Gravitational Wave Experiment on the Moon

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Jet Propulsion Laboratory
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Ground-based and space gravitational wave detectors

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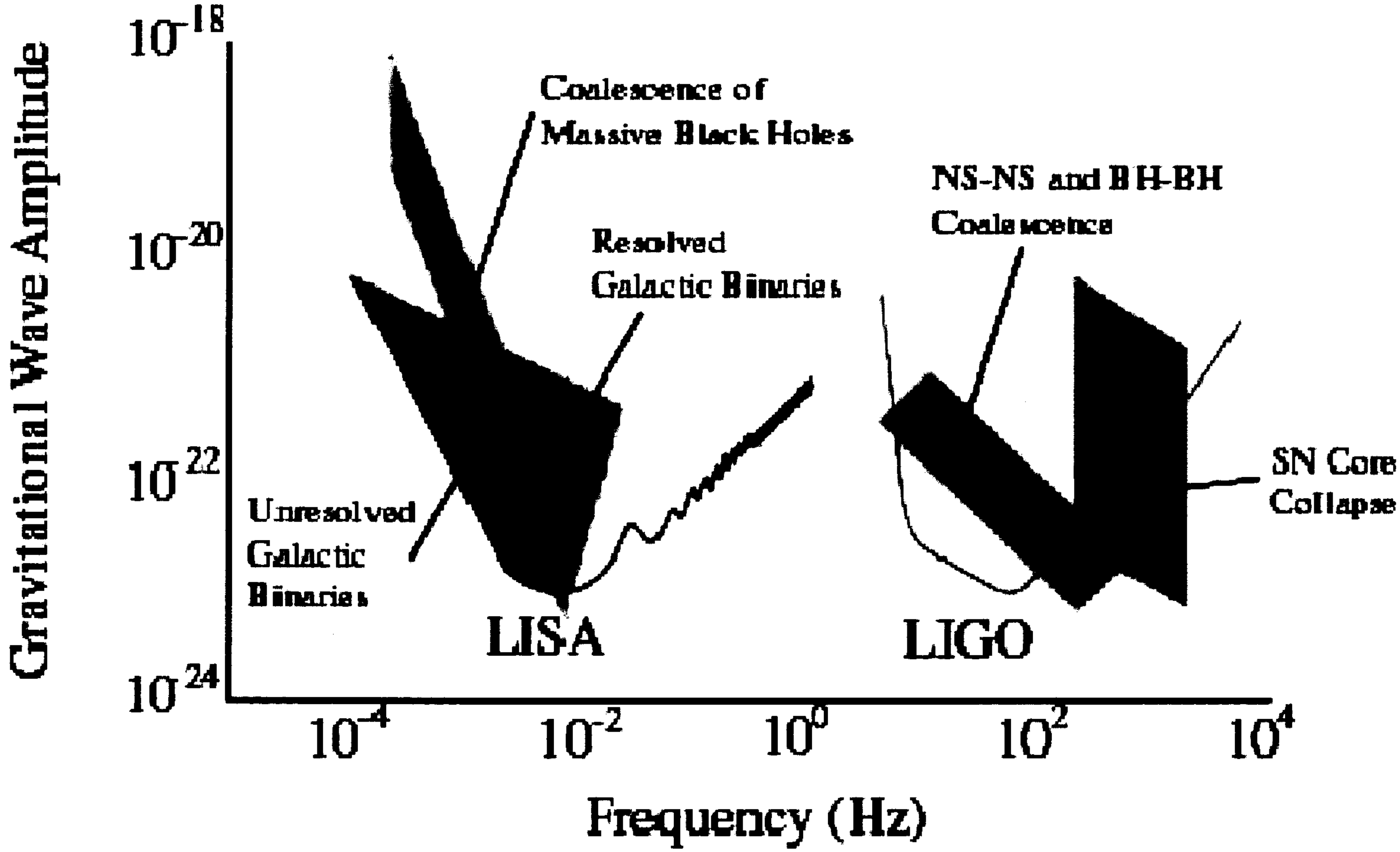
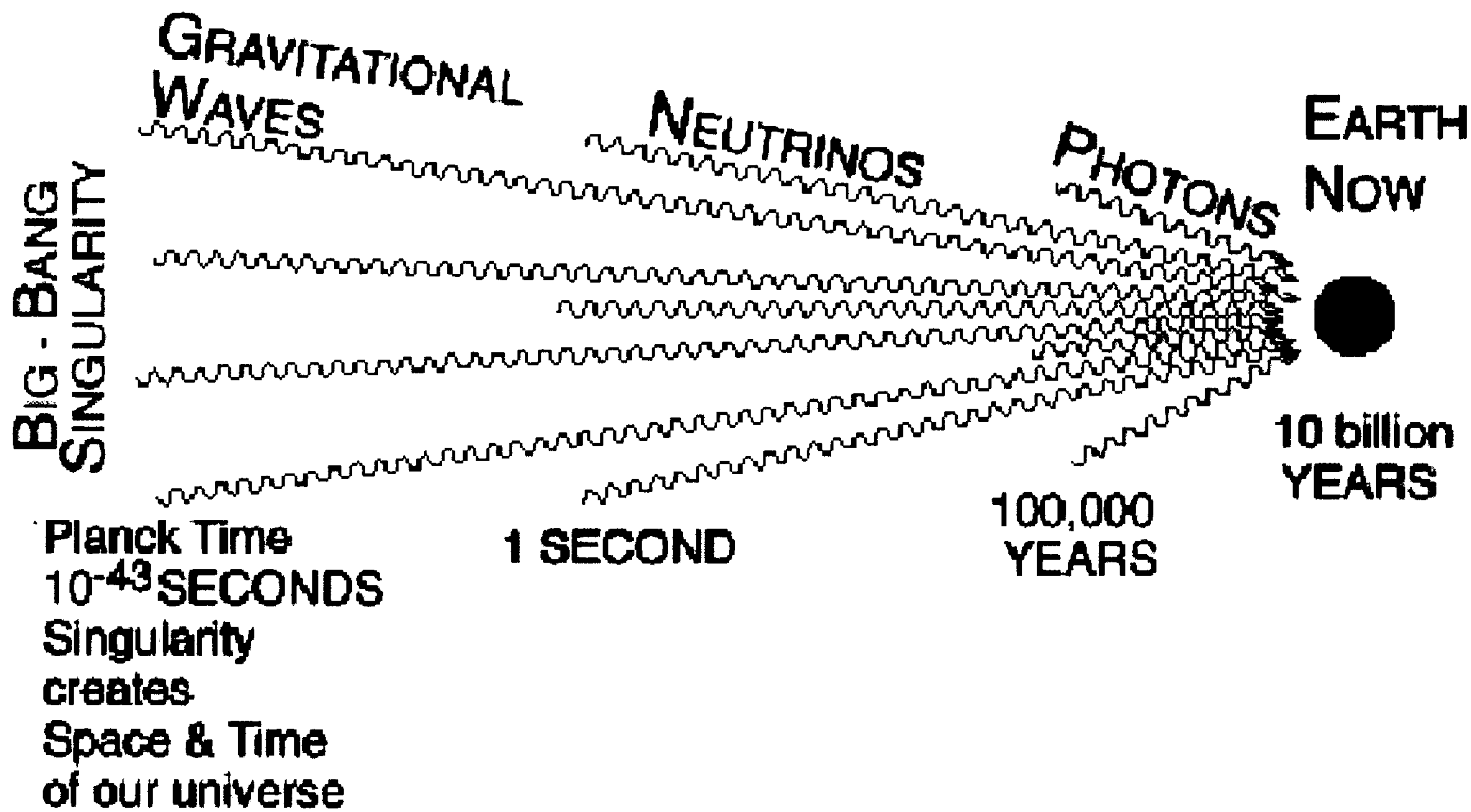


