

CURRENT STATE OF GRAVITATIONAL WAVE DETECTION BY INTERFEROMETRY ON THE EARTH AND IN SPACE

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Mitchell Symposium on Observational
Cosmology

Texas A&M University

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Australian National University ACIGA
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California State Dominguez Hills
Caltech CACR
Caltech LIGO
Caltech Experimental Gravitation CEGG
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697

SITZUNGSBERICHTE

1916.

XXXIII.

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN.

688 Sitzung der physikalisch-mathematischen Klasse vom 22. Juni 1916

AS.A. 311

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Näherungsweise Integration der Feldgleichungen
der Gravitation.

Von A. EINSTEIN.

$$\gamma'_{\mu\nu} = \alpha_{\mu\nu} f(x_1 + i x_4) = \alpha_{\mu\nu} f(x - t). \quad (15)$$

Dabei sind die $\alpha_{\mu\nu}$ Konstante; f ist eine Funktion des Arguments $x - t$. Ist der betrachtete Raum frei von Materie, d. h. verschwinden die $T_{\mu\nu}$, so sind die Gleichungen (6) durch diesen Ansatz erfüllt. Die Gleichungen (4) liefern zwischen den $\alpha_{\mu\nu}$ die Beziehungen

$$\left. \begin{aligned} \alpha_{11} + i\alpha_{14} &= 0 \\ \alpha_{12} + i\alpha_{24} &= 0 \\ \alpha_{13} + i\alpha_{34} &= 0 \\ \alpha_{14} + i\alpha_{44} &= 0 \end{aligned} \right\}. \quad (16)$$

Von den 10 Konstanten $\alpha_{\mu\nu}$ sind daher nur 6 frei wählbar. Wir können die allgemeinste Welle der betrachteten Art daher aus Wellen von folgenden 6 Typen superponieren

$$\left. \begin{array}{lll} \text{a) } \alpha_{11} + i\alpha_{14} = 0 & \text{b) } \alpha_{12} + i\alpha_{24} = 0 & \text{d) } \alpha_{22} \neq 0 \\ \alpha_{14} + i\alpha_{44} = 0 & \text{c) } \alpha_{13} + i\alpha_{34} = 0 & \text{e) } \alpha_{23} \neq 0 \\ & & \text{f) } \alpha_{33} \neq 0 \end{array} \right\}. \quad (17)$$

$$\begin{aligned} \text{d) } \frac{1}{i} t_{22} &= \frac{f'^2}{4\kappa} \alpha_{22}^2 = \frac{1}{4\kappa} \left(\frac{\partial \gamma'_{22}}{\partial t} \right)^2 \\ \text{e) } \frac{1}{i} t_{23} &= \frac{f'^2}{4\kappa} \alpha_{23}^2 = \frac{1}{4\kappa} \left(\frac{\partial \gamma'_{23}}{\partial t} \right)^2 \\ \text{f) } \frac{1}{i} t_{33} &= \frac{f'^2}{4\kappa} \alpha_{33}^2 = \frac{1}{4\kappa} \left(\frac{\partial \gamma'_{33}}{\partial t} \right)^2 \end{aligned}$$

Es ergibt sich also, daß nur die Wellen des letzten Typs Energie transportieren, und zwar ist der Energietransport einer beliebigen ebenen Welle gegeben durch

$$I_x = \frac{1}{i} t_{41} = \frac{1}{4\kappa} \left[\left(\frac{\partial \gamma'_{22}}{\partial t} \right)^2 + 2 \left(\frac{\partial \gamma'_{23}}{\partial t} \right)^2 + \left(\frac{\partial \gamma'_{33}}{\partial t} \right)^2 \right]. \quad (18)$$

THE RADIATION FIELD

Transverse Plane Wave Solutions with “Electric”
and “Magnetic” Terms

Geometric Interpretation

$$ds^2 = g_{ij} dx^i dx^j$$

$$g_{ij} = \eta_{ij} + h_{ij} \quad \text{weak field}$$

$$\eta_{ij} = \begin{pmatrix} 1 & & & 0 \\ & -1 & & \\ 0 & & -1 & \\ & & & -1 \end{pmatrix} \quad \begin{array}{l} \text{Minkowski Metric of} \\ \text{Special Relativity} \end{array}$$

Gravity Wave Propagating in the x_1 Direction

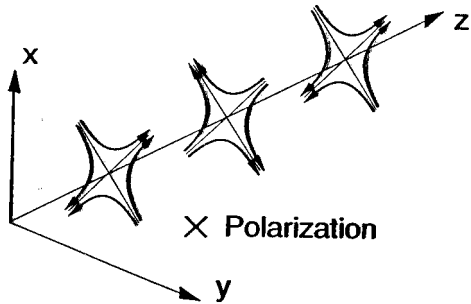
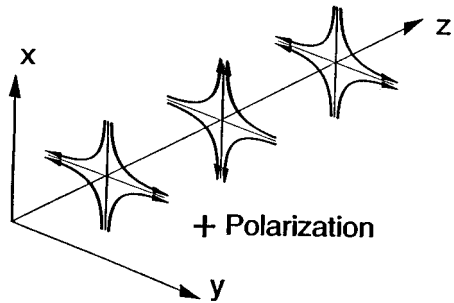
$$h_{ij} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & h_{22} & h_{23} \\ 0 & 0 & h_{32} & h_{33} \end{pmatrix} \quad \text{all } h_{ij} \ll 1$$

Plane Wave

$$\mathbf{h}_{22} = -\mathbf{h}_{33} \quad \mathbf{h}_{23} = \mathbf{h}_{32}$$

+ polarization × polarization

And All Only Function of $x_1 - ct$



Die in (23), (23 a) und (23 b) auftretenden Integrale, welche nichts anderes sind als zeitlich variable Trägheitsmomente, nennen wir im folgenden zur Abkürzung J_{22} , J_{33} , J_{23} . Dann ergibt sich für die Intensität I_x der Energiestrahlung aus (18)

$$I_x = \frac{\kappa}{64 \pi^2 R^2} \left[\left(\frac{\partial^3 J_{22}}{\partial t^3} \right)^2 + 2 \left(\frac{\partial^3 J_{23}}{\partial t^3} \right)^2 + \left(\frac{\partial^3 J_{33}}{\partial t^3} \right)^2 \right]. \quad (20)$$

SPHERICALLY SYMMETRIC MOTION RADIATES GRAVITATIONAL WAVES

1918

VI VII VIII

SITZUNGSBERICHTE

DER

KÖNIGLICH PREUSSISCHEN

AKADEMIE DER WISSENSCHAFTEN

Sitzung der physikalisch-mathematischen Klasse am 7. Februar. (S. 139)

Sitzung der philosophisch-historischen Klasse am 7. Februar. (S. 141)

J. KIRCHNER: Archon Euthios. (S. 142)

Gesamtsitzung am 14. Februar. (S. 153)

EINSTEIN: Über Gravitationswellen. (Mitteilung vom 31. Januar.) (S. 154)

E. FREUNDLICH: Über die singulären Stellen der Lösungen des n -Körper-Problems. 1. Mitteilung.
(Mitteilung vom 31. Januar.) (S. 168)

BERLIN 1918

VERLAG DER KÖNIGLICHEN AKADEMIE DER WISSENSCHAFTEN

IN KOMMISSION BEI GEORG REIMER

Über Gravitationswellen.

VON A. EINSTEIN.

(Vorgelegt am 31. Januar 1918 [s. oben S. 79].)

Die wichtige Frage, wie die Ausbreitung der Gravitationsfelder erfolgt, ist schon vor anderthalb Jahren in einer Akademiearbeit von mir behandelt worden¹. Da aber meine damalige Darstellung des Gegenstandes nicht genügend durchsichtig und außerdem durch einen bedauerlichen Rechenfehler verunstaltet ist, muß ich hier nochmals auf die Angelegenheit zurückkommen.

Wie damals beschränke ich mich auch hier auf den Fall, daß das betrachtete zeiträumliche Kontinuum sich von einem »galileischen« nur sehr wenig unterscheidet. Um für alle Indizes

$$g_{\mu\nu} = -\delta_{\mu\nu} + \gamma_{\mu\nu} \quad (1)$$

Sind die Bedingungen (15) erfüllt, so stellt (14) eine mögliche Gravitationswelle dar. Um deren physikalische Natur genauer zu durchschauen, berechnen wir deren Dichte des Energiestromes $\frac{t_{41}}{i}$. Durch Einsetzen der in (15) gegebenen $\gamma_{\mu\nu}^i$ in Gleichung (9) erhält man

$$\frac{t_{41}}{i} = \frac{1}{4\kappa} f'^2 \left[\left(\frac{\alpha_{22} - \alpha_{33}}{2} \right)^2 + \alpha_{23}^2 \right]. \quad (16)$$

$$\mathfrak{J}_{uv} = \int x_u x_v \rho dV_0 \quad (23)$$

gesetzt; \mathfrak{J}_{uv} sind die Komponenten des (zeitlich variablen) Trägheitsmomentes des materiellen Systems.

Auf analogem Wege erhält man

$$\int (T_{22} - T_{33}) dV_0 = \frac{1}{2} (\ddot{\mathfrak{J}}_{22} - \ddot{\mathfrak{J}}_{33}). \quad (24)$$

Aus (7a) ergibt sich auf Grund von (22) und (24)

$$\gamma'_{23} = -\frac{\kappa}{4\pi R} \ddot{\mathfrak{J}}_{23}. \quad (25)$$

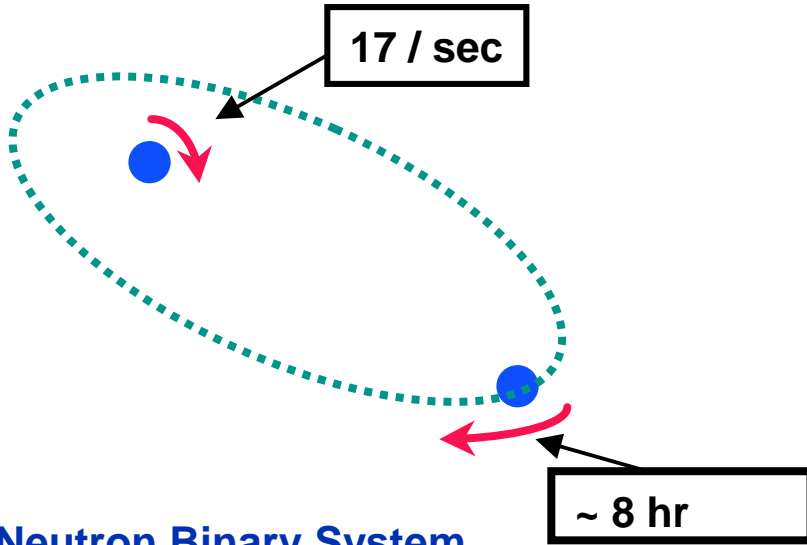
$$\frac{\gamma'_{22} - \gamma'_{33}}{2} = -\frac{\kappa}{4\pi R} \left(\frac{\ddot{\mathfrak{J}}_{22} - \ddot{\mathfrak{J}}_{33}}{2} \right). \quad (26)$$

Die \mathfrak{J}_{uv} sind nach (7a), (22), (24) für die Zeit $t-R$ zu nehmen, also Funktionen von $t-R$, oder bei großem R in der Nähe der x -Achse auch Funktionen von $t-x$. (25), (26) stellen also Gravitationswellen dar, deren Energiefluß längs der x -Achse gemäß (16) die Dichte

$$\frac{t_{41}}{i} = \frac{\kappa}{64\pi^2 R^2} \left[\left(\frac{\ddot{\mathfrak{J}}_{22} - \ddot{\mathfrak{J}}_{33}}{2} \right)^2 + \ddot{\mathfrak{J}}_{23}^2 \right] \quad (27)$$

Neutron Binary System – Hulse & Taylor

PSR 1913 + 16 -- Timing of pulsars



Neutron Binary System

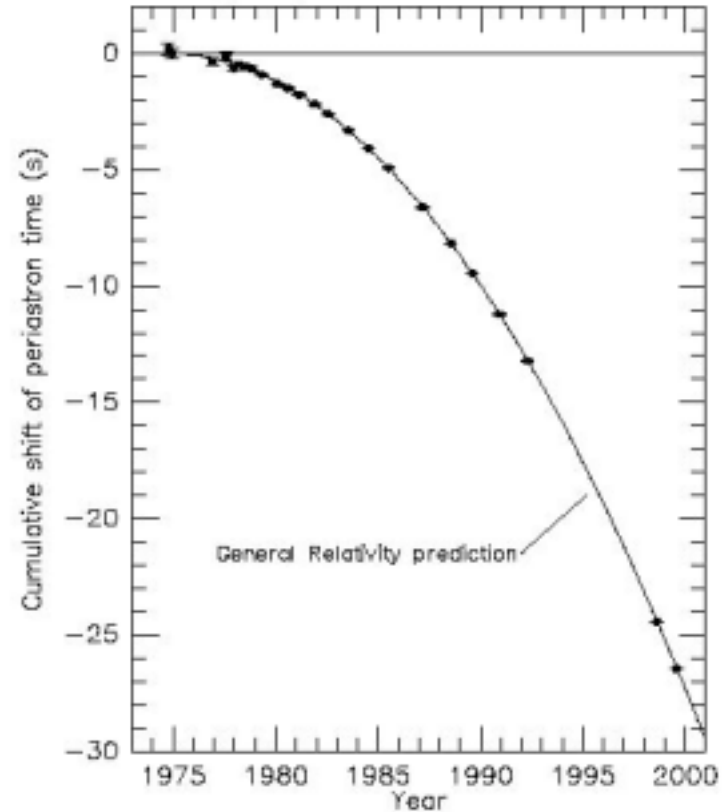
- separated by 10^6 miles
- $m_1 = 1.4m_{\odot}$; $m_2 = 1.36m_{\odot}$; $\varepsilon = 0.617$

