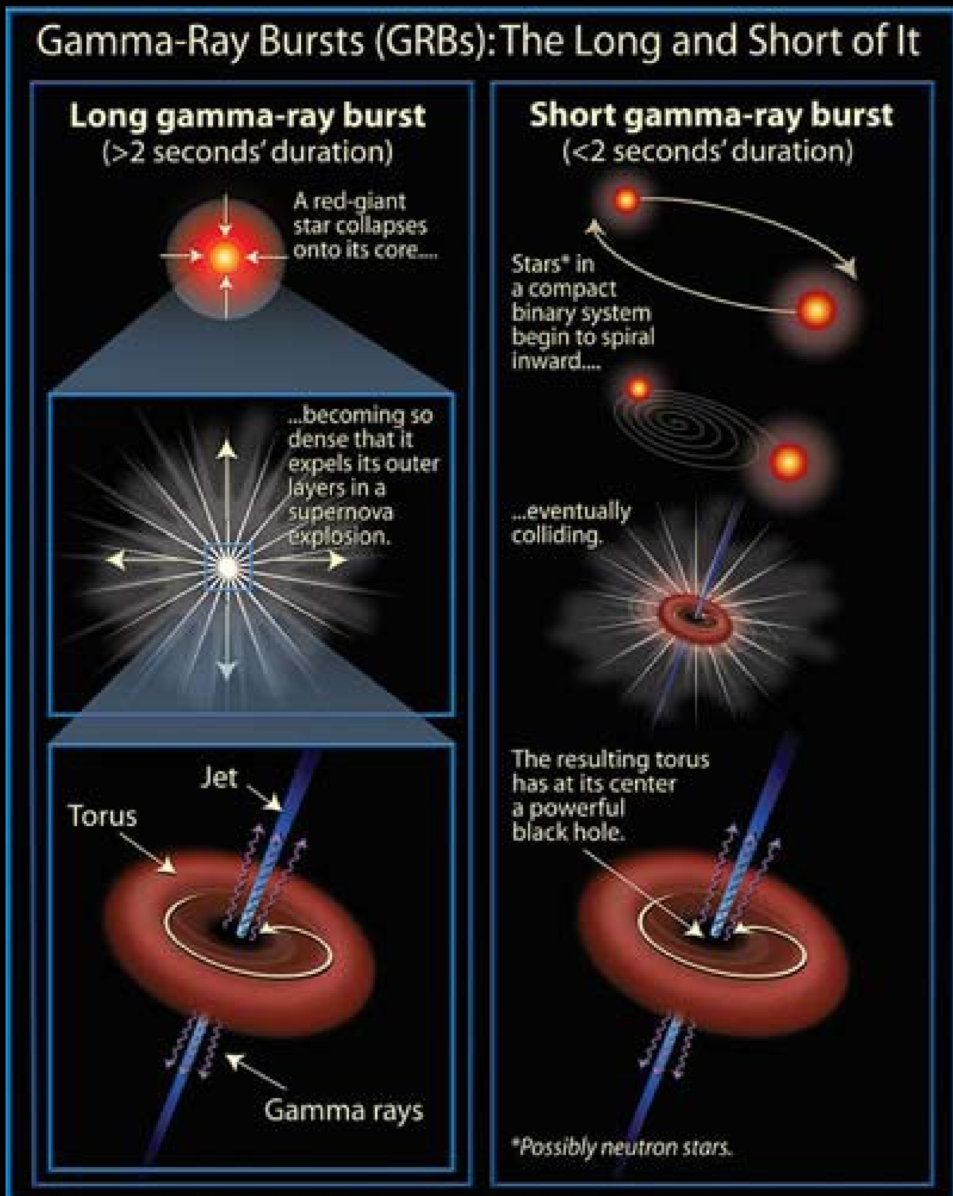
Physics of GRBs

- Two populations:
  - Short & Hard, t $\lesssim$ 2s & peaks at higher energy
  - Long & Soft, t $\gtrsim$ 2s & peaks at lower energy





GRBs models



Long GRBs

- Massive rapidly spinning star collapse and explosion (*hypernova*)

Short GRBs

- Coalescence of a neutron star and a compact object

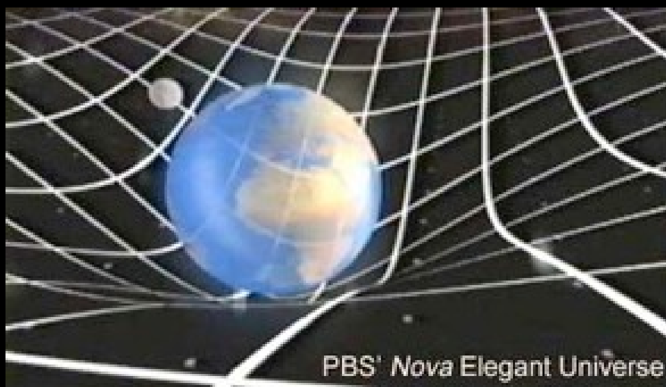
Both:

- Asymmetric, compact, relativistic

Typical distance ~ 1 Gpc

Physics of Gravitational Waves

Gravitational Waves



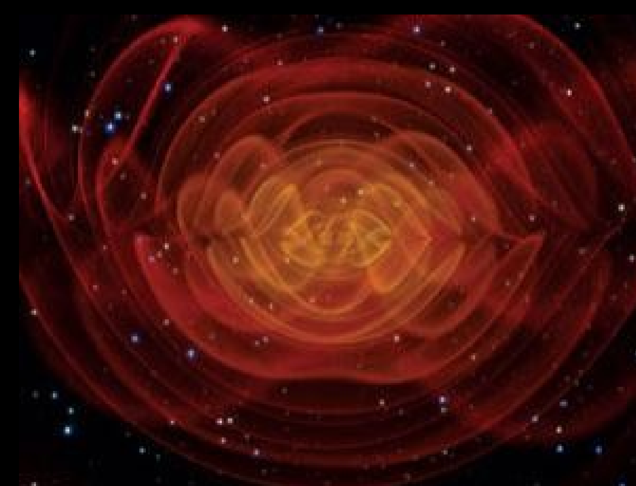
General Relativity $G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$

Mass/Energy tells spacetime how to *curve*

Curved spacetime tells mass/energy how to *move*

One of the predictions of GR: spacetime curvature can **propagate as a wave** (not *in* but *of* spacetime itself)