Stochastic backgrounds from the early universe



- GWs can probe the universe from 10^{-35} s after the Big Bang!

Foregound and background GW signals

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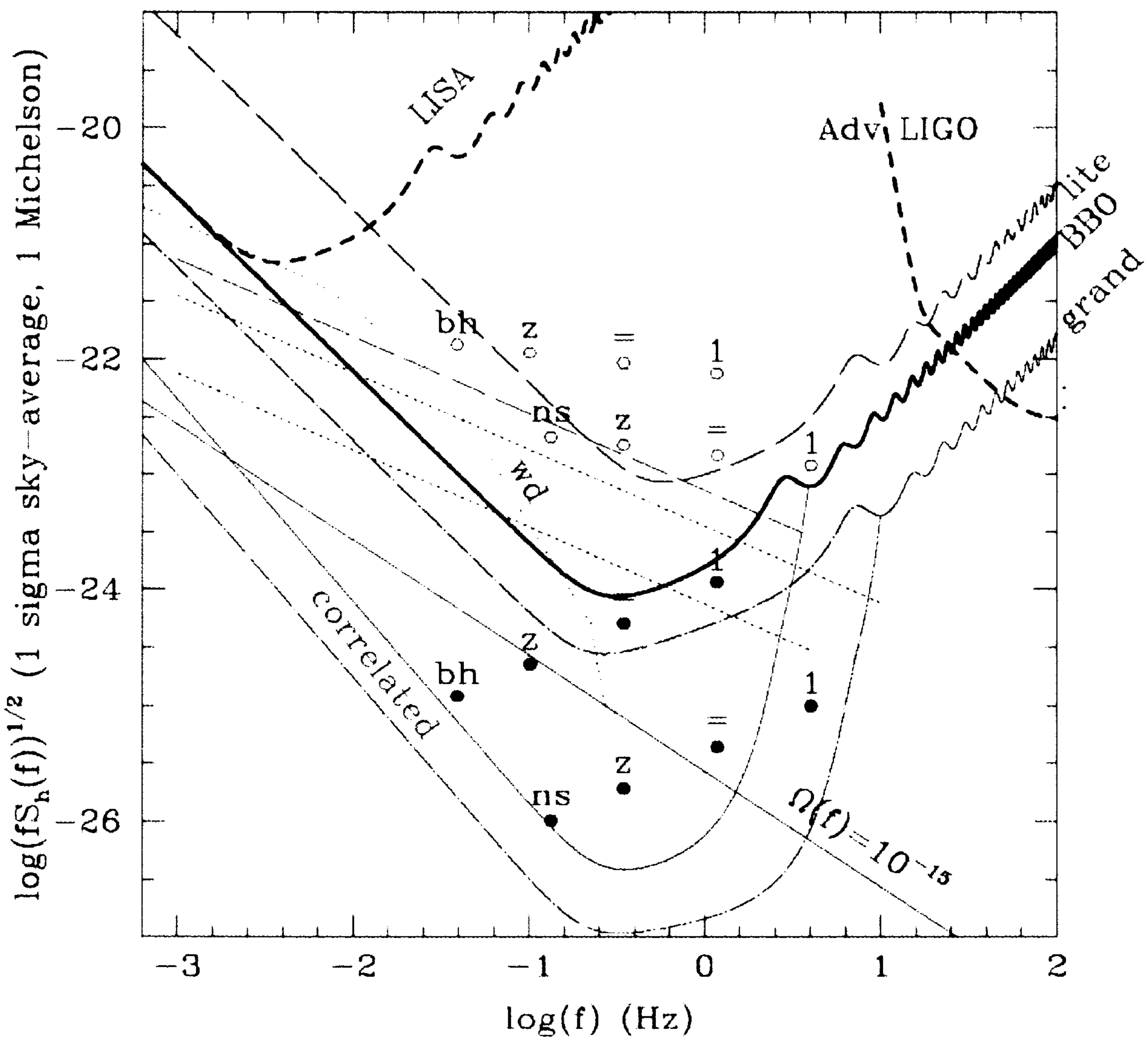

Big Bang Observer (BBO)

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- At < 0.1 Hz, the confusing foreground from astrophysical sources is hopelessly large. At > 10 Hz, the expected signal from inflation becomes too weak to detect.
- At 0.1-10 Hz, the primary source of foreground signals is neutron star binaries several months before coalescence, and these are few enough that they can be identified and removed.

  ⇒ Present concept of BBO: A constellation of four LISA-type interferometers at 1 AU with a baseline of 5×10^4 km.
- To reduce the risks, it may be desirable to begin with a less sensitive pathfinder mission to make the first exploration of the Universe in this gravitational wave frequency window.
- The astrophysical sources for this pathfinder mission include merging neutron star and stellar mass black hole binaries, mountains of ordinary pulsars, the seeds of black hole formation, etc.

Advantages of the Moon

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- Due to lack of plate tectonics, the Moon is extremely quiet seismically. The energy release per year is 10^8 times lower than the Earth.
  - ⇒ Moonquakes are driven mainly by tidal deformation (excluding impacts) and occur when the Moon is near the perigee.
  - ⇒ "Strong" quakes: $\sim 10^{-9}$ m $Hz^{-1/2}$ at 0.1-1 Hz, 0.5-1.3 on Richter!
  - ⇒ With the absence of ocean waves and winds, the seismic noise level between moonquakes may be extremely low.

    But how low?
- The Moon does not have atmosphere or water.
  - ⇒ Vacuum is cheap.
  - ⇒ The Moon is thermally quiet except at sunrise and sunset.
  - ⇒ A more stable thermal environment could be achieved by burying the instrument under the Moon dust.
  - ⇒ The Moon is gravitationally quiet.

