Gravitational waves search: principles, status and perspectives

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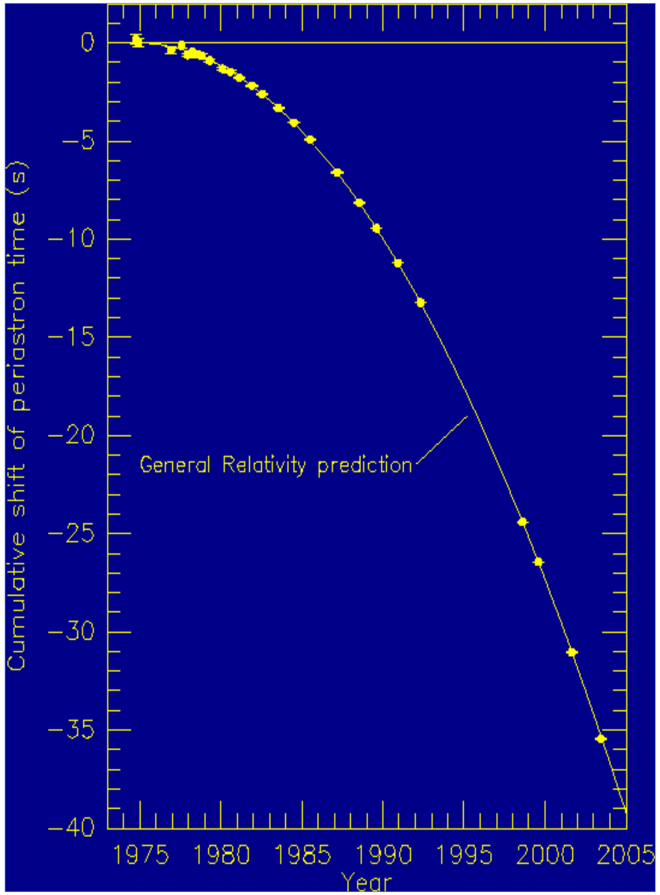
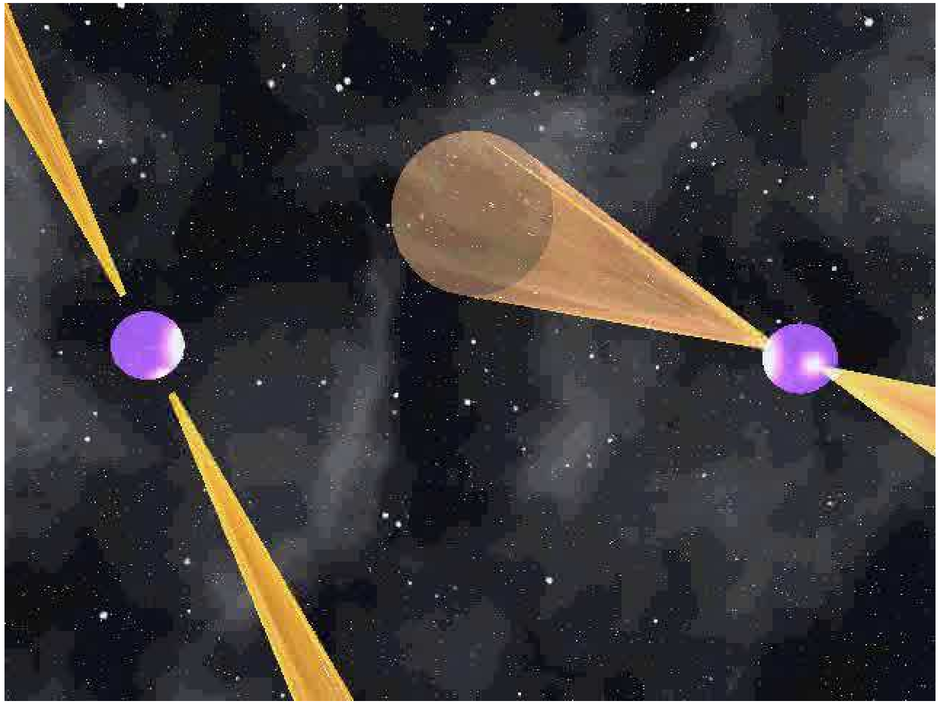
Gravitational waves are there

- Binary pulsar 1913+16 (Hulse and Taylor)
  - binary system formed by two neutron stars (one pulsar)
  - orbital period (~ 8 h) is decreasing
  - due to energy loss via GW emission
  - excellent agreement with general relativity

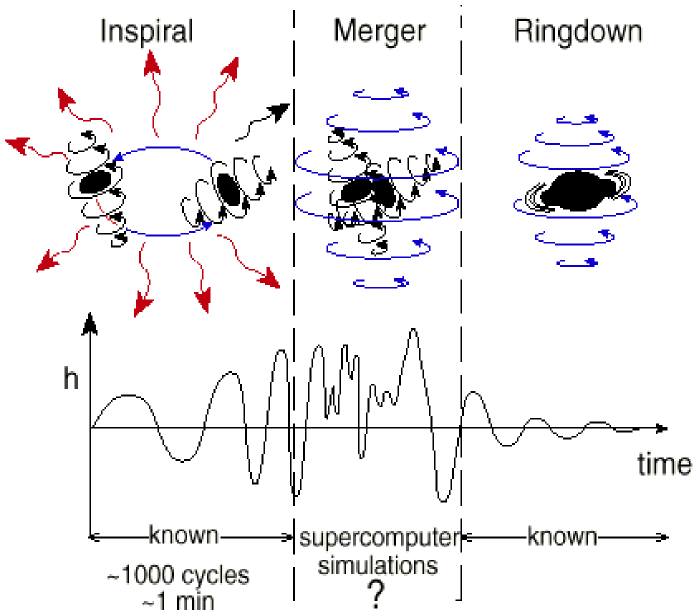


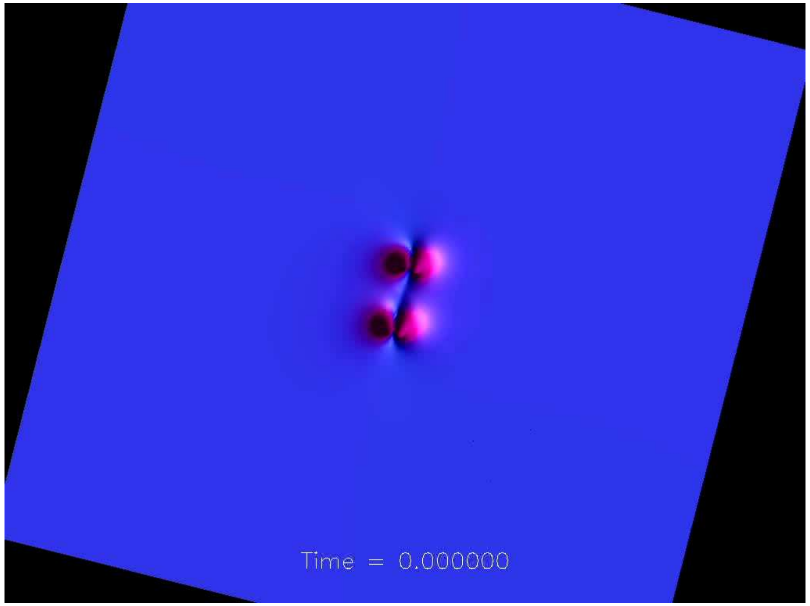


- Six binaries of this kind known in the galaxy
- When stars coalescence occurs frequency of emitted GW will sweep across the detectors bandwidth

Coalescing binaries (I)

- Binaries formed by two compact stars
  - Binary neutron stars (BNS): best candidate for short γ-ray bursts
  - Binary black holes (BBH)
  - One Neutron star and one black hole
- Three main phases
  - Inspiral, merger, ring-down
  - First simulation of merger (non spinning black holes) now available



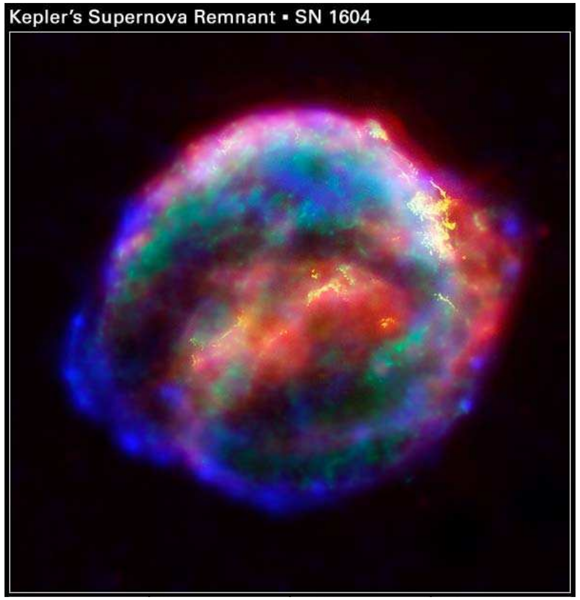


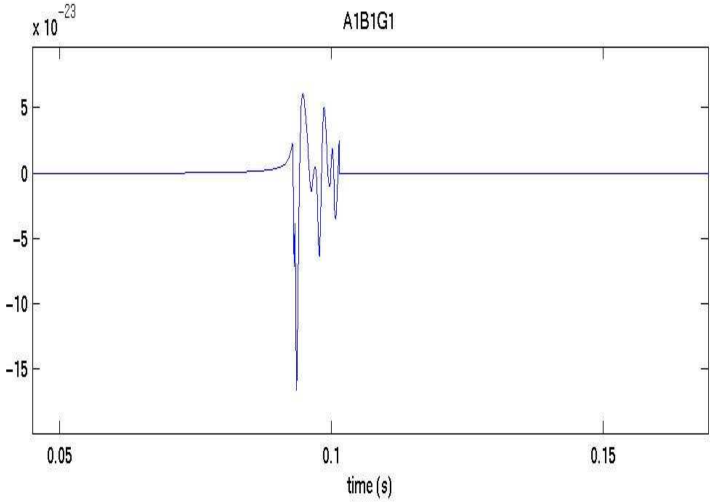
Coalescing binaries (II)

- Strong scientific potentials:
  - *Standard candles*
    - » distance of the source can be found out of the waveform
  - *Test of GR*
    - » accurate measurements of inspiral waveform can test gravity in the strong field regime
  - *Nuclear physics*
    - » before coalescence waveform sensitive to the equation of state
- Rates
  - Binary neutron stars: 10/yr – 160/yr within 300 Mpc (deduced from observation in our galaxy. Rate ~ $2 \cdot 10^{-5}$ to $3 \cdot 10^{-4}$ /yr)
  - Binary black holes: might be more but prediction is uncertain (only theoretical models)

Supernovae

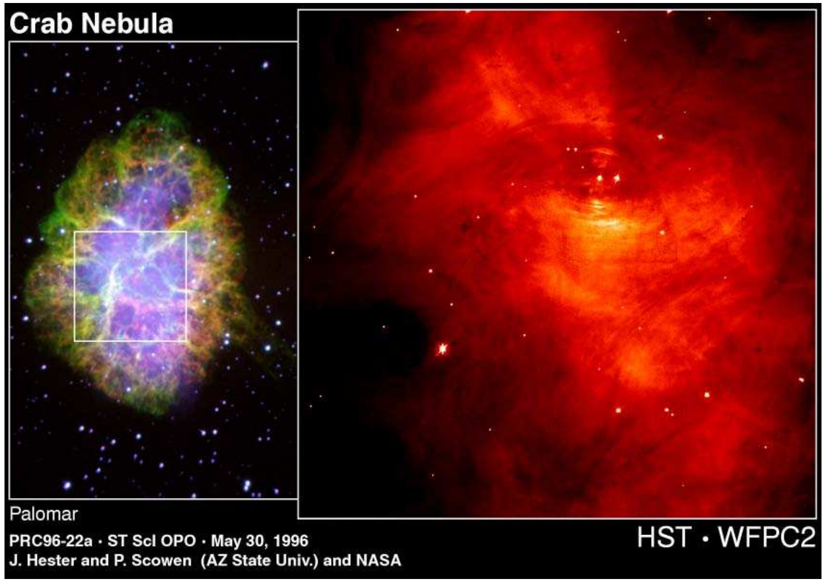
- Star core collapse
  - non-spherical collapse needed
- Impulsive event: ms
- Waveform and amplitude difficult to predict
- Rates:
  - one/century in the Galaxy
  - tens/year in the VIRGO cluster

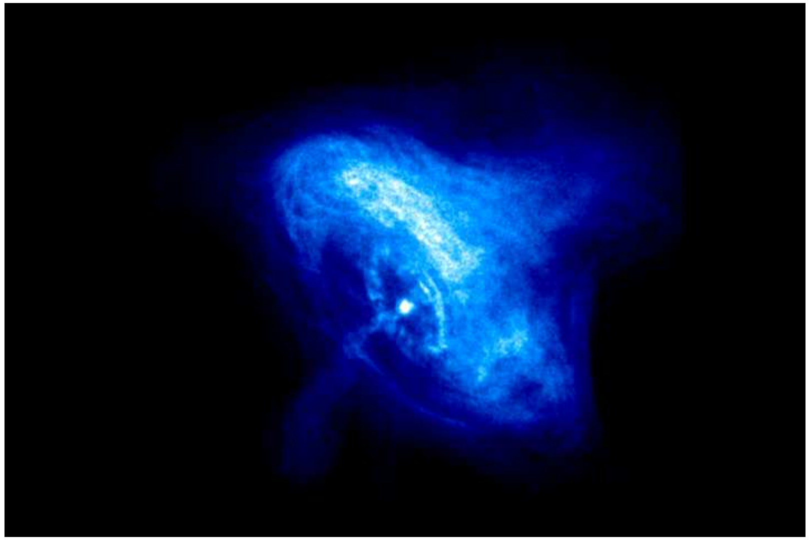




Pulsars

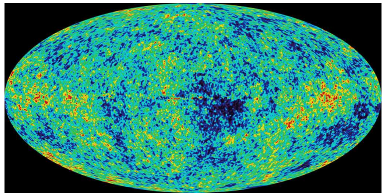
- Rotating neutron stars
- Periodical signals ($f_{GW} = 2\ f_{rot}$) modulated by earth motion (Doppler effect)
- GW emitted if non perfectly spherical star
- Amplitudes unknown; depends on star asymmetry
- Upper limits from pulsars slow down
- Information on deformation provide constrain on the star equation of state
- How many ?
  - ~10^3 pulsars known today
  - ~10^9 expected neutron stars in the galaxy

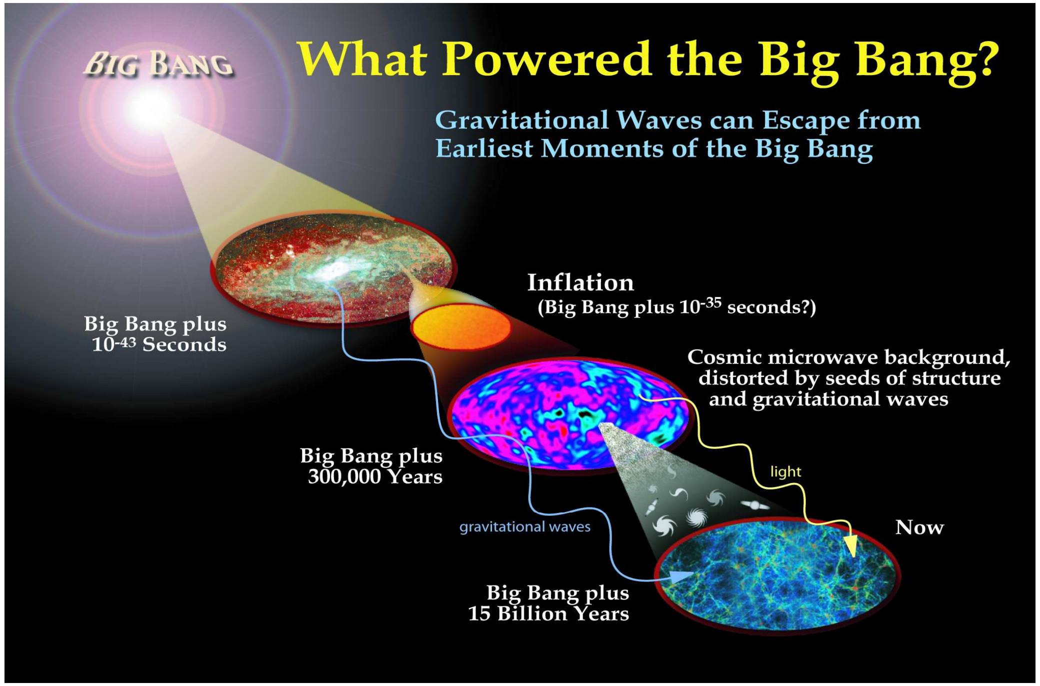




The Big Bang

- Relic stochastic background
- Imprinting of the early expansion of the universe
- Signal too weak if standard inflation
- Larger signals from some string models
- Stochastic signals (correlation between two detectors needed)





