Feasibility of measuring the Shapiro time delay over meter-scale distances

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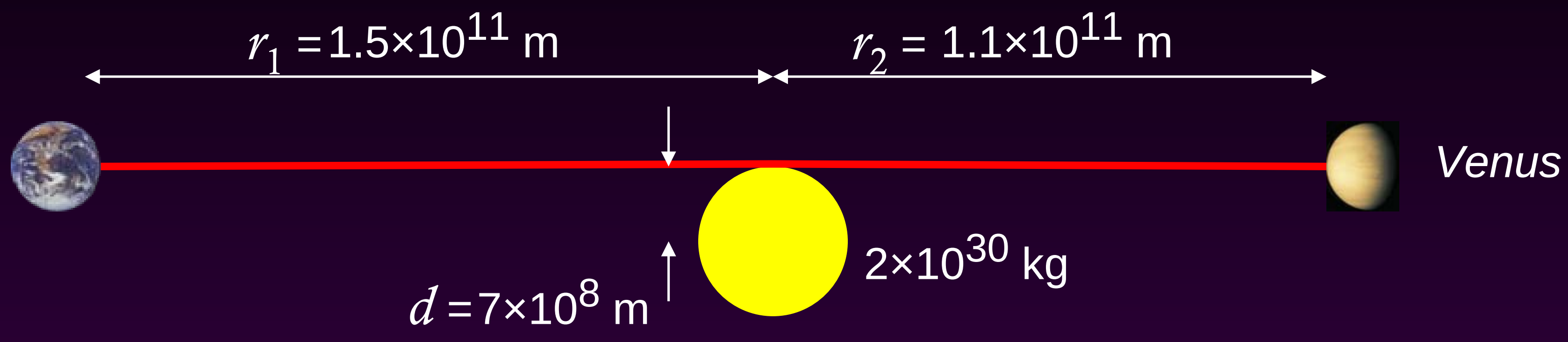
The Shapiro Time Delay



Light or radio beam passing by limb of Sun is delayed by

$$\delta t = (1+\gamma)\frac{GM_\odot}{c^3}\ln\left(\frac{4r_1 r_2}{d^2}\right)$$

= 0.12 ms for Venus (one way)

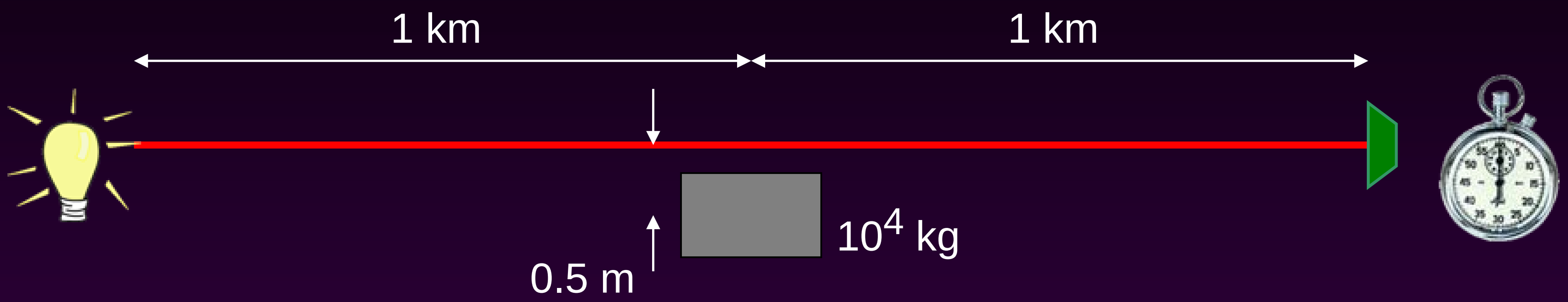
General relativity predicts $\gamma=1$

Radio ranging to planets and spacecraft; binary pulsar timing

Tightest limit: $\gamma - 1 = (2.1 \pm 2.3) \times 10^{-5}$

Question: Does this also apply over <u>short</u> distances?

Laboratory Measurement of Time Delay ?

