LAUREE AD HONOREM

Lauree ad Honorem in Physics to B.C. Barish and S.L. Glashow

ALMA MATER STUDIORUM
UNIVERSITÀ DI BOLOGNA

Detection of Gravitational Waves

- Introduction : gravitational waves
- Acoustic Detectors
- Laser Interferometers
- Future Prospect
- Summary and Conclusions

Last MACRO Meeting Gran Sasso January 2000

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Gravitational Waves

for weak field almost galilean metric with the addiction of a small terms

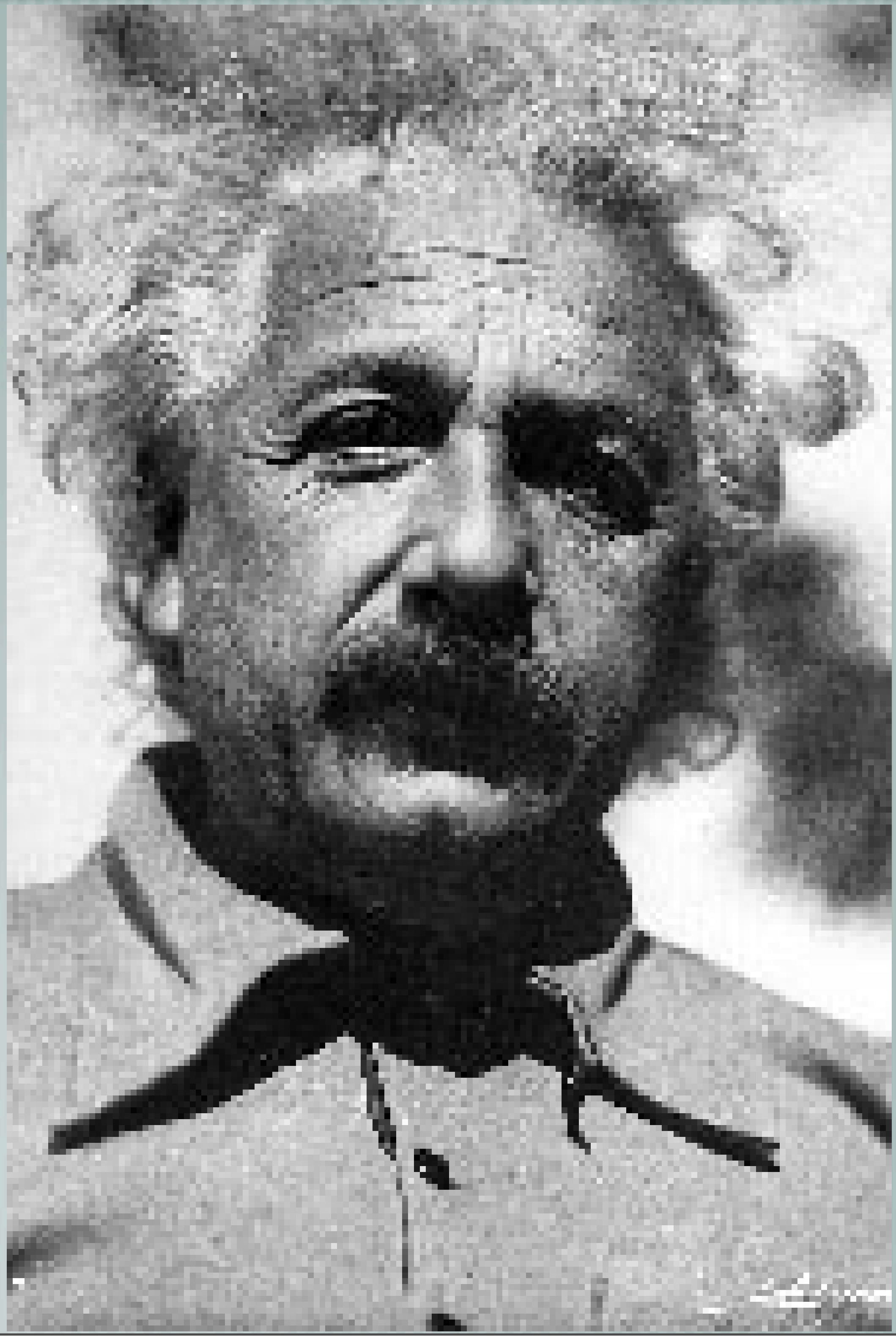
$$h_{ik} << 1$$

in absence of matter and in a transverse traceless gauge

$$h_{23} = h_{32}$$
$$h_{22} = -h_{33}$$

$$\left(\frac{\partial^2}{\partial x^2} - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} \right) h_{ik} = 0$$

This is the equation of transversal waves with velocity c



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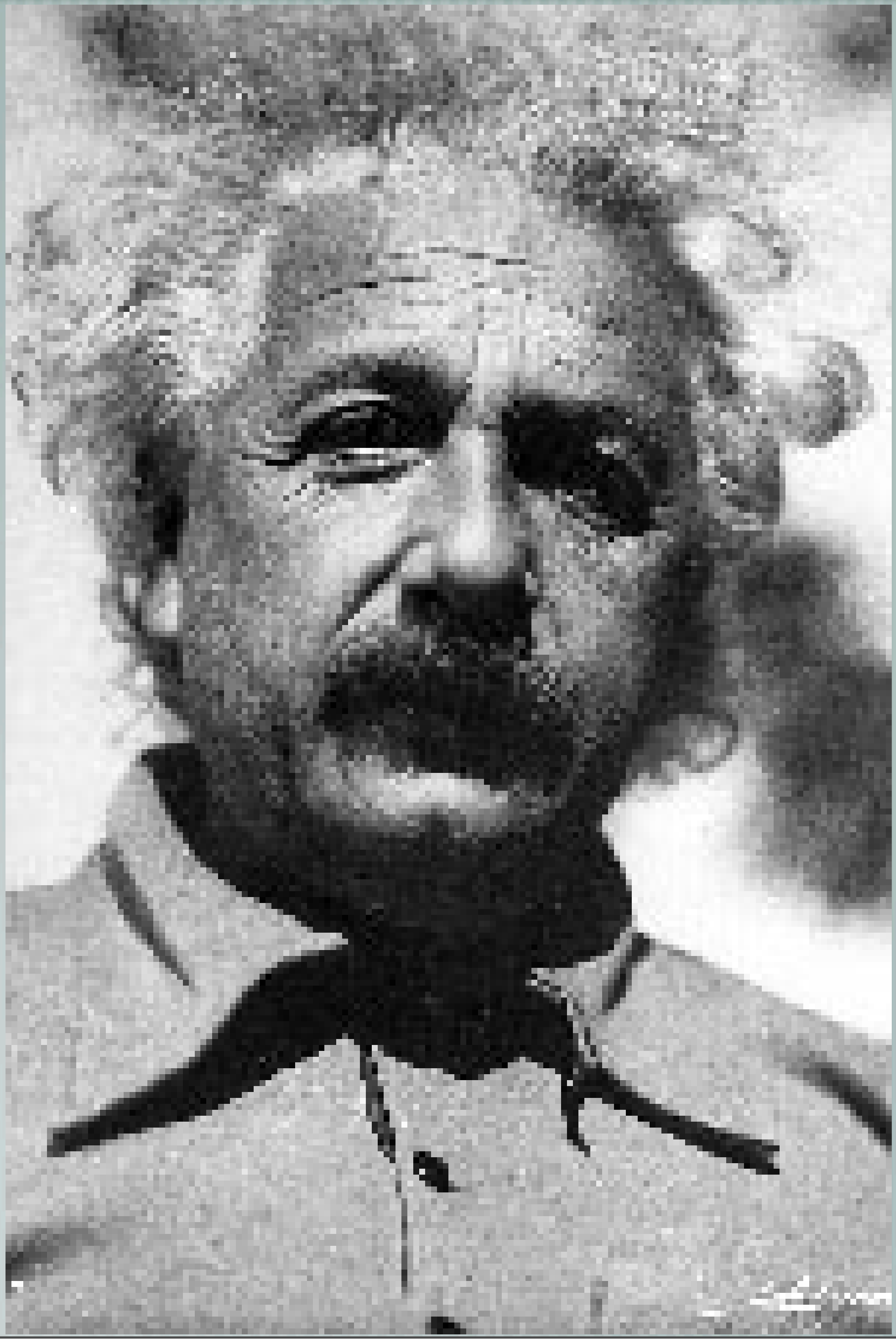

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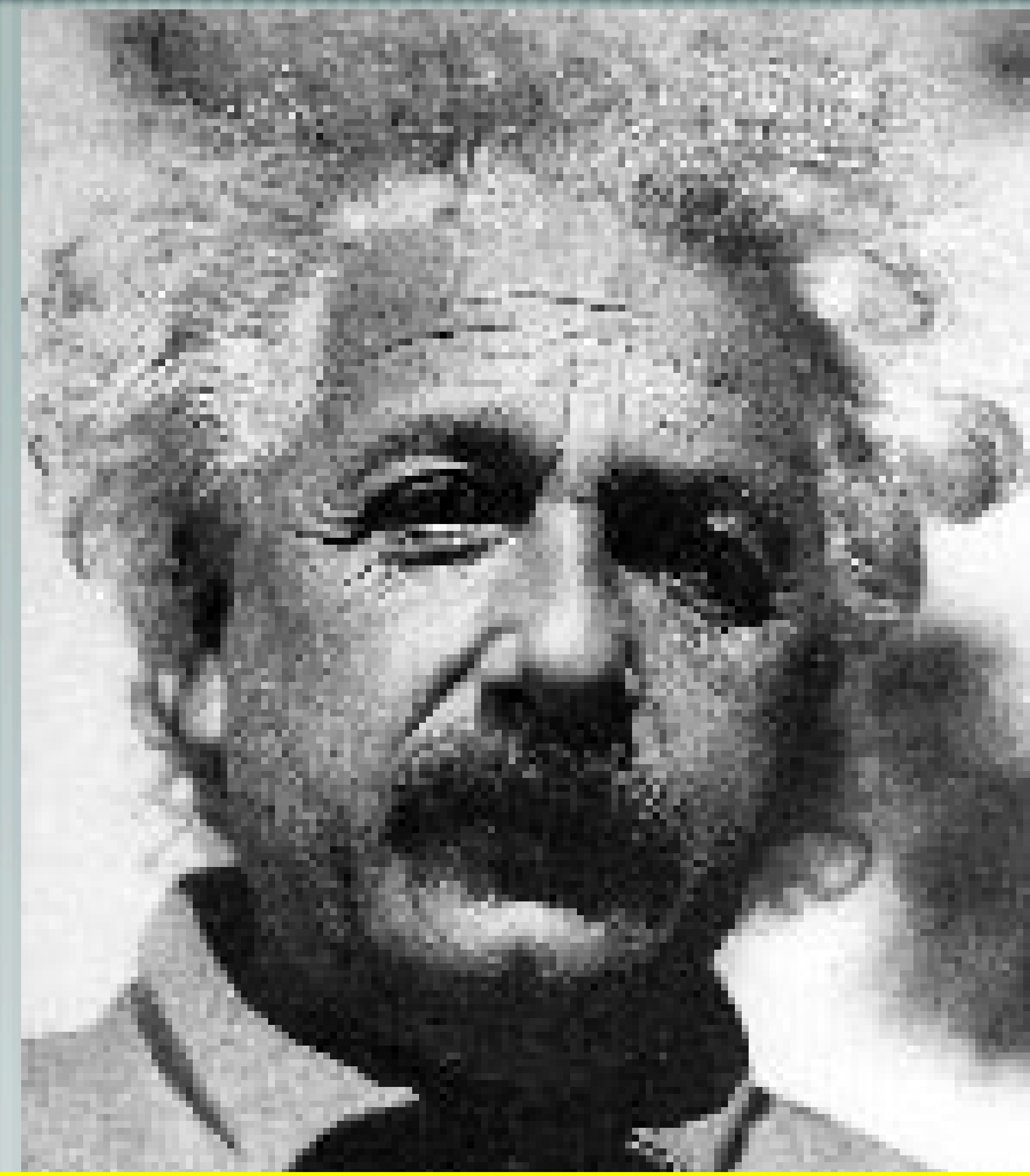

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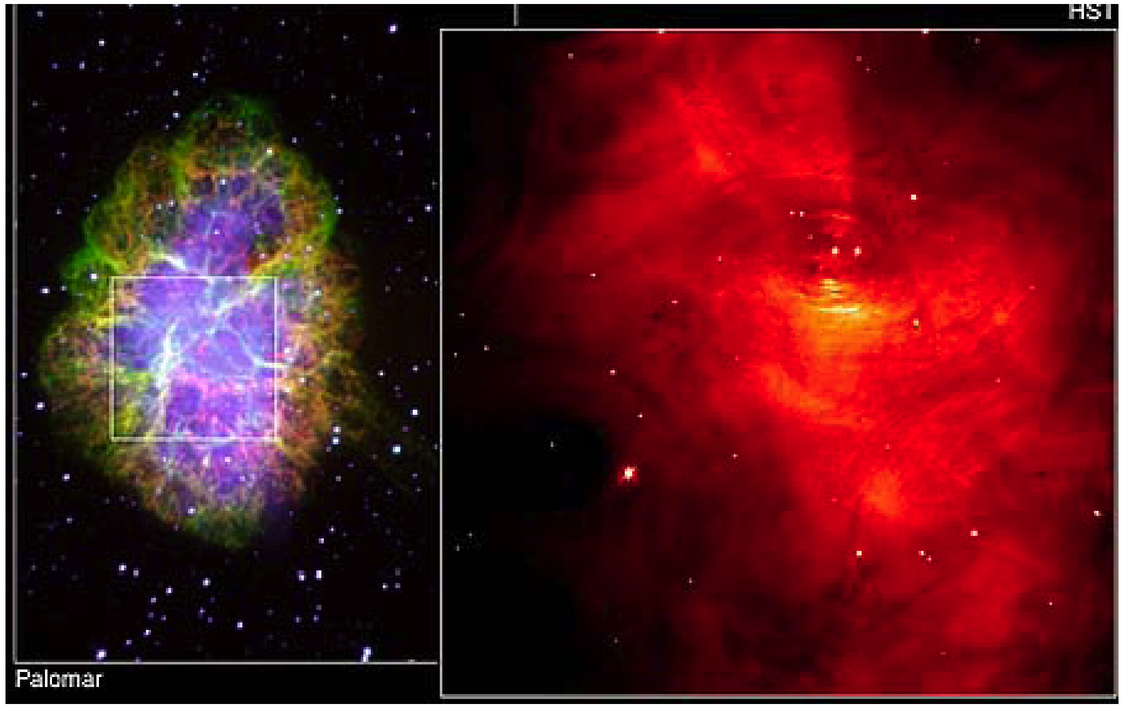
Importance of gravitational waves astronomy:
Universe is transparent only to gravitational waves and neutrinos!

Indirect evidence for GW emission



- neutron binary system PSR 1913+16 7 kpc from the eart
- period speeds up 35 sec fron 1975 to 2004
- apparently loss is due to GW agreement with general relativity at 0.1% level
- 1993 Nobel to Russel Taylor

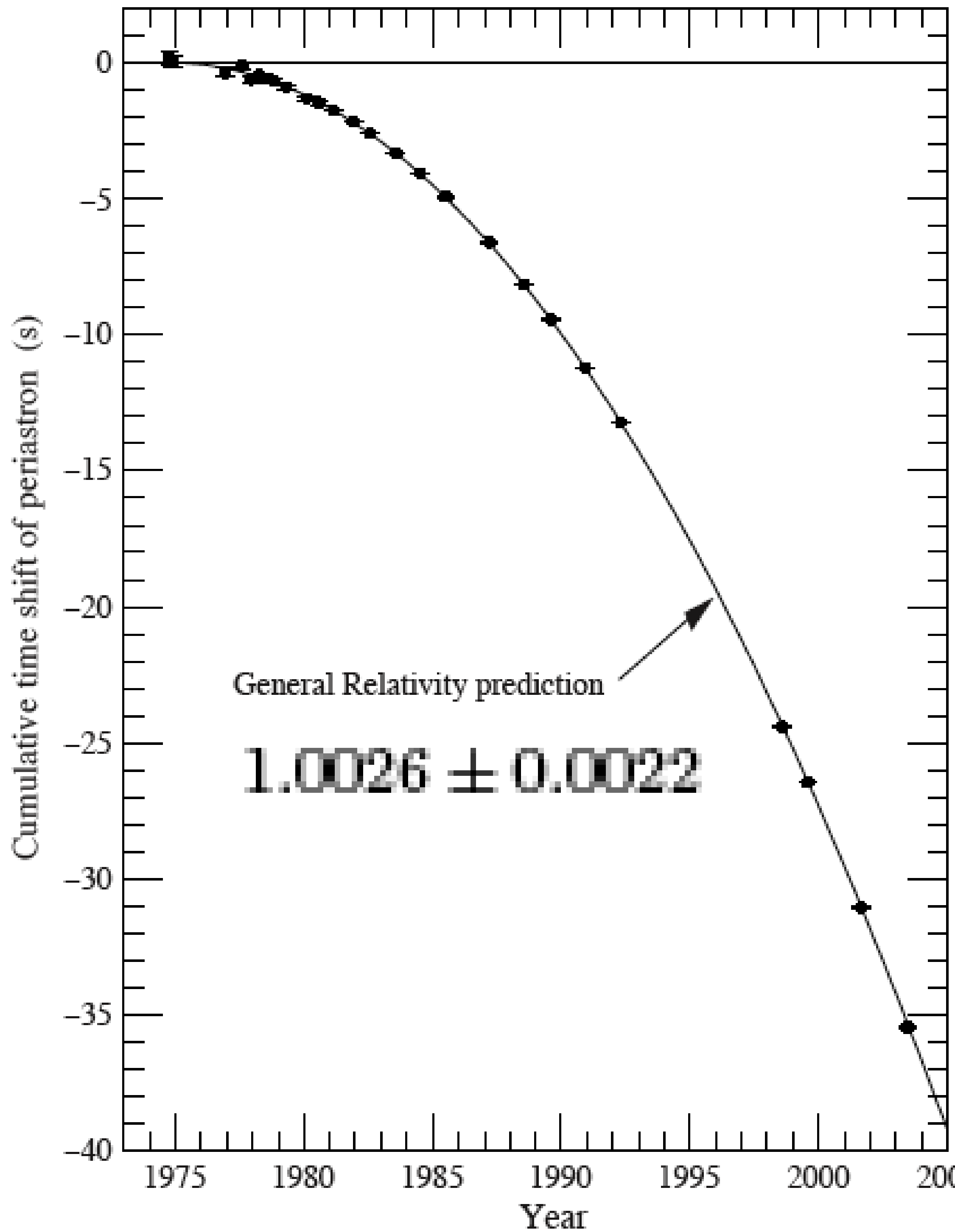
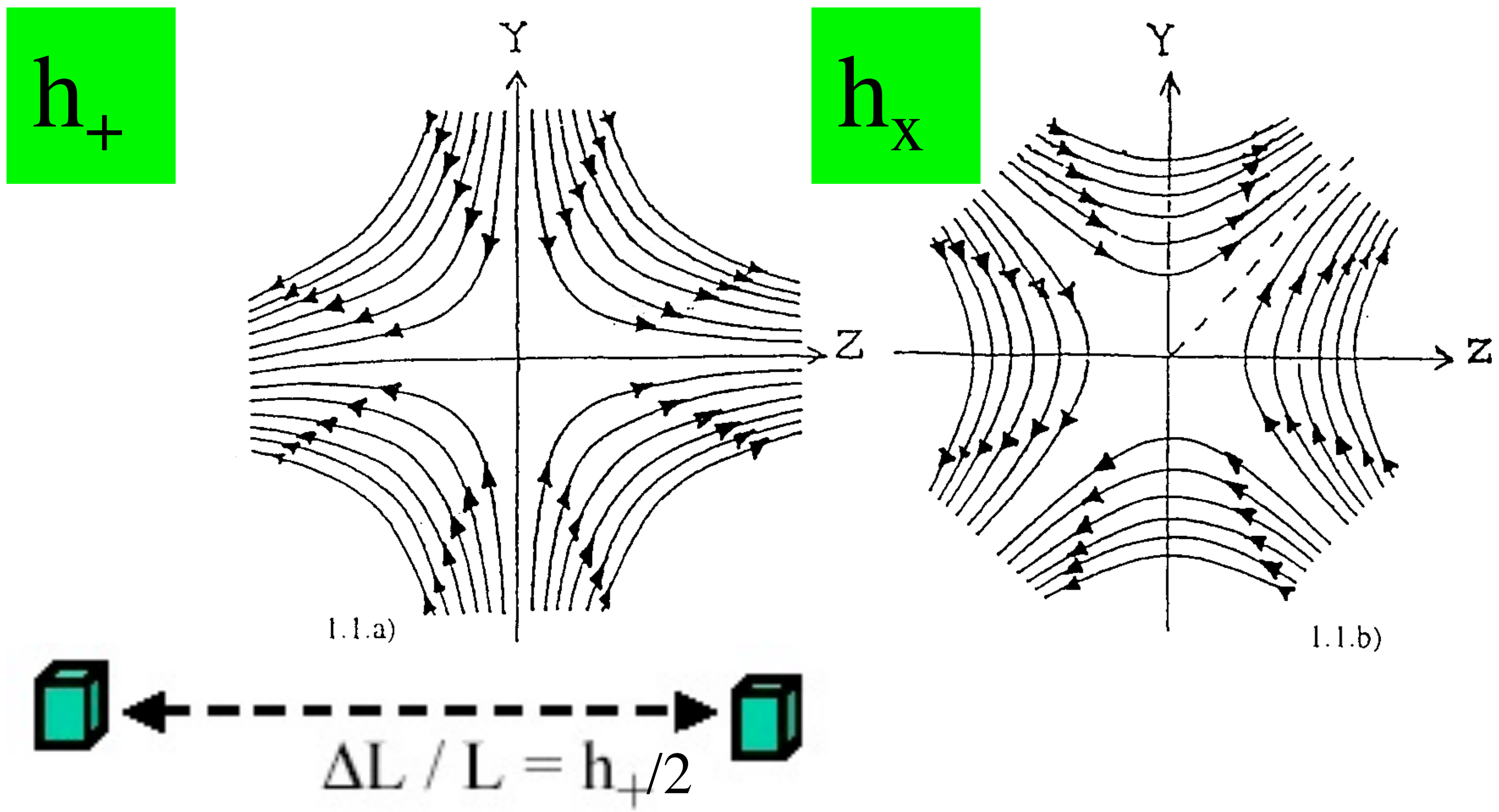
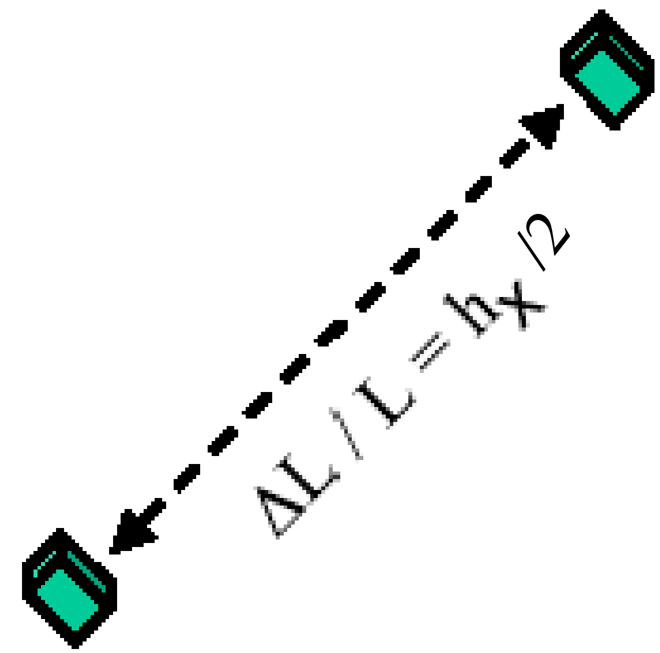


Figure 18.1: Accumulated shift of the times of periastron passage in the PSR 1913+16 system, relative to an assumed orbit with a constant period. The parabolic curve represents the general relativistic prediction, modified by Galactic effects, for orbital period decay from gravitational radiation damping forces. (Figure obtained with permission from Ref. 40.)

Gravitational waves : some characteristic

1) 2 independent transversal quadrupolar components producing variations in the length ortogonally to the propagation axis





Detectors should measure ΔL

2) Invariance for 180^o rotations. Electromagnetic waves 360^o

Two polarizations “+” and “x”

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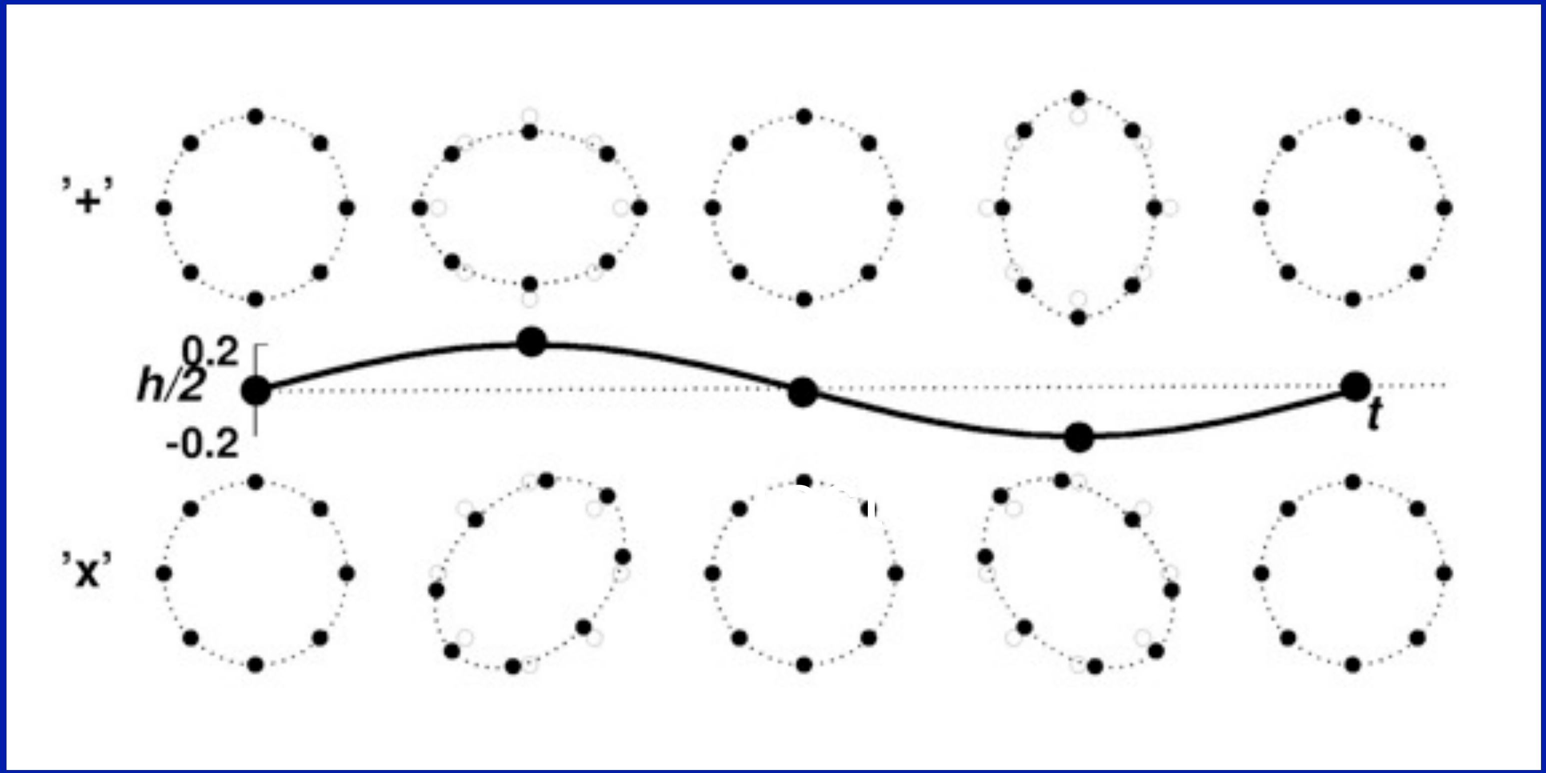

Detectors are sensitive to the polarization and to the angle of incidence

A measurement of the degree of circular polarization determines the inclination of a simple binary orbit.

To fully reconstruct a gravitational wave several cylinders/ interferometers are need or a spherical detector!

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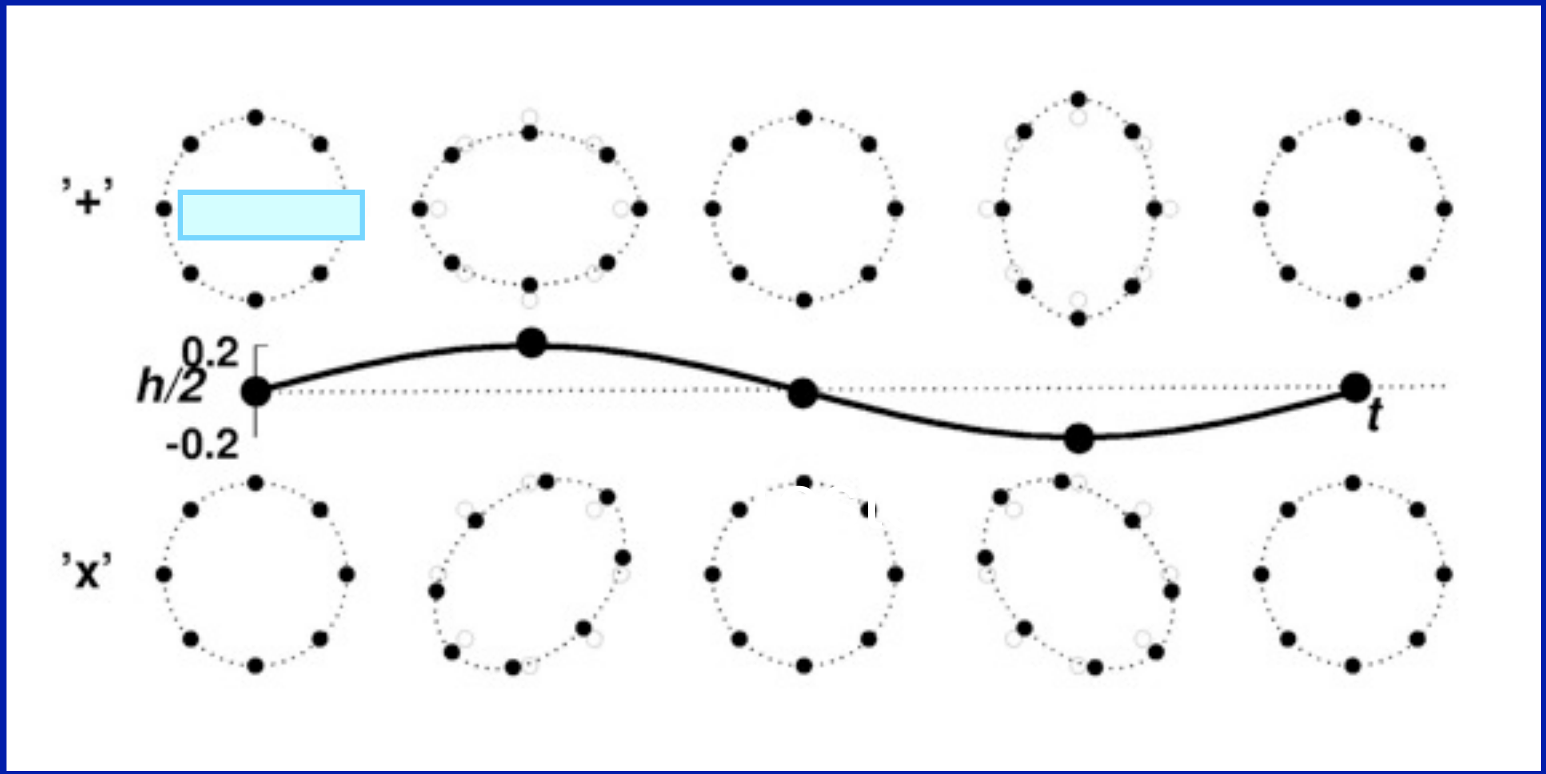

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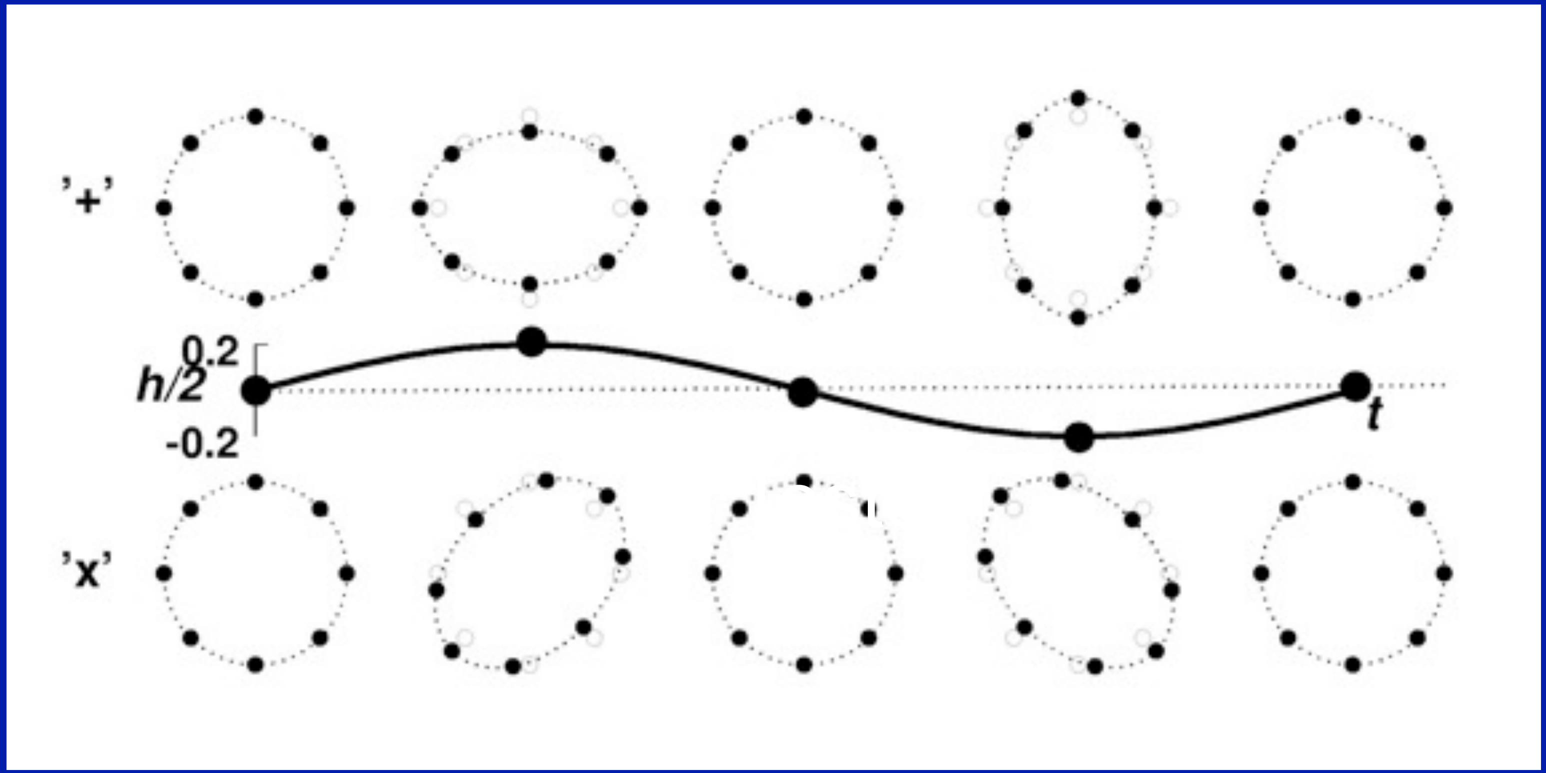

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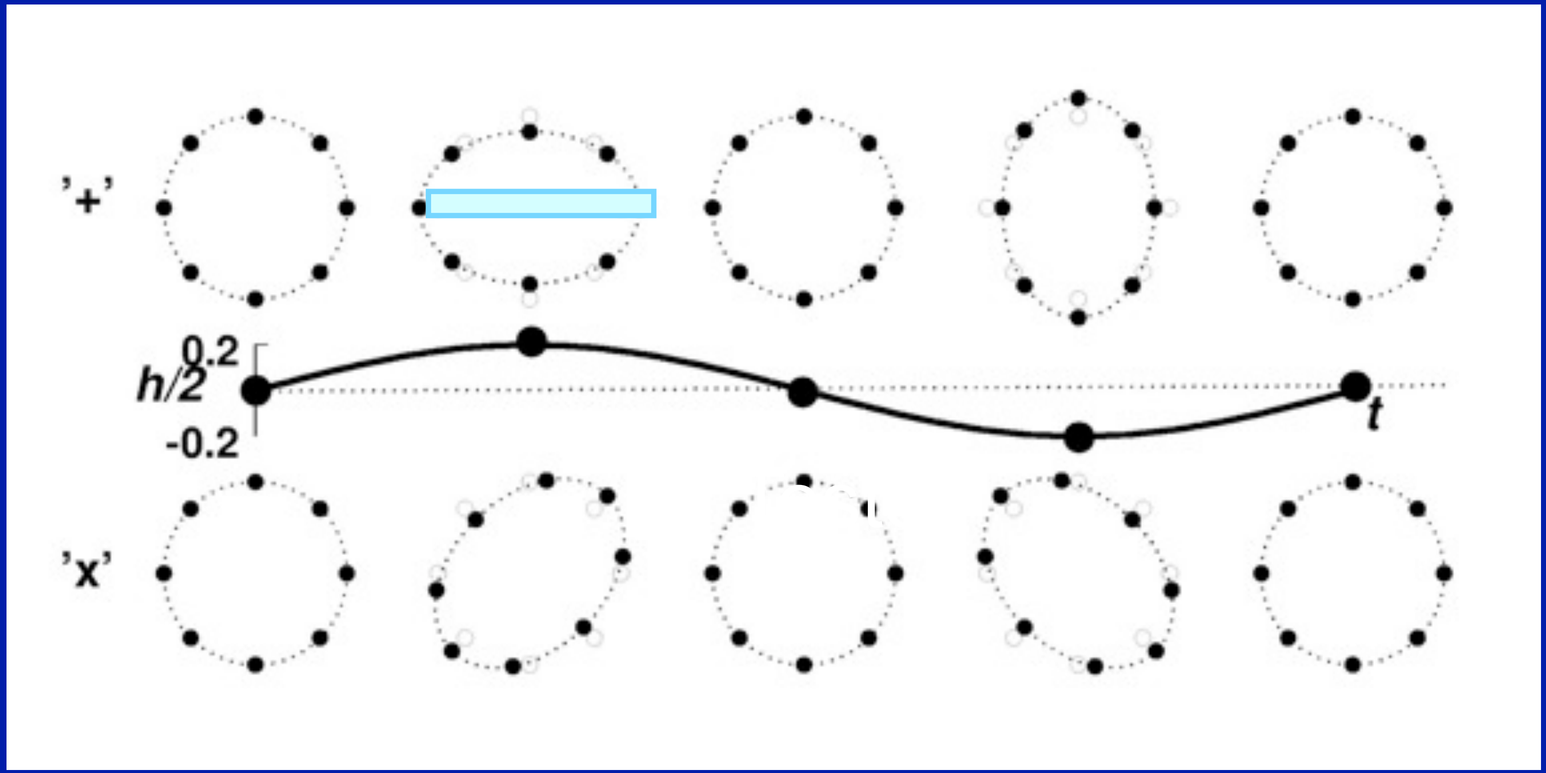

