Gravitational wave experiments on the Moon

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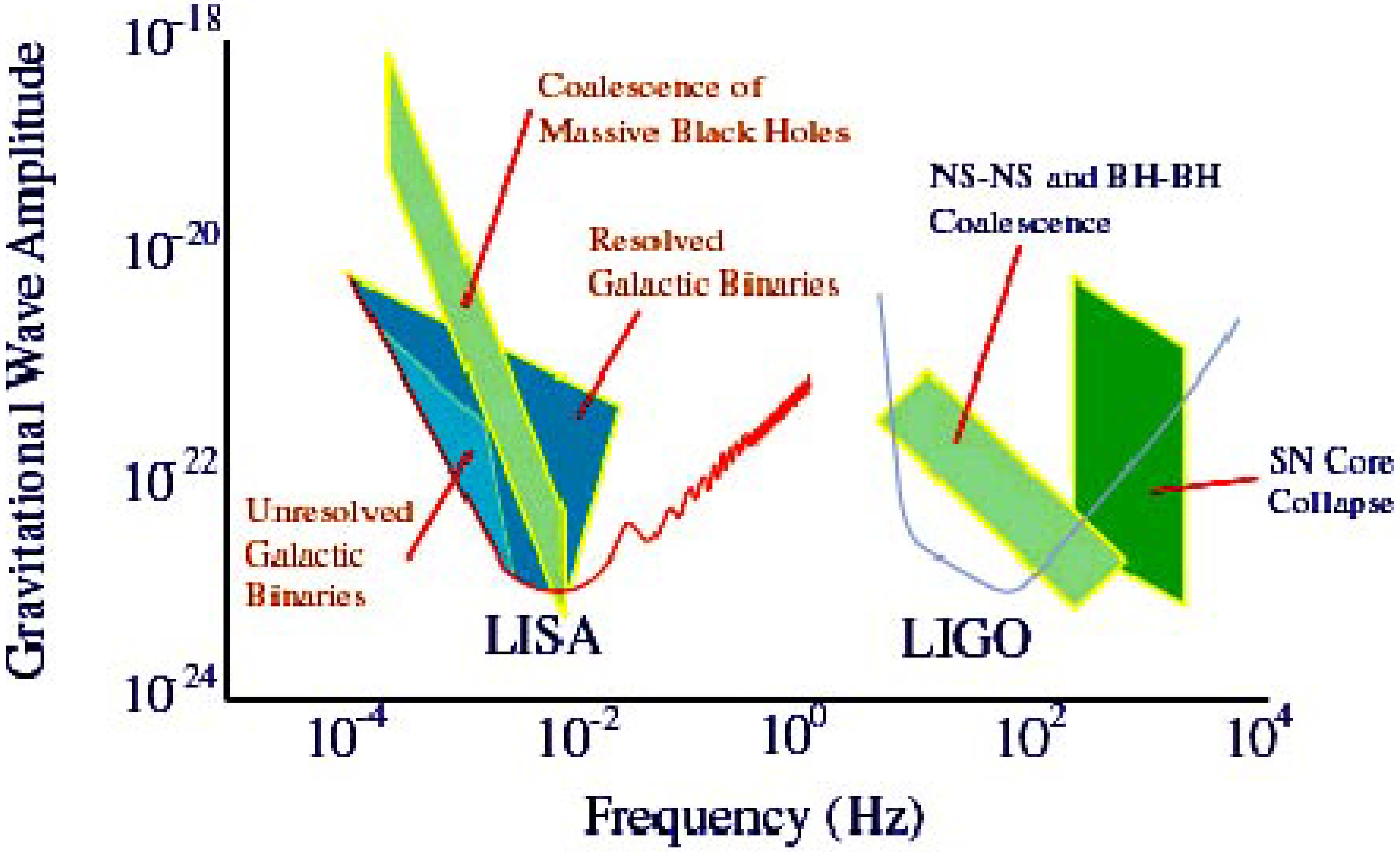
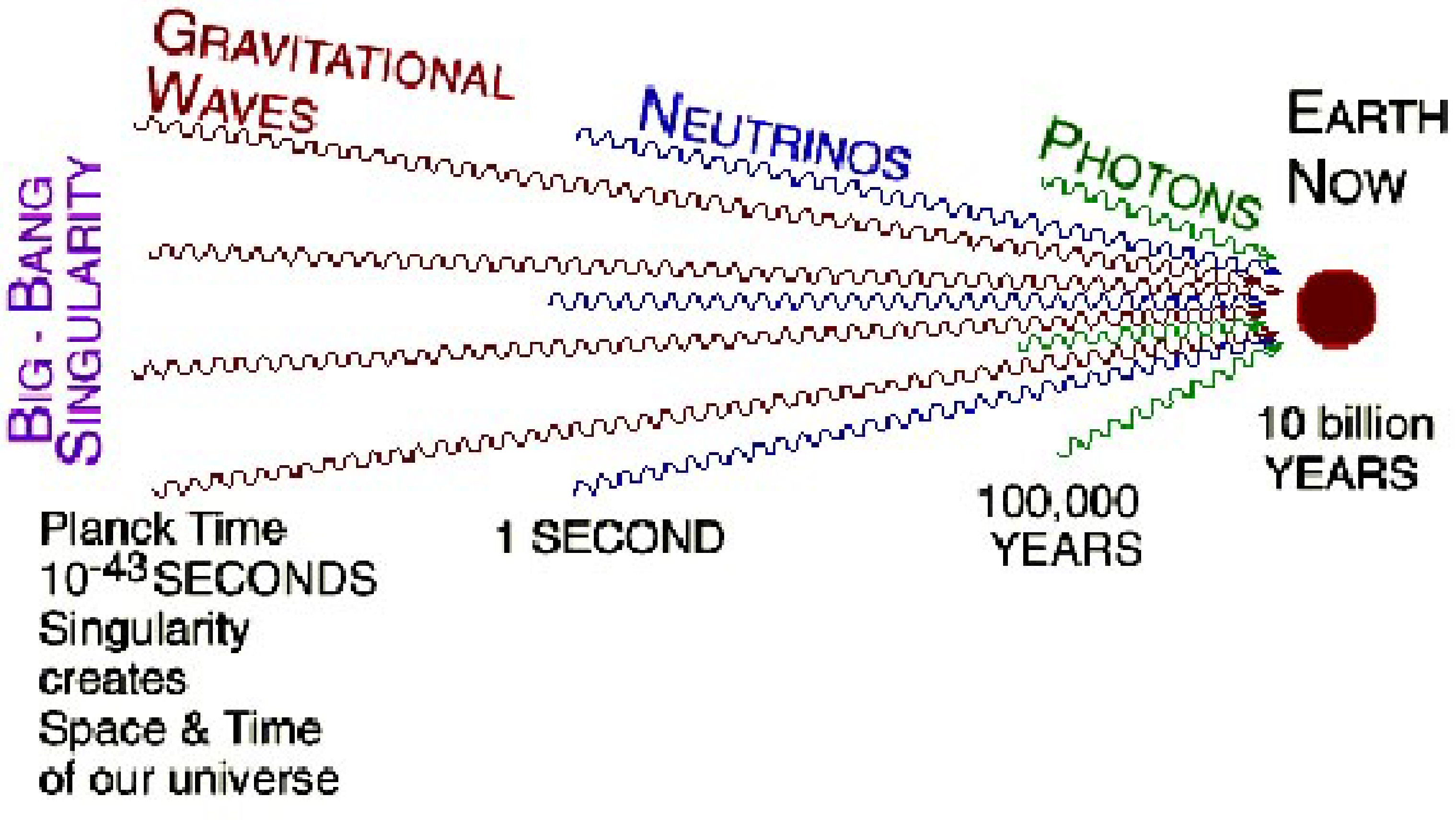
Ground-based and space gravitational wave detectors