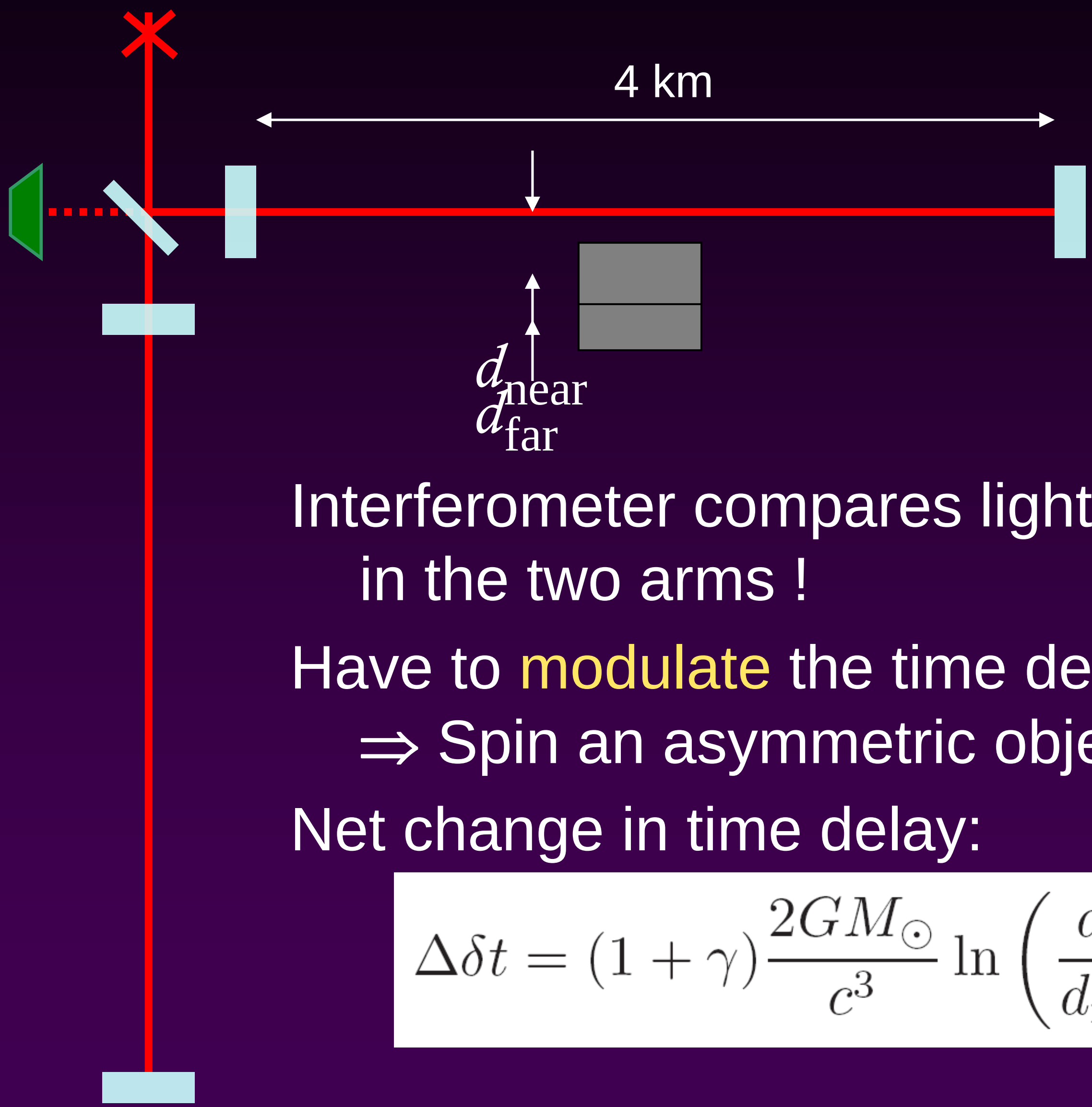


Time delay for these parameters: $\sim 10^{-30}$ s

Equivalent to a distance change of 3×10^{-22} m

How can we measure this ??

Advanced LIGO as a Stopwatch



Interferometer compares light travel times in the two arms !

