gravitational wave detection

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CHIPP Workshop on Astroparticle Physics, Lausanne, June 3, 2009 - jo@nikhef.nl

Motivation

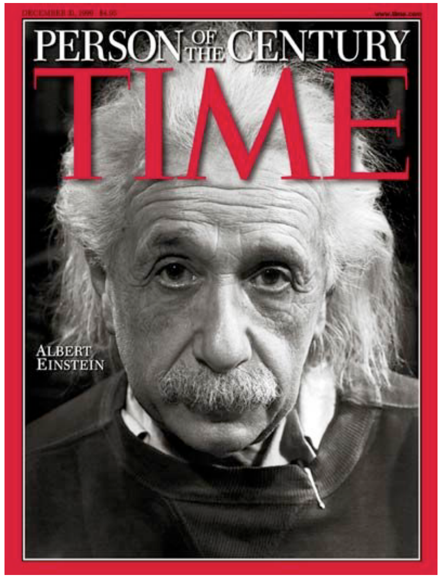
Einstein gravity :

$$G_{\alpha\beta} = 8\pi T_{\alpha\beta}$$

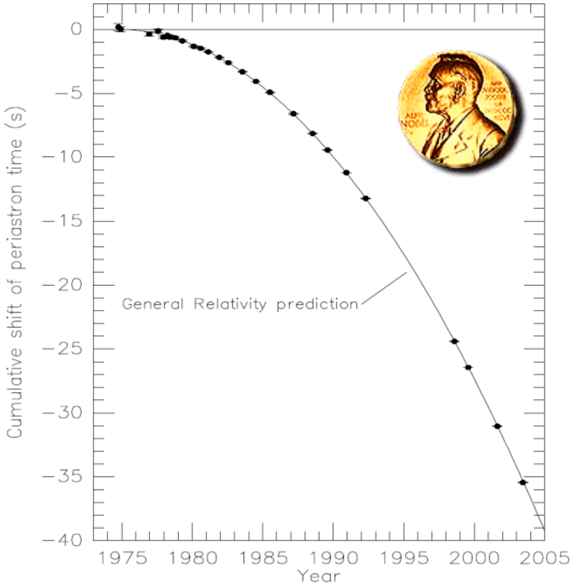
Gravity as a geometry

Space and time are physical objects

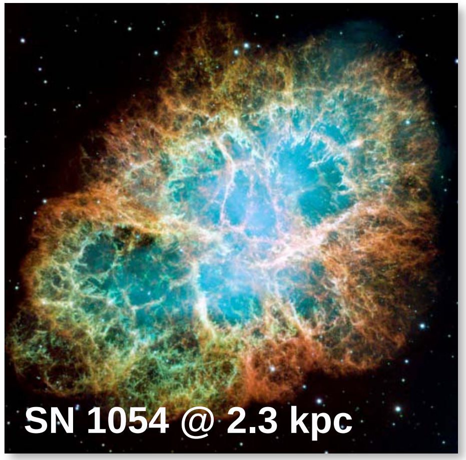
- Gravitation
  - Least understood interaction
  - Large world-wide intellectual activity
    - Theoretical: ART + QM, Cosmology
    - Experimental: Interferometers on Earth and in space
- Gravitational waves
  - Dynamical part of gravitation, all space is filled with GW
  - Ideal information carrier, almost no scattering or attenuation
  - The entire universe has been transparent for GWs, all the way back to the Big Bang



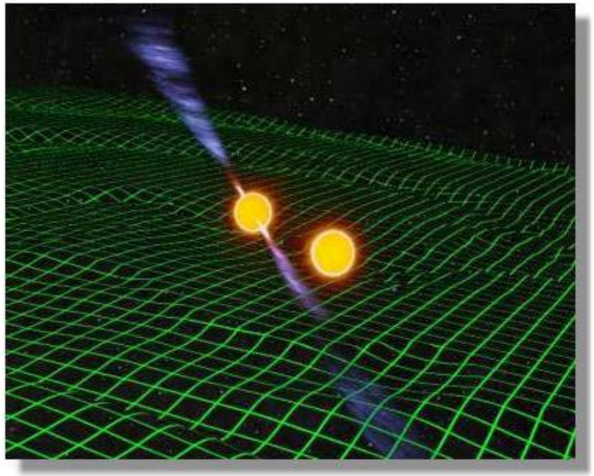
R.A. Hulse and J.H. Taylor Jr (1993)

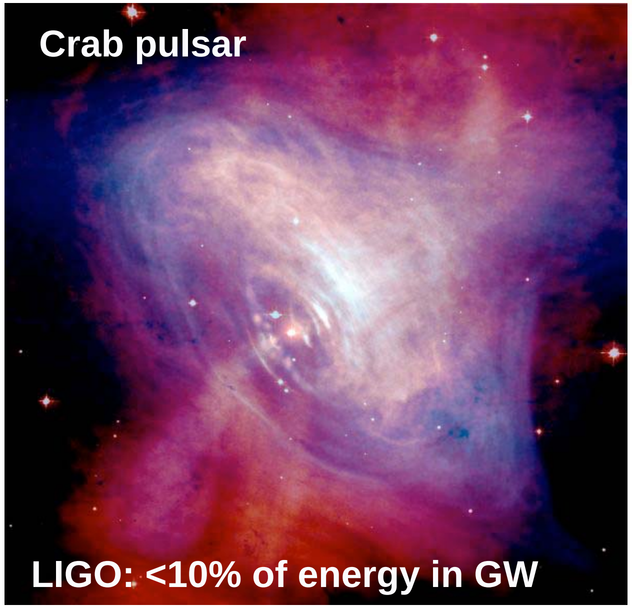


GW sources

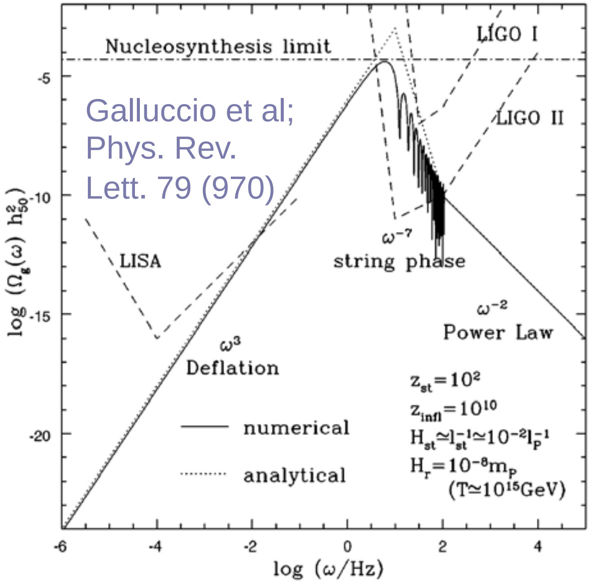


- Transient signals
  - Supernovae
  - Compact coalescing binaries
    - BNS, BBH, NS-BH
    - `Standard candles'





- Periodic signals
  - Rotating neutron stars



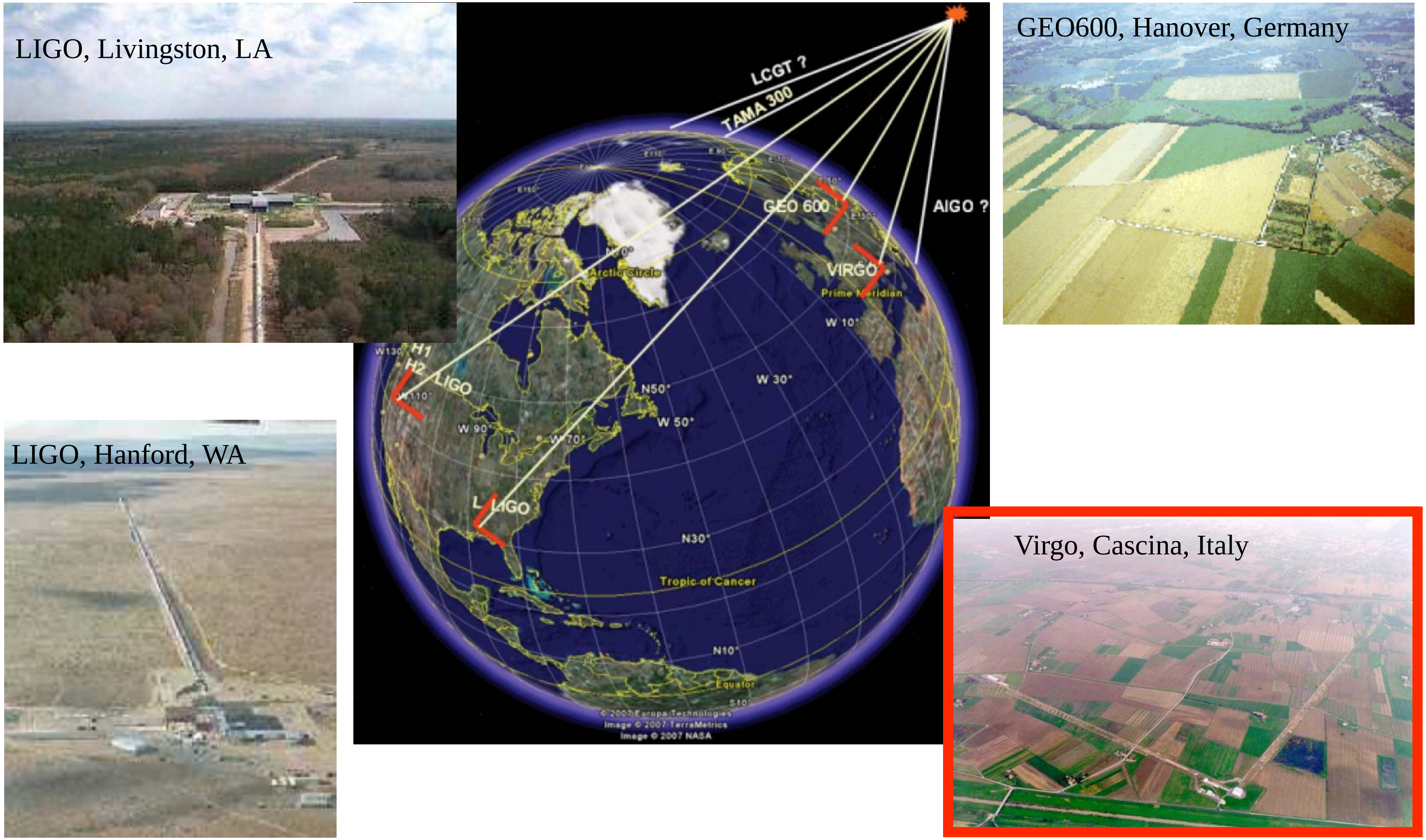
Galluccio et al; Phys. Rev. Lett. 79 (970)

Mechanisms producing GRBs are likely to produce GW as well

Several GW sources are potential sources of *e.g.* neutrino's

- Stochastic signals
  - Early Universe GW signals
  - Cosmological (super)strings