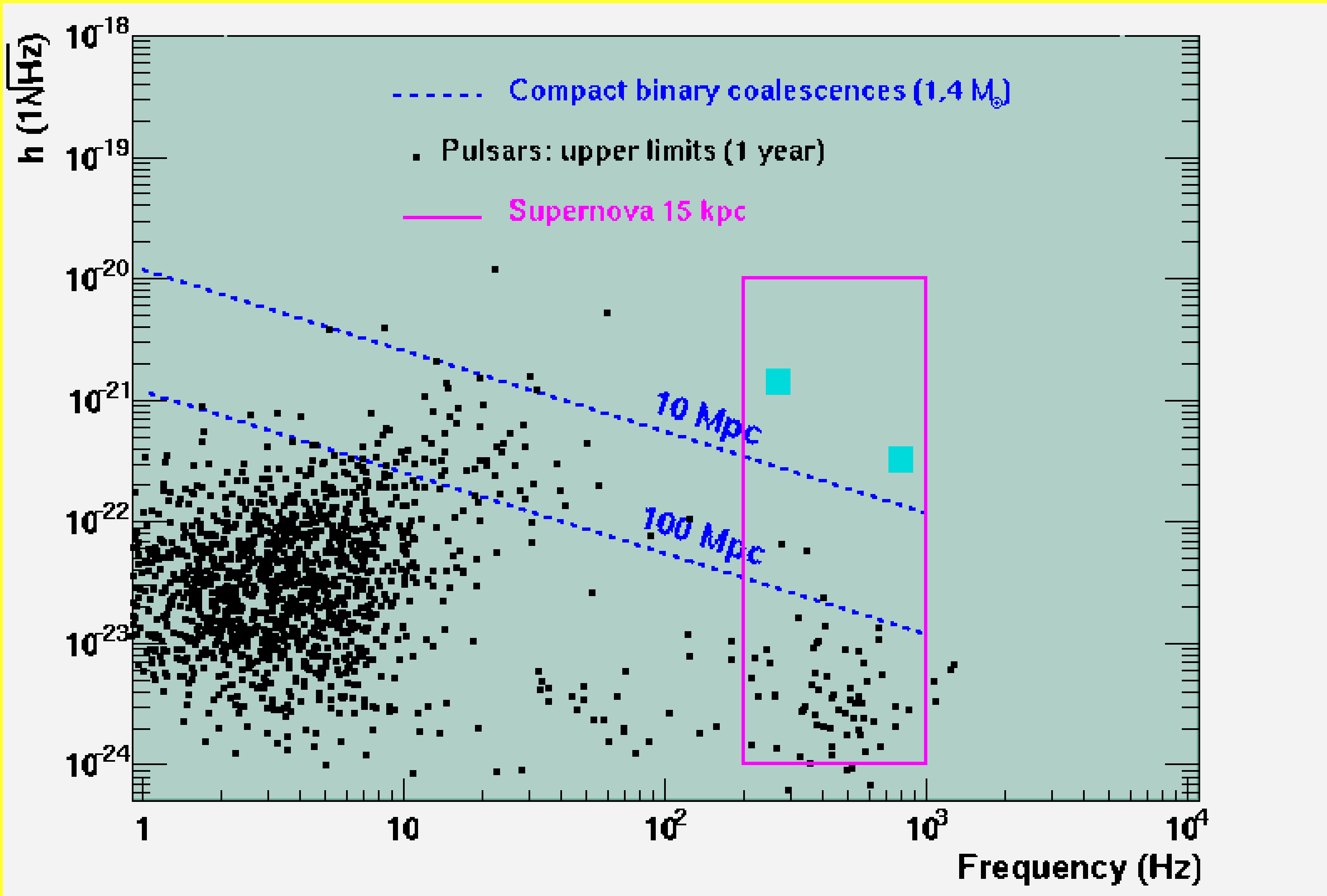
Scientific motivations

- First direct detection of gravitational waves

- Study of the gravitational force
  - GW can be generated by pure space-time (black holes)
  - GW can reveal the dynamic of strongly curved space-time

- New window to observe the universe
  - GW are produced by coherent relativistic motion of large masses
  - GW travel through opaque matter
  - GW dominate the dynamics of interesting astrophysical systems

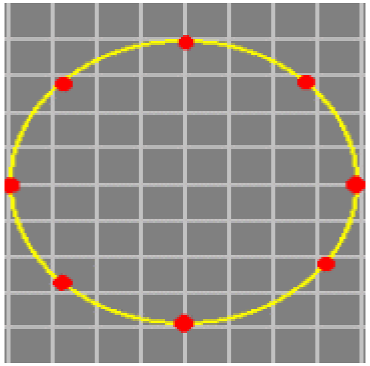
Sources: amplitude and frequency

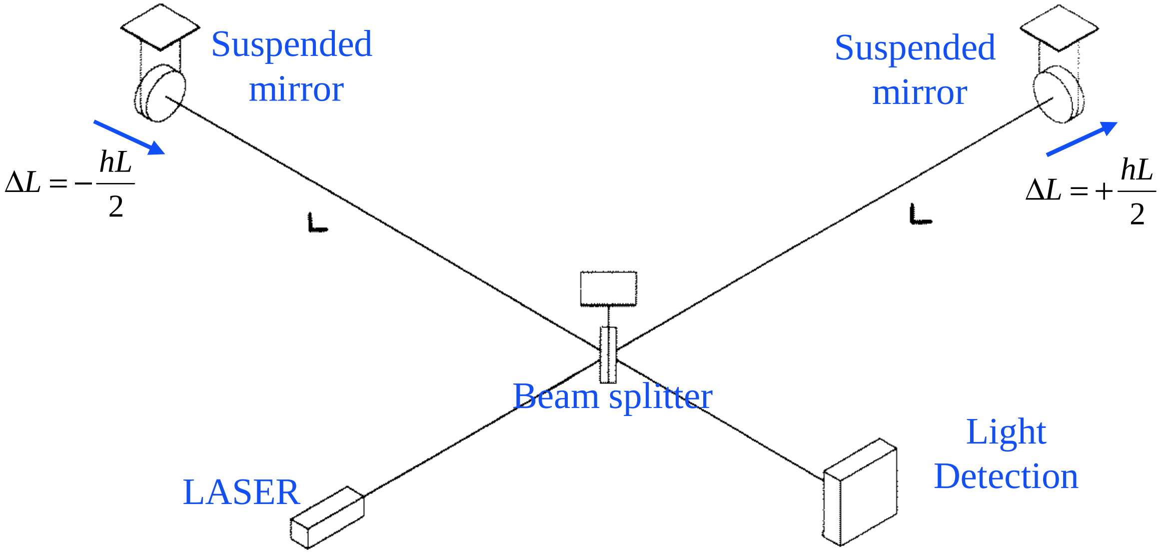


 Required sensitivity to start with ~ 10^{-22} /√Hz

Interferometers: principle

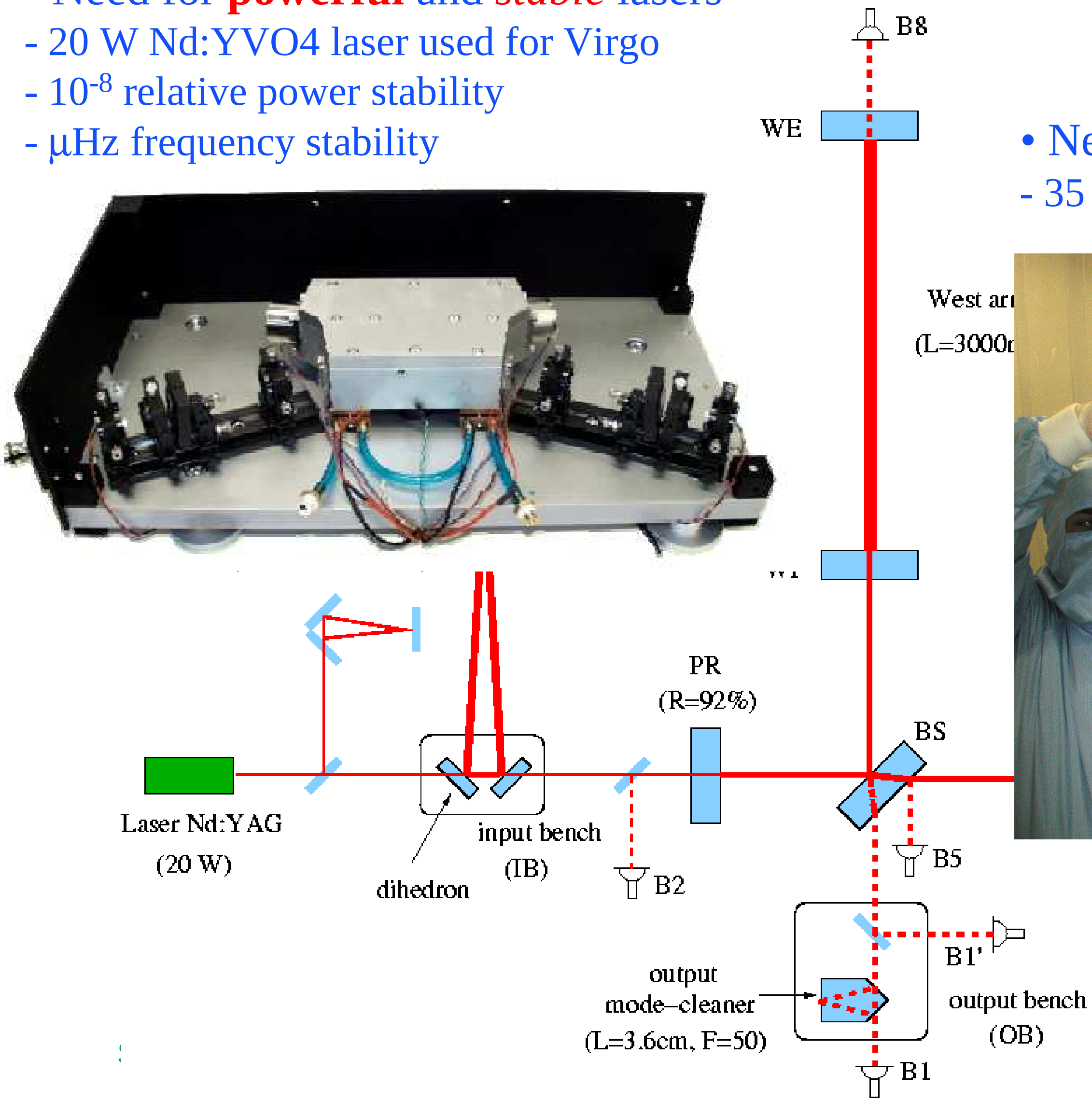
- GW are quadrupolar (spin 2 wave)
- Michelson interferometer ideal tool
- All mirrors suspended through pendulums
  = ‘free falling masses’
- h = 10^{-22} , L = 3 km $\Rightarrow$ dL $\approx$ 3 10^{-19} m
- GW detection
  = measure tiny displacements
  = measure tiny phase shift



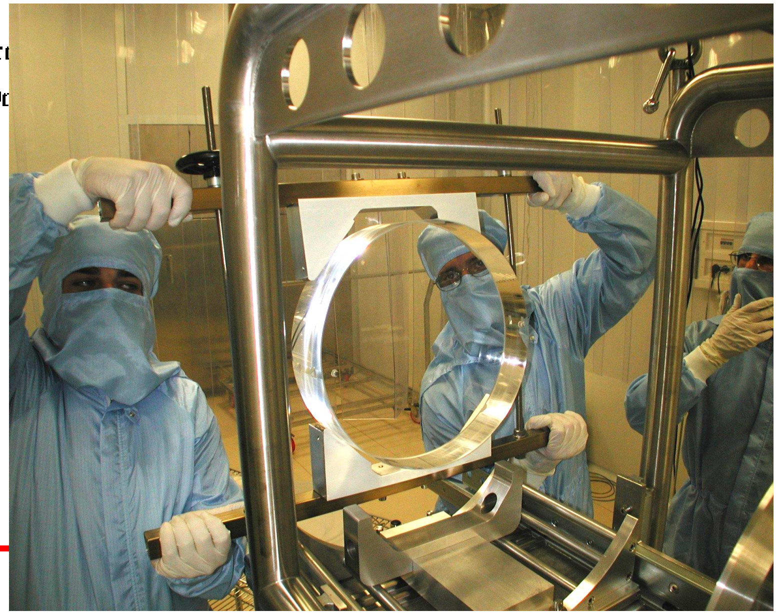


Virgo optical lay-out

- Need for **powerful** and *stable* lasers
  - 20 W Nd:YVO4 laser used for Virgo
  - 10^{-8} relative power stability
  - μHz frequency stability