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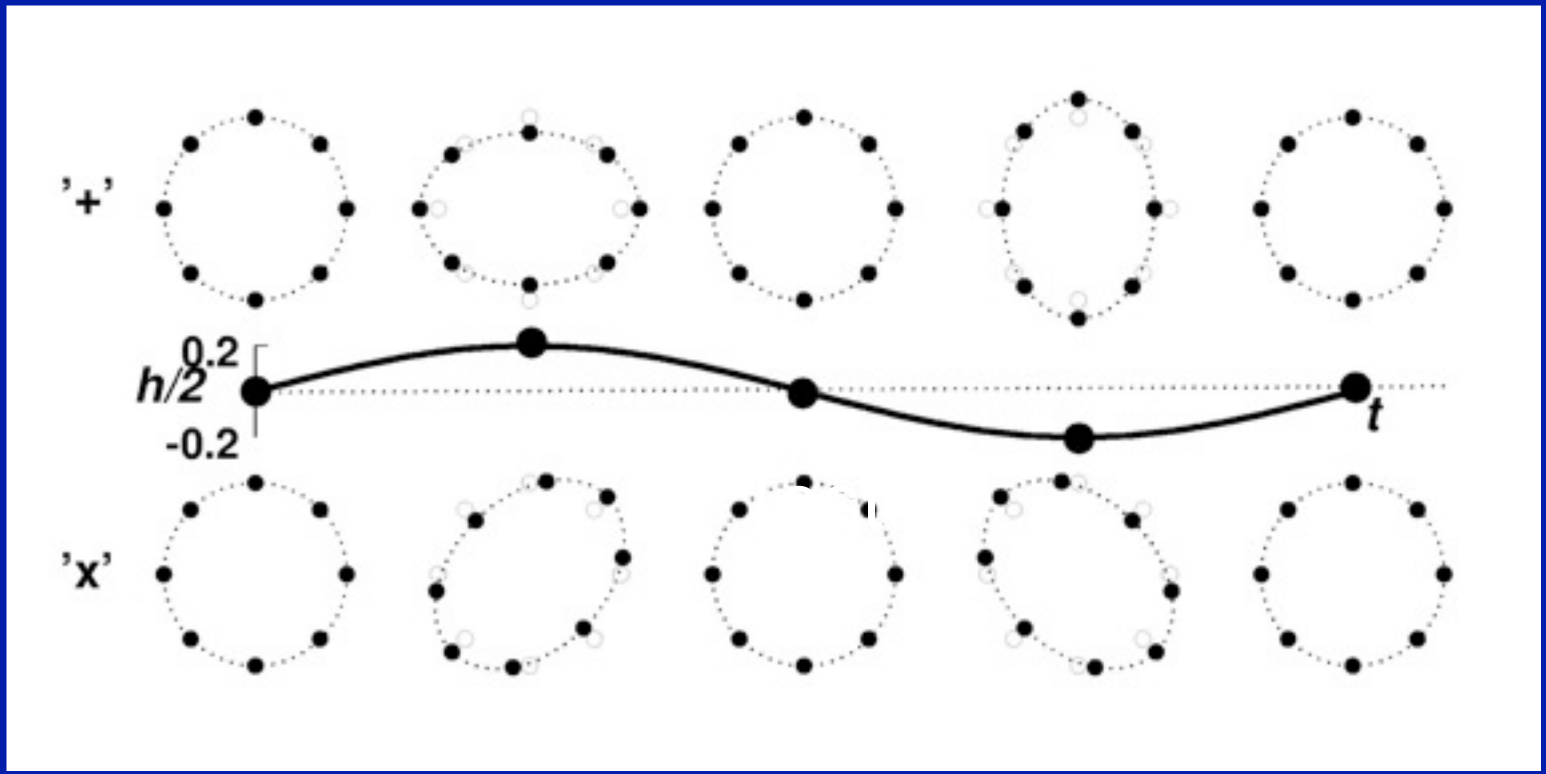

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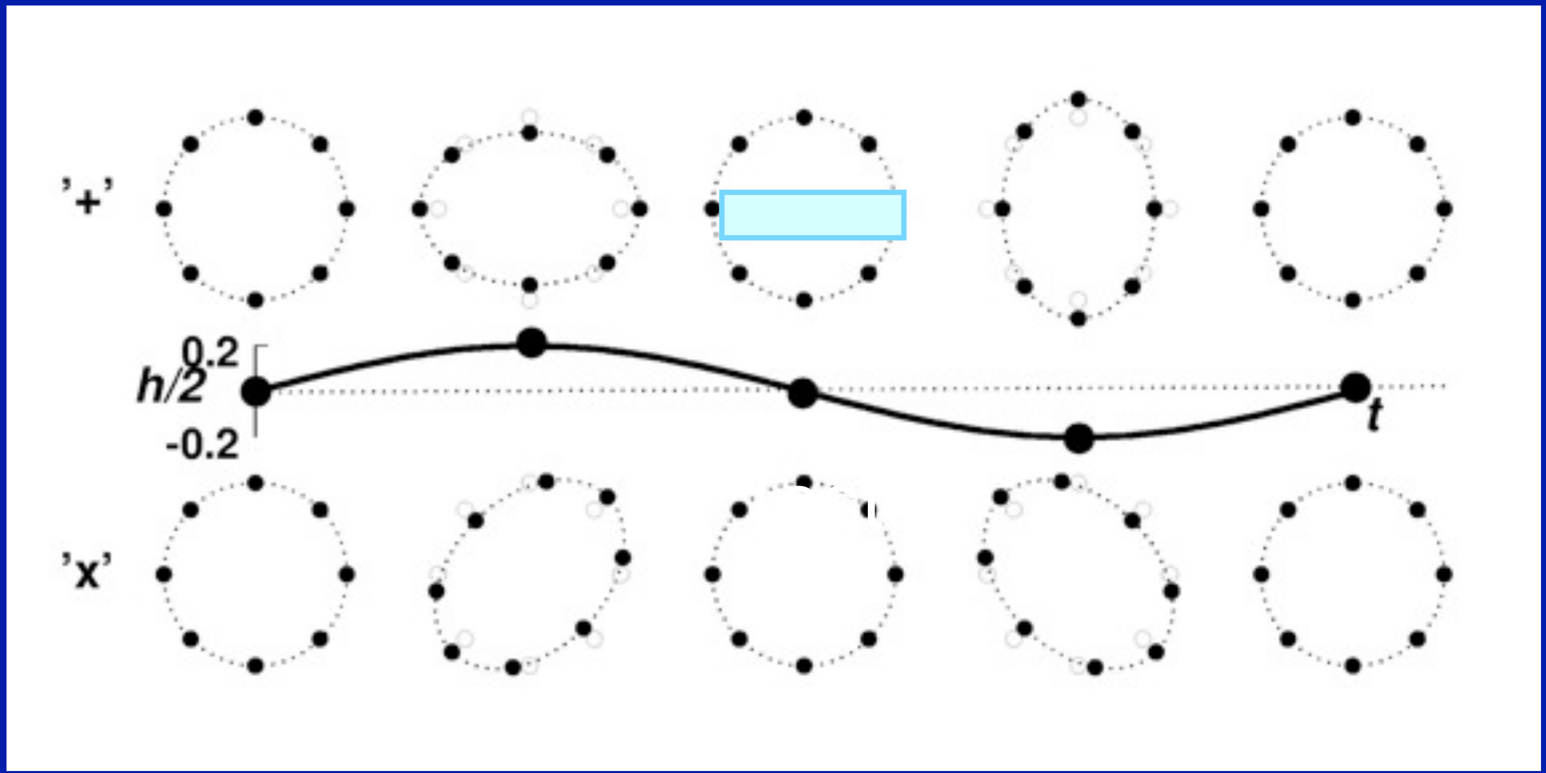

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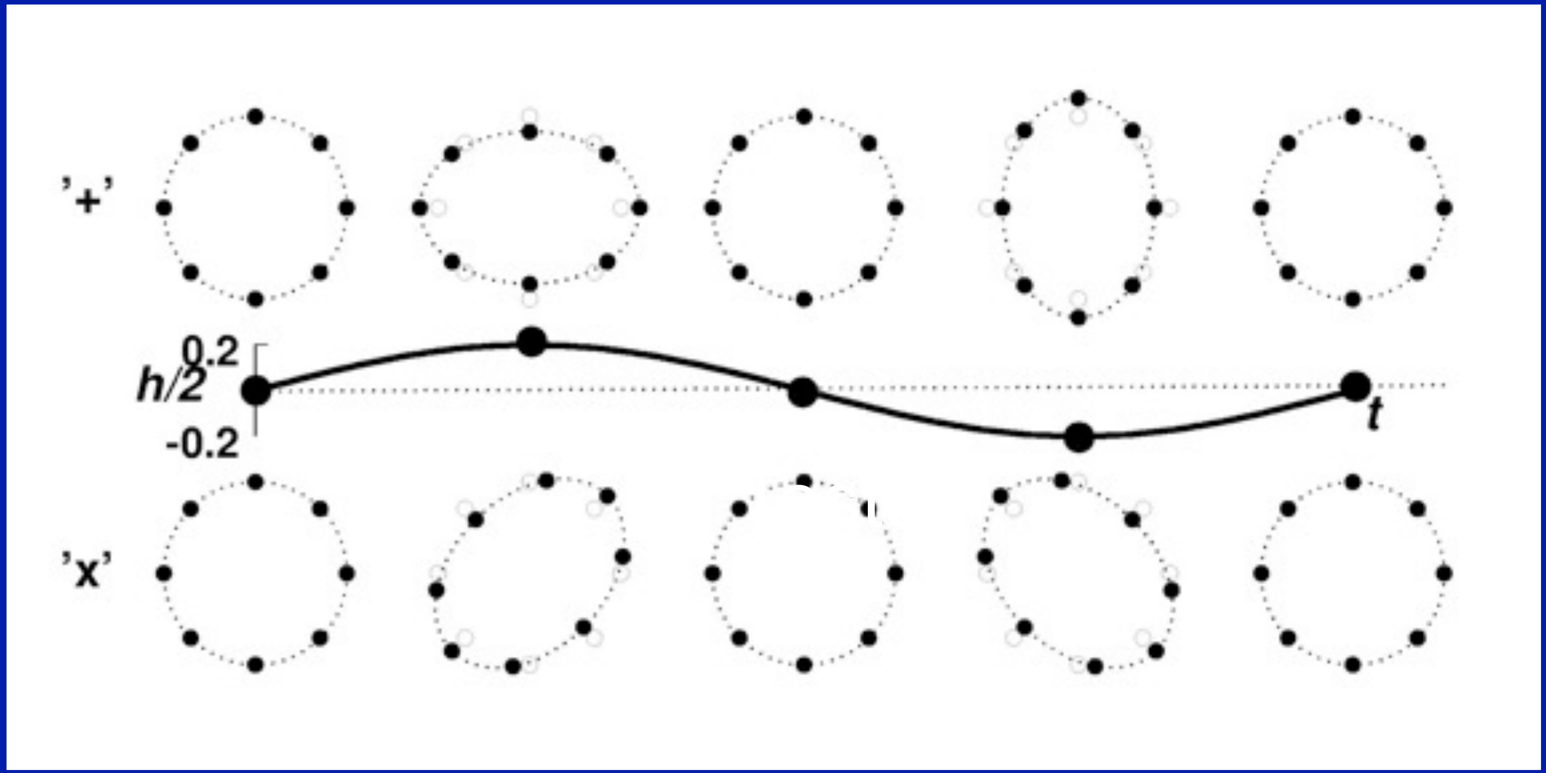

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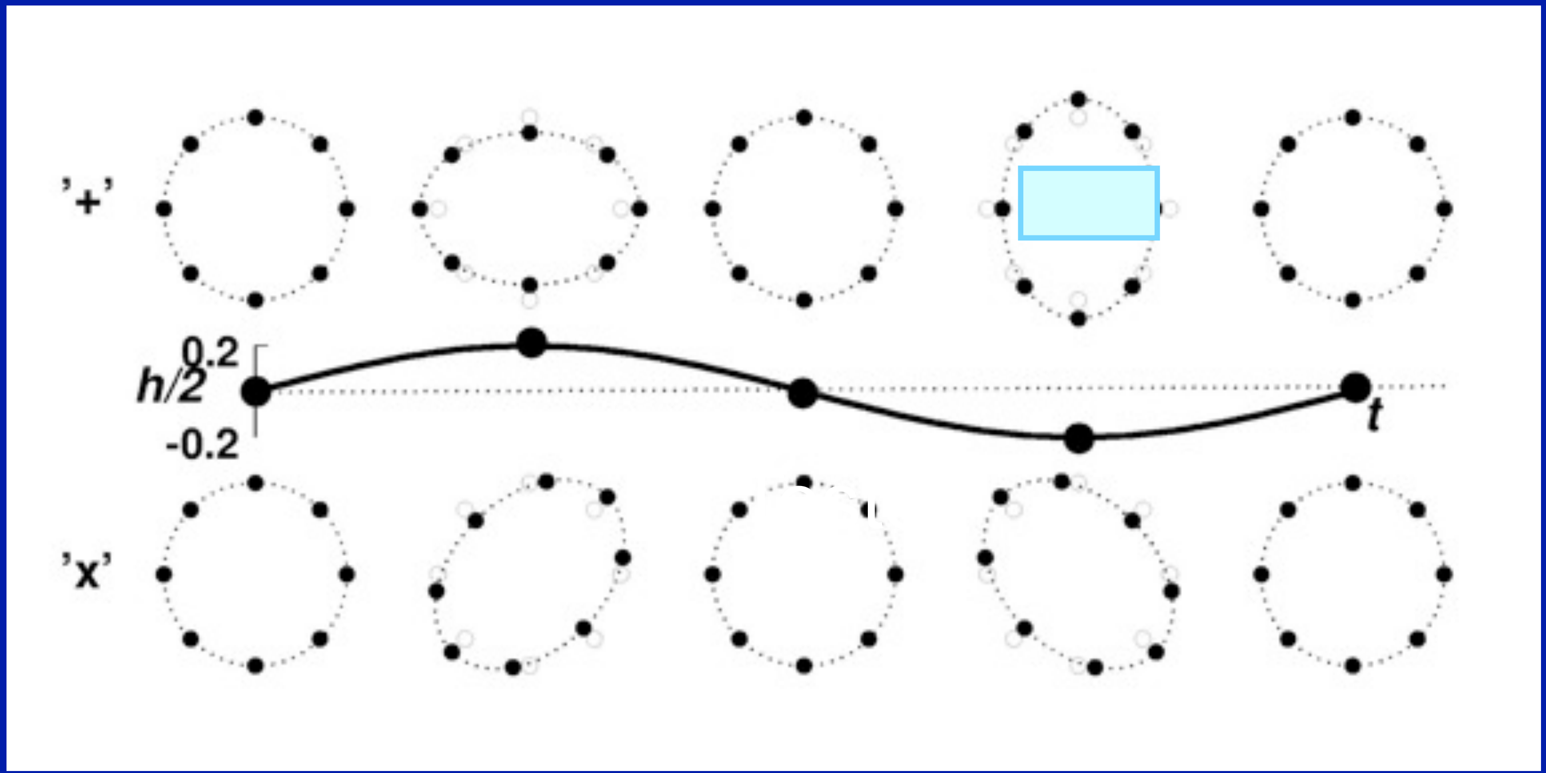

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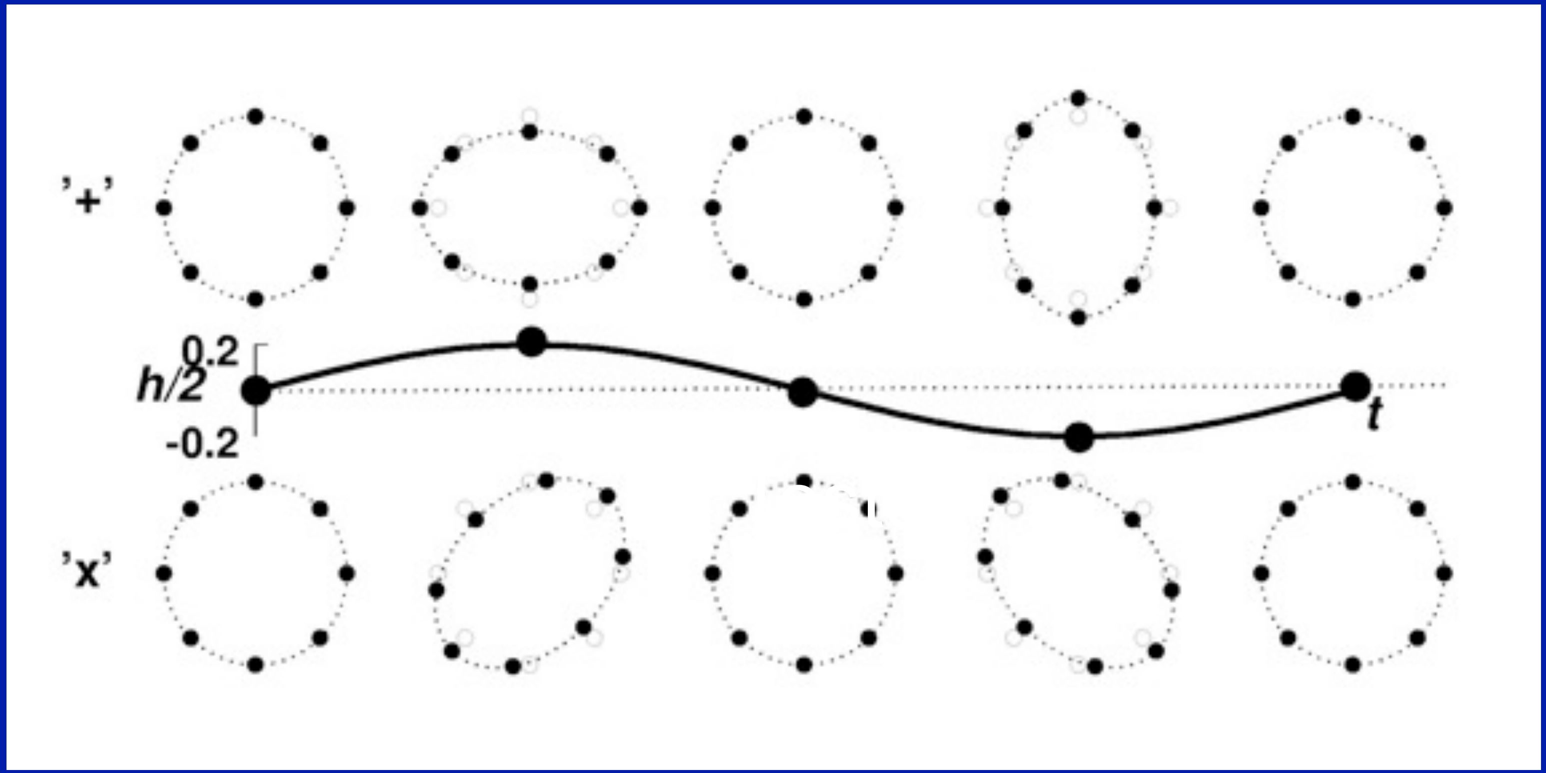

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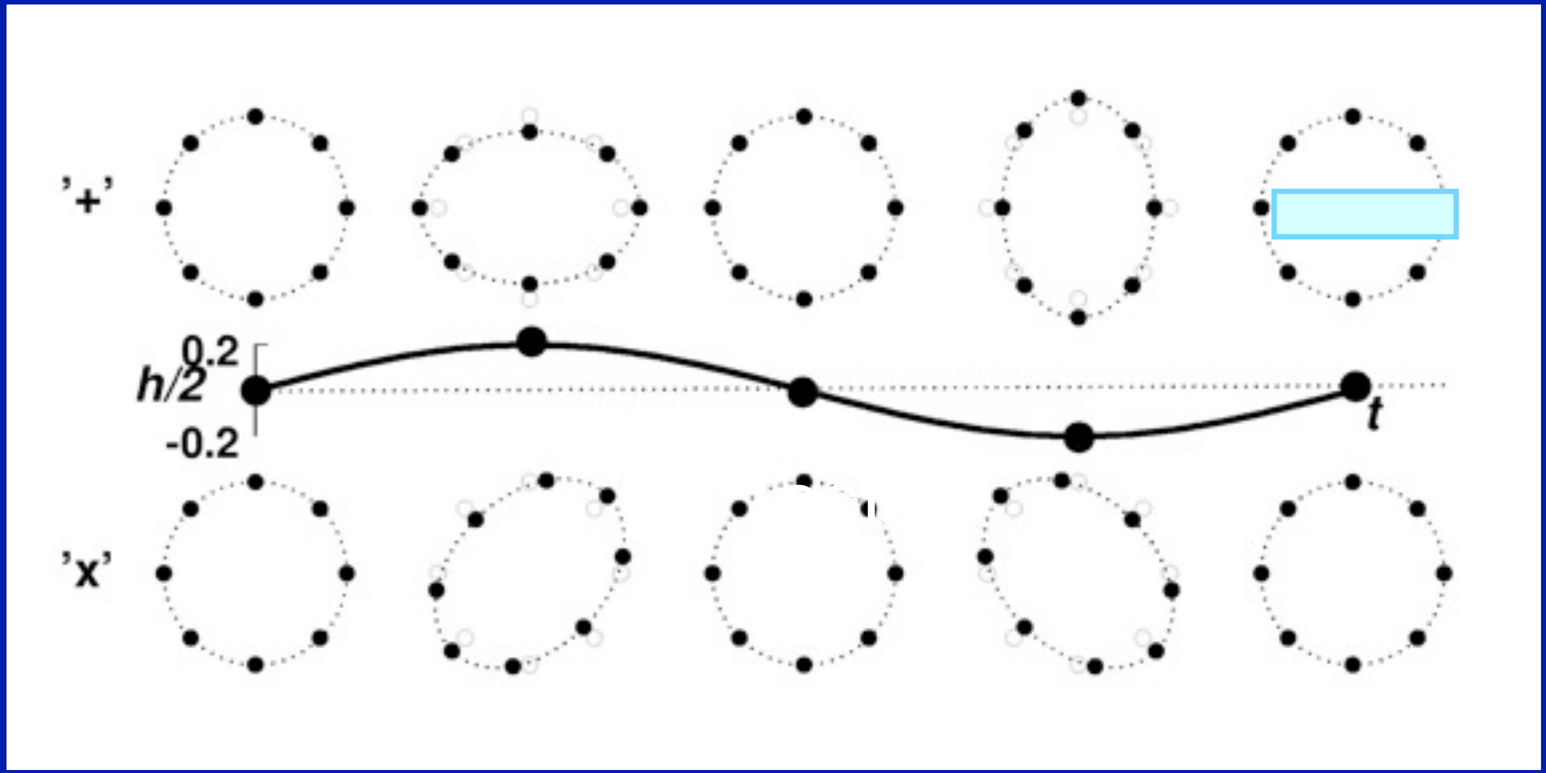

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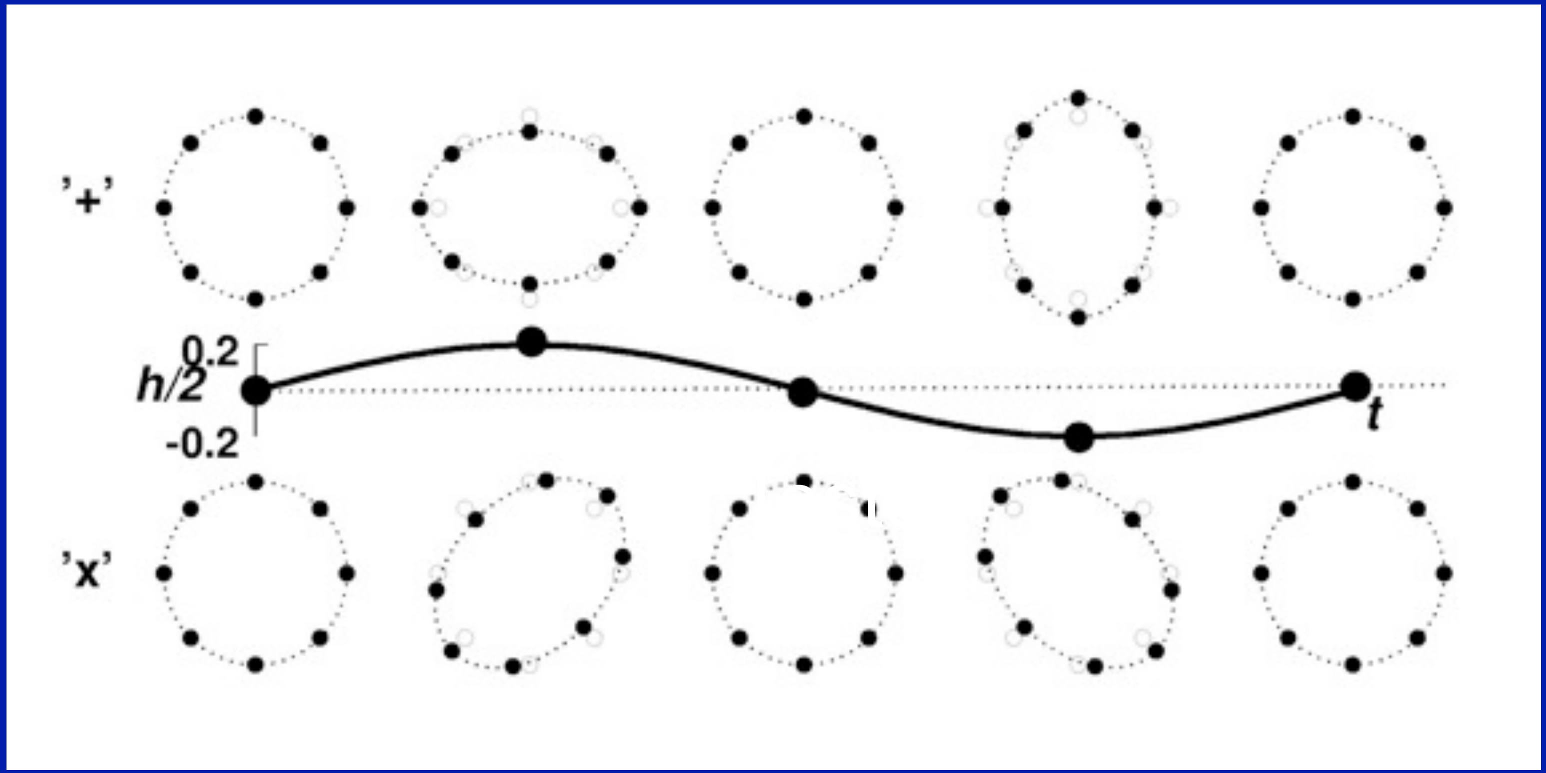

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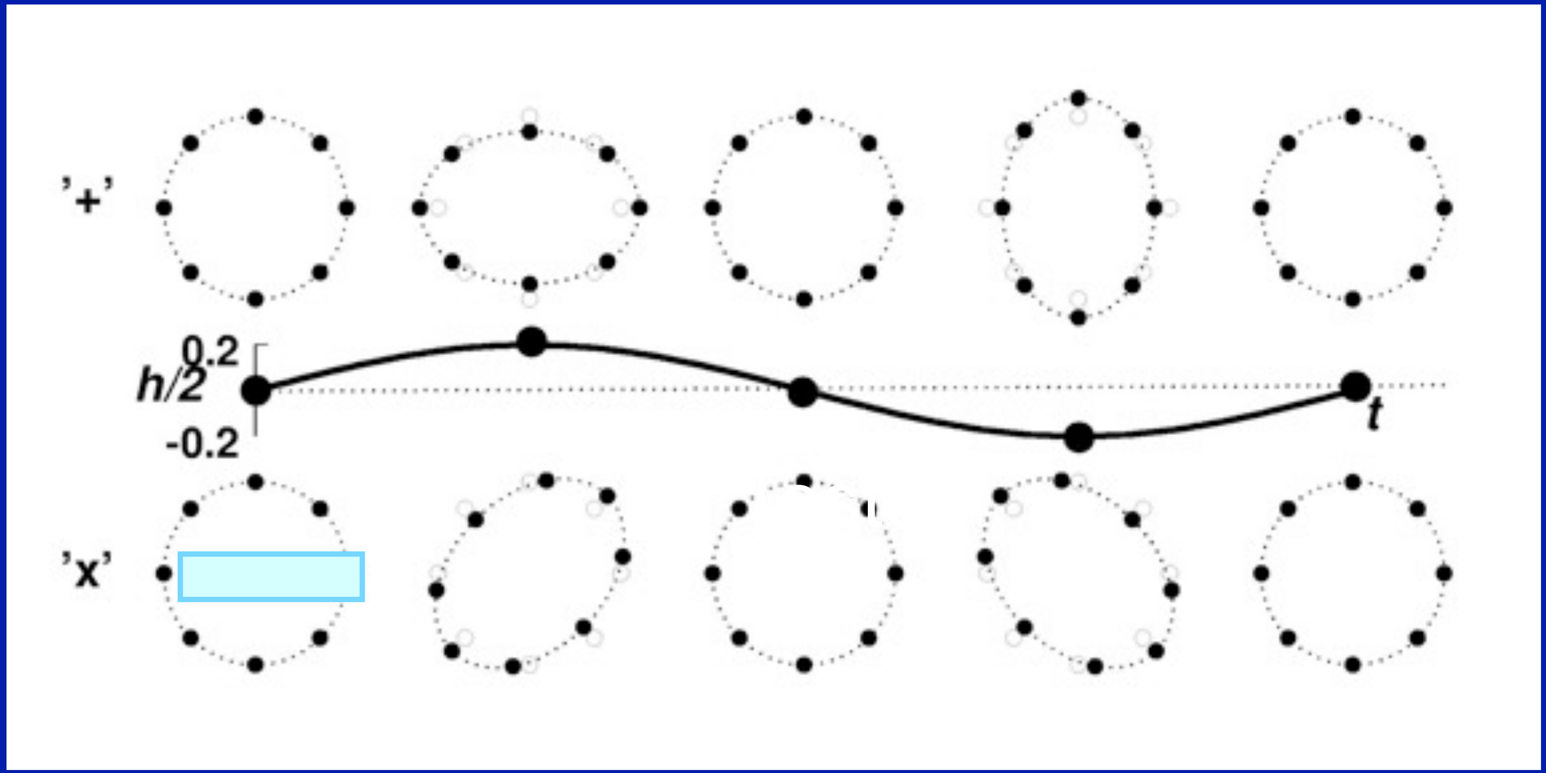

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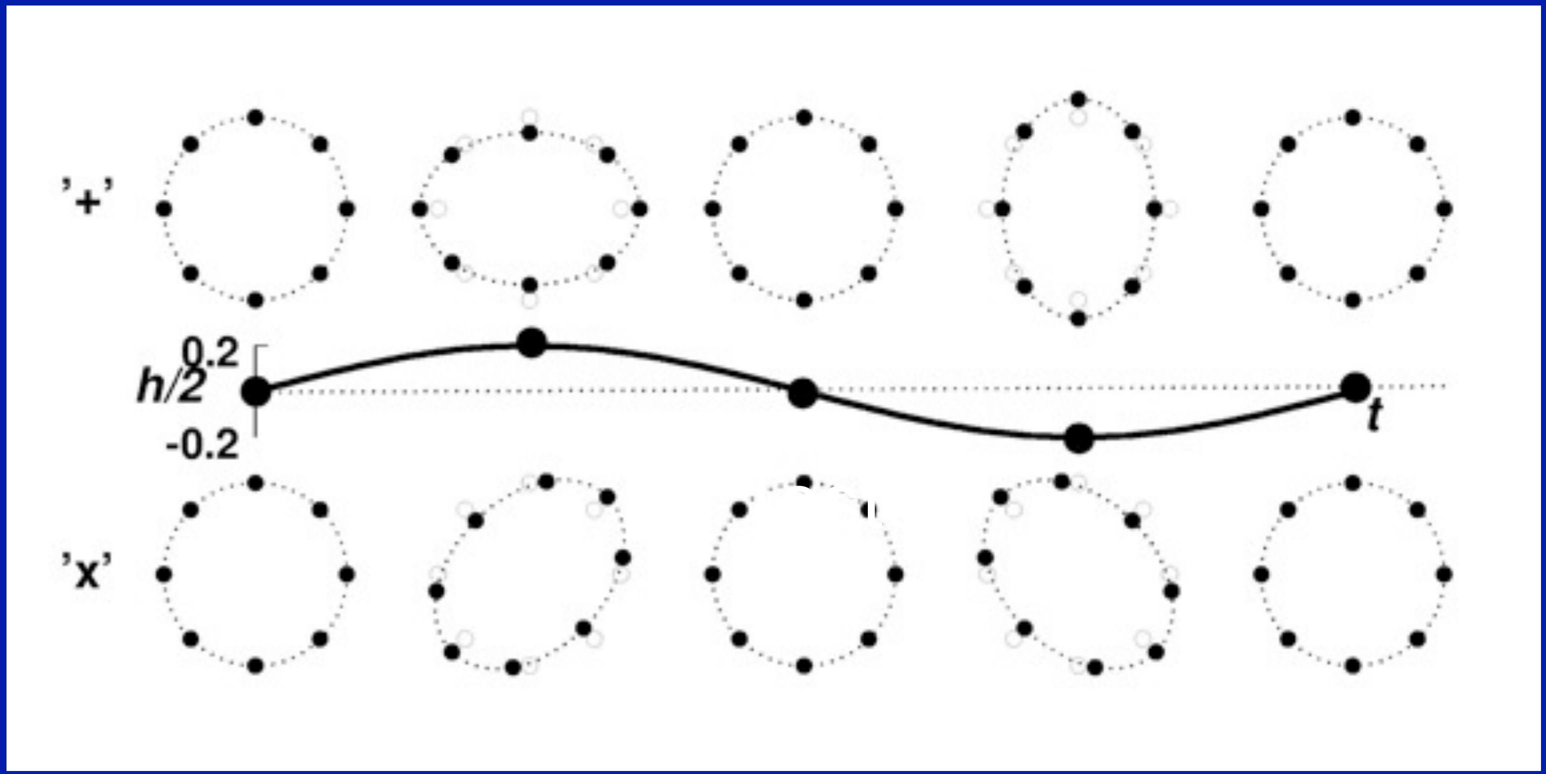

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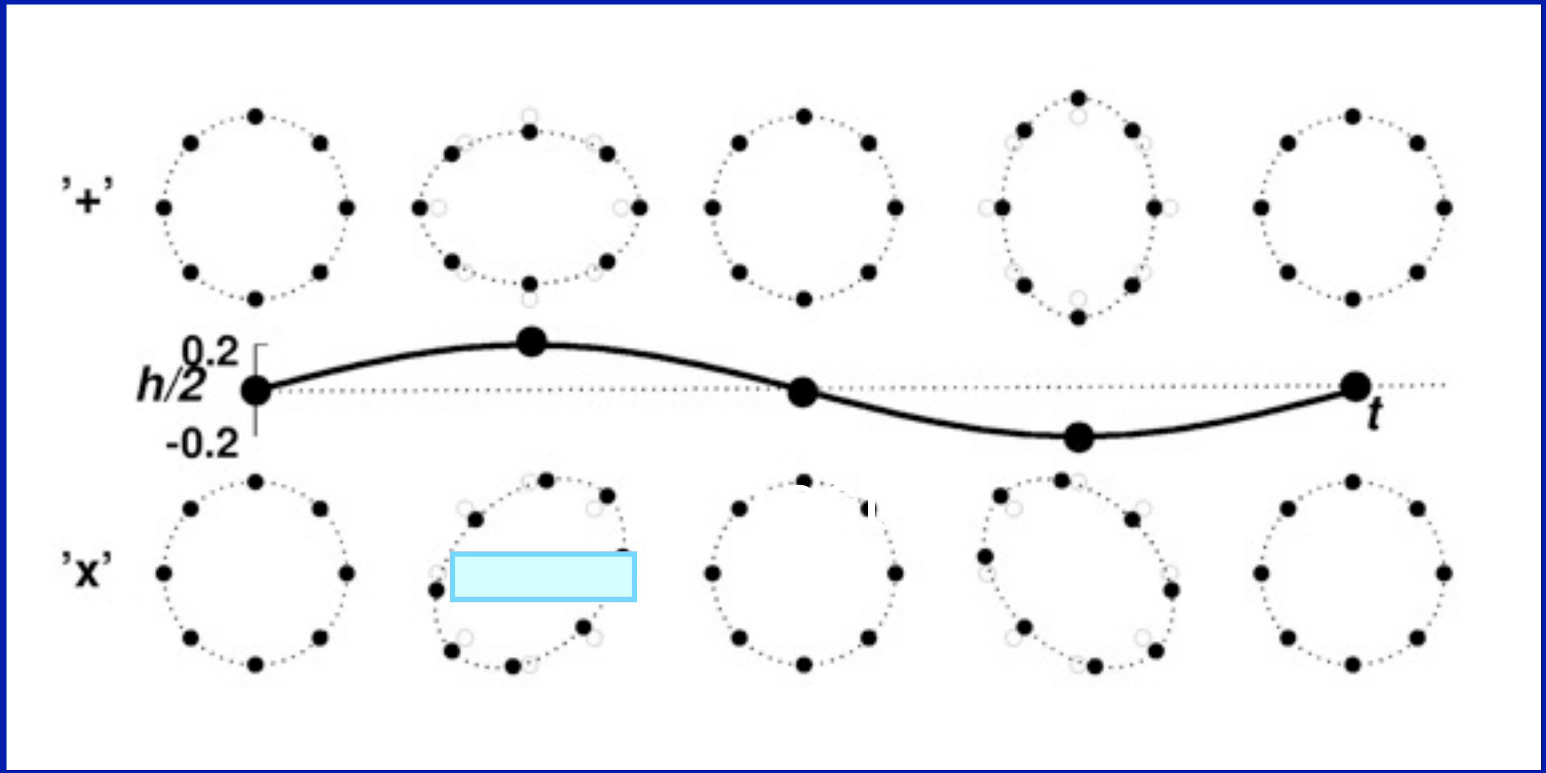

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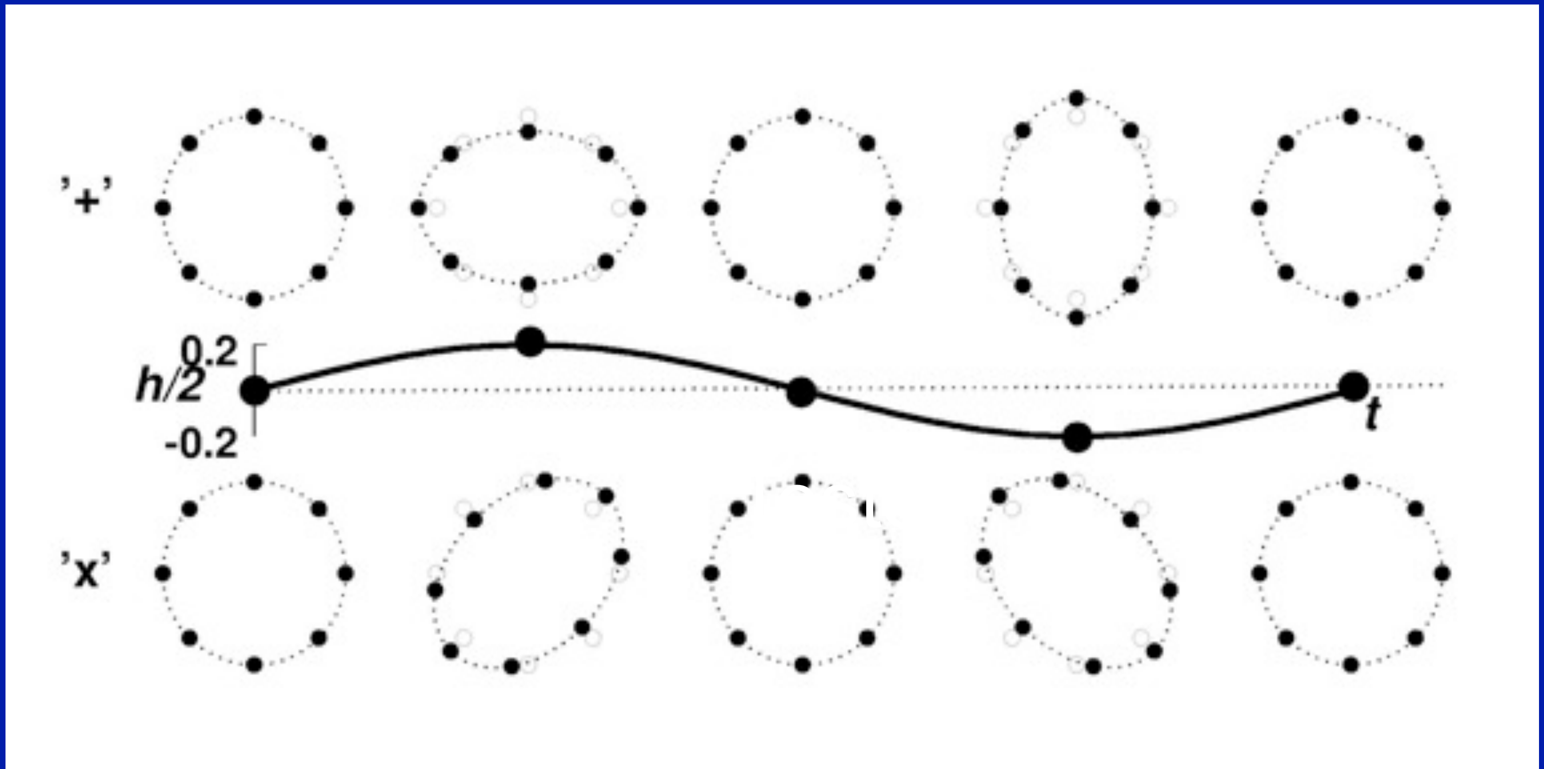

