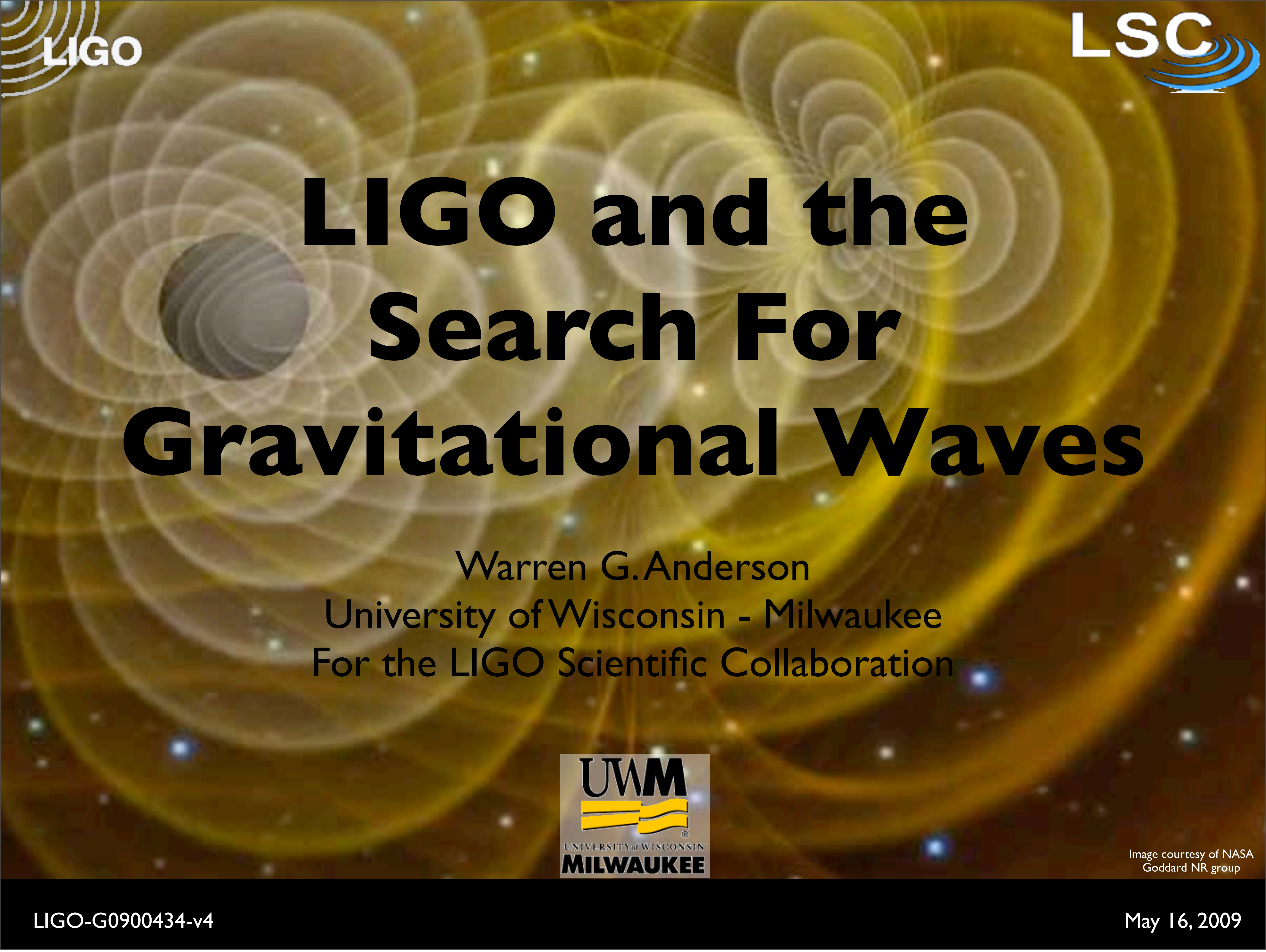

LIGO and the Search For Gravitational Waves

Warren G. Anderson
University of Wisconsin - Milwaukee
For the LIGO Scientific Collaboration

Image courtesy of NASA Goddard NR group

Outline

- Gravitational Wave (GW):
    - Theory
    - Detectors
    - Sources
    - Data Analysis
    - Results
    - Future

Outline

- Gravitational Wave (GW):
  - Theory

GW Theory

- Assume $g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$
- EFEs to linear order in $h_{\mu\nu}$ (Lorenz gauge $\nabla^{\mu}\bar{h}_{\mu\nu} = 0$)

$$\Box\bar{h}_{\mu\nu} = -16\pi T_{\mu\nu},$$

where

- $\bar{h}_{\mu\nu} = h_{\mu\nu} - \eta_{\mu\nu} h/2$ is the trace reverse of $h_{\mu\nu}$.
- $\Box$ is the wave operator for Minkowski metric $\eta_{\mu\nu}$.
- $T_{\mu\nu}$ is the stress energy of the source of $h_{\mu\nu}$.

Homogeneous solutions describe wave propagation.

Inhomogeneous solutions describe wave production.

GW Theory

- **Propagation** (homogeneous equation):

  Solutions to $\Box\bar{h}_{\mu\nu} = 0$ are

  $$h_{\mu\nu} = A_{\mu\nu} \sin\left(k_\alpha x^\alpha + \phi\right)$$

  where
  - $A_{\mu\nu}$ is the symmetric *amplitude tensor*.
  - k^α is the wave 4-vector, $k^0 = \omega$ is the frequency.

  Wave eqn: $k^\alpha k_\alpha = 0$. Lorenz cond: $k^\mu A_{\mu\nu} = 0$.

- In TT gauge:
  - transverse condition: $A_{\mu 0} = A_{\mu z} = 0$
  - traceless condition: $A^\mu{}_\mu = 0 \rightarrow A_{xx} = -A_{yy}$
  - remaining components: $A_{xx} \equiv A_+$ and $A_{xy} \equiv A_\times$.

GW Theory

- **Production** (inhomogeneous equation):

Einstein (1916) found that an approximate solution of $\Box \bar{h}_{\mu\nu} = -16\pi T_{\mu\nu}$ is

$$h^{TT}_{jk}(t) = \frac{2}{r}\frac{\partial^2}{\partial t^2}\left[\int T^{00}(t-r)\, x^j x^k d^3x\right]^{STF} ,$$

where:
- r is the distance from the source to the observer,
- t is the proper time of the observer, and
- STF denotes a symmetric trace-free projection.

This *quadrupole formalism* is valid when the gravitational wavelength is much greater than the size of the source.

GW Theory

- *Question*: How do gravitational waves effect matter?

GW Theory

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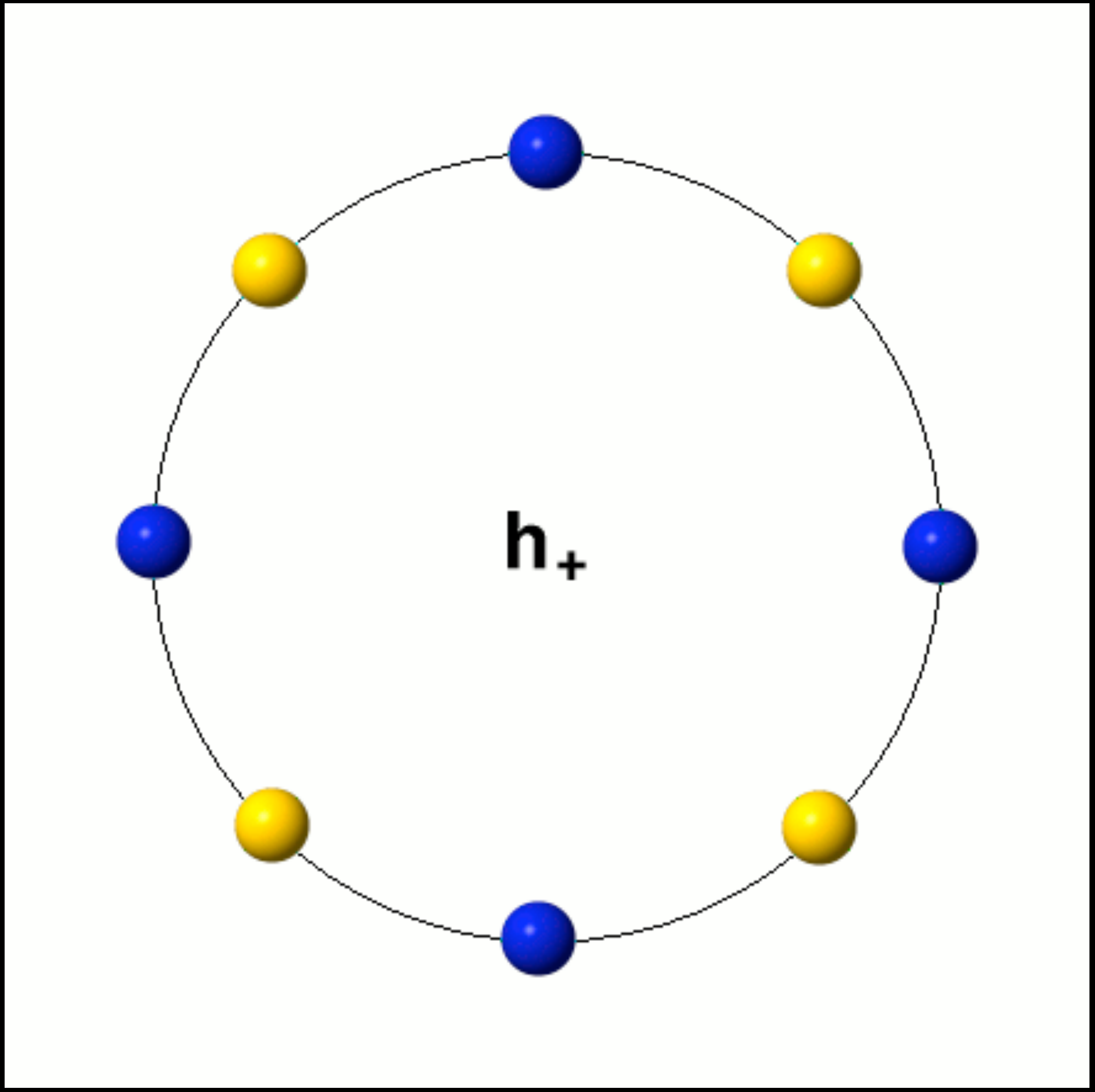

GW Theory

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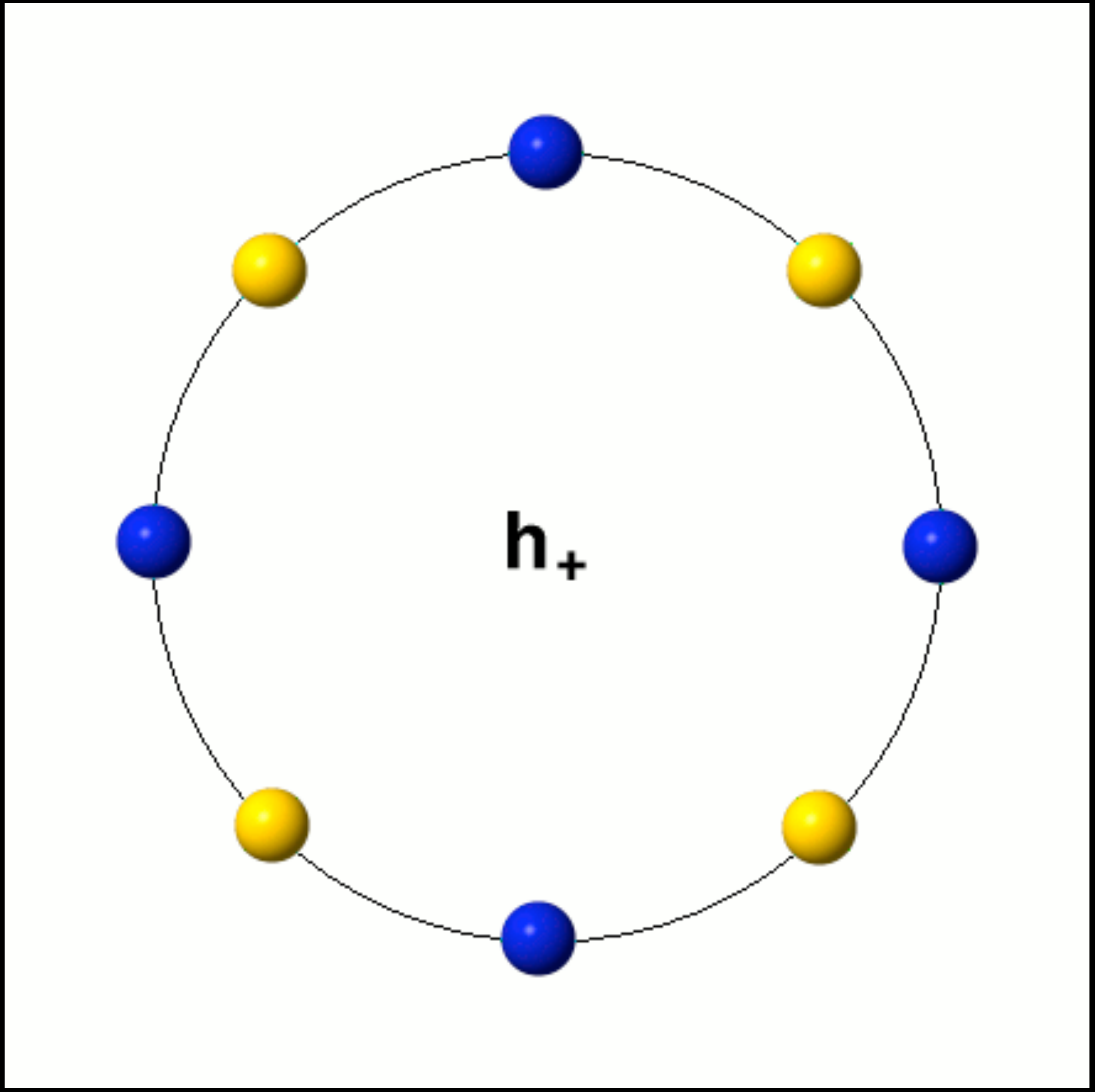

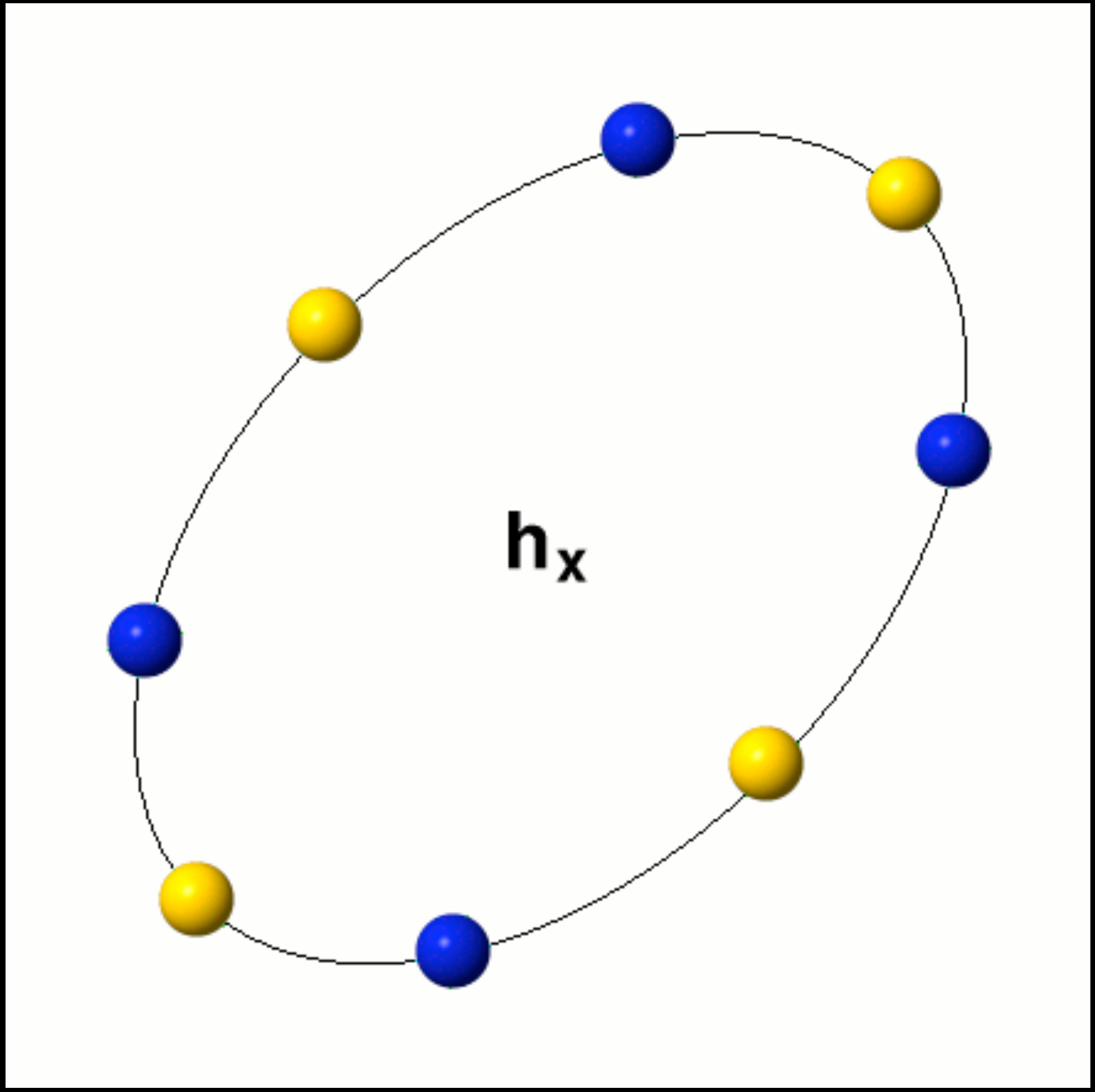

GW Theory

- Direct observation of GWs is a daunting prospect.

  Toy calculation:
  Particle of mass m in orbit of radius R and frequency ω .

$$T^{00} = m\,\delta(x - R\cos\omega t)\delta(y - R\sin\omega t)\delta(z)$$

$$\begin{aligned} h_+ &= -\frac{4GmR^2\omega^2}{rc^4}\cos(2\omega(t-r)) \\ h_\times &= -\frac{4GmR^2\omega^2}{rc^4}\sin(2\omega(t-r)) \end{aligned}$$

For a star in the virgo cluster:

$$m \sim 10^{30}\mathrm{kg}, R \sim 10^5\,\mathrm{m}, r \sim 10^{24}\,\mathrm{m}, \omega \sim 100\mathrm{Hz}$$

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$$\Delta\ell/\ell \sim |h| \sim 10^{-22}$$

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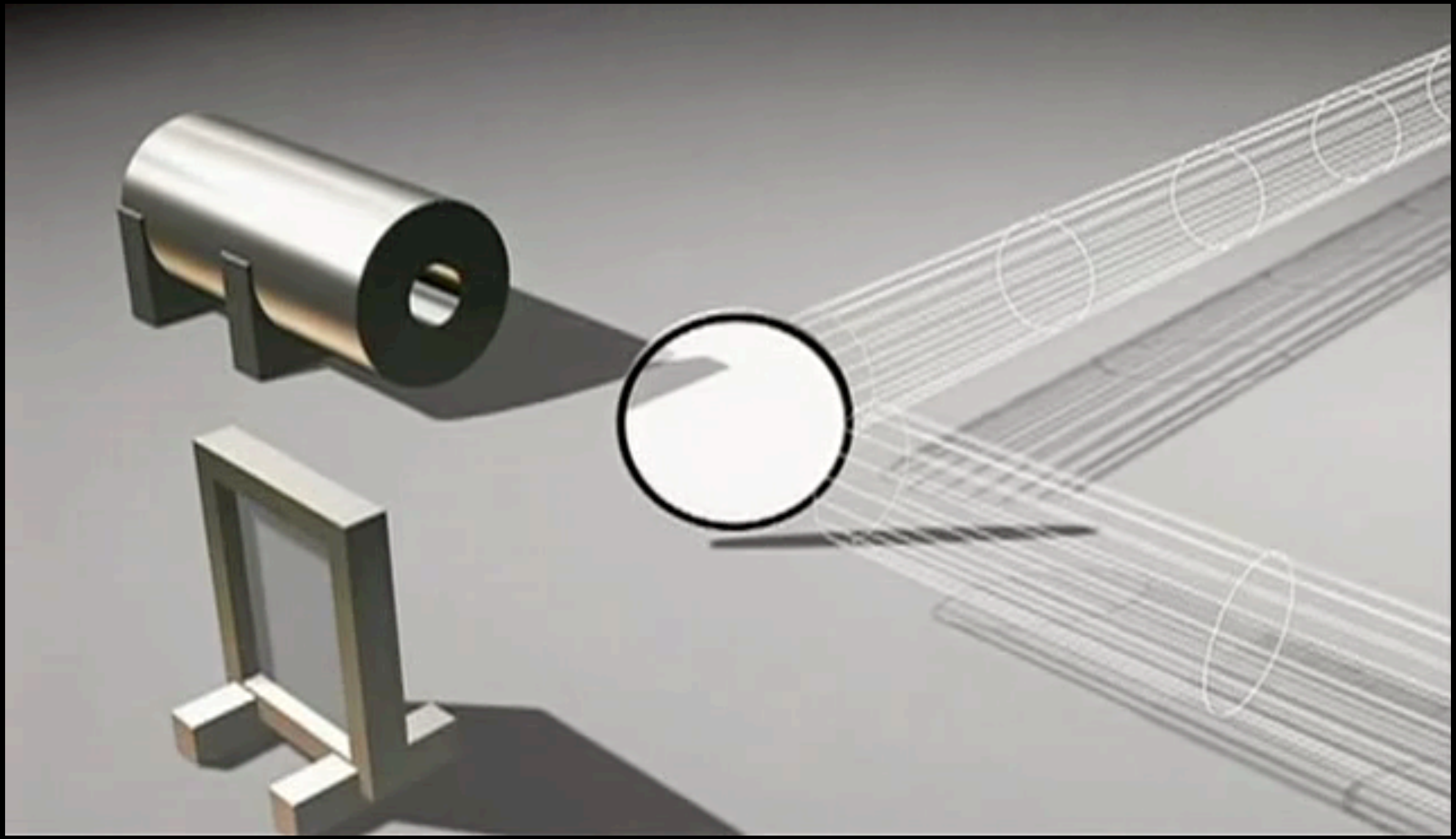
GW Detectors

- Most sensitive GW detectors are interferometers.



From "Einstein's Messengers"
National Science Foundation

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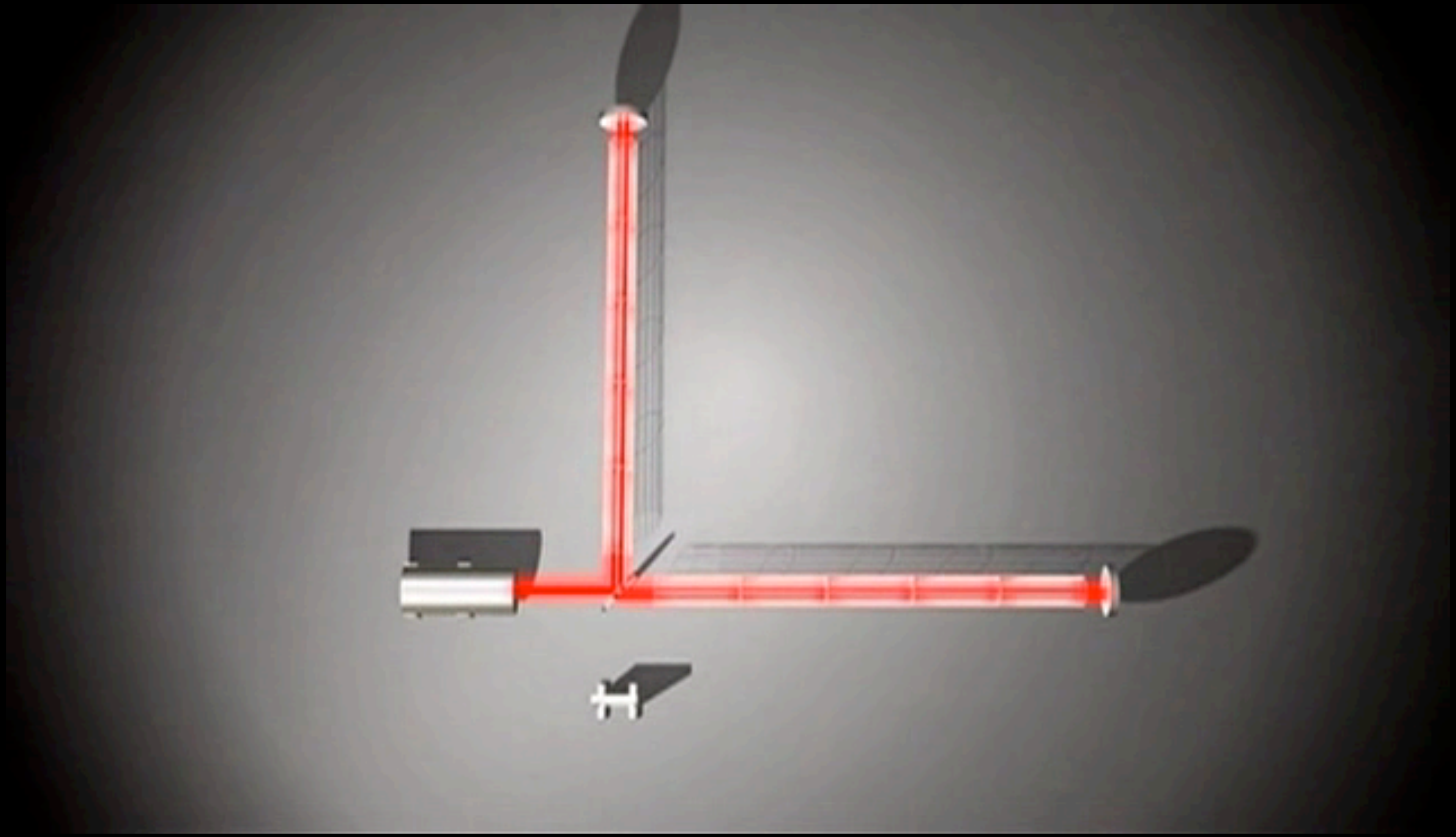

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GW Detectors

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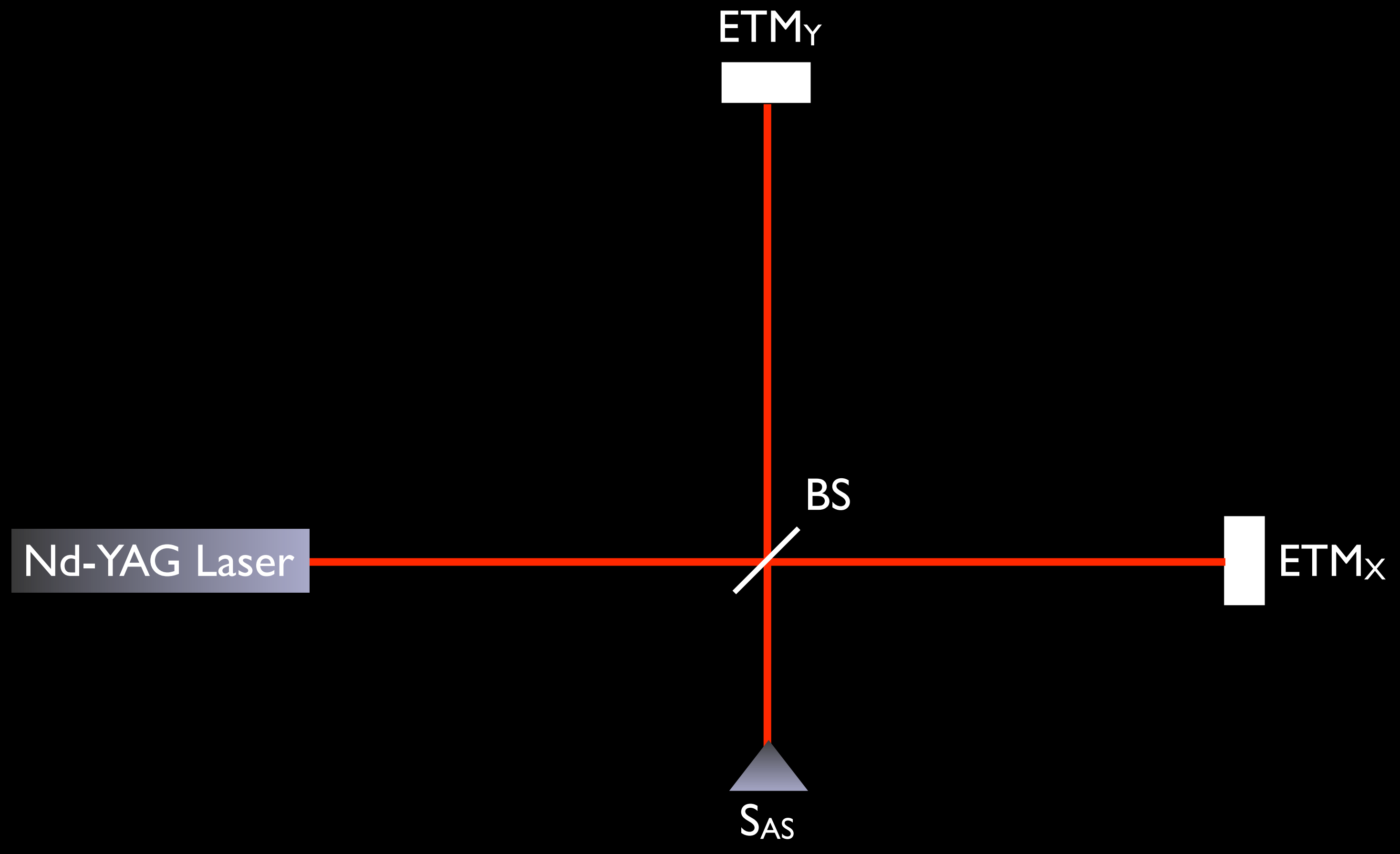

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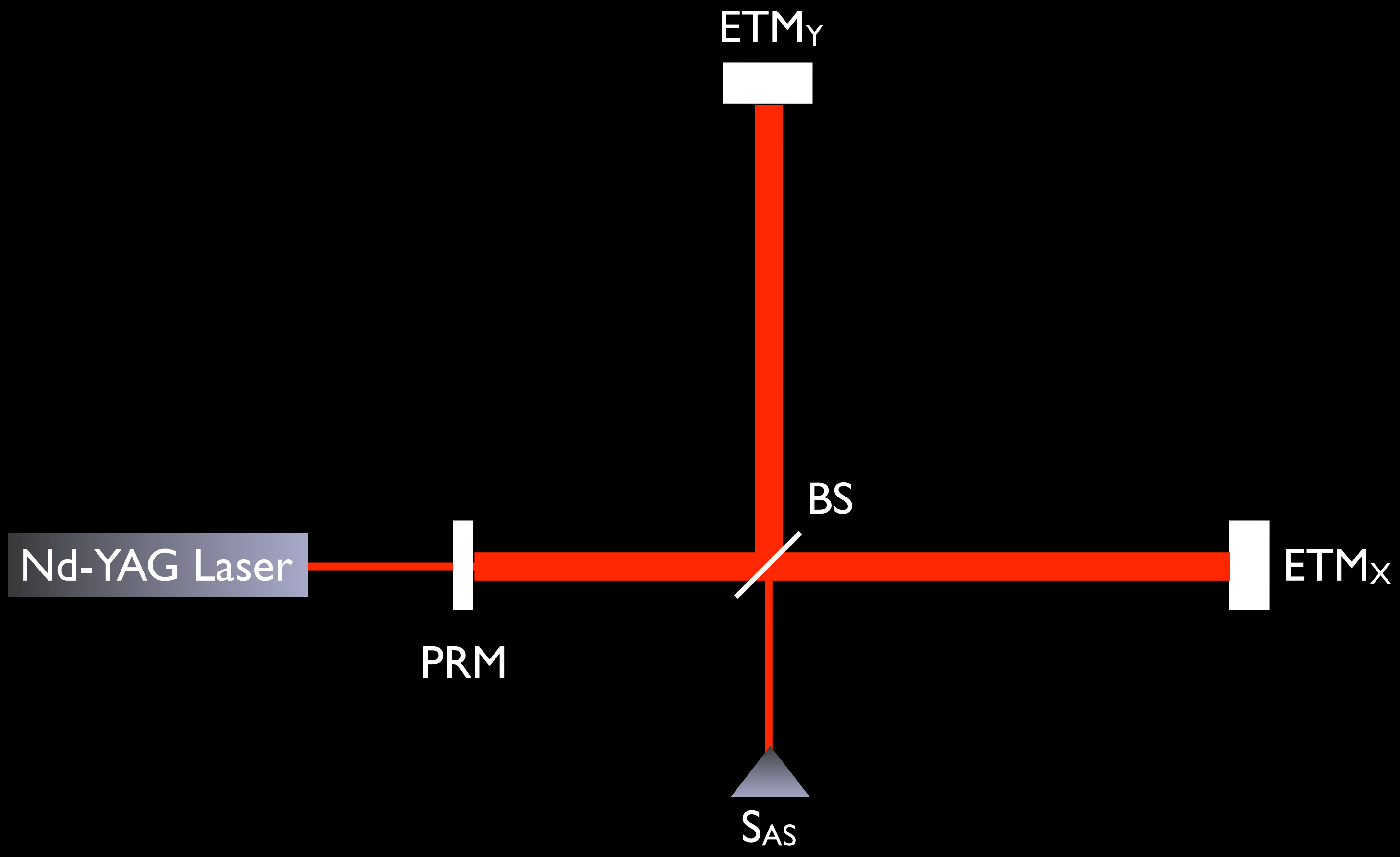

