Gravitational wave search with ground based detectors: status and plans

Raffaele Flaminio

European Gravitational Observatory and CNRS/LAPP

Summary

I. A bit of gravitational wave physics

II. Gravitational wave detectors

III. Status of present detectors

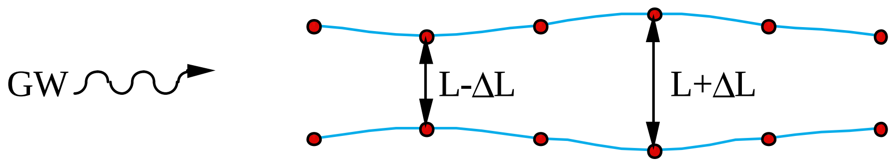
IV. Plans for the future

I. A bit of gravitational wave physics

Gravitational waves

- Waves of the space-time metric

  ⇒ effect? distances variation



- Transverse

  ⇒ effect perpendicular to the wave direction of propagation

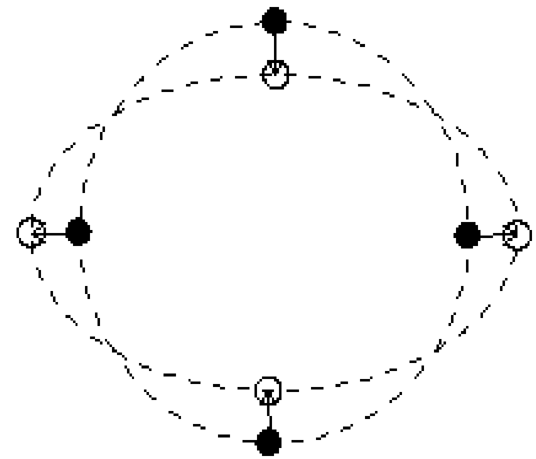
$$DL = \frac{1}{2} hL$$ h = GW amplitude

- Quadrupolar

  ⇒ opposite effect along x and y

- Tide-like

  ⇒ effect larger on longer distances



- Produced by time varying quadrupole moment

$$h \approx \frac{2G}{c^4} \frac{d^2 Q}{dt^2} \frac{1}{d}$$

d = source distance

Q = quadrupole moment

- Small coupling factor ("gravity is weak")

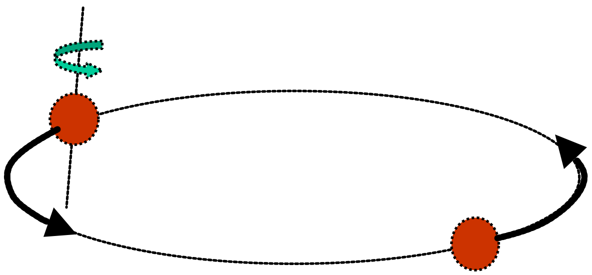
  ⇒ GW generation on earth not possible

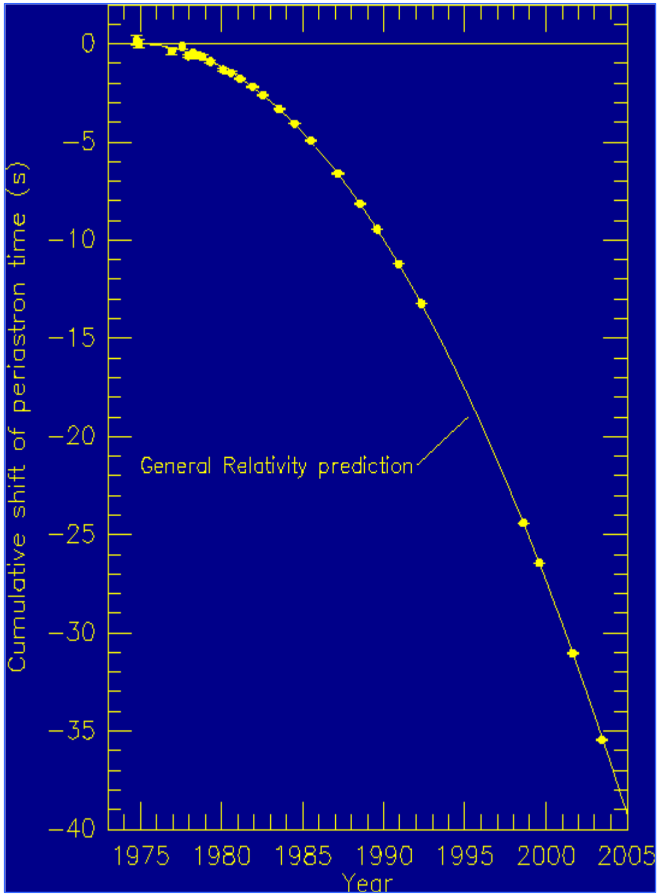
  ⇒ Astrophysical sources

Gravitational waves exist

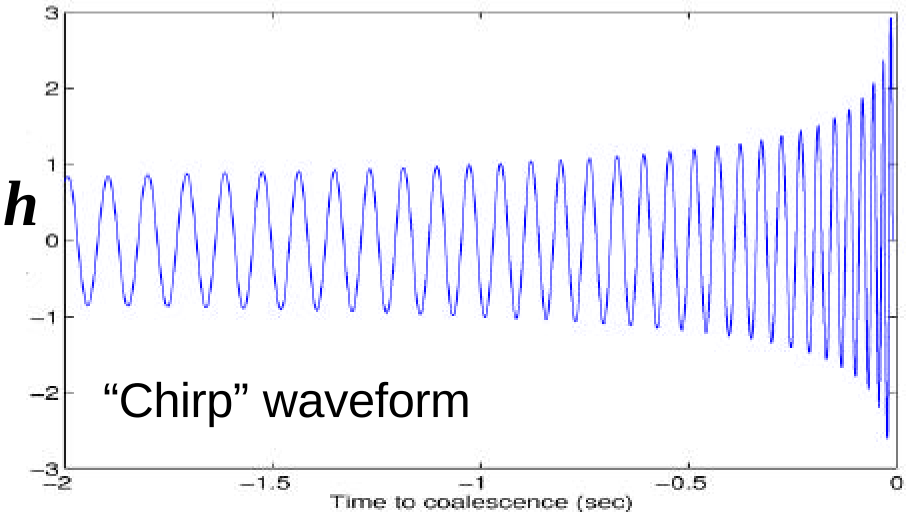
- Binary pulsar 1913+16 (Hulse and Taylor)

- binary system formed by two neutron stars (one pulsar)
- orbital period (~ 8 h) is decreasing
- due to energy loss via GW emission





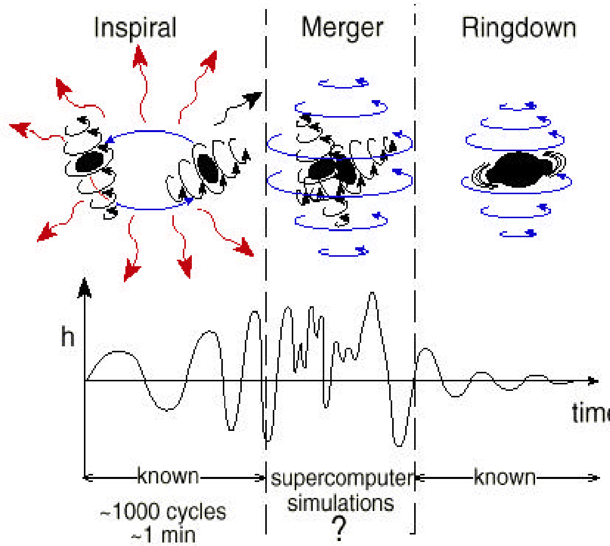
- Excellent agreement with general relativity
- Stars will coalescence in 100 Myears
- Frequency of emitted GW will sweep across the detectors bandwidth



Sources of gravitational waves

• Binaries formed by compact stars (NS/NS, NS/BH, BH/BH)

- Inspiral predictable with GR (a lot of tests to be done)
- Merger unknown, Ring-down predictable (a lot to learn)
- Rates: NS-NS 2/yr-3/day in a range of 300 Mpc

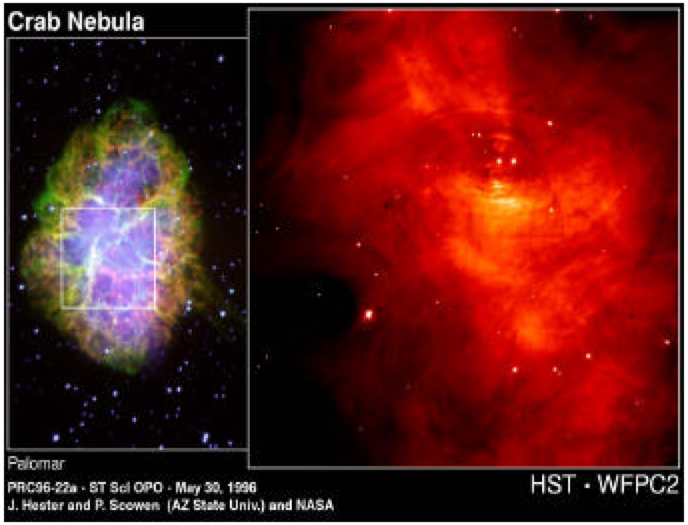


• Supernovae

- Star core collapse (non-spherical collapse)
- Impulsive event, difficult to predict
- Rates: tens/year in the VIRGO cluster

• Rotating neutron stars

- GW emitted if non perfectly spherical star
- Periodical signals, amplitudes unknown,
   upper limits from pulsars slow down
- ~ 10^3 pulsars known today, ~10^9 neutron stars in the galaxy



