LIGO SCIENCE

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GRAVITATIONAL & E.M. WAVES CONTRASTED

	EM WAVES	GRAV'L WAVES
NATURE	Oscillations of EM field propagating through spacetime	Oscillations of the "fabric" of spacetim itself
EMISSION MECHANISM	Incoherent superposition of waves from molecules, atoms, particles	Coherent emission by bulk motion of energy
INTERACTION WITH MATTER	Strong absorption & scattering	Essentially NONE!
FREQUENCY BAND	$f \gtrsim 10^7$ Hz	$f \lesssim 10^4$ Hz

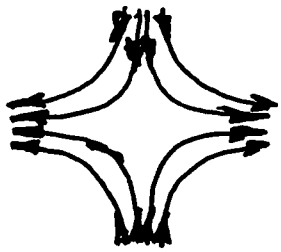
- IMPLICATIONS:
  - Most gravitational sources not seen EM's - and conversely
  - Potential for great surprises
  - Uncertainty in strengths of waves

The Forces Exerted by a Gravitational Wave

If: (Detector Size) << (Wavelength)

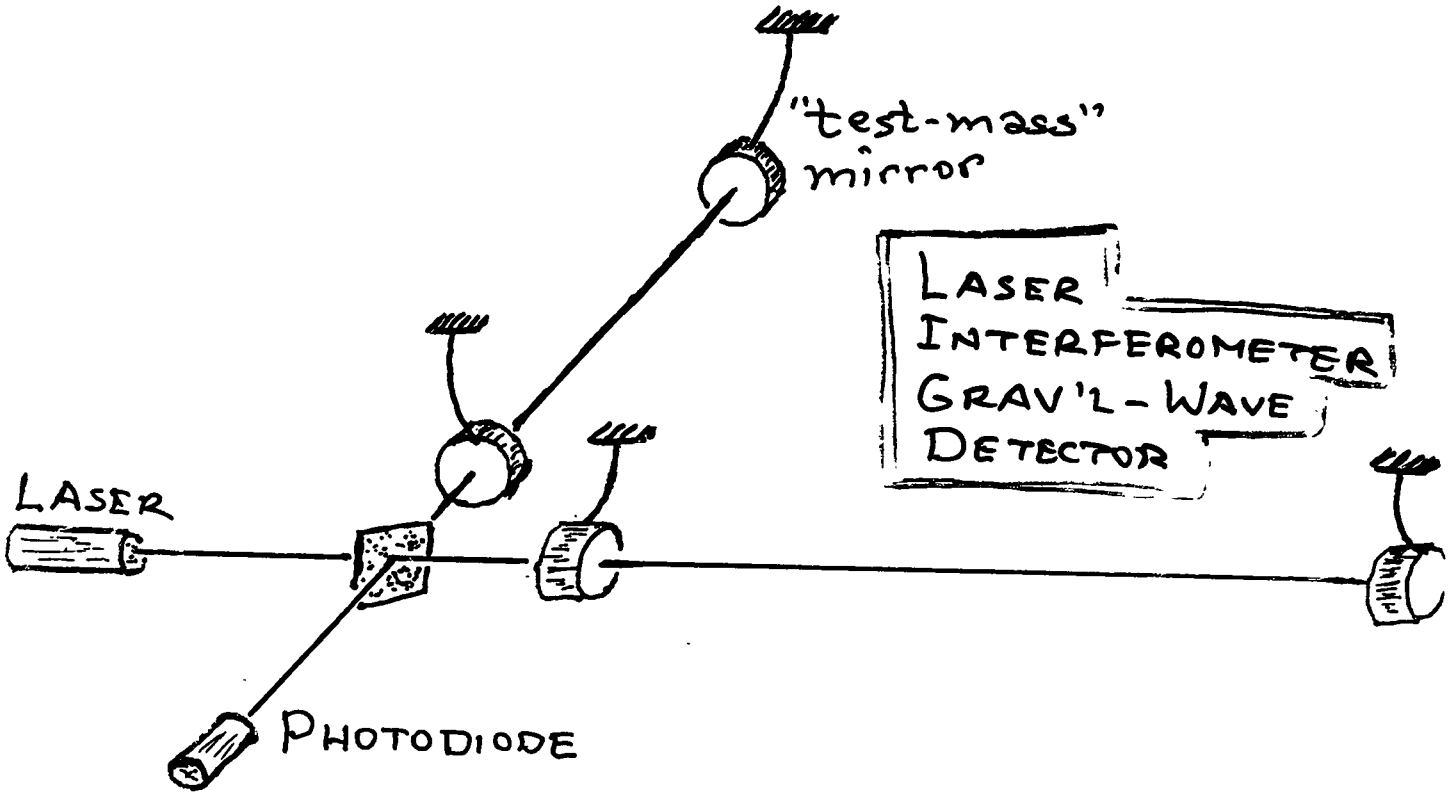
