Gravitational Waves Detection techniques

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Overview

1. Gravitational Waves in General Relativity

2. Astrophysical sources

3. Interferometric detection

4. The LIGO-Virgo network and observational results

Gravitational waves in General Relativity

What are Gravitational Waves ?

Gravitational Waves (GW) are ripples of space-time

Theory of GW :

1. **Einstein equations:** $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$
2. **Far from sources:** $$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 0$$
3. **Linearization:** $$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$
4. **Gauge TT:** $$\nabla^2 h_{\mu\nu}^{TT} = 0$$

Propagation of some tensor field – *h* - on flat space-time

Prediction in 1916 !

Gravitational Wave general properties

- GW propagate at speed of light
- GW have two polarizations “+” and “x”
- GW emission is quadrupolar at lowest order

Example: plane wave propagating along z axis with 2 polarization amplitudes h_+ and h_x:

$$h_{\mu\nu}^{TT} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & h_+ & h_\times & 0 \\ 0 & h_\times & -h_+ & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

Gravitational Wave emission: **Orders of magnitude**

Luminosity (Einstein quadrupole formula):

$G/5c^5 \sim 10^{-53}\ W^{-1}$

$$P = \frac{G}{5c^5} \left\langle \dddot{Q}_{\mu\nu} \dddot{Q}^{\mu\nu} \right\rangle$$

source	distance	*h*	*P* (W)
Steel bar, 500 T, ∅ = 2 m L = 20 m, 5 cycles/s	1 m	2×10^{-34}	10^{-29}
H bomb, 1 megatonne Asymmetry 10%	10 km	2×10^{-39}	10^{-11}
Supernova 10 $M_\odot$ asymmetry 3%	10 kpc	10^{-21}	10^{44}
Coalescence 2 black holes 10 $M_\odot$	10 Mpc	10^{-20}	10^{50}

Gravitational Wave emission and compact stars

© J. Weber (1974)

Pb: G/c^5 is very « small ». c^5/G would be much better !!!

Source : mass M, size R, period T, asymmetry a $\Rightarrow$ $\dddot{Q} \approx a\, M\, R^2 / T^3$

Quadrupole formula becomes : $$P \approx \frac{G}{c^5} a^2 \frac{M^2 R^4}{T^6}$$

New parameters

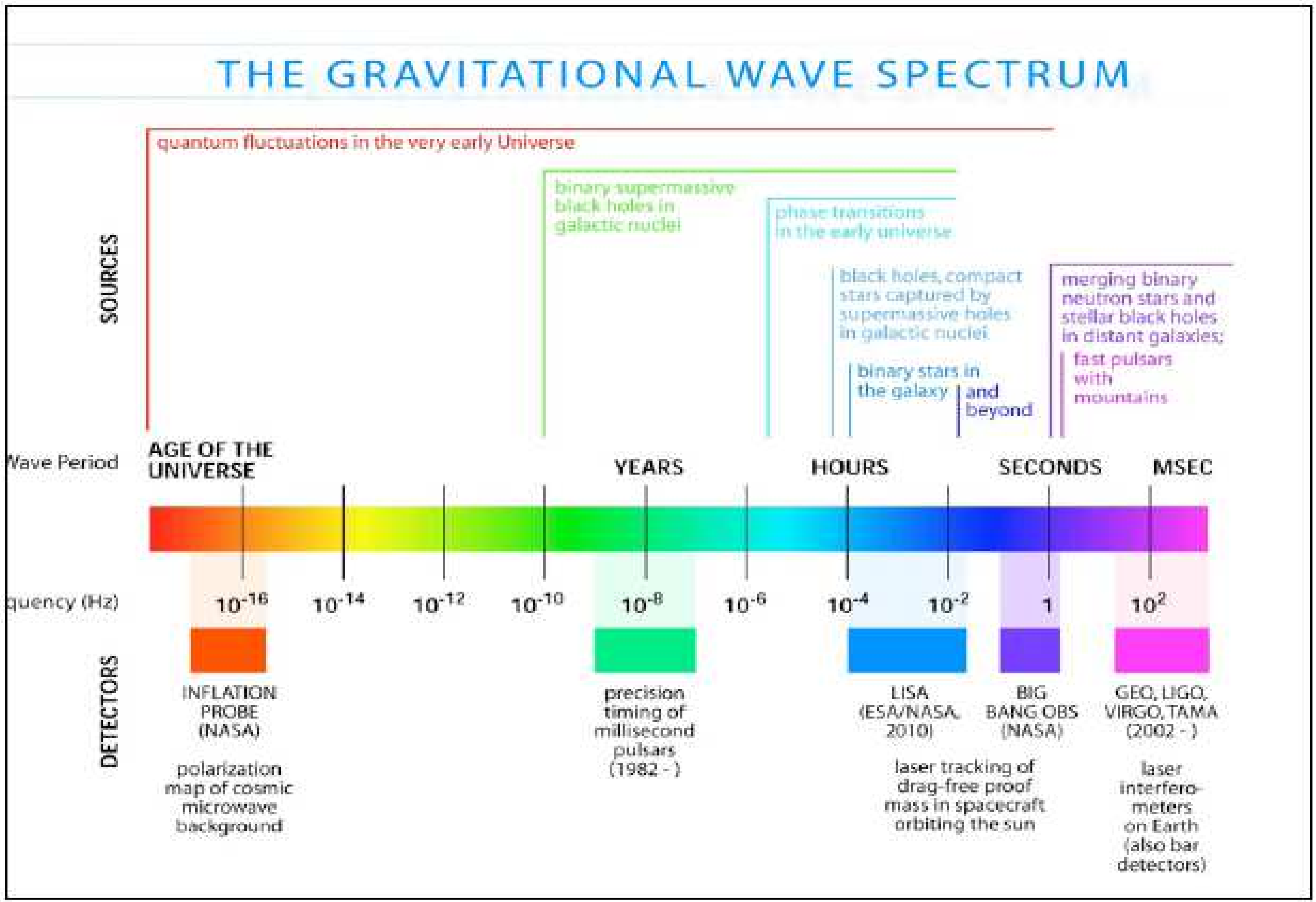
- caracteristic speed v
- Schwarzchild Radius $R_s = 2GM/c^2$

$$P \approx \frac{c^5}{G} a^2 \left(\frac{R_S}{R}\right)^2 \left(\frac{v}{c}\right)^6$$

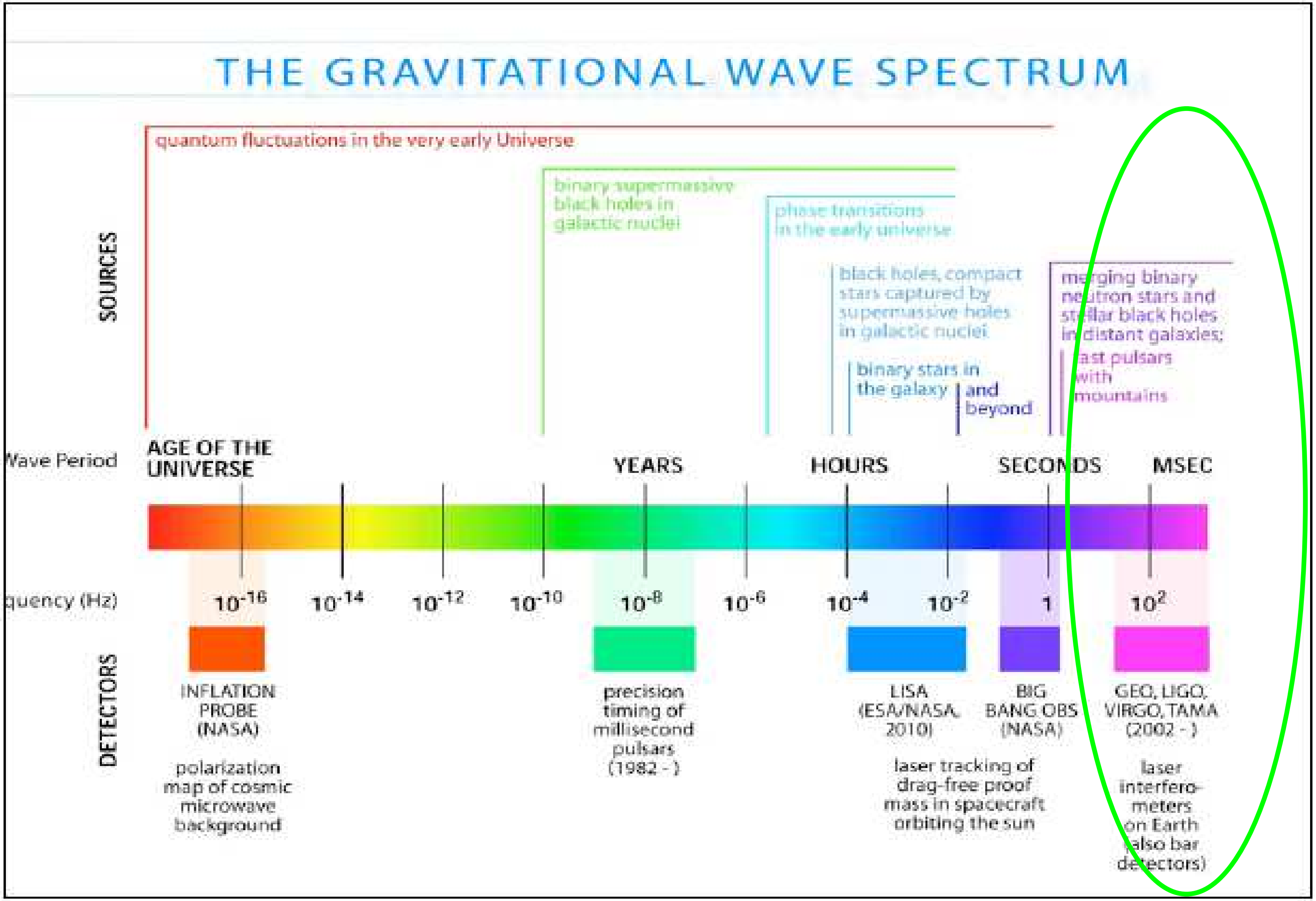
Huge luminosity if

- $R \rightarrow R_s$
- $v \rightarrow c$
- $a \rightarrow 1$

compact stars



THE GRAVITATIONAL WAVE SPECTRUM
SOURCES
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^-16
10^-14
10^-12
10^-10
10^-8
10^-6
10^-4
10^-2
1
10^2
DETECTORS
INFLATION PROBE (NASA)
polarization map of cosmic microwave background
precision timing of millisecond pulsars (1982 -)
LISA (ESA/NASA, 2010)
BIG BANG OBS (NASA)
laser tracking of drag-free proof mass in spacecraft orbiting the sun
GEO, LIGO, VIRGO, TAMA (2002 -)
laser interferometers on Earth (also bar detectors)



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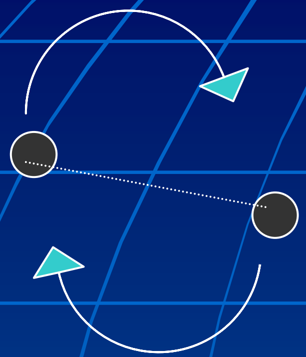
Astrophysical sources of Gravitational waves

(@“high” frequencies)

Binary inspirals: GW amplitudes



System of 2 close compact stars

- Varying quadrupole -> GW emission
- GW emission -> loss of energy and angular momentum
- Loss of (gravitational) energy -> stars become closer
- Finally 2 stars merge (or disrupt)

Spiraling phase (lowest order)

$$h_+^{TT}(t) = \frac{4(G\mathcal{M})^{5/3}}{Rc^4}\,\frac{1+\cos^2 i}{2}\,(\pi f(t))^{2/3}\cos\varphi(t)$$

$$h_\times^{TT}(t) = \frac{4(G\mathcal{M})^{5/3}}{Rc^4}\,\cos i\,(\pi f(t))^{2/3}\sin\varphi(t)$$

A "**chirp**"

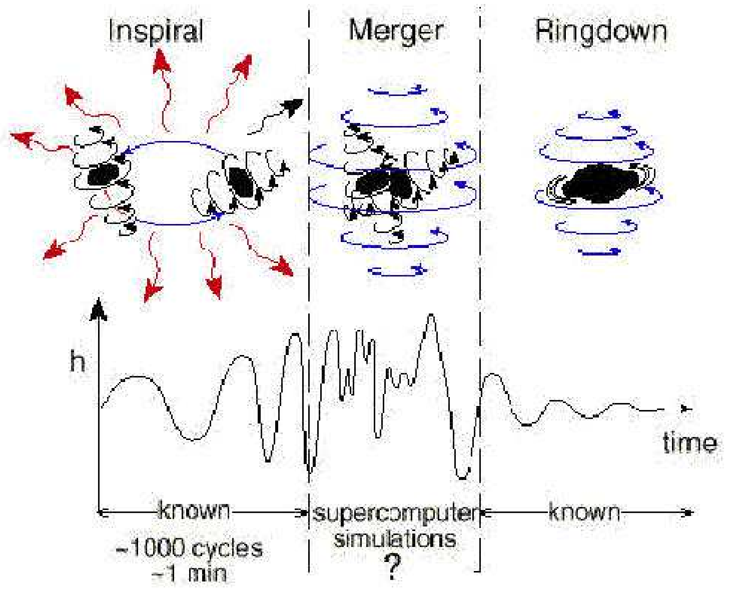
$$h(t) \propto \left(t_c - t\right)^{-1/4}$$

where

- Chirp mass: $\mathcal{M} = \mu^{3/5} M_{tot}^{2/5}$
- frequency: $f(t) = \frac{1}{\pi}\left(\frac{256}{5}\frac{(G\mathcal{M})^{5/3}}{c^5}(t_c - t)\right)^{-3/8}$
- Phase: $\varphi(t) = -2\left(\frac{G^{5/3}}{c^5}\right)^{-3/8}\left(\frac{t_c - t}{5\mathcal{M}}\right)^{5/8} + cste$