A worldwide network of interferometers



Evolution of ground-based GW detectors

- 1st generation interferometric detectors
  - Initial LIGO, Virgo, GEO600

Unlikely detection

Science data taking
Set up network observation

We are here

- Enhanced LIGO, Virgo+

Plausible detection

Lay ground for multi-messenger astronomy

- 2nd generation detectors
  - Advanced LIGO, Advanced Virgo, GEO-HF

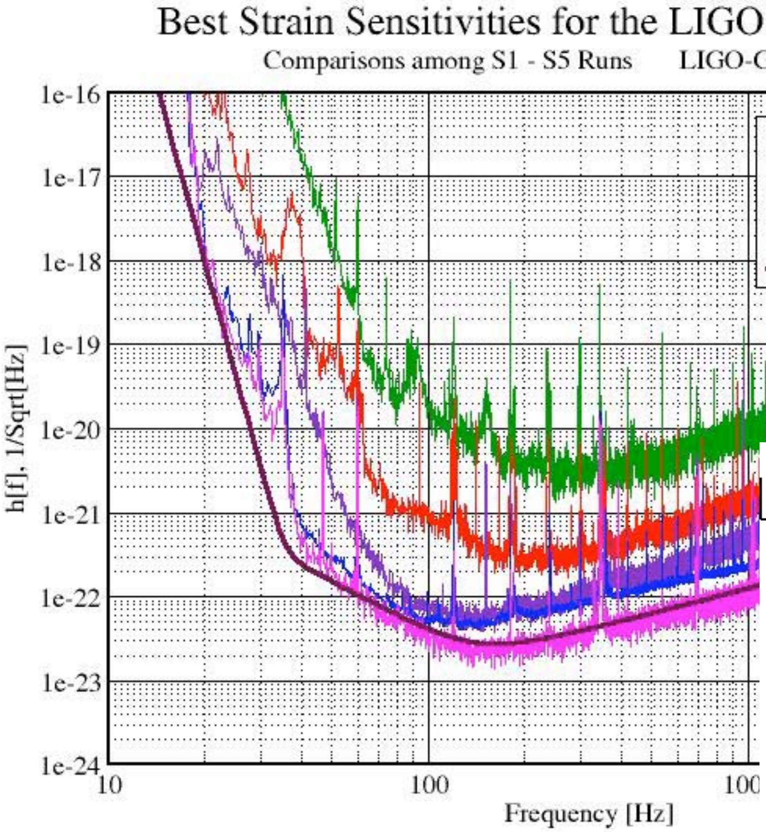
Likely detection

Routine observation
Towards GW astronomy

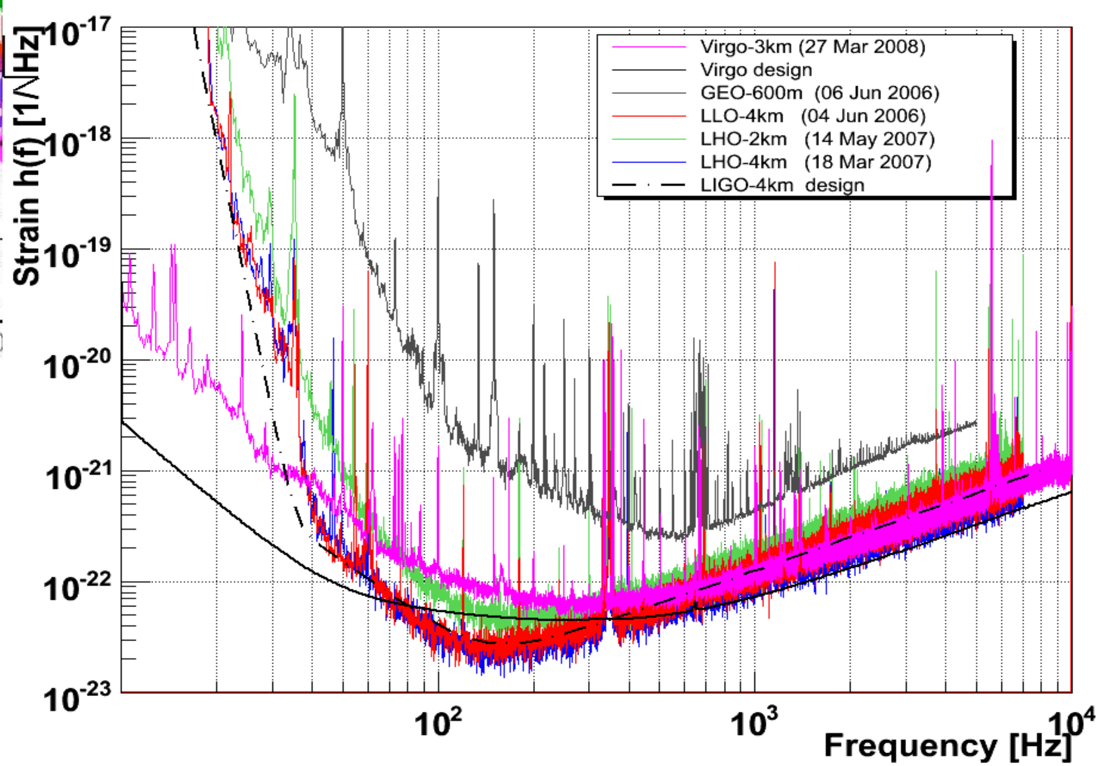
- 3rd generation detectors
  - Einstein Telescope, US counterpart to ET

Thorough observation
of Universe with GW

Reaching design sensitivity

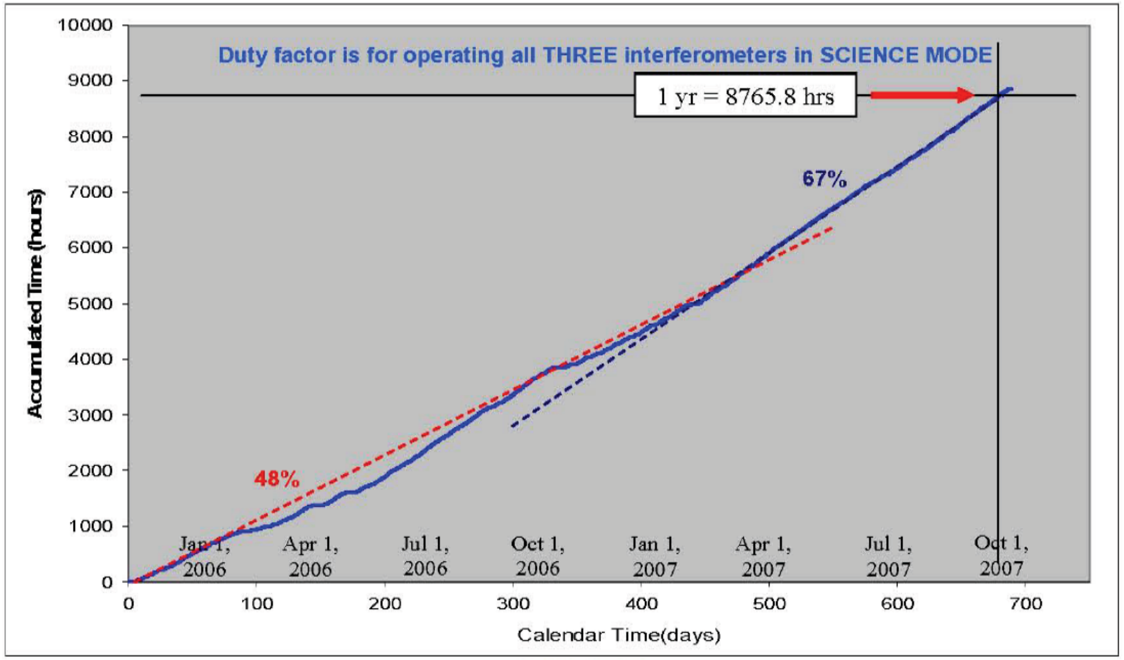


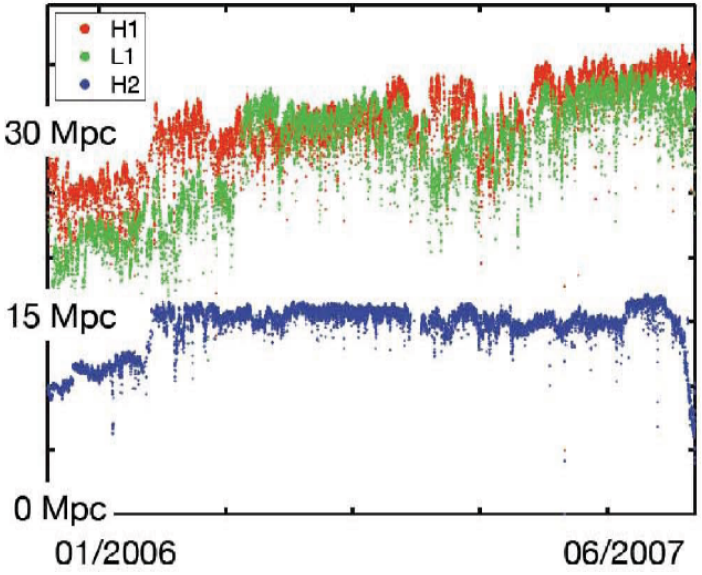
- Reaching design sensitivity has been a long process
- The LIGO detectors reached their design sensitivities for the fifth science run (S5)



LIGO S5

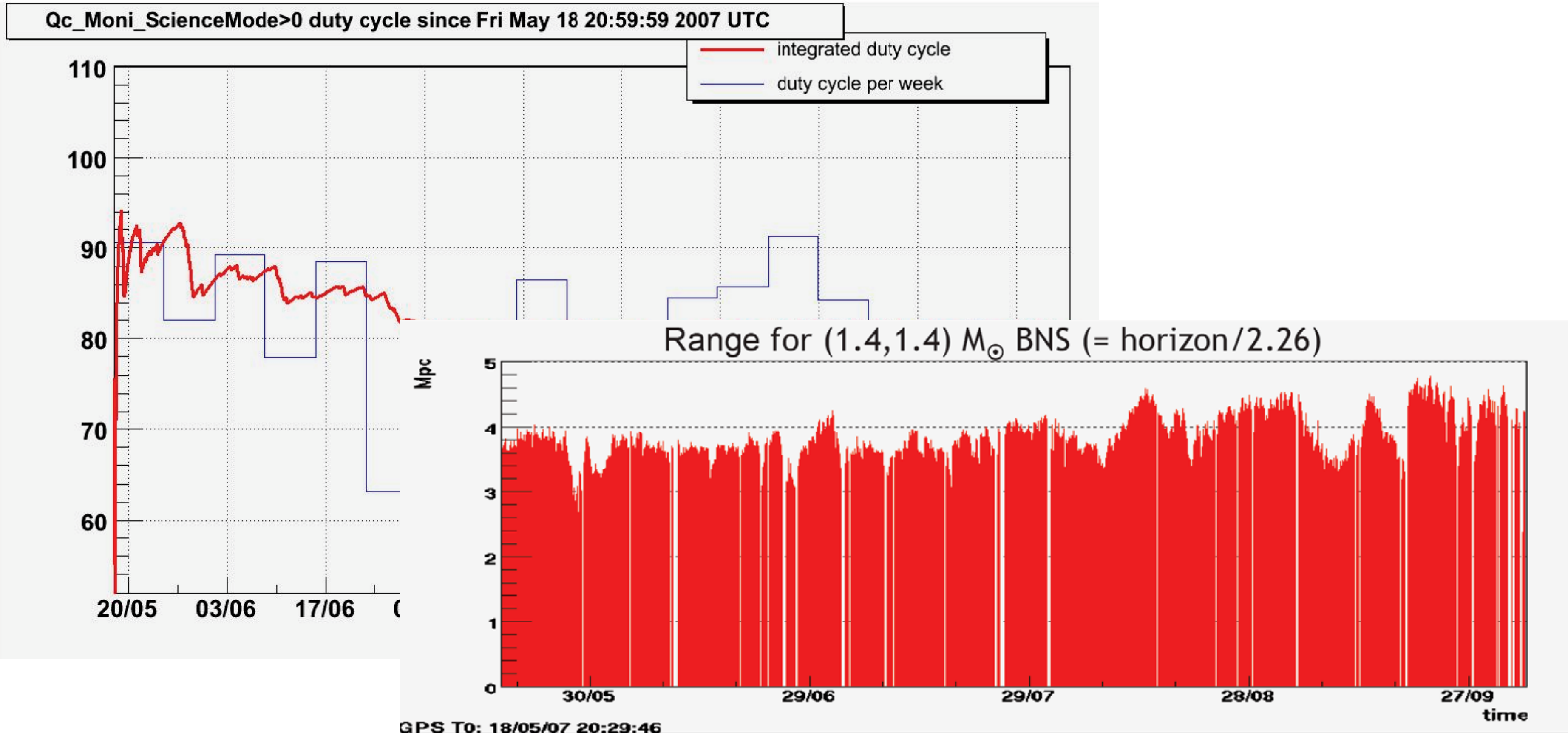
- November 2005 – October 2007
- Accumulated triple-coincidence time = 1 year
- Horizon distance for (1.4,1.4) $M_\odot$ BNS
  - optimally located and oriented source giving an SNR of 8





