Gravitational Waves

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1) Introduction

2) Working Principle

3) VIRGO detector

4) The Future

What are Gravitational Waves ?

A gravitational wave is a perturbation to the space-time metrics propagating at the speed of light

$$\begin{pmatrix} -1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$R_{ij} - \frac{1}{2} g_{ij} R^{\lambda}{}_{\lambda} = -\frac{8\pi G}{c^4} T_{ij}$$

Einstein Field Equations

$$g_{ik} \approx \eta_{ik} + h_{ik} \qquad |h_{ik}| \ll 1$$

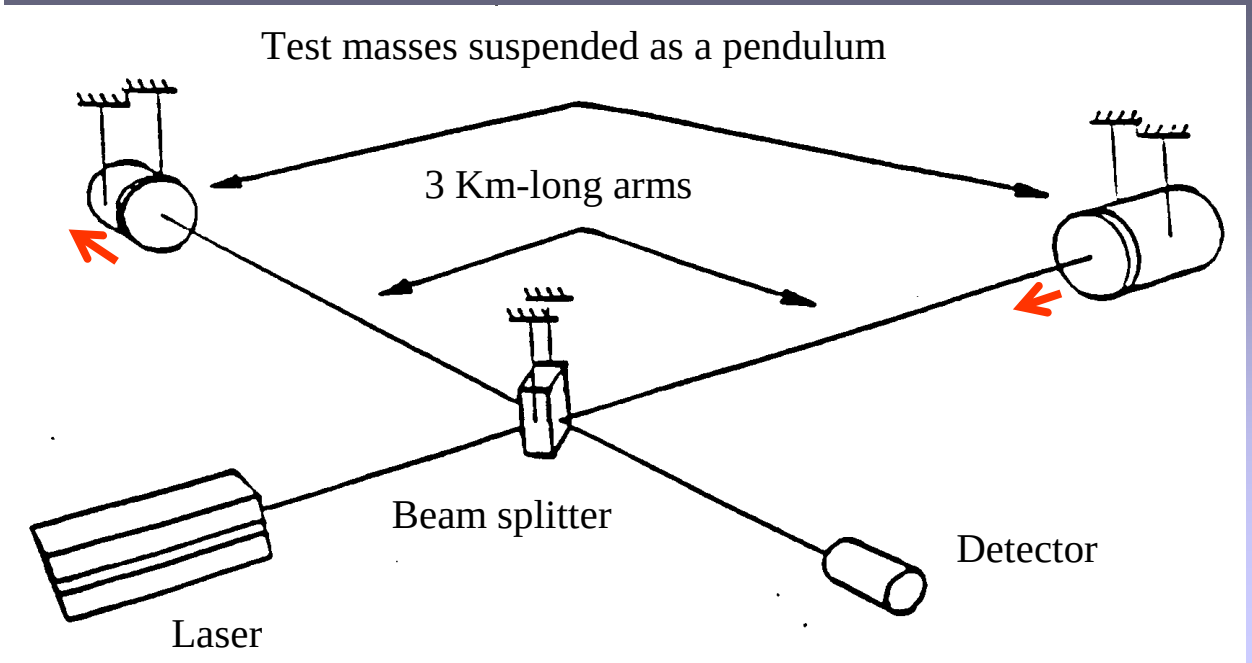
Weak Field Approximation

$$\Box h_{ik} = 0$$

In a vacuum…….

Wave Equation ruling the evolution of the perturbation

Effect on a suspended interferometer



$$\Delta L(t) \approx h(t) L$$

$L \sim 10^{3}$ m

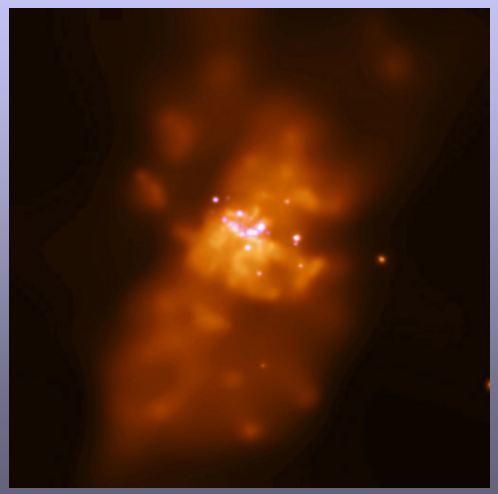
$\Delta L \sim 10^{-18}$ m

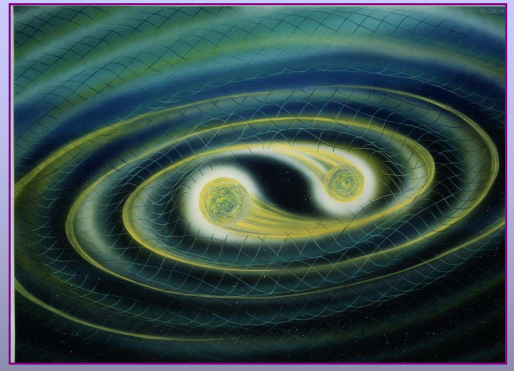
$h \sim 10^{-21}$

(Supernova)

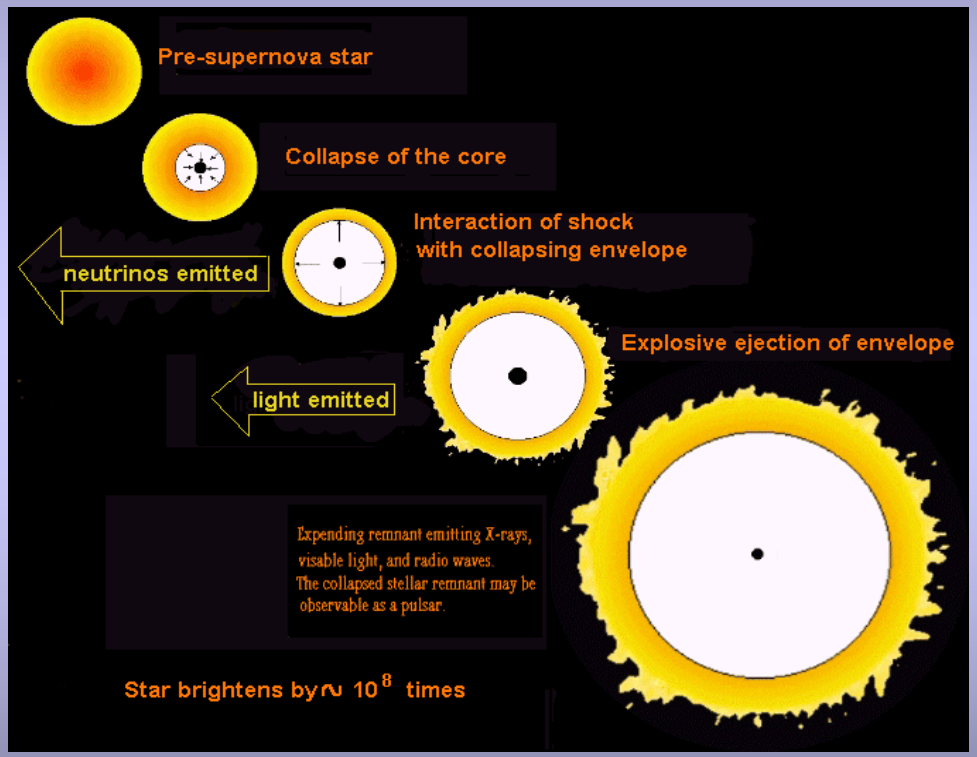
Sources of GW burst … detectable by ITF

- Massive star collapses
- Instabilities in newborn neutrons stars
- Mergers of couples of compact stars
- Black hole ring down
- Others ….





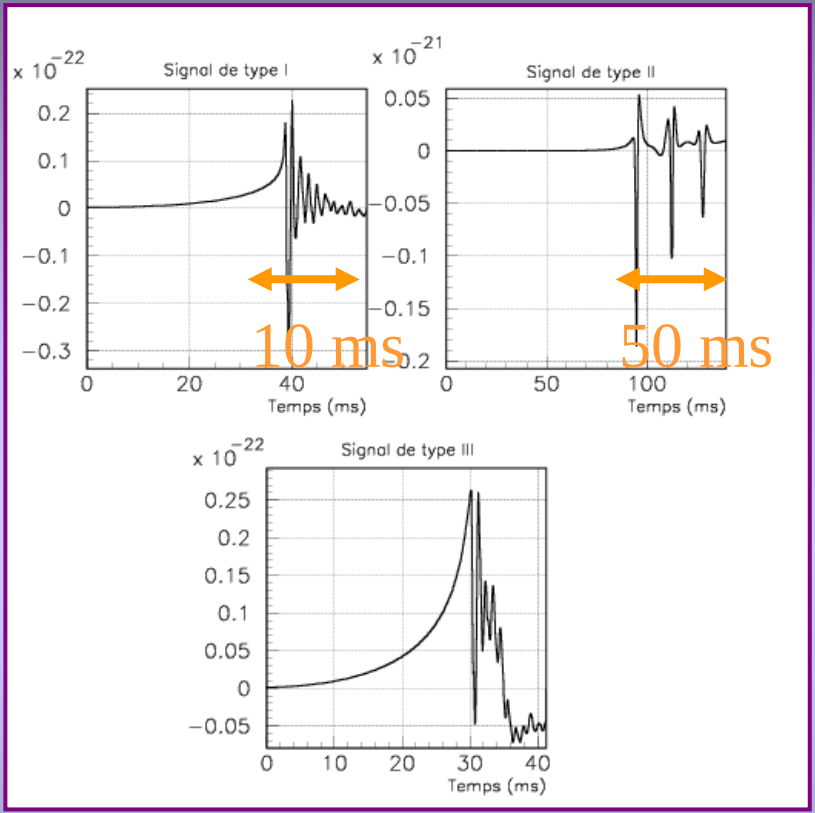
Sources

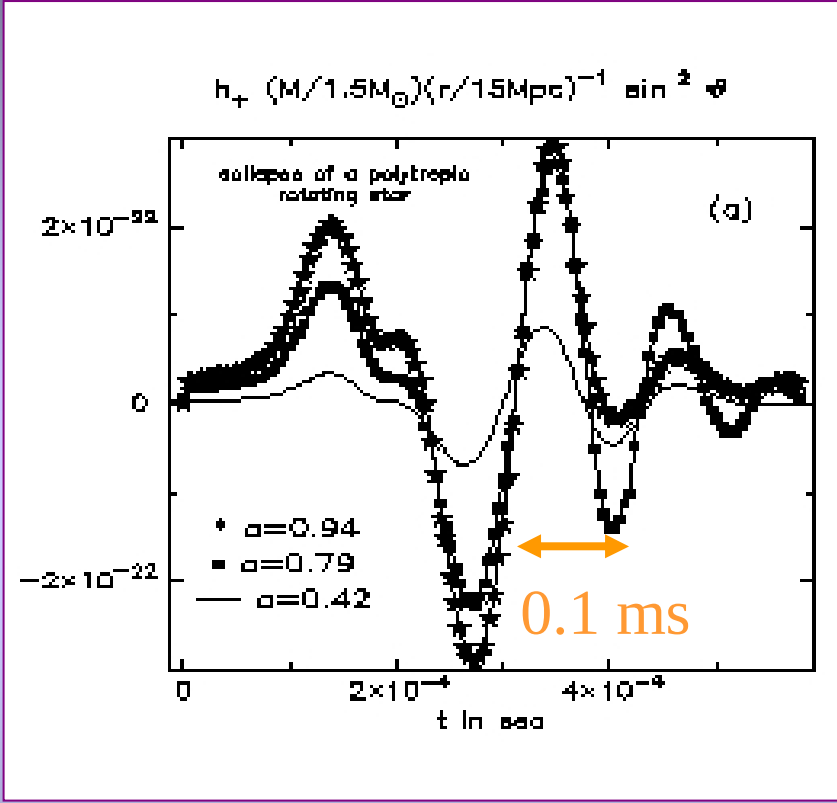


Supernova Bursts

Pulse of ms duration
(no template available)