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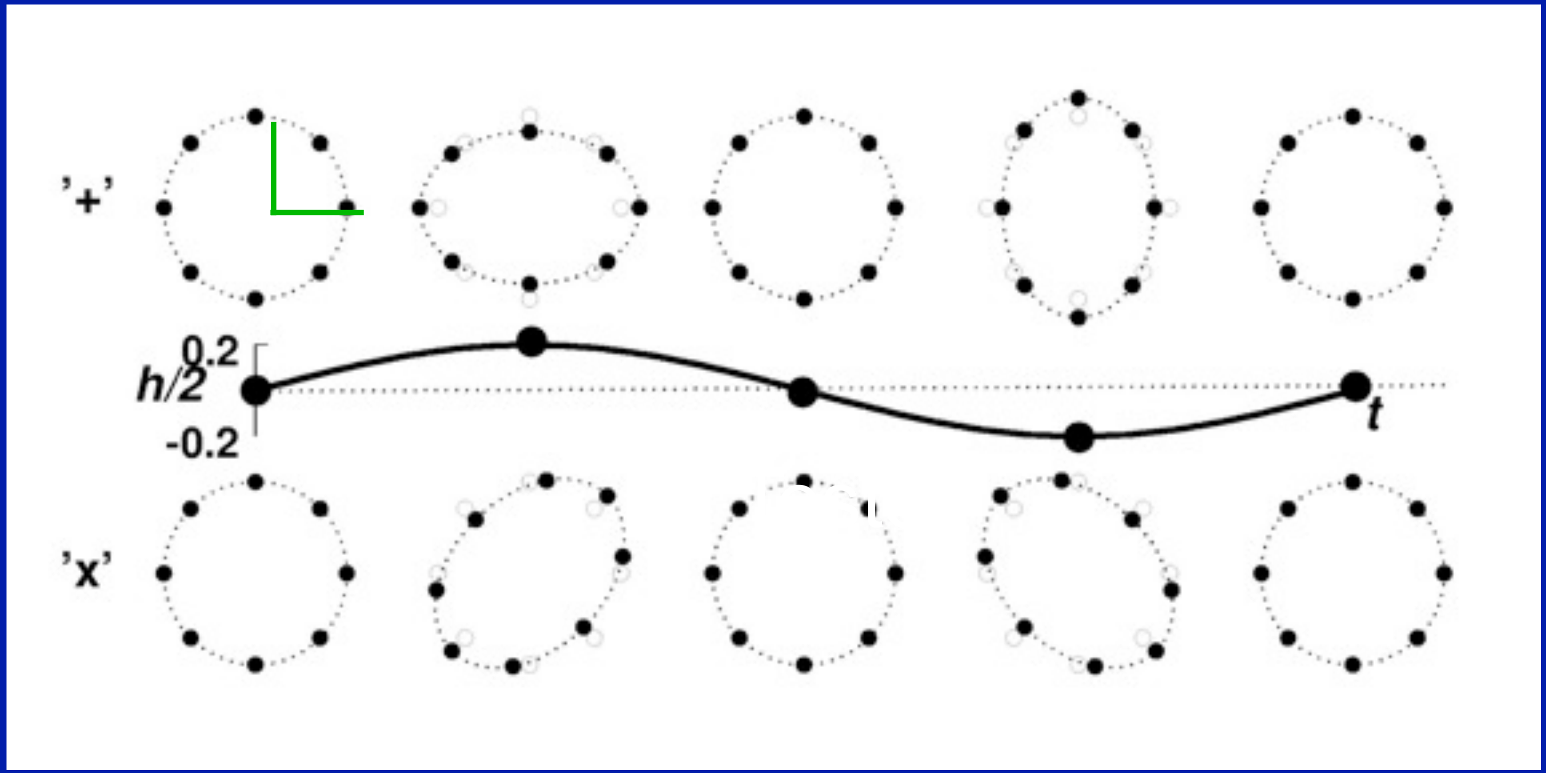

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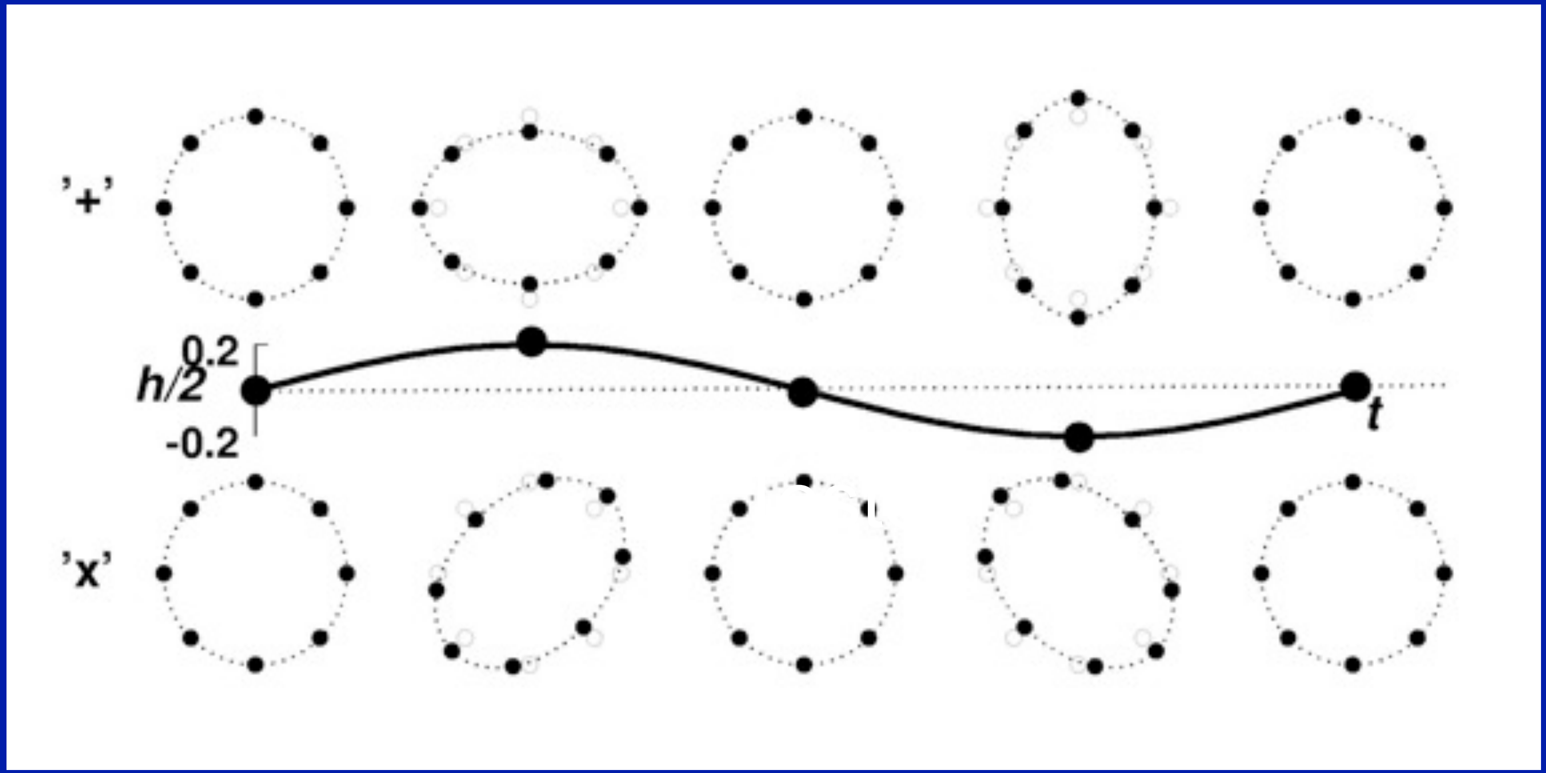

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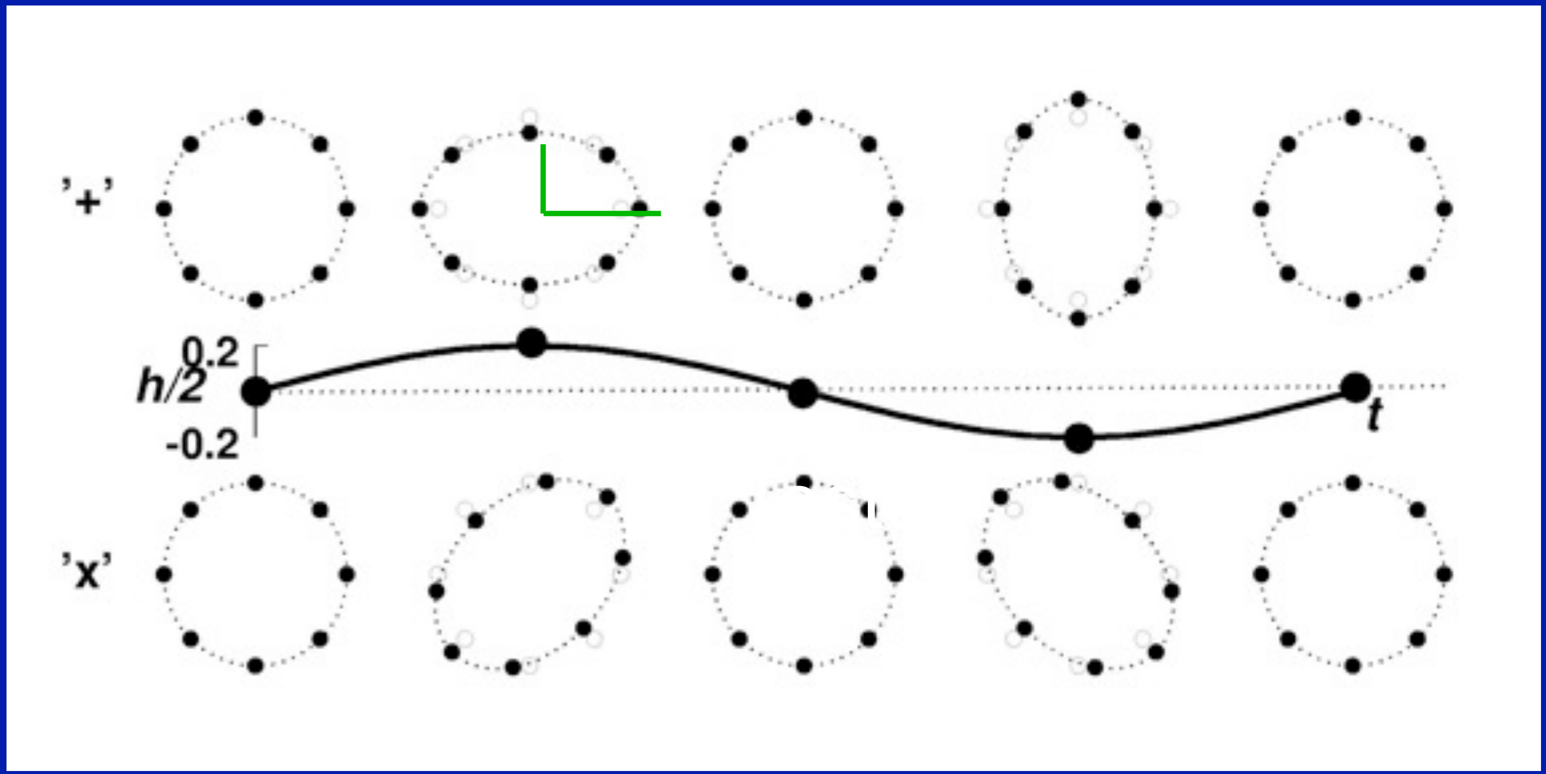

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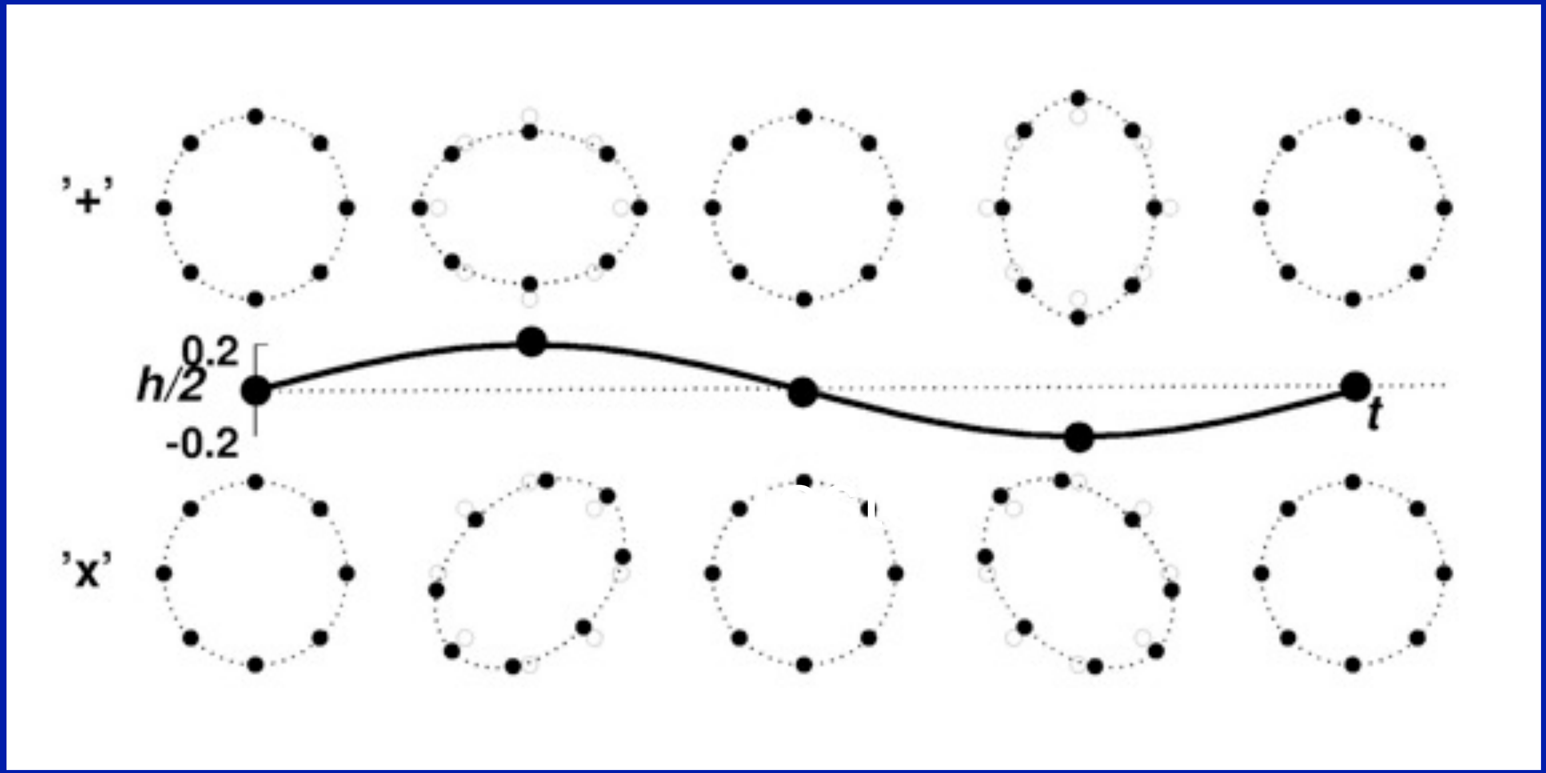

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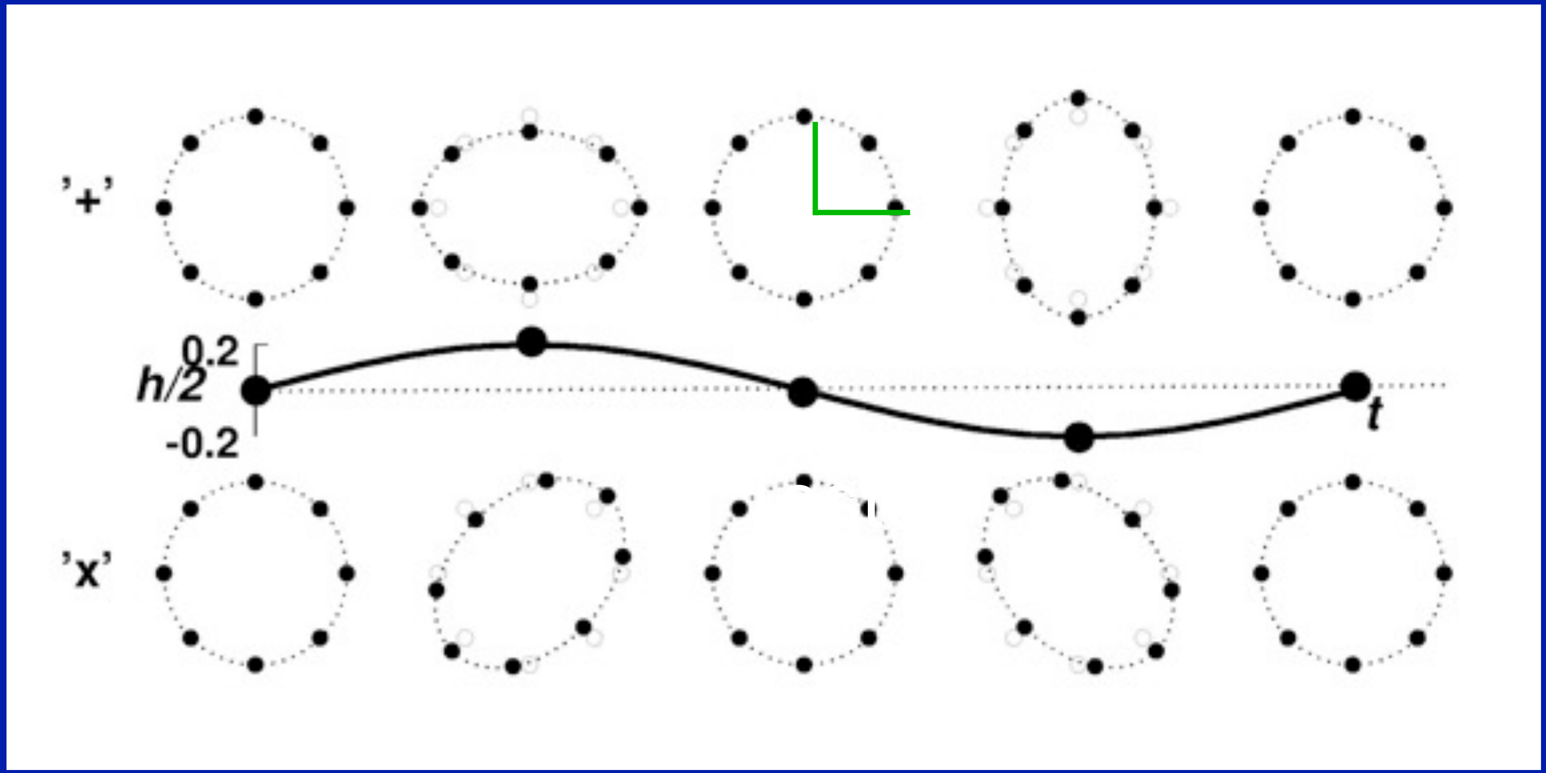

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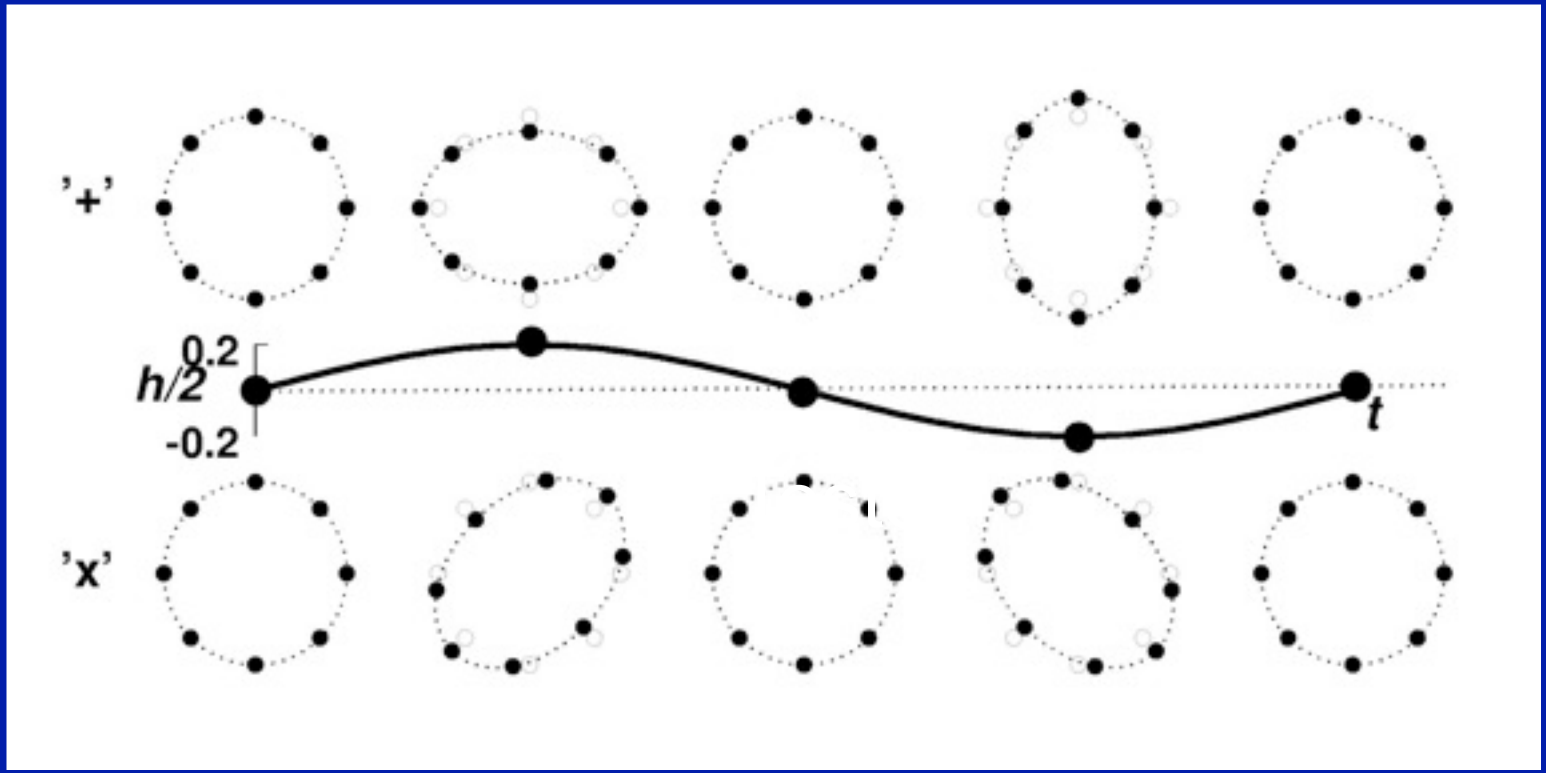

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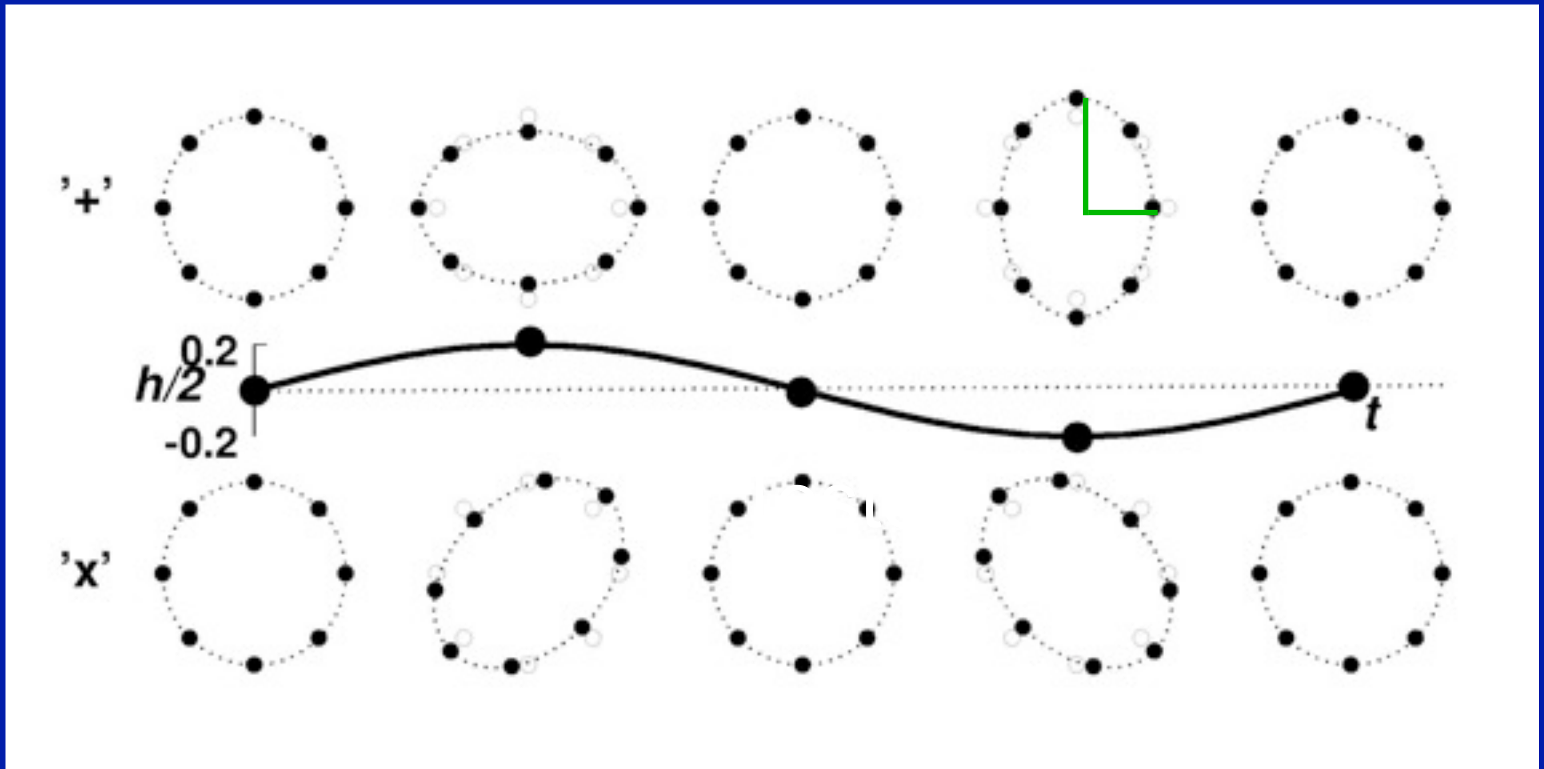

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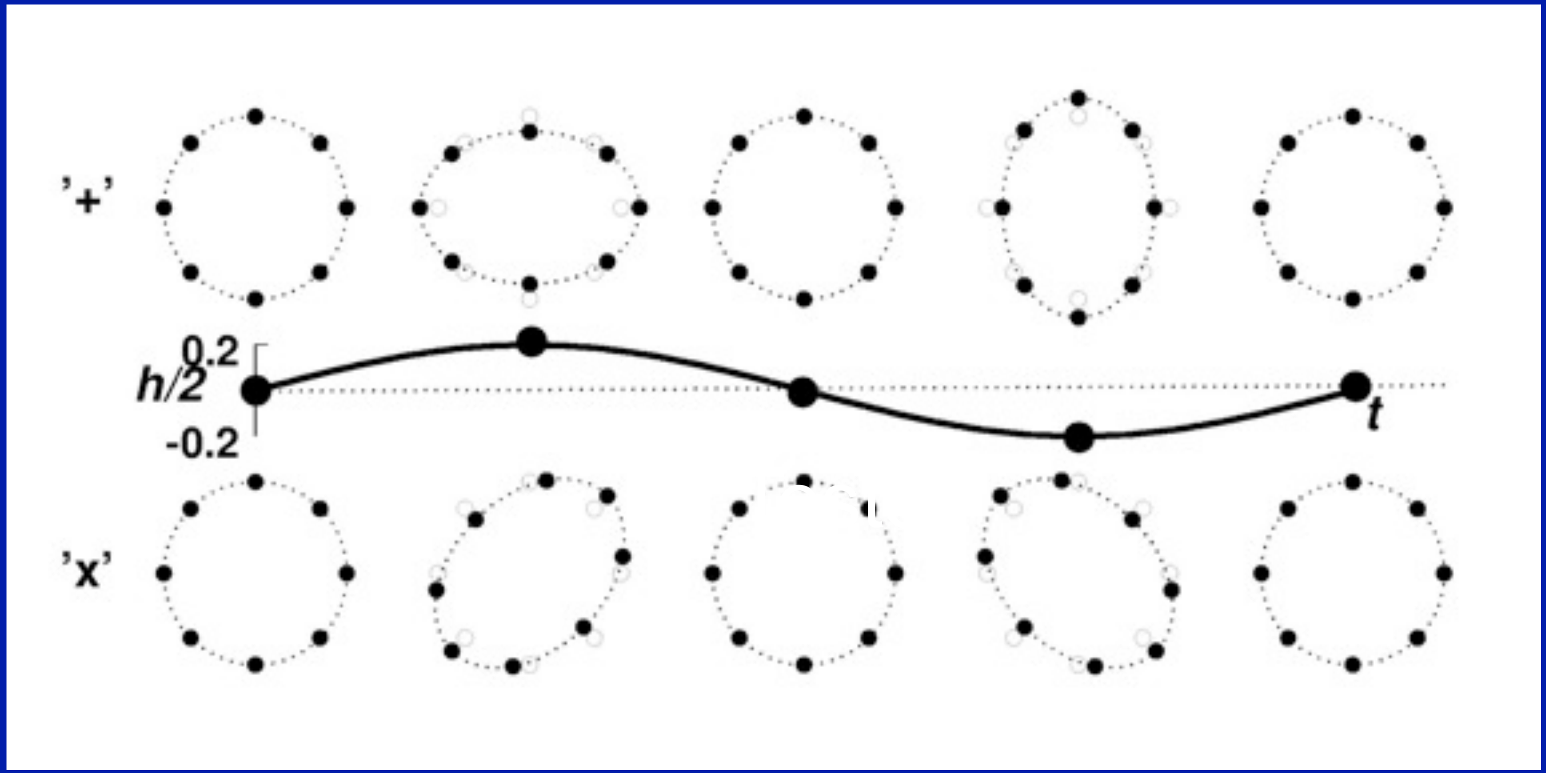

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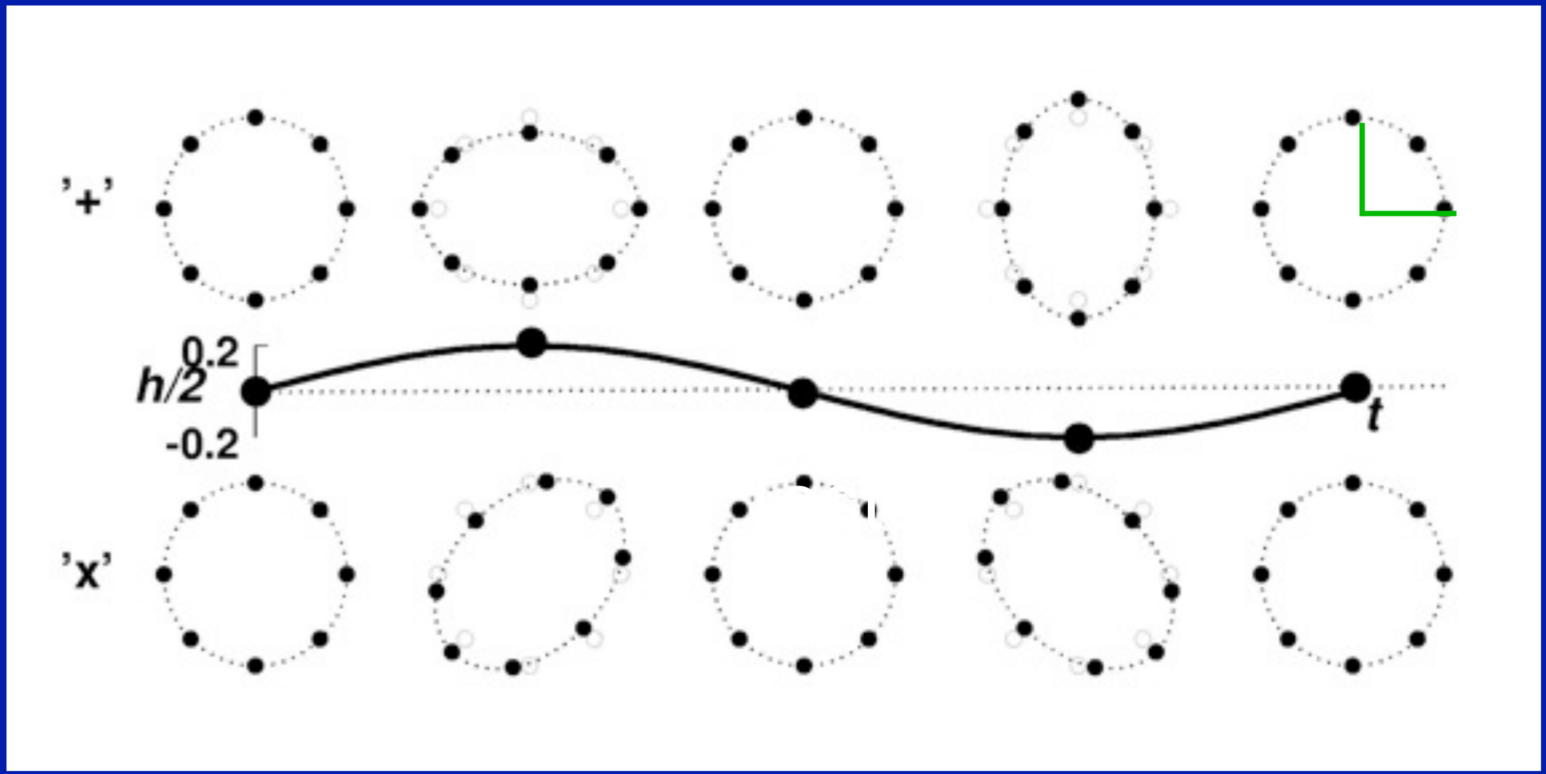

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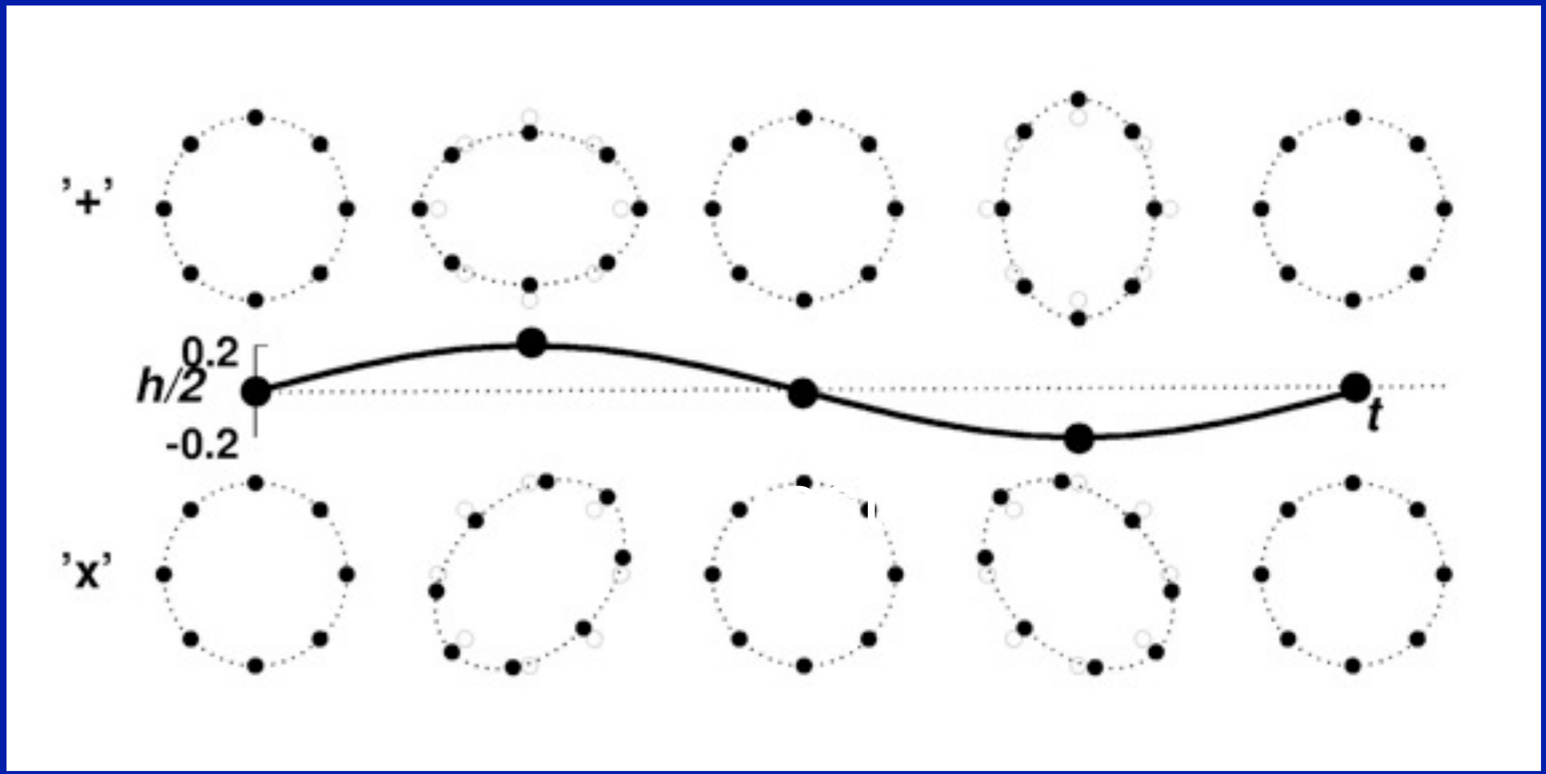

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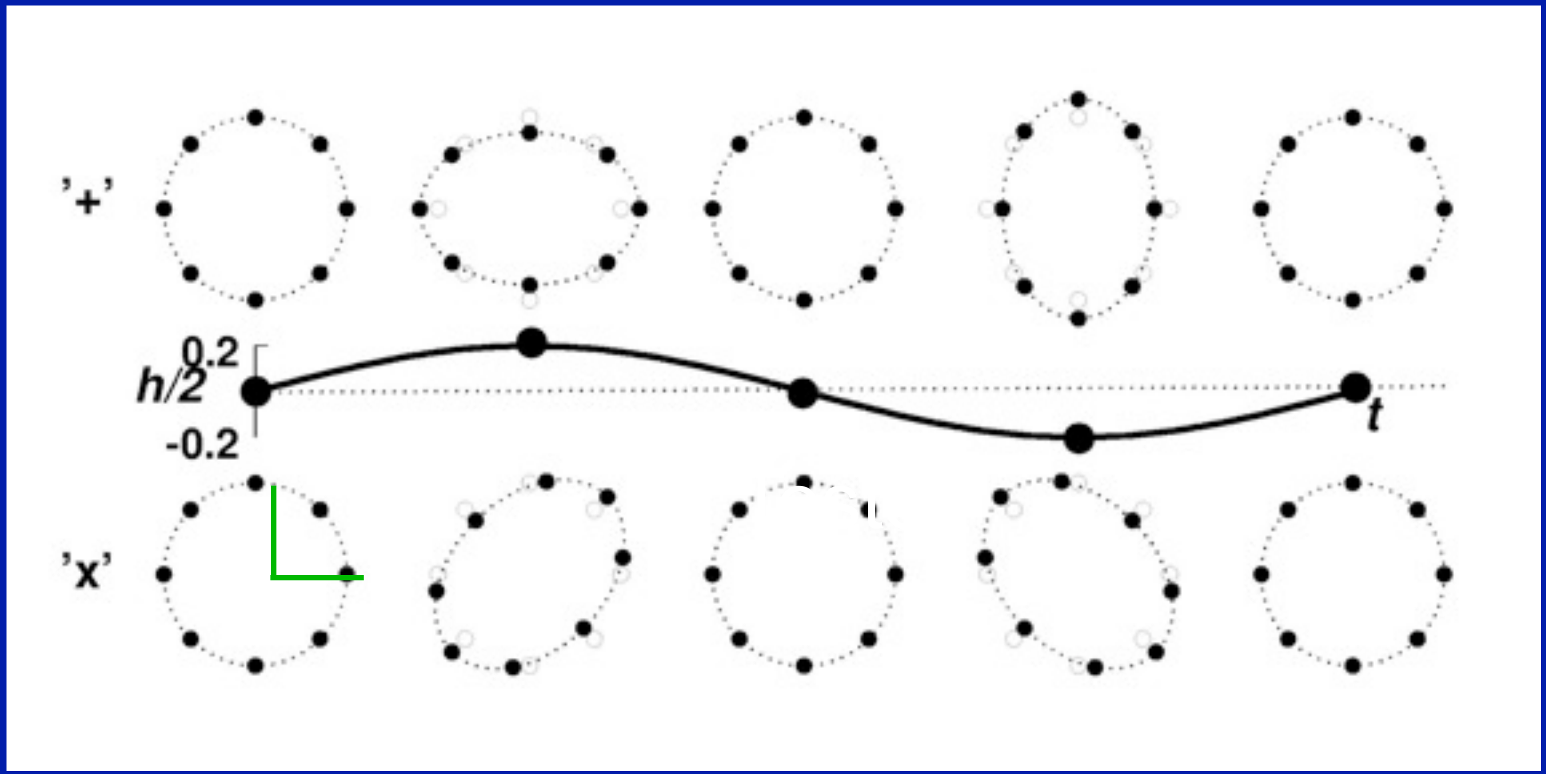