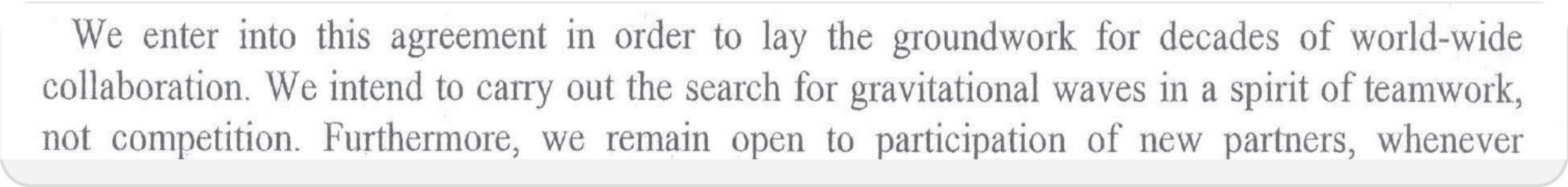
Virgo VSR1

- May 18 – October 01, 2007
  - Coincident with the last months of LIGO S5
- Long locks: 20 locks > 40 hours (longest 94 hours)
- Duty cycle: 81% science mode



LIGO – Virgo agreement

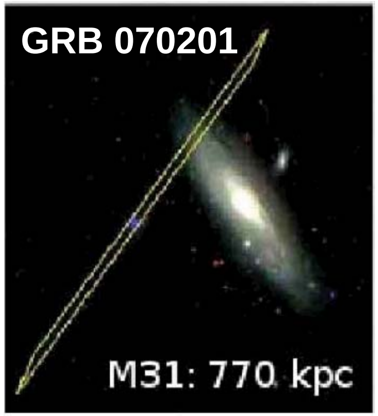
- Early 2007, for three years
    - Long term spirit



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

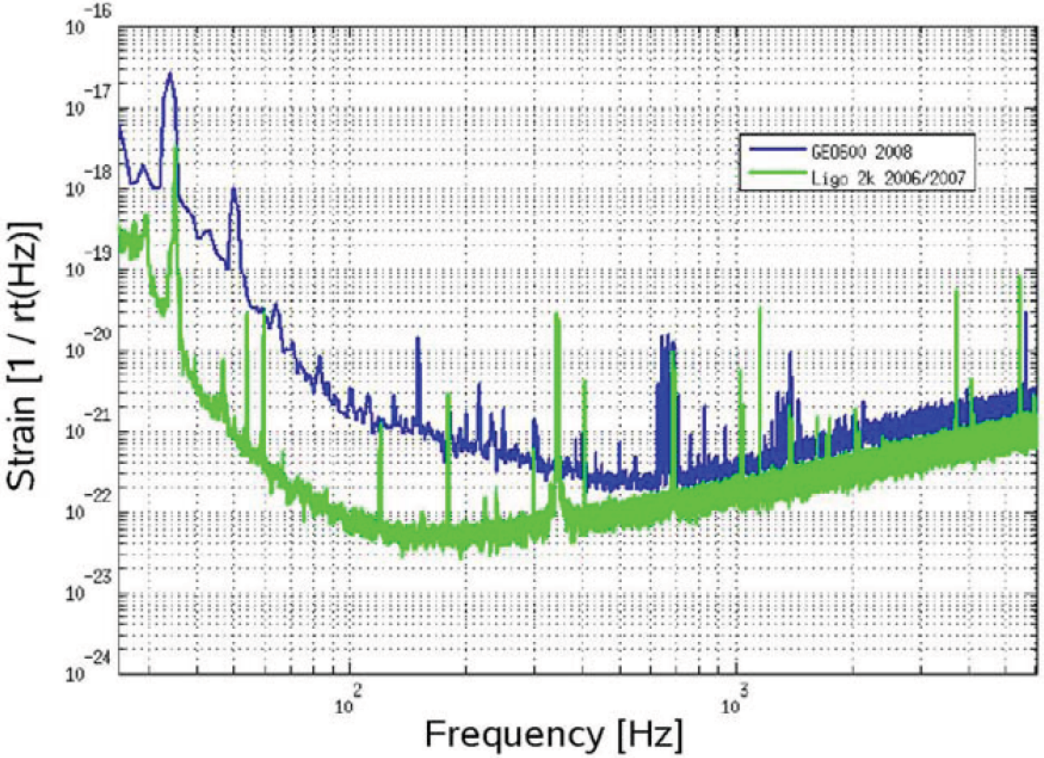
- Full data exchange started with VSR1
- Three sites are needed to extract more science

- LSC published 30 observational papers on S1 … S4
- So far, 7 papers published or submitted on S5
    - Beating spin-down limit of GW from Crab pulsar
    - Possible merger in Andromeda?
    - Many more to come including joint LSC Virgo papers



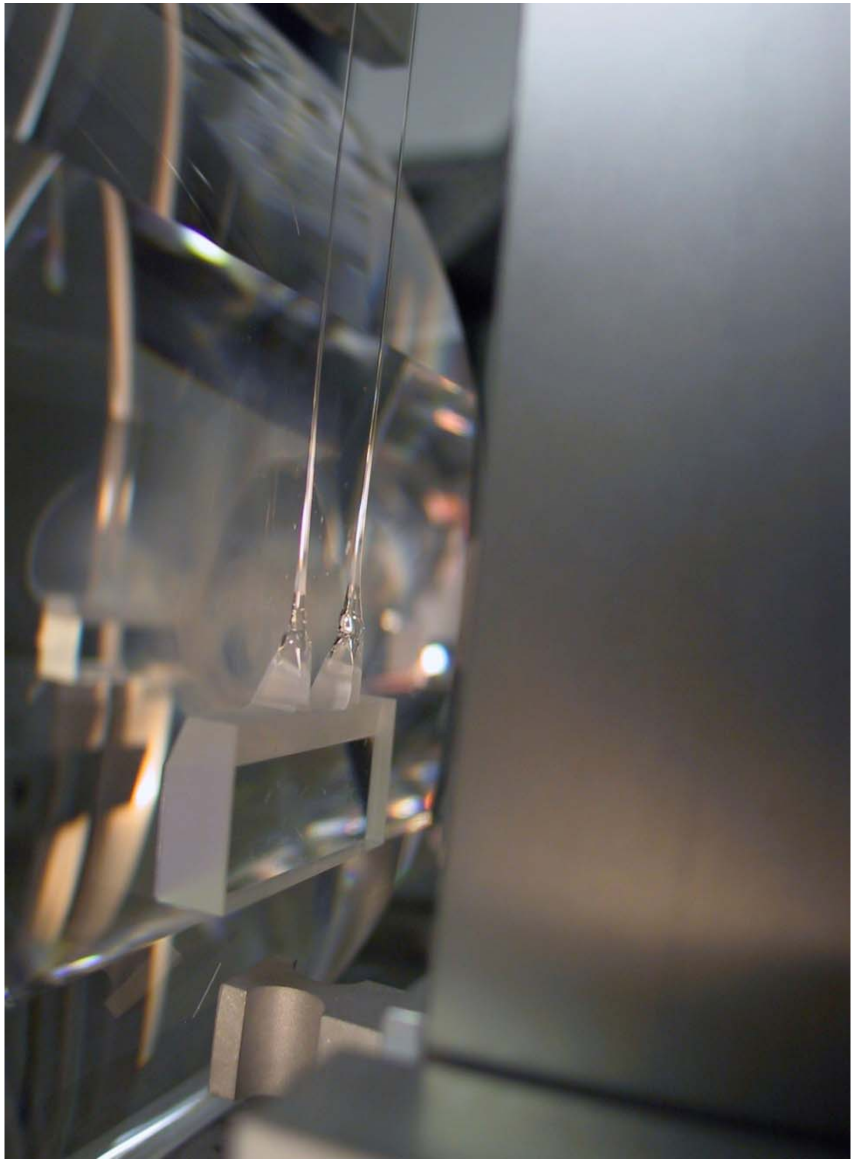
Astrowatch

- While LIGO H1 and L1 and Virgo were being upgraded in view of S6 – VSR2, LIGO H2 and GEO600 have been taking data in Astrowatch mode
  - Keep detectors up as much as possible in order not to miss any extraordinary event that might occur, *e.g*. a supernova in the Galaxy
  - High duty cycle achieved