GW astronomy: a new window on the universe

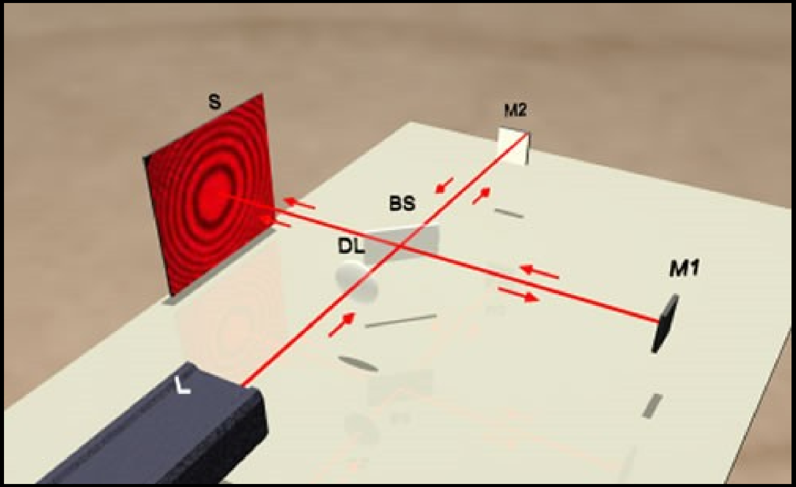


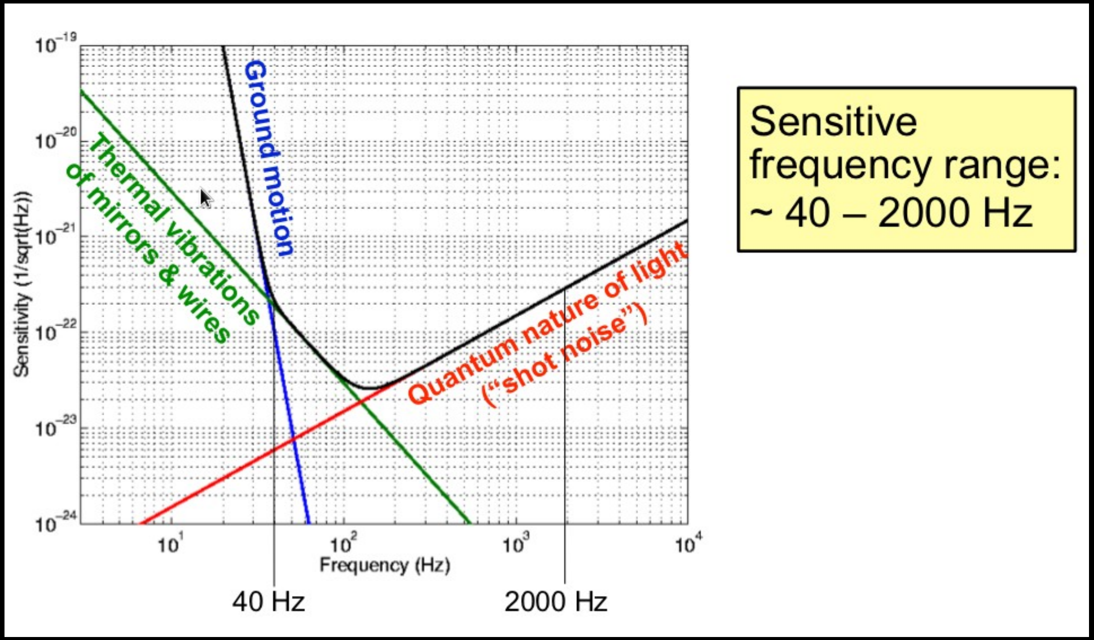
GWs vs EM waves

EM waves	GWs
Space as **medium** for the field	Spacetime **itself**
Incoherent superposition from particles	Coherent motions of huge masses/energy
Wavelengths small compared to sources: images	Wavelength larger than sources: poor spatial resolution
Detectors have small beams	Detectors have large solid angle acceptance
10 MHz and up	Few kHz and down
Absorbed, scattered, dispersed by matter	Very weak interaction
Can measure energy (sensitivity ~ $1/r^2$)	Can measure amplitude (sensitivity ~ $1/r$)
Lots of signal	No direct signal... **yet**