Prediction from general relativity

- spiral in by 3 mm/orbit
- rate of change orbital period

Emission of gravitational waves

Comparison between observations of the binary pulsar PSR1913+16, and the prediction of general relativity based on loss of orbital energy via gravitational waves



From J. H. Taylor and J. M. Weisberg, unpublished (2000)

Direct detection of gravitational waves from astrophysical sources

□ Physics

- » Observations of gravitation in the strong field, high velocity limit
- » Determination of wave kinematics – polarization and propagation
- » Tests for alternative relativistic gravitational theories

□ Astrophysics

- » Measurement of coherent inner dynamics – stellar collapse, pulsar formation....
- » Compact binary coalescence – neutron star/neutron star, black hole/black hole
- » Neutron star equation of state
- » Primeval cosmic spectrum of gravitational waves

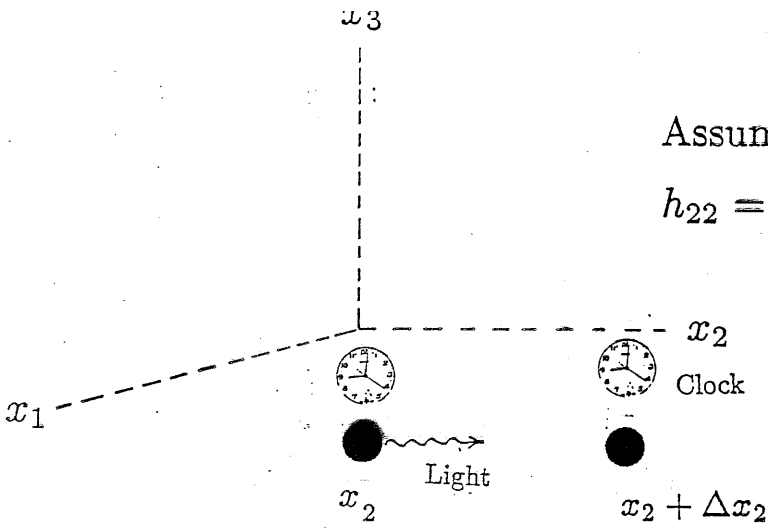
□ Gravitational wave survey of the universe

Measurement challenge

- Needed technology development to measure:

$$h = \Delta L/L < 10^{-21}$$

$$\Delta L < 4 \times 10^{-18} \text{ meters}$$



Assume + Polarization

$$h_{22} = h \sin(kx_1 - \omega t)$$

$$\Delta s^2 = 0 = c^2 \Delta t^2 - \left(1 + h \sin(kx_1 - \omega t)\right) \Delta x_2^2$$

LIGHT RAY

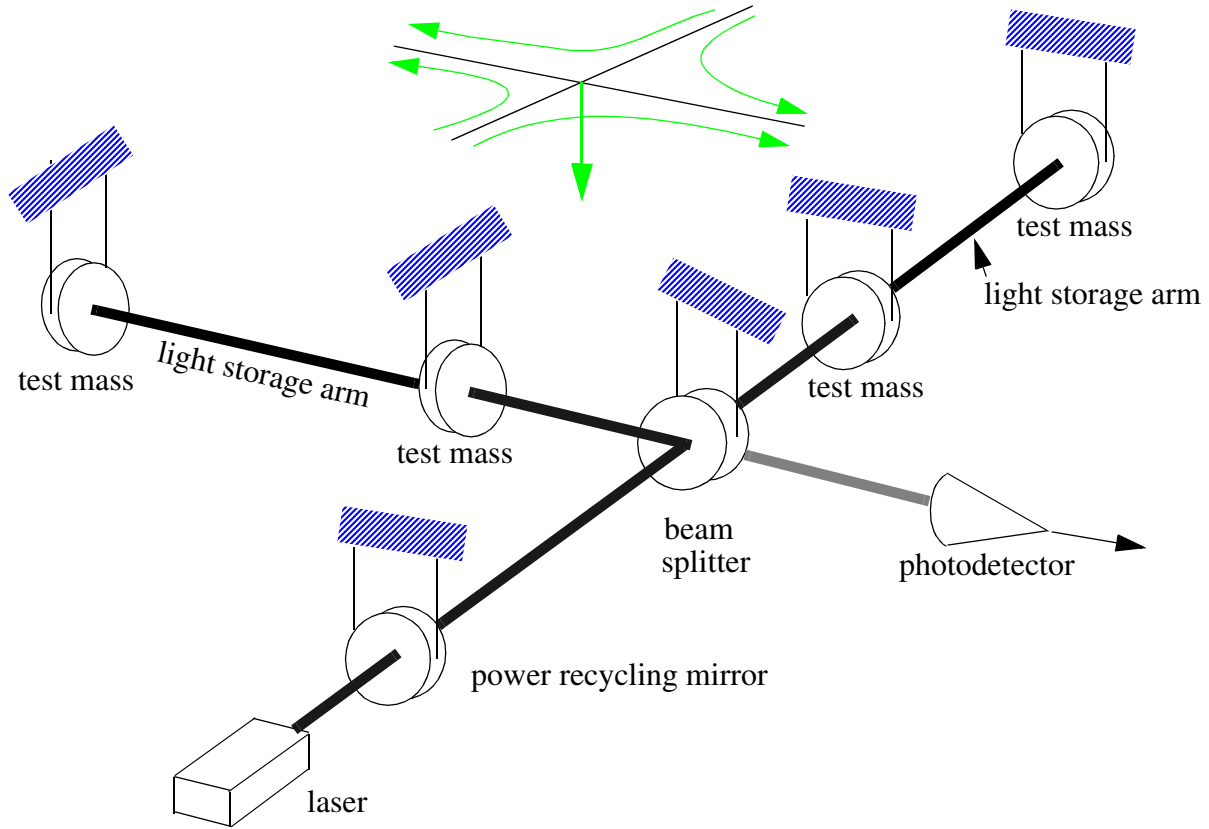
Let $\Delta t \ll \frac{1}{\omega}$ $h \ll 1$

$$c \Delta t \cong \left(1 + \frac{h}{2} \sin(kx_1 - \omega t)\right) \Delta x_2$$

↙ INFERRED DISTANCE BETWEEN POINTS

$$\frac{\delta(c \Delta t)}{\Delta x_2} = \frac{h}{2} \sin(kx_1 - \omega t) \quad \text{Time Dependent Strain}$$