Some waveforms



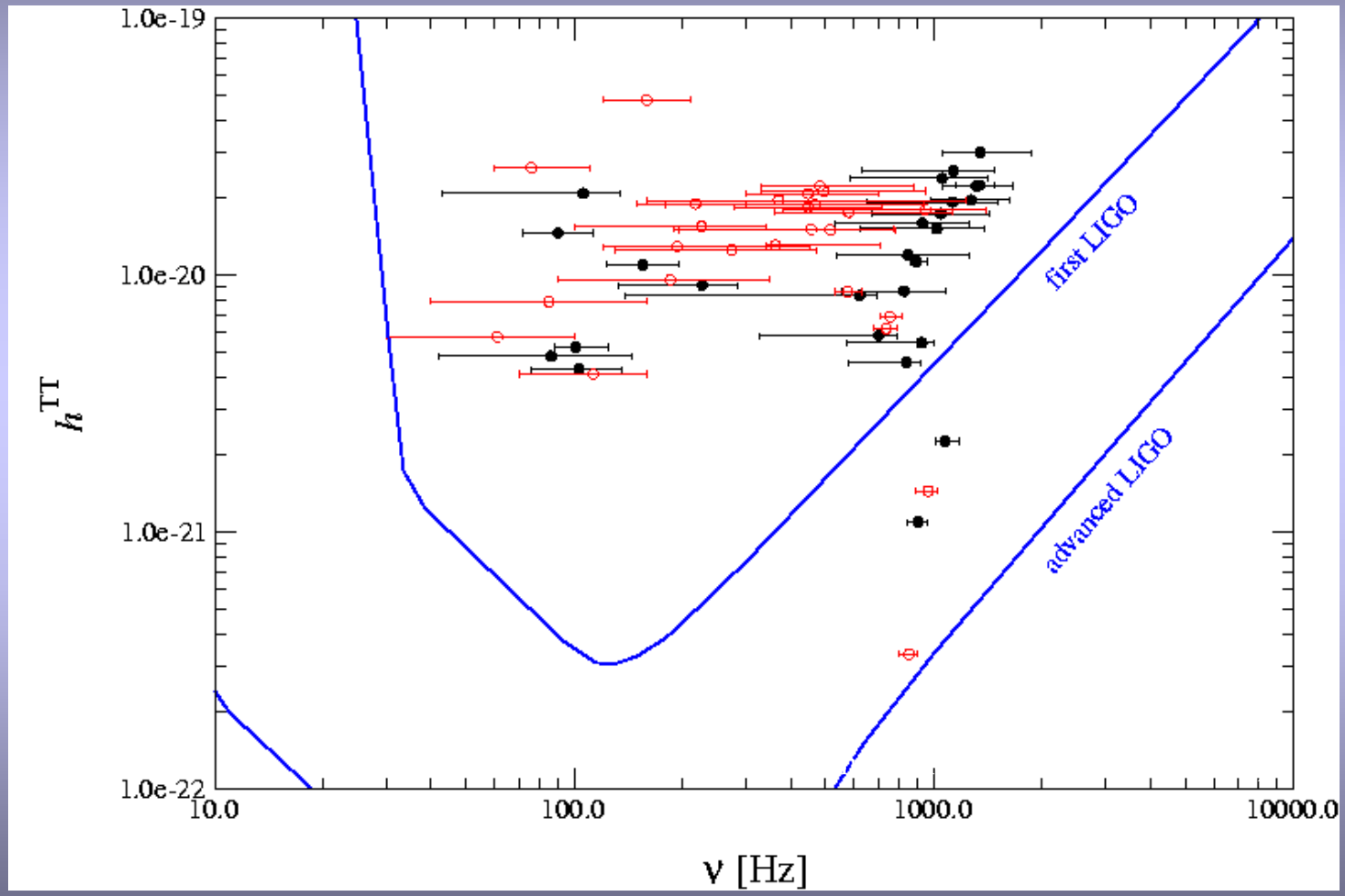


Type II supernovae: amplitude simulated
by Zwerger & Muller (A&A 97)
by Dimmelmeir et al (A&A 02)

Collapse to Black Hole:
Stark & Piran (PRL 95)

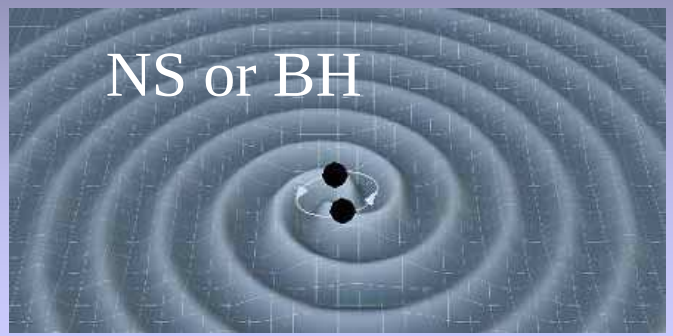
Predictions are not robust →huge variety of waveforms!

Models core collapse simulation GW strength



Sources @ 10 kpc

Sources

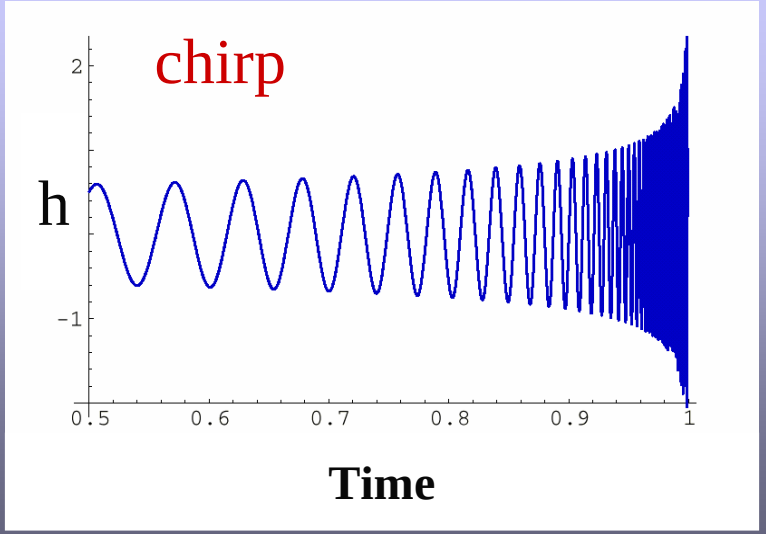


Coalescing Binaries

…minutes…

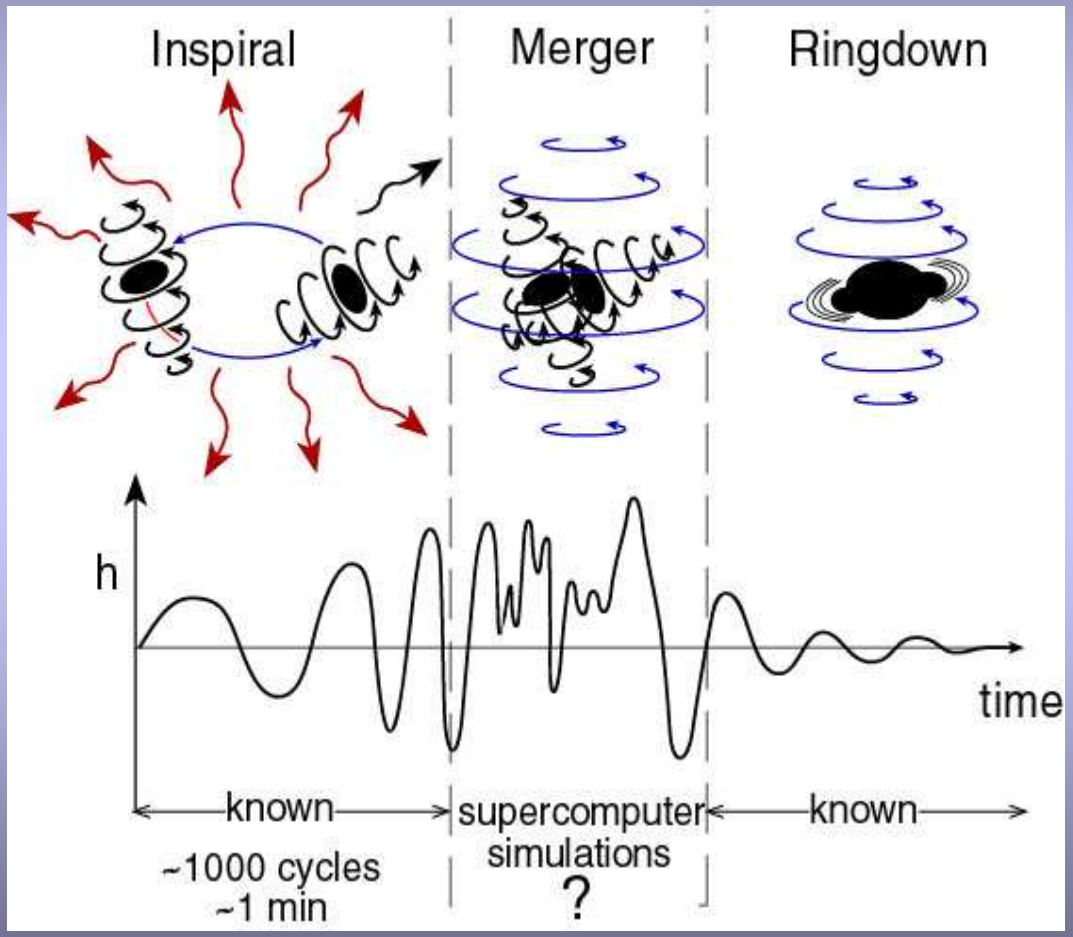
Hz ⟶ kHz

Signals can be exactly computed
(except for final part)



Mergers of compact stars

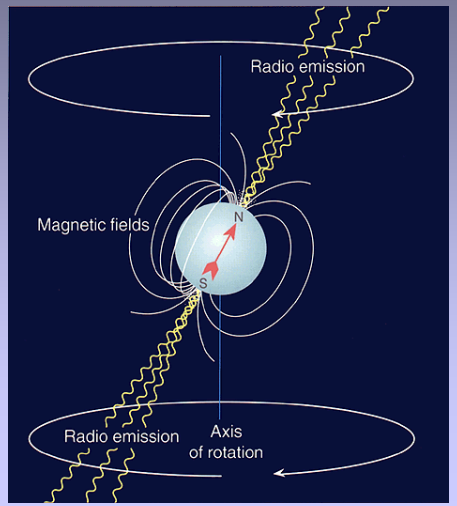
unknown waveform !



known waveform:
Damped sine and cosine !

Sources

Neutron Stars

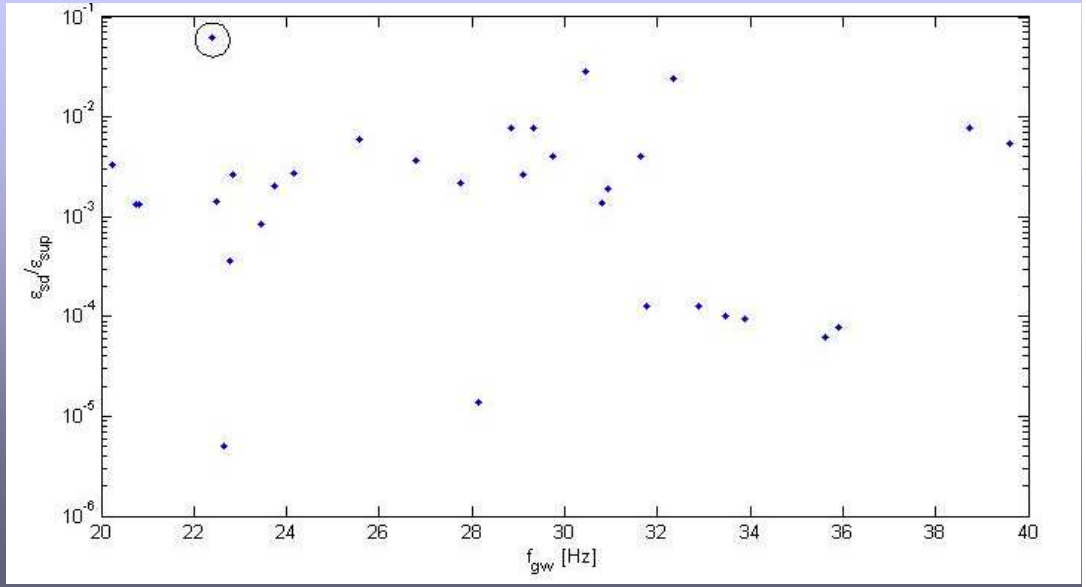


Emits periodic signals at $f=2f_{spin}$ but ….weak

$$h \approx 3\cdot 10^{-27}\left(\frac{10\,\mathrm{kpc}}{r}\right)\left(\frac{I}{10^{45}\,\mathrm{g\,cm^2}}\right)\left(\frac{f}{200\,\mathrm{Hz}}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