Interferometers for GWs Detection

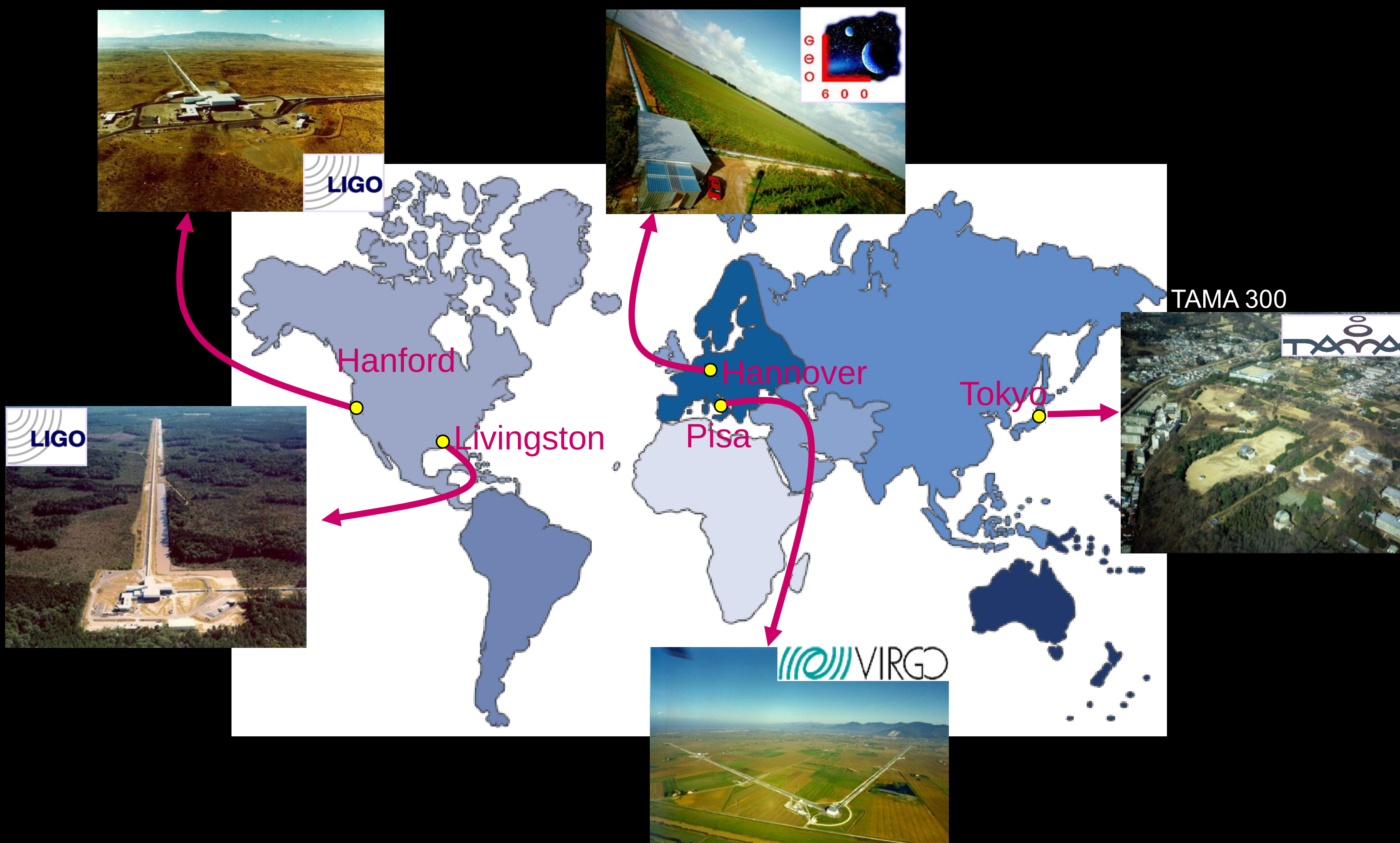
GW Detection with an Interferometer



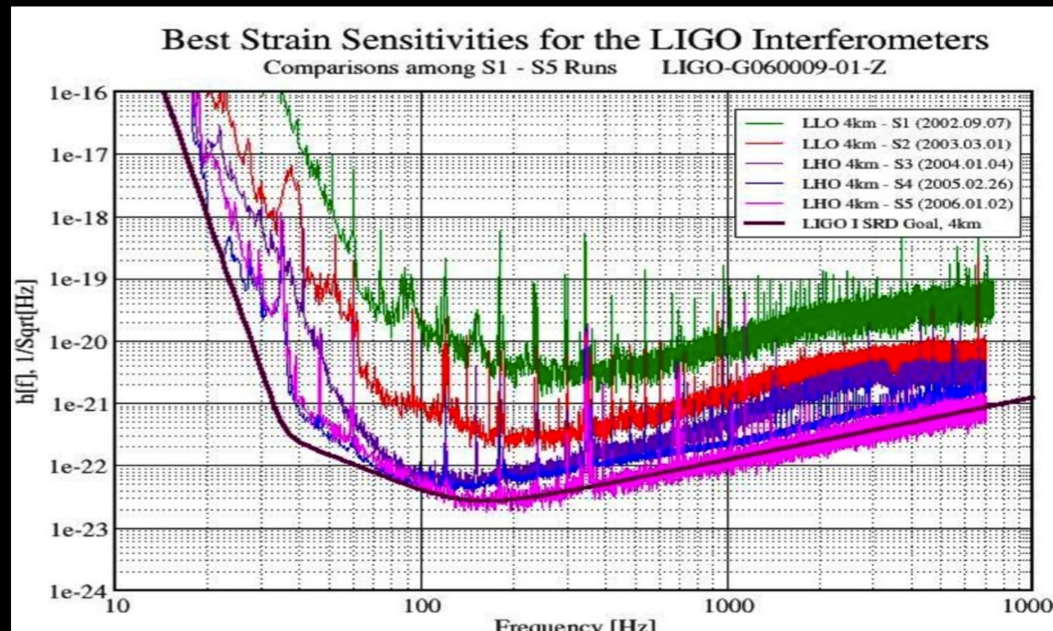


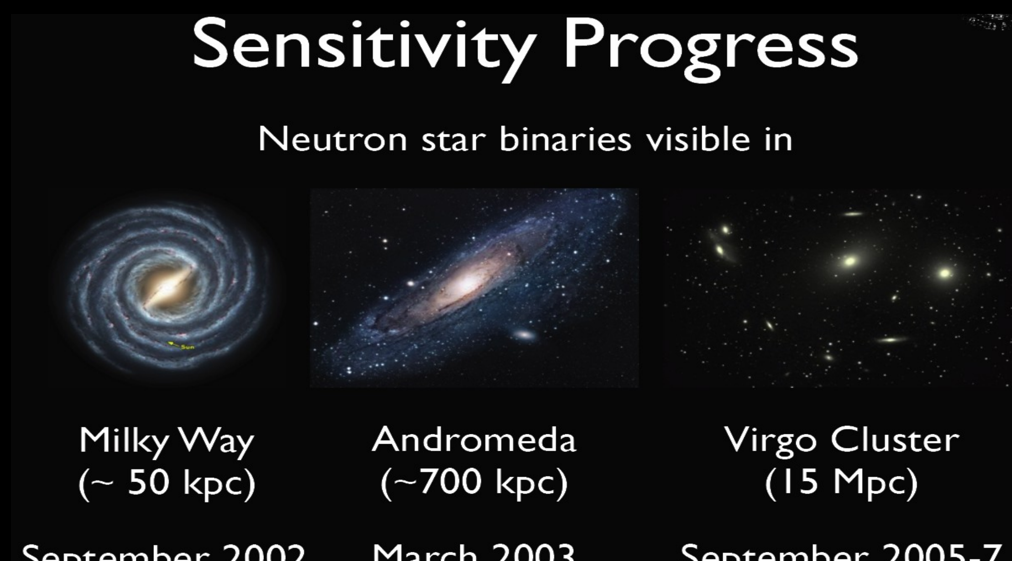
- Photodetector signal depends on the **difference** in **light travel times** in arms
- GWs change differential lengths of arms
- Need to measure ~ 10^{-18} m (proton: ~ 10^{-15} m)

Existing GW Detectors



The LIGO Detectors





LIGO Scientific Collaboration

- Australian Consortium for Interferometric Gravitational Astronom
- The Univ. of Adelaide
- Andrews University
- The Australian National Univ.
- The University of Birmingham
- California Inst. of Technology
- Cardiff University
- Carleton College
- Charles Sturt Univ.
- Columbia University
- Embry Riddle Aeronautical Univ.
- Eötvös Loránd University
- University of Florida
- German/British Collaboration for the Detection of Gravitational Waves
- University of Glasgow
- Goddard Space Flight Center
- Leibniz Universität Hannover
- Hobart & William Smith Colleges
- Inst. of Applied Physics of the Russian Academy of Sciences
- Polish Academy of Sciences
- India Inter-University Centre for Astronomy and Astrophysics