t_c : coalescence time

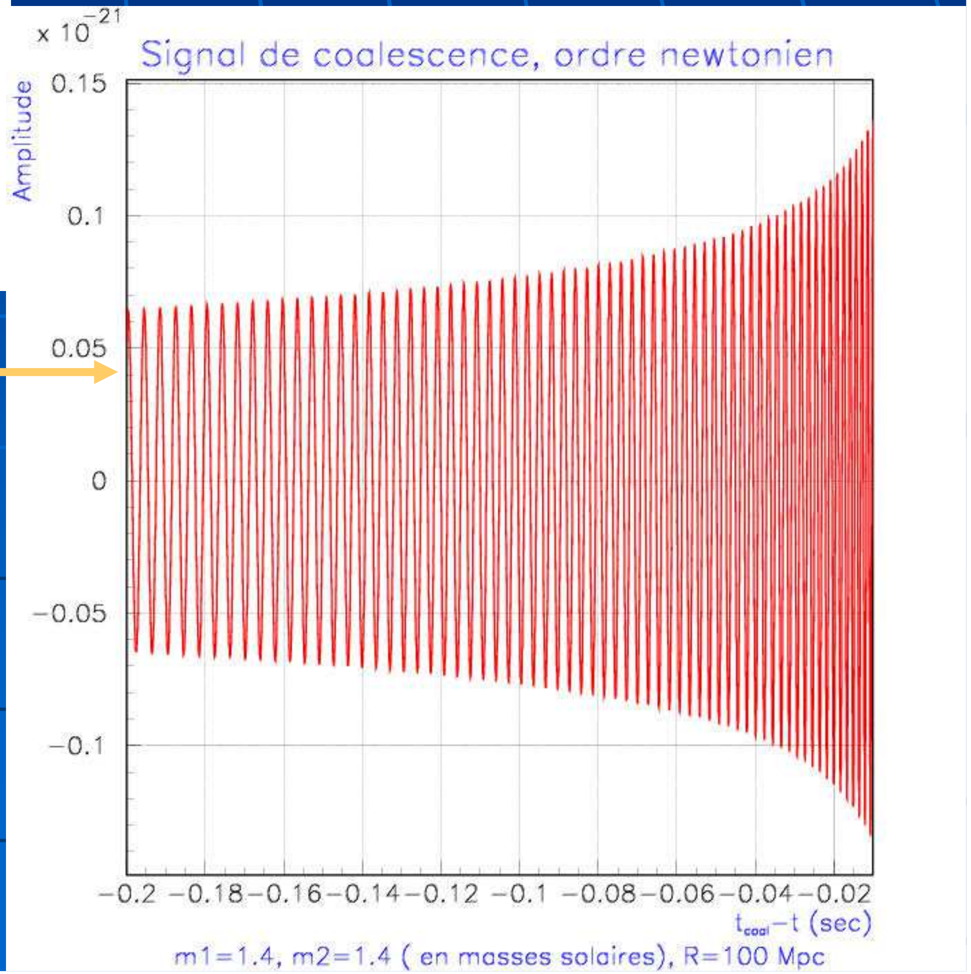
Binary inspirals: the chirp signal



2 neutron stars @ 10Mpc

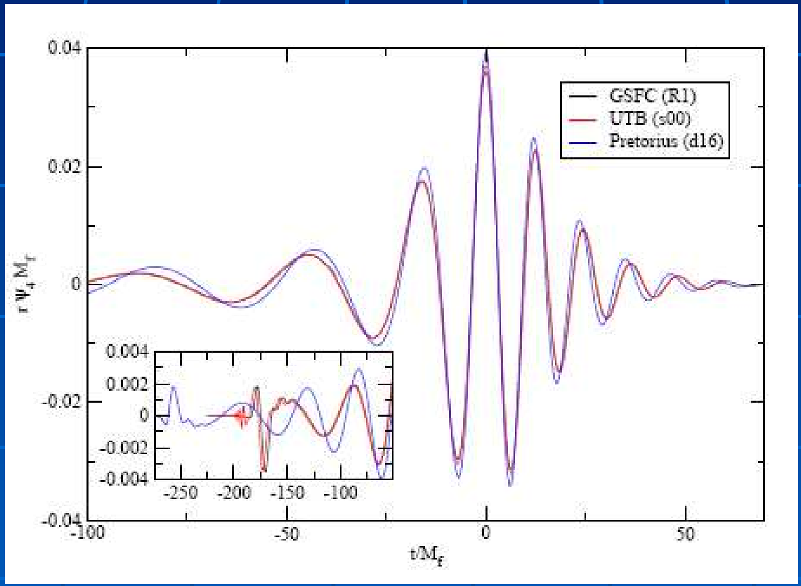
h_{max} ~10^{-21}

f_{max} (last stable orbit)~ 1 kHz



- « *inspiral* » : *h(t)* is a chirp
- « *merger* » : recent numerical progress
- « *ringdown* » : black hole quasi normal modes

Binary inspirals: the merger signal



Baker et al. 2007

Simulation of 2 inspiraling Black holes

Numerical "tour de force"

Gravitational Supernovae

type II SN = gravitational collapse of the core (Fe) of a massive star (> 10 $M_\odot$) after having burned all the H fuel → **neutron star** formation

GW Emission ? Depends on asymmetry **(poorly known)**

Sources of asymmetry
- fast rotation (instabilities)
- companion star

Modern models :

$h \sim 10^{-23}$ @ 10 Mpc
f peaks between 0.3 and 1 kHz
1 SN/ 40 yrs / galaxy

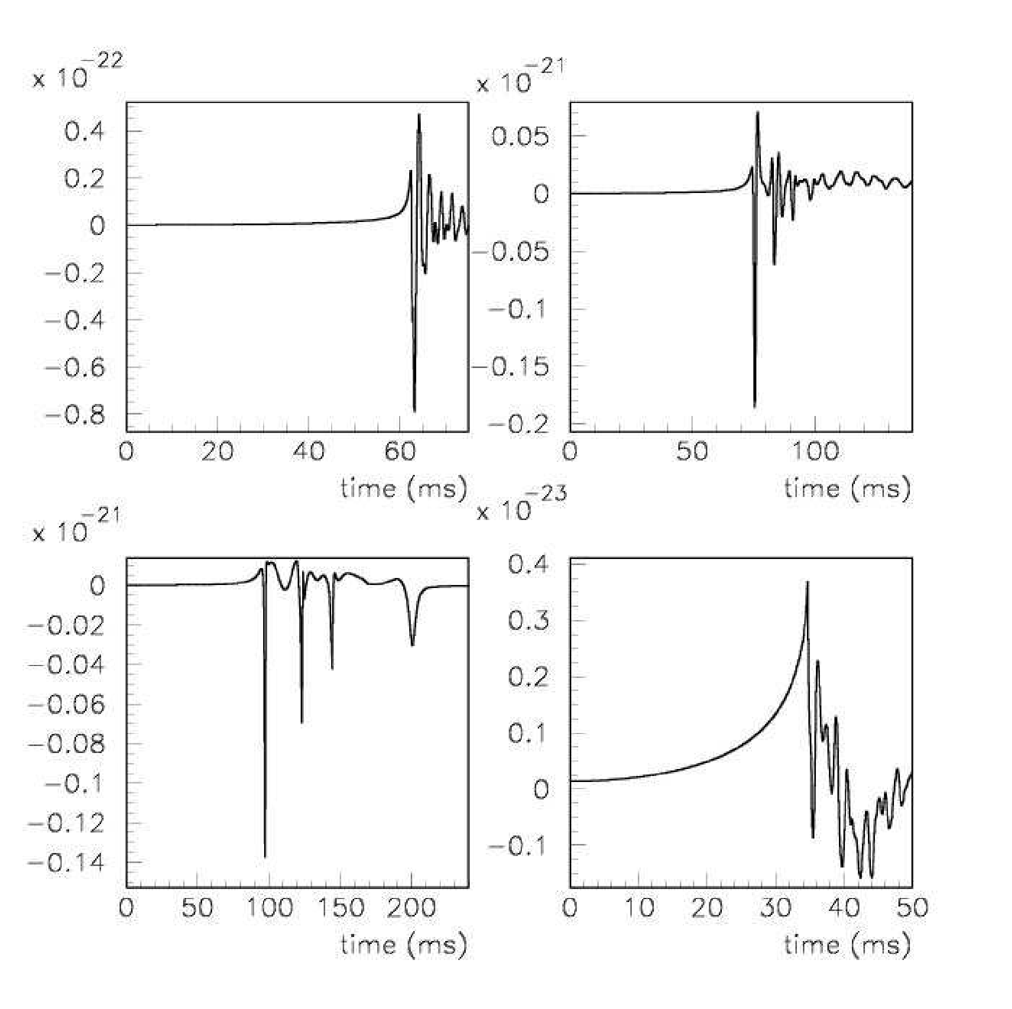
Black hole formation:
Progenitor too massive → collapse → black hole

$h \sim 10^{-22}$ @ 10 Mpc

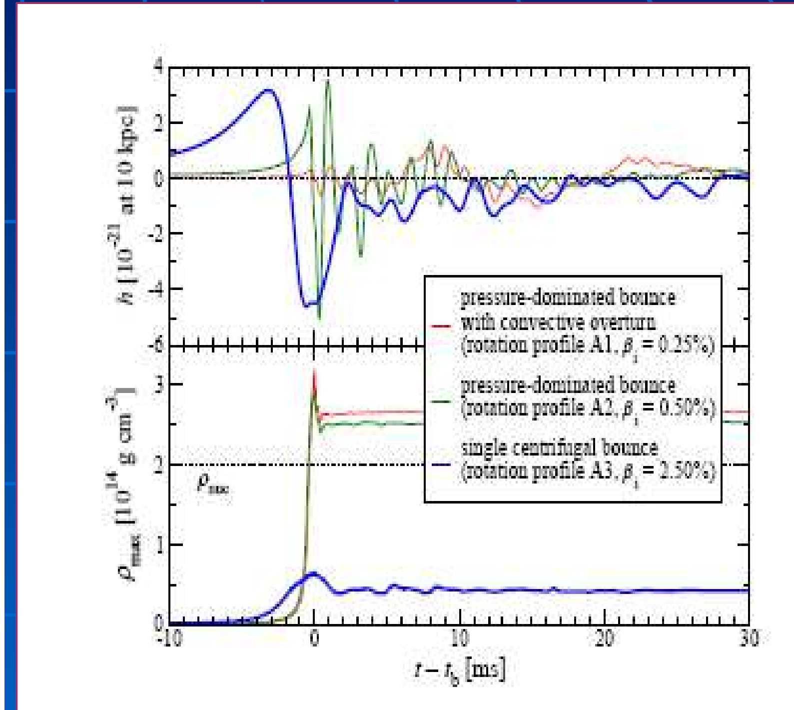
Connection with GRB

Gravitational Supernovae: GW amplitudes

Complex physics => numerical studies



Zwerger & Müller, 1997.

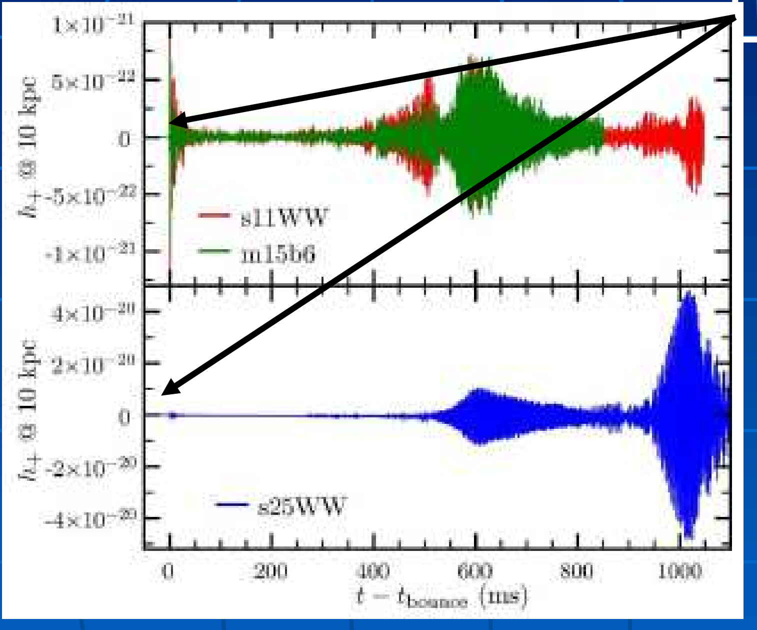


Dimmelmeier et al., 2007.

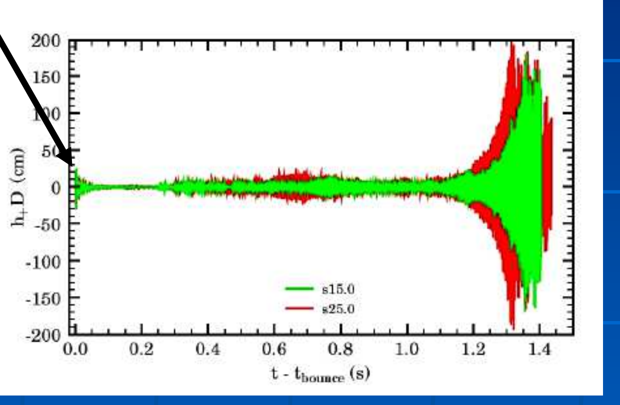
Gravitational Supernovae: GW amplitudes

+ coupling between the proto-neutron star and the envelope
(rotation instabilities induced by turbulence and accretion)

collapse



Ott and Burrows, 2006.



Marek et al., 2008.

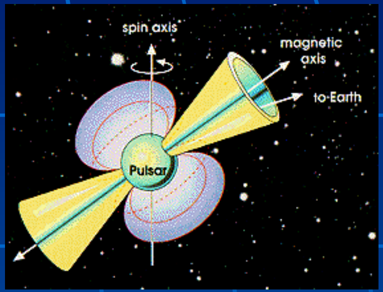
Main conclusions:
+ Waveforms not well predicted
+ weak amplitudes -> only Galactic Supernova detectable ?

Pulsars and rotating Neutron Stars

10^8 (?) pulsars in the Galaxy, several thousands rapidly rotating.

Source of asymmetry ?

- rotation instabilities
- magnetic stress
- "mountains" on the solid crust …



Radio-astronomy observation of pulsar slowdown sets upper limits on GW emission and neutron star asymmetry (if rate of slowdown totally assigned to GW emission)

$\Rightarrow$Expected amplitudes are weak **($h<10^{-24}$)**

$$h \sim 10^{-26} \left(\frac{10\ \mathrm{kpc}}{\mathrm{distance}}\right)\left(\frac{f}{100\mathrm{Hz}}\right)^2\left(\frac{\varepsilon}{10^{-6}}\right)$$

But the signal is periodic ! ("simple" Fourier analysis)

Signal to noise ratio $\mathrm{S/N} \propto \sqrt{T}$ where *T* is the observation time

Gravitational Waves and GRBs

GRB progenitors are GW sources :

- Mergers of 2 NS or NS+BH: **short GRBs**?
- Massive star gravitational collapses: **long GRBs**?

$\Rightarrow$ GW searches triggered by GRB events

Interest: location of the source + time window
(see S. Fairhust's talk)

$\Rightarrow$ Follow up of GW candidates

In particular by "subprime GRB events"
(see N. Christensen's talk)

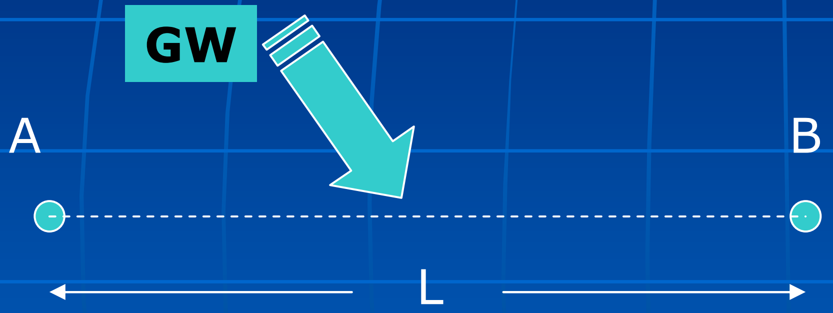
$\Rightarrow$ **Multi-messenger astronomy!**

(see F. Pannarale's and V. Pelassa's talks)

Which is the physical effect we can detect on Earth ?