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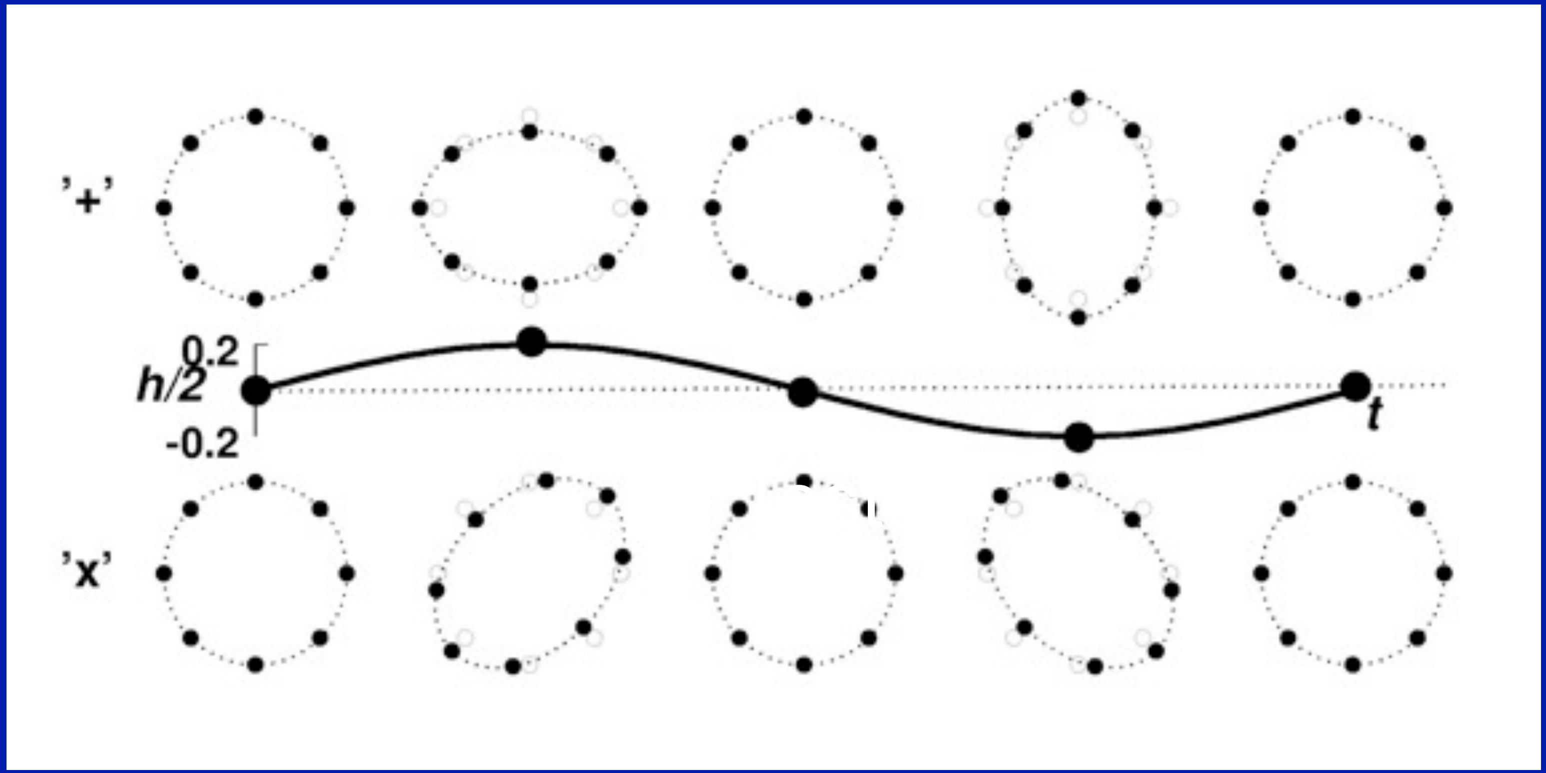

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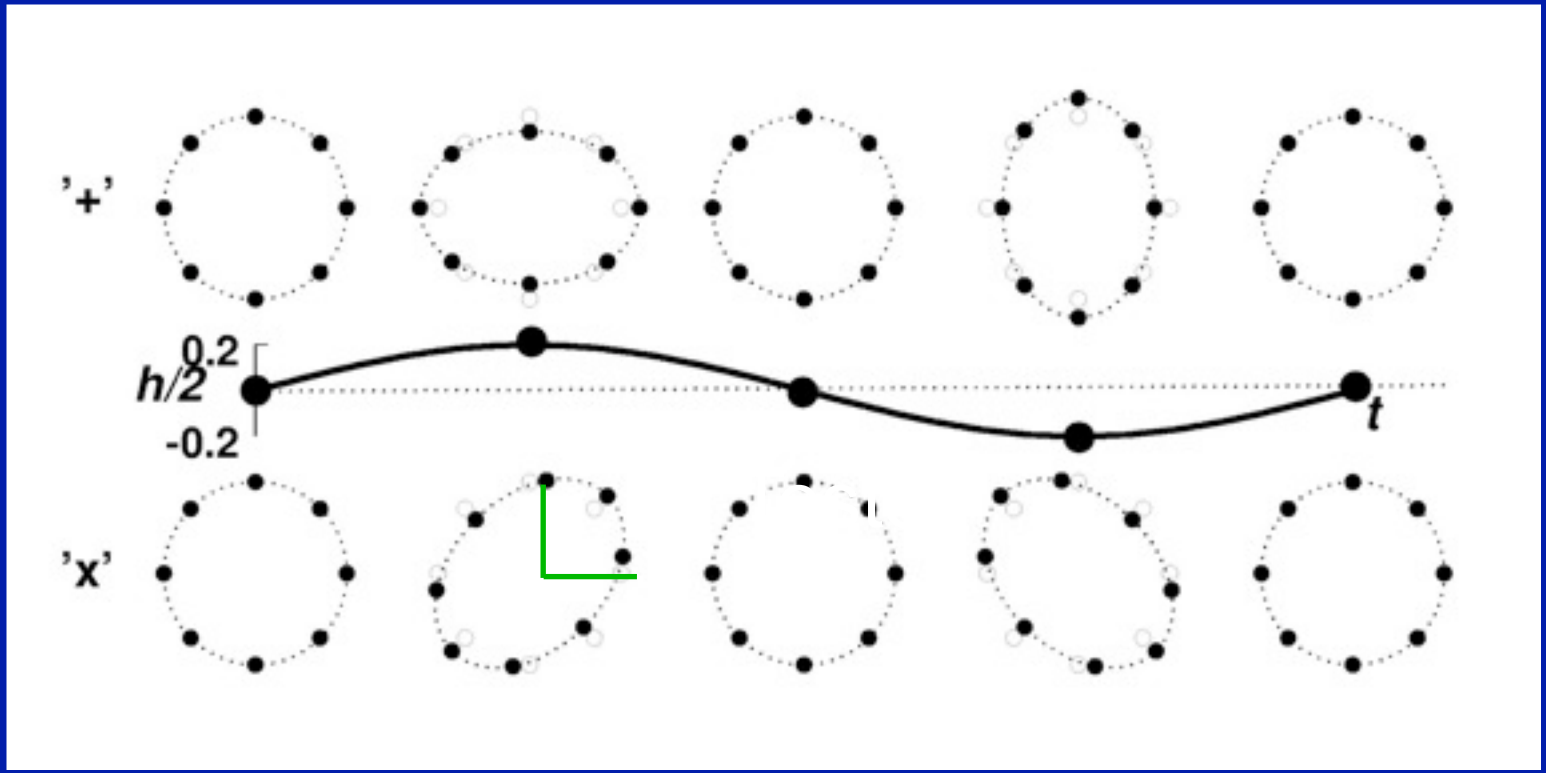

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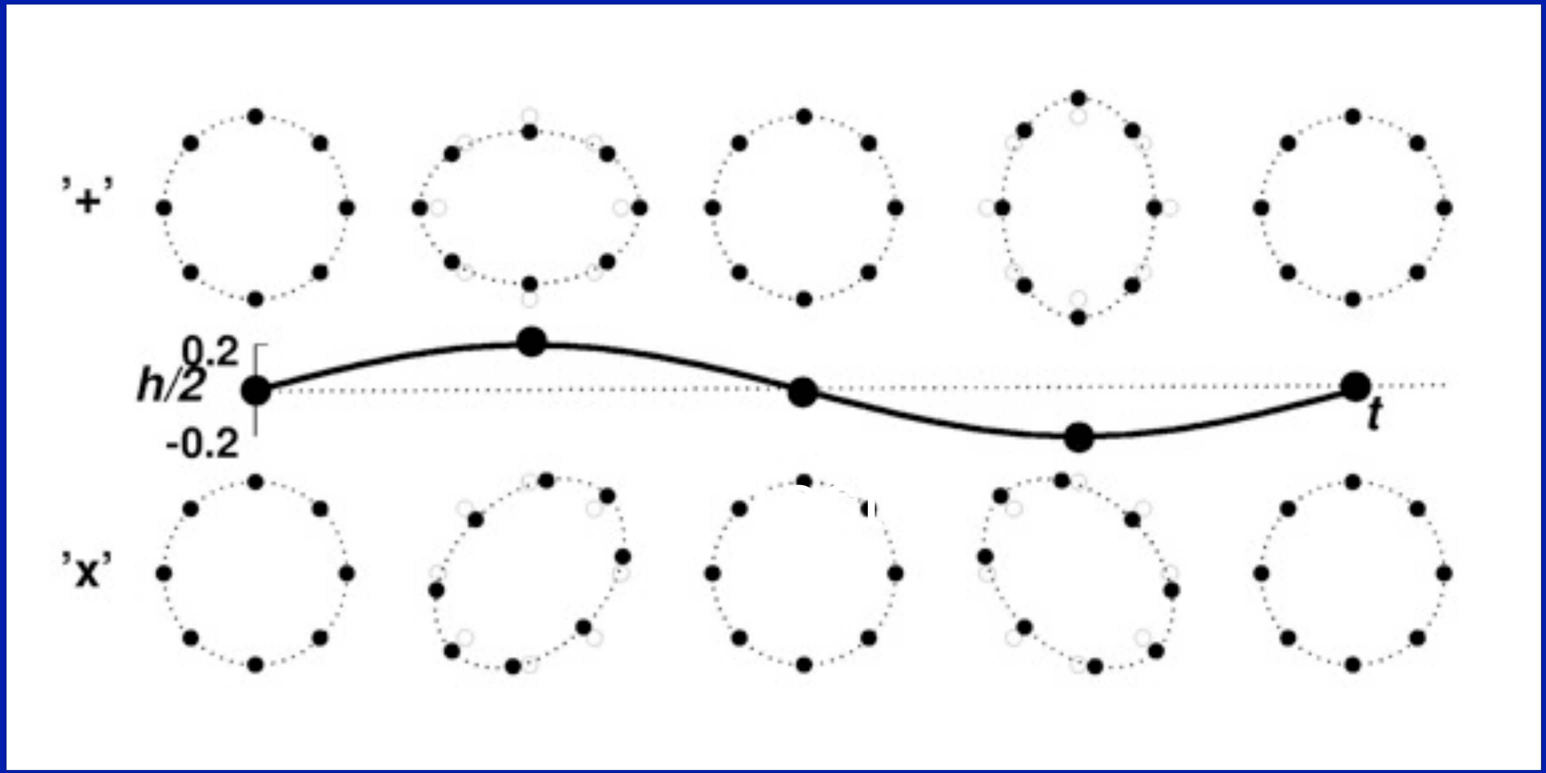

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Gravitational waves :production

very weak waves; needed big astrophysical object with large masses and quadrupolar mass distributions

Production upper limit: $$h \leq \frac{1}{c^4}\left(\frac{GM}{r}\right)\left(\frac{GM}{R}\right)$$

Newtonian potential at the source of radius R

Newtonian potential at the detection distance r

Example $h \leq$ 10^{-21} for a neutron star R=10Km at 10Mparsec

Energy flux $$F = \frac{c^3}{G}\frac{1}{16\pi}\frac{\partial}{\partial t}\left(h_+^2 + h_x^2\right)$$ ≈ 0.3 watt/m^2 (h=10^{-21},f=1KHz)

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Current interferometers have sensitivity ~1 watt/m^2 f=1KHz

Gravitational waves : frequency

The maximum emission frequency is related to the dimension and the mass of the astrophysical object

$$f \approx \frac{v}{2\pi R} \qquad v^2 \approx \frac{GM}{R} \qquad \text{(virial teorem)}$$

maximum

$$f = \frac{1}{2\pi}\sqrt{\frac{GM}{R^3}}$$

Current antennas are sensitive to **f≈0.1-10Khz :** could detect continuos waves produced in “small” objects as rotating neutron stars, merging of two neutron stars, and “burst sources’ (characteristic time 1 msec or less) as supernova explosions and black hole formation .
sources of lower frequencies : space interferometers (LISA)

Possible sources - earth detectors

1) "chirp" : merging of a binary system (like the Hulse Taylor). The signal start at low and end at high frequency. The Hulse Taylor end ~ 300 My. Binary system with two neutron star reference for the gravitational wave community

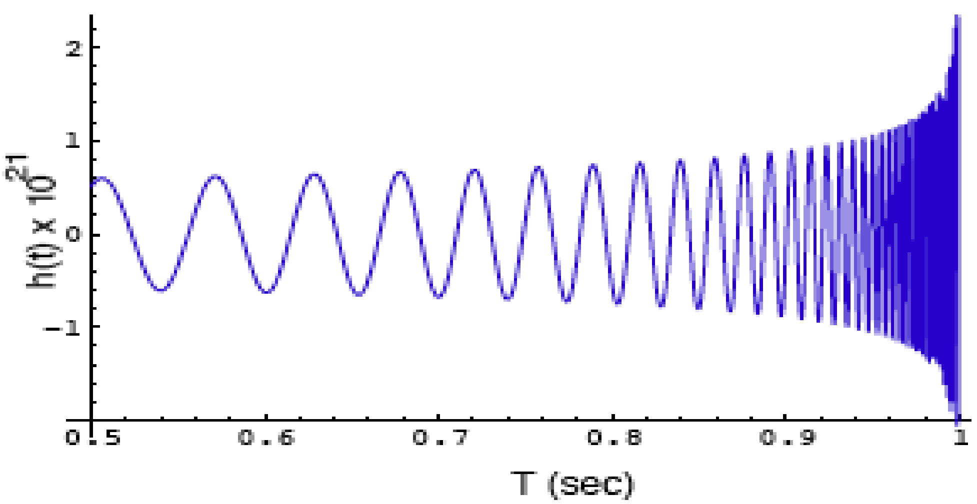
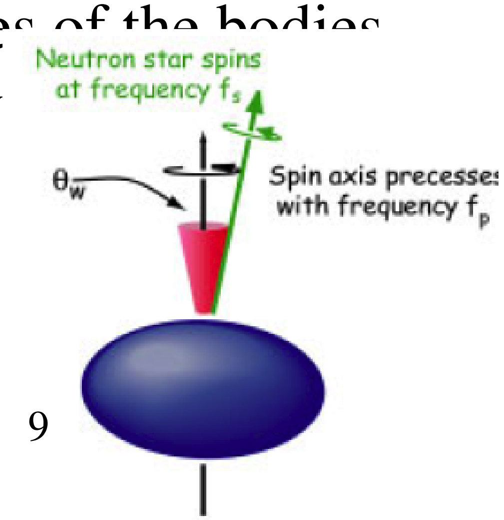


Figure 3: "Chirped" Strain Signal Produced by a Binary Neutron Star Inspiral

• signal can be computed accurately: we can detemine distance from the earth, masses of the bodies orbital eccentricity and orbital inlclination. Over constraint : test of general relativity



2) continous waves from a spinning neutron stars, needs a non-spherical pattern.

Pulsar in our galaxy have $10^{-6} < \varepsilon < 10^{-4}$

$$h_c = \frac{16\pi^2 G}{c^4} \frac{\epsilon I f^2}{r}$$

Possible sources - earth detectors

1) “chirp” : merging of a binary system (like the Hulse Taylor). The signal start at low and end at high frequency. The Hulse Taylor end ~ 300 My. Binary system with two neutron star reference for the gravitational wave community

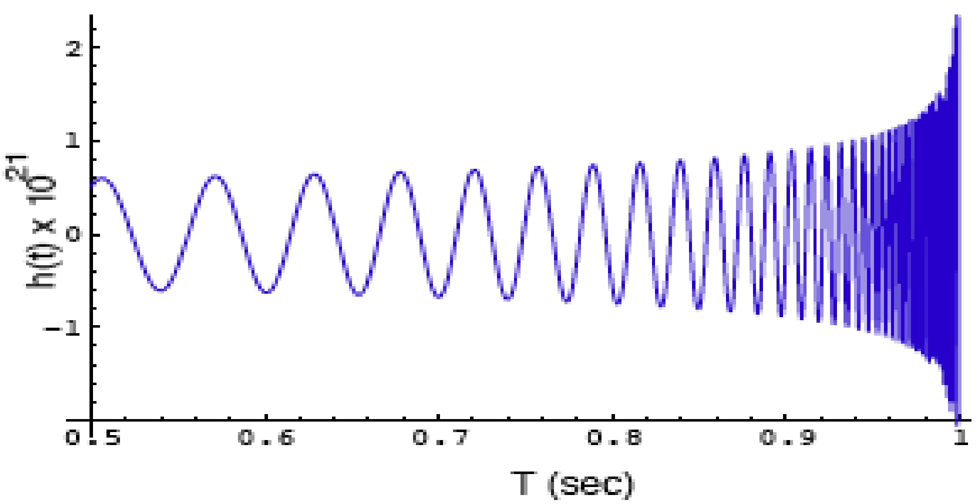
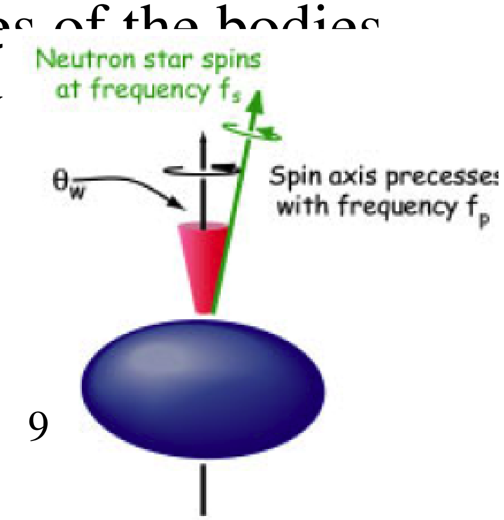


Figure 3: “Chirped” Strain Signal Produced by a Binary Neutron Star Inspiral

• signal can be computed accurately: we can detemine distance from the earth, masses of the bodies orbital eccentricity and orbital inlclination. Over constraint : test of general relativity

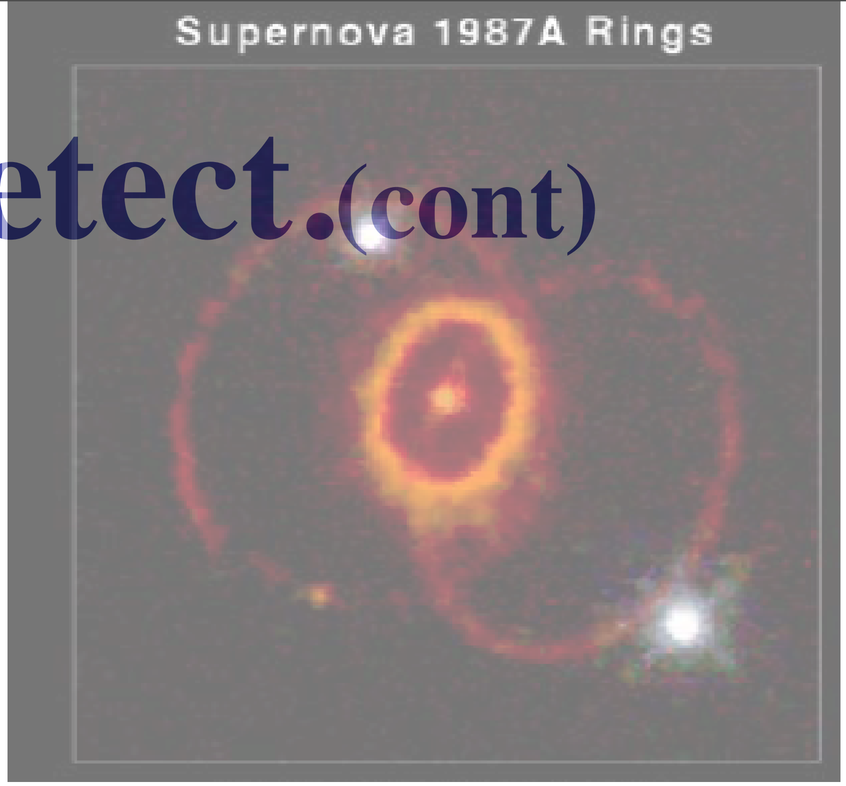


2) continous waves from a spinning neutron stars, needs a non-spherical pattern.

Pulsar in our galaxy have $10^{-6} < \varepsilon < 10^{-4}$

$$h_c = \frac{16\pi^2 G}{c^4}\frac{\epsilon I f^2}{r}$$

Possible sources - earth detect.(cont)



- supernovae (example of a “burst sources”) large uncertainties in the calculations energy in GW from 10^{-2} (1970) to 10^{-9} (1995) to 10^{-4} (2006)
- examples from one of the latest calculation (Ott et al PRL 96 2006)

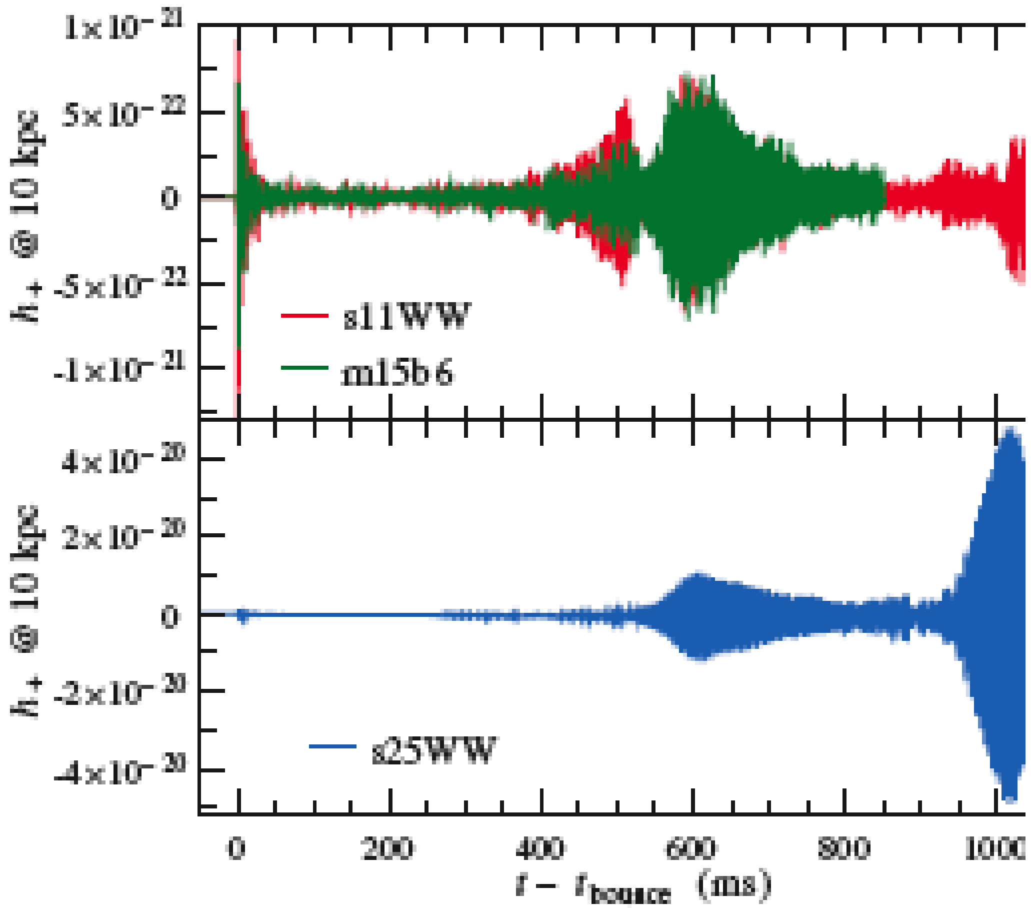


FIG. 1 (color). Dimensionless gravitational-wave str along the equator at a distance of 10 kpc. Note that the of h_+ in the lower panel is almost 50 times wider than tha top panel.

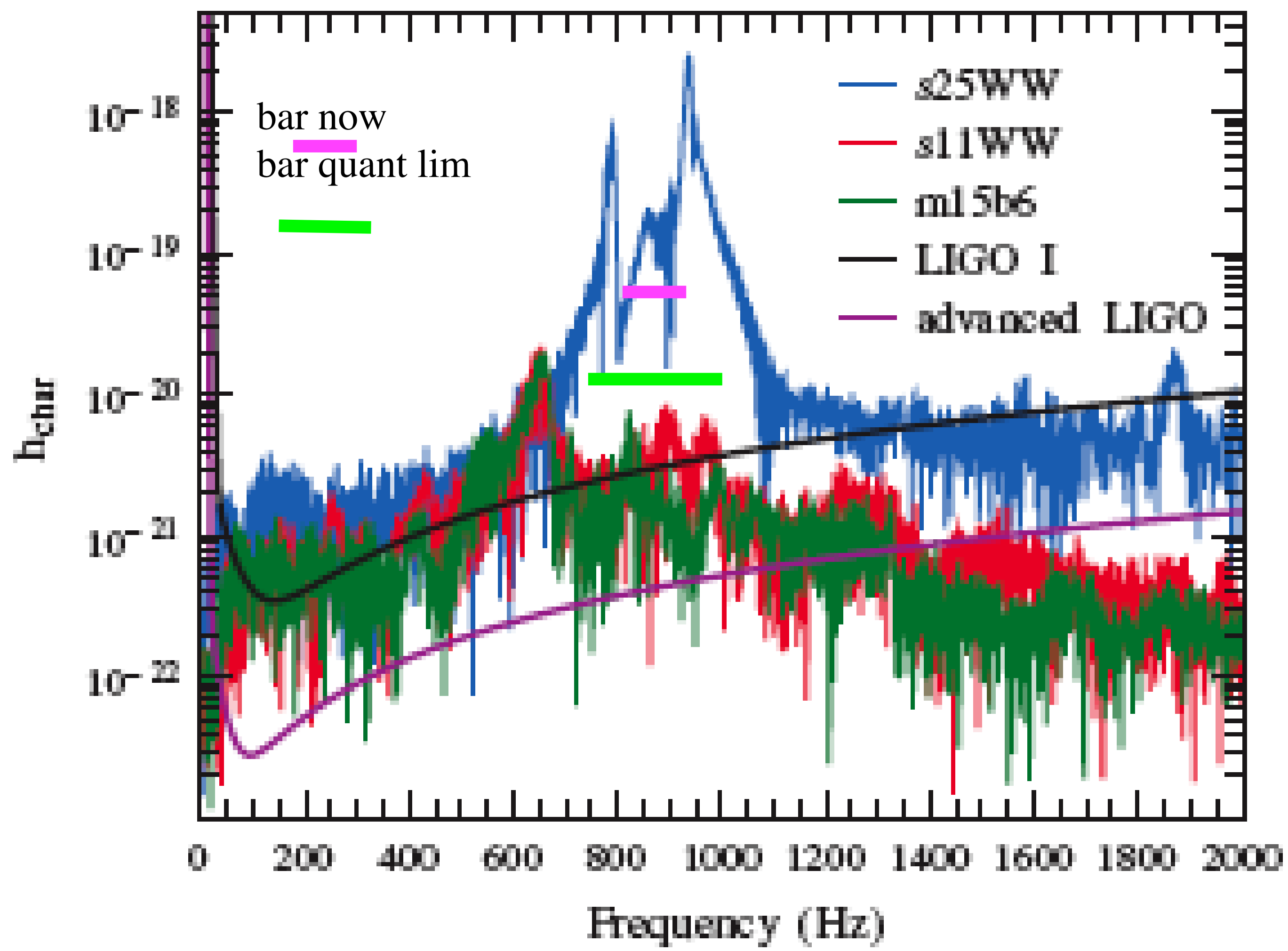
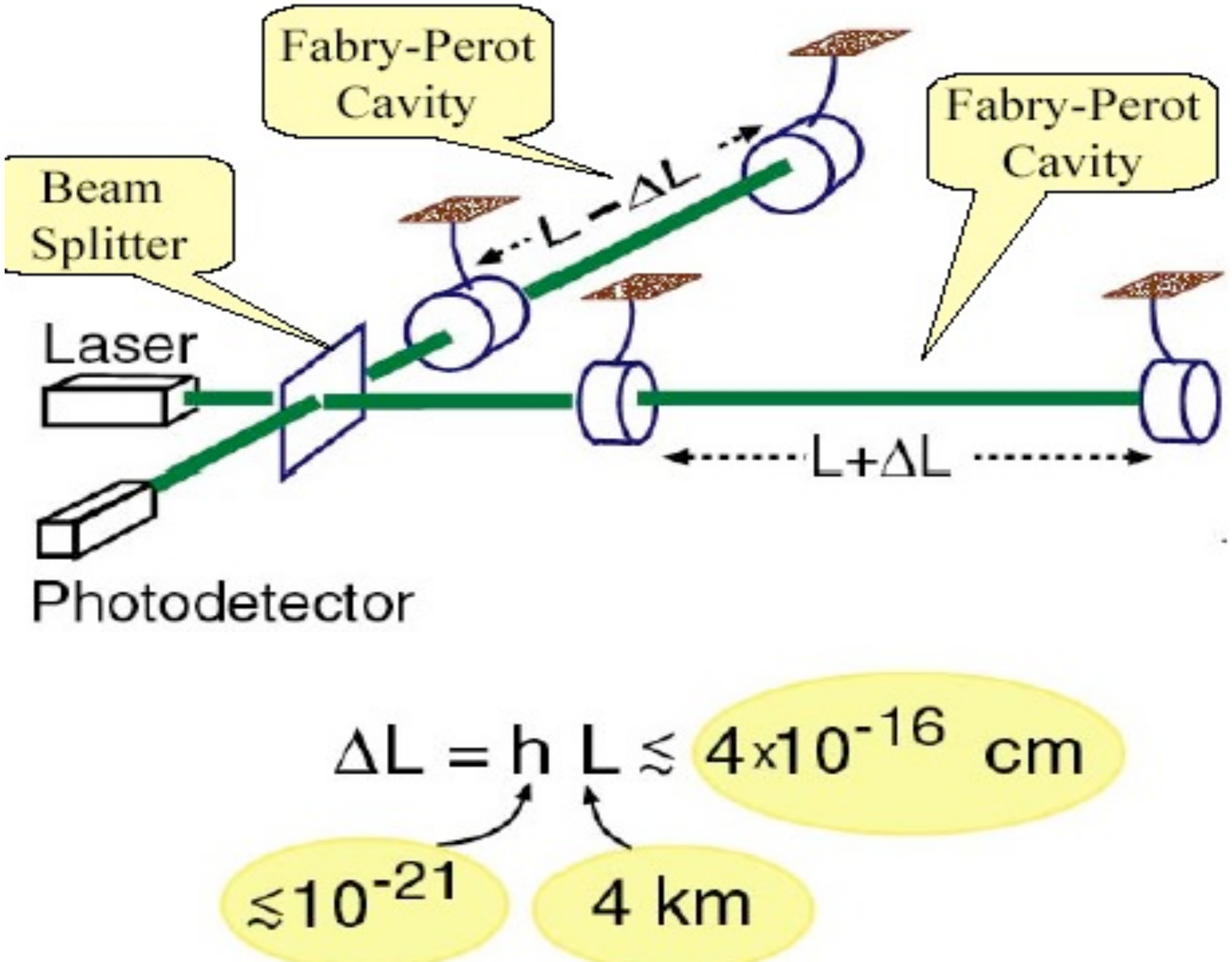


FIG. 4 (color). Characteristic strain spectra contrasted wit initial and advanced LIGO (optimal) rms noise curves.

Detectors

1- laser inteferometer



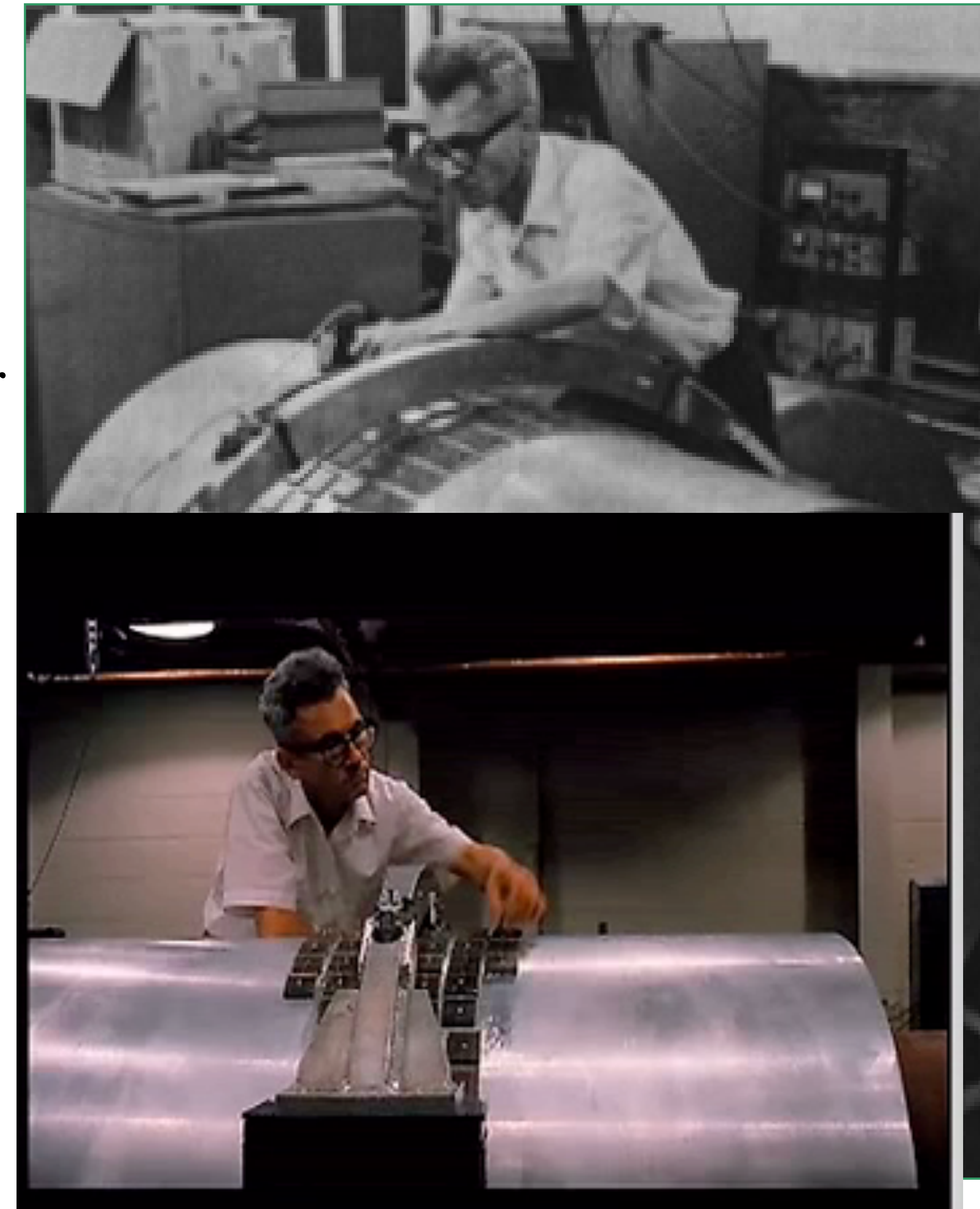
2 - low temperature cylinder

- Michelson interferometers: idea due to several independent peoples: Pirani (1956), Weber and Forward (Weber's student) (~1960-72), Gerstenshtein and Pustovoit (1960-1972), Weiss (1972)

- first interferometer built by Forward at the Hughes Research Laboratories $S_h \sim 2\text{x}10^{-16}\ \text{Hz}^{-1/2}$

J. Weber and gravitational waves acoustic detectors

- Current acoustic detectors quite similar to the first detector due to J.Weber (1969) : aluminum cylinder and piezoelectric crystals.
- The major differences are in the bar temperature and in the extraction of the electric signal.



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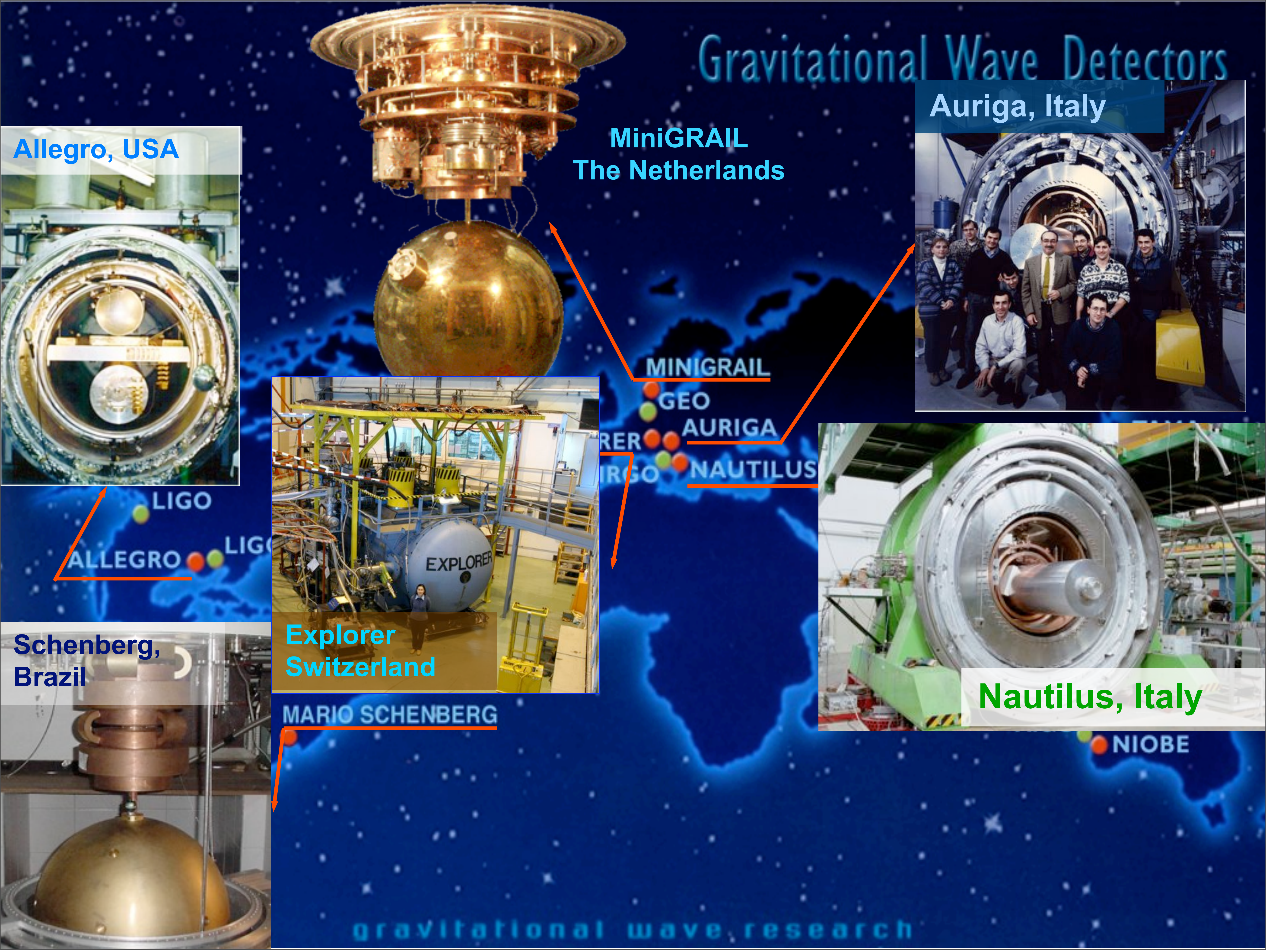
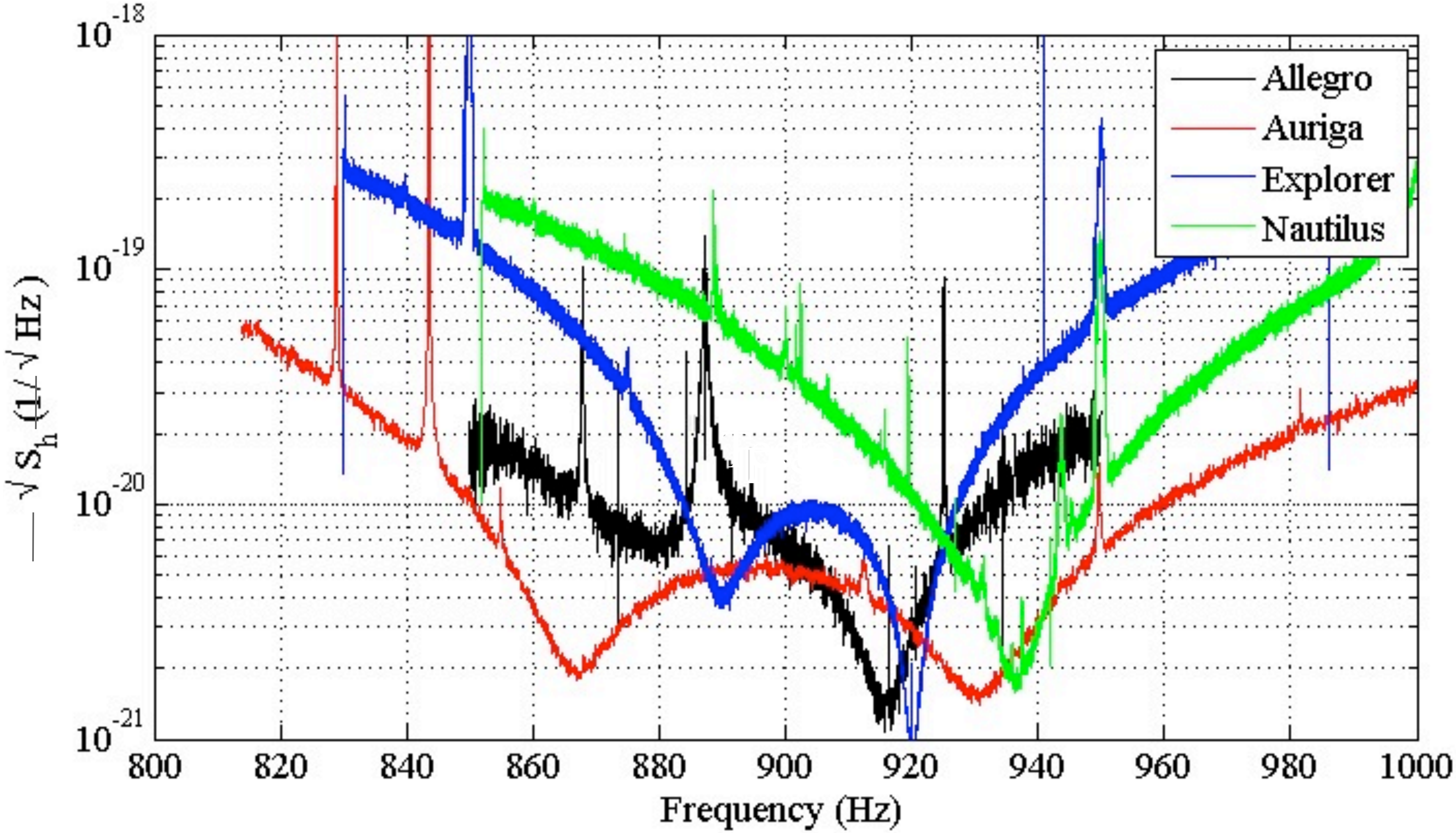
- The major differences are in the bar temperature and in the extraction of the electric signal.