SNR can be increased by integrating the signal for long time (months)

Importance of the low frequency sensitivity (Hz region)



Wide variety of signals expected between fraction of Hz and a few kHz

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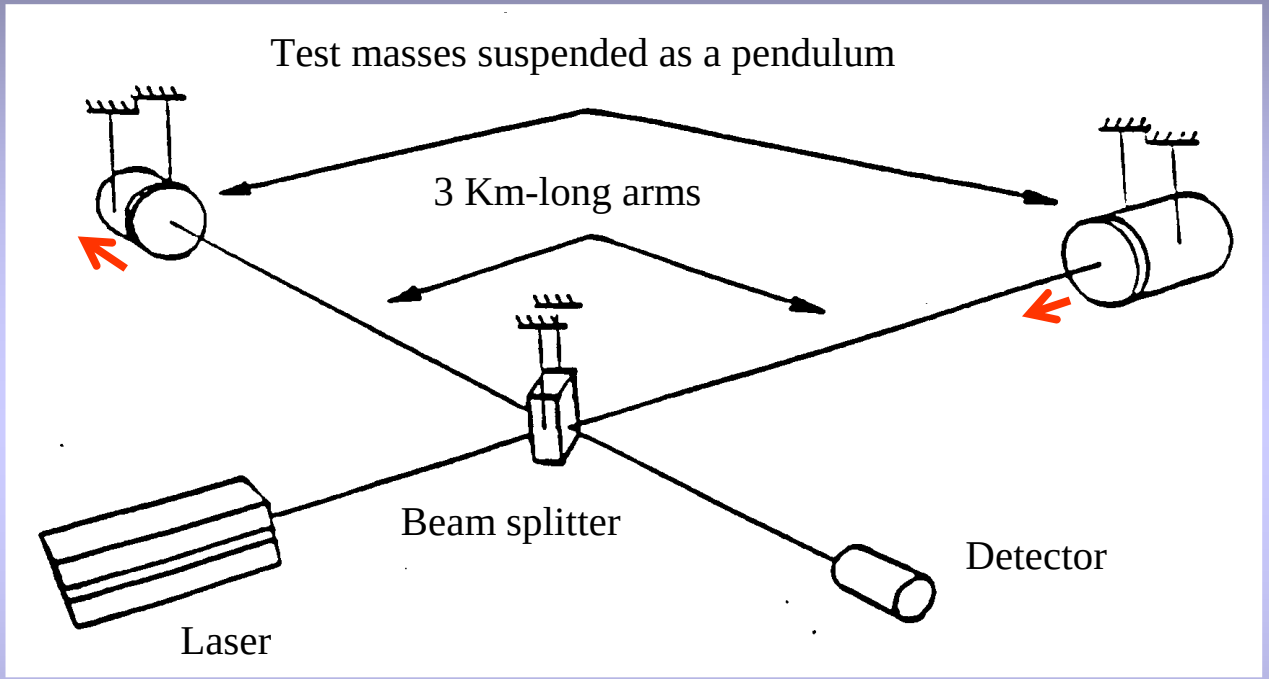
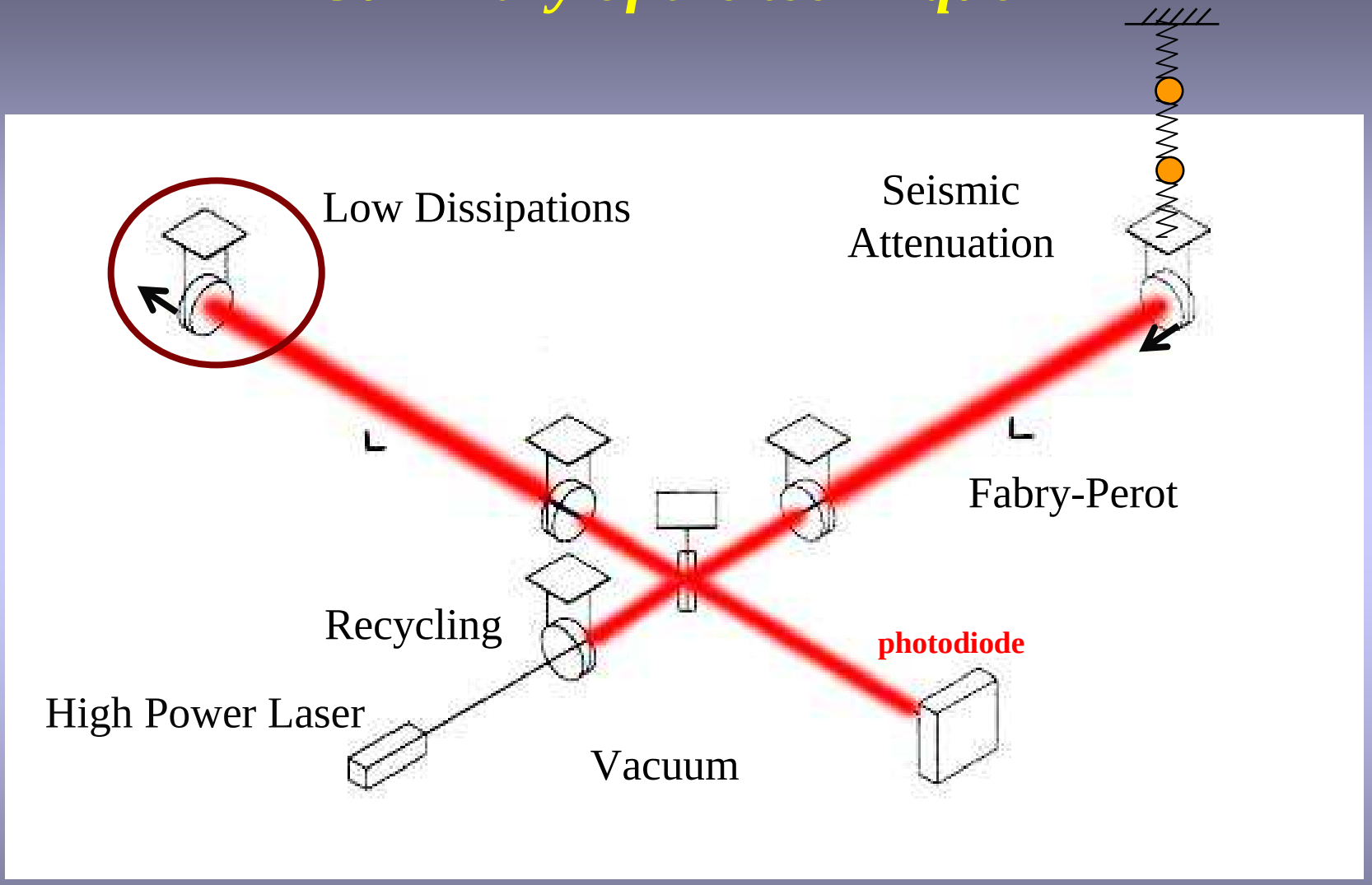
A simple detector



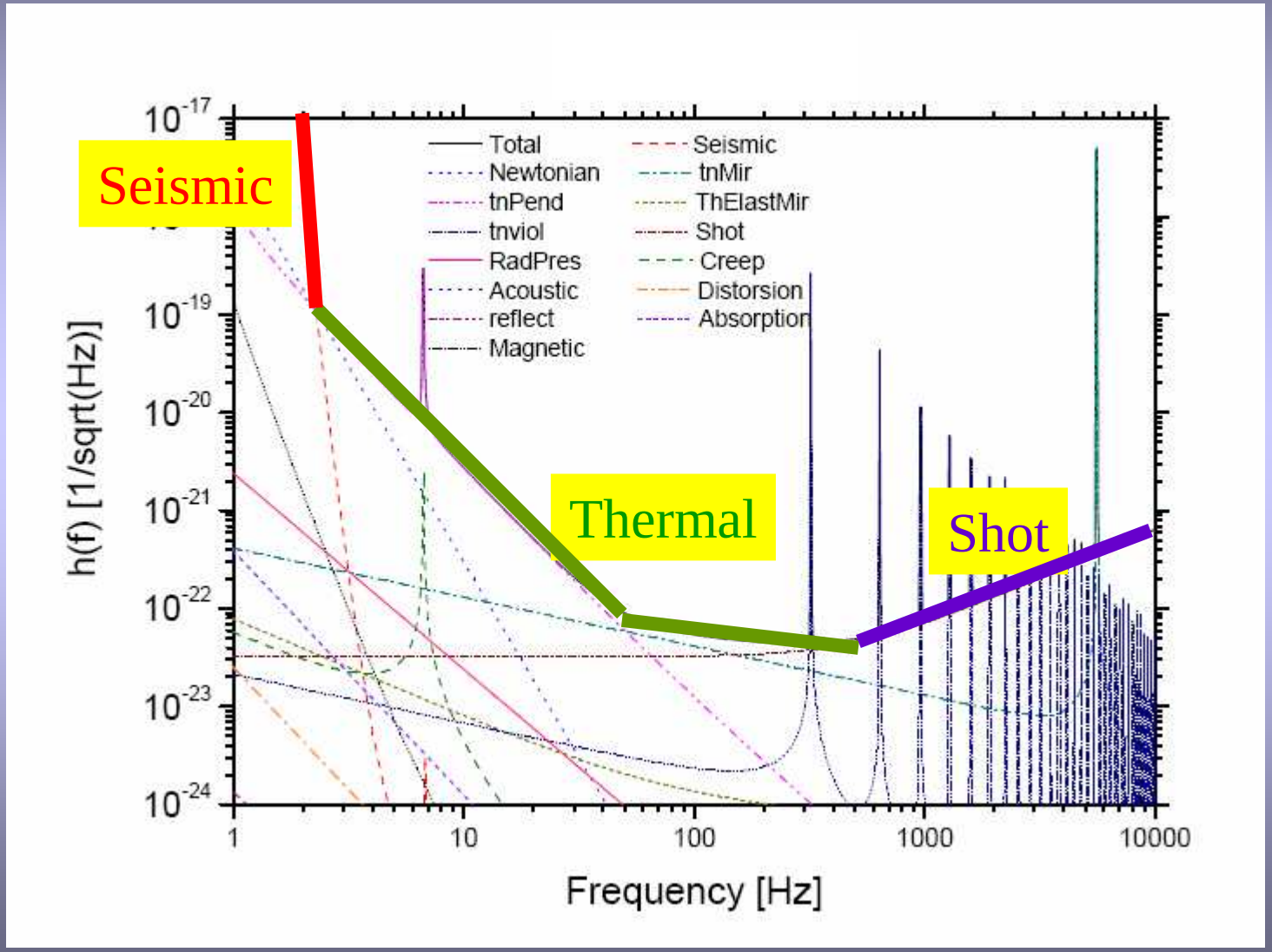
$$\Delta\phi(t) \approx \frac{4\pi}{\lambda} L \cdot h(t)$$