$$\frac{\Delta l}{l} = \frac{h}{2} \quad \text{The Measurable Quantity}$$



FRINGE SENSING

wavelength $1 \times 10^{-6} \text{ m}$

$$h = \frac{x}{L} \sim \frac{\lambda}{Lb \sqrt{N\tau}}$$

arm length = 4000 m

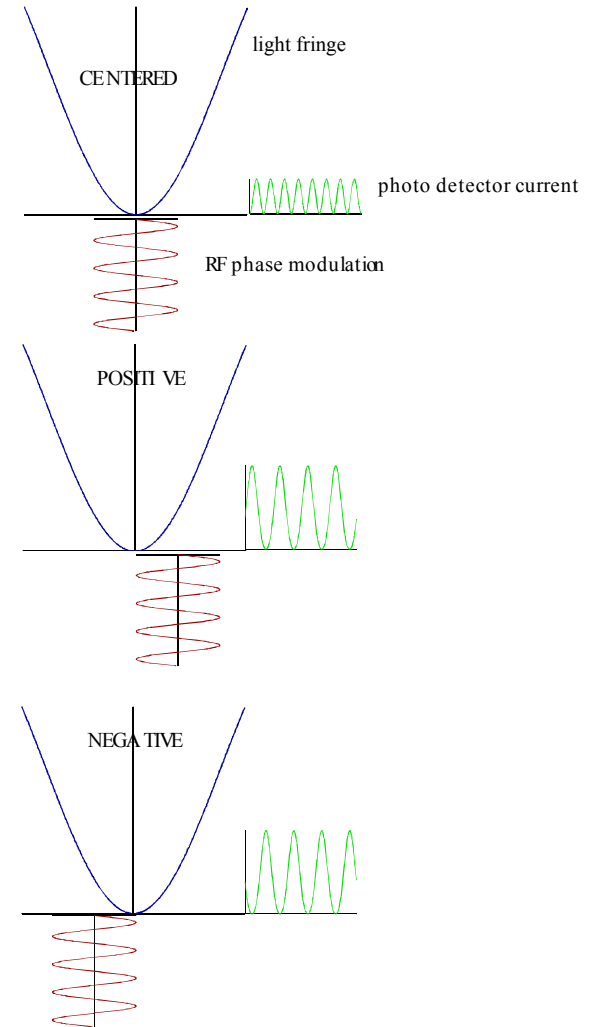
equivalent # of passes = 100

integration time

number of quanta/second at the beam splitter

300 watts at beam splitter = 10^{21} identical photons/sec

$$h = 6 \times 10^{-22} \quad \text{integration time } 10^{-2} \text{ sec}$$



PENDULUM THERMAL NOISE

Pendulum Brownian motion

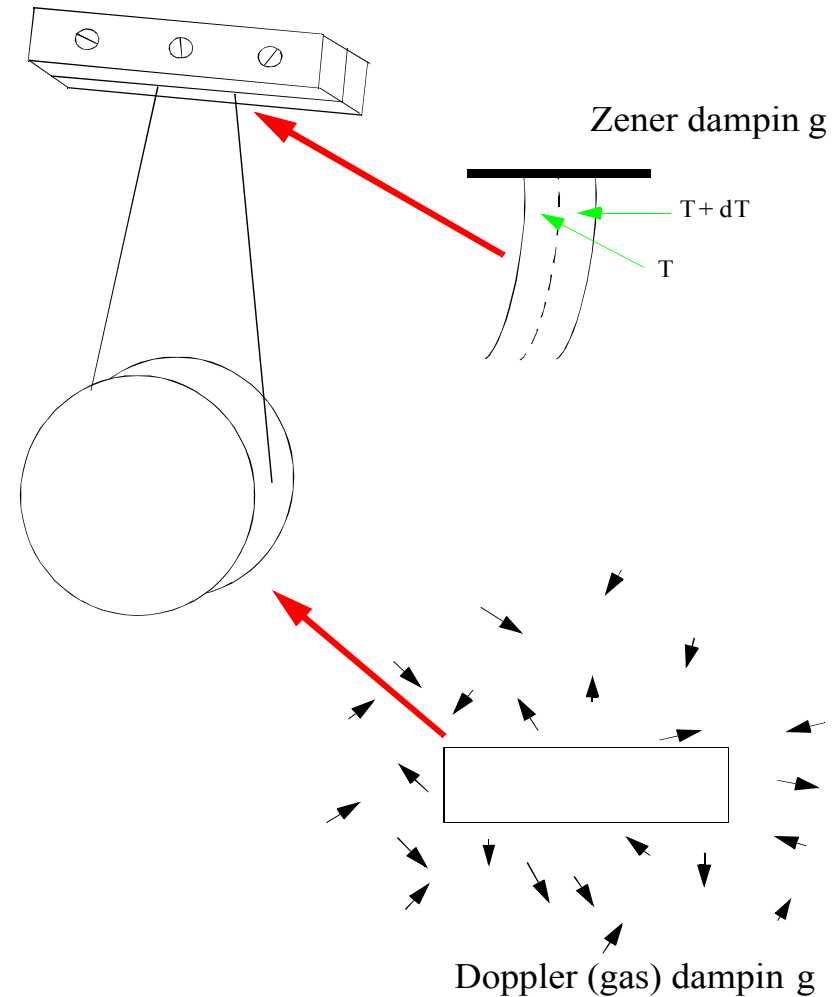
Dissipation leads to fluctuations

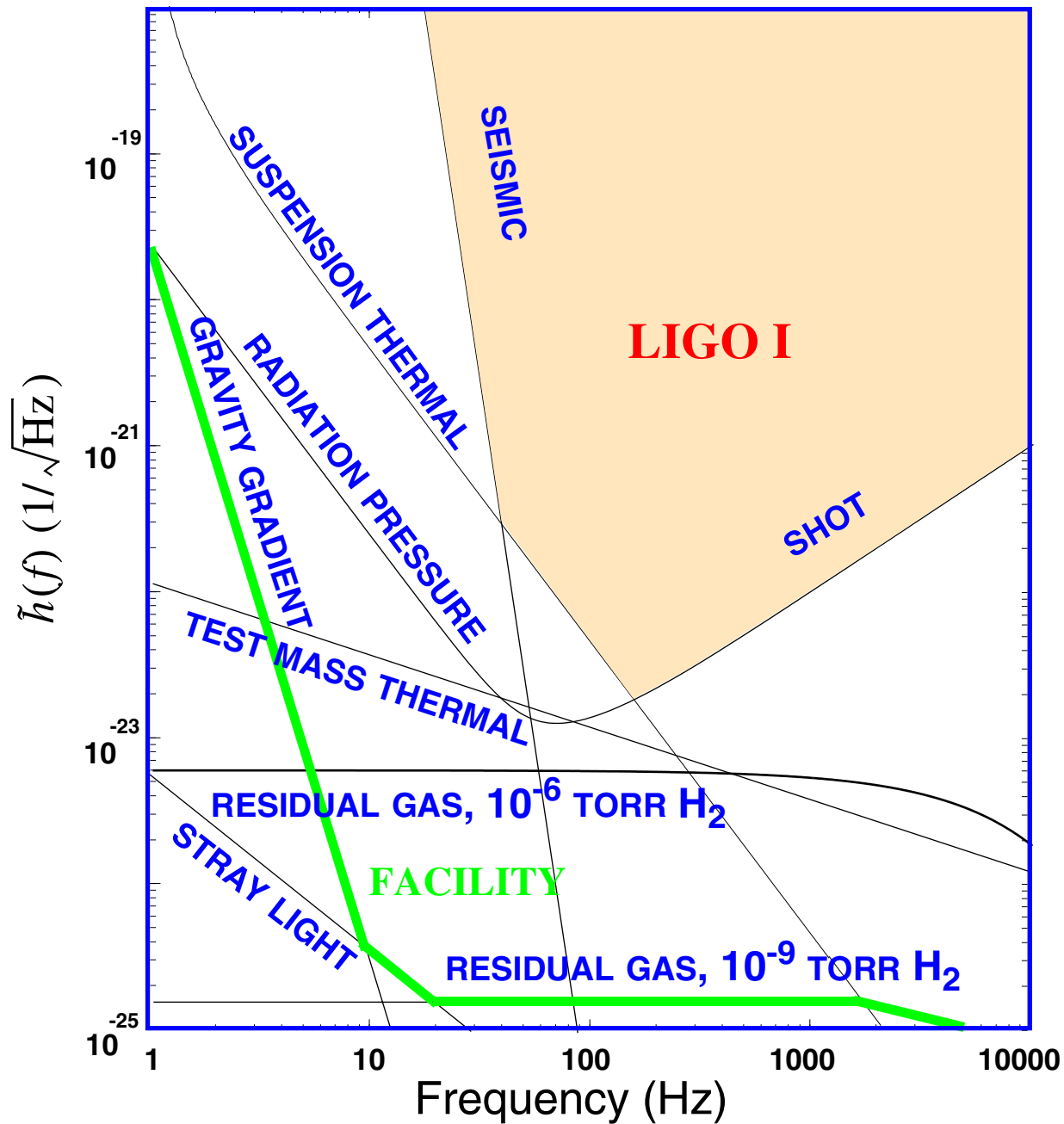
T_c = coherence or damping time
= $Q \times$ period of oscillator

Exchange with surroundings:

$$E(\text{thermal}) = \frac{kT t}{T_c}$$

Large $T_c \Rightarrow$ smaller fluctuations

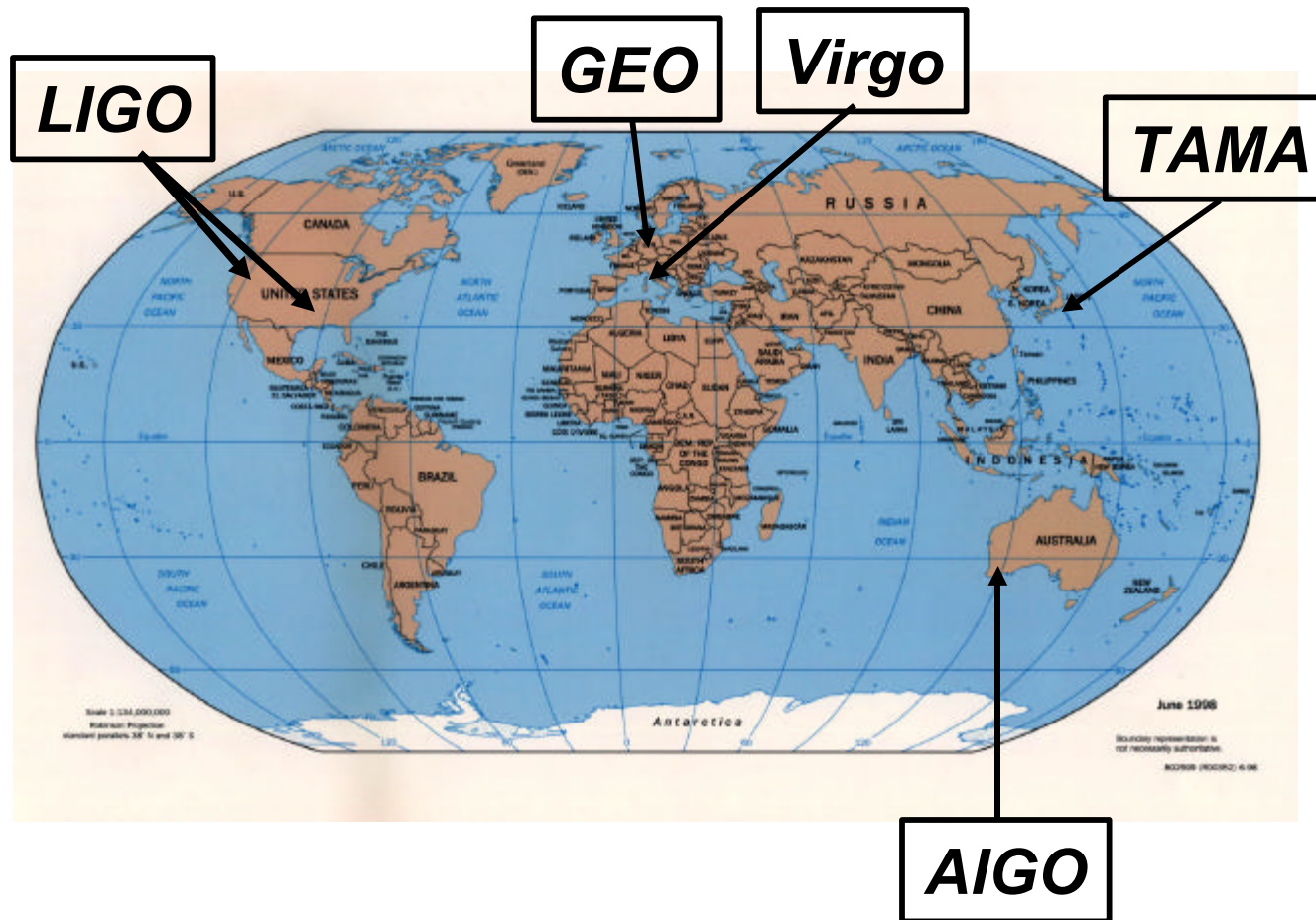




Interferometers

international network

Simultaneously detect signal (within msec)



detection
confidence

locate the
sources

decompose the
polarization of
gravitational
waves



LIGO Observatory Facilities



LIGO Hanford Observatory [LHO]

26 km north of Richland, WA

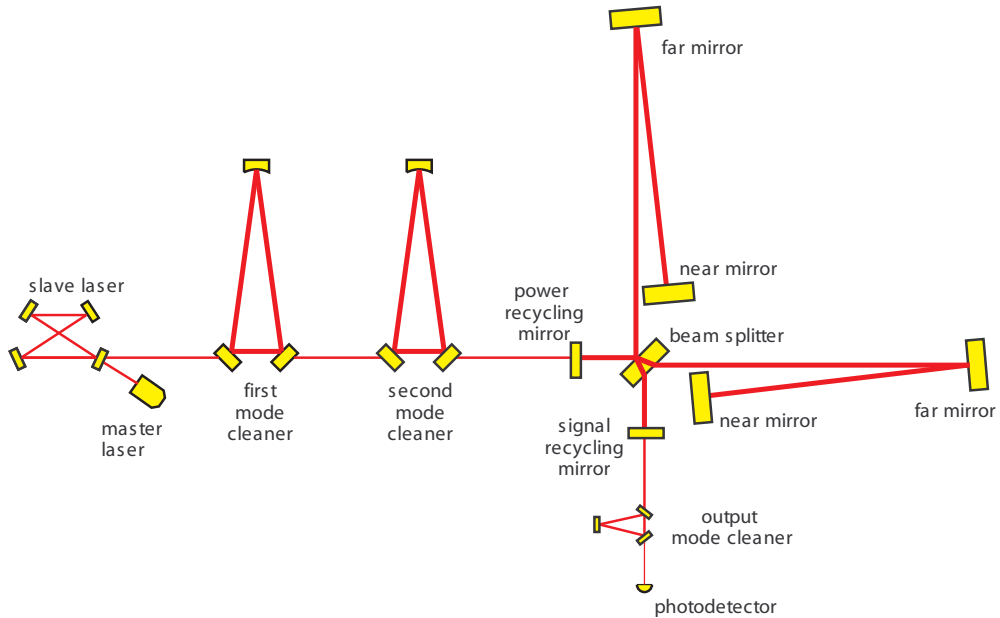
2 km + 4 km interferometers in same vacuum envelope



LIGO Livingston Observatory [LLO]