• Relic stochastic background

- Imprinting of the early expansion of the universe
- Stochastic signals (two correlated detectors needed)
- Signal too weak if standard inflation, signals
  larger from some string models

• The unknown

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

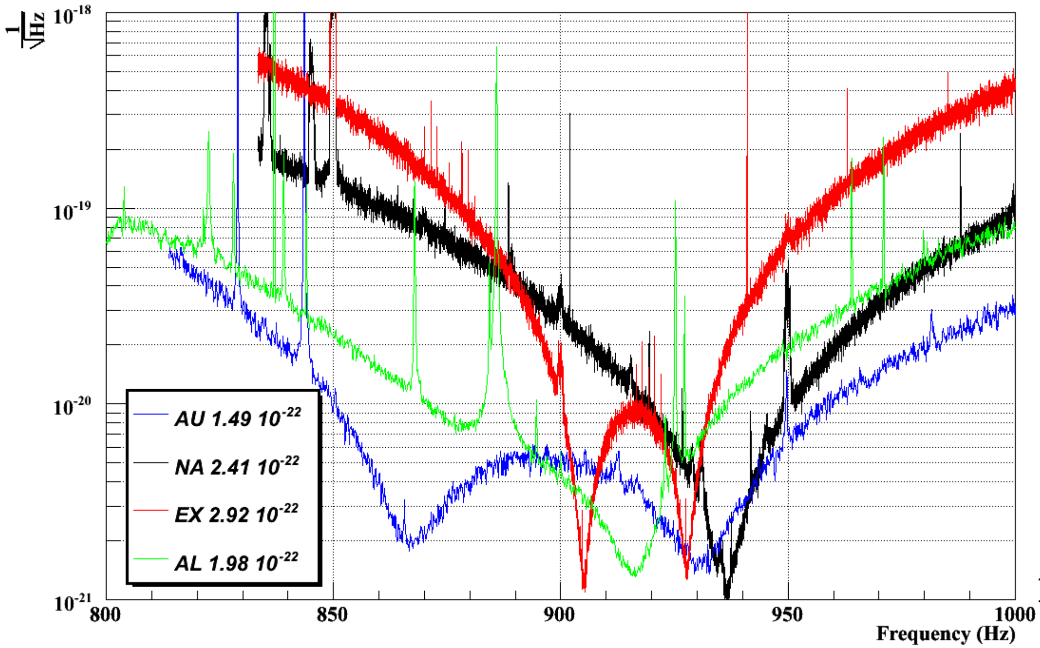
• New window to observe the universe

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

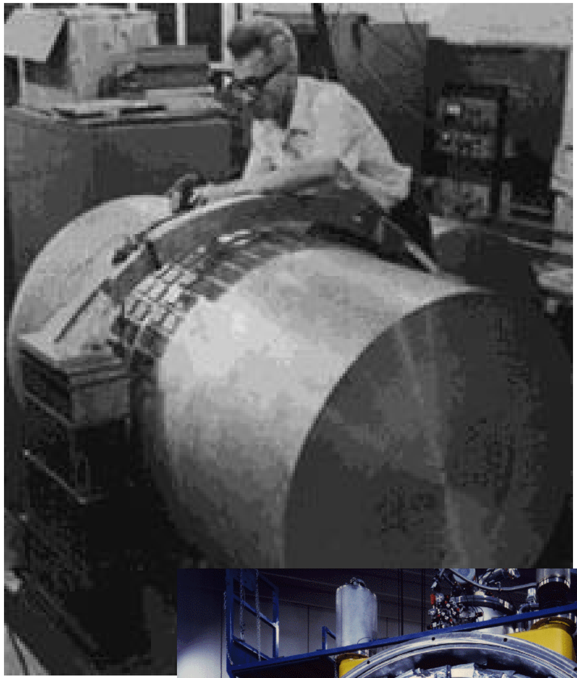
II. Gravitational wave detectors

GW detection: resonant bars

- Resonant bars developed since the 60's
- Principle:
  - *GW excite bar resonance (~1 kHz)*
  - *monitoring of bar resonance amplitude*

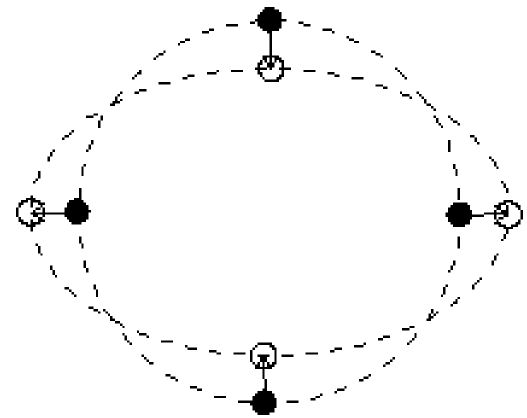


10^{-21}/ÖHz



- Most sensitive detectors until a few years ago
- Main limitation: limited bandwidth (tens of Hz)

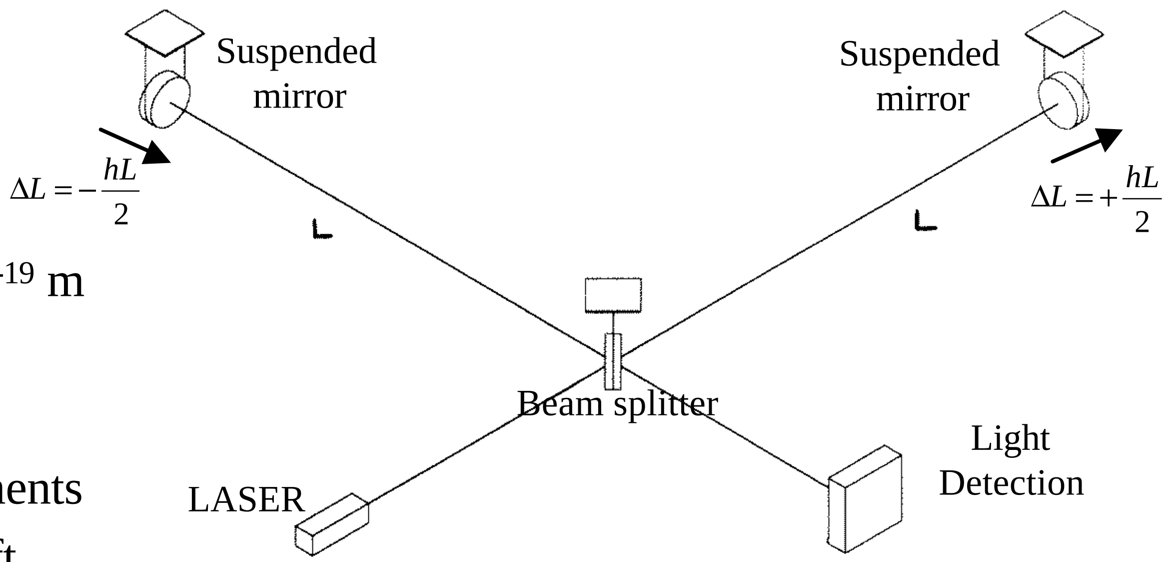
GW detection: laser interferometers



- GW are quadrupolar (spin 2 wave)

- Michelson interferometer ideal tool

- All mirrors suspended through pendulums
  = ‘free falling masses’



- h = 3 10^{-23} , L = 3 km $\Rightarrow$ ΔL $\approx$ 10^{-19} m

- GW detection
  = measure tiny displacements
  = measure tiny phase shift

Limitations: sensing noise

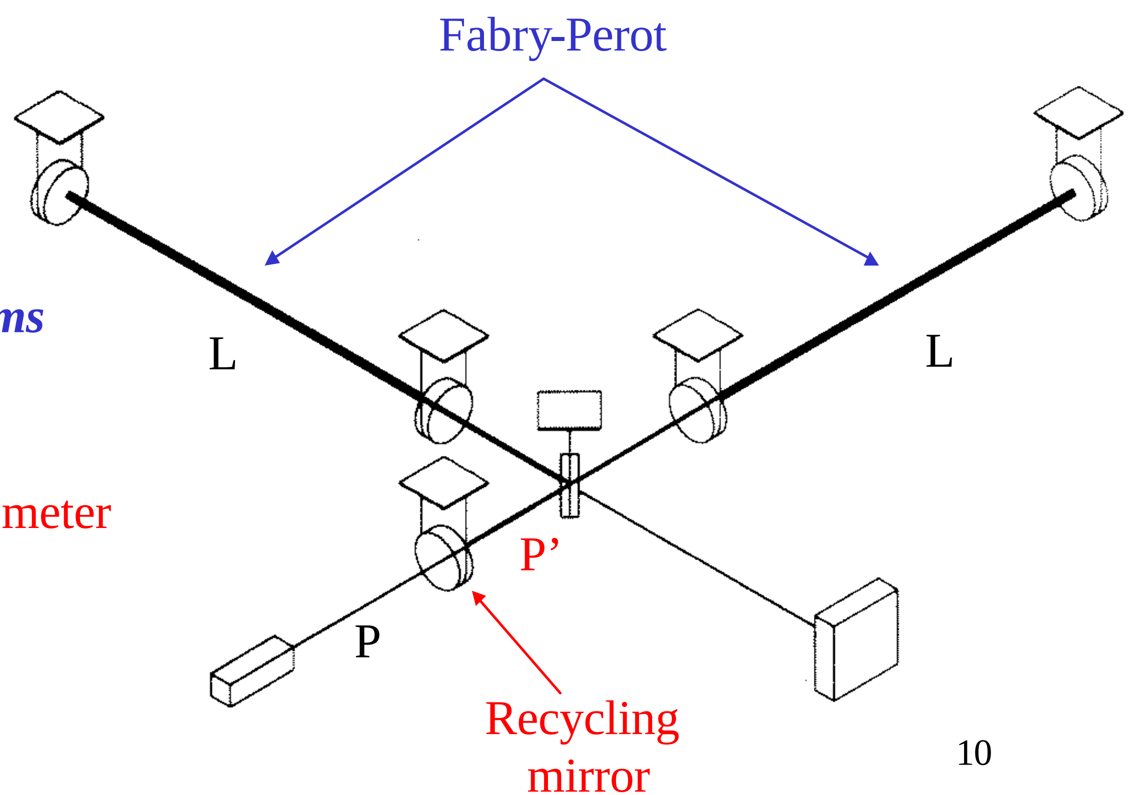
- GW $\Rightarrow$ phase shift $DF = \frac{4p}{l} hL$
- Minimum measurable phase shift $DF > 1 / \sqrt{N_{photons}}$
- ***To get h ~ 3·10^{-23} need L = 100 km and P = 1 kW***