Nature of the moonquakes

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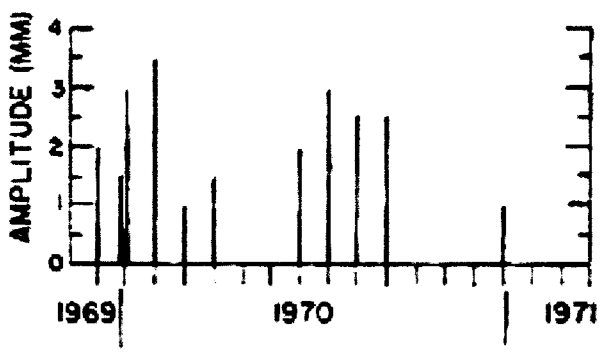
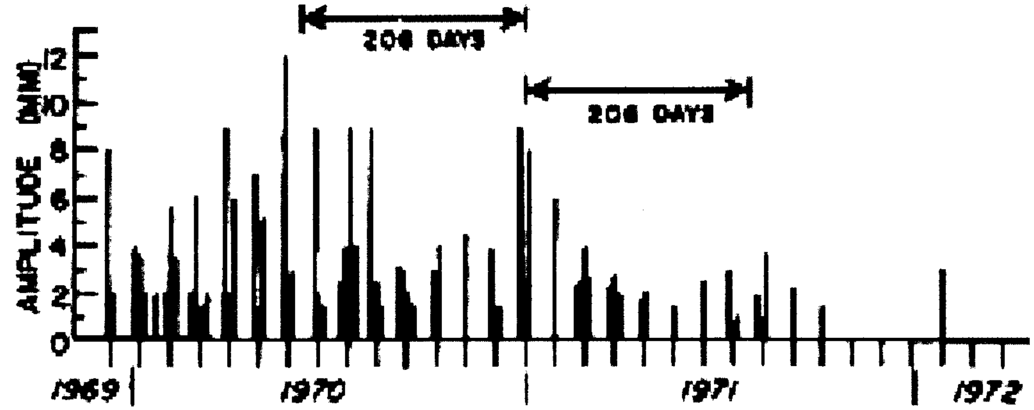
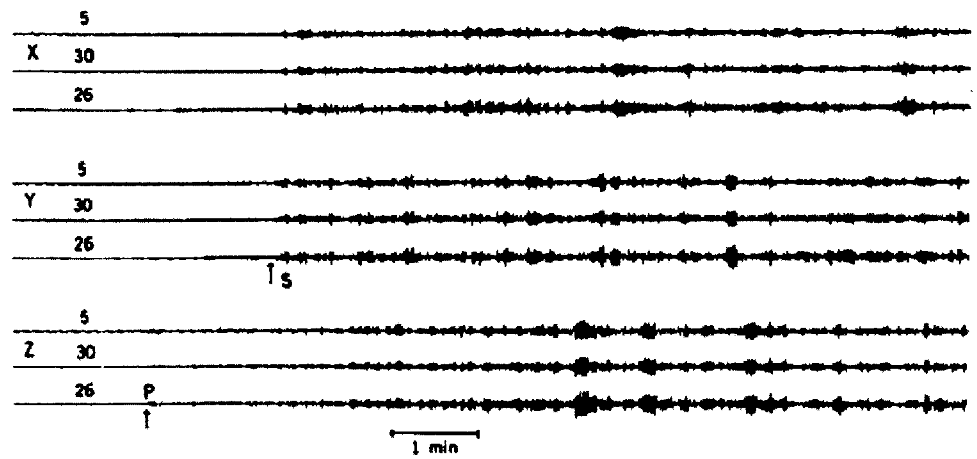
- "Strong" quakes occur within a few days from the perigee.





- Signals are reproducible within some 40 types and could therefore be identified and removed.
- It is crucial to detect the background seismic noise level of the Moon!