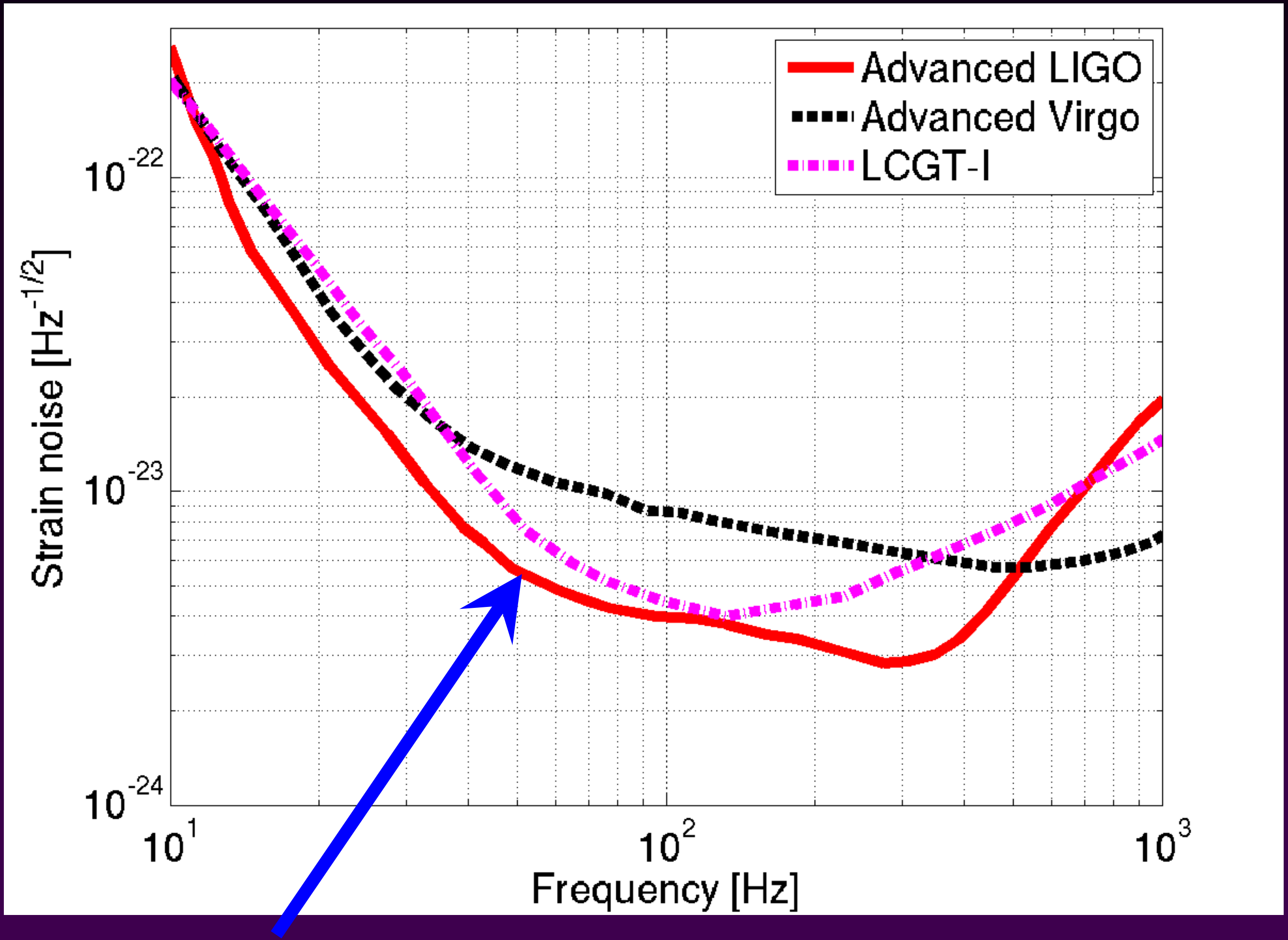
Have to modulate the time delay

⇒ Spin an asymmetric object

Net change in time delay:

$$\Delta\delta t = (1+\gamma)\frac{2GM_\odot}{c^3}\ln\left(\frac{d_{\text{far}}}{d_{\text{near}}}\right)$$