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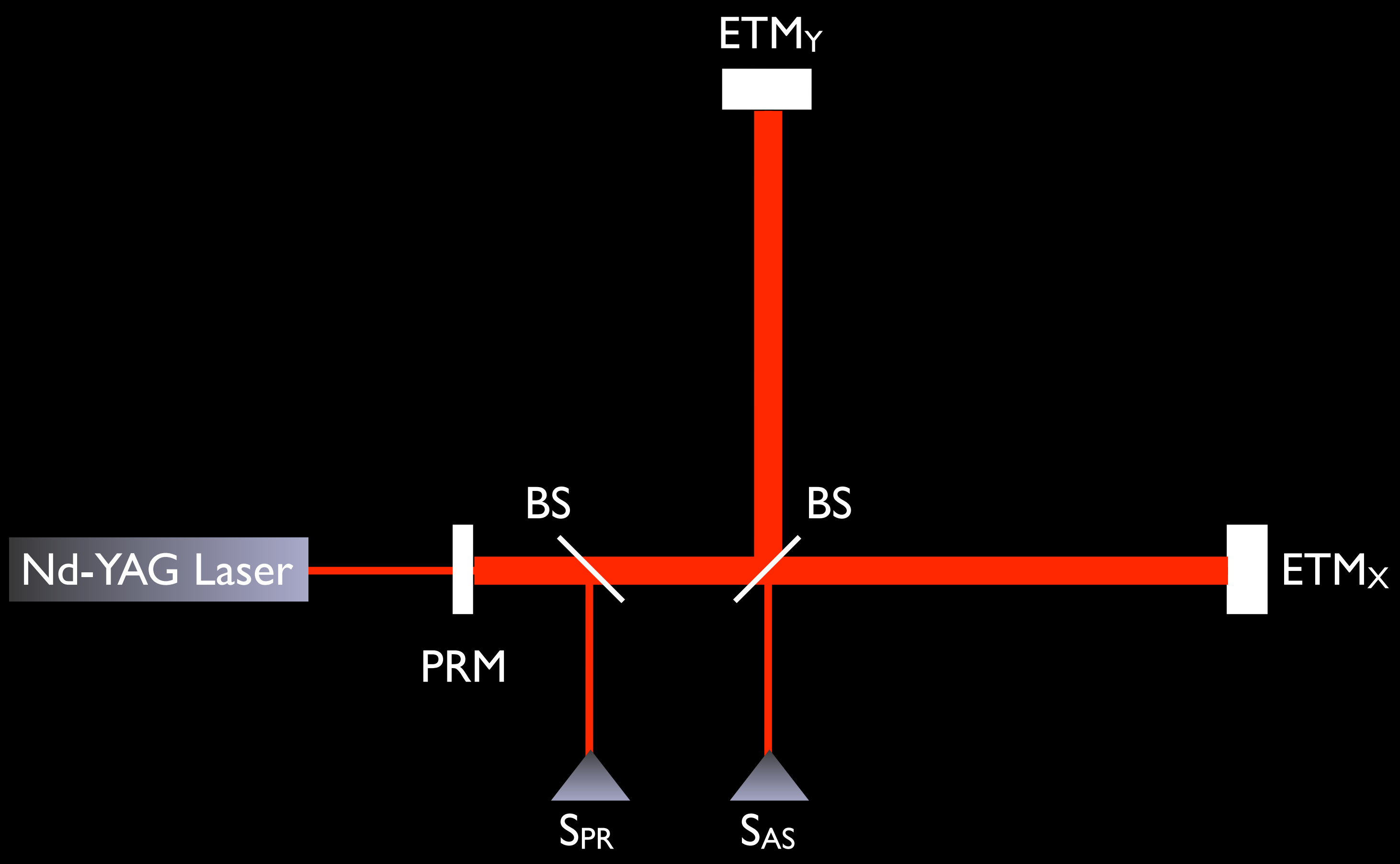

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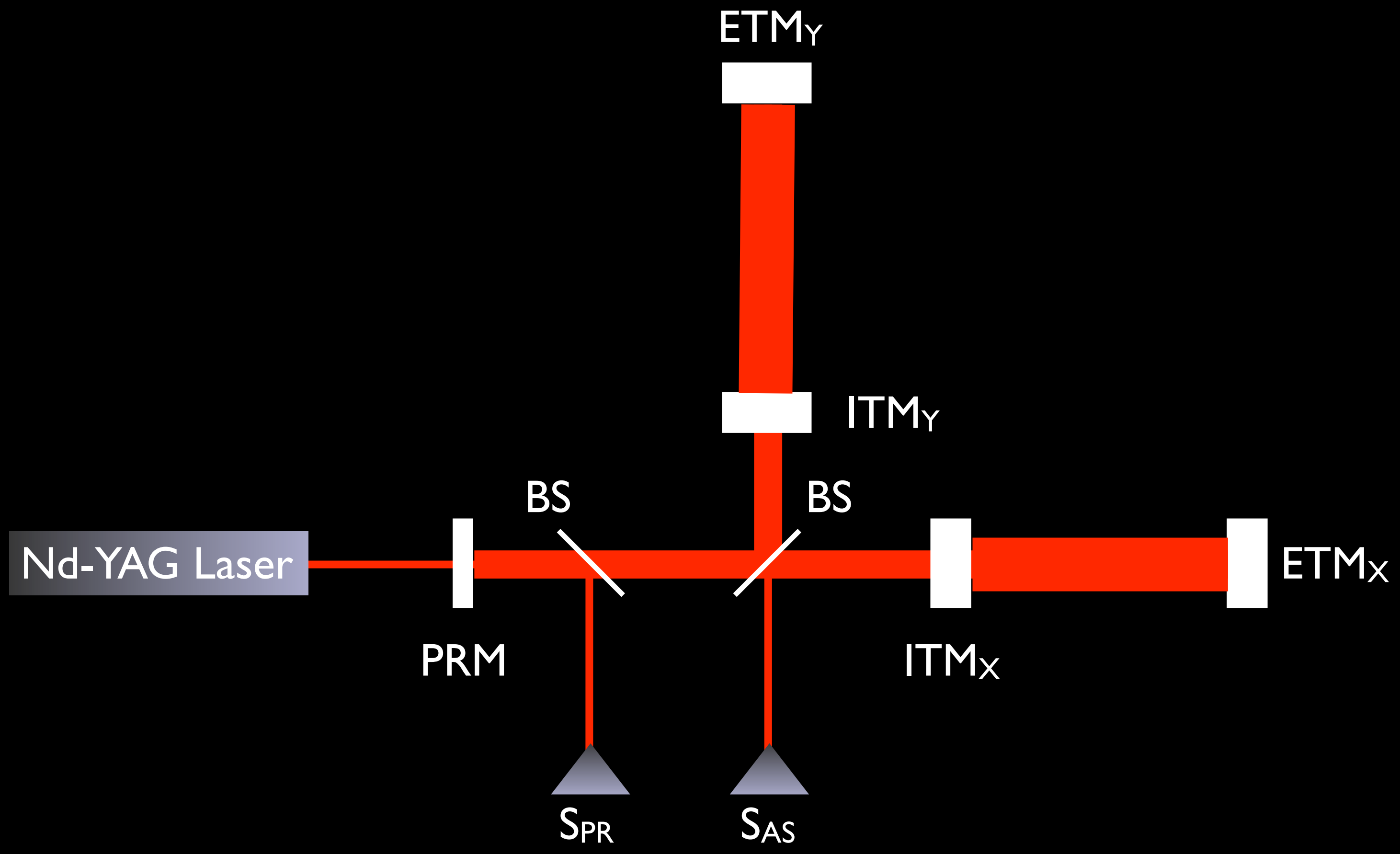

GW Detectors

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Legend:

ETM - End Test Mass
ITM - Input Test Mass
BS - Beam Splitter
PR - Power Recycling
AS - Antisymmetric
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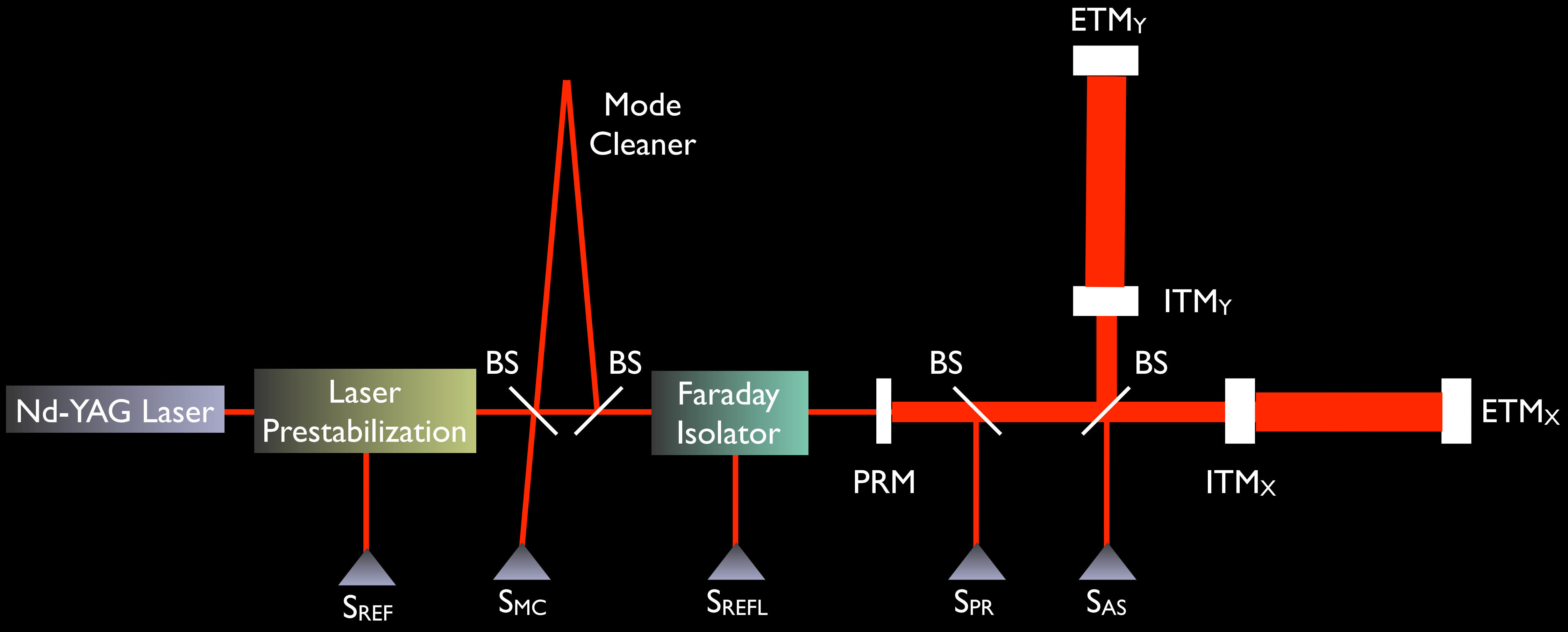
Ref - Reference



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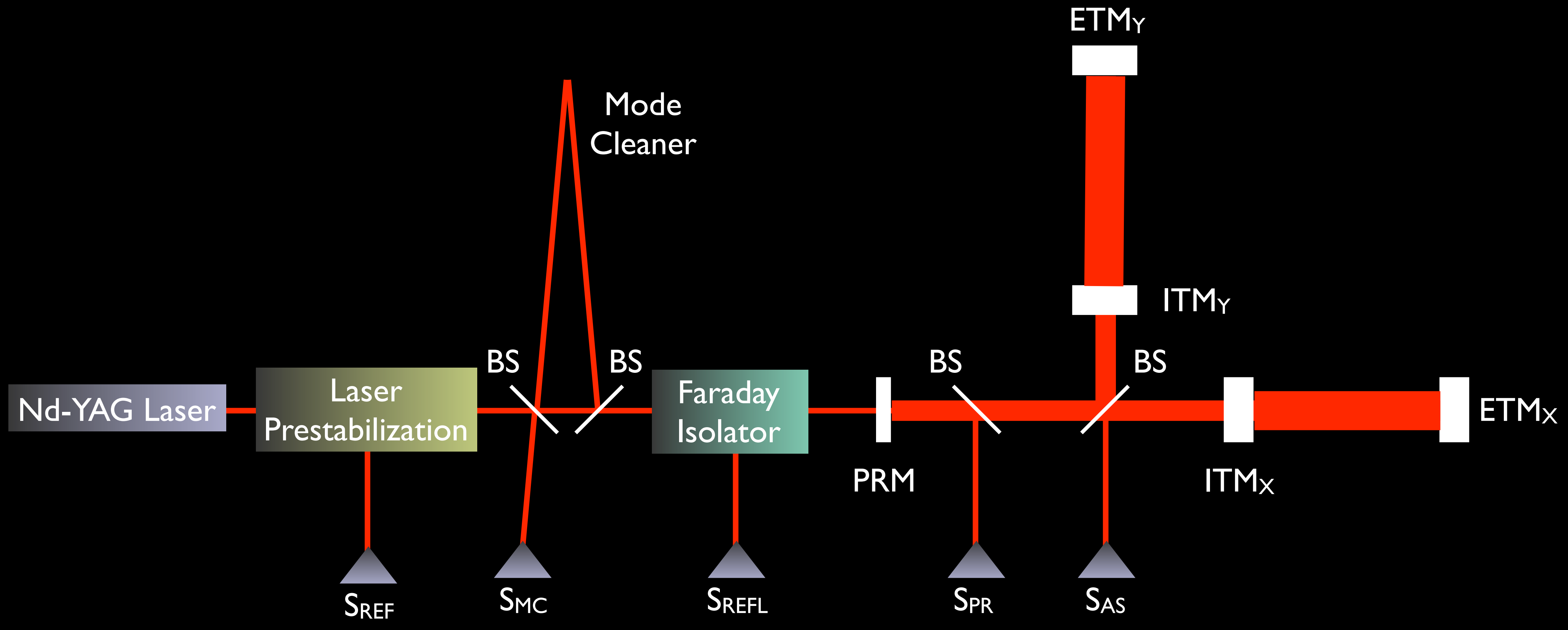
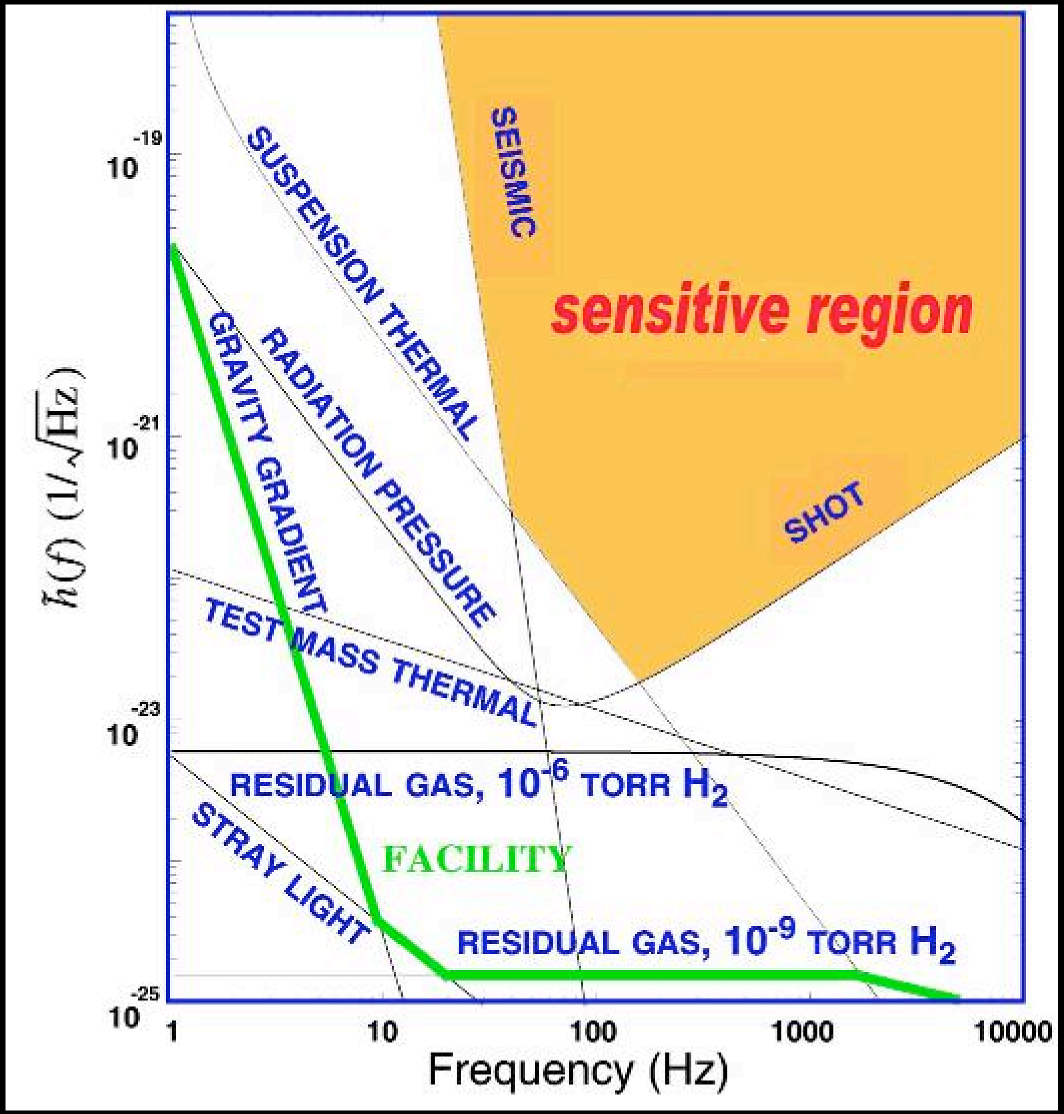
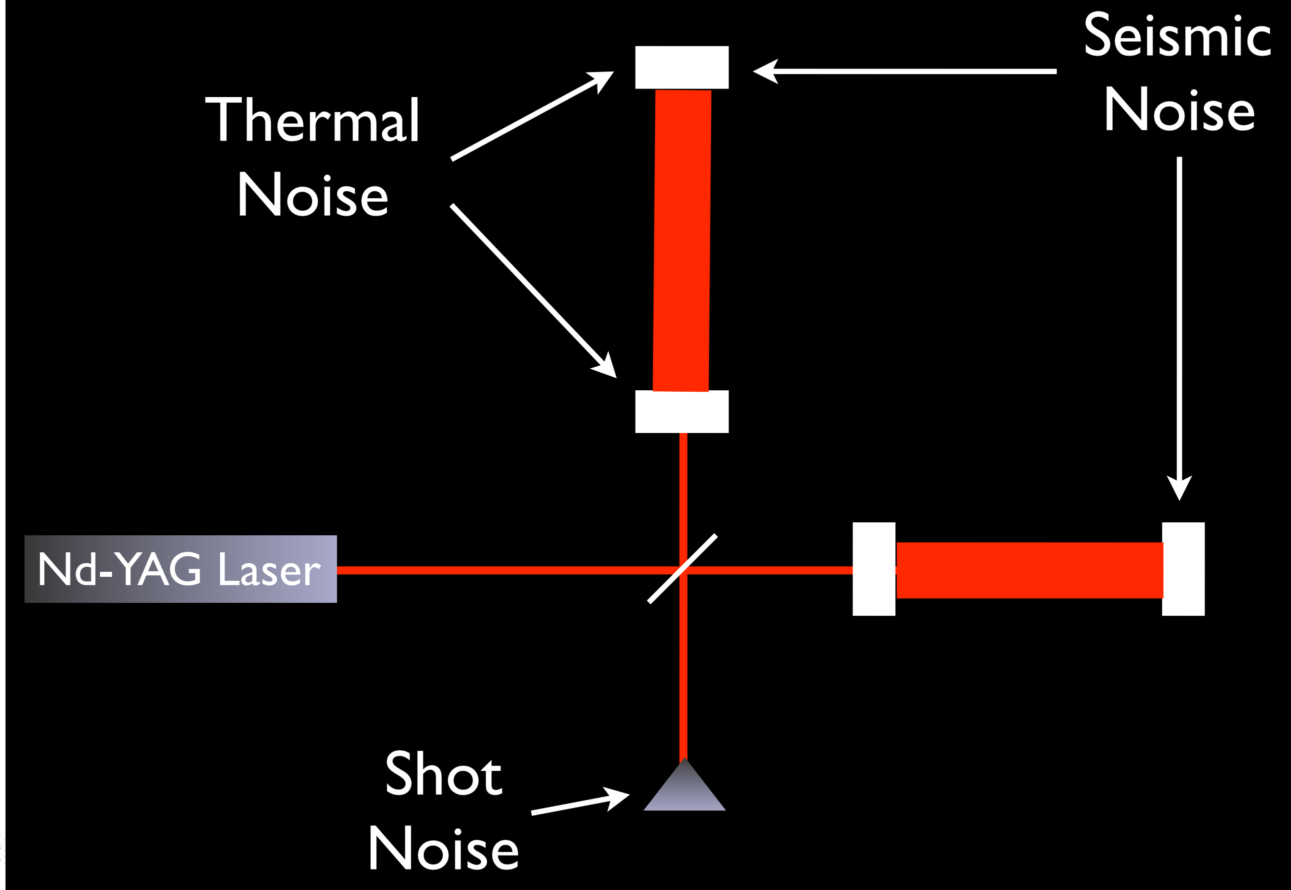


Fabry-Perot Interferometer - arms are locked at low frequencies by feedback loops from output signals.

GW Detectors

- Interferometers are subject to many noise sources.





Thermal Noise

Seismic Noise

Nd-YAG Laser

Shot Noise

- thermal noise and seismic noise move the test masses.
- shot noise is phase noise due to uncertainty principle.

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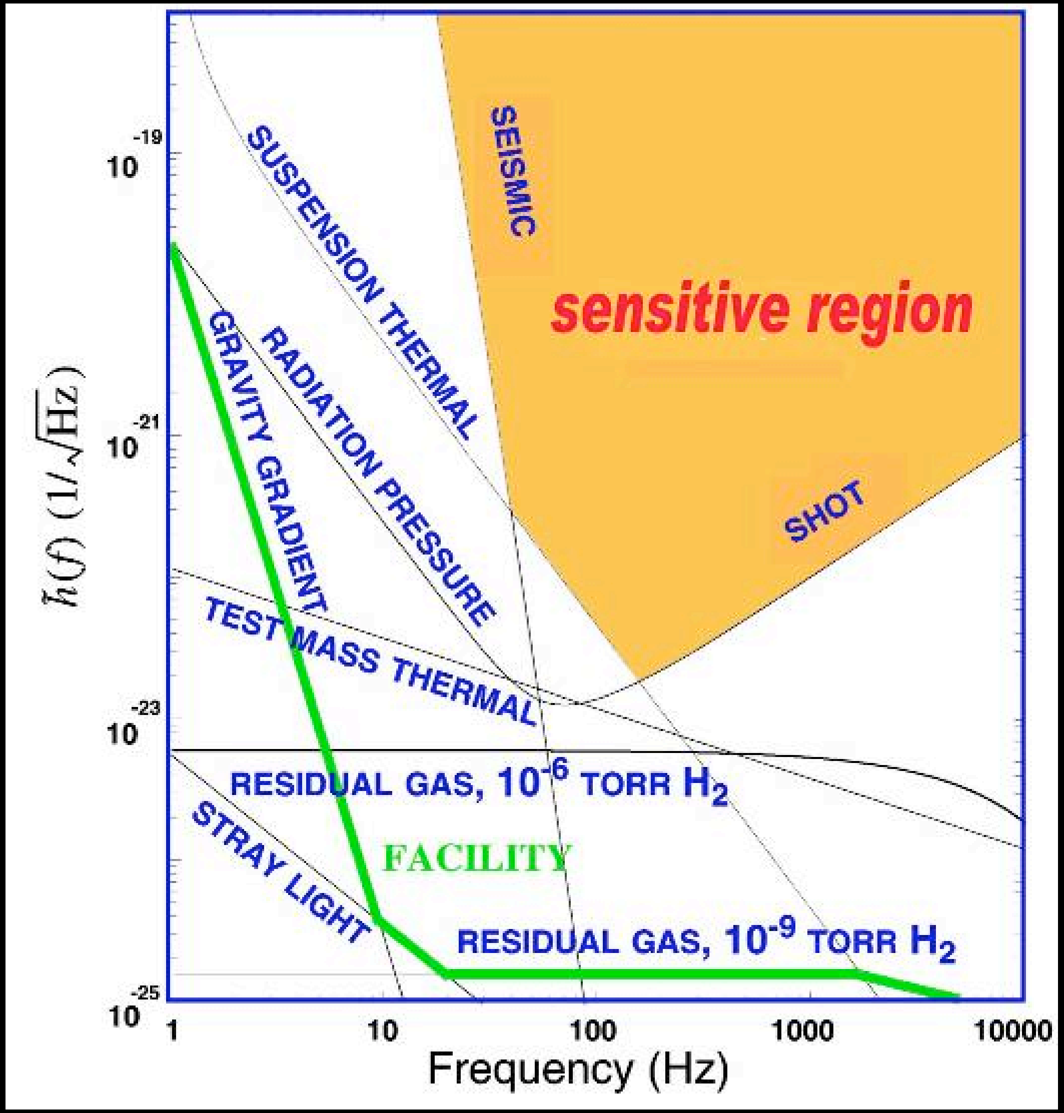

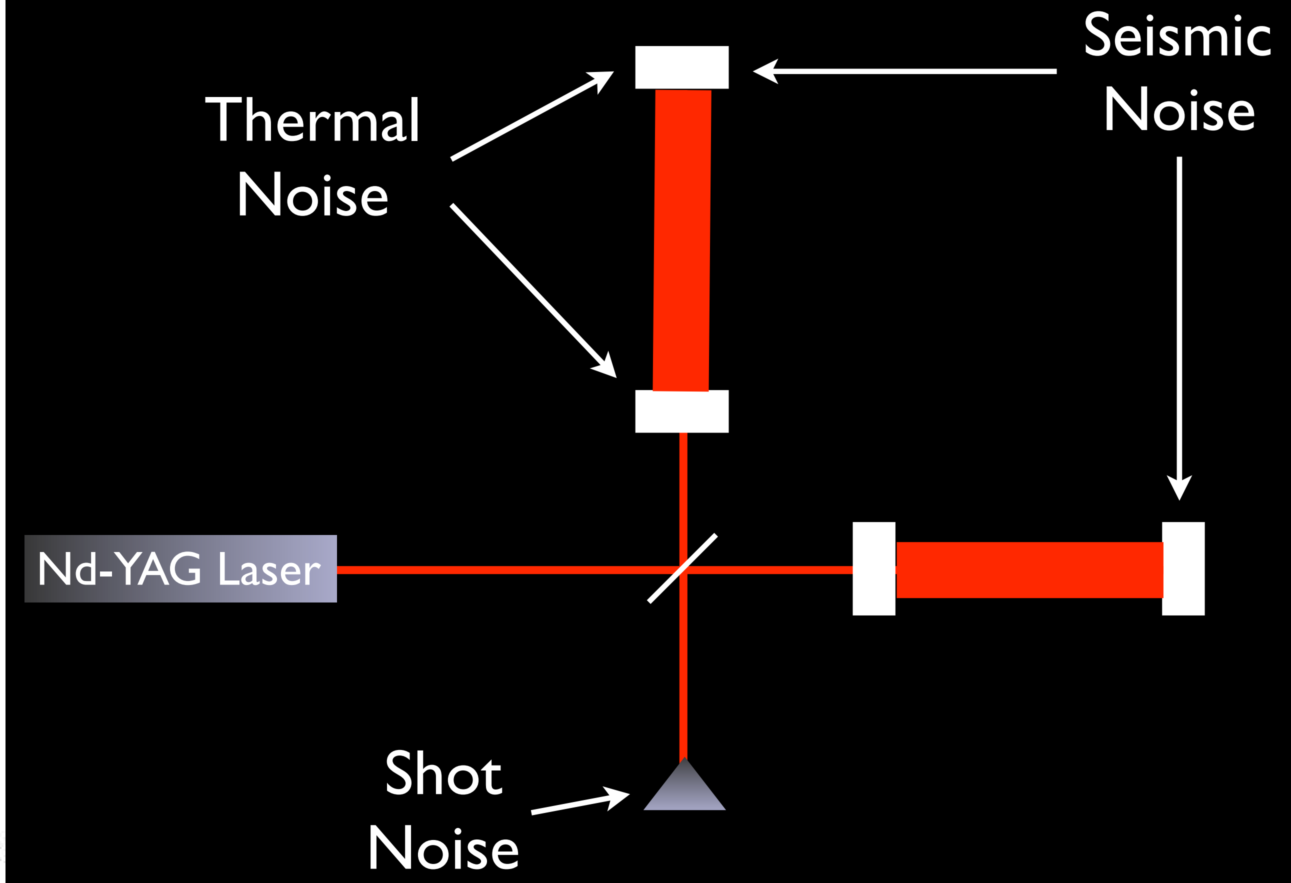

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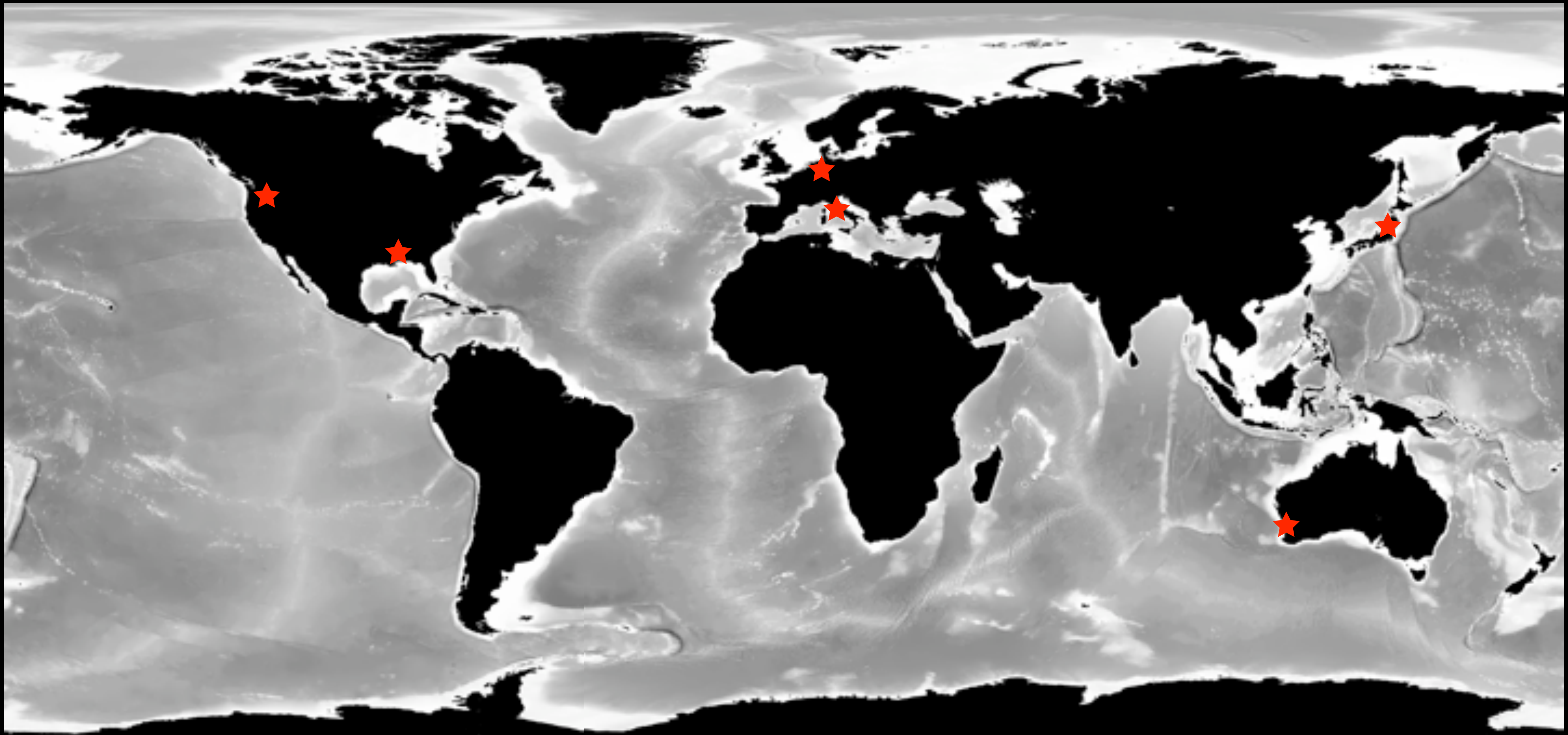
GW Detectors

- A world-wide network of GW interferometers has been constructed.