- Louisiana State University
- Louisiana Tech University
- Loyola University New Orleans
- University of Maryland
- Max Planck Institute for Gravitational Physics
- University of Michigan
- University of Minnesota
- The University of Mississippi
- Massachusetts Inst. of Technology
- Monash University
- Montana State University
- Moscow State University
- National Astronomical Observatory of Japan
- Northwestern University
- University of Oregon
- Pennsylvania State University
- Rochester Inst. of Technology
- Rutherford Appleton Lab
- University of Rochester
- San Jose State University
- Univ. of Sannio at Benevento, and Univ. of Salerno
- University of Sheffield
- University of Southampton
- Southeastern Louisiana Univ.
- Southern Univ. and A&M College
- Stanford University
- University of Strathclyde
- Syracuse University
- Univ. of Texas at Austin
- Univ. of Texas at Brownsville
- Trinity University
- Universitat de les Illes Balears
- Univ. of Massachusetts Amherst
- University of Western Australia
- Univ. of Wisconsin-Milwaukee
- Washington State University
- University of Washington

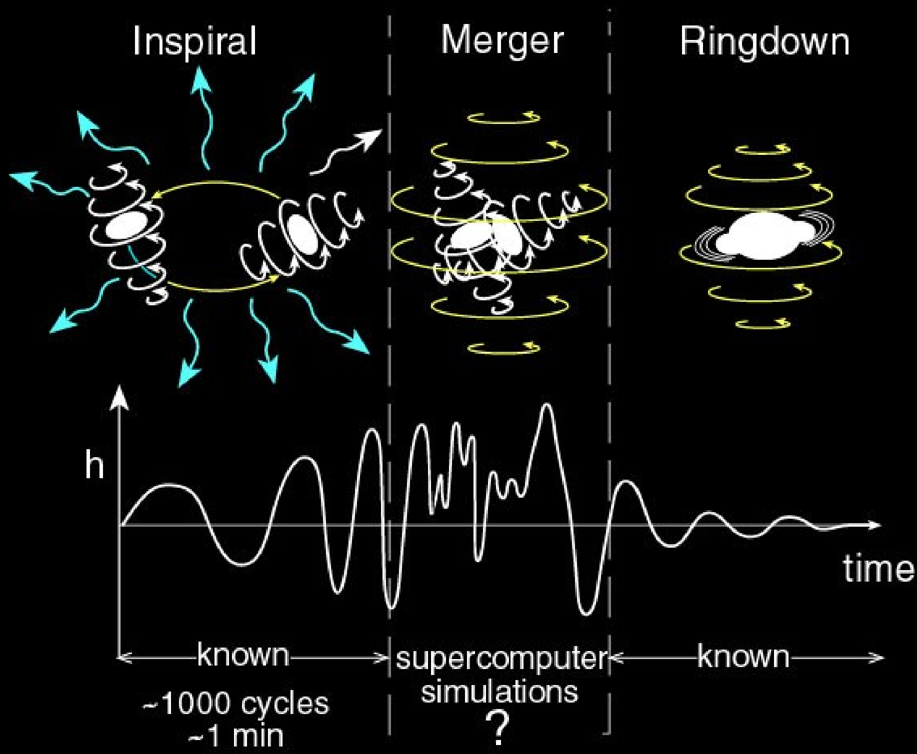
GWs Data Analysis – GRB Search

What Can We Learn?