Detectable effect of GW

GW
⇒ perturbation of the metric
⇒ measurements of distances (*) are affected



Geodesic equation (weak field):

$$\frac{d^2 x^\mu}{dt^2} = -\frac{1}{2}\frac{d^2 h_{\mu\nu}}{dt^2} x^\nu$$

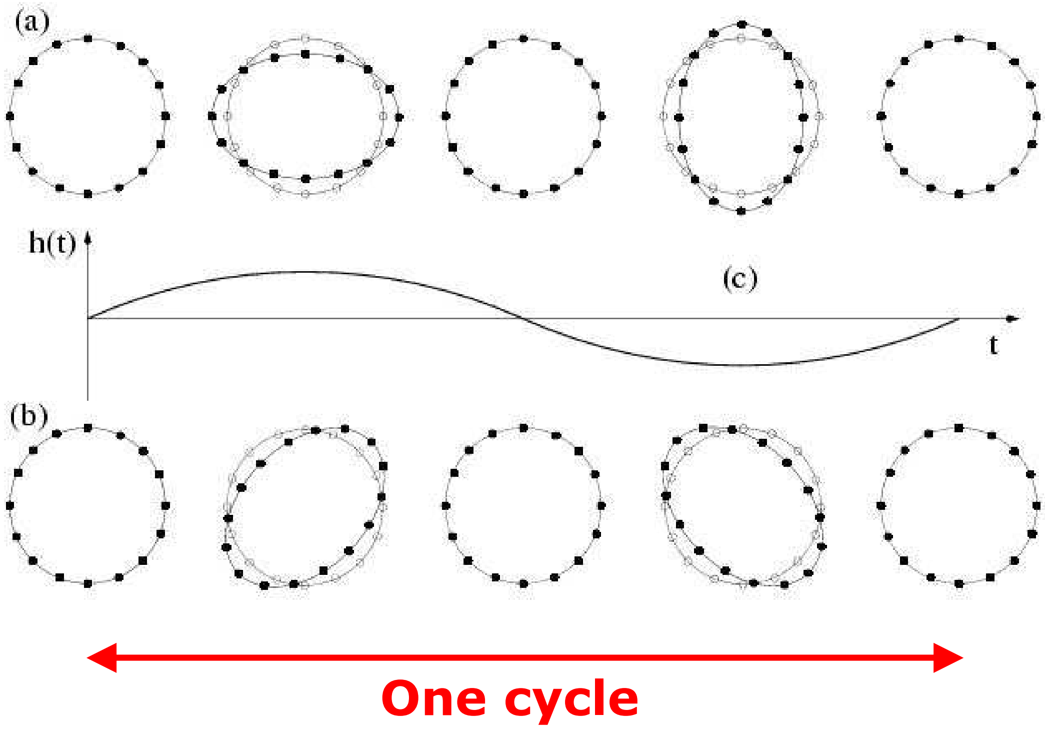
⇒ Variation of measured distance between A and B $\delta L \approx \frac{1}{2} hL$

Amplitude *h*(t) ⇔ *rate of deformation of space-time*

Effect of GW on a set of test masses

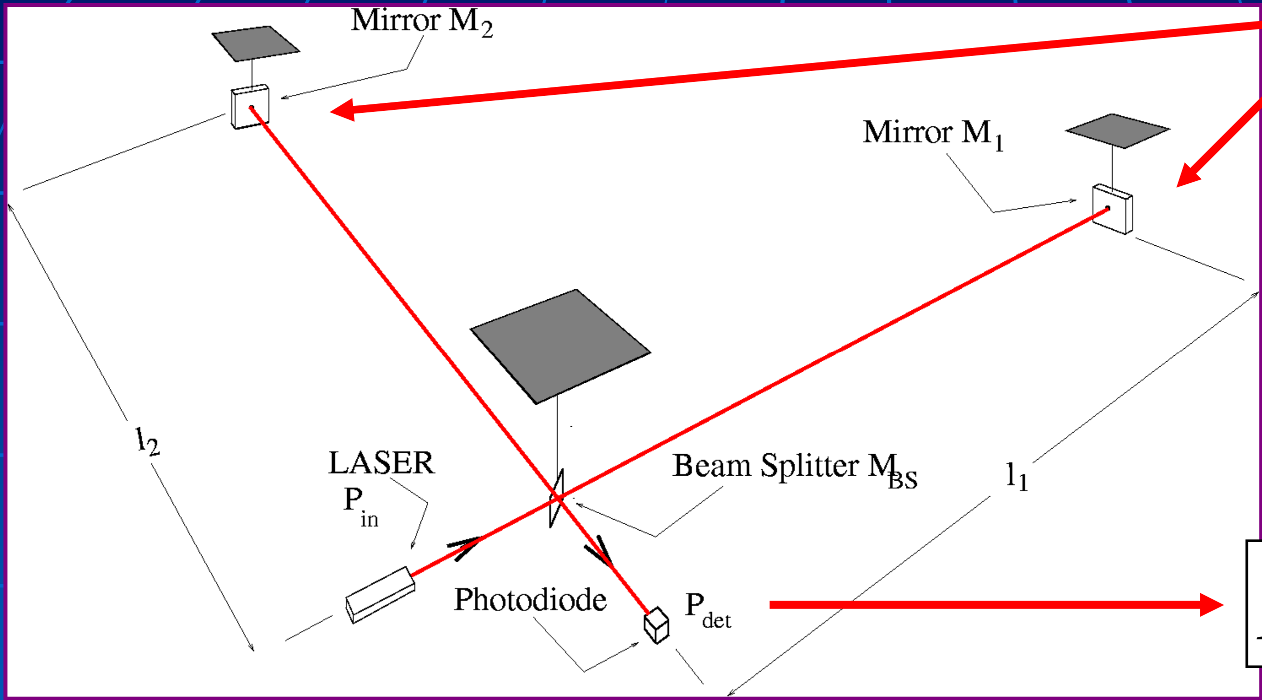
Effect of $\mathbf{h}_+$

Effect of $\mathbf{h}_\times$



Interferometric detection of Gravitational Waves

Itf detection principle



Suspended mirrors
⇔ Test masses

$$P_{det} = \frac{P_0}{2}\left[1 + C\cos(\Delta\phi)\right]$$

GW → optical paths are modified → detected power is modified

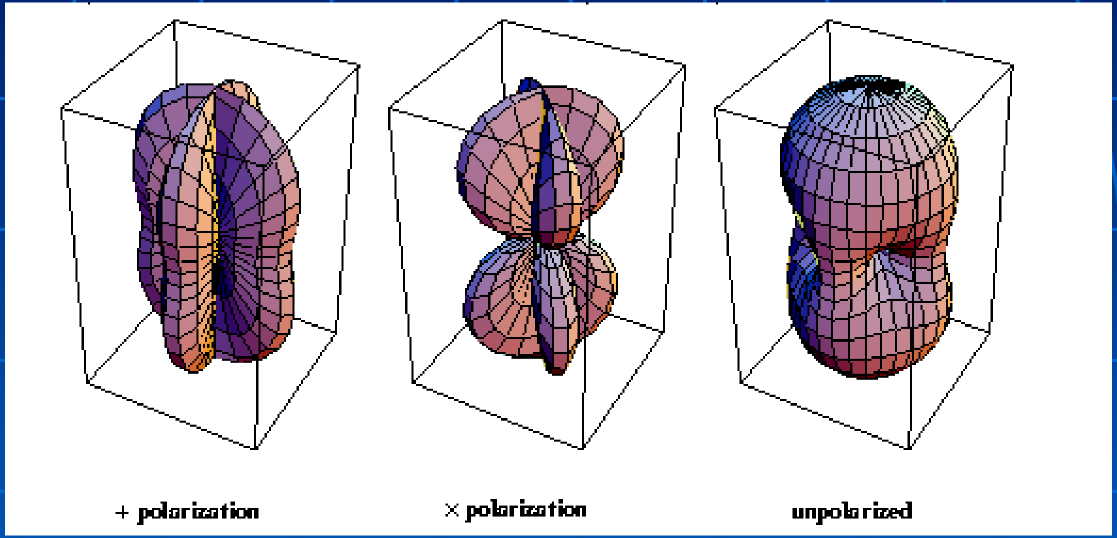
$$\Delta\phi = \Delta\phi_{OP} + \delta\phi_{GW}(t) = \frac{2\pi\,\Delta L}{\lambda} + \frac{4\pi\,L\,h(t)}{\lambda}$$

$$P_{det} \approx \frac{P_0}{2}\left[1 + \cos(\Delta\phi_{OP}) - \sin(\Delta\phi_{OP}) \times \delta\phi_{GW}(t)\right]$$

The detected signal is proportional to *h(t)* !

The interferometric detector is not directional

Antenna patterns



Response if not directional => impossible to reconstruct completely *h*(t) with a single itf

but not uniform either => detector can be blind (null response along bisectors)

⇒ **<u>2 (very good) reasons to operate more than one detector !</u>** **(at least 3)**

Noises in interferometric detectors

- **optical readout noise** (photon counting noise + radiation pressure noise)
  => high power lasers, Fabry-Perot cavities, power recycling …

- **seismic noise**
  => (active) seismic isolation ("super-attenuator" in Virgo)

- **thermal noise**
  => Good materials (high mechanical "Q"), large beams …

- others …

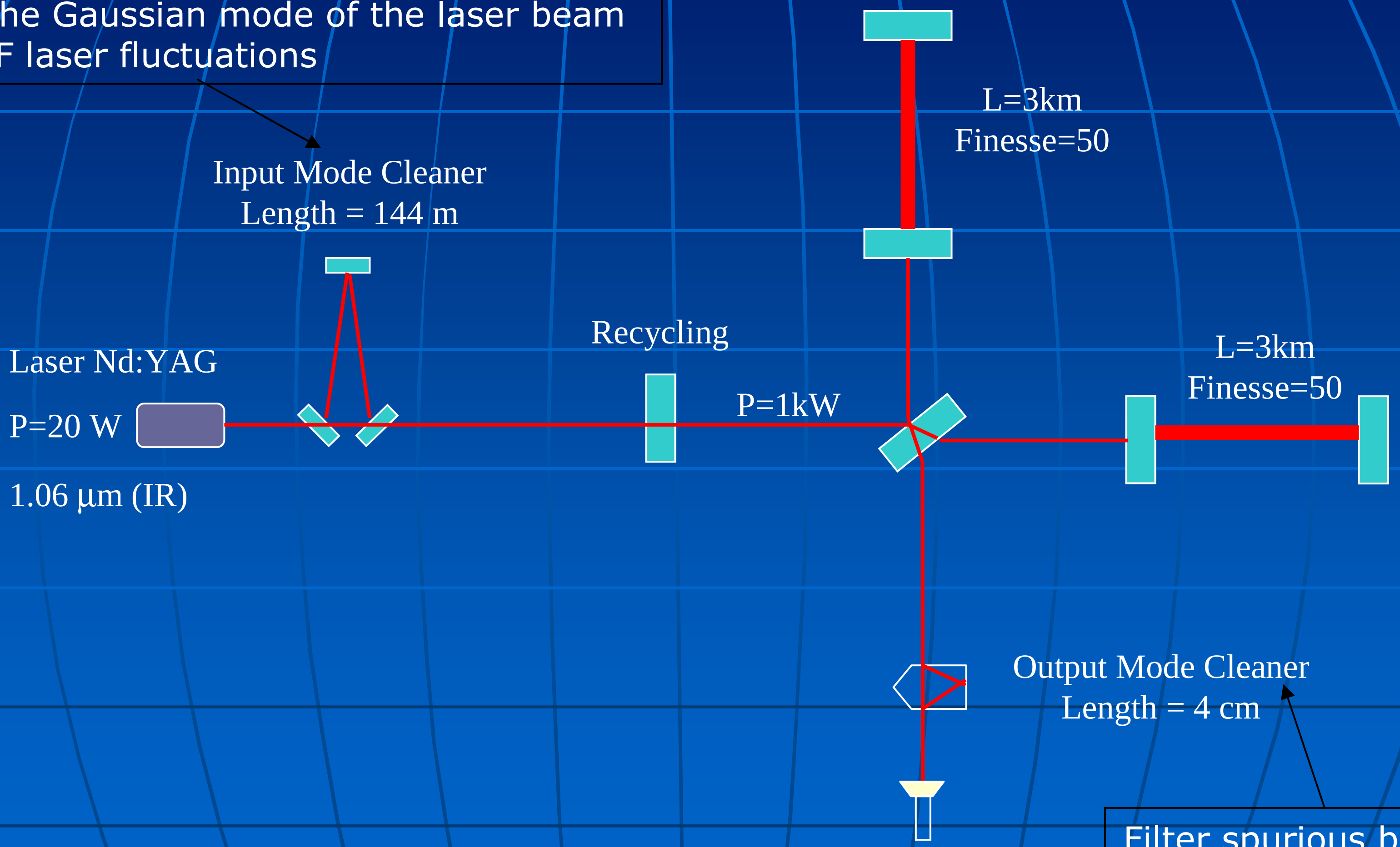
- + ultra vacuum required.

$\Rightarrow$ General design of itf detectors

Optical design (1st generation)

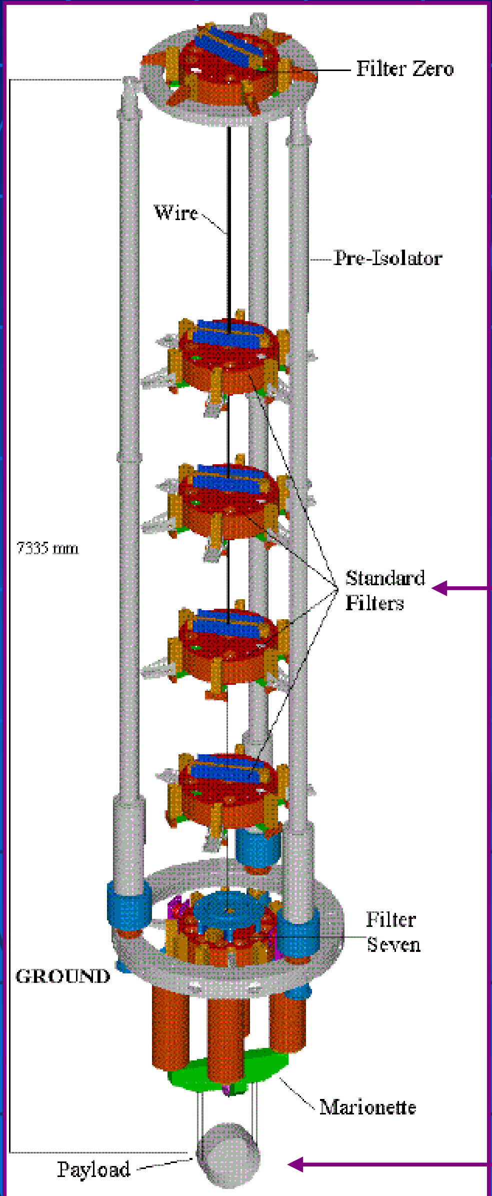
Example of Virgo

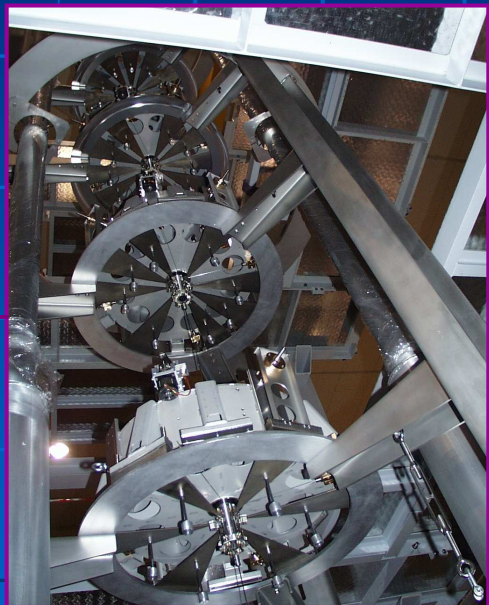
+ Clean the Gaussian mode of the laser beam
+ filter HF laser fluctuations



Filter spurious beams
(increase the contrast)

Virgo « superattenuator »