↑ 4 km ↑ 300 to 30,000 km

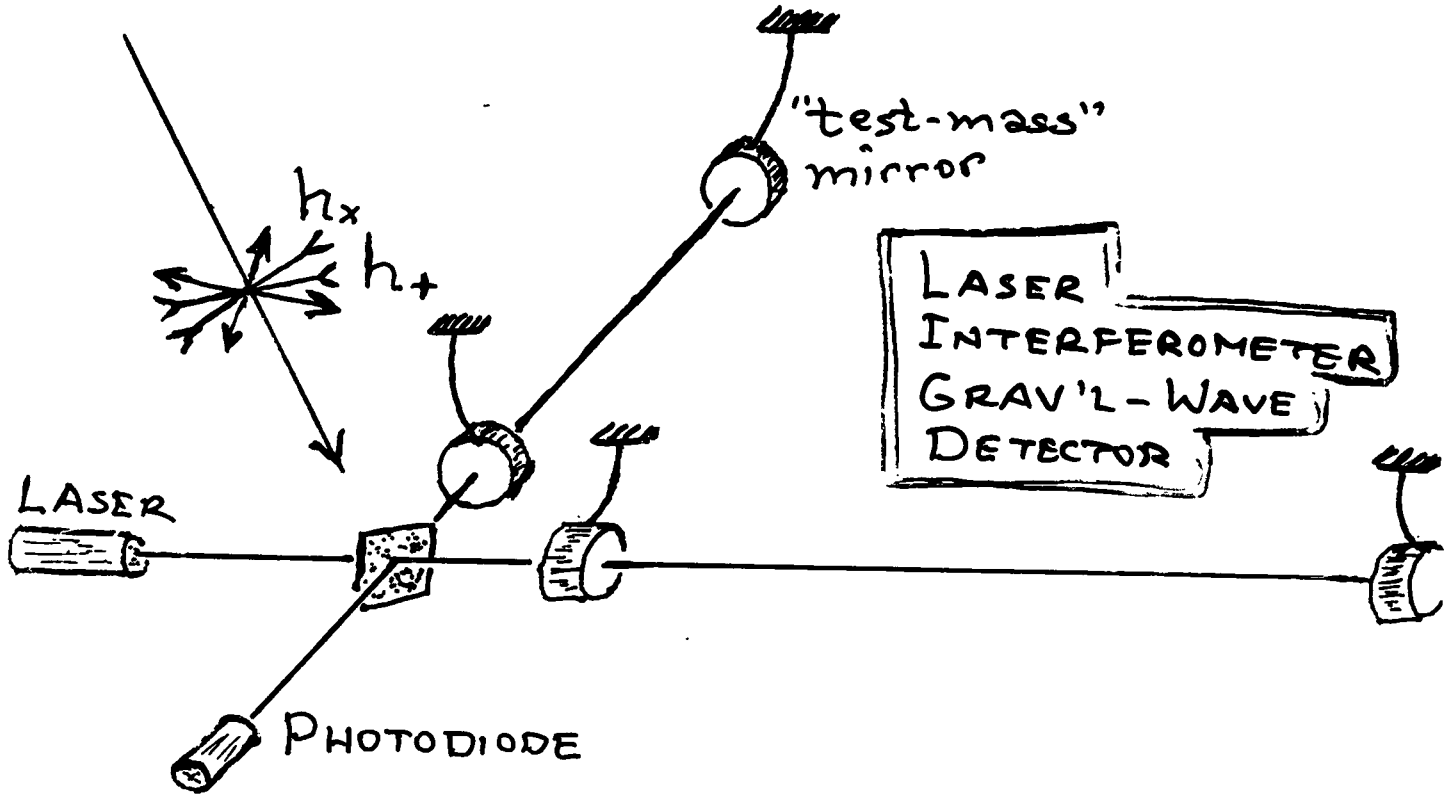
Then: Quadrupolar Lines of Force



+ Polarization

× Polarization


"test-mass"
mirror
LASER
INTERFEROMETER
GRAV'L-WAVE
DETECTOR
LASER
PHOTODIODE



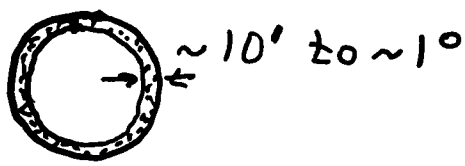
$$\frac{\Delta L}{L} \equiv h = F_+(\text{direction})\, h_+(t) + F_\times(\text{direction})\, h_\times(t)$$

Antenna Patterns

Waveforms

- LIGO measures one waveform;
  - Hanford WA
  - Livingston LA

  Direction in ring

- LIGO + VIRGO measure both waveforms;
  - Pisa Italy

  Direction

Wave Strengths

- $h \sim \frac{G(E^{ns}_{kin}/c^2)}{r}\frac{1}{c^2}$
- For $E^{ns}_{kin}/c^2 \sim M_\odot$,

  $h \sim 10^{-20}$ @ Virgo Cluster of Galaxies

  $\sim 10^{-23}$ @ Hubble Distance

- Detection: $\Delta L = hL$

  LIGO goal, $h \sim 10^{-22}$, requires

