The Einstein Telescope: a 3rd generation gravitational wave observatory

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On behalf of the ET Design Study Team
http://www.et-gw.eu/

Talk Outline

- Introduction to the Gravitational Wave (GW) search
- Gravitational wave detectors
  - Today
  - Immediate future
- 3rd generation of gravitational wave observatories
  - The Einstein Telescope
- Conclusions

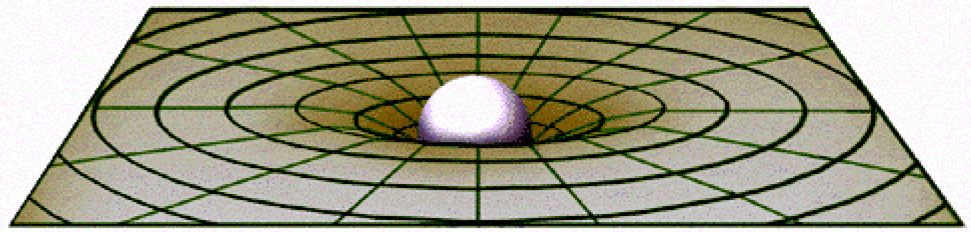
General Relativity and GW

- GW are predicted by the Einstein General Relativity (GR) theory
  - Formal treatment of the GW in GR is beyond the scope of this talk and only the aspects important for the GW detection will be considered

Einstein field equation links the source of the space-time deformation ($T_{\mu\nu}$ Energy-impulse tensor)

$$T_{\mu\nu} = -\frac{c^4}{8\pi G} G_{\mu\nu}$$

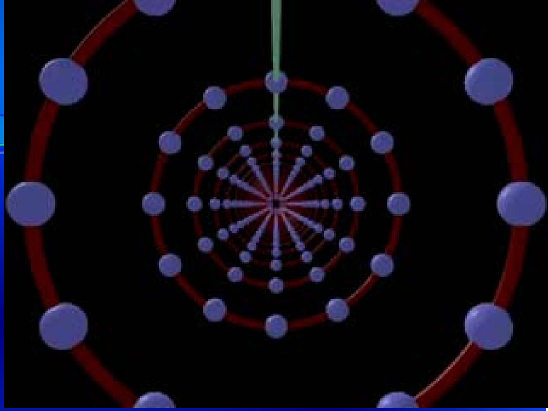
to the effect of the deformation ($G_{\mu\nu}$ the deformation tensor)



Far from the big masses Einstein field equation admits (linear approximation) wave solution (small perturbation of the background geometry)

$$\mathbf{g} = \eta + \mathbf{h} \text{ with } \left|h_{\mu\nu}\right| << 1 \Rightarrow \left(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2}\right) h_{\mu\nu} = 0$$

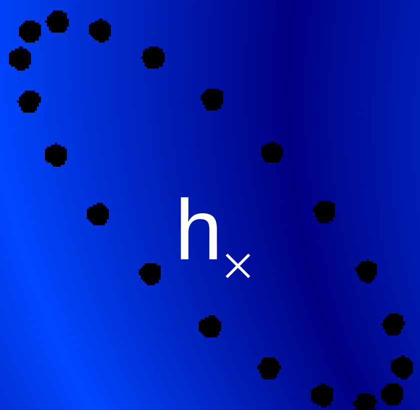
Gravitational Waves

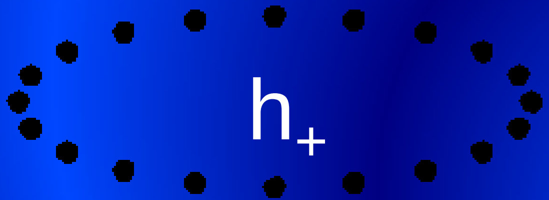


- Gravitational waves are a perturbation of the space-time geometry
- They present two polarizations

$$\mathbf{h}(z,t) = e^{i(\omega t - kz)} \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

- The effect of GWs on a mass distribution is the modulation of the reciprocal distance of the masses





Let quantify the “deformation”

- Should we expect this?
- Coupling constant (fundamental interactions)

strong	*e.m.*	*weak*	*gravity*
0.1	1/137	10^{-5}	10^{-39}

- Or “space-time” rigidity (Naïf):

$$G_{\mu\nu} = -\frac{8\pi G}{c^4} T_{\mu\nu} \quad \Rightarrow \frac{8\pi G}{c^4} = 4.8 \cdot 10^{42}\, N$$

$$\sigma_{ij} = C_{ijkl}\varepsilon_{kl} \quad \Rightarrow \quad Y_{Steel} \approx 2 \times 10^{11}\, Pa$$

- Very energetic phenomena in the Universe could cause only faint deformations of the space-time

Let quantify the "deformation"

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- The amplitude of the space-time deformation is:

$$h_{\mu\nu} = \frac{2G}{c^4} \cdot \frac{1}{r} \ddot{Q}_{\mu\nu}$$

Where $Q_{\mu\nu}$ is the quadrupolar moment of the GW source

and r is the distance between the detector and the GW source

- Let suppose to have a system of 2 coalescing neutron stars, located in the Virgo cluster (r~10Mpc):

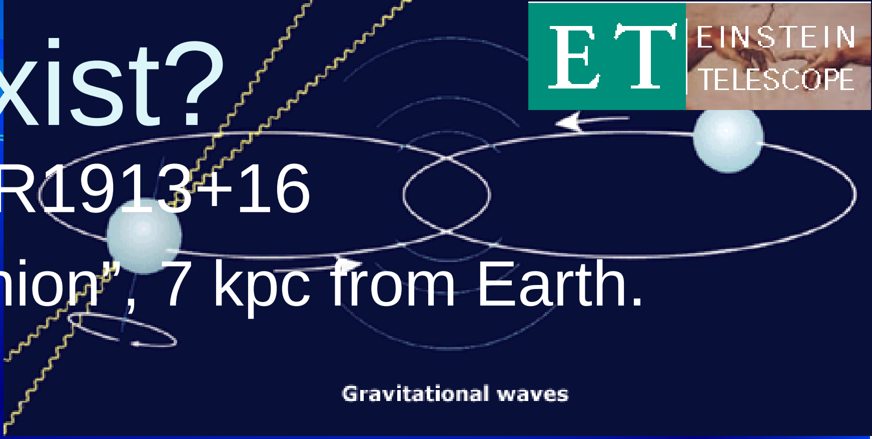
$$h \approx 10^{-21} - 10^{-22}$$

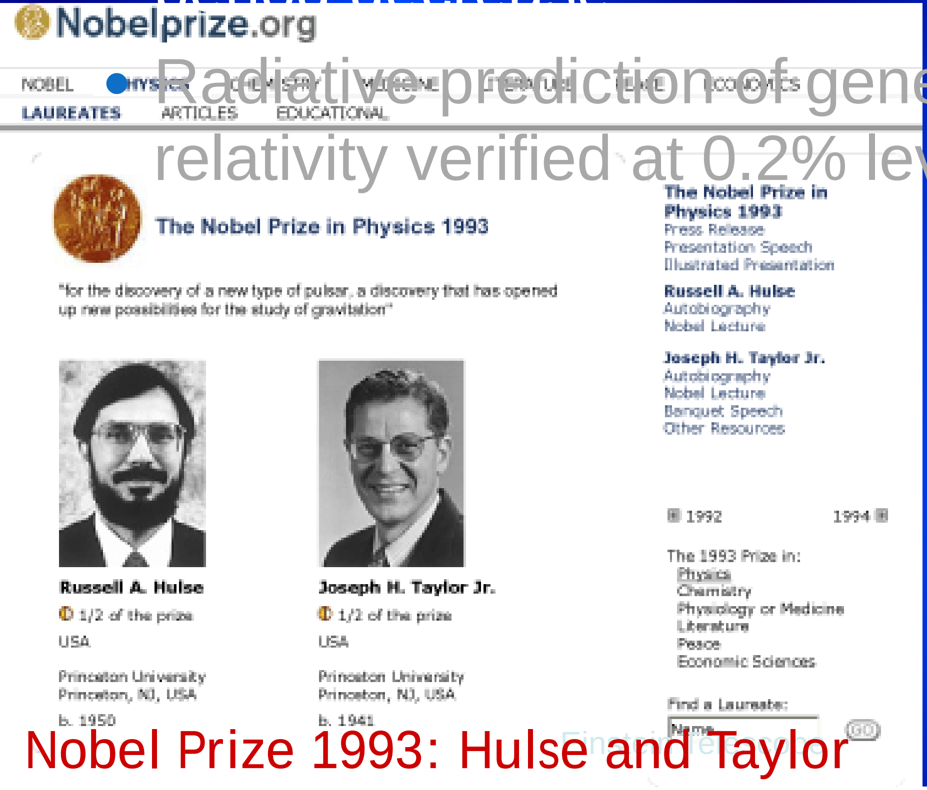
$$\left.\begin{array}{l} \delta L \approx \frac{h}{2} \cdot L_0 \\ L_0 \approx 10^3 m \end{array}\right\} \Rightarrow \boxed{\delta L \approx 10^{-18} - 10^{-19} m}$$

Extremely challenging for the detectors

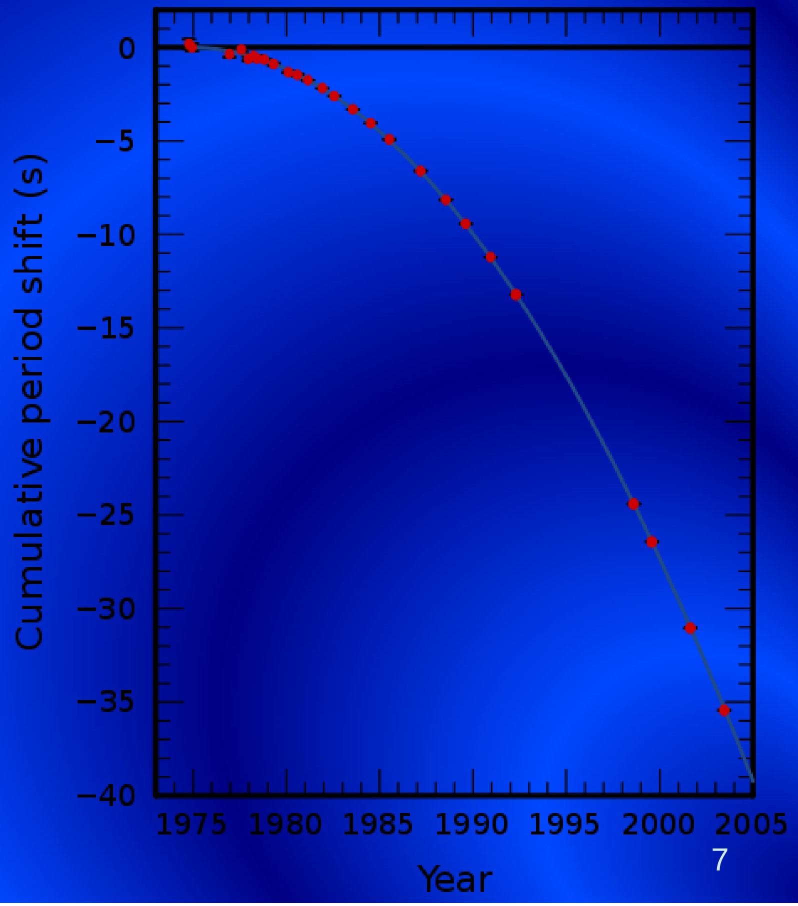
But, GWs really exist?

- Neutron star binary system: PSR1913+16
  - Pulsar bound to a “dark companion”, 7 kpc from Earth.
  - Relativistic clock: $v_{max}/c \sim 10^{-3}$
  - GR predicts such a system to loose energy via GW emission: orbital period decrease





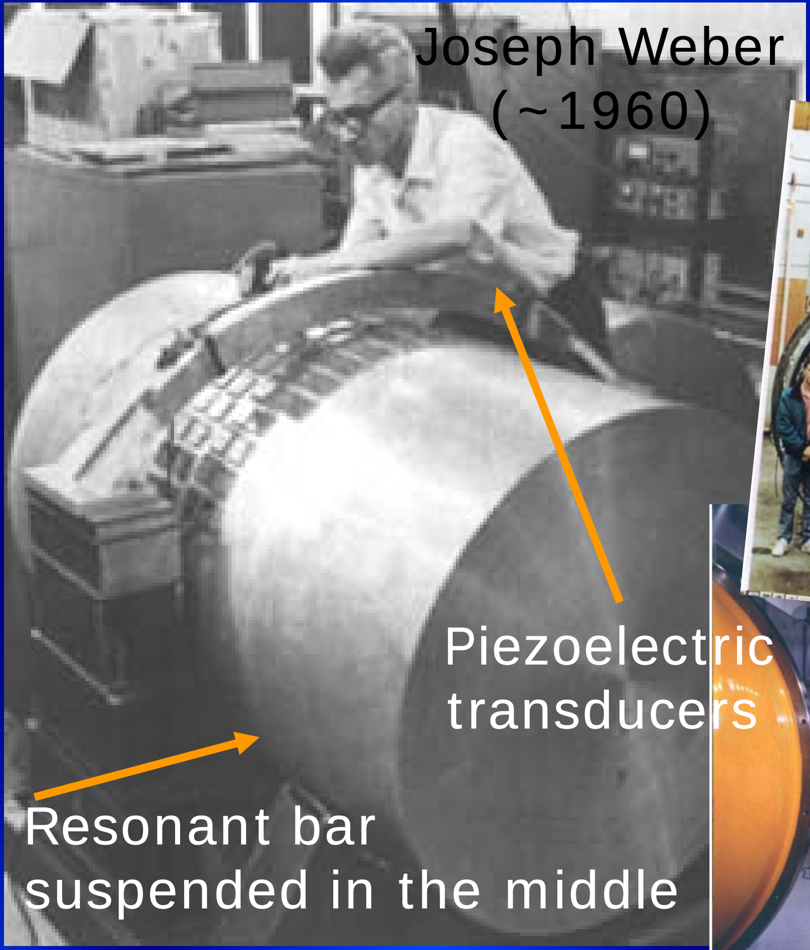
Radiative prediction of general relativity verified at 0.2% level



Nobel Prize 1993: Hulse and Taylor

GW detectors: the resonant bars

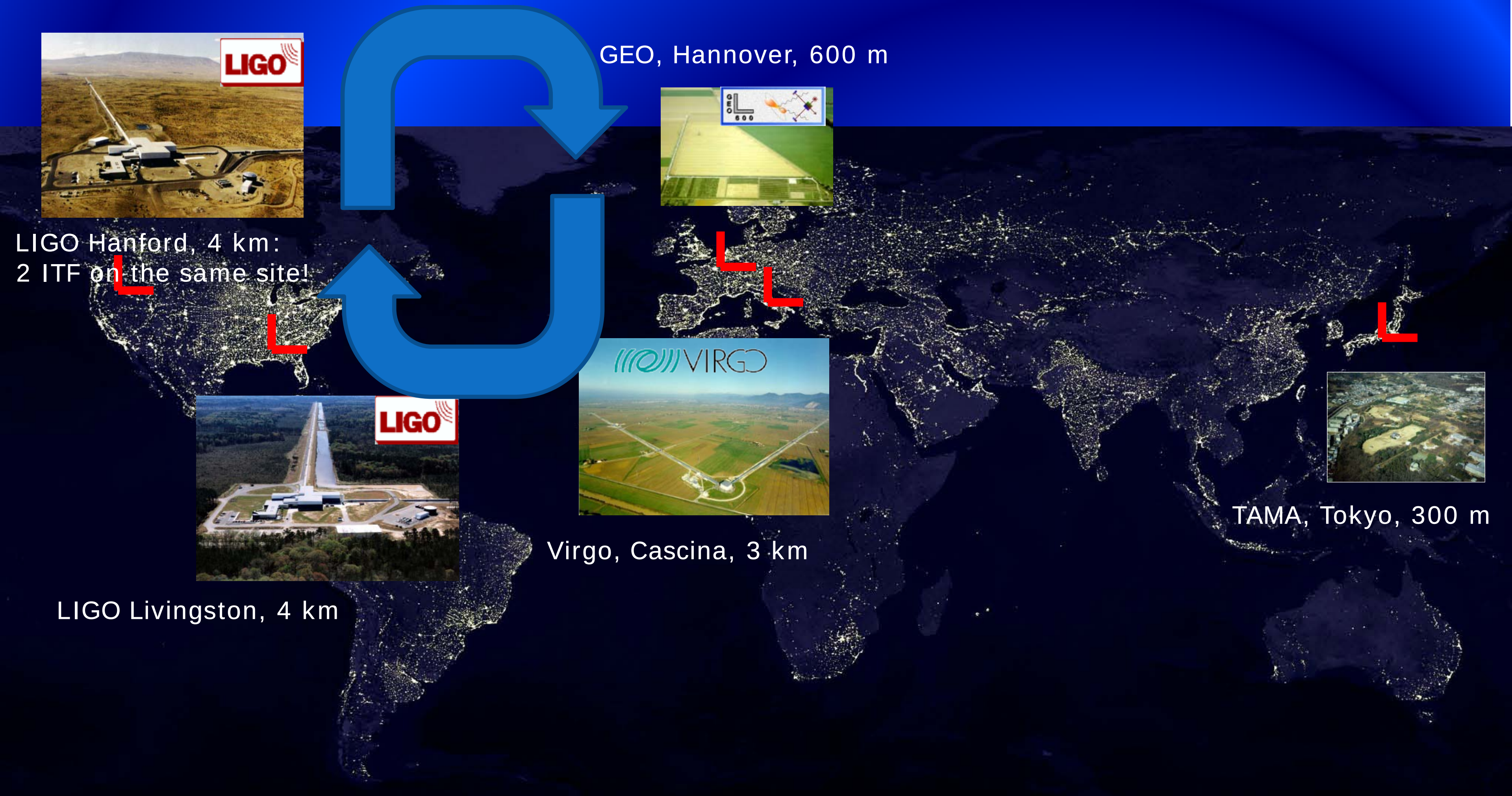
- The epoch of the GW detectors began with the resonant bars



