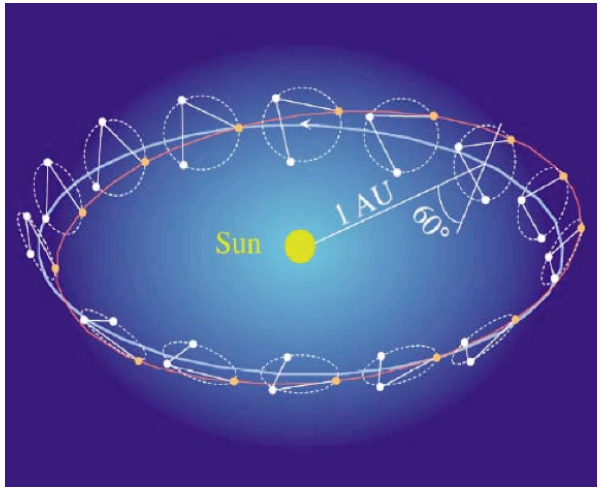
Gravitational waves search with earth based detectors

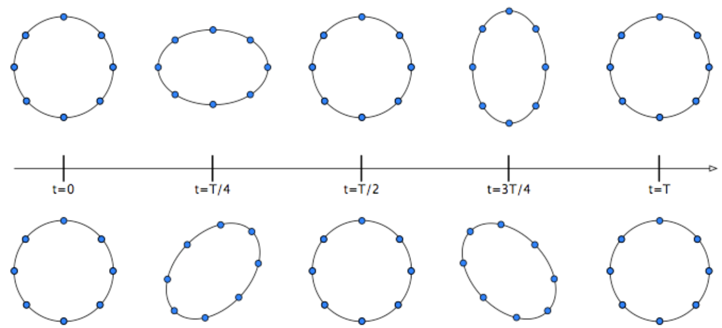


Matteo Barsuglia
Laboratoire AstroParticule et Cosmologie – CNRS

IPGP, April 17th 2012

The gravitational waves (GW)

- Perturbations of the space-time metrics



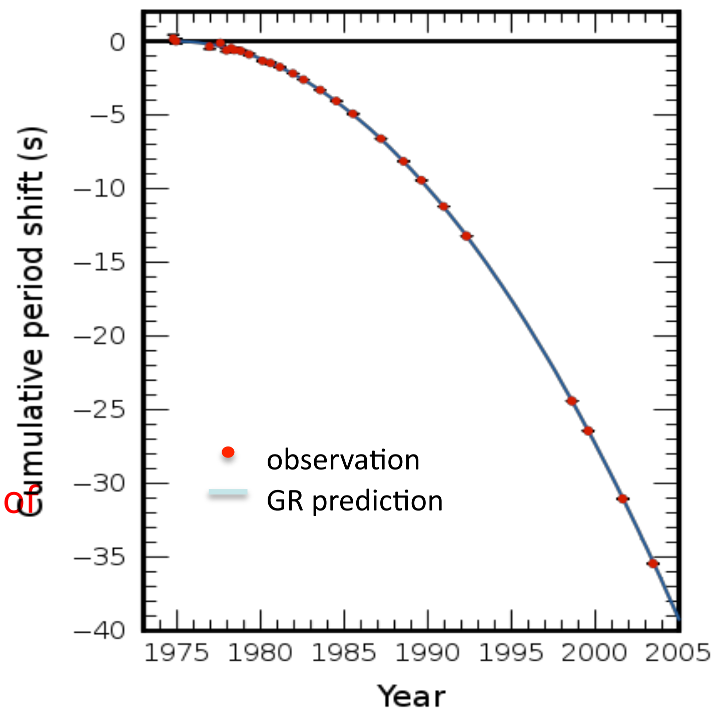
General Relativity

- Propagation at the speed of light
- Tranverses, 2 polarisations at 45 degrees
- Generated by mass quadrupole acceleration

- Order of magnitude: coalescence of neutron stars of 1.4 Msun at 15 Mpc

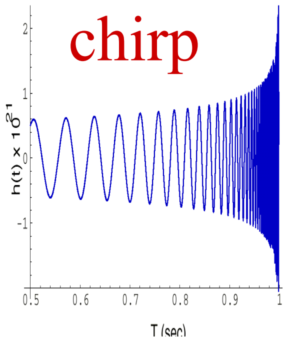
$$h \approx \delta L / L = 10^{-21}$$

- No direct detection
- Indirect detection: decrease of orbital period of PSR1913+16 (and other similar systems)

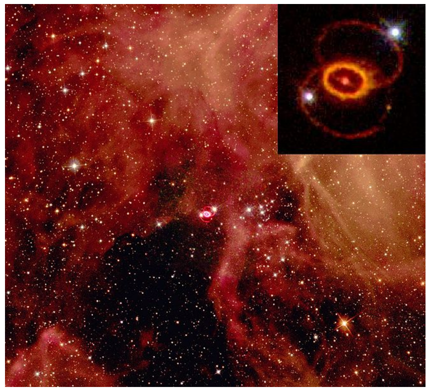


GW sources

- Final evolution stage of compact stars
  - Two neutron stars, two BH, BH + neutron star
  - Waveforms can be predicted

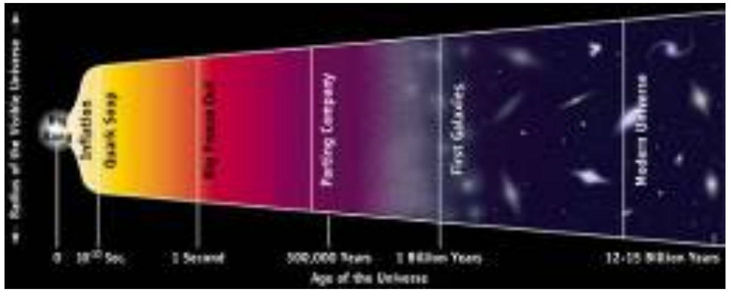


- Spinning neutron stars
  - Amplitudes unknown, depend on star asymmetry
  - SNR can be increased by integration



- Supernovae
  - GW from non spherical collapse
  - GW amplitudes difficult to model

- Cosmological GW background
  - Predicted by standard inflation and by some string models