  $\boxed{L \simeq 4\ km}$

  $\Delta L \sim 10^{-16}$ cm

  → Stringent Specifications for

  Vacuum

  Seismic & Acoustic Isolation

  Test-mass Suspensions

  Optics

  ⋮

SOURCES - in decreasing order of our understanding

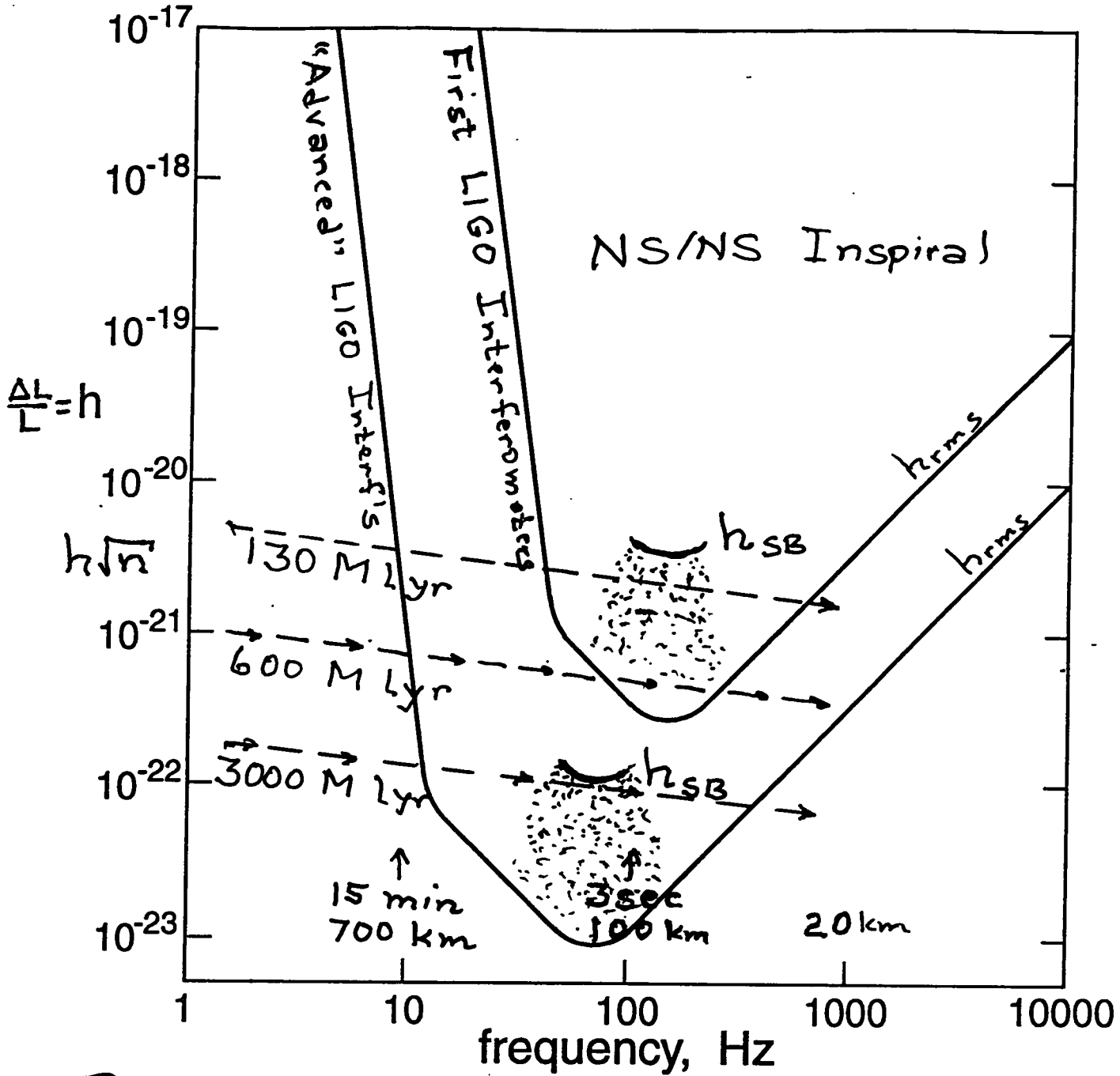
- NS/NS Binary Coalescence (last 15 min, (last 15 min; 20,000 cycles; $\sim 6 \times 10^8$ l.yr.)
- NS/BH Coalescence
- BH/BH Coalescence
- Supernovae
  - axisymmetric (Our galaxy; Magellanic Clouds)
  - nonaxisymmetric ($\sim 3 \times 10^8$ l. yr.)
- Spinning N.S. (pulsars)
  (our galaxy)
- Vibrating Cosmic Strings
  (early universe)
- Vacuum Phase Transitions in Early Universe
  (colliding bubbles of "true" vacuum in the "false" vacuum)
- The Big Bang
  (parametric amplification of vacuum fluctuations from Planck Era)
- The Unknown