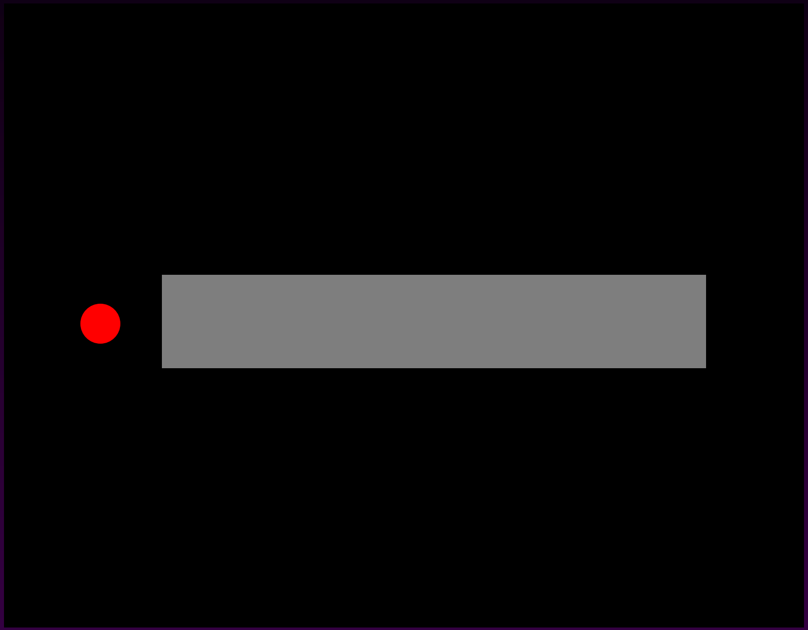
Advanced LIGO Noise Curve



Choose 50 Hz for signal frequency

Integrate for a long time ⇒ SNR grows as $\sqrt{T}$

A Rotating Mass Design: Simple Slab



Spin frequency = 25 Hz

Problems:

- Only part of the mass comes close to the laser beam
- Pushes the tensile strength limits of ordinary metals if the slab has a length of 3 meters, say

A Better Rotating Mass Design

1.5 m

Steel weight

Carbon fiber composite “shell”

Total mass = 30 tons

⇒ total length = 10 meters, divided into several units

In vacuum (separate from beam)

