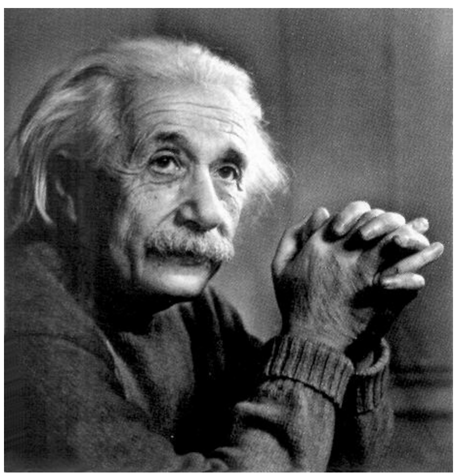
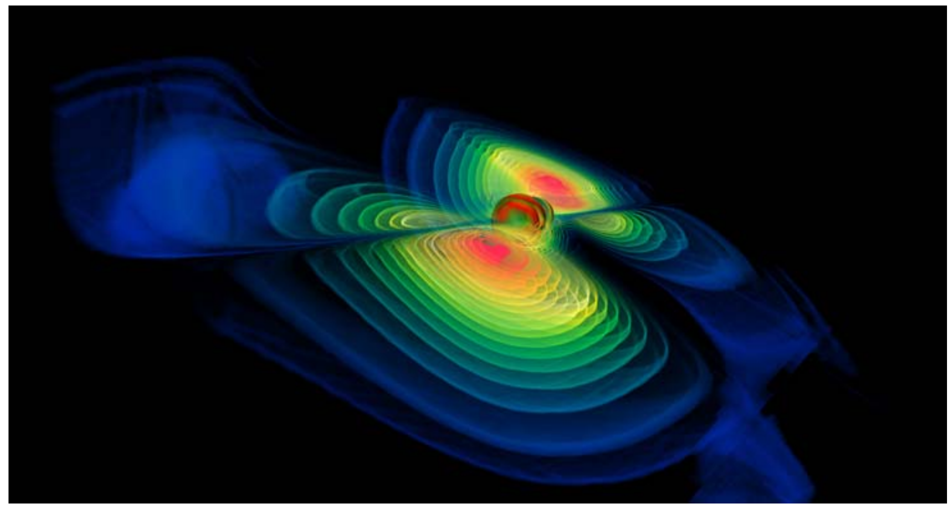
Across the Gravitational Wave Spectrum





"Colliding Black Holes"
Credit: Werner Benger

Stan Whitcomb
LIGO/Caltech

Workshop: GW Detection with Atom Interferometry

23 February 2009

LIGO-G0900081-v1

Outline of Talk

- Quick Review of GW Physics
- The GW Spectrum:
  - » Sources in different bands
- Detection techniques in different bands
- Some personal thoughts
  - » A new technology displacing an older one

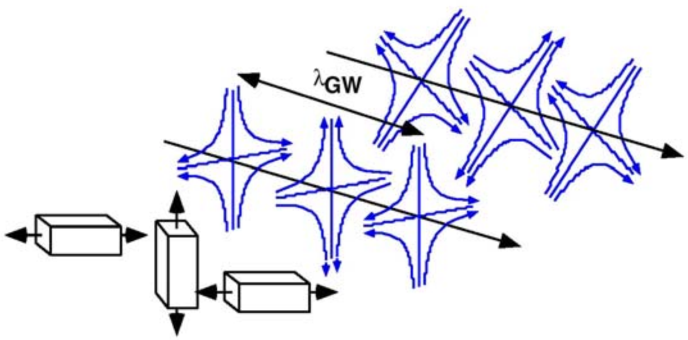
Physics of Gravitational Wave Detection

- In the Minkowski metric, space-time curvature is contained in the metric as an added term, $h_{\mu\nu}$

$$(\nabla^2 - \frac{1}{c^2}\frac{\partial^2}{\partial t^2})h_{\mu\nu} = 0$$

- Strain $h_{\mu\nu}$ takes the form of a transverse plane wave propagating with the speed of light (like EM)

- Strain $h = \Delta L/2L$ which is the measured property in all active GW detection efforts

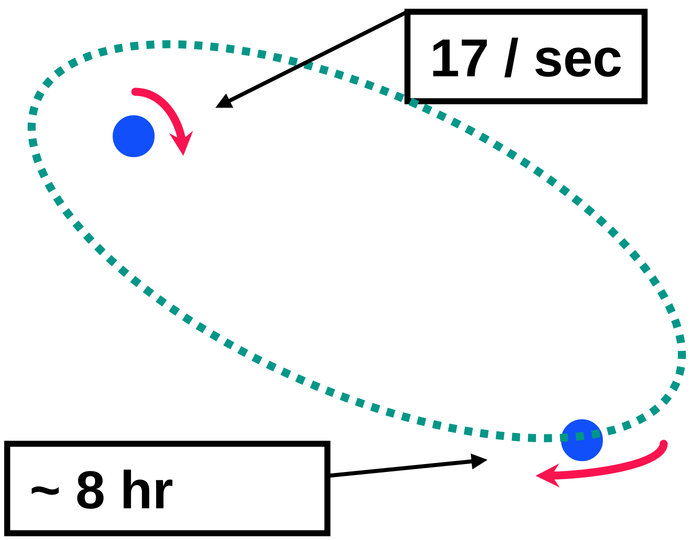


- Since gravity is described by a tensor field (EM is a vector field),
  - » gravitons have spin 2 (cf. spin 1 for photons)
  - » the waves have two polarization components, but rotated by 45^0 instead of 90^0 from each other (as in EM)

Evidence for Gravitational Waves

Neutron Binary System

PSR 1913 + 16

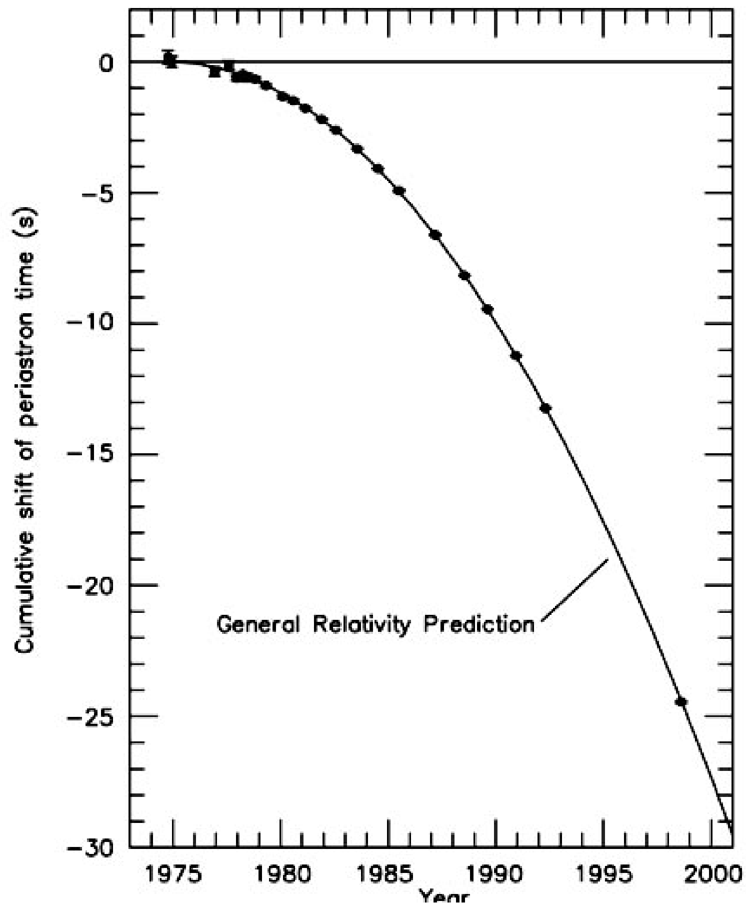


- **Discovered by Hulse and Taylor in 1975**
- **Unprecedented laboratory for studying gravity**
  - » **Extremely stable spin rate**
- **Possible to repeat classical tests of relativity (bending of “starlight”, advance of “perihelion”, etc.**

Binary Pulsar Timing Results

- After correcting for all known relativistic effects, observe loss of orbital energy
- Advance of periastron by an extra 25 sec from 1975-98
- Measured to ~50 msec accuracy
- Deviation grows quadratically with time

Emission of gravitational waves consistent with GR



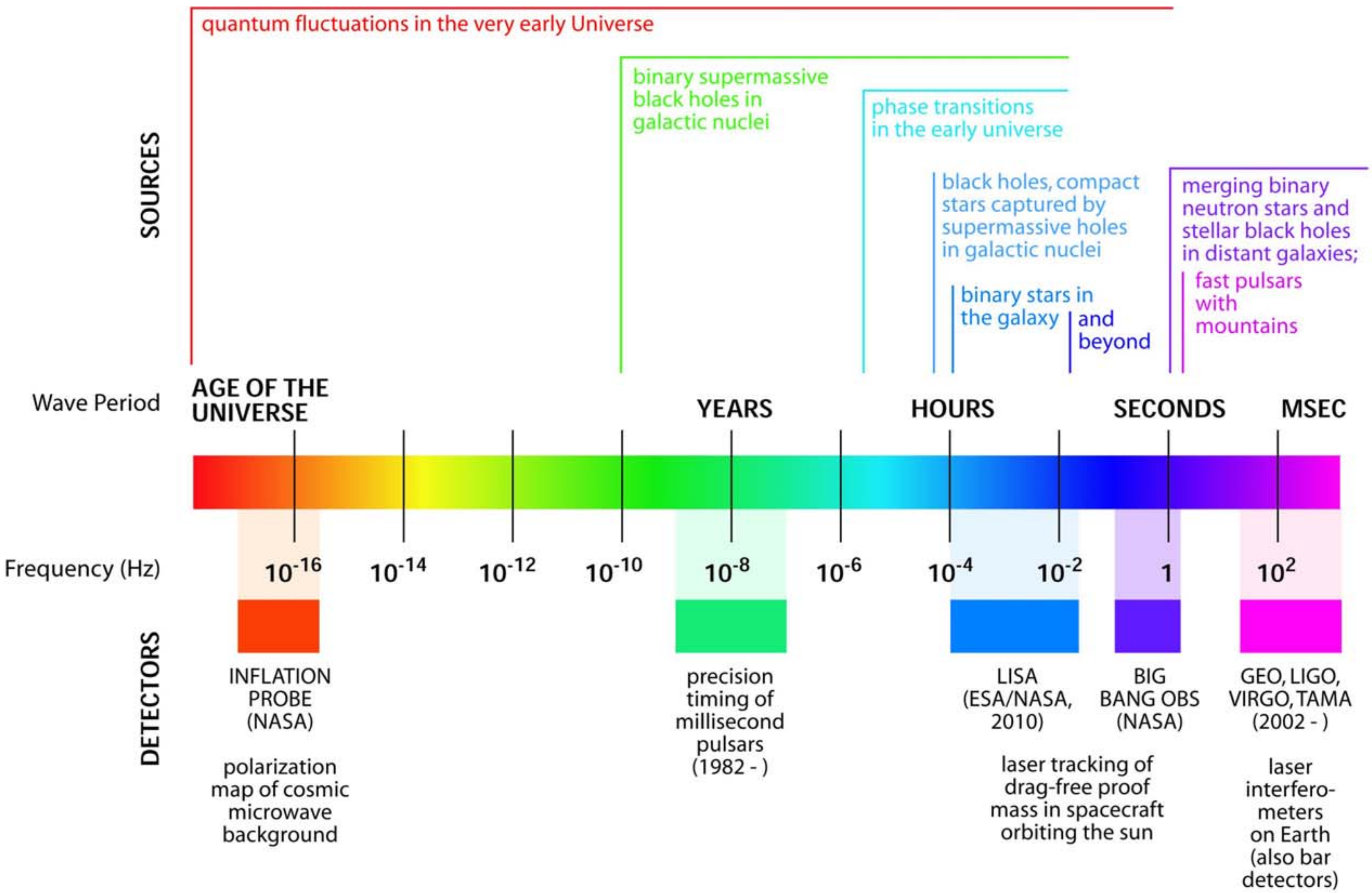
How Big is h?