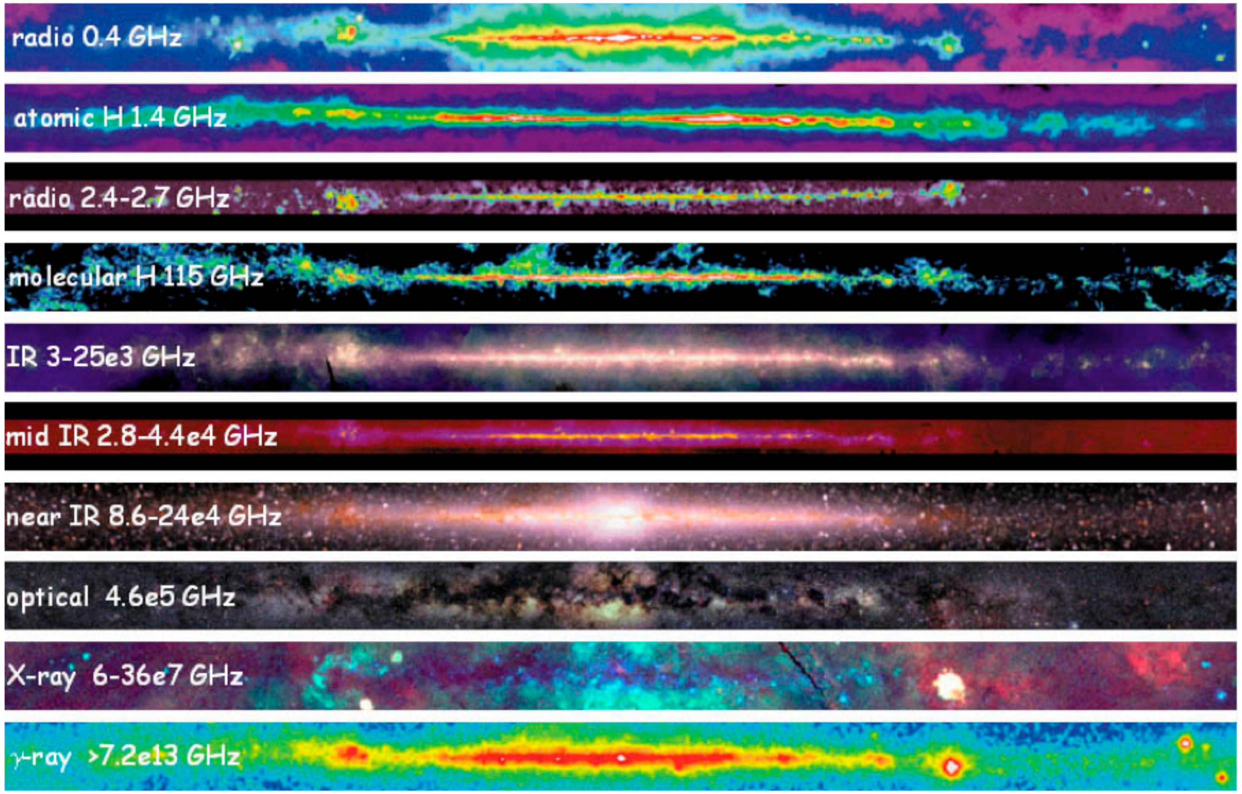
Science with the gravitational waves

- Fundamental tests of the General Relativity (polarization states, speed of the GW)
- BH-BH are a laboratory for the GR in strong field regime
- Understand Gamma ray bursts progenitor
- Information on the equation of state of neutron stars
- Study of supernovae Physics
- Cosmography: standard candles
- Physics of the early universe through a cosmological background of GW

Physics, *Astrophysics and Cosmology With Gravitational Waves*, Satyaprakash and Shultz
Living review in Relativity

A new *messenger*

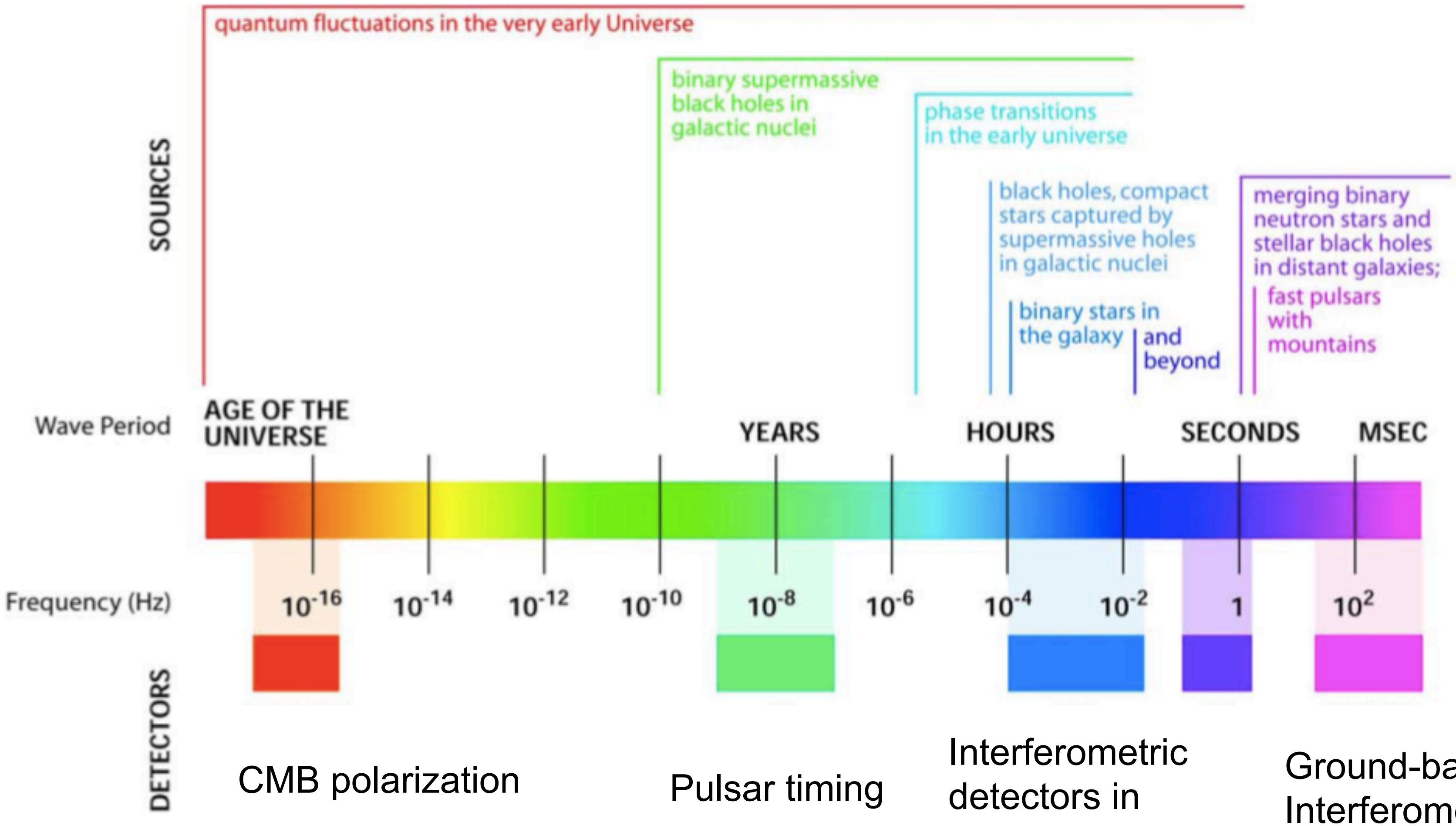
- GW are produced by coherent relativistic motion of large masses
- GW travel through opaque matter
- Gravity dominate the dynamics of several interesting astrophysical systems



Images:NASA

Gravitational-wave sky ?