- Confirm the origin of GRBs
- Determine masses and spins of binary system
- Luminosity Distance: independent of distance ladder
- Neutron Star Equation of State
- Test of strong-field GR

GWs Data Analysis

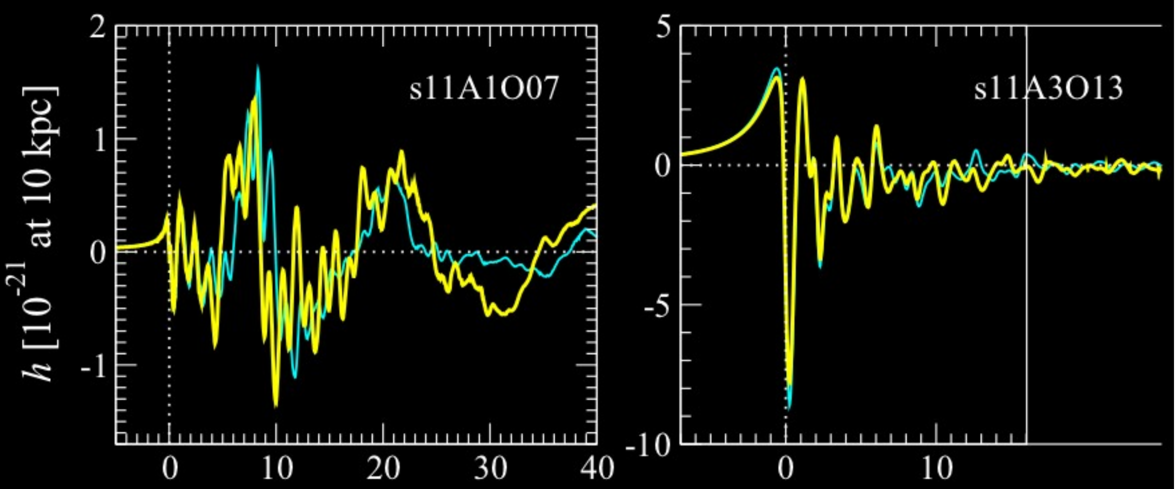
Binary Coalescence



Waveform mostly *known*

→ Template matched filtering

Hypernova



[Dimmelmeier et al., 2008]

Waveform, amplitude *uncertain*

Main emission mechanism unknown

→ "Unmodeled" search

Matched Filtering

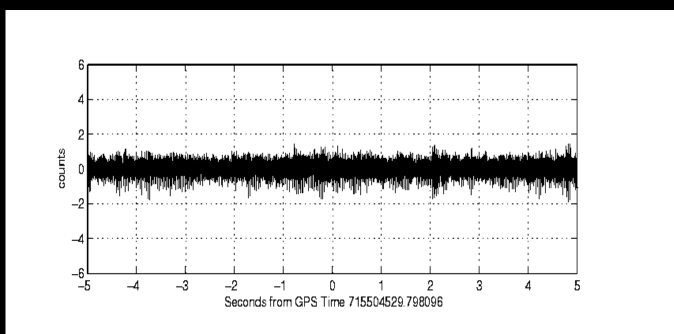
- Filtering method within **signal processing**
- Best filter method for **Gaussian noise**
  - Data is not strictly Gaussian, but can be *trimmed* (χ^2-test)
- Method:
  - Cross correlation of data with a template (waveform)
  - Returns a signal-to-noise ratio (SNR)

$$\rho^2 \propto \int \frac{s(f)\, h^*(f)}{S_h(f)}\, df$$

SNR: ρ^2 — data: $s(f)$ — template: $h^*(f)$ — Power spectral density: $S_h(f)$

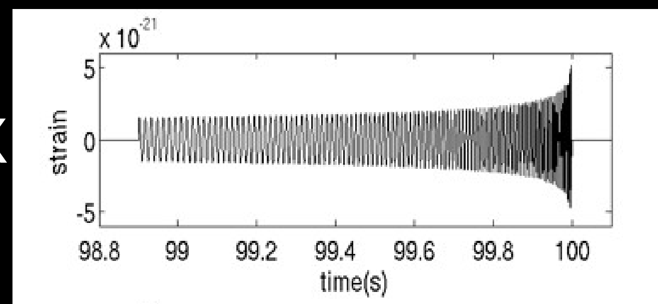
Matched Filtering

Data



X

Template



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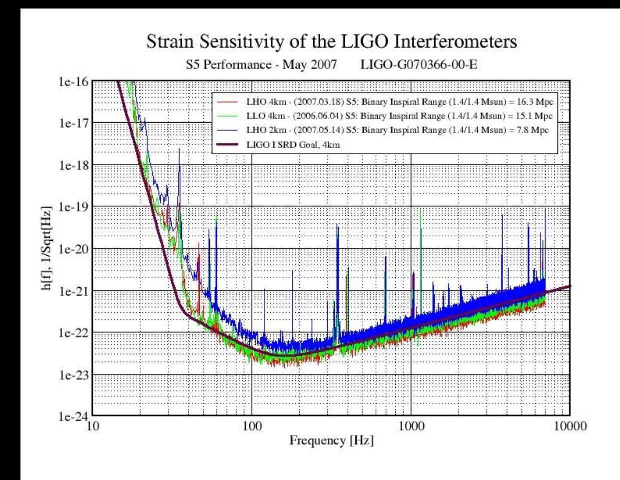
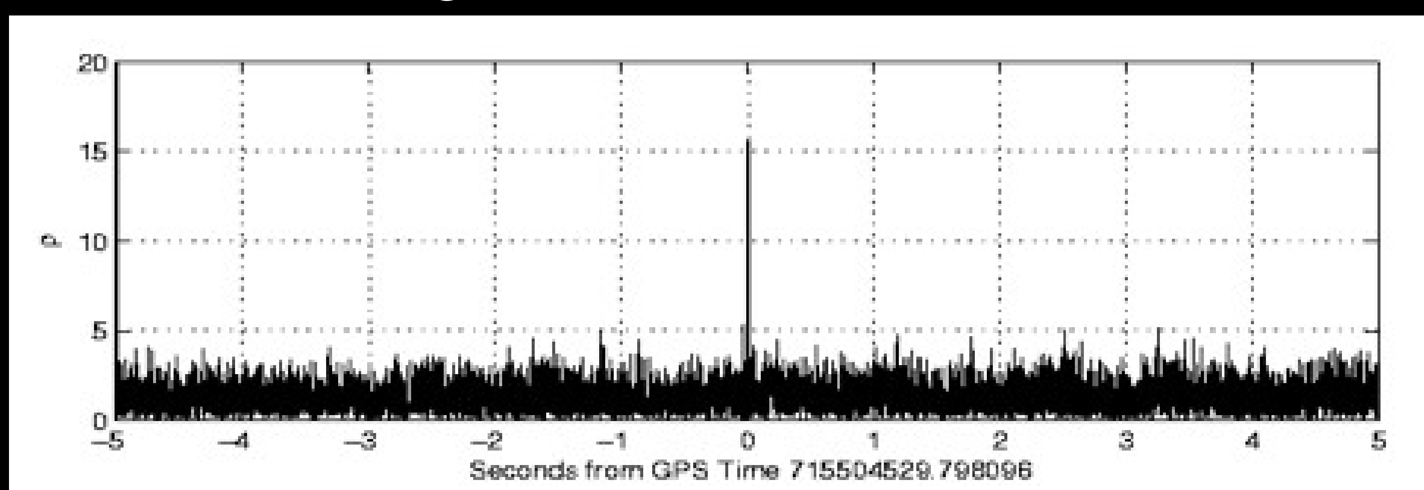
Power Spectrum