- Then a network of cryogenic bars has been developed in the past

GW interferometric detectors

- Currently, a network of detectors is active in the World

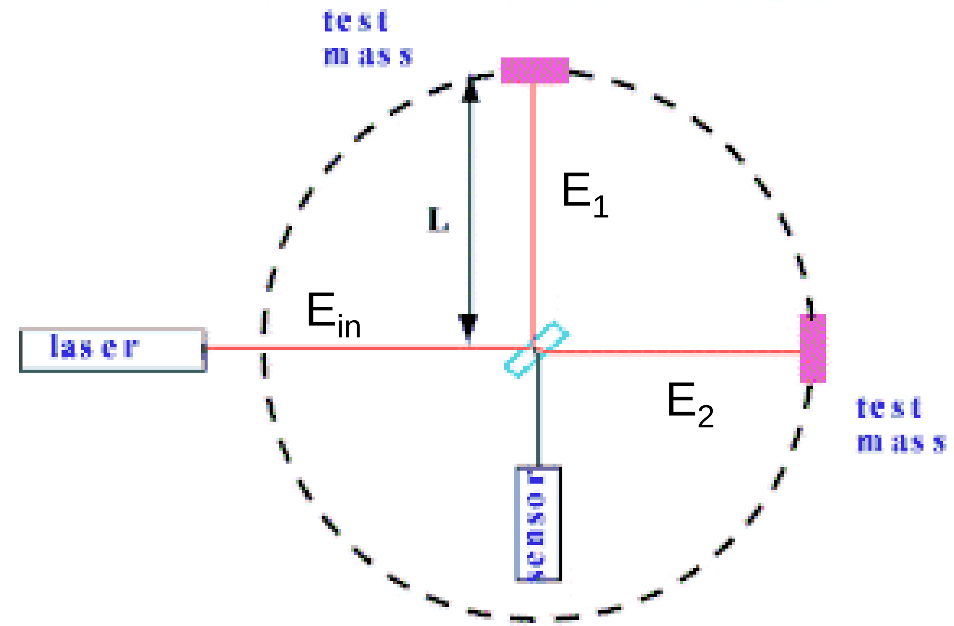


Working principle

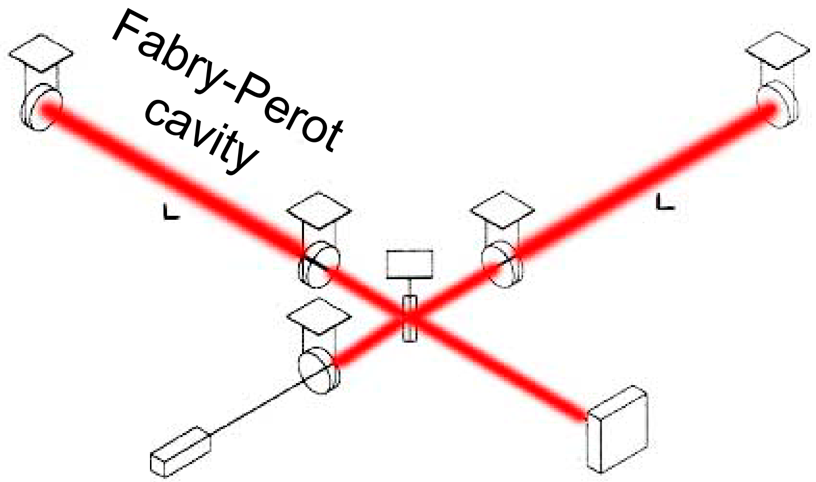
- The quadrupolar nature of the GW makes the Michelson interferometer a "natural" GW detector

$$\delta L \approx \frac{h}{2} \cdot L_0$$

$10^2 \leq L_0 \leq 10^4$ m in terrestrial detectors



- We need a "trick" to build ~100km long detectors on the Earth

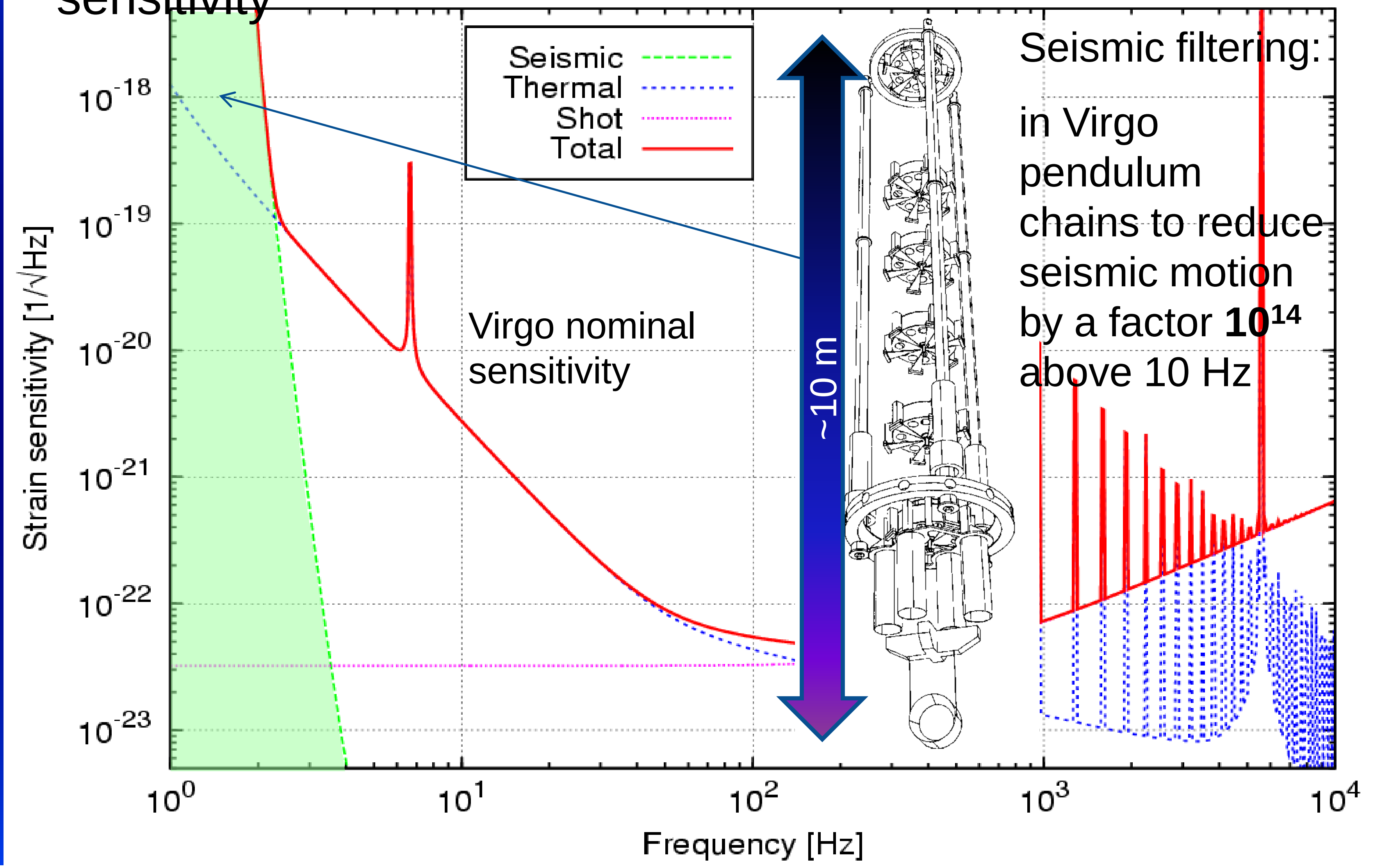


Effective length:

$$L' = L_0 \times \frac{2F}{\pi}$$

Detector sensitivity

- The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity



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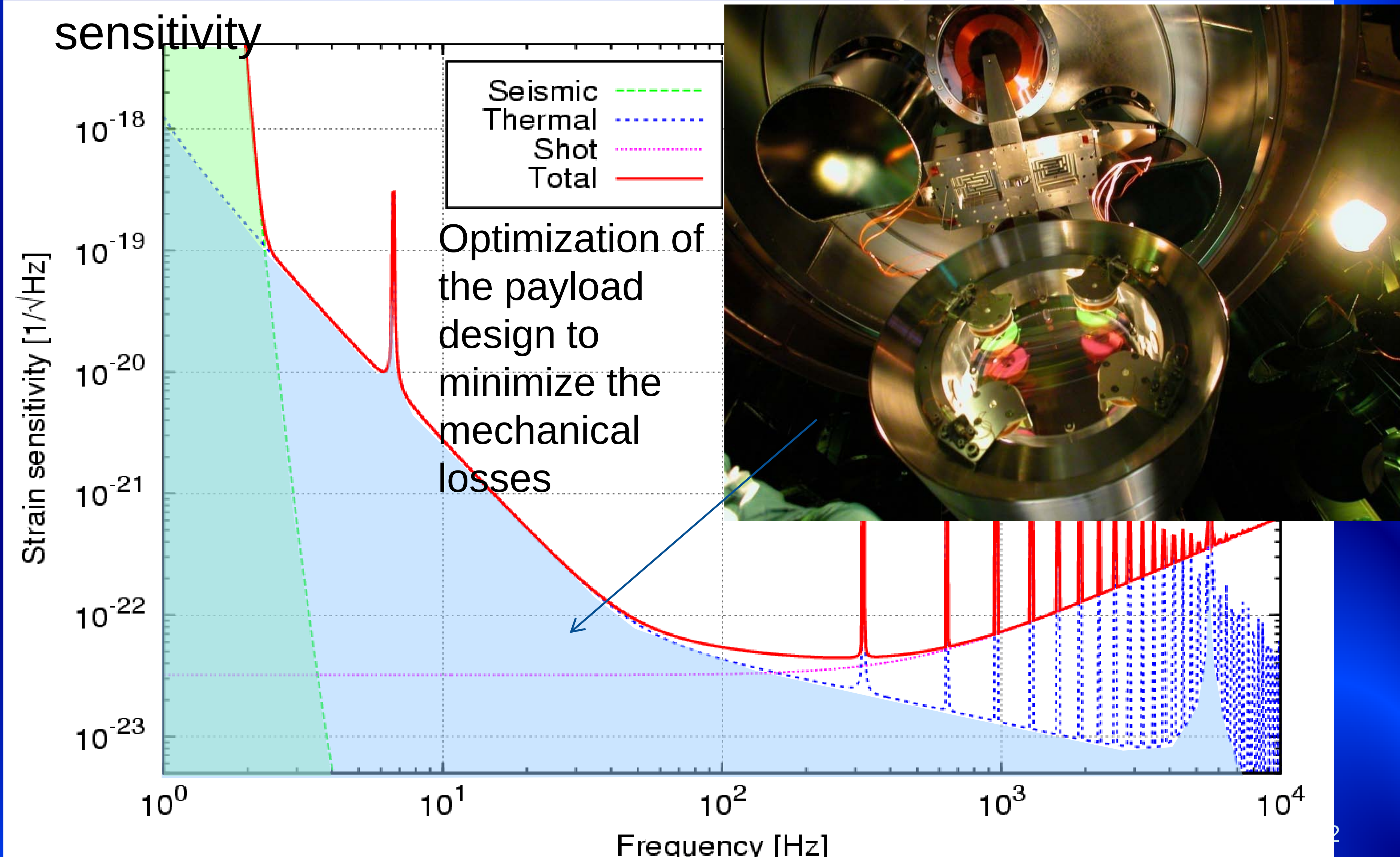
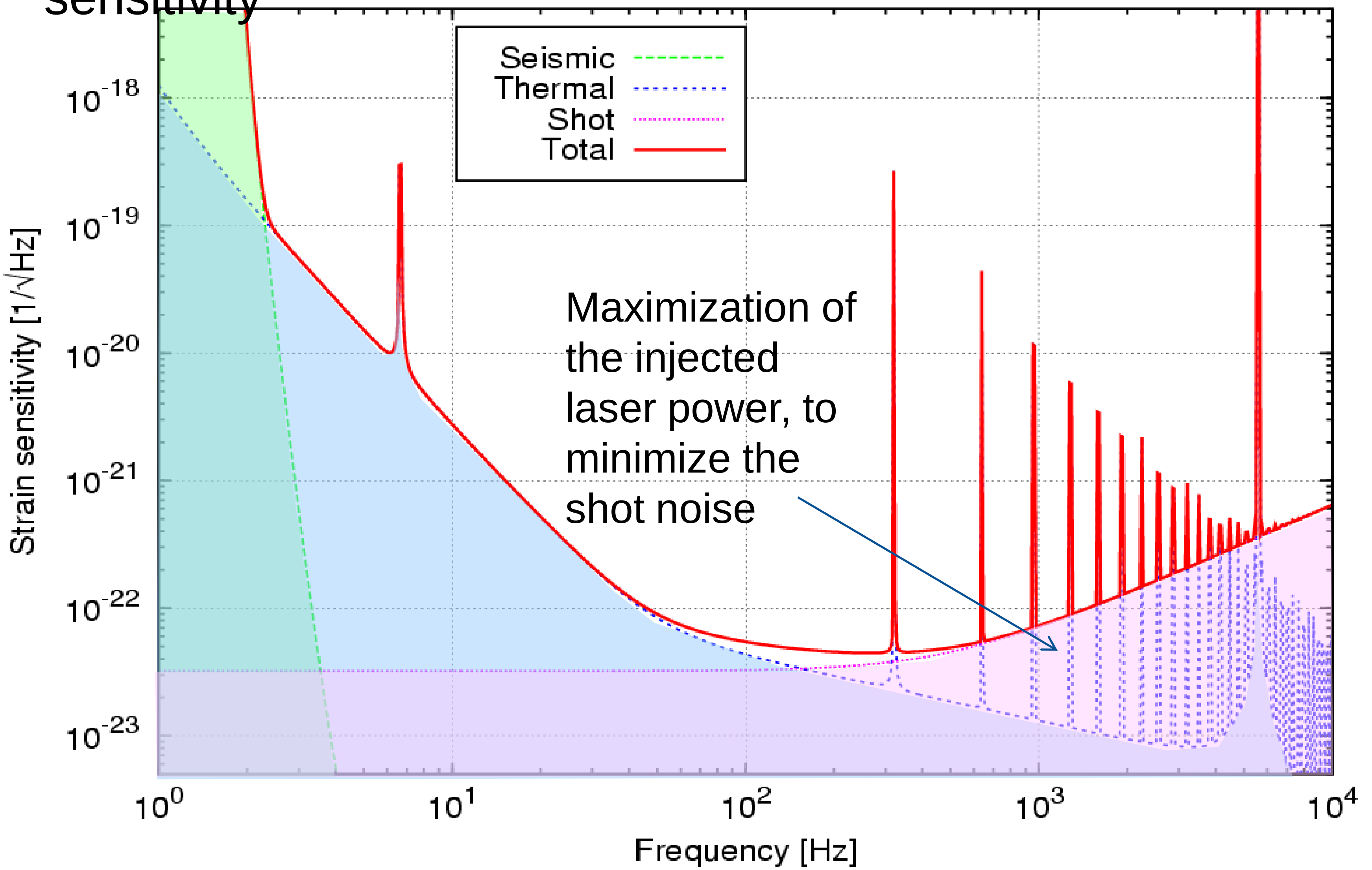


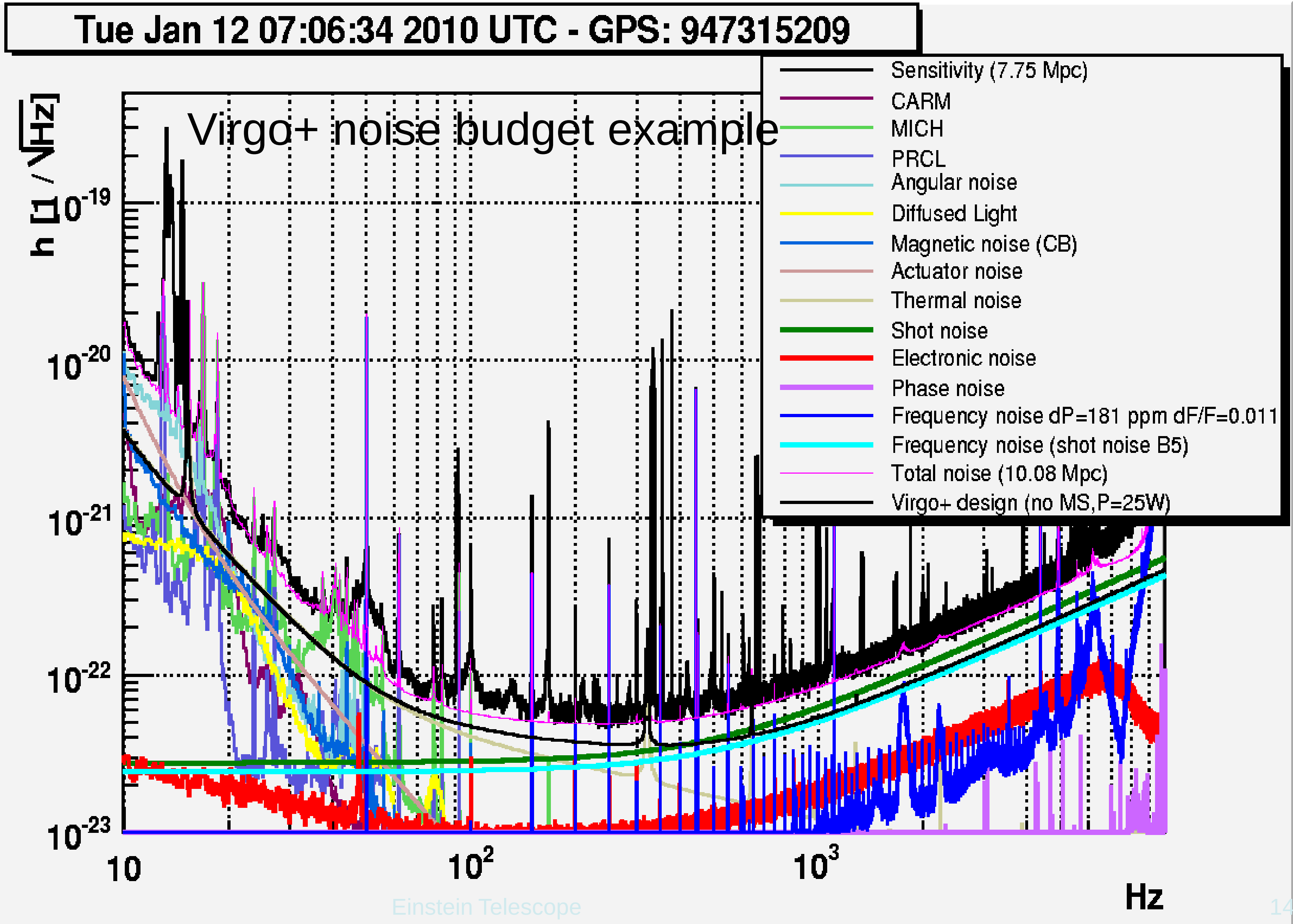
Optimization of the payload design to minimize the mechanical losses

Detector sensitivity

- The faint space-time deformation measurement must compete with a series of noise sources that are spoiling the detector sensitivity



Sensitivity: real life



GW interferometer past evolution

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- Evolution of the GW

THE ASTROPHYSICAL JOURNAL, 713:671–685, 2010 April 10 doi:10.1088/0004-637X/713/1/671
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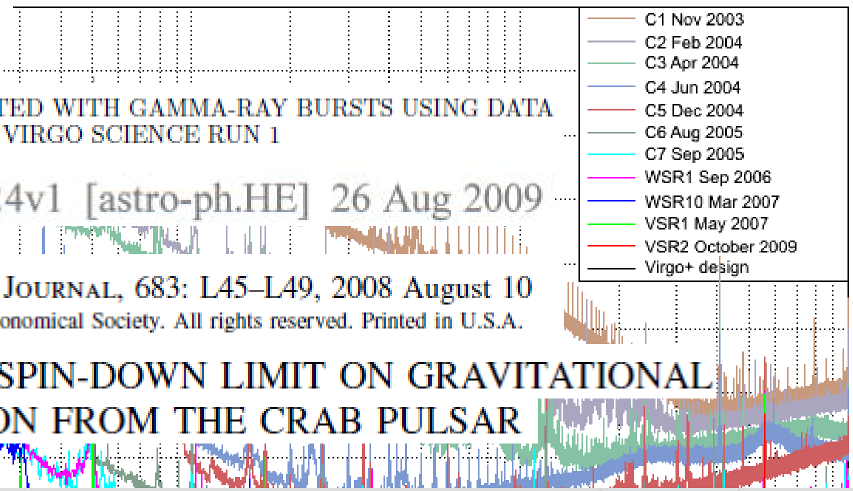
SEARCHES FOR GRAVITATIONAL WAVES FROM KNOWN PULSARS WITH SCIENCE RUN 5 LIGO DATA

IOP PUBLISHING CLASSICAL AND QUANTUM GRAVITY
Class. Quantum Grav. 25 (2008) 225001 (20pp) doi:10.1088/0264-9381/25/22/225001

Search for gravitational waves associated with GRB 050915a using the Virgo detector



SEARCH FOR GRAVITATIONAL-WAVE BURSTS ASSOCIATED WITH GAMMA-RAY BURSTS USING DATA FROM LIGO SCIENCE RUN 5 AND VIRGO SCIENCE RUN 1

arXiv:0908.3824v1 [astro-ph.HE] 26 Aug 2009

Proof of the working principle

Upper Limit physics

Commissioning & first runs

THE ASTROPHYSICAL JOURNAL, 683: L45–L49, 2008 August 10
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BEATING THE SPIN-DOWN LIMIT ON GRAVITATIONAL WAVE EMISSION FROM THE CRAB PULSAR

nature Vol 460 | 20 August 2009 | doi:10.1038/nature08278

LETTERS

An upper limit on the stochastic gravitational-wave background of cosmological origin

The LIGO Scientific Collaboration* & The Virgo Collaboration*

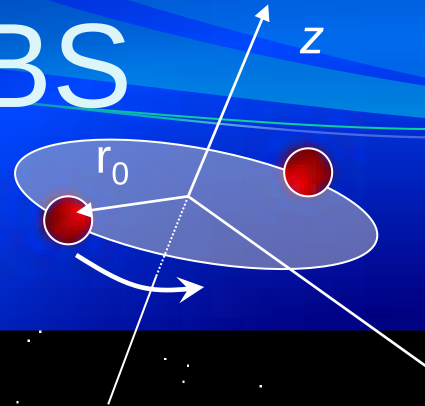
Infrastructure realization and detector assembling	Same infrastructure