The gravitational-wave spectrum



CMB polarization

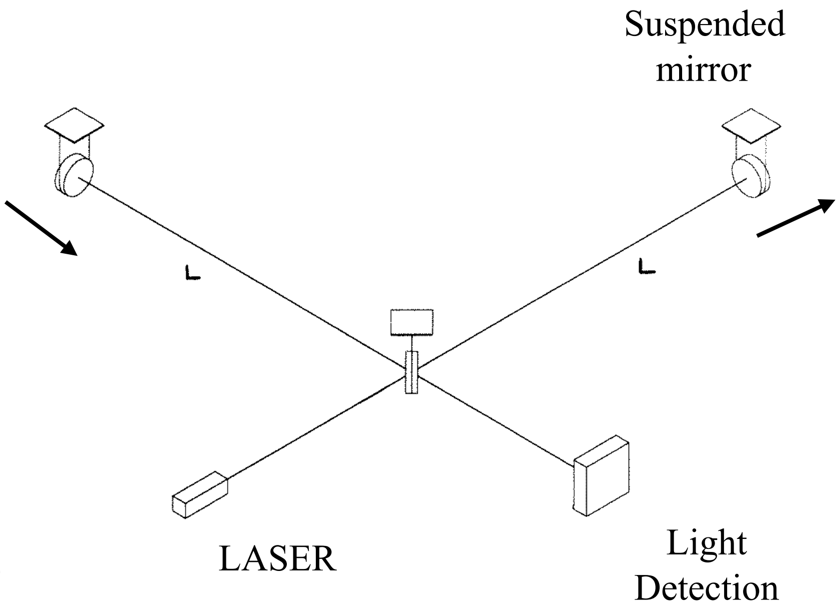
Pulsar timing

Interferometric detectors in space

Ground-based Interferomeric detectors

Interferometers

- Michelson interferometer (sensing device) with mirror suspended to pendula (free masses)
- Limited by **sensing** noise and **displacement** noises



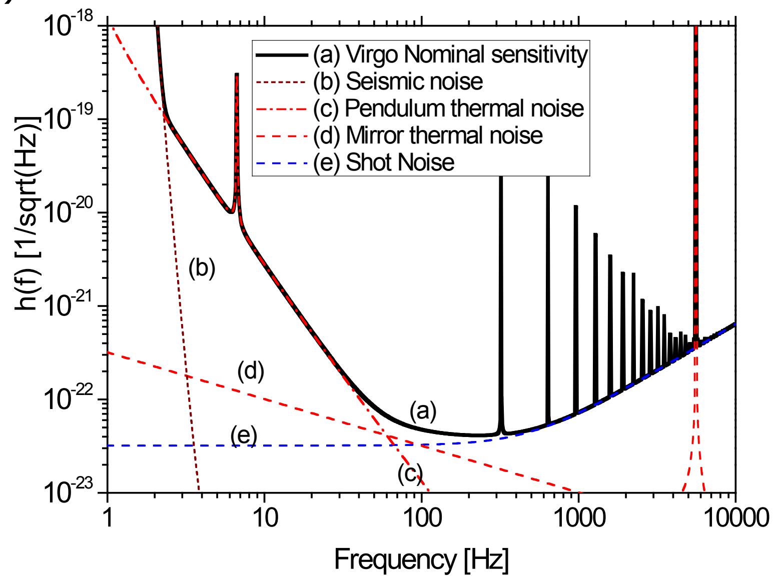
- More like an *ear* than an *eye*
  - Not directional
  - Only a scalar number (not an image)
  - Audio band (for interferometer on earth)

If target h ~ 10^{-21}

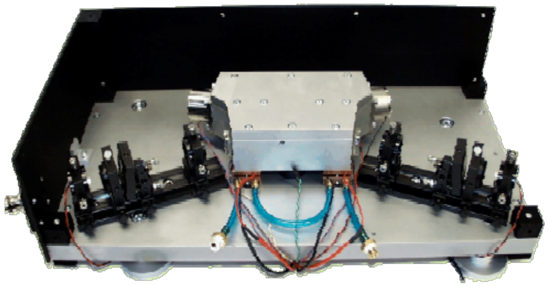
(NS/NS @Virgo Cluster)

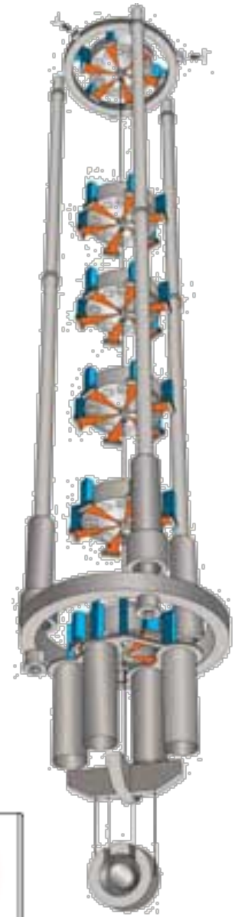
and L ~ 10^3 m

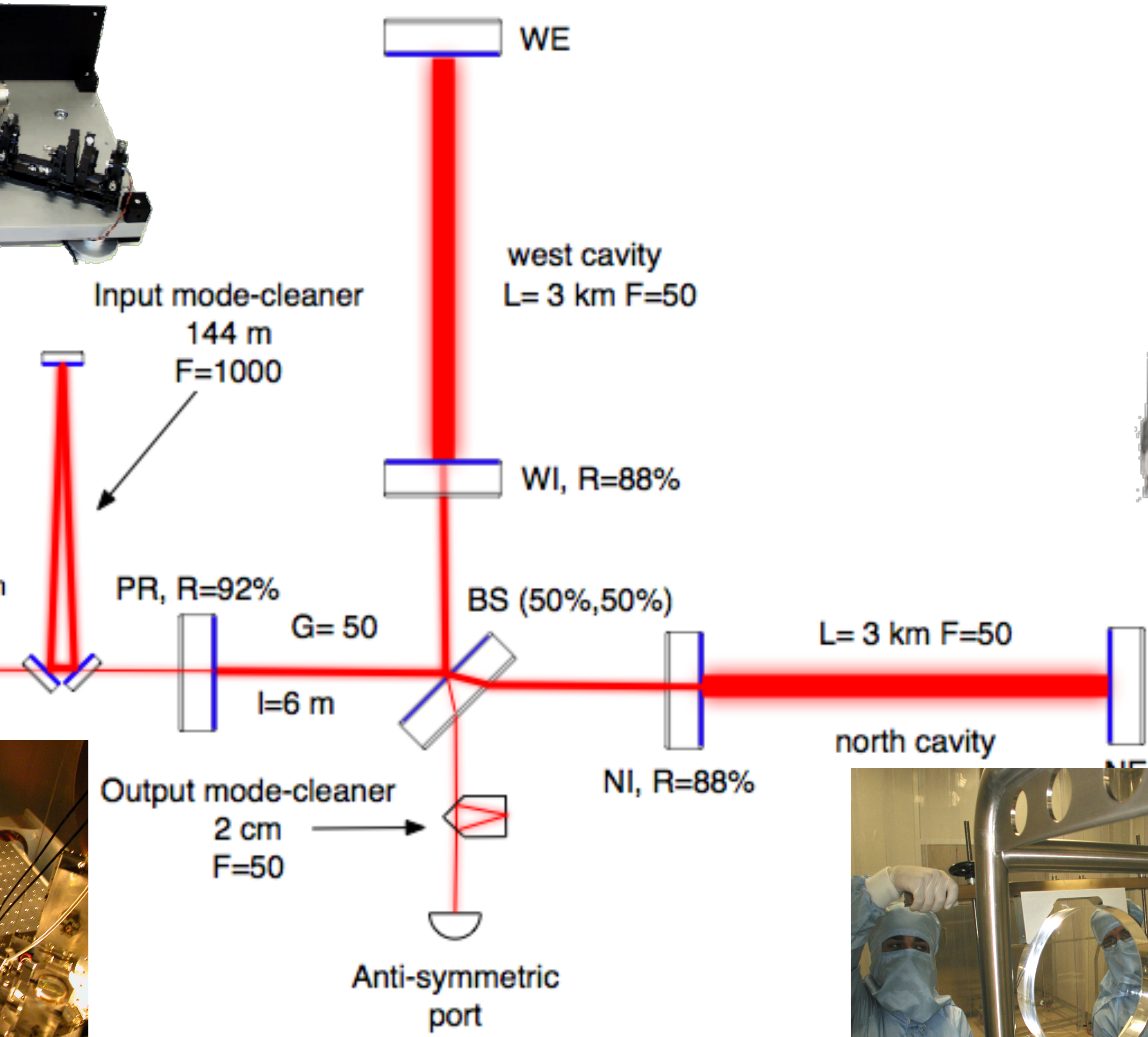
Need to measure: $\Delta L \sim 10^{-18}$ m