- Increase effective length

  use Fabry-Perot in the arms

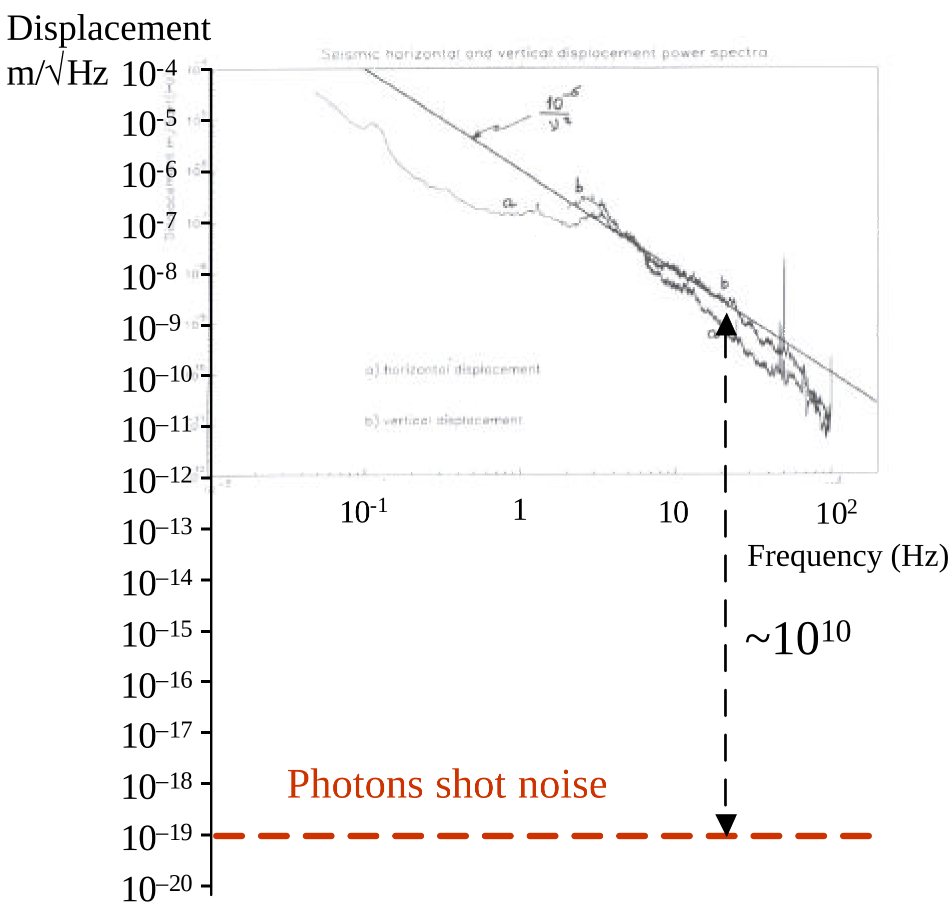
- Increase photons stored in interferometer

  use light recycling



Limitations: displacement noise

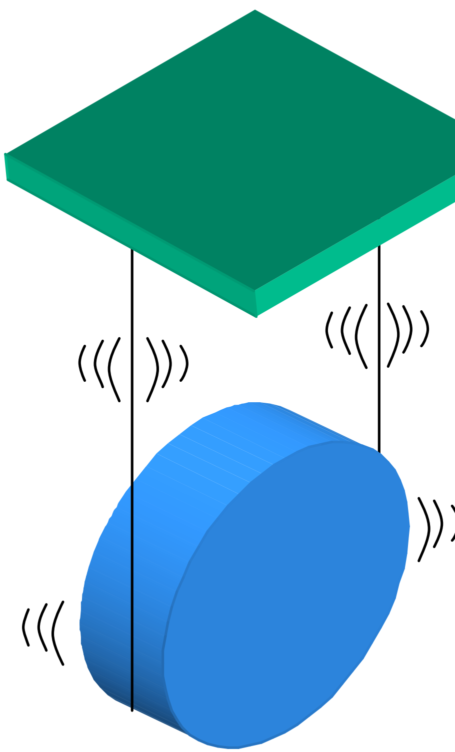
- Seismic noise



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

B

- Thermal noise



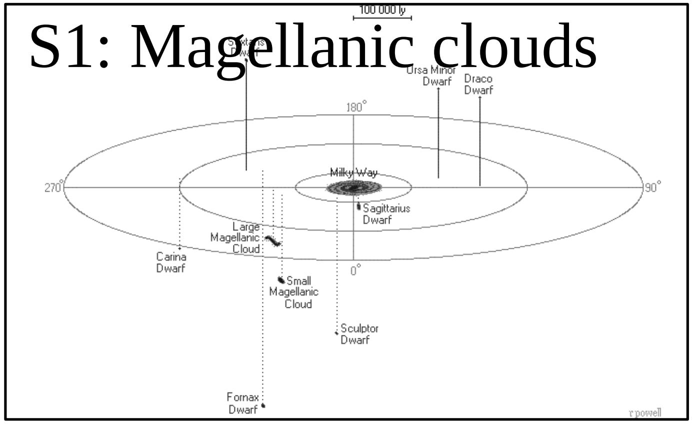
- Use high mechanical quality suspension
- Use high mechanical quality mirrors
- … or cool down

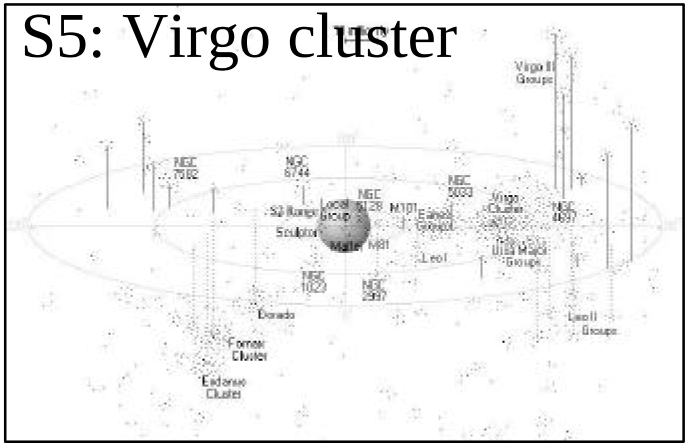
III. The status today

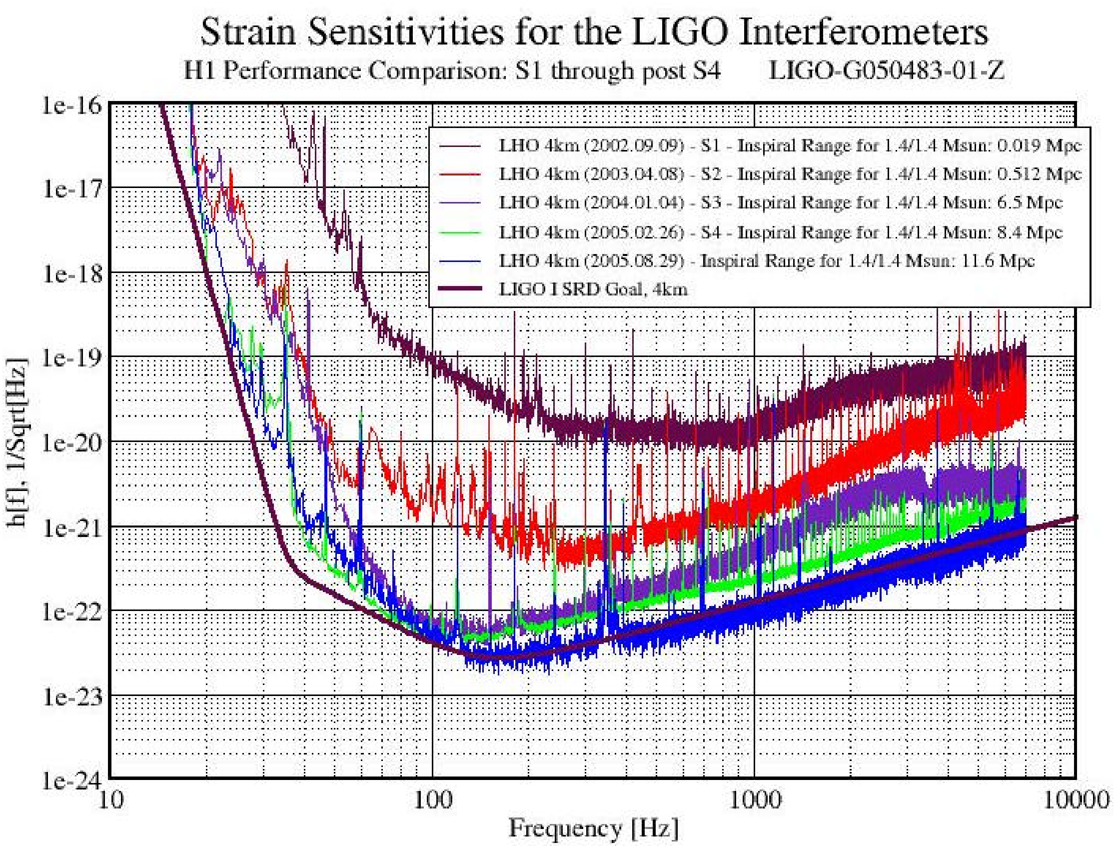
LIGO (USA)

- Two sites
- Three interferometers
- two in Hanford (2km, 4km)
- one in Livingston (4km)
- Recycled Fabry-Perot
- 10 kg mirrors
- Simple pendulums
- Stack for seismic isolation

LIGO at design sensitivity !