$h = 10^{-21} \Rightarrow \phi_{gw} = 3 \cdot 10^{-11}$ *rad*

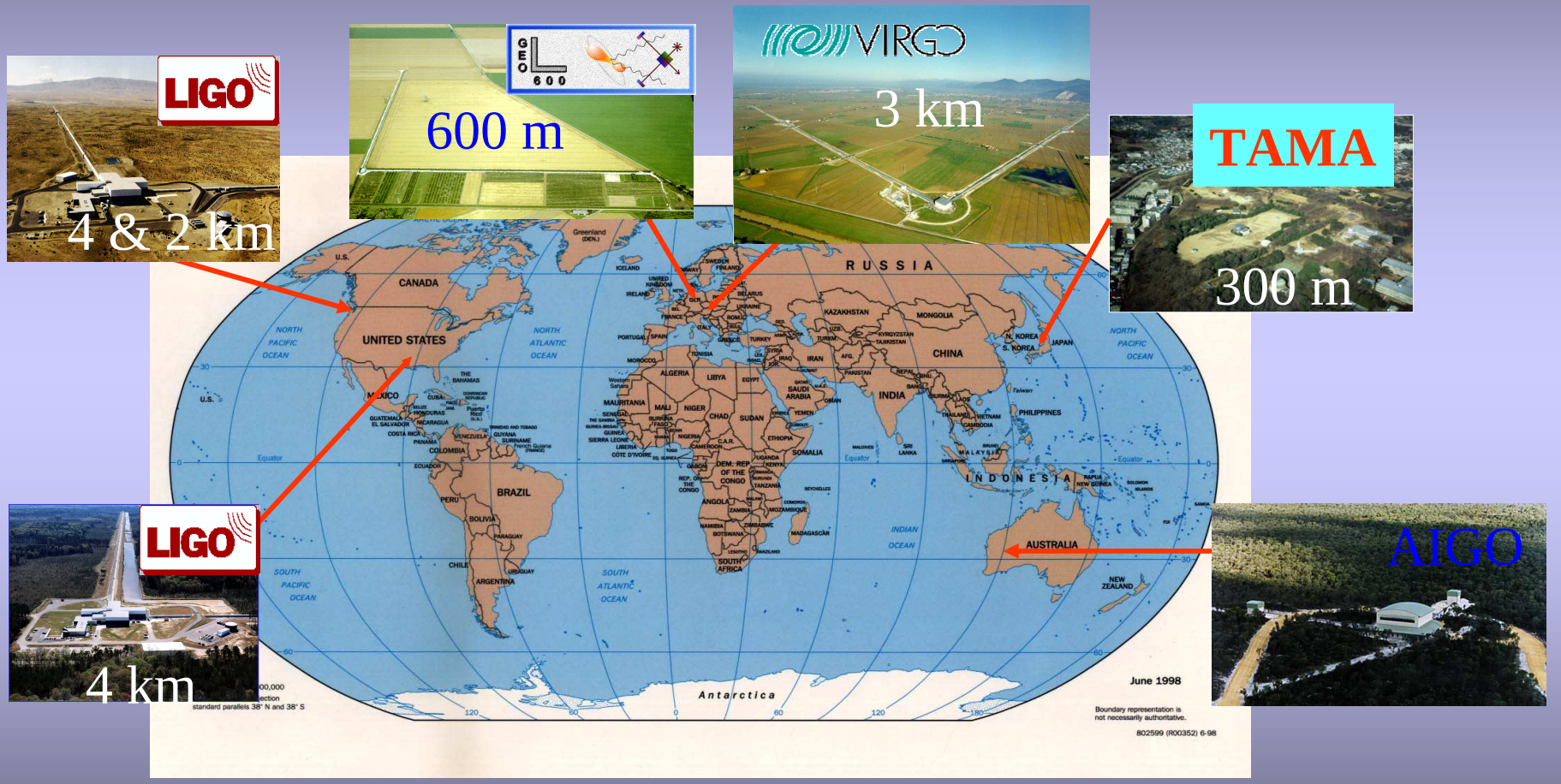
Summary of the technique



What is a sensitivity curve ?



Ground-Based Network



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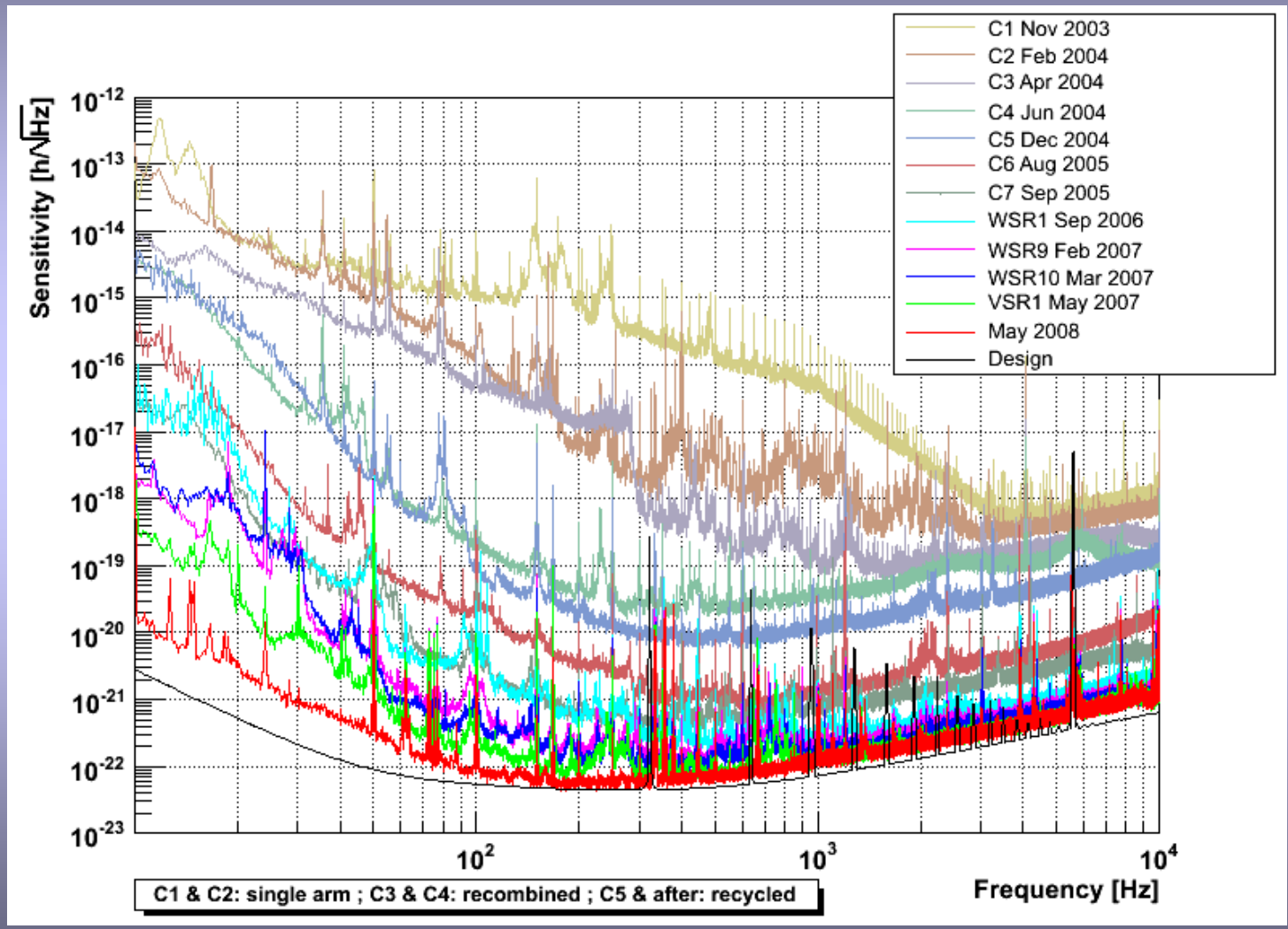
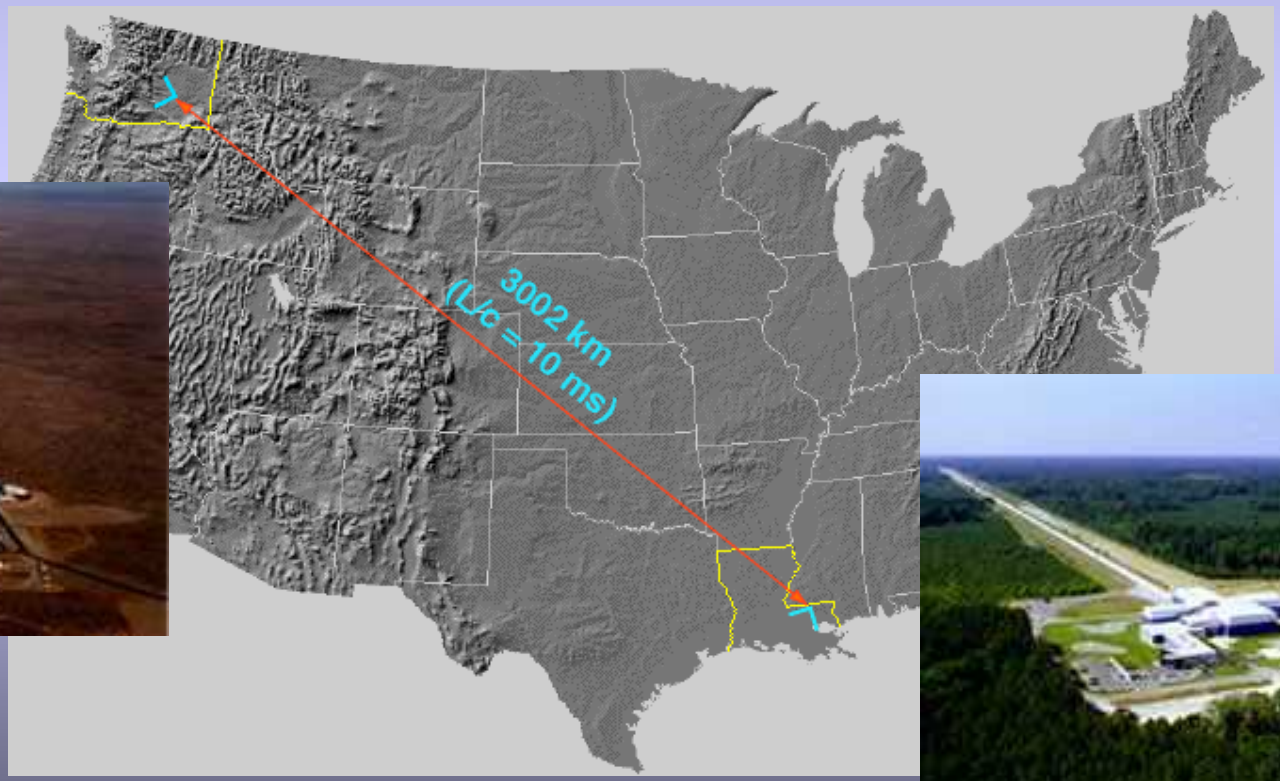
VIRGO

VIRGO Sensitivity Evolution

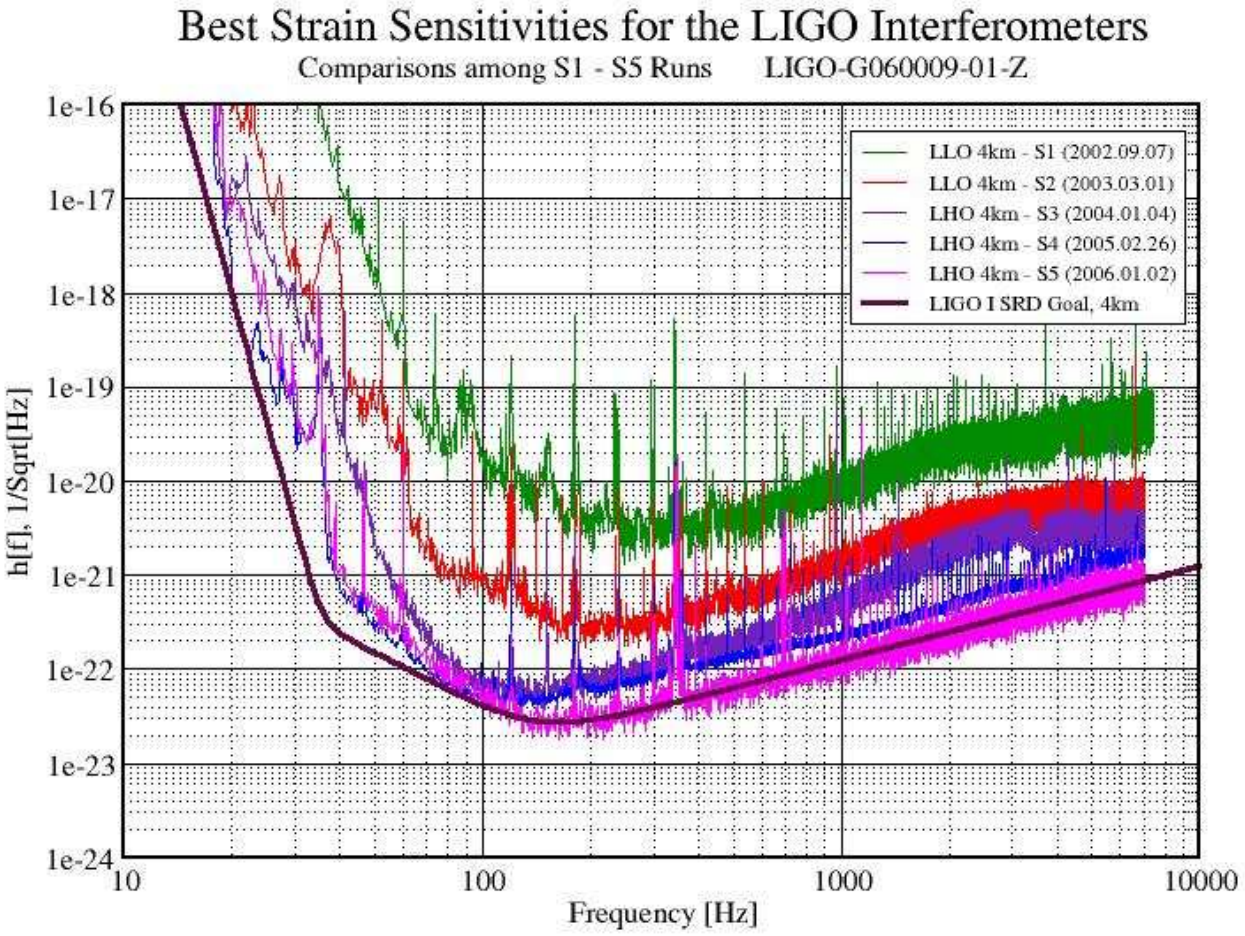


LIGO

- 3 ITF: Hanford (4 km, 2 km), Livingston (4 km)
- Same optical scheme as VIRGO, simpler suspensions
- Five science runs performed