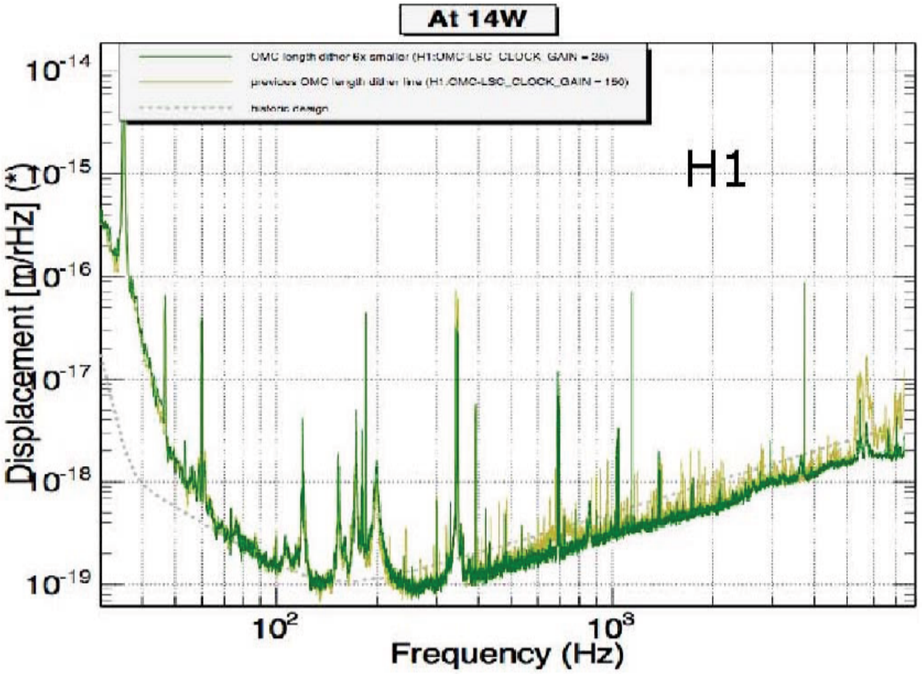
Enhanced LIGO and Virgo+

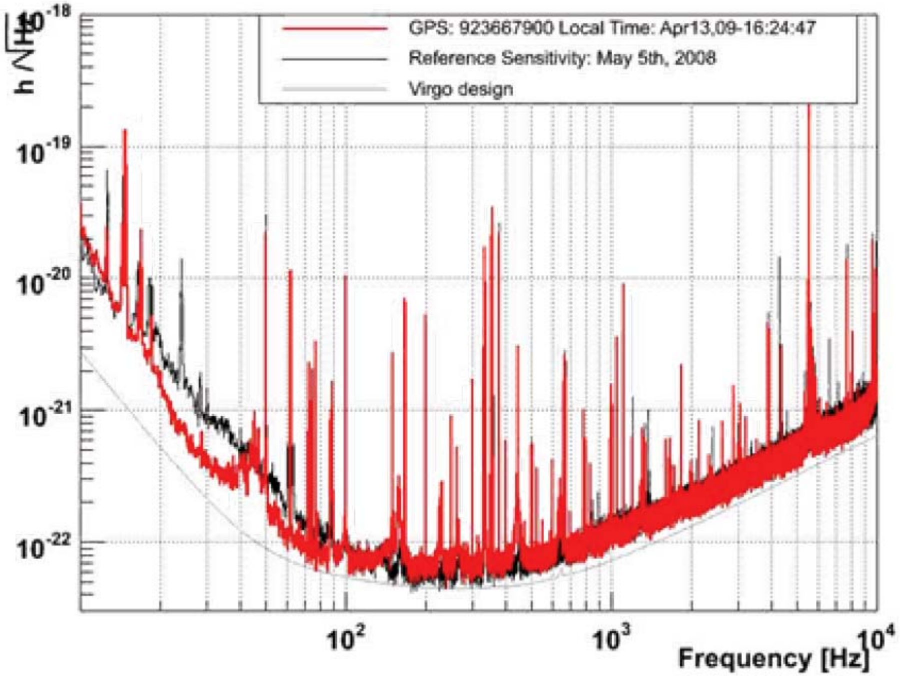
- Do `easy’, `quick’, and `cheap’ yet significant upgrades within unchanged infrastructure
  - *e.g.* increase laser power
  - Aim at a factor ~2 improvement (make detection plausible if not likely)
- Include a few challenging techniques that will be needed for Advanced LIGO and Advanced Virgo
  - A step taken toward 2nd generation detectors (leverage GEO work)
  - DC detection in eLIGO
  - Monolithic suspensions in Virgo+



Present status: Enhanced LIGO and Virgo+

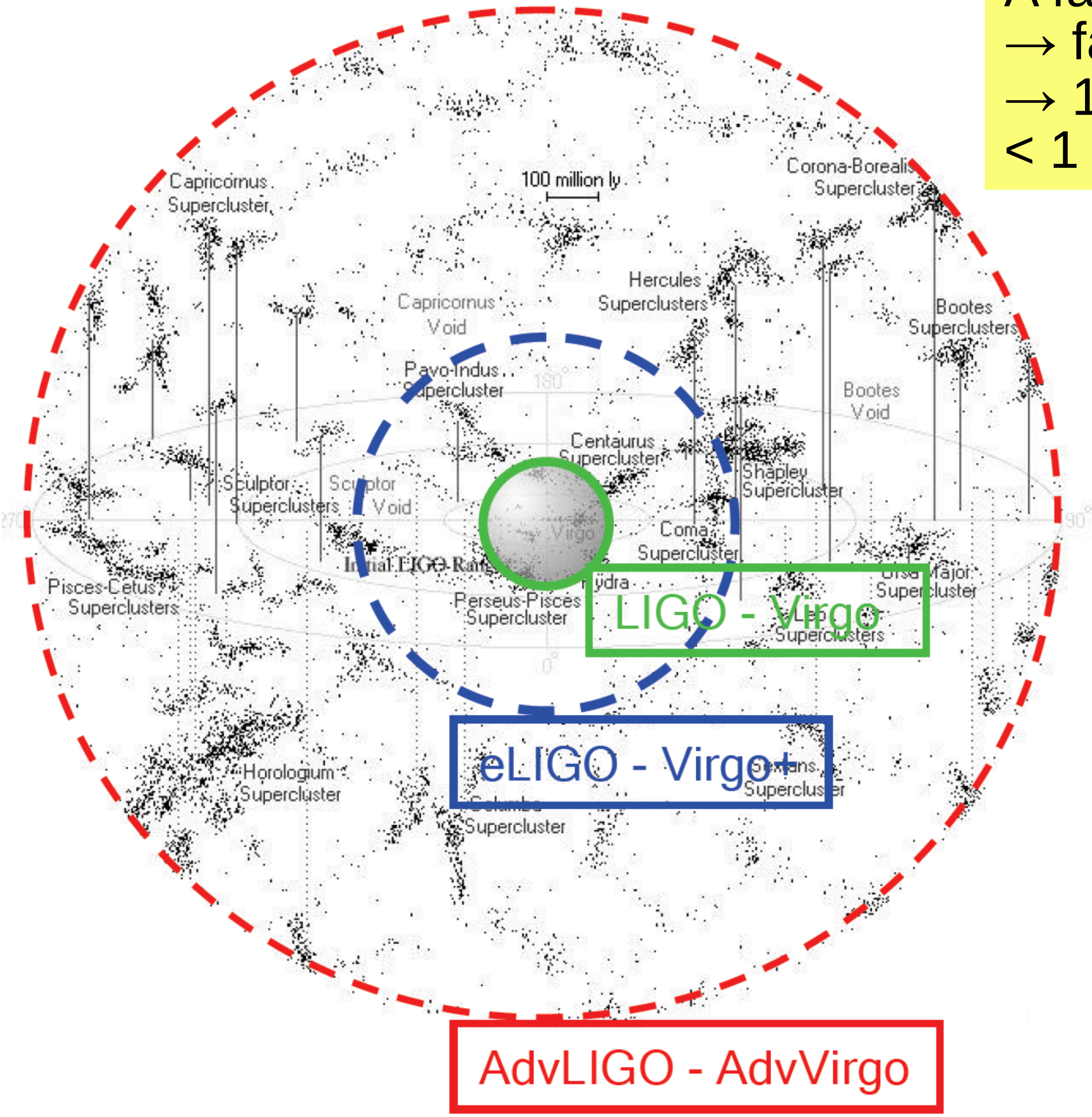
- Commissioning and noise hunting effort since last fall
- Target date for start of runs S6 and VSR2
  - July 7, 2009
  - Virgo+ monolithic suspension





Advanced detectors

A factor 10 on the sensitivity
→ factor 1000 on the rate of events
→ 1 year of initial detectors
< 1 day of advanced detectors!

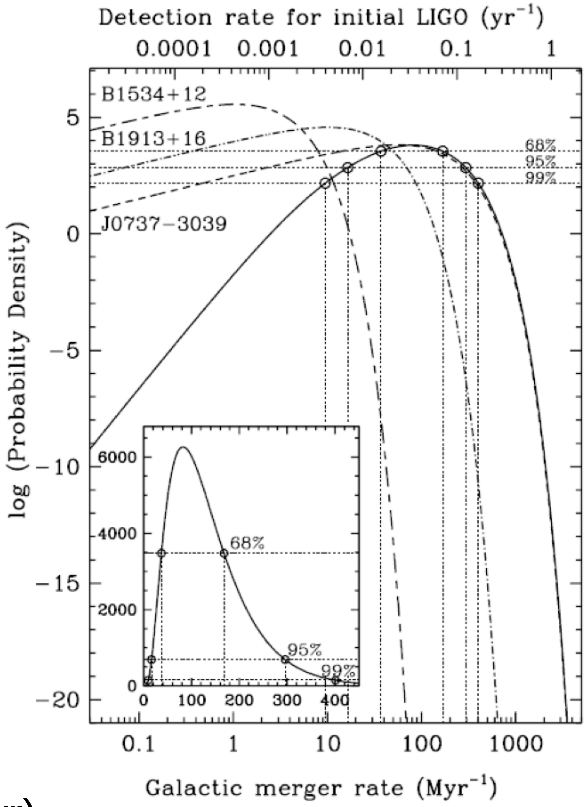


- Rate of detectable binary neutron stars coalescences
  - Initial detectors ~ 1/100 years
  - Advanced detectors ~ 40/year
- Binary black hole coalescences
  - Similar rates expected
  - Visible up to ~ 1 Gpc!
- Pulsars
  - Limit on ellipticity $\varepsilon \sim 10^{-8}$

Direct discovery of GW

- Probable sources
  - Binary neutron star coalescence
  - Binary black holes mergers, supernovae, pulsars

- Horizon (Virgo+)
  - BNS: 150 Mpc (optimal orientation)
  - BBH: 750 Mpc (optimal orientation)



- BNS Rates: (most likely and 95% interval)
  - Initial Virgo (30Mpc) 1/100yr (1/500 - 1/25 yr)
  - Enhanced LIGO (60Mpc) 1/10yr (1/50 - 1/2.5yr)
  - 2009: Virgo+ limit (150Mpc) 1.2/yr (1/4 - 5/yr)
  - 2014: Advanced detectors (350Mpc) 40/yr (8 - 160/yr)

Astronomy: we know GW sources exist!

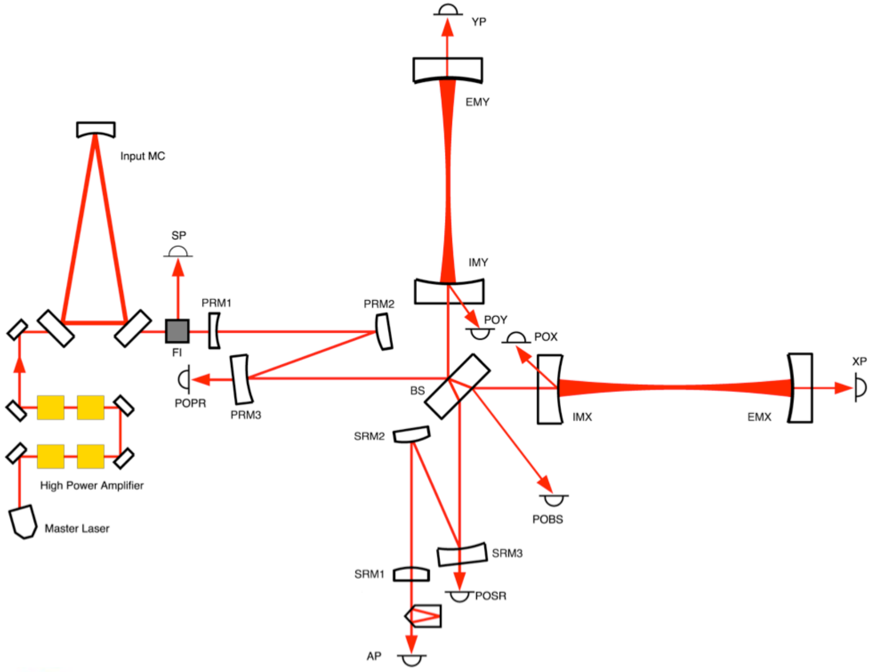
Kalogera et al; astro-ph/0312101; Model 6