NS/NS Coalescence Rates

Method	Our Galaxy	Distance for 3/yr
Progenitor Death Rate	$\sim \frac{1}{1000\,yr}$	130 Million l.yrs.
Binary Pulsar Searches & Discoveries (3)	$\sim \frac{1}{10^{5\pm1}\,yr}$	600 M. l.yrs. ($\pm$ factor 2)
Ultraconservative Limit From Binary Pulsar Searches	$\sim \frac{1}{10^{7}\,yr}$	3000 M. l.yr.

NS/BH & BH/BH Rates

Progenitor Death Rate	$\sim \frac{1}{10^{5}\,yr}$	600 M. l.yr.



- Rate $\propto 1/h_{SB}^{3}$
- If rate is 3/yr out to 600 M Lyr

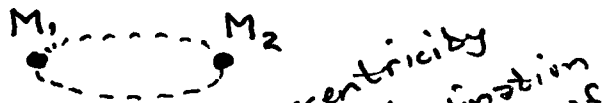
Then "Advanced detectors" should see
~1 per day

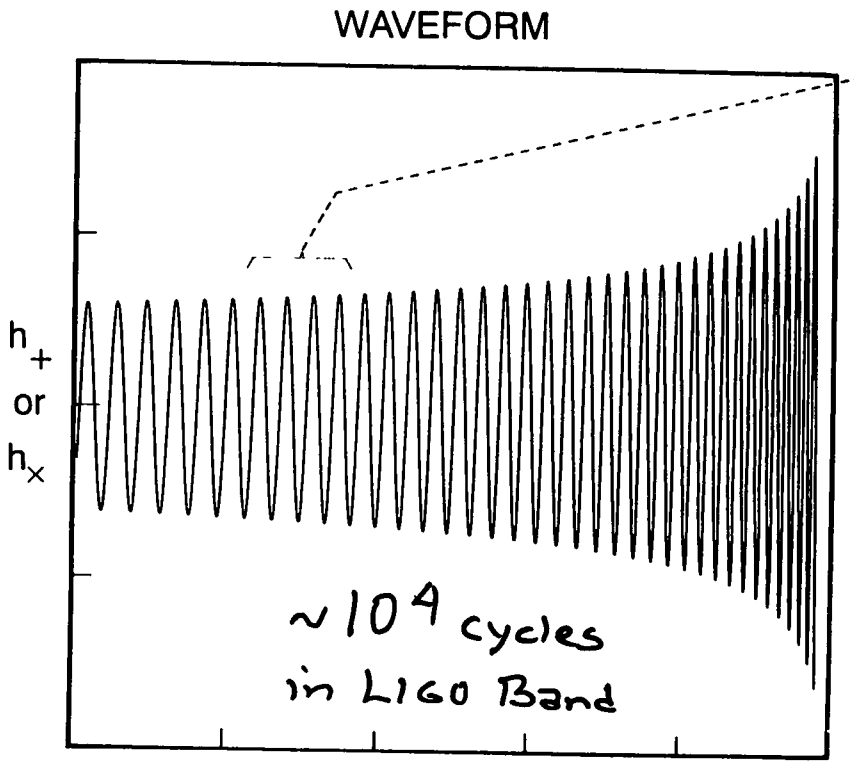
NS/NS out to 3×10^{9} L.yr.

NS/BH, BH/BH } out to cosmological distances

Waveforms From Binary Inspiral

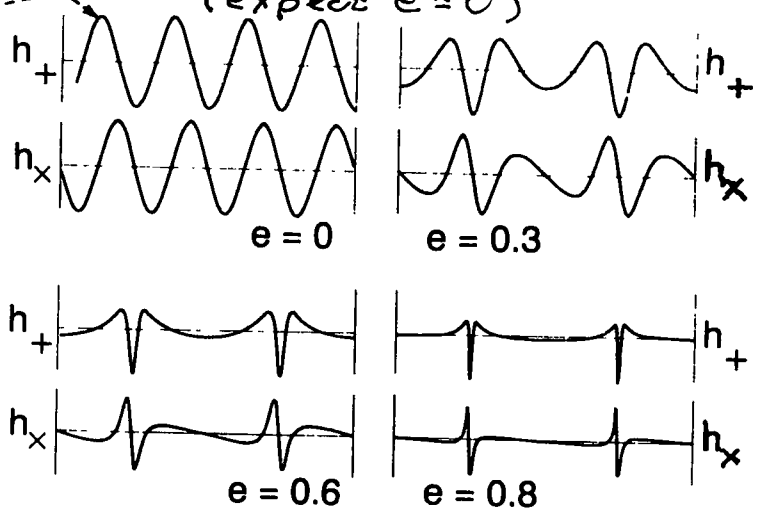