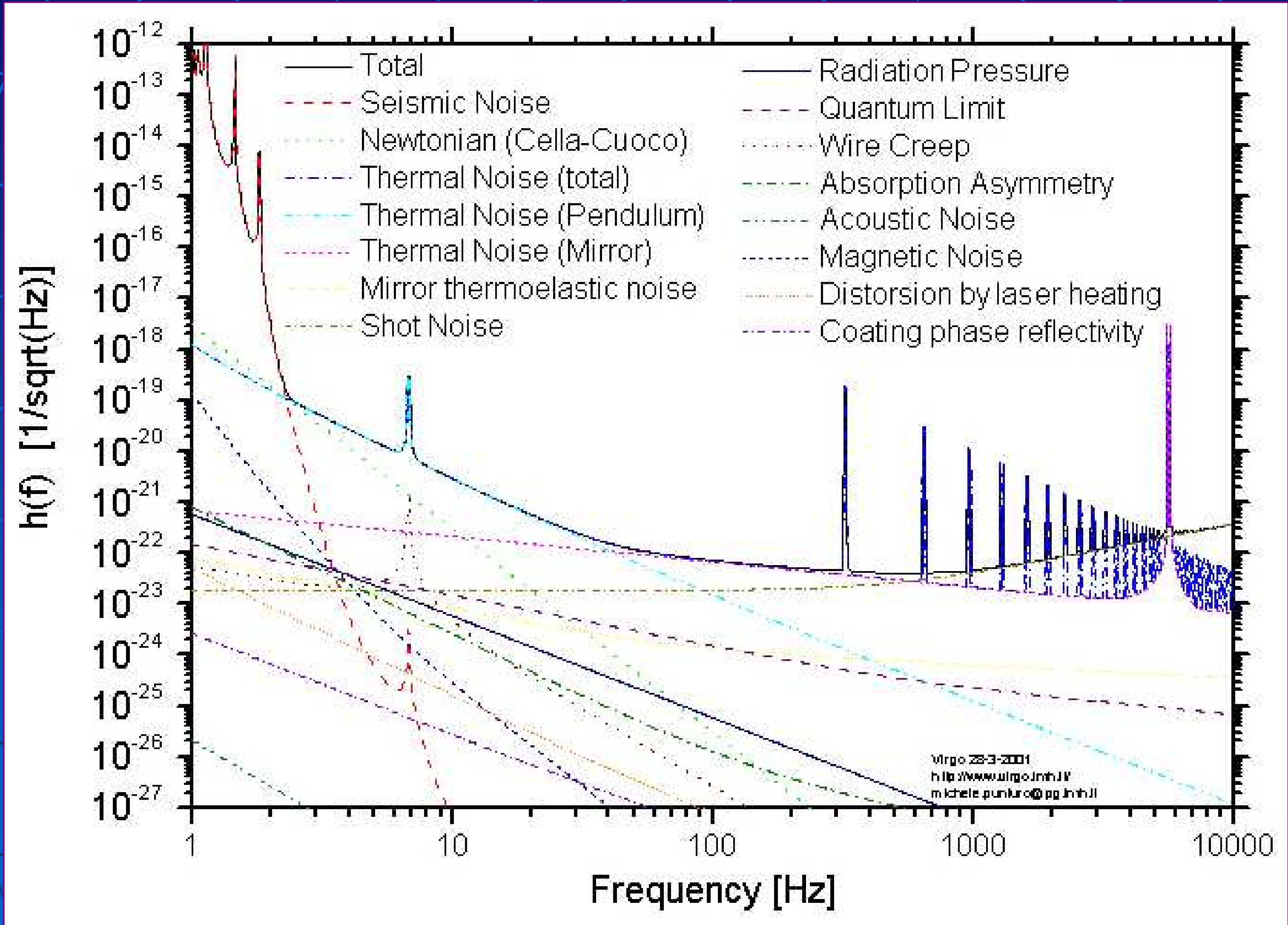
L ~ 7 m; M ~ 1 ton
+ inverted pendulum

$$f_{res} = \frac{1}{2\pi}\sqrt{\frac{k}{m} - \frac{g}{l}}$$

$\Rightarrow f_{res} \sim 30$ mHz

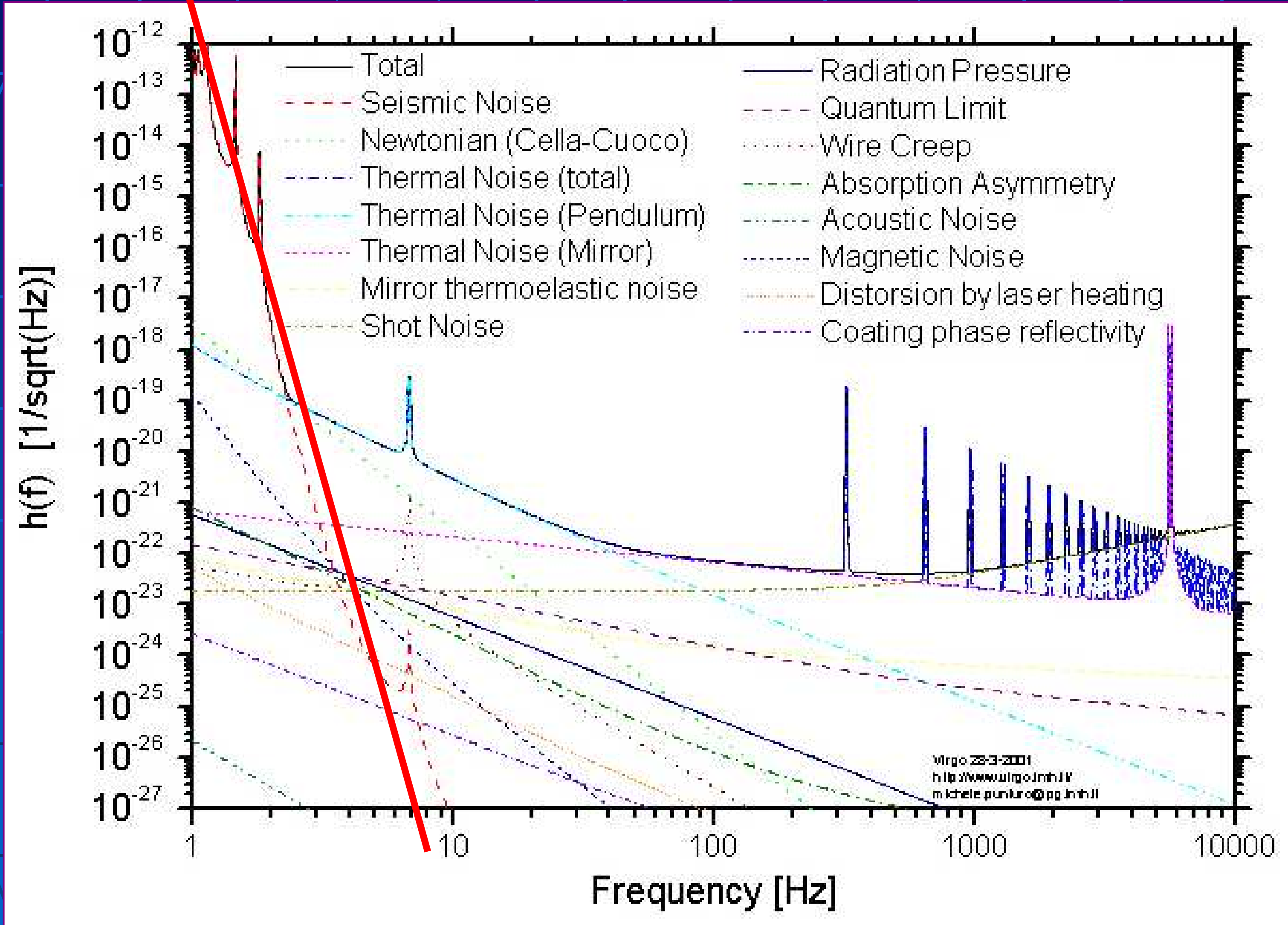
Seismic attenuation:
~ 10^{14} @ 10 Hz
(measured)

Sensitivity curve
(*Virgo design example*)



Sensitivity curve
(*Virgo design example*)

Seismic noise



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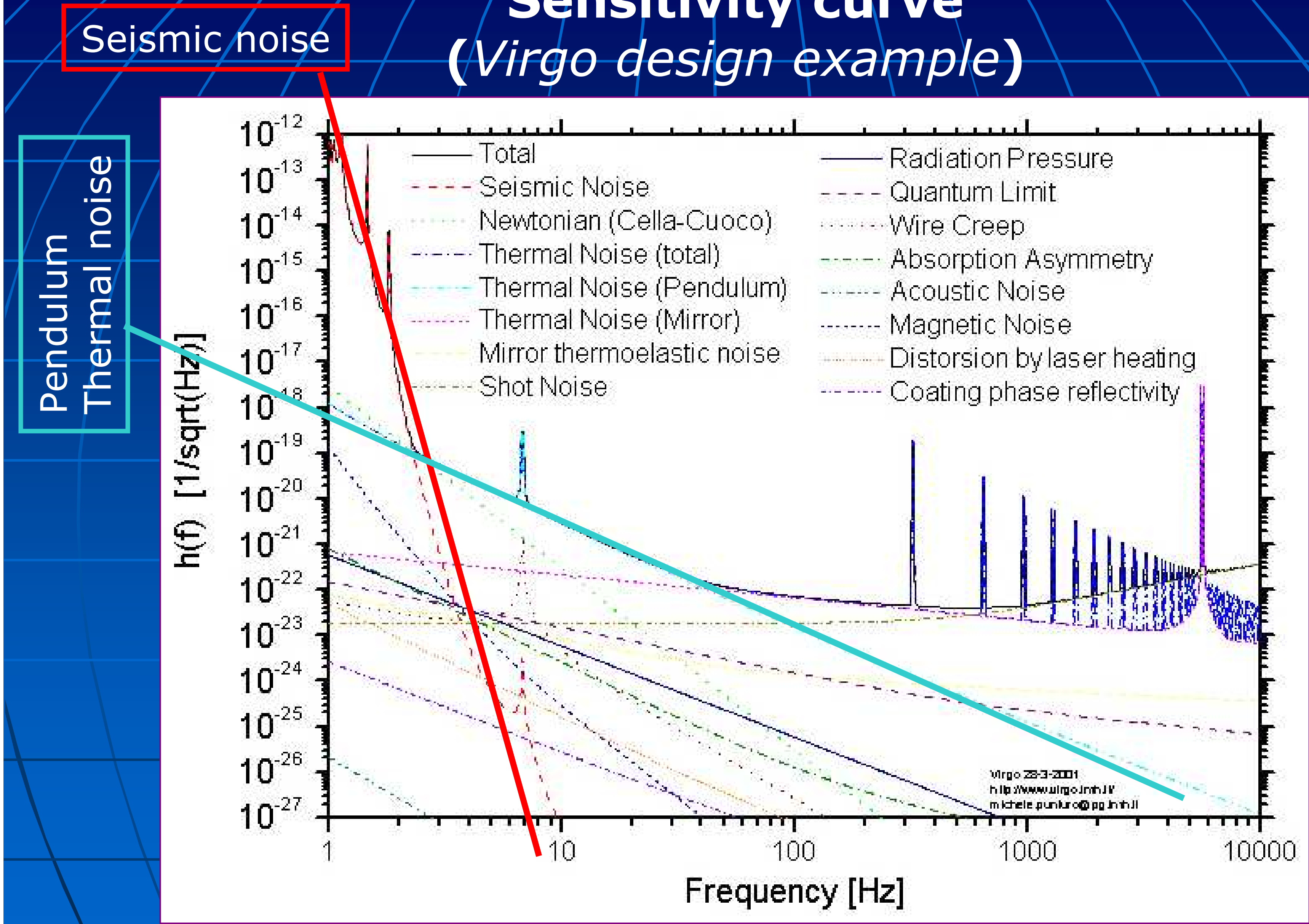

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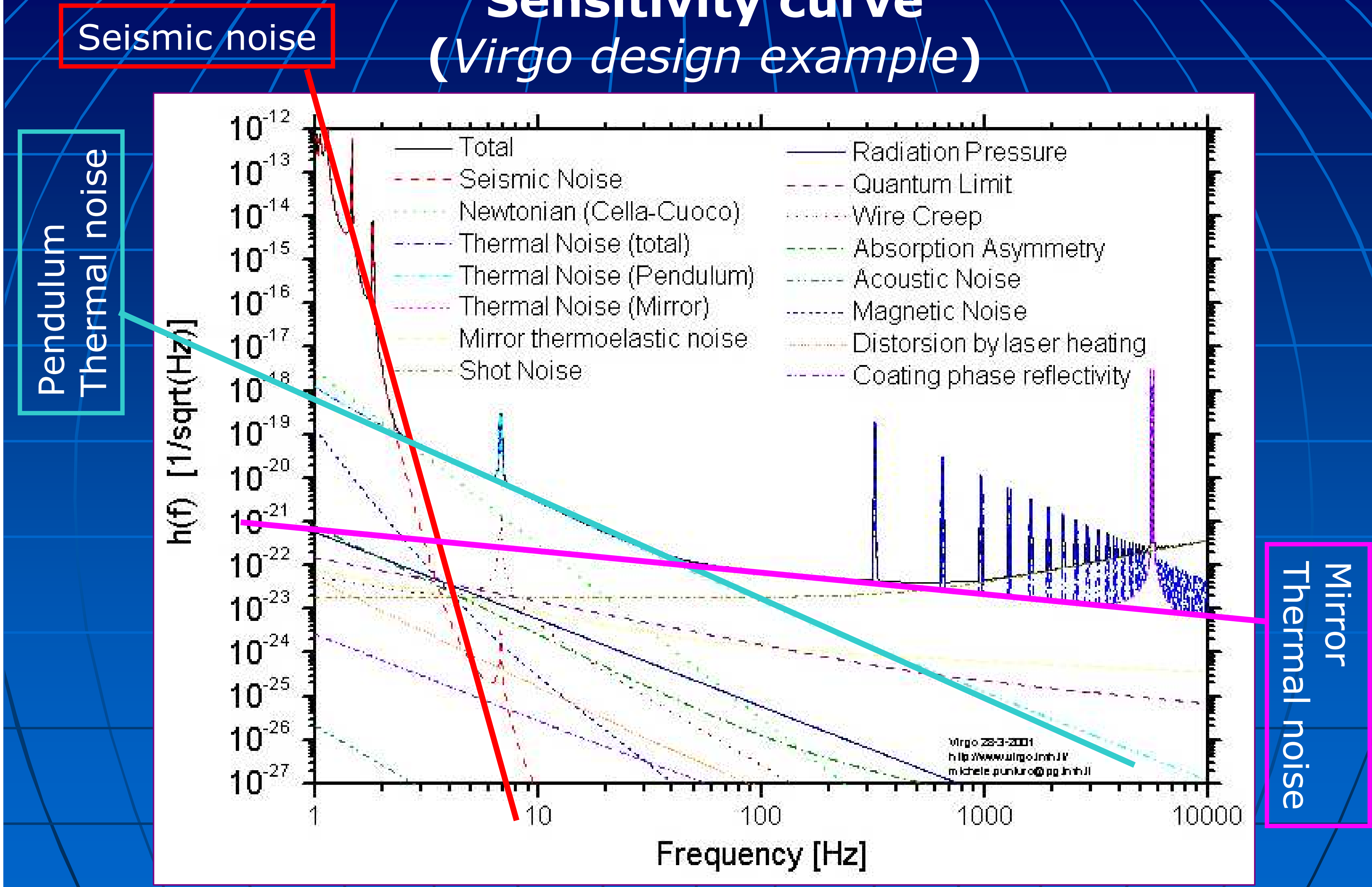