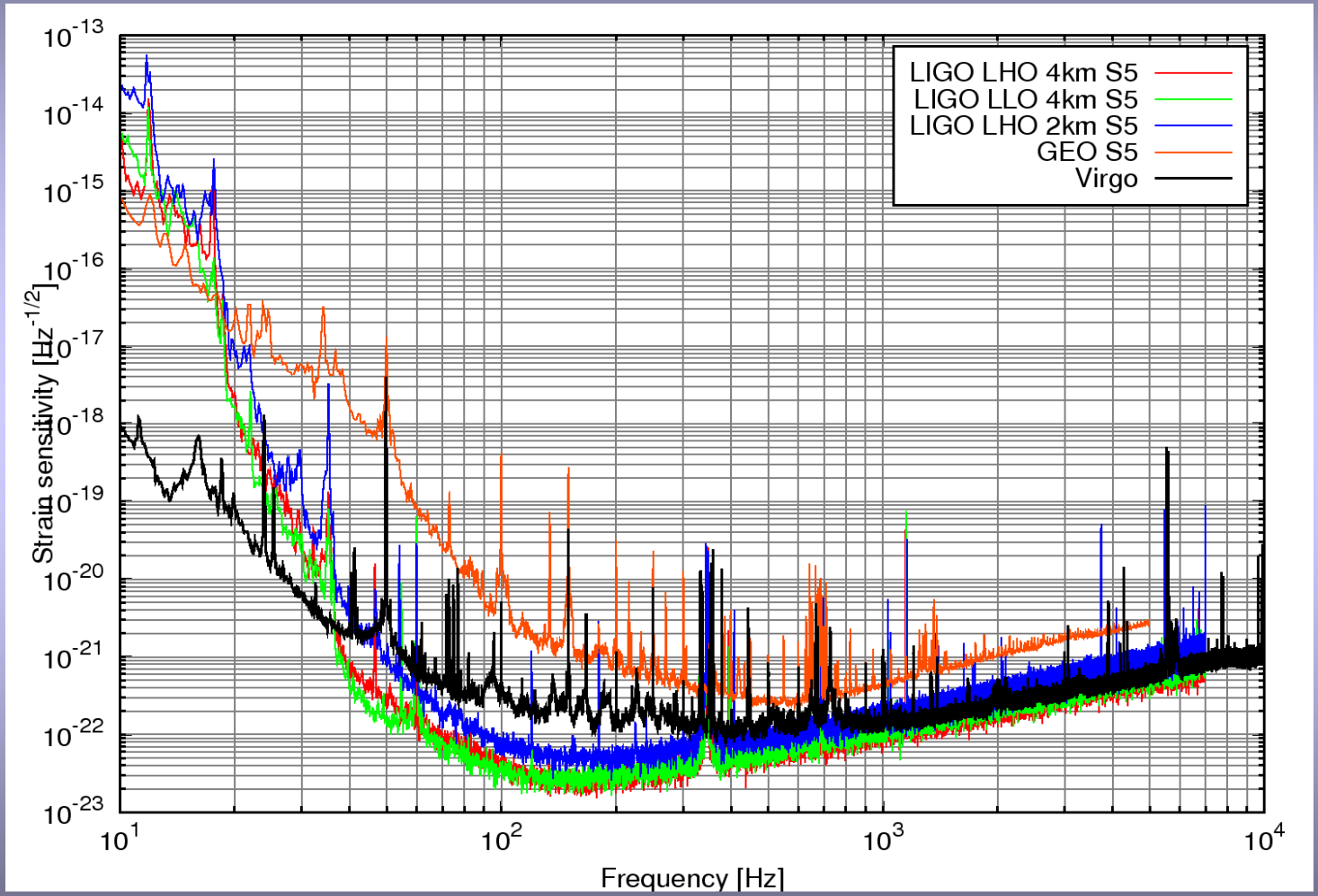


LIGO Commissioning



LIGO in action at the design sensitivity

VSR1 Start - 18 May 2007



LSC-VIRGO Agreement

Data Analysis Joint Working Groups

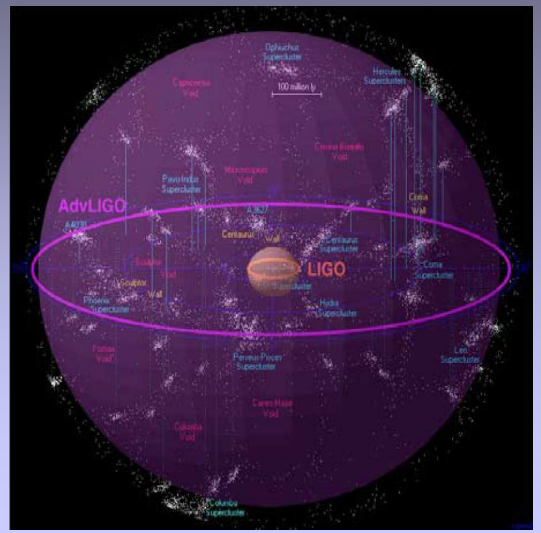
Coalescing binaries

Bursts

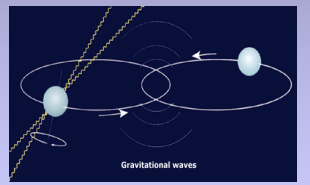
Continuous Waves

Stochastic background

Limited Detection Potentiality

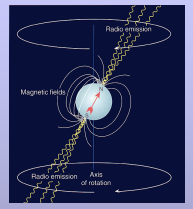


Coalescing Binaries (Horizon 32 Mpc):
1/70 years



Supernovae (Just Galaxy):
1/100 years

Galaxy Neutron Stars (only upper limits)



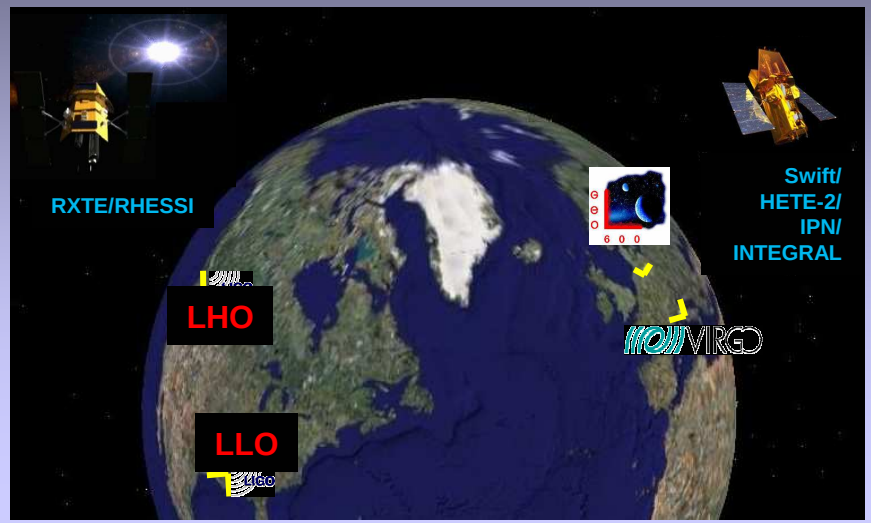
Astrophysical Event Triggered Searches

Gamma-ray transients (GRBs, SGRs)

Optical transients

Neutrino events

…



Correlation in time

Correlation in direction

Information on the source properties

…

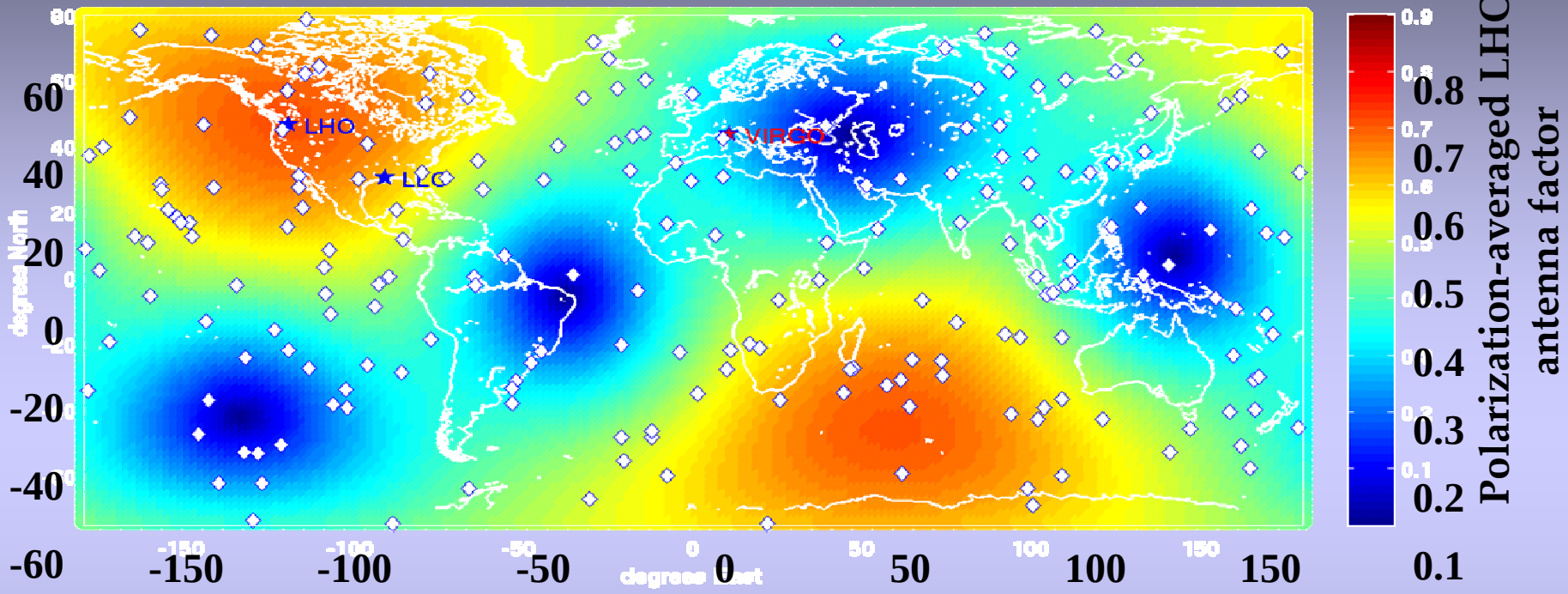
Confident detection of GWs (eventually).

Better background rejection, Higher sensitivity to GWs.

More information about the source/engine.

Even upper limits can have interesting implications.