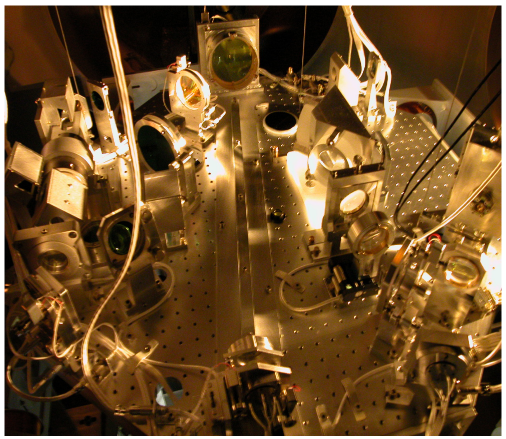


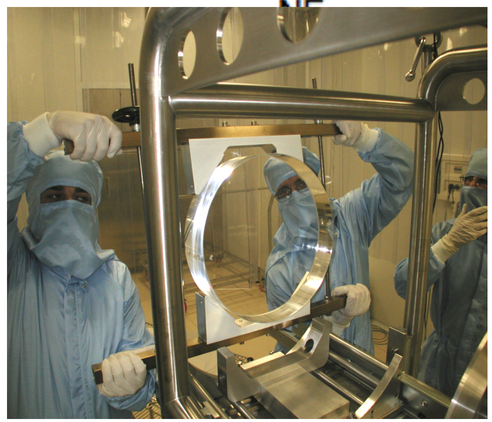
Detector highlights (Virgo)



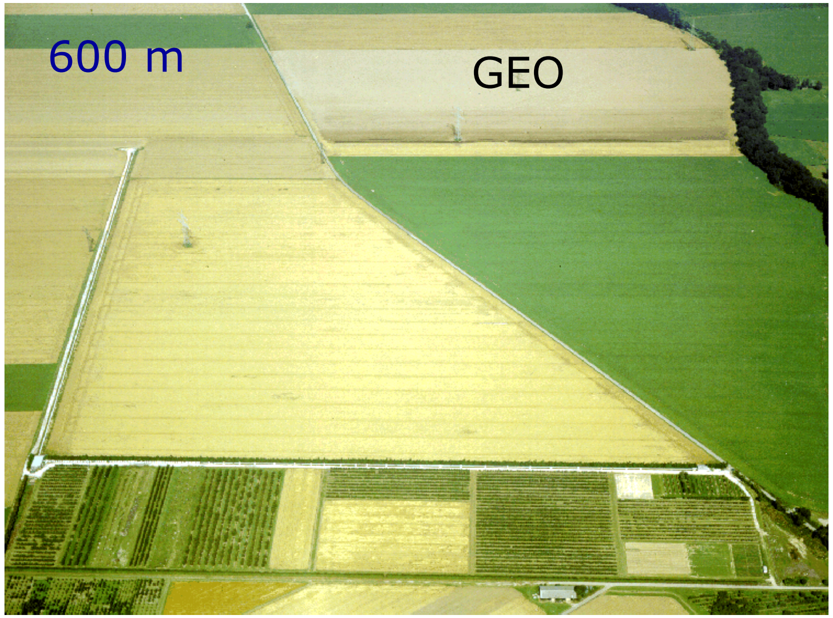


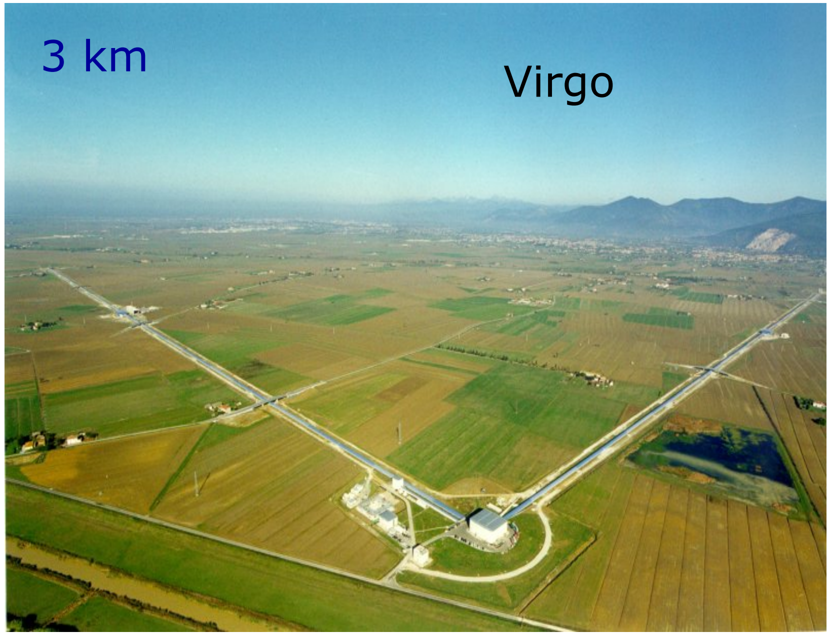






First generation detectors

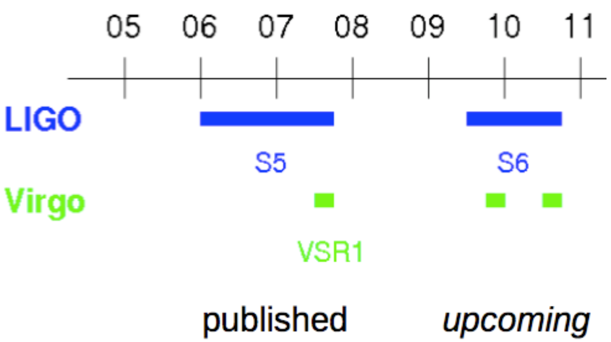




An international GW network

- Ligo Scientific Collaboration (LSC) + Virgo
- 5 interferometers (2 LIGO 4km, 1 LIGO 2 km, 1 GEO)