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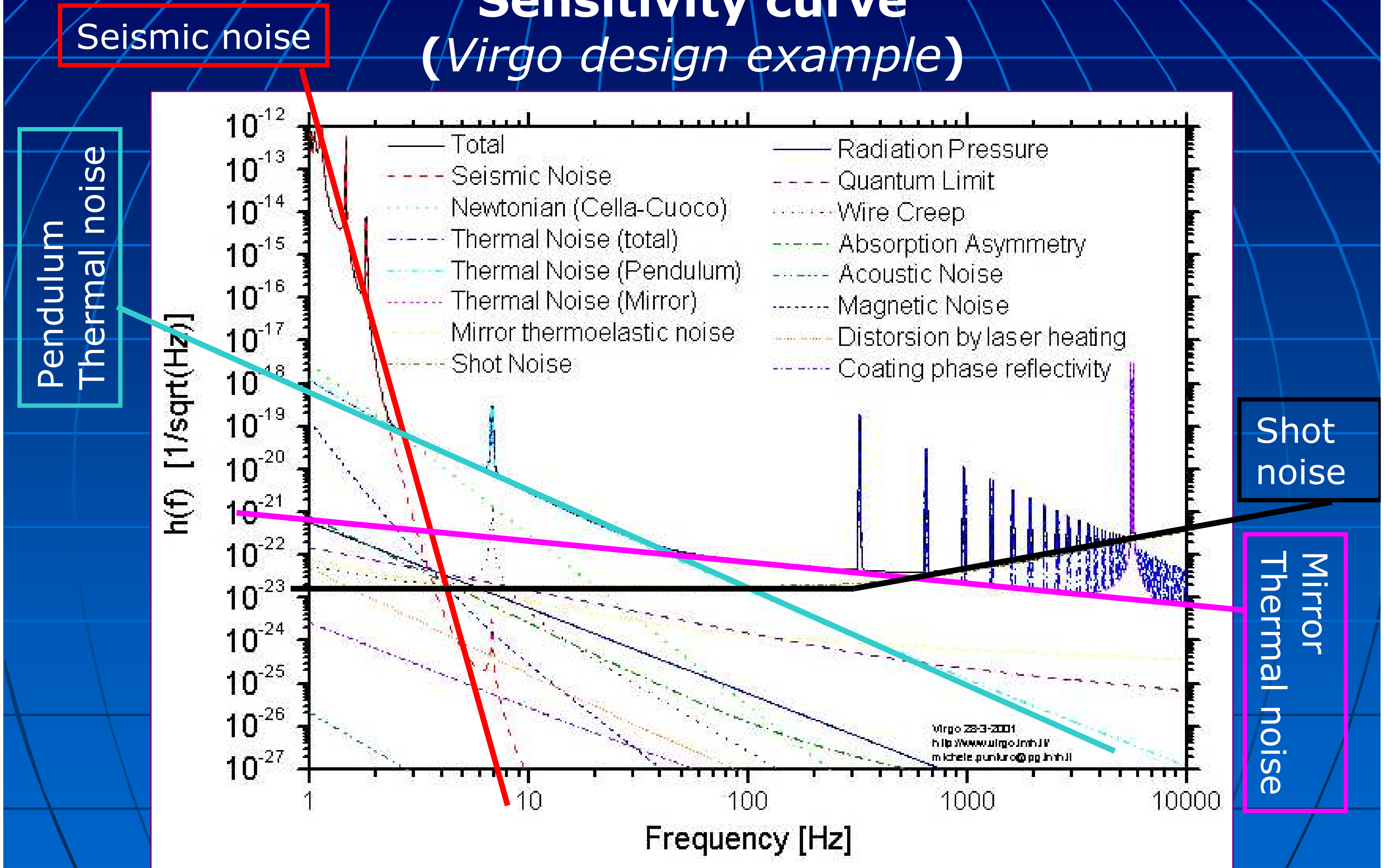
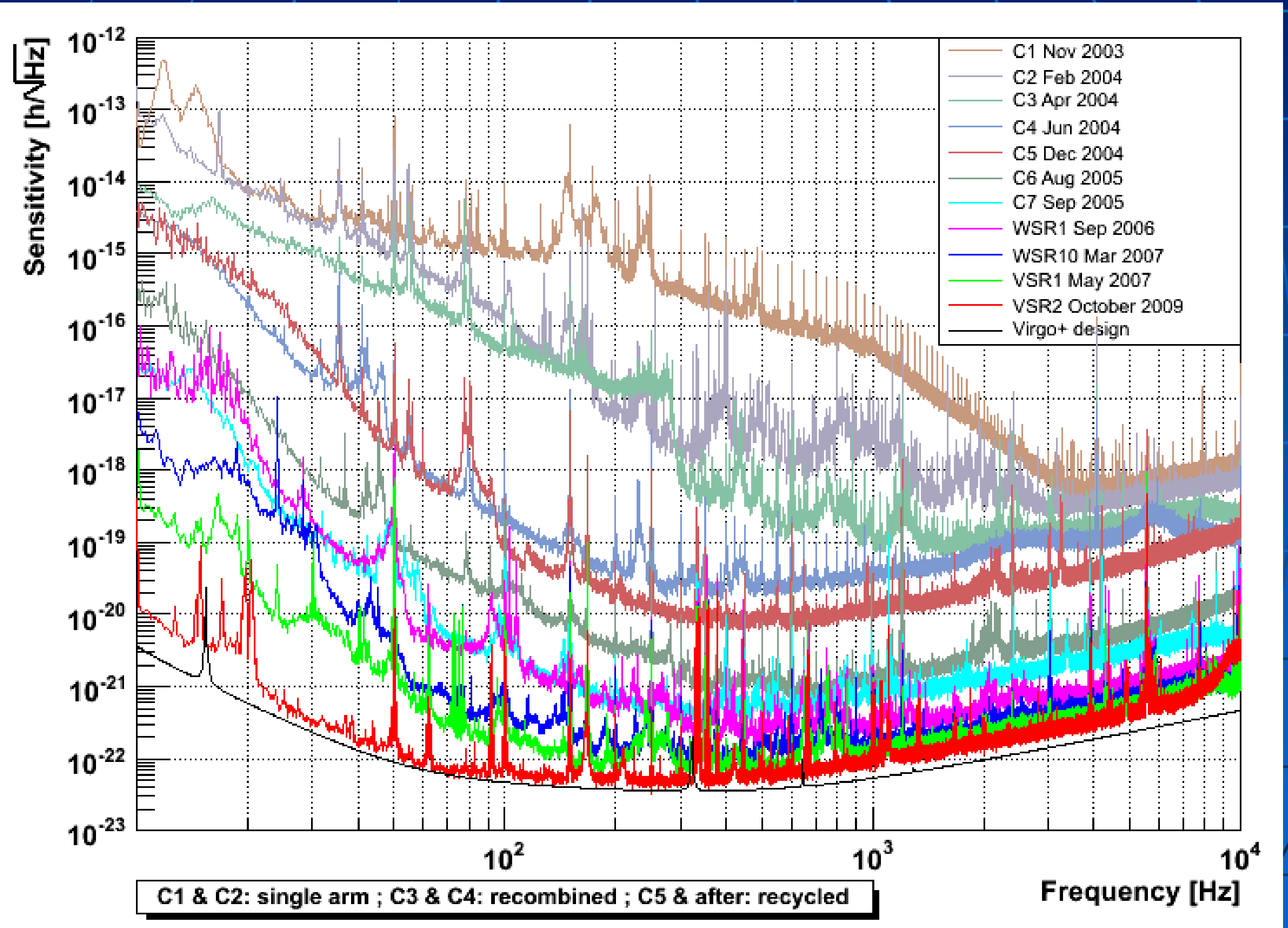


Virgo sensitivity evolution

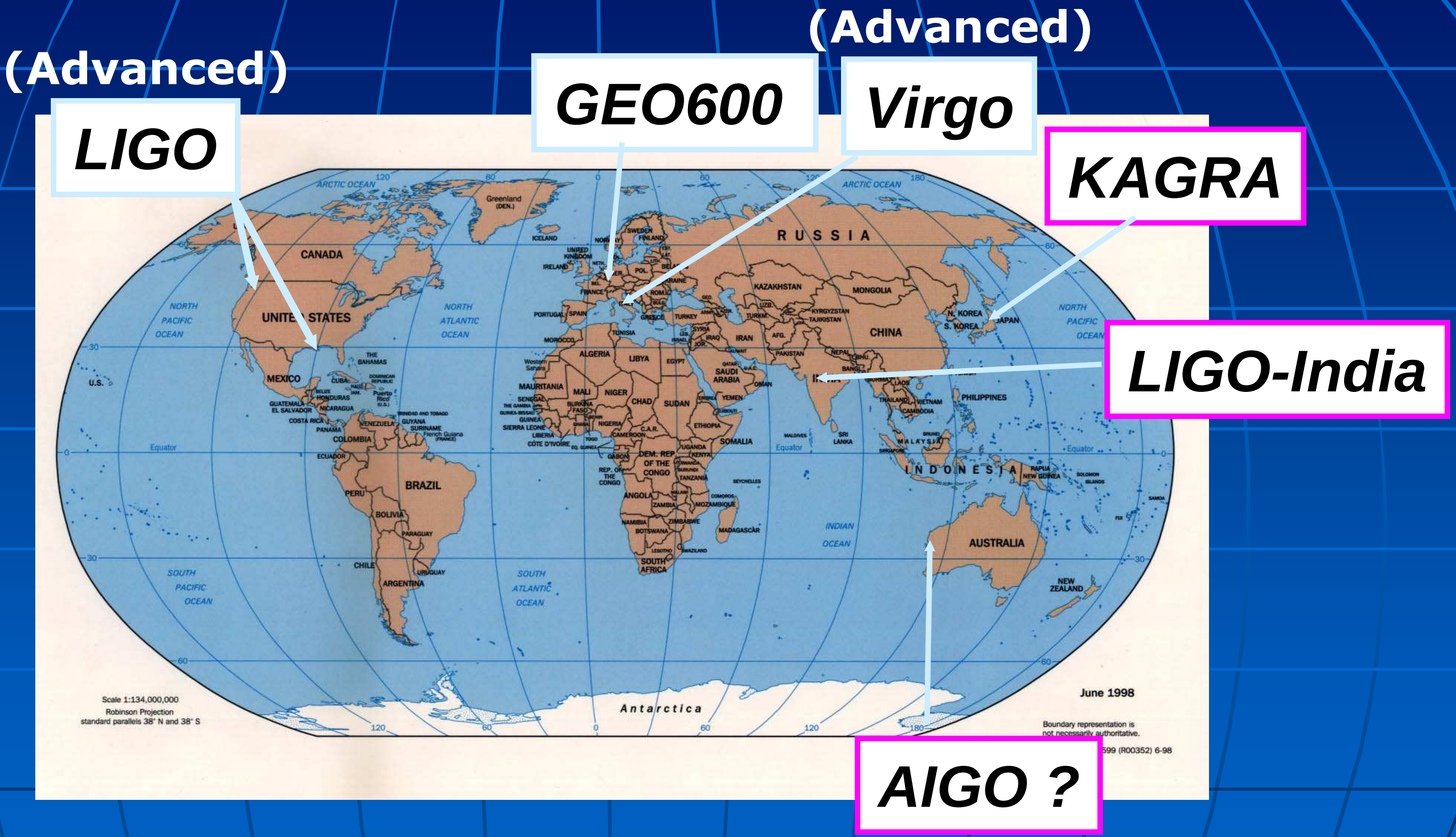
Not an easy task to reach the design sensitivity !



The LIGO-Virgo network

Some observational results and perspectives

The GW detectors (near-future) world



A worldwide collaboration

LIGO + LIGO Science Community (aggregate GEO600)
and **Virgo**
have joined their forces in 2007

- joint data takings
- full data sharing
- 4 joint search groups with co-chairs from each collaboration
  - bursts
  - compact binary coalescences
  - continuous waves (pulsars)
  - stochastic GWs
- Joint run and planning committee

Agreement renewed this year (2014) -> cover the Advanced detectors era
+ Ongoing discussions with Japan (KAGRA collaboration)

The LIGO-Virgo network

Light time of flight : HL ~ 10 msec., VL ~ 26 msec. and VH ~ 27 msec.

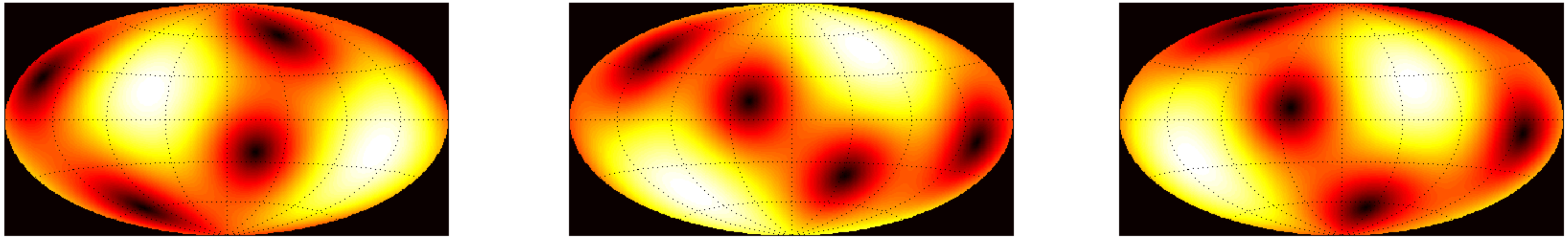
Times delays set the Source Reconstruction Accuracy:

Minimal angular resolution ~ 1°

(could be much worse)