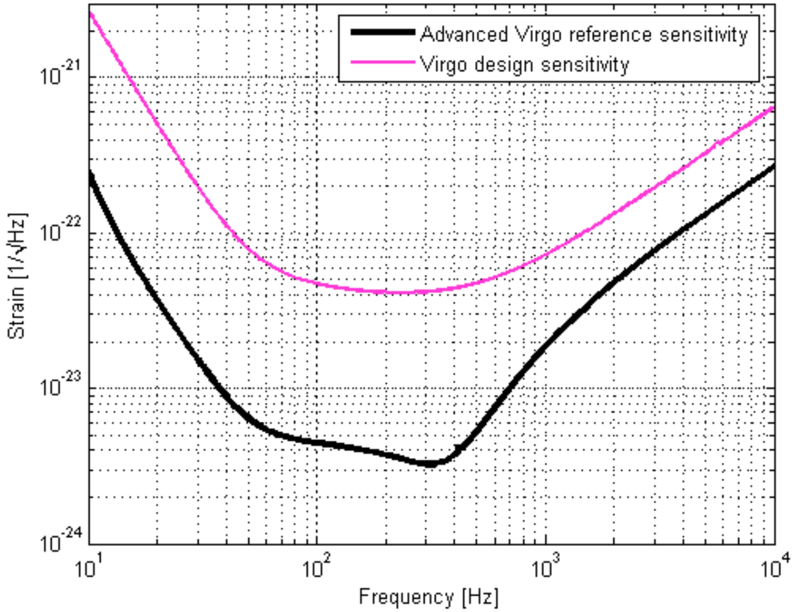
- BBH and other sources rates are more difficult to predict

Advanced Virgo (AdV)

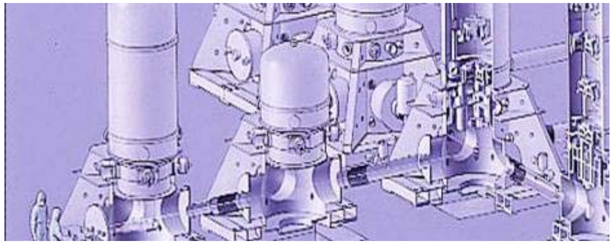
PROJECT GOALS

- Upgrade Virgo to a 2nd generation detector. Sensitivity: 10x better than Virgo
- Be part of the 2nd generation GW detectors network. Timeline: in data taking with Advanced LIGO

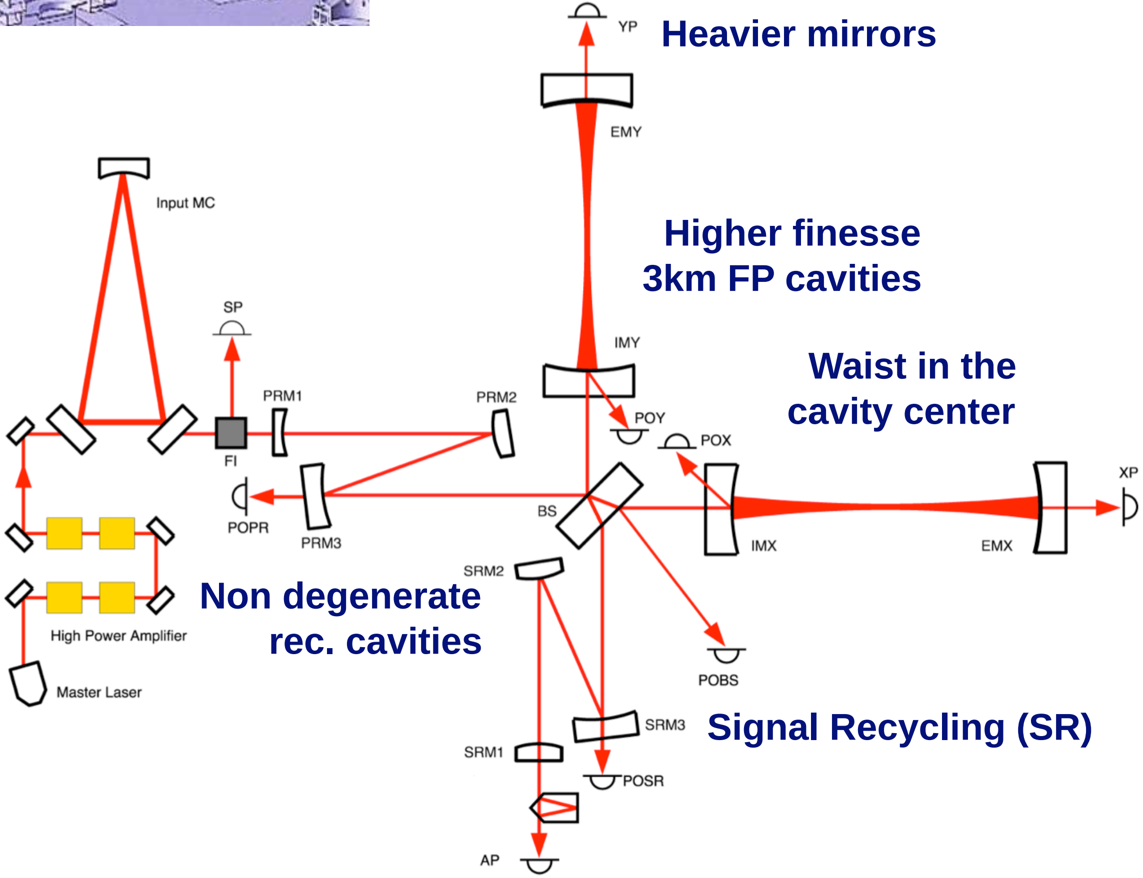




Main required upgrades



Larger central links
Cryotraps



Heavier mirrors

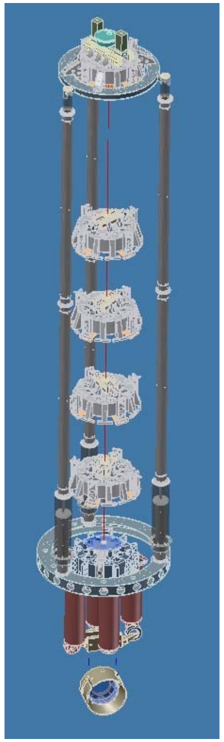
Higher finesse
3km FP cavities

Waist in the
cavity center

200W laser

Non degenerate
rec. cavities

Signal Recycling (SR)

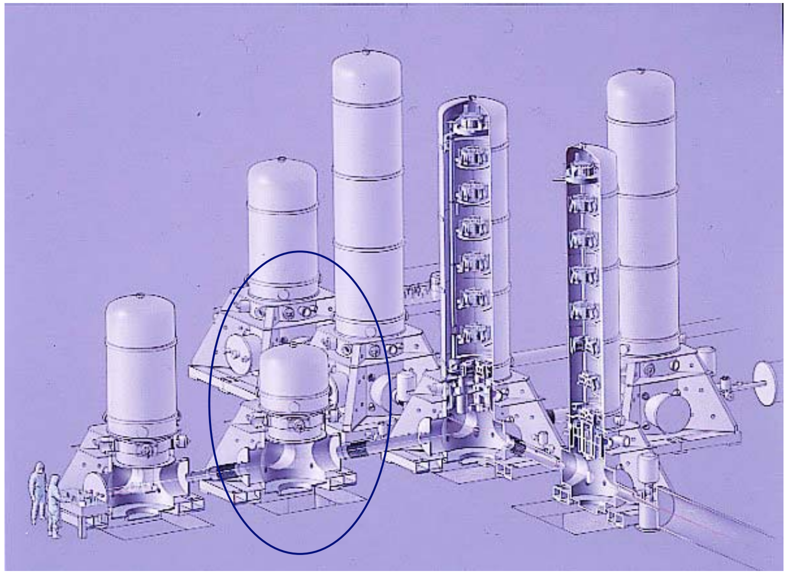


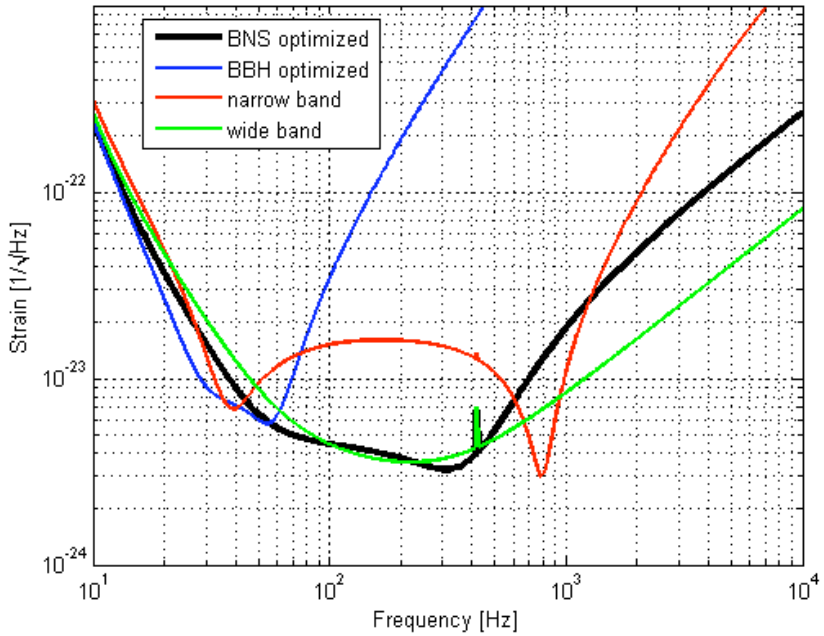
Monolithic
suspensions

Optical configuration - SR

SIGNAL RECYCLING

- **WHY?:** Allows shaping of the detector sensitivity
- Requires one more SA (tower base available)
- Adds complexity, commissioning more difficult

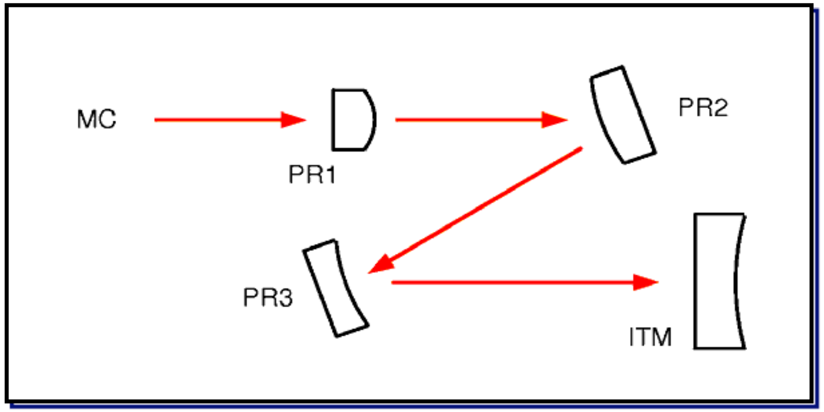




Optical configurations – NDRC

NON DEGENERATE RECYCLING CAVITY

- **WHY?:** Avoid high order modes to be resonant
  - much “cleaner” ITF dynamics
  - reduces sensitivity to misalignments, thermal effects, ROC errors
  - provides more control signals
- Requires:
  - larger vacuum links
  - extra seismic isolation for injection and detection benches
- Promises to simplify commissioning