Data takings



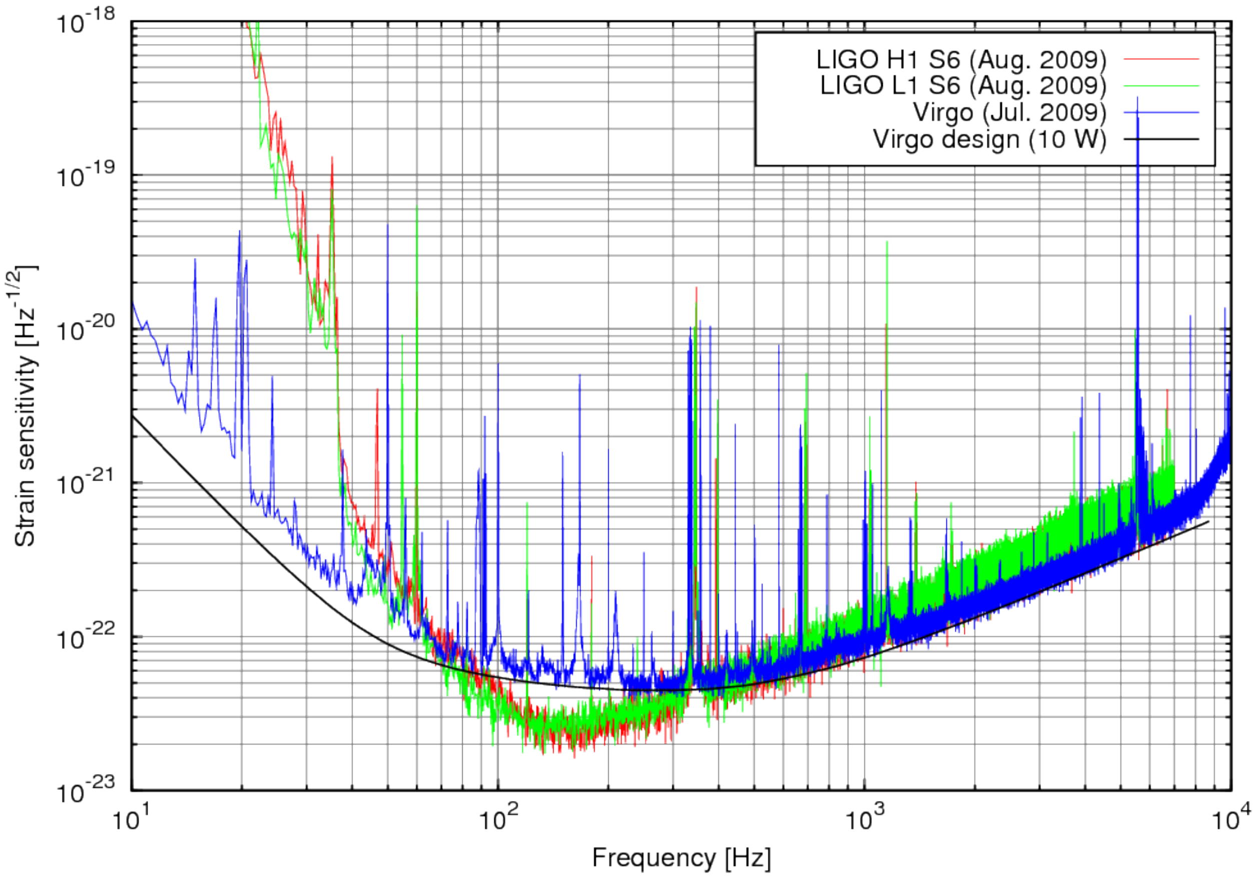
Agreement Virgo-LSC (2007)

- Full data exchange and analysis joint publication policy
- Science runs coordination
- Collaborative technical research

Benefits:

- Confidence in detection
- Sky coverage
- Duty cycle
- Sky position localization

First generation detectors: sensitivities



Best NS-NS horizon

LIGO ~ 20 Mpc
Virgo ~ 10 Mpc

- ❑ Sensitivities at design level
- ❑ Excellent duty cycles (up to ~80%)
- ❑ km scale GW interferometer technology demonstrated
- ❑ ...but expected rates of events expected very low

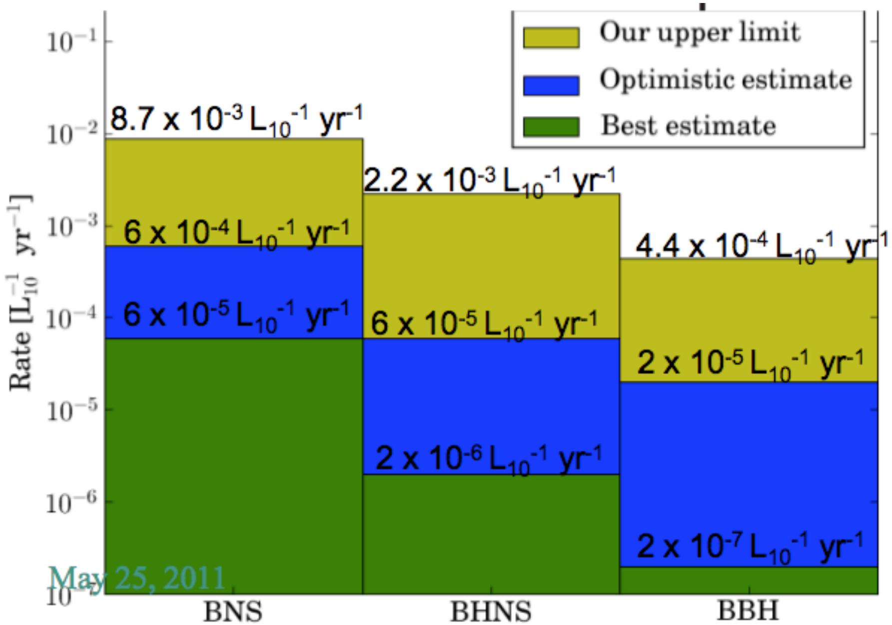
Coalescing binaries: estimates for initial detectors and upper limits

Deduce rate of coalescence from:

- pulsar binary in Milky Way
- star population models

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}	$\dot{N}_{max}$ 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	



May 25, 2011

Credit:F.Marion

- Rate upper limits from LIGO-S5/Virgo-VSR1 data
- 1-2 orders of magnitude above optimistic estimates

Search for Gravitational Waves from Compact Binary Coalescence in LIGO and Virgo Data from S5 and VSR1, PRD 82 (2010) 102001

Pulsars - upper limits

Upper limits on GW energy release by pulsar, and on pulsar ellipticity

GW upper limits beating spin-down limit for two pulsars

- Crab @ ~60 Hz (LIGO data)
  - » GW energy < 2% of spin-down energy
  - » $\varepsilon < 1.3\times10^{-4}$
- Vela @ ~22 Hz (Virgo data)
  - » GW energy < 35% of spin-down energy
  - » $\varepsilon < 1.1\times10^{-3}$