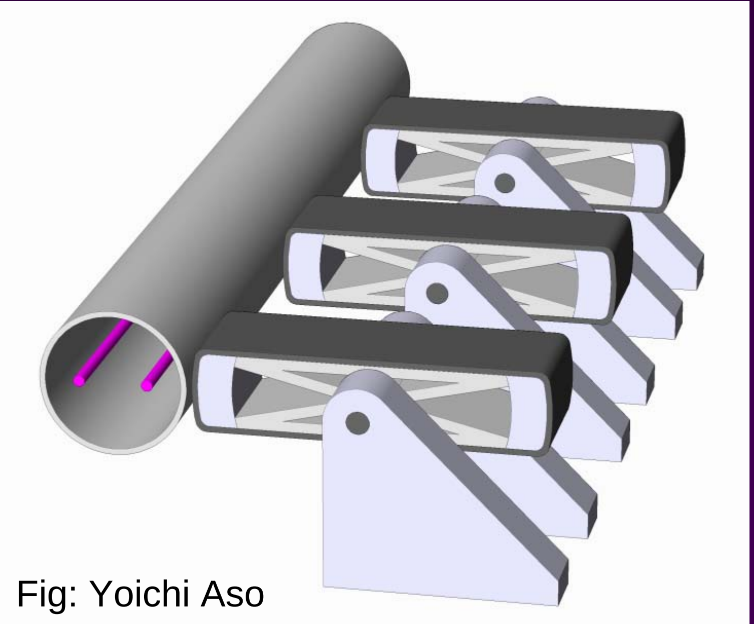
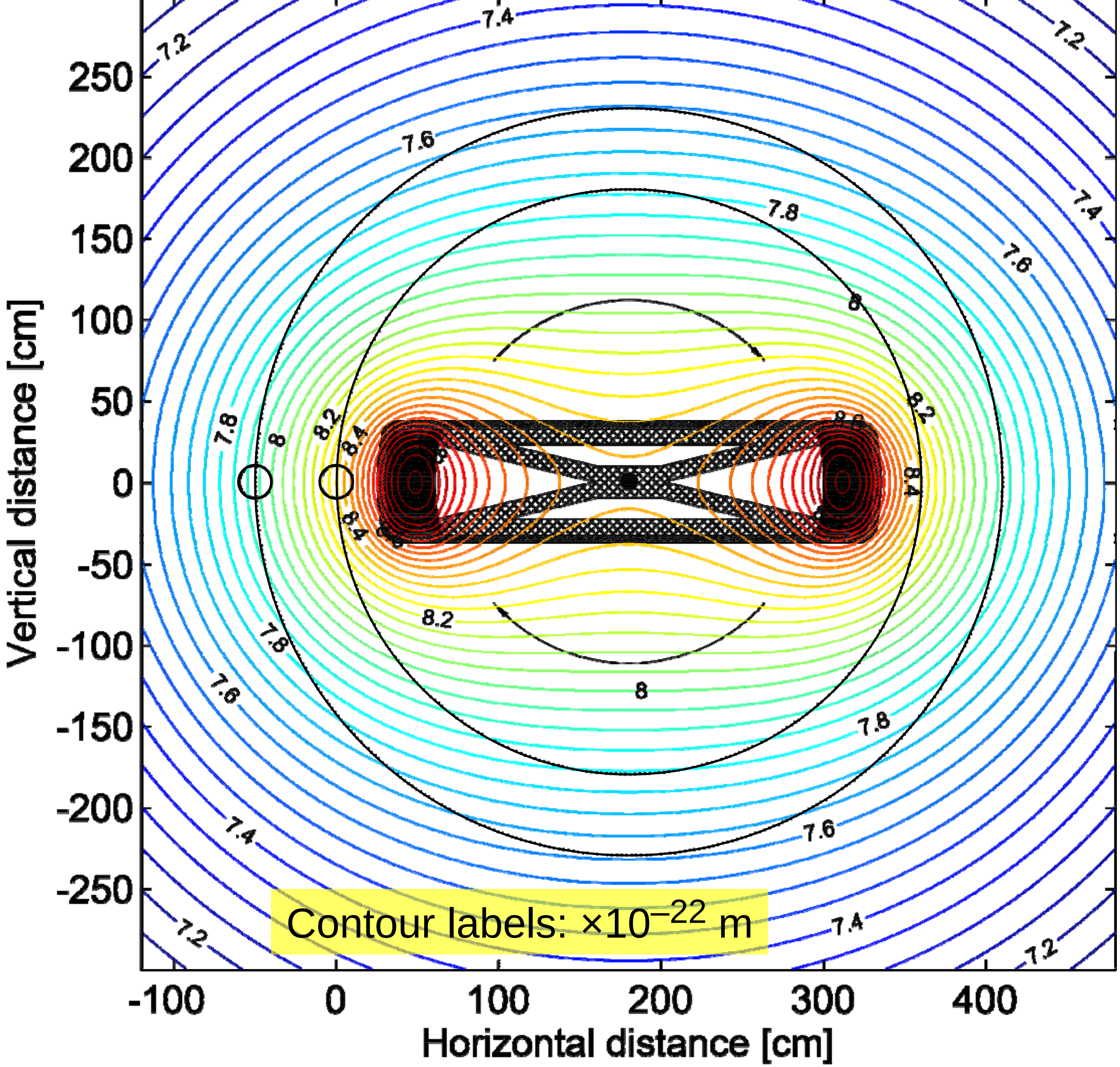