Signal to Noise Ratio

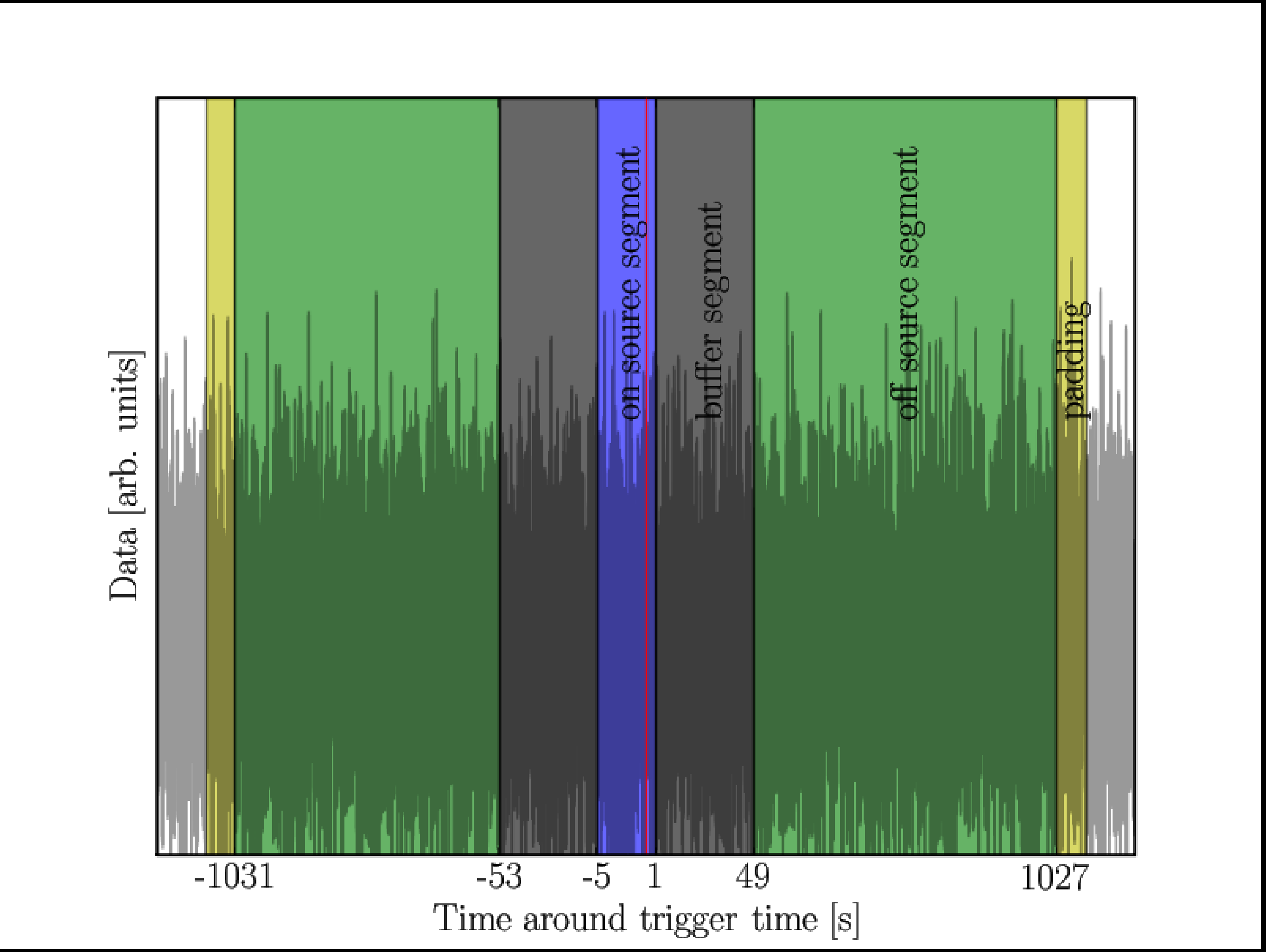
=

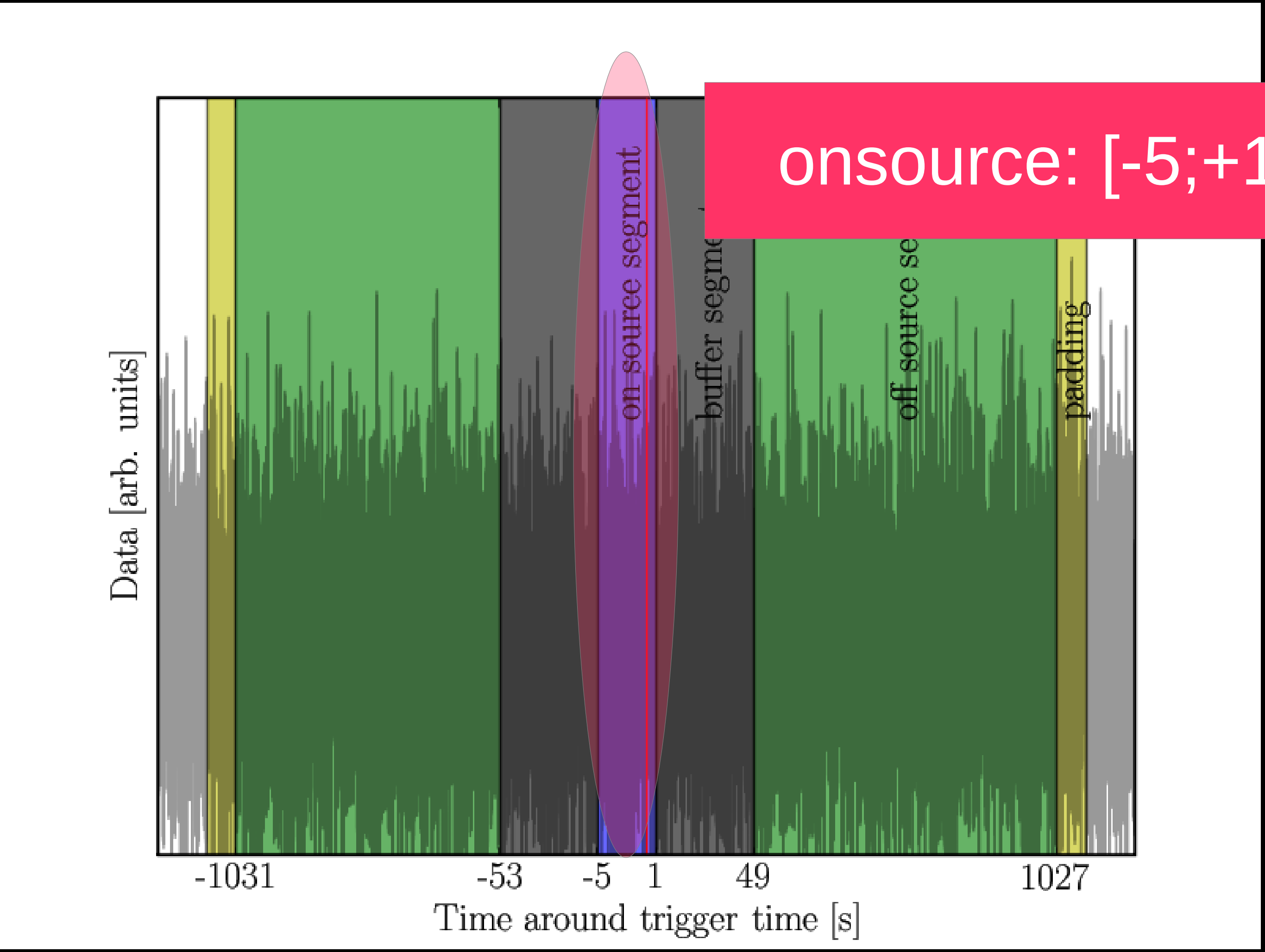


GRB Search Characteristics

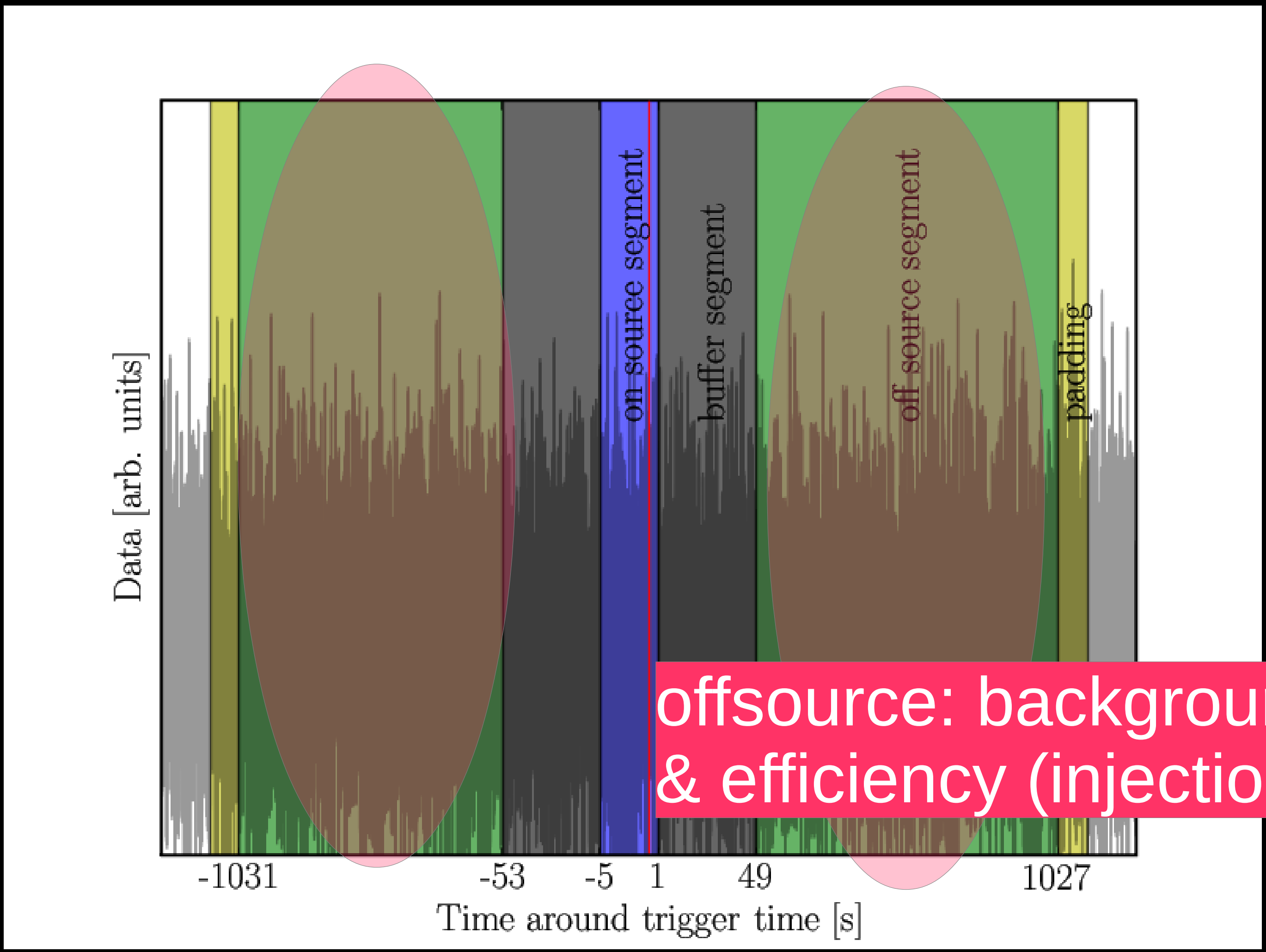
- Arrival of GW and GRB expected to be **within few seconds**
    - Geometrical considerations and high Lorentz factor: GW should precede GRB by ms
    - Semi-analythical description give <1 second [M.B. Davies,Mon. Not. R. Astron. Soc. 356,54 (2000)]
    - Numerical simulations: ms [M. Shibata, PRD 66, 084015 (2008)] to ~1 second [J.A.Faber, AIP Conf Proc, 861, 622 (2006)]