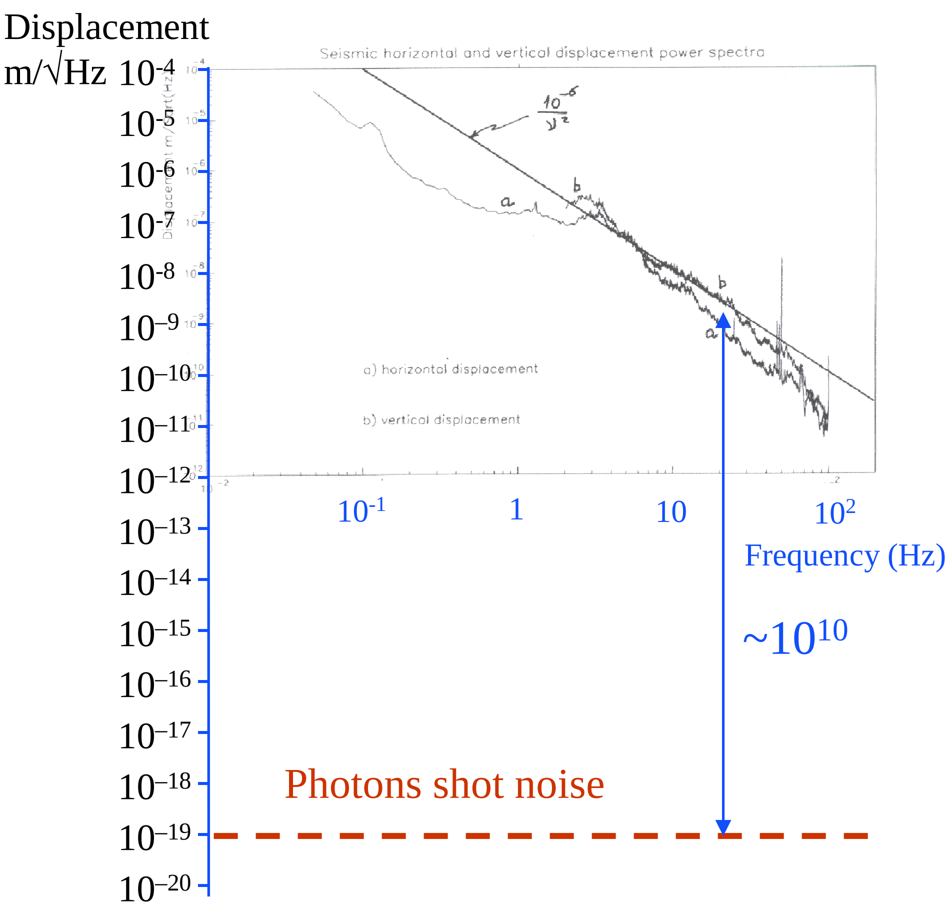


- Need for LARGE high quality mirrors
  - 35 cm diameter, 20 kg mirrors used



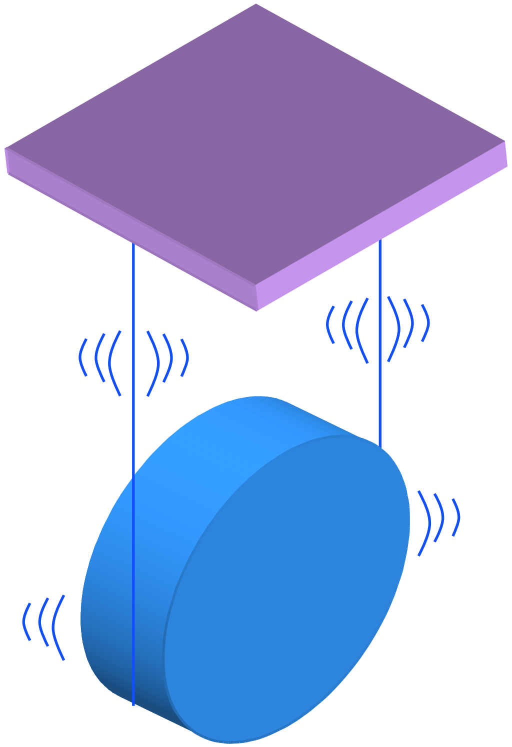
Displacement noises

- Seismic noise



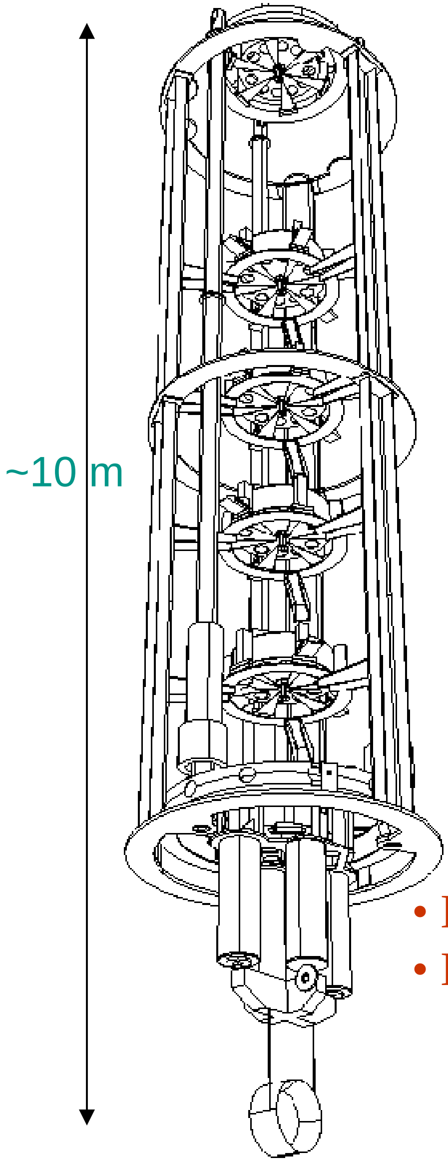
- Need for good seismic isolation
- Determines lower frequency cut-off "seismic wall"

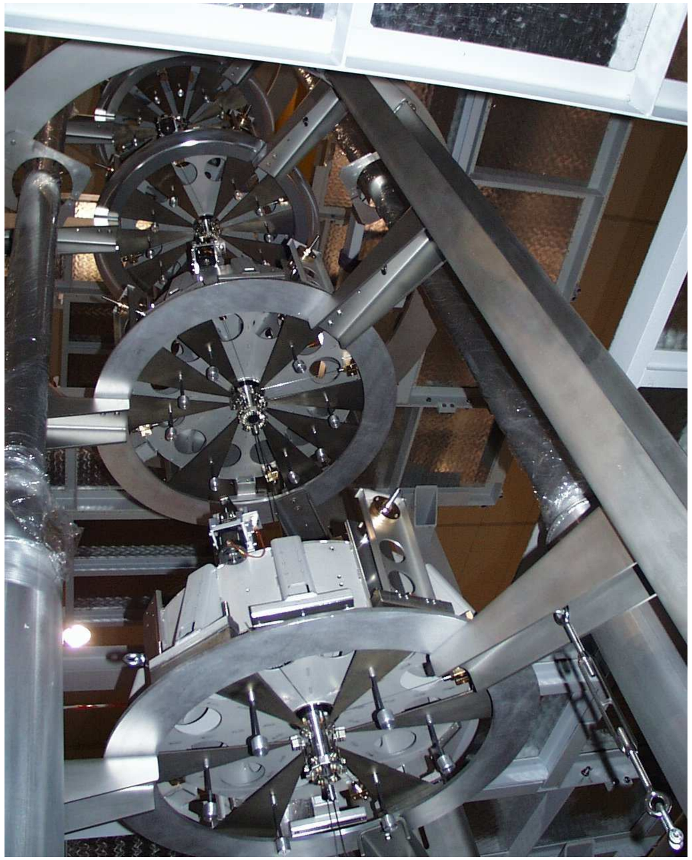
- Thermal noise



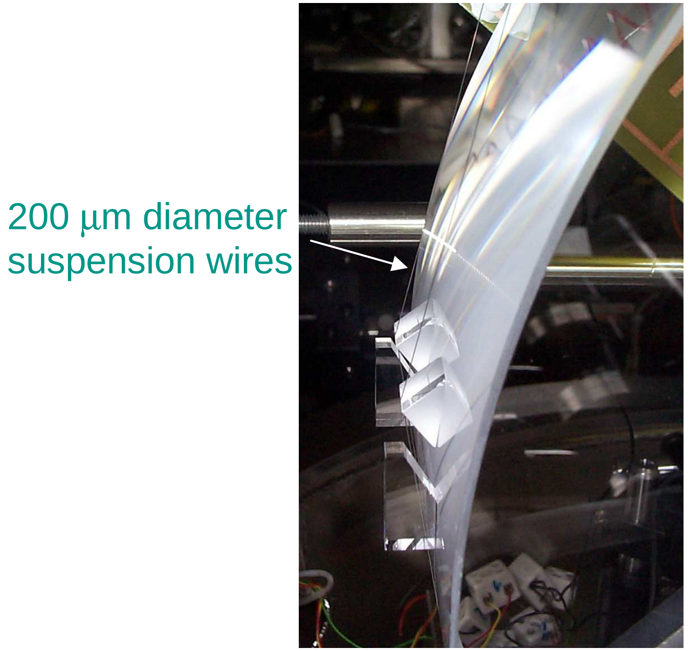
- Use high mechanical quality suspension
- Use high mechanical quality mirrors
- … or cool down

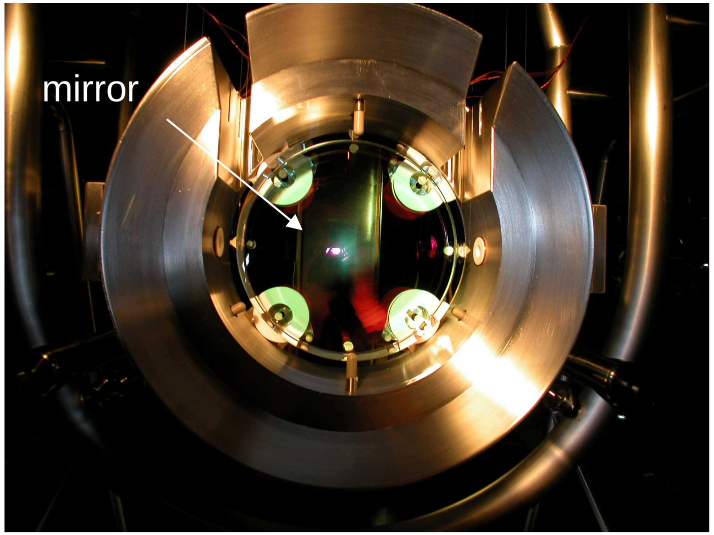
Virgo mirrors suspensions





- Expected attenuation > 10^{14} @ 10 Hz
- Low thermal noise

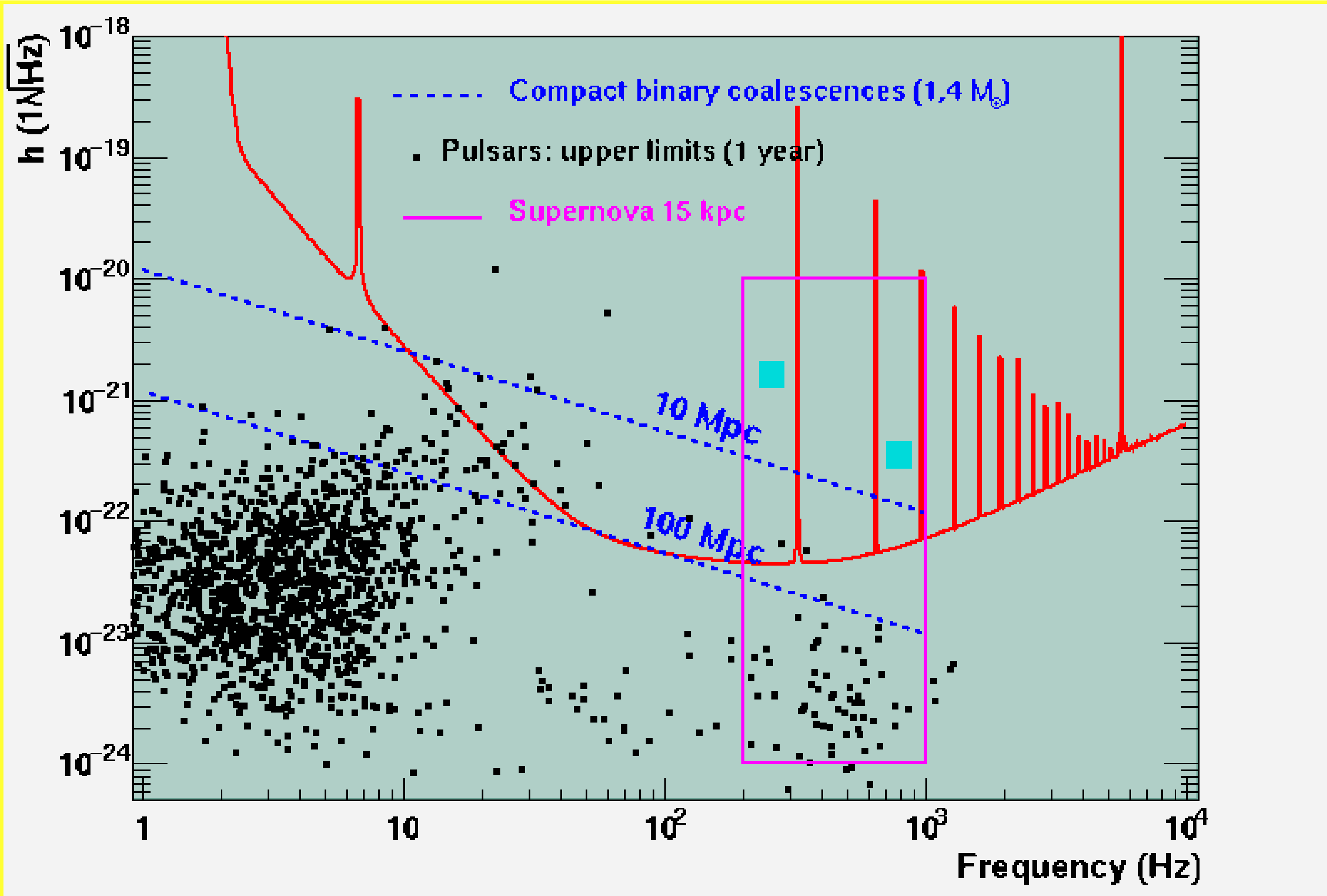




Virgo vacuum system

- Protect against acoustic noise and air refraction index fluctuations
- 3 km long tubes, 1.2 diameter
- One 10 m high vacuum chamber per suspension
- 10^{-9} mbar

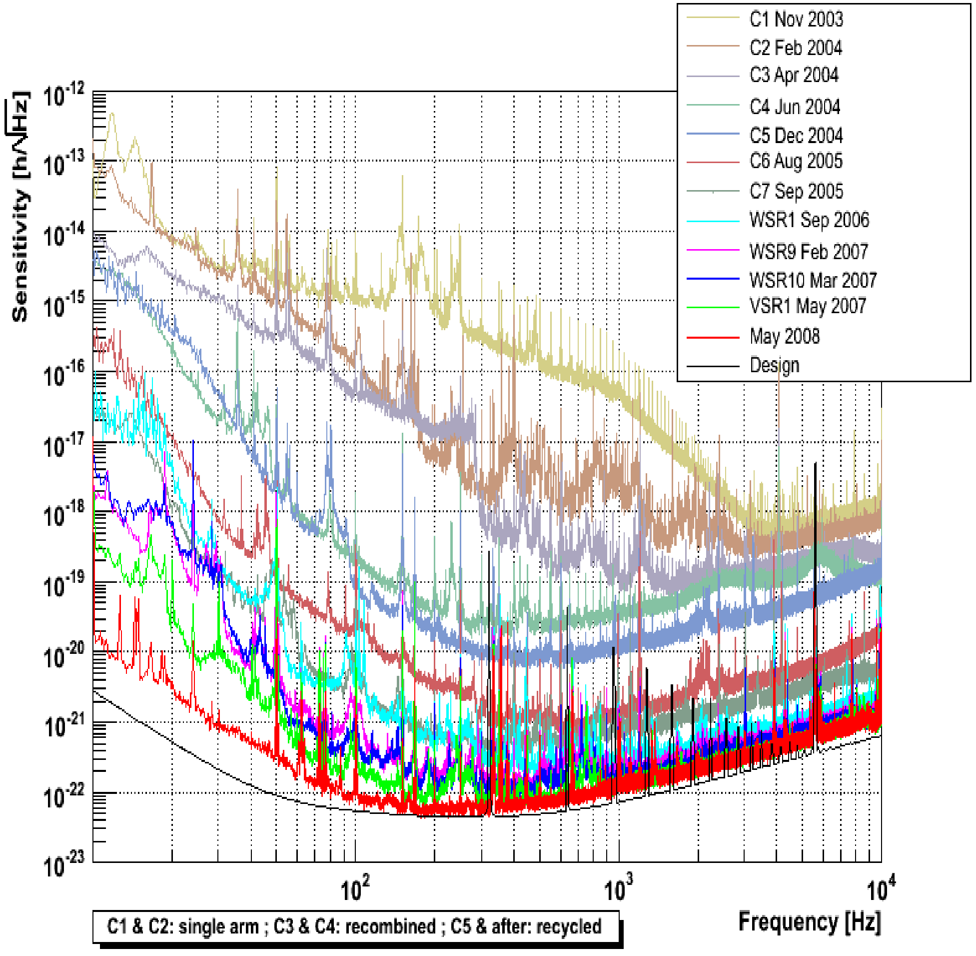
Virgo design sensitivity



- First detection is possible (or test of upper limits)