42 km east of Baton Rouge, LA

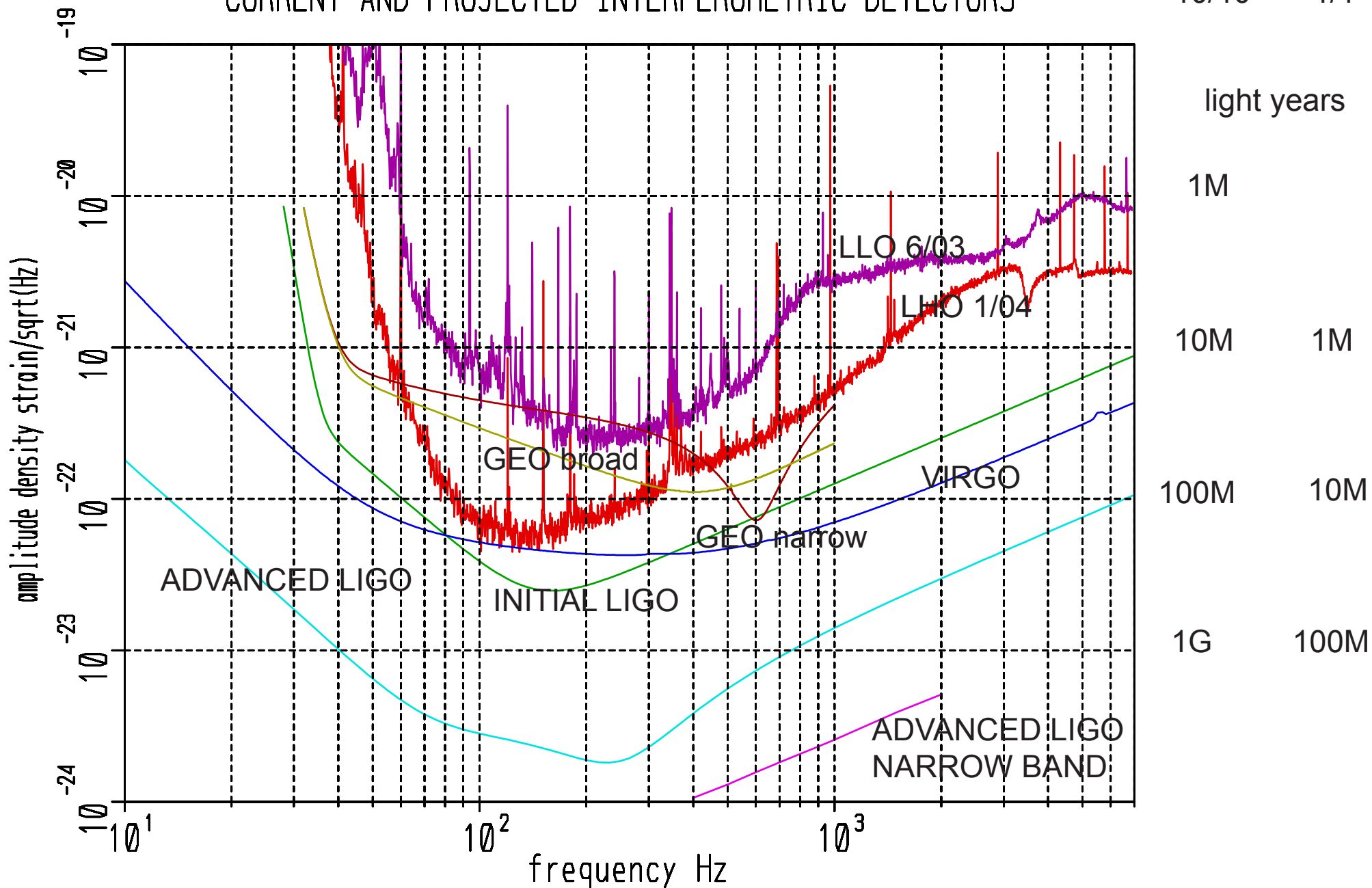
Single 4 km interferometer





CURRENT AND PROJECTED INTERFEROMETRIC DETECTORS

BH/BH 10/10
NS/NS 1/1



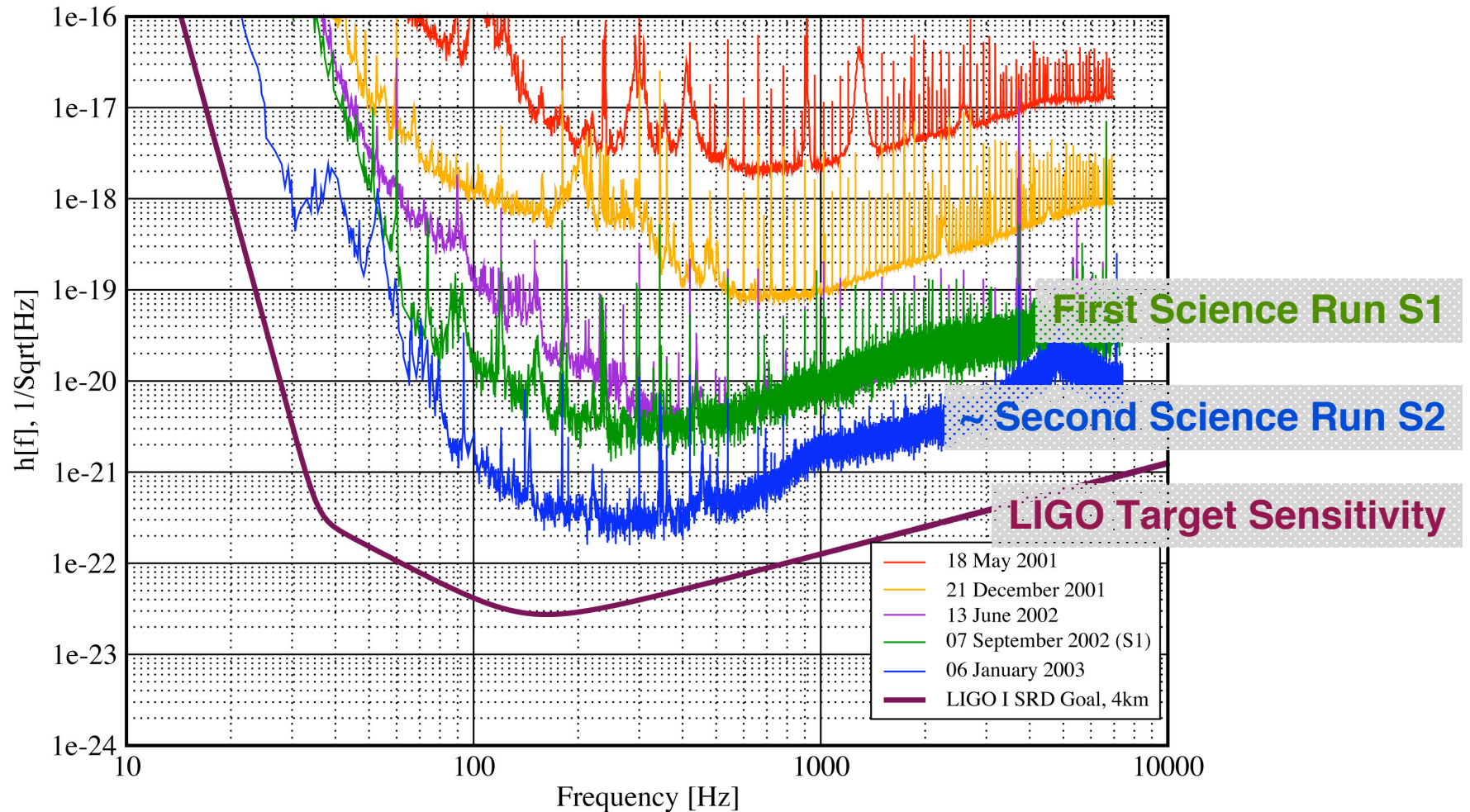


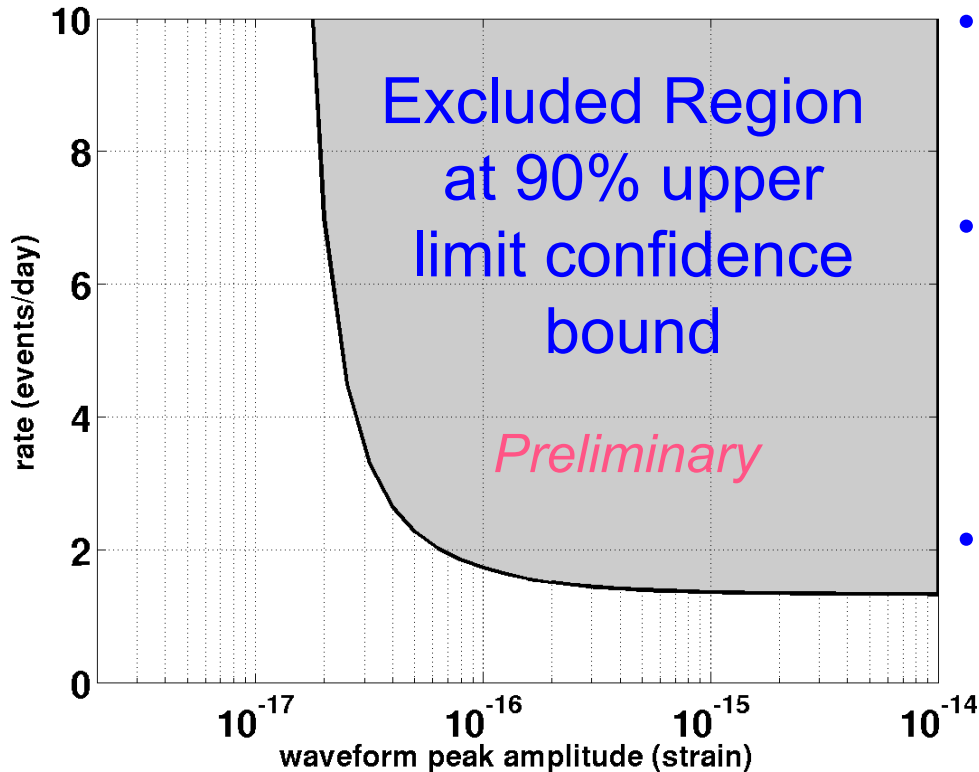
Gravitational Radiation and Detectors: LIGO Sensitivity Improvements

Strain Sensitivity for the LLO 4km Interferometer

31 January 2003

LIGO-G030014-00-E



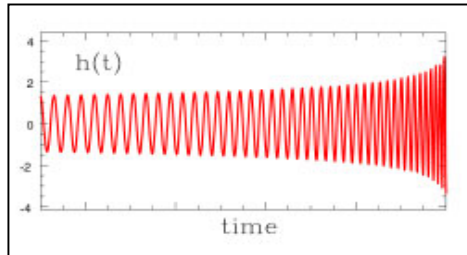


- *Able to exclude gravitational wave bursts of peak strength h above rate r*
- *Burst model --*
 - » *1 ms width Gaussian pulse*
 - » *Linear polarization with random orientation*
 - » *Arriving from random directions*
- *Upper limit in strain sensitivity with regard to prior (cryogenic bar) observations:*
 - » *Within 5X of IGEC 2000¹ results*
 - *ICEG observation time was much longer than S1 - 90 days (triple bars)*
 - » *Within 25X of Astone² et al. 2001 sensitivity*

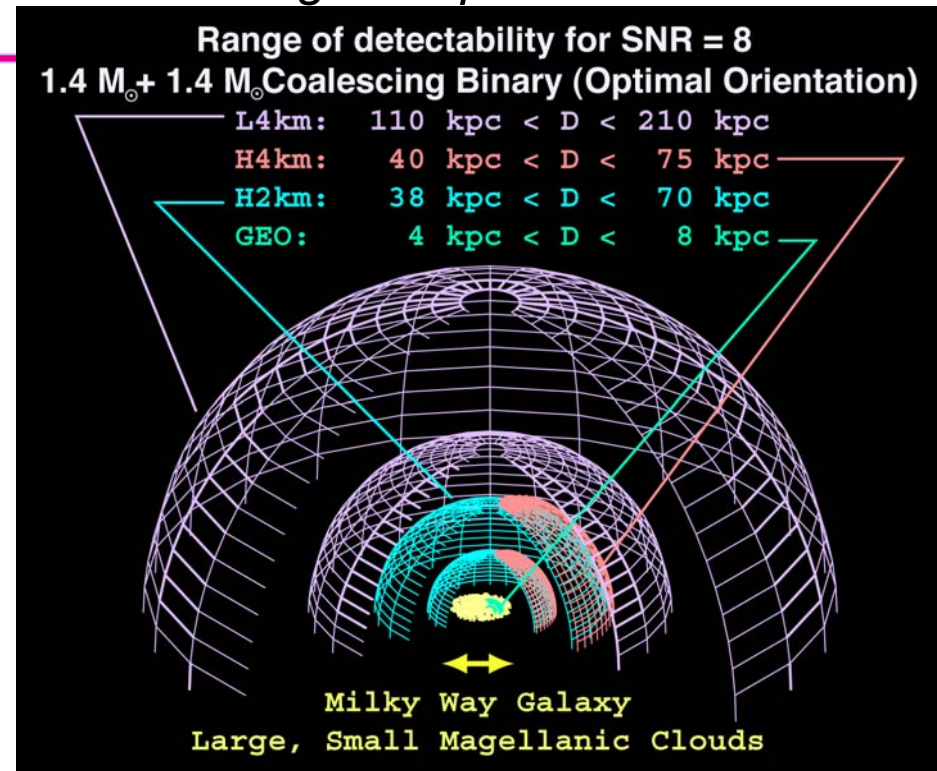
Work in progress:

- *Correlations with gamma ray bursts*
- *Observed Type II SNe*

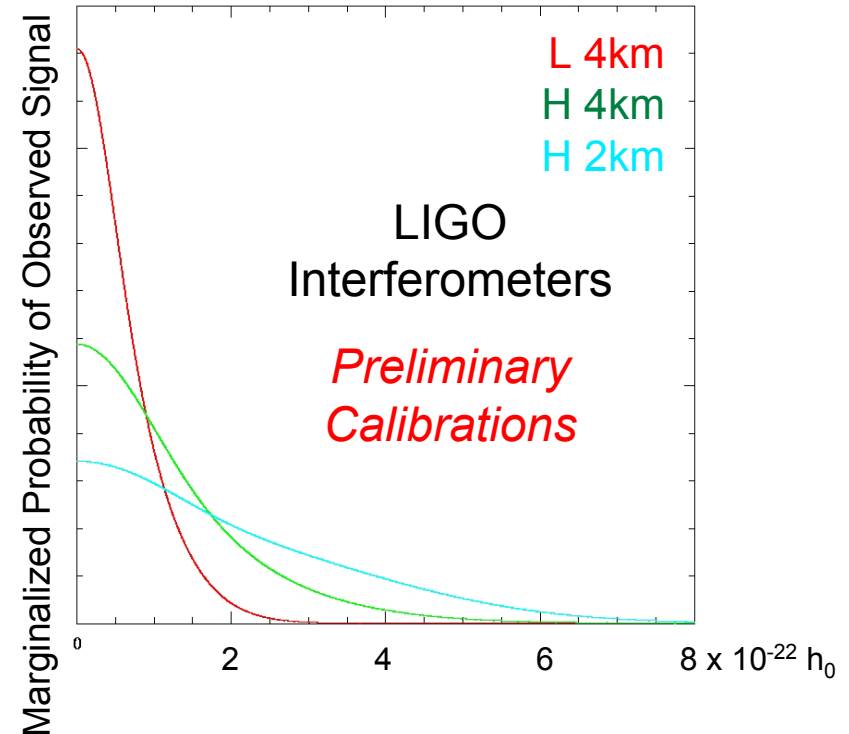
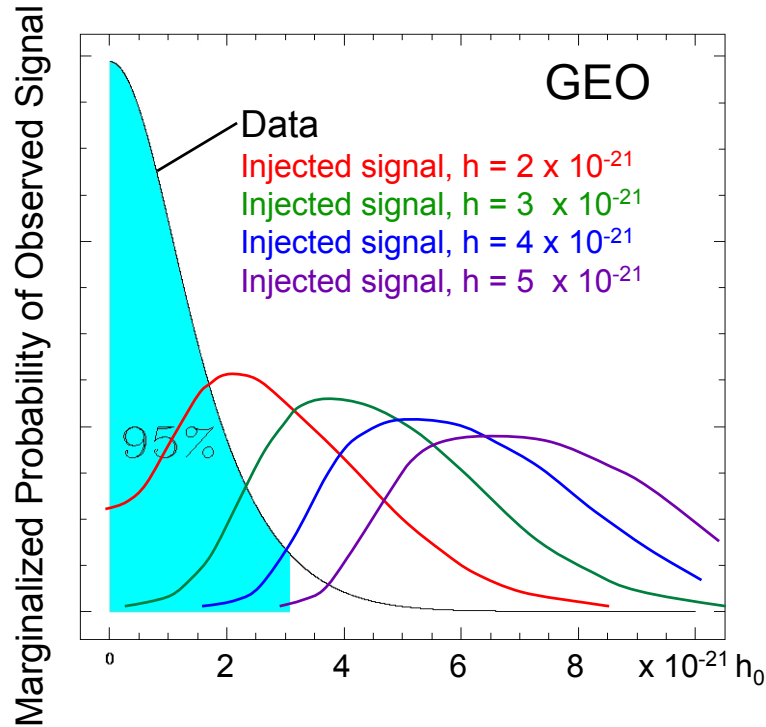
- Three targets:
 - » Neutron star binaries ($1-3 M_{\text{sun}}$)
 - » Black hole binaries ($> 3 M_{\text{sun}}$)
 - » MACHO binaries ($0.5-1 M_{\text{sun}}$)
- Search method
 - » template based matched filtering



