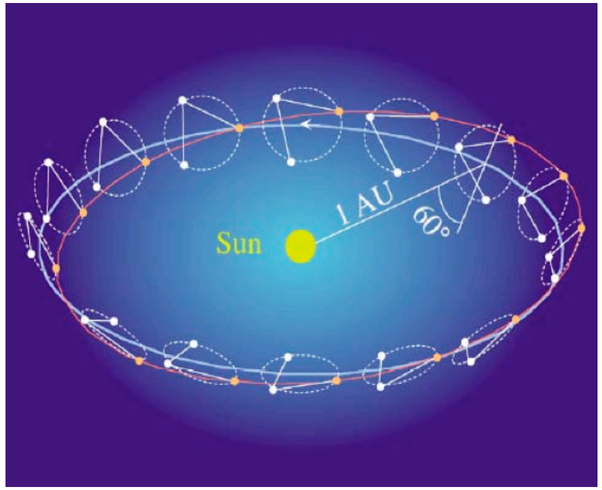
# Gravitational waves: status and plans

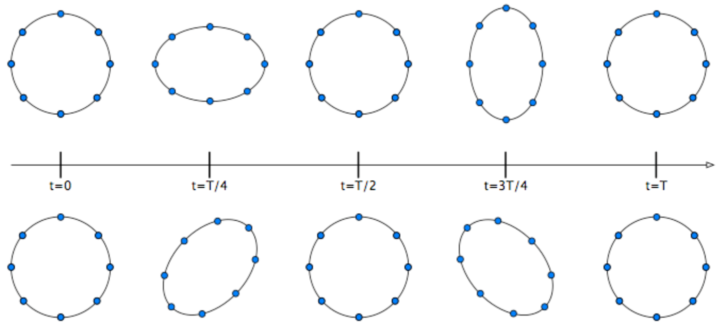




Matteo Barsuglia
Laboratoire AstroParticule et Cosmologie - CNRS

Les recontres de Blois, 2011

# The gravitational waves (GW)

- ❑ Perturbations of the space-time metrics

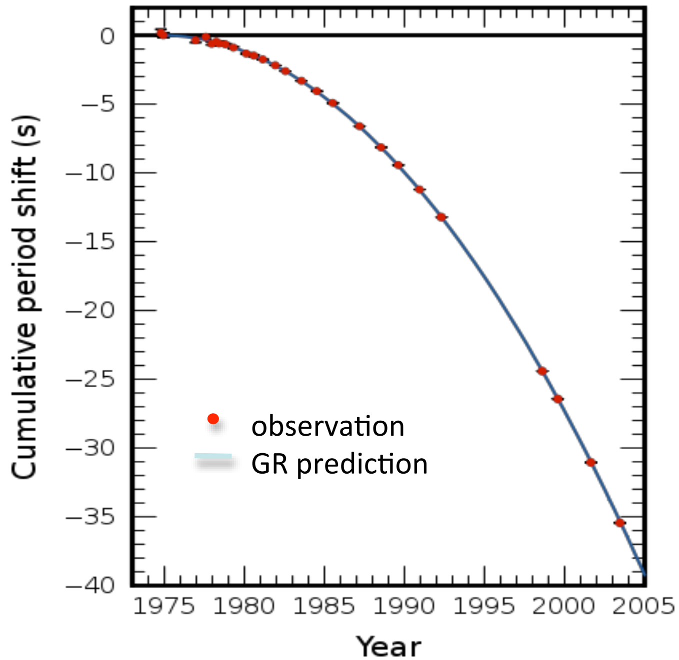



General Relativity

- ❑ 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

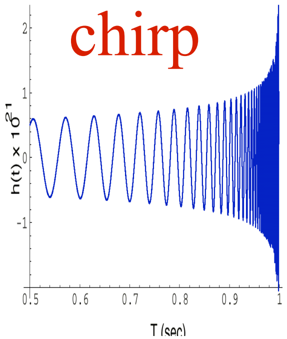
$$h \approx \delta L / L = 10^{-21}$$



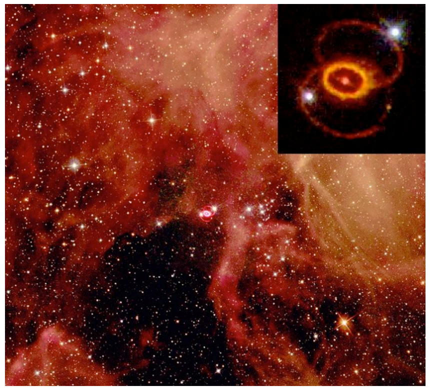

- ❑ No direct detection
- ❑ Indirect detection: decrease of orbital period of PSR1913+16 (and other similar systems)

# GW sources

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

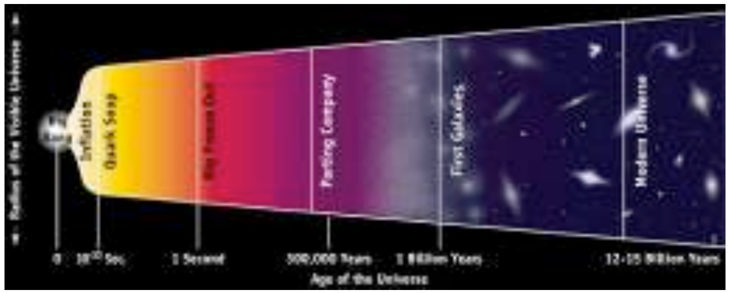



- Spinning neutron stars
  - Amplitudes unknown, depend on star asymmetry
  - SNR can be increased by integration



- 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

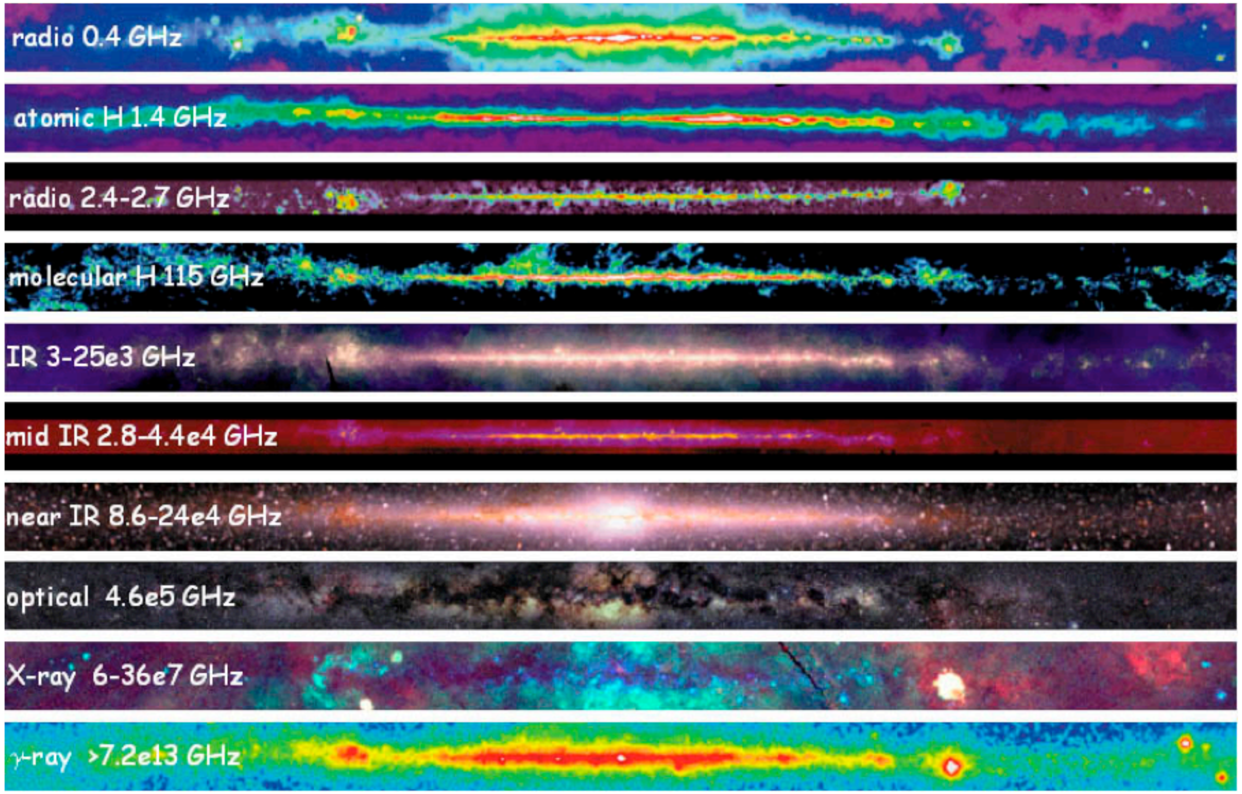
- Fundamental tests of the General Relativity (polarization states, speed of the GW)
- BH-BH are a laboratory for the GR in strong field regime
- Understand Gamma ray bursts progenitor
- Information on the equation of state of neutron stars
- Study of supernovae Physics
- Cosmography: standard candles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