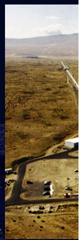
Interferometers development

- Early 70's: first studies
  - R. Weiss
- The 70's: R&D, 1 m scale prototypes
  - R.L. Forward 1974
- The 80's: R&D, 10 m scale prototy
  - E.g. the Garching 40m interferometer
- Late 80's: proposals for constructi
  scale laser interferometers
  - LIGO, Virgo, GEO
- The 90's: 100 m scales detectors
  - TAMA (Japan, 300 m)
  - GEO (Germany, 600 m)
- Mid 90's: start construction of km
  interferometers (LIGO, Virgo)
  - 1994: LIGO
  - 1996: Virgo
- 2000-2003: start commissioning
  - A relatively long phase of tuning



Interferometers around the world

LIG
2 IT



LIG

0 m

Memorandum of Understanding

between

VIRGO

on one side

and the

Laser Interferometer Gravitational Wave Observatory (LIGO)

on the other side

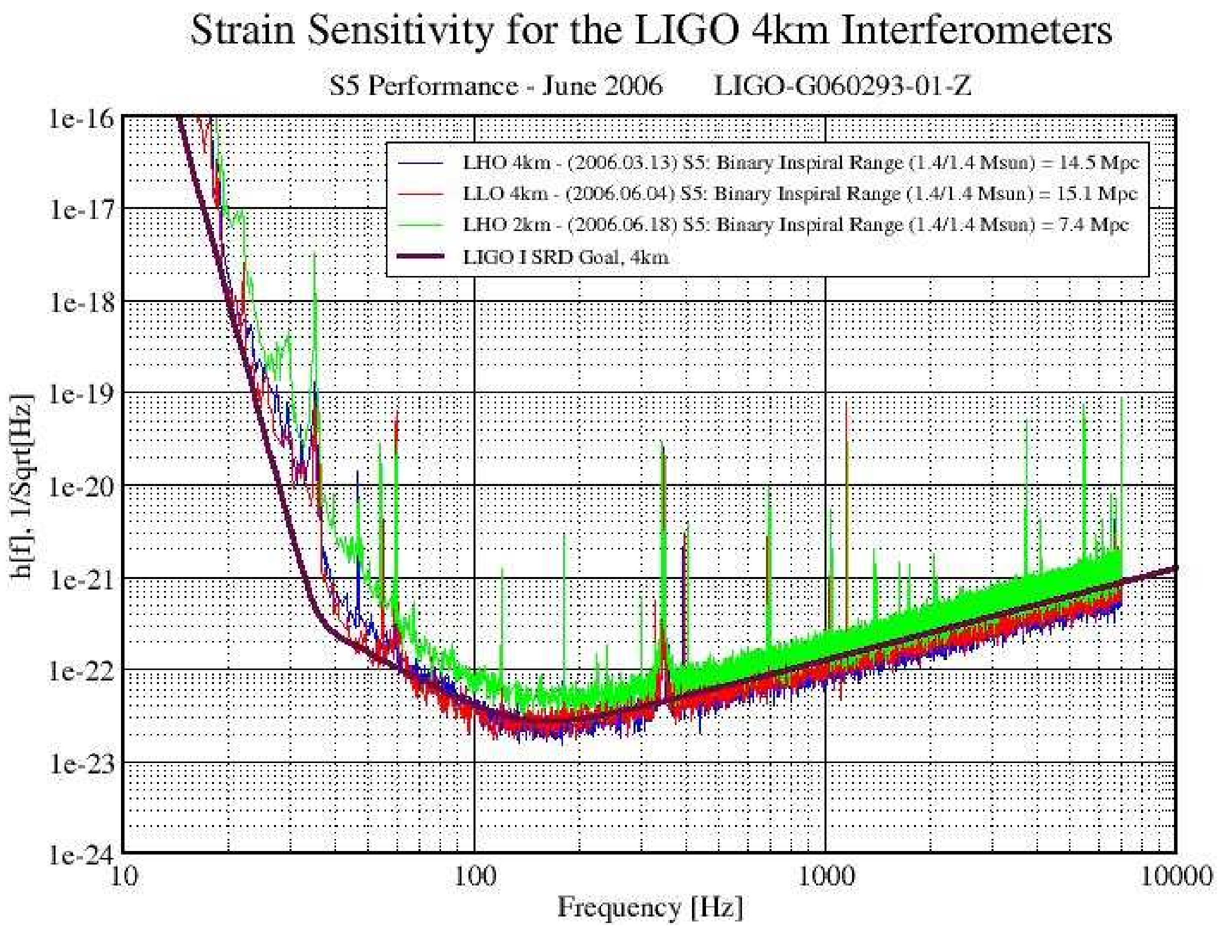
Purpose of agreement:

The purpose of this Memorandum of Understanding (MOU) is to establish and define a collaborative relationship between VIRGO on the one hand and the Laser Interferometer Gravitational Wave Observatory (LIGO) on the other hand in the use of the VIRGO, LIGO and GEO detectors based on laser interferometry to measure the distortions of the space between free masses induced by passing gravitational waves.

We enter into this agreement in order to lay the groundwork for decades of world-wide collaboration. We intend to carry out the search for gravitational waves in a spirit of teamwork, not competition. Furthermore, we remain open to participation of new partners, whenever additional data can add to the scientific value of the search for gravitational waves. All partners in the collaborative search should have a fair share in the scientific governance of the collaborative work.

Among the scientific benefits we hope to achieve from the collaborative search are: better confidence in detection of signals, better duty cycle and sky coverage for searches, and better source position localization and waveform reconstruction. In addition, we believe that the intensified sharing of ideas will also offer additional benefits.

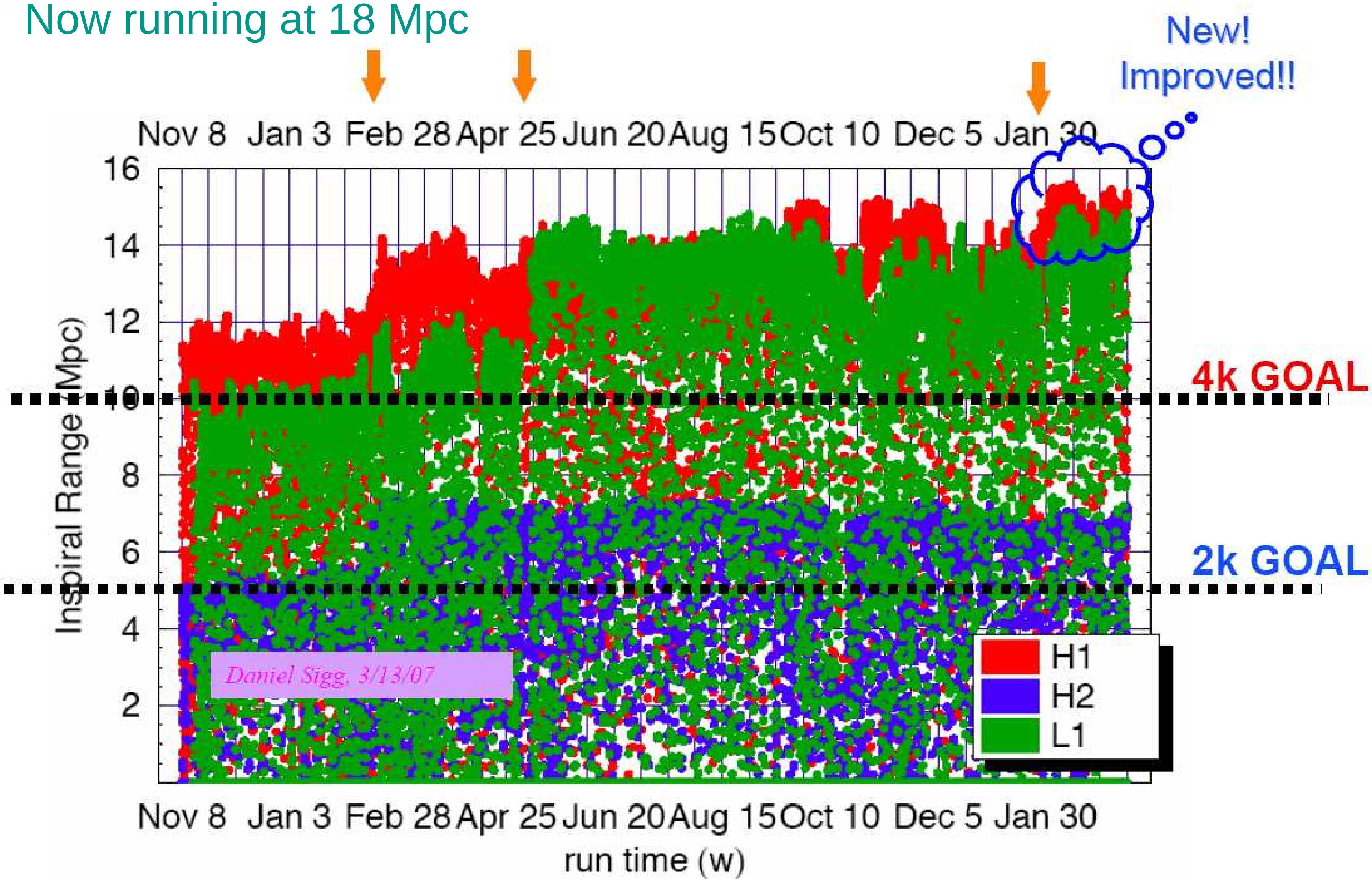
LIGO sensitivity



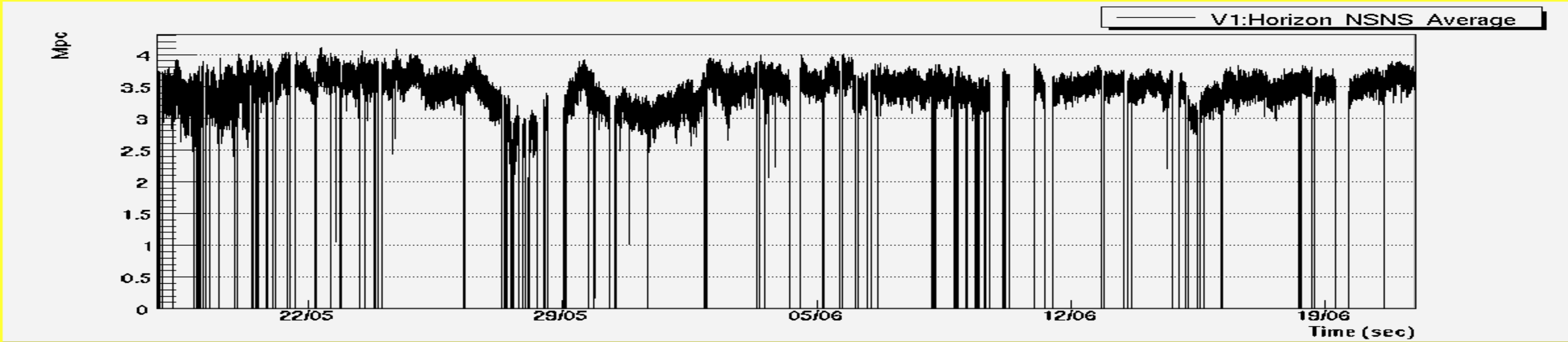
- LIGO at design sensitivity
- Long data taking in 2005-2007 (S5)
- More than one year of coincident data (2 sites) collected

LIGO ‘Horizon’ during S5

- Maximum distance at which a binary neutron stars is visible (LIGO-S5) ~ 15 Mpc
- Now running at 18 Mpc

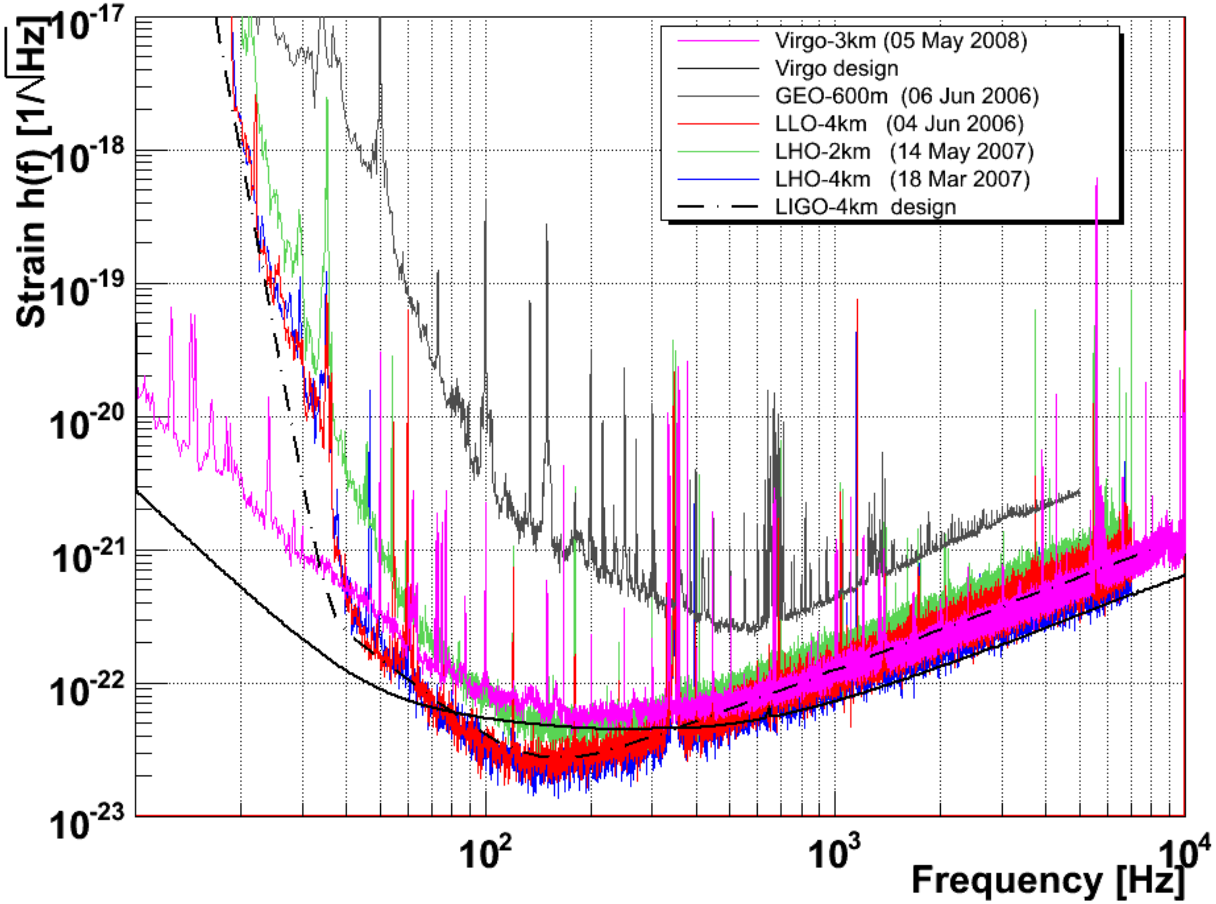


First Virgo Science Run (VSR1)



- First long data taking in May-Sep 2007
- Four months of data collected in coincidence with LIGO
- Duty cycle ~ 85%
- Virgo horizon during VSR1 (~3.5 Mpc)

Virgo sensitivity today



- Similar to LIGO S5 for frequencies above 700 Hz
- A factor 2 from LIGO in the middle frequencies (**Virgo BNS horizon now ~ 7-8Mpc**)
- Better than LIGO at low frequency