Search Details





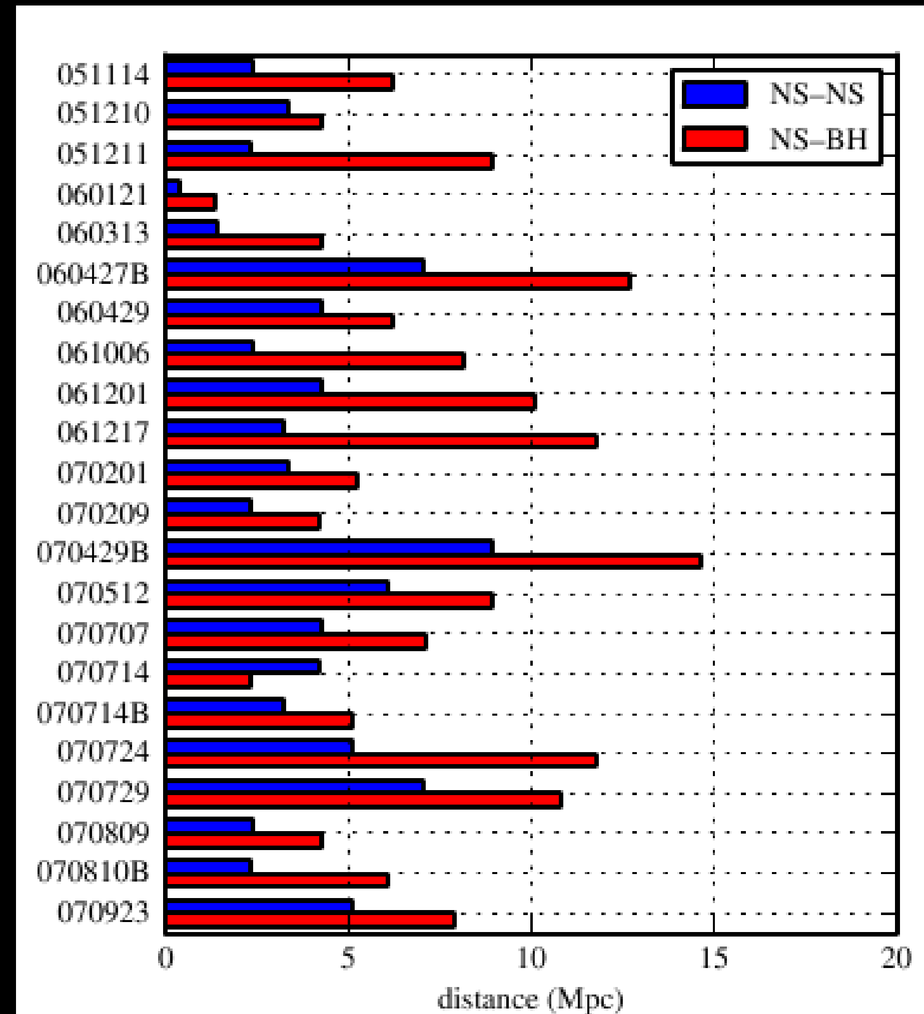
onsource: [-5;+1] seconds



offsource: background estimation & efficiency (injections)

Recent Results

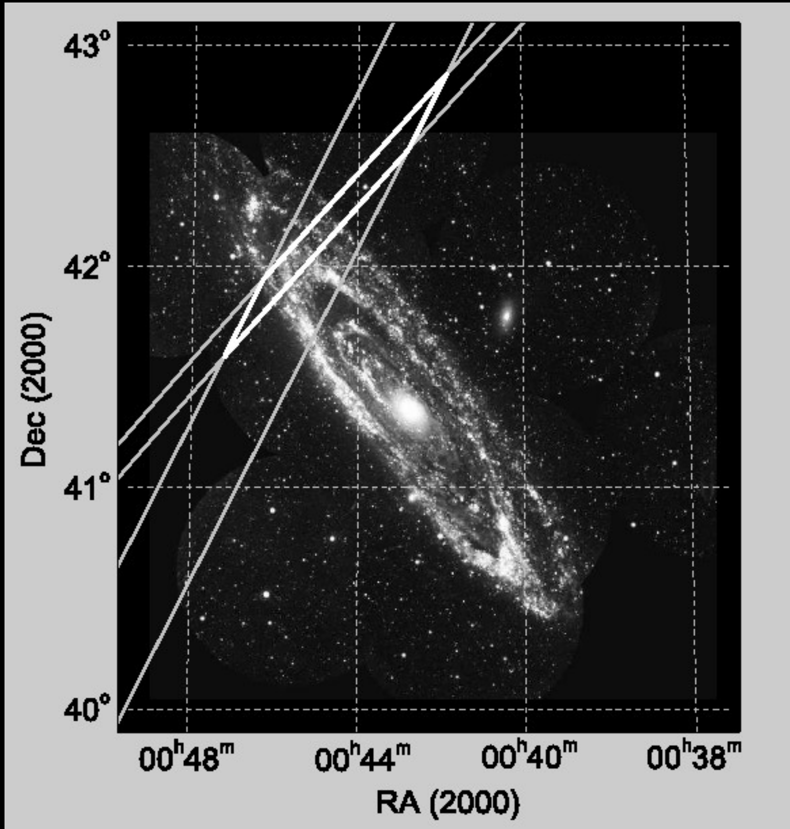
- S5 search
  (Nov 2005 to Sep 2007):
    - 21 short GRBs
- **No detections**
- S6 search
  (Jul 2009 to Oct 2010):
    - 23 short GRBs
    - **In preparation**



Abadie et.al (LIGO Scientific Collaboration and Virgo Collaboration), arXiv:1001.0165v1 (2010)

GRB 070201

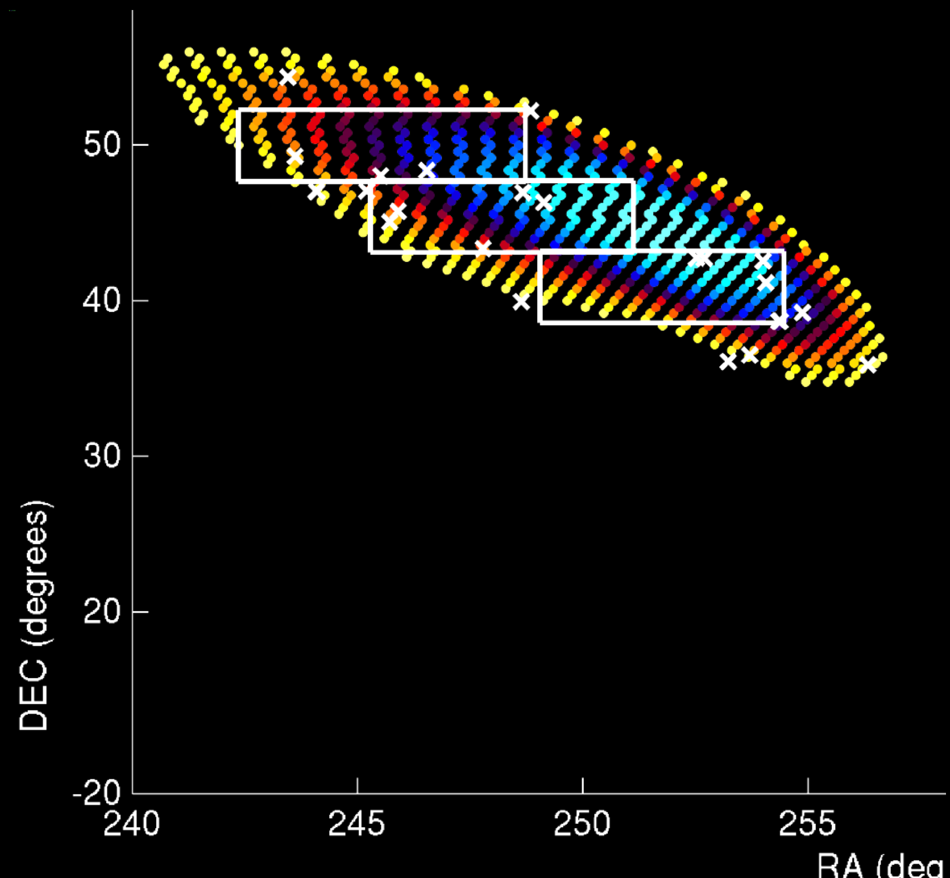
- A very bright short GRB detected in direction of M31
- Performed accelerated data analysis of GW data
- Merger in M31 excluded at > 99% C.L. [1]
- GRB probably merger farther away or a SGR in M31 [2,3]