See presentation
by Luciano Rezzolla

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

# A new *messenger*

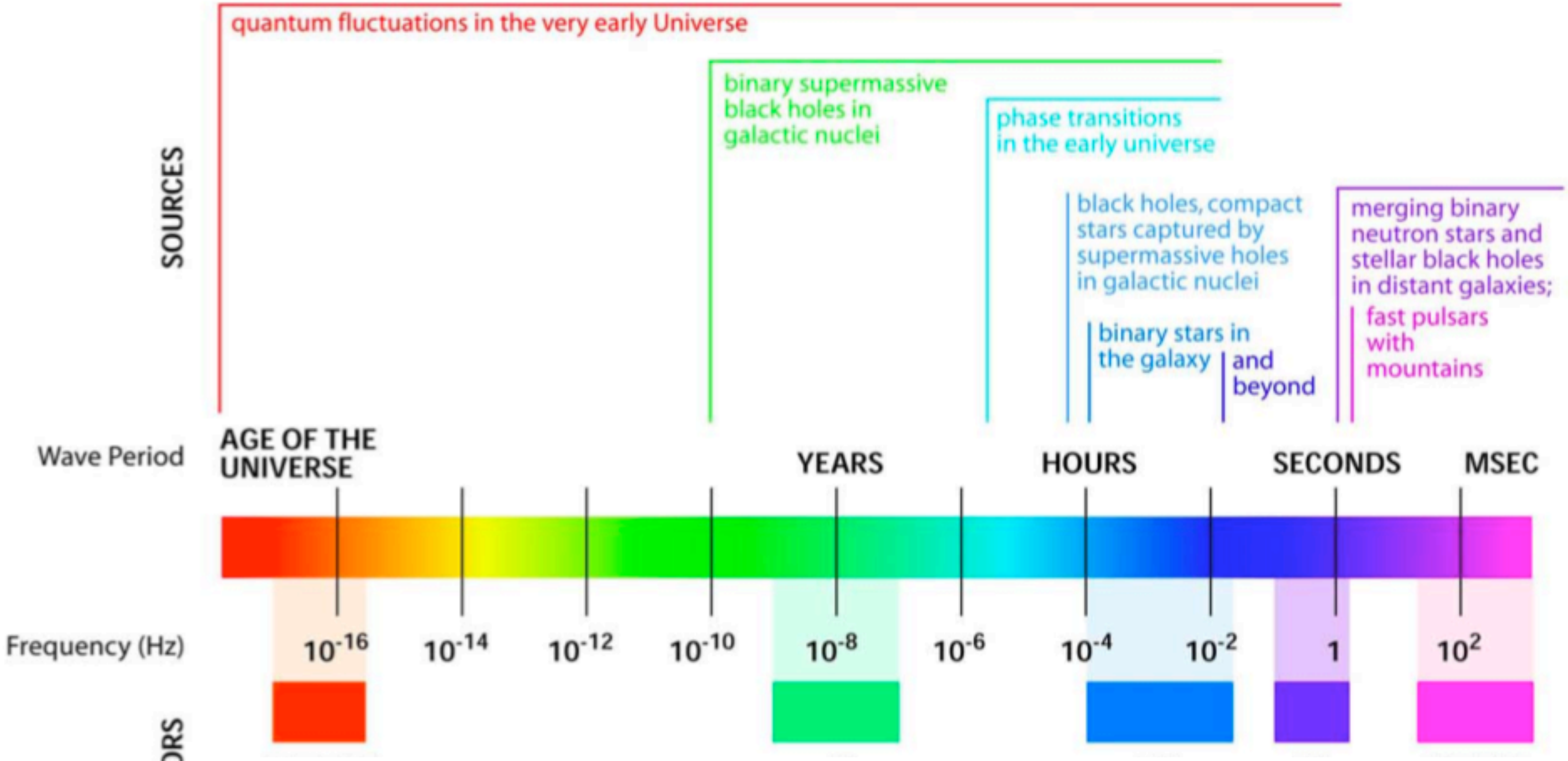
- GW are produced by coherent relativistic motion of large masses
- GW travel through opaque matter
- Gravity dominate the dynamics of several interesting astrophysical systems




Images:NASA

Gravitational-wave sky ?