- Source energetics : Energy flux in wave is

$$E_{GW} \sim \left(\frac{c^3 D_L^2}{4G} \right) \int_{-\infty}^{\infty} \left| \frac{dh}{dt} \right|^2 dt$$

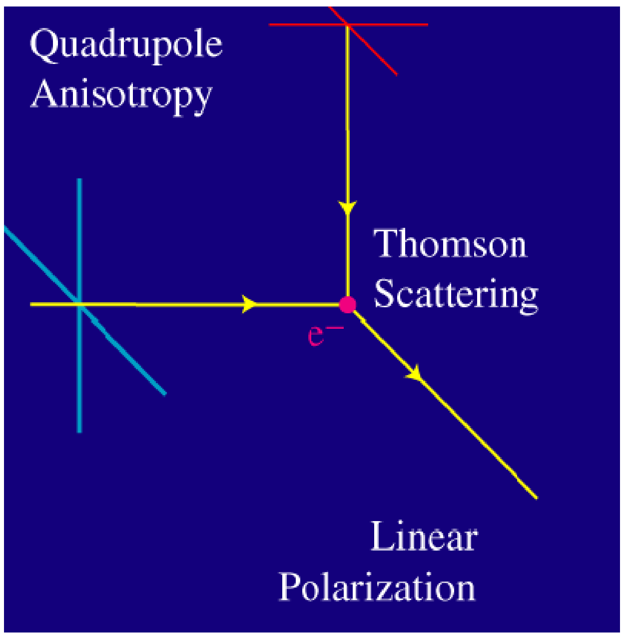
- Available energy to be radiated in GWs is a fraction of the rest mass of the system $E_{GW} \le \varepsilon M_{Tot} c^2$
- Maximum frequency $f_{\max} \le c / M_{source}$
- Duration typically increases $\sim f^{-1}$
- Distance to source increases as mass decreases
  - ► "Interesting" *h* $h_{interesting} \sim f^{-\alpha}, \ \alpha < 1$

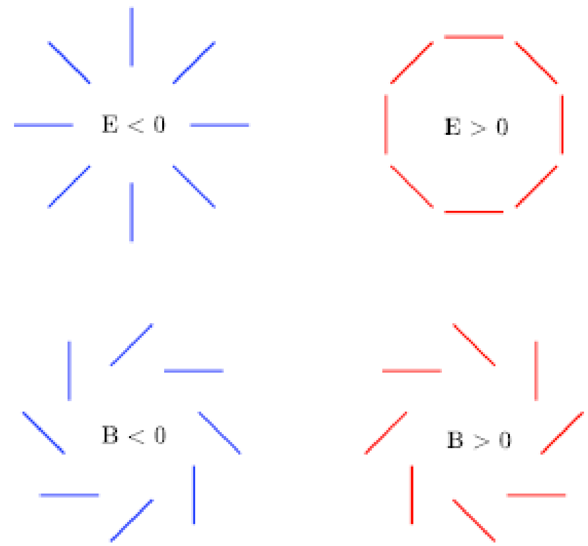
The Gravitational Wave Spectrum



CMB Polarization

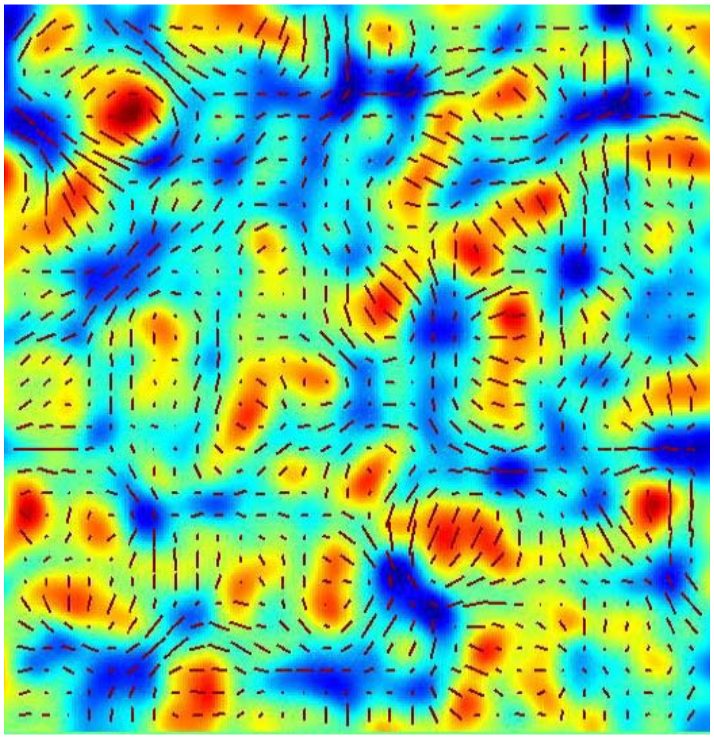
Polarization via Thompson scattering just before recombination



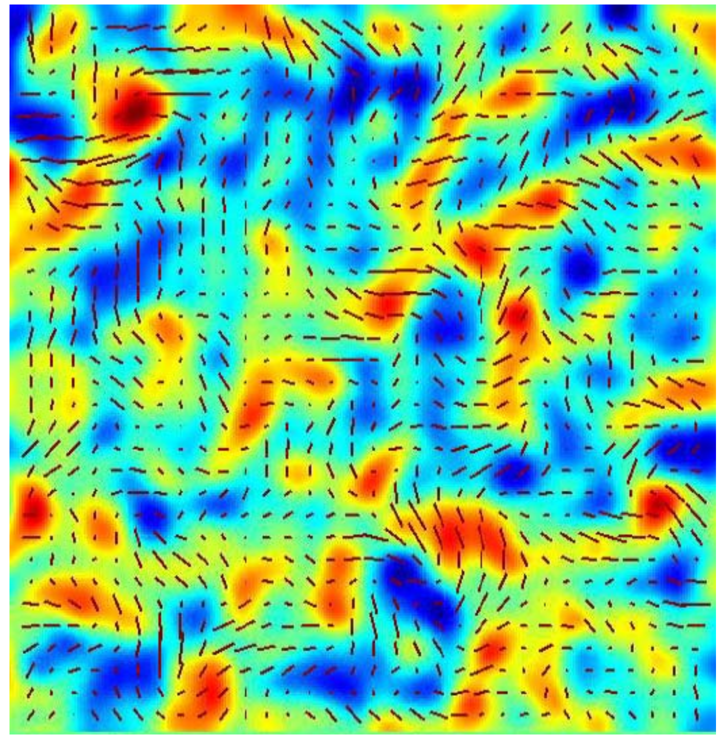


CMB Polarization Fields

E mode (simulation!)



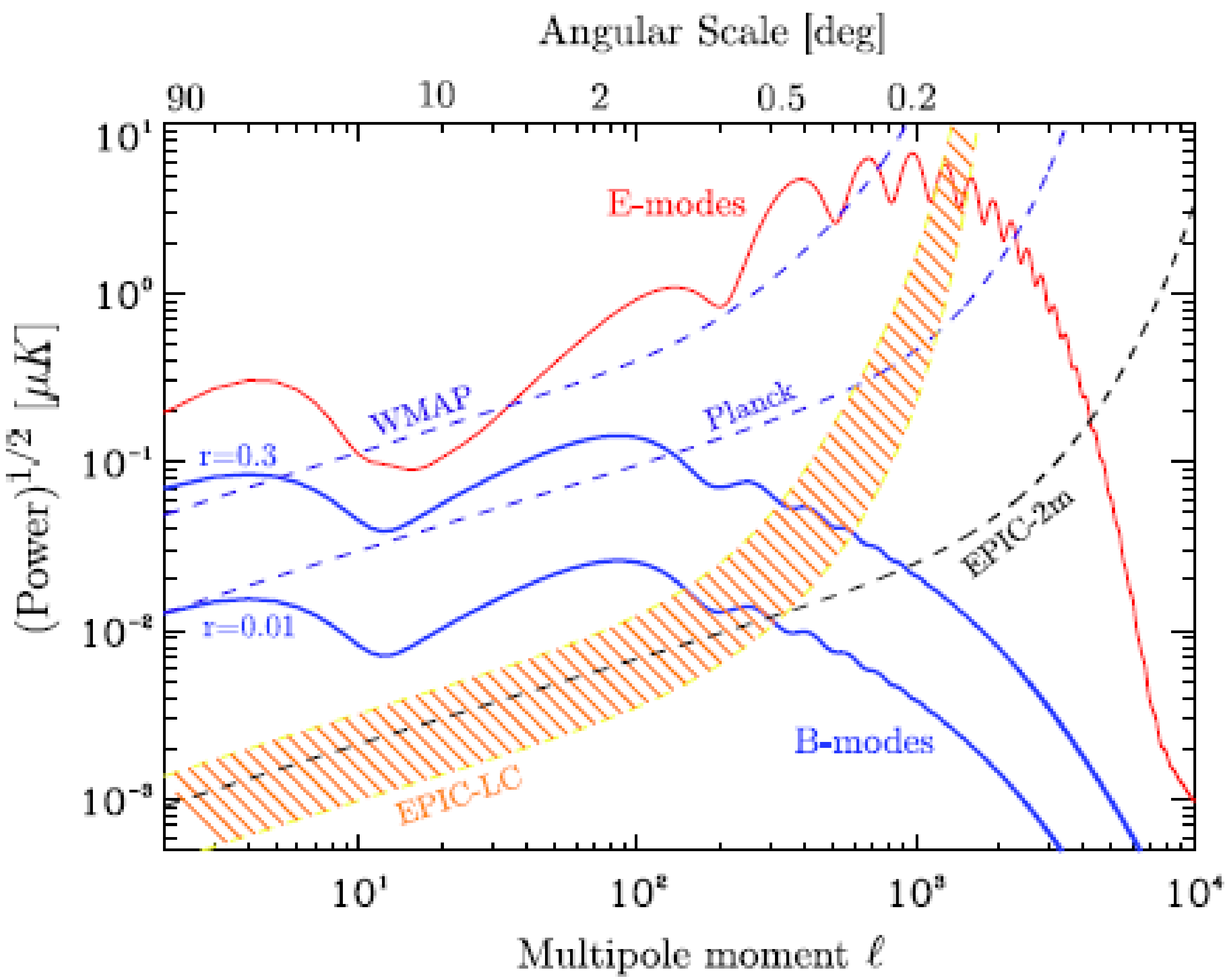
B mode (simulation!)