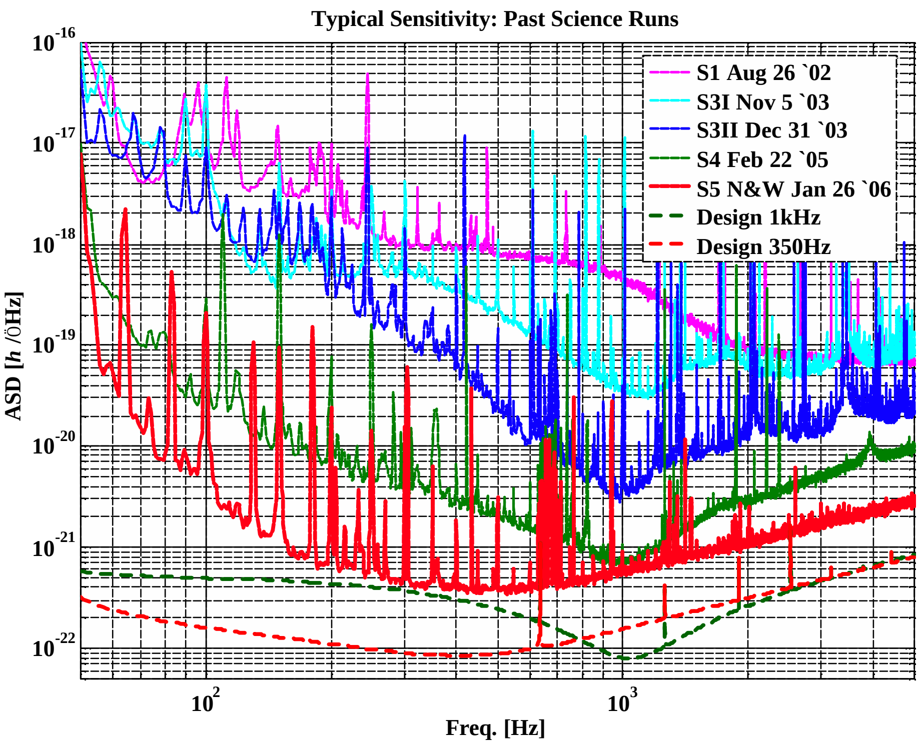


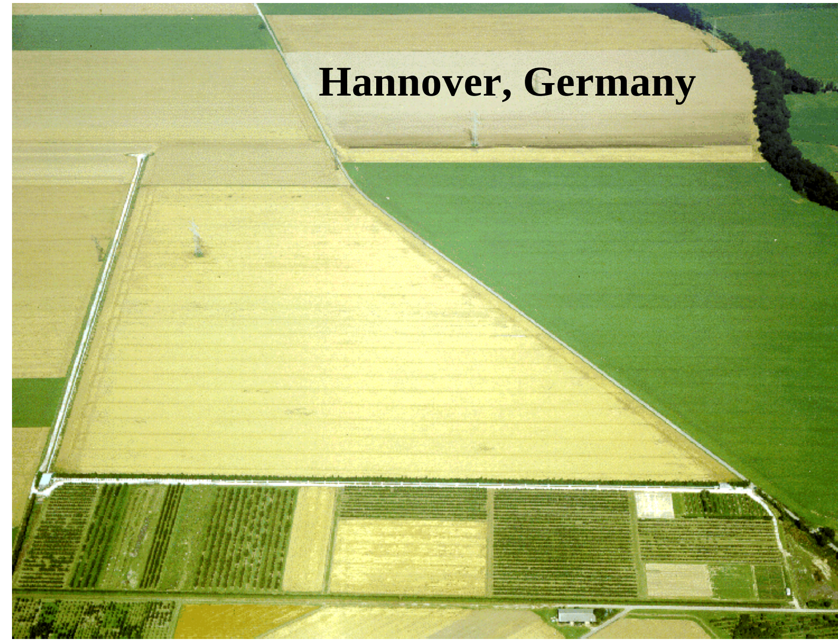
- Four data taking since 2002 (S1-S4) and first upper limits
- LIGO Scientific Collaboration driving data analysis effort
- Long data taking (S5) started in November 2005

Goal: collect >1 yr of data

GEO near the design goal !

- Germany/UK
- 0.6 km arm interferometer
- Signal recycled interferometer
- 5 kg mirrors
- Fused silica suspensions
- Double pendulums
- Stack + cantilevers for seismic isolations





- Double objective
- *contribute to first detection*
- *but also test innovative technical solutions*

- Status: < 4x design sensitivity above 400 Hz

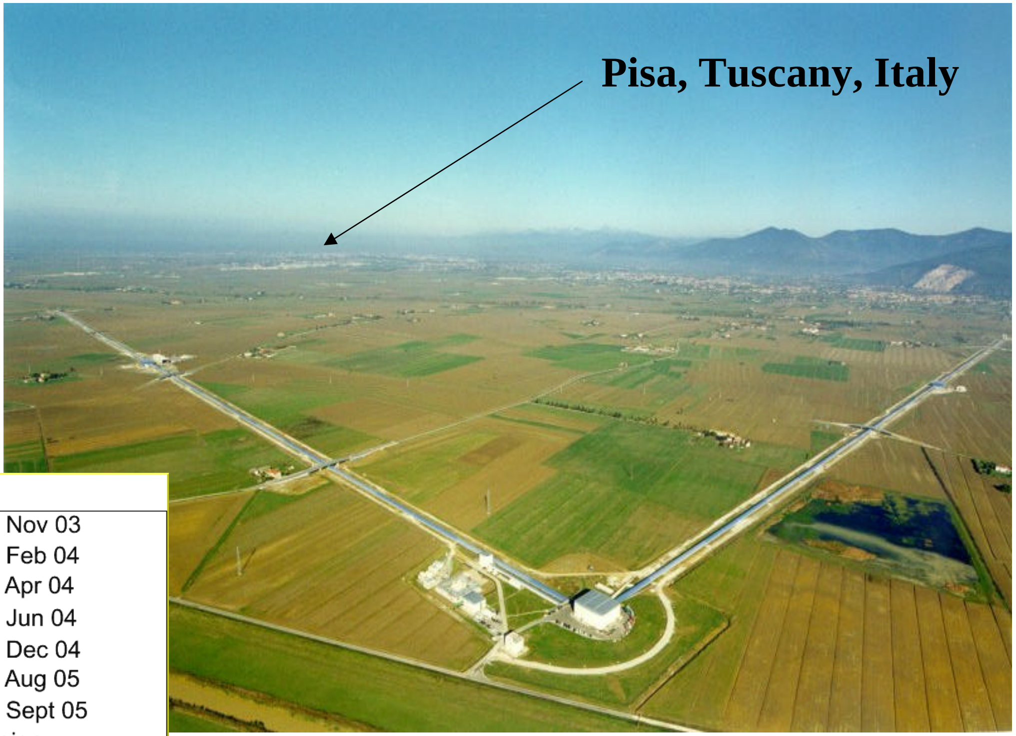
  Data taking during nights and weekends

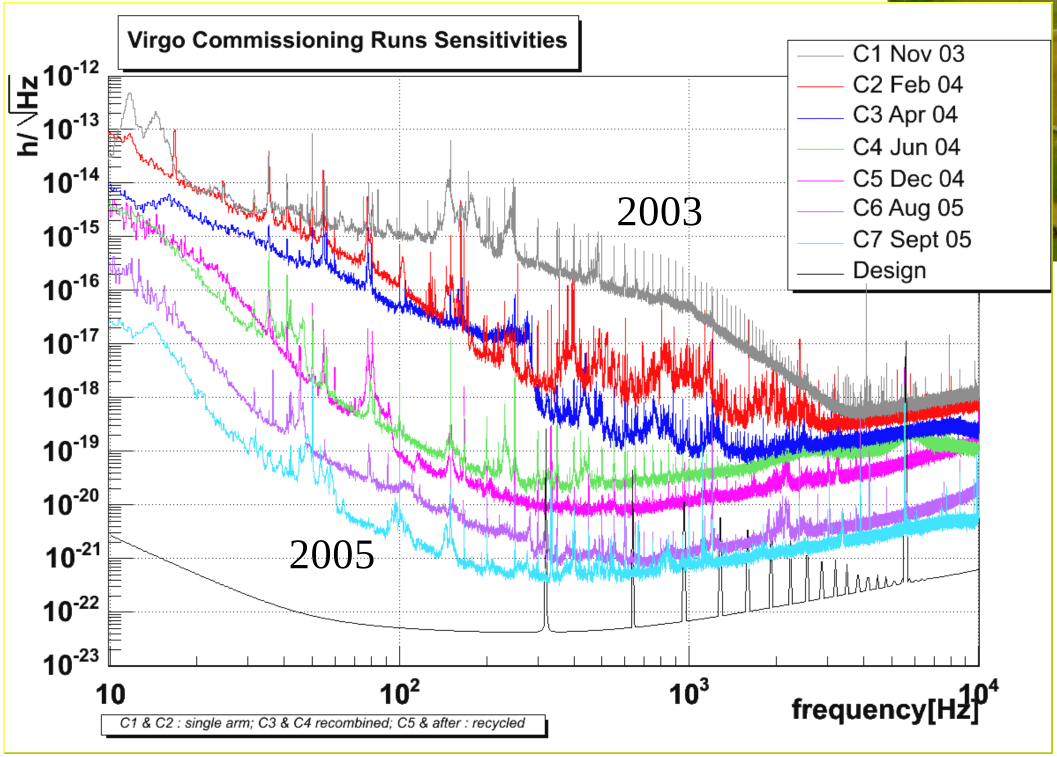
  Goal: join LIGO S5 run next May

Virgo approaching !