# The gravitational-wave spectrum




CMB polarization

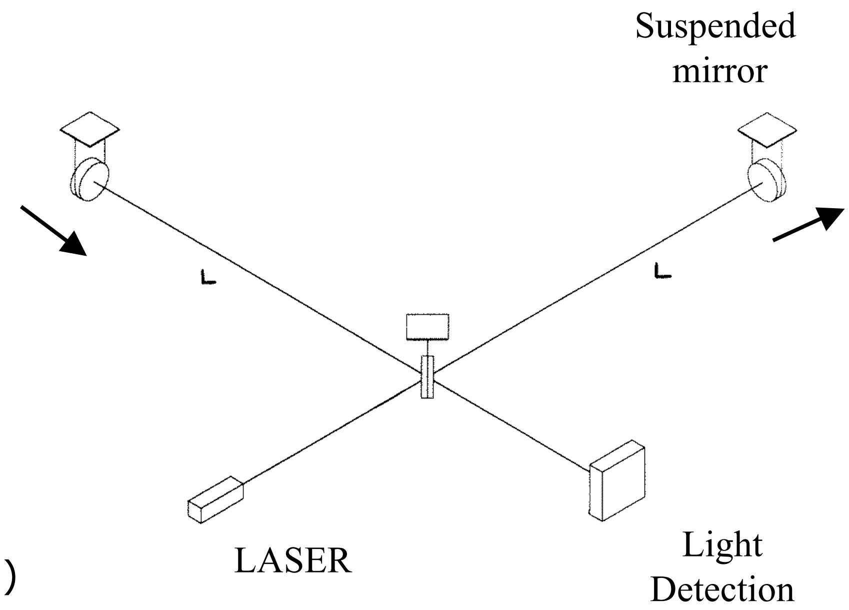
Pulsar timing

Interferometric detectors in space

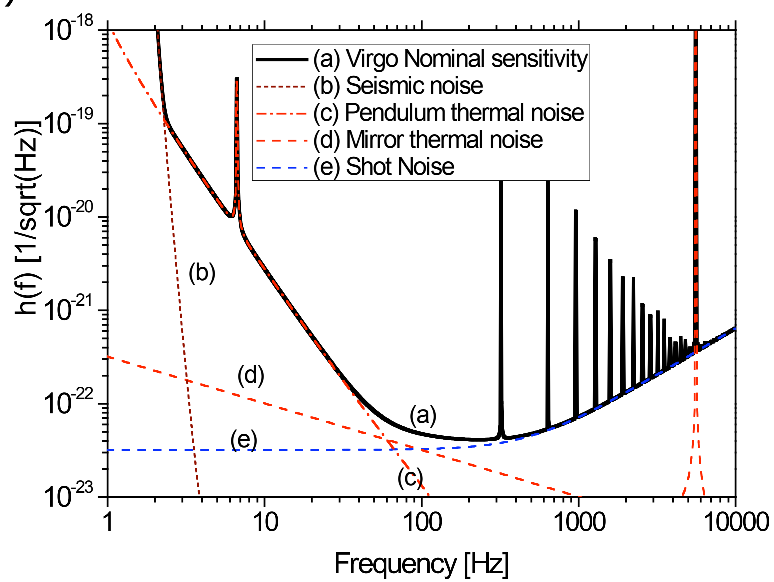
Ground-based Interferomeric detectors

# 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)

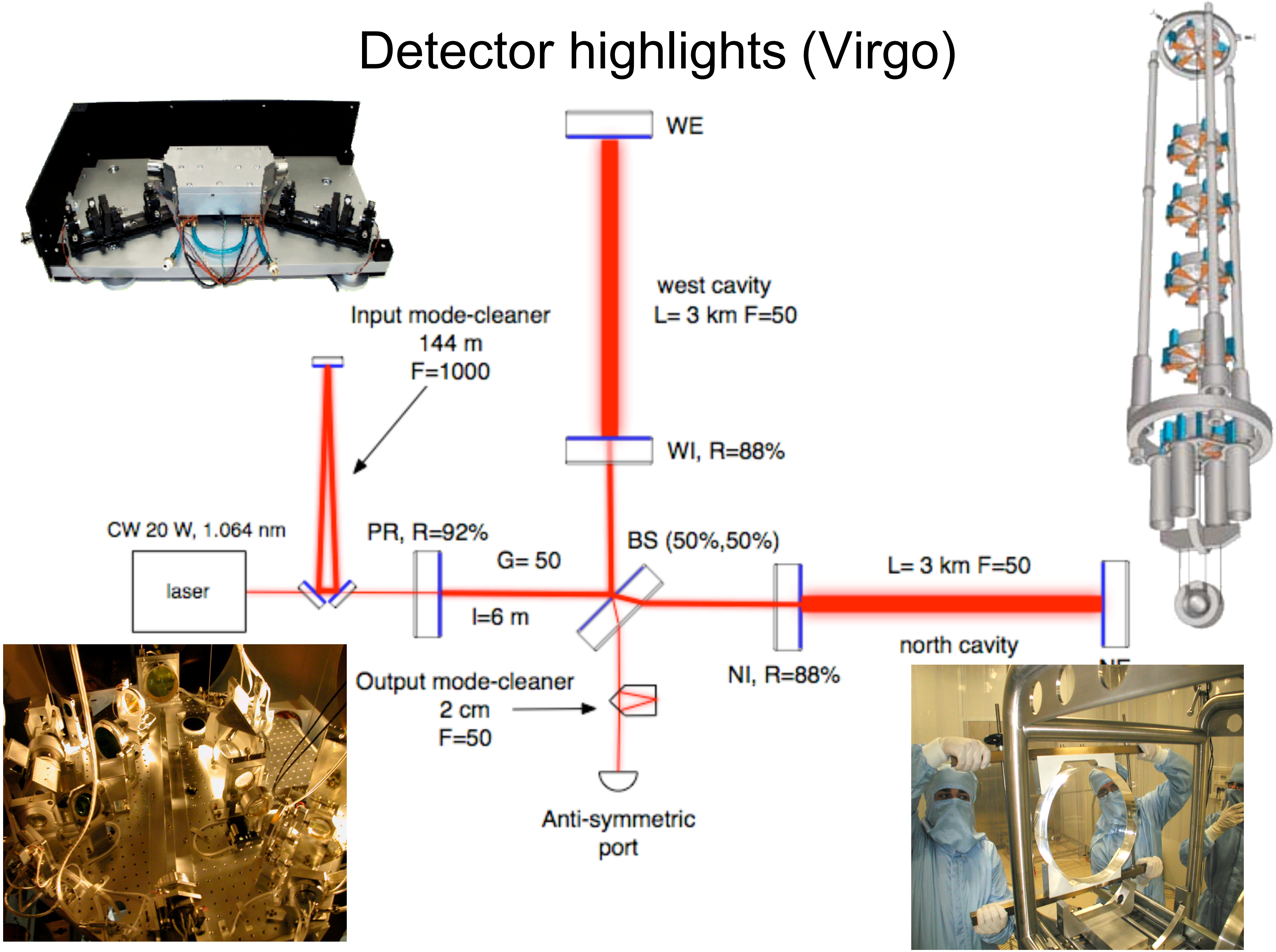



If target h ~ $10^{-21}$
*(NS/NS @Virgo Cluster)*

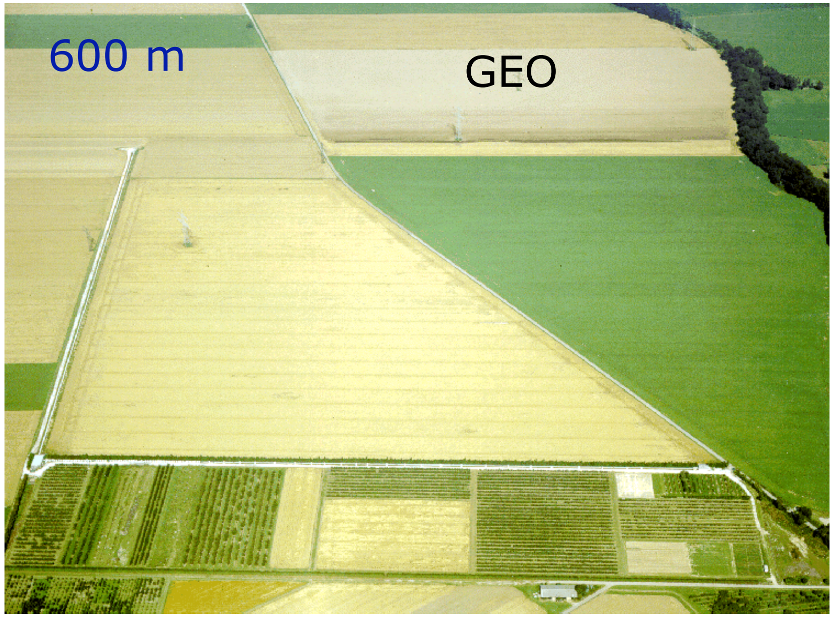
and L ~ $10^3$ m

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

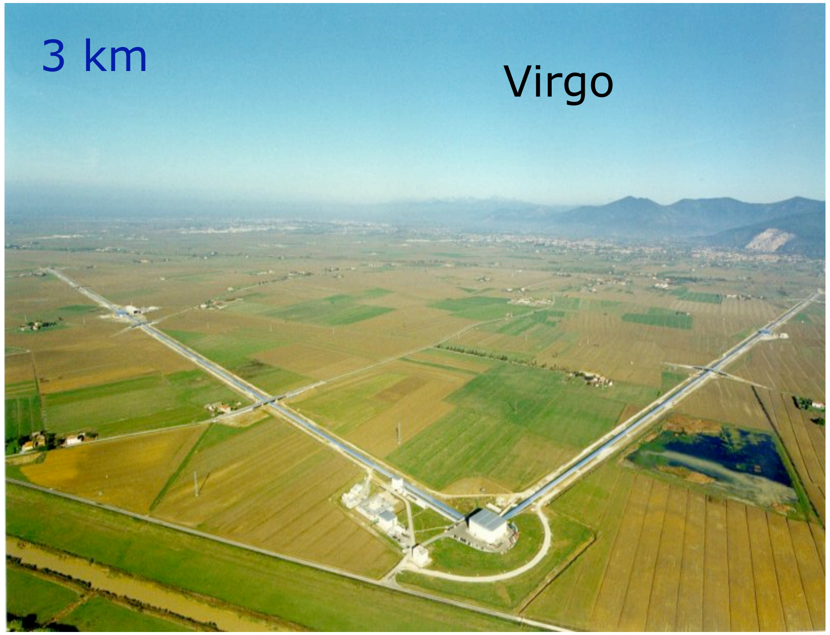
# Detector highlights (Virgo)