The LIGO-Virgo network

The LIGO-VIRGO Network : **Beam patterns**



VIRGO HANFORD LIVINGSTON

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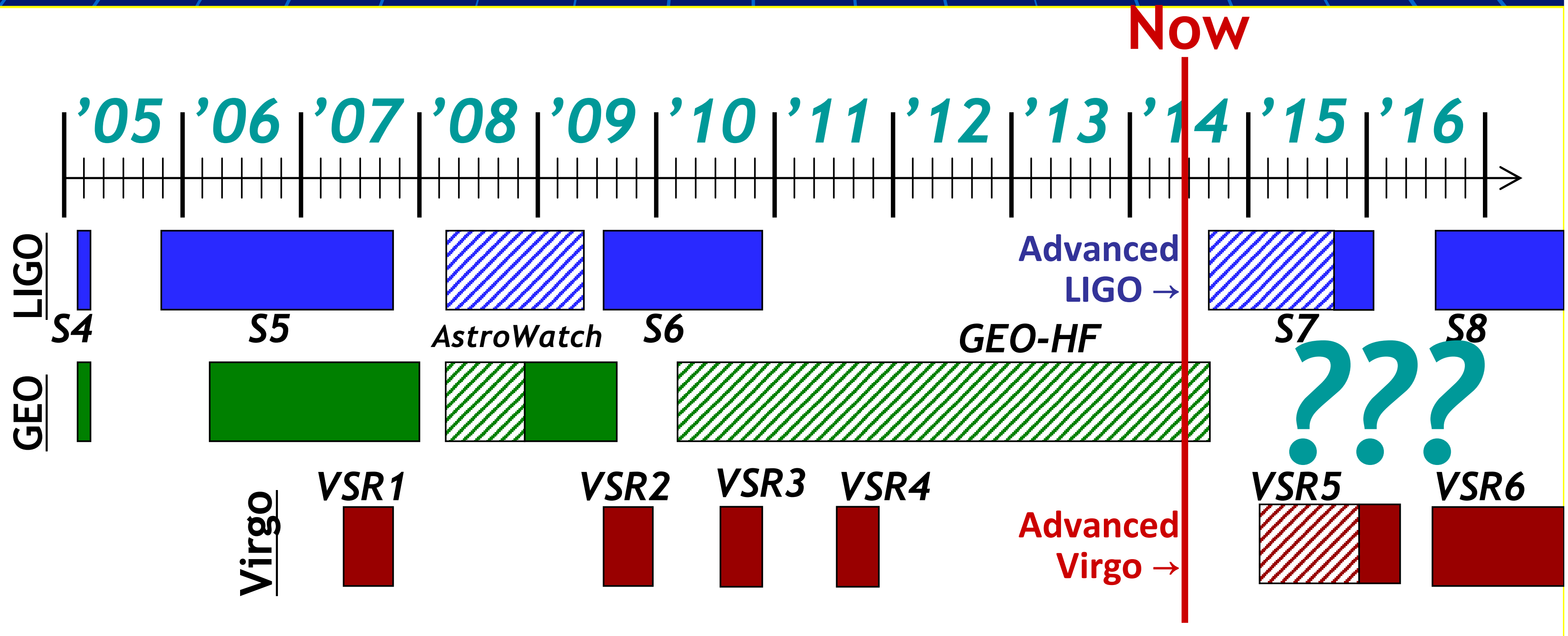
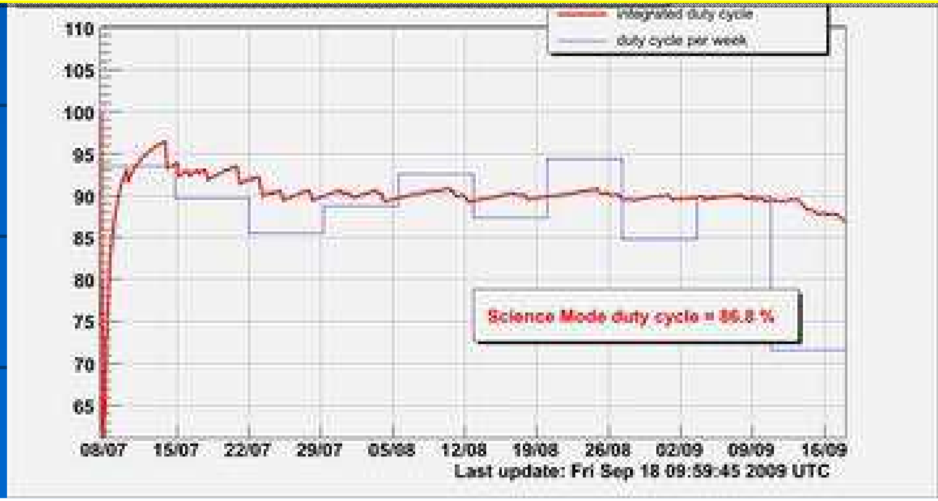
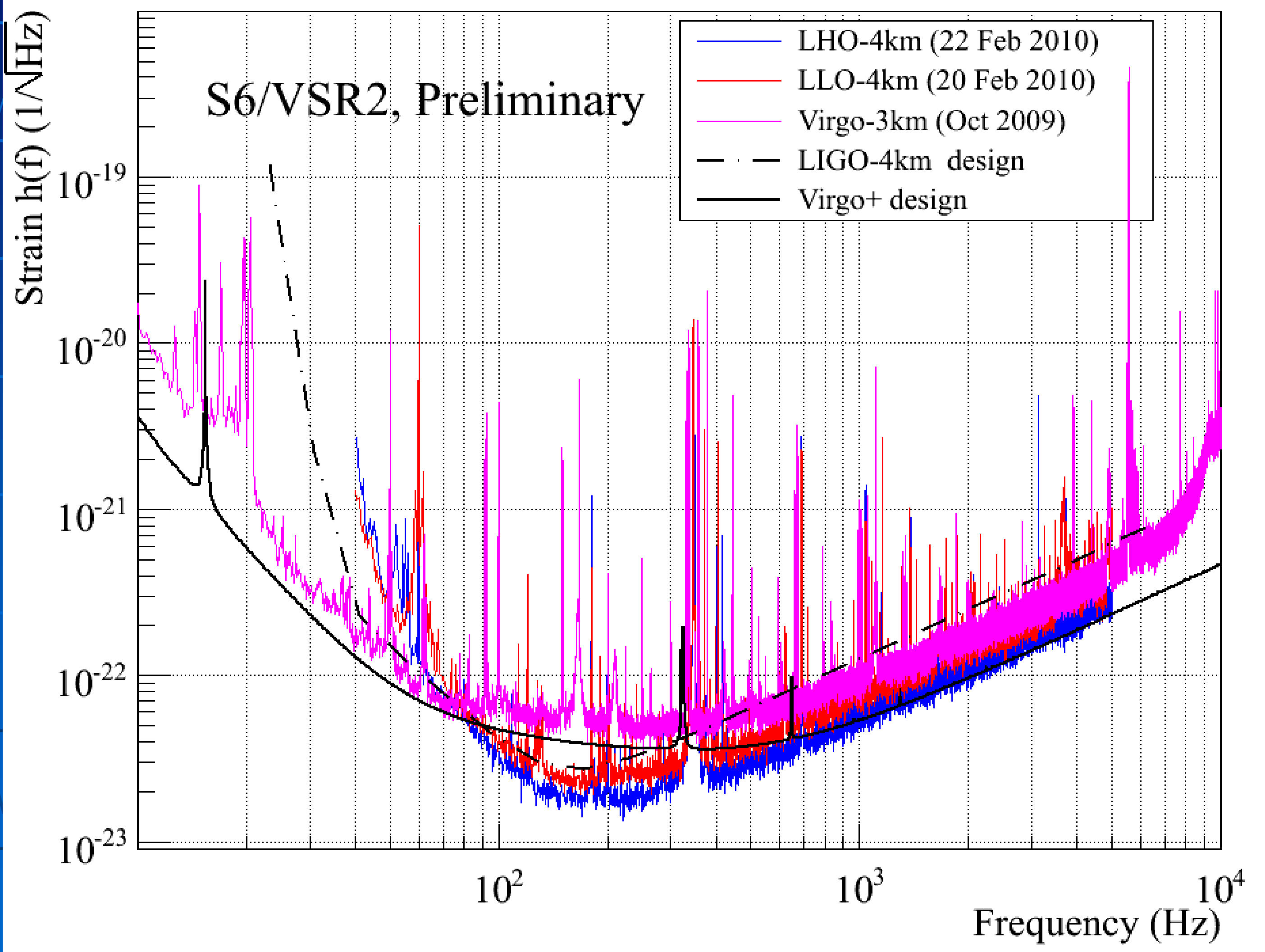
LIGO-Virgo joint data takings



Virgo duty cycle ~90%



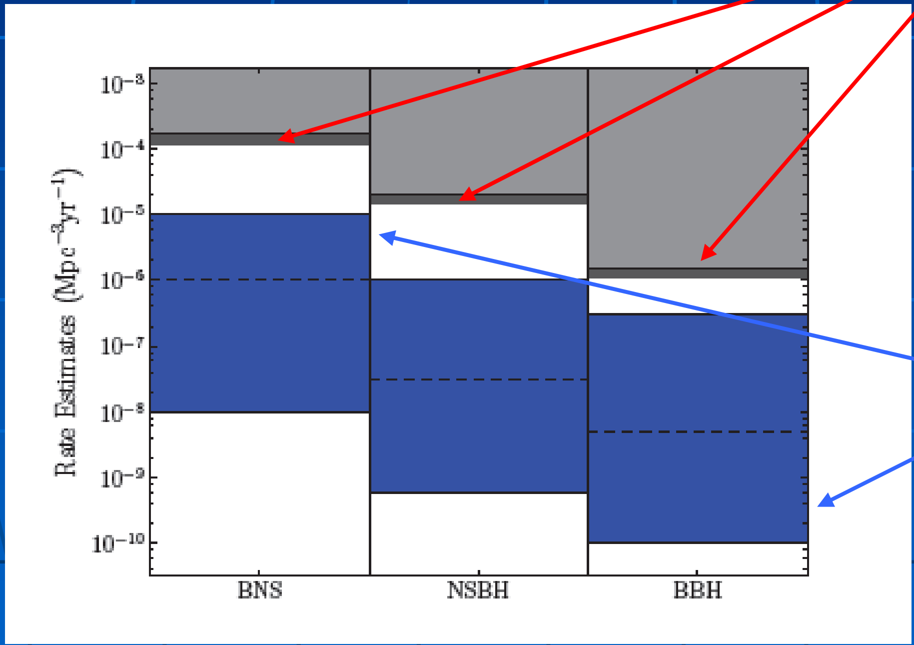
The LIGO-Virgo network
Compared sensitivities



The LIGO-Virgo network
A selection of scientific results

Search for compact binary coalescences:
No detection (yet)
–> ***upper limits*** on event rates

Today best UL's



Range of astrophysical predictions

LIGO&Virgo coll., Phys.Rev.D **85**:082002 (2012)

The gap is less than 1 order of magnitude!
(important for advanced detectors)

The LIGO-Virgo network
A selection of scientific results

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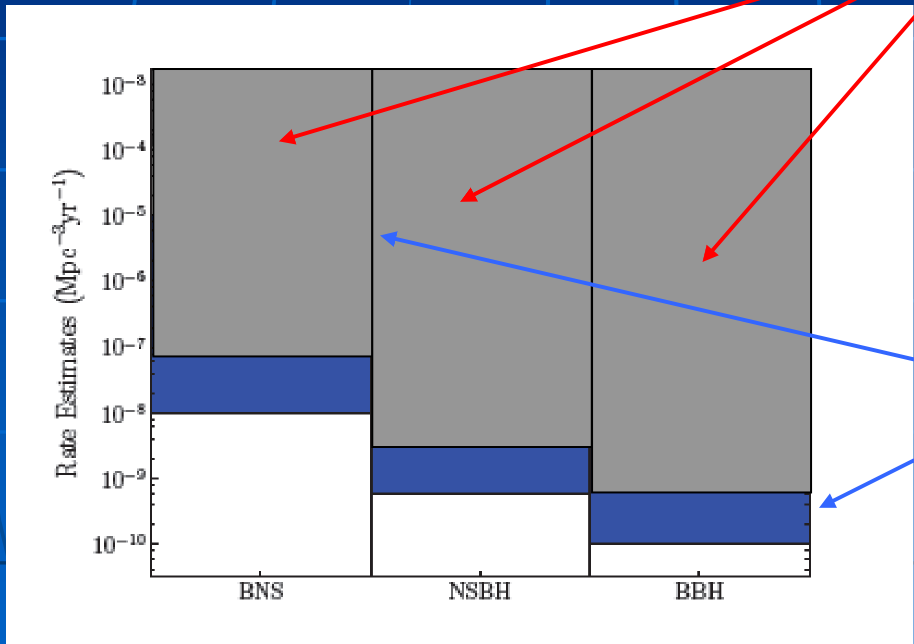

Range of astrophysical predictions

LIGO&Virgo coll., Phys.Rev.D **85**:082002 (2012)

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The LIGO-Virgo network
A selection of scientific results

Search for bursts: upper limits on event rates Vs signal strength (here generic SineGaussian signals)

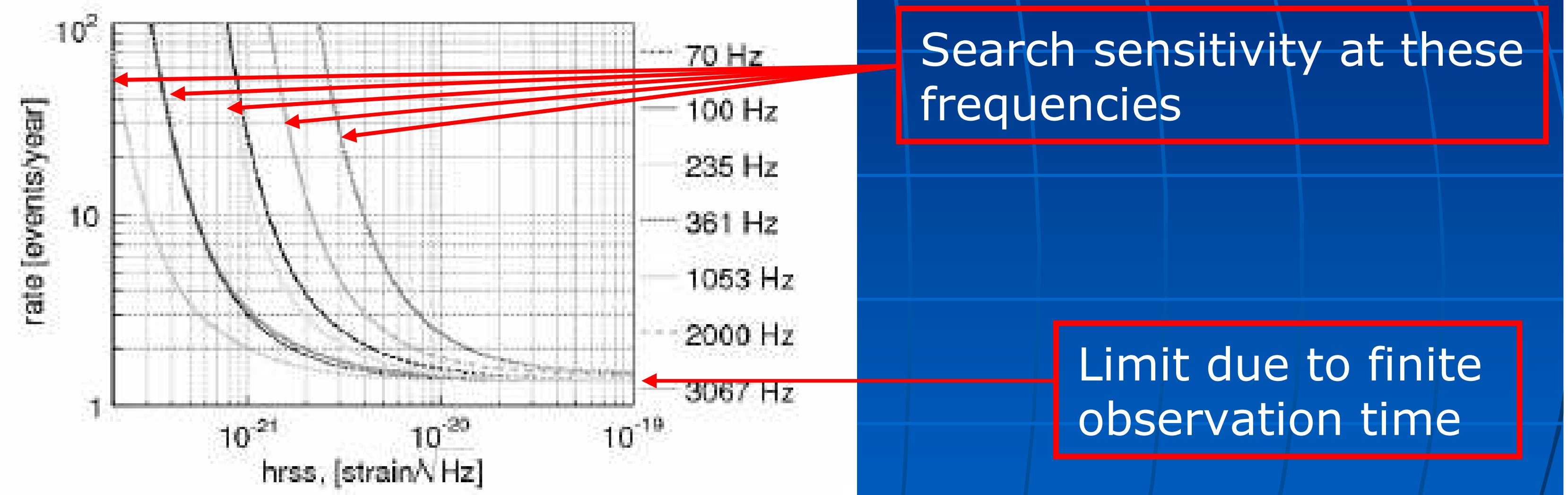


FIG. 5: Upper limits at 90% confidence on the rate of gravitational-wave bursts at Earth as a function of h_{rss} signal amplitude for selected sine-Gaussian waveforms with $Q = 9$. The results include all the LIGO and LIGO–Virgo observations since November 2005.

LIGO&Virgo coll., Phys. Rev. D **85**, 122007 (2012).