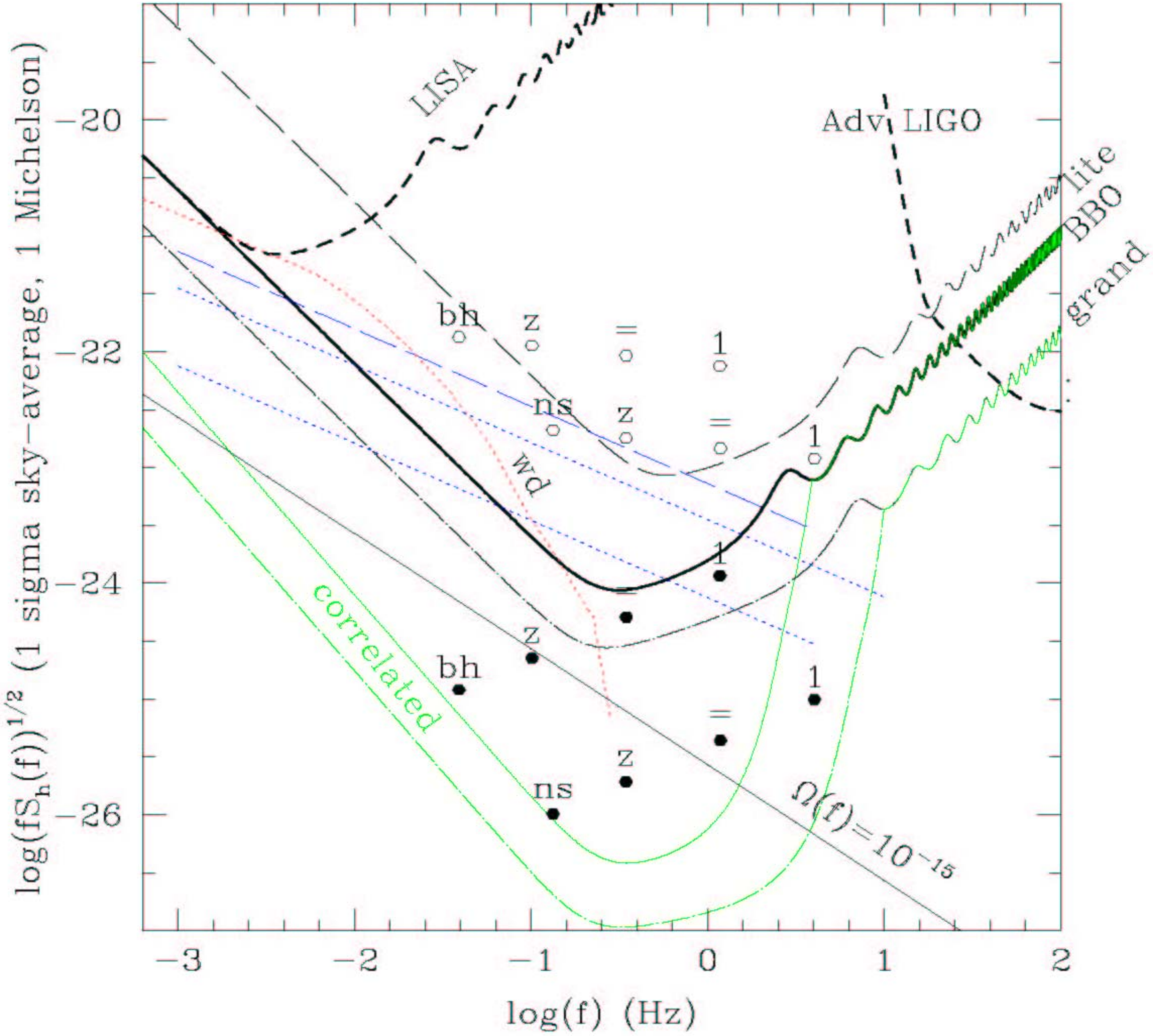


Stochastic backgrounds from the early universe



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

GW background and foreground sources



Big Bang Observer (BBO)

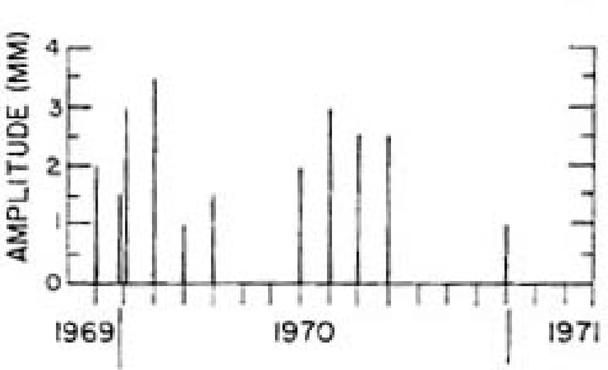
- At longer periods (> 10 s), the confusing foreground from astrophysical sources is hopelessly large.
- At shorter periods (< 0.1 s), the expected signal from inflation becomes too weak to detect.
- At periods of 0.1-10 s lies a window of opportunity. In this frequency range, the primary source of foreground signals is neutron star binaries several months before coalescence, and these are few enough that they can be identified and removed.
- 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

- Due to lack of plate tectonics, the Moon is extremely quiet seismically. The energy release per year is 10^{-14} times lower than the Earth.
  - ⇒ Moonquakes are driven only by the 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!
  - ⇒ The seismic noise level between the moonquakes may be extremely low.
- The Moon does not have atmosphere and 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