Weber published his results in *Physical Review Letters* (1969), claiming evidence for observation of gravitational waves based on coincident signals from two bars separated by 1000 km. Great excitement in the early 1970s : **Beginning of the gravitational waves searches.**



Gravitational Wave Detectors
Allegro, USA
MiniGRAIL
The Netherlands
Auriga, Italy
MINIGRAIL
GEO
AURIGA
NAUTILUS
LIGO
ALLEGRO
EXPLORER
Explorer
Switzerland
Schenberg,
Brazil
MARIO SCHENBERG
Nautilus, Italy
NIOBE
gravitational wave research

SENSITIVITY OF PRESENT DETECTORS



Improvement in sensitivity and bandwidth in the last couple of years but interfometers have done a better job (S_h~10^{-22} @ 900 Hz) factor >10 possible at quantum limit

Burst search :expected performances of IGEC-2

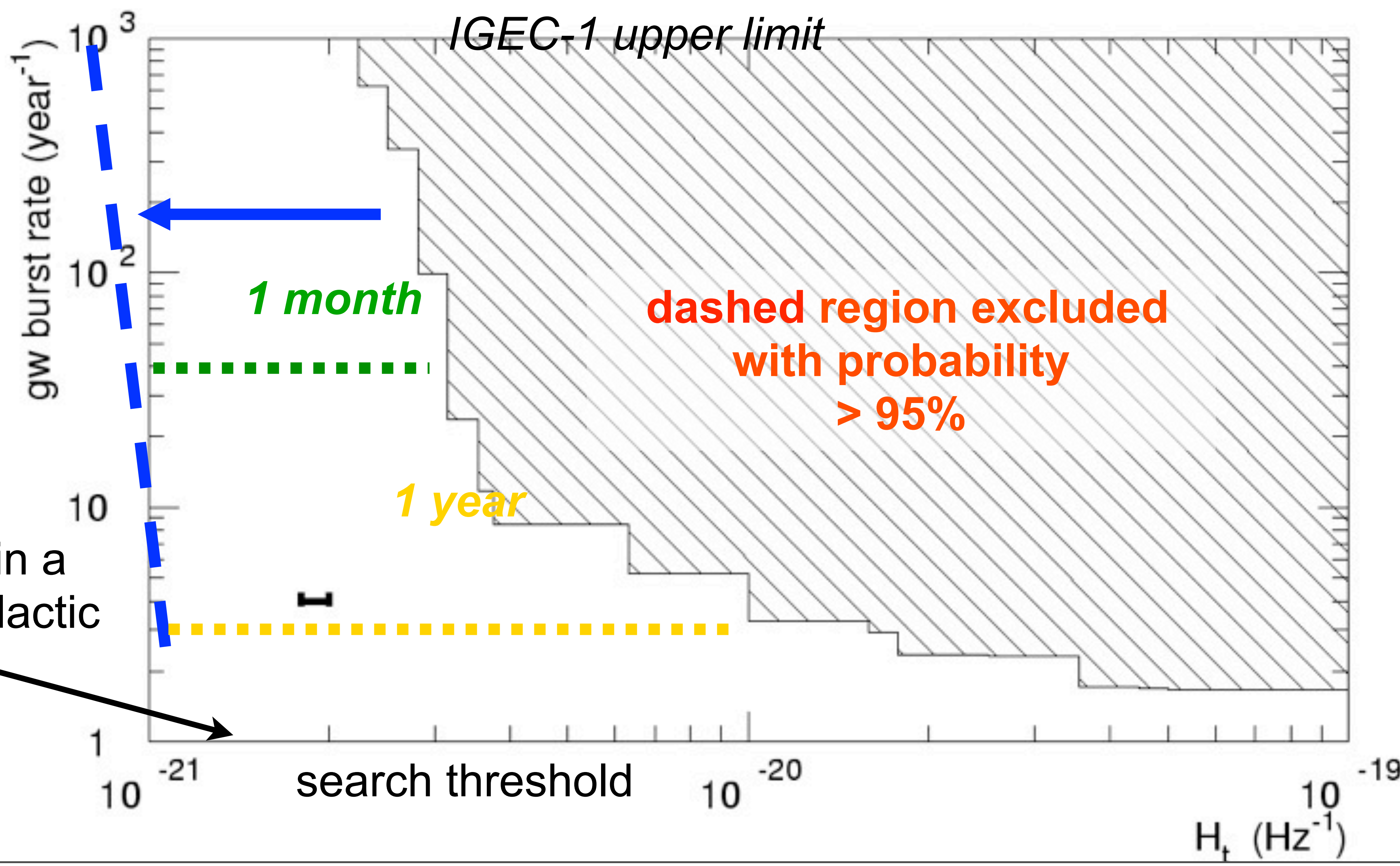
Agreement for a joint search for gravitational waves based on our previous experience (IGEC 1997-2000)

Participating groups: ALLEGRO, AURIGA and ROG (4 detectors). First search: time coincidence search for bursts *2004 May → 2005 ,2006 Feb + …*

Triple coincidences: < 1/100 years for SNR>5

Best guess on the achievable upper limit improvement by IGE-2 (Prodi Amaldi 2005)

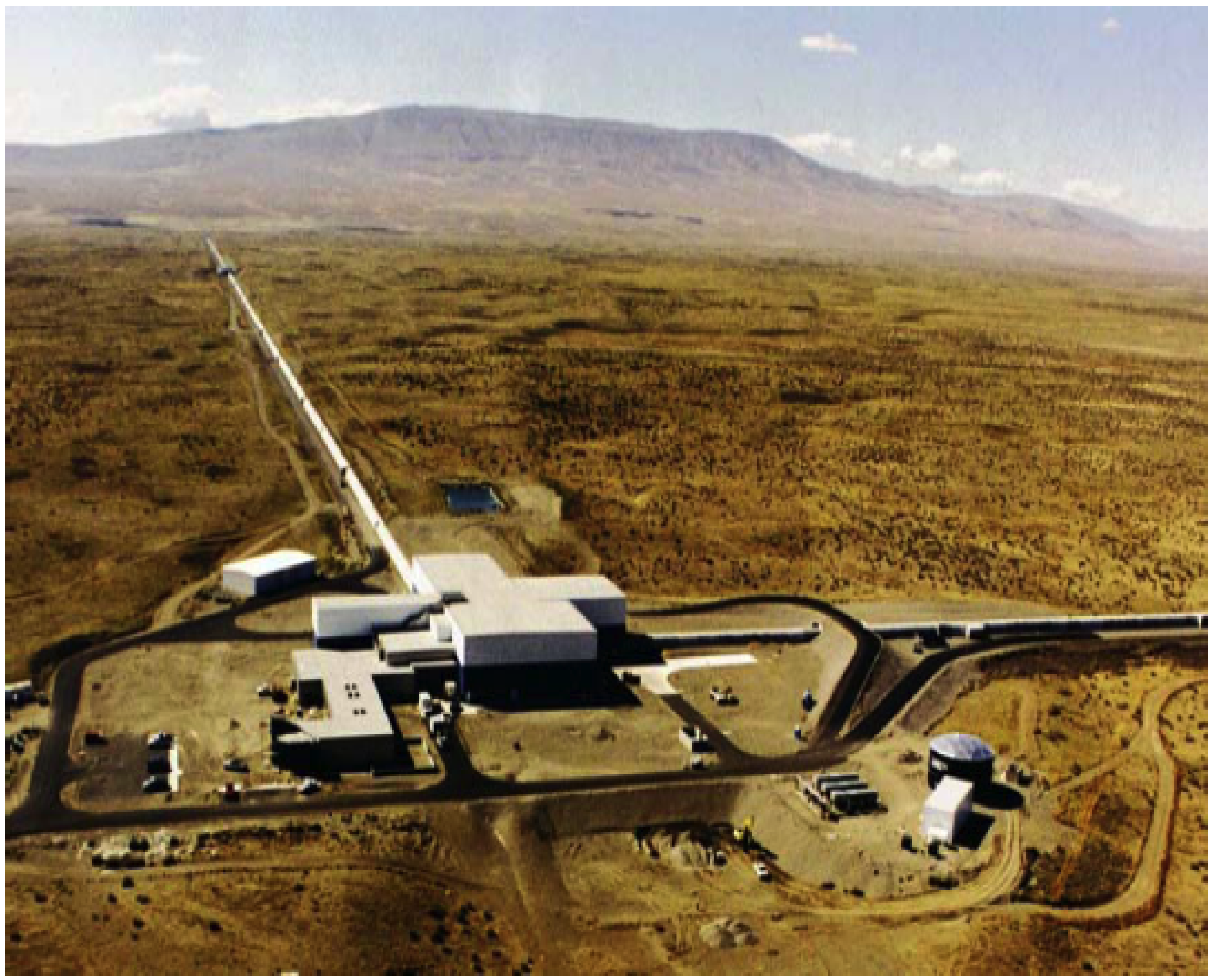
rate [*year*$^{-1}$]



0.01 solar mass in GW in a time <<1msec at the galactic center

Running Interferometers

LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

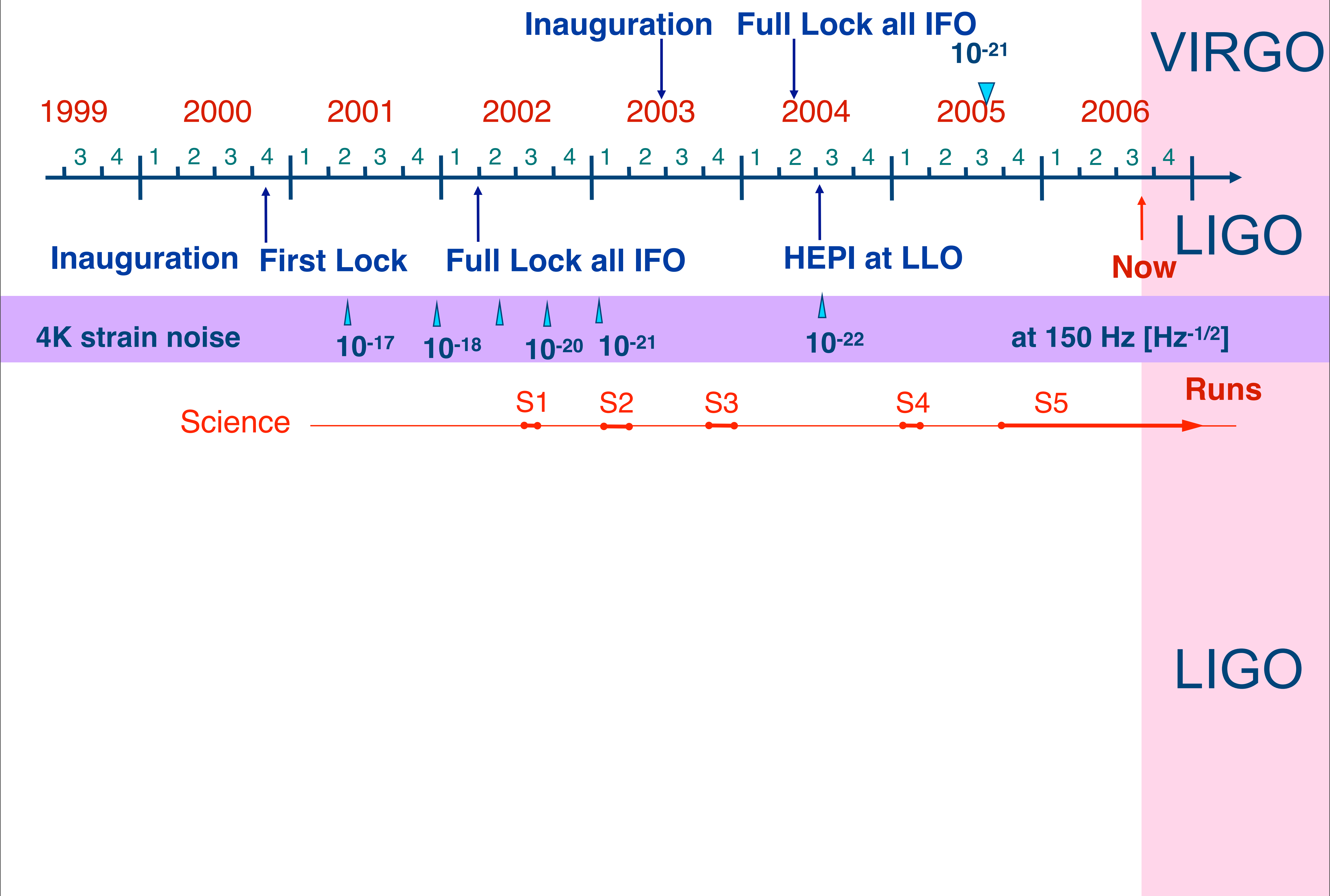
2 km + 4 km interferometers in same vacuum envelope

LIGO Livingston Observatory [LLO]

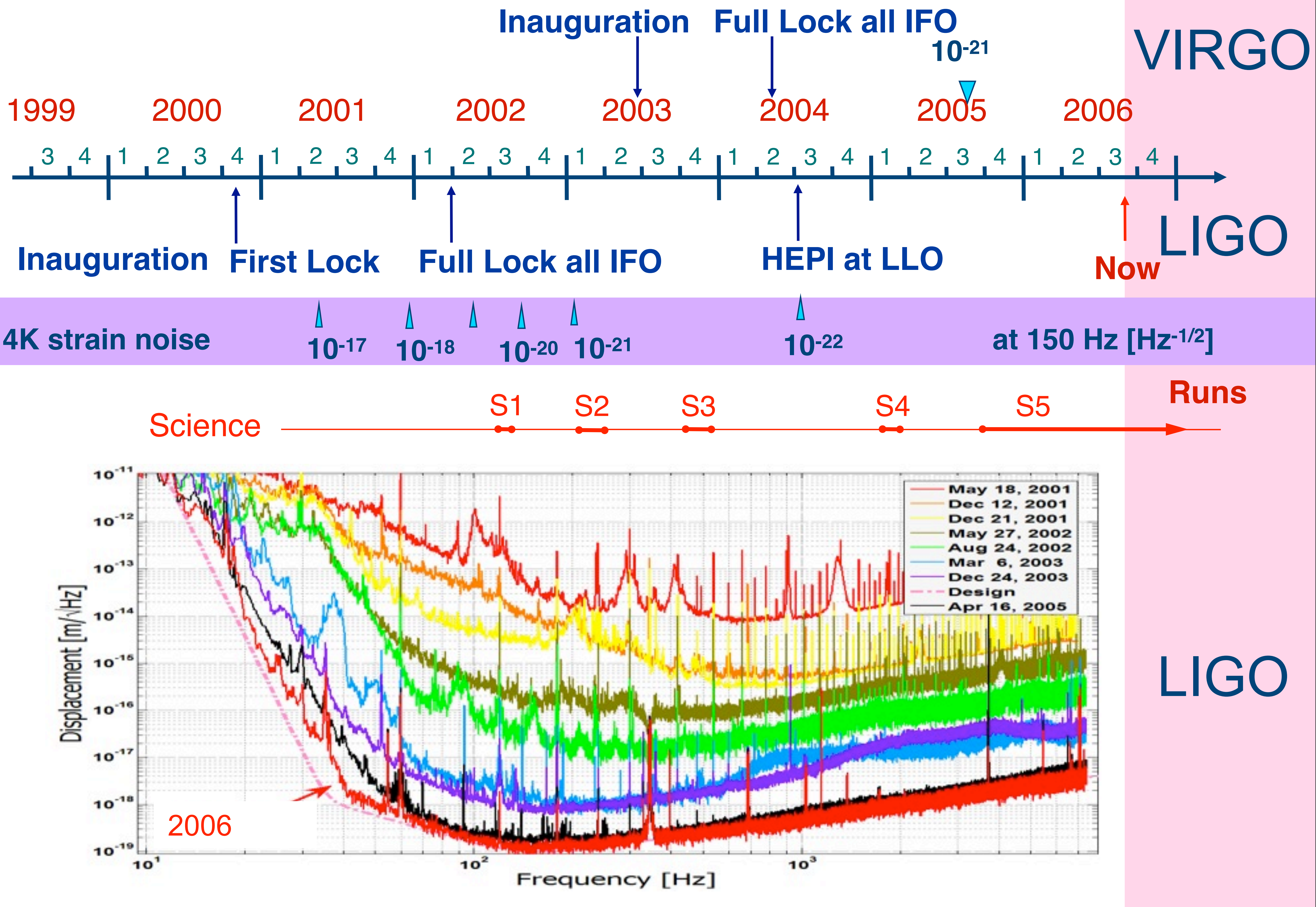
42 km east of Baton Rouge, LA

Single 4 km interferometer

VIRGO/LIGO Time Line

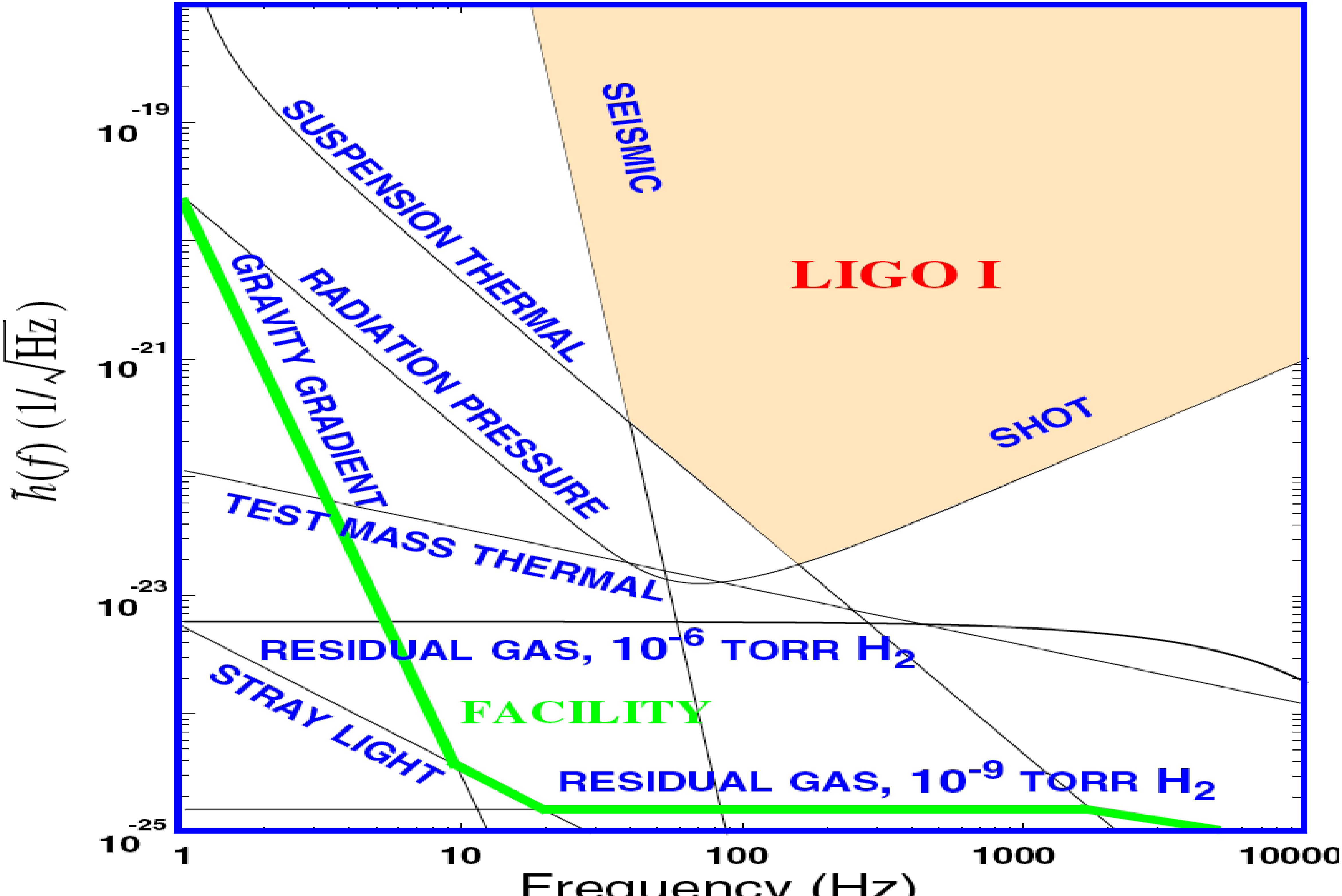


VIRGO/LIGO Time Line



LIGO/VIRGO noise budget

main contributions:
high frequency :laser shot noise
low frequency : seismic noise, suspension thermal



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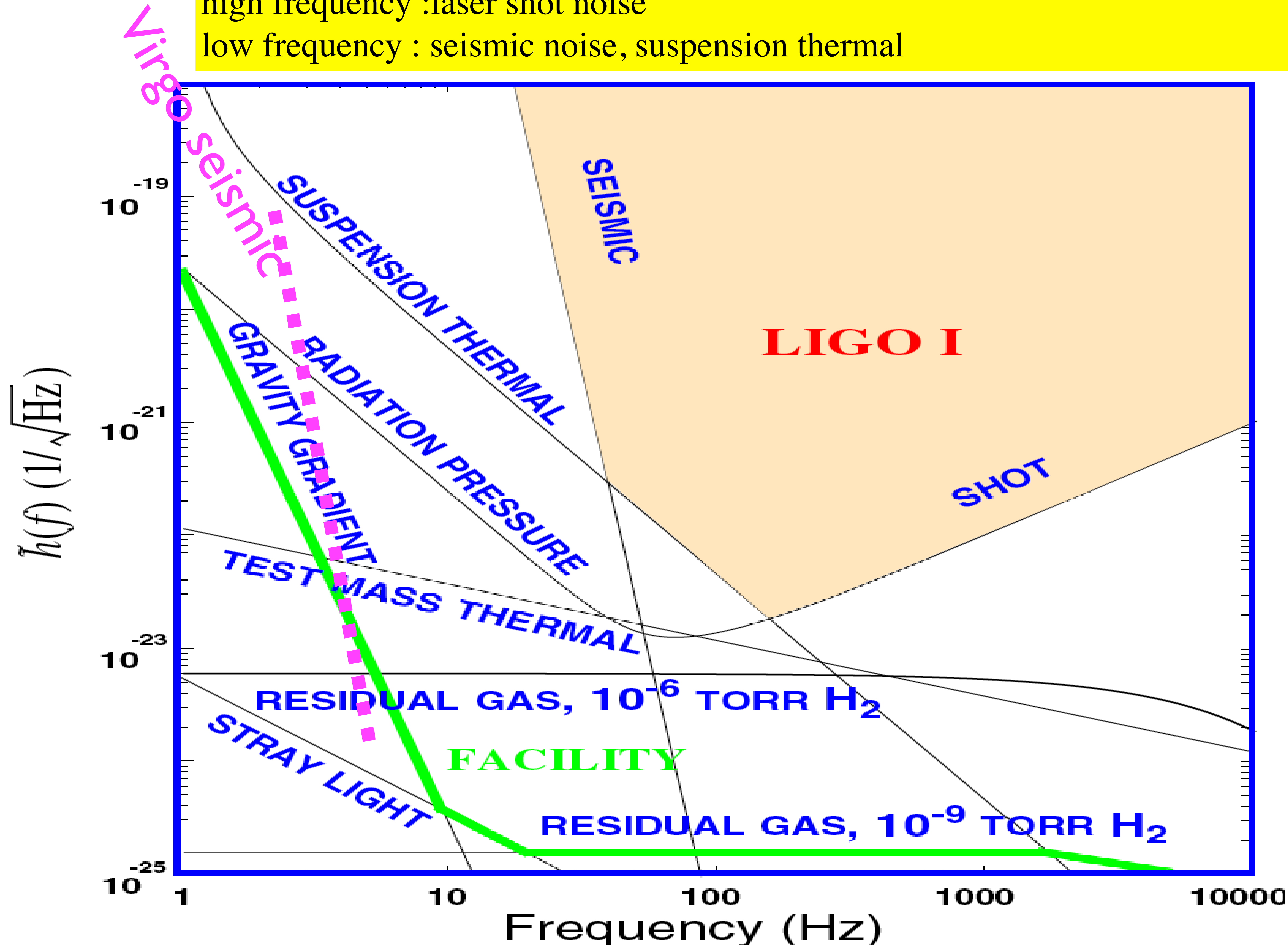
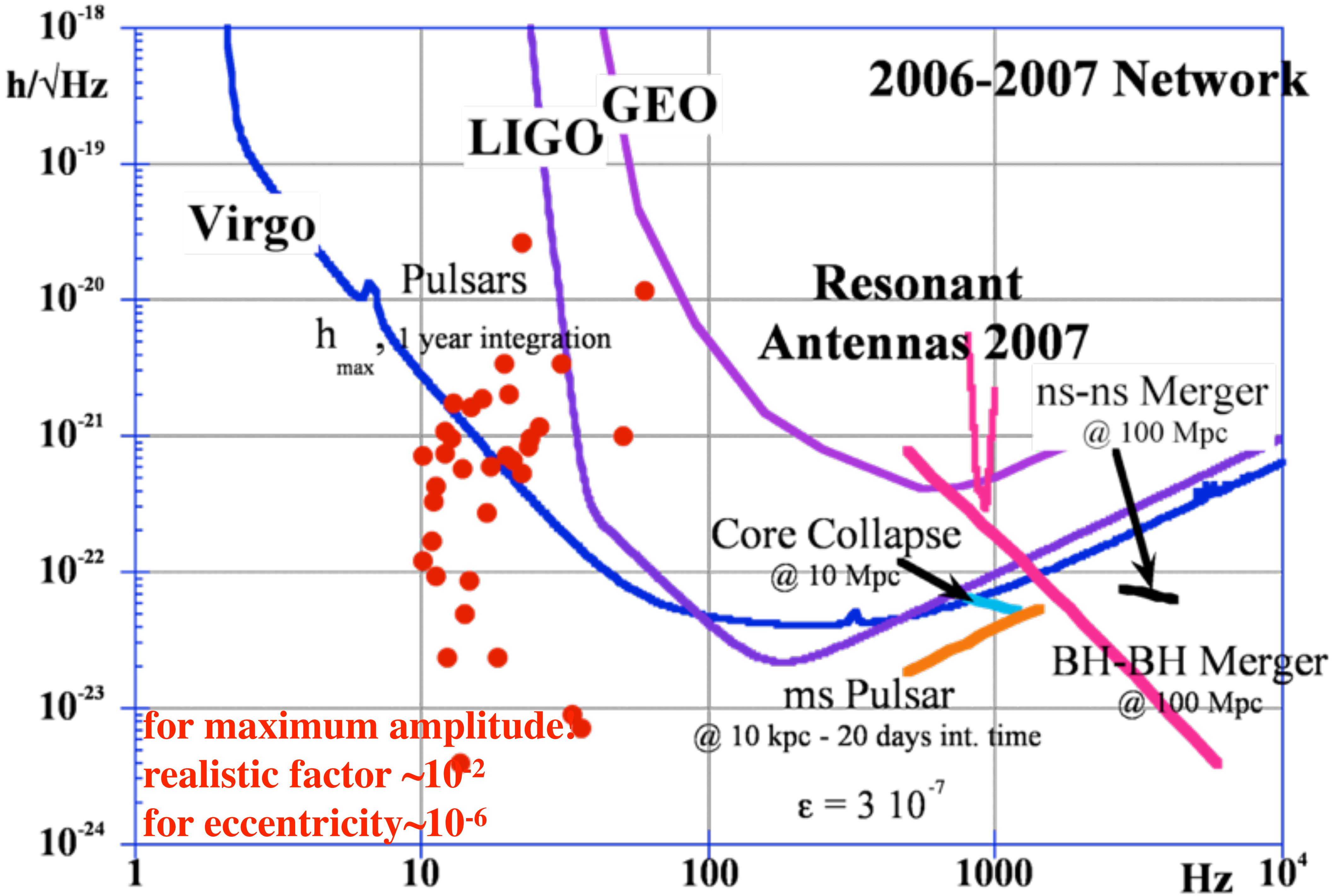


Interfermeters Science Run (LIGO, GEO and VIRGO

- **The fifth LIGO science run started in November 2005**
- **S5 goal is to collect one year of triple coincidence data at the design sensitivity**
- **Optimistic event rates: NS/NS ~3/year, BH/NS ~30/year**
  Nakar, Gal-Yam, Fox, astro-ph/0511254
- **Plan to reach the Crab pulsar spin down limit**
- **Expect to beat the Big-Bang Nucleosynthesis limit on gravitational wave density in the LIGO band**
- **GEO interferometer joined the S5 run in January 2006.**
- **Virgo interferometer joined S5 this month (in the week ends)**

Current detectors

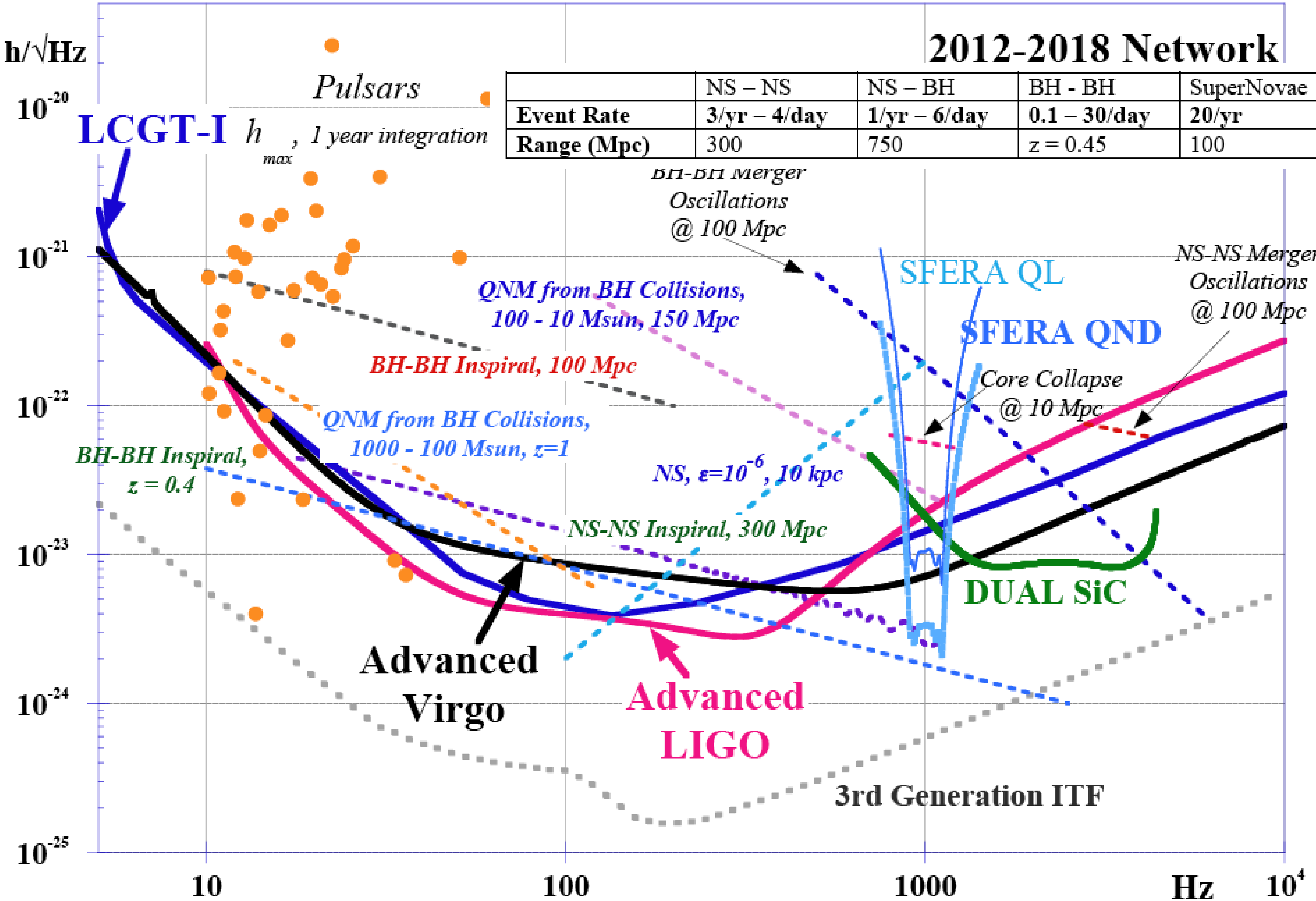
(design sensitivity for Virgo at low frequencies)



: **Sensitivity for GEO – LIGO - Virgo – Explorer - Nautilus – Auriga, with levels of possible sources. The Pulsars points show SNR with respect to background noise of Virgo after one year of integration, for maximum amplitude of the emitted GW.**

FUTURE

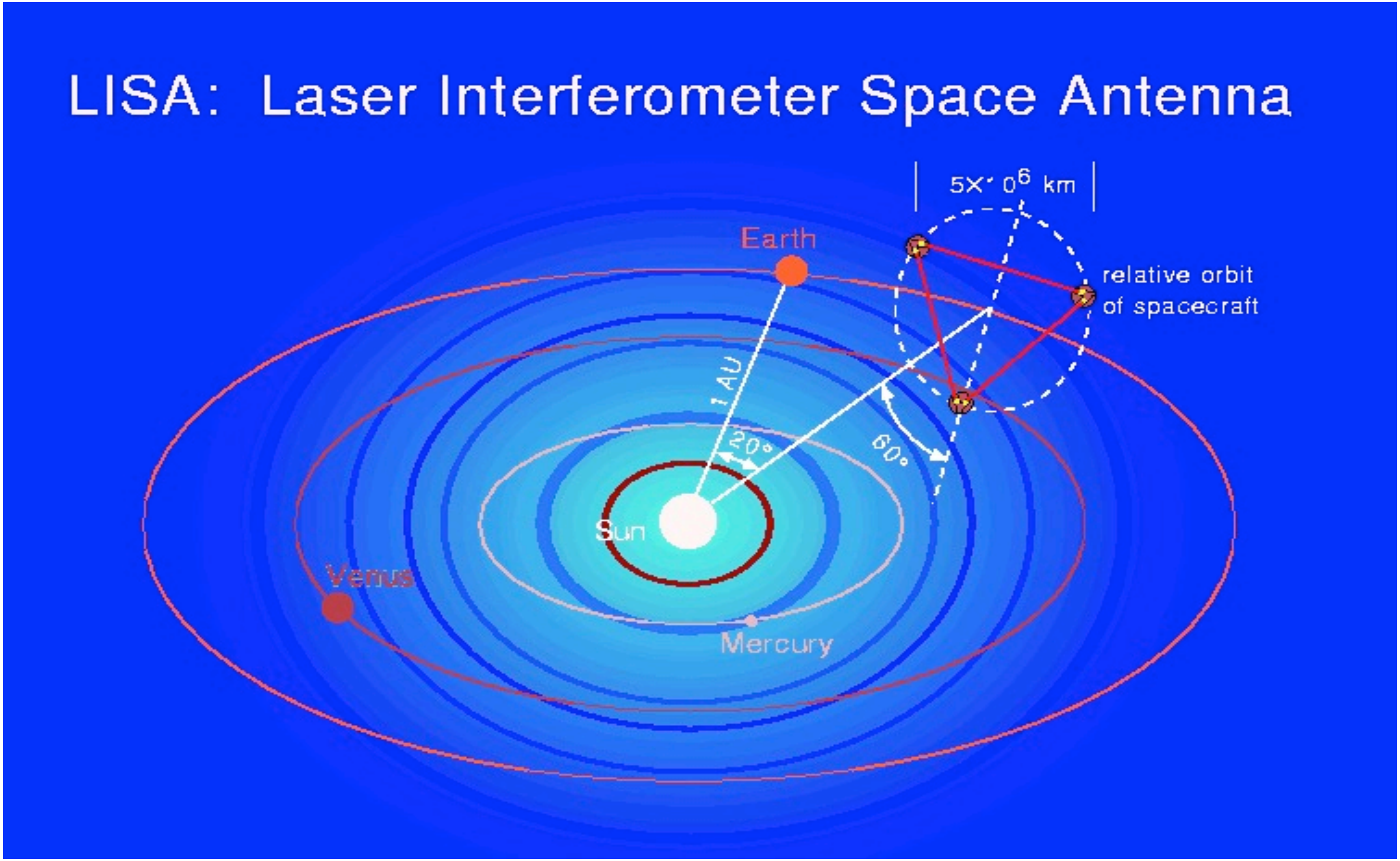
- In my opinion current run very important, future could change if gravitational waves will be discovered
- If not discovered : proceed as soon as possible to the “advanced upgrade” of the LIGO,VIRGO, ...detectos on the earth
- new space detector (LISA)



	NS – NS	NS – BH	BH - BH	SuperNovae
Event Rate	**3/yr – 4/day**	**1/yr – 6/day**	**0.1 – 30/day**	**20/yr**
Range (Mpc)	300	750	z = 0.45	100

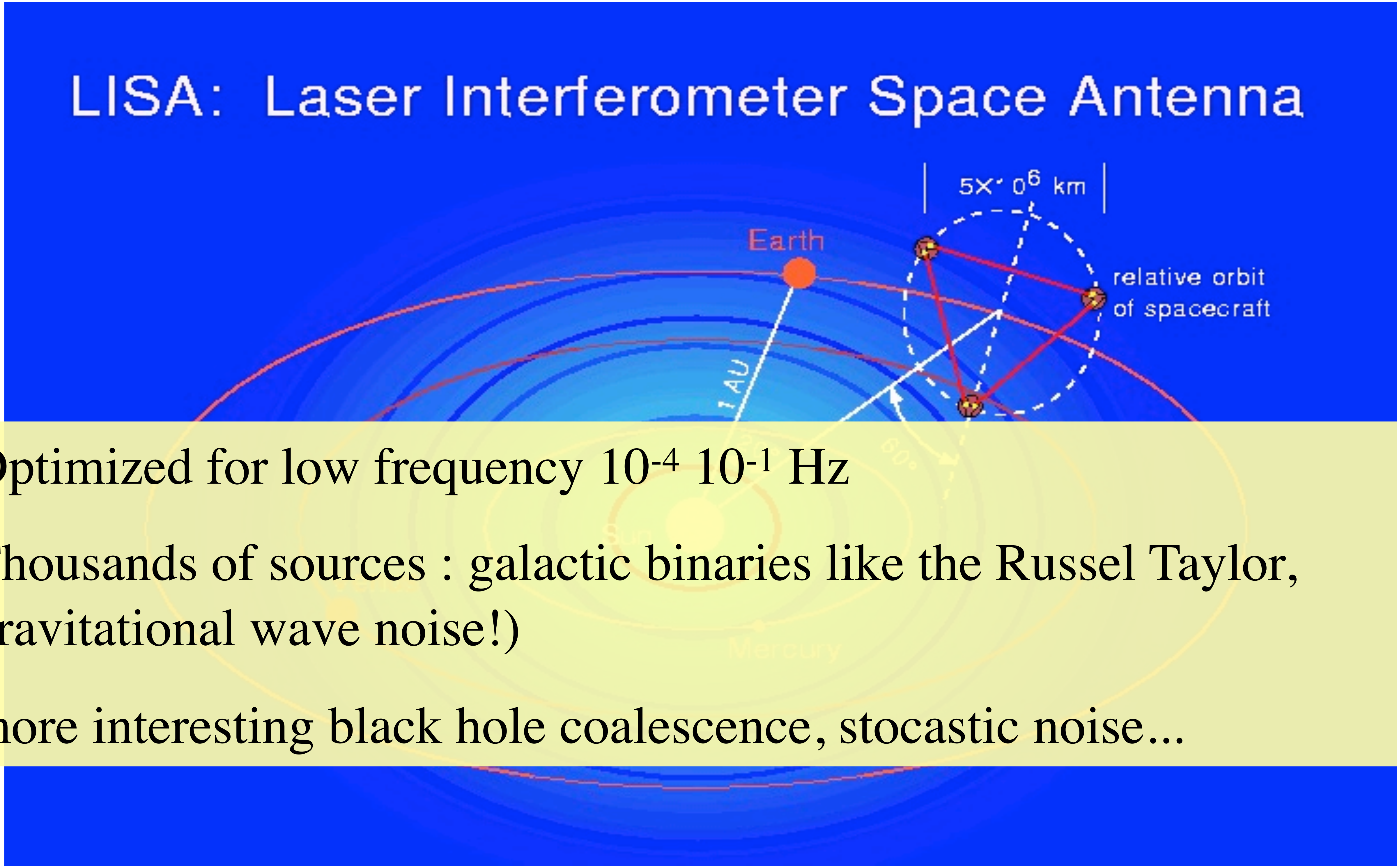
Figure 4: Sensitivity of Advanced Virgo Advanced – Advanced LIGO – DUAL SiC at Quantum Limit, with the stimated levels of some sources. The difference between the LCGT-I, Advanced LIGO and Advanced Virgo sensitivity curves is due mainly to a different configuration of signal recycling.