Map Credit: NASA 's Earth Observatory

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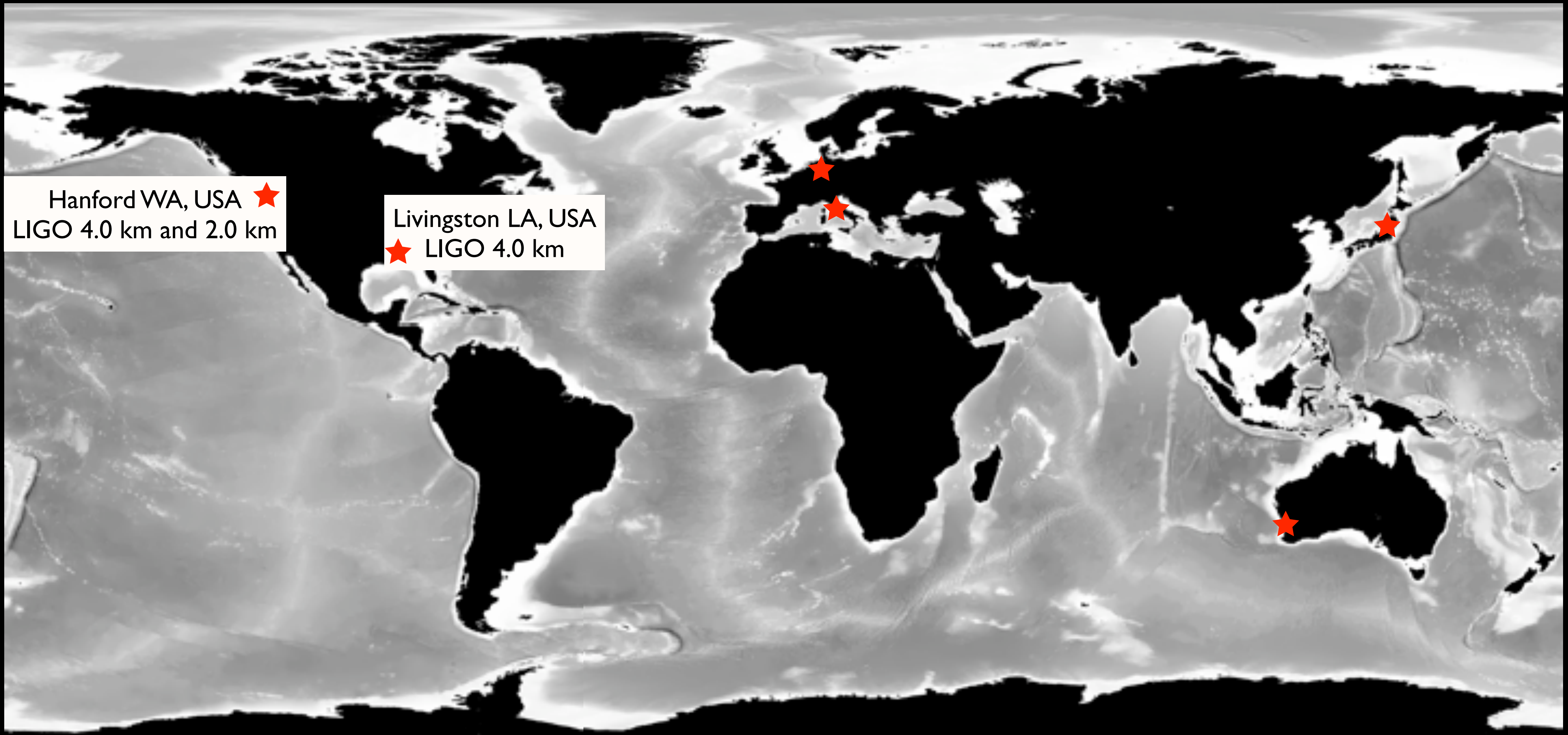

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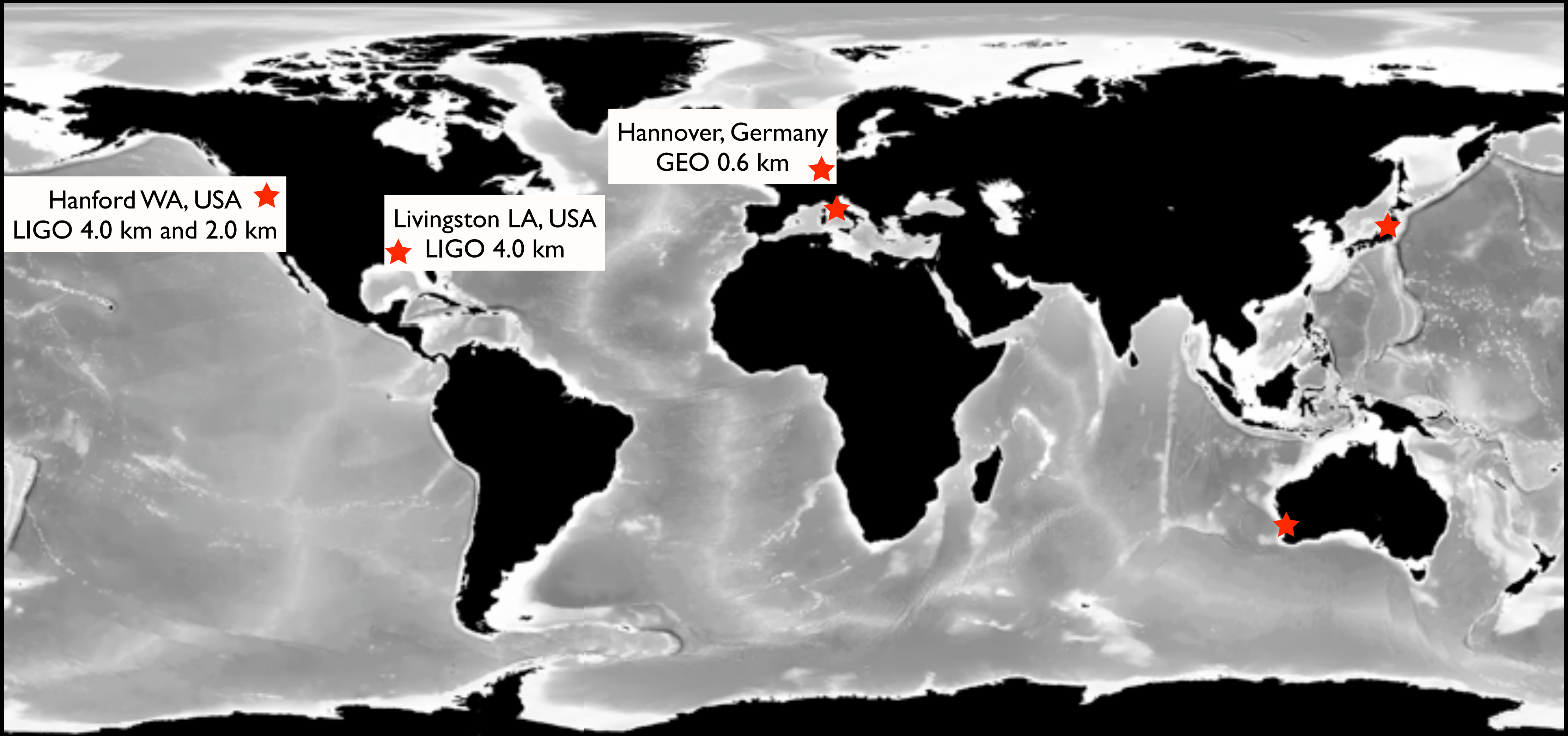

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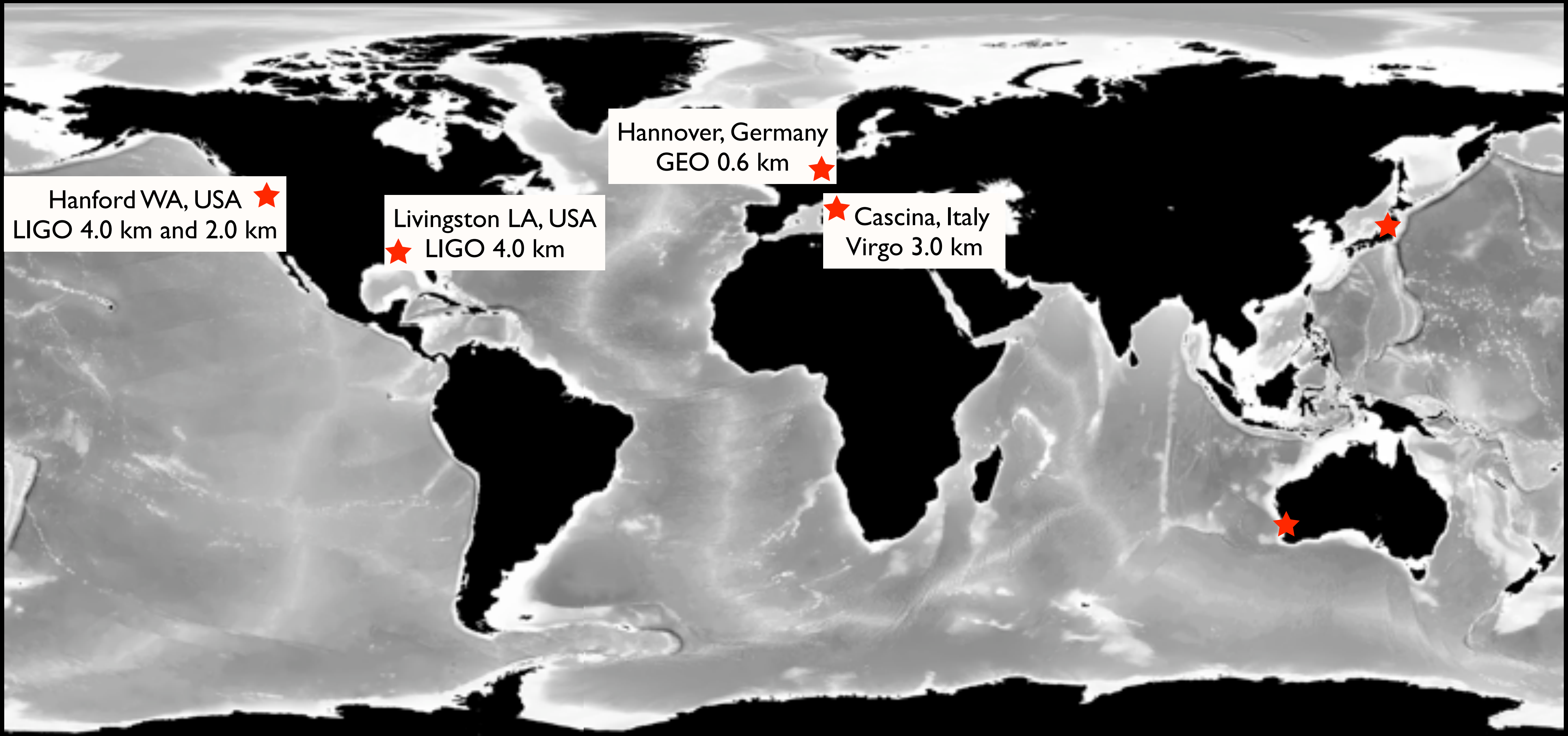

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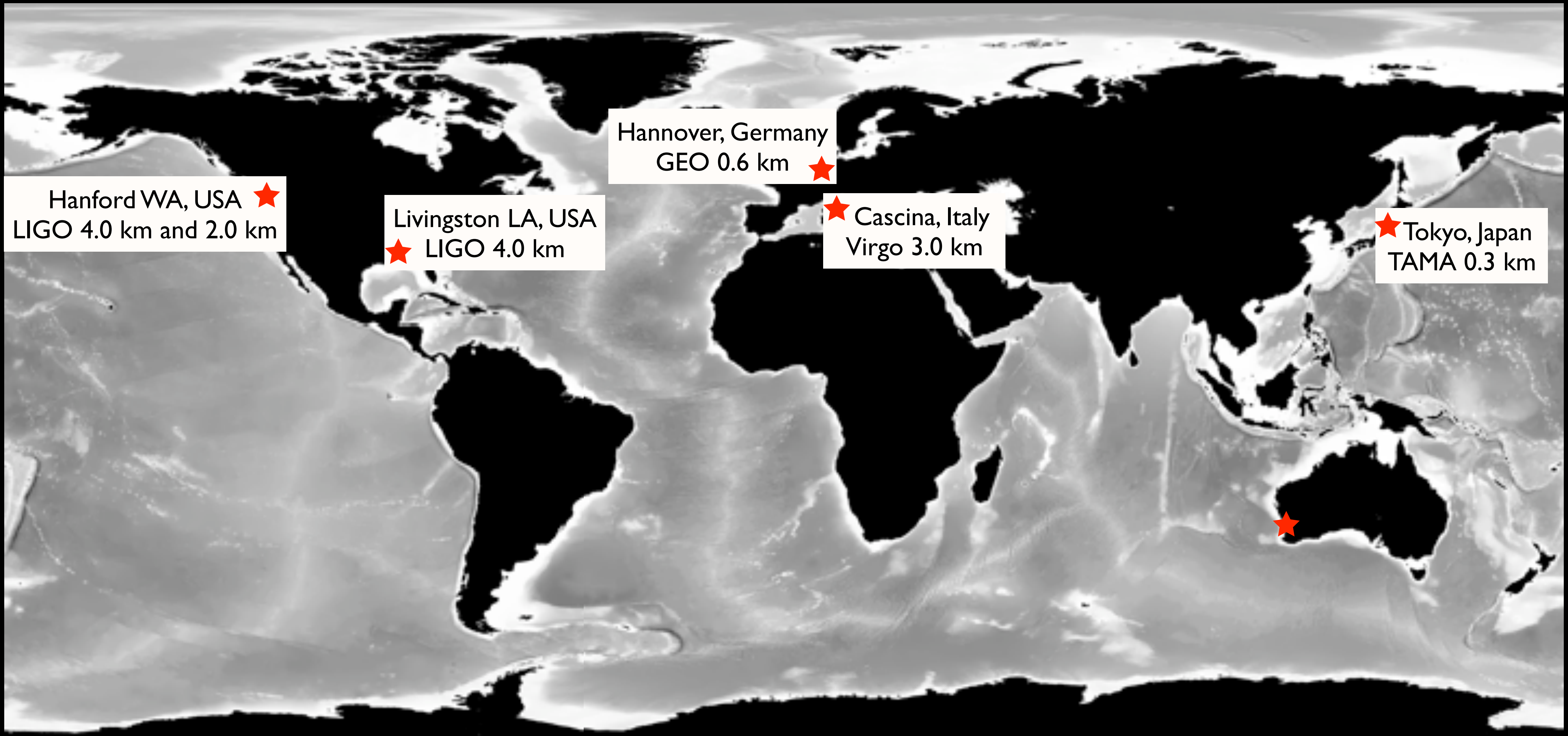

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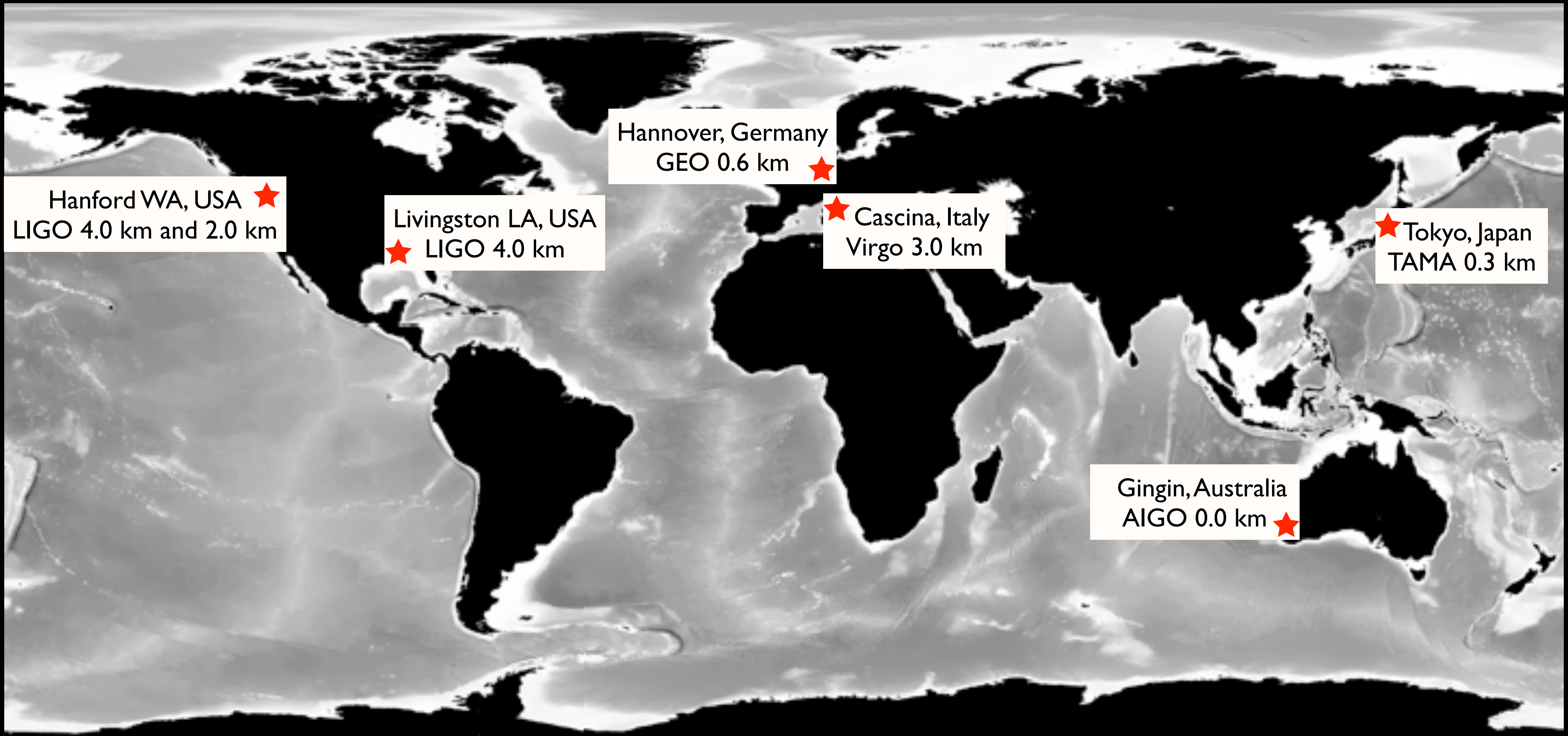

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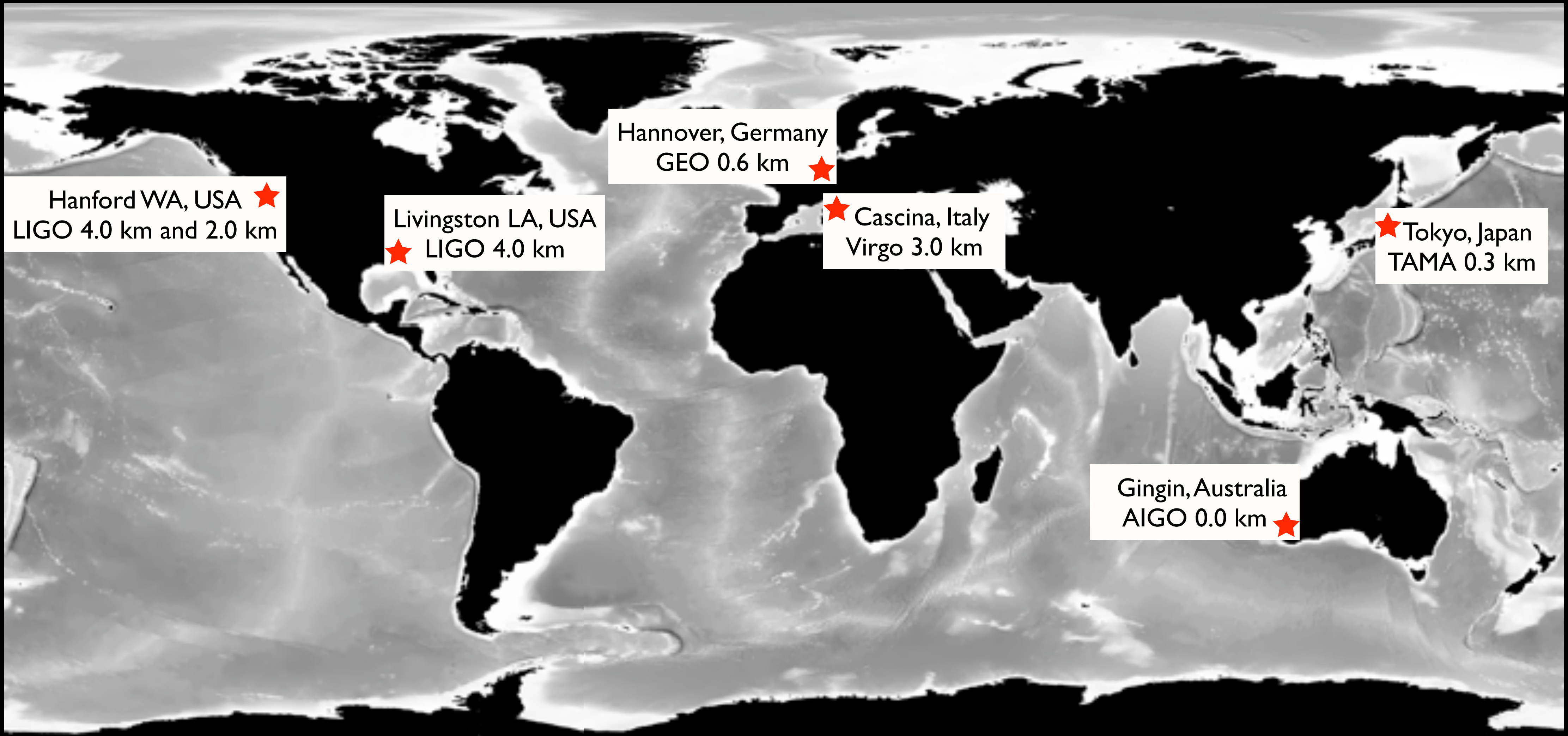
GW Detectors

- The North American interferometers are the Laser Interferometer Gravitational-Wave Observatory Lab.



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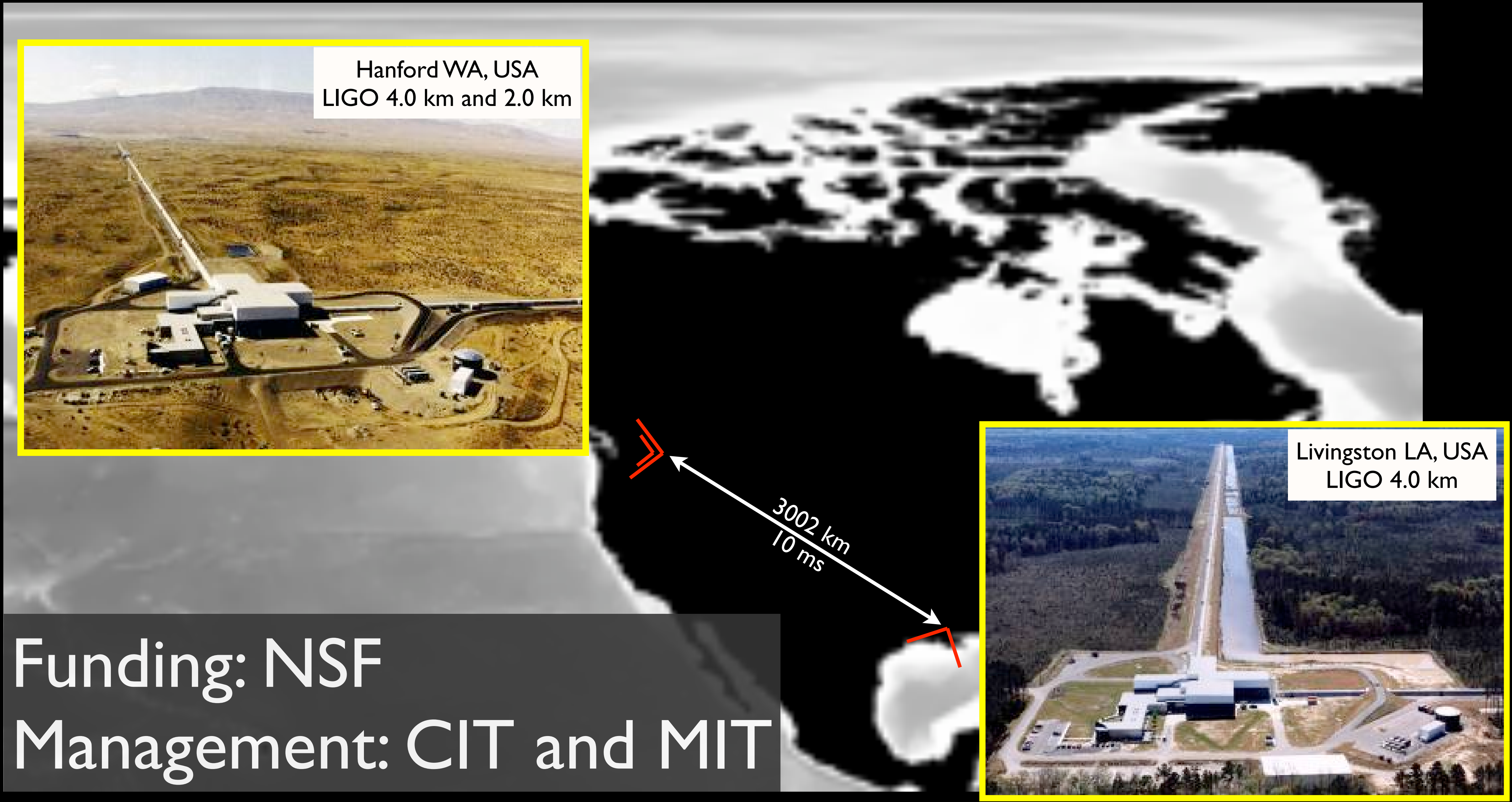
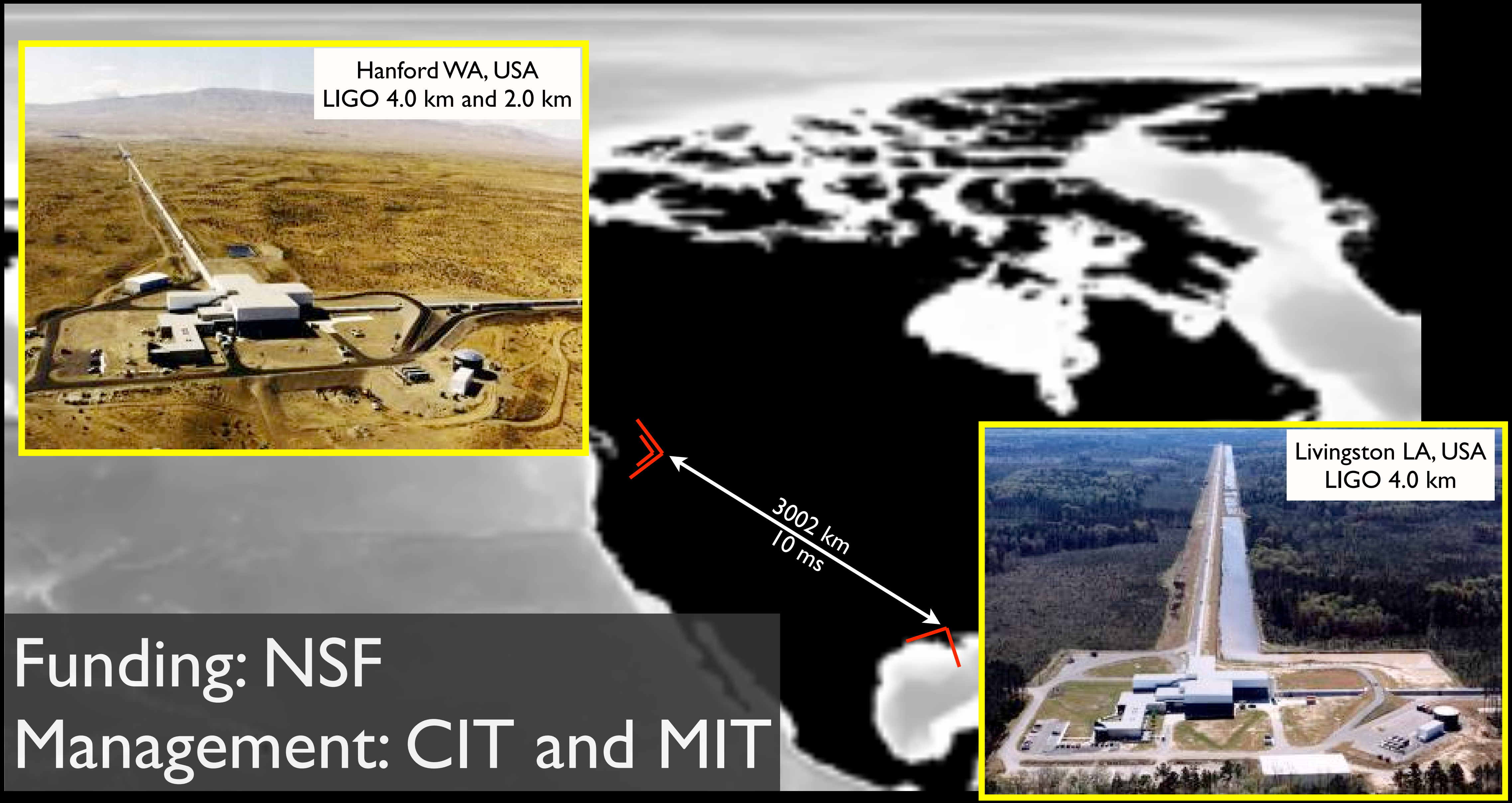


Funding: NSF

Management: CIT and MIT

GW Detectors

- The North American interferometers are the LIGO Lab. LIGO Lab + LIGO Scientific Collaboration (LSC) = LIGO.