(Very "clean"; depend only on $M_1, M_2, \vec{S}_1, \vec{S}_2, r$, orbital elements)





DEPENDENCE ON e, FOR $\iota = 90°$

(expect e = 0)



DEPENDENCE ON ι, FOR e = 0:

$$\frac{\text{Amp}\ (h_\times)}{\text{Amp}\ (h_+)} = \frac{2\cos\iota}{1+\cos^2\iota}$$

FOR e = 0

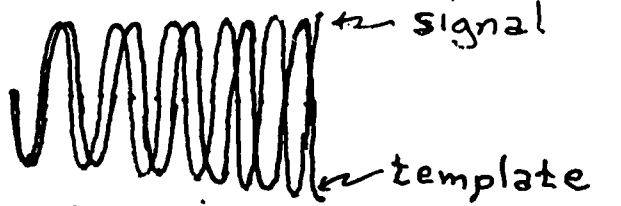
$$\frac{df}{dt} \propto \frac{M_1 M_2}{(M_1+M_2)^{1/3}} f^{11/3} + \left(\begin{array}{l}\text{relativistic corrections}\\ \text{that depend on } M_1, M_2, \vec{S}_1, \vec{S}_2\end{array}\right)$$

$$\text{Amplitude} \propto \underbrace{\frac{M_1 M_2}{(M_1+M_2)^{1/3}}}_{\text{"Chirp Mass"}} \frac{f^{2/3}}{r}$$

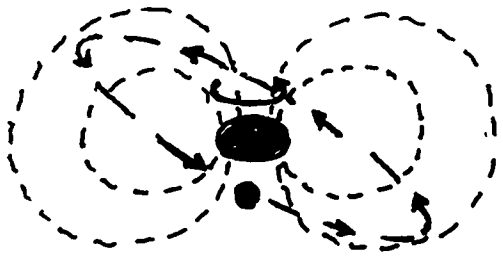
"Chirp Mass" $\Delta M/M \sim 0.001$

↑ Distance $\Delta r/r \sim .05$ to $.5$ STANDARD CANDLE!