Network data analysis
The use of other messengers

External triggers may ease the search !
$\Rightarrow$ Have to look for events only in a **restricted time window** around the event and for a **known location** in the sky

Lot of studies for instance with
- **GRB** (Swift, Fermi, IPN …)
- **Soft Gamma Repeaters**
- **High Energy Neutrinos** (ICECUBE, Antares)
- **Low Energy Neutrinos** (SuperK)
- **Pulsar glitches**
- **etc…**

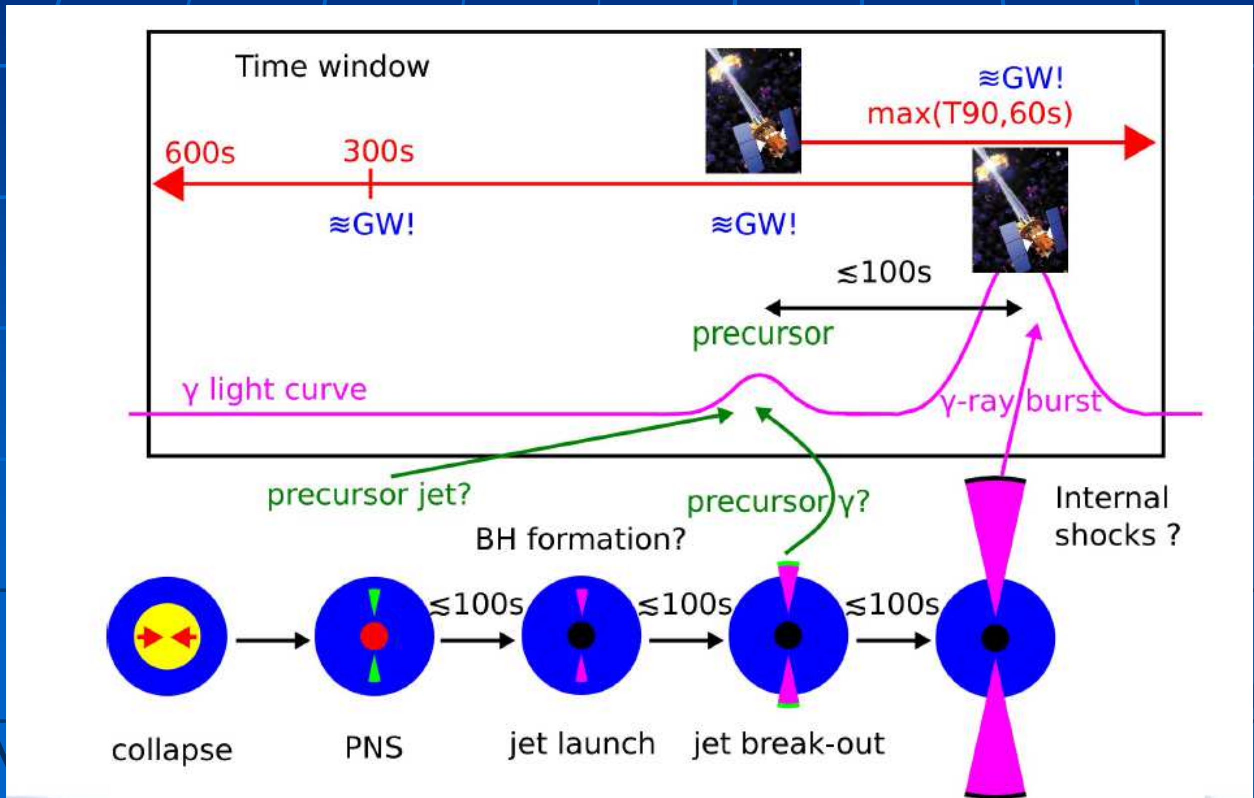
$\Rightarrow$ Main outcome (up to now) is upper-limit on possible GW emission

In general **GAIN of a FACTOR 2-3** w.r.t. all sky blind analysis (“see” ~ 1 order of magnitude further)

Network data analysis
The use of other messengers
An exemple: GRB analysis

GWs and GRBs

Short GRB <-> NS-NS coalescence
Long GRB <-> Gravitational collapse (hypernova)



Analysis window
~10 minutes
fits astrophys. scenario

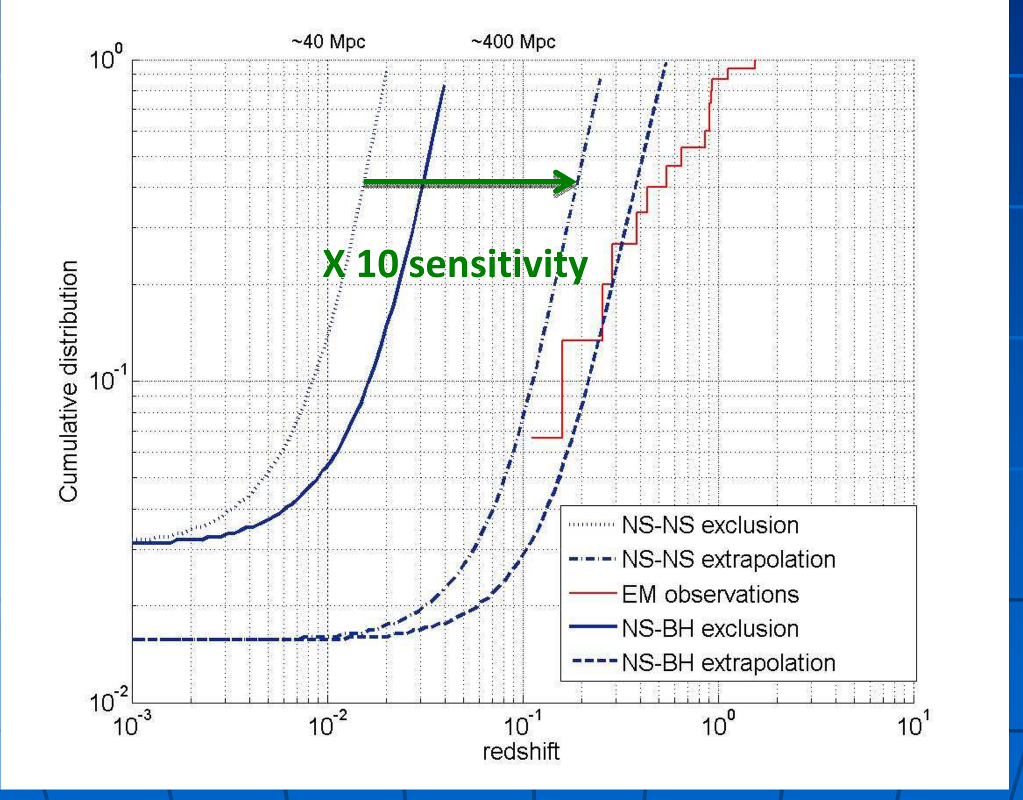
M.Was' thesis, Orsay, 2011.

Network data analysis

The use of other messengers

An exemple: GRB analysis

69 short GRB observed by γ-ray satellites (Swift, Fermi, IPN) during LIGO-Virgo 2009-2010 data takings

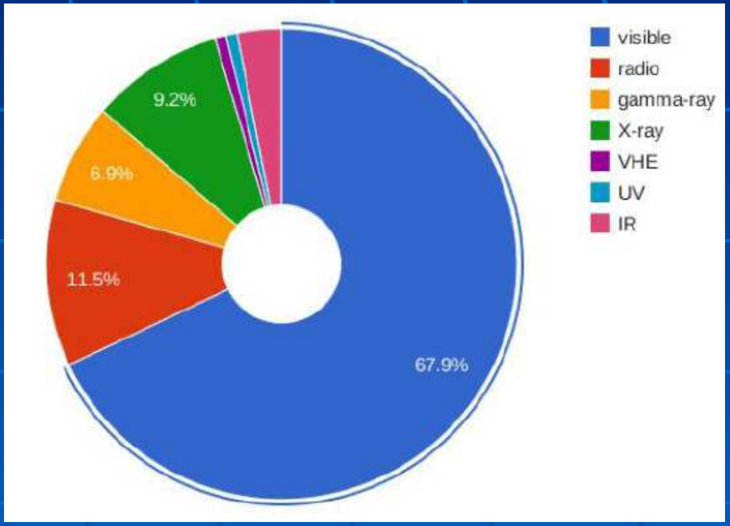


LIGO and Virgo coll., arXiv:1403.6639, to appear in Phys. Rev. Lett.
LIGO and Virgo coll., Astrophys. J. **760**, 12 (2012)

Network data analysis
The use of other messengers

EM follow-up program

- A call for electromagnetic follow-up for GW alerts have been done beginning of 2014
  - Many (>60) groups showed their interest
  - Large span from radio to TeV



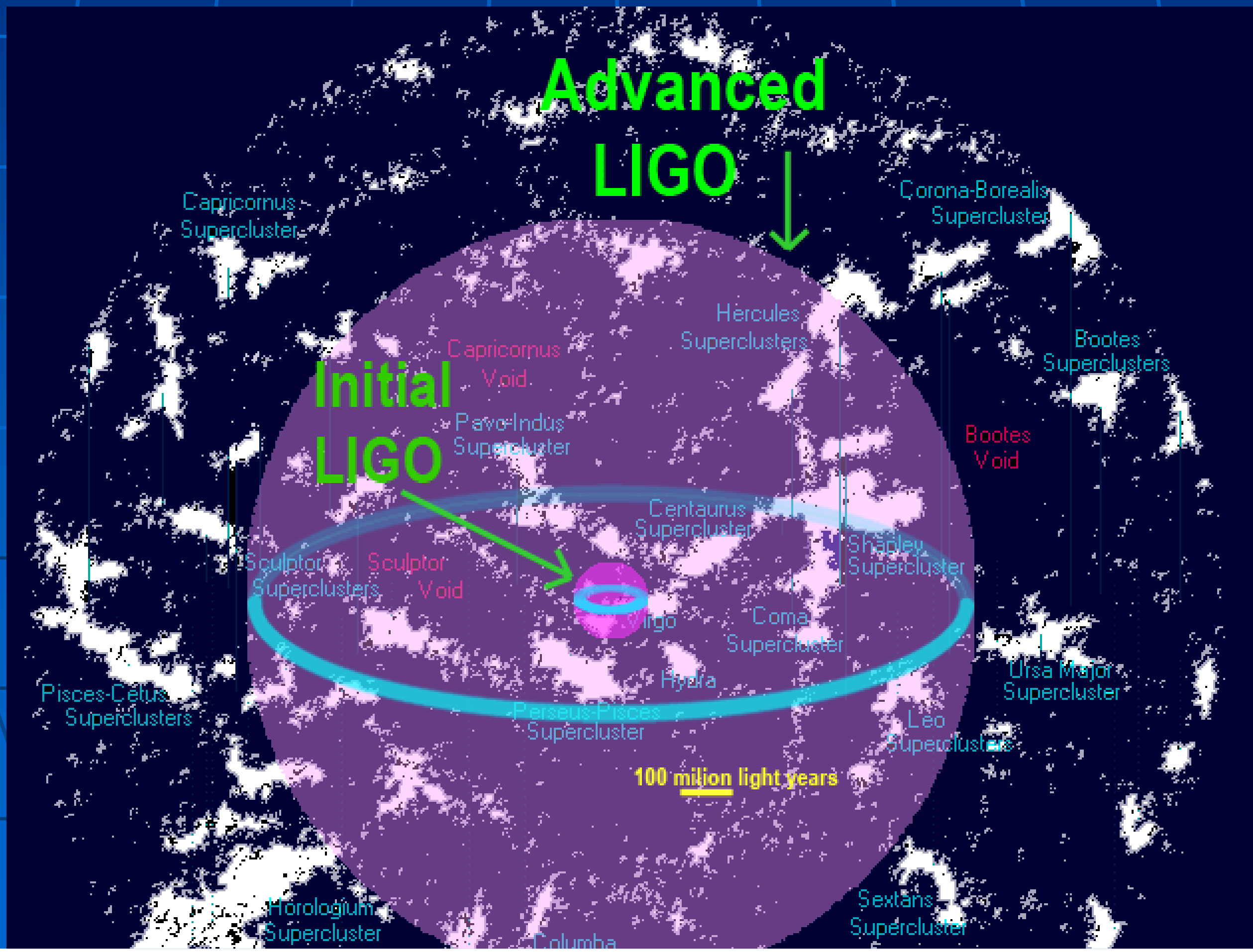
- 60% of MoU's already signed.
- Creation of a private network is under construction to share information about GW alerts.
- Confidentiality required up to the first detections.
- Plan to release public alerts after the first 4 GW detected events.
- New call planned for 2015.

The LIGO-Virgo (and others) network
The Future

The itf detectors are sensitive to amplitude $h(t)$ so increasing the sensitivity by a factor **10** increase the detection range also by 10 and the volume of observable universe by $\mathbf{10^3}$!

Detection of binary inspirals almost guaranteed with adv. detectors !

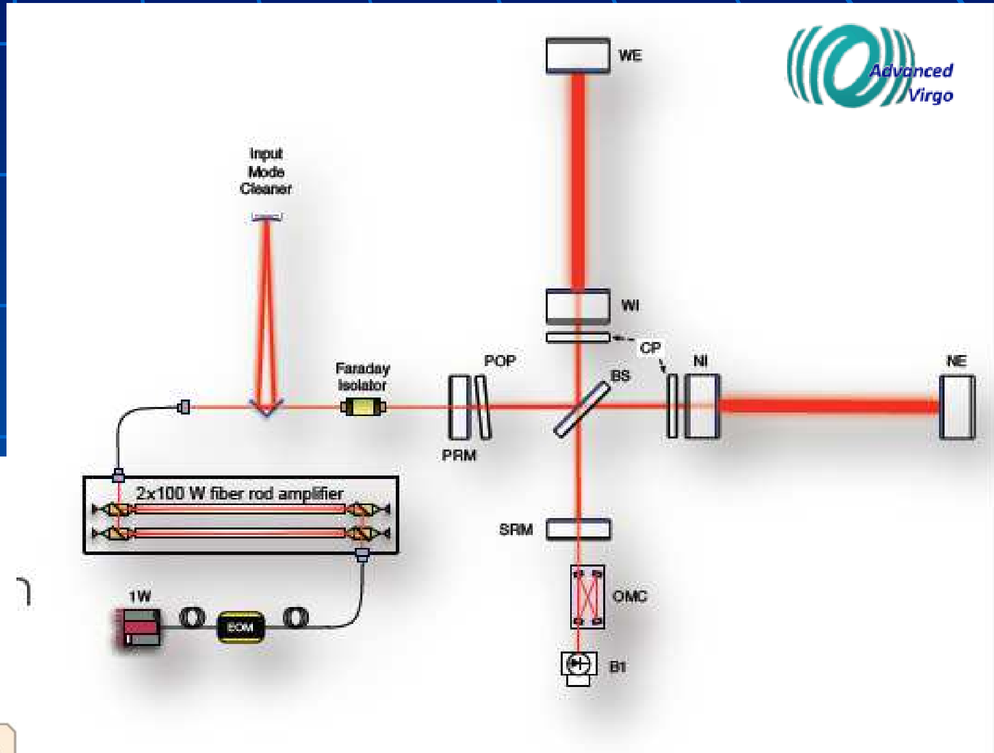
(event rate > 1/yr)

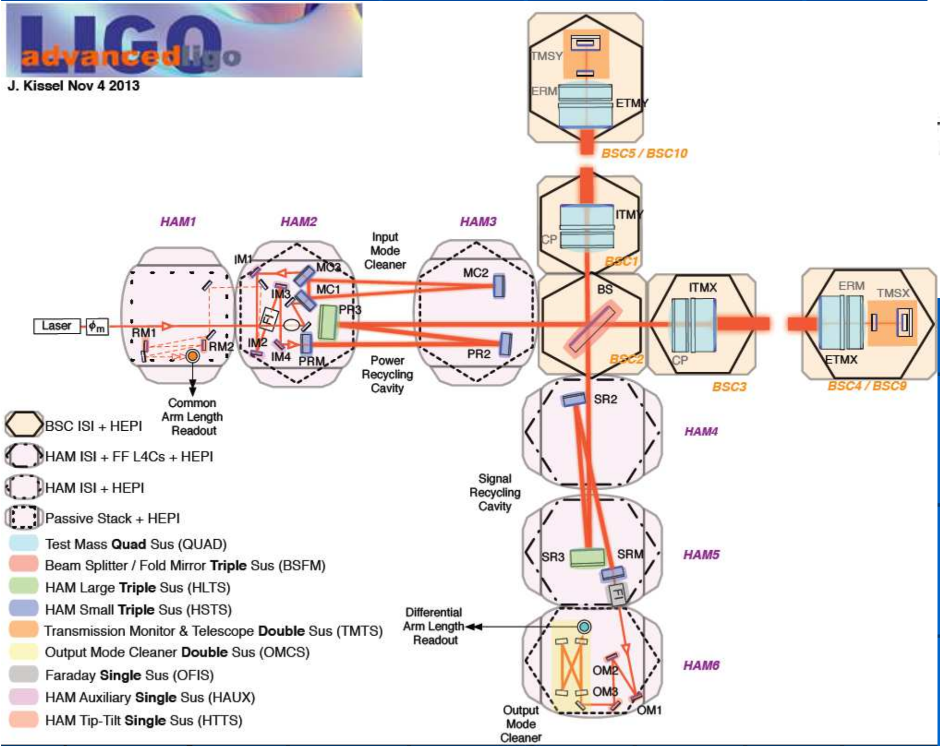


On the path to Advanced Detectors

Changes in optical configuration:

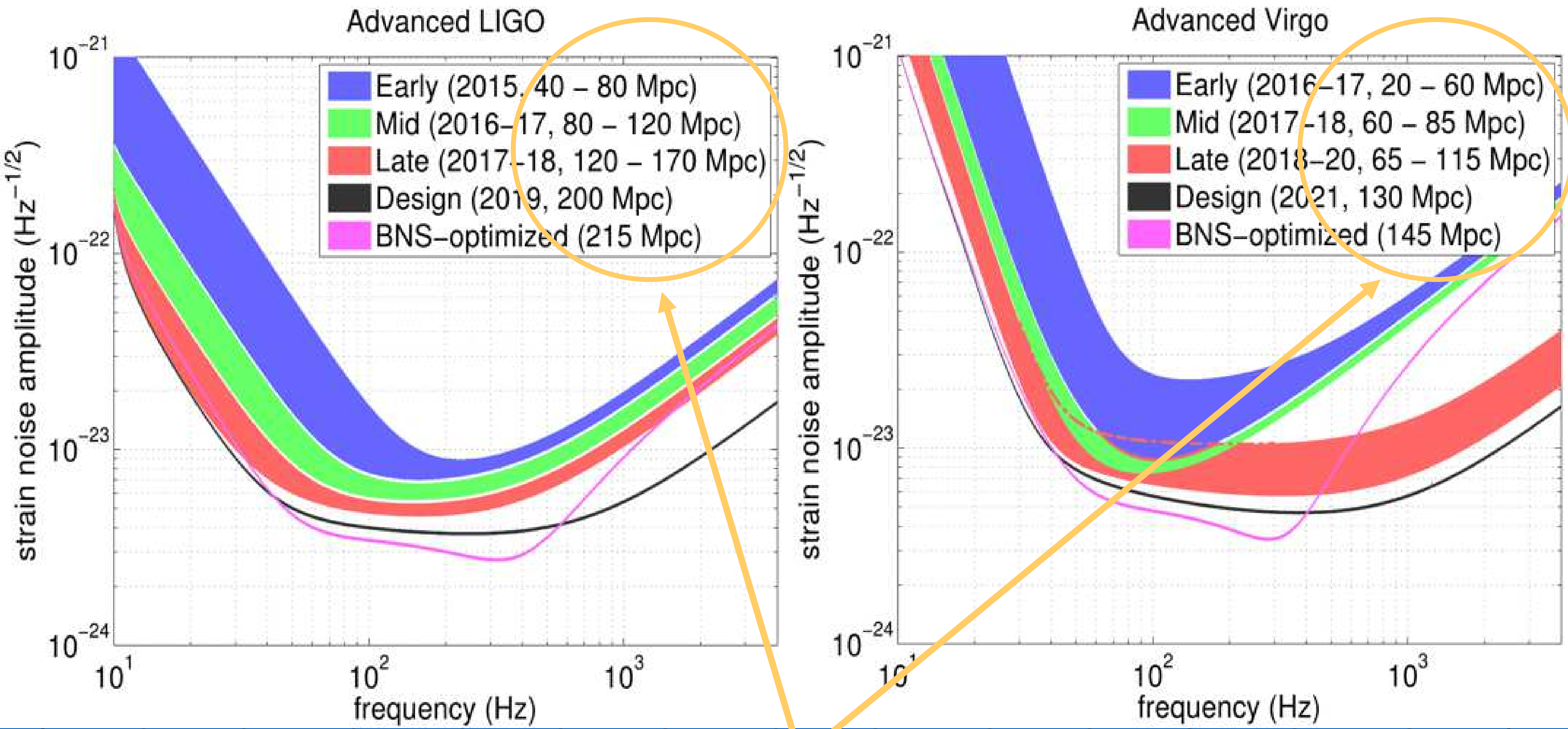
- Laser power increase
- Higher finesse cavities
- Signal recycling
- Larger beam sizes





The (Advanced) LIGO-Virgo network

A probable path

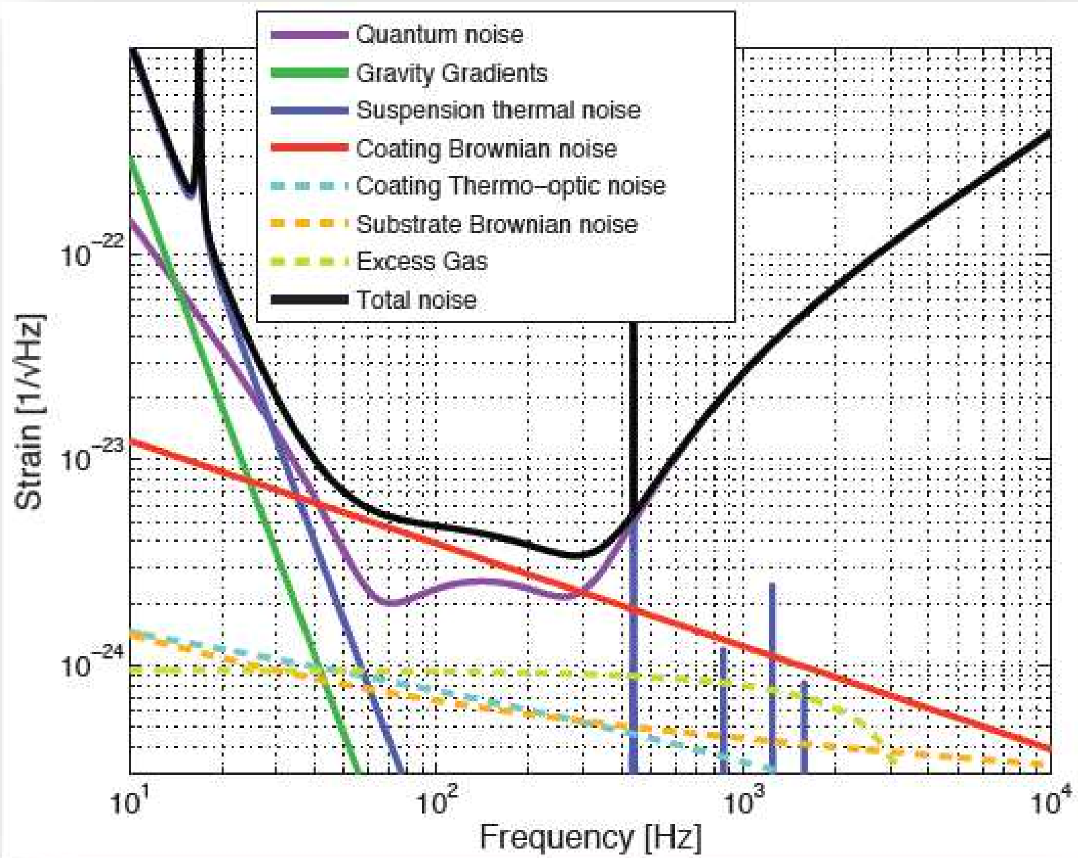


Range for binary neutron stars coalescences

LIGO and Virgo coll., arXiv:1304.0679, to appear in Living Reviews in Relativity

On the path to Advanced Detectors

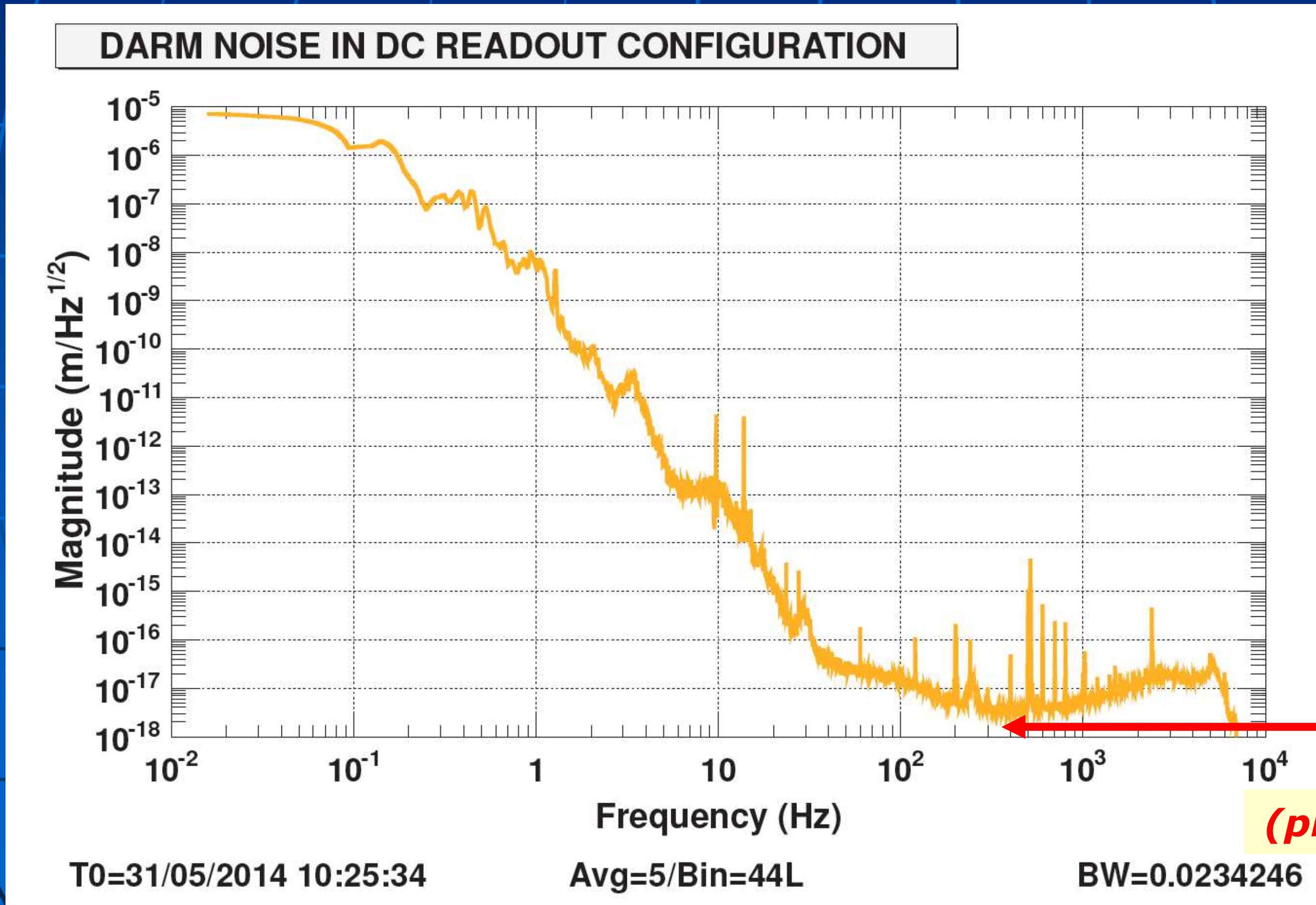
Advanced Virgo Noise Budget



Signal recycling: sensitivity can be ***tunable***

On the path to Advanced Detectors

First Spectrum from the Livingston interferometer, several days after the first Lock



$\tilde{h} \sim 10^{-21} / \sqrt{\text{Hz}}$

(preliminary calibration)

On the path to Advanced Detectors

KAGRA (prev."LCGT") itf in Japan

- Located in the Kamioka site
- Underground (less seismic noise)
- Cryogenic (less thermal noise)

And after!!!
(The 3rd generation)

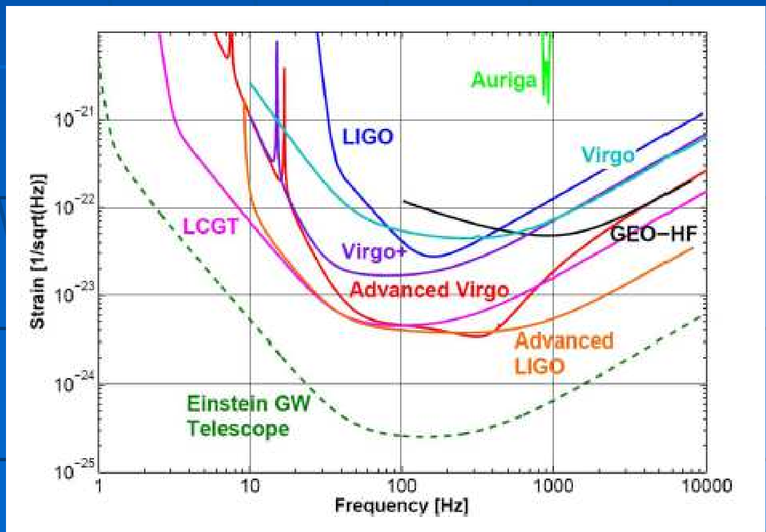
Cryogenic interferometric detectors

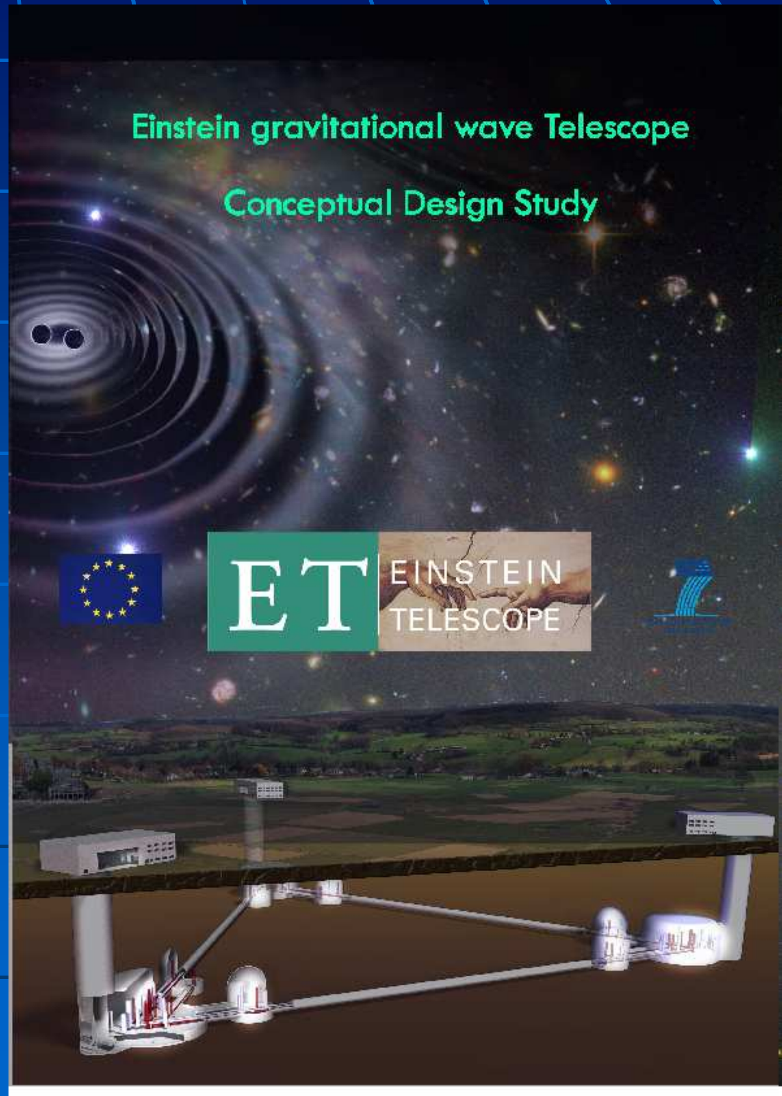
Underground detectors

All reflective optics
(gratings as beamsplitters etc …)

Triangular detectors

Capacitive drivers for mirror control





Conclusions

A new experimental field !

(astro)physics is not yet there … but be patient

Binary inspirals detection likely to be routine in the next decade

GW detectors matched for Galactic Supernovae (likely to be the case forever…)

GW astronomy full partner of multi-messenger HE astrophysics

Some science prospects:

- Tests of gravitation (GW celerity and polarization …)
- First direct Black Hole observations
- Collapse dynamics
- Equation of state of compact stars
- **GRB engines**
- Cosmology (compact binaries as standard candles)
- …

New messenger … new vision of the Universe ?