Data analysis

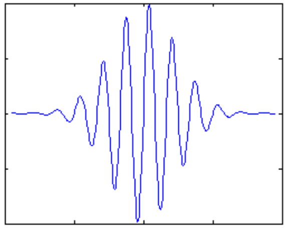
- Relatively small amount of data (a few MBytes/s)
  - Most for monitoring channels
  - Physics channels a small fraction
- But 24h/24h and 365 days/year
  - ~ 100 TB/yr
- Large computing power needed in some case
  - E.g. pulsars search
- Search for very rare events
  - Very good rejection of non gaussian noise event needed
  - Many monitoring channels
- Coincidence between several detectors needed
  - Reduction of false alarms
  - Triangulation for source pointing
  - Same data format adopted by all detectors

MOU LIGO-VIRGO signed in 2007

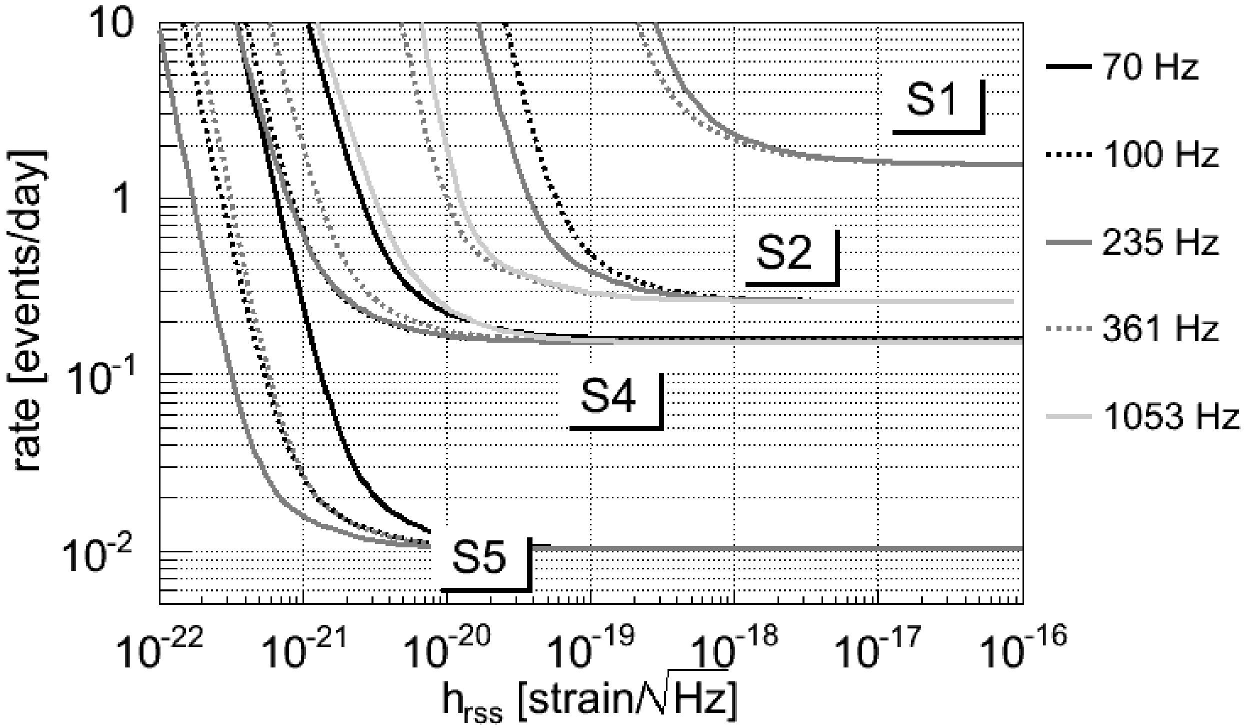
Full data exchange

Joint data analysis

Bursts: un-triggered searches

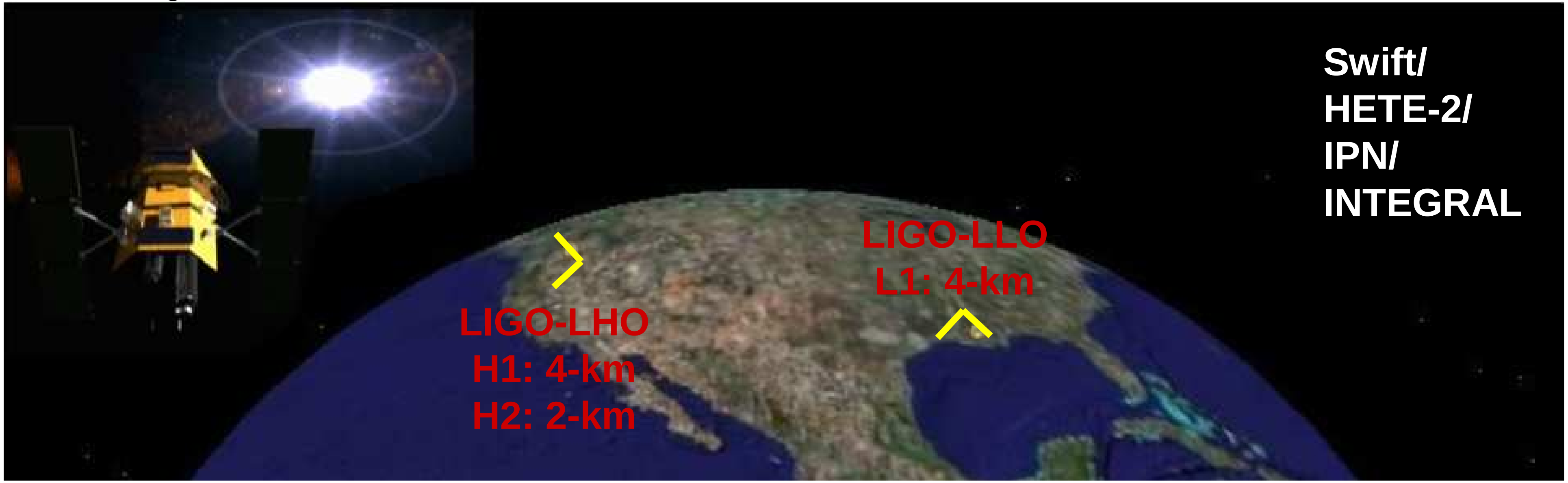


- Sensitivity
  - For a 153 Hz Q=8.9 sine-gaussian LIGO-S5 can see with 50% probability
    - » ~ 1.7 × 10–8 $M_{\odot}c^2$ at 10 kpc
  - Comparison with theoretical prediction shows LIGO-S5 can detect supernovae in the Milky Way



Bursts triggered searches

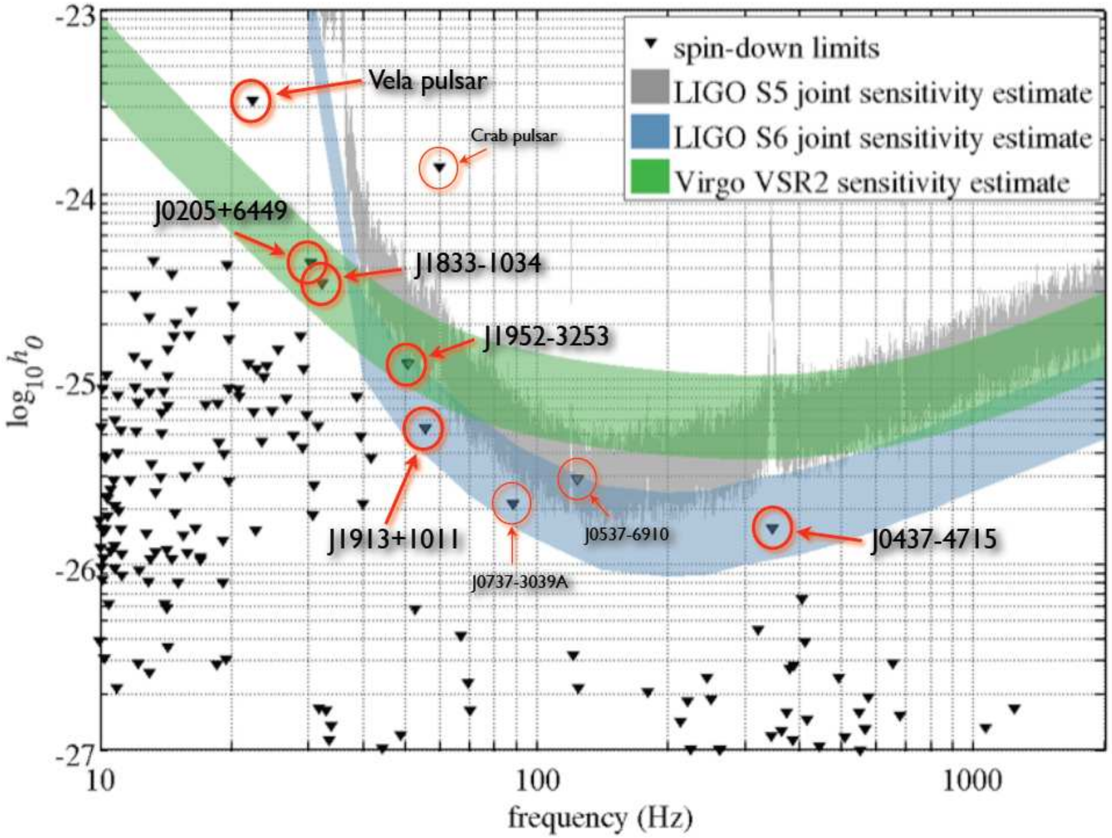
- Gamma ray bursts are potential GW sources
  - Short GRB expected to be coalescing binaries, Long GRB expected to be core collapse
- Search data surrounding GRB trigger
  - No GW signal found associated with 39 GRB in S2, S3, S4 LIGO runs
  - S5: 212 GRB triggers during S5 being analysed
    - ~70% with two ITF running, ~45% with three ITF running
- Sensitivity en 2007 ~ ΔE 0.1 $M_{\odot}c^2$ at 50 Mpc
- Agreement with Swift for the forthcoming LIGO-Virgo run
  - Target-of-Opportunity (ToO) imaging by Swift to follow up a limited number of gravitational-wave transient candidates



Searches: spinning compact objects

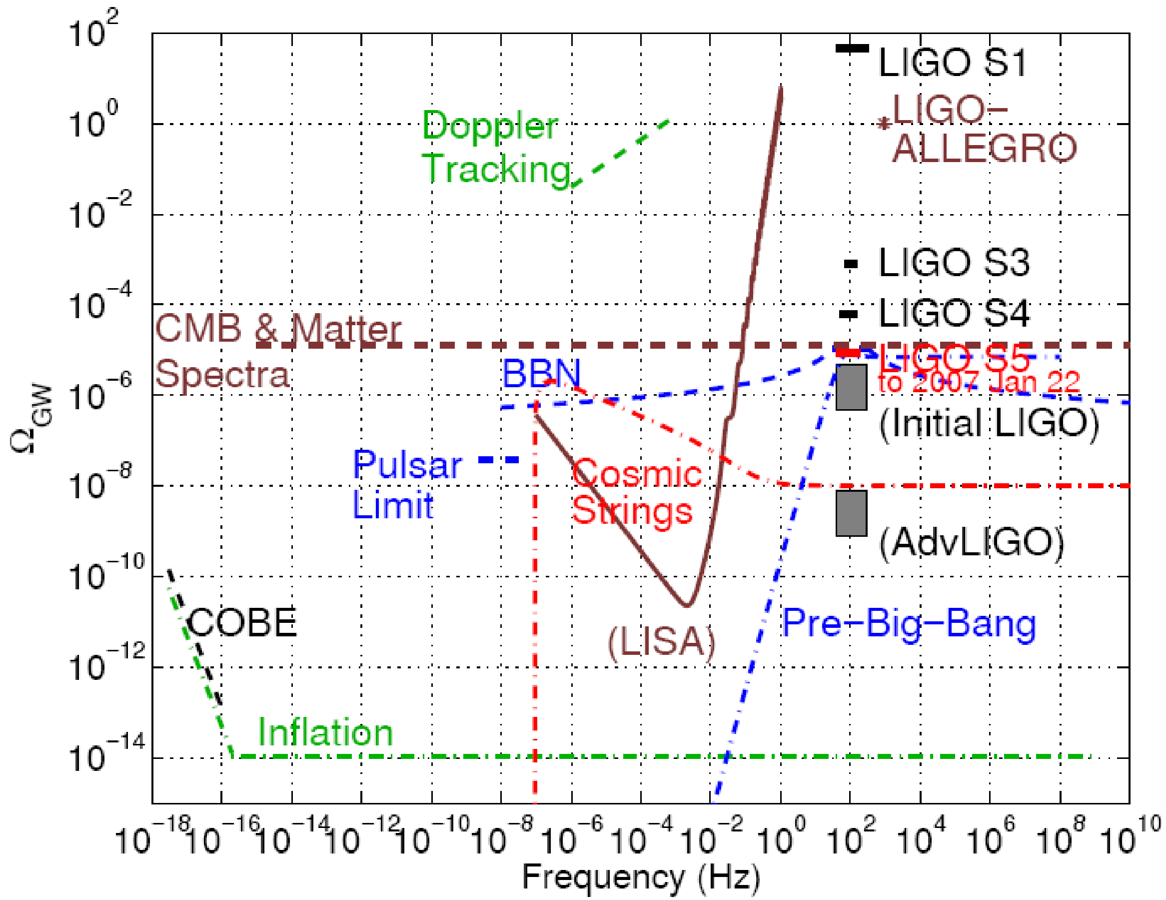
- Rotating neutron stars
- Many known pulsars in the galaxy
  - Targeted searches from 97 knows radio or x-ray pulsars in S5 data
  - Use of known pulsar phase and position
- Many more non pulsar rotating neutron stars expected in the galaxy
  - Blind search of sinusoidal signal modulated by Earth motion and spinning down
  - Computationally expensive

- Lowest ellipticity upper limit
  - PSR J2124-3358 e<1.1x10-7
- Limit on Crab pulsar
  - LIGO beat the spin-down limit
- Limit on Vela
  - Spin-down limit accessible to Virgo