2003 2008

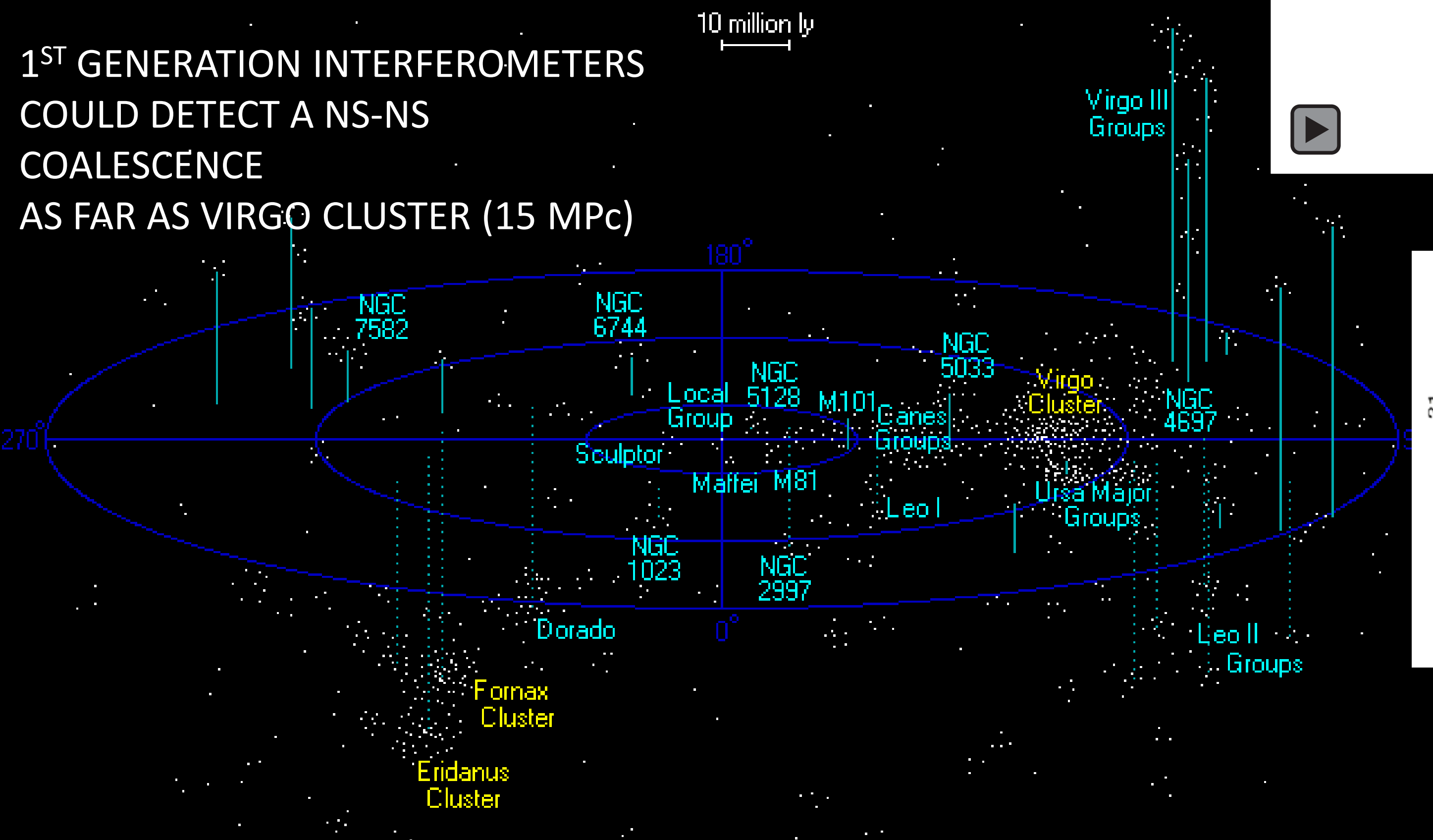
GW sources: BS

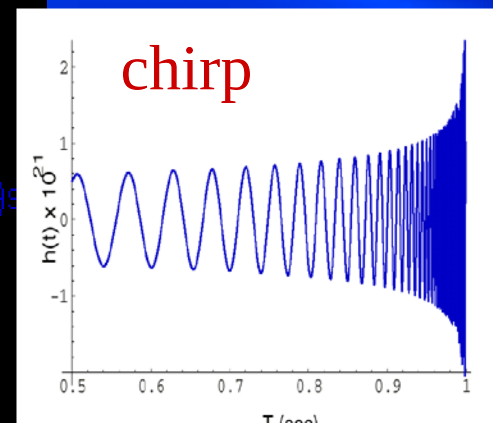
BH-BH

- Binary systems of massive and compact stellar bodies:
  - NS-NS, NS-BH, BH-BH



1ST GENERATION INTERFEROMETERS COULD DETECT A NS-NS COALESCENCE AS FAR AS VIRGO CLUSTER (15 MPc)

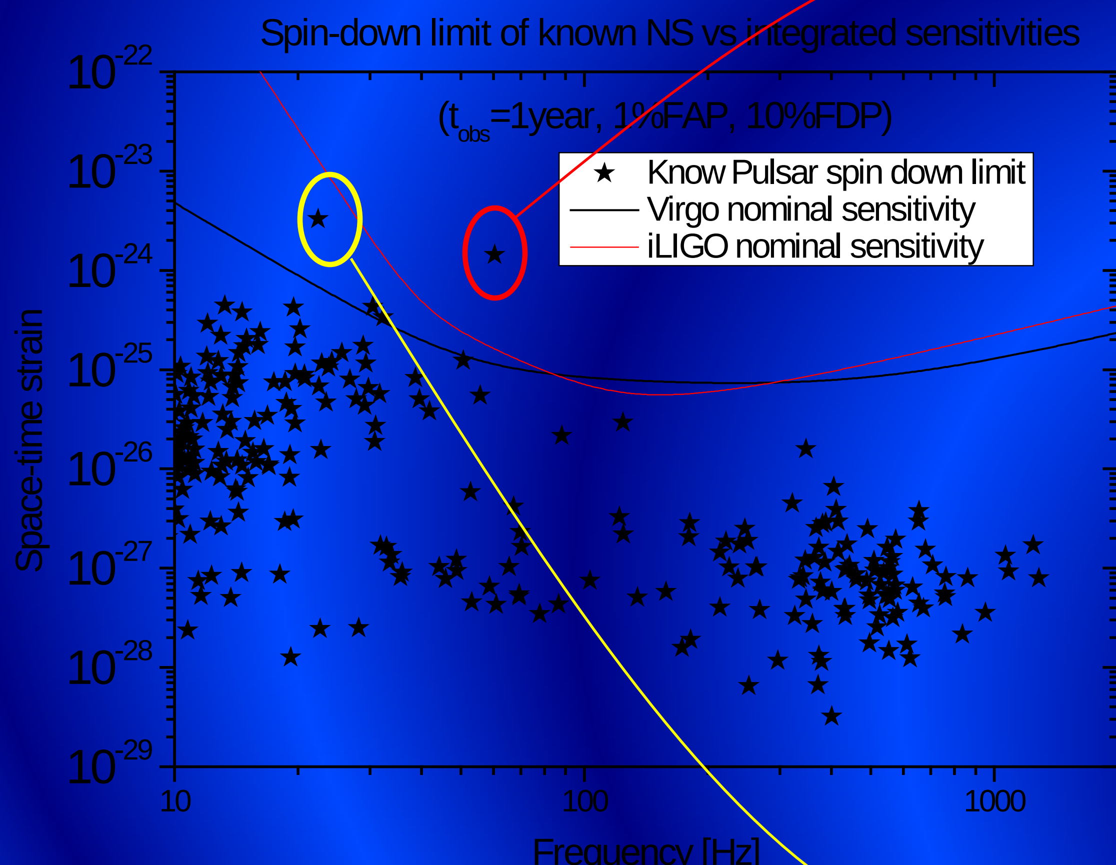


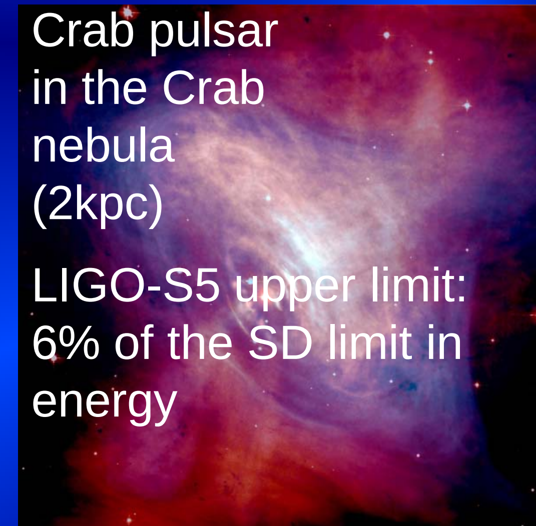


LOW EXPECTED EVENT RATE:
0.01-0.1 ev/yr (NS-NS)

GW sources: isolated NS

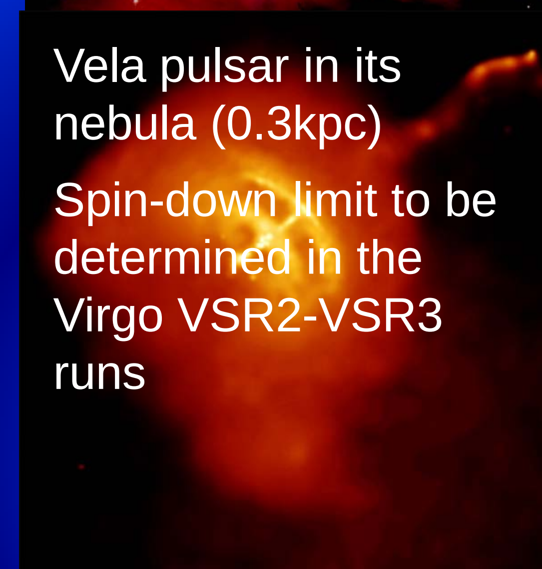
- Isolated NS are a possible source of GW if they have a non-null quadrupolar moment (ellipticity)





Crab pulsar in the Crab nebula (2kpc)

LIGO-S5 upper limit: 6% of the SD limit in energy



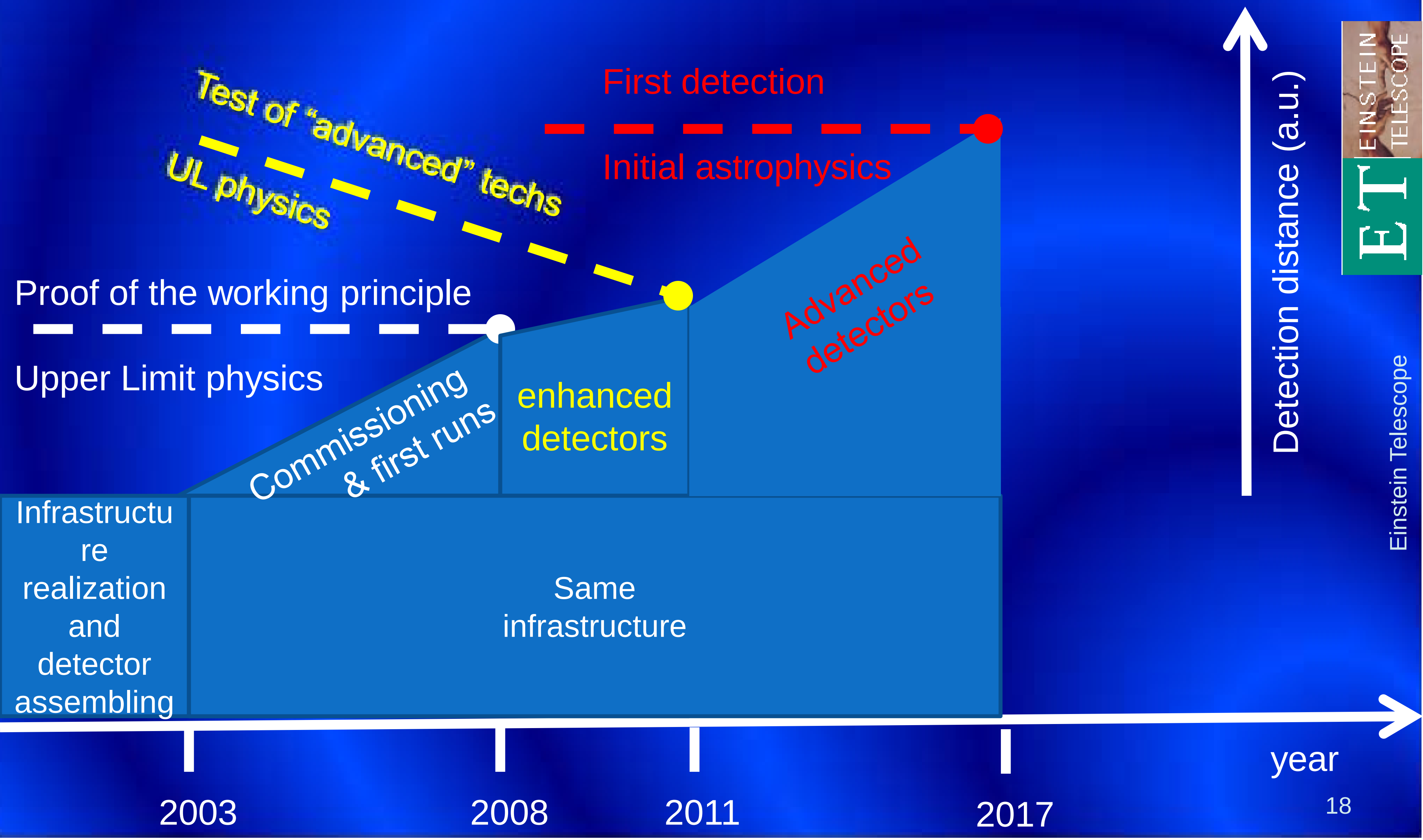
Vela pulsar in its nebula (0.3kpc)

Spin-down limit to be determined in the Virgo VSR2-VSR3 runs

Credits: C.Palomba

GW interferometer present evolution

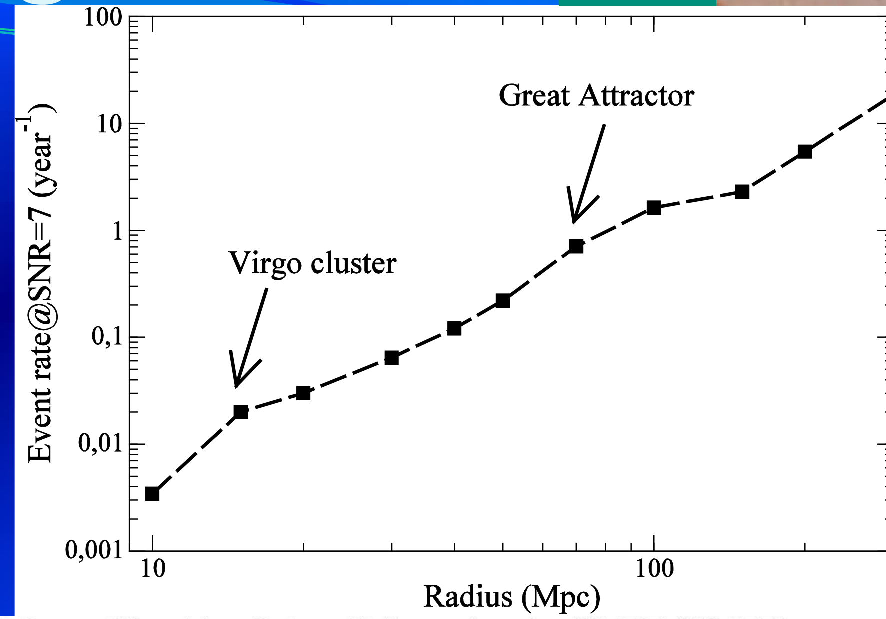
- Evolution of the GW detectors (Virgo example):



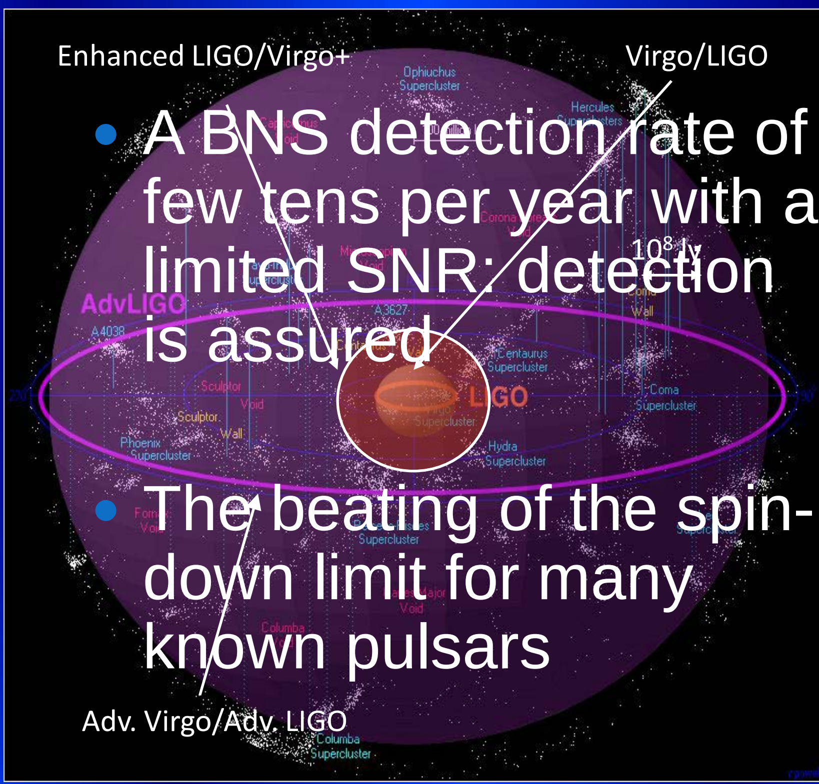
Einstein Telescope

Advanced detectors

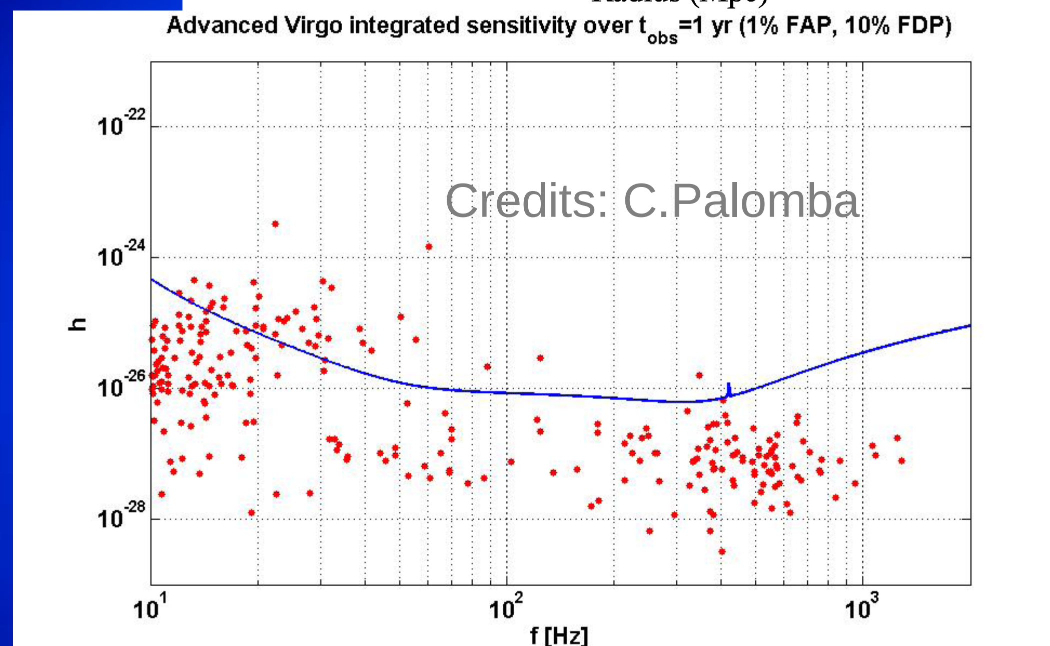
- Advanced detectors are, for example, promising:
  - An increase of the BNS detection distance up to 200 MPc