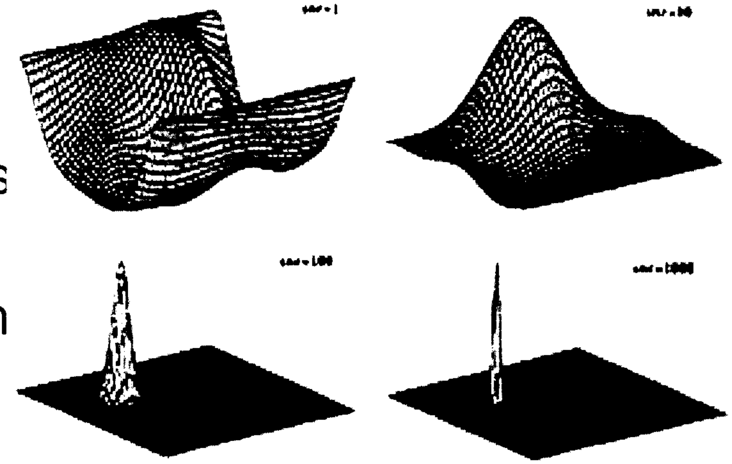
Detector options

- Laser interferometer with a baseline of 50~100 km
  - ⇒ Wideband detector at 0.1-100 Hz.
  - ⇒ In principle, light could be bent to extend the baseline further.
  - ⇒ Dust may be a problem and the instrument too complex.
- Sensitive superconducting displacement sensors detecting local displacements of the Moon. (Weber 1972)
  - ⇒ Wideband spherical detector detecting all the quadrupole modes between 0.001 and 10 Hz (LISA and BBO bandwidths).
  - ⇒ Wideband spherical detector with a baseline of 3500 km below 0.001 Hz (a new frequency window).
  - ⇒ Complementary to LIGO and LISA.
- Local displacement sensors should be easier to construct than a long-baseline laser interferometer and give a richer science.

Spherical antenna

- A sphere has a spherical symmetry and 5 degenerate quadrupole modes.
  - ⇒ Full-sky coverage with uniform cross section.
  - ⇒ **Can determine both** source direction (θ, ϕ) **and** wave polarization (h_+, $h_\times$).
  - ⇒ **Due to overdetermination,** non-GW disturbances can be vetoed.

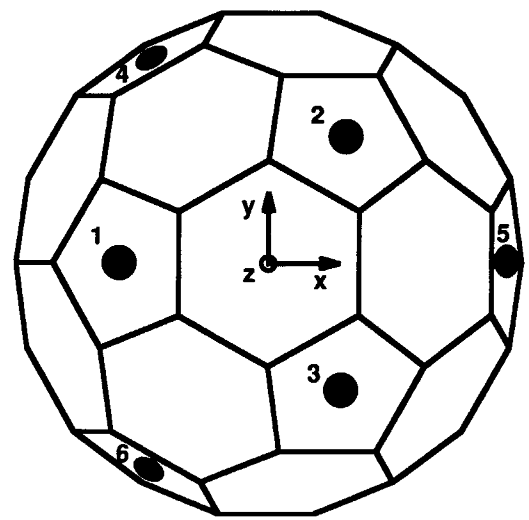
  (Wagoner & Paik, 1976)



(Zhou and Michelson, 1995)

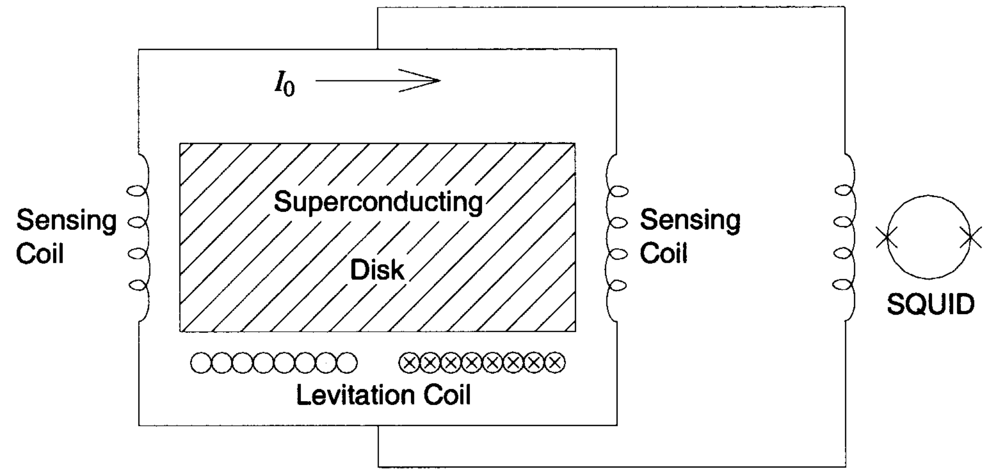
- **Mount 6** radial **transducers on** truncated icosahedral **configuration.**
  - ⇒ "Spherically symmetric" detection **of the sphere** (Johnson & Merkowitz, 1993)
  - ⇒ **Unfortunately,** $2R \leq 3$ m, $M \leq 30$ tons.