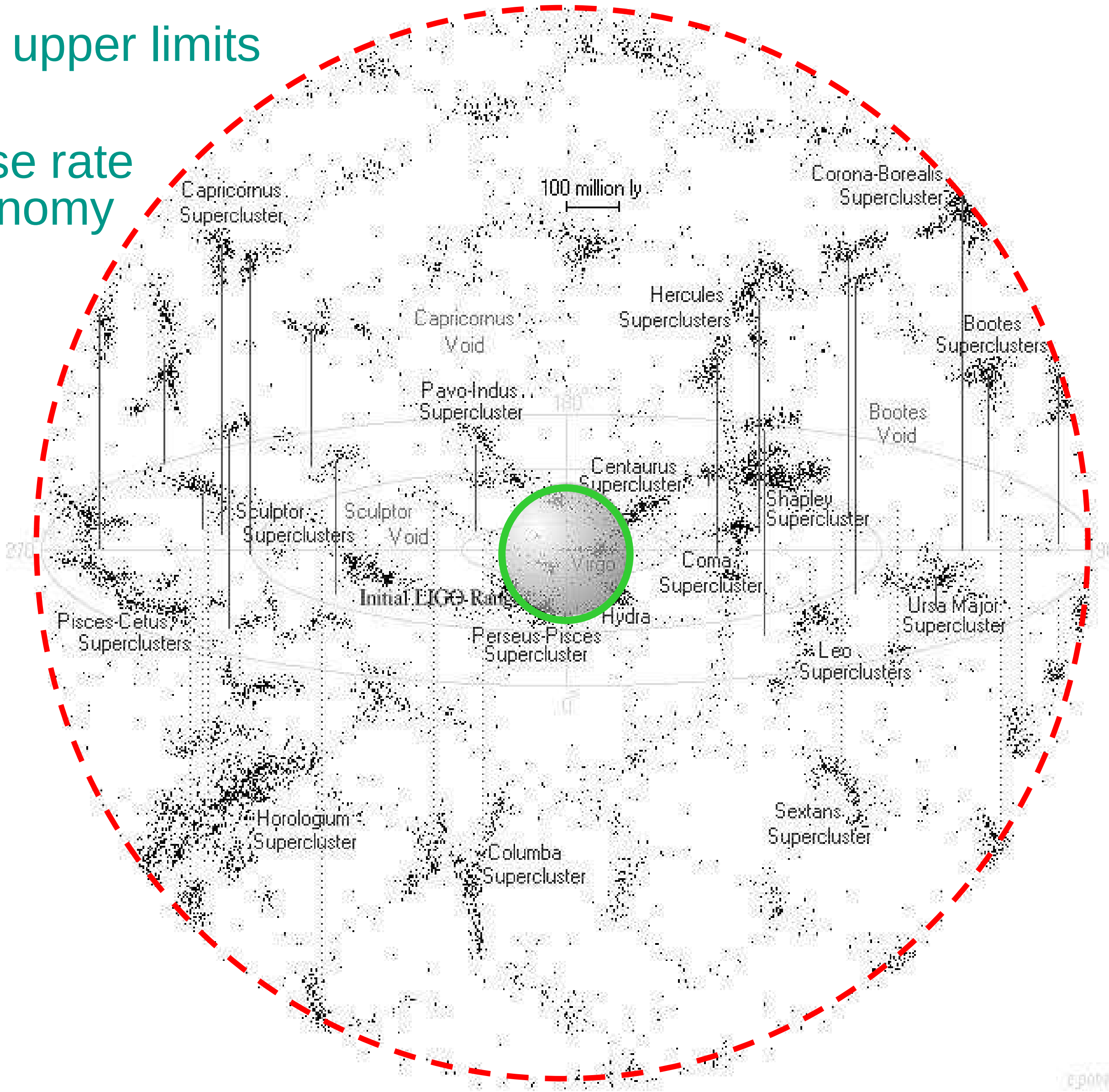
Searches: gravitational background

- Stochastic background signal
- Searched from cross-correlation of different pairs of detectors
- All sky search with LIGO-S4 data
  - Ω_{GW}< 6.5 10-5
  - Still weaker then the BBN limit
- **LIGO-S5 data beat the BBN limit**

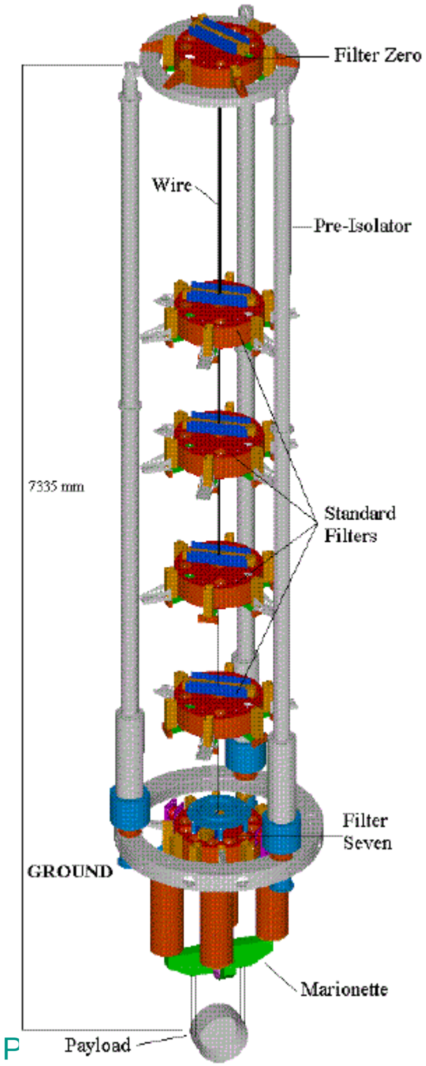


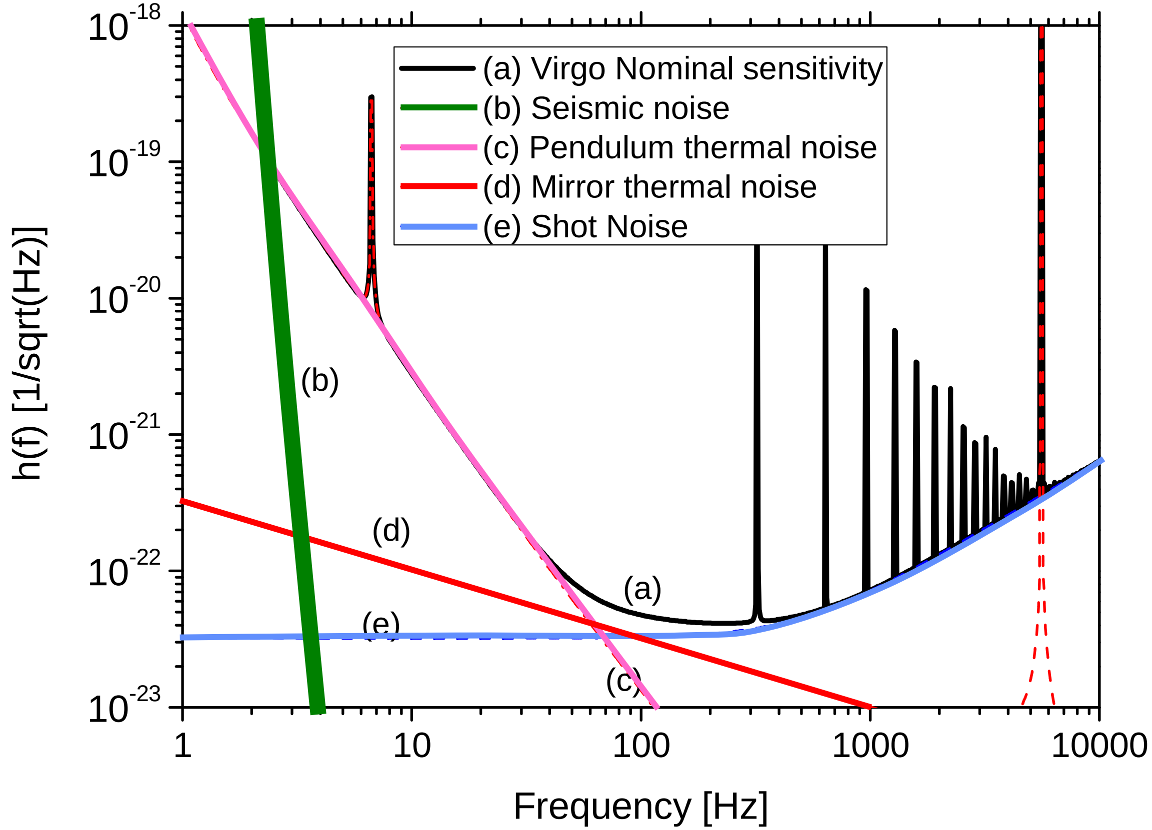
Toward GW astronomy

- Present detectors testing upper limits
- Even in the optimistic case rate too low to start GW astronomy
- Need to improve the sensitivity
- Increase the sensitivity by 10 ⇒ increase the probed volume by 1000
- Plans to improve the present detectors



Improving the sensitivity (I)



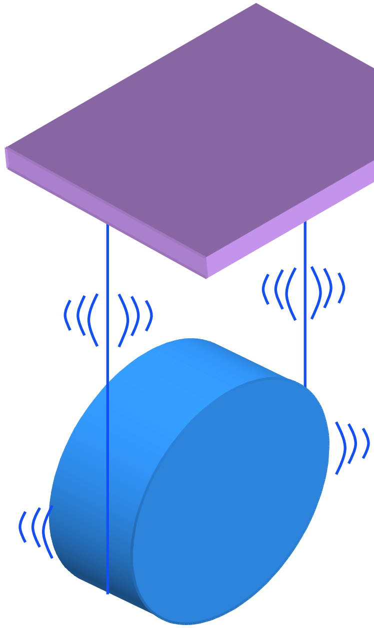


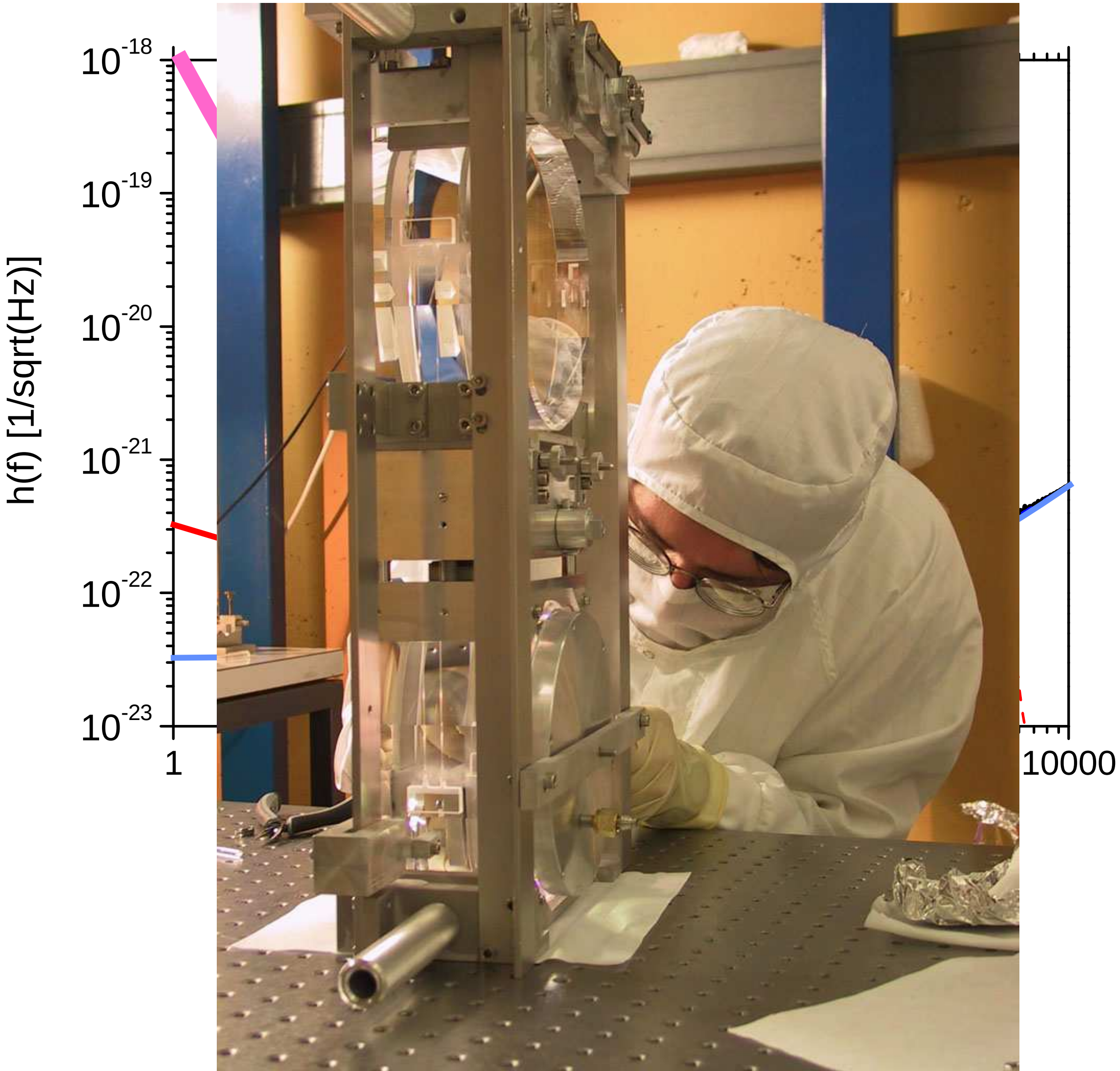
- **Seismic noise**

- better active seismic isolation
- longer and softer seismic isolation system
- seismic noise reduction !

Go underground/Go to space

Improving the sensitivity (II)

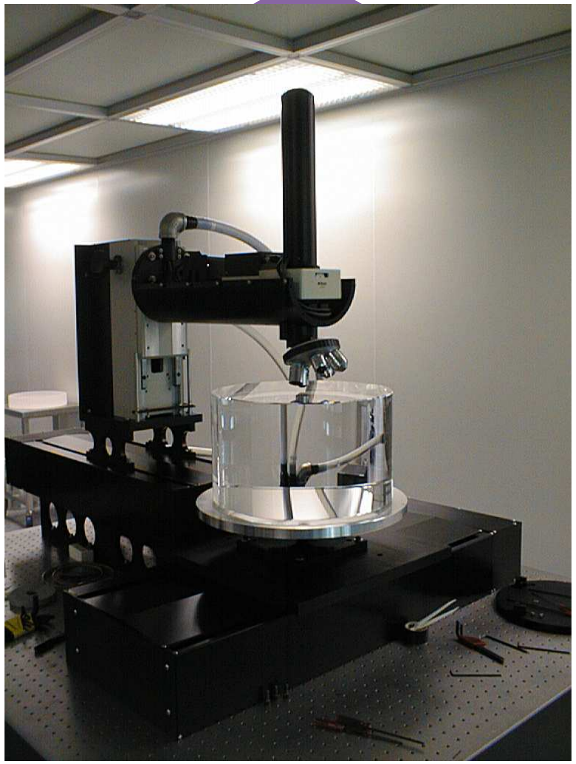


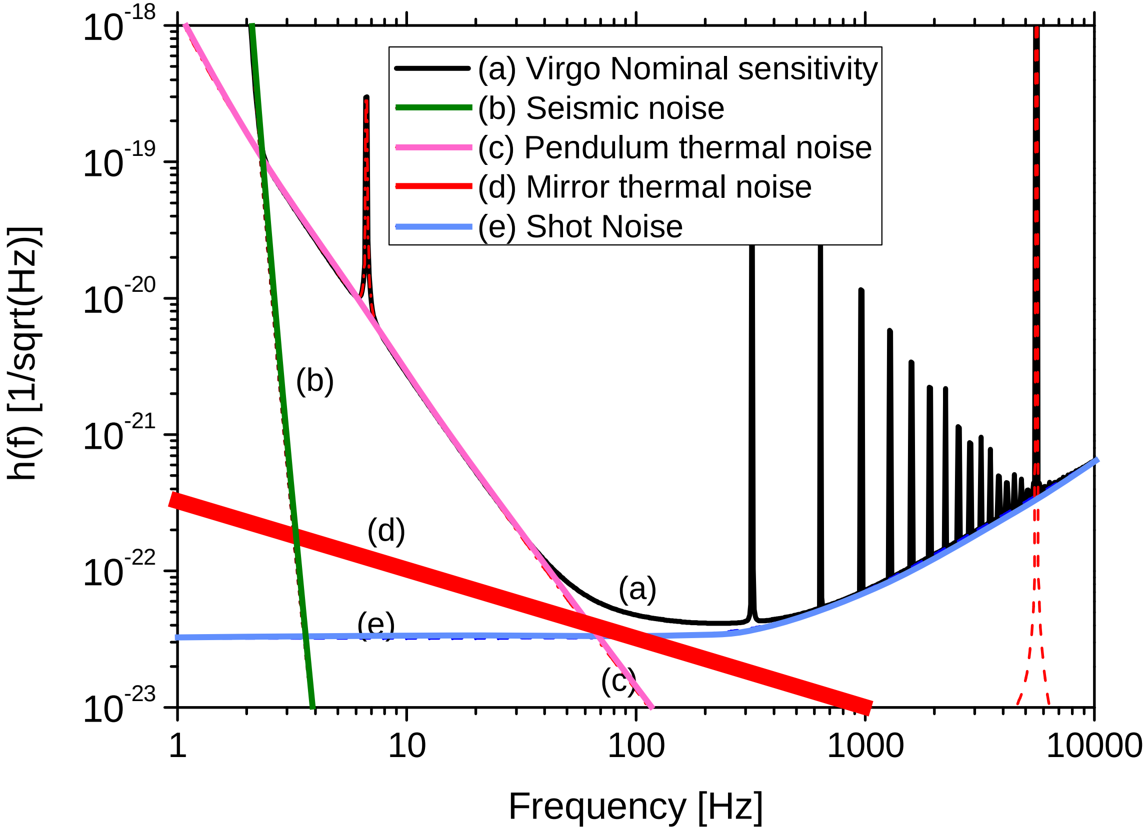


- **Pendulum thermal noise**

- decrease pendulum friction
- better suspensions wires
- better wire clamping
- monolithic suspensions
- cryogenic suspensions