- French-Italian, CNRS/INFN
- 3-km long interferometer
- Recycled Fabry-Perot
- 20 kg mirrors
- Multi-pendulum suspension

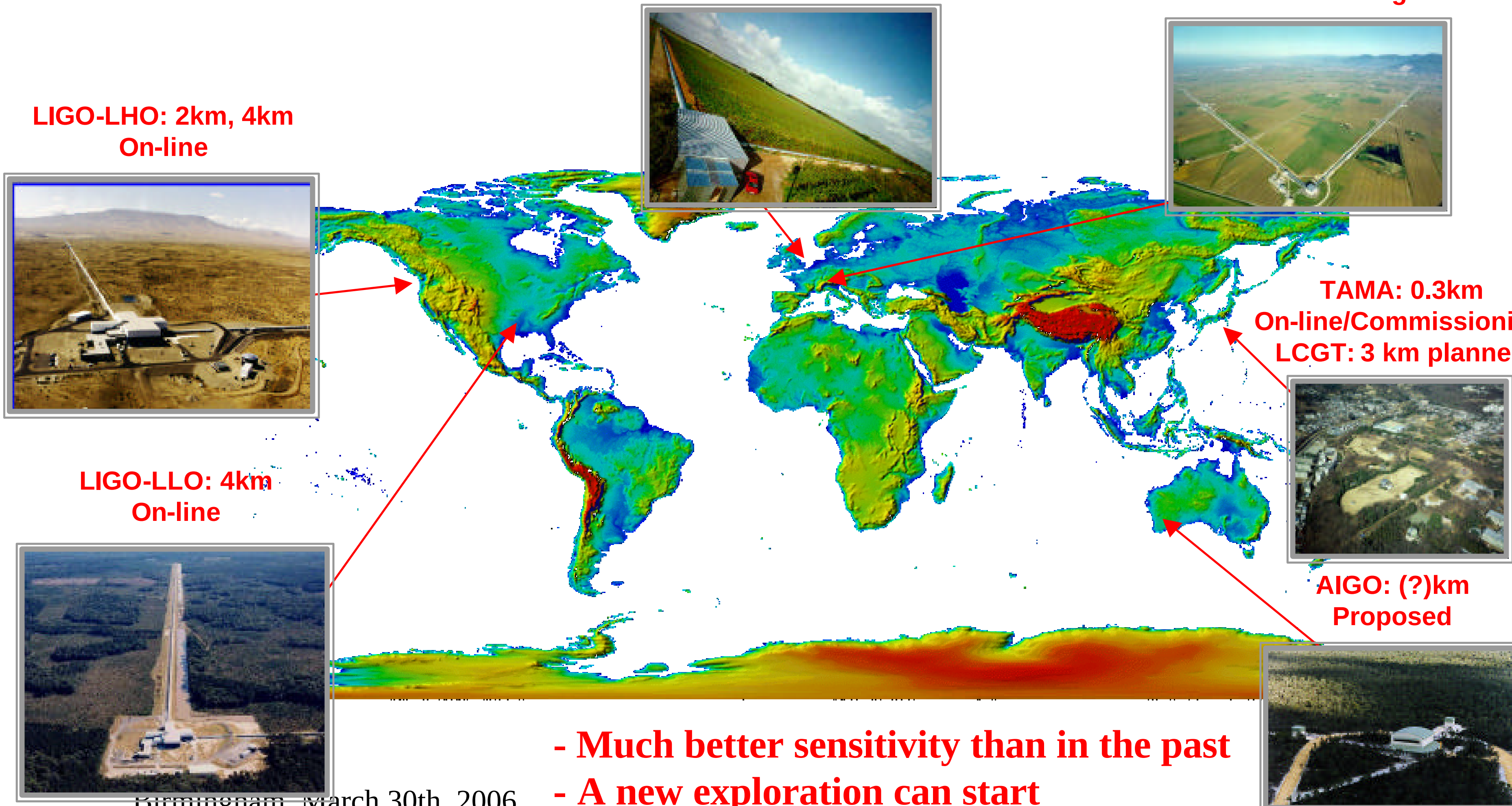
  Attempt to push seismic wall down to 10 Hz





- 2001-02 Commissioning of central area
- >2003 Commissioning full interferometer
- Status: design x 10 above 200 Hz
- Goal: joins LIGO before the end of S5

A network of GW detectors based on laser interferometer coming on-line



- Much better sensitivity than in the past
- A new exploration can start
- Discovery potential

Toward the single machine concept

- **Gravitational waves will produce a “coincident” signals in all detectors**
- Detection will require the coincident observation of the same signal in different detectors
  - *Common interest that all detectors work at their best possible level*
  - *Need to exchange data between the various projects*
  - *Need to coordinate the detectors upgrade/shut down and plan together the future developments*
- Common data format (“frame format”) developed and agreed
- GEO and LIGO data already exchanged within the LIGO Scientific Collaboration (LSC)
- LIGO-Virgo collaboration started in 2004

  exchange of simulated data with injected GW signal
  compare data analysis pipelines
  verify benefits and performances of the network
- New LIGO-Virgo MOU in preparation

  Goal: start exchanging real data as soon as Virgo approaches LIGO sensitivity
- Next step: coordinate shut down and upgrades to minimize network down-time

IV. Plans for the future

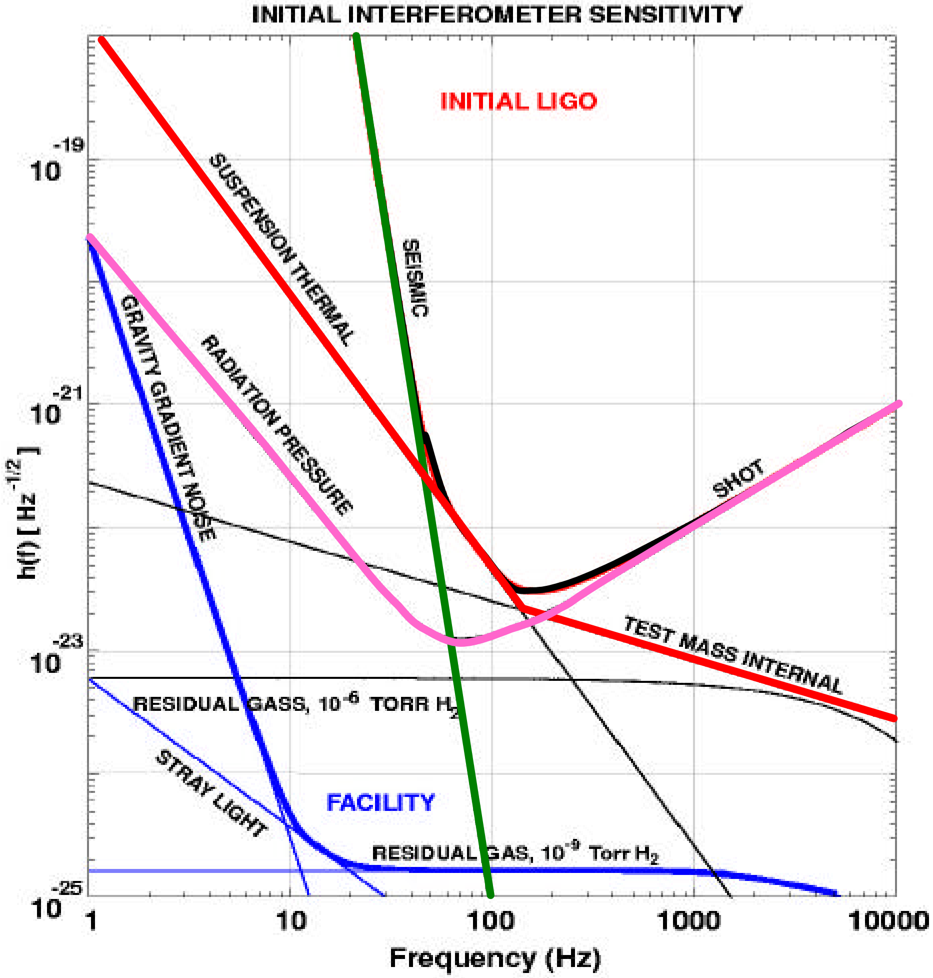
Improve the sensitivity

- Push seismic wall to lower frequencies
- *better seismic isolations*

- Decrease thermal noise/friction
- *lower friction in suspension wires*
- *decrease friction in mirror substrates and coatings*