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GW Detectors

- The LSC is itself an international collaboration.

UNIVERSITY OF MARYLAND 18 56
MICHIGAN
UNIVERSITY OF STRATHCLYDE
ACIGA
LELAND STANFORD JUNIOR UNIVERSITY 1891
MONTANA STATE UNIVERSITY
РАН
UNIVERSITY OF WASHINGTON
SYRACUSE UNIVERSITY FOUNDED AD 1870 SUOS CULTORES SCIENTIA CORONAT
UNIVERSITY of GLASGOW
Università degli Studi del Sannio
TRINITY UNIVERSITY
San José State UNIVERSITY
UNIVERSITY of WISCONSIN UWMILWAUKEE
ANU THE AUSTRALIAN NATIONAL UNIVERSITY
LSU
UTB TSC
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PER ARDUA ALTA
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NORTHWESTERN UNIVERSITY
R·I·T
Andrews University
MASSACHUSETTS INSTITUTE OF TECHNOLOGY 1861
SOUTHEASTERN LOUISIANA UNIVERSITY
THE UNIVERSITY OF TEXAS AT AUSTIN
Moscow State University
UNIVERSITY OF MASSACHUSETTS AMHERST 1863
THE UNIVERSITY OF ADELAIDE AUSTRALIA
PAN
GEO 600
SIGILL. COLL. CARLETON NORTHFIELD MINN. AD 1866
EMBRY-RIDDLE AERONAUTICAL UNIVERSITY
University of Southampton
PENNSTATE 1855
CARDIFF UNIVERSITY
UIB Universitat de les Illes Balears
WASHINGTON STATE UNIVERSITY
UF UNIVERSITY of FLORIDA
The University of Mississippi 1848
CHARLES STURT UNIVERSITY
UNIVERSITY OF ROCHESTER
NAOJ
UNIVERSITY OF MINNESOTA
SOUTHERN UNIVERSITY Agricultural & Mechanical College
HOBART COLLEGE
WILLIAM SMITH COLLEGE 1908
Science & Technology Facilities Council Rutherford Appleton Laboratory
Universität Hannover

GW Detectors

- The LSC is itself an international collaboration.

  - 689 scientists at 63 institutions

  - 10 countries on four continents

  - Data sharing agreement with GEO

  - Experimental design partnership with AIGO

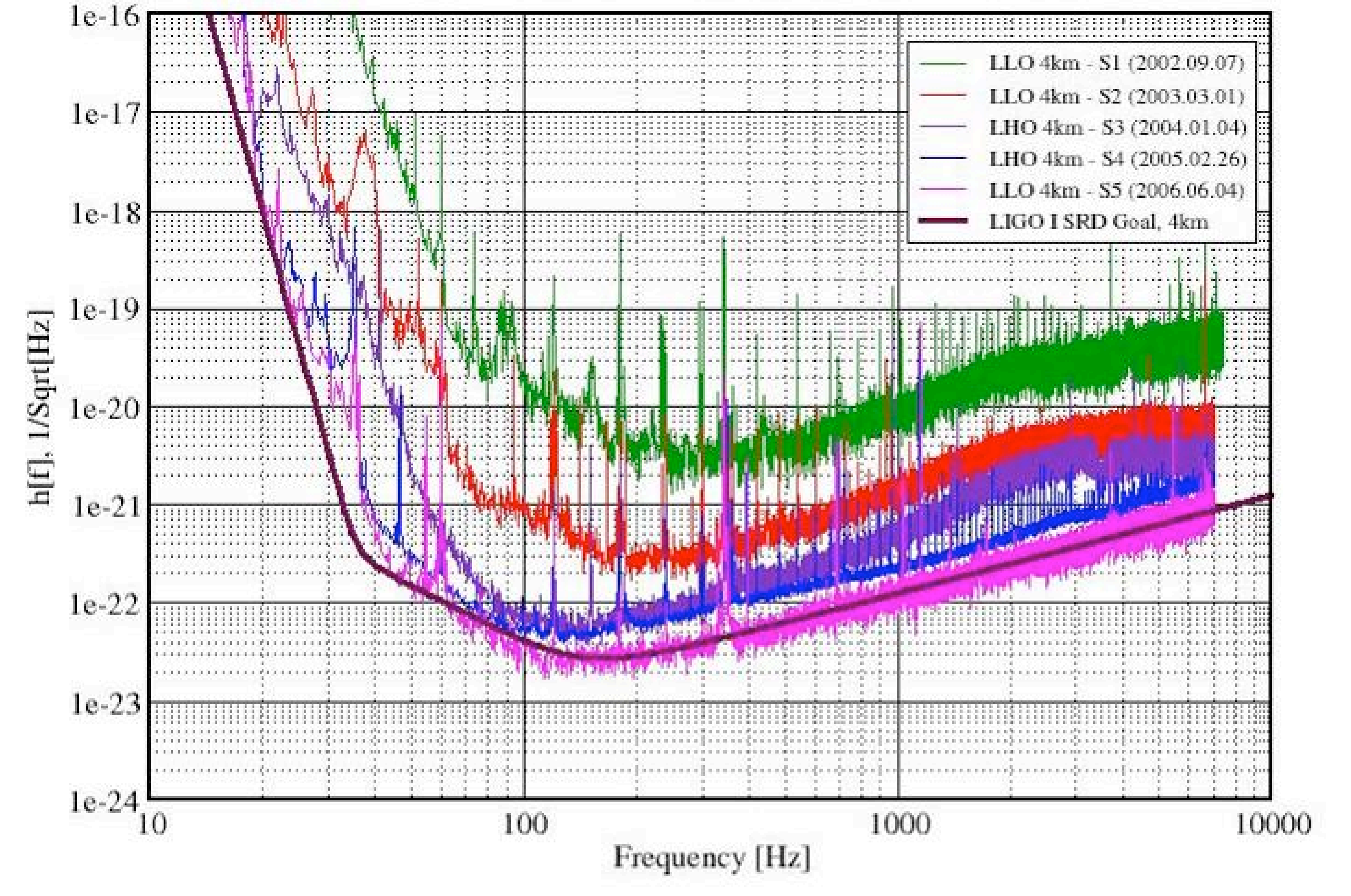
  - Data sharing agreement with Virgo

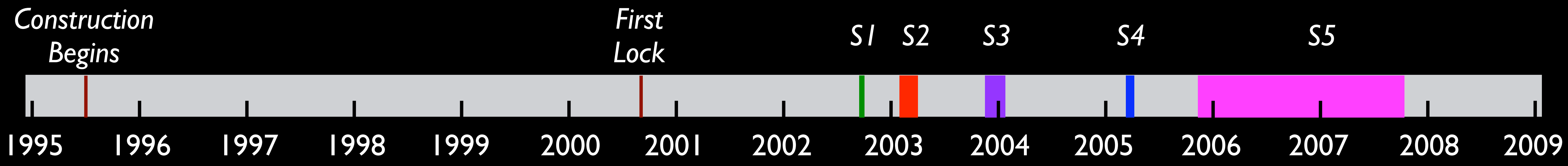
  - Joint papers published with TAMA

GW Detectors

GW Detectors

- We have achieved our initial science objective - one year of coincident data at design sensitivity.





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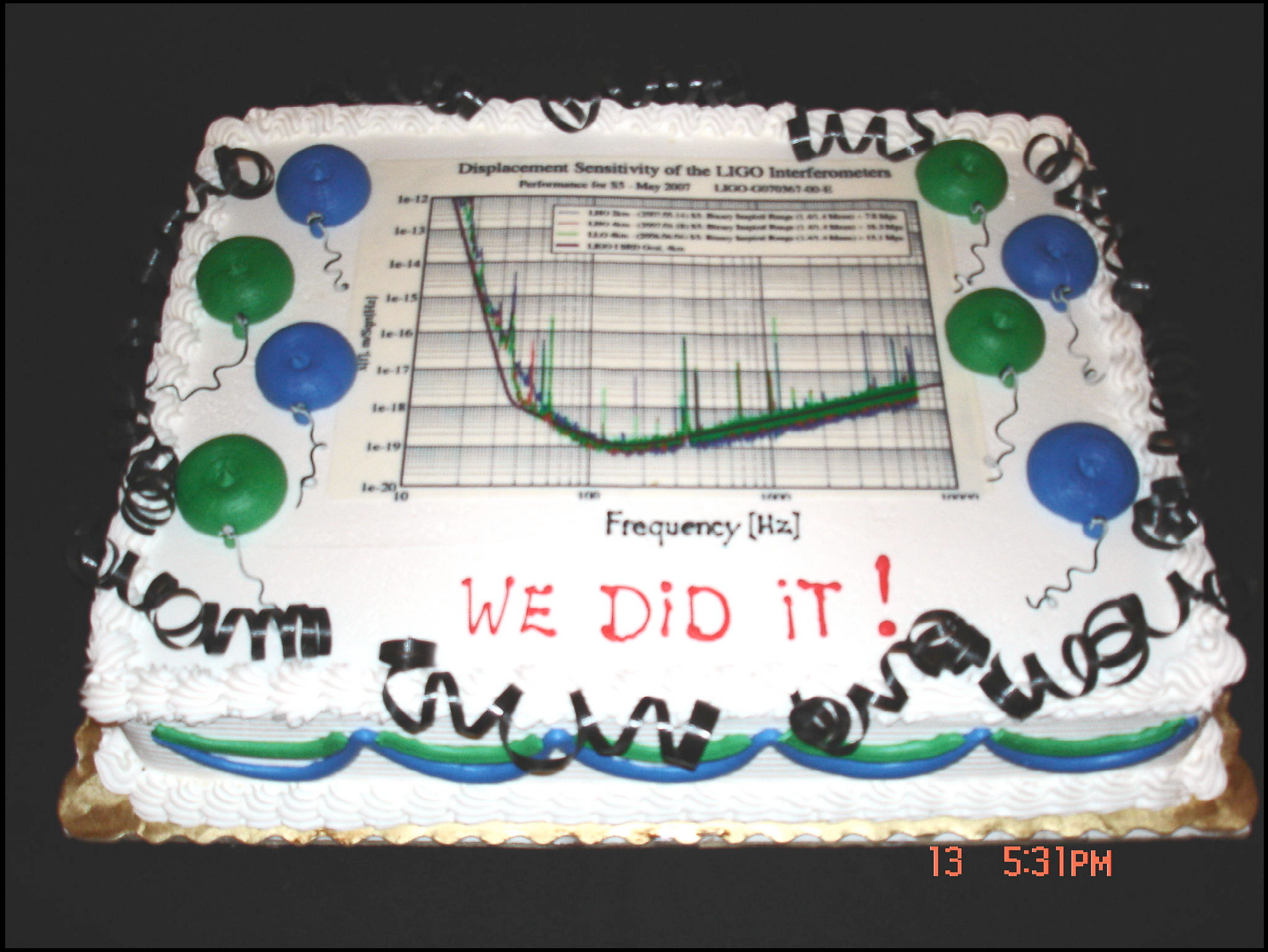

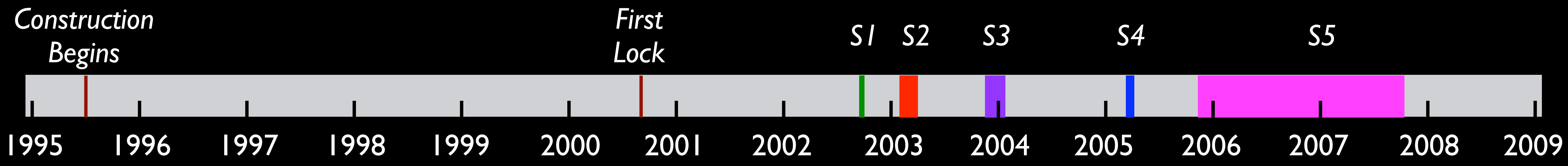
Construction Begins

First Lock

S1 *S2* *S3* *S4* *S5*

1995 1996 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007 2008 2009

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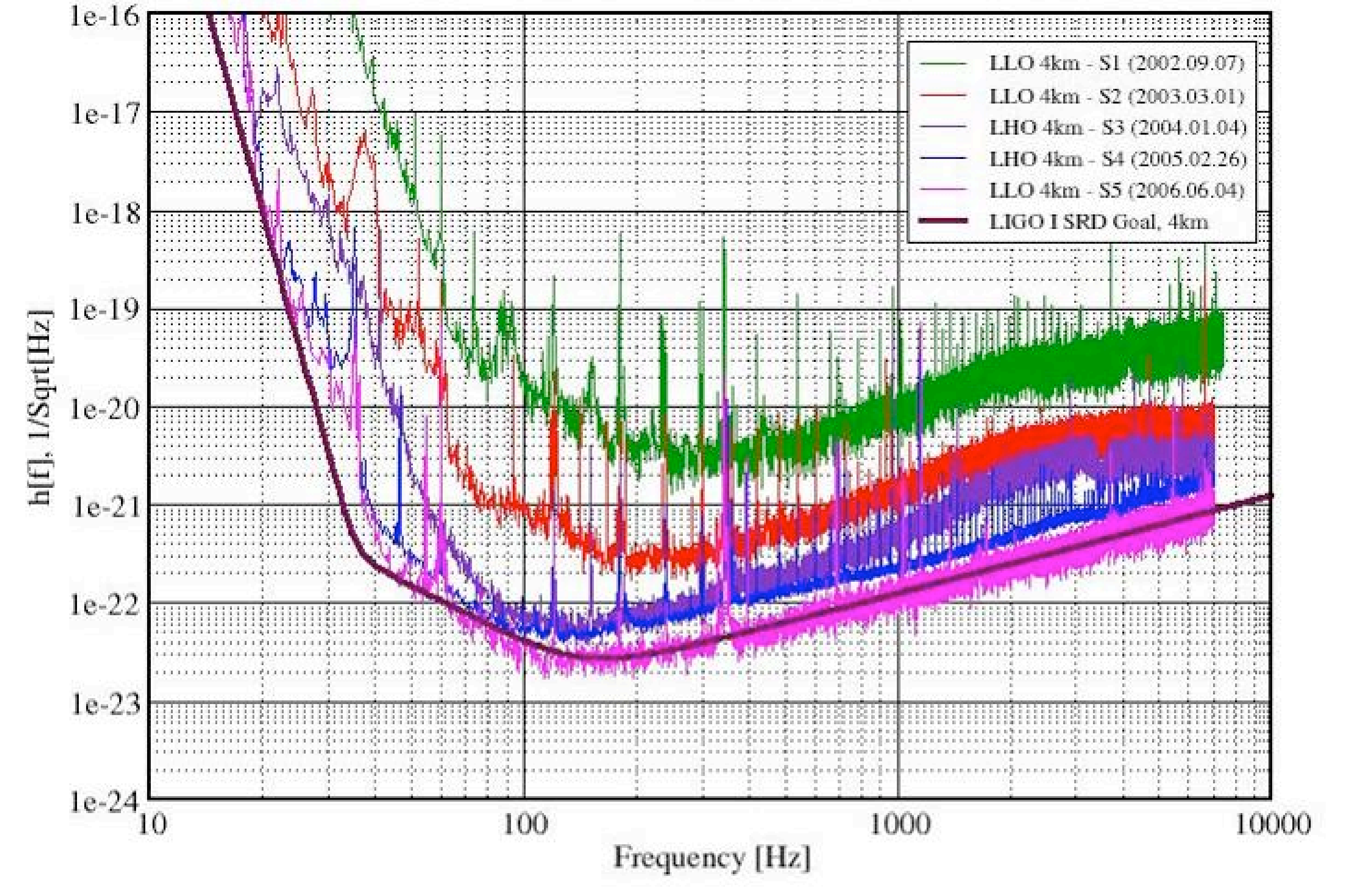
GW Sources

- Detectable sources are dictated by the sensitive frequency band of the detectors.



Interferometric detectors are sensitive to gravitational waves in the 50-1000 Hz range.

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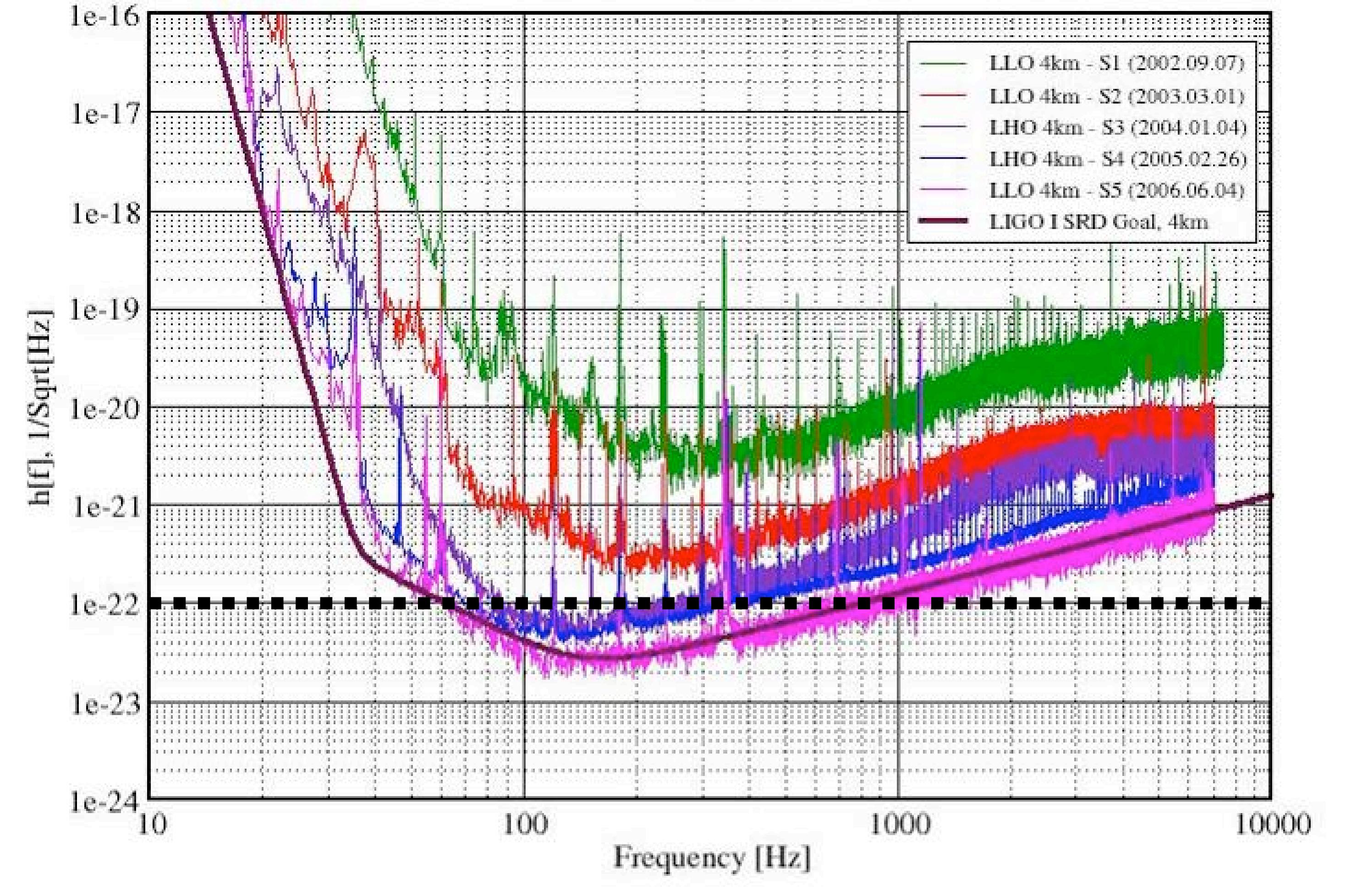

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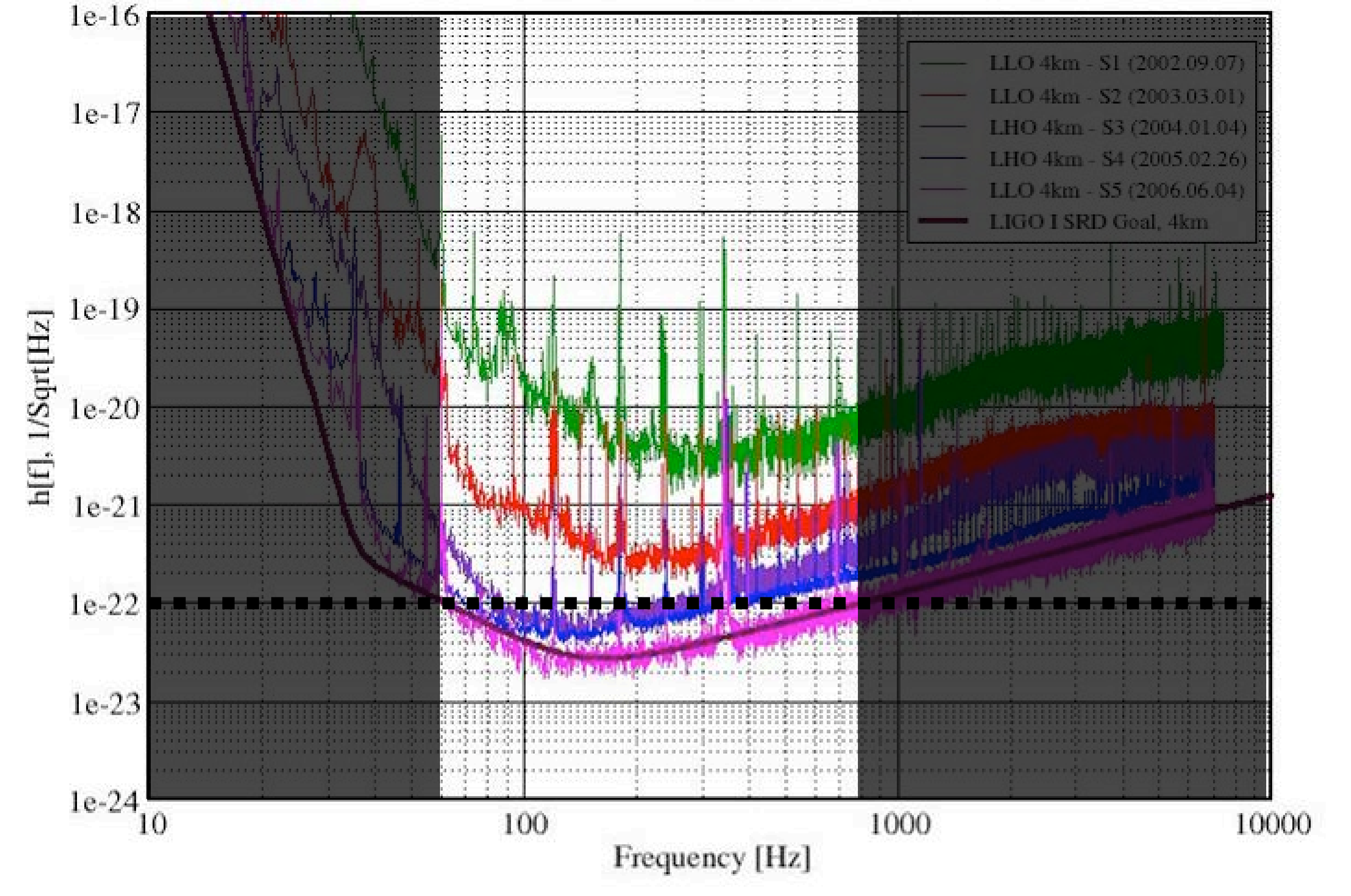

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GW Sources

- Detectable sources are dictated by the sensitive frequency band of the detectors.

  - minimum frequency implies maximum size

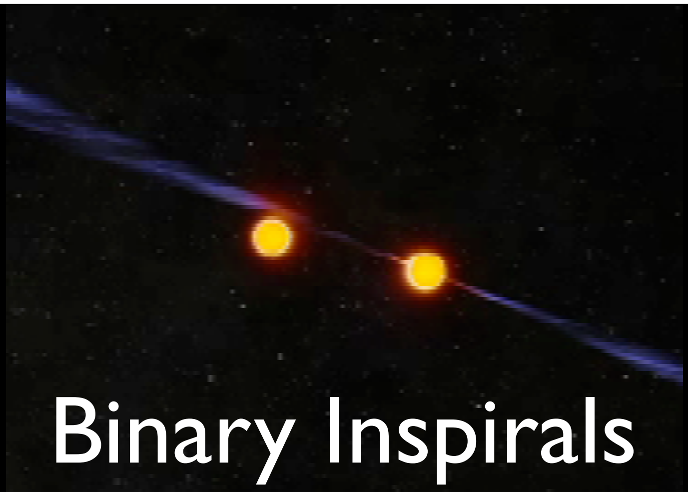
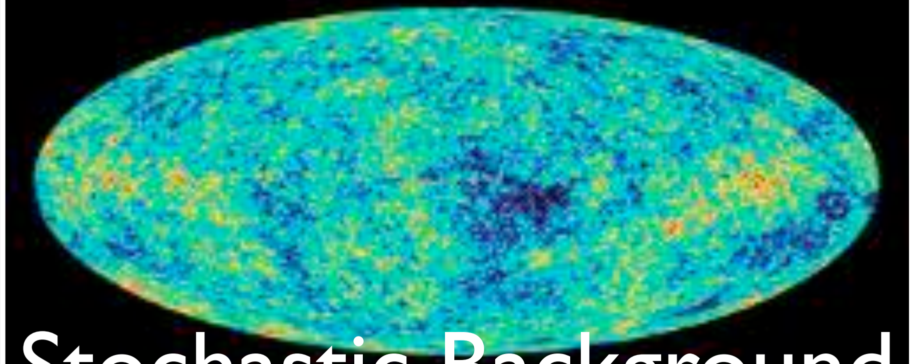
$$\ell_{max} \approx c\,/\,60\mathrm{Hz} \;\; = 0.007\,\mathrm{R}_{\odot}$$

  - This is smaller than any main sequence stars or even white dwarfs.

  - Sources will be systems containing neutron stars or black holes or other dense objects.

GW Sources

- For the purpose of gravitational wave detection, it is convenient to divide GW sources as follows:

Source Categories	Short Duration	Long Duration
Theoretical Waveform	 Binary Inspirals	 Neutron Stars
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

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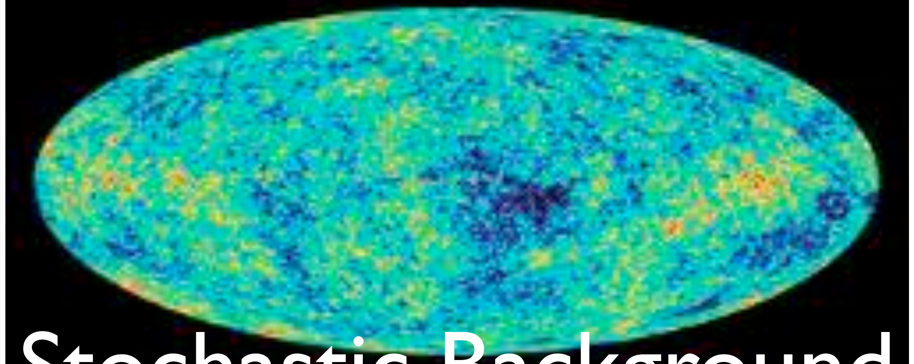
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

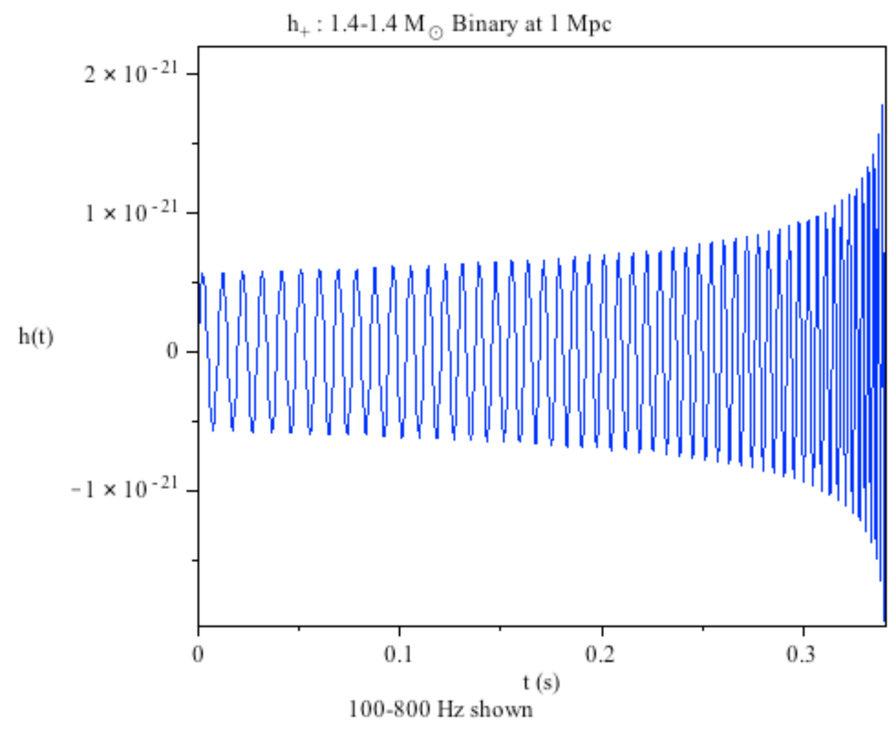
GW Sources

- **Compact binary inspiral** is the orbital motion of the binary companions (black holes or neutrons stars).

  - modeled using post-Newtonian formalism. 2PN is sufficient for detection of all but the last 10's of cycles.
  - extends from formation of binary to end of secular evolution, $0 < f \lesssim 4100 M_\odot / M_{\rm bin}$. For detection by LIGO, $M_{\rm bin} \lesssim 4100 {\rm Hz}\, M_\Omega / 60 {\rm Hz} \approx 70 M_\odot$.
  - for binary or orbital radius $a(t)$ and frequency ω,

$$h \sim \frac{\partial^2}{\partial t^2} a^2(t) \sim \omega^2 a^2(t)$$

From Kepler's law, $\omega^2 \sim a^{-3}$,
so $h \sim 1/a(t) \sim \omega^{2/3}$.