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



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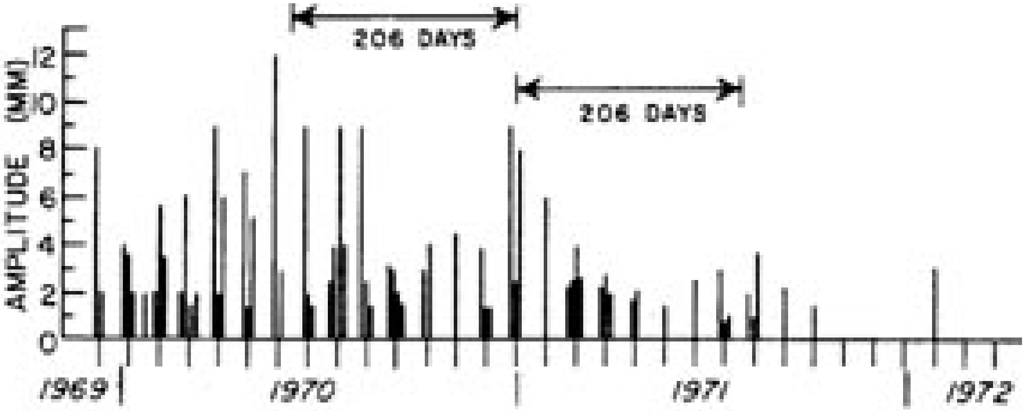
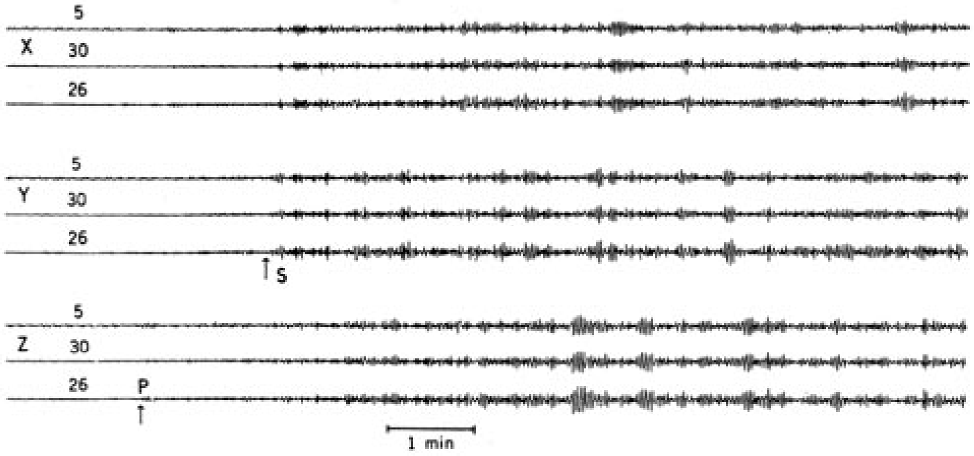


- Signals are reproducible within some 20 types and could therefore be identified and removed.
- It is crucial to detect the background seismic noise level of the Moon!



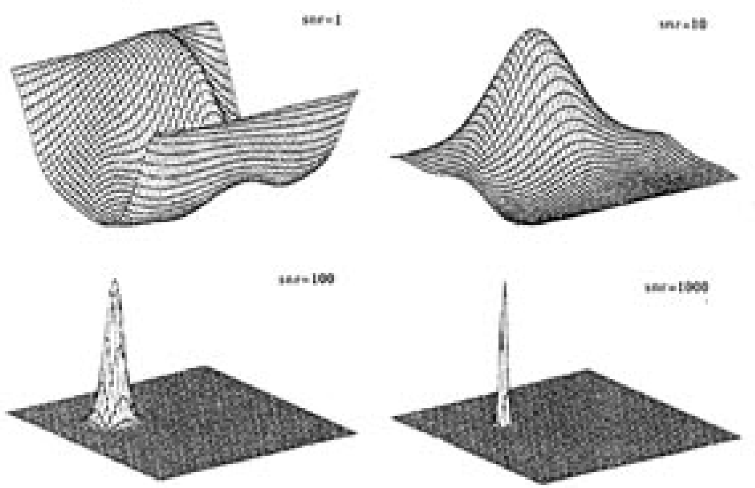
Detector options

- Laser interferometer with a baseline of 50~100 km
  - ⇒ Wideband detector at 0.1-100 Hz.
  - ⇒ Dust may be a problem and the instrument too complex.
- Sensitive displacement sensors detecting the lowest two quadrupole modes of the Moon. (Weber 1972)
  - ⇒ Resonant spherical detector at 0.001 and 0.002 Hz (within the LISA bandwidth).
  - ⇒ Science may be too restrictive.
- Sensitive displacement sensors operated as a wideband detector with a baseline of ~3000 km
  - ⇒ Wideband "spherical" detector at 0.1-10 Hz.
  - ⇒ Complementary to LIGO and LISA.
  - ⇒ Should be simpler to construct than a laser interferometer.

Spherical antenna

- A sphere has 5 quadrupole modes.
  - ⇒ A single antenna can determine both source direction (θ, ϕ) and polarization (h_+, $h_\times$).
  - ⇒ Due to overdetermination, seismic noise can be discriminated against.