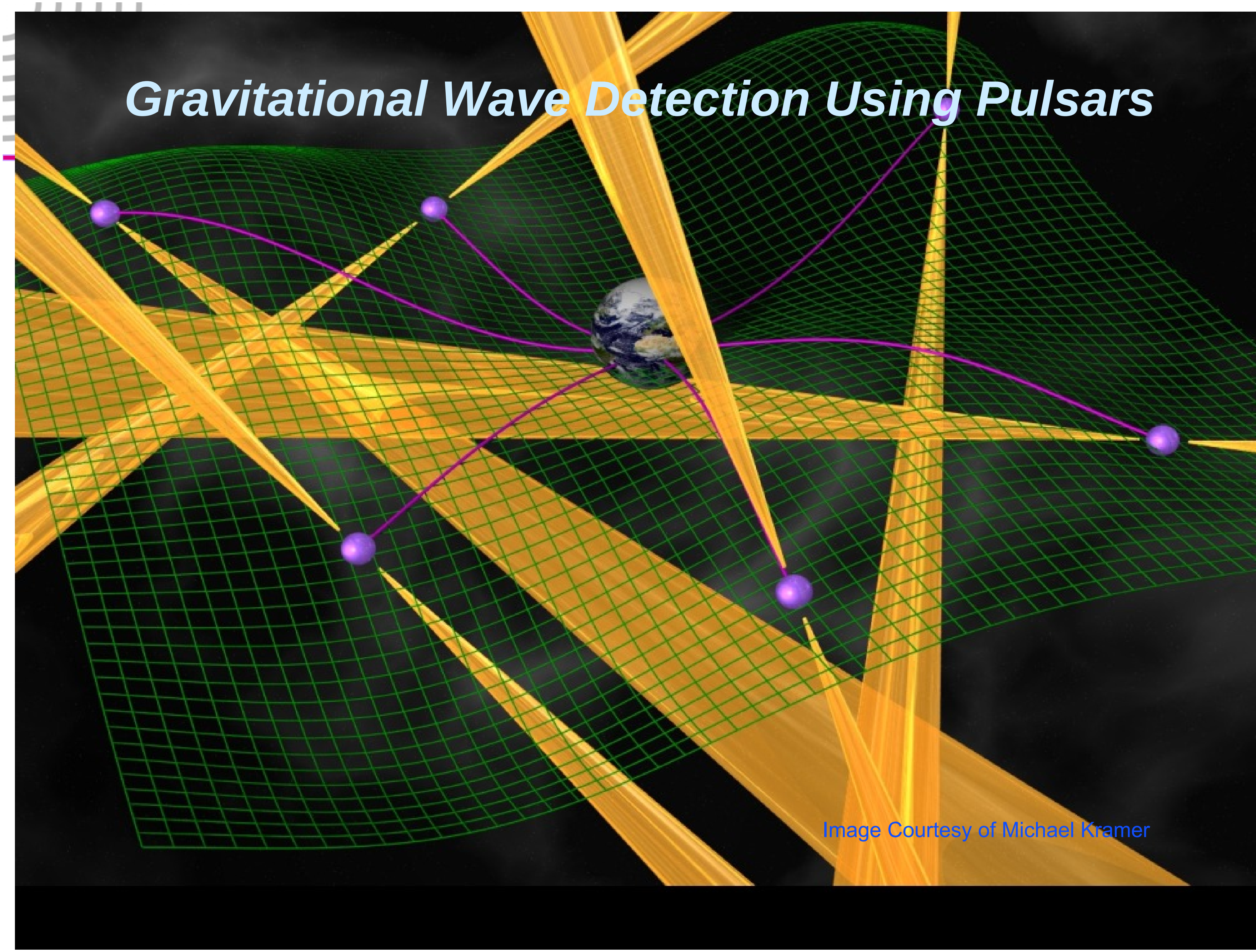
Seljak and Zaldarriaga, astro-ph/980501

B modes are evidence for primordial gravitational waves

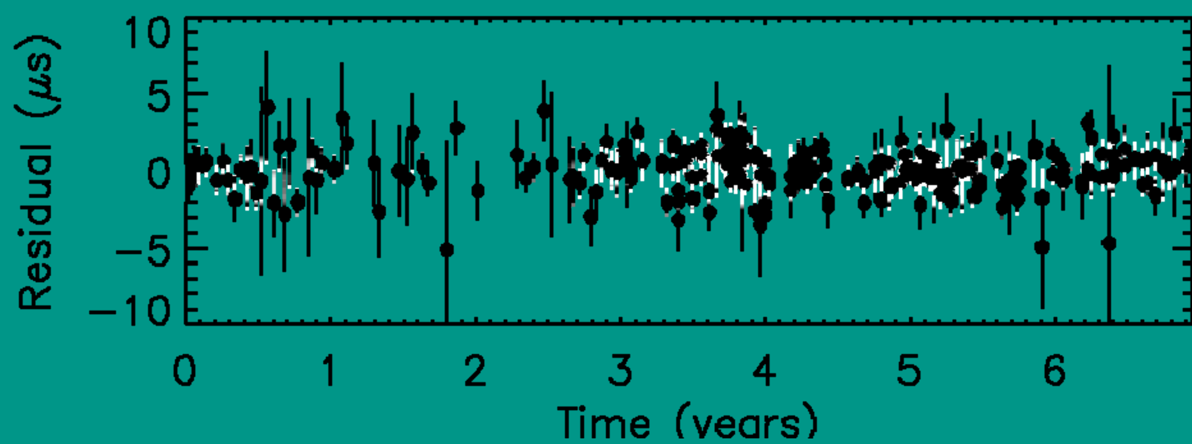
Prospects for GW Observations



Gravitational Wave Detection Using Pulsars



Timing residuals from PSR B1855+09



From Jenet, Lommen, Larson, & Wen, ApJ , May, 2004

Data from Kaspi et al. 1994

Period =5.36 ms

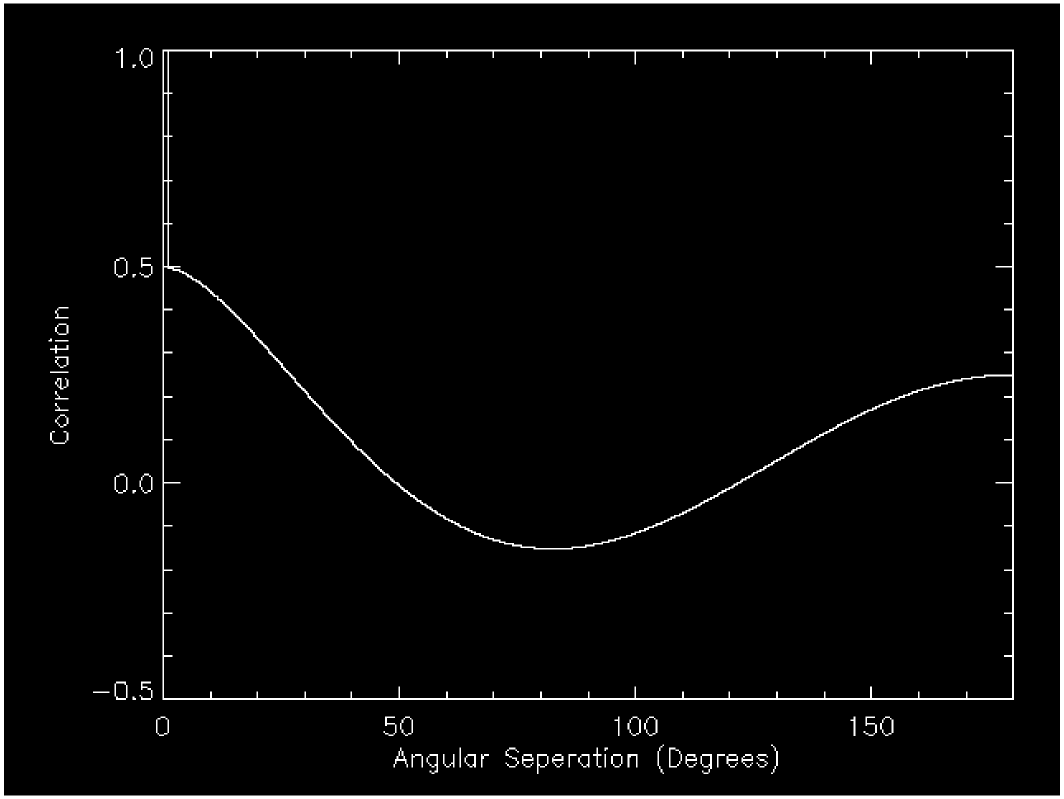
Orbital Period =12.32 days

Stochastic Background Signature

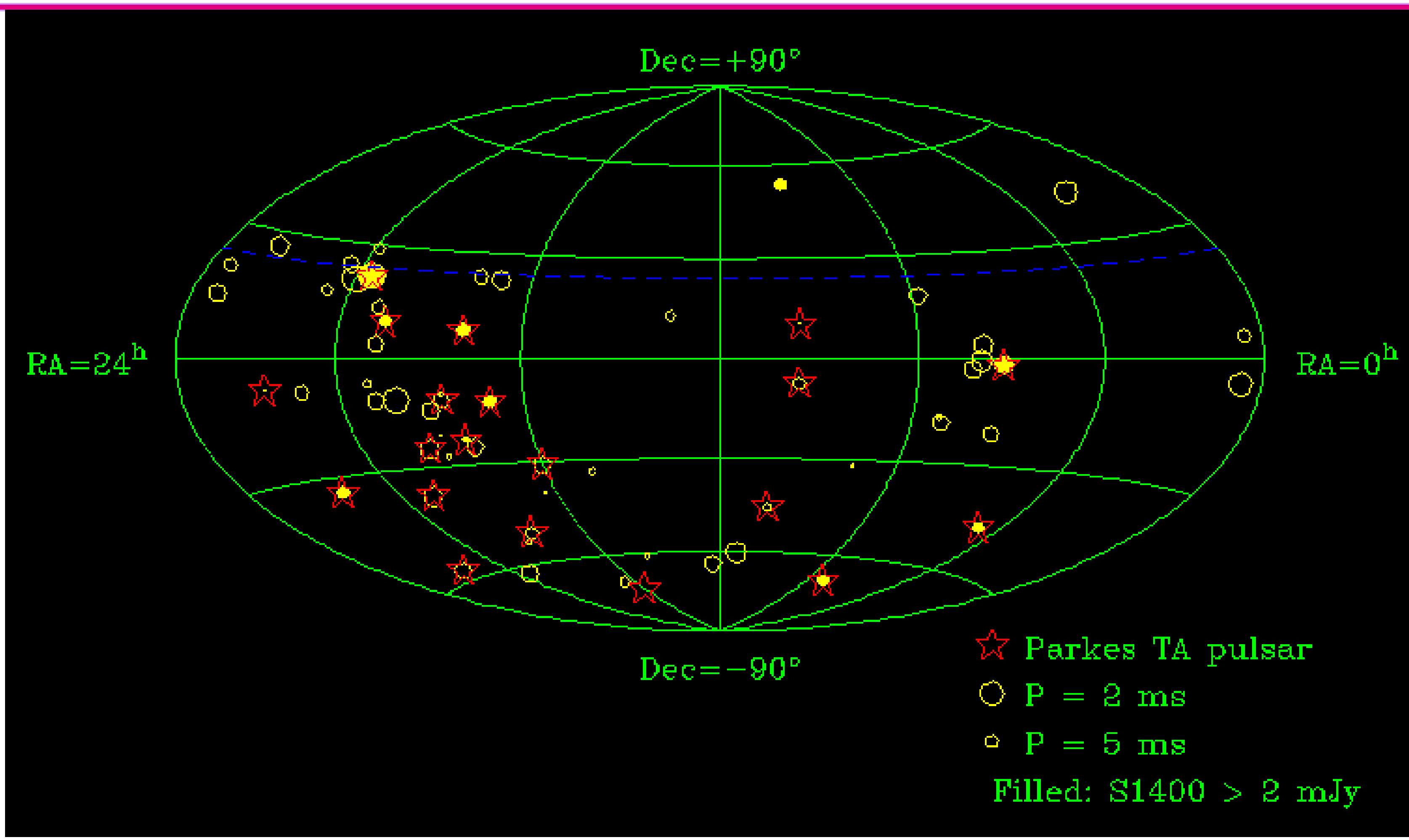
Pulse arrival time fluctuations from different pulsars will be correlated:

$C(\theta_{ij}) = \langle R_I R_j \rangle$

Will need ~ 20 pulsars at 100ns to do this In 5-10 years time.