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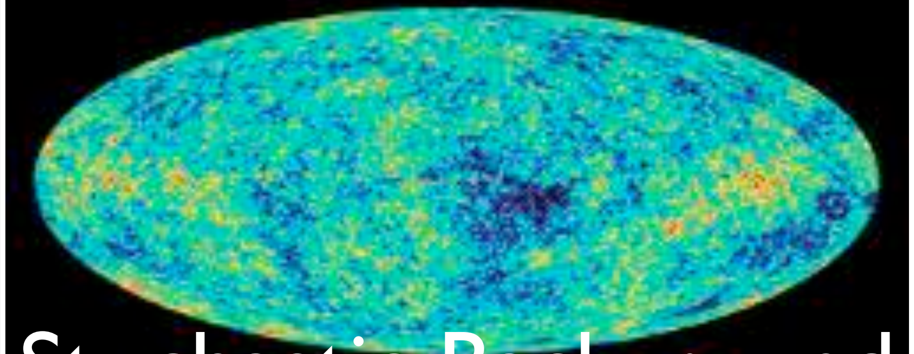
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

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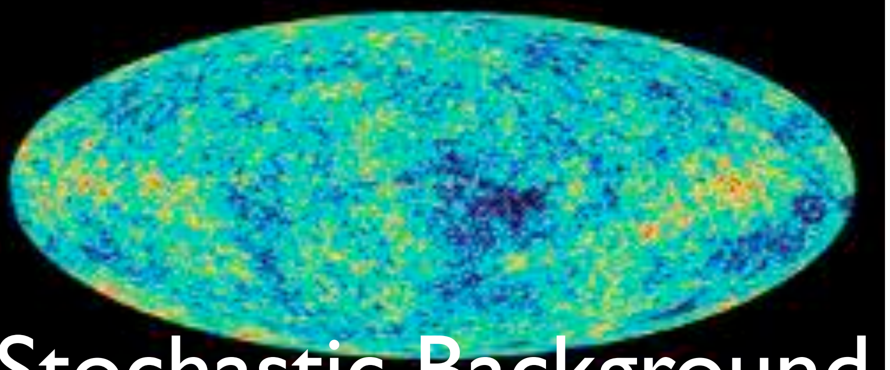
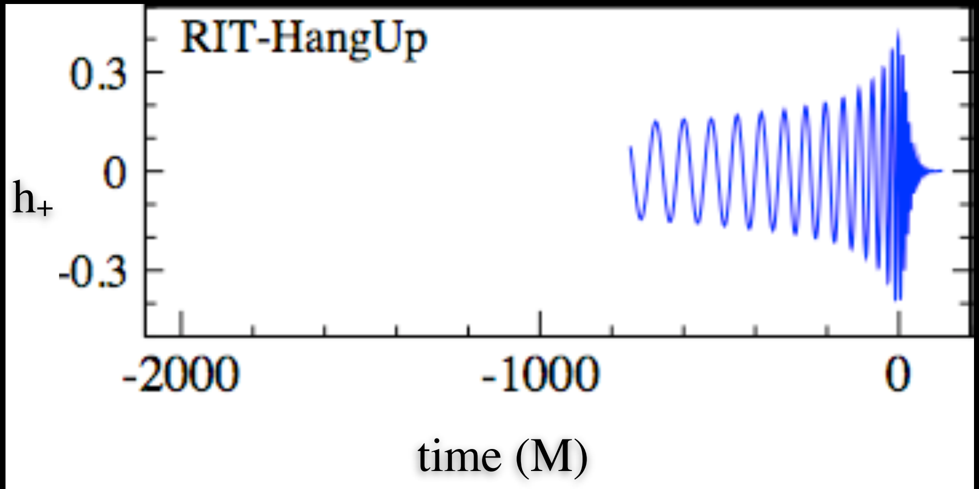
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

GW Sources

- **Unmodeled Burst Sources** are any short duration ($\lesssim 1$ second) source which is not well modeled.

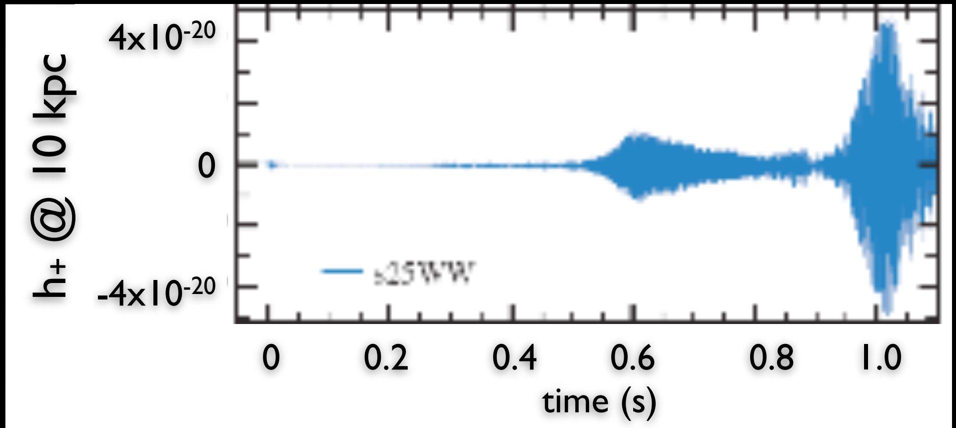
  - examples include supernovae, soft gamma repeaters, gamma ray bursts, and black hole binary mergers, etc.
  - models may exist, but are not considered sufficient to base detection algorithms on.
  - this is the best category for serendipitous discoveries.

Black Hole Merger Simulation



Campanelli, Lousto, Faber, Nakano, Zlochower

Supernova Simulation



Ott, Burrows, Dessart and Livne

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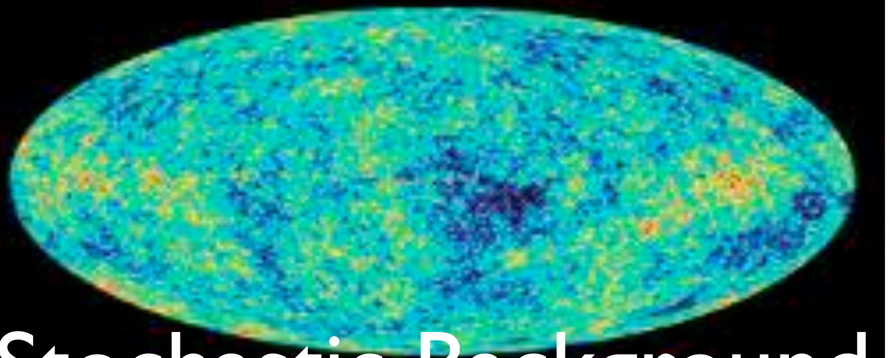
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

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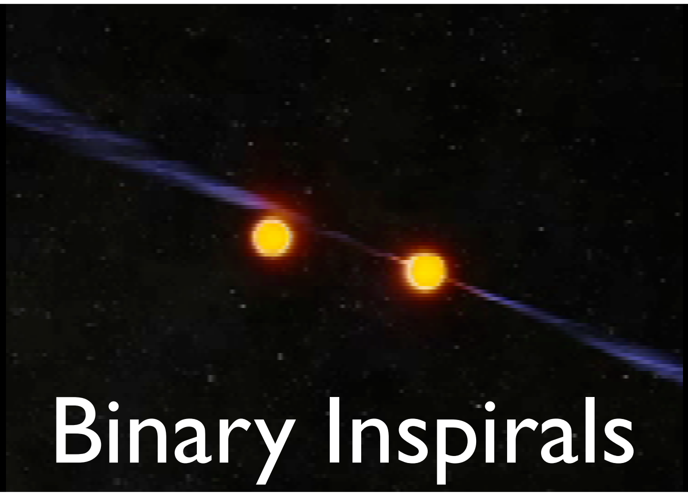
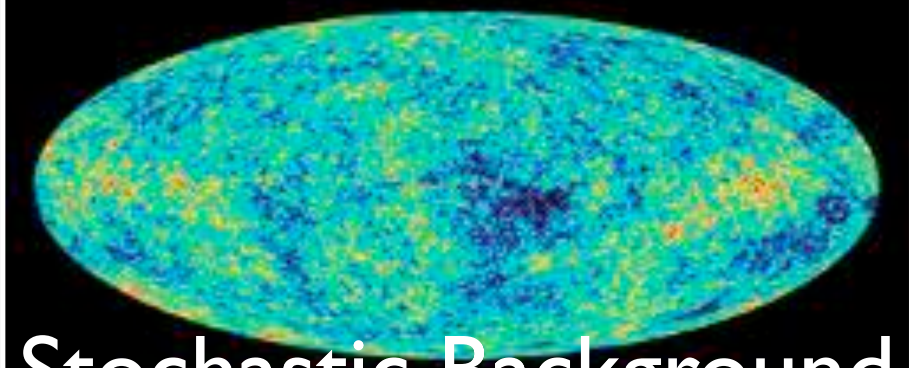
Theoretical Waveform	 Binary Inspirals	 Neutron Stars
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

GW Sources

- **Neutron Stars** will produce gravitational waves if they are not axisymmetric.

  - Assuming a neutron star is a rigid, asymmetric triaxial body then it will emit GWs at twice the rotational frequency ν.
  - Rotational period has to be ~ 0.5 - 40 ms for detection.
  - GW frequency will be approximately constant at solar system barycenter - we know what signal looks like.
  - Some neutron stars are pulsars, so we know their parameters such as sky position, frequency, spin-down, ...
  - The GW strain from a neutron star with moment of inertia I about the axis of rotation is bound by $h \lesssim \sqrt{I\dot{\nu}/r^2\nu} \approx 10^{-24}$ for neutron stars.

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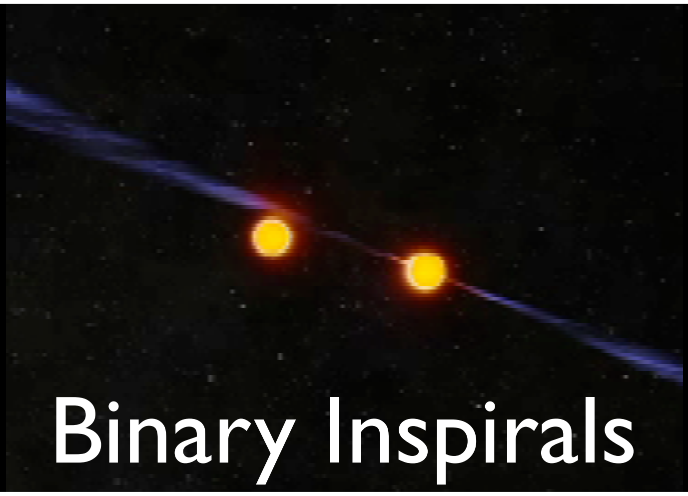
Theoretical Waveform	 Binary Inspirals	 Neutron Stars
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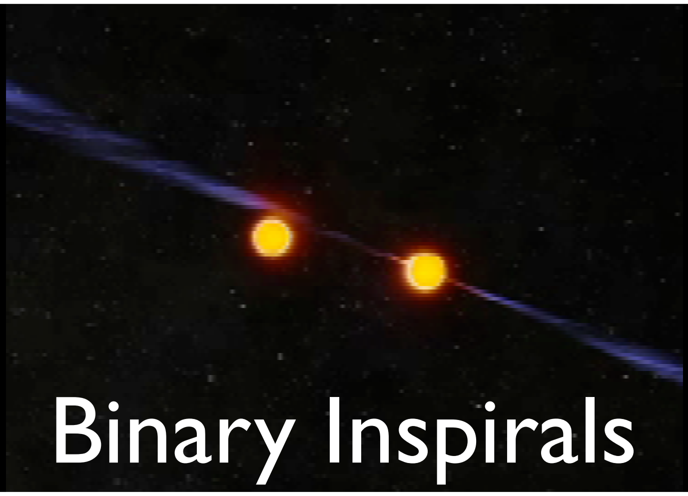
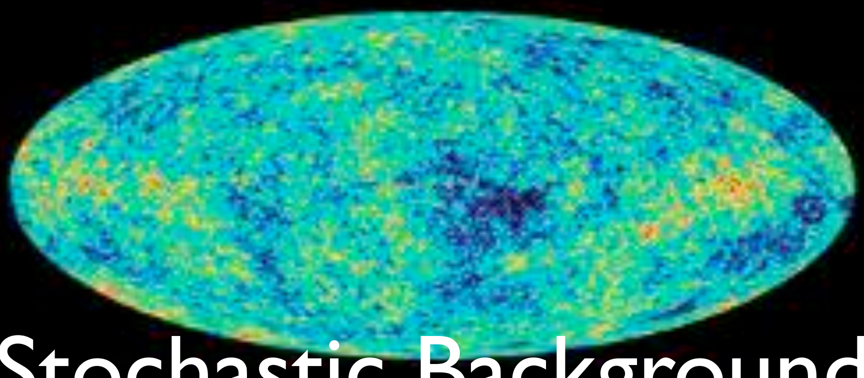
Theoretical Waveform	 Binary Inspirals	 Neutron Stars
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

GW Sources

- **Stochastic background sources** are any isotropic population of sources which emit overlapping GWs.

  - Population of astrophysical or cosmological sources.
  - Examples include GWs from inflation, stringy cosmologies, unresolvable binary populations, etc.
  - Produces unpolarized, isotropic, Gaussian GWs.
  - Could allow us to see back to GUT times or earlier.
  - GW energy described by $\Omega_{GW} := \frac{f}{\rho_c}\frac{d\rho_{GW}}{df}$.

  - Theory allows for a wide range: $10^{-14} < \Omega_{GW} < 1.$
  - Big Bang Nucleosynthesis provides observational constraint on gravitational wave energy density at all frequencies. Implies $\Omega_{GW} \lesssim 10^{-5}$.

Outline

- Gravitational Wave (GW):
  - Theory
  - Detectors
  - Sources
  - Data Analysis
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Outline

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GW Data Analysis

- We sample the GW output of the interferometer to get strain values $s_j = s(j\,\Delta t), j \in \mathbb{N}\,.$

  - when there is no signal, the data are noise, $s_j = n_j\,.$
  - if there is a signal, the data are sums of noise and GW signal strains, $s_j = n_j + h_j\,.$
  - noise at each frequency is (approximately) Gaussian, but low frequency noise dominates the data.

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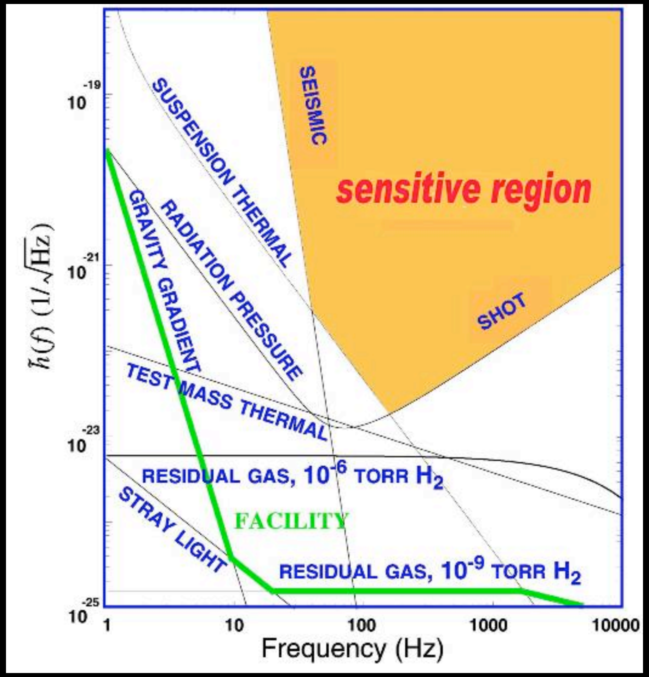

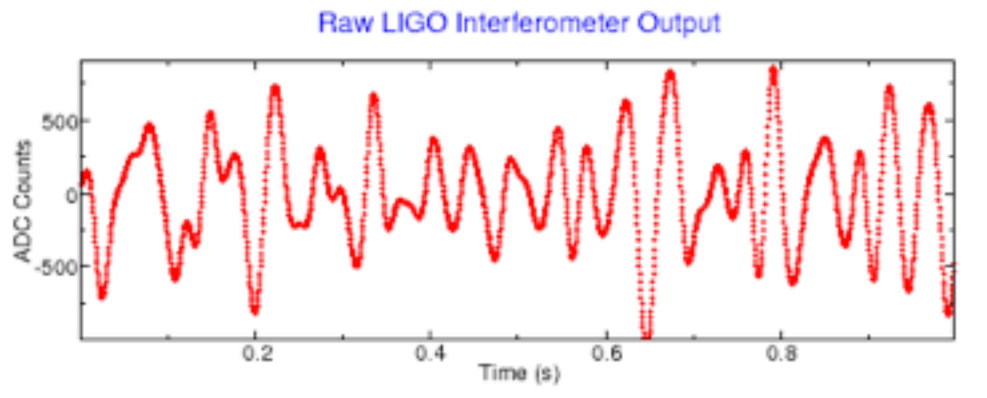

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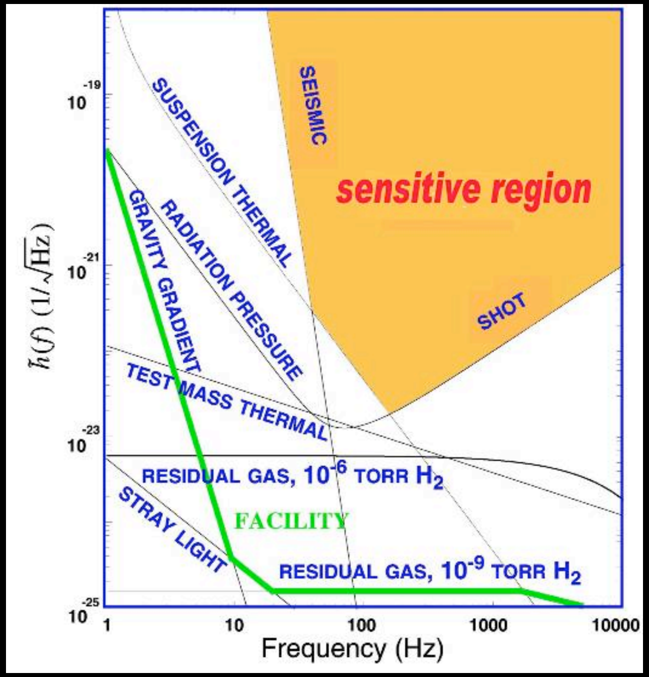

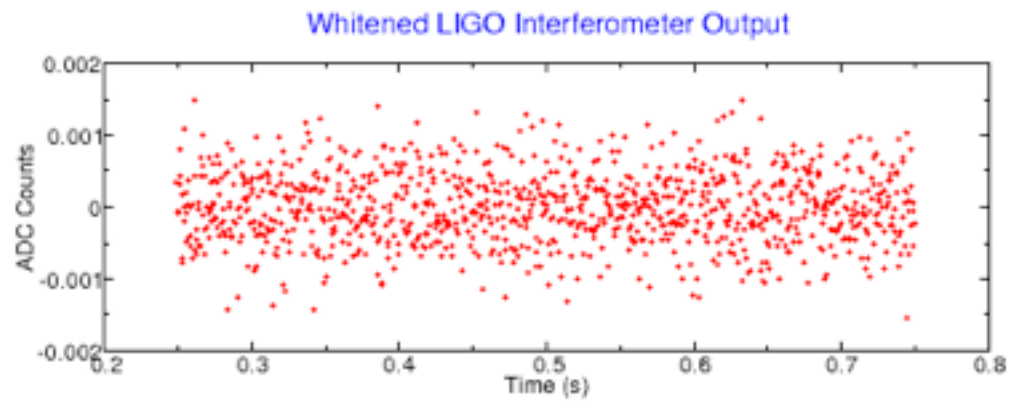

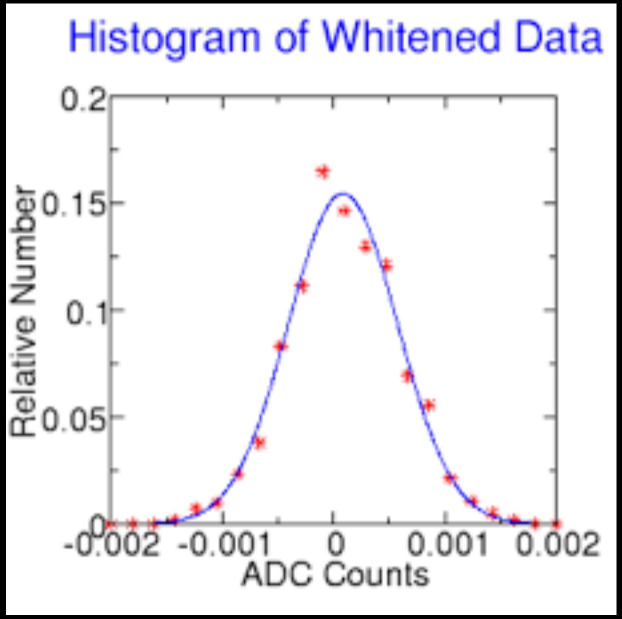

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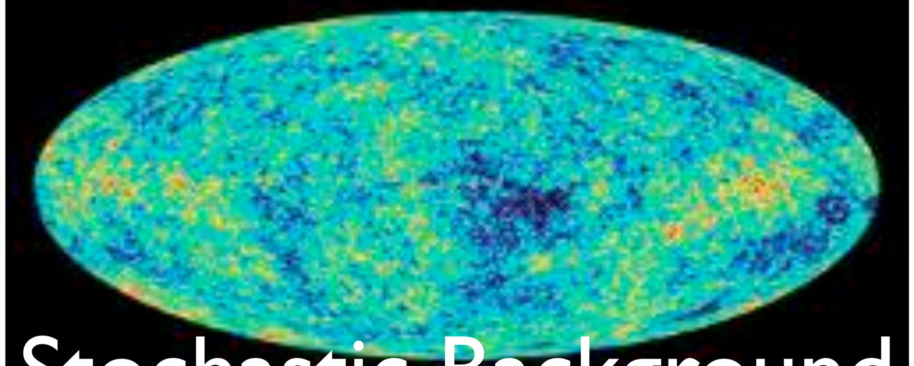
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

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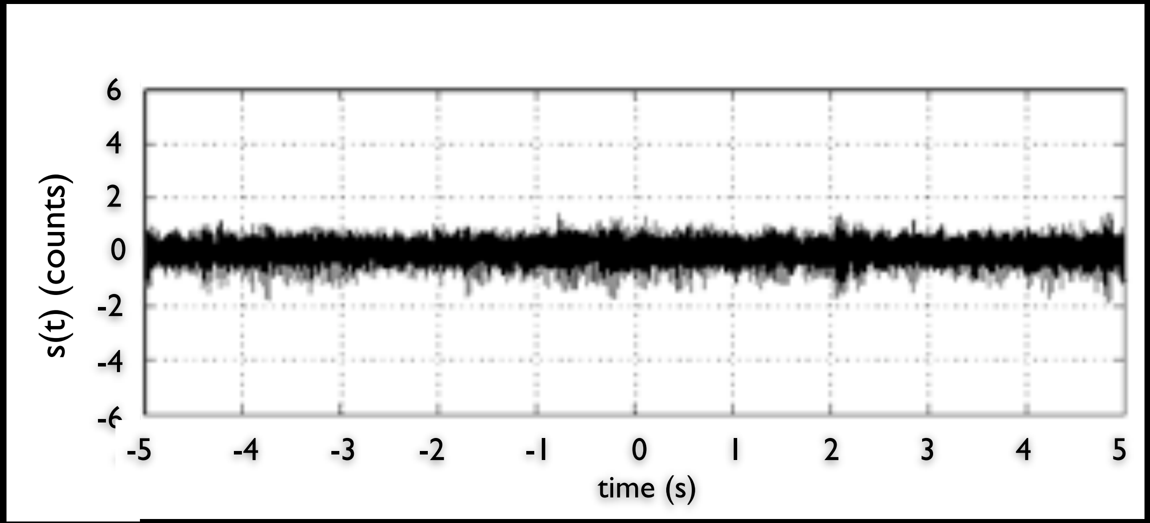

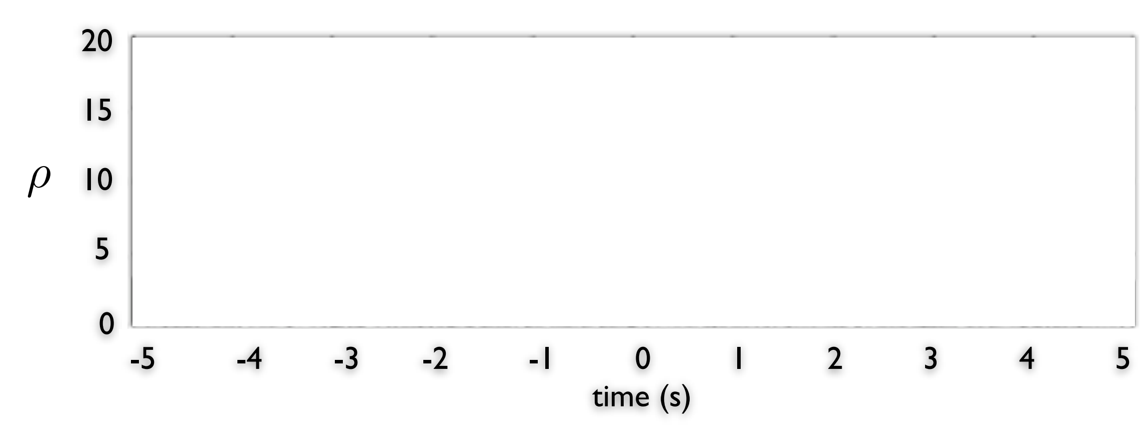

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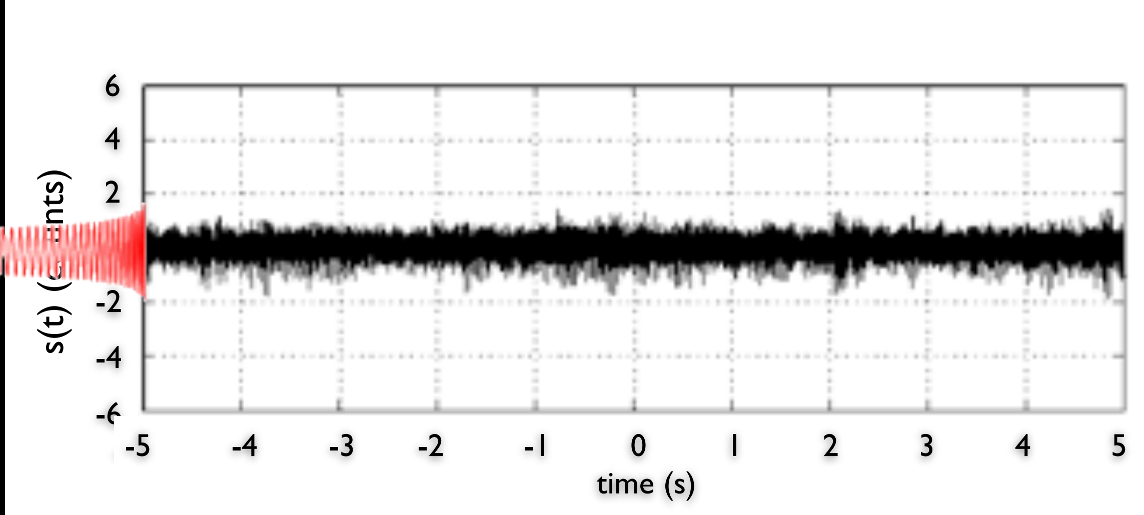

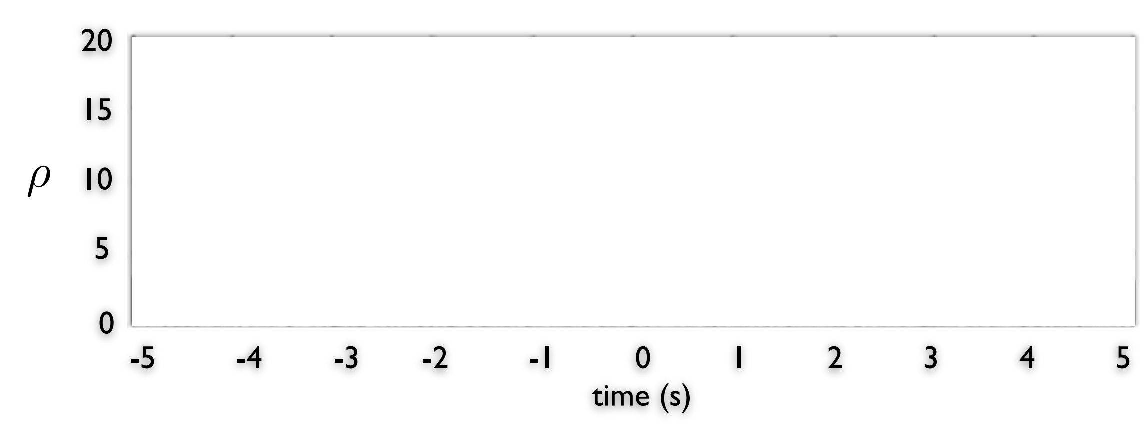

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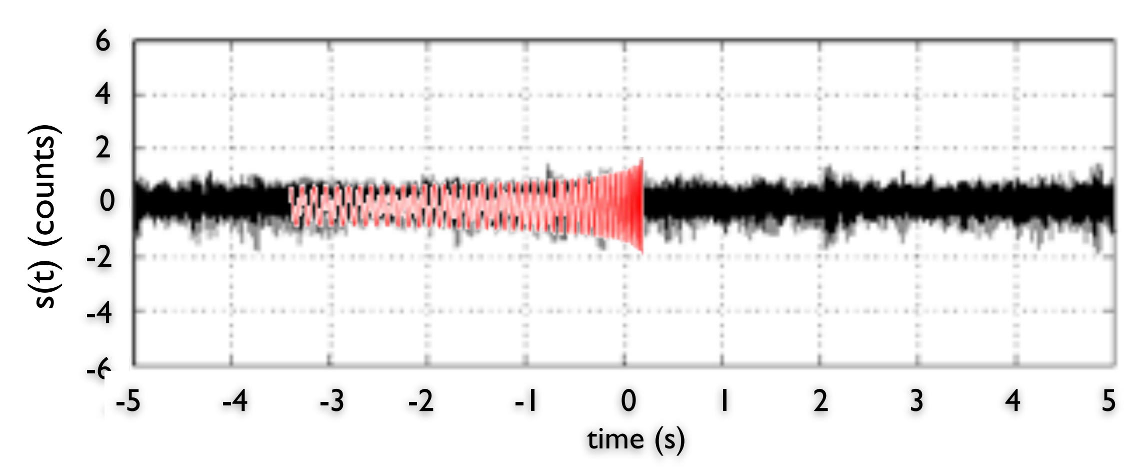

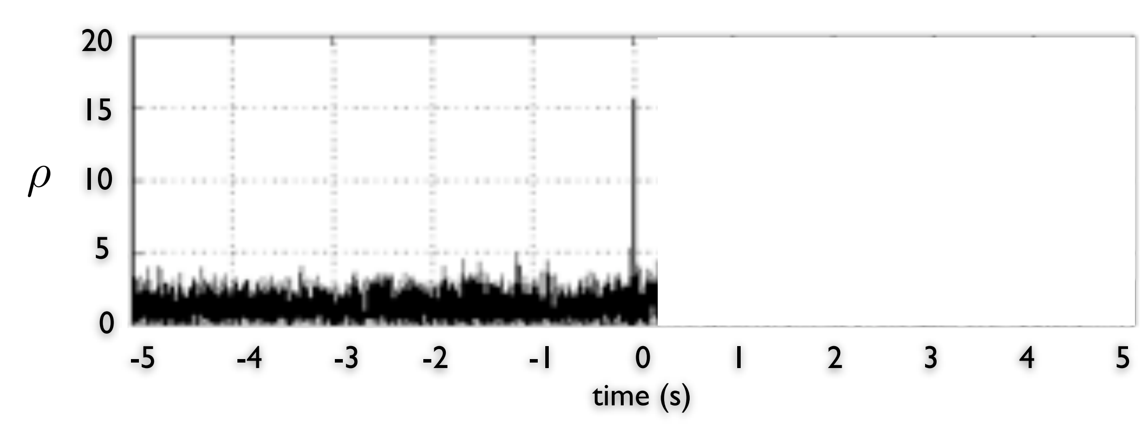

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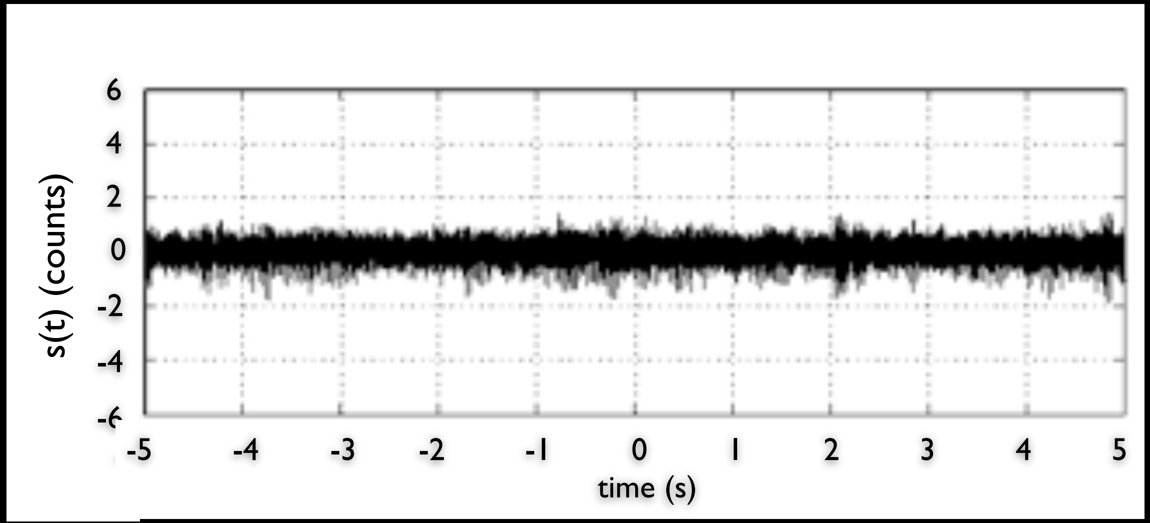