Did God cast the Moon for GW experiment?



Superconducting motion sensor

- A superconducting disk is levitated magnetically.
  - ⇒ Almost free horizontally.
- Horizontal displacement is sensed in two directions with a superconducting circuit.
- Intrinsic displacement noise:



$$S_x(f) = \frac{4}{m\omega^4}\left\{k_B T \frac{\omega_0}{Q} + E_A(f)\frac{1}{2\beta\eta\omega_0^2}\left[(\omega_0^2 - \omega^2)^2 + \left(\frac{\omega_0\omega}{Q}\right)^2\right]\right\}$$

- With $m = 10$ kg, $f_0 = 0.3$ Hz, $T = 2$ K, $Q = 10^6$, $2\beta\eta = 0.5$, $E_A(f) = 2 \times 10^{-31}$ J Hz^{-1} $(1 + 0.1\ \text{Hz}/f)$,

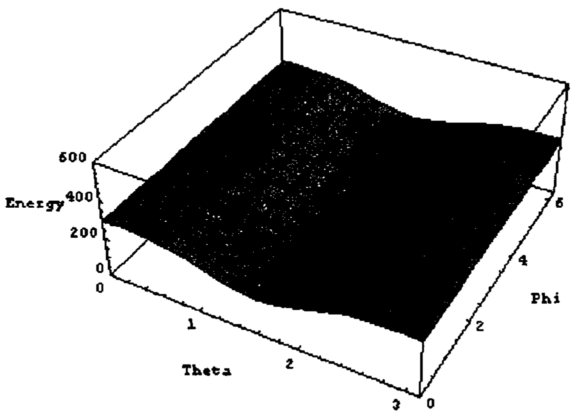
  $S_x^{1/2}(f) \approx 10^{-15}$ m $\text{Hz}^{-1/2}$, $f \geq 0.3$ Hz (10^5 better than lunar seismometers)

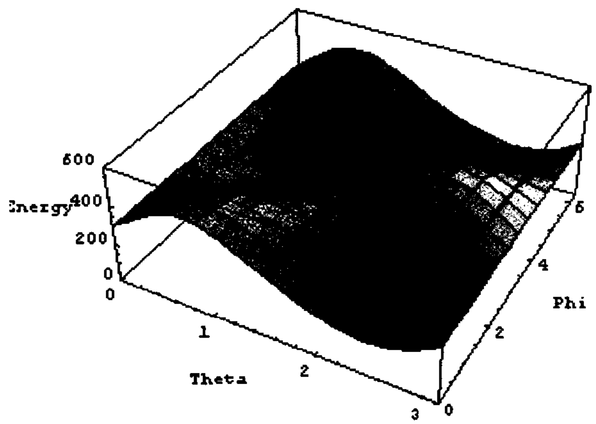
  ⇒ $S_h^{1/2}(f) \approx 2S_x^{1/2}(f)/R \approx 10^{-21}\ \text{Hz}^{-1/2}$ for $f \geq 0.3$ Hz

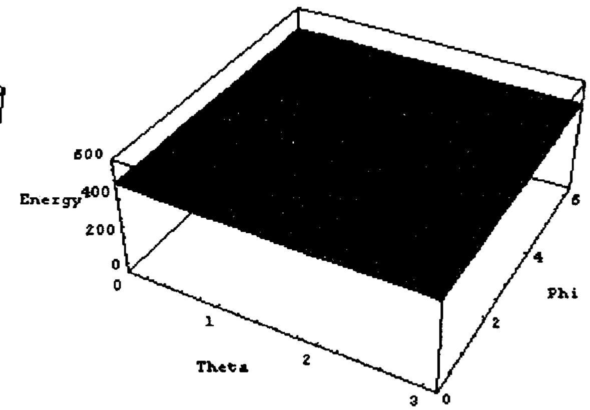
Resonant spherical detector

- Moon's quadrupole modes (0.001 to 10 Hz) are monitored.
- Directionality of various configurations:

<u>Triangle at great circle</u> <u>Tetrahedral configuration</u> <u>Icosahedral configuration</u>