Distribution of Millisecond Pulsars



P < 20 ms and not in globular clusters

Sensitivity of pulsar timing to GWs

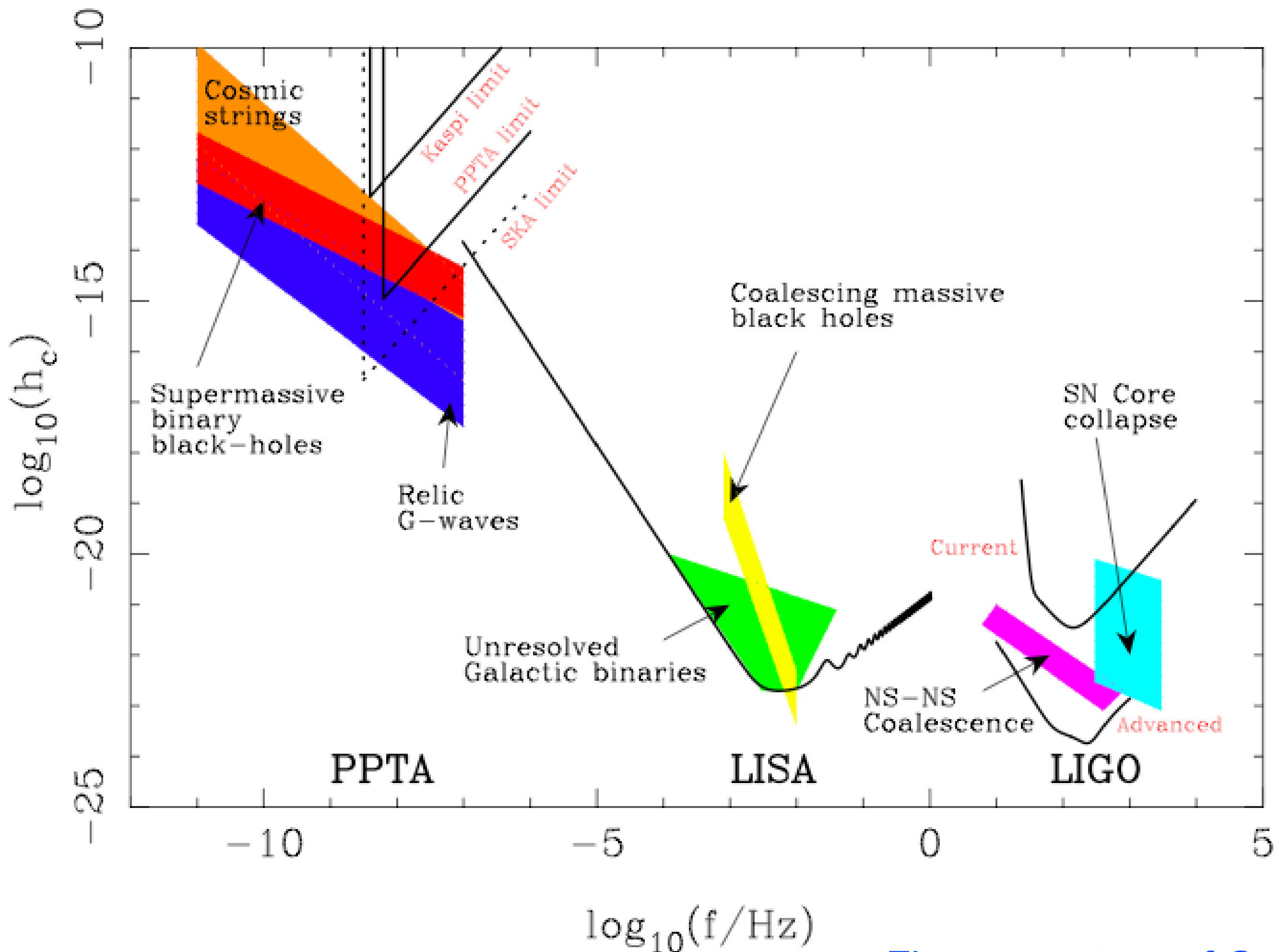
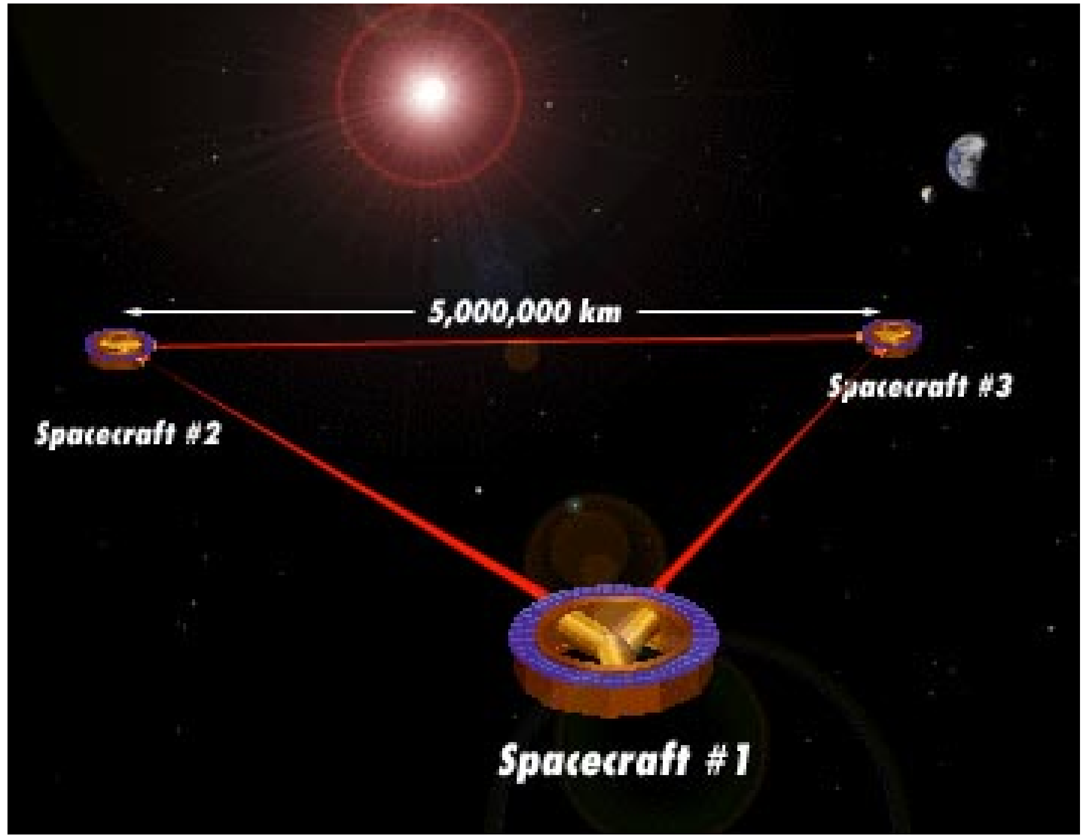


Figure courtesy of George Hobbs

Gravitational Wave Detection in Space

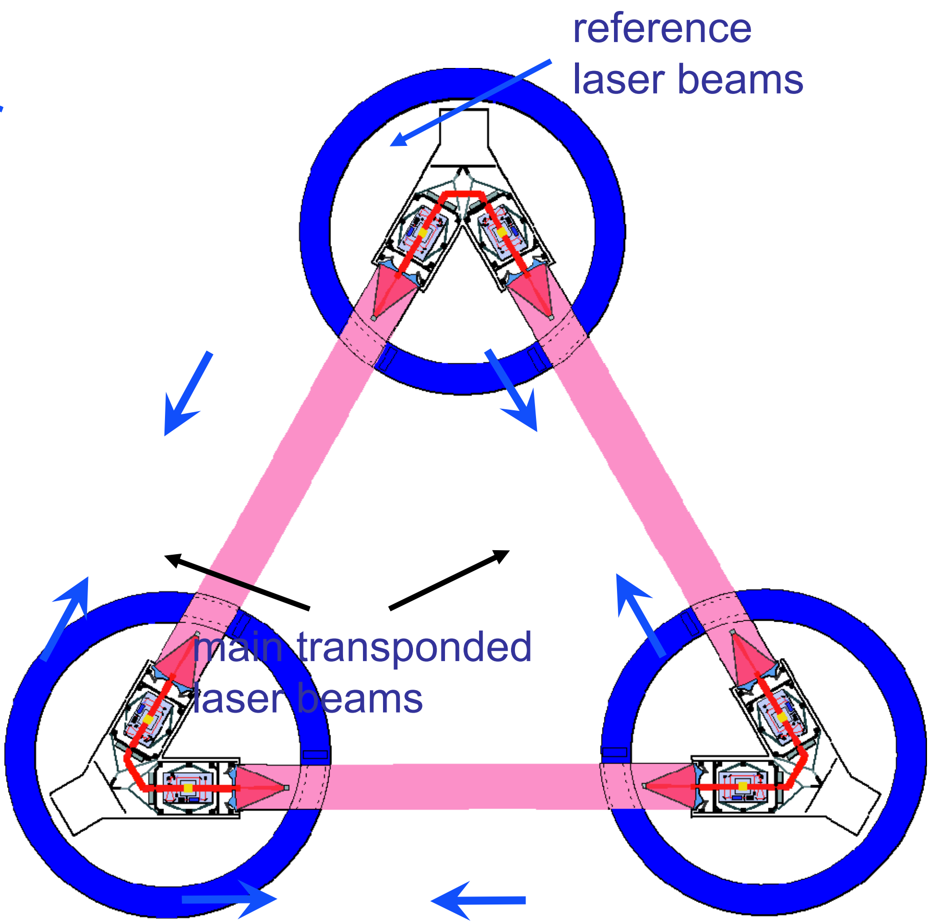
The Laser Interferometer Space Antenna
LISA



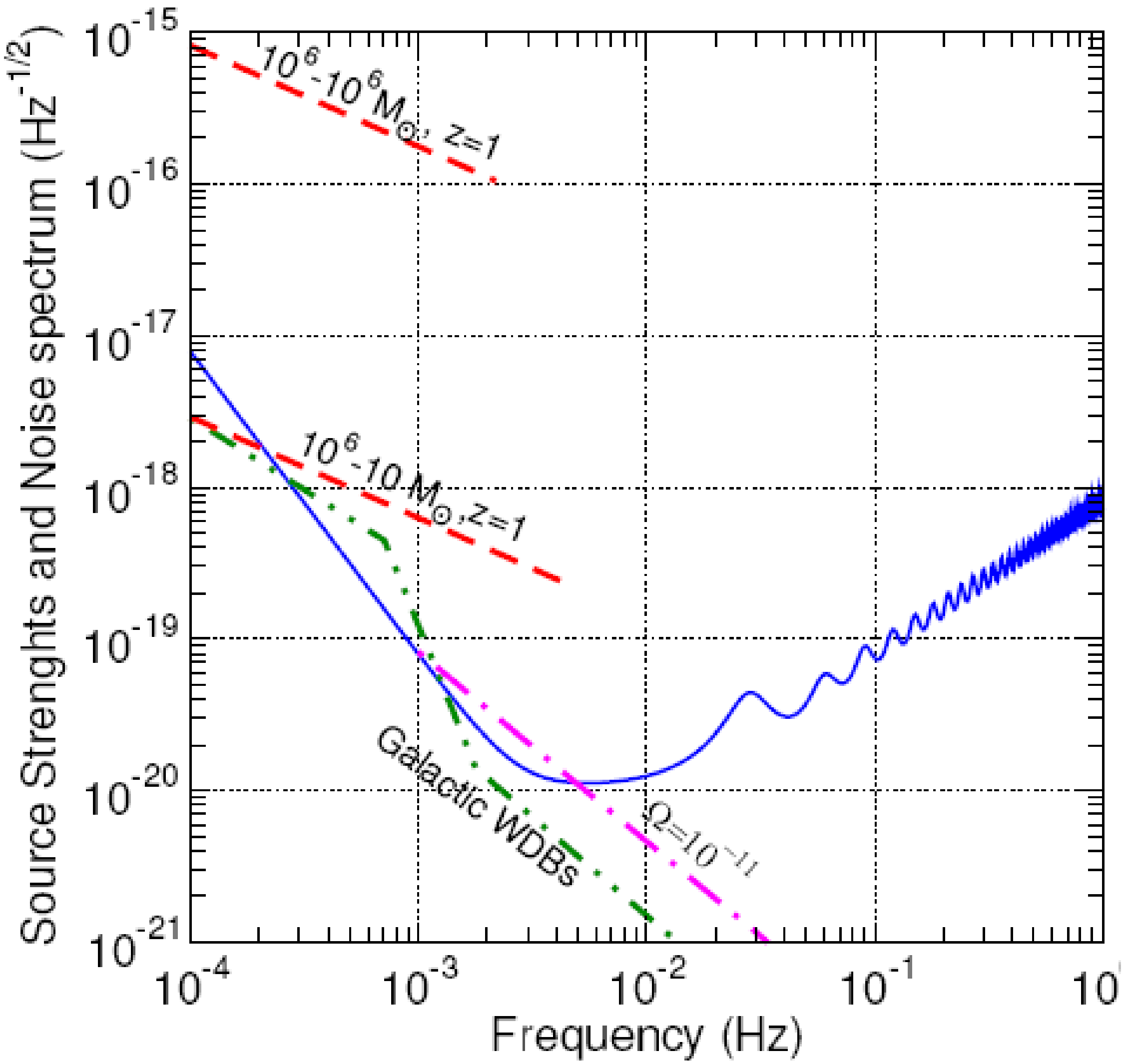
- Center of the triangle formation is in the ecliptic plane
- 1 AU from the Sun and 20 degrees behind the Earth.