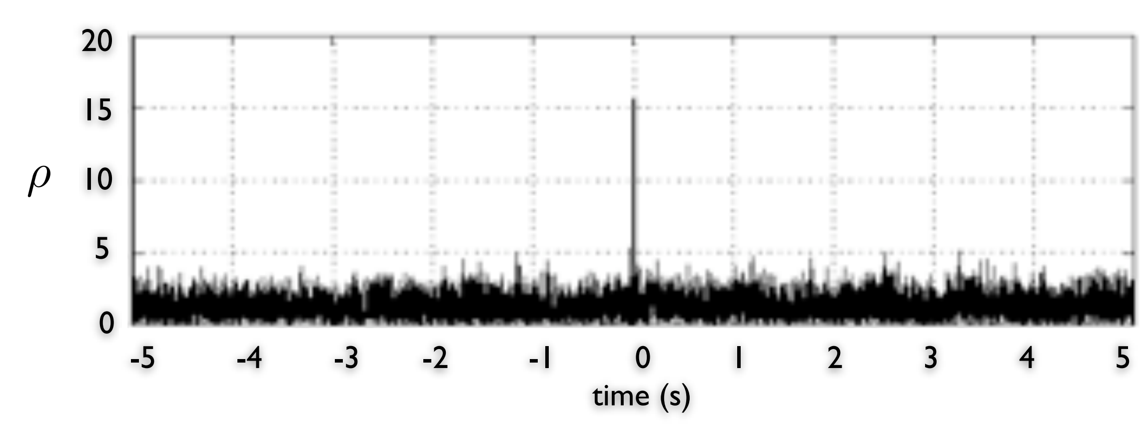

GW Data Analysis

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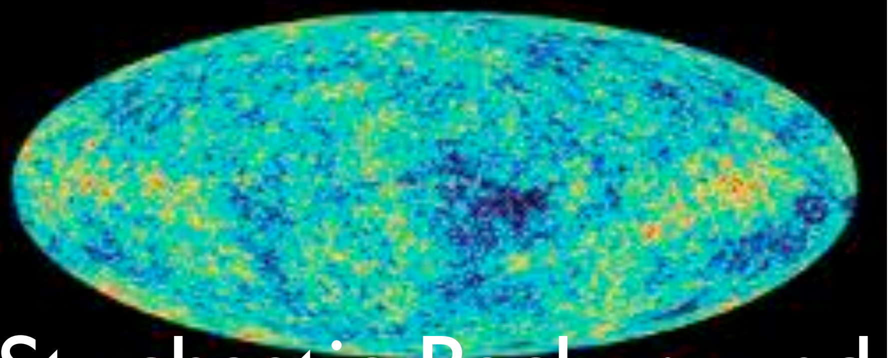
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

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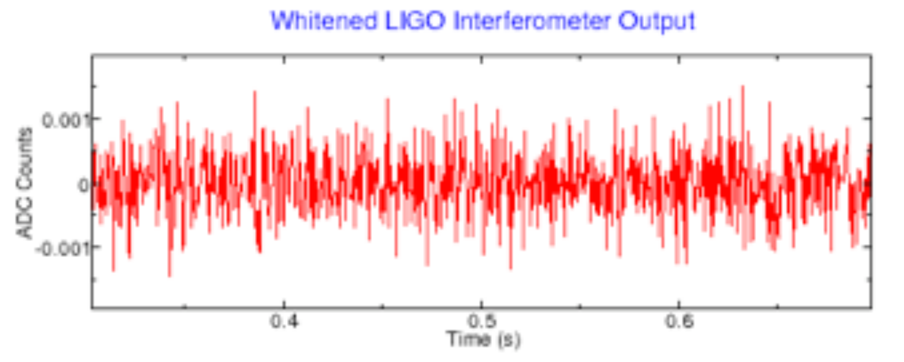

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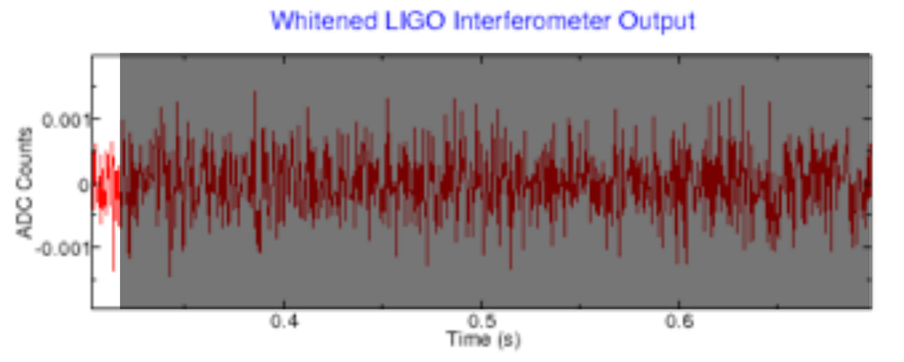

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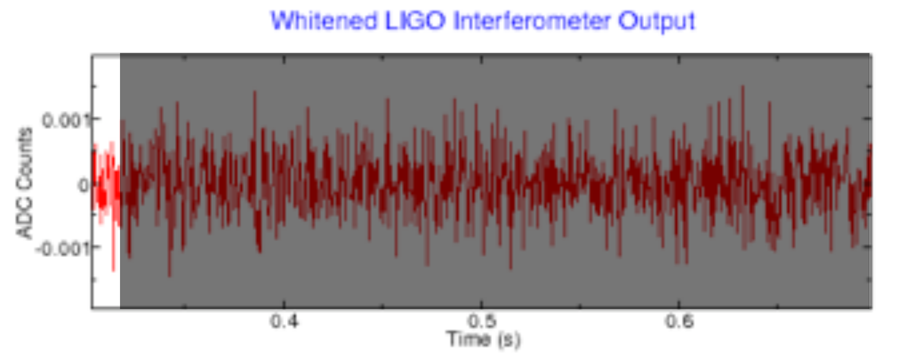

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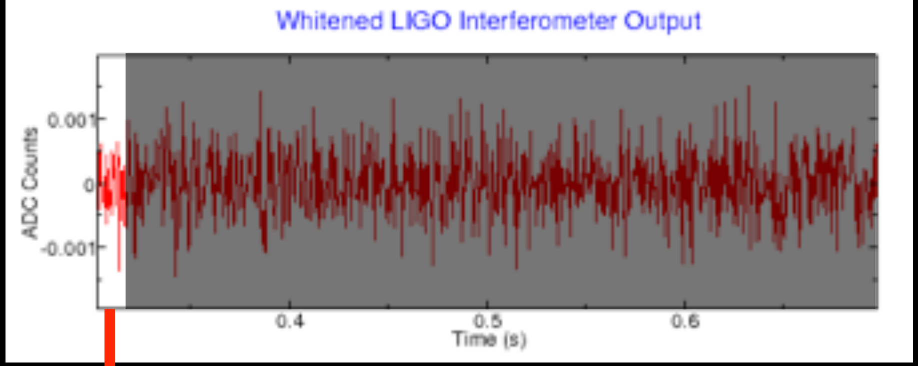

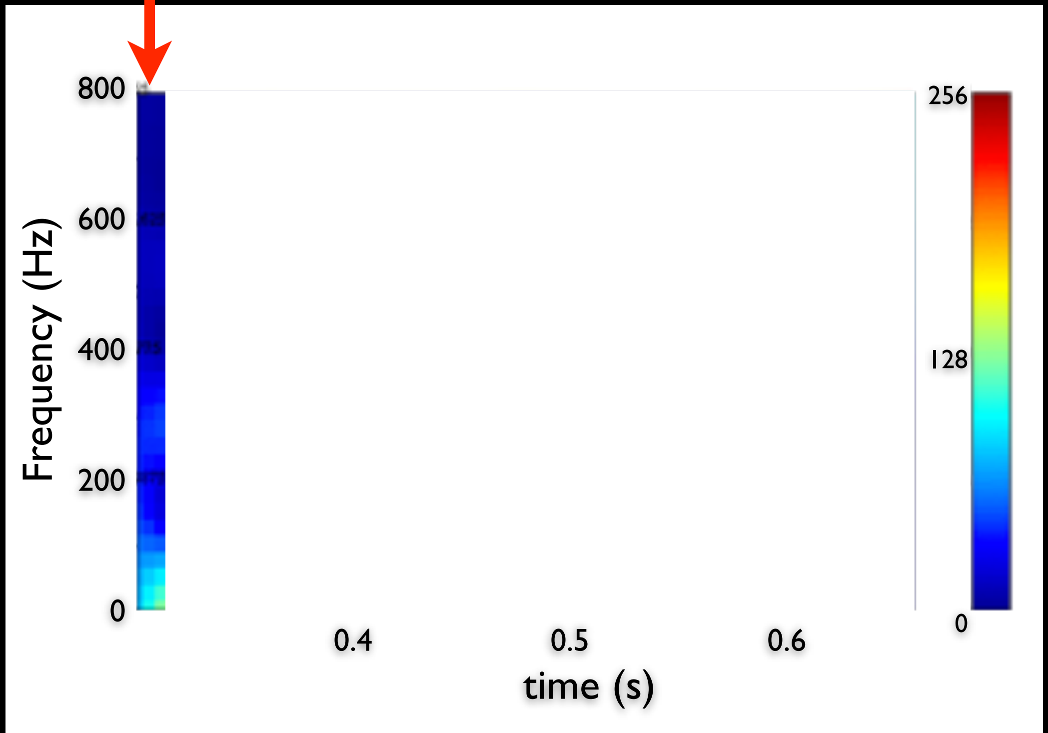

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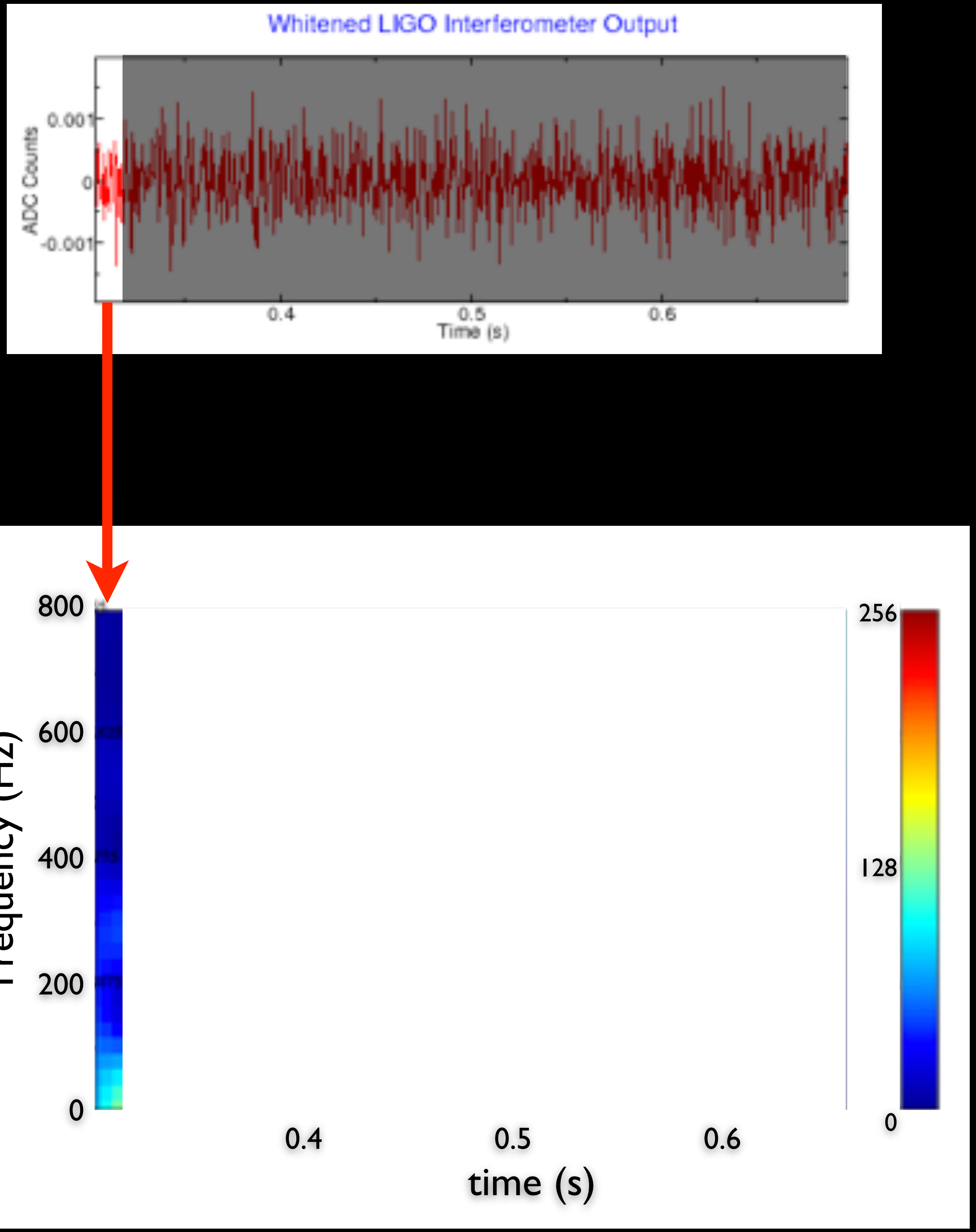

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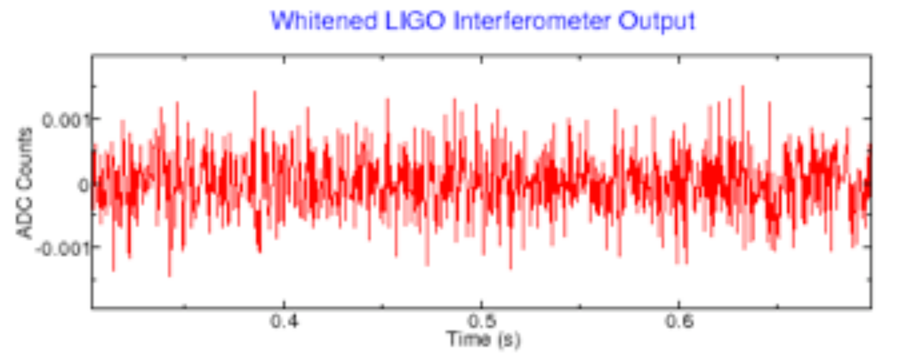

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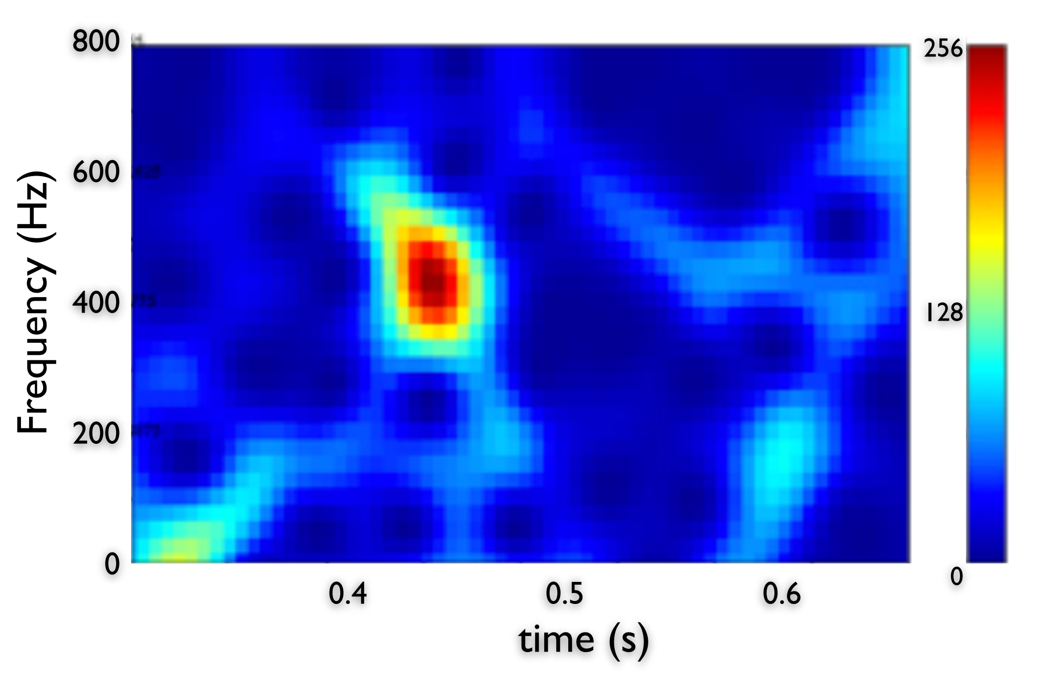

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  - take a slice of interferometer data and Fourier transform it.
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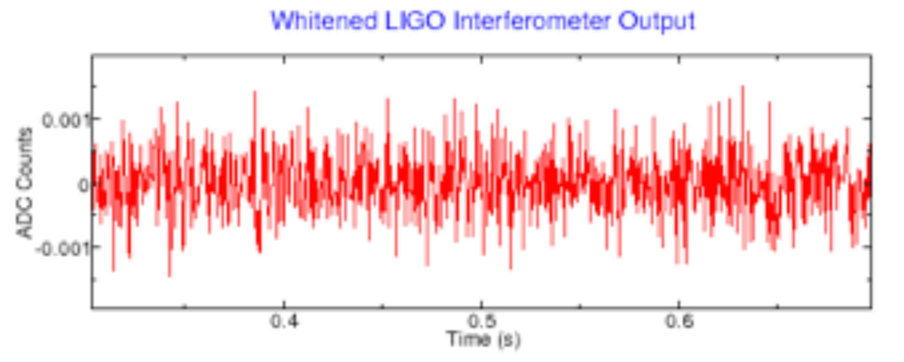
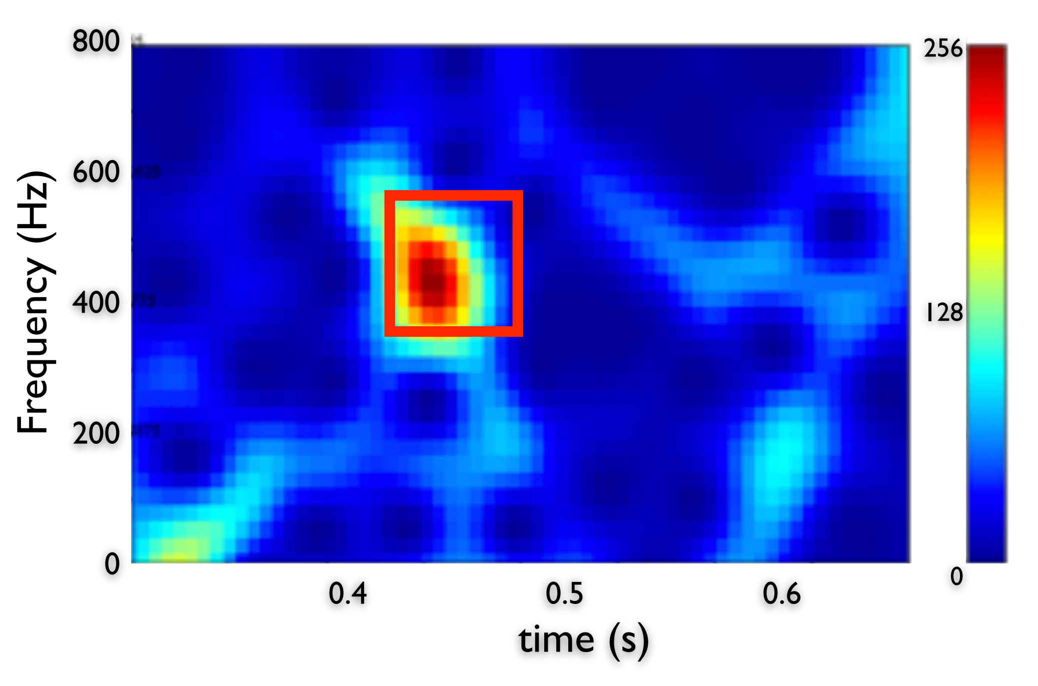
  - repeat for subsequent slices of data.
  - search for boxes with statistical significance.





GW Data Analysis

- Neutron stars emit signals at almost fixed frequency. However, frequency at detector is doppler modulated.

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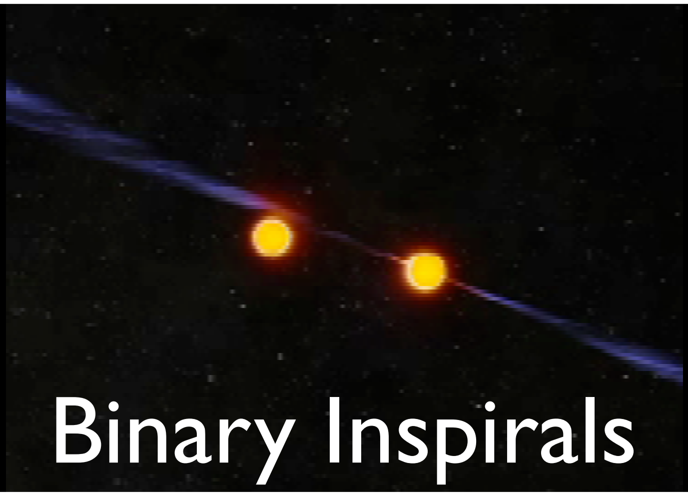
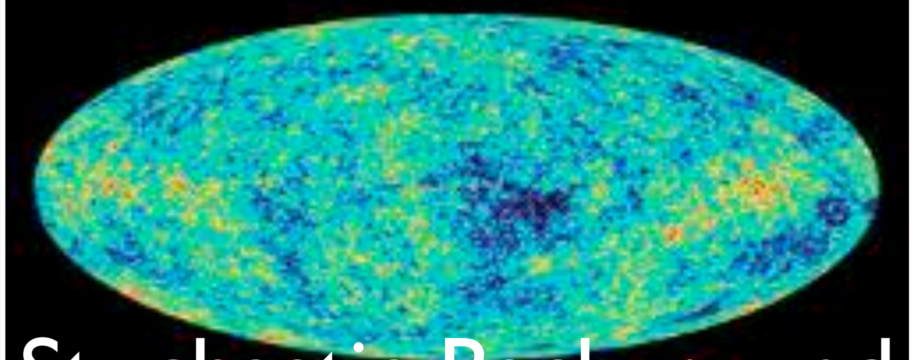
Theoretical Waveform	 Binary Inspirals	 Neutron Stars
No Theoretical Waveform	 Unmodeled Bursts	 Stochastic Background

GW Data Analysis

- Neutron stars emit signals at almost fixed frequency. However, frequency at detector is doppler modulated.

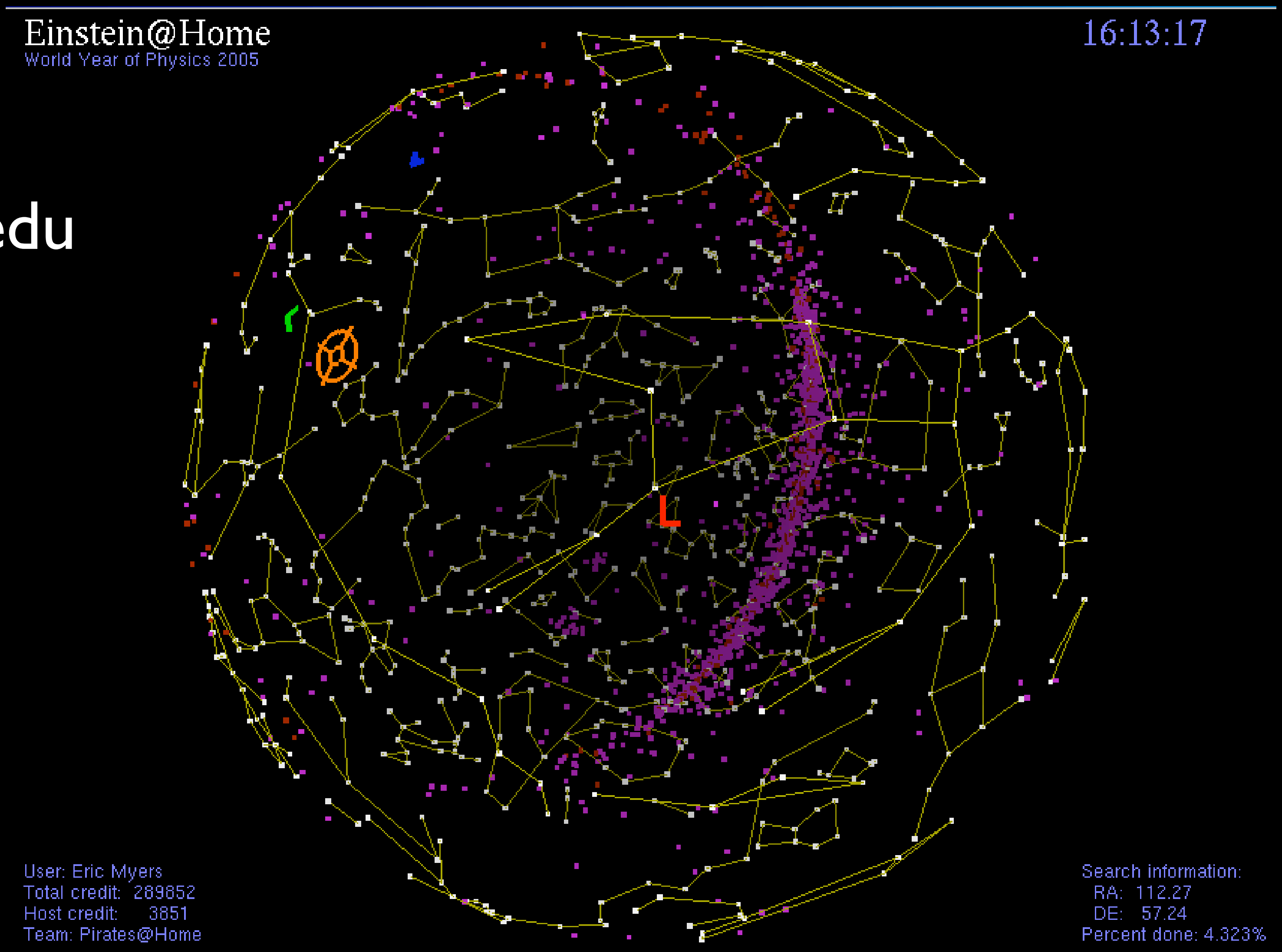
  - choose a length of time τ such that the doppler shift $\Delta f < 1/\tau$. Neutron star signal stays in single freq. bin.
  - Fourier transform data slices of length τ .
  - add slices with frequency offset to account for doppler modulation for that slice (using Earth ephemeris).
  - complex phase of noise is random and noise amplitude grows with total observation time T as $\sqrt{T}$.
  - signal phase is grows linearly, and signal amplitude grows linearly with observation time.
  - sensitivity therefore grows with time, and the minumum detectable signal amplitude decreases as $h_s \propto \sqrt{h_n/T}$.

GW Data Analysis

- To search for neutron stars at every sky position, LIGO frequency and with every possible set of spin down parameters is computationally prohibitive.

http://einstein.phys.uwm.edu

> 225,000 users
> 875,000 hosts
> 200 countries
> 140 Tflops



Einstein@Home
World Year of Physics 2005

16:13:17

User: Eric Myers
Total credit: 289852
Host credit: 3851
Team: Pirates@Home

Search information:
RA: 112.27
DE: 57.24
Percent done: 4.323%

GW Data Analysis

- Stochastic background signals from the early universe are Gaussian signals embedded in Gaussian detector noise.

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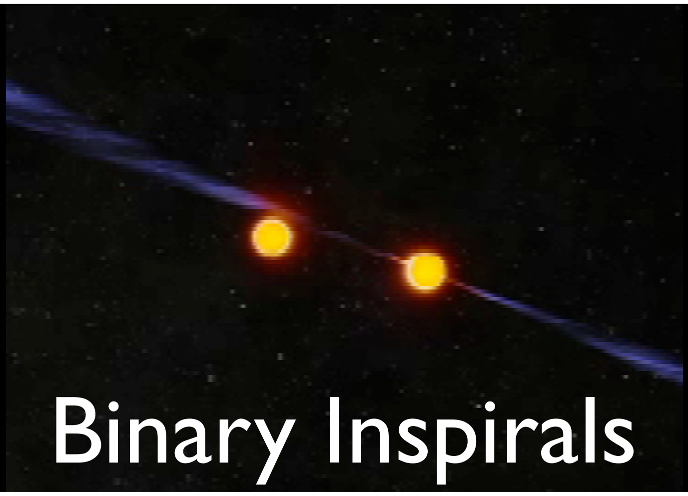
Theoretical Waveform	 Binary Inspirals	 Neutron Stars
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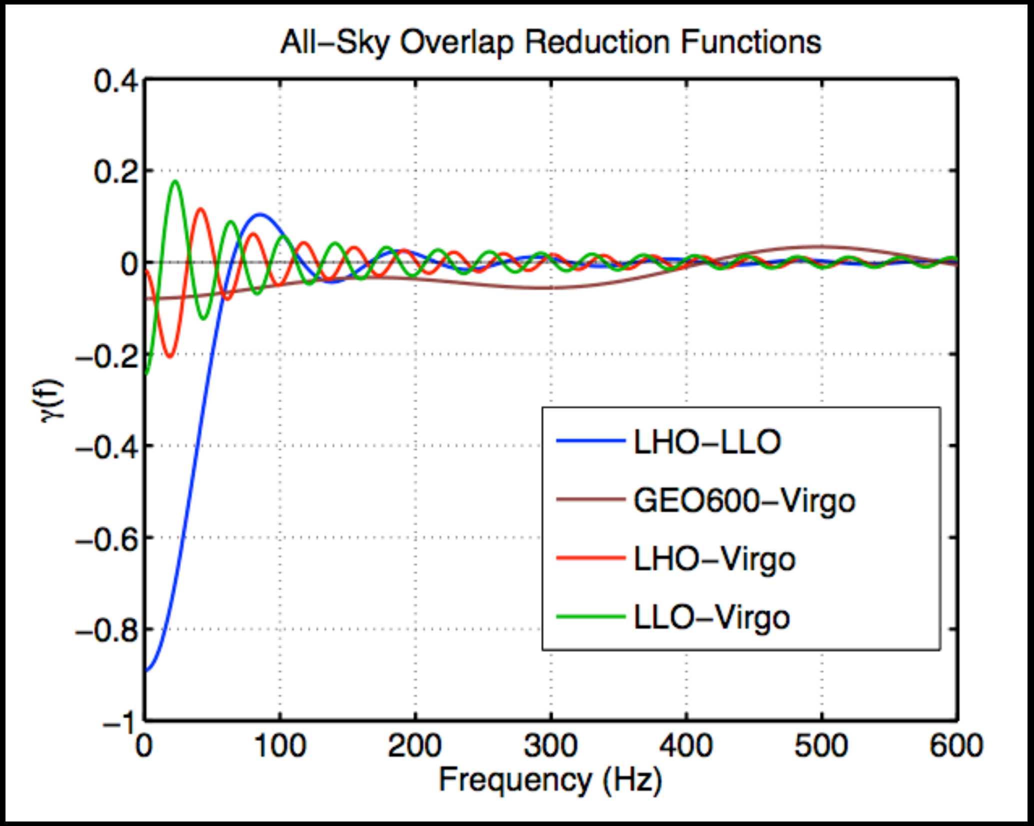
GW Data Analysis

- Stochastic background signals from the early universe are Gaussian signals embedded in Gaussian detector noise.