# First generation detectors

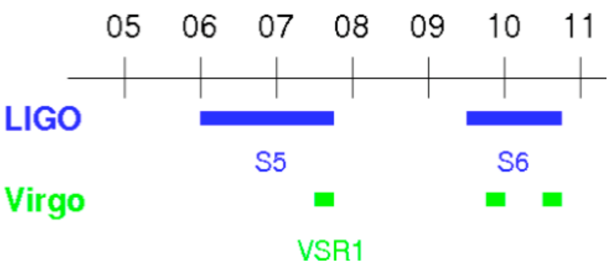




# An international GW network

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


Data takings



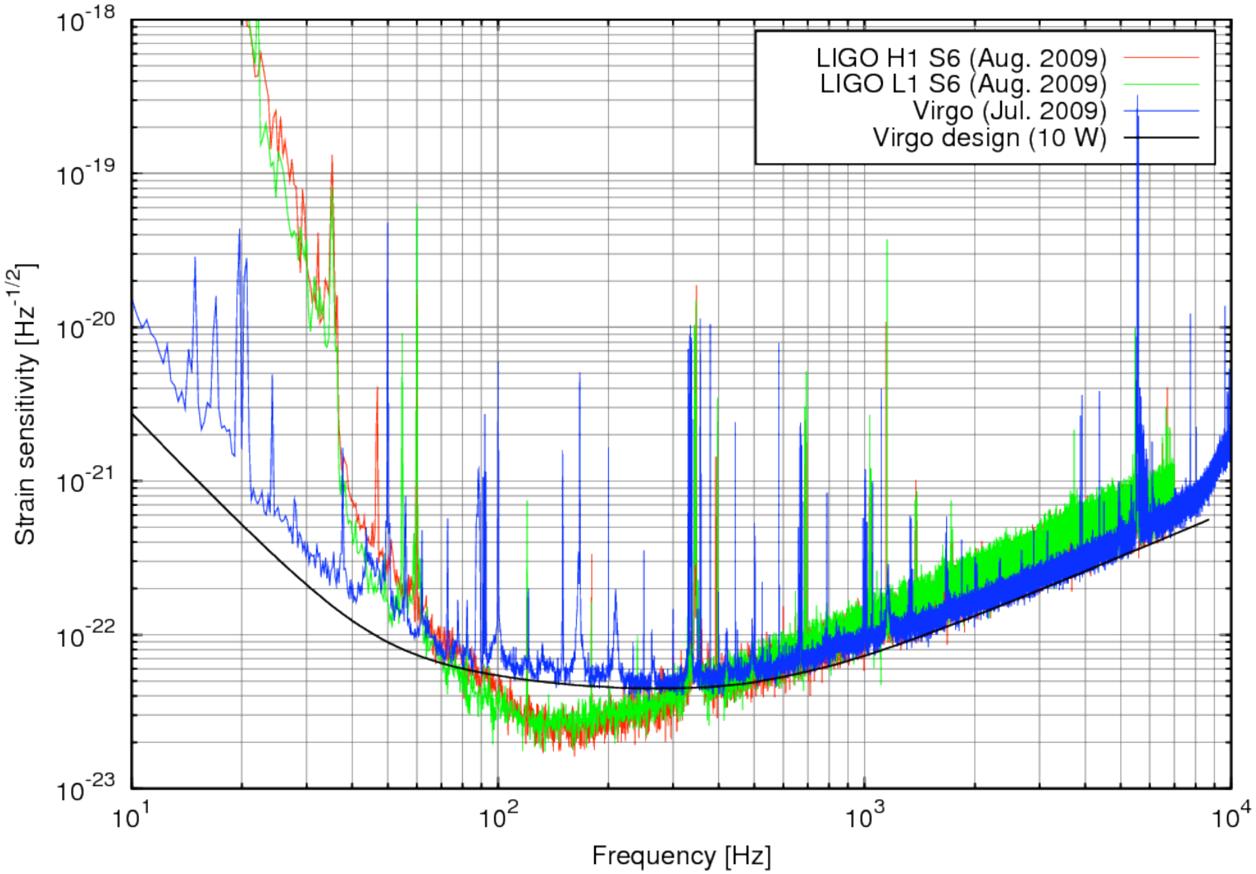

Agreement Virgo-LSC (2007)

- 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

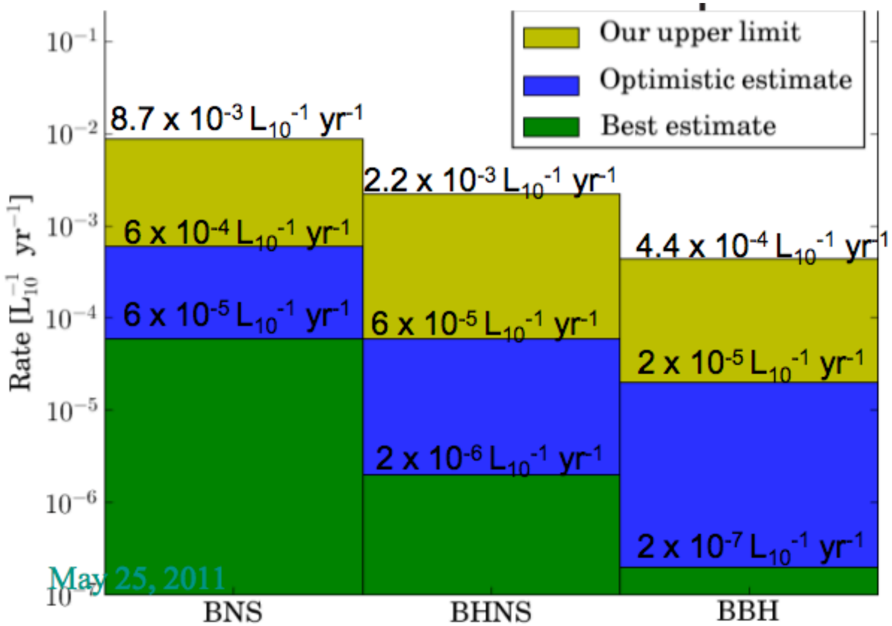
# Coalescing binaries: estimates for initial detectors and upper limits

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] | $\dot{N}_{\rm low}$ yr$^{-1}$ | $\dot{N}_{\rm re}$ yr$^{-1}$ | $\dot{N}_{\rm high}$ yr$^{-1}$ | $\dot{N}_{\rm max}$ yr$^{-1}$ |
|---|---|---|---|---|---|
| | NS–NS | $2 \times 10^{-4}$ | 0.02 | 0.2 | 0.6 |
| | NS–BH | $7 \times 10^{-5}$ | 0.004 | 0.1 | |
| Initial | BH–BH | $2 \times 10^{-4}$ | 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
  - $\varepsilon < 1.1\times10^{-3}$