LISA Layout

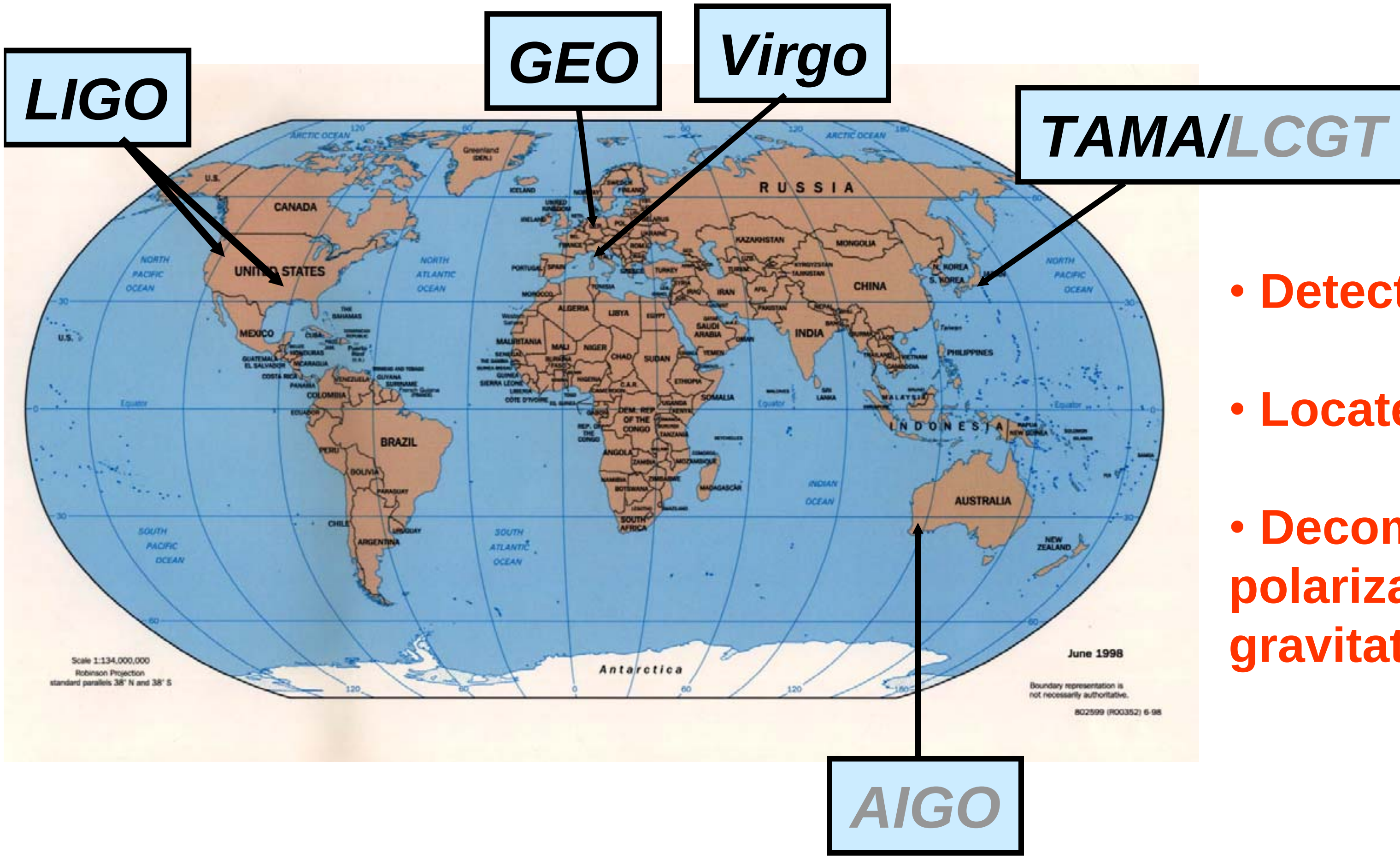
- Laser transponder with 6 links, all transmitted to ground
- Diffraction widens the laser beams to many kilometers
  - » 1 W sent, 100 pW received by 40 cm telescope
- Use time-delay interferometry to cancel laser frequency noise
- Can distinguish both polarizations of a GW



LISA Sensitivity



Terrestrial GW Detectors

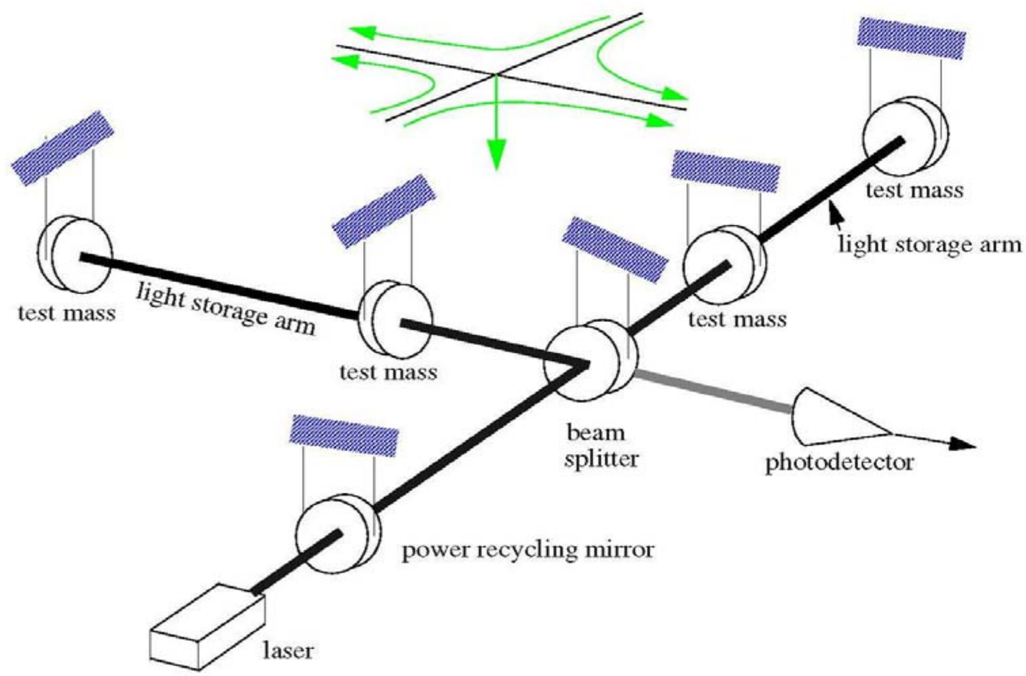


- Detection confidence
- Locate sources
- Decompose the polarization of gravitational waves

Detecting GWs with Interferometry

Suspended mirrors act as "freely-falling" test masses (in horizontal plane) for frequencies $f \gg f_{pend}$

$$h = \Delta L / L$$



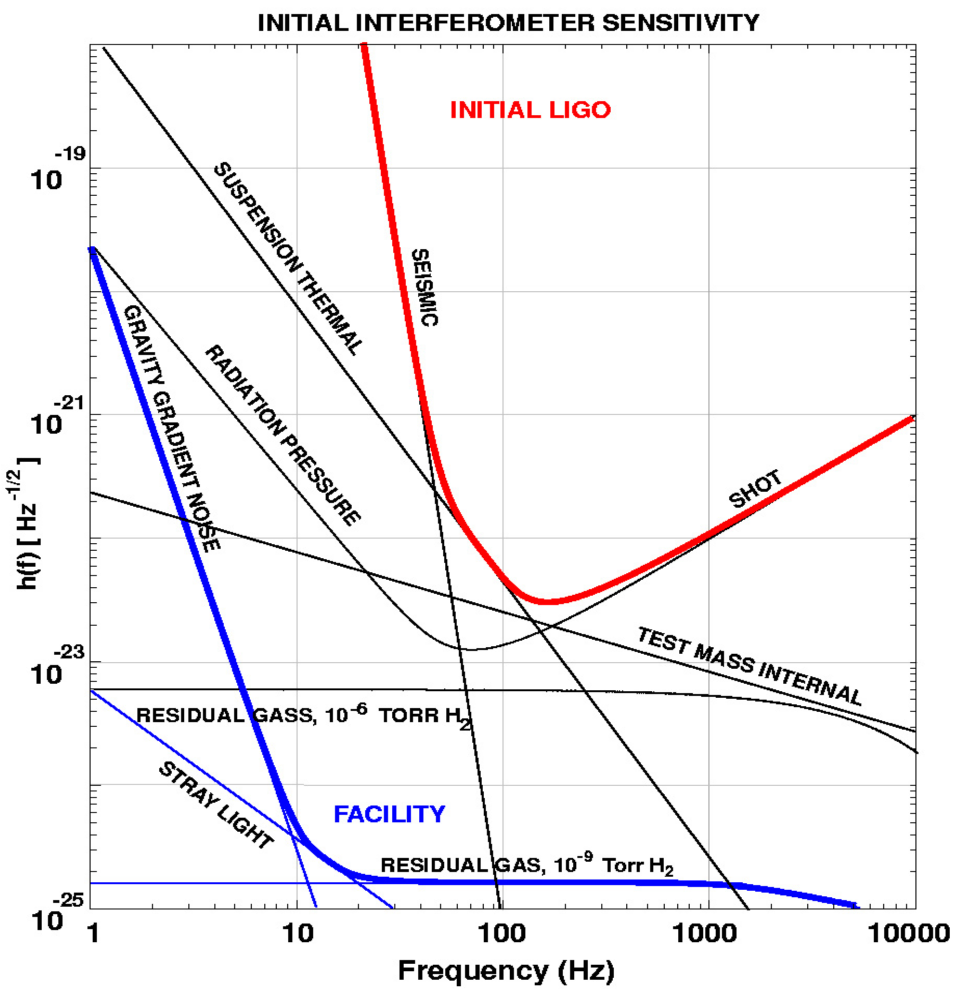
Terrestrial detector

For $h \sim 10^{-22} - 10^{-21}$

$L \sim$ 4 km (LIGO)