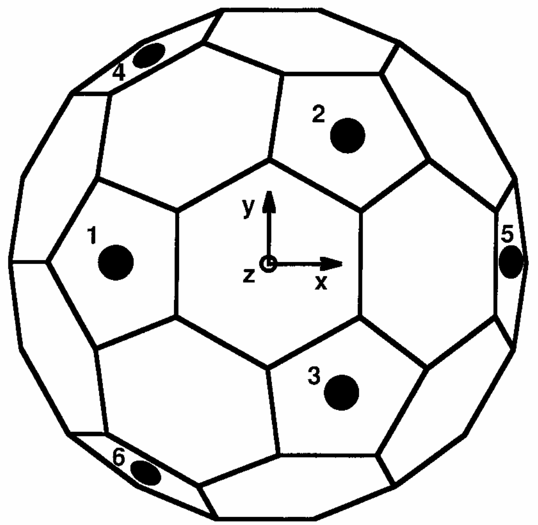
  (Wagoner & Paik, 1976)



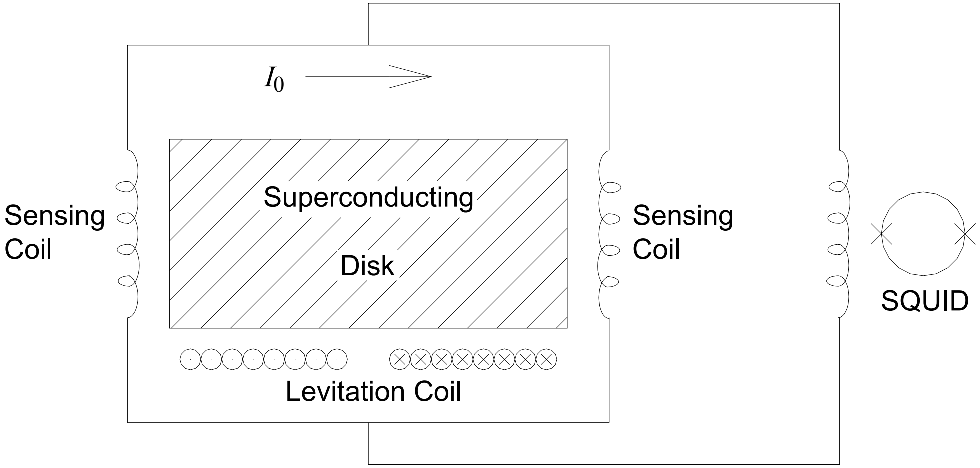
(Zhou and Michelson, 1995)

- Spherical symmetry
  - ⇒ Full-sky coverage with uniform cross section.
- 6 radial transducers on a truncated icosahedral configuration
  - ⇒ “Spherically symmetric” detection of the sphere modes.

  (Johnson & Merkowitz, 1993)



Superconducting motion sensor



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

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

- With design values: $m = 100$ kg, $f_0 = 0.3$ Hz, $T = 2$ K, $Q = 10^6$, $2\beta\eta = 0.5$, $E_{SQ}(f) = 5 \times 10^{-31}\,\mathrm{J\,Hz^{-1}}(1 + 0.1\ \mathrm{Hz}/f)$,

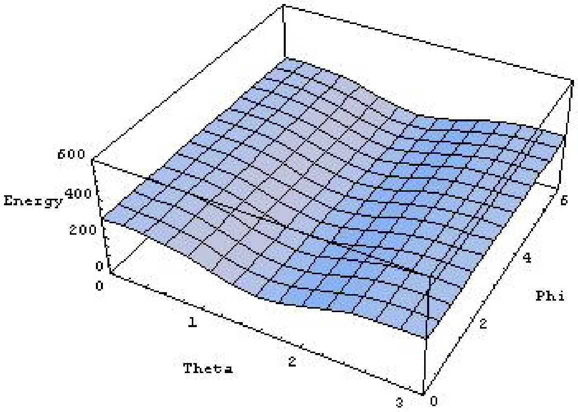
$$S_x^{1/2}(f) \approx 10^{-16}\ \mathrm{m\,Hz^{-1/2}}\ \text{for}\ f > 0.3\ \mathrm{Hz}\ (10^5\ \text{improvement from Weber})$$

$$\Rightarrow\quad S_h^{1/2}(f) \approx S_x^{1/2}(f)/R \approx 10^{-22}\ \mathrm{Hz^{-1/2}}\ \text{for}\ f > 0.3\ \mathrm{Hz}$$