  - Detection with a single detector unfeasible. However, signal will be correlated in different detectors.
  - Cross correlate data from one or more detector pairs to look for stochastic background.
  - Detector geometry determines degree of correlation signal has at each frequency.
  - For constant $\Omega(f) = \Omega_0$

$$Y \sim \int_{-\infty}^{\infty} df \, \frac{s_1(f)\, \gamma(f)\, s_2(f)}{n_1(f)^2\, n_2(f)^2}$$

$$\langle \rho_Y \rangle \equiv \frac{\langle Y \rangle}{\sigma_Y} \propto \Omega_0 \sqrt{T} \longleftarrow \text{obs. time}$$



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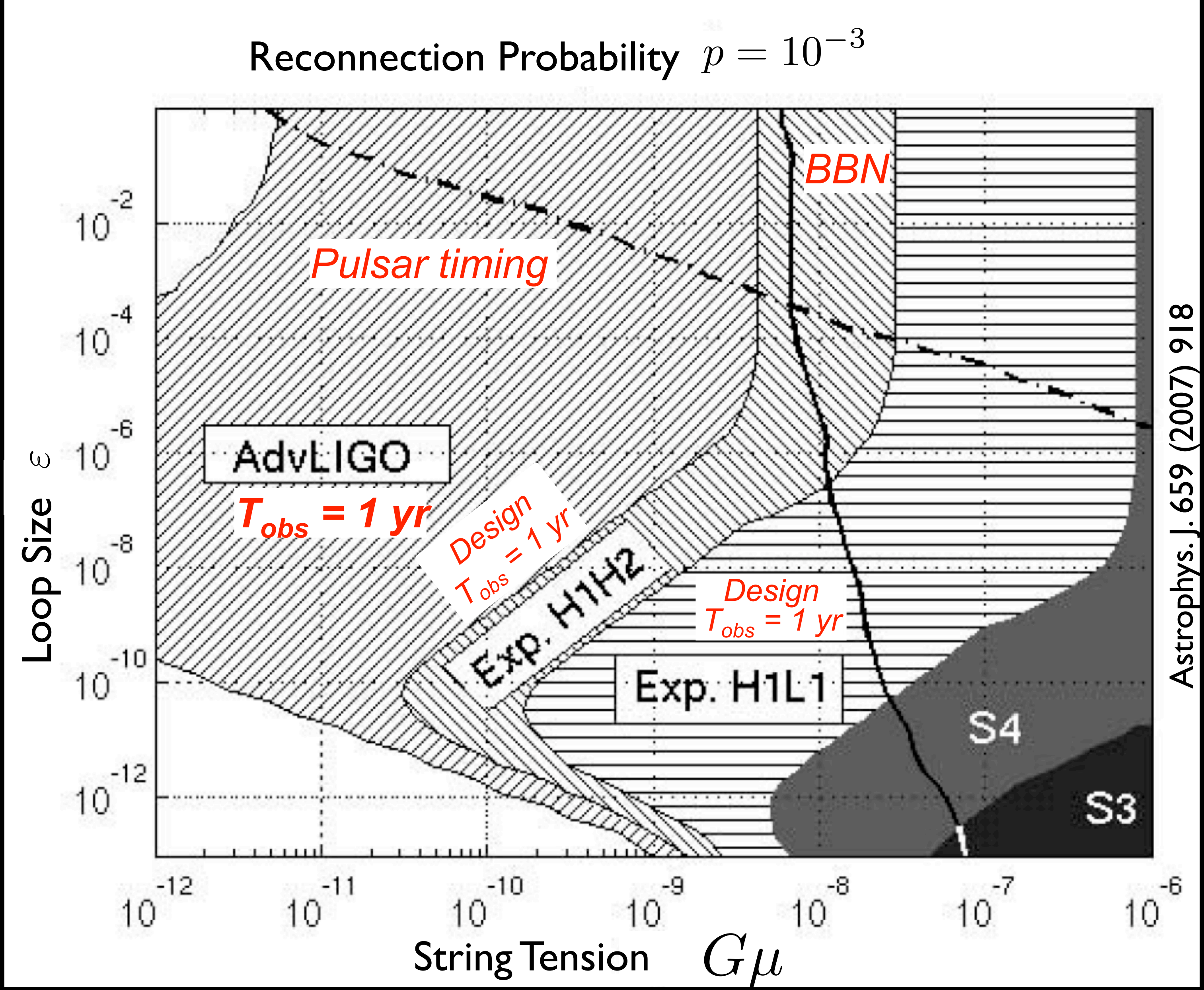
GW Results

- No gravitational waves have been detected yet.
- S5 results just beginning to be published.
- Observational results on:
  - neutron star binaries, black hole binaries, macho binaries.
  - GRBs, SGRs, things that go bump in the night.
  - SCO-X1, radio pulsars, unidentified neutron stars.
  - stochastic backgrounds from inflation, string cosmologies.
- I will present only some of the highlights (in my opinion).

GW Results

- We are starting to constrain parameter space for string cosmologies (Jones, Sarangi, Tye; Damour & Vilenkin):

  - predicted in string-theory inspired inflation.
  - string cusps act as GW sources.
  - loop size scale set by gravitational back-reaction.
  - allowed range for reconnection probabilities 1-10^{-3}.



Astrophys. J. 659 (2007) 918

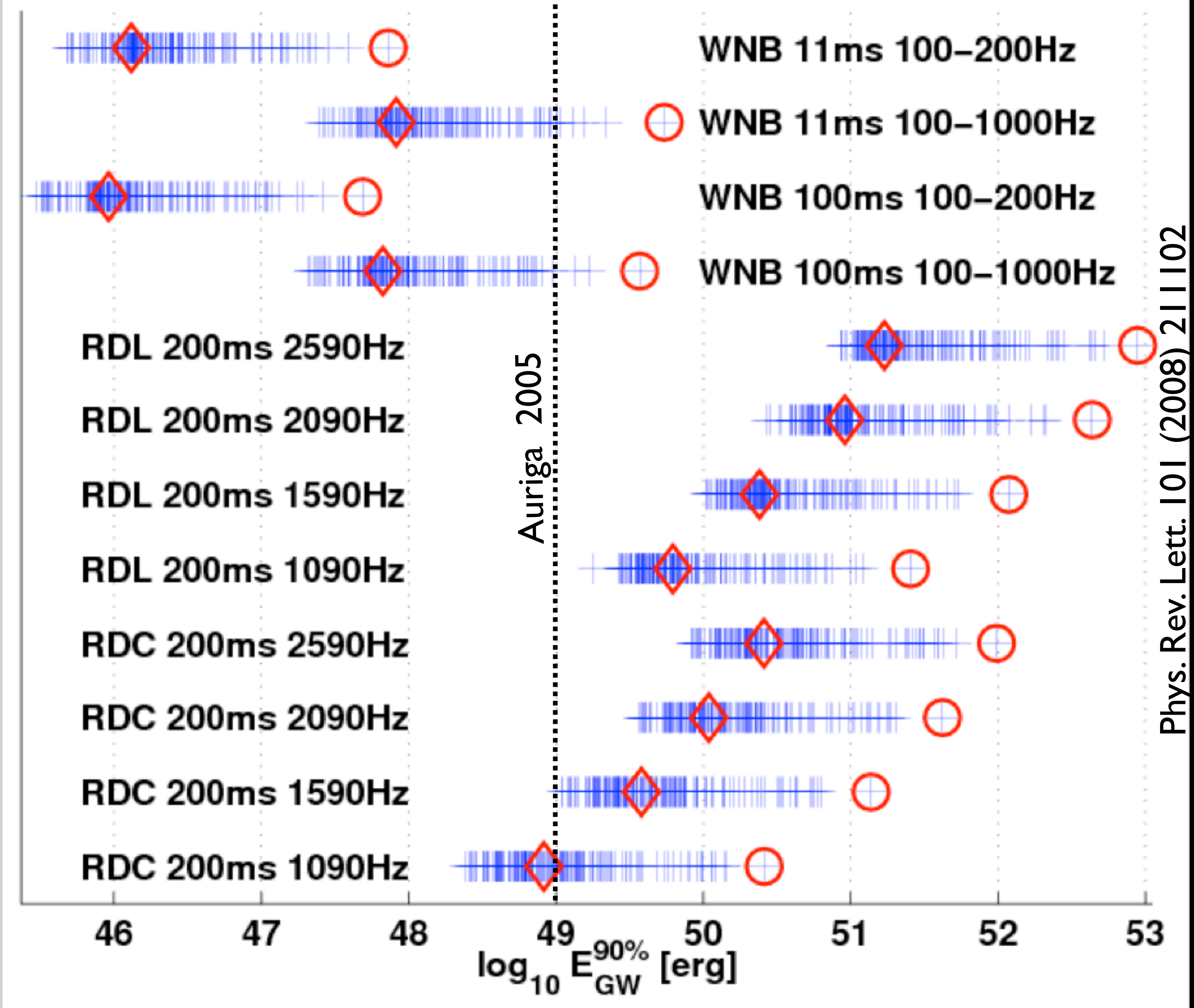
GW Results

- Soft Gamma Repeaters (SGRs) are modeled as magnetars whose B fields occasionally violently disrupt their crusts.

- SGR EM emissions
  - peak for ~ 0.1 - 1.0 s.
  - ~ 10^{42} - 10^{45} erg/s.
- 4 known SGRs
- distances ~ 15 kpc
- GW emission models?
  - non-radial modes (rd)
  - Gaussian bursts (wnb)
- predicted GW energy

$$E_{GW} \lesssim 10^{48} ergs$$

(Ioka, MNRAS, 2001).



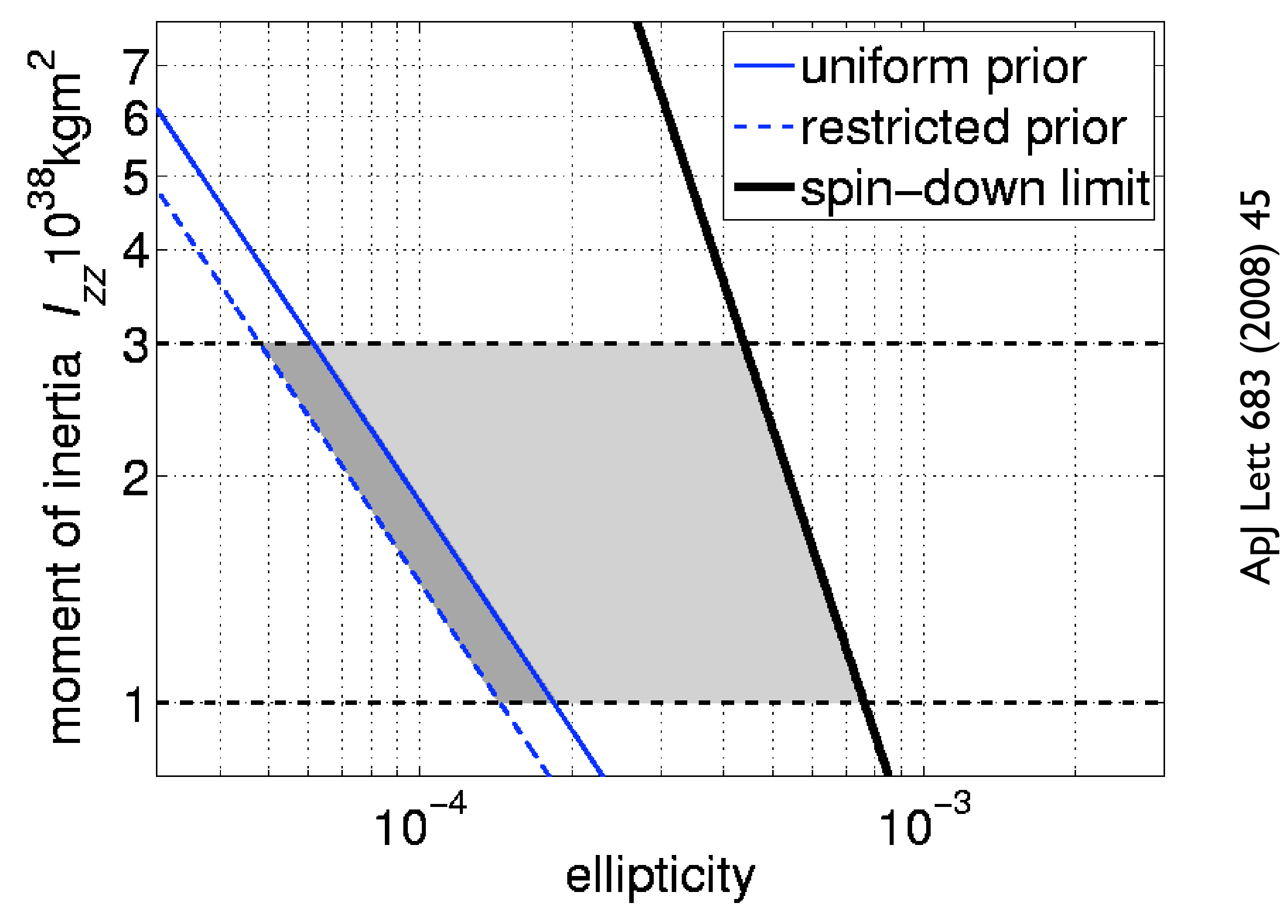
Phys. Rev. Lett. 101 (2008) 211102

Assumed: distance - 10 kpc, freq. band - 1- 3 kHz.

GW Results

- The pulsar with the highest spin down rate in LIGO's band is the crab pulsar. Likely energy loss mechanisms include magnetic dipole radiation, particle acceleration in the magnetosphere, and GWs.

- with errors in parameter estimation, as much as 80% of energy loss could have been from GWs.
- S5 analysis shows that it is less than 6%.
- these ellipticities begin to inform quark matter equations of state.



ApJ Lett 683 (2008) 45

GW Results

- GRB 070201 gamma ray burst (T90=0.15 s) Feb 1, 2007.
  - Location consistent with M31 spiral arms (0.77 Mpc).
  - Short GRB: could be inspiral of compact binary system (NS/BH), or perhaps soft gamma repeater.
  - Hanford 4 km and 2 km interferometers were taking data during this GRB.

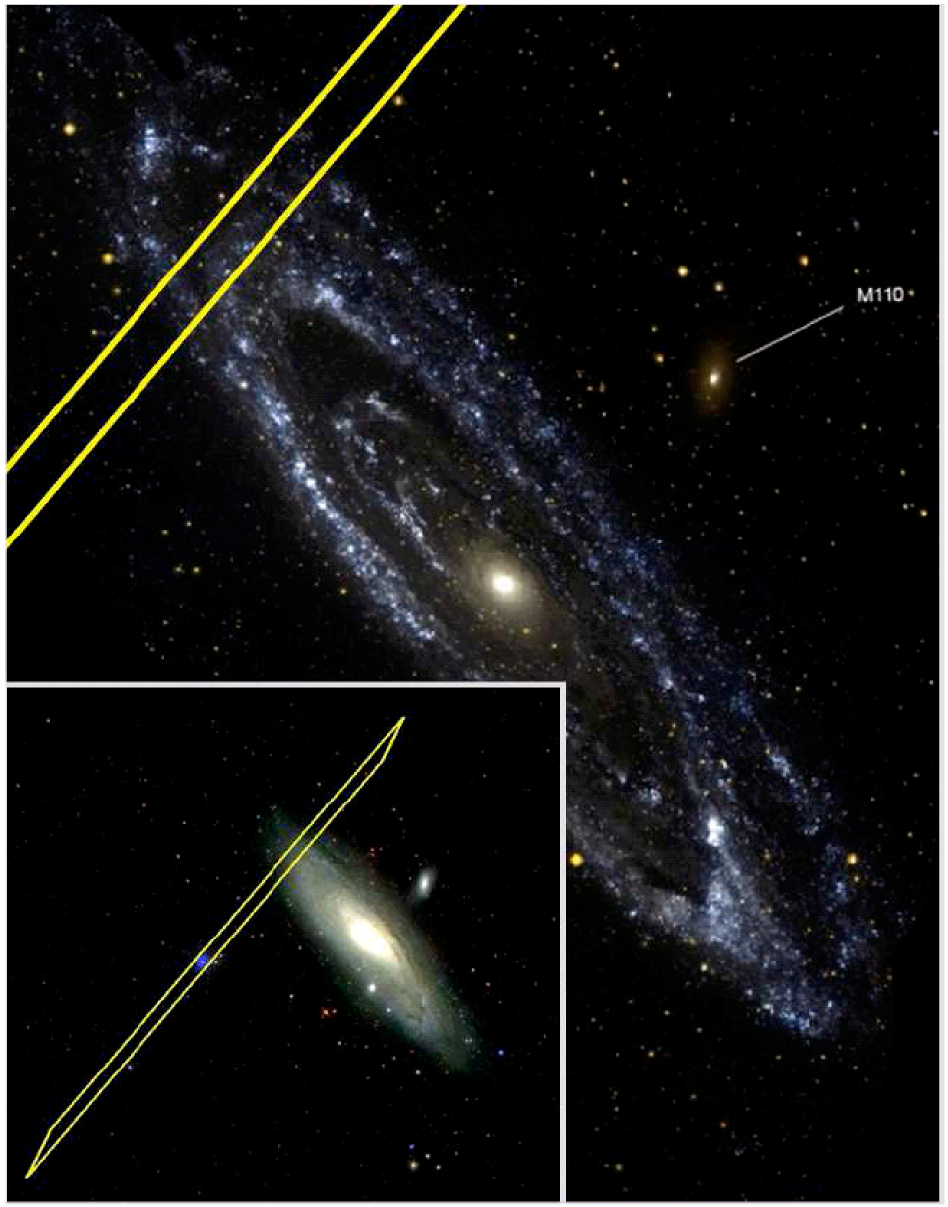


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).

GW Results

- Matched filter analysis for inspiral signal.

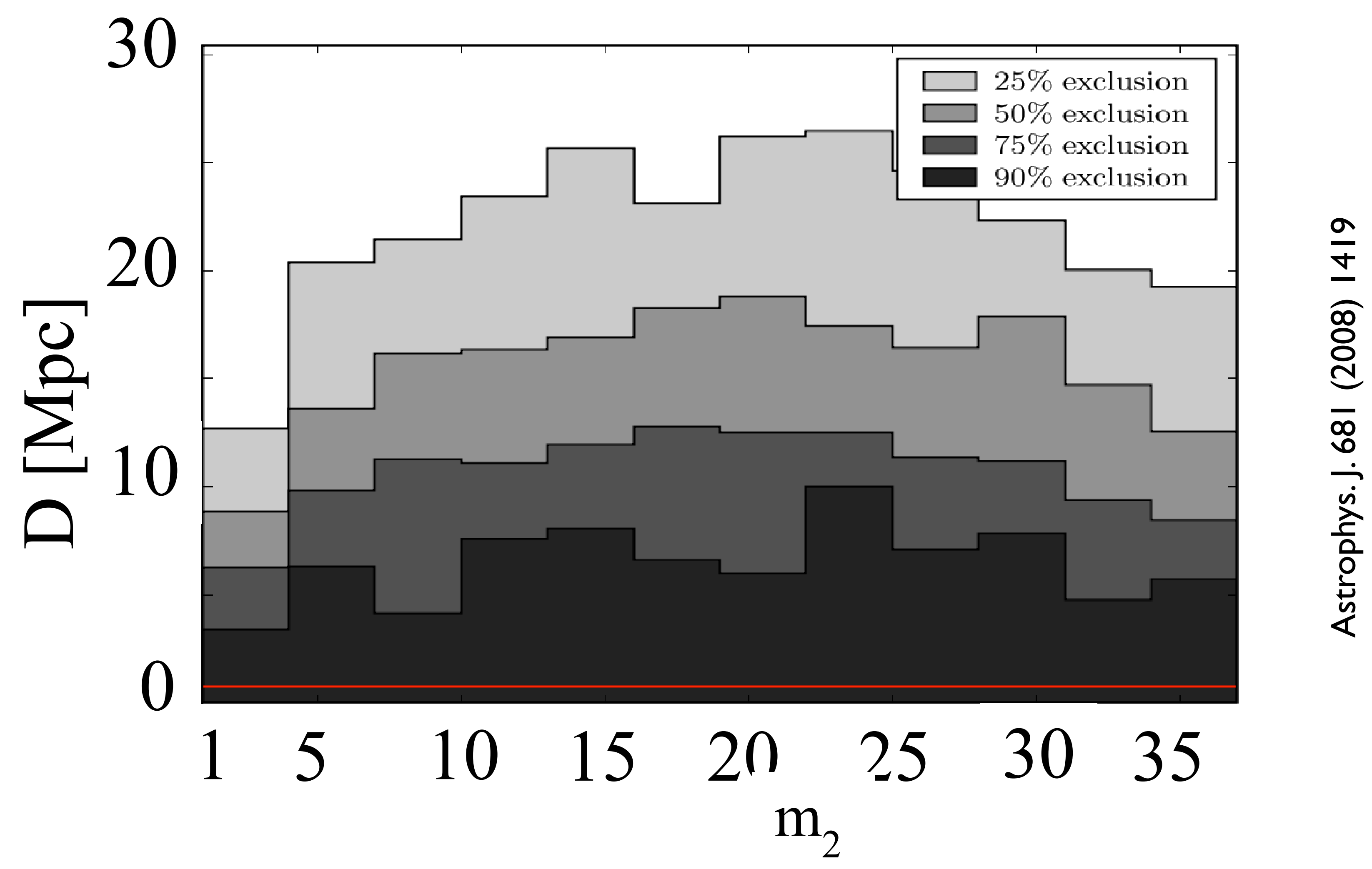
Search parameters:

$$M_\odot \le m_1 \le 3M_\odot$$

$$M_\odot \le m_2 \le 40M_\odot$$

Search results:

Compact binary in M31 ruled out at 99% confidence.



Astrophys. J. 681 (2008) 1419

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GW Future

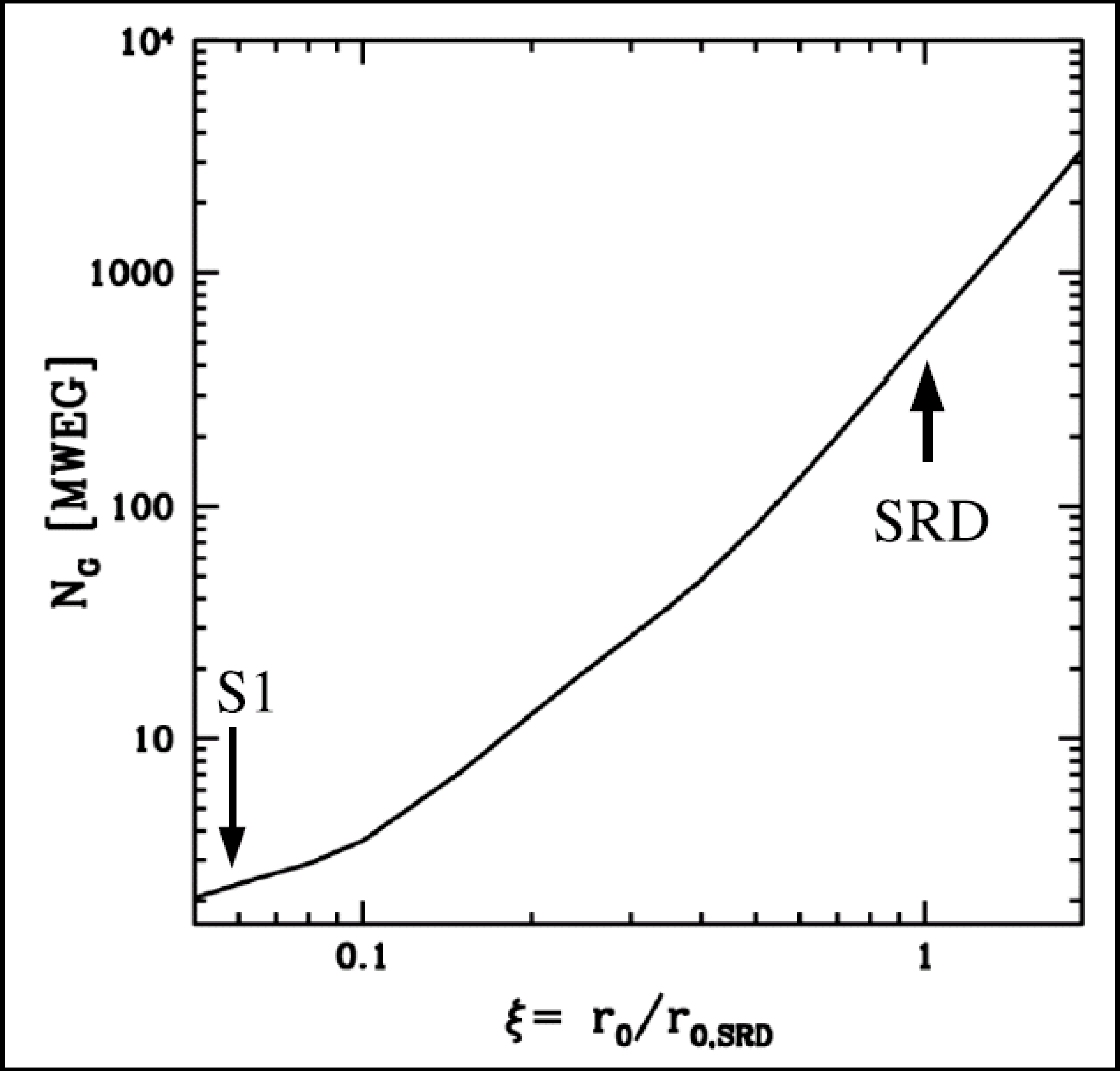
- Now underway:
  - more S5 results are being calculated and will be published soon. Many will be joint LSC/Virgo papers.
  - Advanced LIGO, with new technologies to lower noise, by factor ~10 is now funded and under development.
  - Enhanced LIGO, with some new technologies to lower noise by factor ~2 is now being comissioned.

- Next few months:
  - Enhanced LIGO comes on line and S6 begins.
  - Real time event sharing with EM astronomers.

- Farther on:
  - S6 scheduled to end late 2010, early 2011.
  - Advanced LIGO scheduled to begin ops ~2015.

GW Future

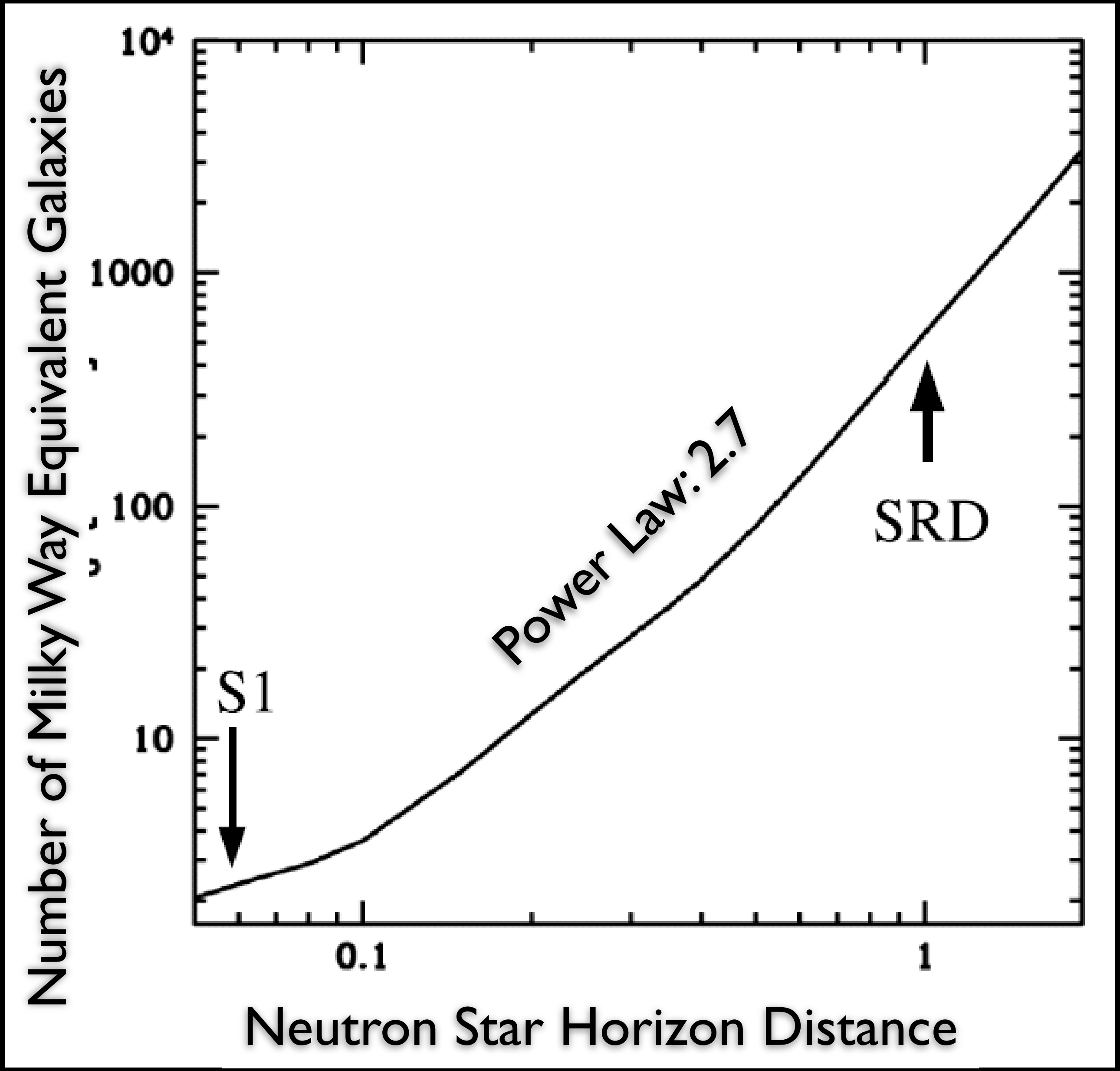
- What does enhanced LIGO get us?



astro-ph/0402091, Nutzman et al.

GW Future

- What does enhanced LIGO get us?



astro-ph/0402091, Nutzman et al.

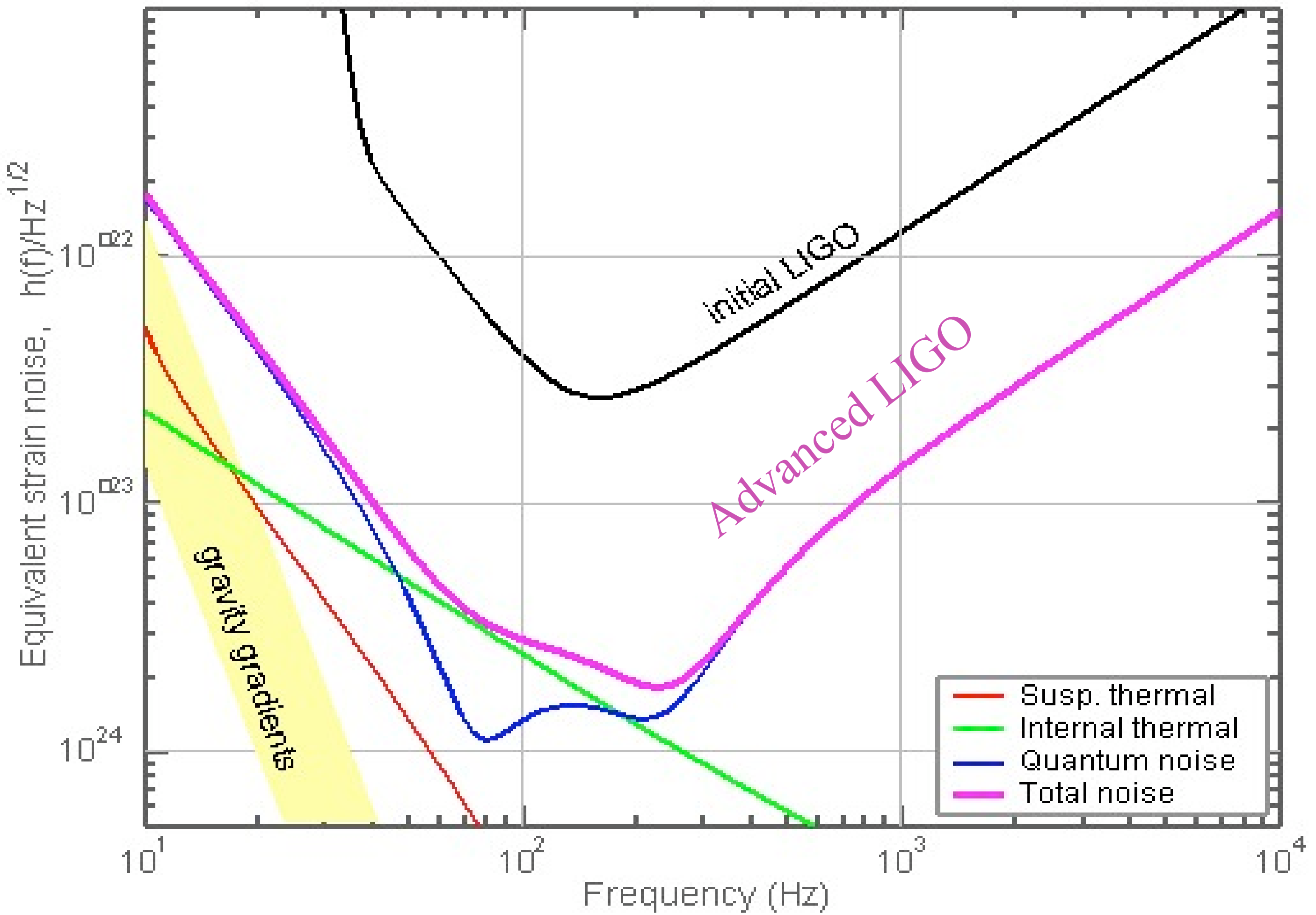
- a factor of 2 in horizon NS-NS binary rate goes up by 6.5 times.