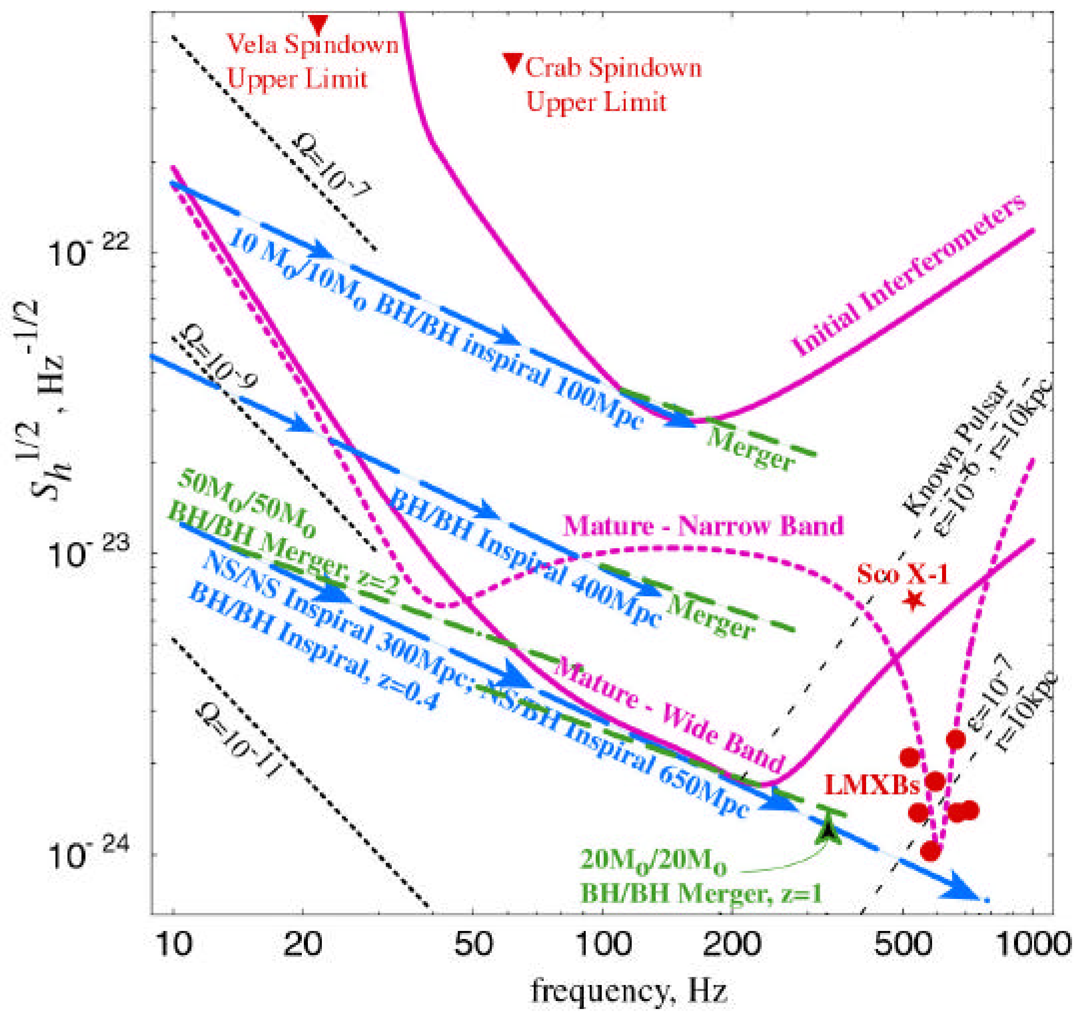
- Shot noise at high frequency
- *increase photons stored in the interferometer*
- *danger!: radiation pressure*
- *look for alternative optical/readout scheme*

- Technical noise
- *alignment sensor noises*
- *electronics noise*
- *control noise (actuators)*



Advanced LIGO

- Same infrastructure
- New interferometers
  - *new seismic isolation (active)*
  - *fused silica suspension*
  - *heavier and better mirrors*
  - *20x laser power*
  - *signal recycling*
- Much better sensitivity:
  - *~ 10x lower noise (10^{-24} range)*
  - *~ 4x lower frequencies*
  - *tunable sensitivity*
- Timeline
  - *approved by NSF*
  - *financing expected in FY2008*
  - *shut down in 2010*
  - *operative in 2013*
  - *some small scale improvements could be done before 2010*

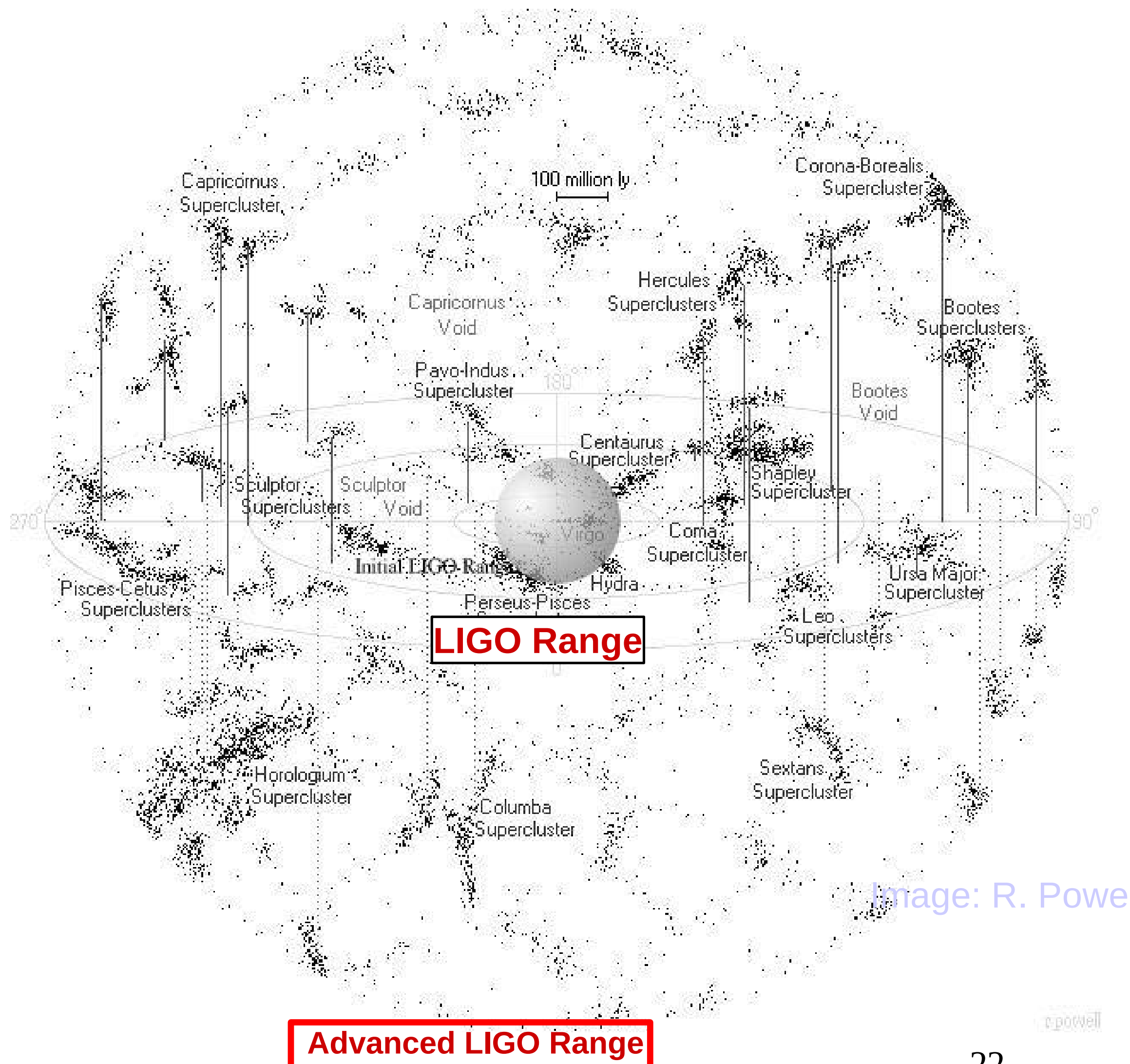


Proposed by LIGO and the LSC
With GEO participation

Advanced LIGO's reach

- Neutron star binaries
  - *Range = 300 Mpc*
  - *N ~ 2/yr – 3/day*
- Black holes binaries
  - *Range = 1.7 Gpc*
  - *N ~ 1/month-1/hr*
- BH/NS binaries
  - *Range = 750 Mpc*
  - *N ~ 1/yr – 1/day*

- Stochastic background
  - *Initial LIGO* $W \sim 3\ 10^{-6}$
  - *Adv LIGO* $W \sim 3\ 10^{-9}$



From Virgo to Virgo+

- Virgo has already an “advanced” seismic isolation system

- Possibility to improve the sensitivity with a set medium scale incremental improvements