Optical configuration – spot size

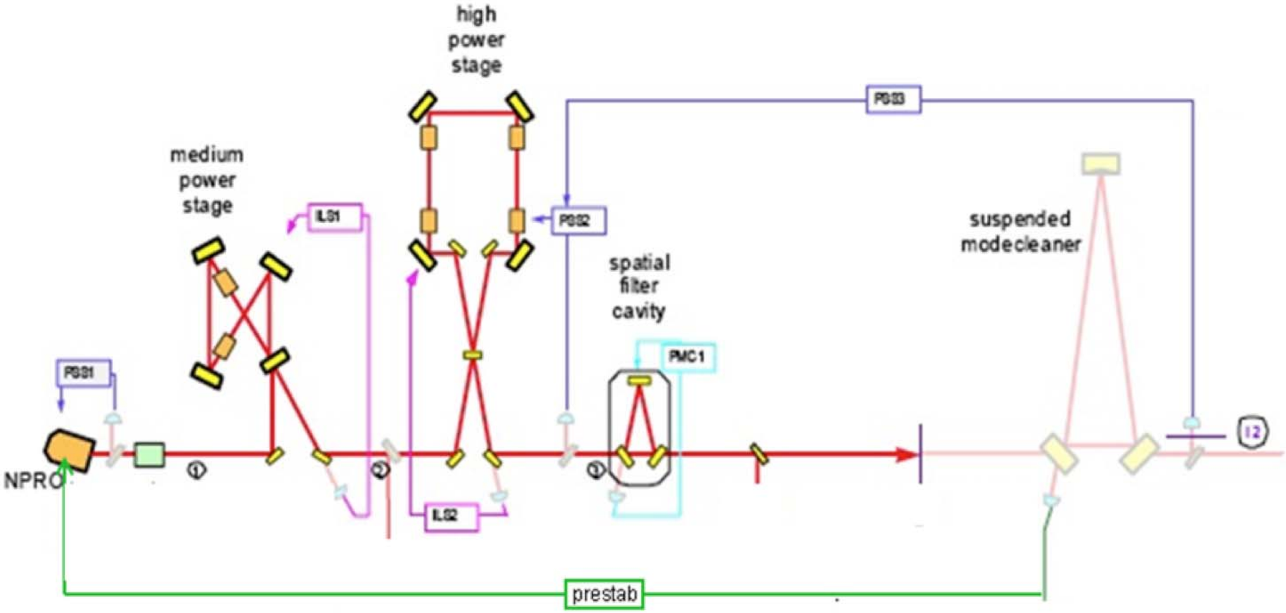
LARGER SPOT SIZE

- **WHY?:** Reduces mirror thermal noise and thermal effects on input mirrors
- Requires larger vacuum links and larger beam splitter

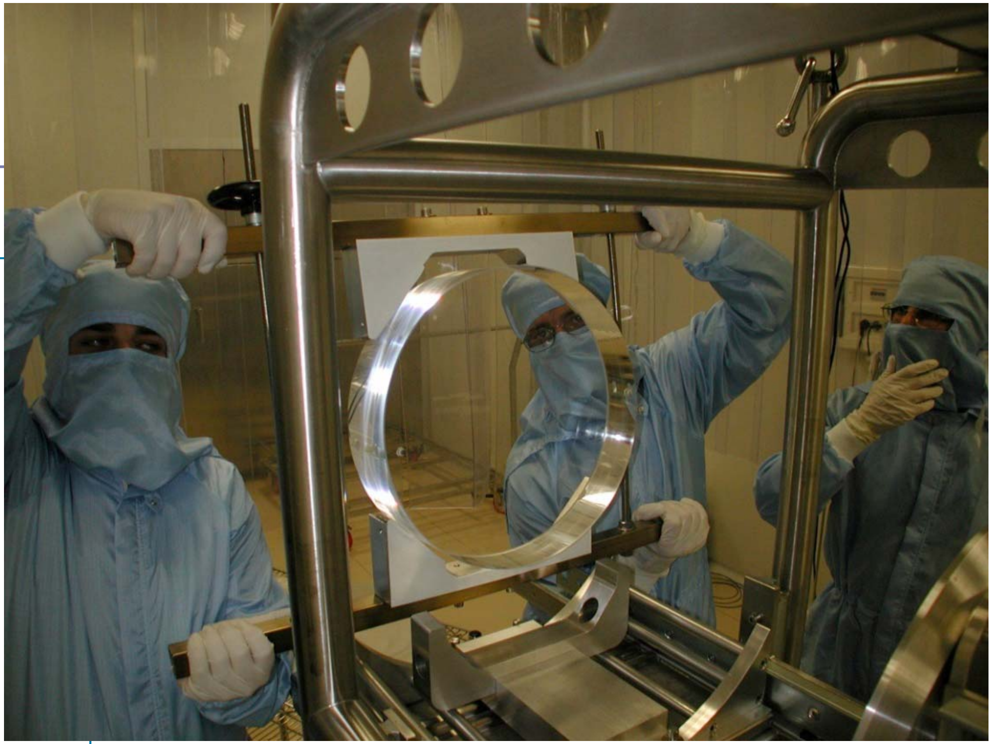
$$h_{coat}(f) = \frac{1}{\bigcirc\!\!\!\!\!\;r_0}\sqrt{\frac{4k_BTd}{\pi^2 f\,Y}\phi_{eff}}$$

Pre-stabilized laser

- AdV laser to provide up to 200 W
- High power stage bases on the LZH design for the Adv LIGO laser
- Pre-stabilized in frequency and amplitude



Mirrors

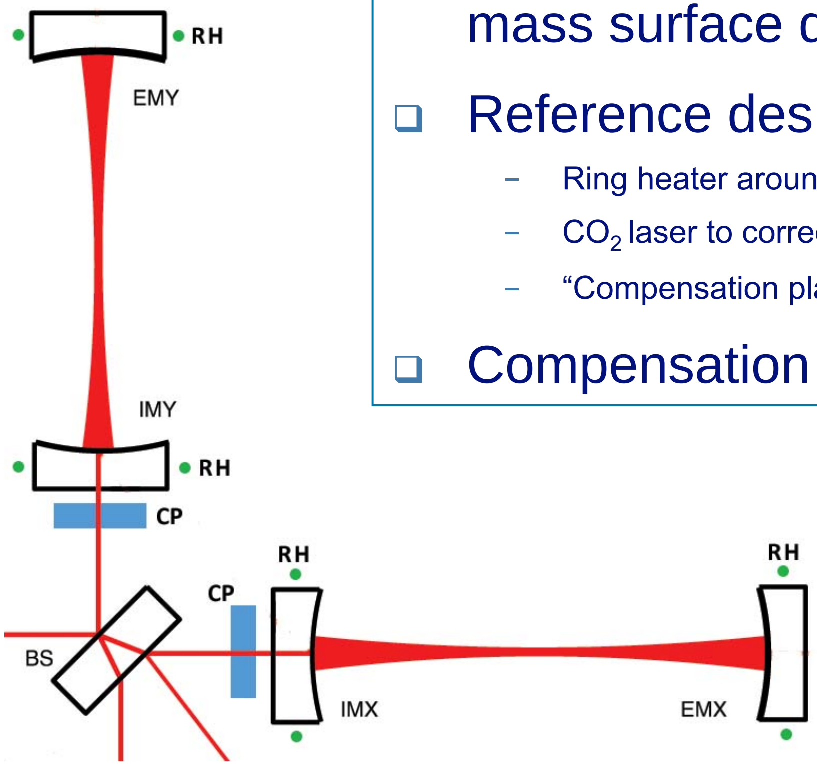


HEAVIER TEST MASSES

- **WHY?** Cope with radiation pressure
- Require payload modification and silica fibers optimization
- Reference design:
  - 35 cm Ø, 20 cm thick, 42 Kg FP mirrors
  - Flatness requirements: 0.5 nm
  - Larger BS
  - 2010 state of the art coating
- Corrective coating might allow to further improve the flatness and give more flexibility
- 63 kg mirrors considered
  - technically feasible, though payload modifications more risky
  - science gain limited by newtonian/susp thermal noises

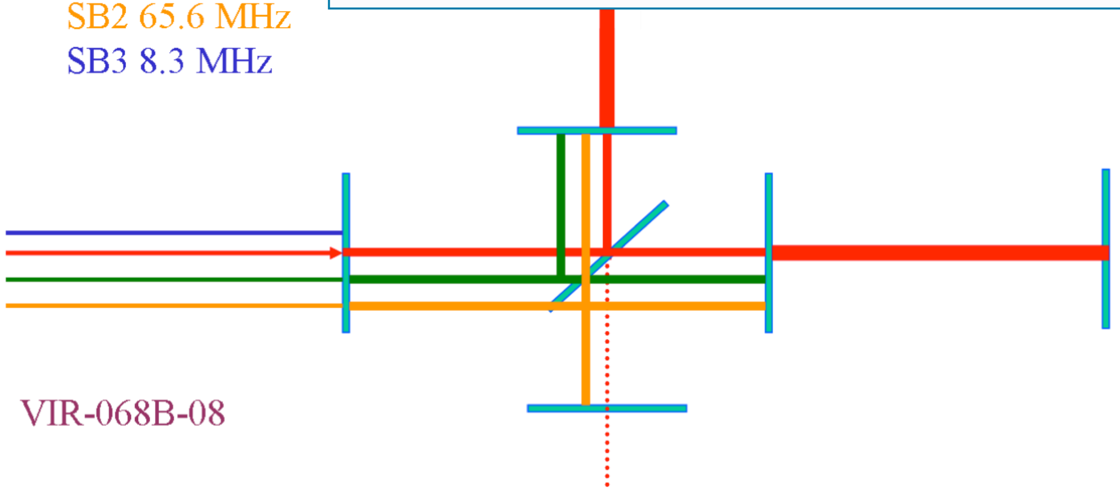
Thermal compensation

- **WHY?** Compensate for wavefront distorsion and test mass surface deformation
- Reference design:
  - Ring heater around test masses to correct for ROC
  - CO_2 laser to correct for wavefront distorsion on recycling cavities
  - "Compensation plates" needed in front of input test masses
- Compensation plates to be suspended from SA



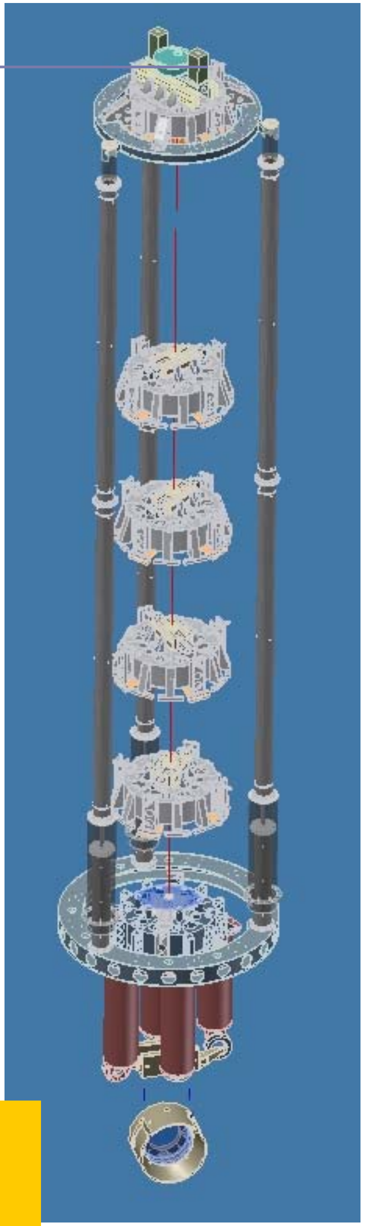
Sensing and control

- Reference design:
  - Auxiliary laser to lock the high finesse cavities
  - Extended Variable Finesse technique for full lock
  - Requirements, a set of cavity lengths and mod. frequencies defined
  - Linear control scheme defined
- The reference control strategy requires to move all the long towers in the central building