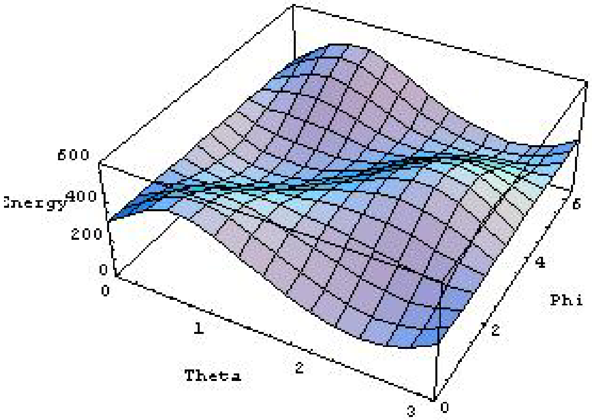
Resonant spherical detector

- Moon’s two quadrupole modes (0.001 and 0.002 Hz) are monitored.
- Directionality of various configurations:

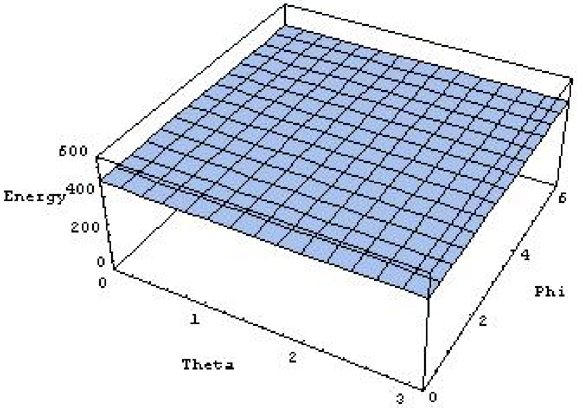
Triangle at great circle



Tetrahedral configuration



Icosahedral configuration



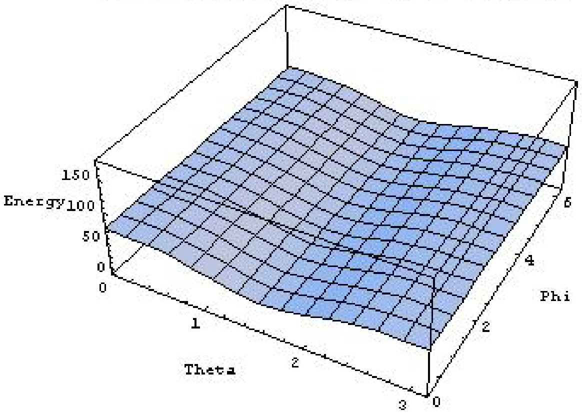
- 6 horizontal motion sensors in truncated icosahedral configuration
  - ⇒ Full-sky coverage with uniform cross section.
  - ⇒ Detection of source direction and wave polarization.
  - ⇒ Discrimination against seismic noise.

(Paik and Raj, 2004)

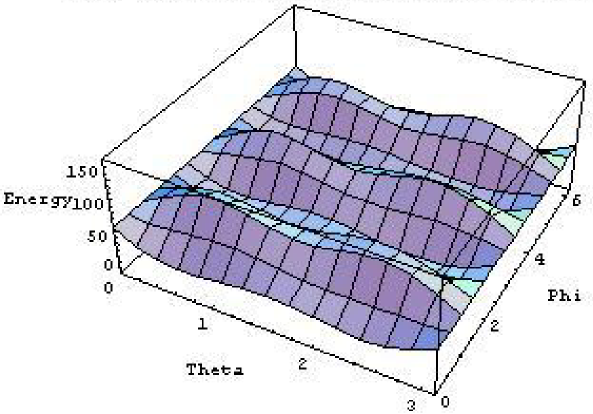
Wideband “spherical” detector

- Wideband response relative to the Moon is monitored (0.01 ~ 10 Hz).
- Directionality of various configurations:

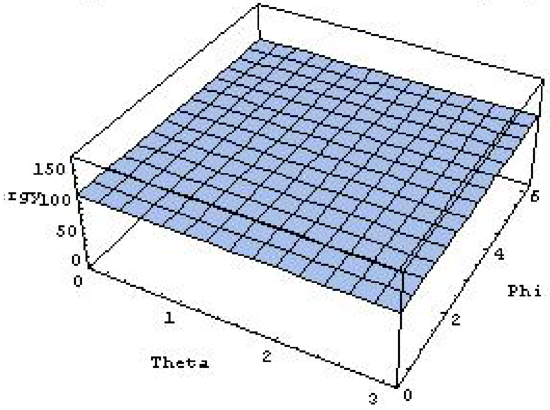
Triangle at great circle



Tetrahedral configuration



Icosahedral configuration



- 6 horizontal motion sensors in truncated icosahedral configuration

⇒ Full-sky coverage with uniform cross section.