  - A BNS detection rate of few tens per year with a limited SNR: detection is assured
  - The beating of the spin-down limit for many known pulsars



Credit: R.Powell, B.Berger



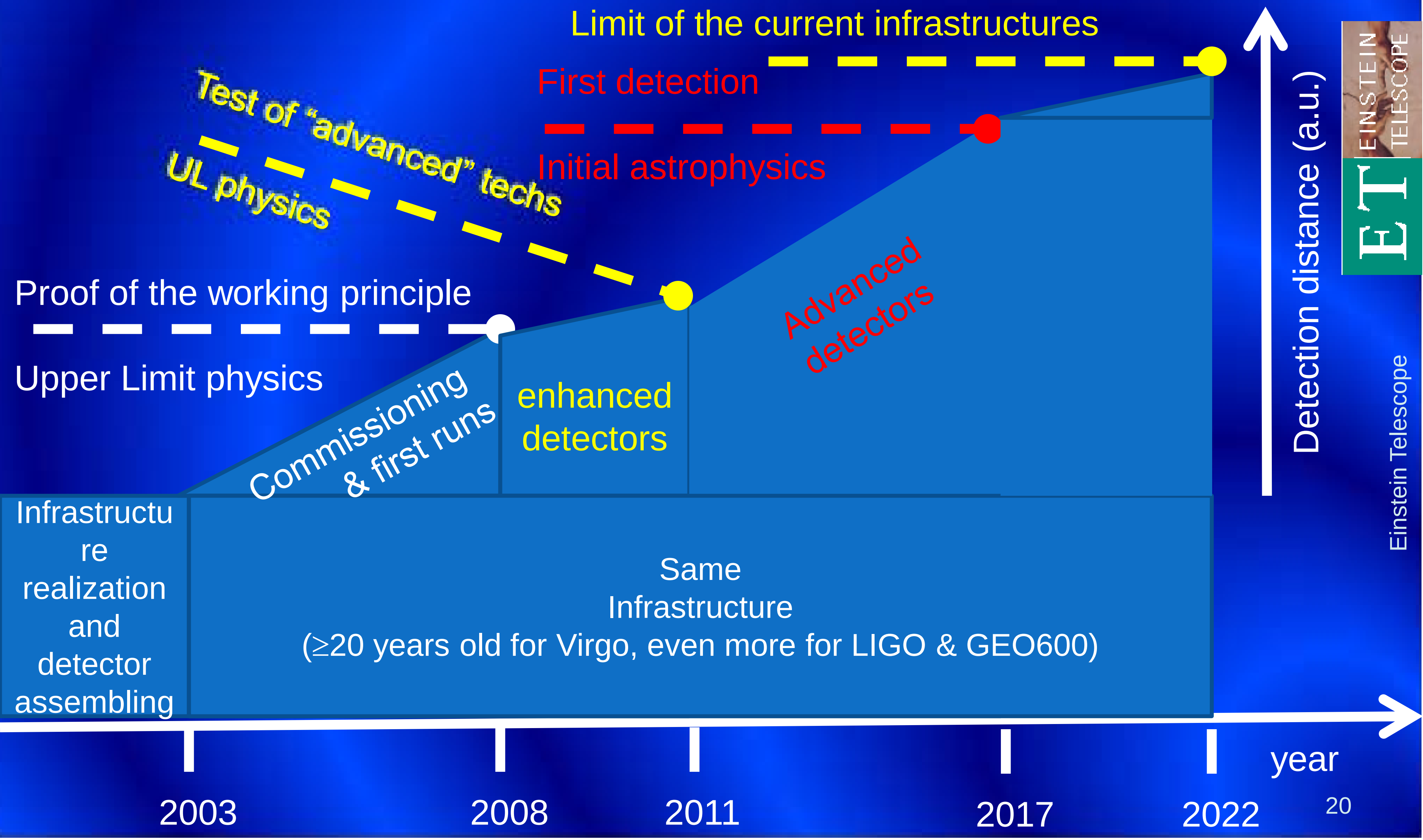
3rd generation?

- Evolution of the GW detectors (Virgo example):

Precision Astrophysics

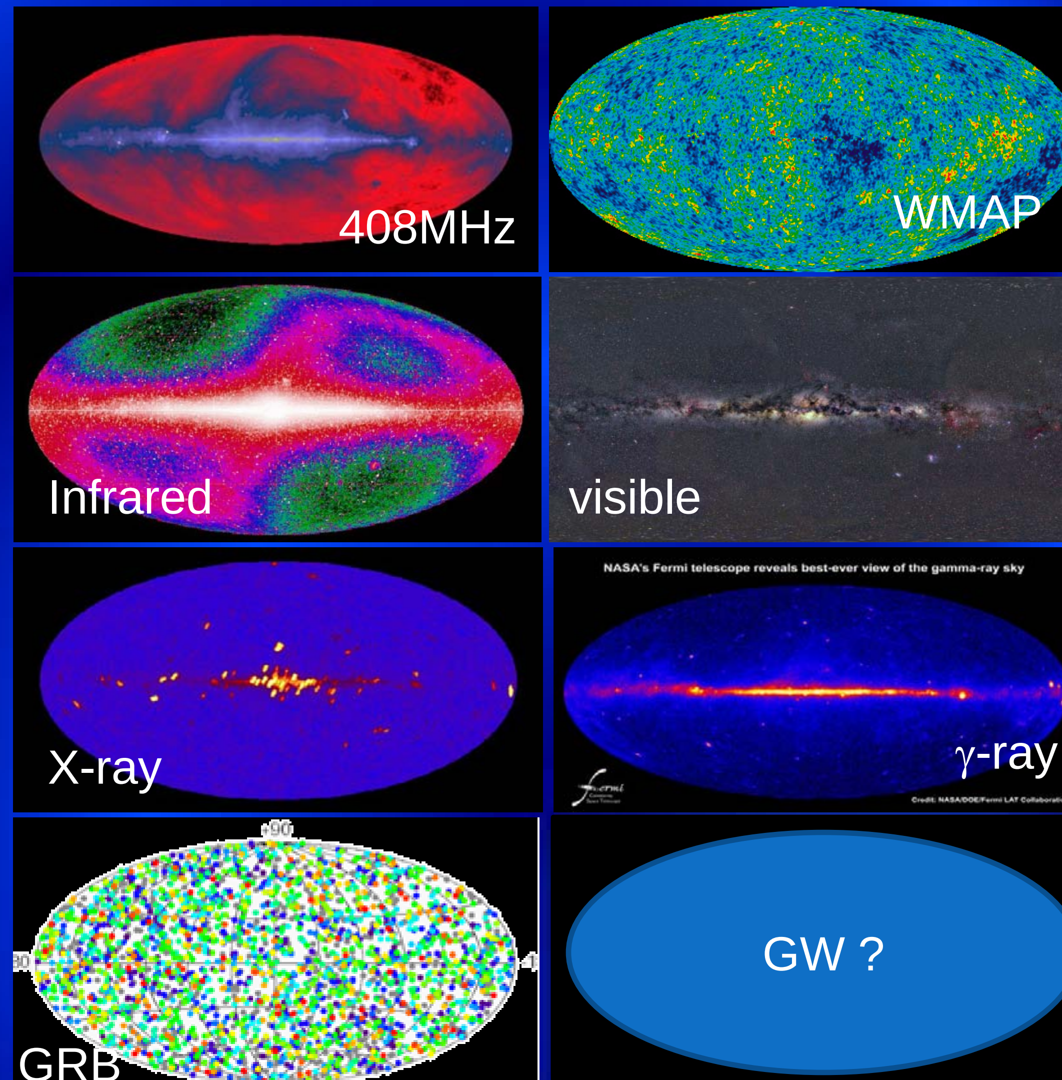
Cosmology

?



GW Astronomy ?

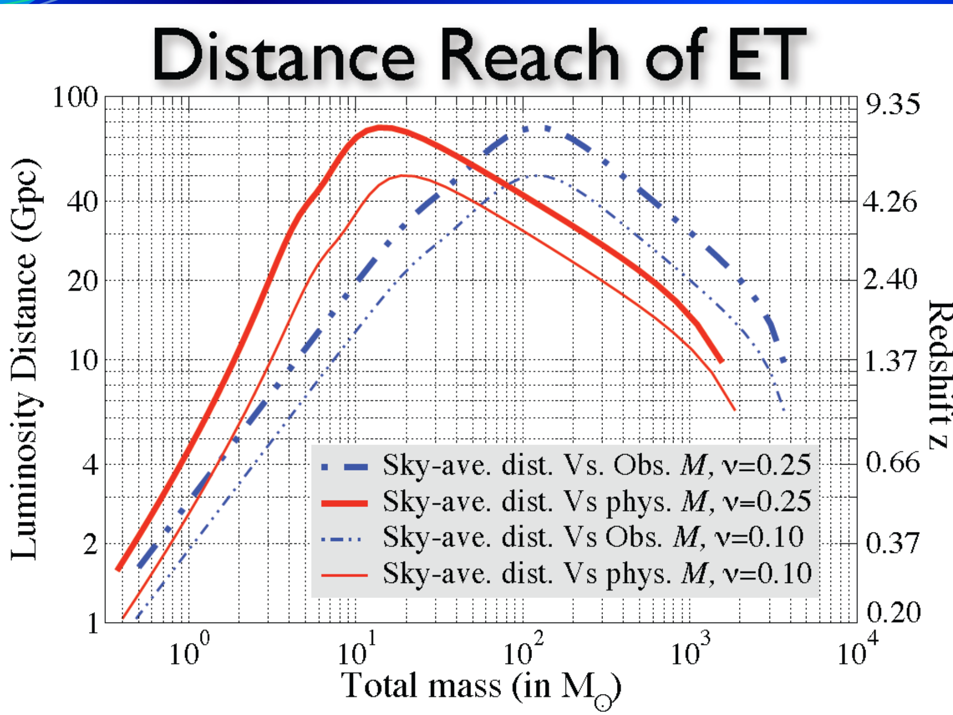
- Current e.m. telescopes are mapping the Universe in all the wavelengths detectable from the Earth and from the space.
- Gravitational wave telescopes, having a comparable sight distance, could complement the e.m. observation opening the GW astrophysics era
- Thanks to the small interaction between graviton and the matter , GW are the best messenger to investigate the first instants of the Universe

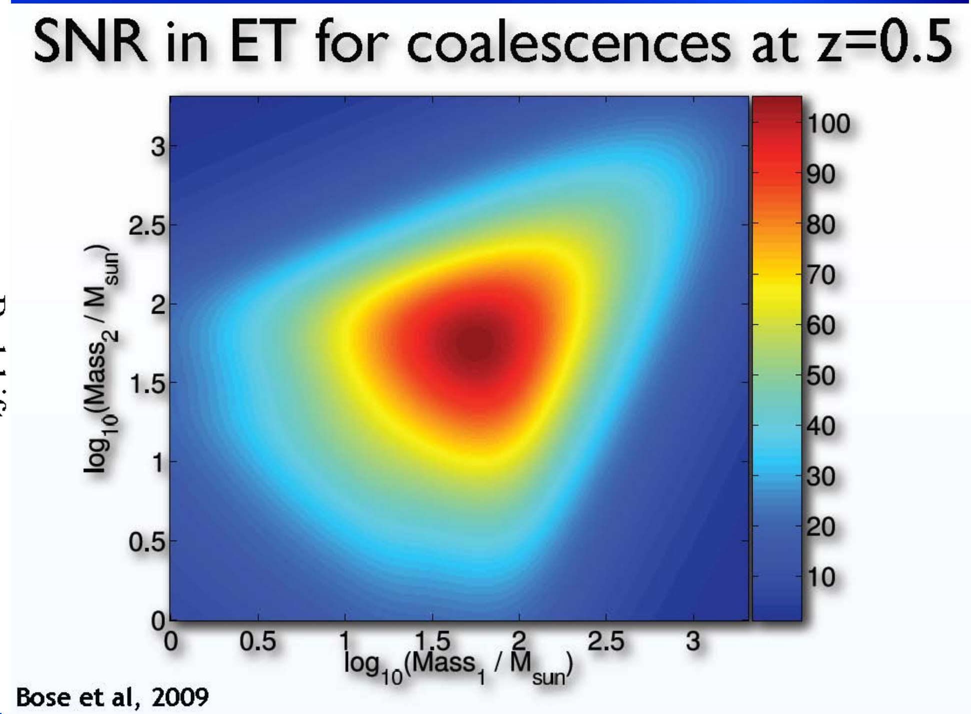


Physics Beyond Advanced Detectors

- GW detection is expected to occur in the advanced detectors. **The 3rd generation will focus on observational aspects:**
- Astrophysics:
  - Measure in great detail the physical parameters of the stellar bodies composing the binary systems
    - NS-NS, NS-BH, BH-BH
    - Constrain the Equation of State of NS through the measurement
      - of the merging phase of BNS
      - of the NS stellar modes
      - of the gravitational continuous wave emitted by a pulsar NS
  - Contribute to solve the GRB enigma
- Relativity
  - Compare the numerical relativity model describing the coalescence of intermediate mass black holes
  - Test General Relativity against other gravitation theories
- Cosmology
  - Measure few cosmological parameters using the GW signal from BNS emitting also an e.m. signal (like GRB)
  - Probe the first instant of the universe and its evolution through the measurement of the GW stochastic background
- Astro-particle:
  - Contribute to the measure the neutrino mass?
  - Constrain the graviton mass measurement

Binary System of massive stars

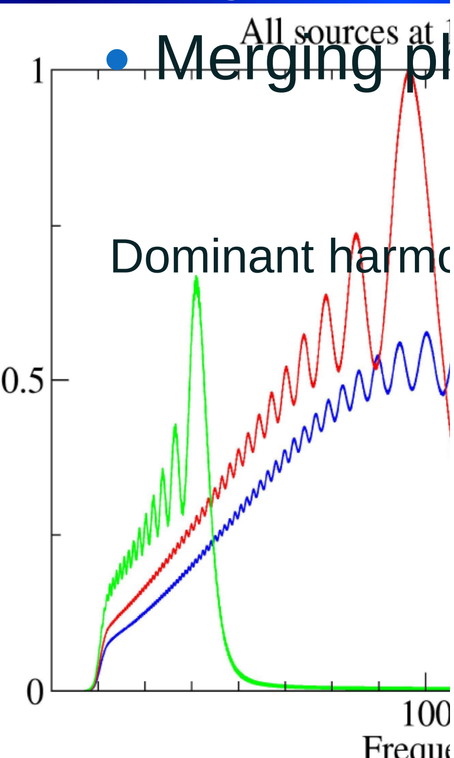


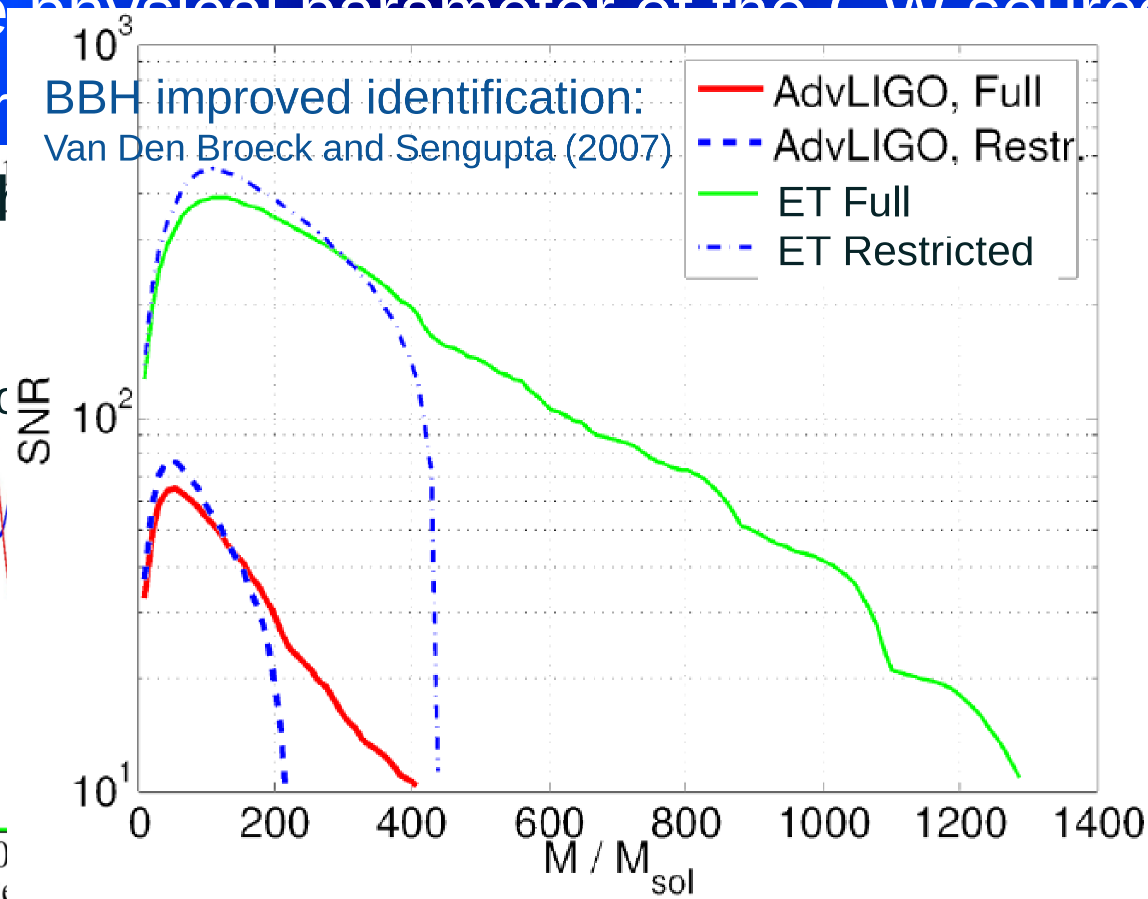


- Let suppose to gain a factor 10 in sensitivity wrt advanced detectors in a wide frequency range: [~1Hz,10 kHz]
- It will be possible to observe binary systems of massive stars:
  - At cosmological detection distance
  - Frequently, with high SNR

What a 3rd gen. GW detector can add to the Binary Systems (BS) physics?