213 GRB triggers from Nov. 4, 2005 to Sept. 30, 2007



- GRB triggers **(mostly from Swift, IPN, INTEGRAL, HETE-2)**

  - **~70% with double-IFO coincidence LIGO data**
  - **~40% with triple-IFO coincidence LIGO data**
  - **~25% with measured redshift**
  - **~15% short-duration GRBs**

Astrophysical observation based search for association between gravitational waves and short hard GRBs (in the context of compact binary inspirals)

EM Observations - GRB 070201

detected by Konus-Wind, INTEGRAL, Swift, MESSENGER

- Described as an *"intense short hard GRB"* (GCN 6088)
- Duration ~0.15 seconds, followed by a weaker, softer pulse with duration ~0.08 seconds
- R.A. = 11.089 deg,
  Dec = 42.308 deg,
  error = 0.325 sq. Deg
- **E_{iso} ~ 10^{45} ergs if at M31 distance** (more similar to SGR energy than GRB energy)

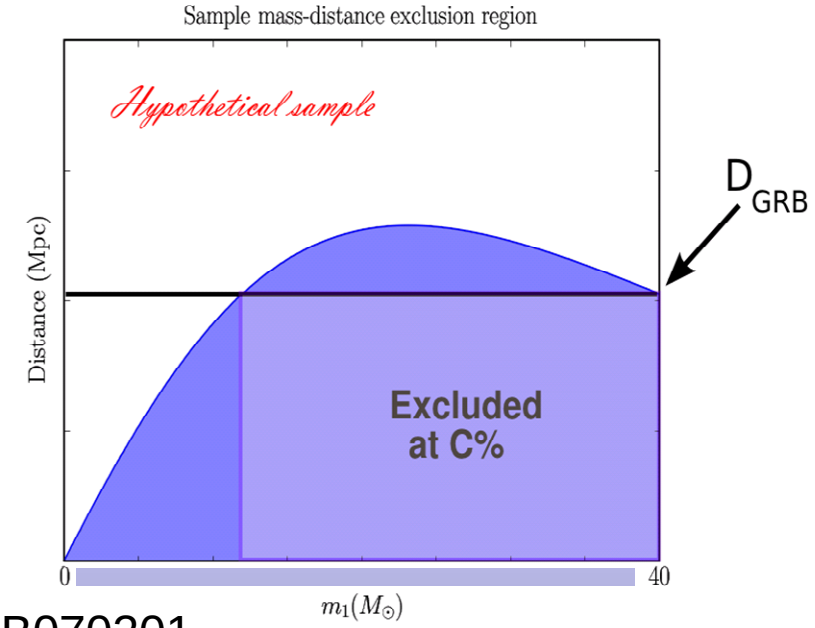
Refs:
GCN: http://gcn.gsfc.nasa.gov/gcn3/6103.gcn3
"…The error box area is 0.325 sq. deg. The center of the box is 1.1 degrees from the center of M31, and includes its spiral arms. This lends support to the idea that this exceptionally intense burst may have originated in that galaxy (Perley and Bloom, GCN 6091)…" from GCN6013

M3
The Andromeda Galax
by Matthew T. Russe
Date Take
10/22/2005 - 11/2/200
Locatio
Black Forest, C
Equipmen
RCOS 16" Ritchey-Chreti
Bisque Paramoune M
AstroDon Series I Filte
SBIG STL-11000
http://gallery.rcopticalsystems.com/gallery/m31.jp

What Can We Learn? -GRB 070201

- In the case of a detection:
  - Confirmation of a progenitor (e.g. coalescing binary system)
  - GW observation could determine the distance to the GR

- No-detection:
  - Exclude progenitor in mass-distance region
  - With EM measured distance to hypothetical GRB, could exclude binary progenitor of various masses
  - Possible statements on progenitor models
  - Bound the GW energy emitted by a source M31



Search for gravitational-waves coincident with GRB070201

- No plausible gravitational waves from compact binary inspiral or short transients were identified that could be related to GRB070201 and inconsistent with the noise
- The achievable sensitivity with the present detectors does not exclude present models of SGRs at the M31 distance
- It is unlikely that a compact binary progenitor in M31 was responsible for GRB070201

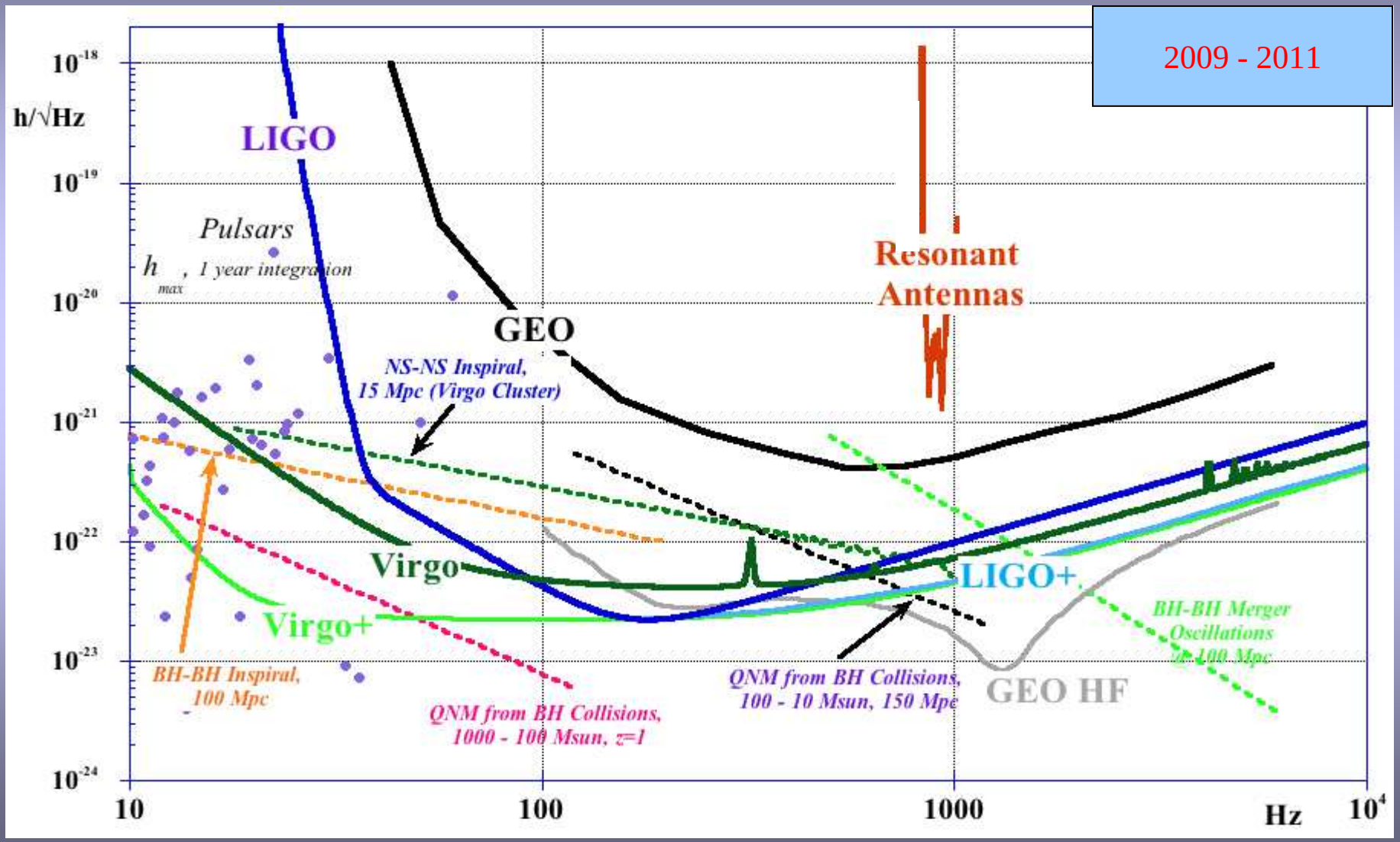
Towards VIRGO+

VIRGO+ Assembly Started (anticipated by a few weeks because of vacuum accident)

1. New laser
2. Mirror thermal compensation
3. Electronics and control system upgrades
4. Monolithic suspension

2009: VIRGO+ Commissioning to start run with Enhanced LIGO

VIRGO+ Sensitivity



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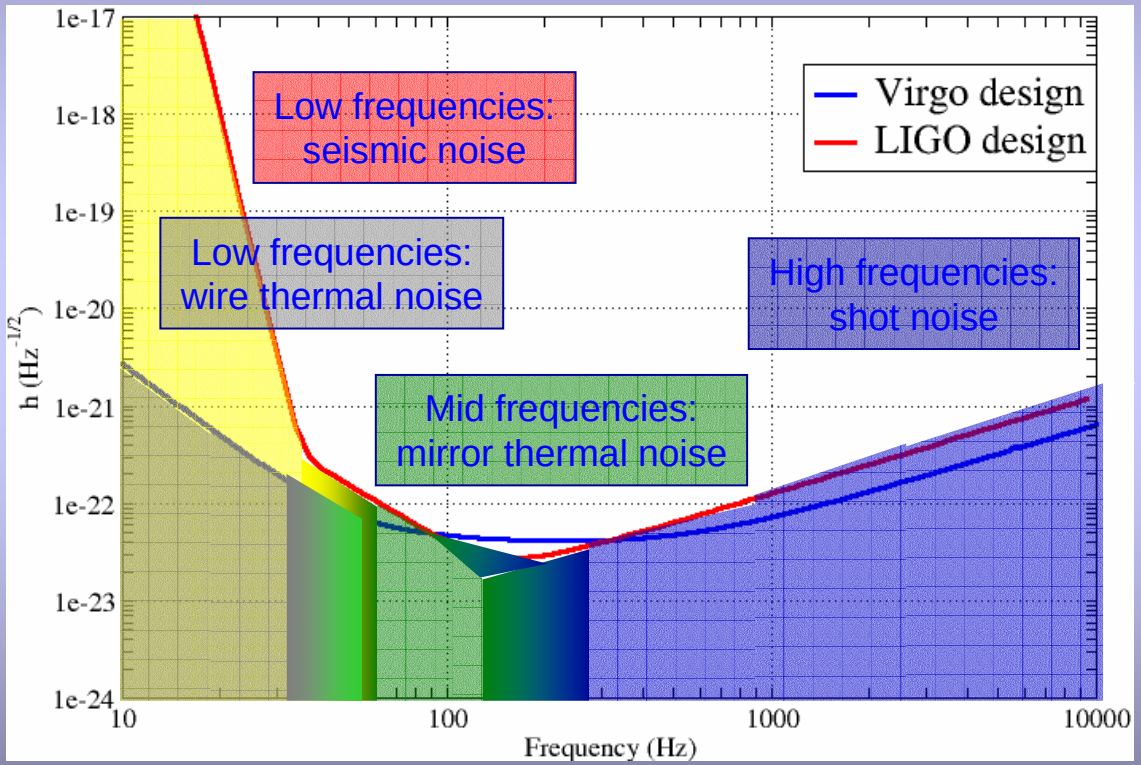
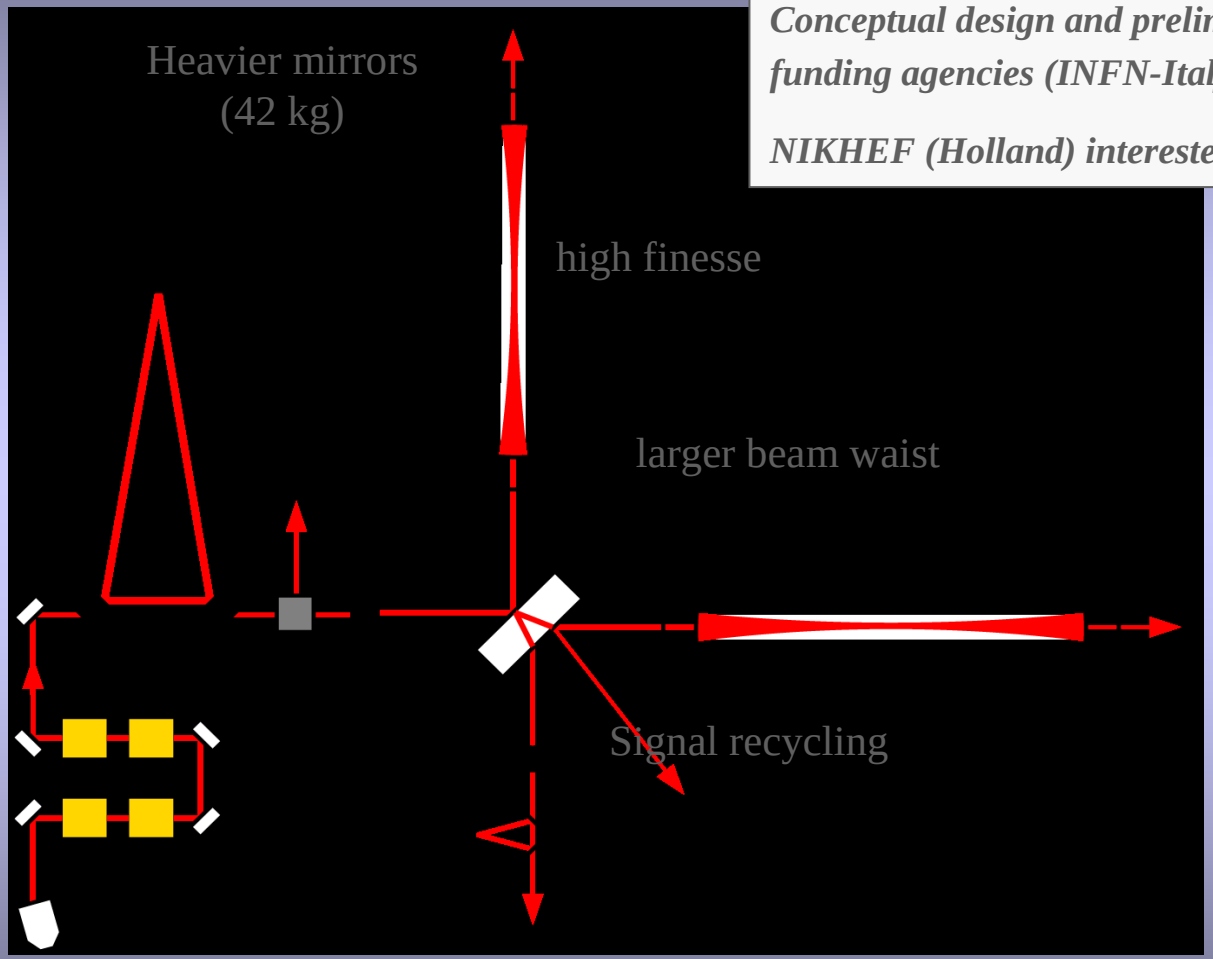
Advanced Plan