⇒ Detection of source direction and wave polarization.

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(Paik and Raj, 2004)

Response at high frequencies

- To find the response of the platform itself, the response of all the quadrupole modes of the Moon must be summed over (per Thorne).
- For a cylinder, the n-th mode responds to a favorably polarized wave:

$$\ddot{B}_n(t) + \tau_n^{-1}\dot{B}_n(t) + \omega_n^2 B_n(t) = \frac{1}{2}\ddot{h}(t)\int_V d_3x U_n(x)x\,, \quad U_n(x) = \sqrt{\frac{2}{V}}\cos\left(\frac{n\pi x}{L}\right),$$

where $\xi(x,t) = \sum_{n=1}^{\infty} B_n(t)U_n(x)$ is the displacement of the cylinder.

- For mode frequencies $\omega_n < \omega$, $B_n = h\sqrt{\frac{V}{2}}\frac{L}{(n\pi)^2}[(-1)^n - 1]$

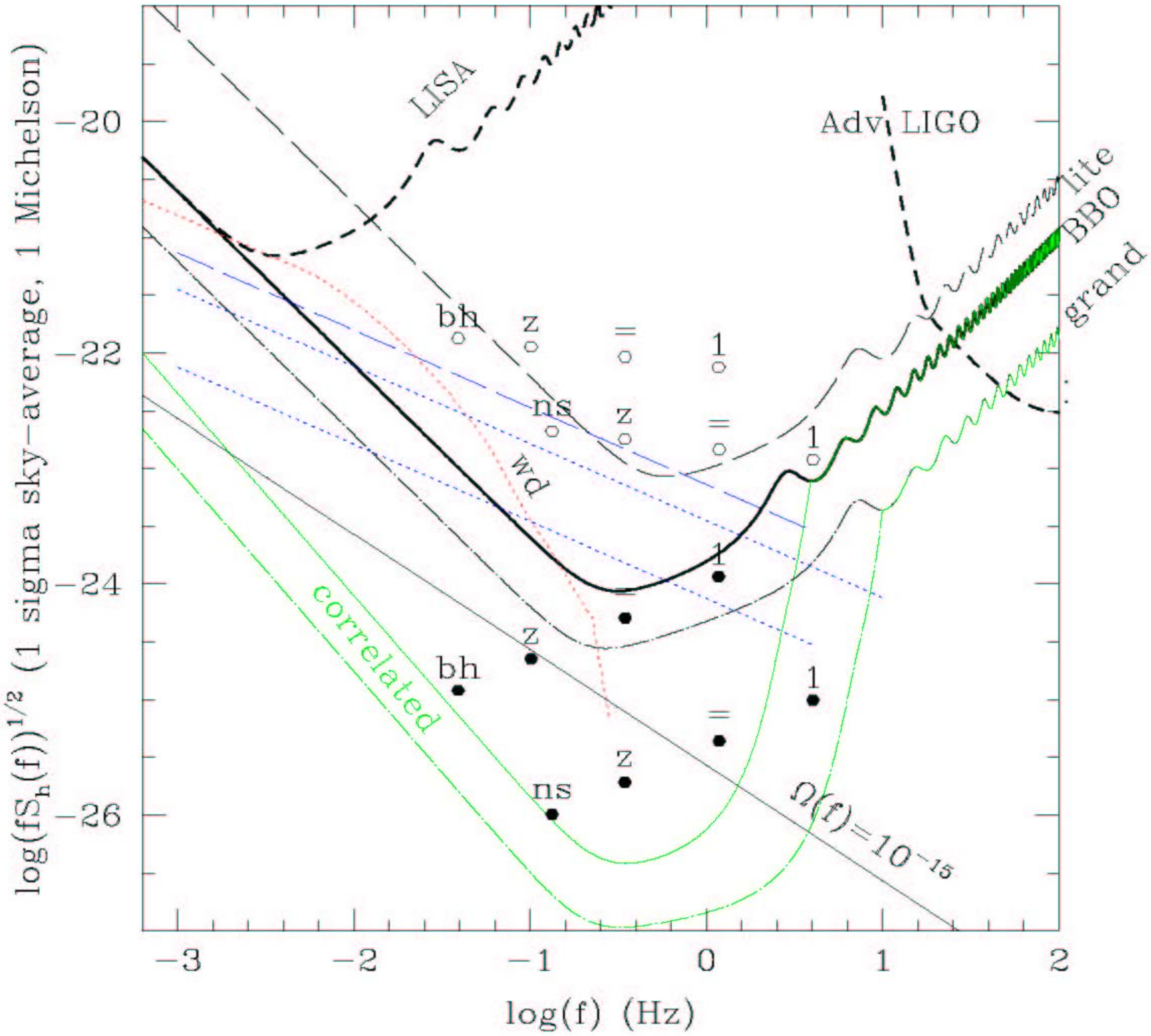
$$\Rightarrow \quad \xi(L) \approx \sum_{n=1}^{\infty} B_n U_n(L) = hL\sum_{n=1}^{\infty}\frac{1-(-1)^n}{(n\pi)^2} = \frac{1}{4}hL\,.$$

$\Rightarrow$ This is half the response of a free mass at the same position.