LISA



R/D (LISA-PF 2009) LISA after 2015?

LISA



• Optimized for low frequency 10^{-4} 10^{-1} Hz

• Thousands of sources : galactic binaries like the Russel Taylor, (gravitational wave noise!)

• more interesting black hole coalescence, stocastic noise...

R/D (LISA-PF 2009) LISA after 2015?

Conclusions

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- 4 alluminium cylindrical detectors are in **“science” run** sensitivity smaller than interferometers, but operation cost much smaller. Monitor during the interferometers upgrades

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- LIGO, GEO interferometers, scientific run for >1 year. VIRGO at the end of the commissioning. VIRGO run at the end of the year.

Conclusions

- 4 alluminium cylindrical detectors are in **"science" run** sensitivity smaller than interferometers, but operation cost much smaller. Monitor during the interferometers upgrades
- LIGO, GEO interferometers, scientific run for >1 year. VIRGO at the end of the commissioning. VIRGO run at the end of the year.
- **Non zero probability to detect G.W. NOW !**

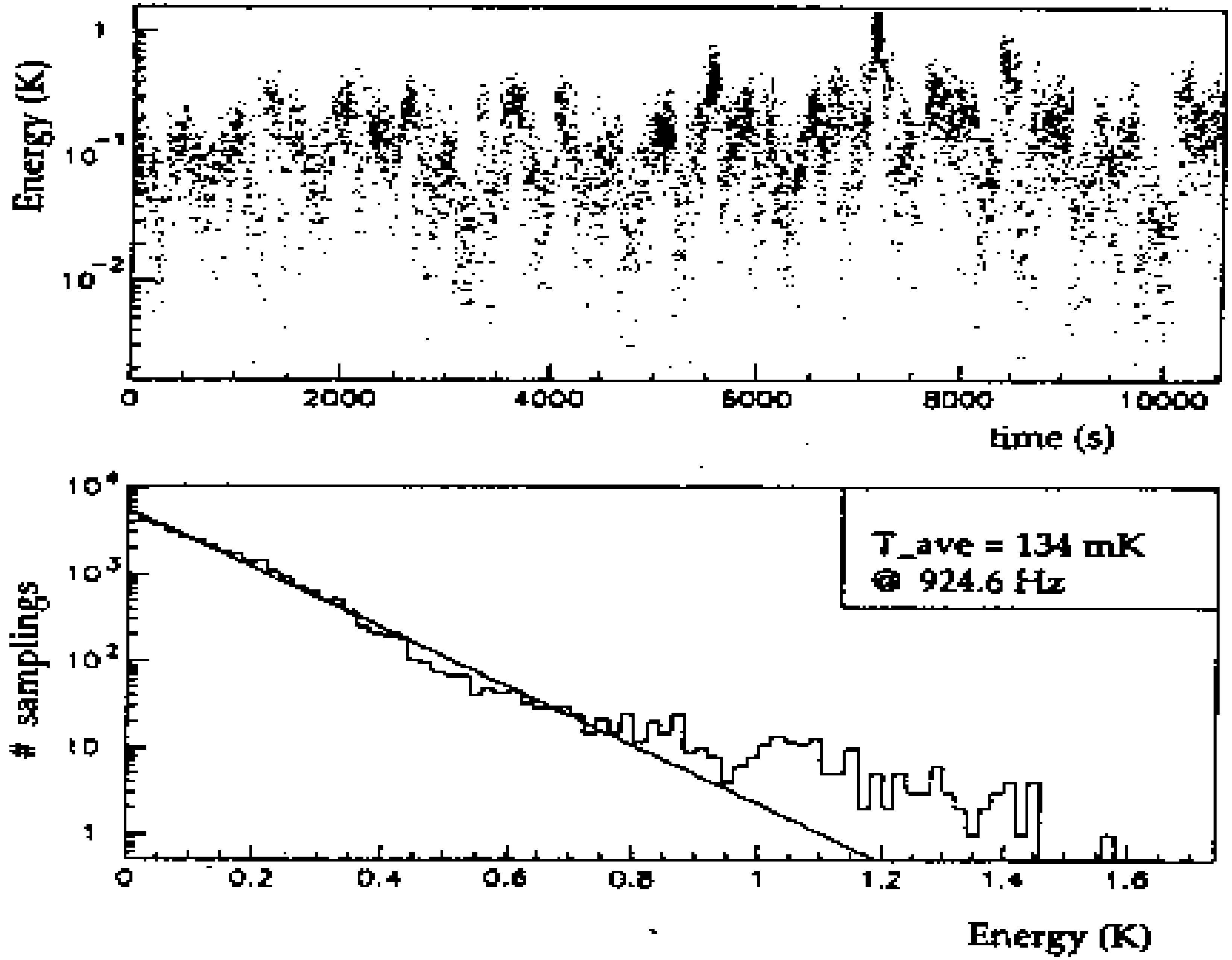
Conclusions

- 4 alluminium cylindrical detectors are in **"science" run** sensitivity smaller than interferometers, but operation cost much smaller. Monitor during the interferometers upgrades
- LIGO, GEO interferometers, scientific run for >1 year. VIRGO at the end of the commissioning. VIRGO run at the end of the year.
- **Non zero probability to detect G.W. NOW !**

- In August 2004 Ladbrokes, the British betting firm, opened a book on the chances of LIGO seeing gravitational waves before 2010. They initially set the **odds at 500:1** but business was so brisk that within a week **the odds had fallen to 6:1and then to 3:1** before Ladbrokes closed the book!

THE END

Misura rumore Browniano

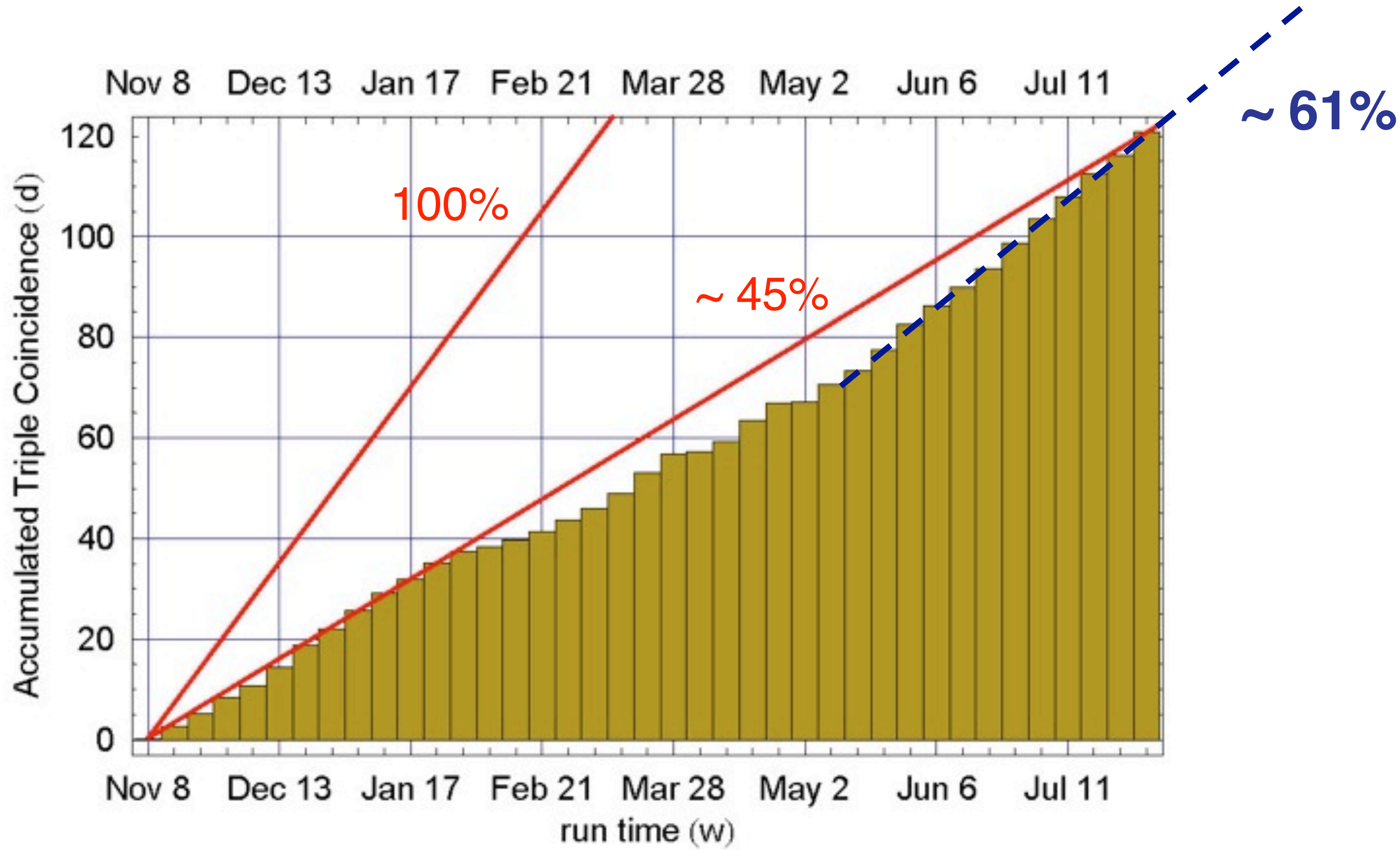


Nautilus 1998

FIG. 9 – Measurement of the Brownian noise: a) history and b) distribution of the vibration energy of the + mode in a three hours period. The average energy is in agreement with the thermodynamic temperature of the bar.

T da termometri ~ 0.1 Kelvin

Triple Coincidence Accumulation



Expect to collect one year of triple coincidence data by summer-fall 2007

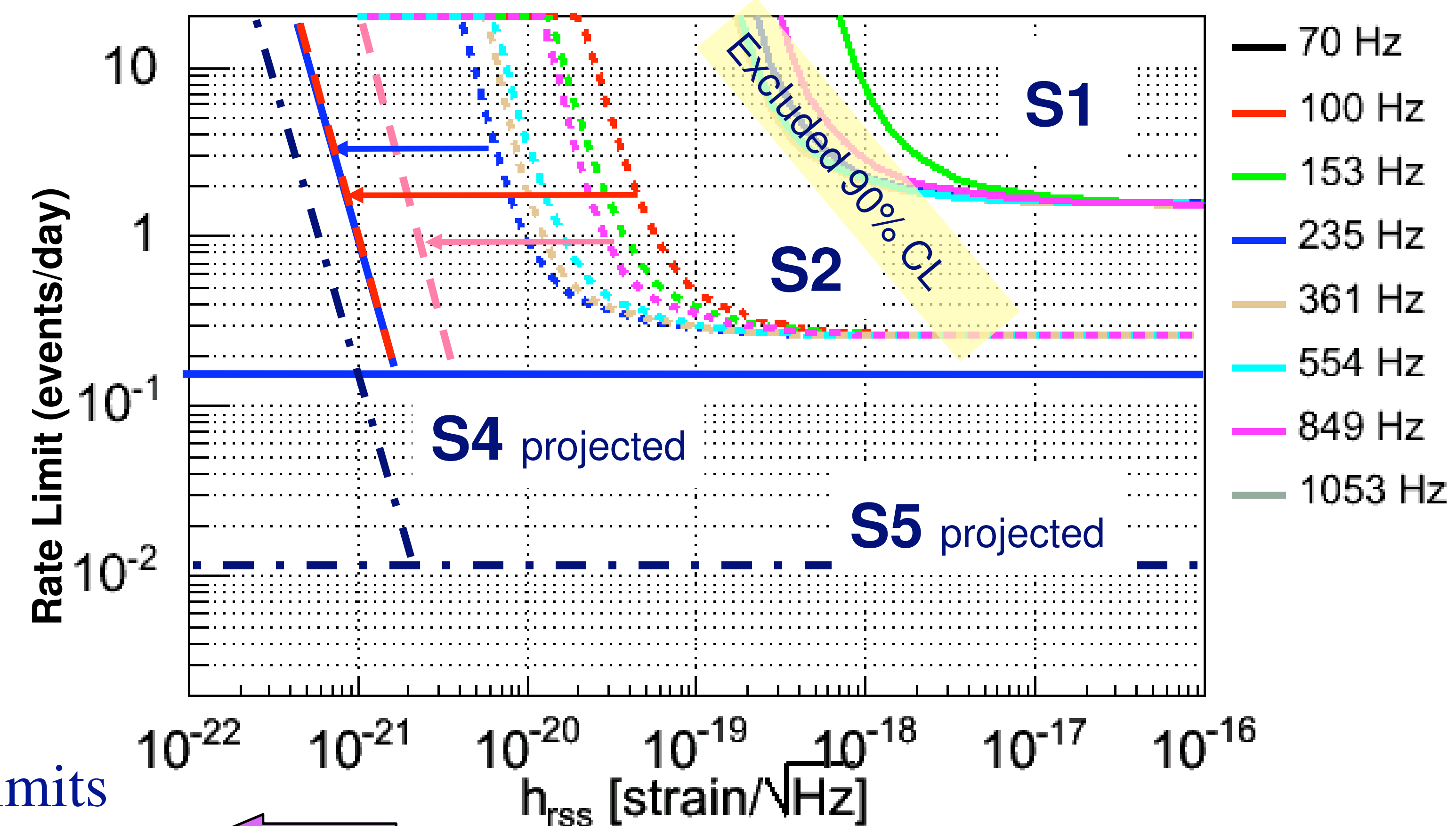
LIGO

Upper Limits

- No GW bursts detected through S4
  - set limit on rate vs signal strength.

$$R \propto \frac{1}{\epsilon(h_{\rm rss})\, T}$$

Lower rate limits from longer observation times

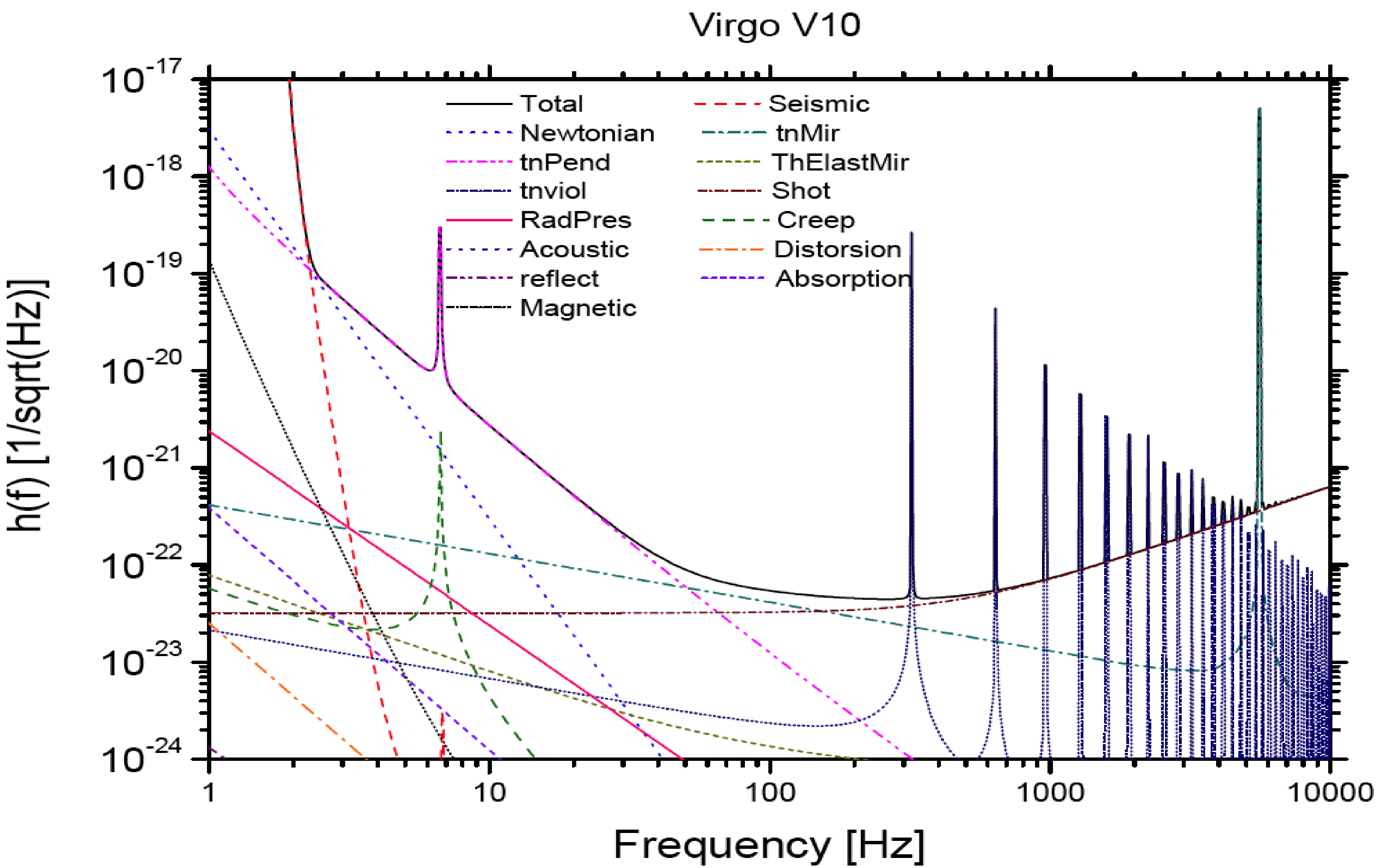


Lower amplitude limits from lower detector noise

LIGO-G060363-00-Z

Virgo /Ligo Noise budget

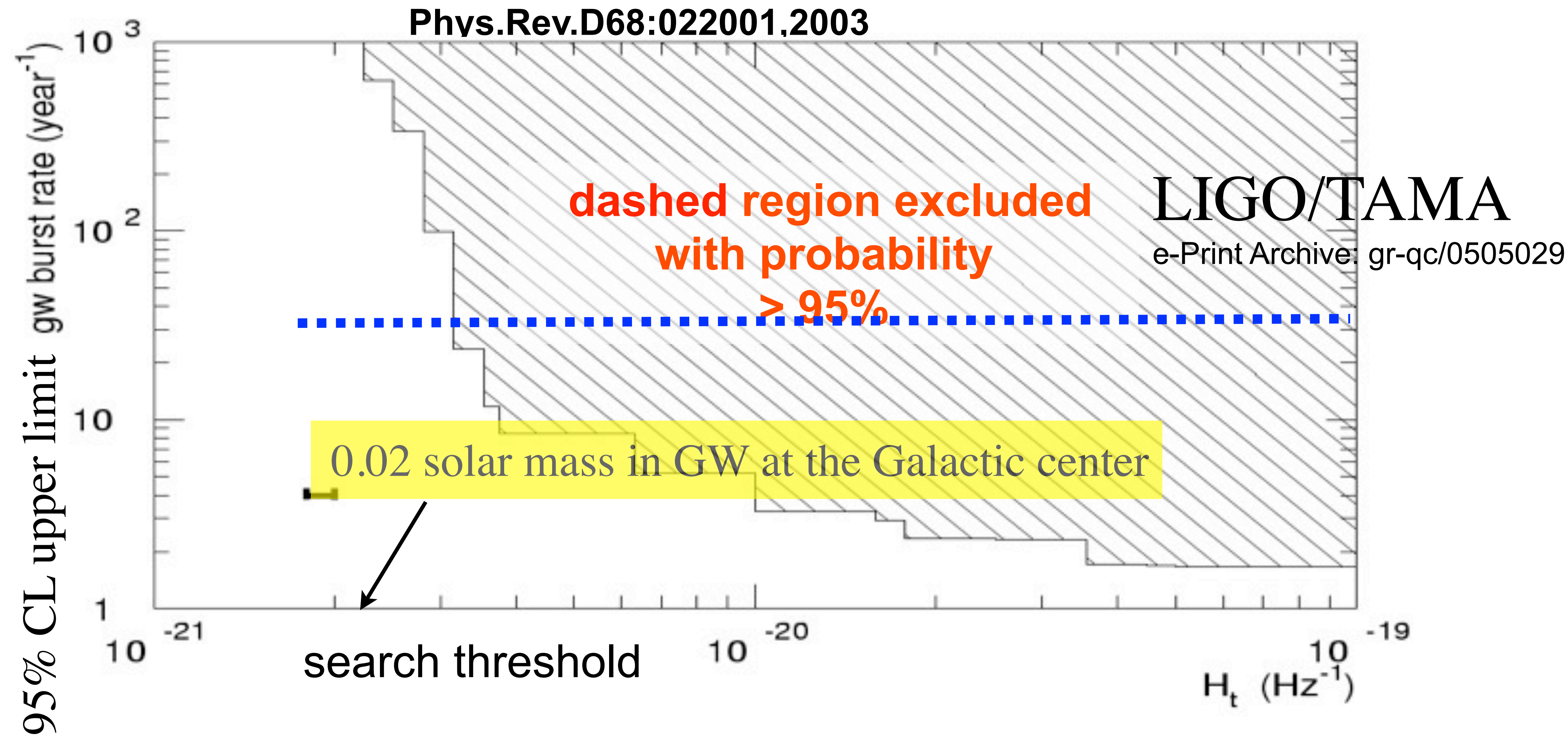
main contributions:
high frequency :laser shot noise
low frequency : mirror pendolum noise, newtonian noise, seismic noise



Burst search : IGEC1 results

Phys.Rev.D68:022001,2003

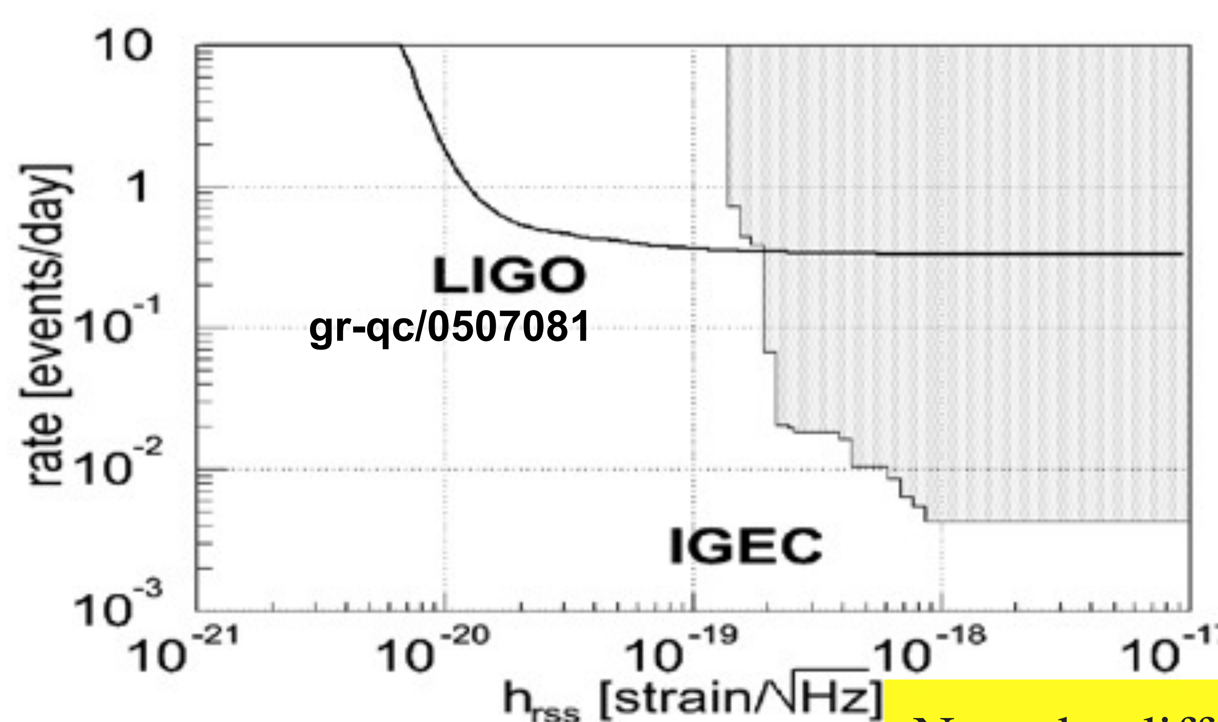
rate
[*year* $^{-1}$]



LIGO/TAMA
e-Print Archive: gr-qc/0505029

Comparison of the search sensitivity with the interferometers could be done in several different ways (due to the different sensitivity band) hrss= is the root sum square of h. Assumed a Gaussian waveform τ=0.1 msec:

$$h(t) = h_{rss}\left(\frac{2}{\pi\tau^2}\right)^{1/4} e^{-t^2/\tau^2}$$



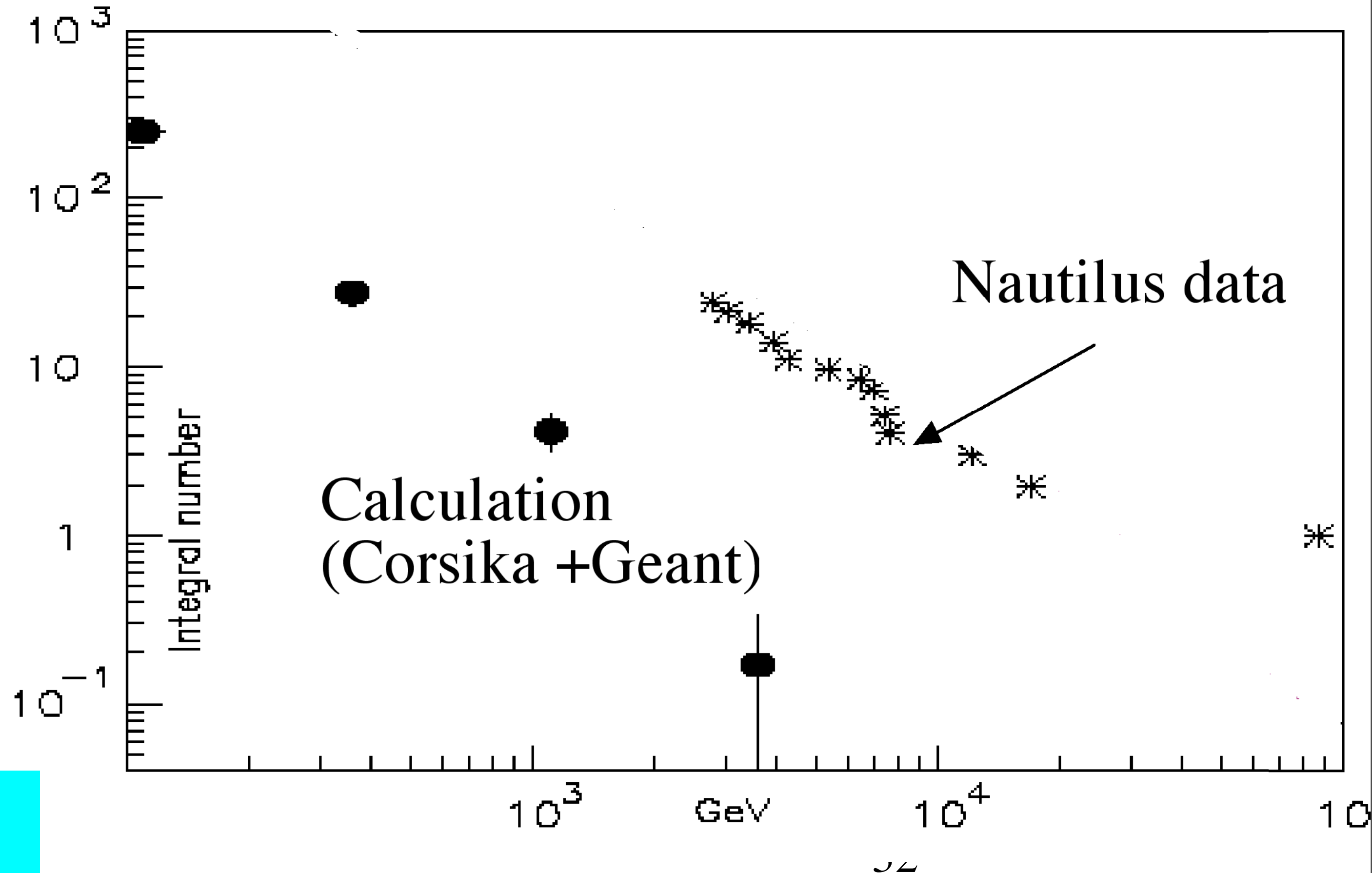
Note the different h units!

Cosmic ray showers detection (Nautilus 1998)

- interesting to study the detector performances and to understand the cosmic rays backgrounds
- In Nautilus at T=130 mKelvin unexpected events of very large energy probably related to the superconductivity

Large energy events expected if hadrons are in the shower, but rate much larger than expected.

In the runs at temperature T >1 Kelvin rate of big events lower

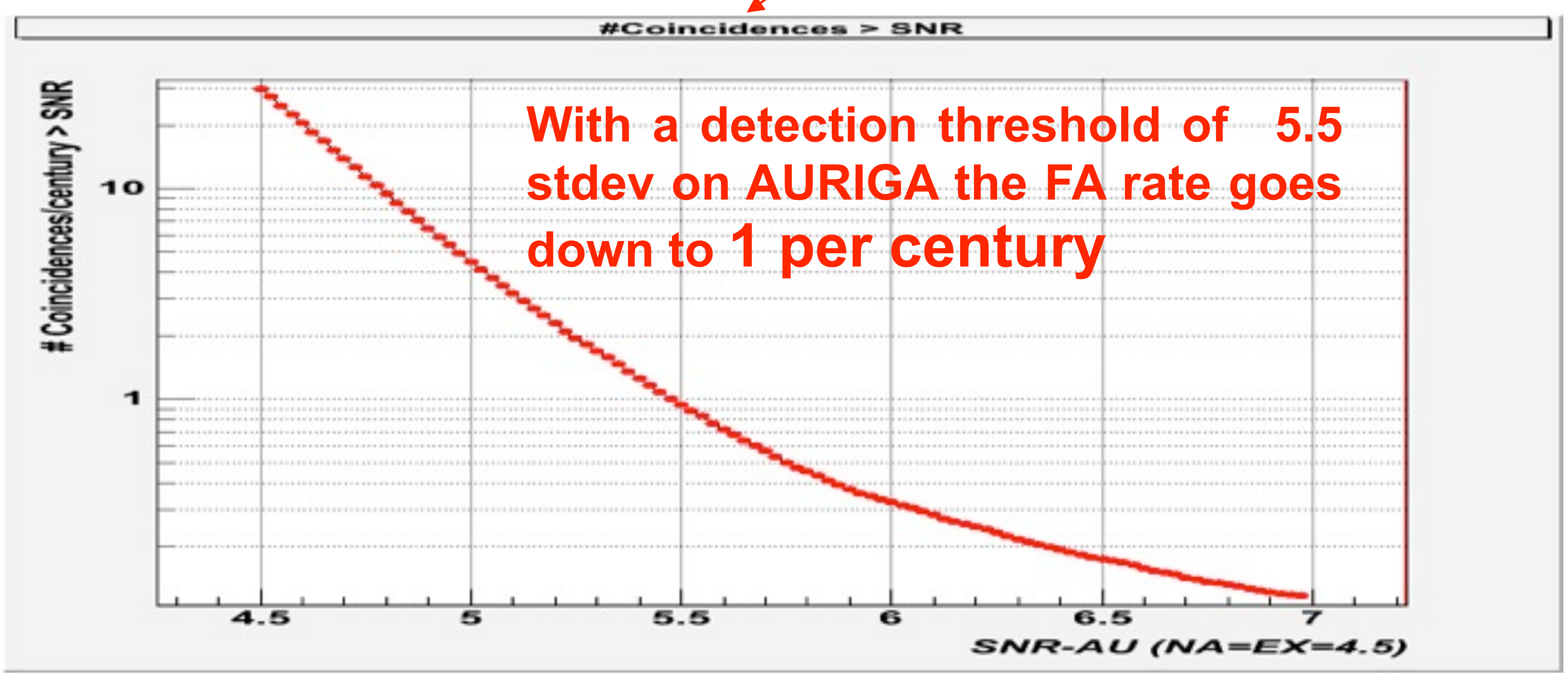


To solve this question: RAP experiment on a particle beam Quintieri's talk this afternoon

Burst search with bar (optimized for length<<1 msec).

• In the past : some excess in the coincidences between tow detectors (Explorer and Nautilus)with small statistical significance
• Now in progress a search with better detectors and at least a triple coincidence

FALSE ALARM RATE vs DETECTION THRESHOLD (AU-EX-NA PRELIMINARY)



Background estimate of **triple coincidence** on the common observation time (130 days) by 10^7 time shifts

EVIDENCE FOR DISCOVERY OF GRAVITATIONAL RADIATION*

J. Weber
Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742
(Received 29 April 1969)

Coincidences have been observed on gravitational-radiation detectors over a base line of about 1000 km at Argonne National Laboratory and at the University of Maryland. The probability that all of these coincidences were accidental is incredibly small. Experiments imply that electromagnetic and seismic effects can be ruled out with a high level of confidence. These data are consistent with the conclusion that the detectors are being excited by gravitational radiation.

Some years ago an antenna for gravitational radiation was proposed.[1] This consists of an elastic body which may become deformed by the dynamic derivatives of the gravitational potentials, and its normal modes excited. Such an antenna measures, precisely, the Fourier transform of certain components of the Riemann curvature tensor, averaged over its volume. The theory has been developed rigorously, starting with Einstein's field equations to deduce[2] equations of motion. Neither the linear approximation nor the energy-flux relations are needed to describe these experiments, but their use enables discussion in terms of more familiar quantities. All aspects of the antenna response and signal-to-noise ratio can be written in terms of the curvature tensor. The theory was verified experimentally by developing a high-frequency source[3] and producing and detecting dynamic gravitational fields in the laboratory.

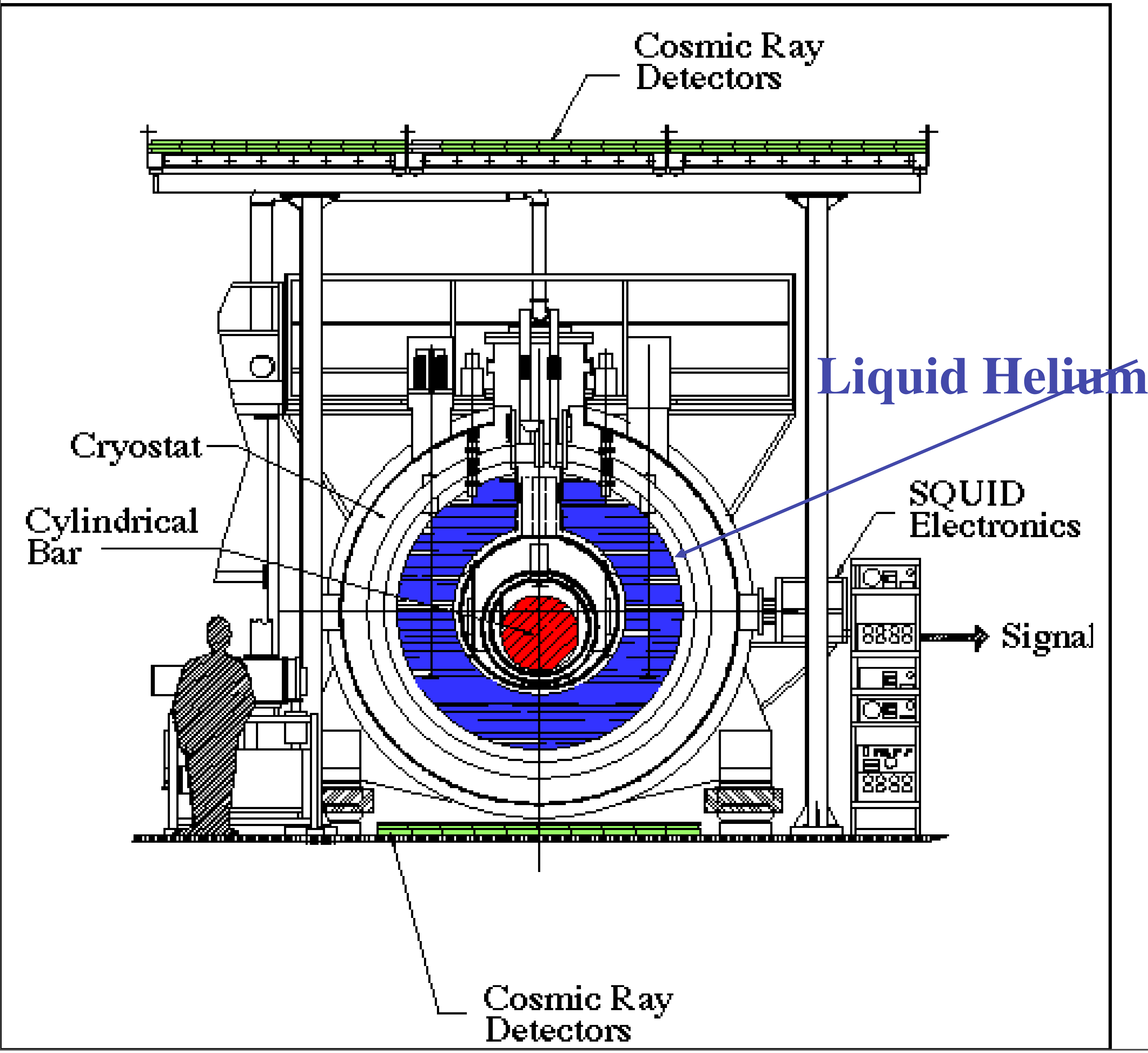
Several programs of research are being carried out. One employs laboratory masses in the frequency range 1-2 kHz.[4] Another is concerned with expected gravitational radiation from the pulsars.[5] Some designs for such antennas suggest a pulsar detection range approaching 1000

array is a new set of windows for studying the universe.

Search for gravitational radiation in the vicinity of 1660 Hz.—A frequency in the vicinity of 1660 Hz was selected because the dimensions are convenient for a modest effort and because this frequency is swept through during emission in a supernova collapse. It was expected that once the technology was refined, detectors could be designed for search for radiation from sources with radio or optical emission, such as the pulsars. A knowledge of the expected frequency and Q of a source enormously increases the probability of successful search.