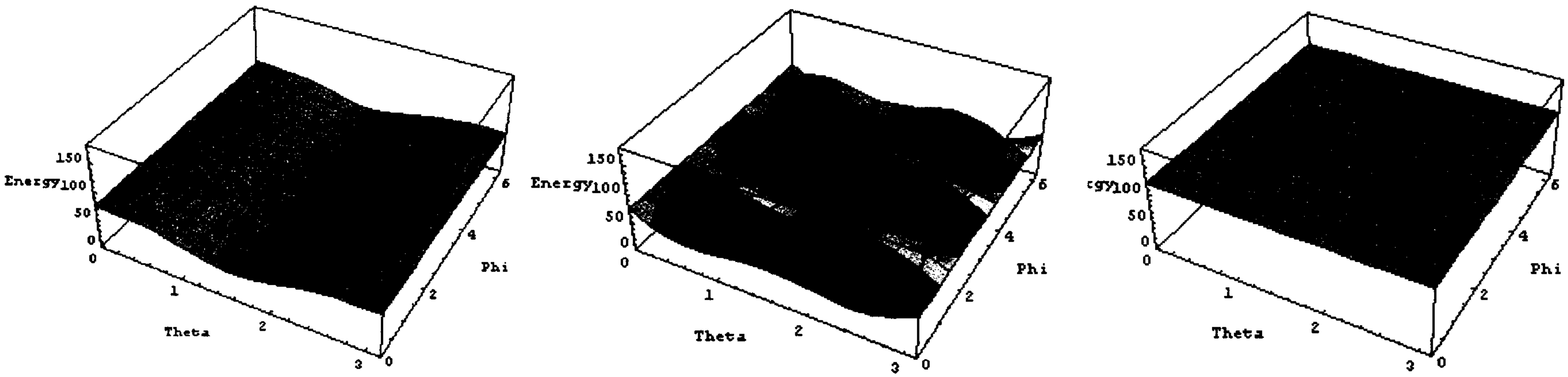
- 6 horizontal motion sensors in truncated icosahedral configuration
  - ⇒ Full-sky coverage with uniform cross section.
  - ⇒ Detection of the source direction and wave polarization.
  - ⇒ Discrimination against seismic and other disturbances.

  (Paik and Raj, 2004)

Wideband "spherical" detector

- Wideband detection against the rigid Moon (< 0.001 Hz).
- Directionality of various configurations:

Triangle at great circle — Tetrahedral configuration — Icosahedral configuration



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Response at high frequencies

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- The equation of motion can be written in the form:

$$(\ddot{x}-\ddot{\xi})+\tau_0^{-1}(\dot{x}-\dot{\xi})+\omega_0^2(x-\xi)=\frac{1}{2}\ddot{h}R-\ddot{\xi}.$$

- The driving terms cancel except at quadrupole modes of the Moon,
- At the quadrupole modes, $\boxed{\xi-\frac{1}{2}hR\approx i\frac{hc_s}{\omega_n}Q_n}$ (Chen and Thorne, 2004).

$\Rightarrow$

$$x-\xi=ihc_s\omega Q_n/(\omega_0^2-\omega^2+i\tau_0^{-1}\omega), \quad \text{at } \omega=\omega_n.$$