VIR-068B-08

Superattenuator

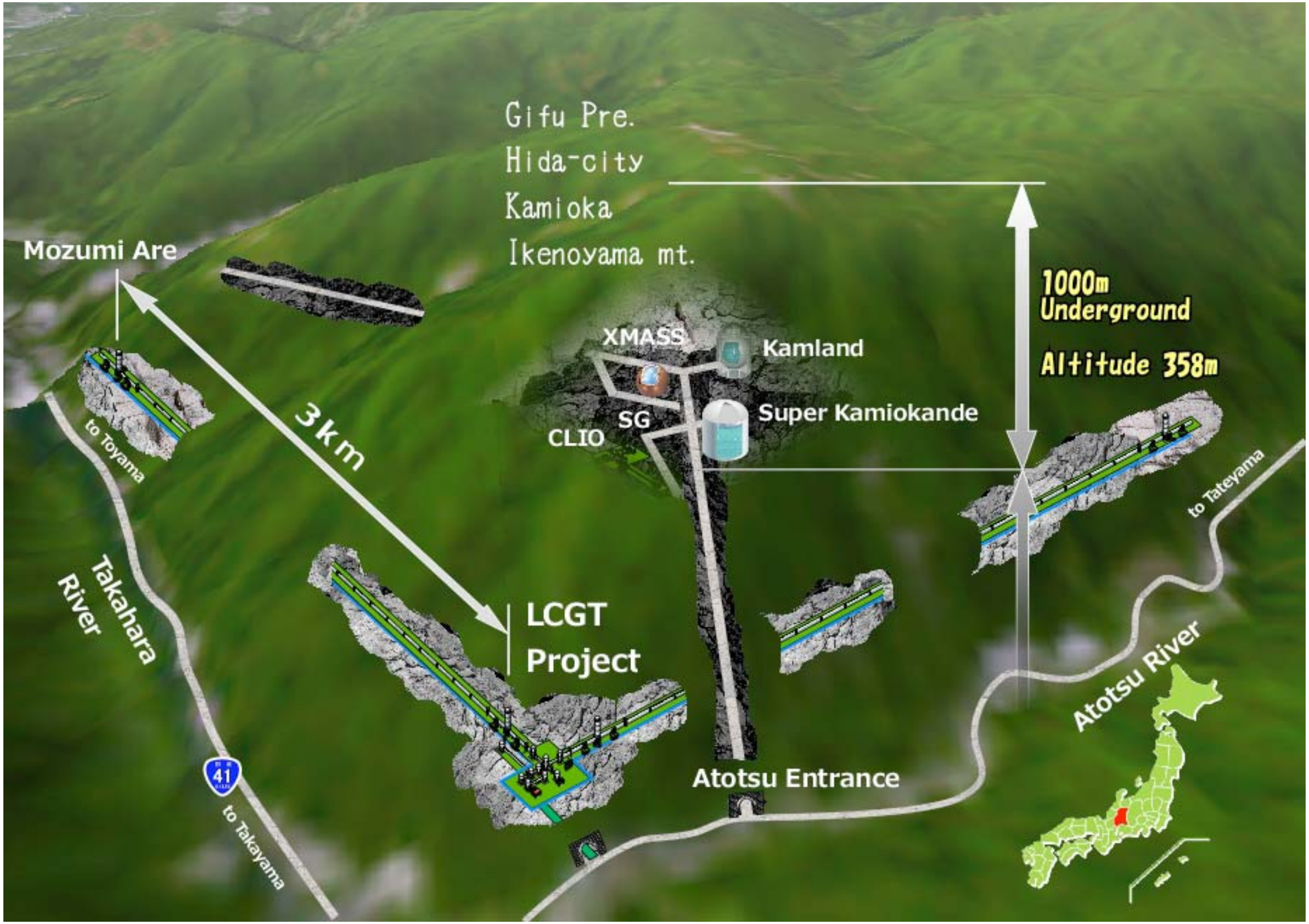


- Vibration isolation provided by the SA is compliant with AdV sensitivity
- Main foreseen change: tilt control of the inverted pendulum (inertial platform controlled in 6 d.o.f.)
- Tilt control allows to cope with wind generated tilt noise, that can spoil the inertial damping performance with bad weather conditions
- Tilt actuation already foreseen in the inverted pendulum design (room for PZT at the base of the legs)

For LIGO and Virgo, all this (and more) is needed to gain our factor 10 in sensitivity!!!

Other GW initiatives

Underground of Kamioka research facility



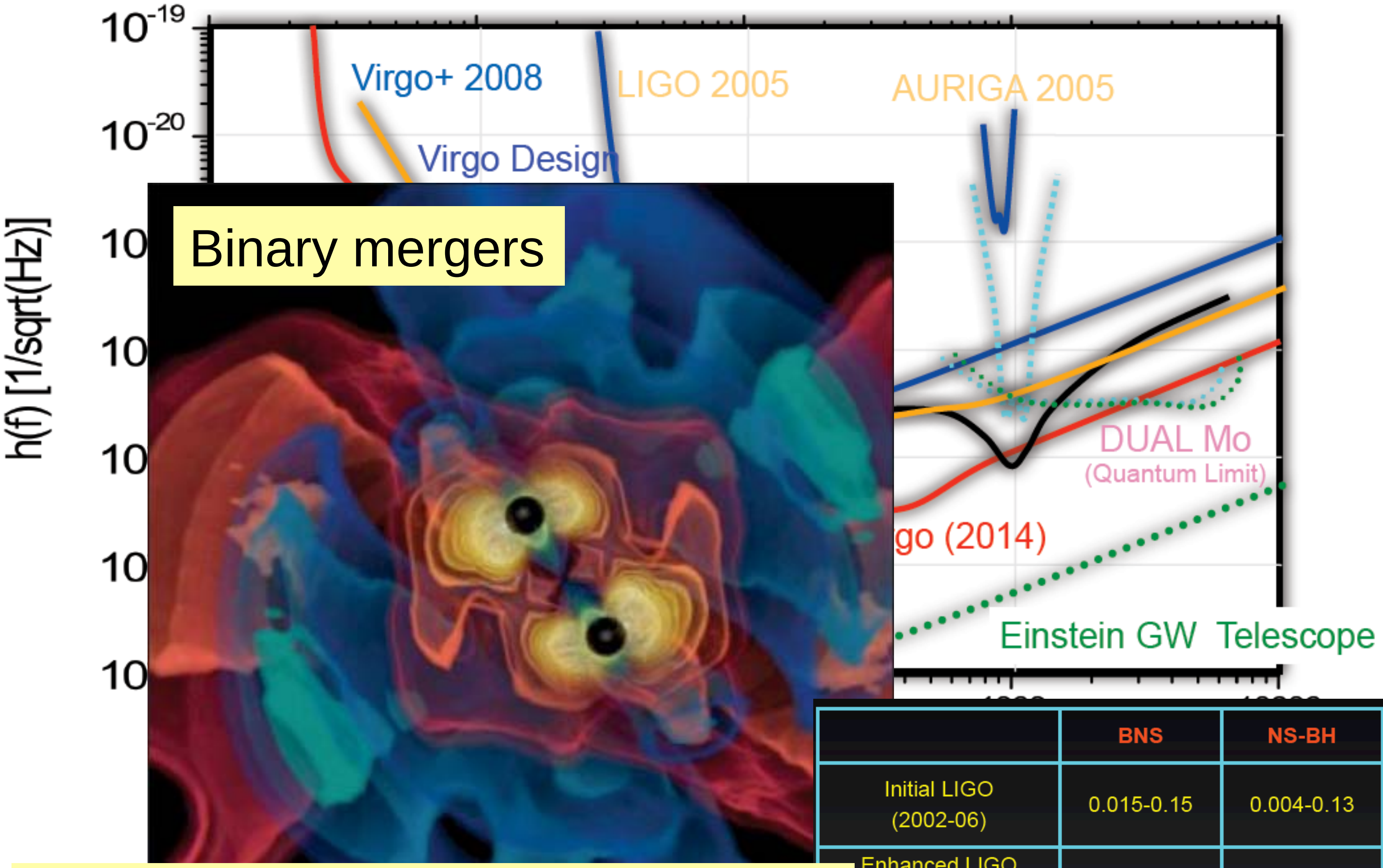
Design Study Proposal approved by EU within FP7

Large part of the European GW community involved

EGO, INFN, MPI, CNRS, Nikhef, Univ. Birmingham, Cardiff, Glasgow

Recommended in Aspera / Appec roadmap

Expected sensitivities – rates

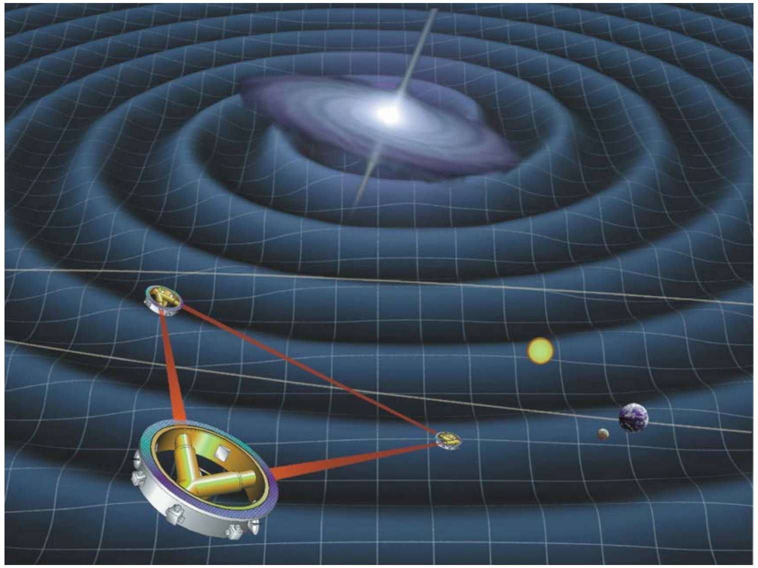


Binary mergers

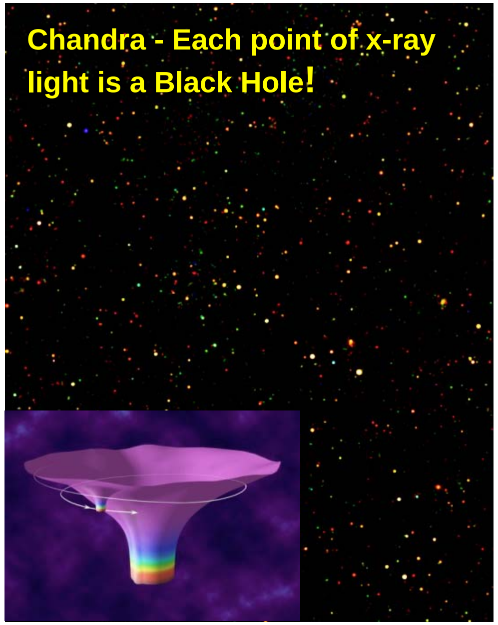
	BNS	NS-BH	BBH
Initial LIGO (2002-06)	0.015-0.15	0.004-0.13	0.01-1.7
Enhanced LIGO x2 sensitivity (2009-10)	0.15-1.5	0.04-1.4	0.11-18
Advanced LIGO 2 sensitivity (2014+)	20-200	5.7-190	16-2700