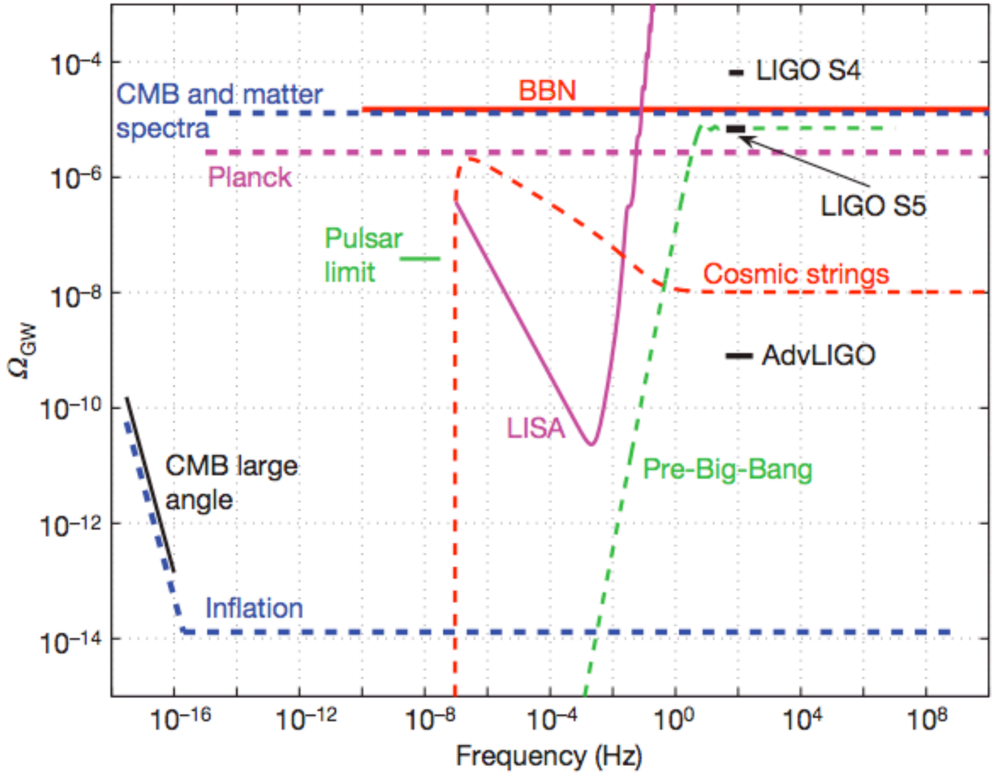
## Other targeted searches

- 116 known millisecond and young pulsars with LIGO S5 data
  - Best h limit $2.3\times10^{-26}$
    - J1603−7202, 135 Hz
  - Best $\varepsilon$ limit $7.0\times10^{-8}$
    - J2124−3358, 406 Hz, 0.2 kpc

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

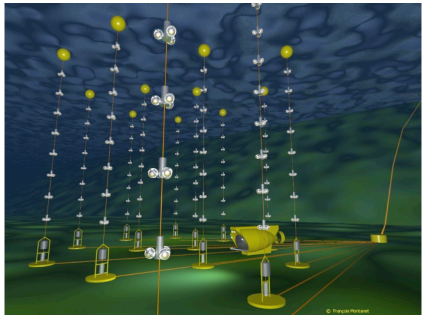
# Stochastic background

- 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

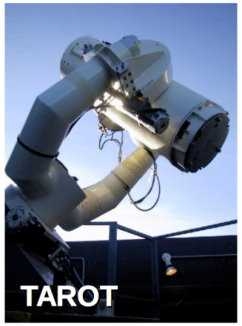


Motivations:

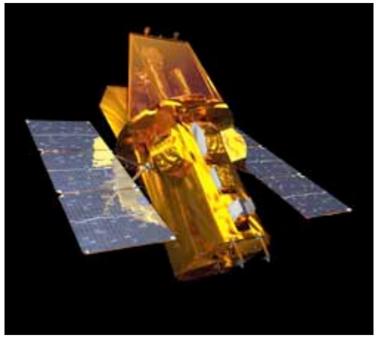
- ❑ GW comes from very energetic astrophysical processes, likely sources of EM radiation or high-energy particles
- ❑ correlate in time & direction observation by GW and other messengeres

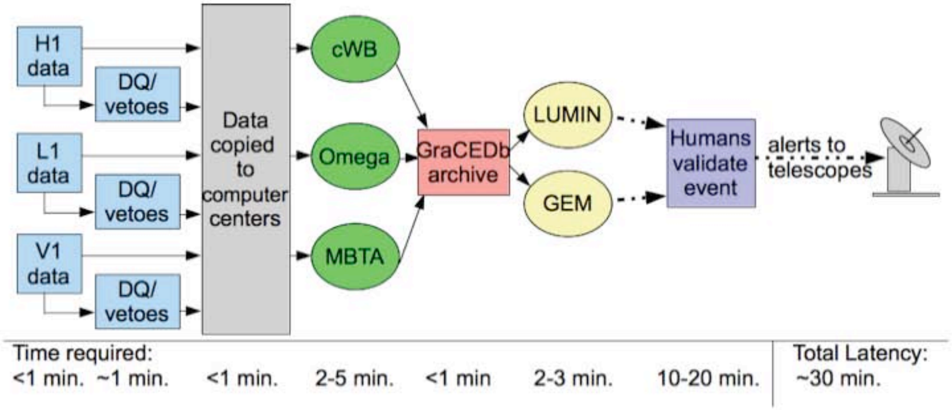
Two approaches:

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

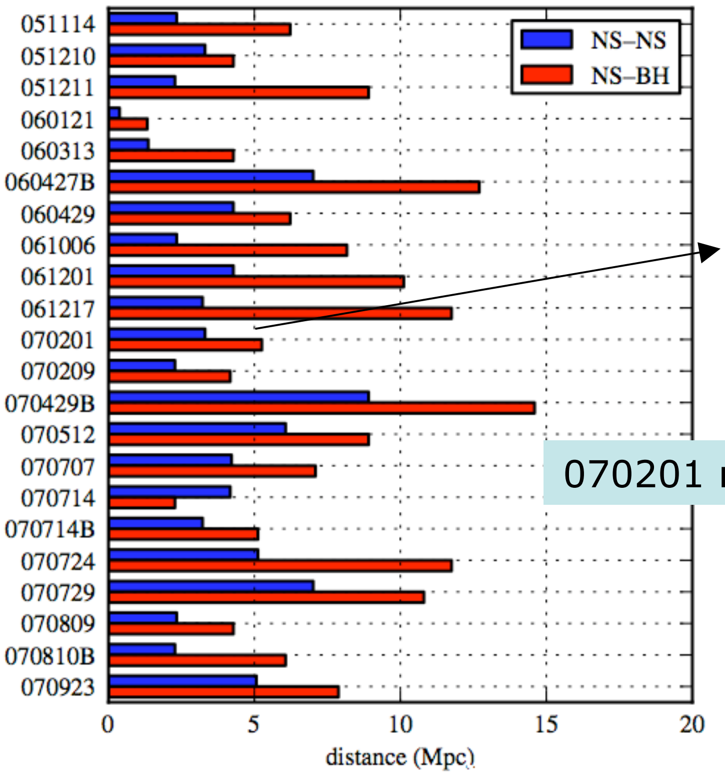

- ❑ Electromagnetic follow-up
  - ❑ SWIFT (gamma, X), LOFAR (radio), ROTSE, TAROT, and others
- ❑ High-energy neutrinos
  - ❑ Exchange of triggers with Antares and IceCube