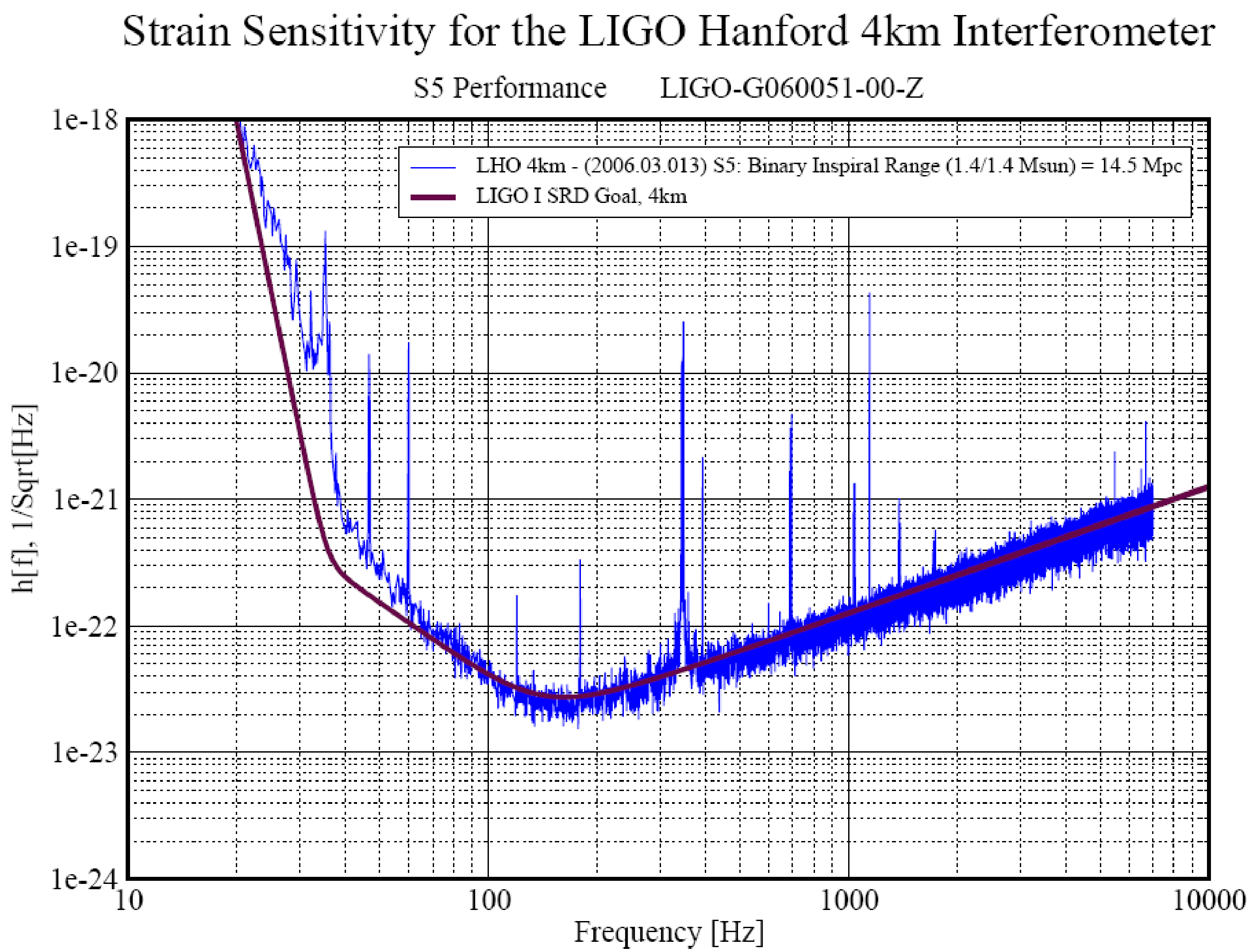
$\Delta L \sim 10^{-18}$ m

Initial LIGO Sensitivity Goal

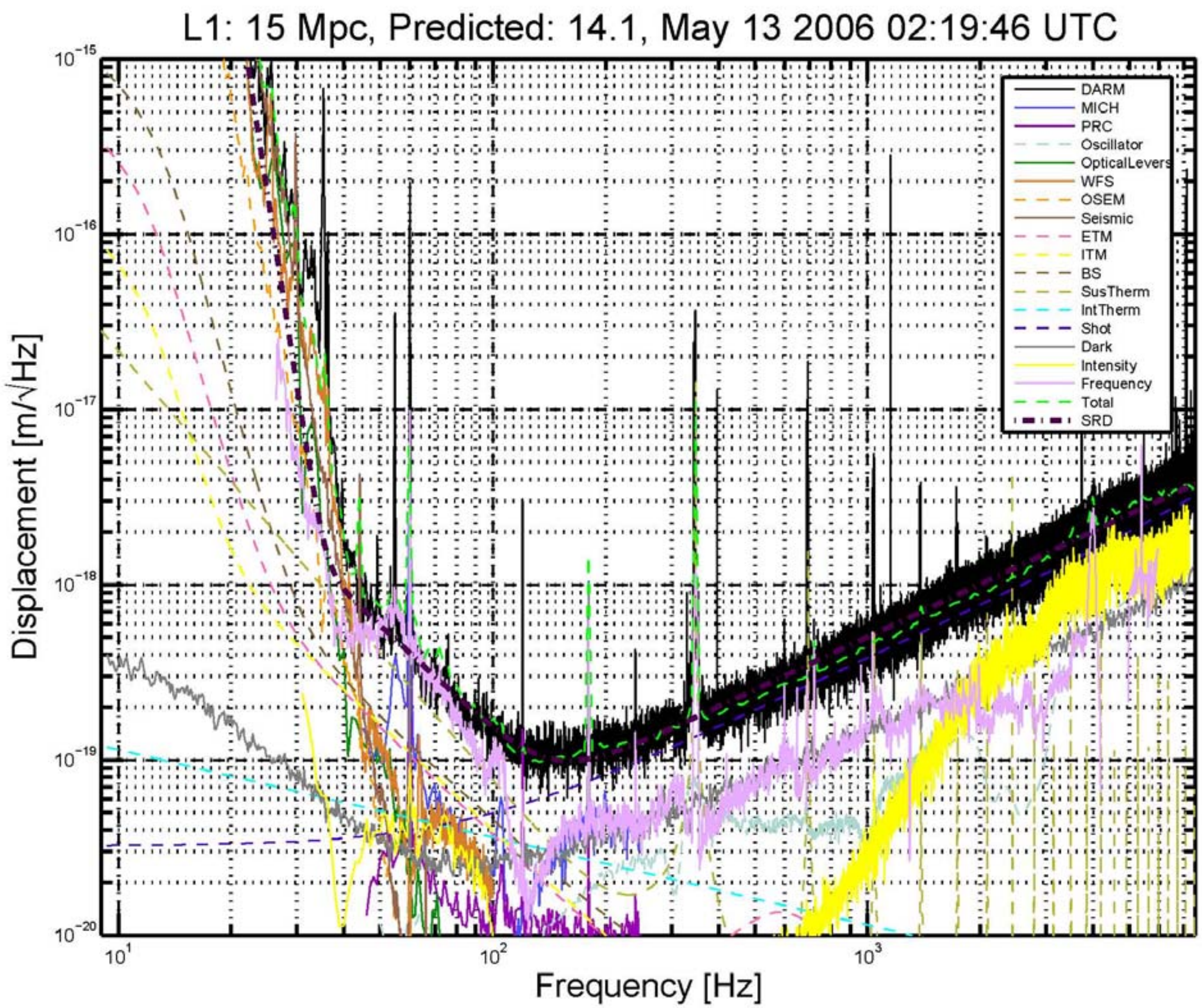


- Strain sensitivity <3x10^{-23} 1/Hz$^{1/2}$ at 200 Hz
- Sensing Noise
  - » Photon Shot Noise
  - » Residual Gas
- Displacement Noise
  - » Seismic motion
  - » Thermal Noise
  - » Radiation Pressure

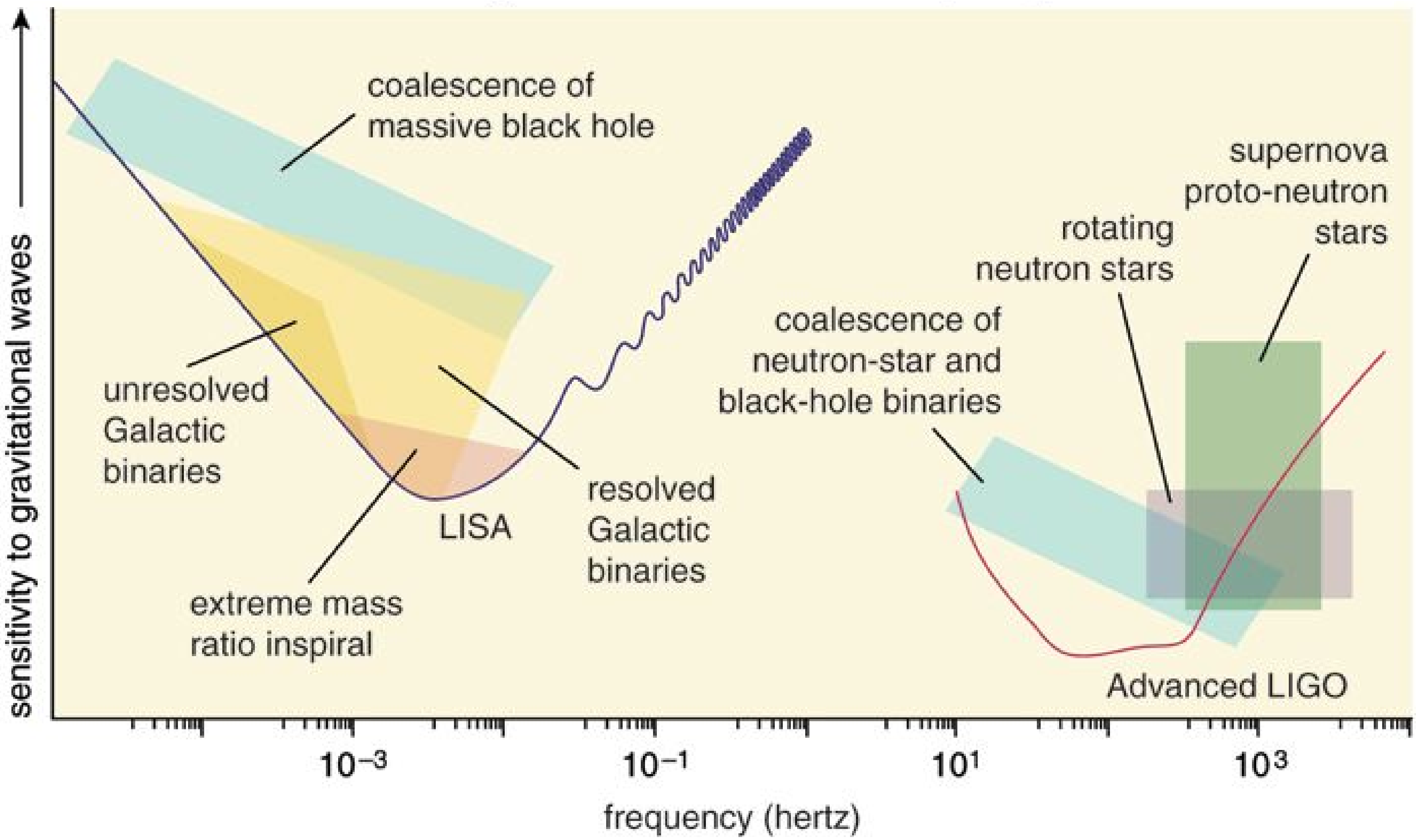
LIGO Sensitivity



Anatomy of a Noise Curve

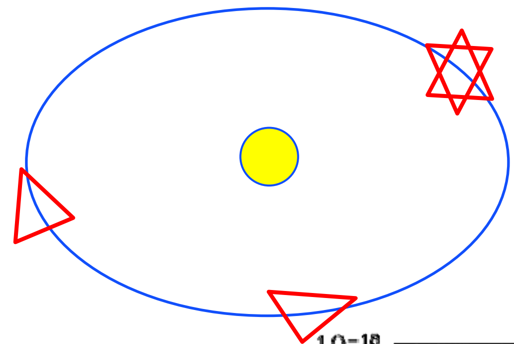


Bridging Between LISA and Ground-based Interferometers

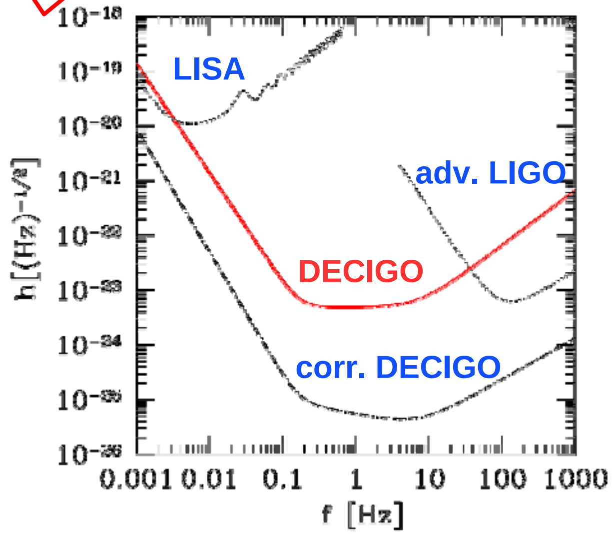


What is DECIGO?