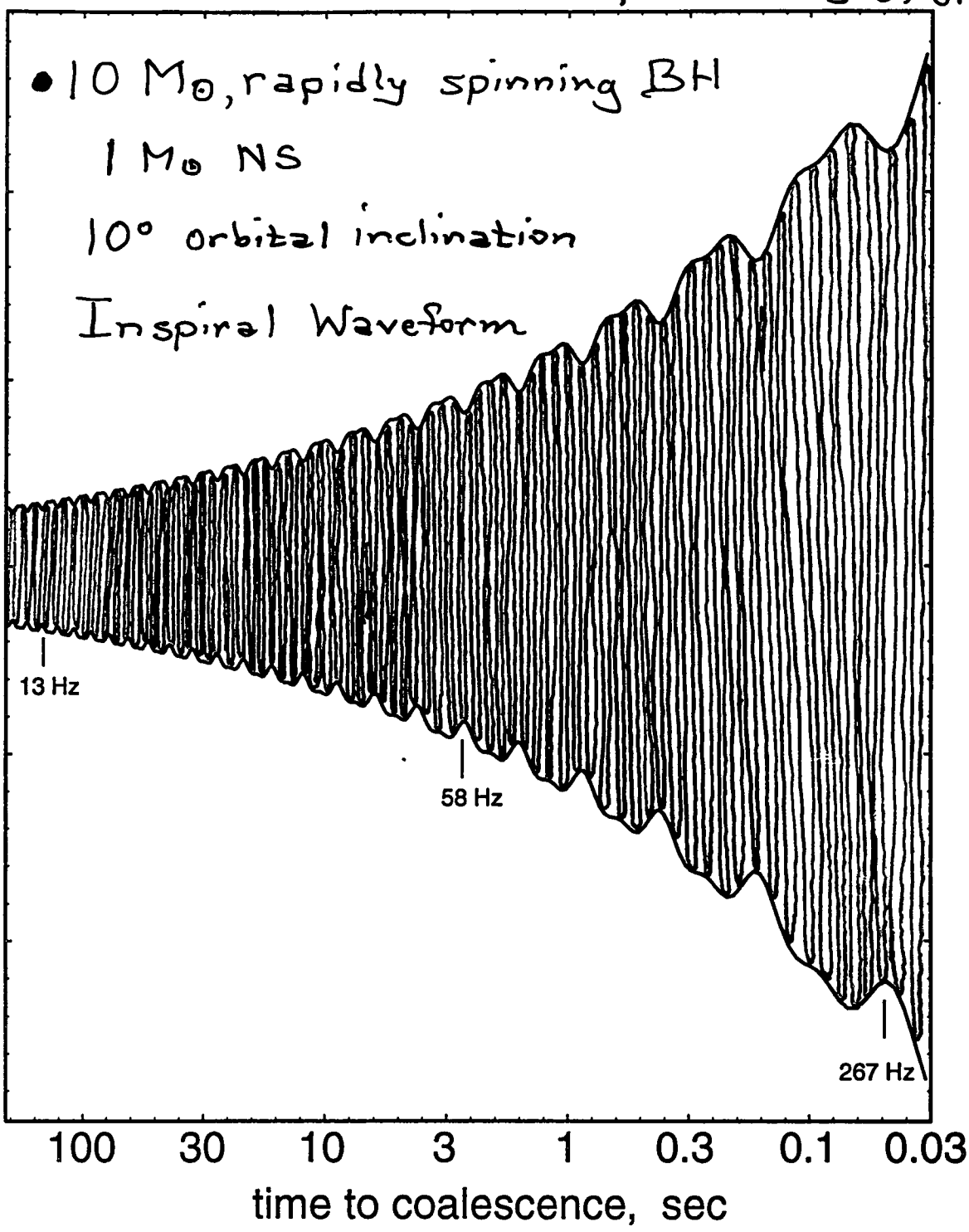
↳ Masses & Spins $\Delta M/M \sim$ few %