Advanced VIRGO Baseline

Conceptual design and preliminary cost plan submitted to funding agencies (INFN-Italy and CNRS-France)

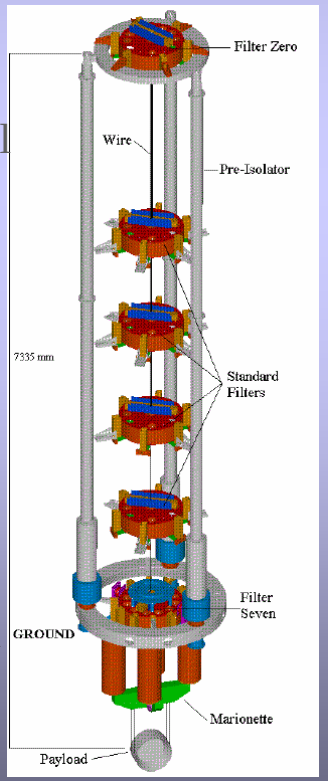
NIKHEF (Holland) interested in the project.



High power SSL
(200 W)

DC detection

New IP
Tilt control

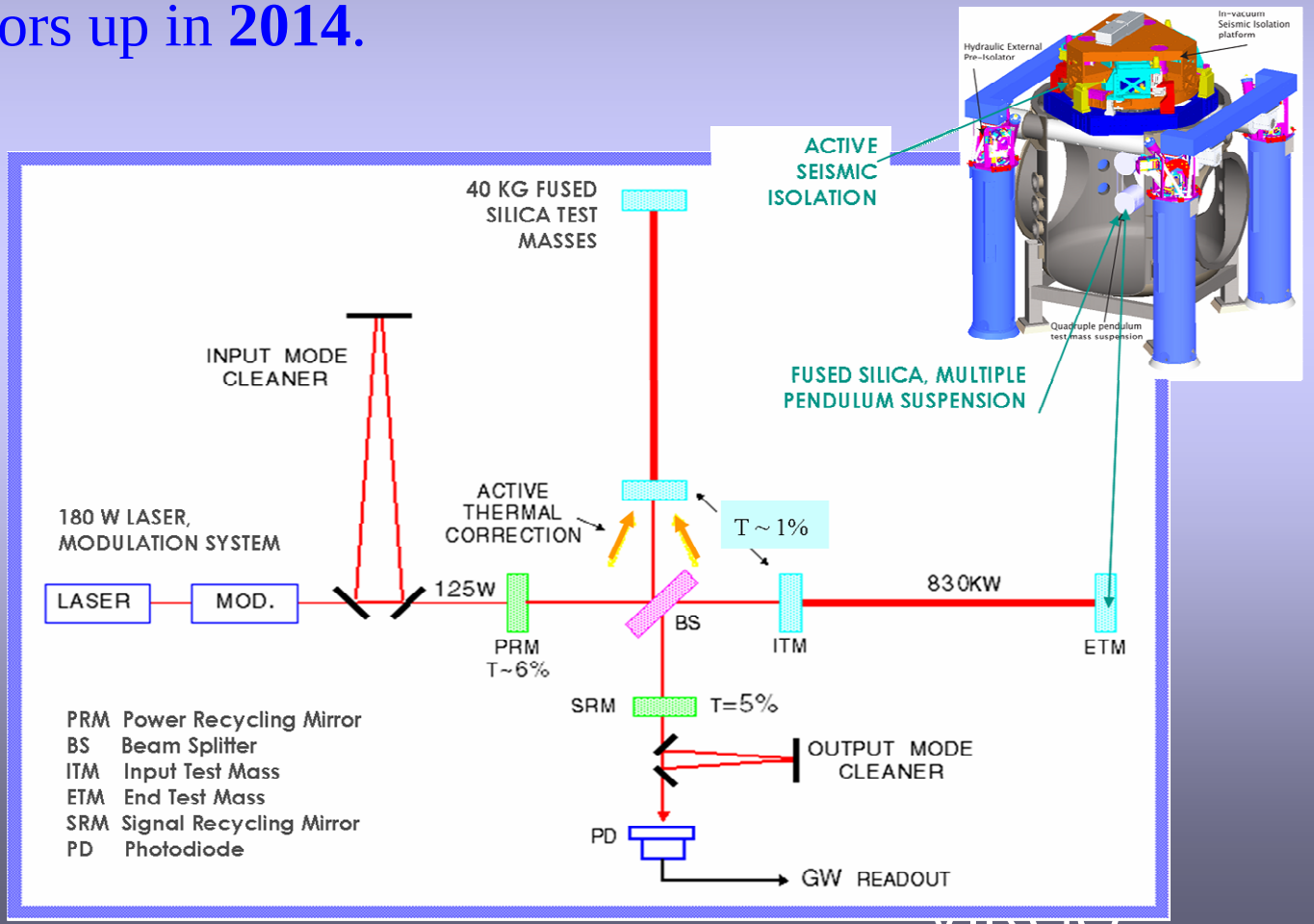


New payload

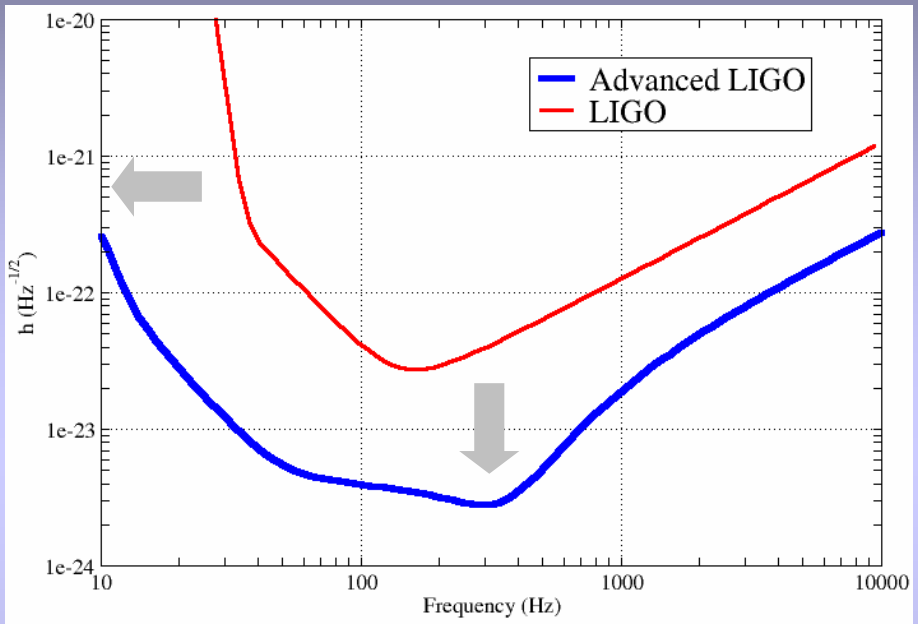
Fused silica
suspensions

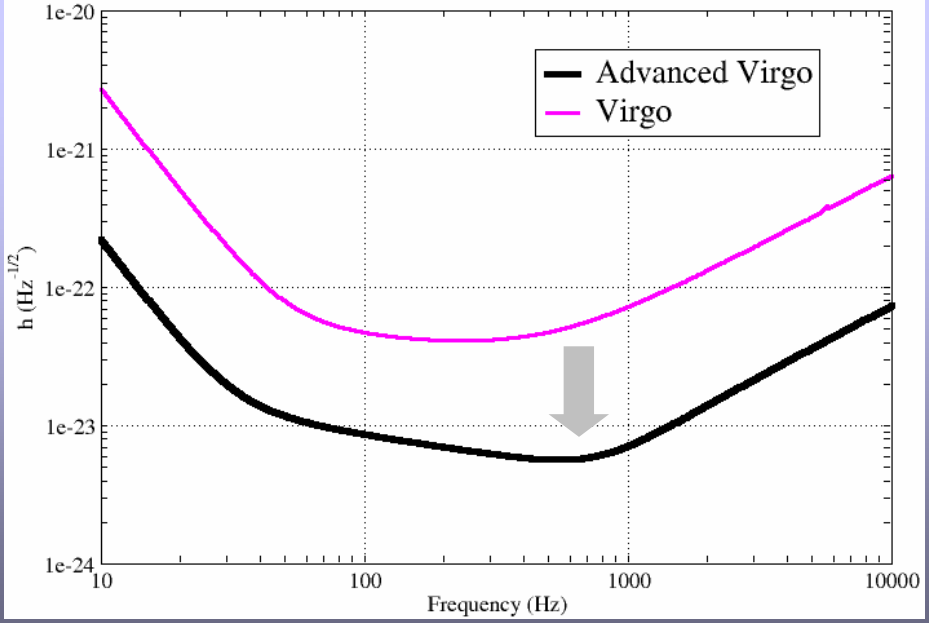
Advanced LIGO

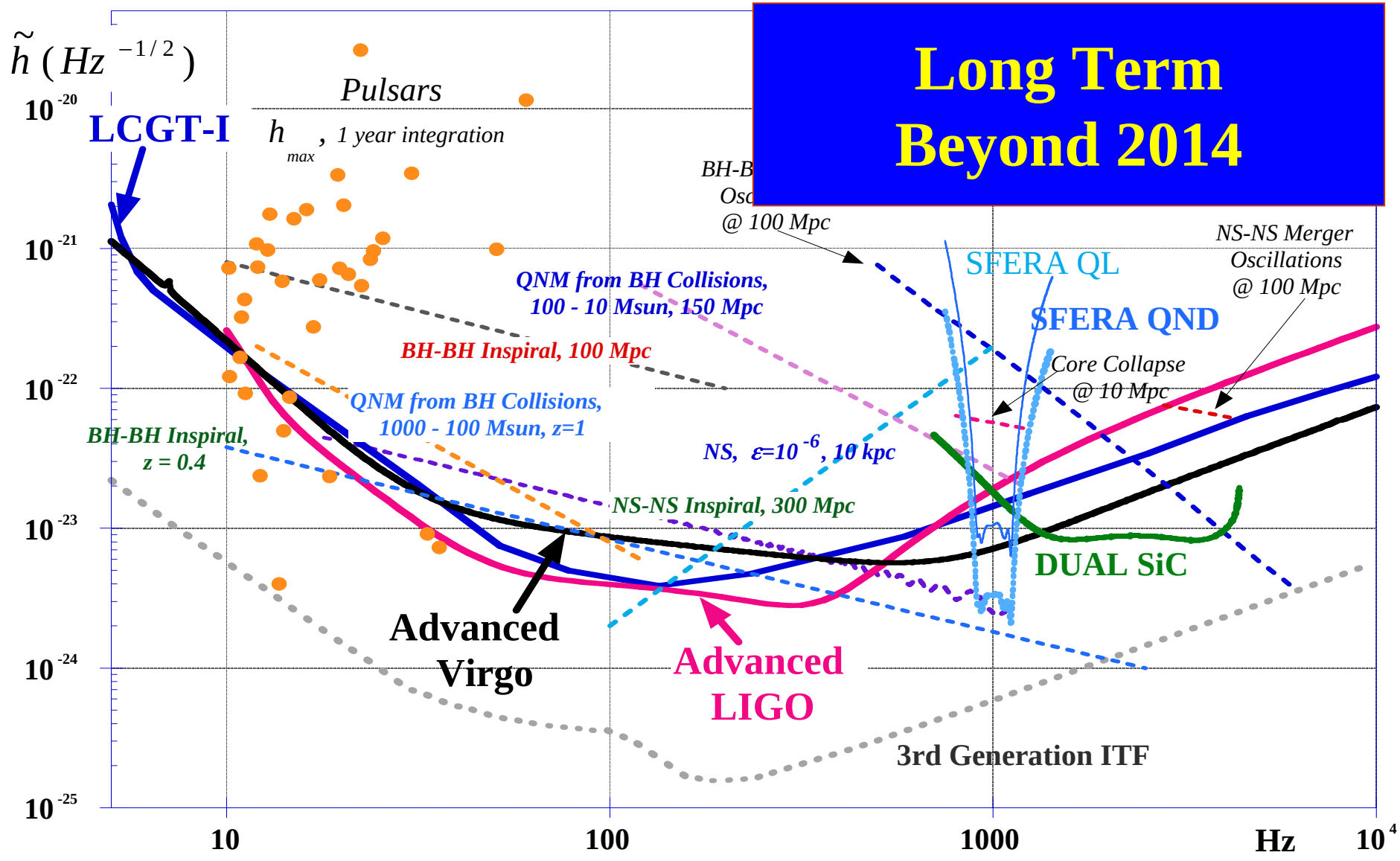
Approved by NSF
READY to start installation in **2011**.
All three detectors up in **2014**.