- Status
 - ✓ Neutron star search complete
 - » MACHO search under way
 - » Black hole search will be done in next science run, S2



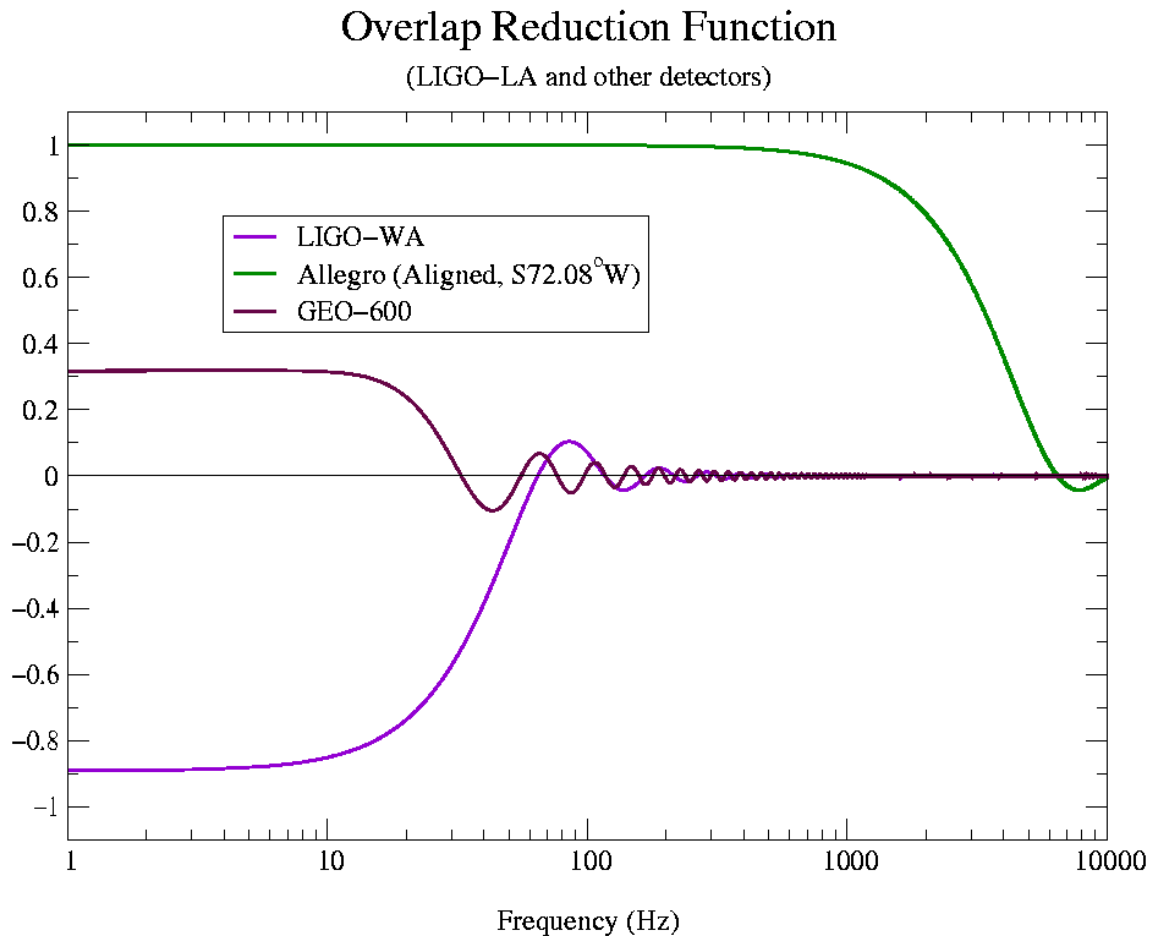
- Limit on binary neutron star coalescence rate:
 - » $R_{90\%} (\text{Milky Way}) < 2.3 / (0.35 \times 295.3 \text{ hr}) = 170 / \text{yr}$
- Use triggers from H 4km and L 4km interferometers: $T = 295.3 \text{ hours}$
 - » Monte Carlo simulation efficiency: $\varepsilon = 35\%$
 - » 90% confidence limit = $2.3 / (\varepsilon T)$
- **26X lower than best published observational limit -- 40m prototype at Caltech¹:**
 - » $R_{90\%} (\text{Milky Way}) < 4400 / \text{yr}$



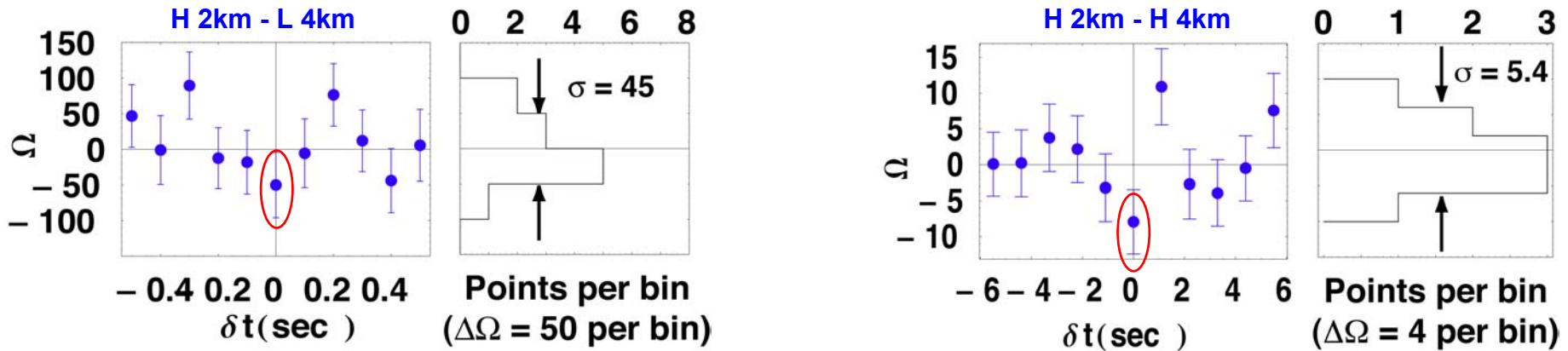
- No evidence of signal from PSR J1939 at $f = 1283.86$ Hz
- 95% of the probability lies below:
 - GEO: $h_{\max} < 3 \times 10^{-21}$
 - H 2km: $h_{\max} < 5 \times 10^{-22}$
 - H 4km: $h_{\max} < 3 \times 10^{-22}$
 - **L 4km: $h_{\max} < 2 \times 10^{-22}$ ($\varepsilon < 7 \times 10^{-5}$ @ 3.6 kpc)**

Overlap reduction function

Specifies the reduction in sensitivity due to the **separation** and **orientation** of the two detectors:

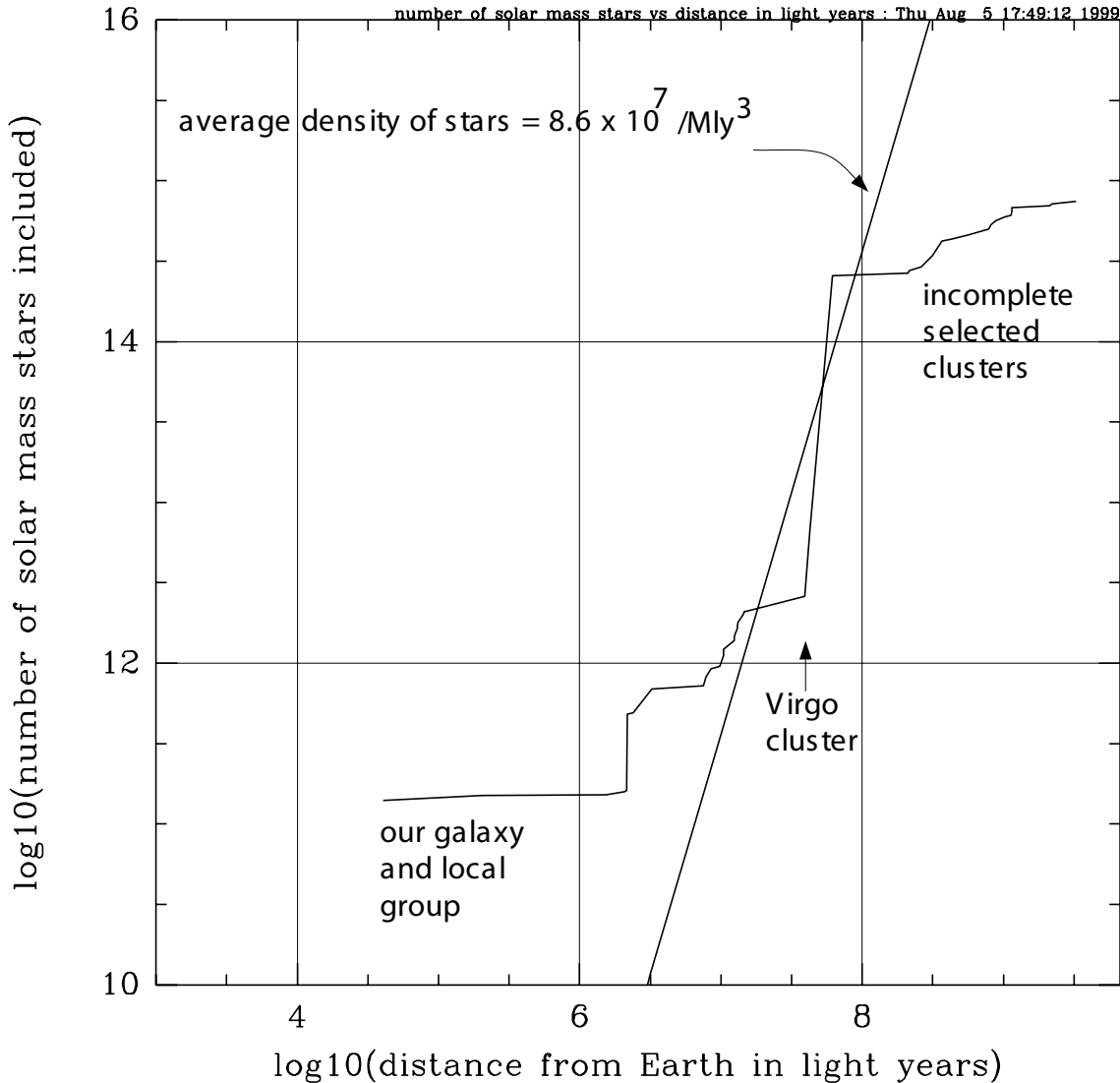


- Preliminary results from 7.5 hr of data -



- Introduce non-astrophysical time lags (>20 ms) to determine backgrounds (*off-source*)
 - $\delta t = 0$ sec (*on-source*) measurements consistent with *off-source* backgrounds
- Extrapolated S1 H 2km - H 4km result covers **240 Hz bandwidth**, is **~10X better** than best published result for *direct measurement* of Ω_{GW} (Astone et al., 1999, cryogenic bar, 907 Hz).
- Ultimate sensitivity for LIGO I: $\sim 1 \times 10^{-5}$ for $T_{\text{obs}} = 4$ months

Interferometer Pair	Measurement Bandwidth	Extrapolated Upper Limit for S1 (by scaling 7.5 hrs to 150 or 100 hrs)	T_{obs}
H 2km - H 4km	40 Hz $< f <$ 300 Hz	$\Omega_{\text{GW}} < 5$ (90% C.L.)	150 hr
H 4km - L 4km	40 Hz $< f <$ 314 Hz	$\Omega_{\text{GW}} < 70$ (90% C.L.)	100 hr
H 2km - L 4km	40 Hz $< f <$ 314 Hz	$\Omega_{\text{GW}} < 50$ (90% C.L.)	100 hr