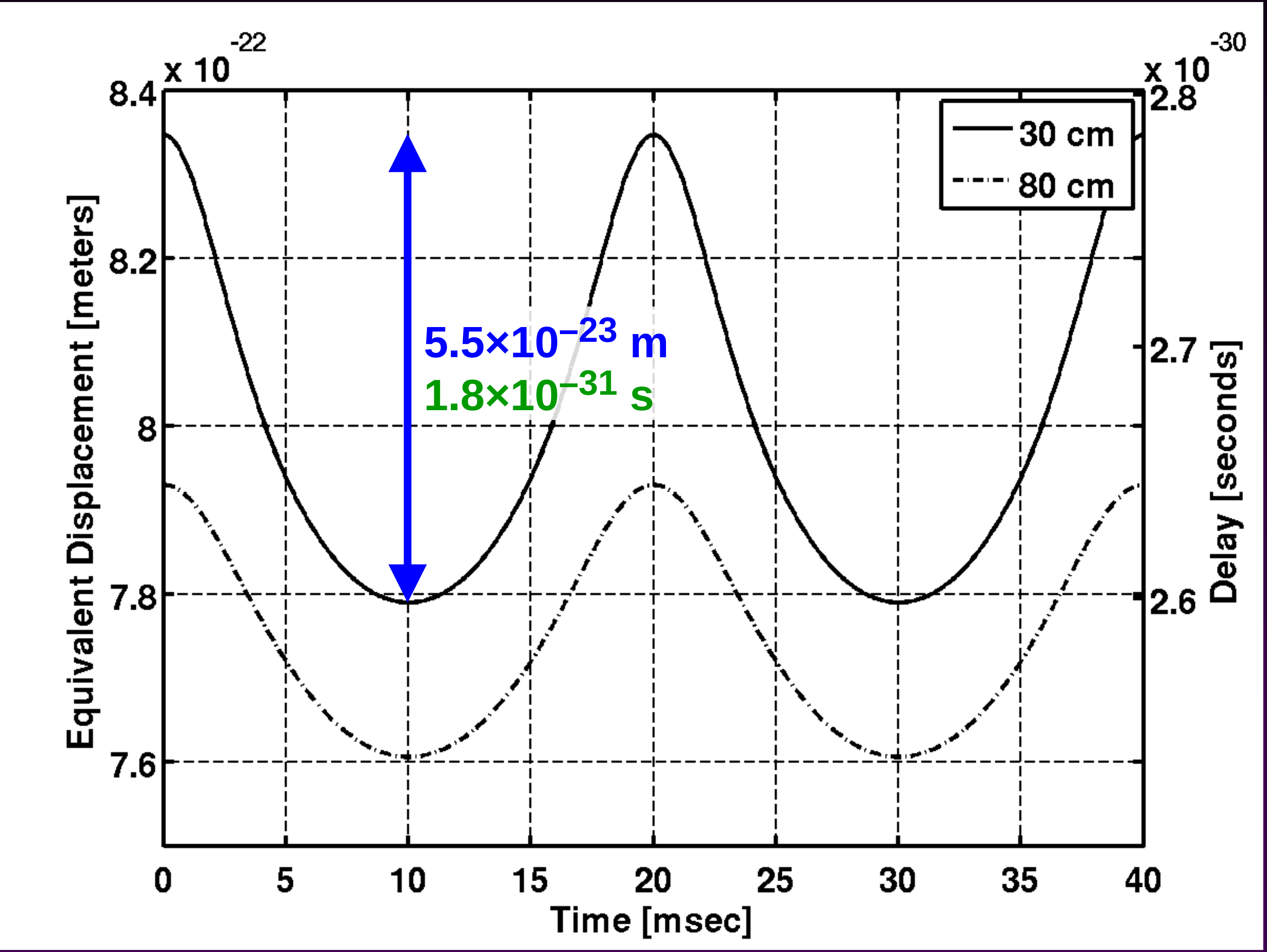
Fig: Yoichi Aso

Isochrones

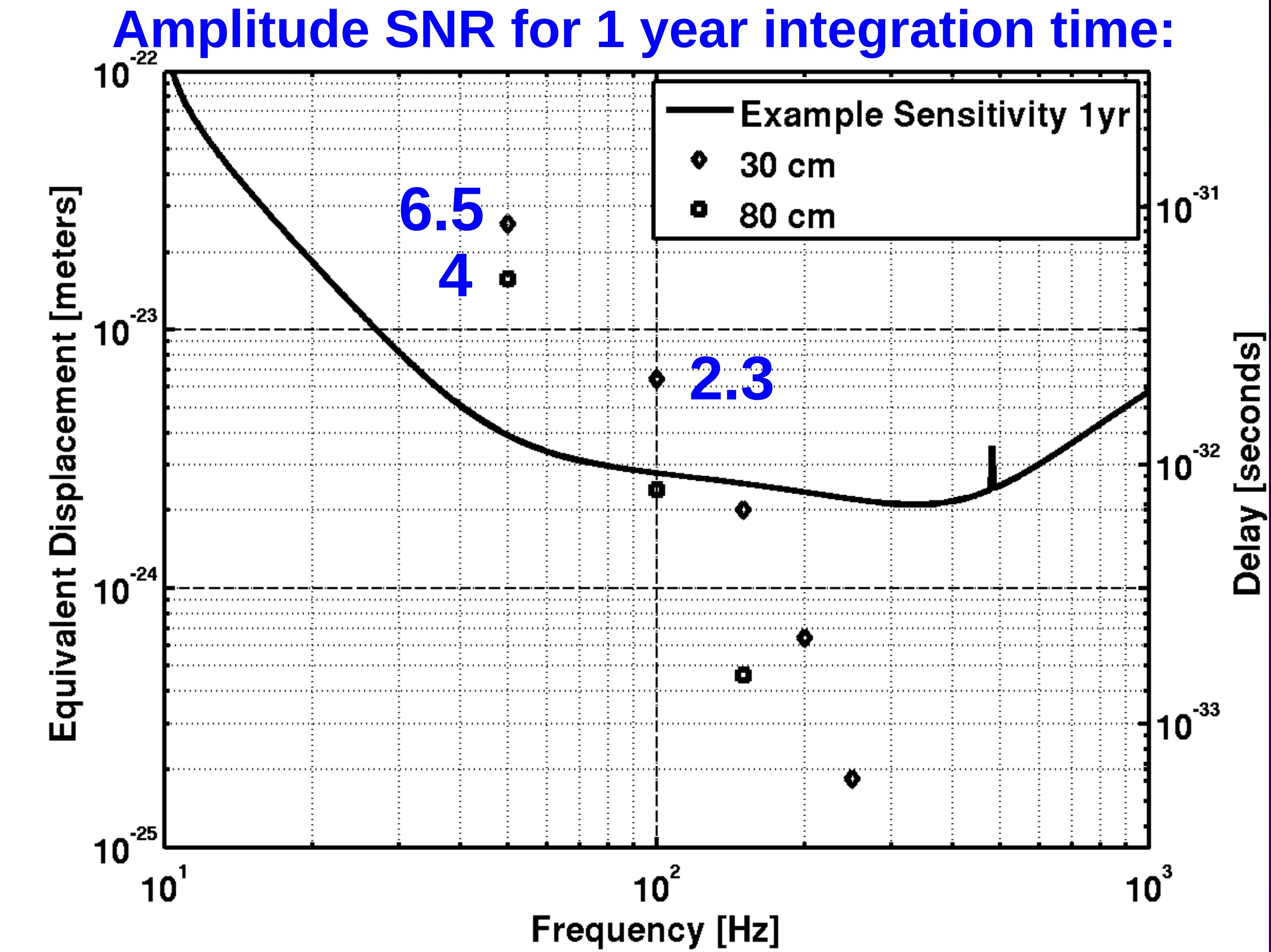


Vertical distance [cm]
Horizontal distance [cm]
Contour labels: ×10^{-22} m

Time Delay Signal



Signal Analysis



Some Implementation Issues

Mechanical tolerances

Determining distance to laser beam

Vibration

- Rotating mass is 2 km away from the interferometer mirrors
- Vibrations will primarily be at the spin frequency
- Possible bigger concern: vibrating beam tube & scattered light

Electrical pickup

Safety !

- Kinetic energy in rotation: ~750 MJ
  (comparable to largest experimental flywheels for energy storage)

Summary

Advanced LIGO *could* measure the Shapiro time delay produced by a rotating apparatus with mass ~30 tons

Would test the curvature of space at short distances

- However, certainly not a precision measurement

The experiment is “feasible”, but challenging

- Requires serious engineering

Would be much easier at lower frequency

- There is interest in future ground-based gravitational-wave detectors that would operate at lower frequencies

(Paper in preparation)