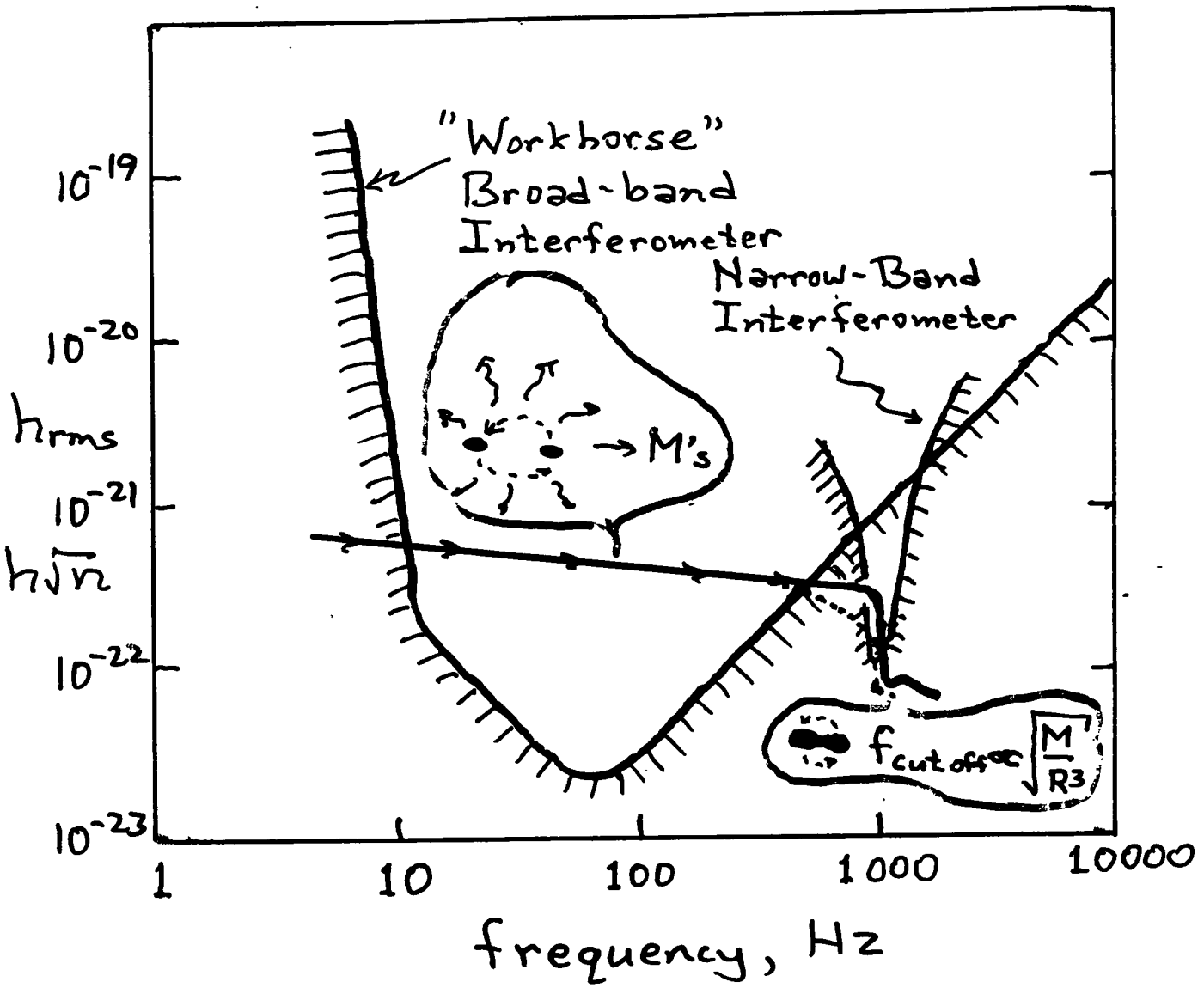
↑ Sensitivity to phase evolution: $\sim 1/10^5$