DATA: Cosmology of the Local Group G.Lake
Astrophysical Quantities C.W.Allen



Binary Coalescence Sources & Science: Binary Neutron Stars: S1 Range

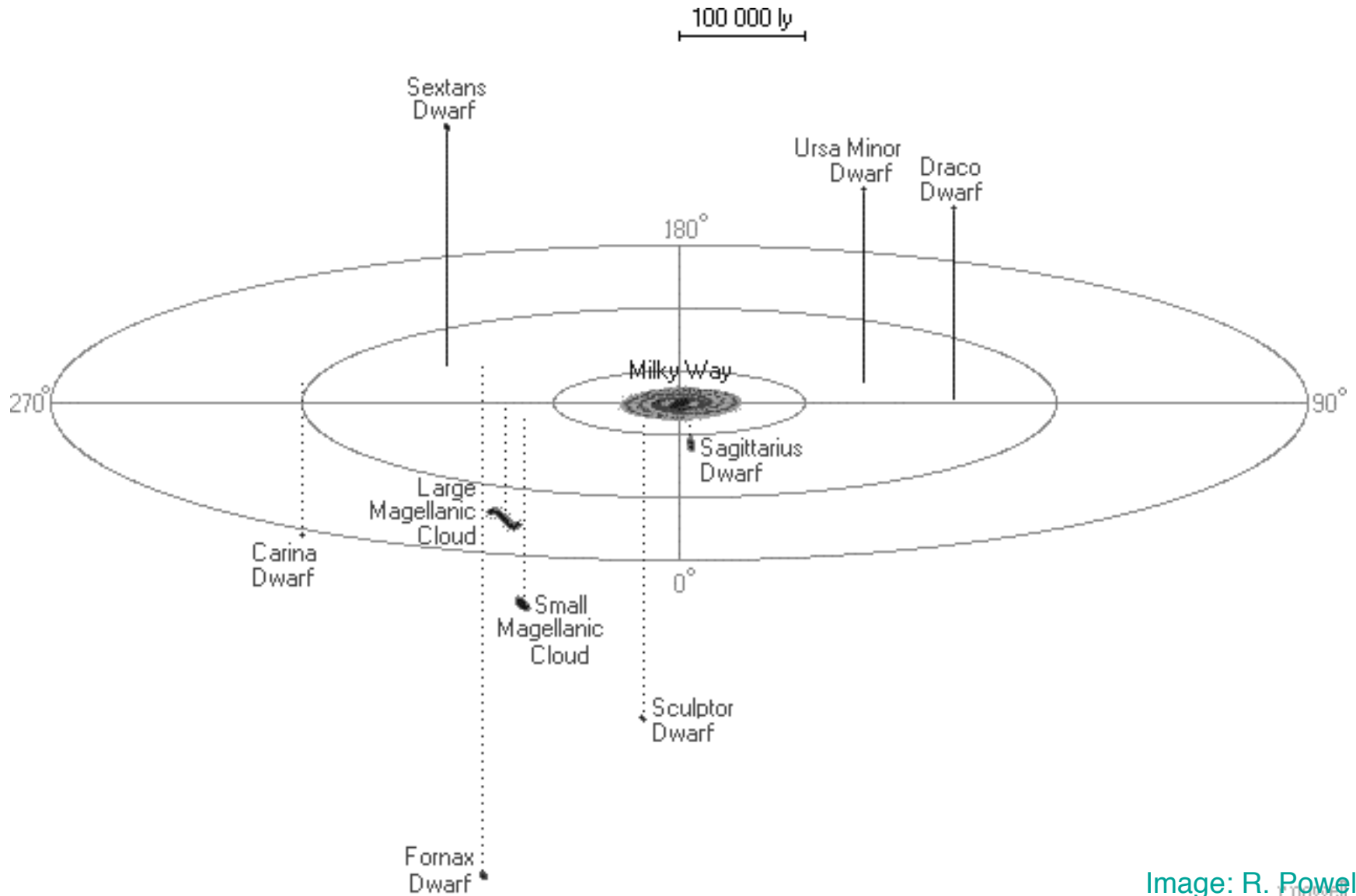


Image: R. Powell



Binary Coalescence Sources & Science: Binary Neutron Stars: S2 Range

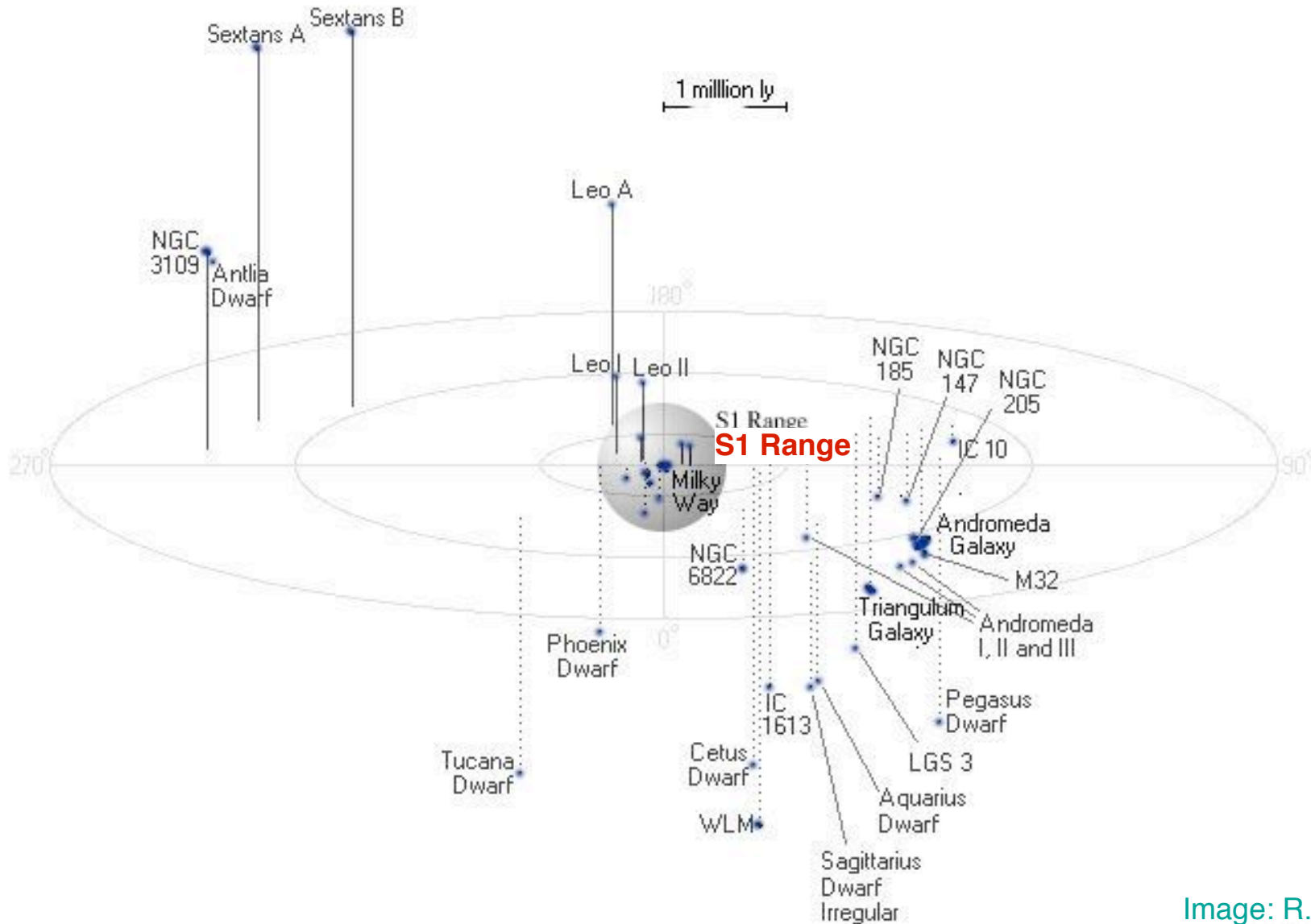


Image: R. Powell
cpowell



Binary Coalescence Sources & Science: Binary Neutron Stars: LIGO Range

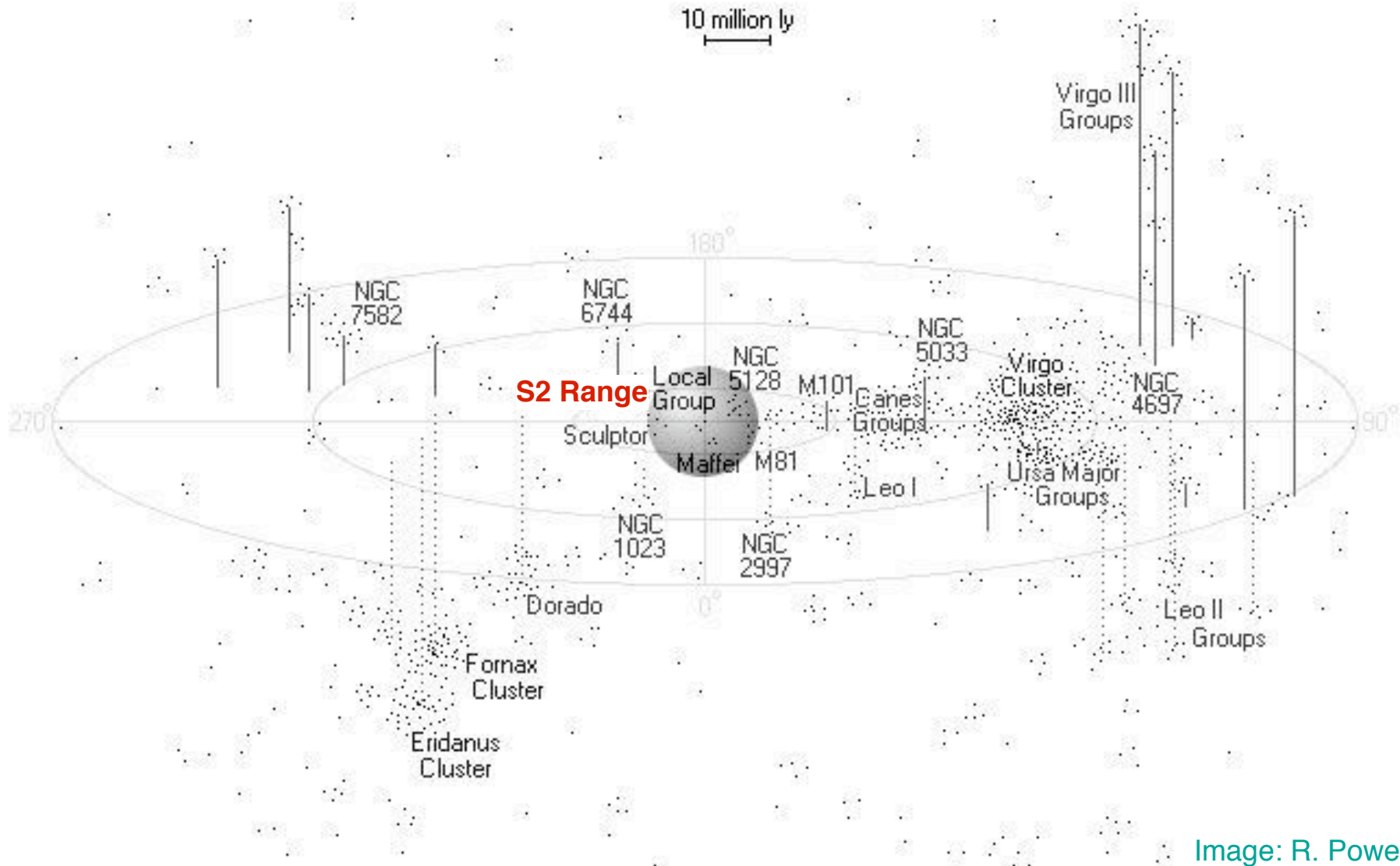
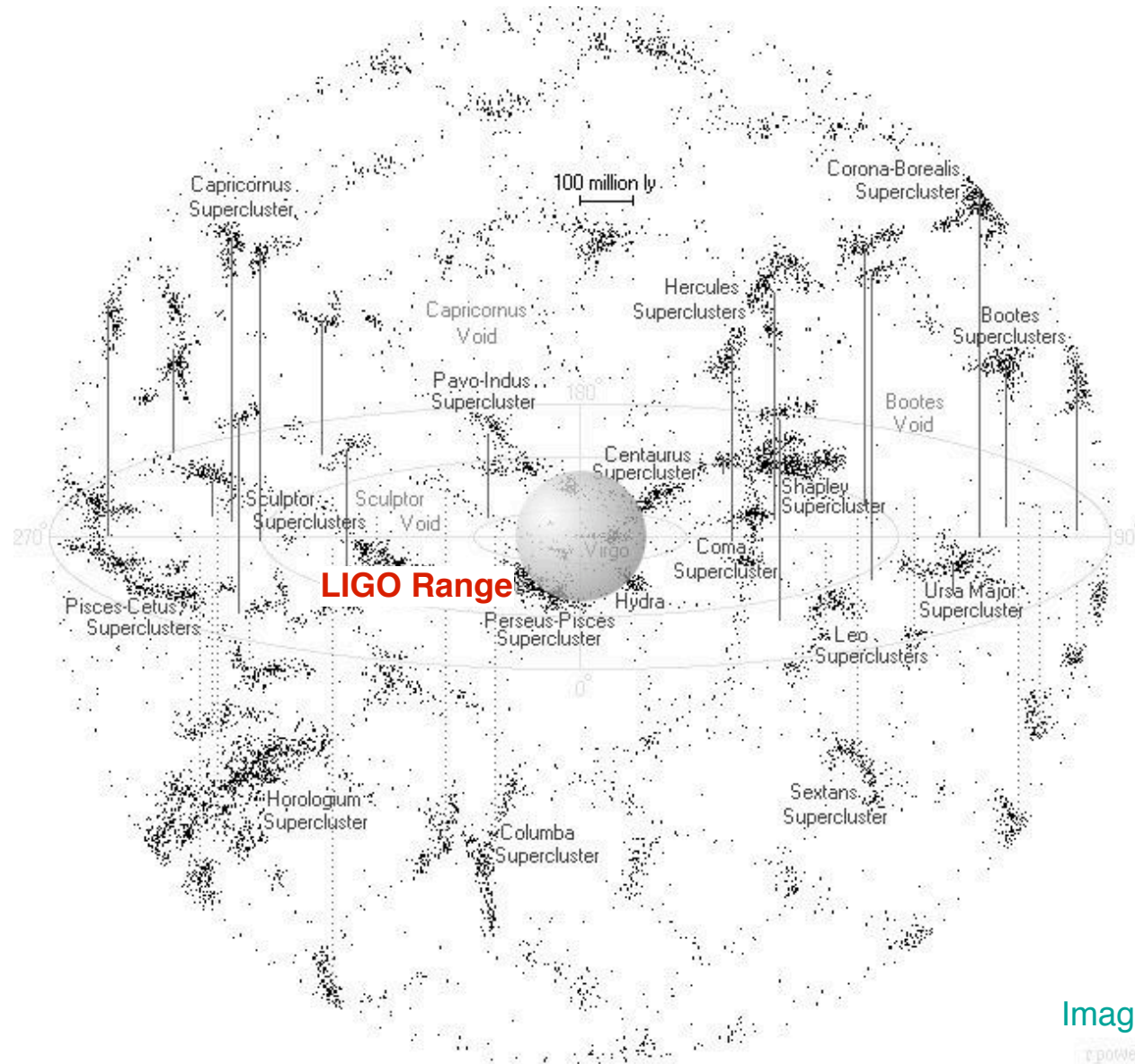