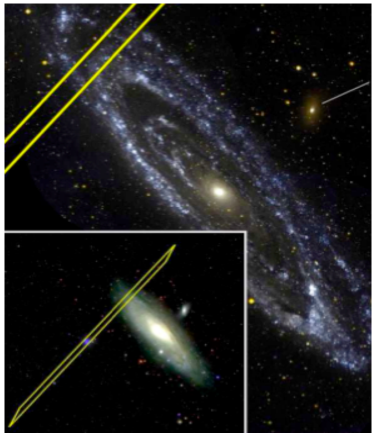




# GRBs

- 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

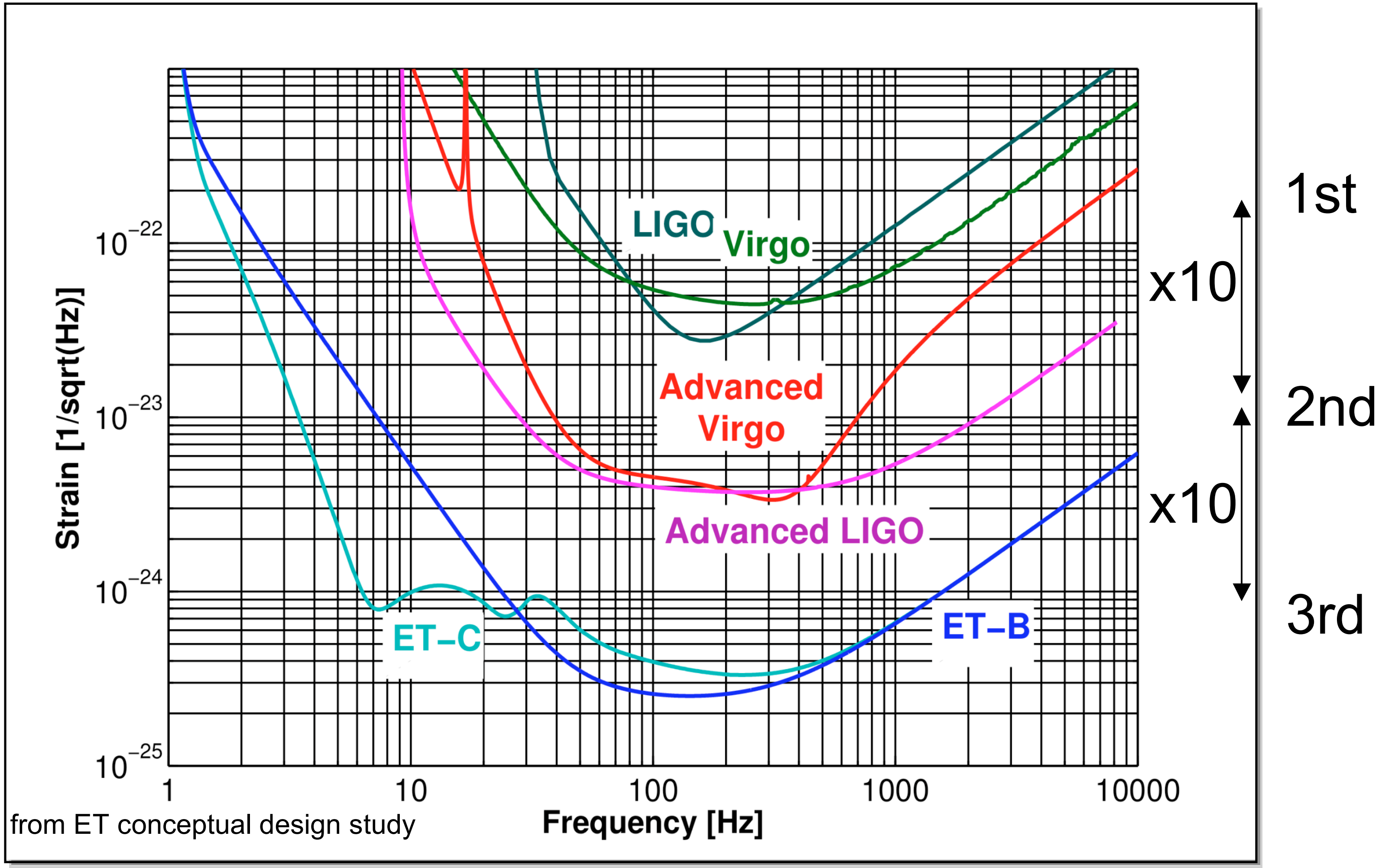


070201 not a merger in M31

- *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

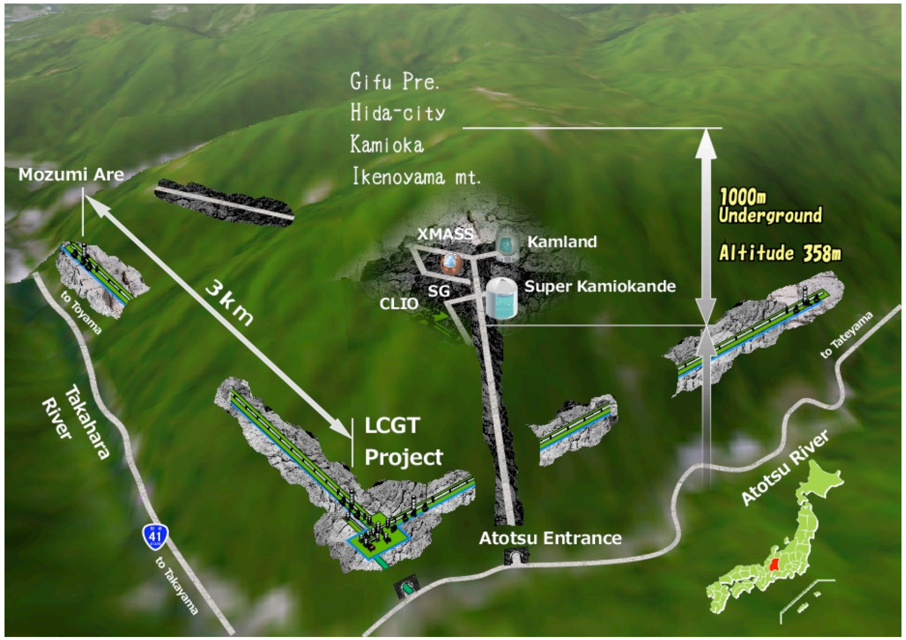



increase in rate ~ (increase in sensitivity) $^3$

# Second generation detectors

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

- ❑ LCGT cryogenic and under vacuum




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

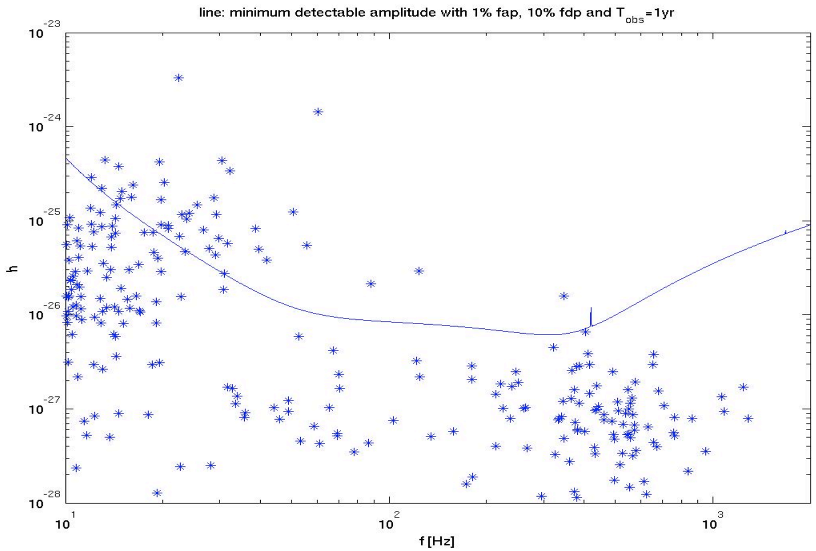
# Some sources for 2nd generation detectors