Improving the sensitivity (III)

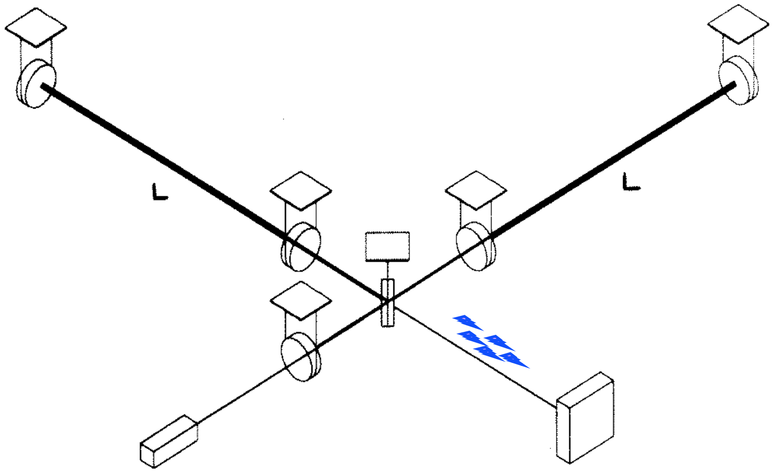


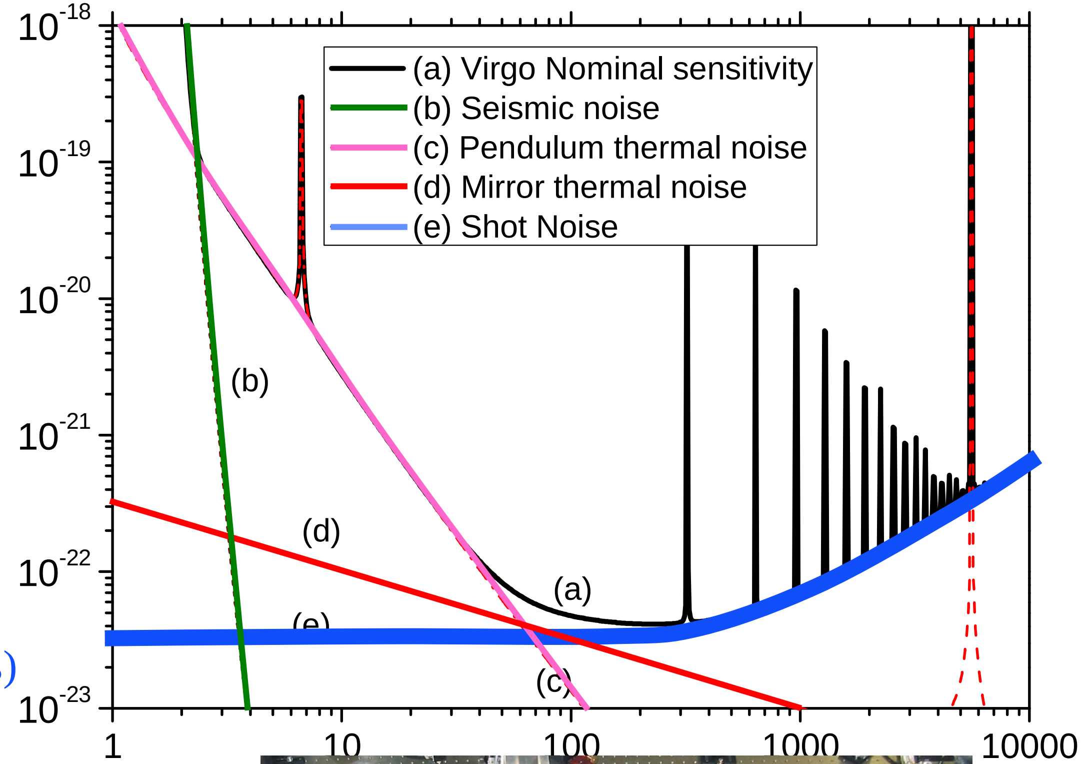


- **Mirror thermal noise**

- decrease mirror internal friction
- presently limited by friction in the coating
- first decrease coating mechanical losses
- then low temperatures (with appropriate mirror substrates)

Improving the sensitivity (IV)

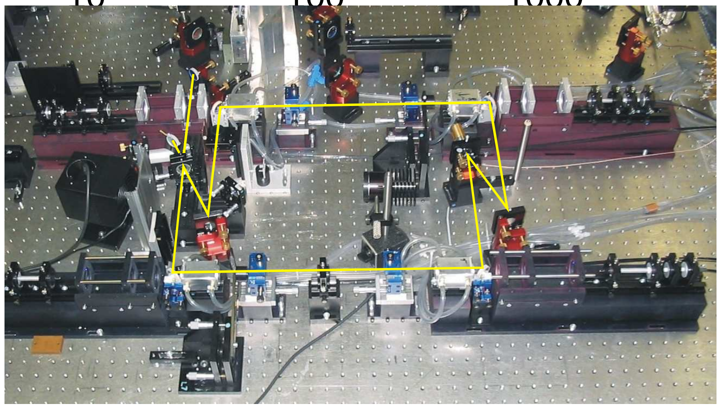




- **Shot noise**

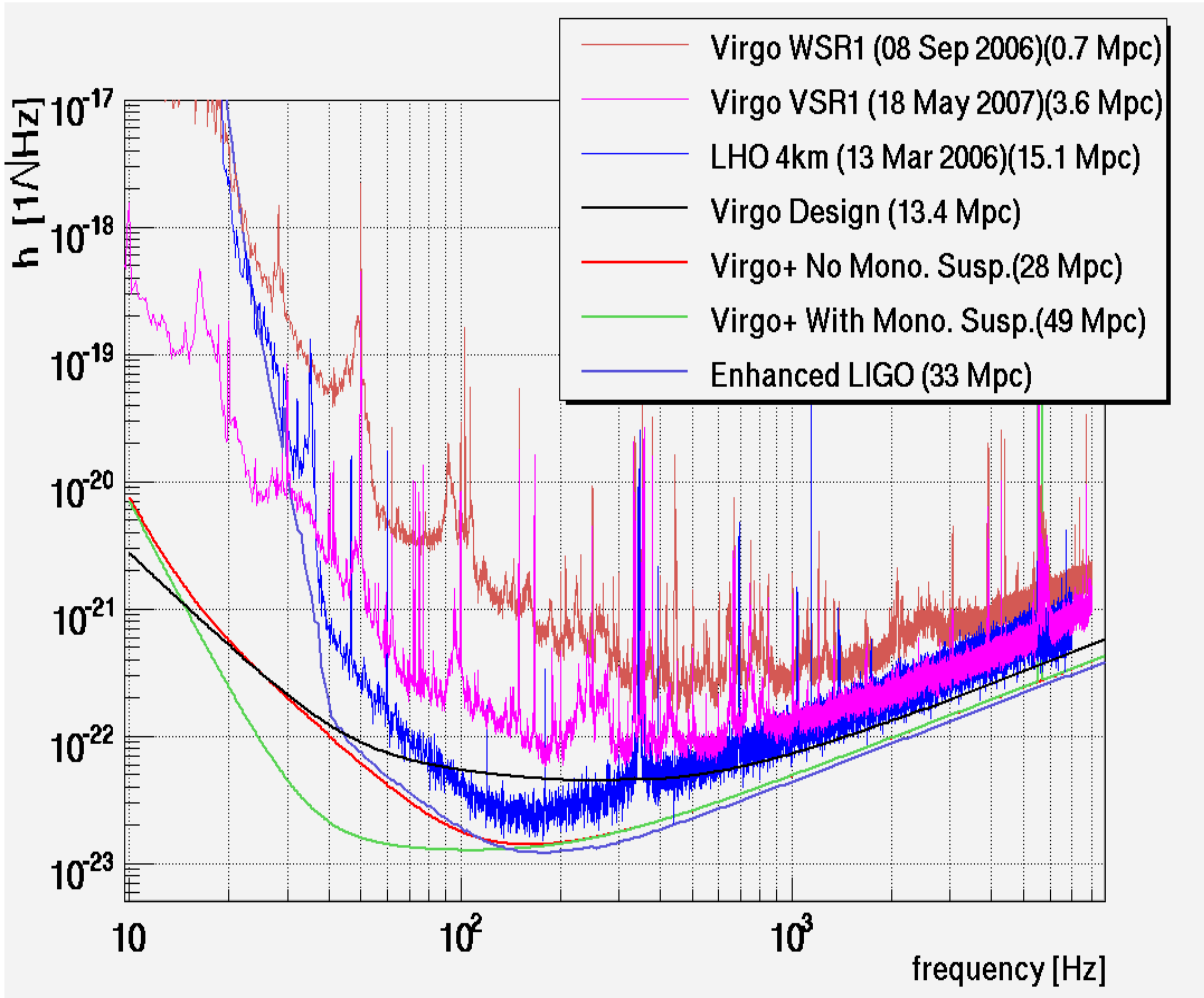
- Increase power stored in the interferometer (increase laser power, decrease optical losses)
- But attention to:

1) thermal deformation
   - improve thermal compensation
   - decrease light absorption
2) radiation pressure noise
   - increase mirror mass
   - optimize optical configuration (signal recycling)
   - use non classical light (light squeezing)



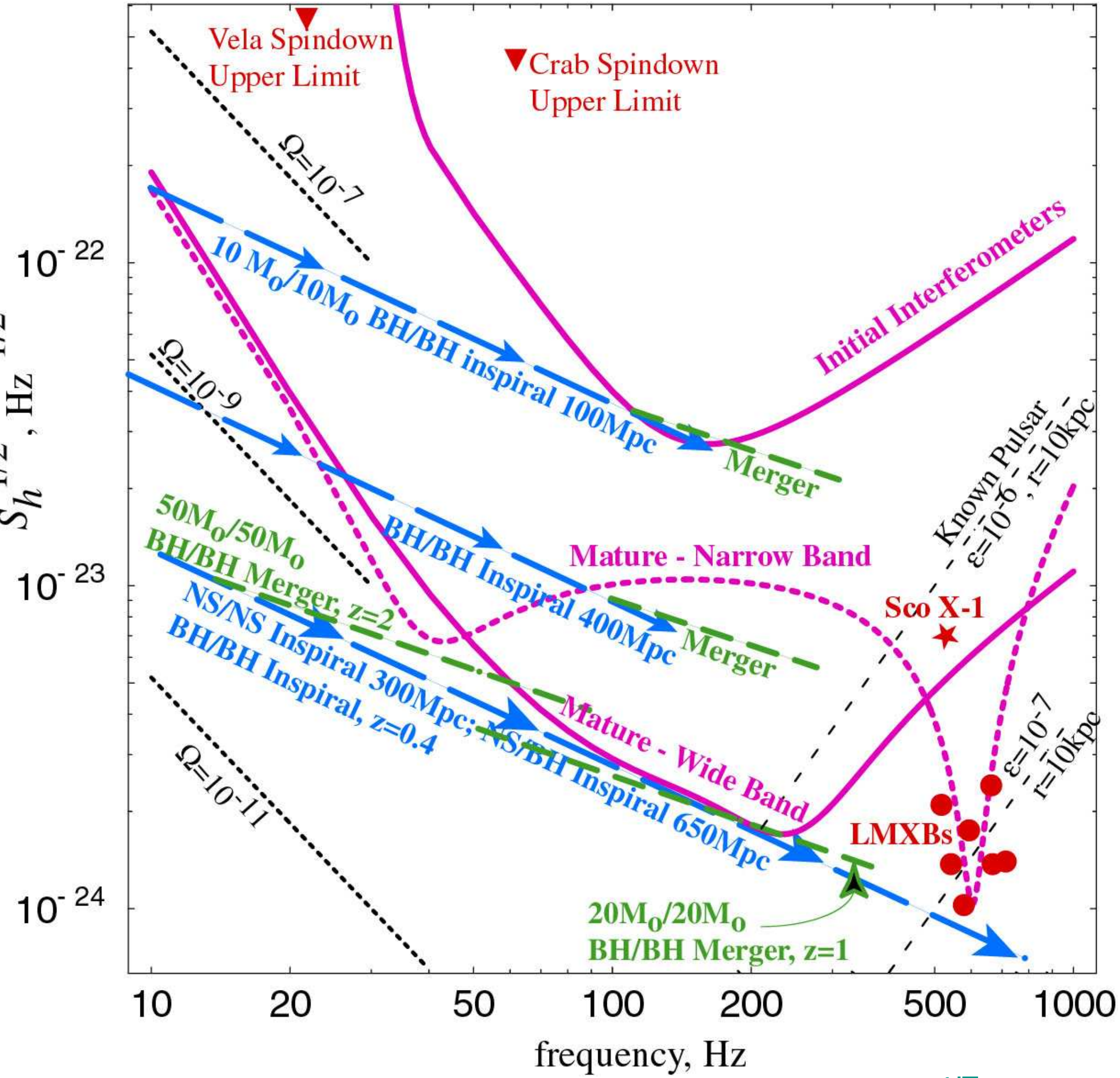
Virgo+ and Enhanced LIGO

- A moderate improvement (horizon x 2-3)
- Explore rates ~ 10-20 times smaller
- Virgo+
  - Larger laser power
  - Larger cavity finesse
  - New better mirrors
  - Monolithic suspensions
    - » being considered
  - BNS horizon ~ 30 Mpc
- Enhanced LIGO
  - Larger power
  - New optical readout
  - BNS horizon ~ 30 Mpc
- Time scale
  - Installation 2007-08
  - Data taking from mid 2009
  - Until 2011