- estimated rate for initial LIGO is 0.015/yr.

- ~ 10% chance of NS-NS in enhanced LIGO.

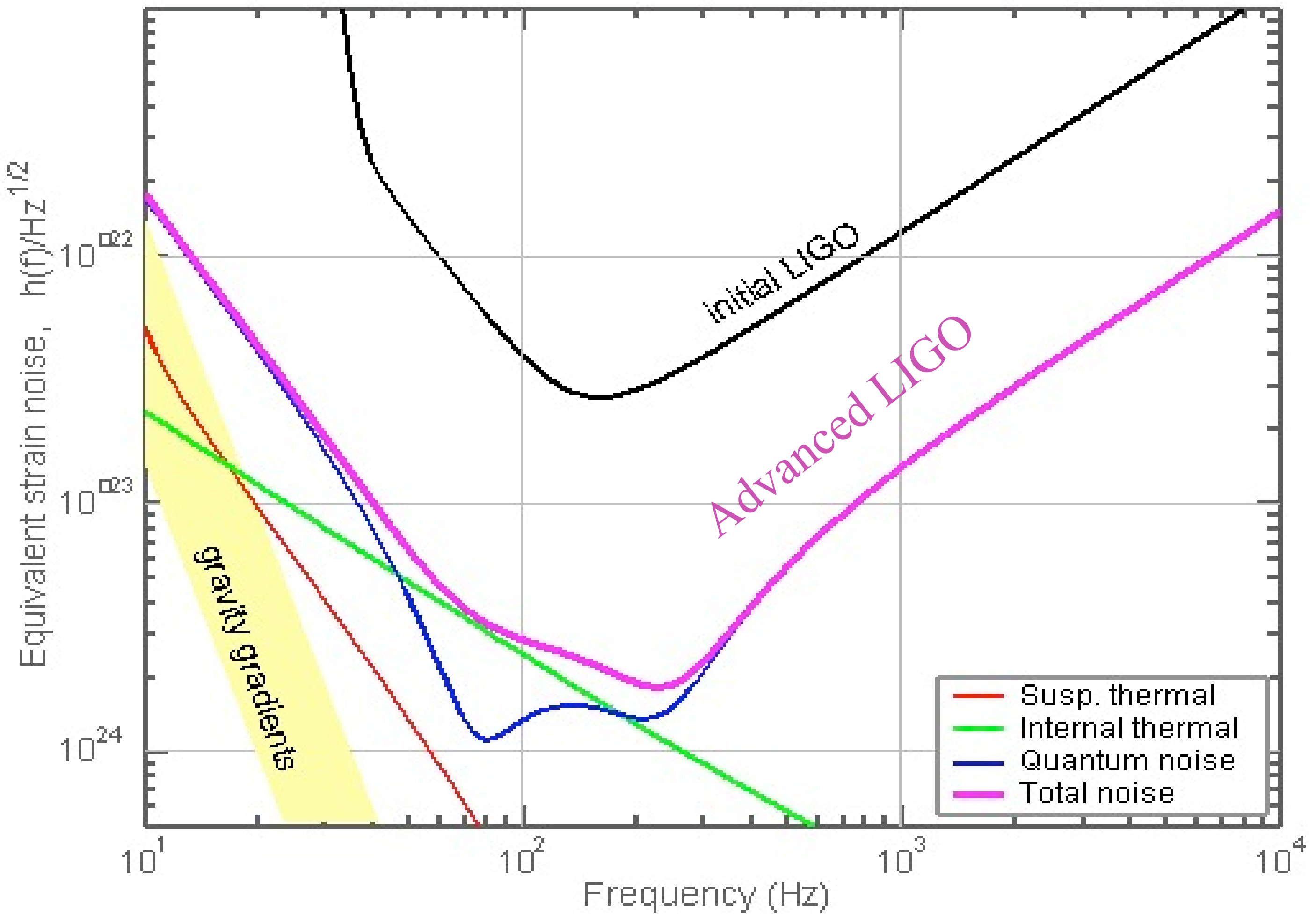
GW Future

- What does advanced LIGO get us?



GW Future

- What does advanced LIGO get us?

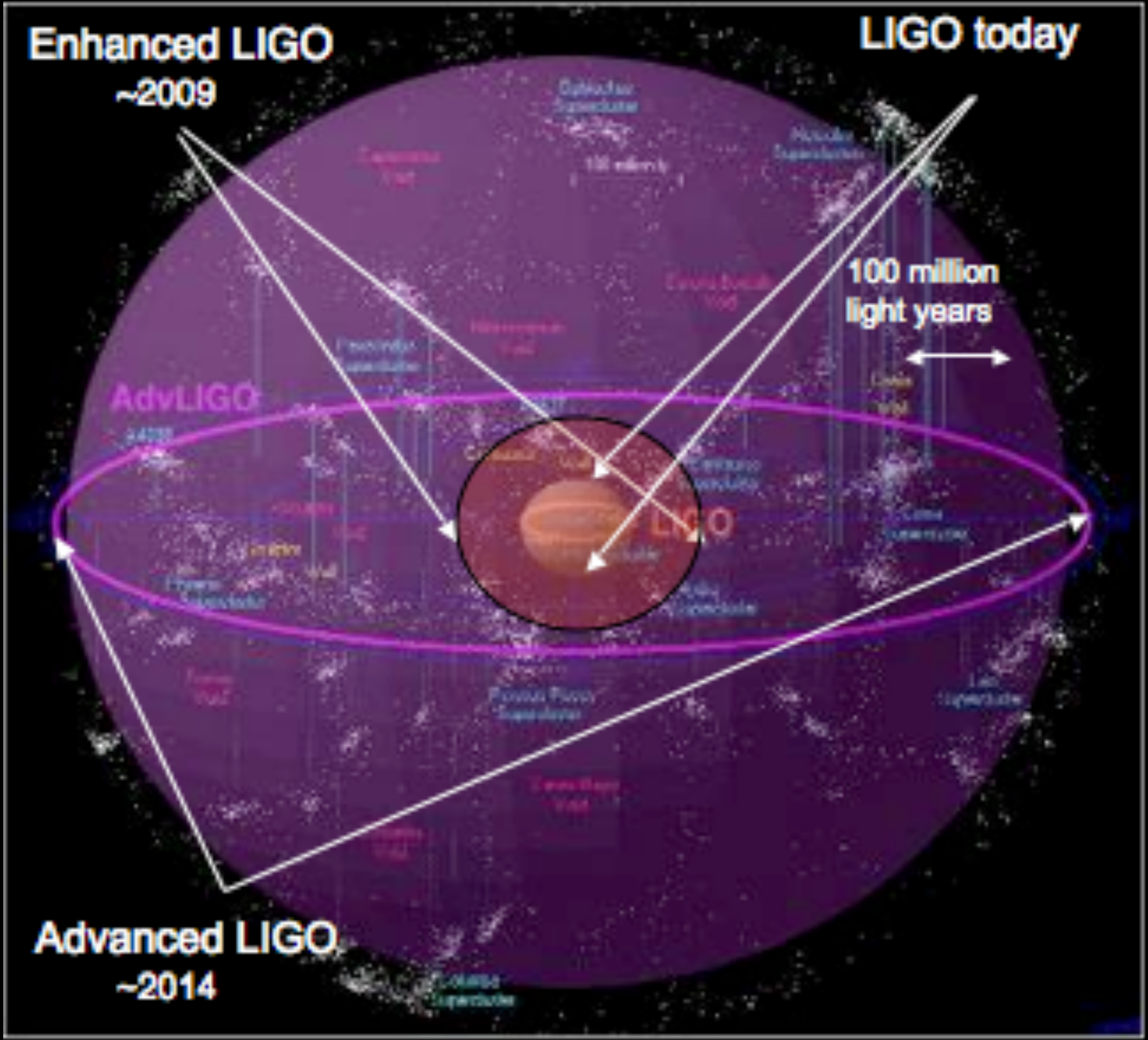


- estimated rate for NS-NS binaries: ~20/year to ~350Mpc

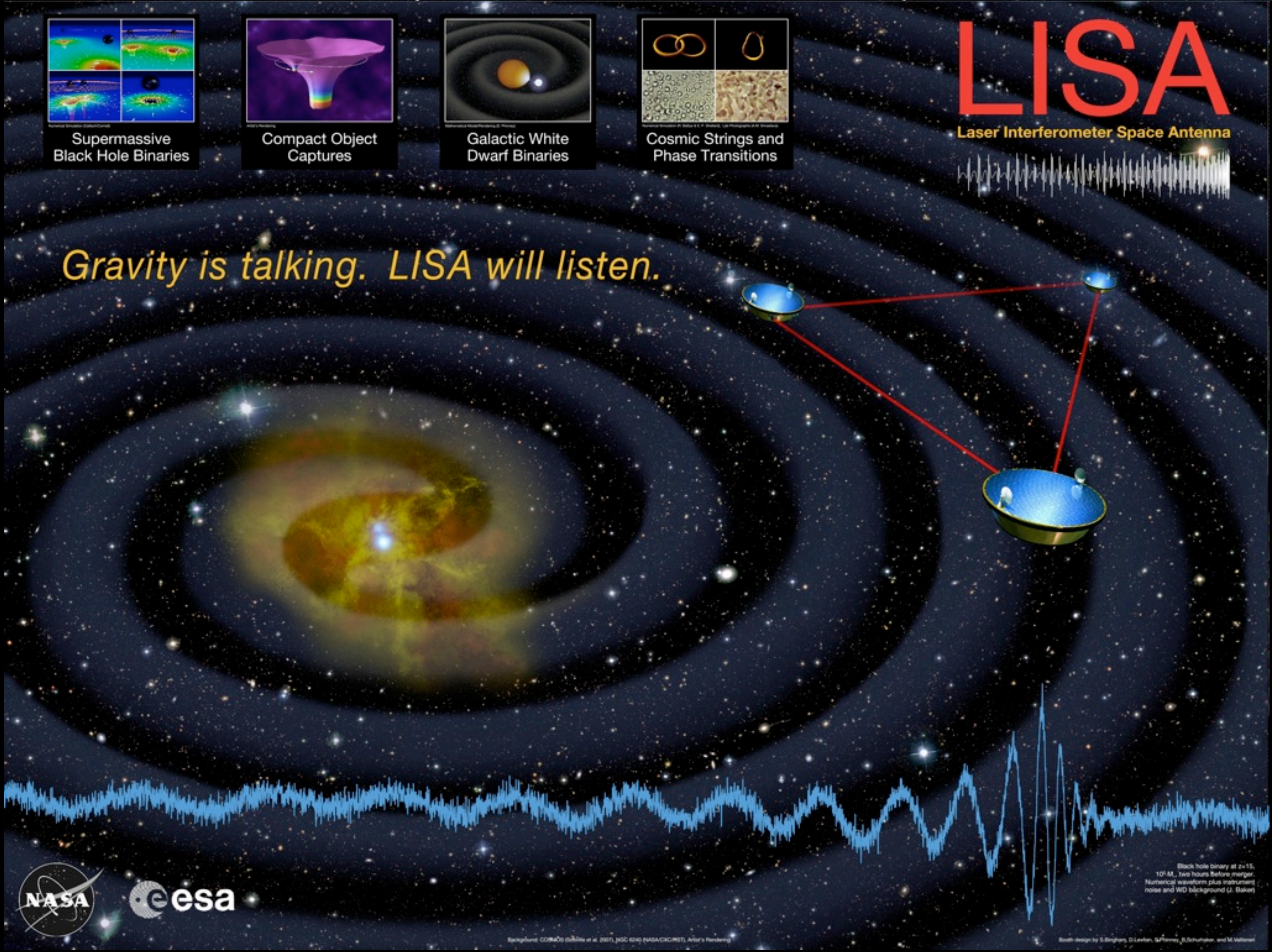
- estimated rate for BH-BH binaries: ~16/year to ~z=2

- 3 minutes of advanced LIGO gives same science opportunity as S5.

GW Future


Enhanced LIGO
~2009
LIGO today
100 million
light years
AdvLIGO
LIGO
Advanced LIGO
~2014

GW Future


Supermassive
Black Hole Binaries
Compact Object
Captures
Galactic White
Dwarf Binaries
Cosmic Strings and
Phase Transitions
LISA
Laser Interferometer Space Antenna
Gravity is talking. LISA will listen.
NASA
esa
Black hole binary at z=15,
$10^5 M_\odot$, two hours before merger.
Numerical waveform plus instrument
noise and WD background (J. Baker)

Extra Slides

GW Theory

- *Question*: How do gravitational waves effect matter?

  Spacetime distortion creates tidal force. Two stationary particles separated by vector ξ^α feel tidal acceleration

  $$\frac{\partial^2}{\partial t^2}\xi^\alpha = R^\alpha{}_{0\beta 0}\,\xi^\beta \ ,$$

  In the TT gauge, the only non-vanishing components of the Riemann tensor are:

  $$R^x{}_{0x0} = -R^y{}_{0y0} = -\frac{1}{2}\frac{\partial^2}{\partial t^2}h_{xx} \ ,$$

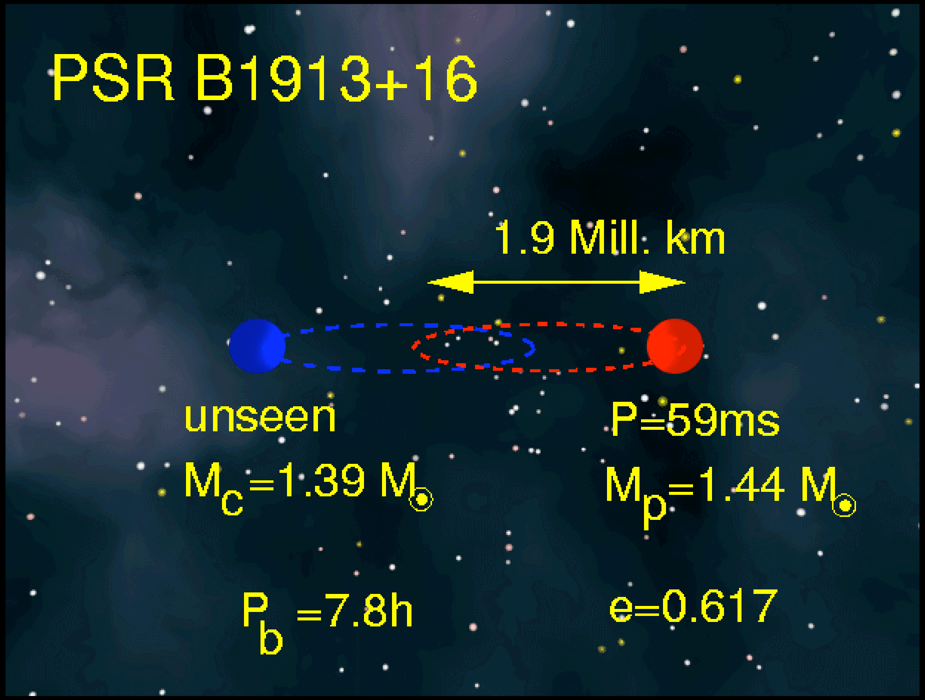
  $$R^x{}_{0y0} = R^y{}_{0x0} = -\frac{1}{2}\frac{\partial^2}{\partial t^2}h_{xy} \ .$$

  So, if tidal displacement $\Delta|\xi| \ll |\xi|$, then tidal *strain* is

  $$\Delta|\xi|/|\xi| = \frac{1}{2}\sqrt{h_{xx}^2 + h_{xy}^2} \ .$$

GW Detectors

- Strong indirect evidence of GWs has already been seen.

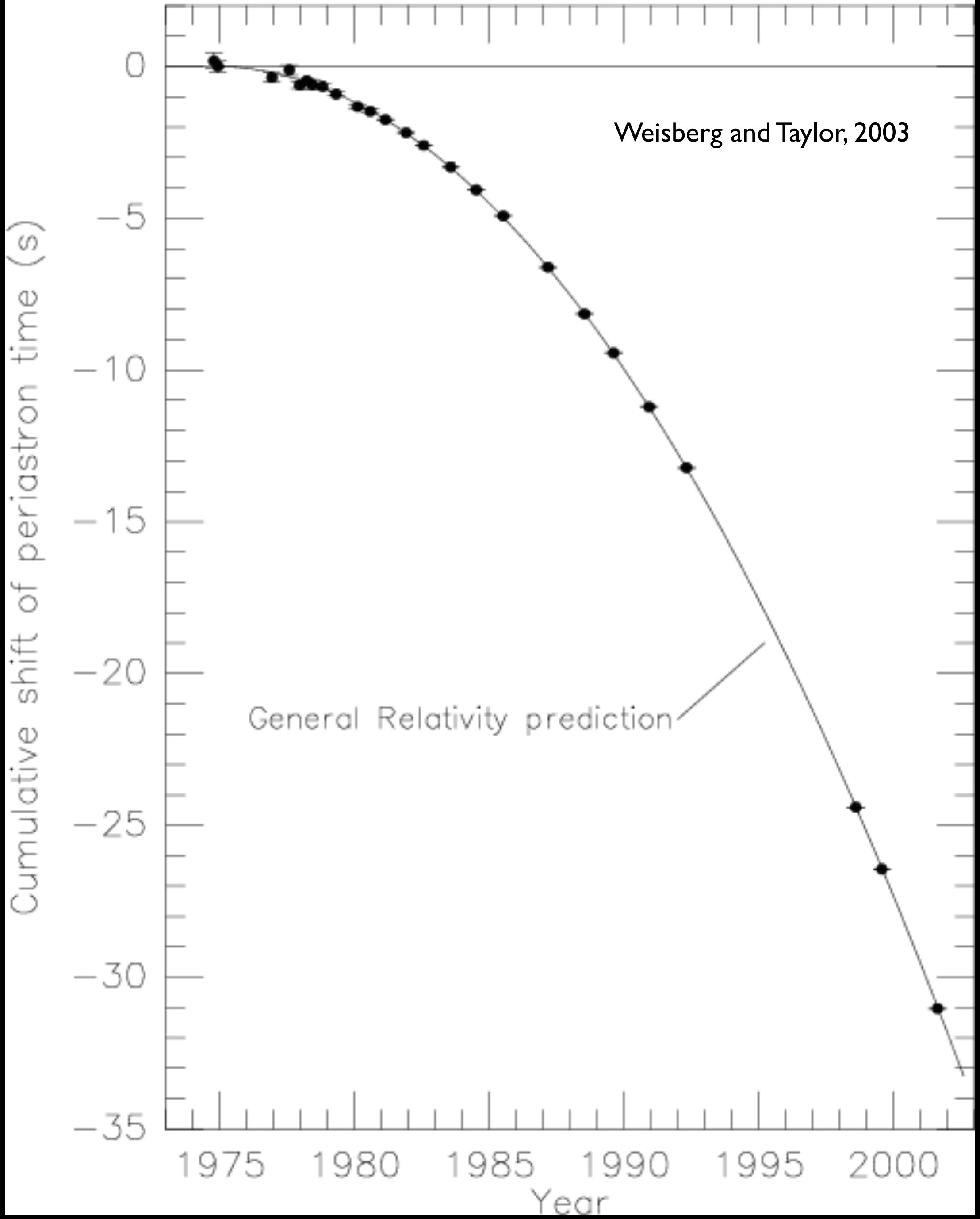


Generic periastron shift:

$$\Delta t_p(N) \approx P\,\dot{P}_b\,N^2/2$$

$\dot{P}_b$ from GW emission:

$$\dot{P}_b \sim -\frac{m_p m_c}{[(m_p+m_c)\,P_b^5\,]^{1/3}}$$



Weisberg and Taylor, 2003

GW Detectors

- Early detectors were resonant mass detectors.

  Tidal force from gravitational wave pulse excites resonant mode of bar.

  Vibrations read by transducer and amplified.

Joseph Weber with his resonant bar.

GW Detectors

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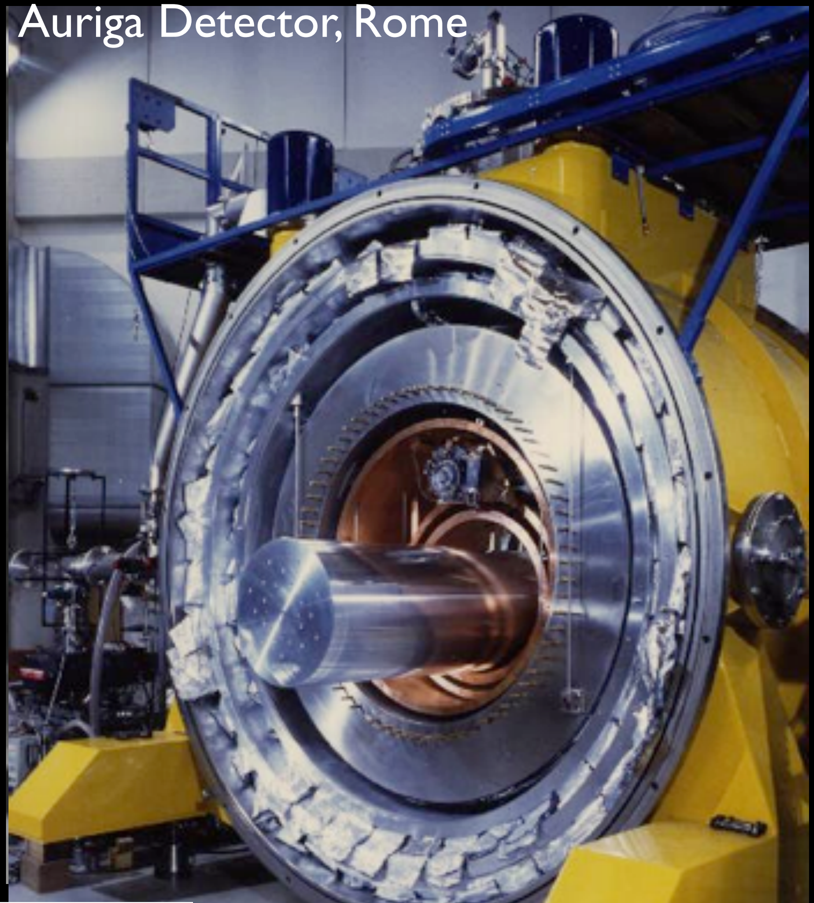
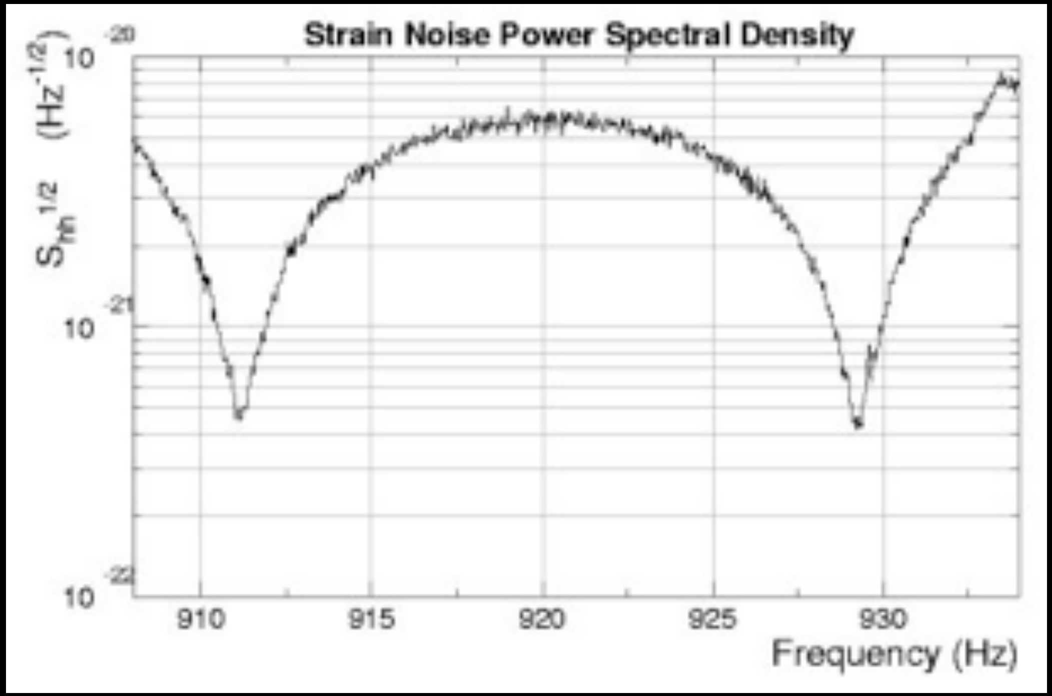
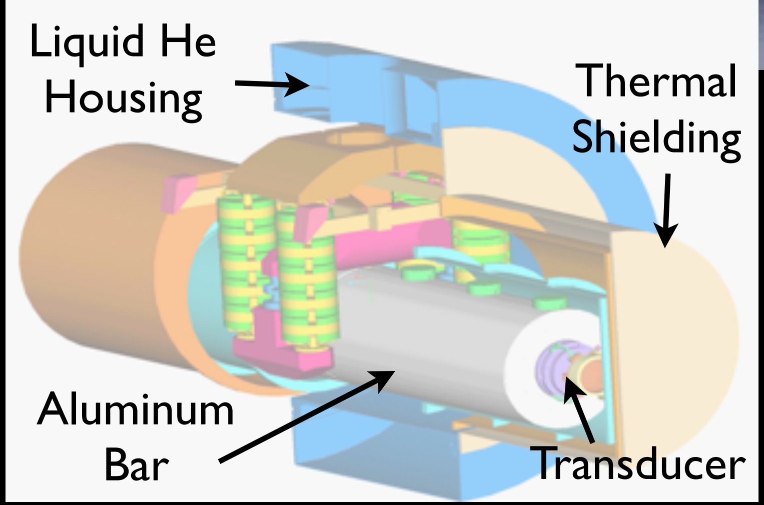
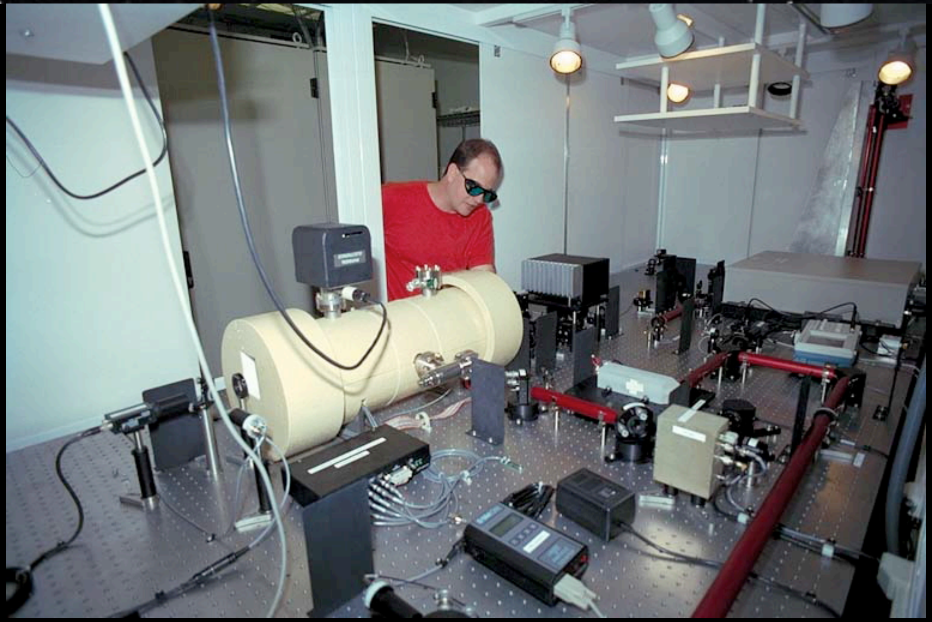

Auriga Detector, Rome



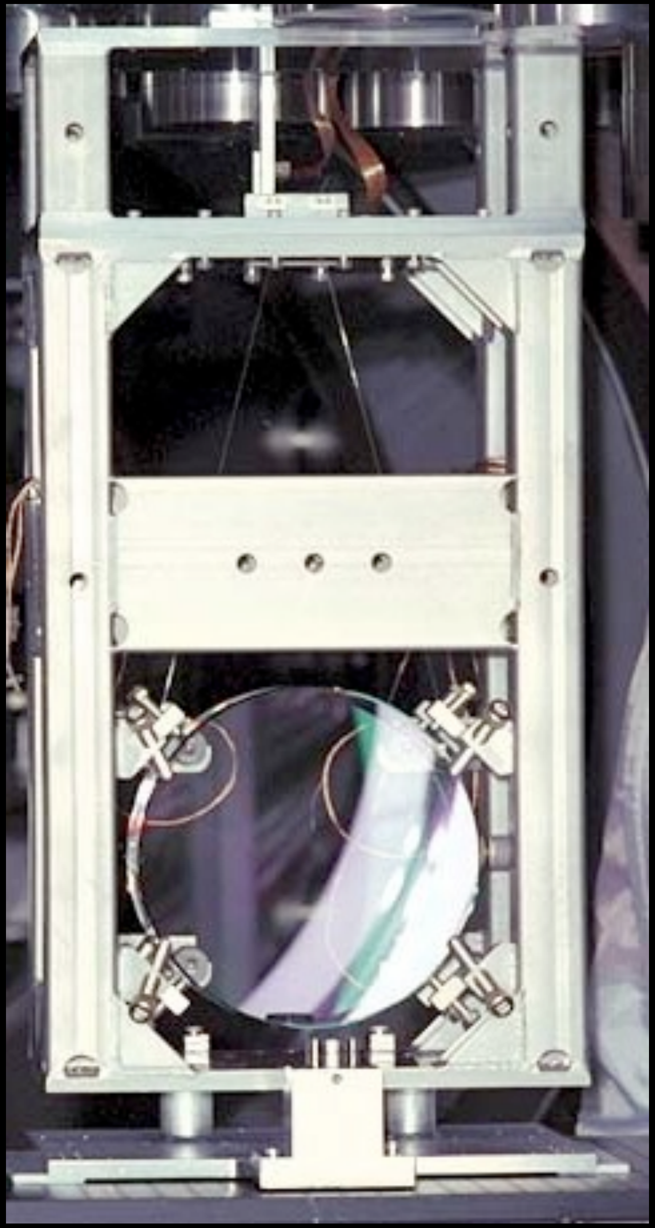


GW Detectors


Input Optics Bench (Laser)


Evacuated Beam Tube


Seismic Isolation Stack


Suspended Silica Test Mass


Optics Vacuum Enclosures

GW Results

- We are excluding compact binary coalescences out to large distances.

  Horizon distance - distance at which an optimally positioned binary has expected SNR $\langle \rho \rangle = 8$.