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 | |

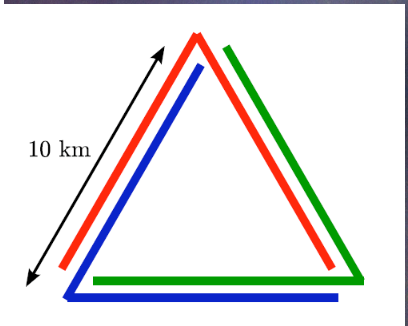
- NS-NS ~ 200 Mpc ⟶
- BH-BH ~ 1 Gpc

Likely detection by second generation interferometers

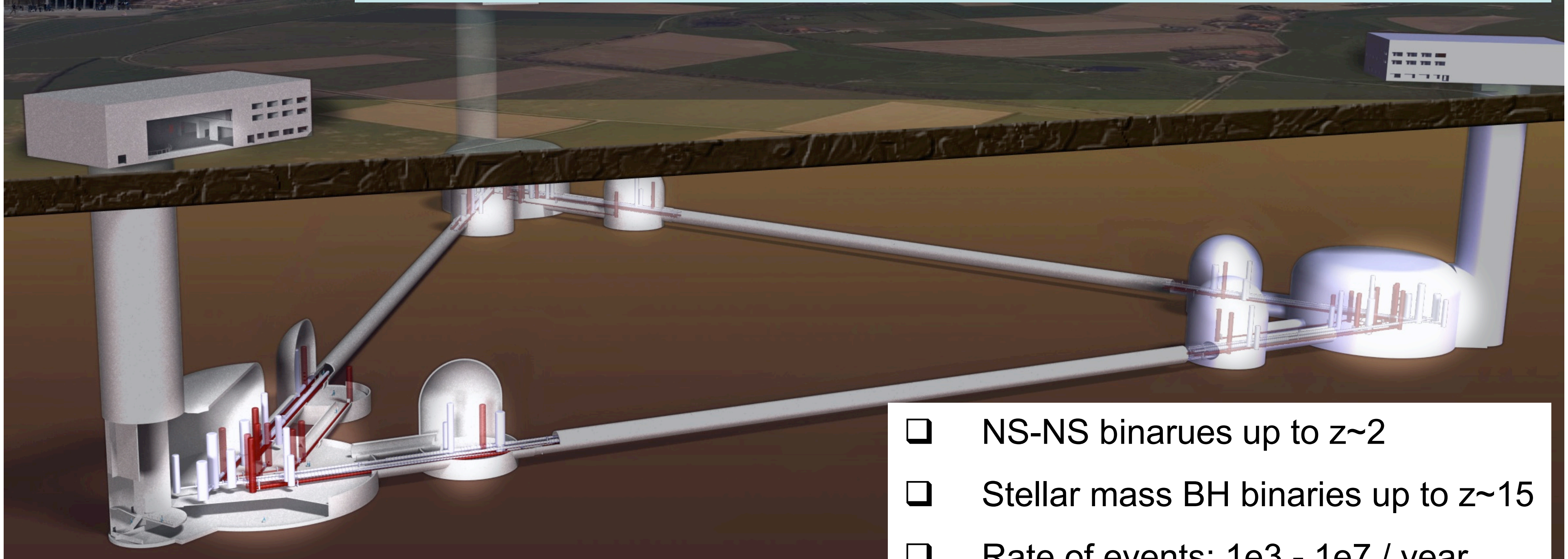



Spin-down limit for ~ 40 known pulsars

# 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 ready (pre-released)
- ❑ Next step - technical design
- ❑ Science data > 2025 (if funded)



- ❑ NS-NS binarues up to z~2
- ❑ Stellar mass BH binaries up to z~15
- ❑ Rate of events: 1e3 - 1e7 / year

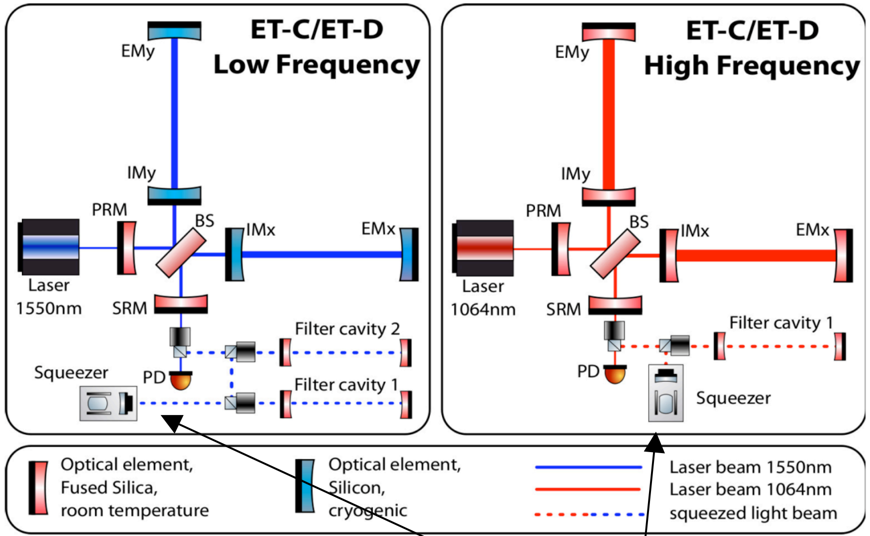
m ET conceptual design study

# Future technologies for Einstein Telescope

Cryogenic (10 K)

Low power input (3 W)

Silicon mirrors

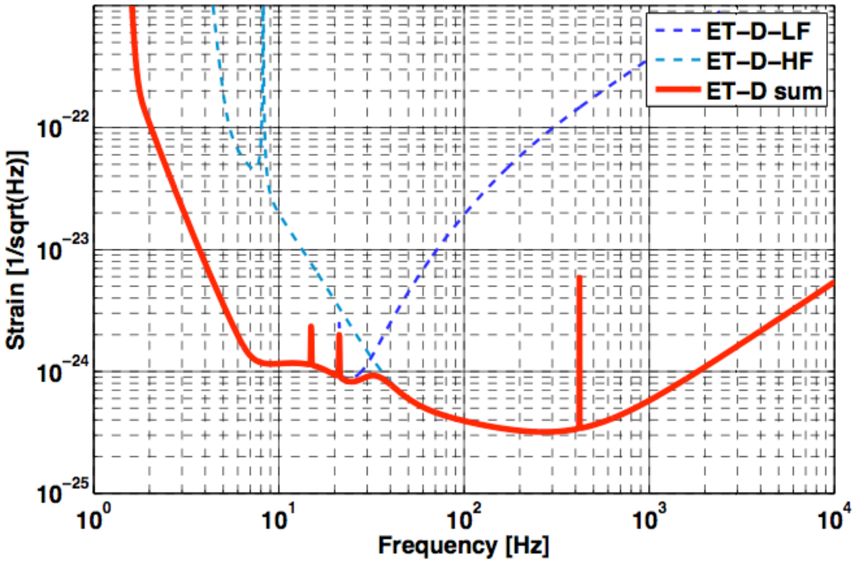



Room temperature

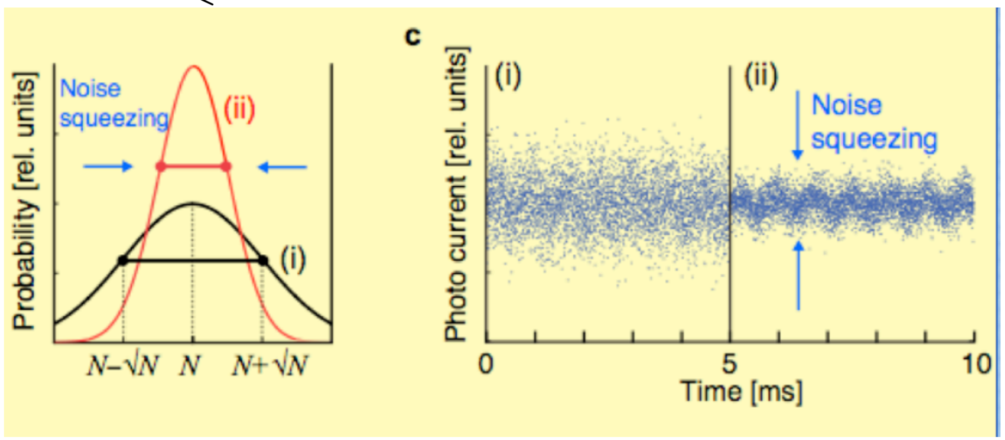
High power input (500 W)