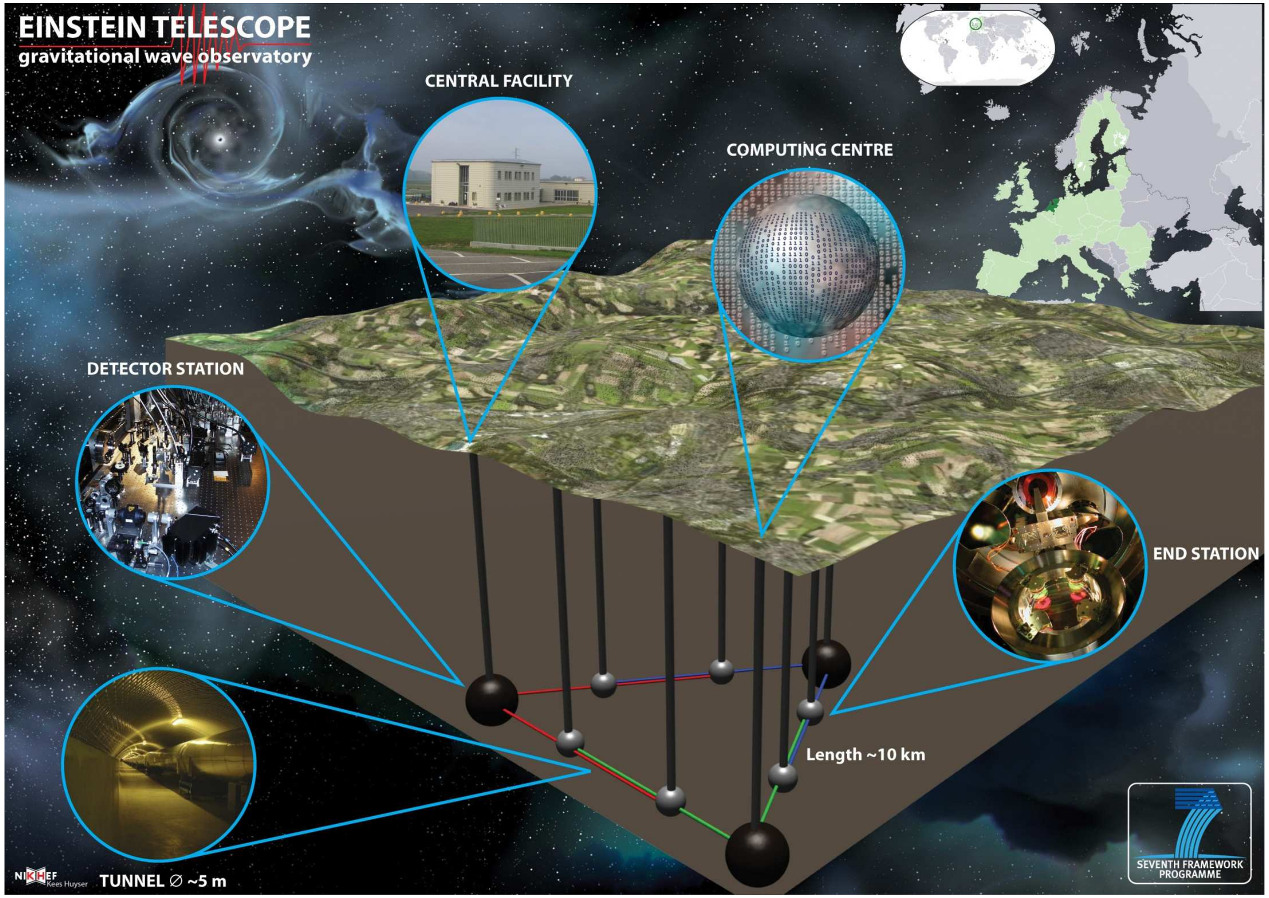
Advanced LIGO and Advanced Virgo

- Sensitivity
  - Goal: noise10 times lower
  - Frequency down to 10 Hz
- A jump by a factor of 1000
  - Push sensitivity to present lower predictions
  - BNS rates: 10-150 /yr
  - Ωgw ~ 10^{-9}
- Advanced LIGO
  - Important hardware changes
  - Approved by NSF
  - Funds started in 2008
- Advanced Virgo
  - Similar goals
  - Unchanged seismic isolation
    - » Shorter shutdown
  - Hopefully approval this year
- Time scale
  - Shutdown from 2011
  - 'First light' from 2014



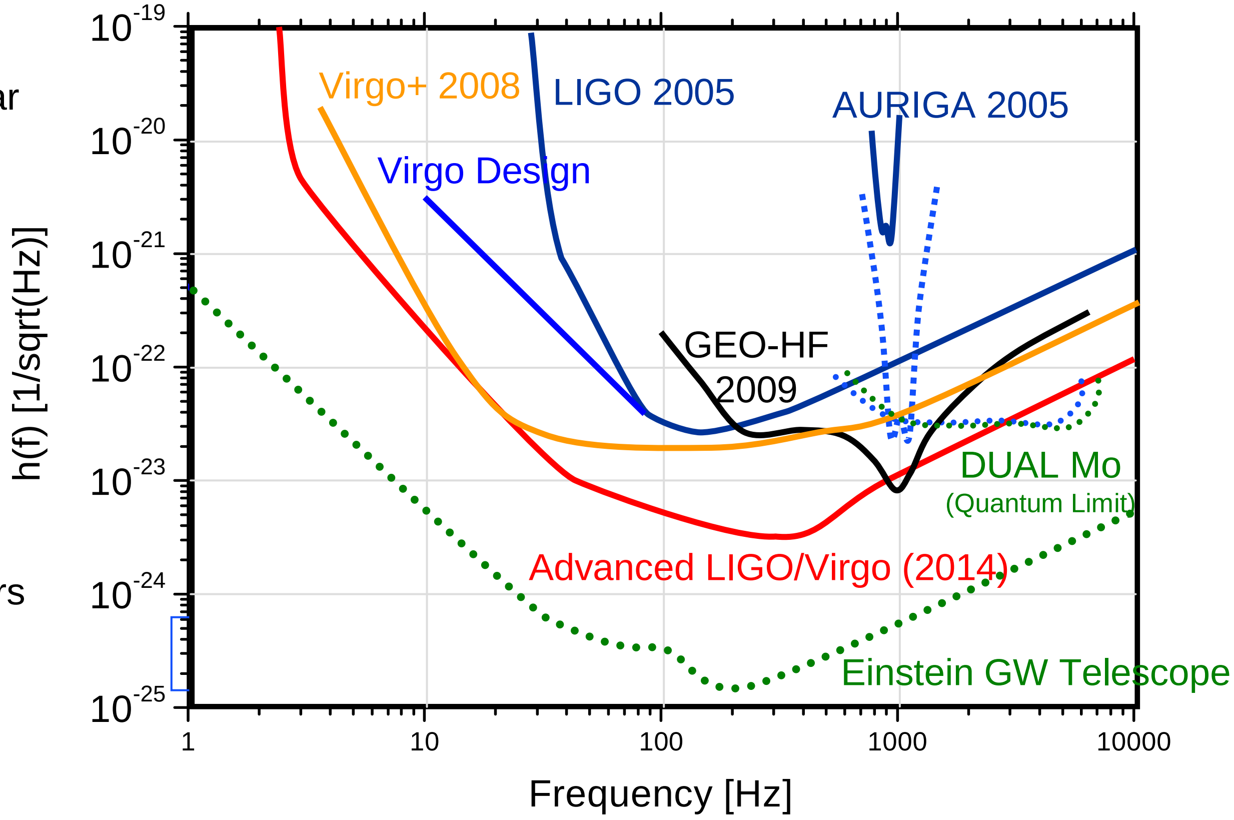
Beyond advanced detectors: ET

- Need to improve sensitivity at low frequencies
  - More physics is there
- Present facilities limited by environmental disturbances
  - Seismic noise
  - Gravity gradients
  - Arm length
- ET Einstein Telescope
- Concepts
  - Underground
    - » Less seismic noise
    - » No wind
    - » Temperature stability
  - Cryogenic
  - 30 km beam tube
  - 100 m suspensions
  - Different geometry
    - » Triangle?



Beyond advanced detectors: ET

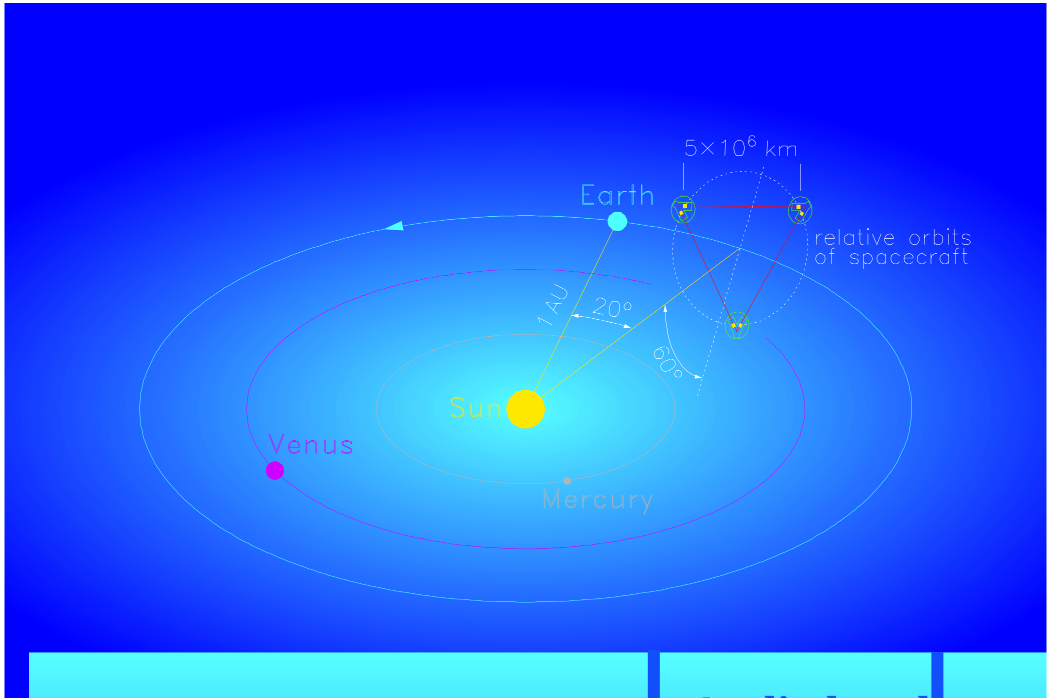
- A possible sensitivity
  - High SNR signals
  - A lot of physics
- Fundamental physics
  - GR tests in strongly non-linear regime
- Black holes physics
  - End state of gravitational collapse
- Cosmology
  - Dark energy
  - Accurate luminosity vs distance relationship from inspirals at z~1
- Astrophysics
  - Census of binary neutron stars at high red-shifts
  - Solve the enigma of γ-ray bursts
- New Sources
  - Detect intermediate mass BH at cosmological distances
  - Can see IMBH in higher harmonics



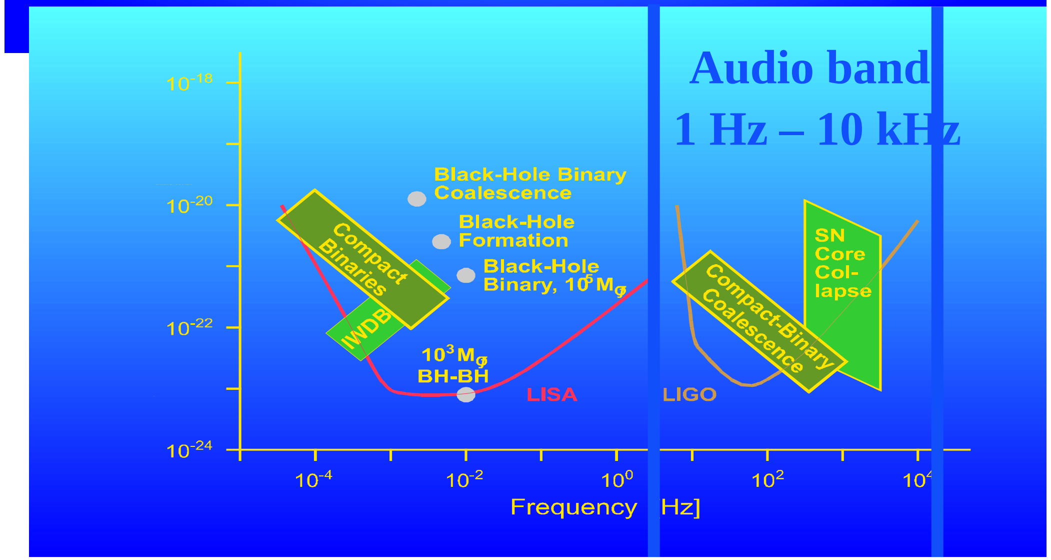
Design study financed by the EU within FP7 (2008-2011)

LISA concept

- Cluster of 3 S/C in heliocentric orbit
- Laser interferometer measures distance changes between free flying test masses inside the S/C
- Trailing the Earth by 20 °(50 million km)
- Equilateral triangle with 5 million km arms
- Inclined against ecliptic by 60 °

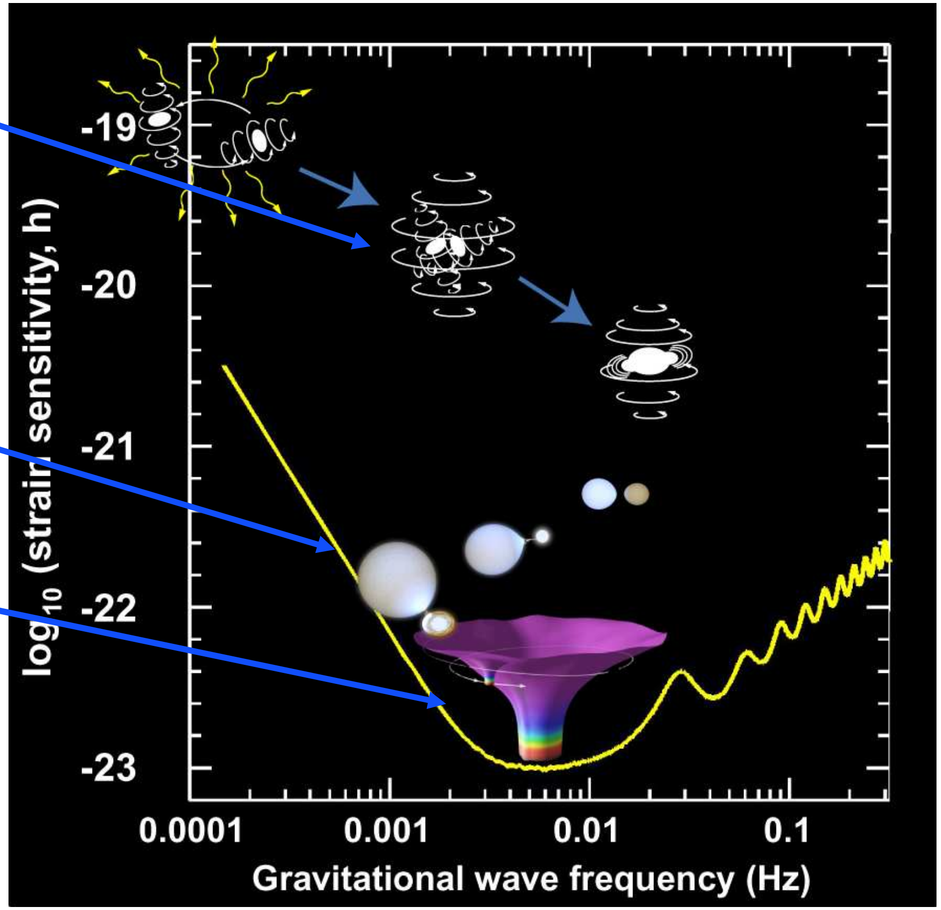


- Sensible to very low frequencies
- Complementary to earth based detectors



LISA physics

- Massive black hole binary inspiral and merger
  - ◆ Dynamical behavior of space-time
  - ◆ Growth of massive black holes
  - ◆ Absolute distances
- Ultra compact binaries
  - ◆ Extreme degenerate stars (mainly WD, NS, BH, …)
- Extreme mass ratio inspirals
  - ◆ Test Kerr black hole solution of GR
  - ◆ Galaxy nuclei
- Cosmological backgrounds
  - ◆ Superstring bursts?



LISA status

- LISA ending the mission formulation phase
  - ESA contract with Astrium
- LISA Pathfinder
  - Test of some crucial LISA technology
  - Construction of flight hardware started
  - Launch 2011
- NASA position in relation to LISA funding
  - Wait for the decadal review result (mid 2010)
  - If highly ranked funding can starts October 2011
- ESA position in relation to LISA funding
  - LISA Pathfinder successful
  - NASA funds available
  - LISA selected by the ESA L1 mission in the 2011 downselection
- Consequences
  - Start of the ESA Definition Phase not earlier than Q1-2012
  - Launch: Nov 2020 (technically LISA can be ready in 2018)

Conclusions

- A new generation of gravitational wave detectors based on laser interferometers is now in operation
  - First joint run in 2007
  - Second joint run starts on July (enhanced LIGO, Virgo+)
- The first detection of GW is possible (but probability is small)
- Advanced detectors planned for 2014 (factor of 10 improvement of the sensitivity)
- Advanced detectors will test the full range of predictions (e.g. binary neutron stars)
- ET and LISA will be able to study signals with very high SNR

Conclusions (End)