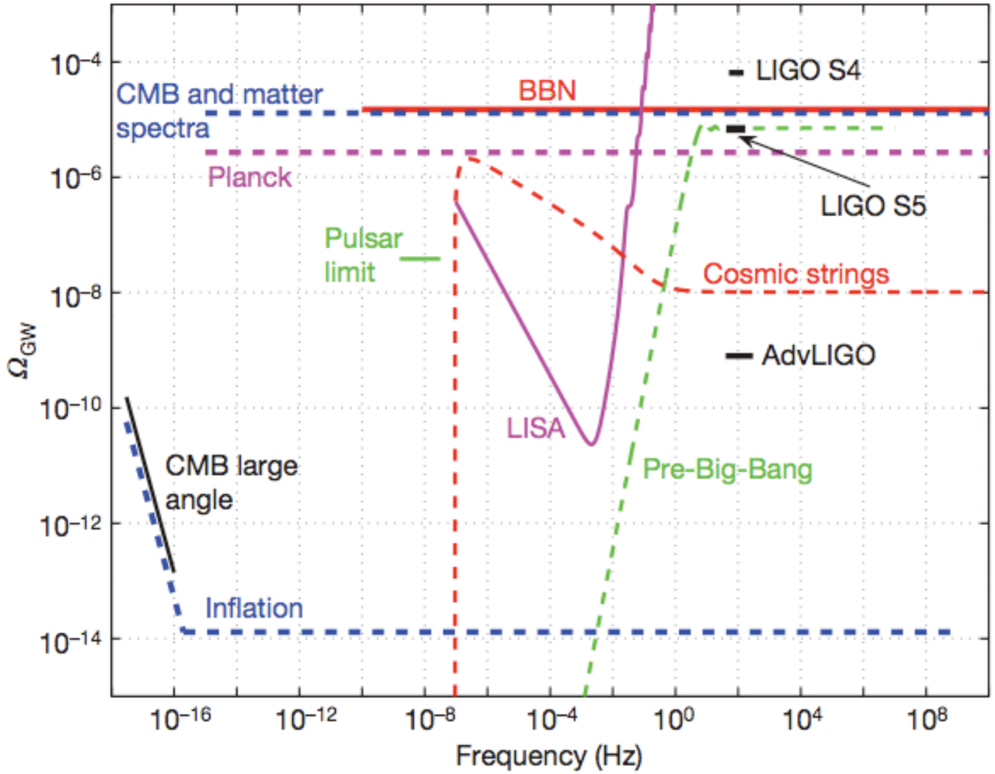
Other targeted searches

- 116 known millisecond and young pulsars with LIGO S5 data
  - » Best h limit 2.3×10^{-26}
    - » J1603−7202, 135 Hz
  - » Best ε limit 7.0×10^{-8}
    - » J2124−3358, 406 Hz, 0.2 kpc

Beating the spin-down limit on gravitational wave emission from the Vela pulsar arXiv:1104.2712v3

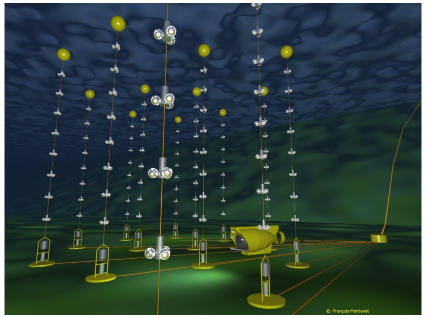
Stochastic background

- Stochastic background predicted by standard inflation and other models
- Correlation between detectors
- Upper limit below BBN using Data from LIGO
- Advanced detectors can rule out some models



An upper limit on the stochastic gravitational-wave background of cosmological origin, Nature 460 (2009) 990

Multi-messenger observations

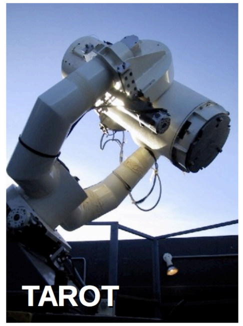


Motivations:

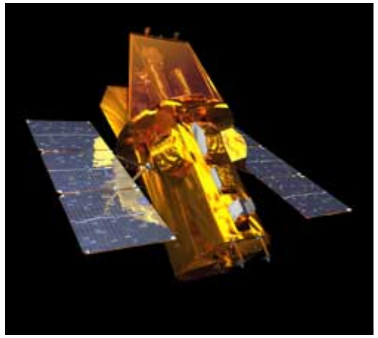
- ❑ GW comes from very energetic astrophysical processes, likely sources of EM radiation or high-energy particles
- ❑ correlate in time & direction observation by GW and other messengeres

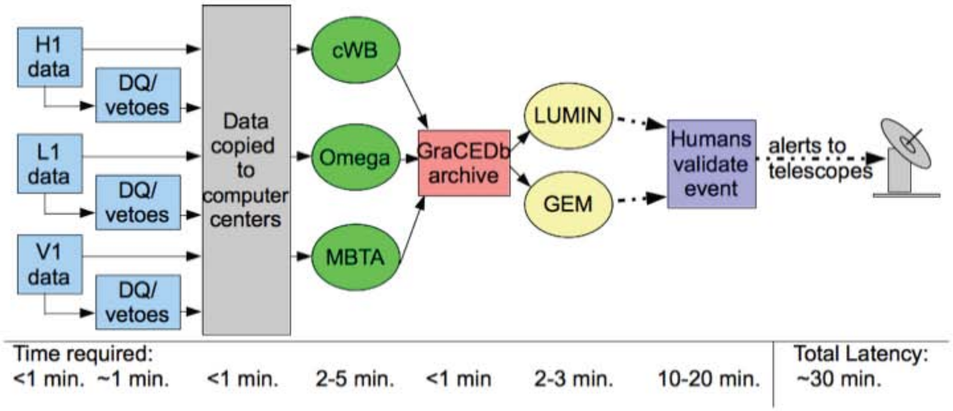
Two approaches:

- ❑ *Other telescopes to GW (e.g. GRB alerts)*
- ❑ *GW to other telescopes (e.g. robotic telescopes)*



- ❑ Electromagnetic follow-up
  - ❑ SWIFT (gamma, X), LOFAR (radio), ROTSE, TAROT, and others
- ❑ High-energy neutrinos
  - ❑ Exchange of triggers with Antares and IceCube