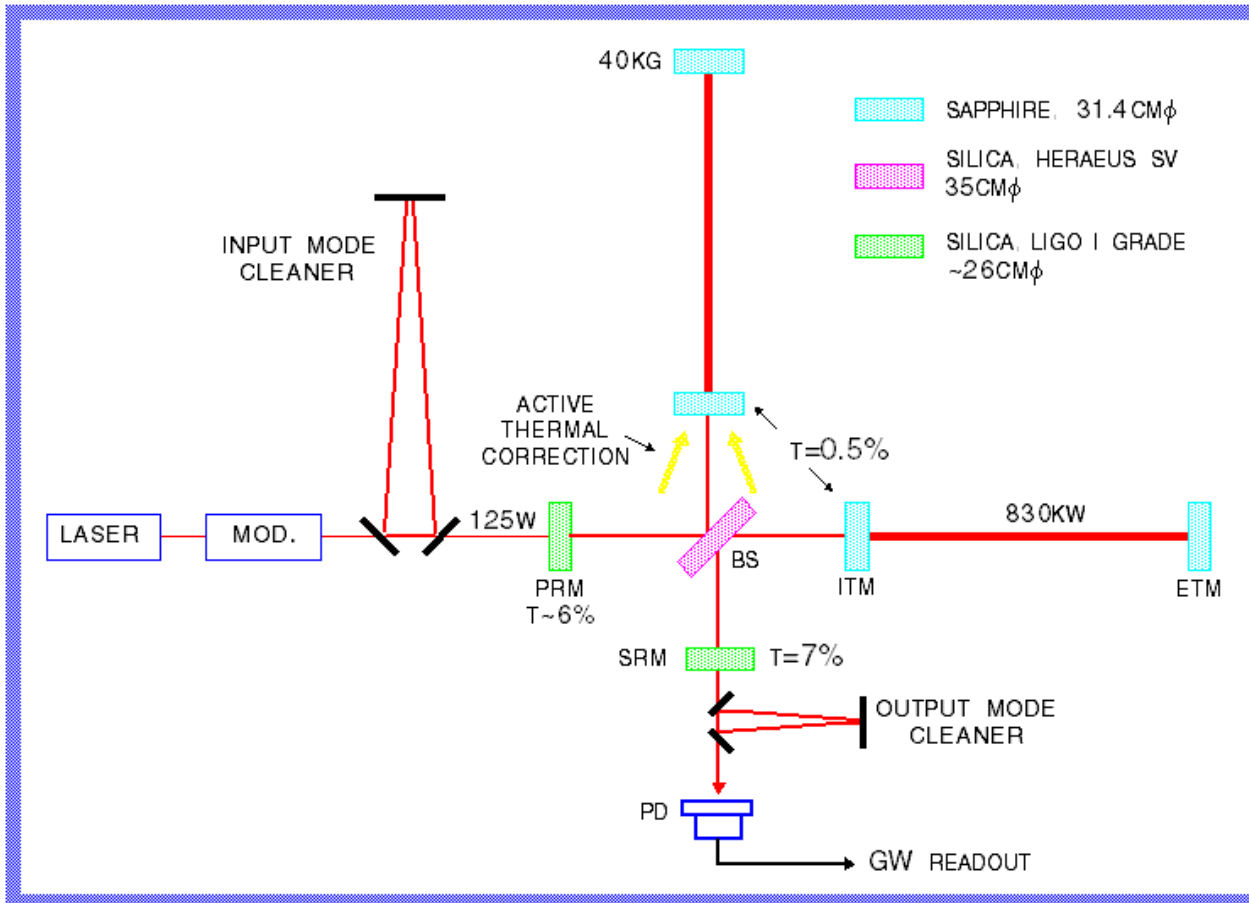
Image: R. Powell



Binary Coalescence Sources & Science: Binary Neutron Stars: AdLIGO Range



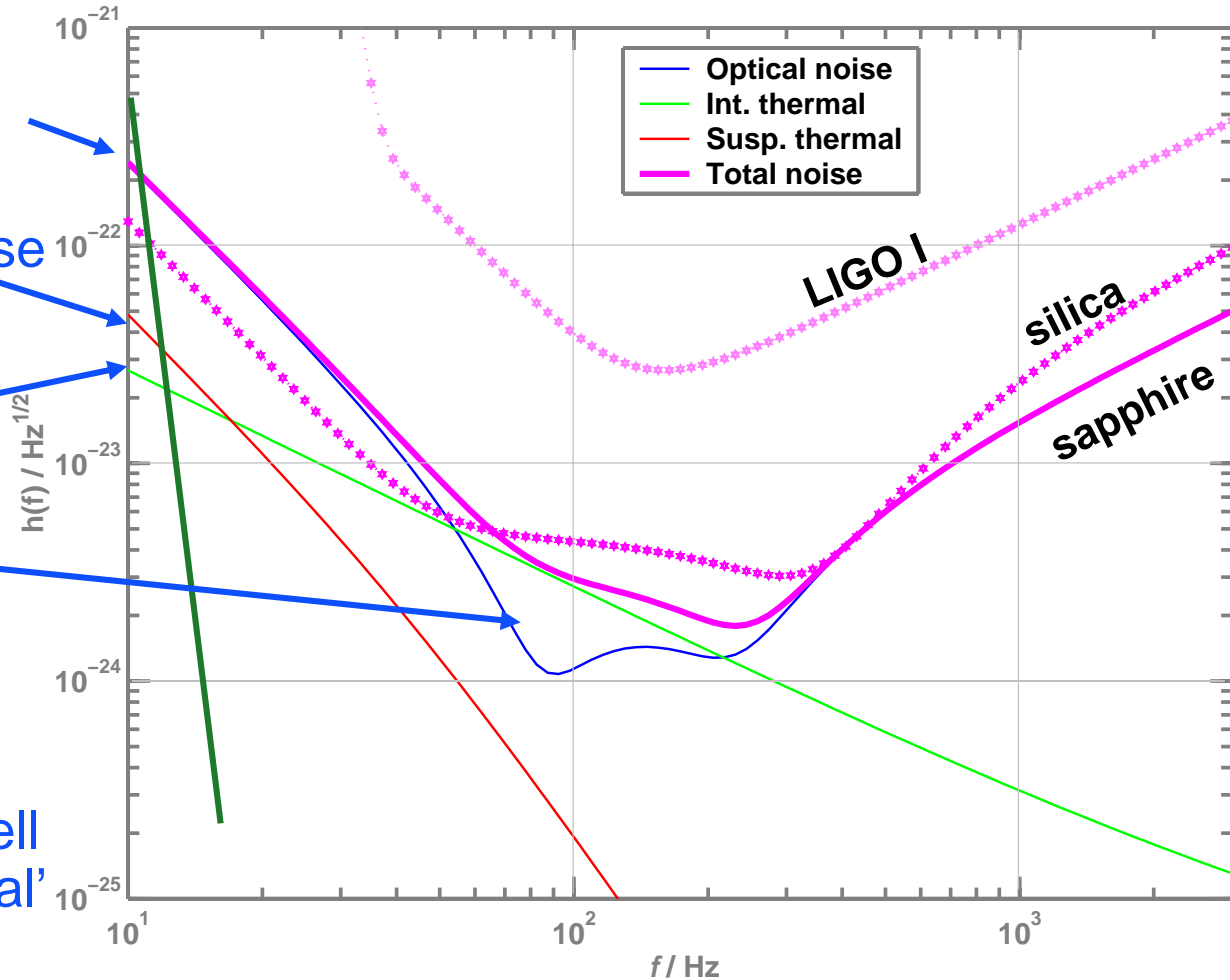
Advanced Interferometer Concept



- » Signal recycling
- » 180-watt laser
- » 40 kg Sapphire test masses
- » Larger beam size
- » Quadruple suspensions
- » Active seismic isolation
- » Active thermal correction
- » Output mode cleaner

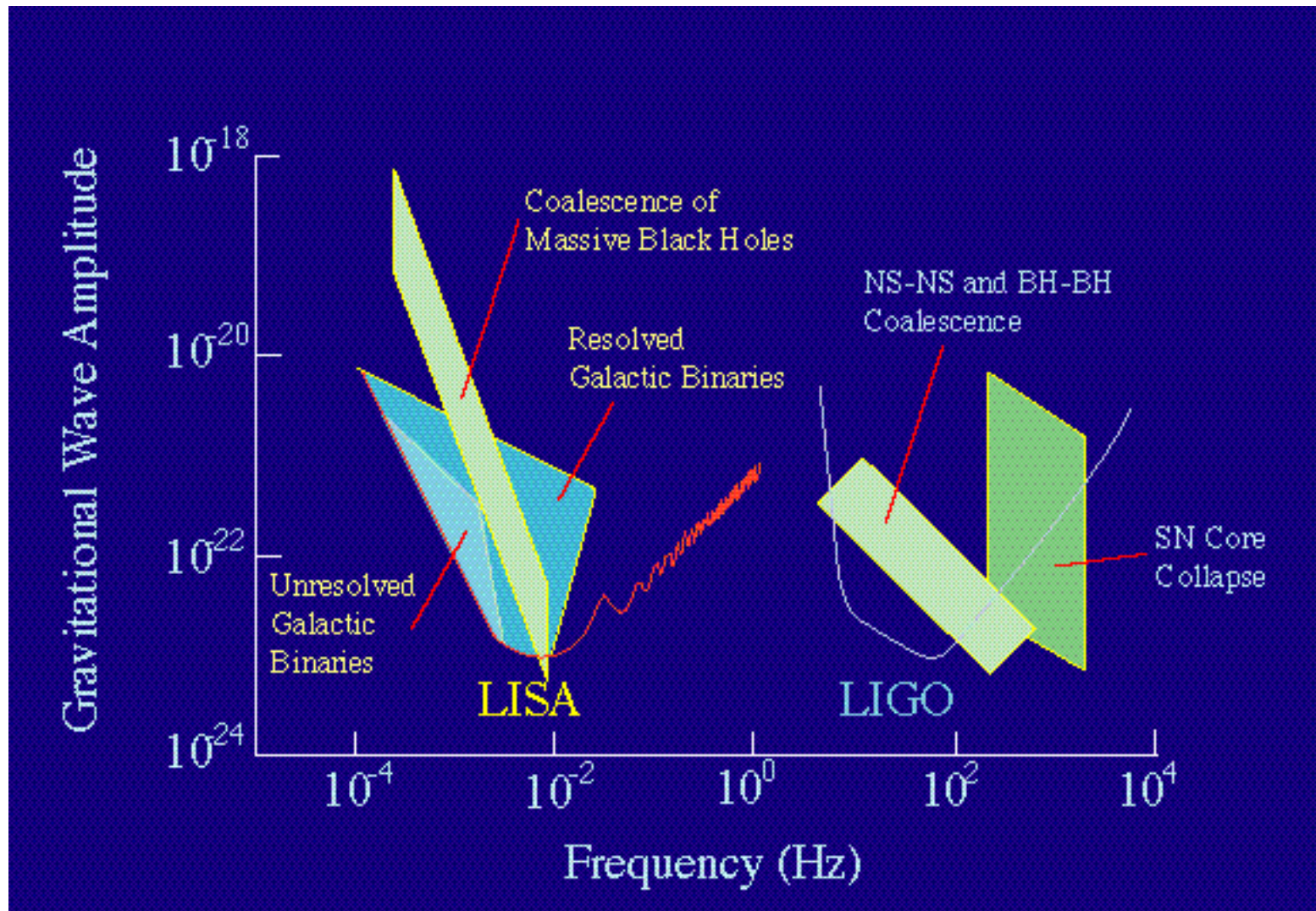
Projected Performance

- Seismic ‘cutoff’ at 10 Hz
- Suspension thermal noise
- Internal thermal noise
- Unified quantum noise dominates at most frequencies
- ‘technical’ noise (e.g., laser frequency) levels held in general well below these ‘fundamental’ noises