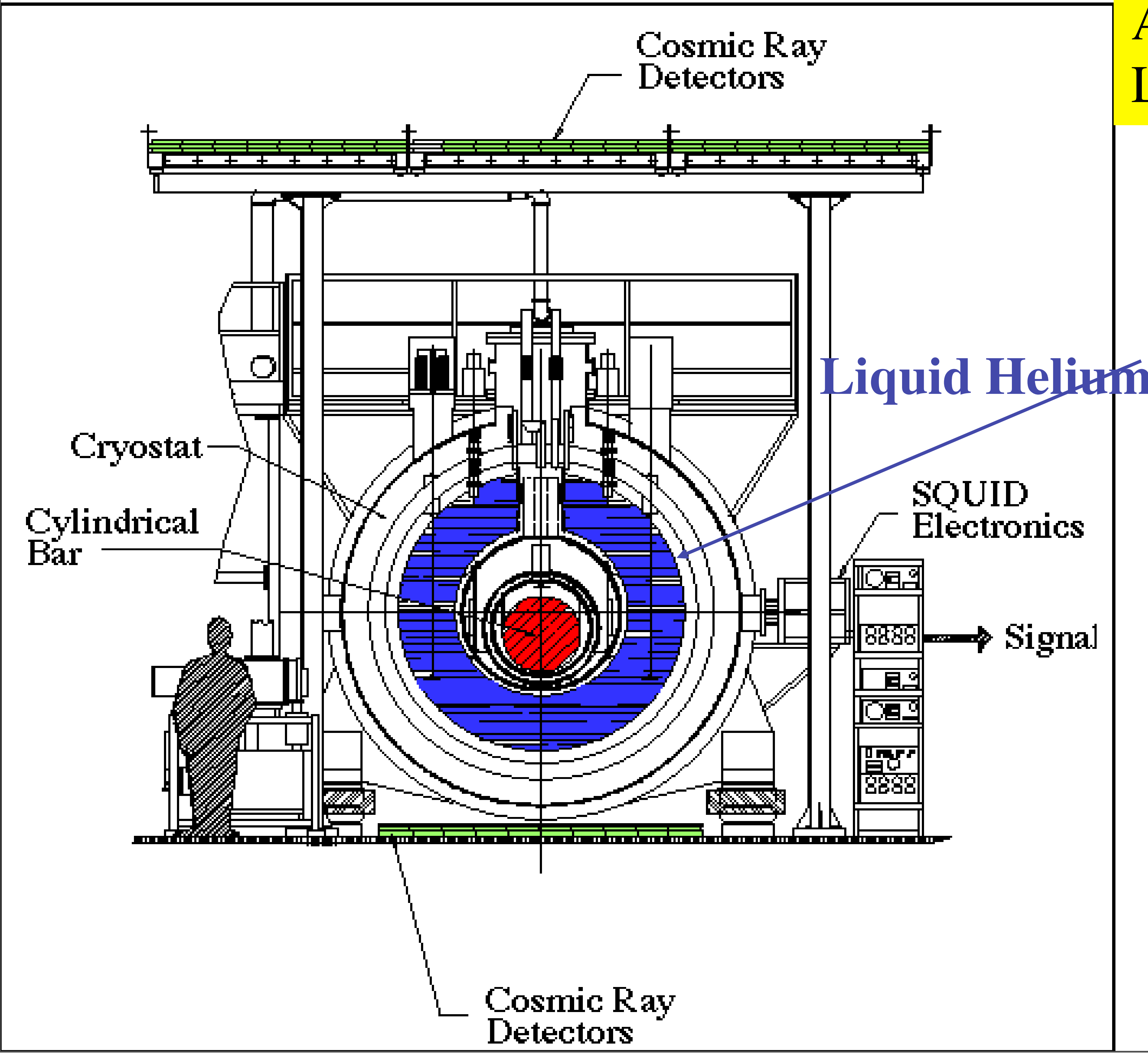
However, occasional signals were seen at 1660 Hz and small numbers of coincidences were observed on detectors[7,8] separated by a few kilometers. To explore these phenomena further, larger detectors were developed. One of these is now operating at Argonne National Laboratory. My definition of a coincidence is that the rectified outputs of two or more detectors cross a given threshold in the positive direction within a specified time interval. For the present experiments the time interval was 0.44 sec. The mag-

Example of a cylindrical resonant detector: Nautilus (the first cooled at 100 mK)



Example of a cylindrical resonant detector: Nautilus (the first cooled at 100 mK)

Al 2036 bar 2300 Kg
L=3 m r=0.3m



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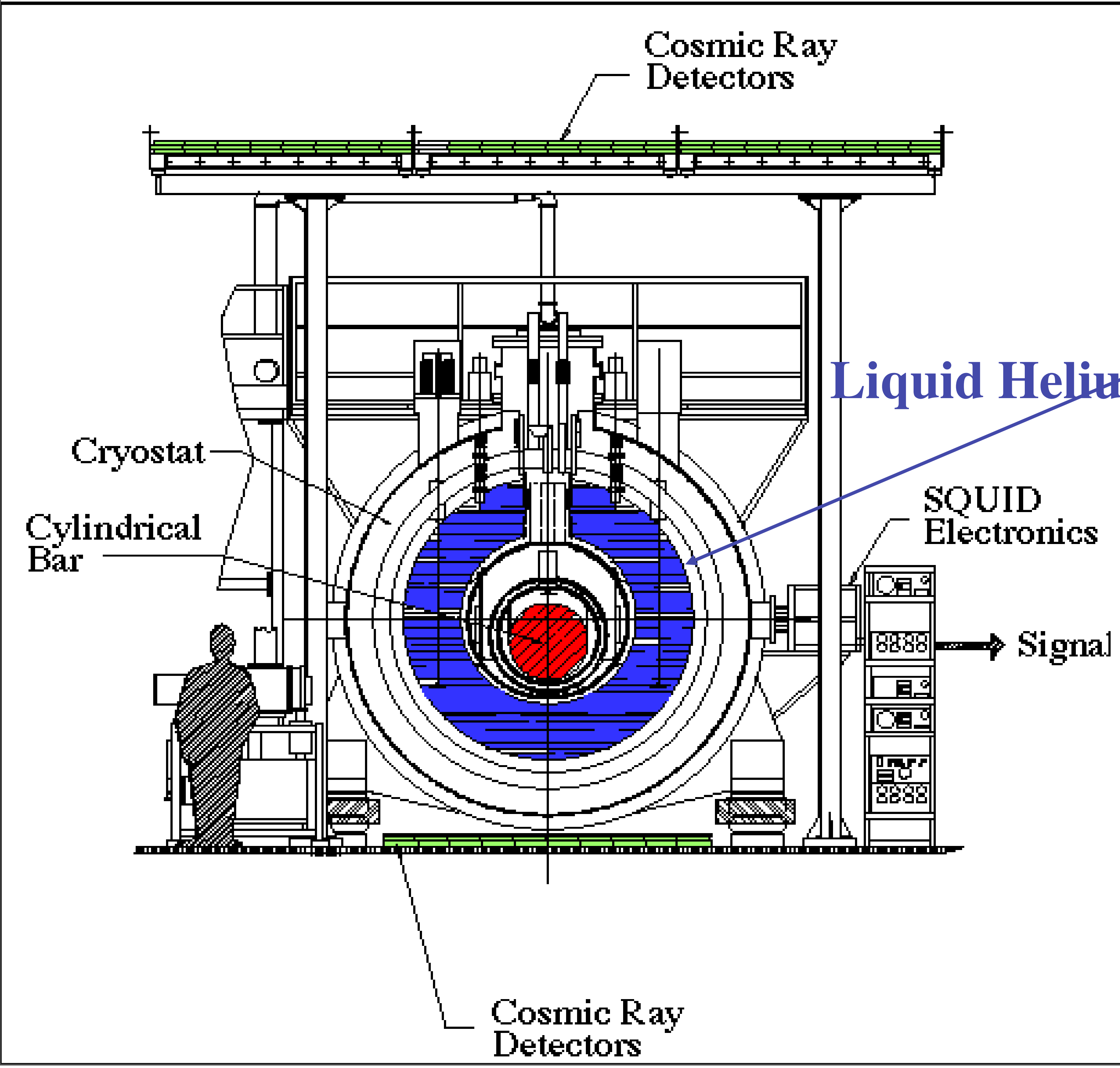
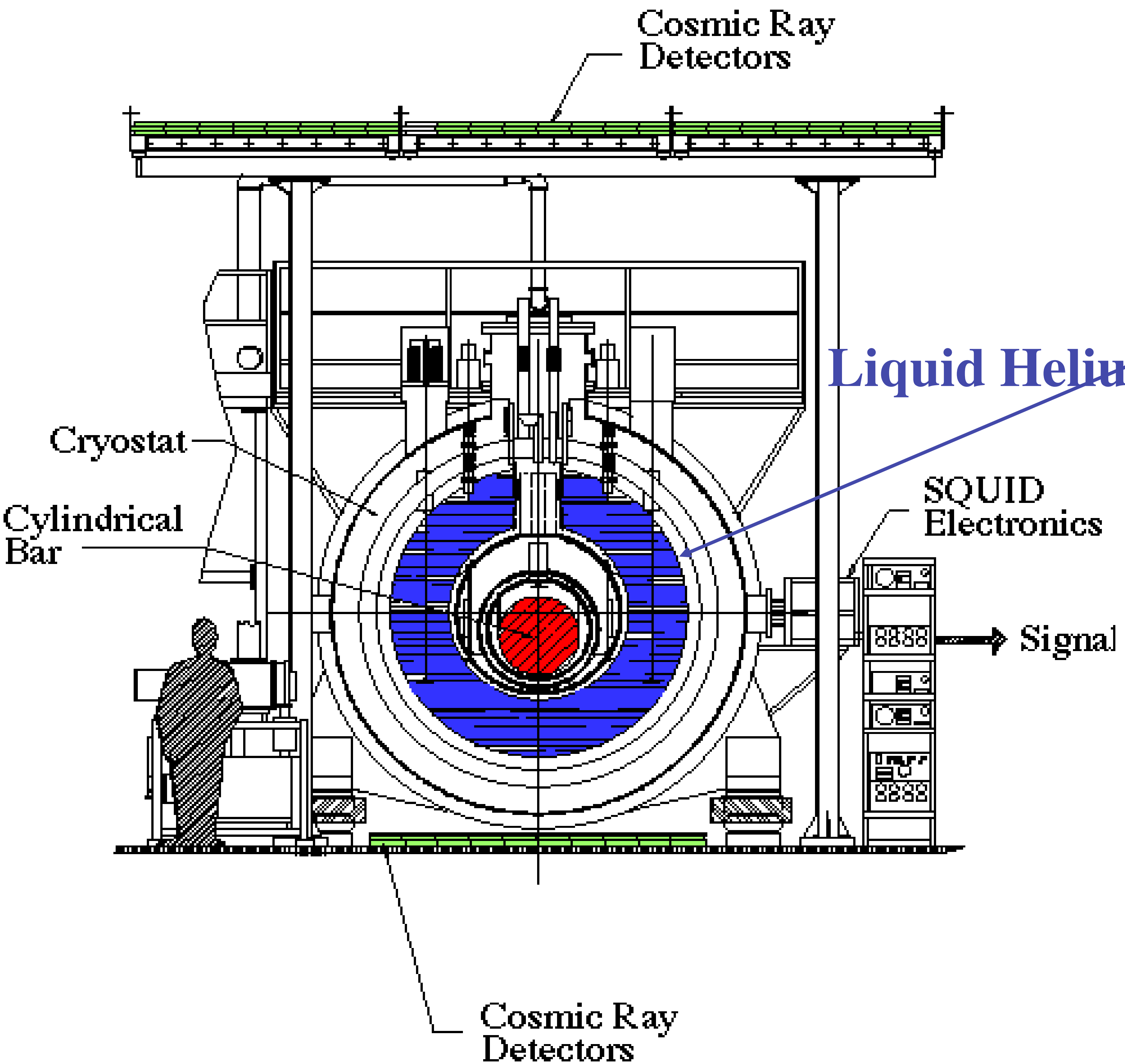


Cross section : 2 aluminum shields, container for helium **2000 liters**, dilution refrigerator with ^{3}He ^{4}He mixture

Example of a cylindrical resonant detector: Nautilus (the first cooled at 100 mK)

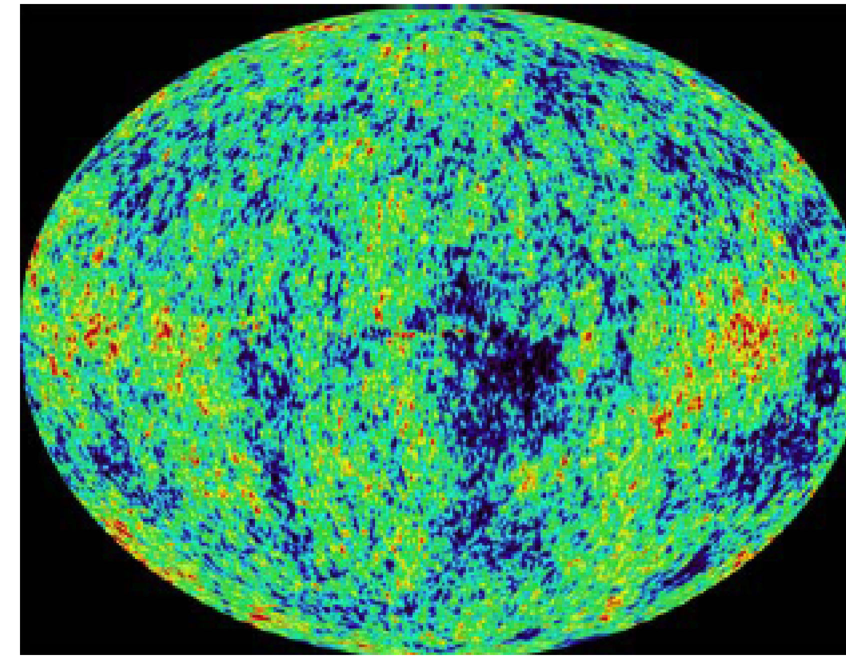


Al 2036 bar 2300 Kg
L=3 m r=0.3m

Cross section : 2 aluminum shields, container for helium **2000 liters**, dilution refrigerator with ^{3}He ^{4}He mixture

Mechanical suspension: shields are suspended in a chains and copper wire around the bar 260 db @ 1 Khz

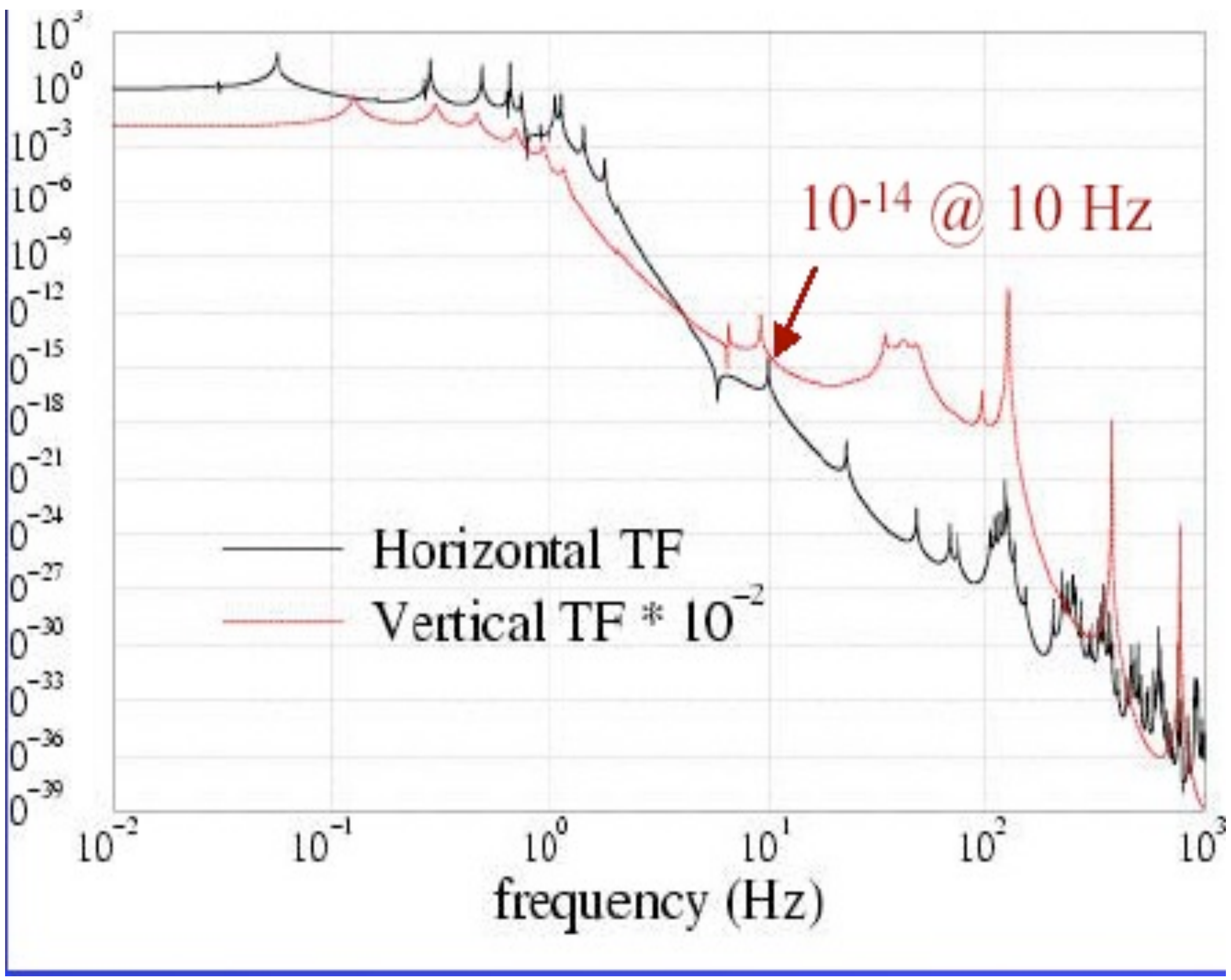
Sources : Gravitational waves from big bang



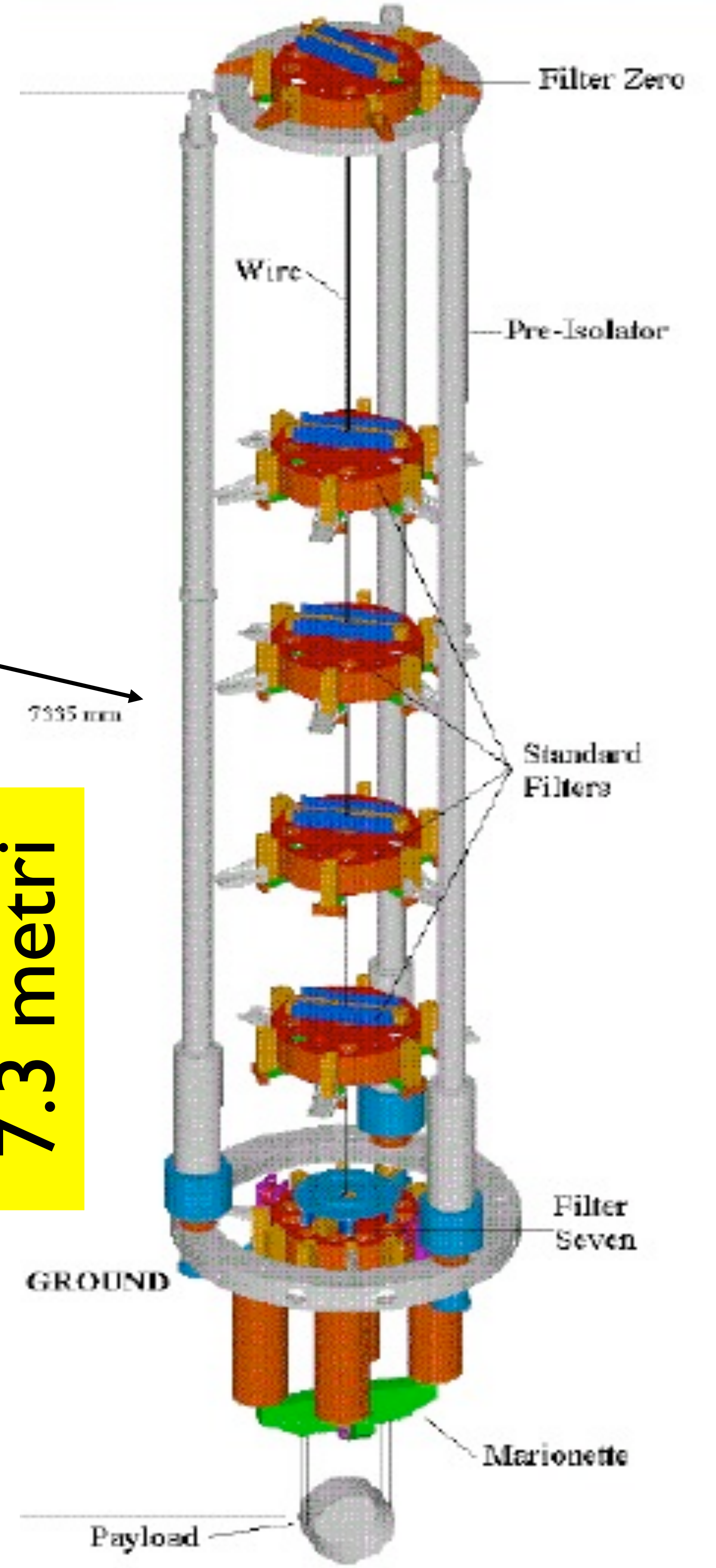
- from big bang : microway radiation, relic particles and gravitational radiation
- searched usually correlating the signal of two antennas optimal distance~

Virgo “superattenuator”

- seismic noise better reduction (low fequency limitation)
  - 10 years development

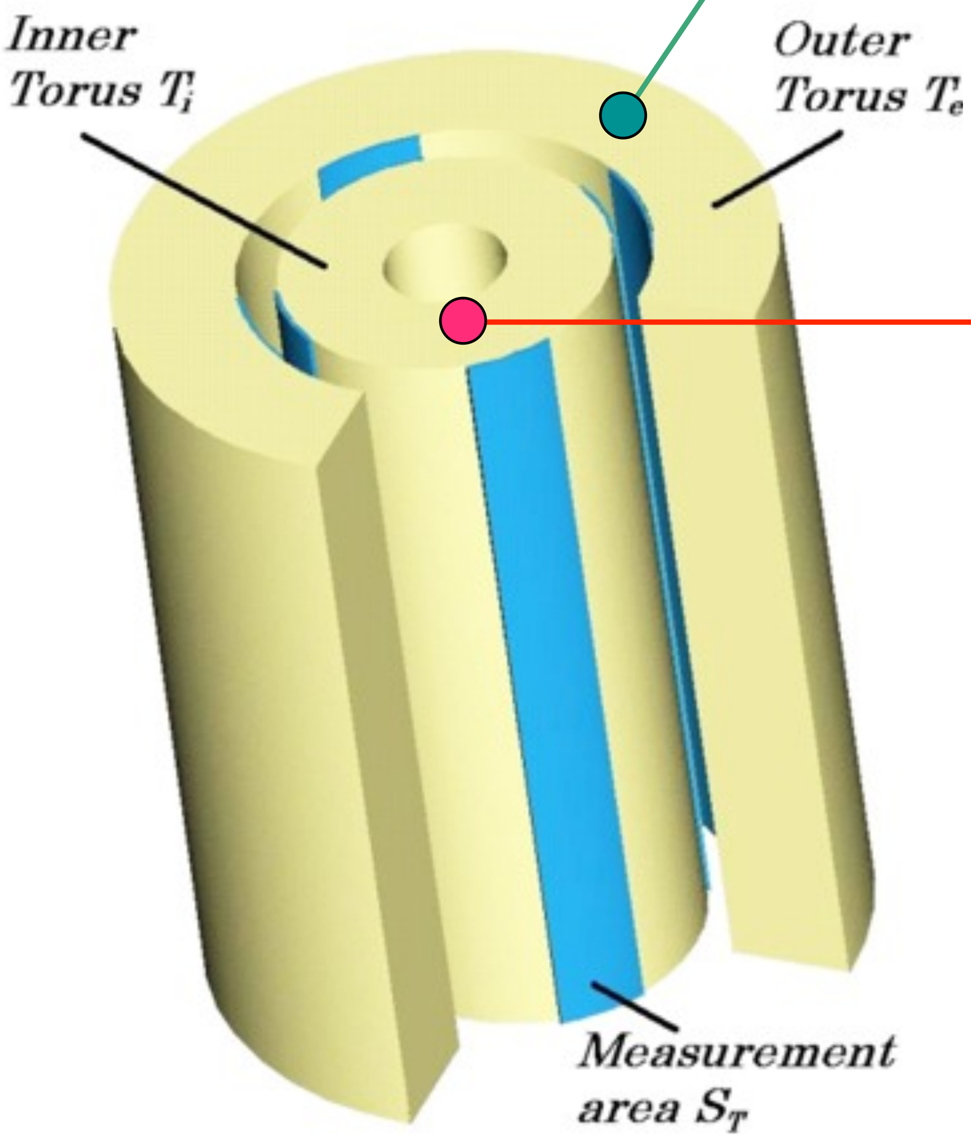


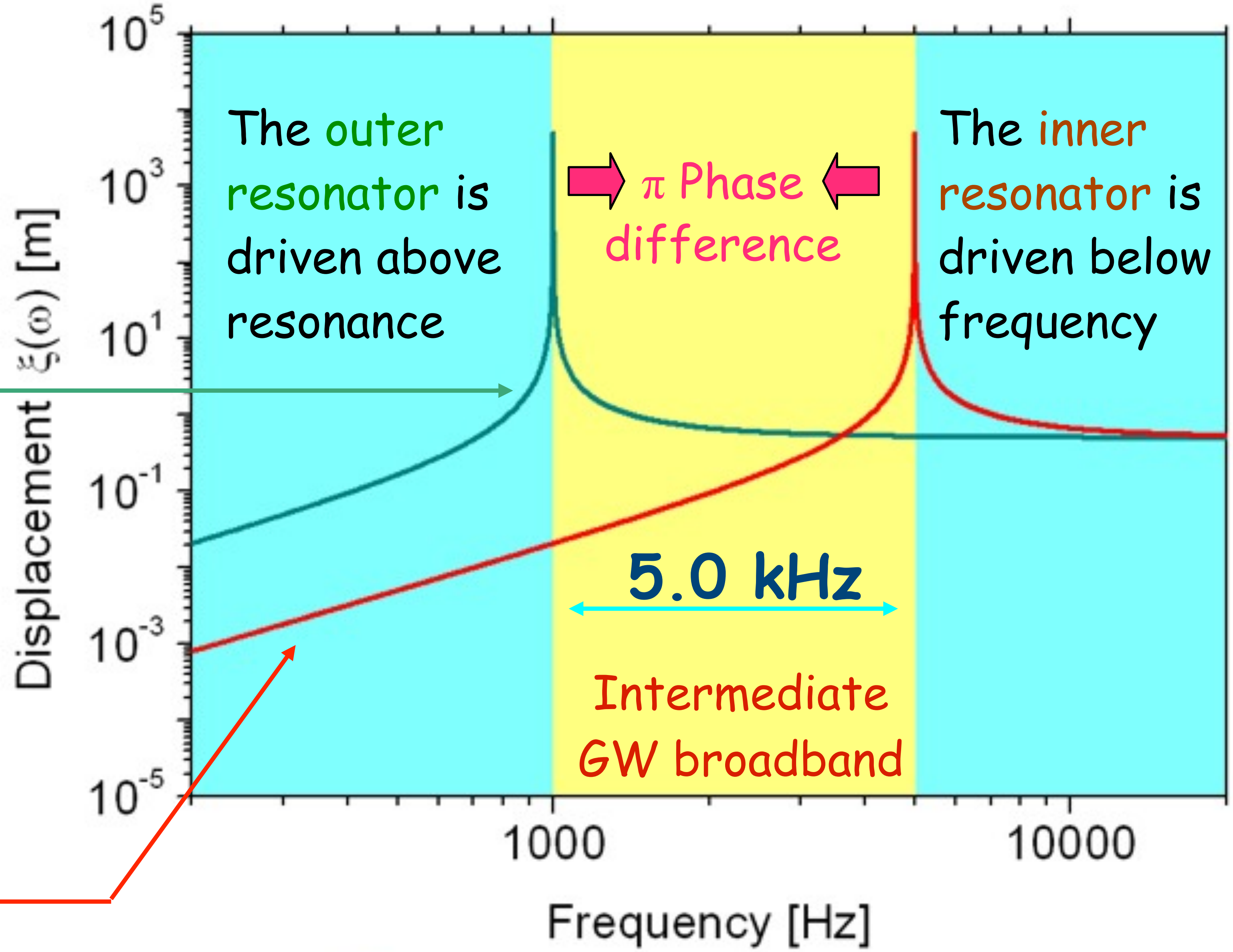
7.3 metri

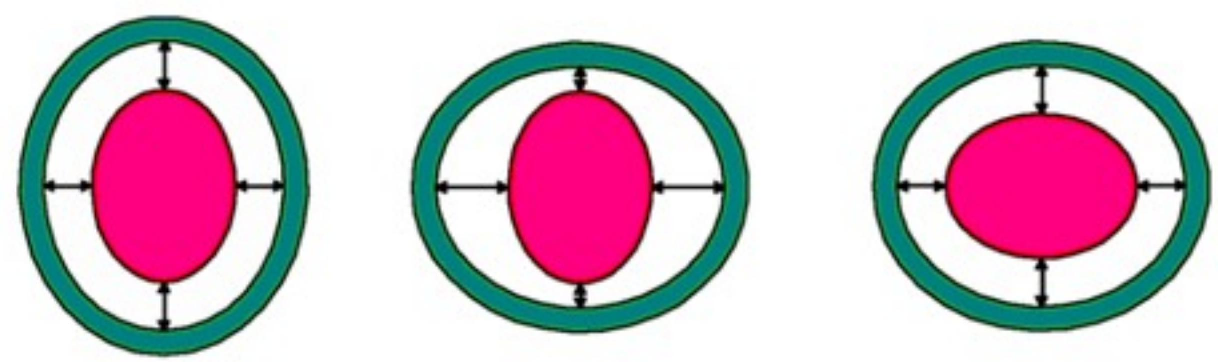


Dual: Main Concept

Measurement of differential deformations of two nested resonators





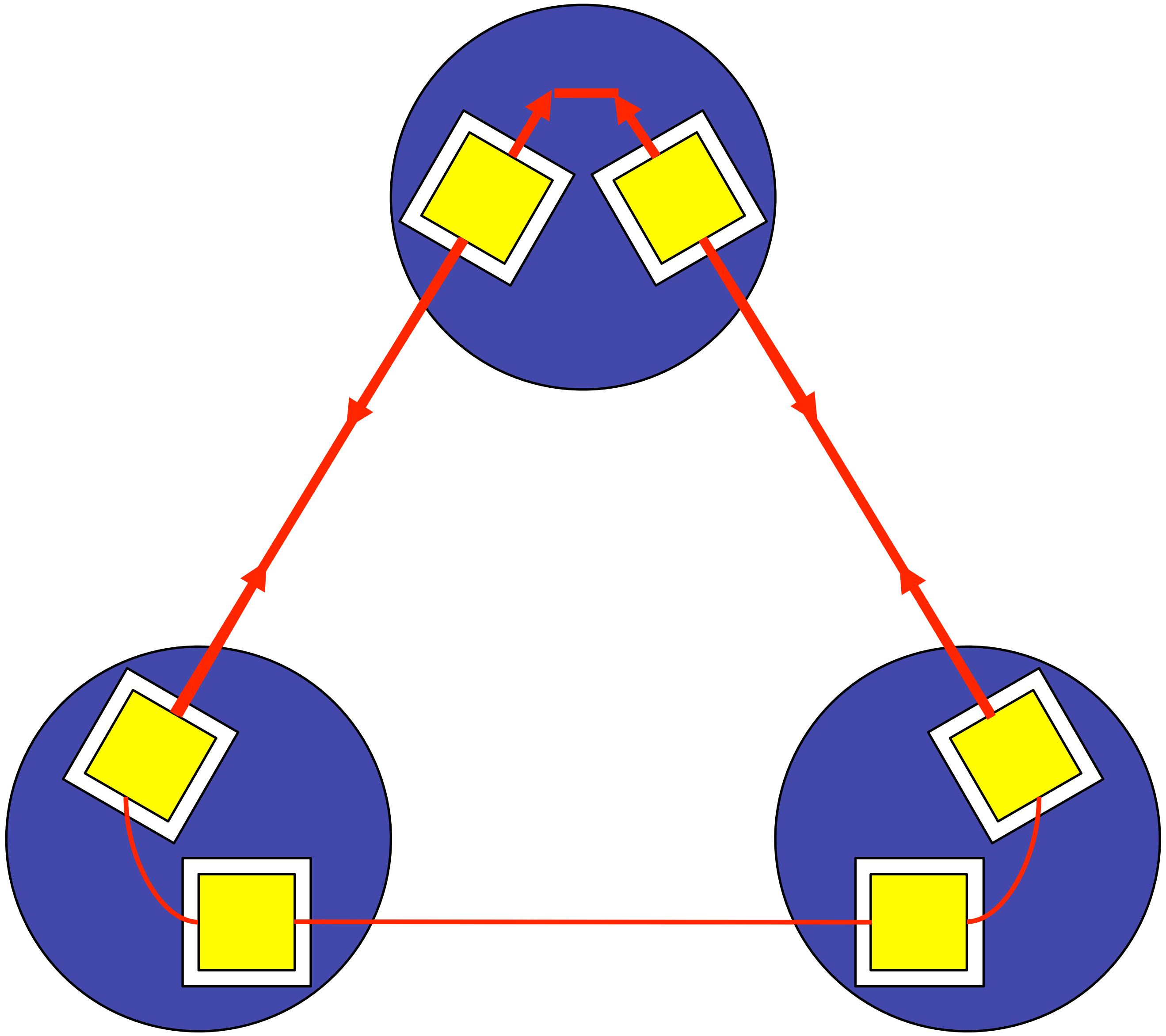


Two detectors studied
Molibdenum 16.4 tons
SiC(ceramic) 62.2 tons

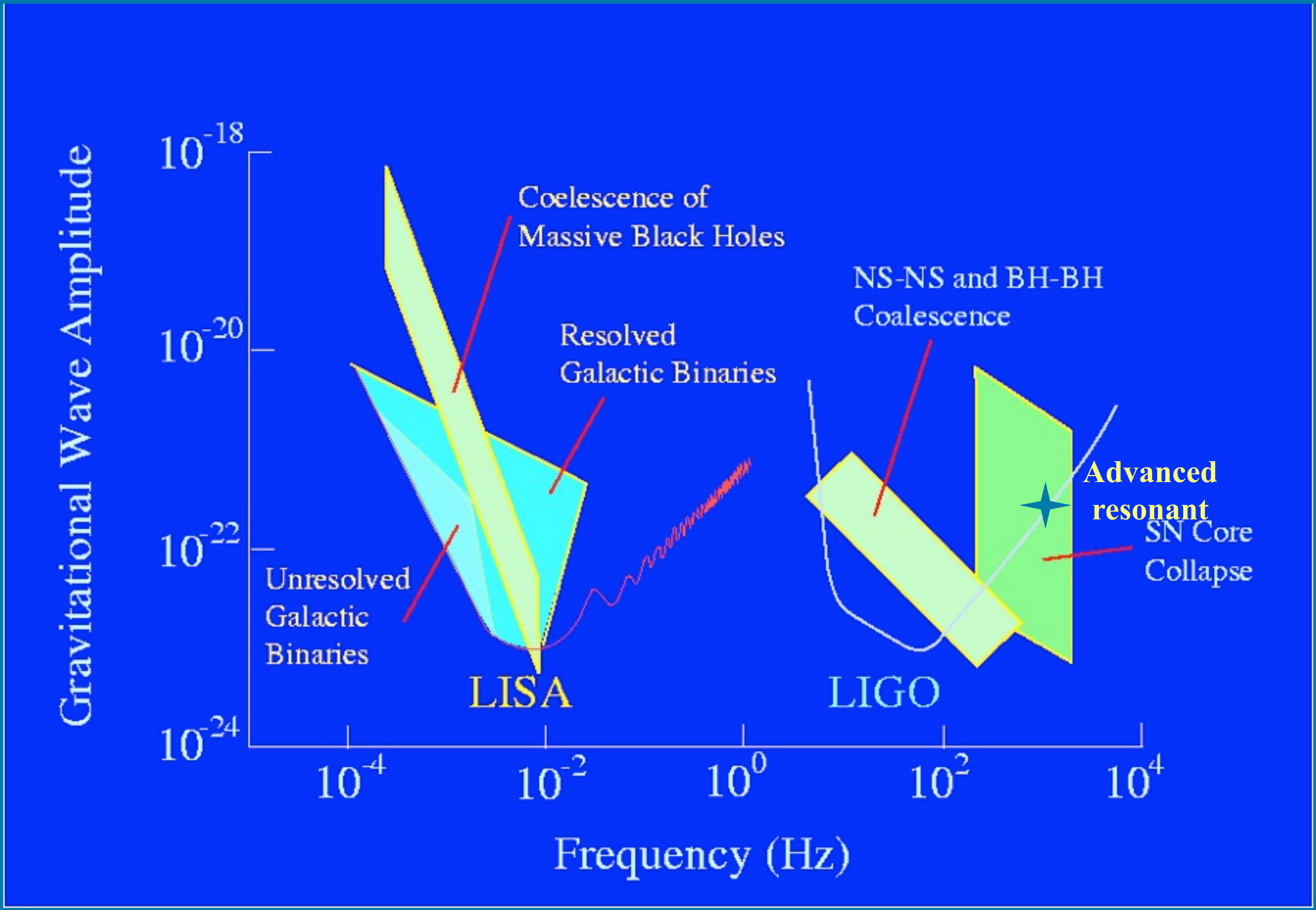
Phys Rev D 68 102004

LISA

- Each S/C carries 2 lasers,
  2 telescopes, 2 test masses
- Local lasers phase-locked
- Lasers on distant S/C phase-locked to incoming light



Complementare agli Esperimenti Terrestri



Bar as cosmic ray and particle detector

VOLUME 61, NUMBER 3 PHYSICAL REVIEW LETTERS 18 JULY 1988

Nuclearite Flux Limit from Gravitational-Wave Detectors

G. Liu and B. Barish
California Institute of Technology, Pasadena, California 91125
(Received 7 March 1988)

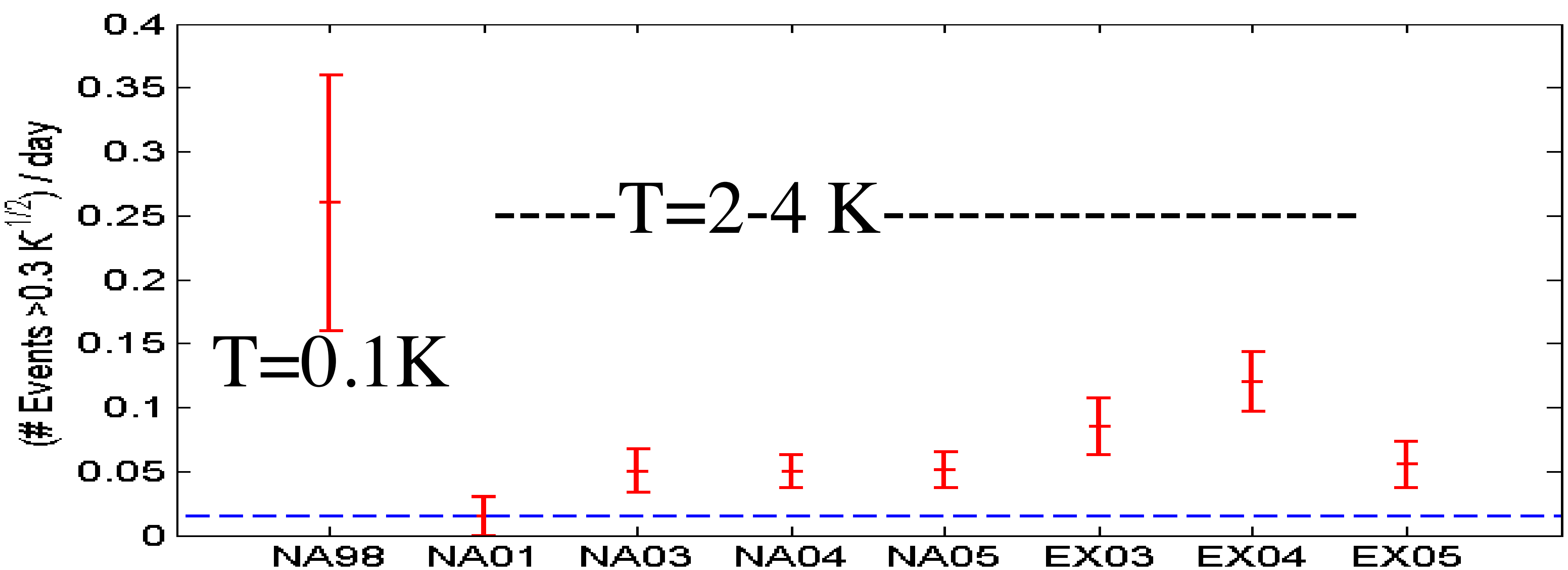
It is shown that present-day resonant-bar gravitational-wave detectors are sensitive to nuclearites of strange matter. The published data from a short test run of the Stanford gravitational-wave detector are used to obtain a flux limit for nuclearites.