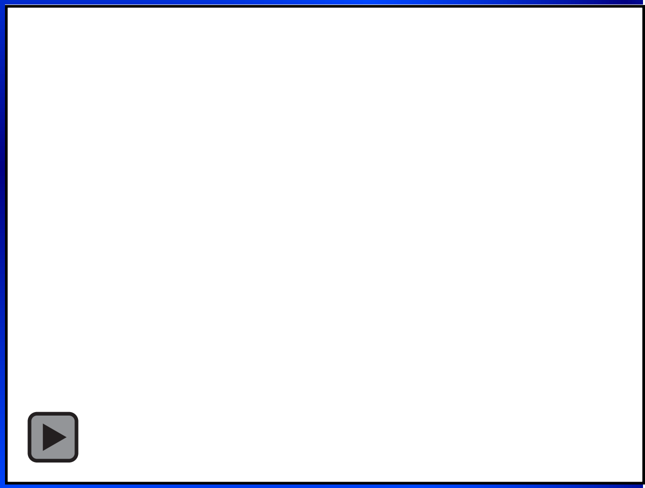
- The great SNR of many detected BS GW sources will permit to access a larger amount of information embedded in the BS (BNS, BH-NS, BH-BH) chirp signal, detailing the physical parameter of the GW source
  - Higher har
  - Merging ph



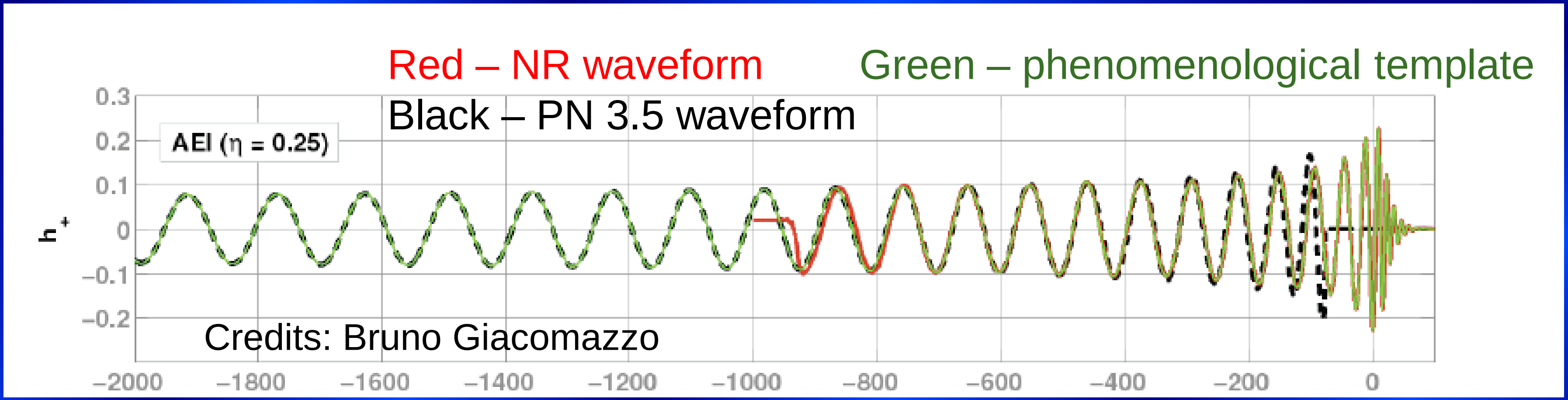


Numerical Relativity probe

- Great recent progresses in the numerical relativity (NR) modeling of the last orbits before the coalescence of two massive objects (BH-BH, NS-NS)
- PN approximation is unable to simulate the very last orbits, because of the huge gravitational fields, the merger and ring-down phases
- A 3rd generation GW observatory can probe the NR predictions (investigating the NS EOS, in case of BNS)

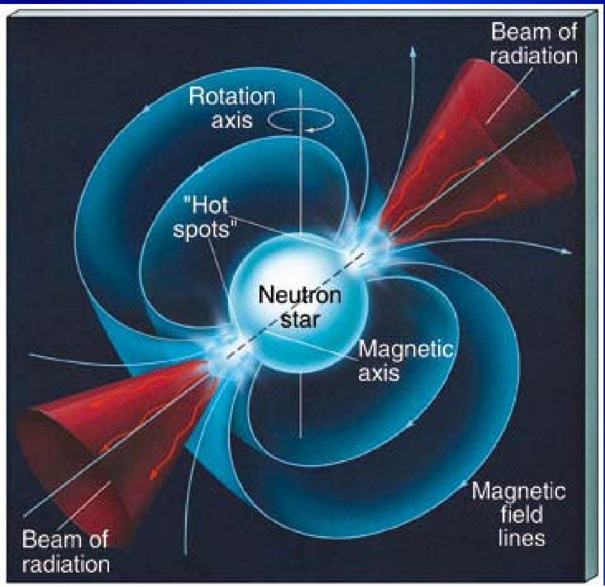


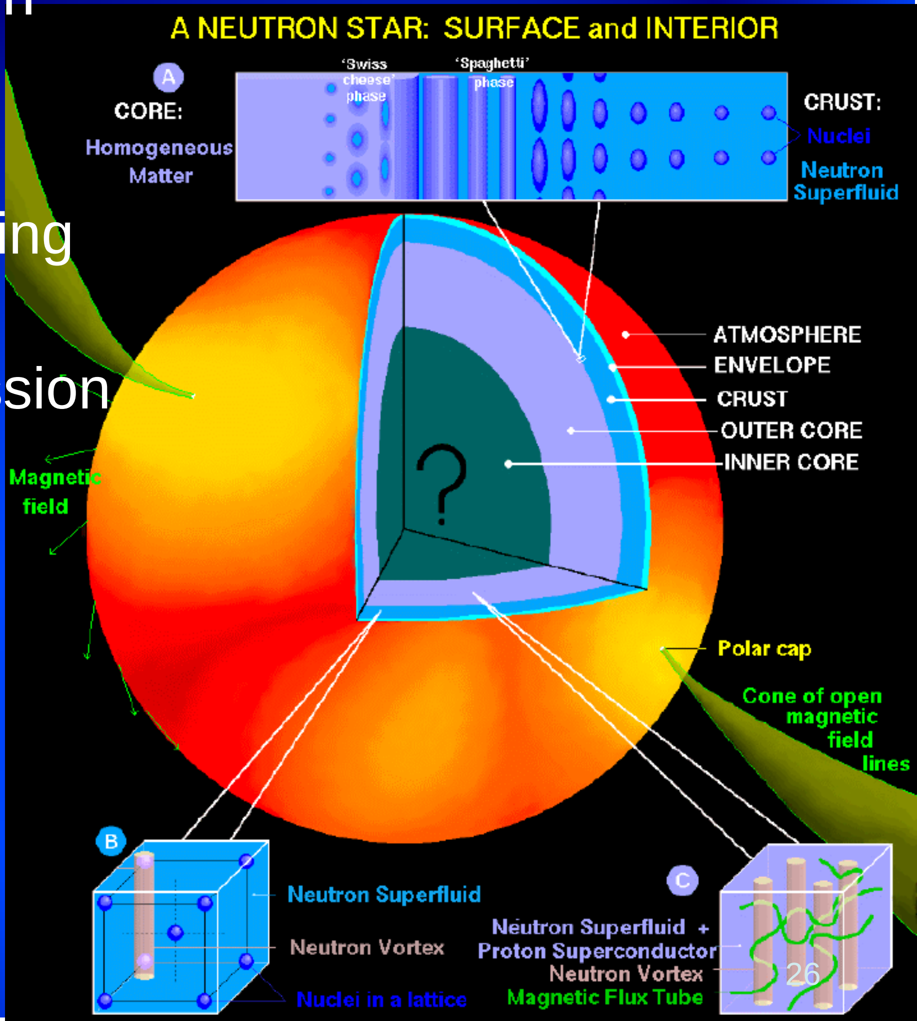
http://numrel.aei.mpg.de



Isolated NS

- EOS of the NS is still unknown
  - Why it pulses?
  - Is it really a NS or the core is made by strange matter?
- Gravitational Wave detection from NS will help to understand the composition of the NS:
  - Trough asteroseismology, revealing the internal modes of the star
  - Trough its continuous wave emission





Continuous Waves from Isolated NS

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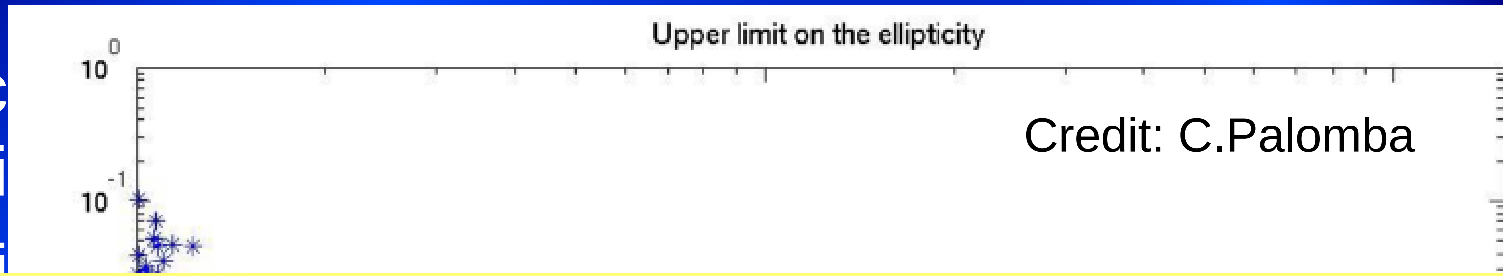
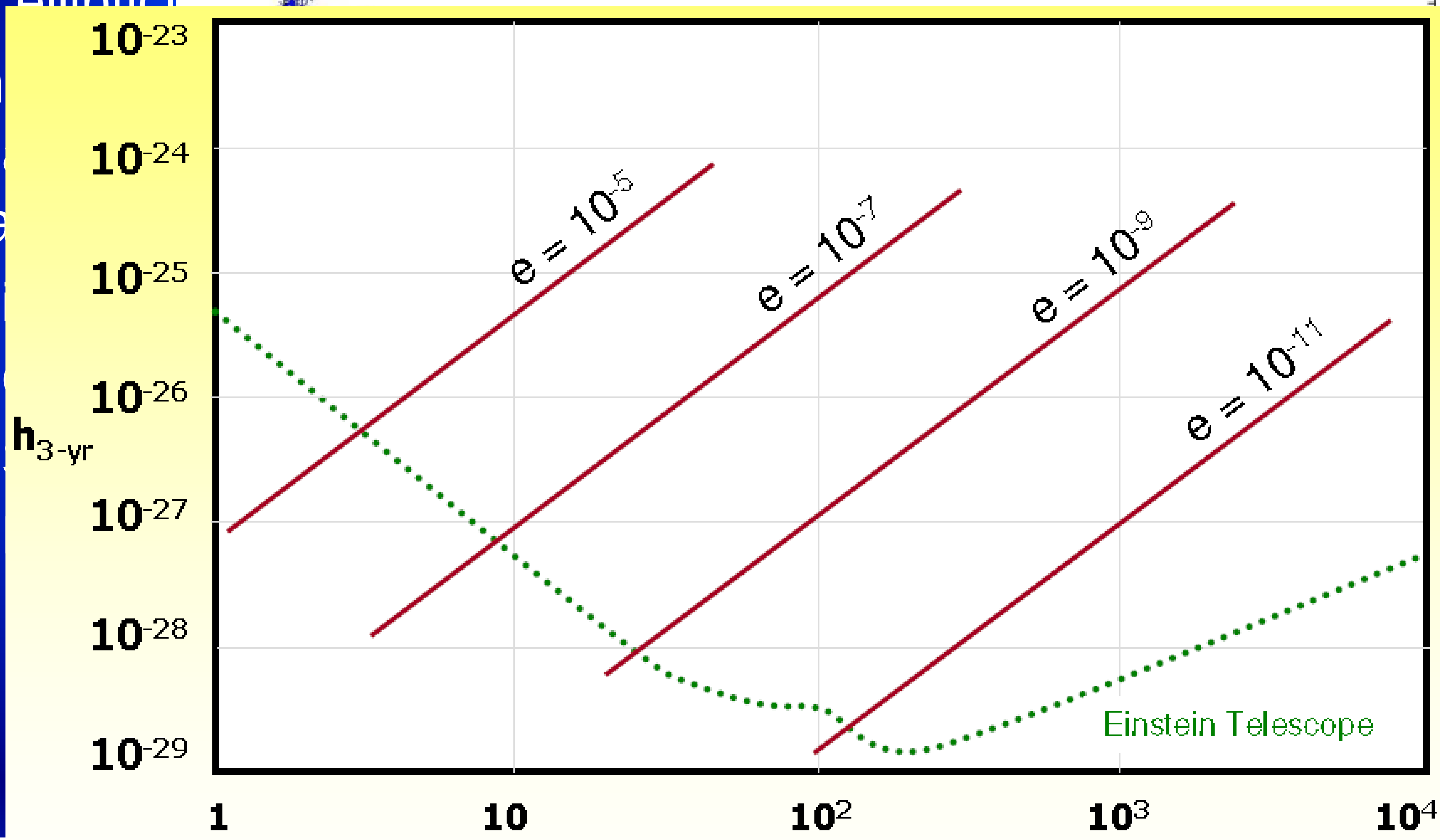
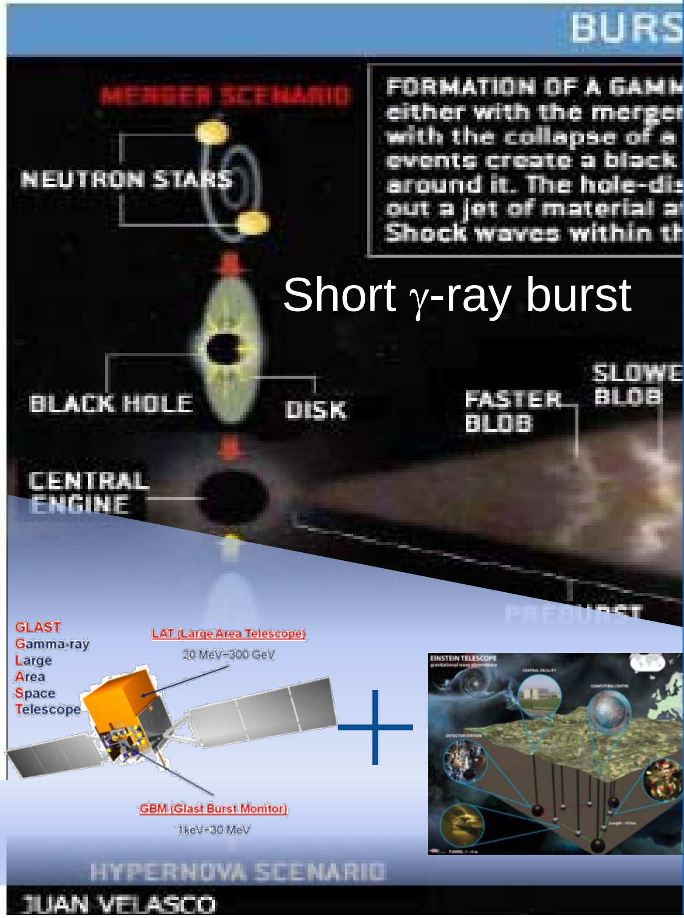




Cosmology with 3rd gen.



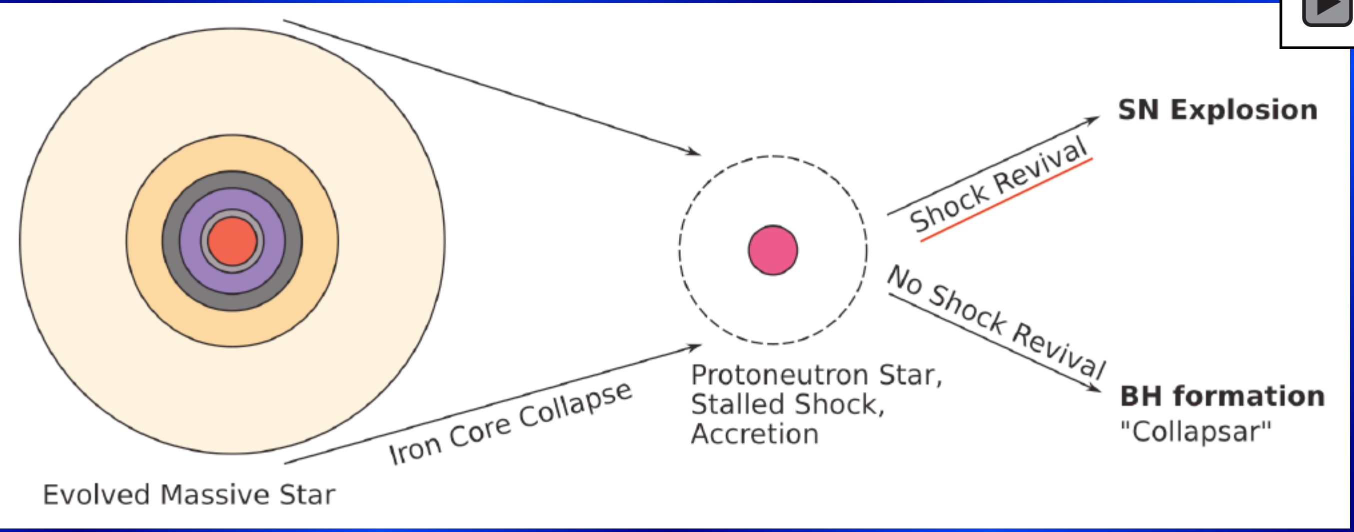
- BNS are "standard sirens" (Schutz 1986) because, the amplitude depends only on the Chirp Mass and luminosity distance
- Through the detection of the BNS gravitational signal, by a network of detectors, it is possible to reconstruct the luminosity distance D_L
- A GRB detector could identify the hosting galaxy and then the red-shift *z*.
- Knowing D_L and *z* it is possible to probe the adopted cosmological model and to constrain the cosmological parameters with limits comparable (i.e.) with Dark Matter missions:

$$D_L(z) = \frac{c(1+z)}{H_0} \int_0^z \frac{dz}{\left[\Omega_M (1+z)^3 + \Omega_\Lambda (1+z)^{3(1+w)}\right]^{1/2}}$$

Ω_M: total mass density
Ω_Λ: Dark energy density
H_0: Hubble parameter
w: Dark energy equation of state parameter

Supernova Explosions

- Mechanism of the core-collapse SNe still unclear
  - Shock Revival mechanism(s) after the core bounce TBC



- GWs generated by a SNe should bring information from the inner massive part of the process and could constrains on the core-collapse mechanisms

SNe rates with 3rd Gen.

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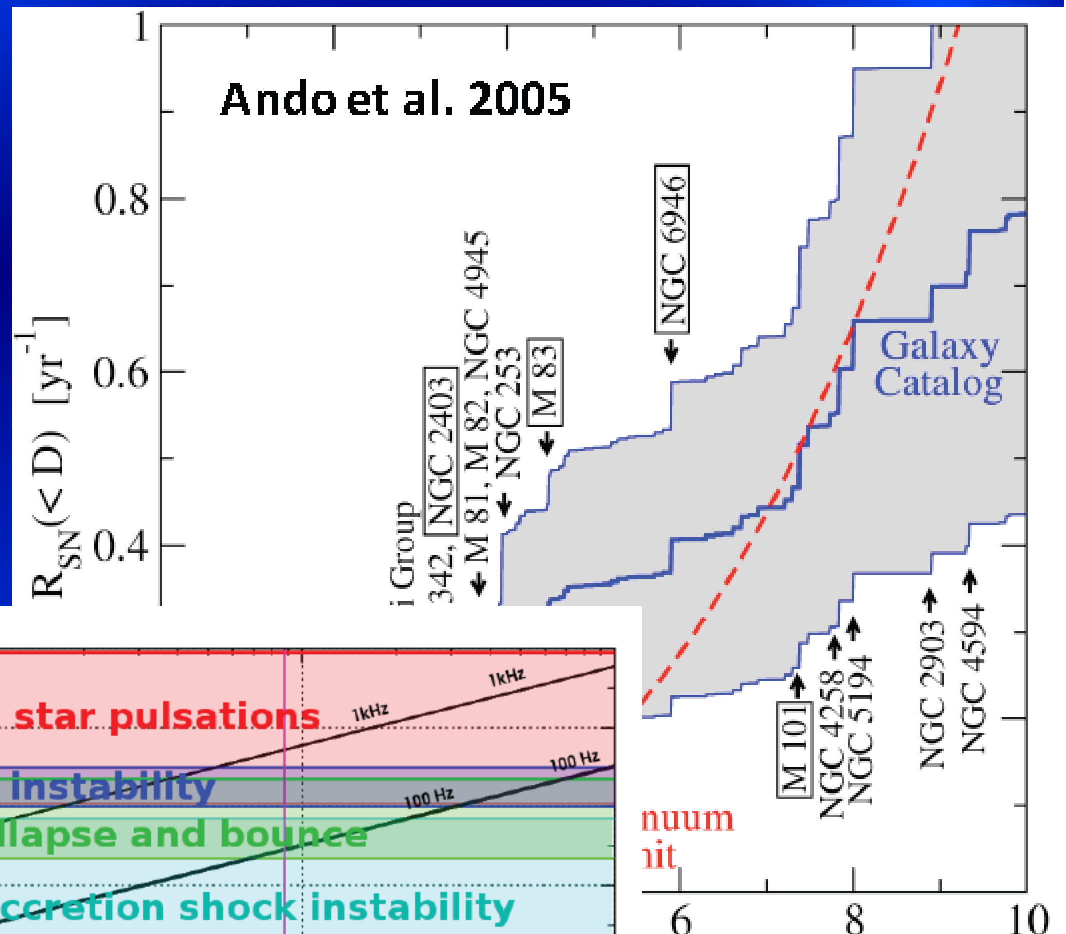
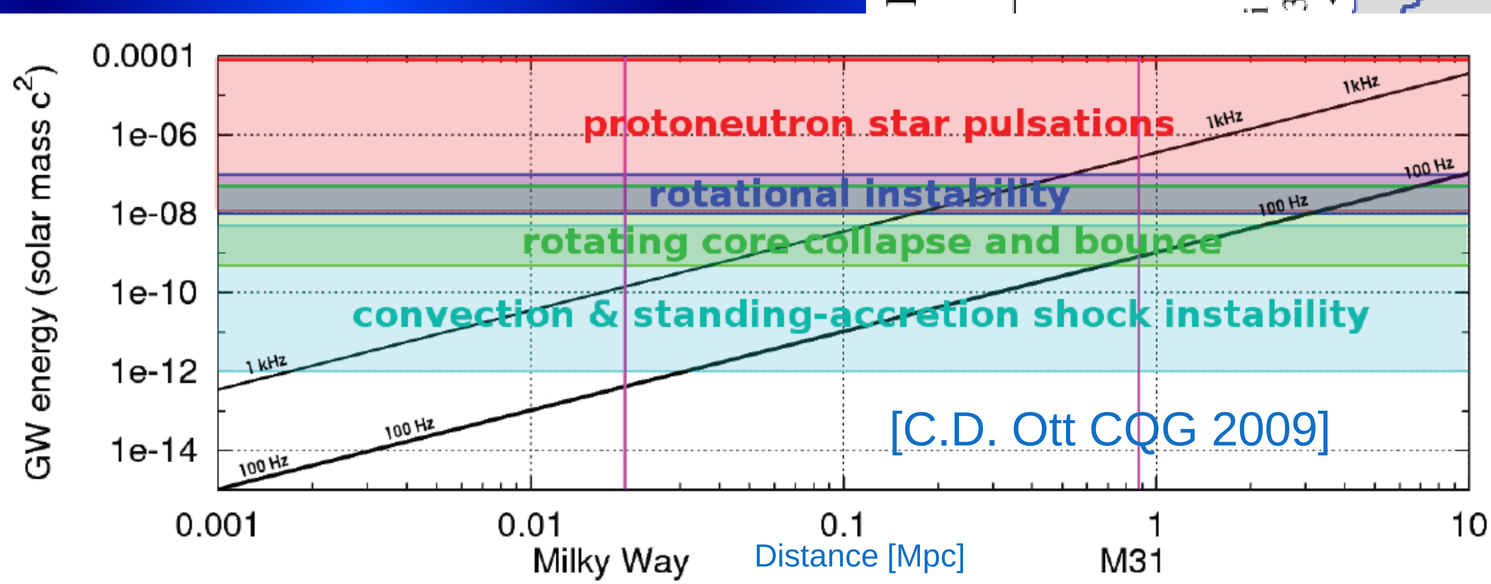
- Expected rate for SNe is about 1 evt / 20 years in the detection range of initial to advanced detectors
  - Our galaxy & local group
- To have a decent (0.5 evt/year) event rate about 5 Mpc must be reached
- 3G sensitivity can promise this target