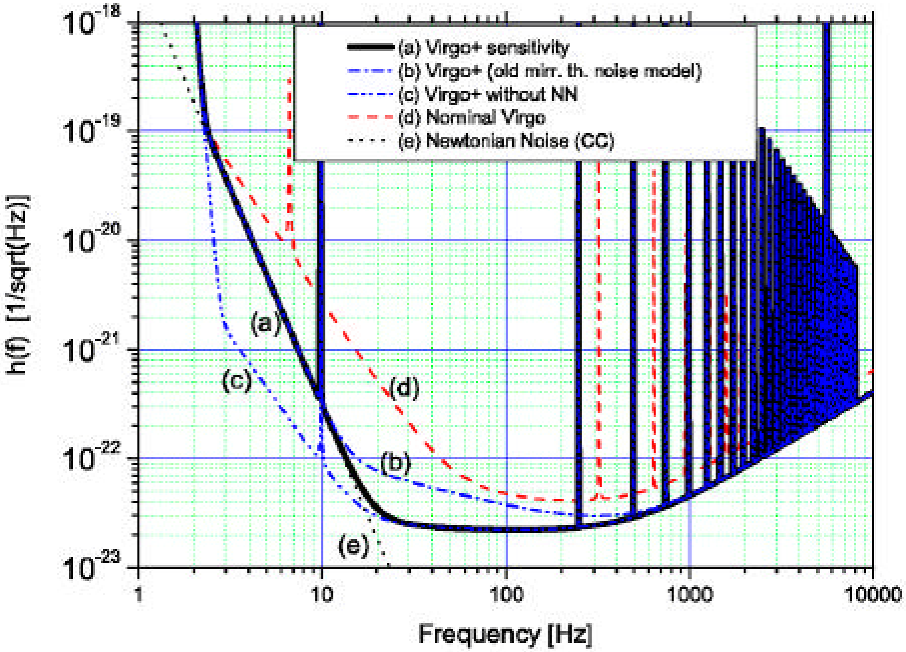
    Compatibility with the main Virgo subsystems
    Same optical lay-out
    Limited shutdown
    Limited commissioning

- Planned upgrades

    - Fused silica suspensions
    - Larger laser power: 20W $\rightarrow$ 50W
        $\Rightarrow$ *mirror shape thermal compensation*
    - Electronics and control system

- Proposed time line:

    start upgrade after extended data taking
    shut down ~2008



Coalescing binaries: accessible volume increases by 7 to 60
(depends on thermal noise model)

Toward advanced Virgo

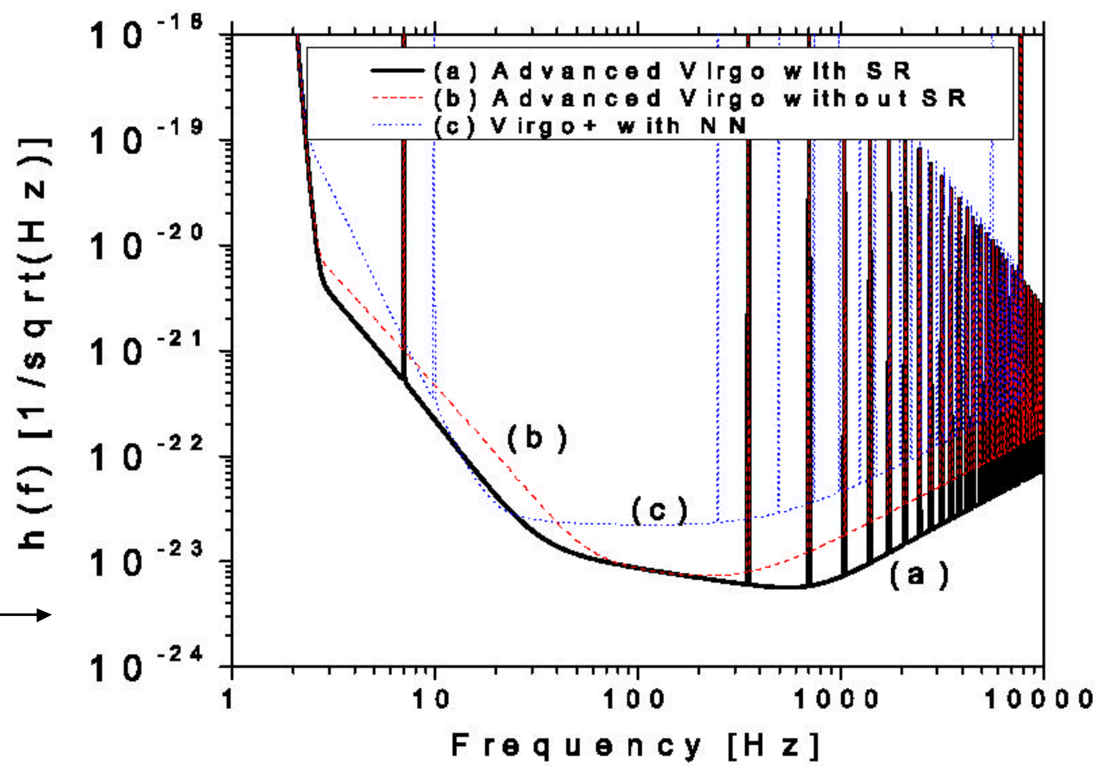
- Sensitivity goal: 10x better than Virgo (similar to Advanced LIGO)

- Main ingredients:
  - *change optical scheme (signal recycling)*
  - *increase further laser power*
  - *improve further thermal noise (new coatings/flat top beams)*

- Four working groups set-up in Virgo with participation of GEO scientists
  - *high power lasers and input optics*
  - *suspensions and mirrors*
  - *optical configuration*
  - *electronics and control*

- Envisaged timeline
  - 2006-08: design
  - 2008-10: engineering
  - > 2010: construction

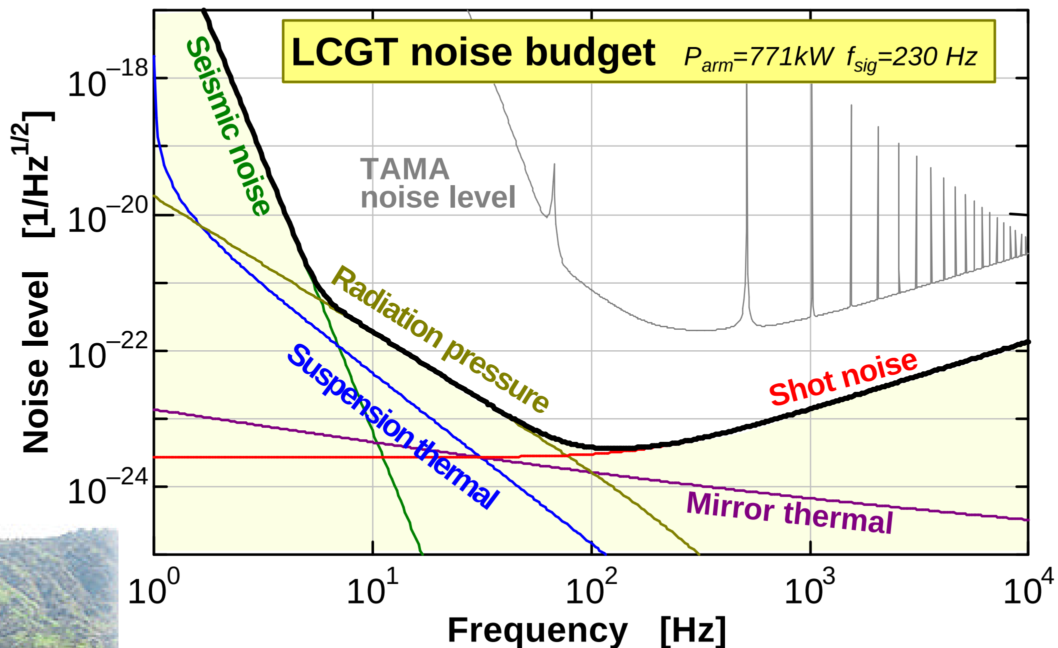
- Possible sensitivity →



Birmingham, March 30th, 2006

LCGT (Japan)

- Two co-located interferometers
- 3km Fabry Perot in the arms
- Signal & power recycling
- Underground (Kamioka mine)
- Cryogenic (20K)
- Sapphire mirrors and suspension
- Multi-pendulum for seismic isolation



- Intensive R&D program in progress
  - *seismic isolation testing in TAMA*
  - *100 m underground prototype (CLIO)*
  - *first cryogenic cavity locked*
- Proposal submitted
- Tentative schedule: on-line in 2012

From GEO to GEO-HF

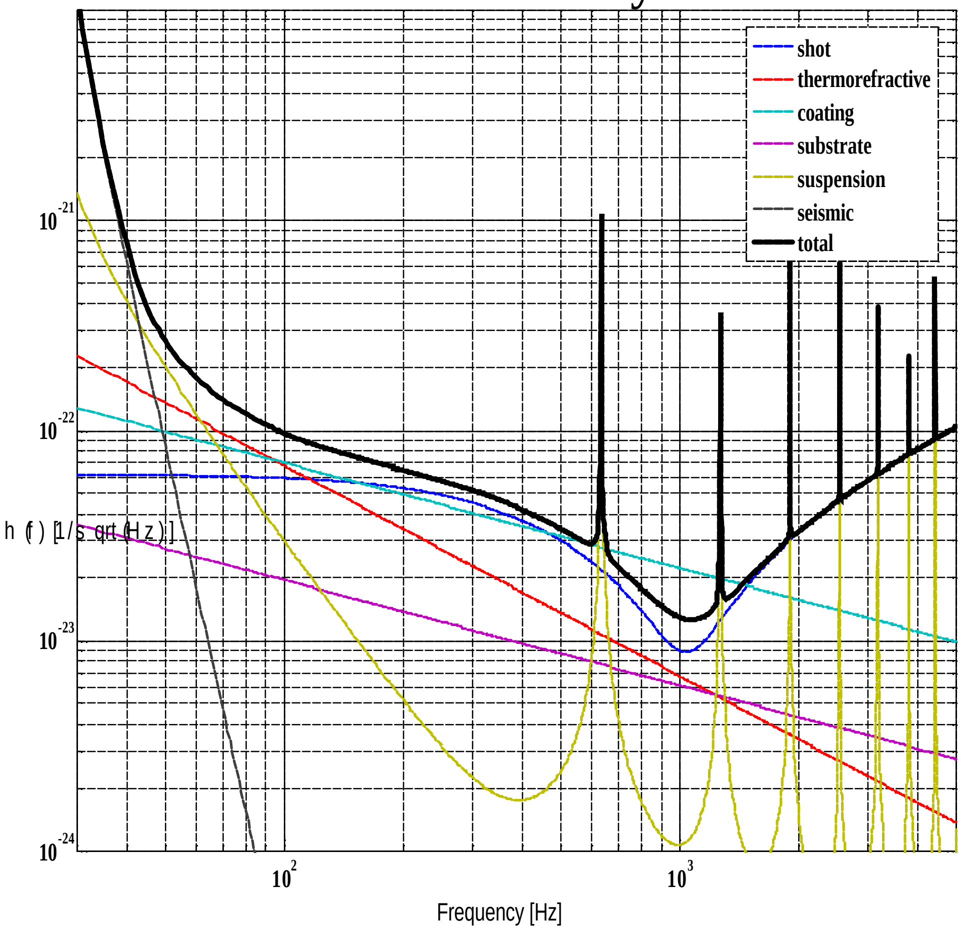
• GEO-HF
- not the name of a new detector but rather the name of a program
- sequential upgrades of GEO and prototype research to prepare these upgrades