- The GW power spectral density becomes

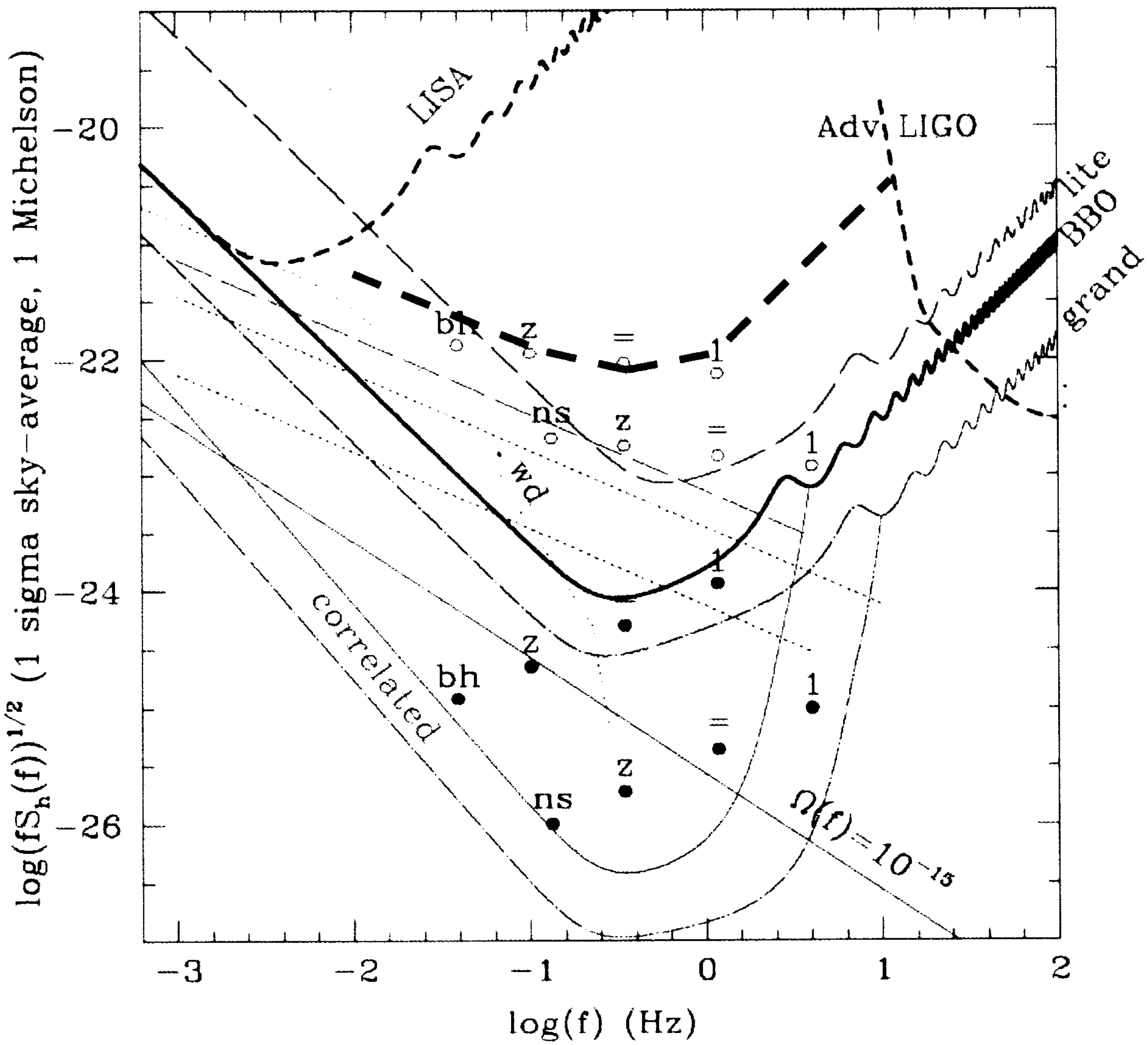
$$\boxed{S_h(f)=\frac{1}{(c_s\omega Q_n)^2}\frac{4}{m}\left\{k_BT\frac{\omega_0}{Q_0}+E_A(f)\frac{1}{2\beta\eta\omega_0^2}\left[(\omega_0^2-\omega^2)^2+\left(\frac{\omega}{\tau_0}\right)^2\right]\right\}.}$$

- With $c_s=8.0$ km/s, $Q_n=2000$, $S_h^{1/2}(f)=1.5\times10^{-22}\ \text{Hz}^{-1/2}$ at $f=f_0=0.3$ Hz.
- The displacement sensor is a wideband detector, detecting all the modes of the Moon.

Major error sources

- Seismic noise from moonquakes, thermal quakes ($f > 1$ Hz, diurnal), meteorite impacts, human activities, cryocooler vibration.
  - ⇒ Most likely the limiting error source.
  - ⇒ Identify and remove, or veto by using the tensor nature of GW.
  - ⇒ A low-vibration cryocooler is essential.
- Gravity noise from tidal deformation of the Moon and thermal expansion of the ground and apparatus.
  - ⇒ Extremely low frequency outside the signal bandwidth.
  - ⇒ Shield the sun or bury the instrument.
- Electrostatic force from charging of the test mass by cosmic rays and the patch effect.
  - ⇒ Extremely low frequency outside the signal bandwidth.
- Magnetic noise from the solar wind.
  - ⇒ Superconducting and mu-metal shield.

Sensitivity of lunar GW detector



Recommendations

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- Map out the seismic background of the Moon as soon as possible with very sensitive displacement sensors.
  - ⇒ Instrument: Three superconducting tunable motion sensors integrated with a turbo-Brayton cryocooler.
  - ⇒ Measurement: Three-axis measurement over 10^{-4} – 10^{2} Hz.
  - ⇒ Will help determine the interior structure, dynamics, and evolution of the Moon.
- If the Moon is indeed quiet enough, instrument the Moon with six horizontal displacement sensors in an icosahedral configuration.
  - ⇒ Sure detection of gravitational waves from many interesting sources in the frequency window between LIGO and LISA.
  - ⇒ A precurser mission to the BBO.
  - ⇒ Very sensitive search for strangelets.