BH Spin → "gravitomagnetic field"
(frame dragging)
~ 20 precessions of orbit



NS/NS Coalescence

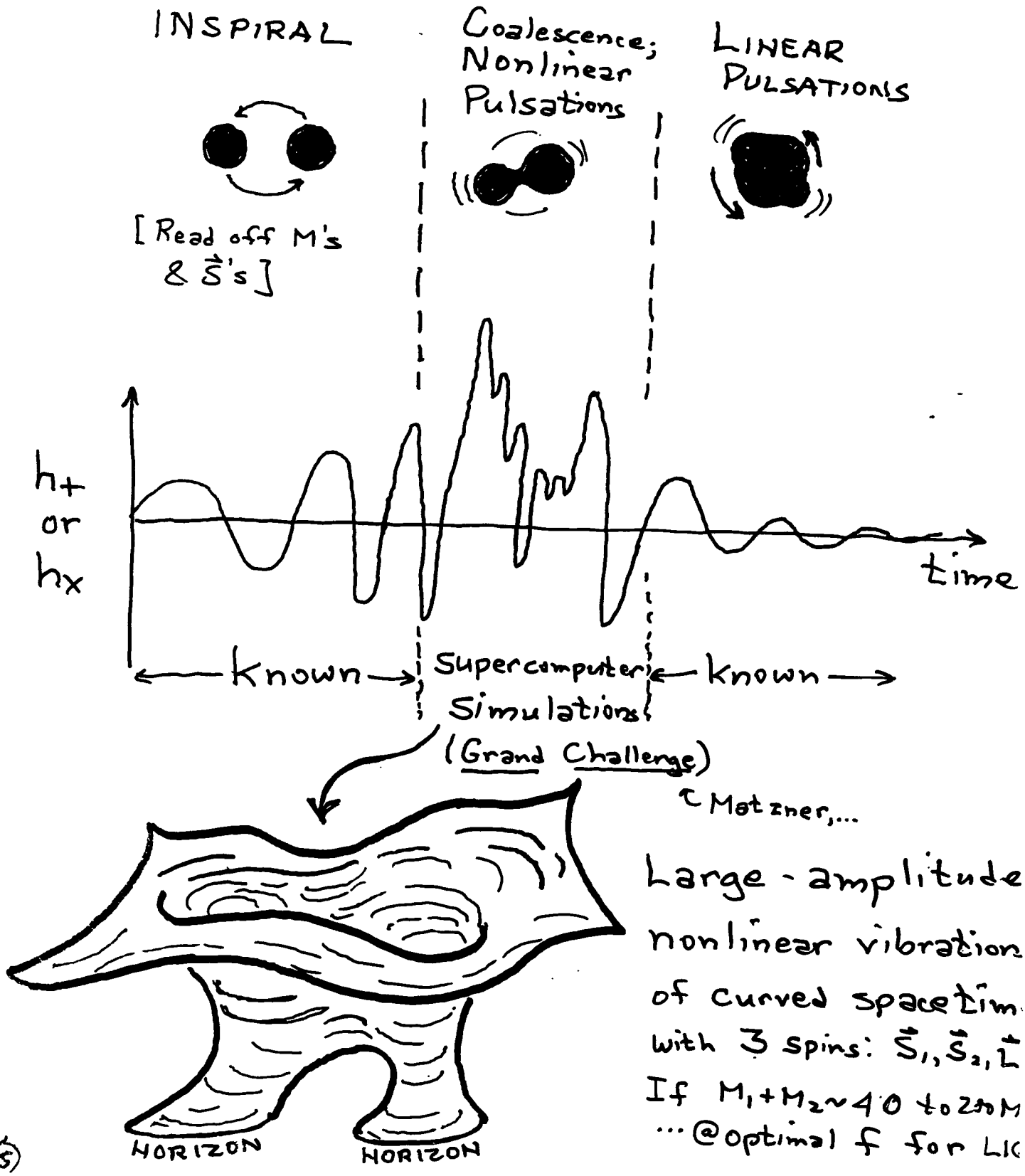


Neutron-Star M(R) → Nuclear Equation of State P(ρ)

- Requires several interferometers, with different optical designs, in same vacuum system

[Possible after future upgrade]

BH/BH Coalescence



↑ Matzner, ...

Large-amplitude nonlinear vibration of curved spacetim with 3 spins: $\vec{S}_1, \vec{S}_2, \vec{L}$

If $M_1 + M_2 \sim 40$ to $2 \odot M$ ... @optimal f for LIC