PACS numbers: 14.80.Pb, 04.80.+z, 29.70.−e, 96.40.Jj

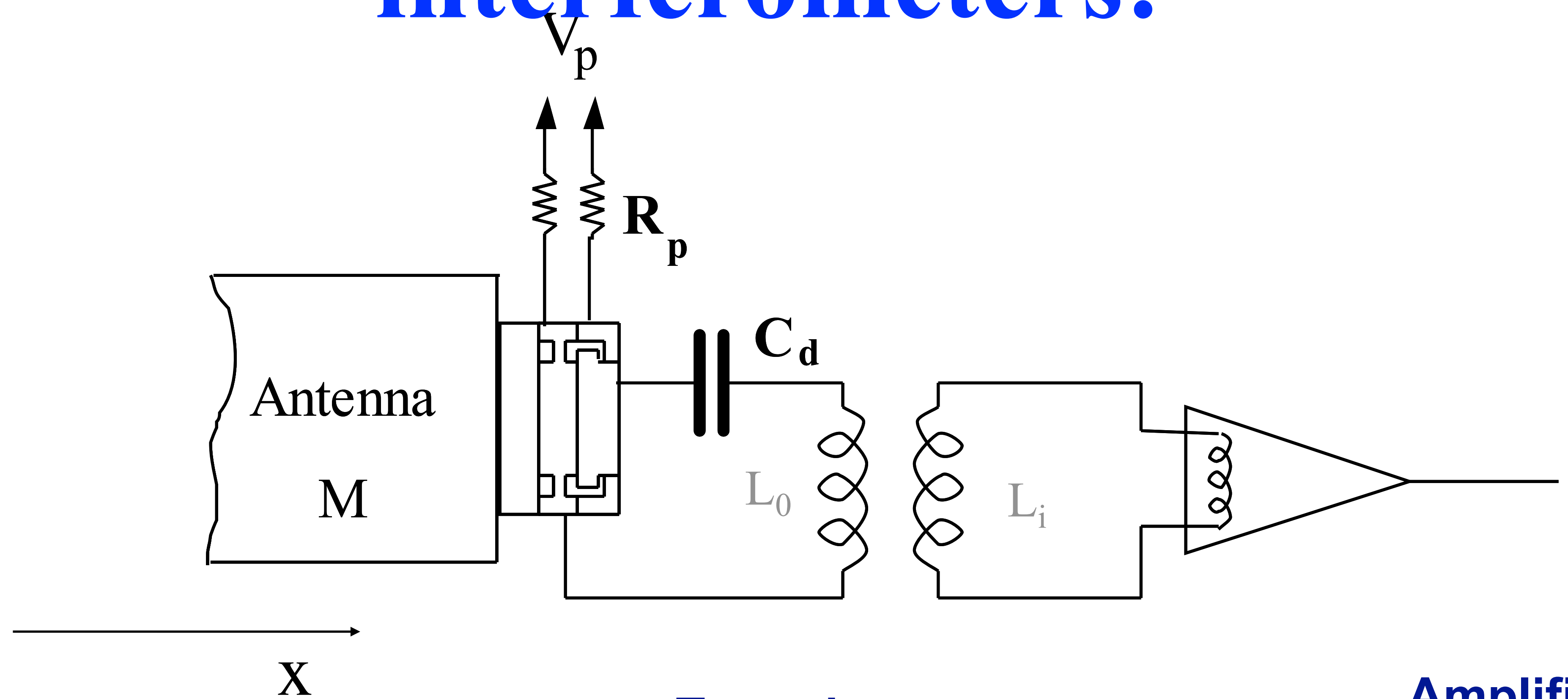
It has been pointed out that,[1,2] when the noise temperature of resonant-bar gravitational-wave detectors are reduced below 10^{-5} K, they will be sensitive to cosmic-ray magnetic monopoles. Recently, another possibility of slow-moving cosmic-ray particles, called "strange matter" or "nuclearites," has been proposed.[3-6] Such a particle consists of up, down, and strange quarks, may be absolutely stable, and may have a mass ranging from a few gigaelectronvolts to the mass of a neutron star. Nuclearites are an attractive candidate for the dark matter, since they depend only on certain effects of QCD, which, unlike the theories of many other candidates, is firmly supported by experiments. According to Eqs. (2) and (4) of Ref. 5, a nuclearite of mass m traversing aluminum with velocity βc has energy loss

Upper limit using Standord data

- first cosmic ray detection in NAUTILUS (1998) T=0.1 K, unexpected big signals, probably due to the superconductivity



To reach the standard quantum limit and to become comparable to the current interferometers:



Mechanical oscillator
Mass **M**
Temperature **T**
Quality factor **Q**
Resonant frequency $\mathbf{f_r}$

Transducer
Energy conversion coefficient β

Amplifier
noise temperature $\mathbf{T_n}$

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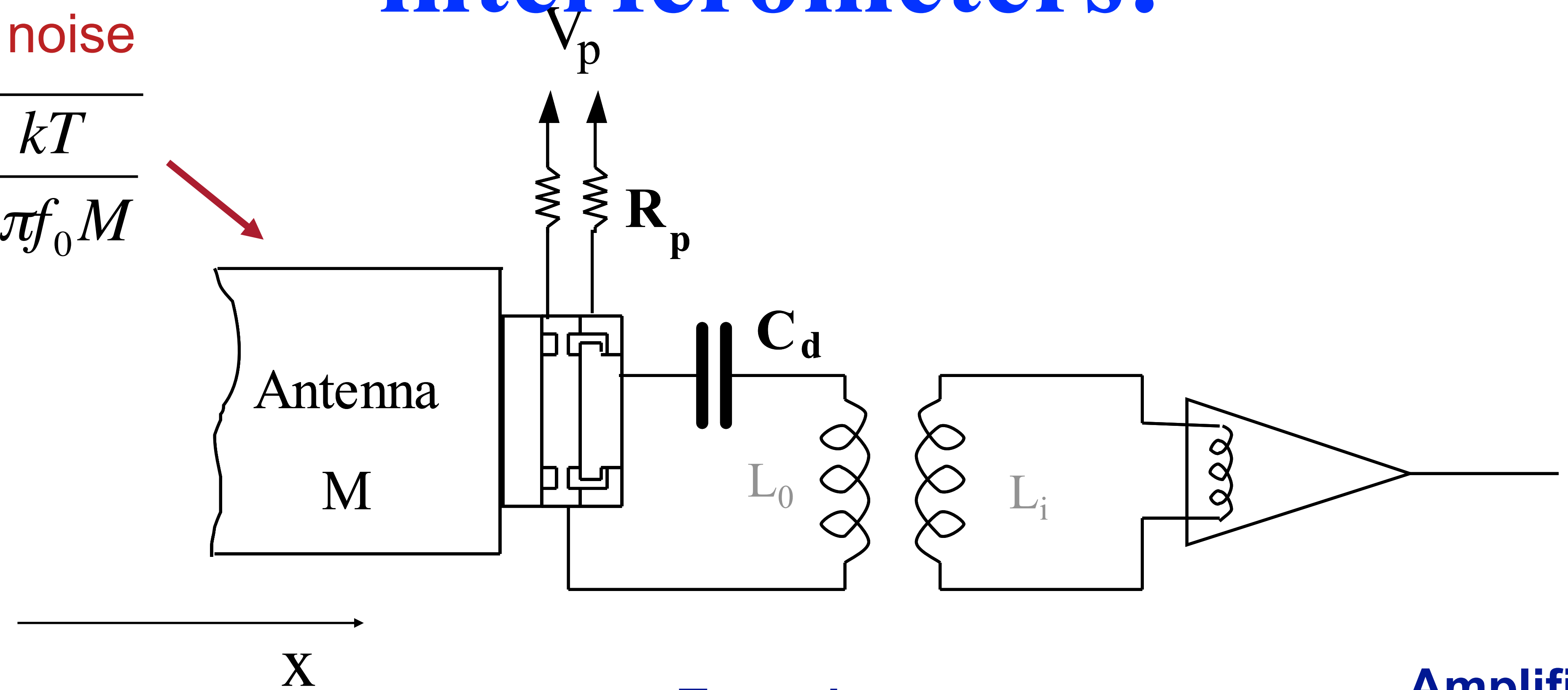
Thermal noise

$$\sigma_x = \sqrt{\frac{kT}{2\pi f_0 M}}$$



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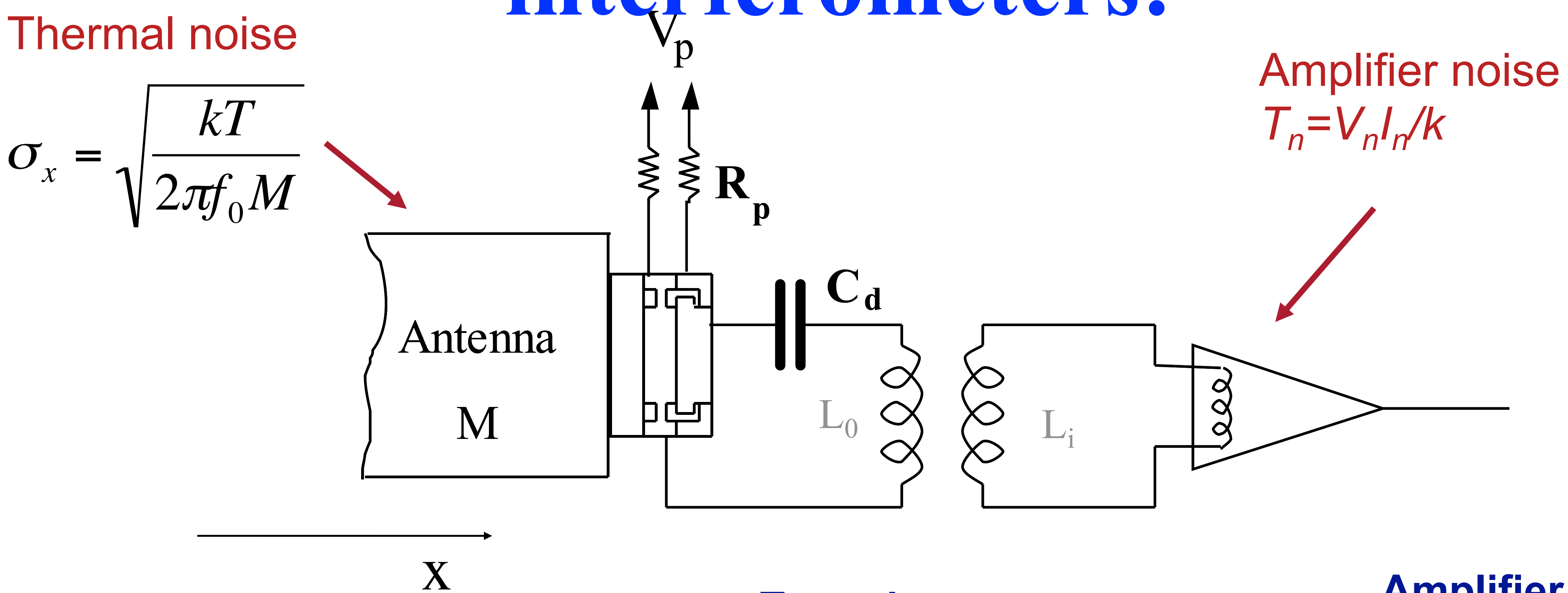

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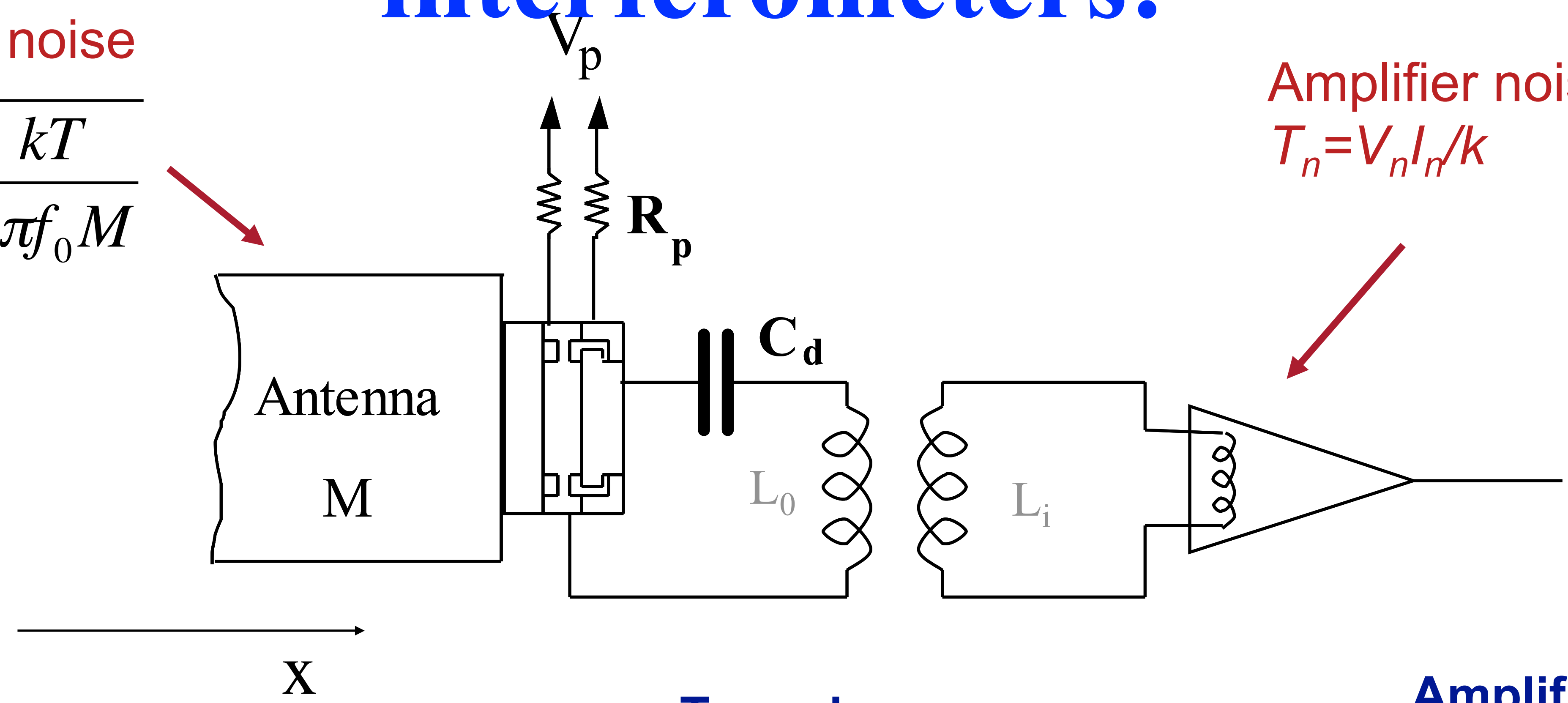

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Large Mass, Low T, High Q

technology ~ ok

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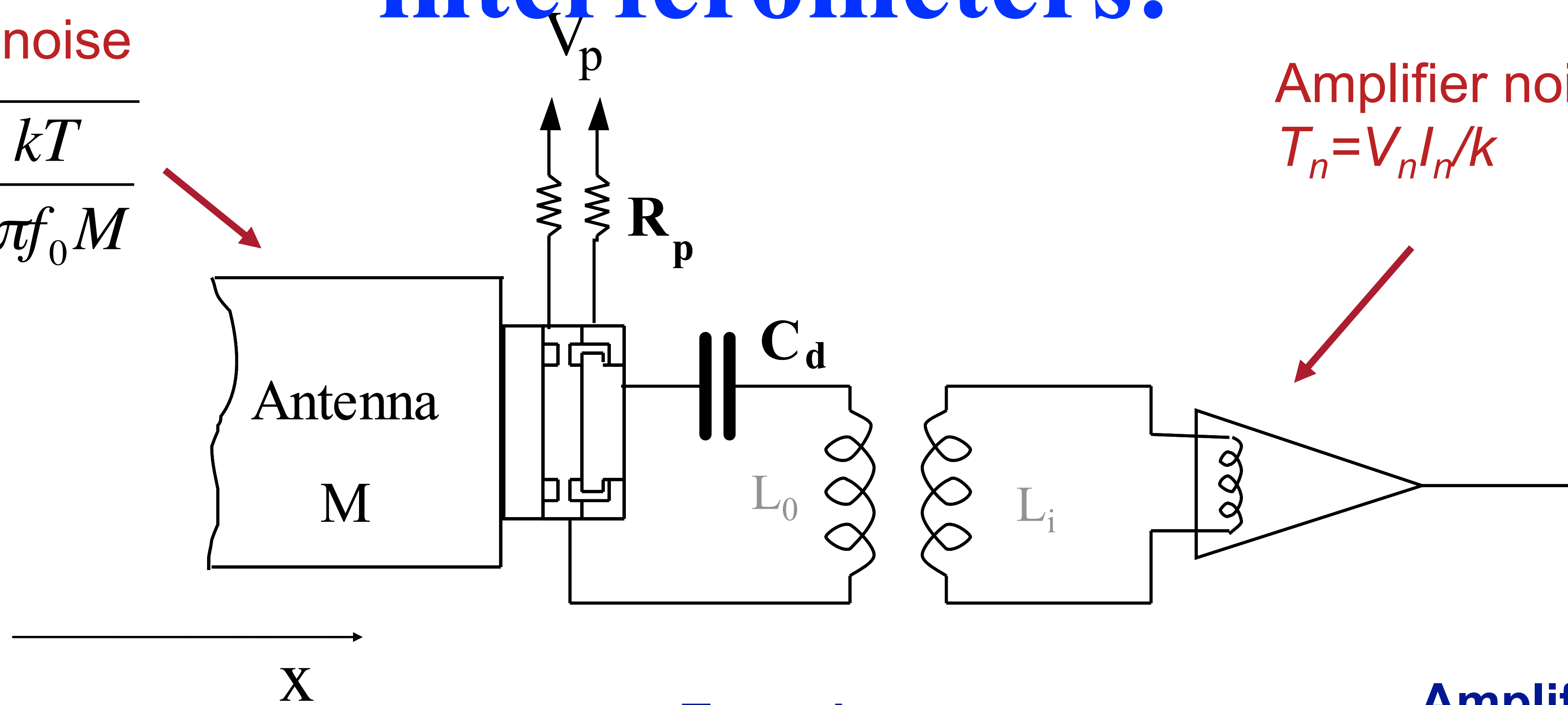

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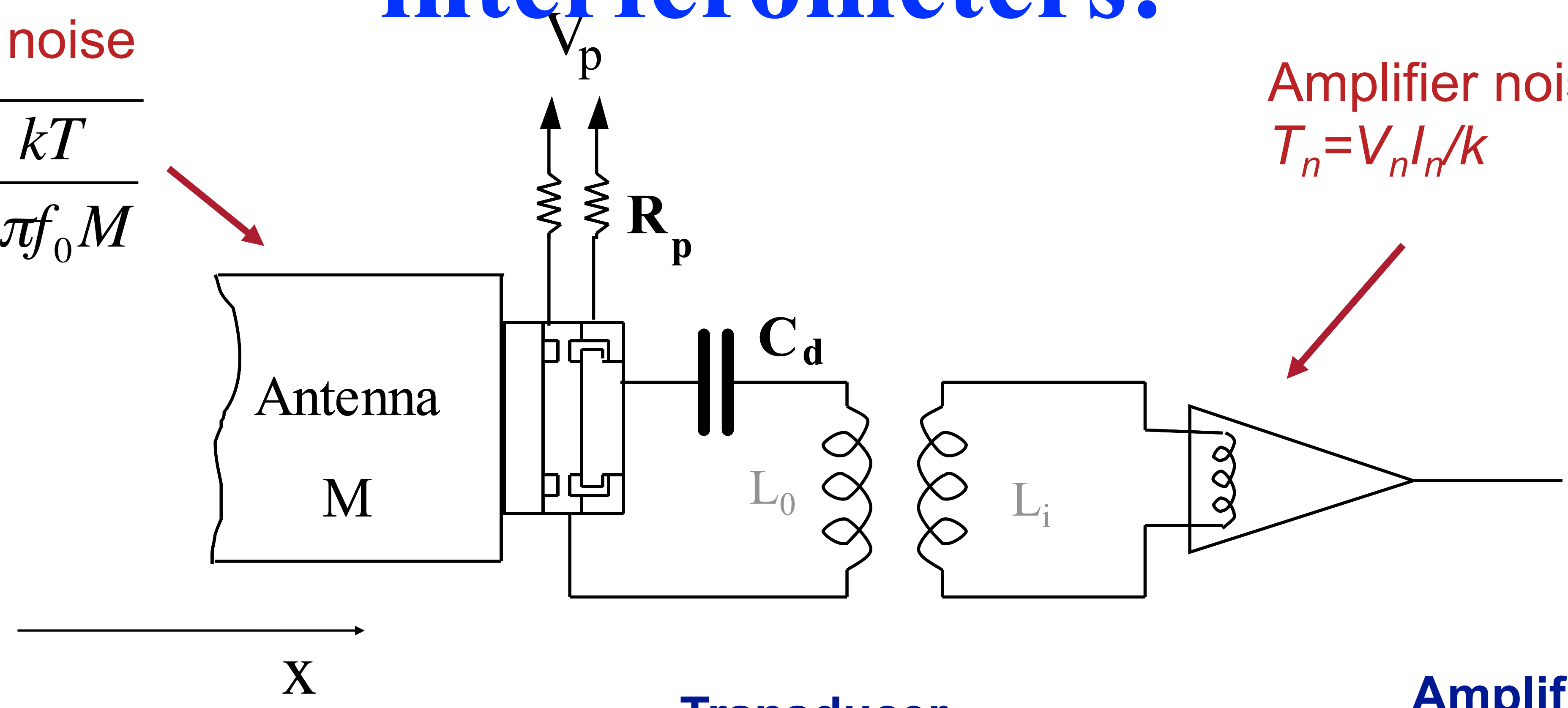

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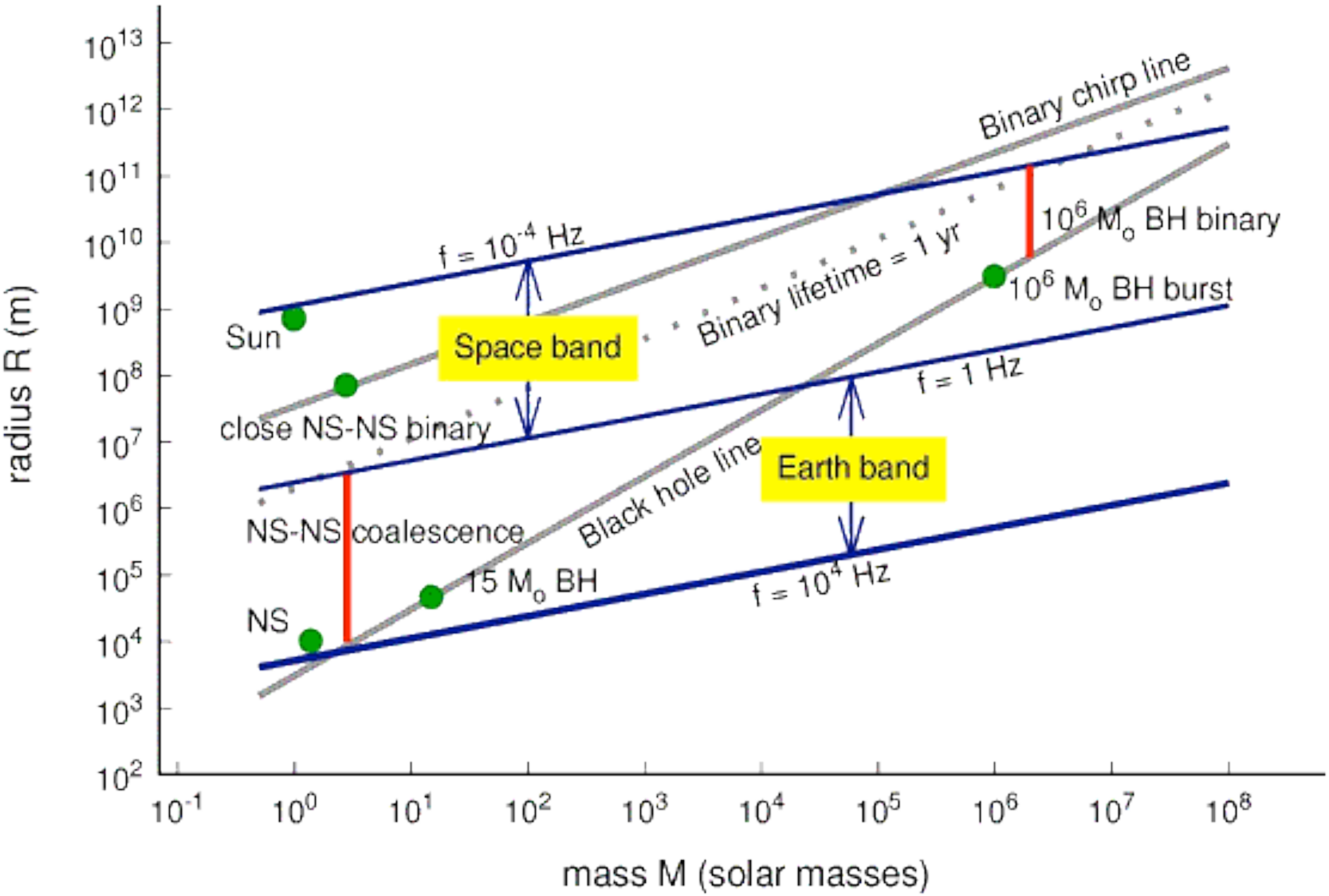
Squid: **technologic improvement**

Sources : Wide frequency range



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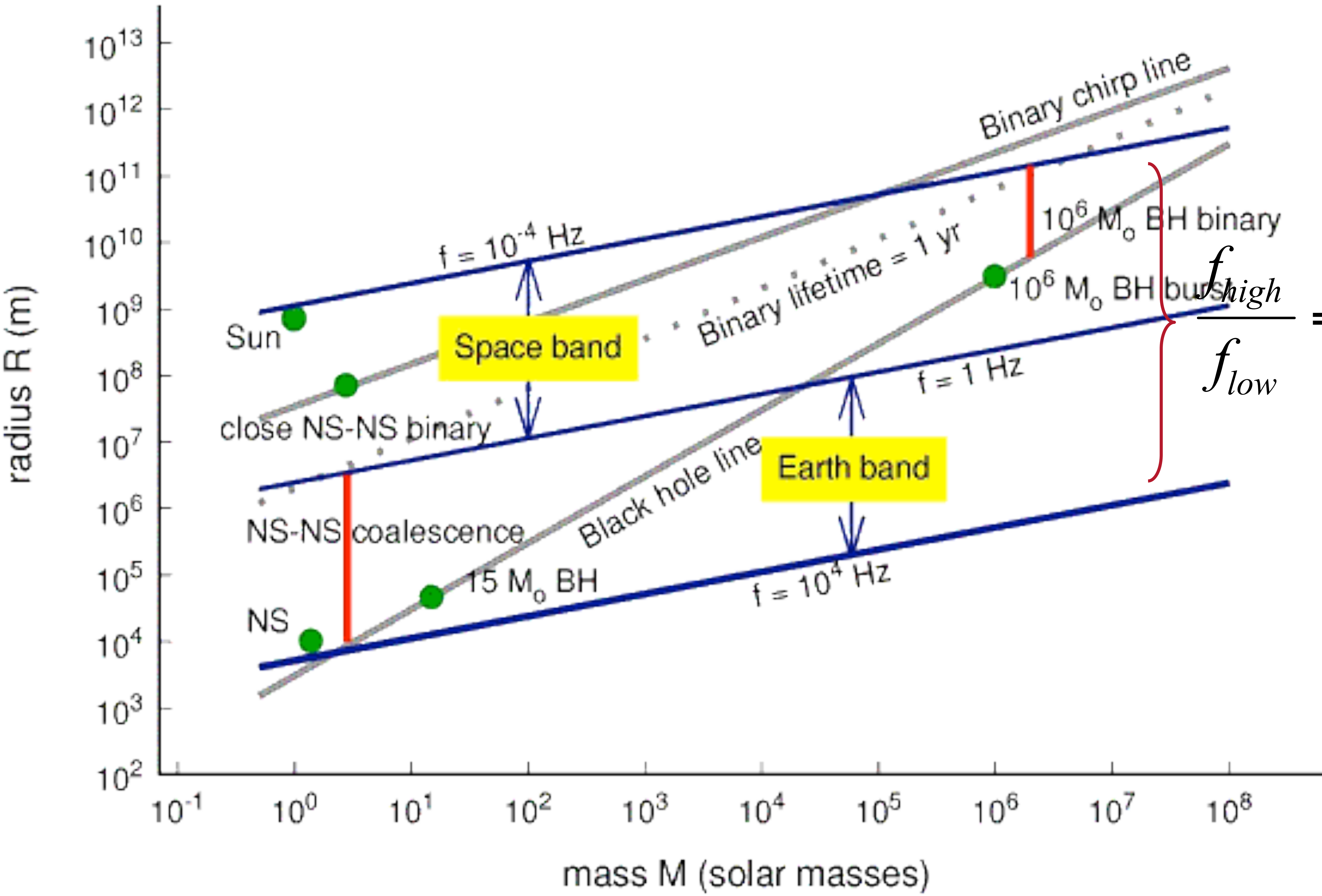

$$\frac{f_{high}}{f_{low}} = 10^8$$

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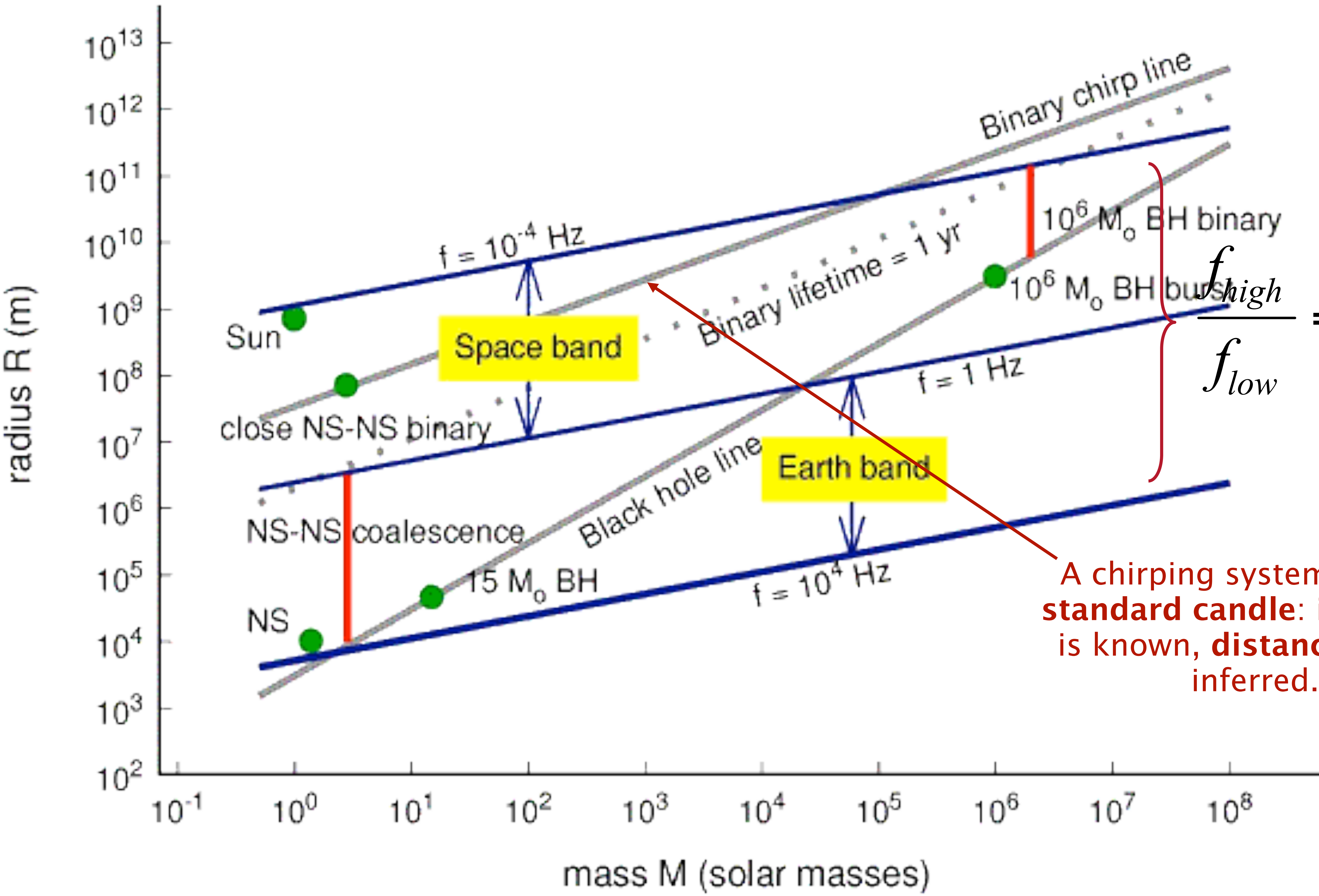

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A chirping system is a GW **standard candle**: if position is known, **distance** can be inferred.

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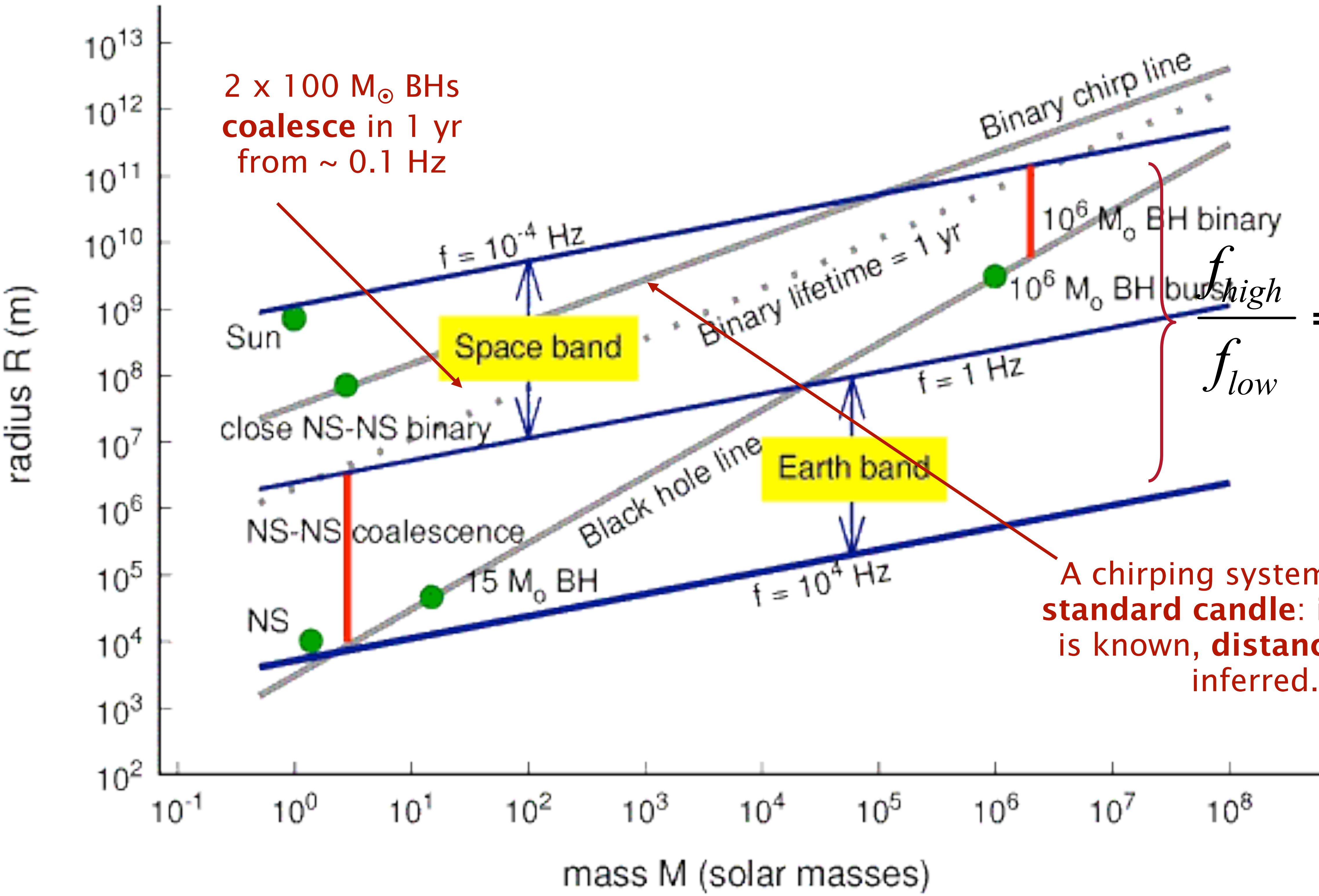

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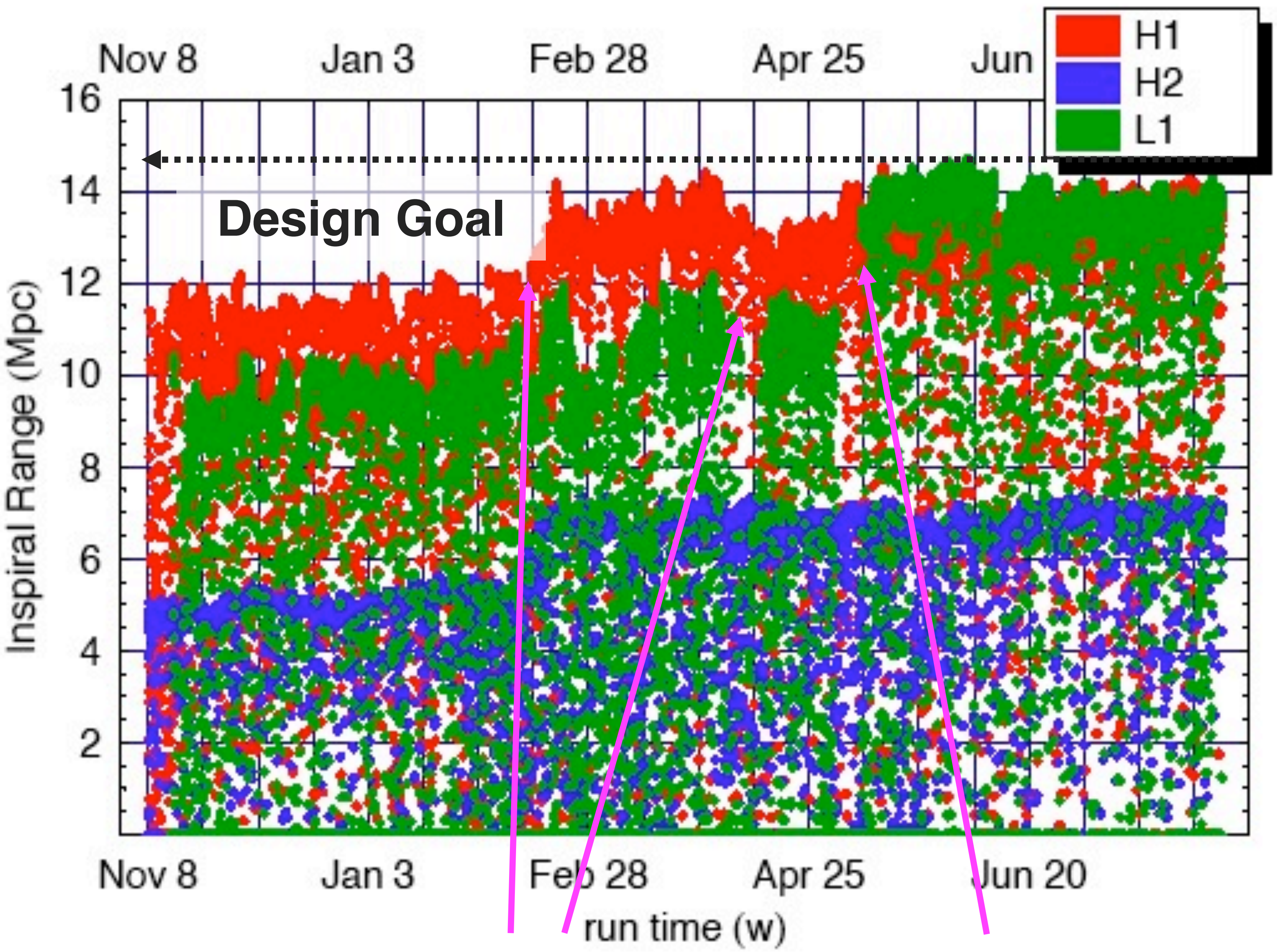
NS-NS Inspiral Range Improvement (LIGO)

Time progression since the start of S5



Commissioning breaks

Stuck ITMY optic at LLO

Histogram