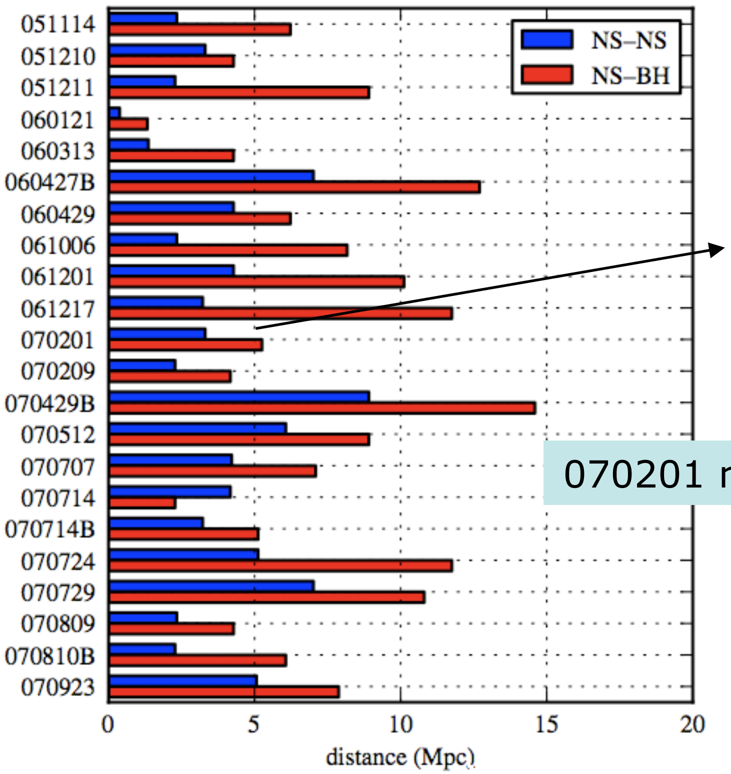


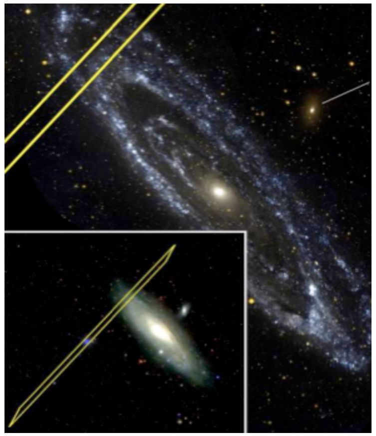


GRBs

- GRB very energetic phenomena, likely emit GW
- Progenitor scenarios for short gamma-ray bursts (short GRBs) include NS-NS or NS-BH coalescence
- Search data around times of GRBs observed by γ-Xray satellite based instruments
- During S5/VSR1 LIGO-Virgo data takings hundreds GRB studied

- NO GW detection, derive limits on the distance

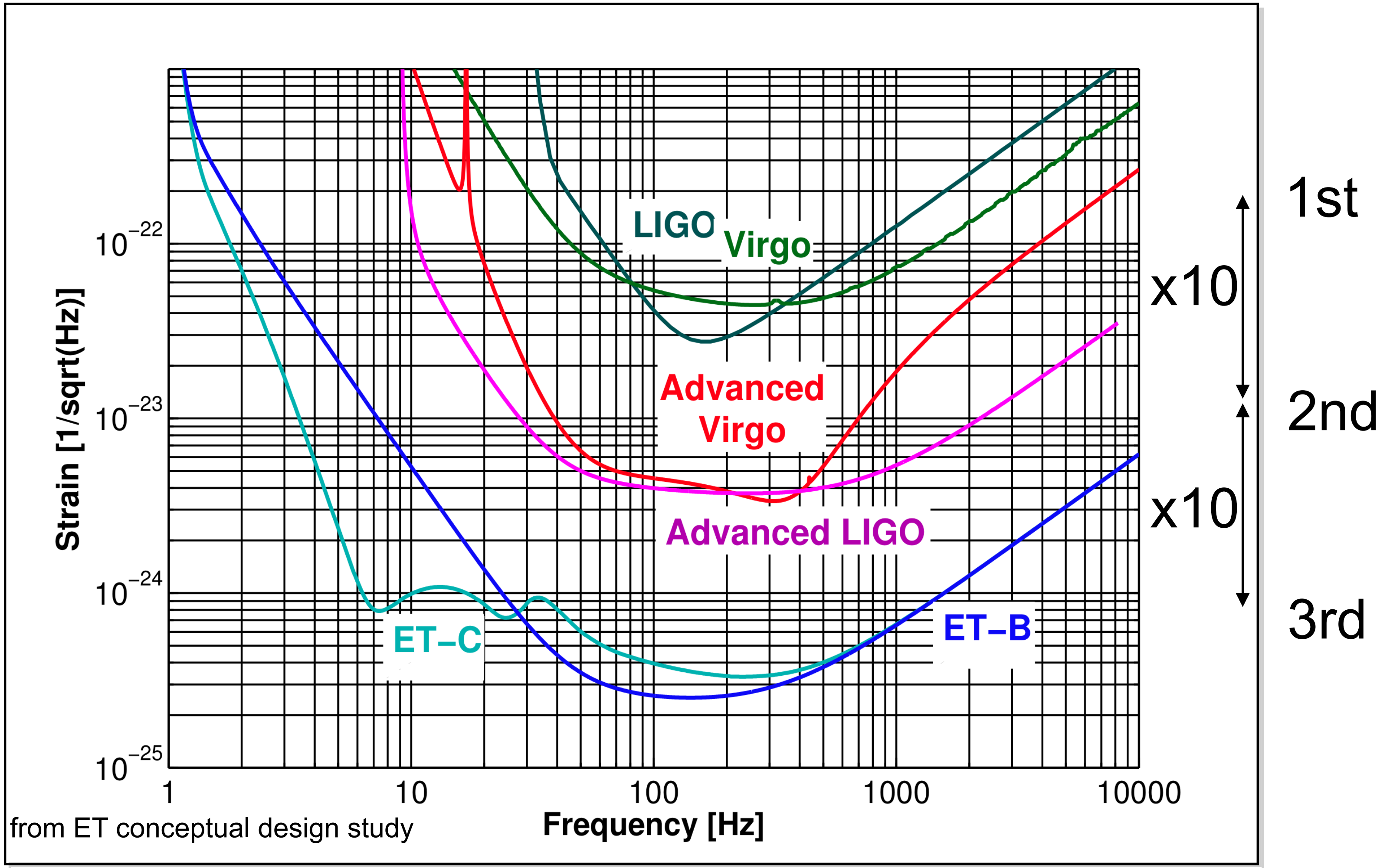




070201 not a merger in M31

- *Search for gravitational-wave inspiral signals associated with short Gamma-Ray Bursts during LIGO fifth and Virgo first science run* , Astrophys. J. 715, 1453 (2010)
- Search for gravitational-wave inspiral signals associated with short Gamma-Ray Bursts during LIGO fifth and Virgo first science run, Astrophys. J. 715, 1438 (2010)

Future ground-based GW detectors

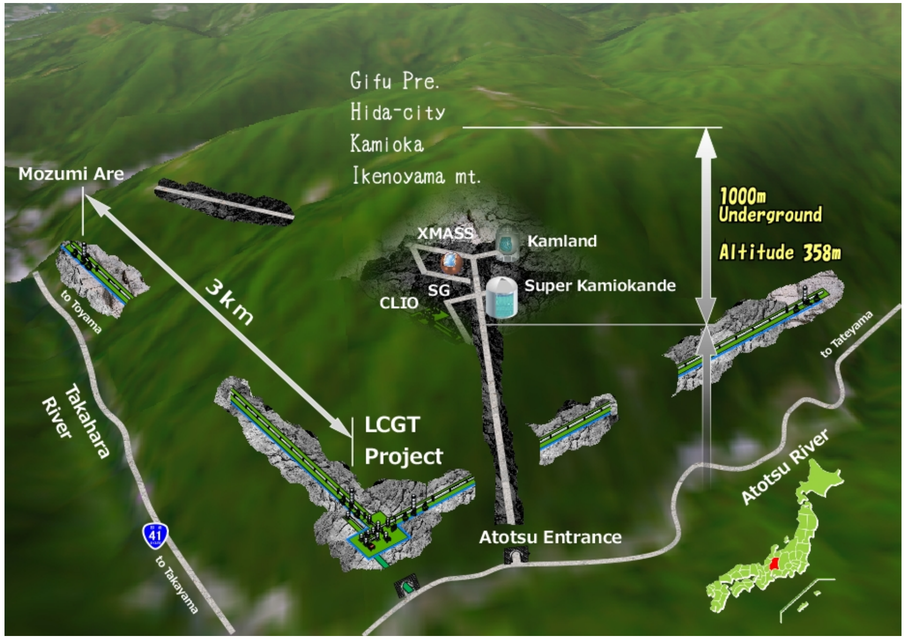


increase in rate ~ (increase in sensitivity) ^{3}

Second generation detectors

- ❑ Advanced Virgo - under construction
- ❑ Advanced LIGO (3 detectors - 2 sites) - under construction
- ❑ LCGT (now KAGRA) (large cryogenic gravitational-wave telescope) - funded