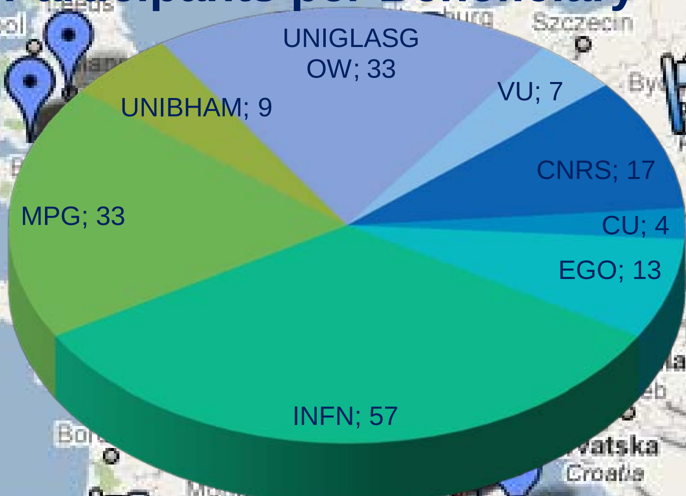




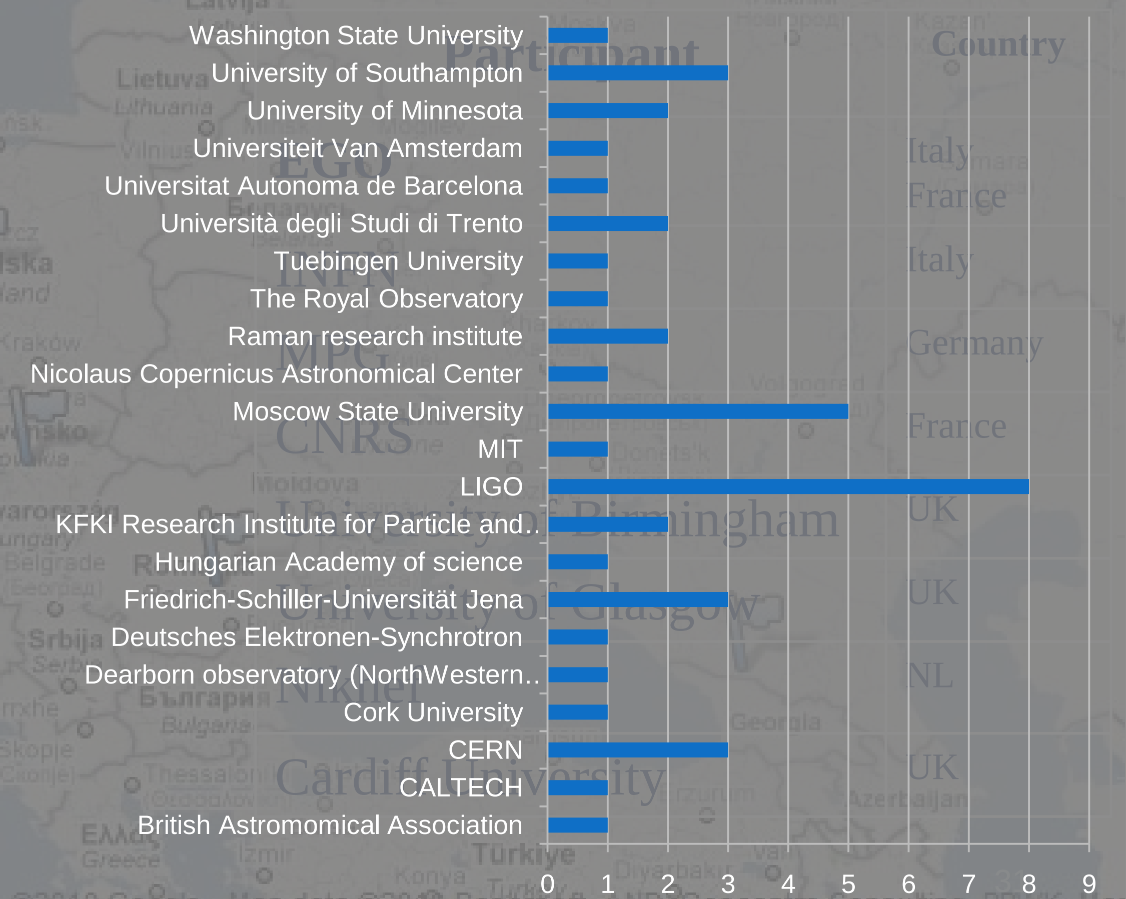
The Einstein Telescope

- The Einstein Telescope project is currently in its conceptual design study phase, supported by the European Community FP7 with about 3M€ from May 2008 to July 2011.

Participants per Beneficiary



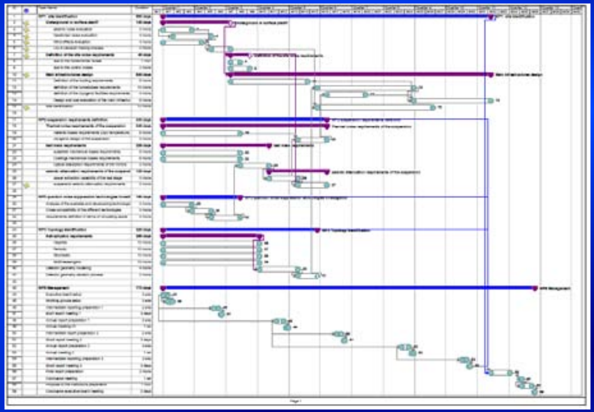
Participants per NON-Beneficiary



Targets of the Design Study

- Evaluate the science reaches of ET
- Define the sensitivity and performance requirements
  - Site requirements
  - Infrastructures requirements
  - Fundamental and (main) technical noise requirements
  - Multiplicity requirements
- Draft the observatory specs
  - Site candidates
  - Main infrastructures characteristics
  - Geometries
    - Size, L-Shaped or triangular
  - Topologies
    - Michelson, Sagnac, …
  - Technologies
- Evaluate the (rough) cost of the infrastructure and of the observatory

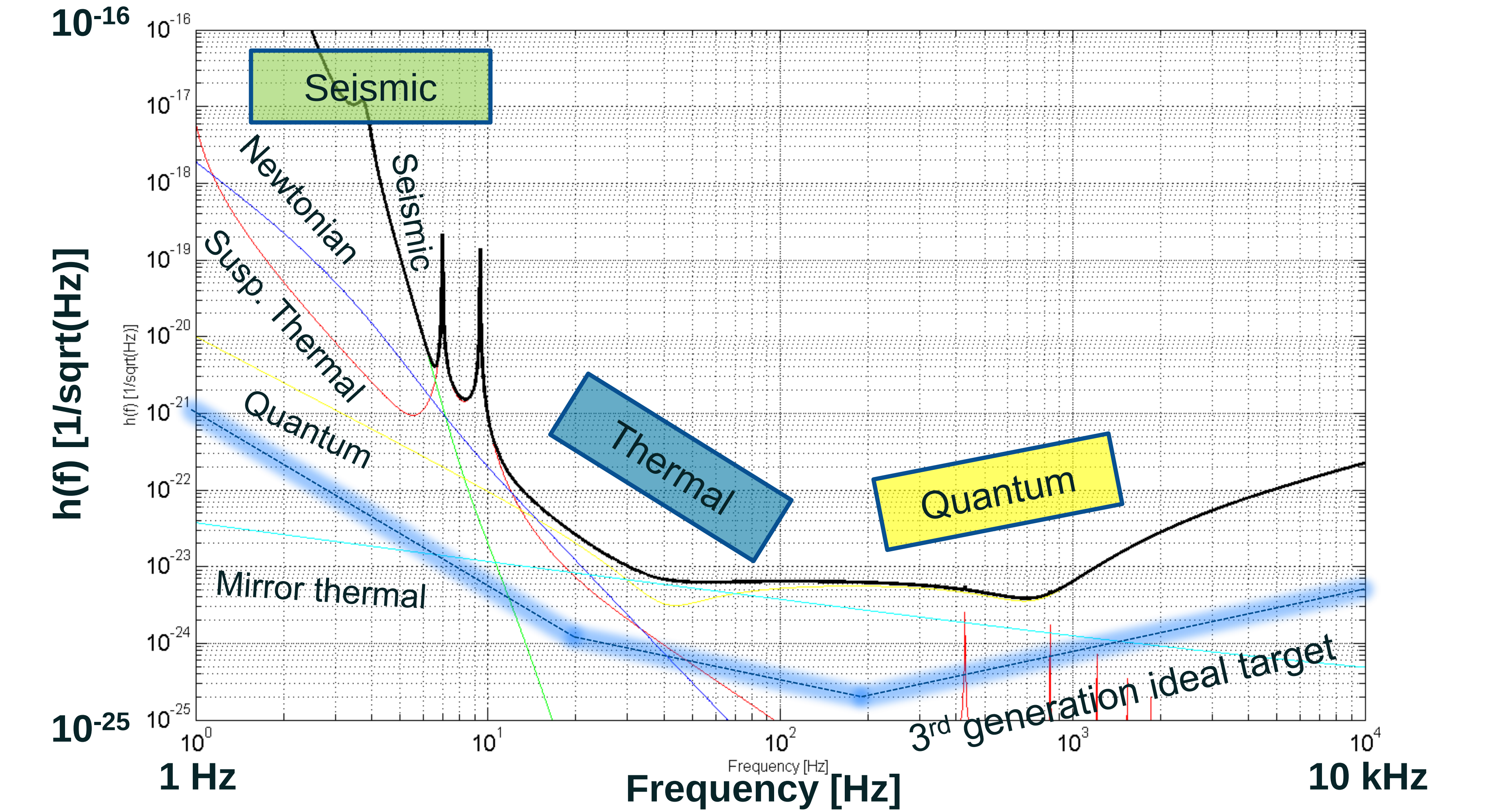
2009



2010

2011

How to go beyond the 2nd generation?



Stressing the current technologies

- Obviously a certain improvement of the sensitivity of the advanced detectors could be achieved by stressing the “current” technologies:
  - High power lasers (1kW laser, shot noise reduction)
  - Larger mirrors and larger beams (lower thermal noise)
  - Better coatings (lower thermal noise, lower scattering)
- But these aren’t the key elements justifying:
  - the transition 2nd $\Rightarrow$ 3rd generation
  - the need of a new infrastructure

3rd generation Technologies in ET

- Injection of squeezed light states (where the phase noise is lowered at the cost of the amplitude noise) permits to reduce HF noise
- Higher order modes (LG33) resonating in the FP cavities permit to reduce the intermediate (thermal) noise effects
- Cryogenic operative temperature (~20K) permits to suppress the thermal noise and improve the low and intermediate frequency sensitivity
  - New materials: Sapphire (LCGT), Silicon
  - New coatings

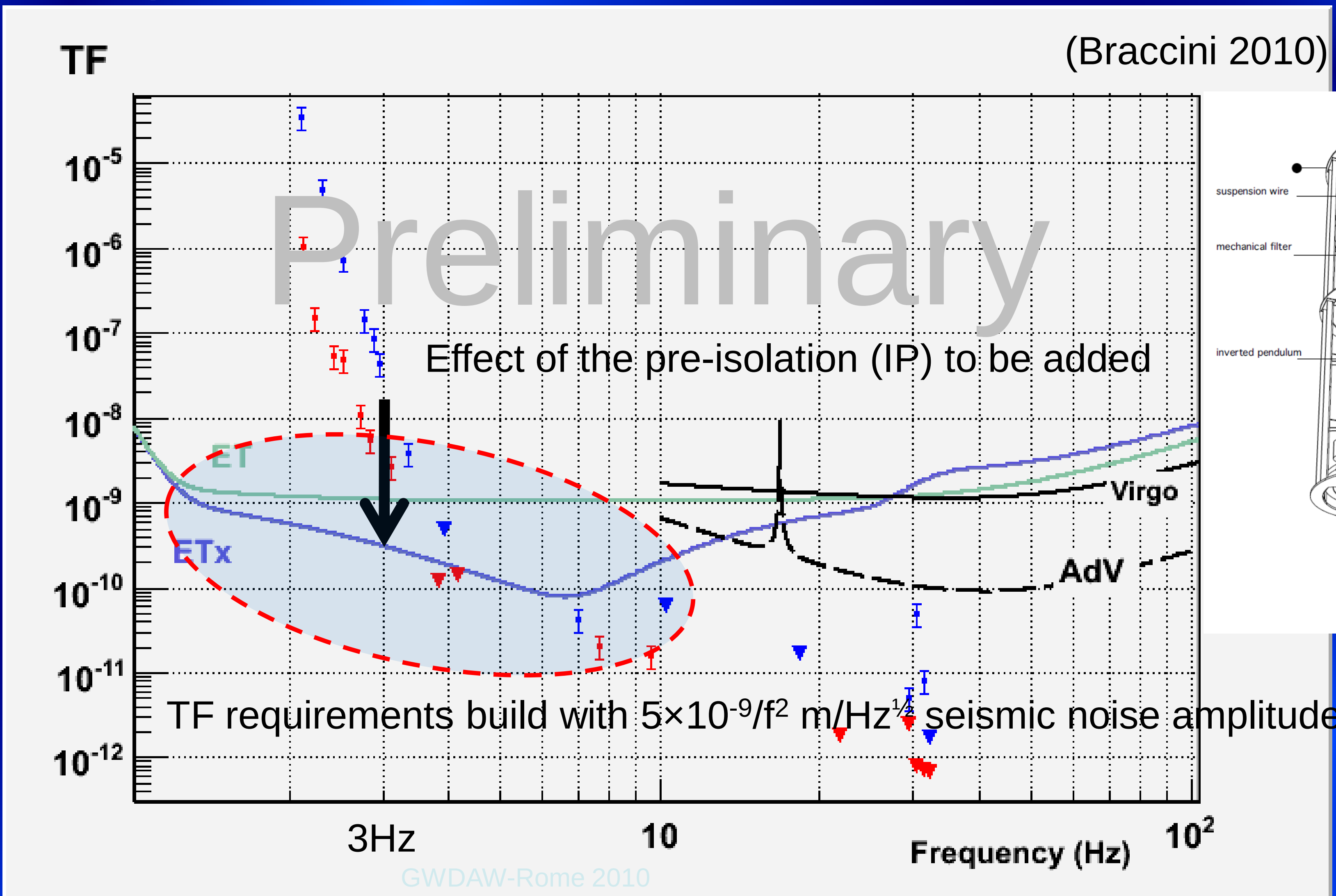
Access the very low frequency

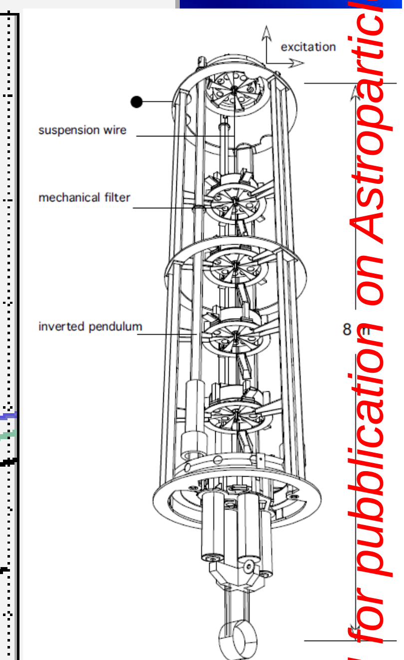
- The most challenging requirement of a 3rd generation GW observatory is to access, as much as possible, the ~1-10Hz frequency range
- The “enemy” to fight is the seismic noise, that acts on the test masses
  1) Indirectly, through the suspension chain
  2) Directly, through the so-called gravity gradient noise

1
- Virgo has implemented a seismic filtering chain
  - The super attenuator (SA)
- Advanced LIGO will implement an active filtering strategy
- Are these solutions compliant with the 3G requirements?