DECIGO: the planned Japanese space GW antenna
would bridge the LISA and Advanced LIGO bands,
reaching down to measure the stochastic background from inflation



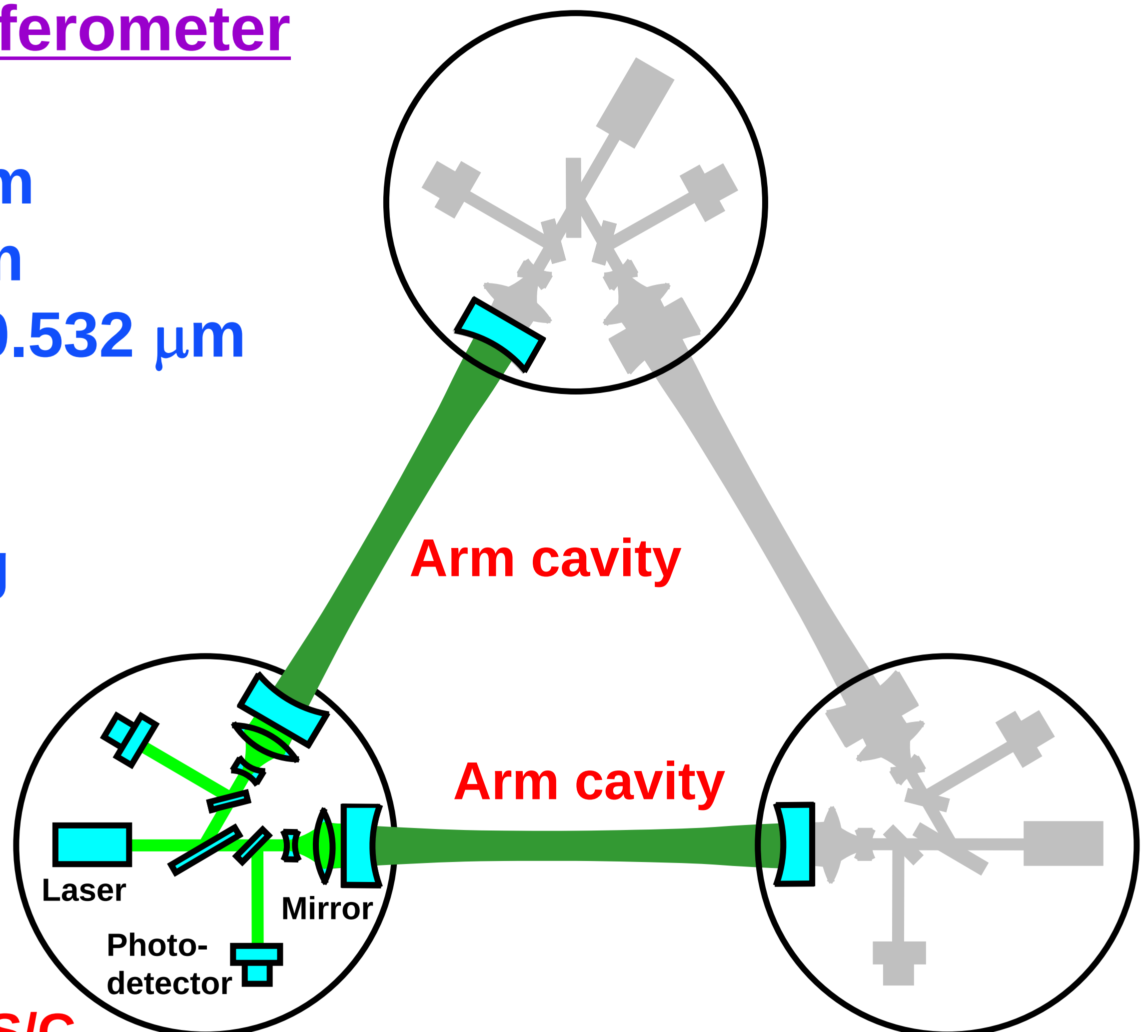
- Differential Fabry-Perot interferometer
  Drag-free operation
- Armlengths: 1000 km
  Mirrors: 1 m, 100 kg
  Laser: 10 W
- Detect stochastic signal from standard inflation
  (Ω~10^{-16}, after removing 10^5 NS–NS/yr)
- Study IMBH inspirals



DECIGO Pre-conceptual design

Differential FP interferometer

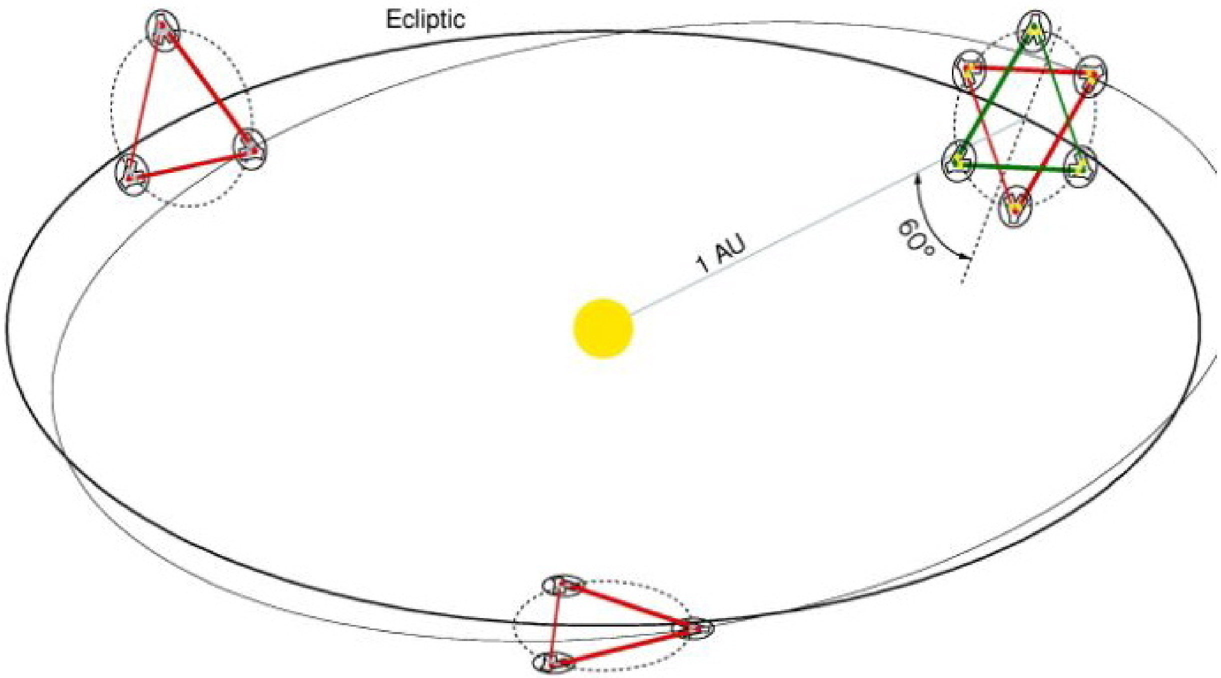
Arm length: 1000 km
Mirror diameter: 1 m
Laser wavelength□0.532 μm
Finesse: 10
Laser power: 10 W
Mirror mass: 100 kg
S/C: drag free
3 interferometers



from Kawamura

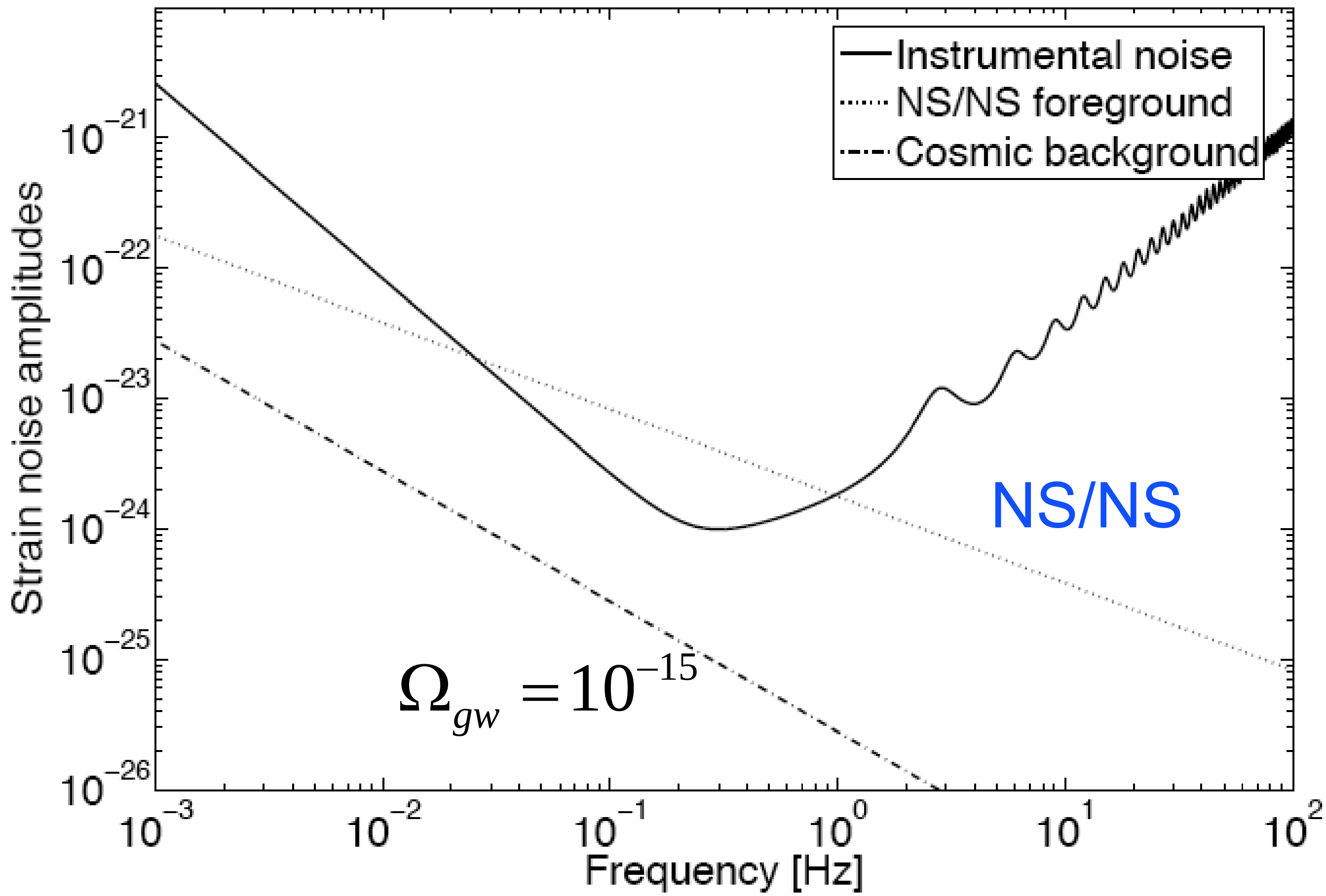
Big Bang Observer (BBO)

Mission to measure stochastic GWs from inflation, in the 0.1-1 Hz band, down to $\Omega_{gw}(f) \geq 10^{-17}$



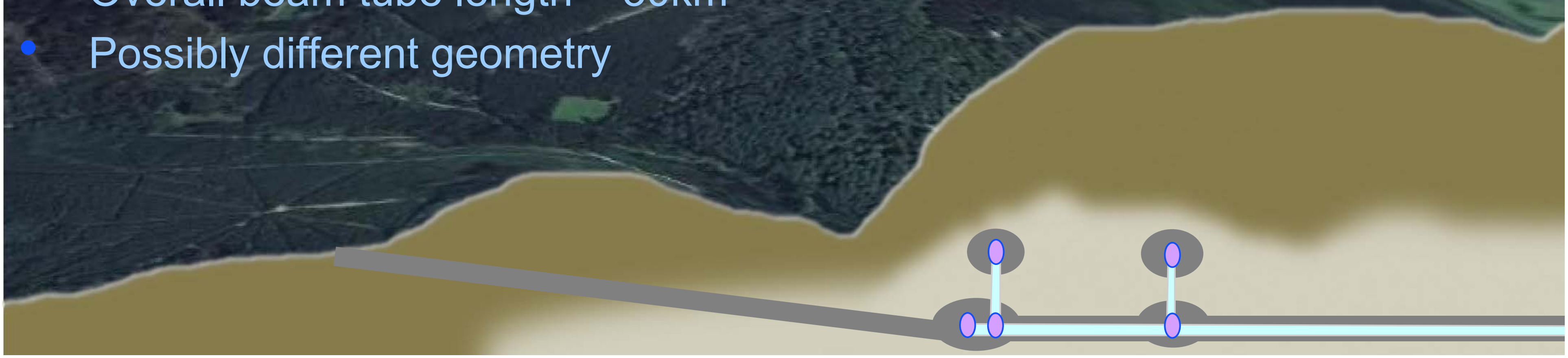
Laser power = 300 x LISA, mirror D =12 x LISA,
arm length = 0.01 x LISA, accel. noise = 0.01 x LISA