Advanced Goal

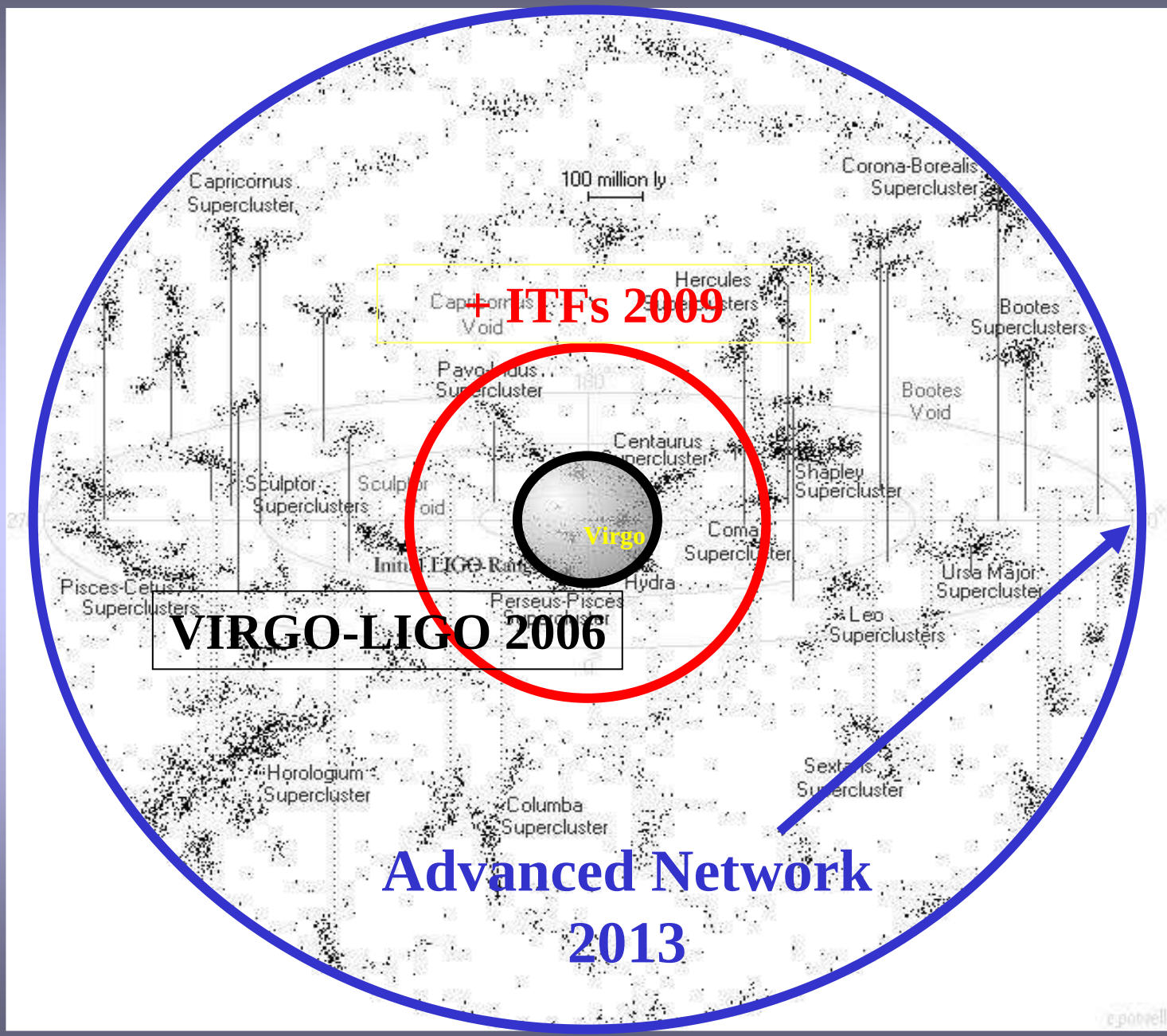






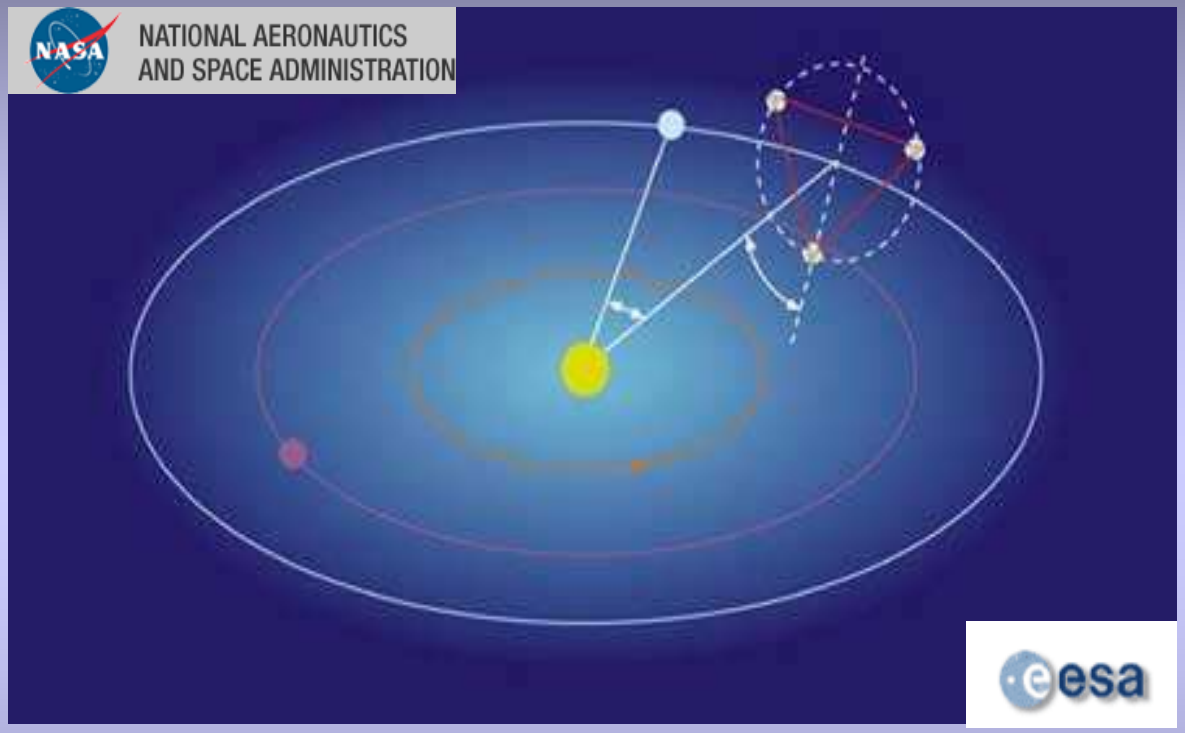
Detection is “sure”

NS/NS detectable at 300 Mpc

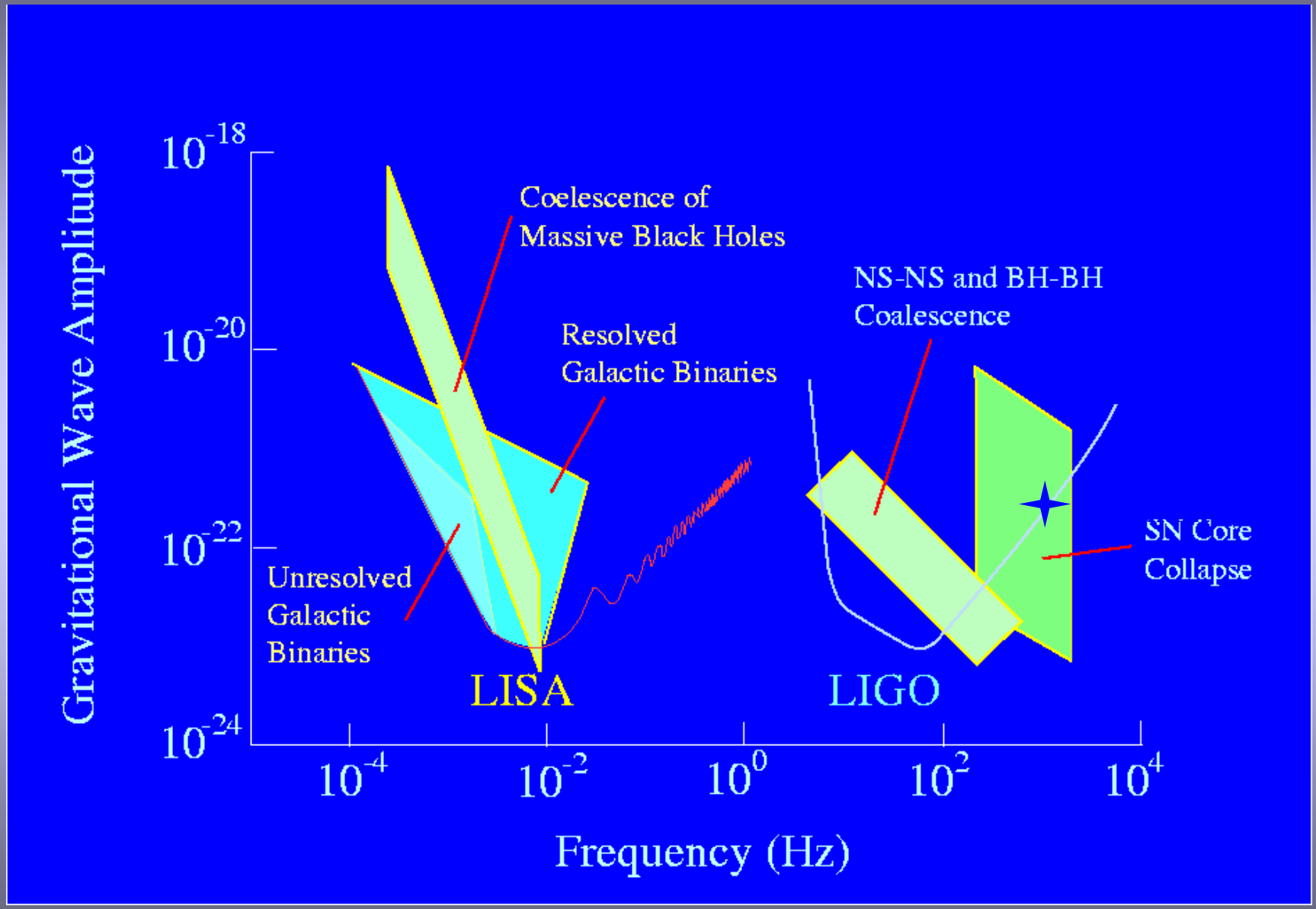


The Future .. LISA

LISA



5 millions of km long-arm interferometer


Gravitational Wave Amplitude
10^{-18}
10^{-20}
10^{-22}
10^{-24}
Coelescence of
Massive Black Holes
Resolved
Galactic Binaries
Unresolved
Galactic
Binaries
NS-NS and BH-BH
Coalescence
SN Core
Collapse
LISA
LIGO
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
Frequency (Hz)