- ❑ LCGT (KAGRA) cryogenic and underground



Credit: LCGT

- **Advanced LIGO**
  - 2013 Installation completed
  - 2014 ITF acceptance
  - 2015 First short run (50-100 Mpc)
  - 2016-17 First extended run (100-140 Mpc)
  - 2018-19 Run at full sensitivity (140-200 Mpc)

- **Advanced Virgo**
  - 2009-2013 Construction
  - 2011-2014 Assembly & Integration
  - 2014-2015 Commissioning
  - 2015 First lock
  - 2016 First run

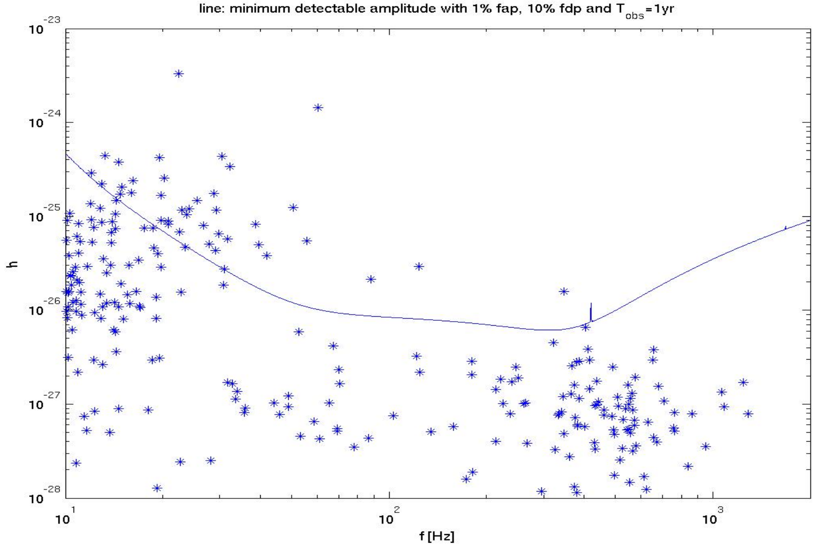
Some sources for 2nd generation detectors

Table 5. Detection rates for compact binary coalescence sources.

IFO	Source[a]	$\dot{N}_{low}$ yr^{-1}	$\dot{N}_{re}$ yr^{-1}	$\dot{N}_{high}$ yr^{-1}	$\dot{N}_{max}$ yr^{-1}
	NS–NS	0.4	40	400	1000
	NS–BH	0.2	10	300	
Advanced	BH–BH	0.4	20	1000	

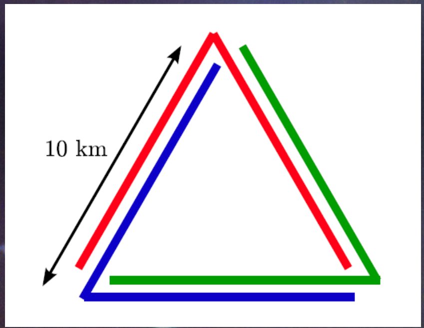
- NS-NS ~ 200 Mpc
- BH-BH ~ 1 Gpc

Likely detection by second generation interferometers

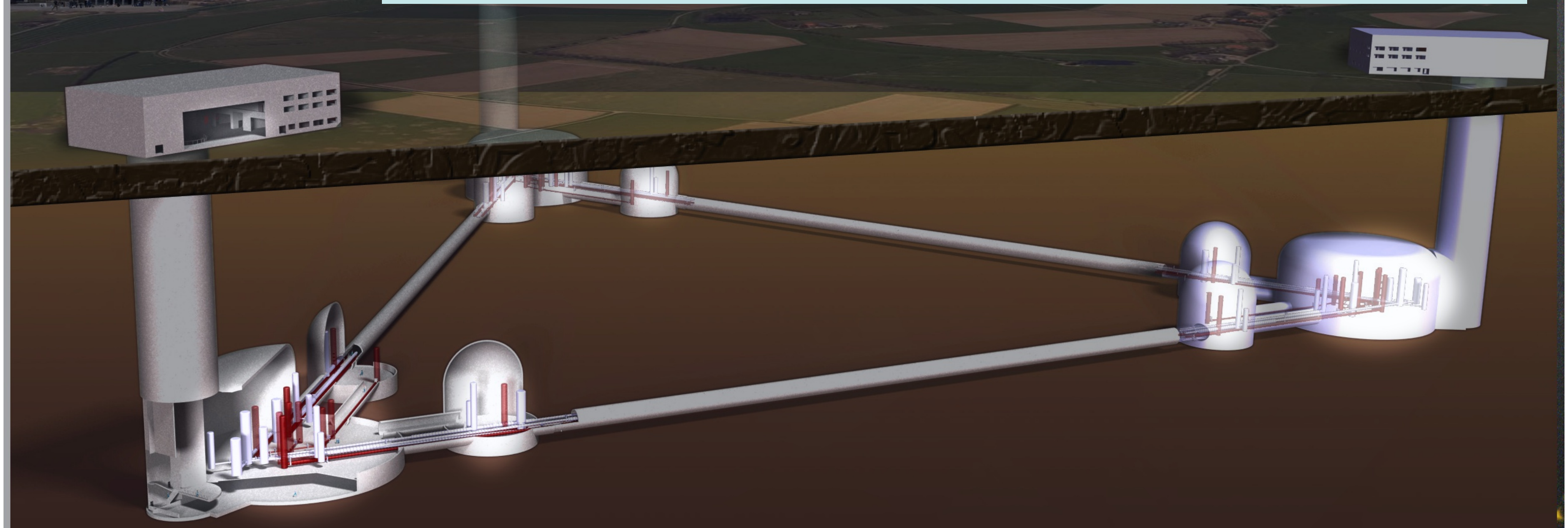


Spin-down limit for ~ 40 known pulsars

Einstein Telescope



- Design study of a 3rd generation European interferometer (under FP7)
  - Goal: increase the sensitivity by a factor 10 with respect to 2nd generation interferometers (Advanced Virgo and Advanced LIGO)
  - Extend the detection band down to 1 Hz
- Underground - triangle - 10 x 3 km of tubes
- design study document released
- Next step - technical design
- Science data > 2025 (if funded)



from ET conceptual design study

Summary

- 1st generation gravitational-wave interferometers work
  - Design sensitivity level - noise understood - technologies behind the first generation demonstrated
  - Several months of data
  - Several upper limits
- 2nd generation detectors under construction (aLIGO, AdVirgo) or funded (Kagra)
  - Science data takings with increasing sensitivity in the period ~ 2016-2020
  - Tens of NS-NS coalescences expected at the full sensitivity - **likely first detection**
- 3rd generation european GW detector conceptual design ready