BBO Noise Curve

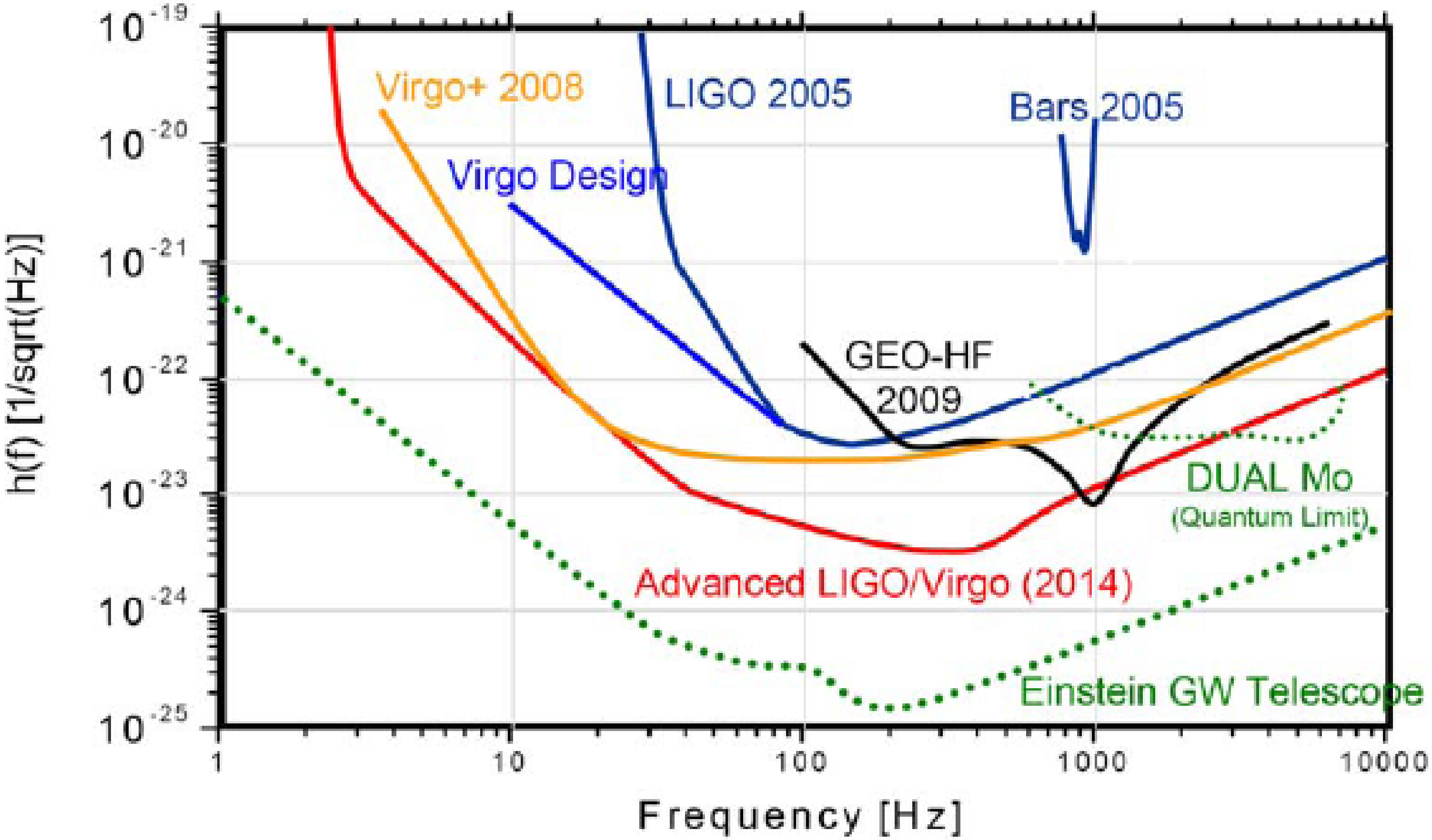


Einstein Telescope: Baseline Concept

- Underground location
  - Reduce seismic noise
  - Reduce gravity gradient noise
  - Low frequency suspensions
- Cryogenic
- Overall beam tube length ~ 30km
- Possibly different geometry



Einstein Telescope: Sensitivity

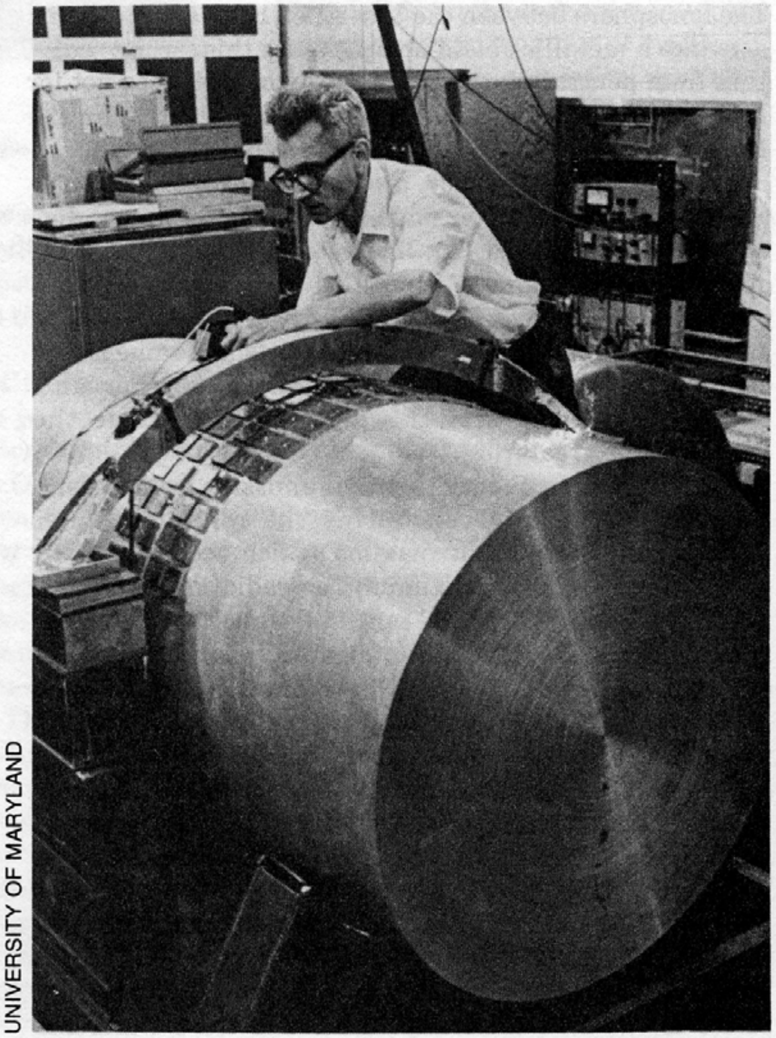


Some Personal Thoughts and Experiences:

How can a New Technology Displace the Old?

Let's Go Back 30 Years: Bar Detectors

- First ground-based detectors—the beginning of GW detection
  - » Joseph Weber 1960's
- Triggered a major new thrust in physics
  - » Studies of astrophysical sources
  - » Significant improvements in sensitivity
- Over the next 3 decades, at least 19 different bar detectors (8 countries) were built and used in searches
  - » Several hundred scientists, students, engineers, and technicians involved in the effort

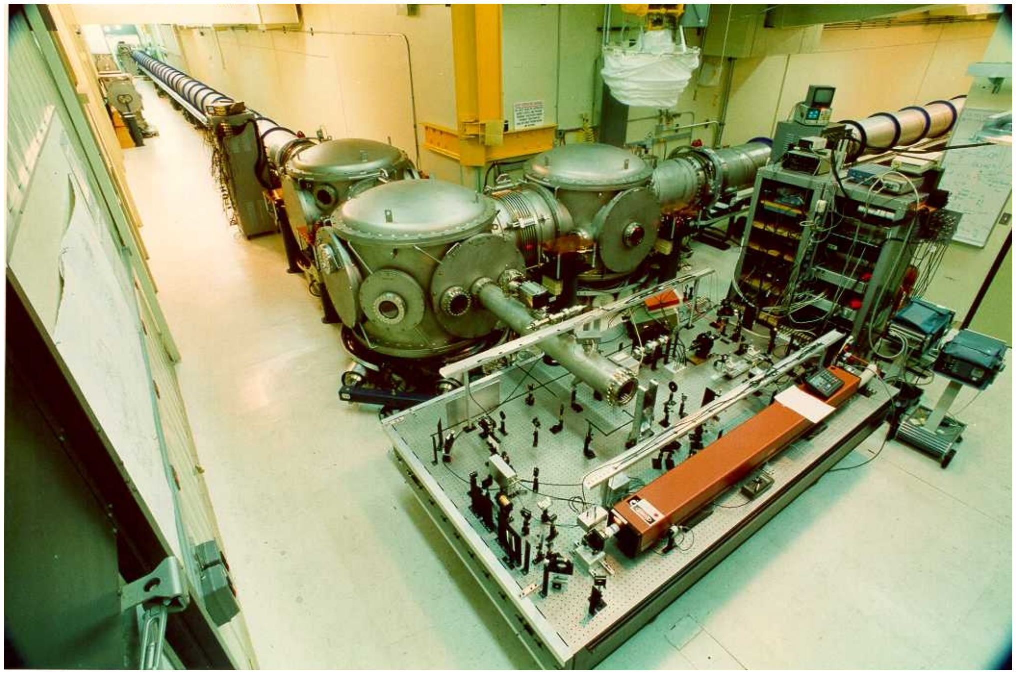

UNIVERSITY OF MARYLAND

Technology of Resonant Bars Matures

- Clear path to future
- Recognition of important noise sources
  - » Thermal noise
  - » Back action/Quantum noise
  - » Seismic/acoustic noise
- Large cryogenic systems
- Recognized the need for multiple detectors
- Community had plans for the future

Then Along Came Interferometers

- New technology pushed by a community outside the mainstream bar community
- Promises of increased sensitivity, wider bandwidth
- Naïve estimates of what would be involved
- Demonstrated performance far from that needed
- Unfamiliar language inhibited communication
- Significant tensions



Confrontation and Resolution

- Trust between the two communities grew, gradually
  - » Skepticism in bar community about claims of interferometry
  - » Some level of distrust in interferometer community because of unverified claims of detection
- Key elements in developing cooperation
  - » Appreciation of common problems
  - » Development of common language (noise spectral densities)
  - » Recognition of common problems (thermal noise, quantum noise)
- Recognition that funding decisions were largely independent
  - » Emphasis on different activities
    - - Bars on observation
    - - Interferometers on development and facility engineering

In the End: for the Interferometers

- Against many people’s expectations, interferometers were able to deliver the promised sensitivity and more
  - » Fundamental limits are fundamental—everything else can be overcome
- The time to achieve the promise was an order of magnitude longer than estimated
  - » Experimenters really are naive when it comes to the real world
- The real challenges were unforeseen
  - » Optical scattering, servo bandwith and noise, alignment, oscillator phase noise, economical vacuum constructon…
  - » “But there are also unknown unknowns, the ones we don't know we don't know. ” --D. Rumsfeld (Feb. 12, 2002)

In the End: for the Bars

- The challenges of improving a mature technology would prove more difficult that expected
  - » Experimenters really are naive when it comes to the real world
- Pressure from the interferometer community would help motivate the bar groups observe
  - » Extended data-taking runs set the standard for later interferometer runs
- New ideas for bar detectors were explored
  - » Spheres, DUAL
  - » May still be used someday
- Much of the bar community eventually moved into the interferometer world

Final Thoughts

- This workshop brings together two communities

- We have much to learn from each other
  - » Rai Weiss's fortune cookie:
    "The wise man will learn more from the fool than the fool will learn from the wise man"

- We will leave with disagreements and questions
  - » Two days will not be enough to resolve the concerns and uncertainties

- Our success in this workshop will depend on the lines of communication that we keep open after we leave