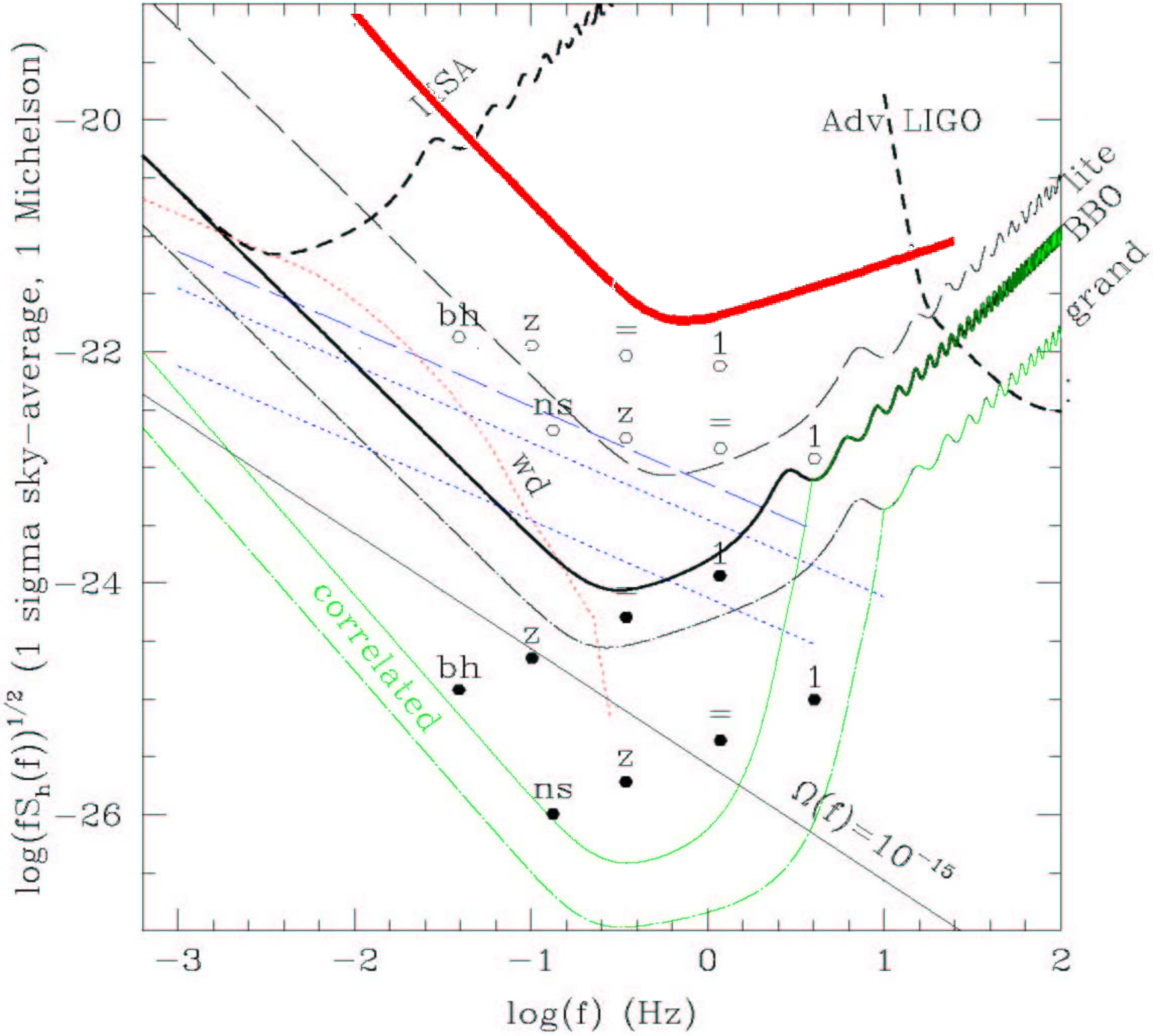
- We expect a similarly reduced response of the Moon to high frequency GWs.

$\Rightarrow$ Response of the levitated masses is only partially reduced!

Sensitivity of lunar GW detector



Sensitivity of lunar GW detector



Recommendations

- 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.