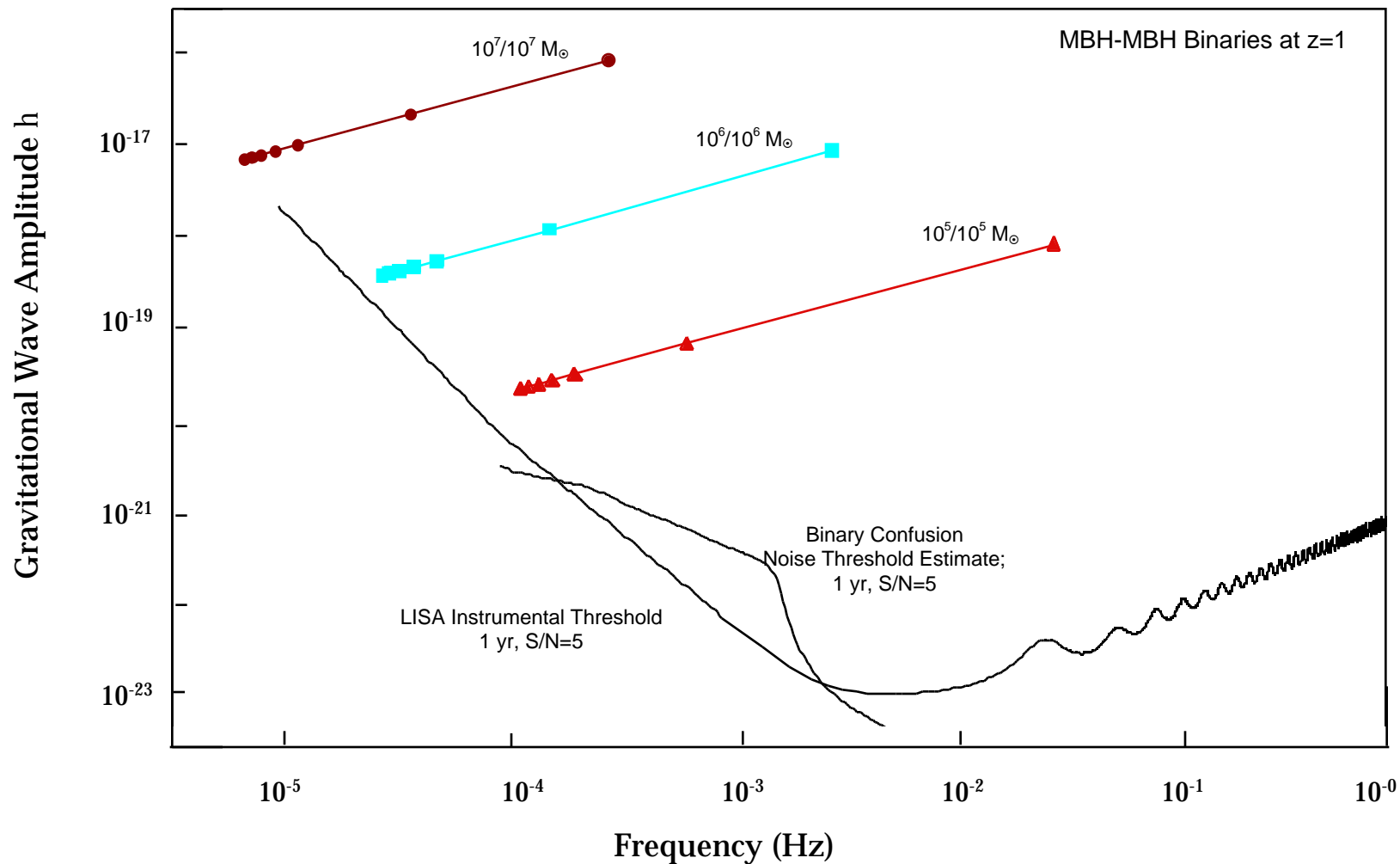


The Gravitational-Wave Spectrum



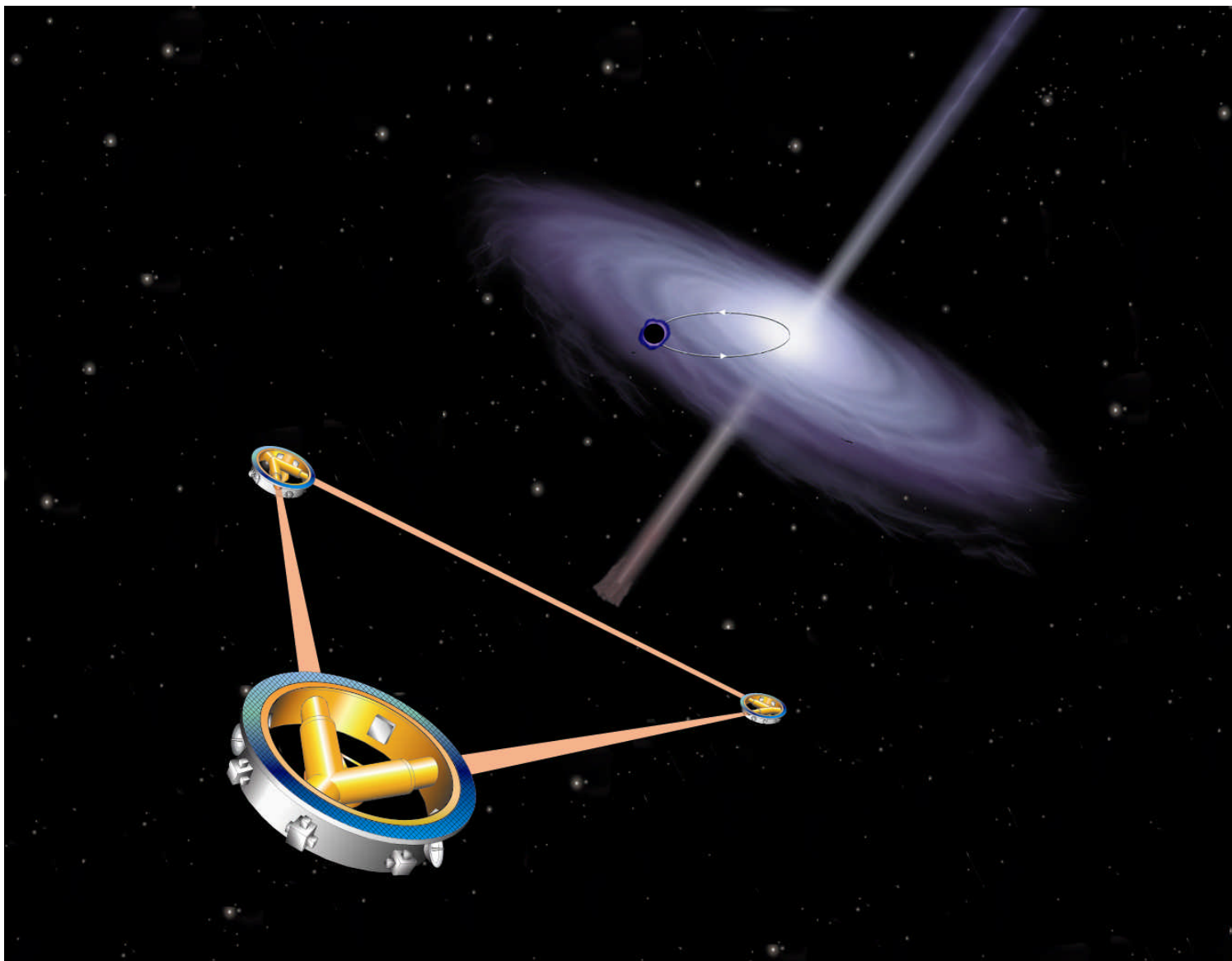


Massive Black Holes in Merging Galaxies





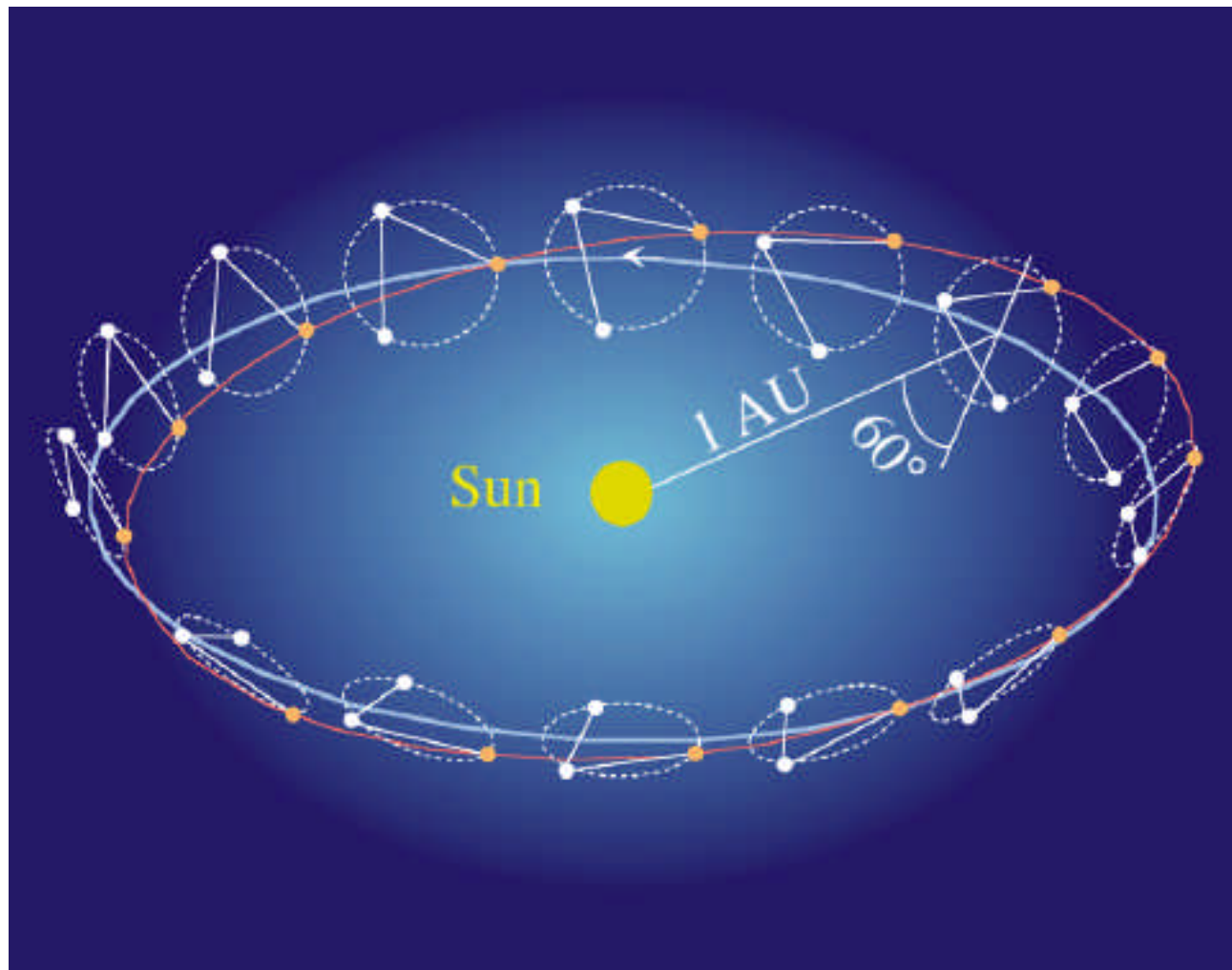
Mission Concept





Spacecraft Orbits

- Spacecraft orbits evolve under gravitational forces only
- Spacecraft fly “drag-free” to shield proof masses from non-gravitational forces





Optical System