• Motivations
- provides useful data until Advanced Interf
- support transit of 3rd generation interferor
  detector configuration (as it was the case v

• Envisaged upgrades:
  - *increase circulating power*
  - *optimise signal recycling*
  - *use of squeezed light*
  - *reduce coating thermal noise (if possible)*

• Timeline: start upgrading after extended data taking 2007/2008

Possible sensitivity curve



Third generation laser interferometer

• Advanced interferometer will reach some of the present infrastructures limitation (seismic)

• Need for a new generation interferometer based on an underground facility

- *reduce "Newtonian" noise*
- *construction of longer arms easier*

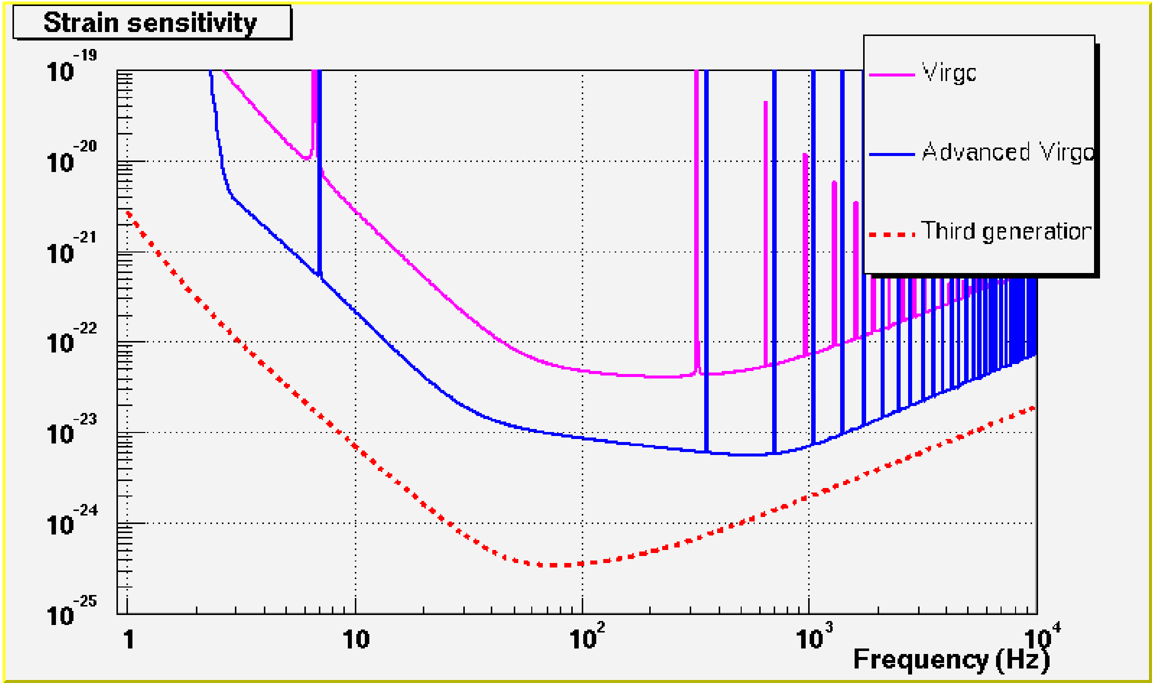
• Third generation ITF keywords:

- *squeezed light*
- *low losses mirrors/suspensions*
- *massive mirrors*
- *cryogenics*
- ….

• Sensitivity goal:

10x better than Adv ITF

Enter the 10^{-25} scale

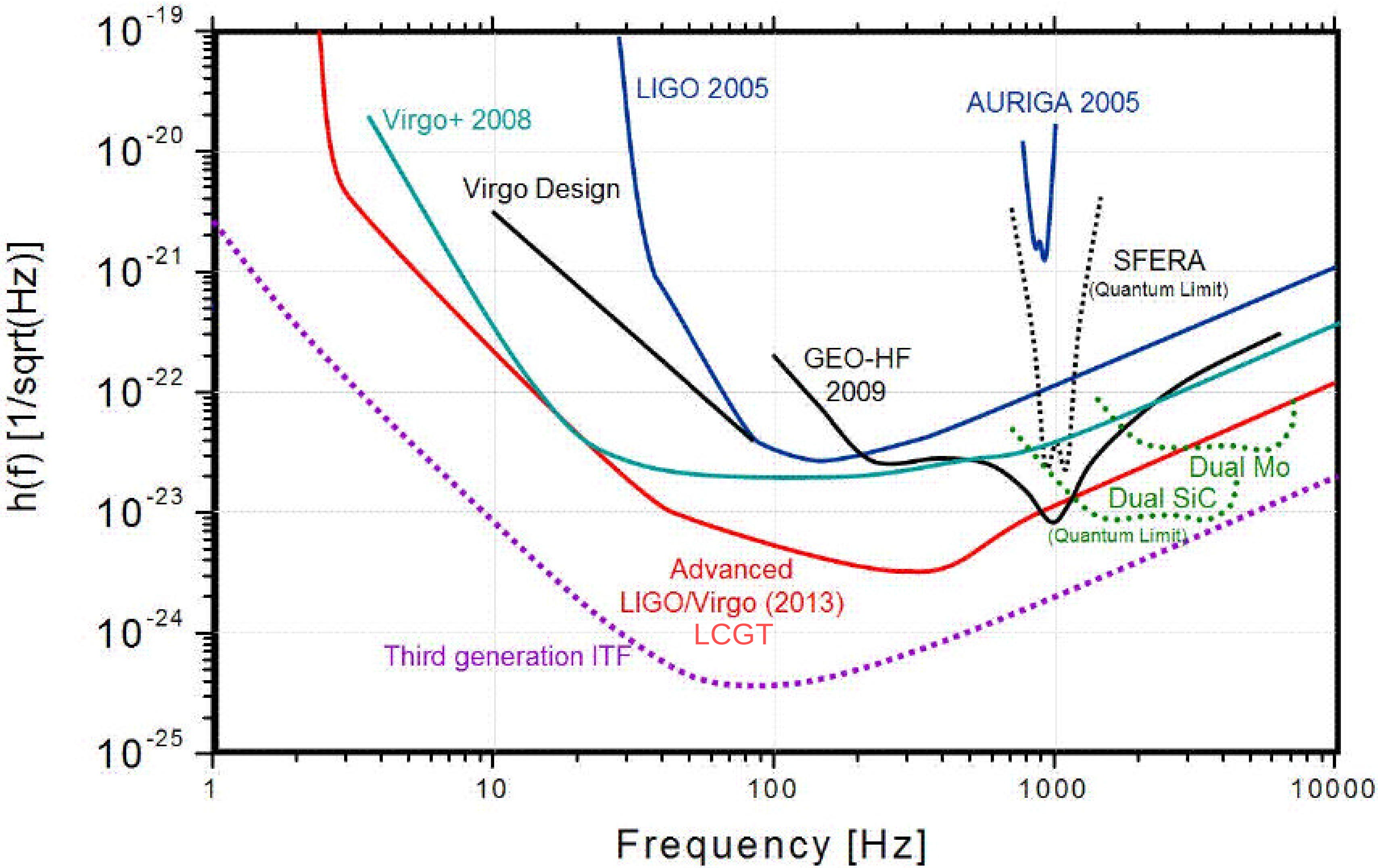


• A will to start a design study in Europe

1) start work within ILIAS-GWA (EU supported network dedicated to GW)

2) prepare a design study proposal for FP7

An exciting experimental program



Conclusion

- The detection of gravitational wave is a unique tool
  - *to study the gravitational force and enlarge our understanding of fundamental physics*
  - *to observe the universe from a totally different point of view*

- A new network of GW detectors based on laser interferometers is coming on-line
  - *much better sensitivity and larger bandwidth*
  - *will explore the wave strengths upper limits*
  - *a new exploration: a first detection is possible*

- Thanks to R&D results the construction of advanced interferometers can start

  these detectors will enter the 10^{-24} scale

  these detectors will assure the detection of known sources

- Ongoing R&D is promising: still a lot of space to improve sensitivity

  the 10^{-25} scale is reachable