Measurements on Virgo SA

- Transfer Function measurement through line injection on the top of the SA





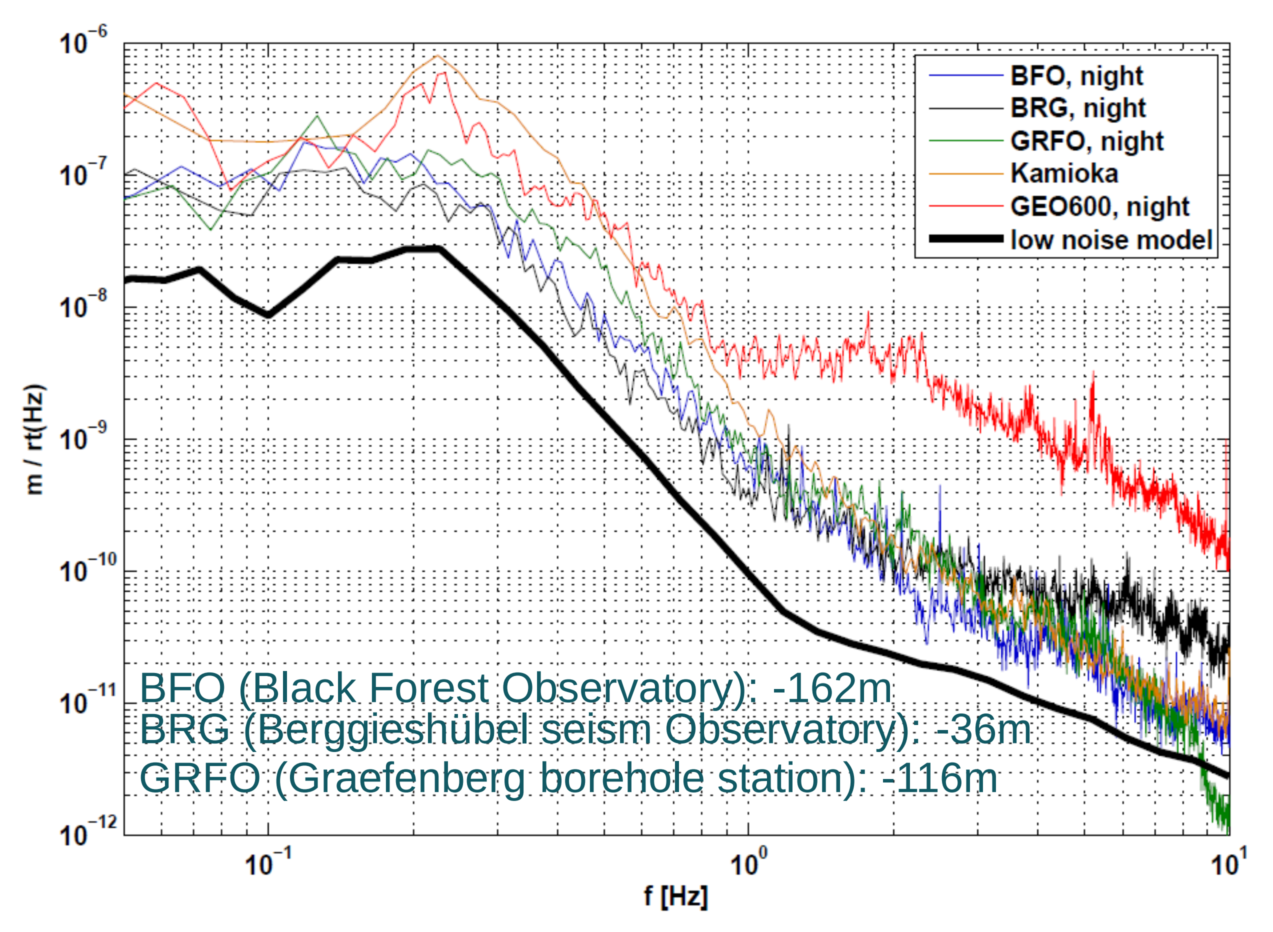
Paper accepted for publication on Astroparticle Physics

Underground site

- Virgo SA filtering capabilities are compatible with the ET requirements from 3Hz, provided that $x_{seims} < 5\times10^{-9}/f^2$ m/Hz$^{1/2}$
  - That is the seismic noise level in the Kamioka LCGT site candidate

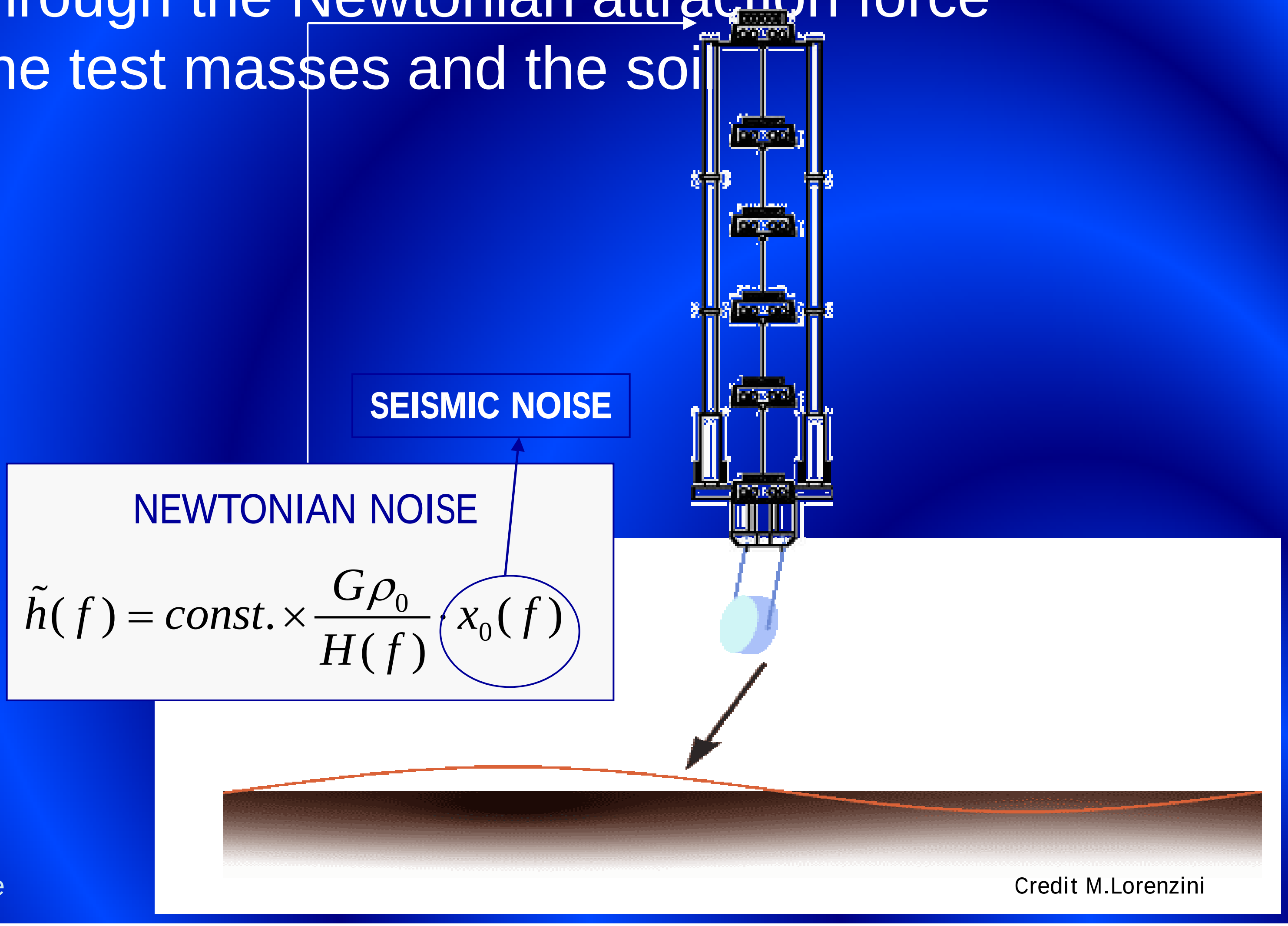
We need an underground site: <u>new infrastructure</u>!

Measurements in Europe:



Gravity Gradient Noise

- The gravity gradient noise is given by the direct coupling of the suspended optics with the soil vibration through the Newtonian attraction force between the test masses and the soil



$$\tilde{h}(f) = const. \times \frac{G\rho_0}{H(f)} \cdot x_0(f)$$

Credit M.Lorenzini

Gravity Gradient Noise reduction

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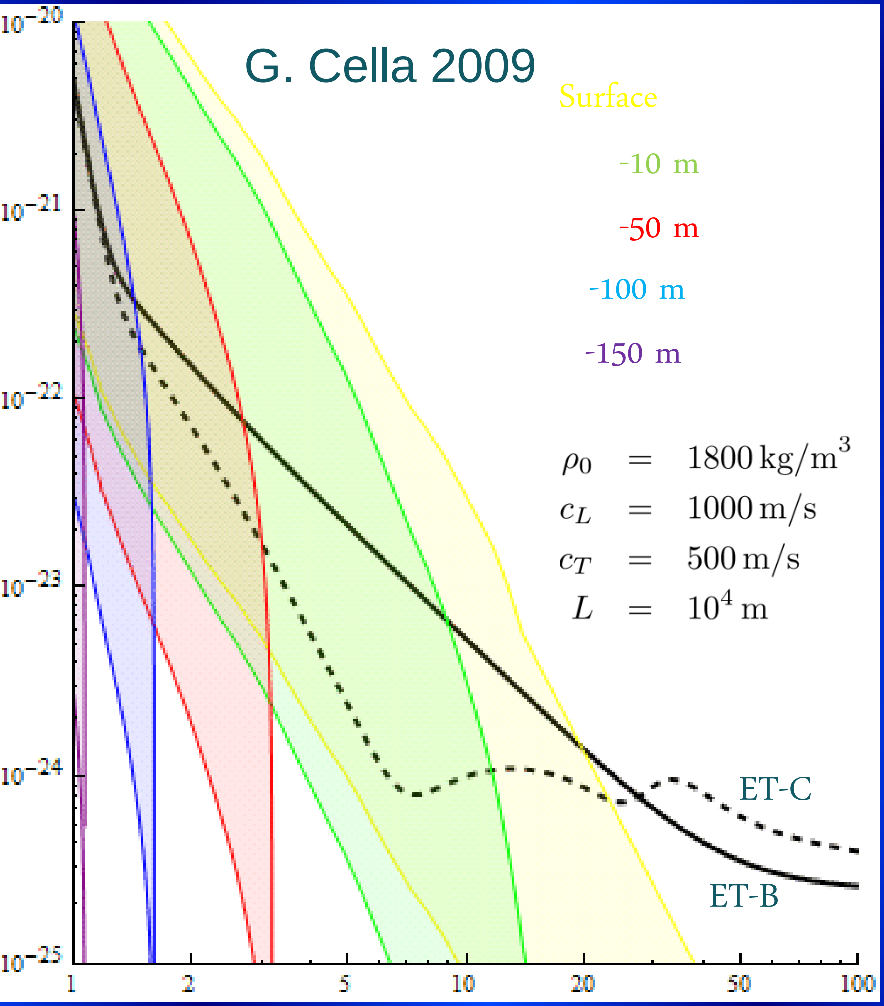
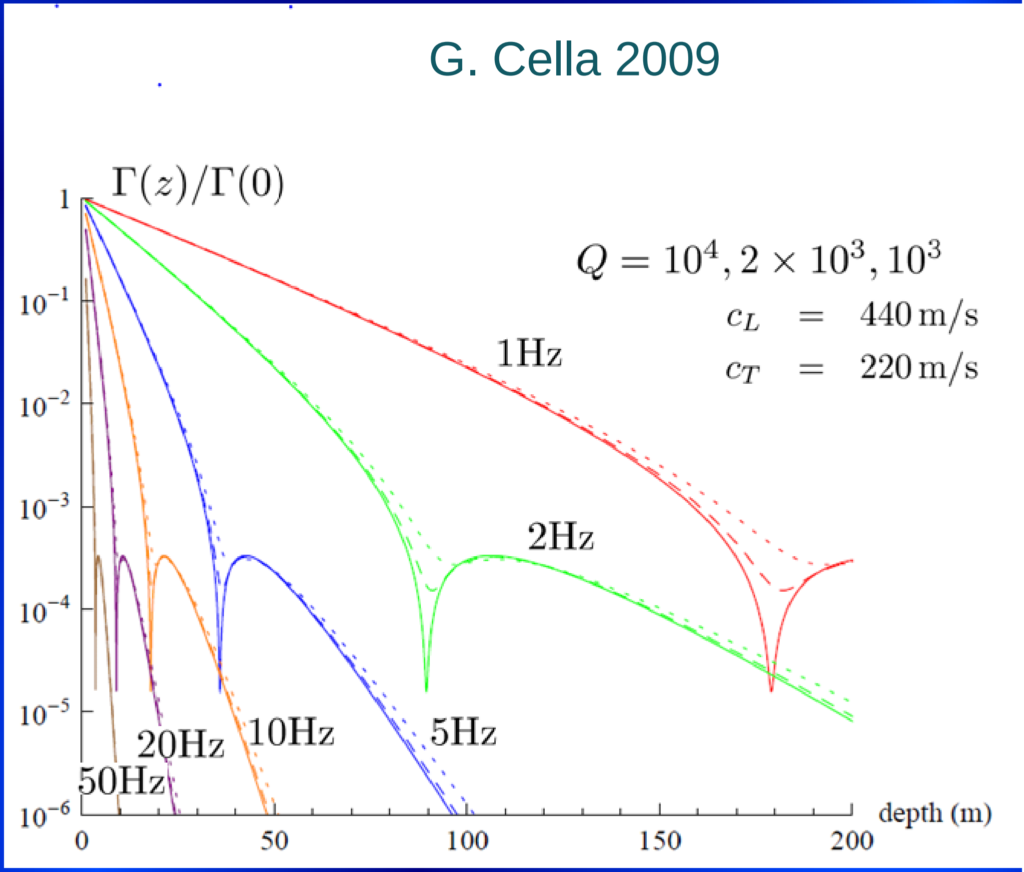
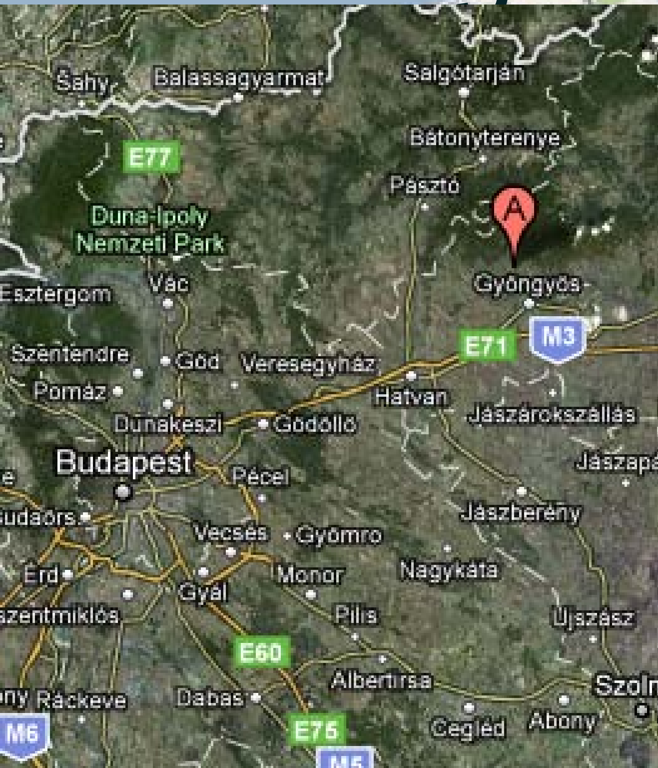
- An underground site permits also to suppress the GGN influence





- Additional noise subtraction schemes under study

Site list generation



Gyöngyösoroszi mine

- Old lead-zinc mine currently being rehabilitated
- 80 km north east of Budapest
- Surrounding rock is Andezit and Andezit-tufa
- Underground depths ranging from 60 - 400 m at an altitude of 400 m
- Entrance by train through west entrance by lift at the eastern shaft

http://www.et-gw.eu/

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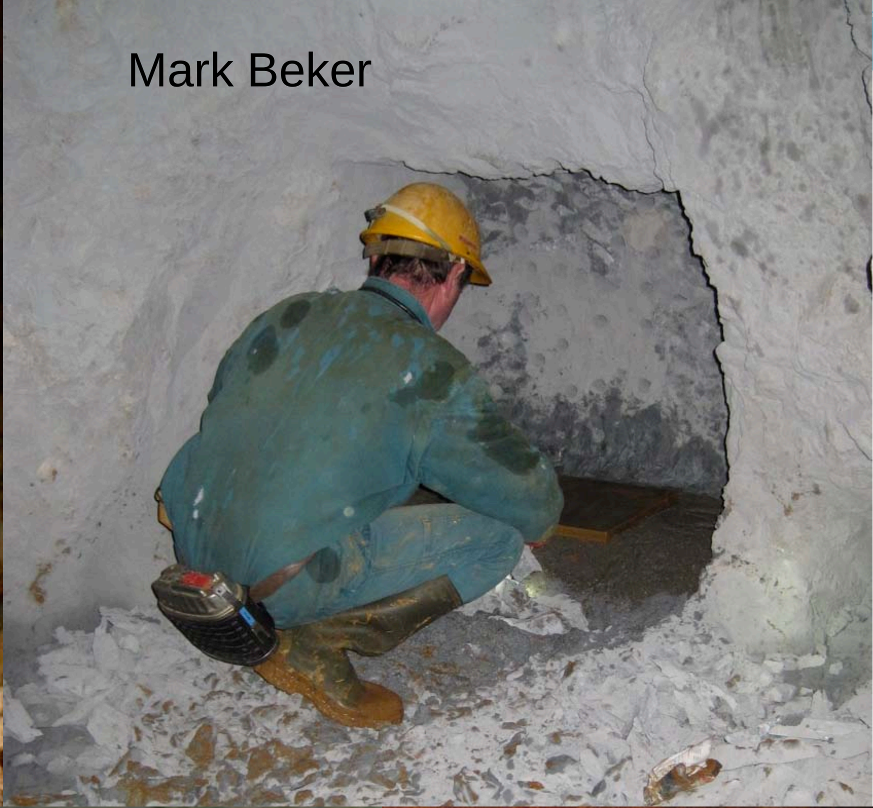
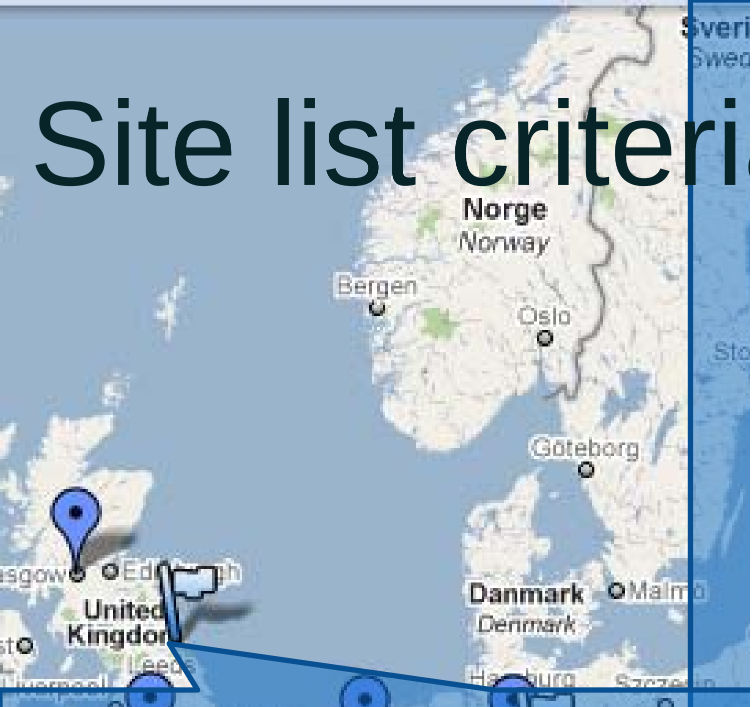
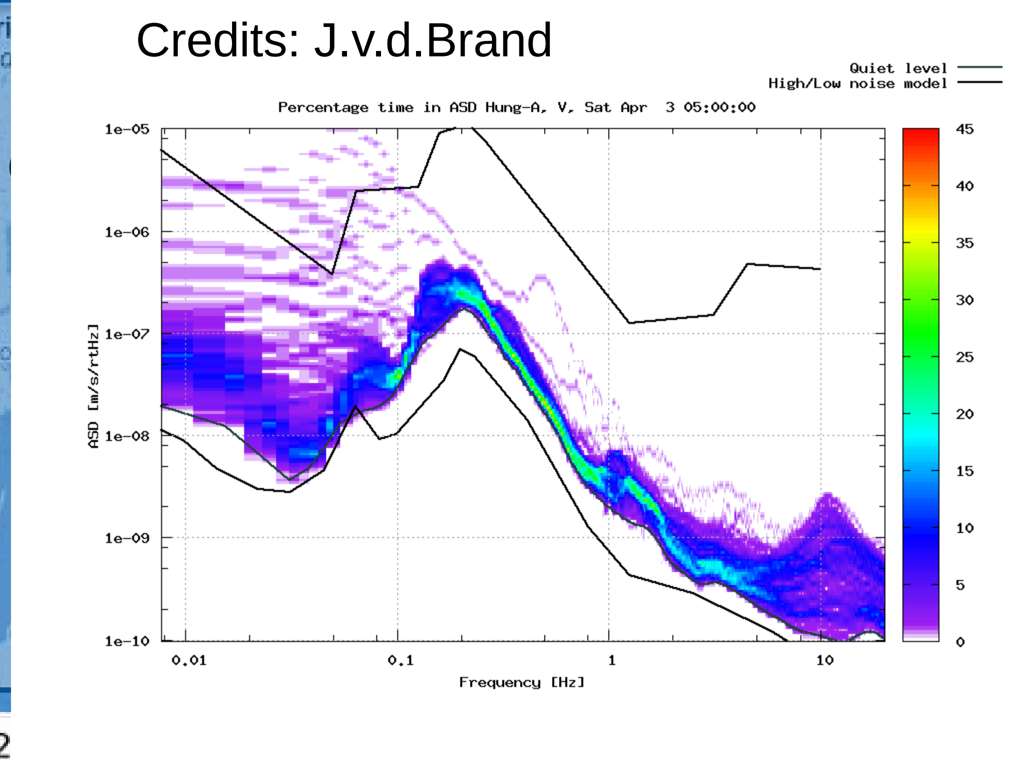
I. Racz