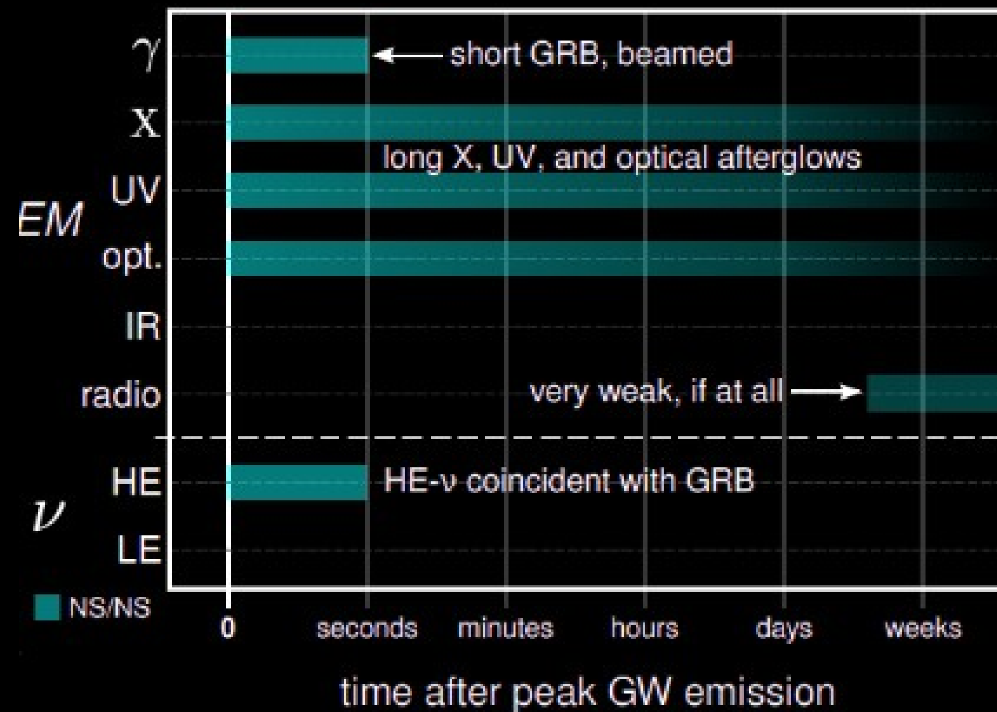


IPN 3σ Sky Localization
Mazets et al, ApJ 2008

[1] Abbott et.al., ApJ 681, 1419 (2008)
[2] Mazets et.al., ApJ 680, 545 (2008
[3] Ofek et.al., 681, 1464 (2008)

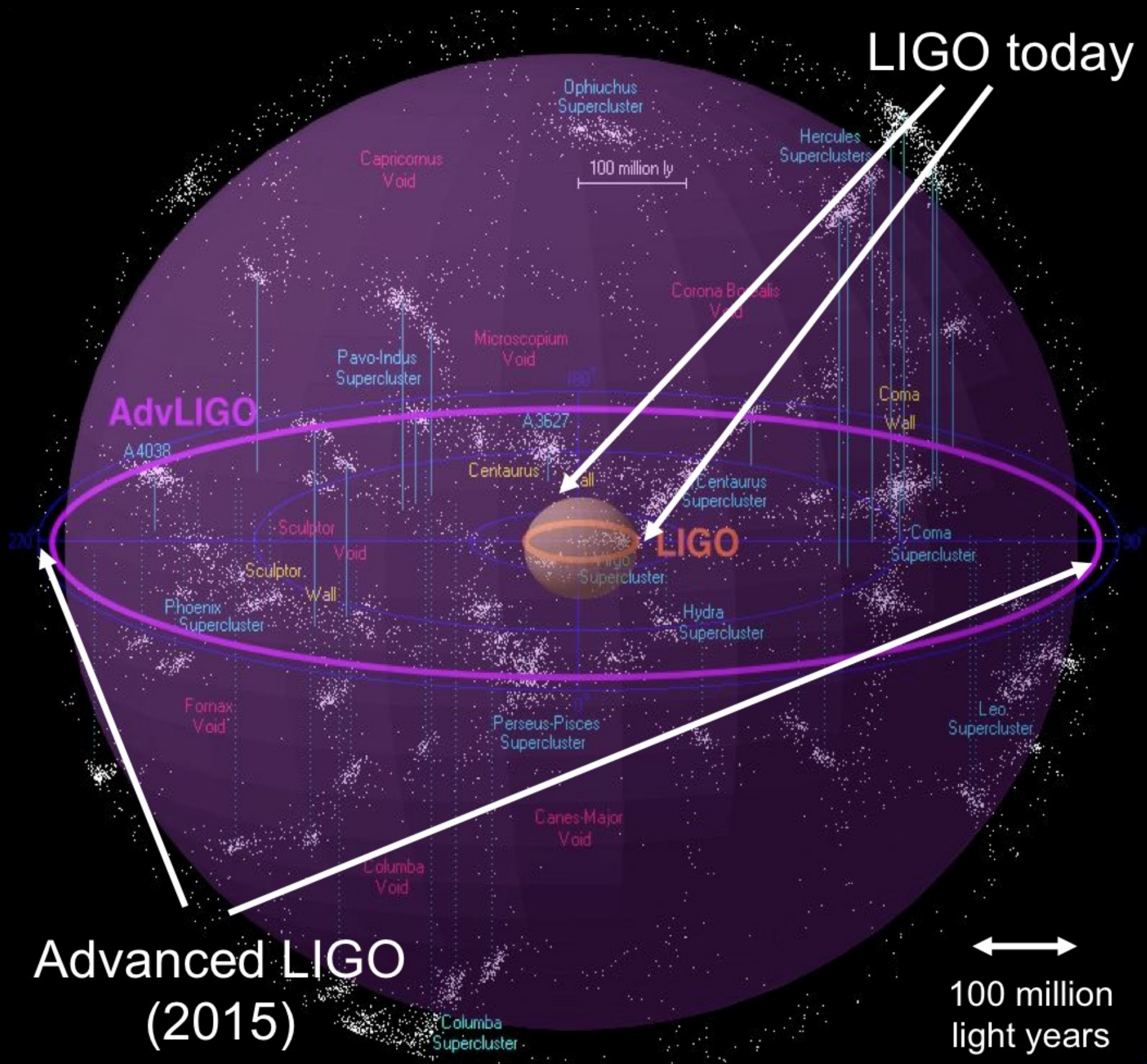
Multimessenger Astronomy





Collaboration with external telescopes: analyse data promptly, reconstruct position and try to capture EM counterparts!

The Near Future: Advanced Detectors



- Sensitivity: x10
- Volume: x1000
- Observable Mergers: 20? 50?
- Observable coincident short GRBs: unknown
- Scientific outcome: likely significant

Conclusions

- Gravitational Waves are an exciting new window on the universe
- GWs in coincidence with GRBs would provide lots of information
- Results becoming astrophysically relevant
- Analysis of current 2009-2010 data nearly done
- Advanced detectors ($\sim$ 2015) will likely start the era of routine detection: GW *astronomy*