3 MW in the arms

Fused silica mirrors

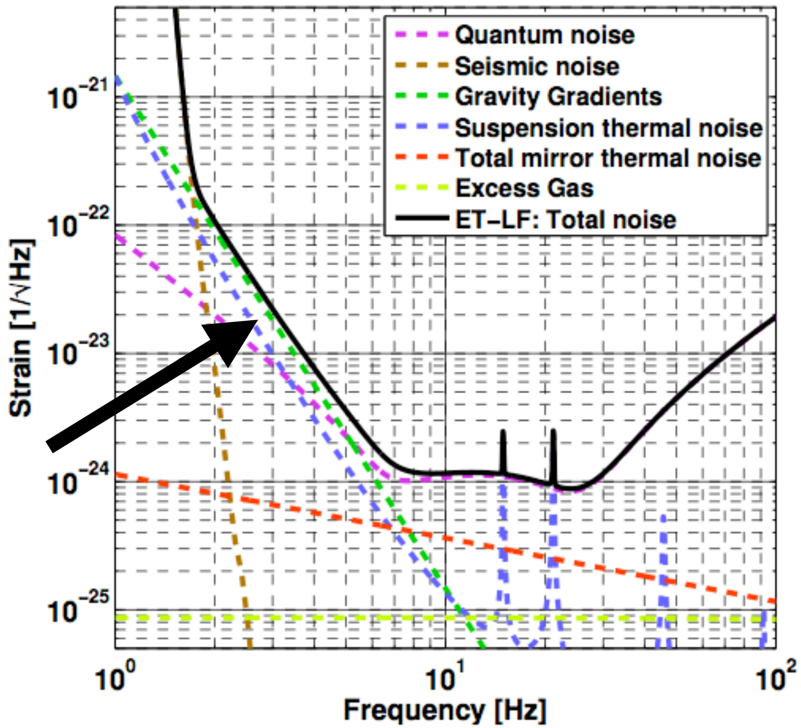



from ET conceptual design study




Use of non-classical states of light

# Seismic and gravity gradient noise




Test mass

density gradients =
gravity gradients

In order to access the low frequency sources (< 1Hz)
**Space detectors**

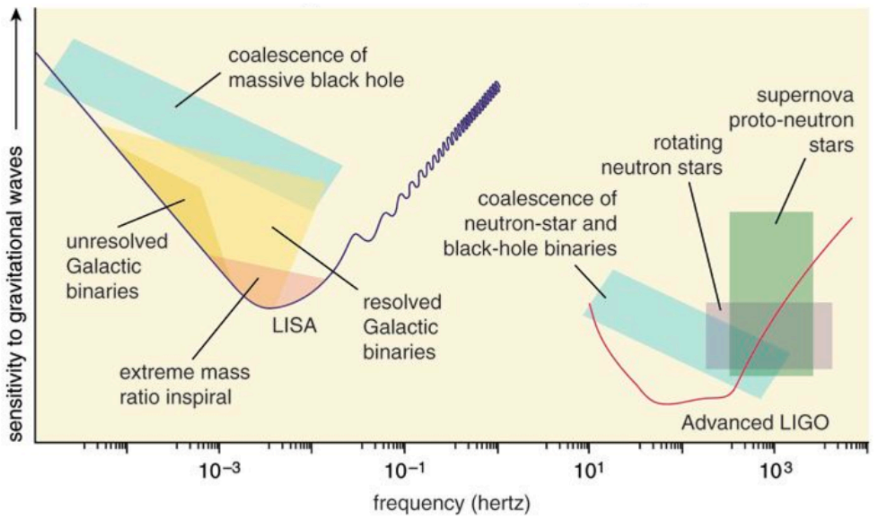
- No seismic noise
- Bigger arm-length

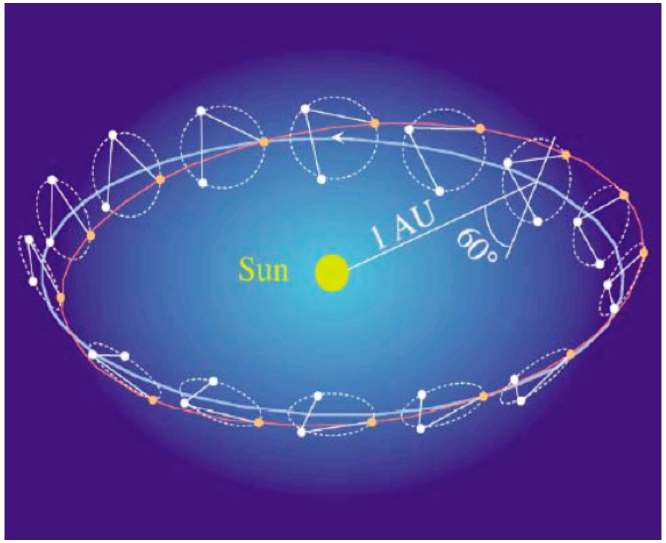
# Laser Interferometric Space Antenna (LISA)

original mission ESA-NASA

- 3 spacecraft separated by 5 millions km
- heliocentric orbits - earth 20 deg behind or in front
- Two Drag-free proof masses inside each space-craft - Laser interferometer measure distance between proof masses

- News: only ESA mission
- Rescaling the mission to fit the ESA envelope without big reduction of the science impact
- More informations at the Concurrent Design Facility study end of June
- LISA path-finder launch not affected (2014/2015)



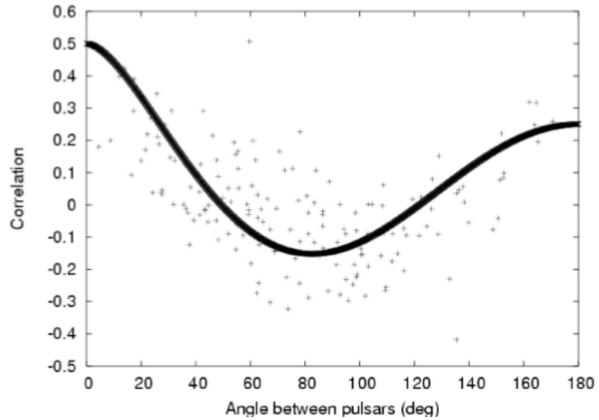




Some of the science possible with LISA:

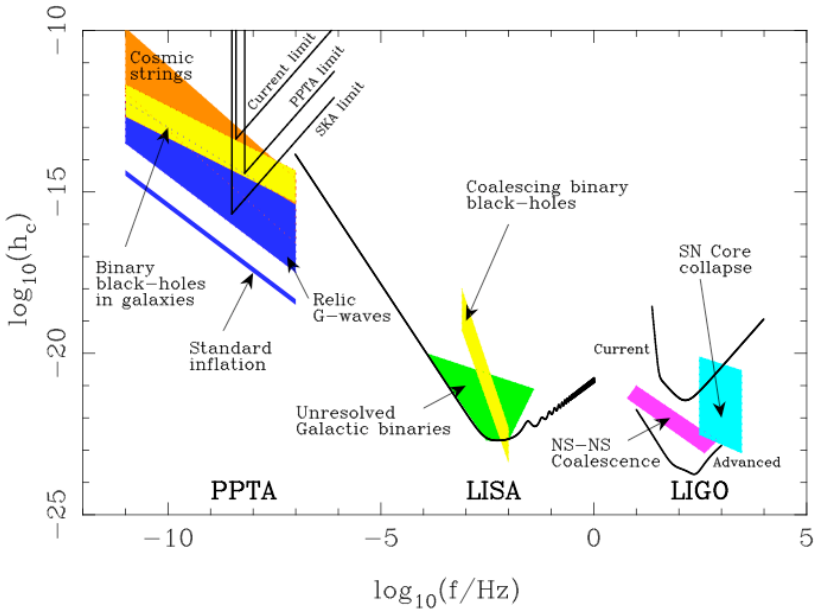
- Test of the General Relativity
- Cosmology: Coalescing binaries are *standard candles* (if the redshift is independently measured)
- Evolution of supermassive black-holes

# Pulsar timing

- Millisecond pulsar very stable clocks
- Search for correlations in the timing residuals of tens of pulsars using several radio-telescopes
- Sensitivity of GW in the 10 μHz range




- International Pulsar Timing Array: EPTA (EU)+ NANOGrav (USA) + PPTA (Australia), 7 telescopes
  - Goal: combine 5 years of data sets from 20 pulsars
- SKA (square kilometer array) ~ 2022




*The international pulsar timing array project: using pulsars as a gravitational-wave detector*
Hobbs et al., arXiv:0911/5206v1

Hobbs,
*Pulsars as gravitational wave detectors*
George Hobbs.
arXiv:1006.3960v1

# Summary

- 1st generation gravitational-wave interferometers work
  - They have collected several months 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 (LCGT)
  - 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
- Interferometry in space is a crucial extension of running ground based interferometers
  - *new-LISA* only ESA mission - news at the end of 2011
  - LISA pathfinder being lunched in 2014-2015
- Pulsar timing array, very promising techniques for ultra-low frequency GW sources