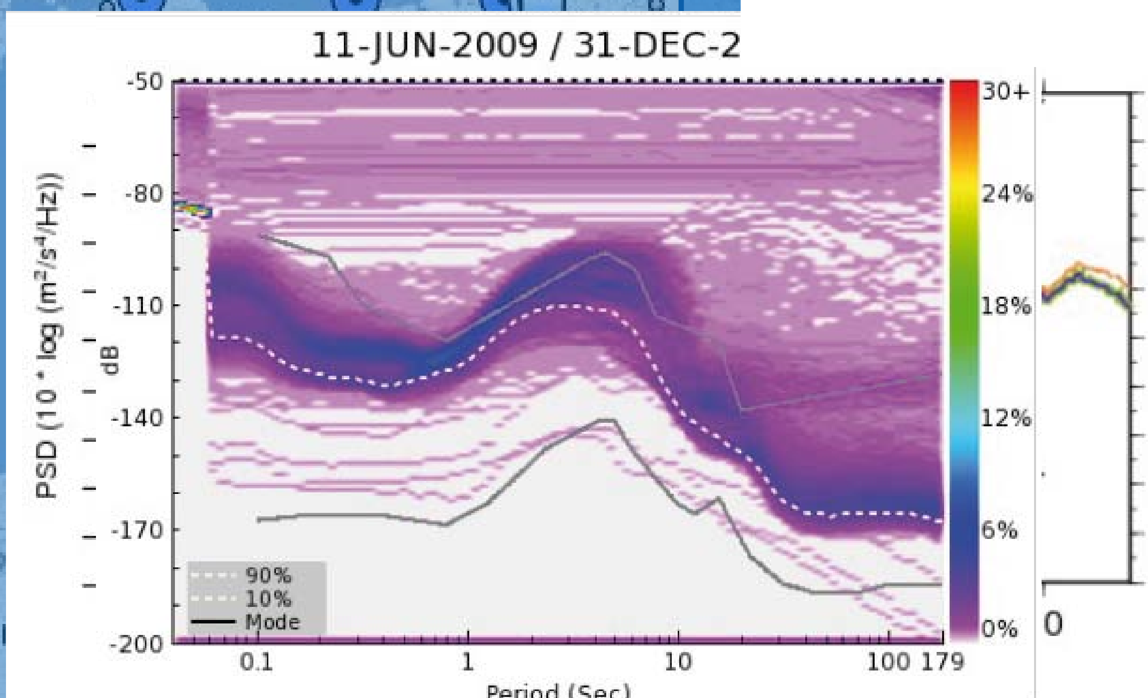

Mark Beker

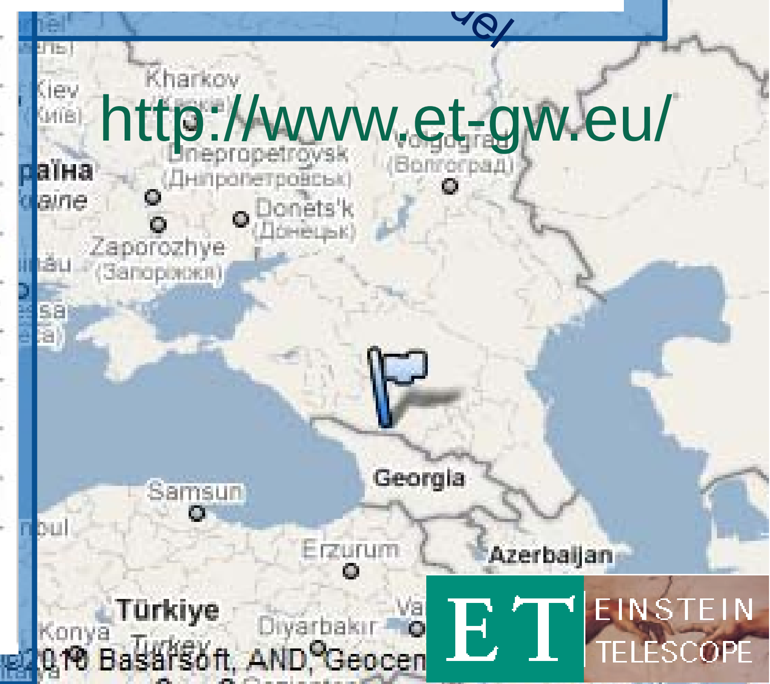
Site list criteri



Credits: J.v.d.Brand







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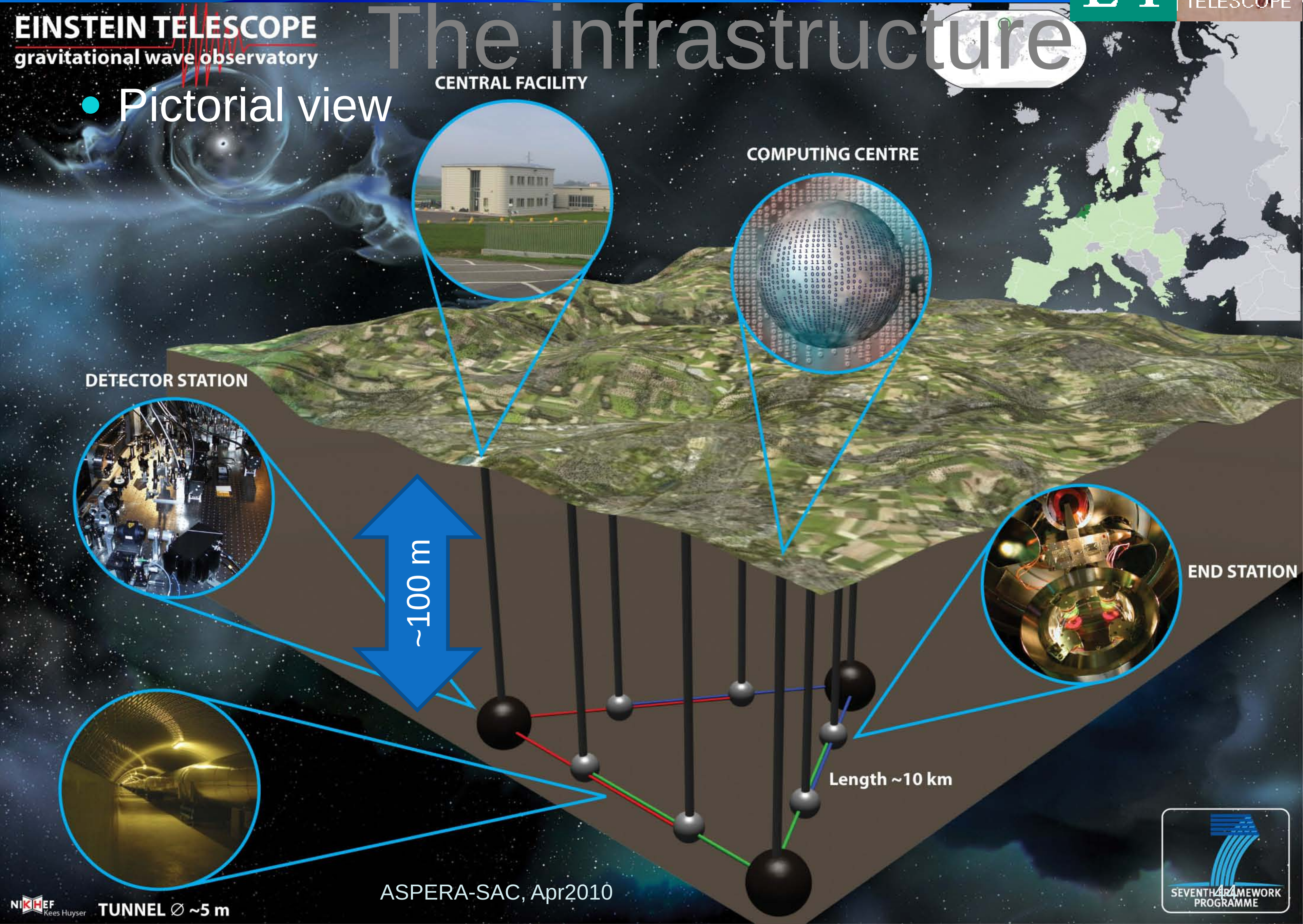
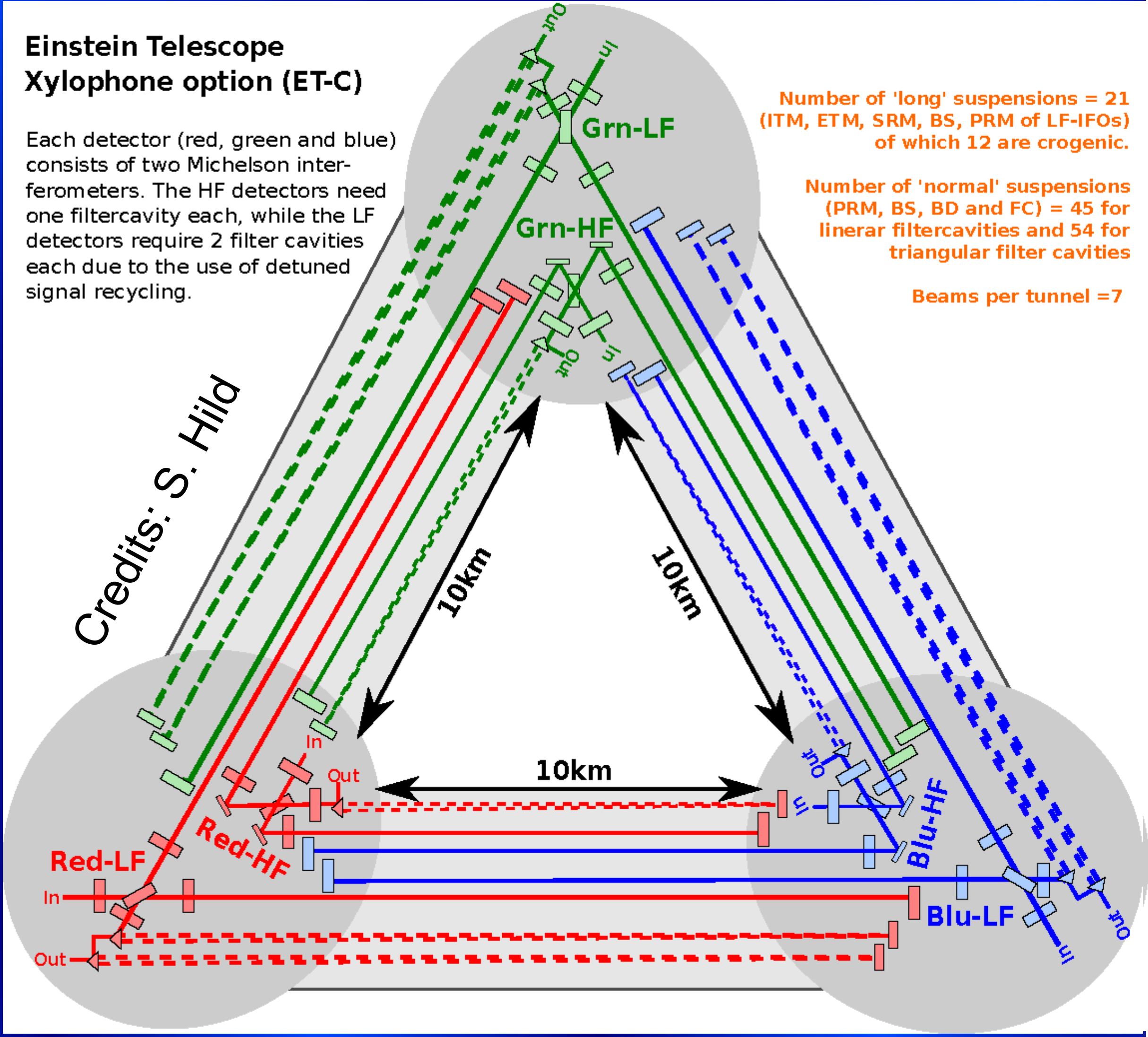
The infrastructure

- Pictorial view



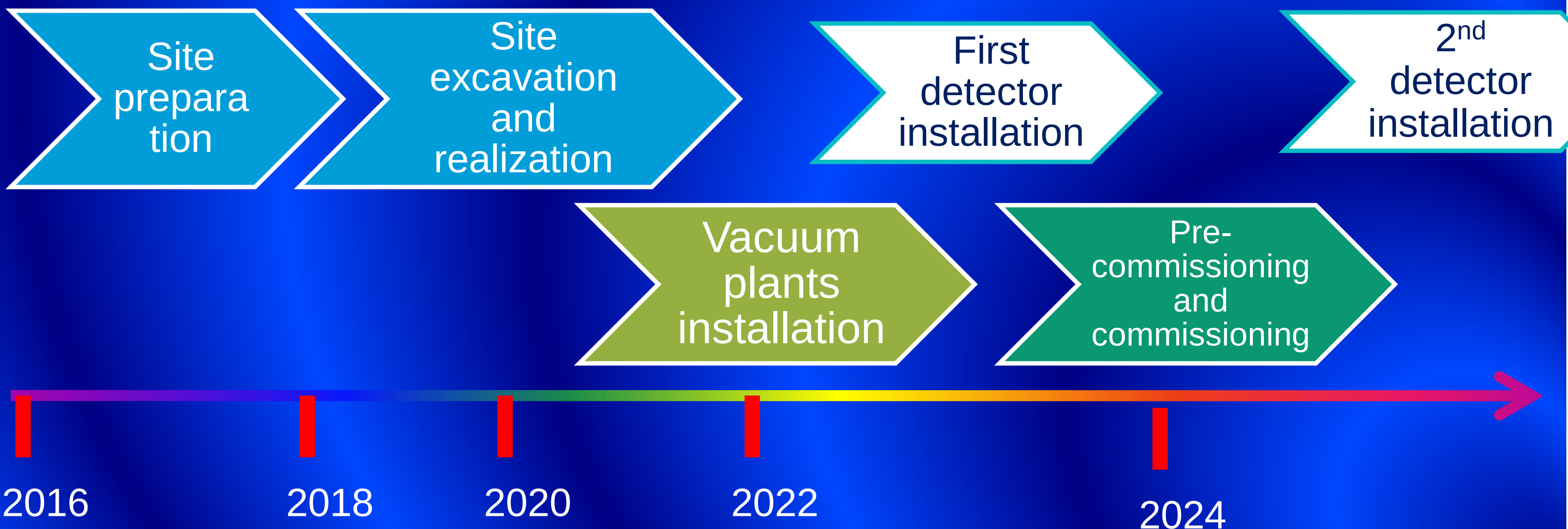
The infrastructure

- Schematic view
- Full infrastructure realized
- Initial detector(s) implementation
  - 1 detector (2 ITF)
  - Physics already possible in coincidence with the improved advanced detectors
- Progressive implementation
  - 2 detector (4 ITF)
  - Redundancy and cross-correlation
- Full implementation
  - 3 detector (6 ITF)
  - Virtual interferometry
  - 2 polarizations reconstruction



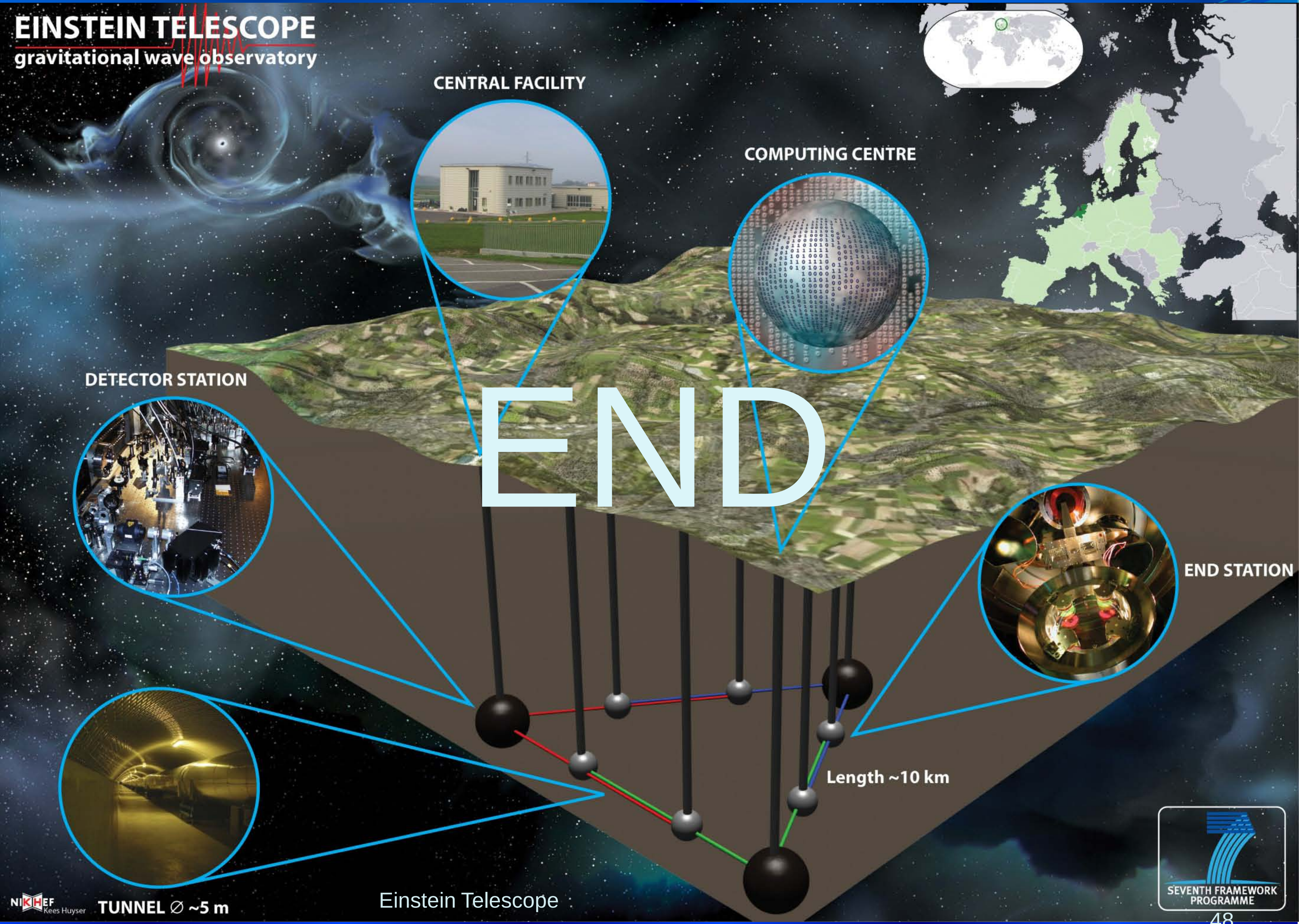
ET Timeline

- The t_0 depends by several constrains:
  - Readiness of the project (completion of the design studies)
  - Detection of GW in Advanced detectors (2017?)
  - Formal decisions
  - …
- We suppose to have a construction t_0=2018, having a decision t_0'=2016-2017



Conclusions

- ET project is really ambitious
  - Huge European infrastructure
  - Large technological difficulties
  - Very appealing science
- Many steps still in front of us
  - Conceptual design, Technical design, Preparatory phase, …
- Currently ET is in several international roadmaps:
  - GWIC, ASPERA, OECD
  - But the competitors are many and strong
- A long exciting research path is in front of us


EINSTEIN TELESCOPE
gravitational wave observatory
CENTRAL FACILITY
COMPUTING CENTRE
DETECTOR STATION
END STATION
Length ~10 km
TUNNEL ∅ ~5 m
NIKHEF
Kees Huyser
SEVENTH FRAMEWORK PROGRAMME

END