Einstein Telescope: ~1000 per day
GW observatory

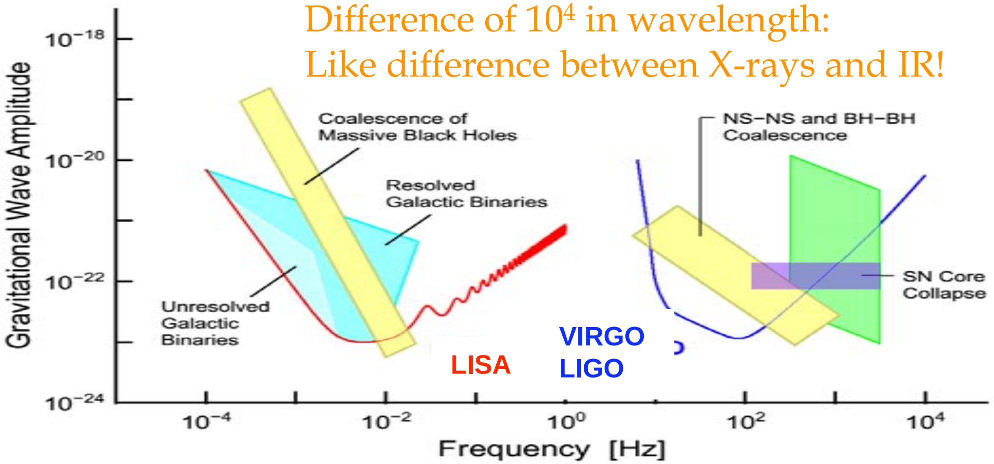
GW antenna in space - LISA



- *3 spacecraft in Earth-trailing solar orbit separated by 5 x10^6 km.*
- *Measure changes in distance between fiducial masses in each spacecraft*
- *Partnership between NASA and ESA*
- *Launch date ~2018+*



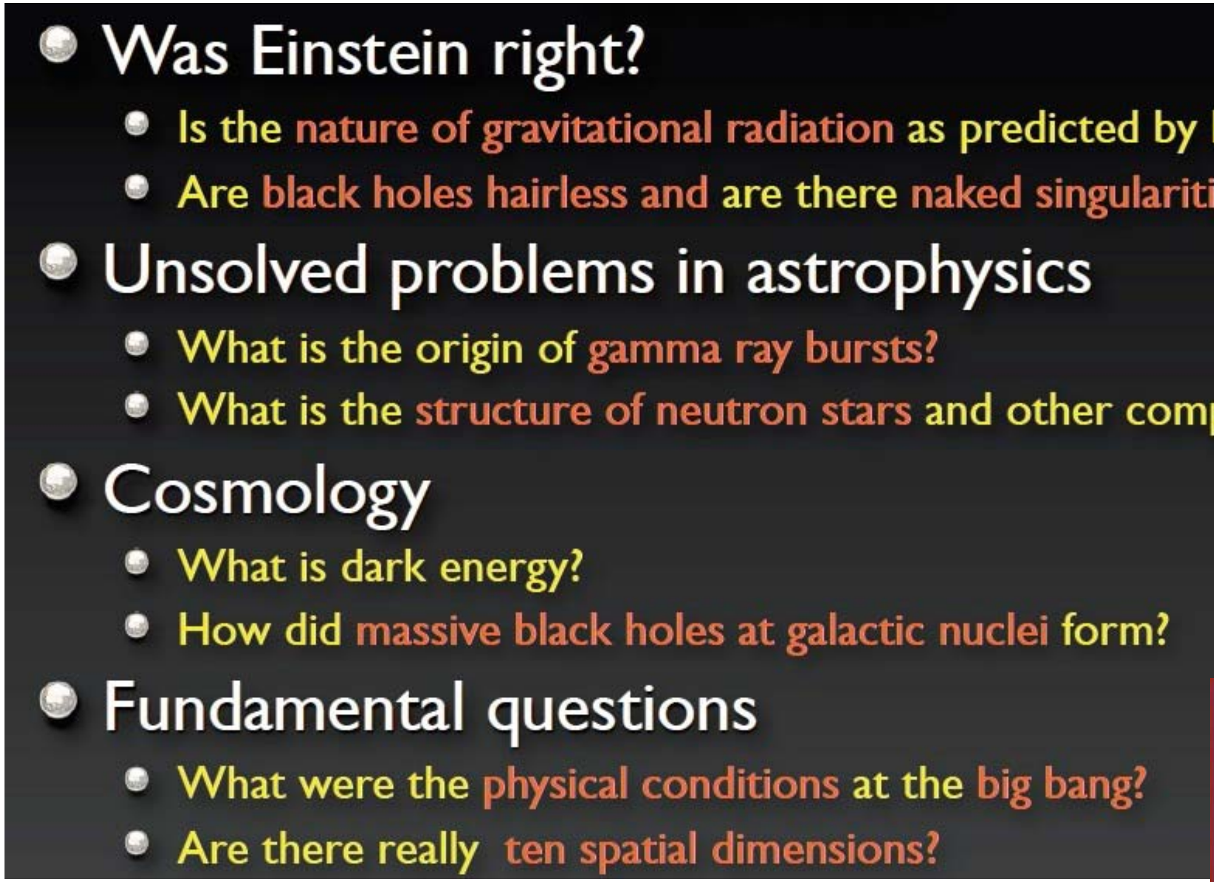
Chandra - Each point of x-ray light is a Black Hole!



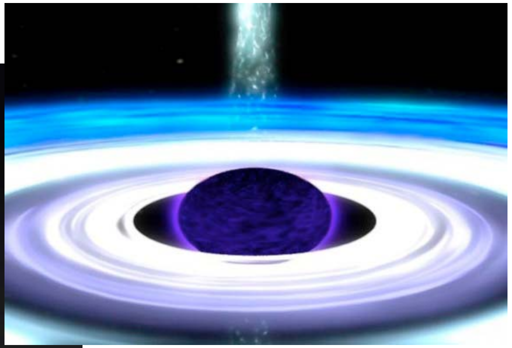
Difference of 10^4 in wavelength:
Like difference between X-rays and IR!

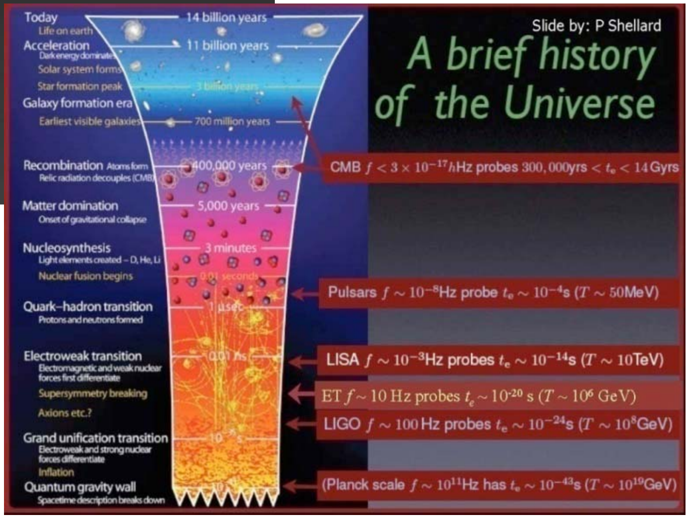
LISA will see all the compact white-dwarf and neutron-star binaries in the Galaxy (Nelemans)

Science goals

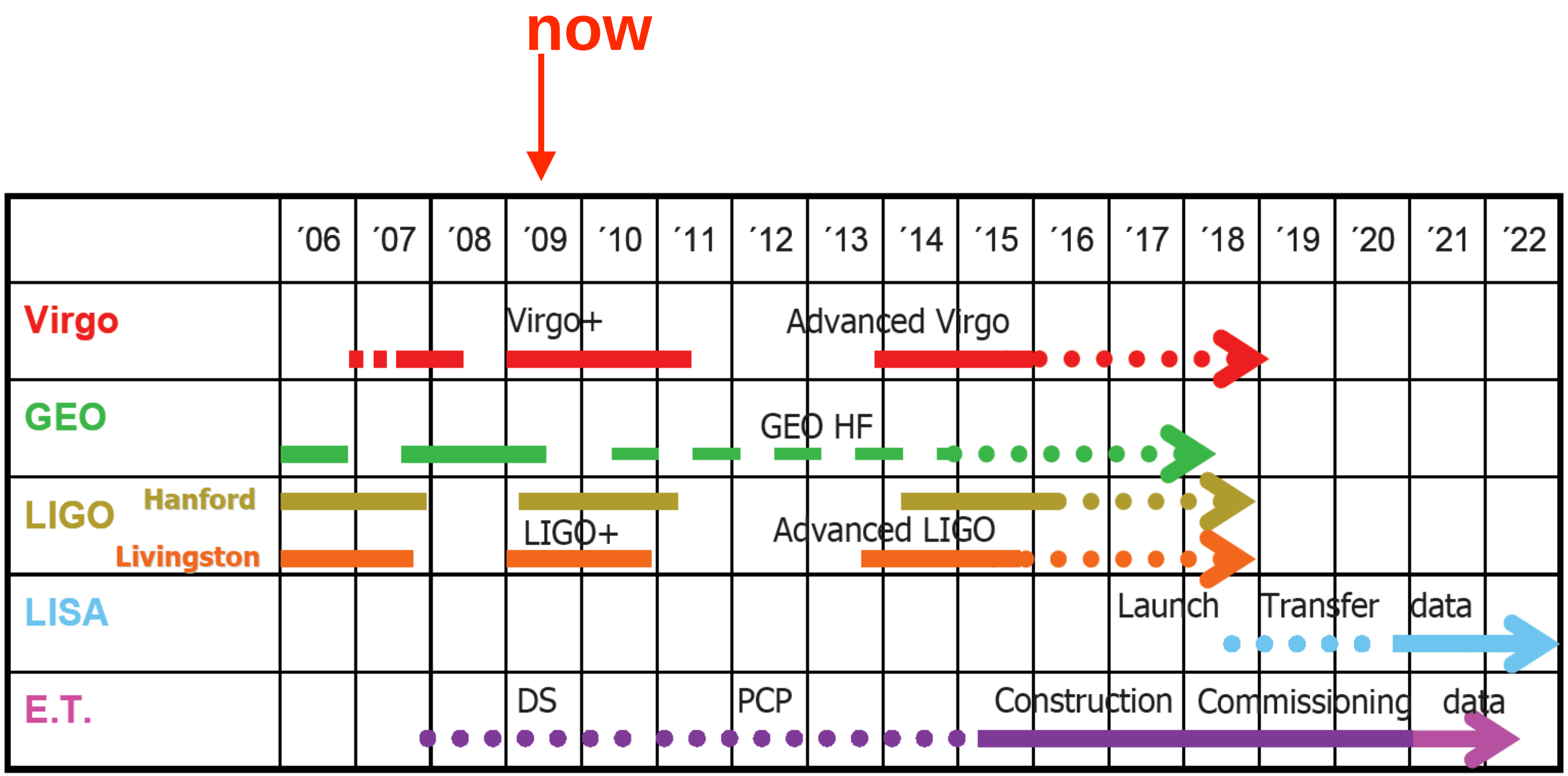


- Was Einstein right?
  - Is the nature of gravitational radiation as predicted by Einstein?
  - Are black holes hairless and are there naked singularities?
- Unsolved problems in astrophysics
  - What is the origin of gamma ray bursts?
  - What is the structure of neutron stars and other compact objects?
- Cosmology
  - What is dark energy?
  - How did massive black holes at galactic nuclei form?
- Fundamental questions
  - What were the physical conditions at the big bang?
  - Are there really ten spatial dimensions?





Timelines Towards Construction



Summary

- Gravitational waves will provide valuable information, complementary to photons, neutrino's and charged cosmic rays
  - Weak probe, small attenuation, probe the dynamics
- Sensitivity of LIGO and Virgo detectors rapidly improving
  - Advanced detectors well underway
- Future GW initiatives under study
  - Einstein Telescope, LISA, LCGT, Decigo, BBO,