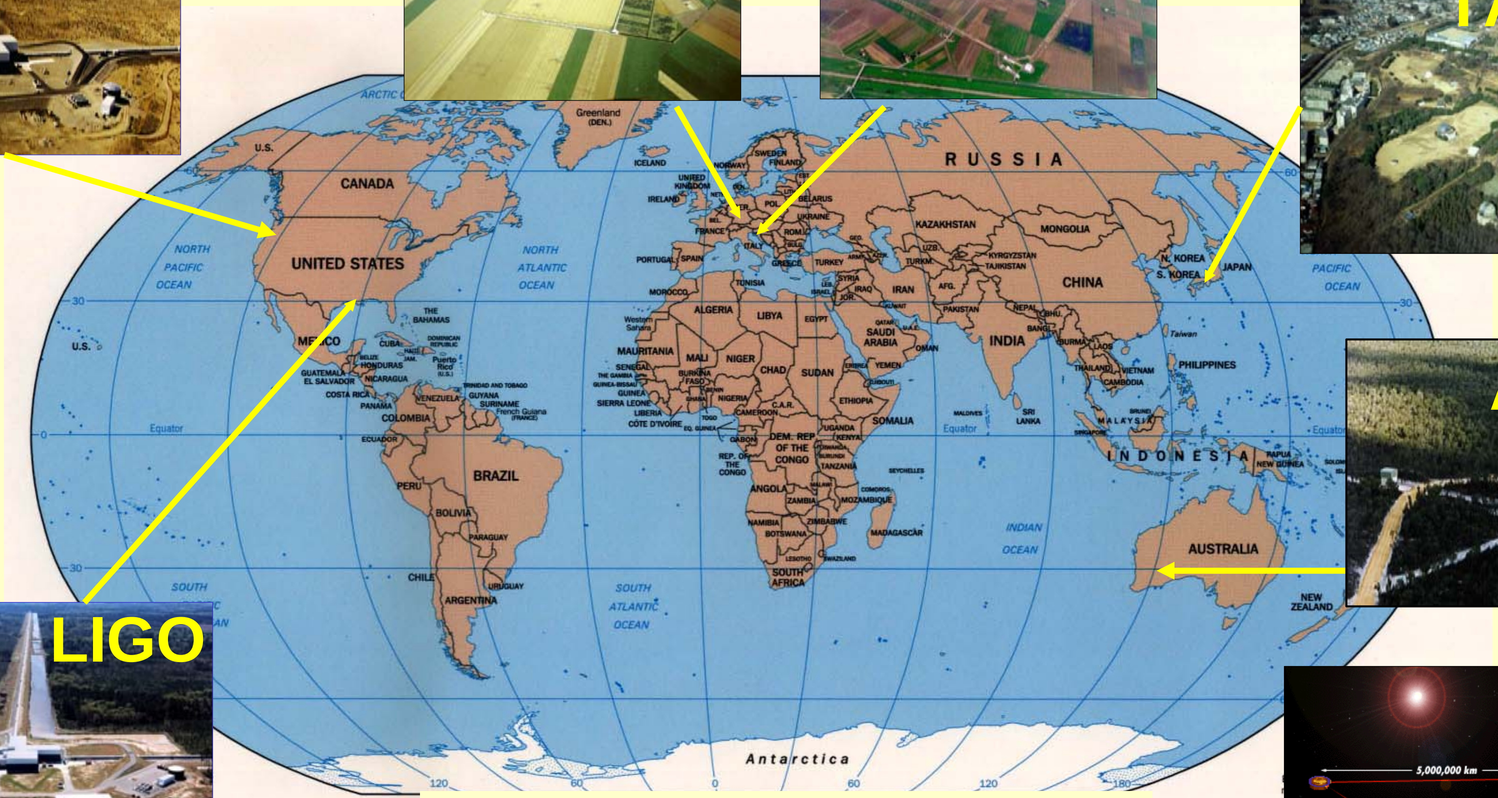
LIGO-G060012-00-R

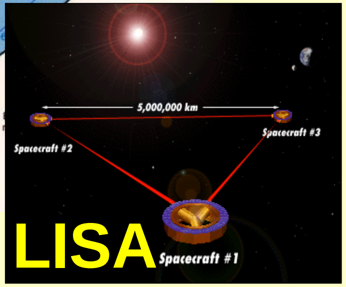
Detection of Gravitational Waves with Interferometers

Giant detectors
Precision measurement
The search for the elusive waves

Nergis Mavalvala
(on behalf of the LIGO Scientific Collaboration)
AAS Meeting, Washington D.C.
January 2006

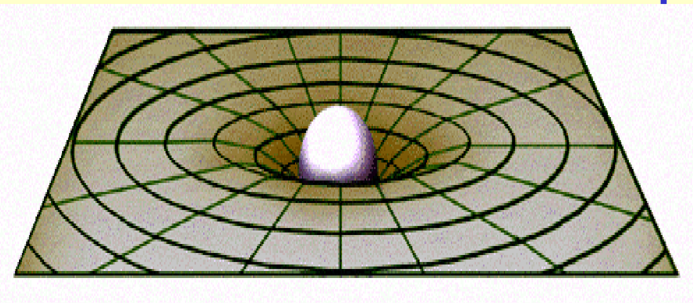
Global network of detectors





- Detection confidence
- Source polarization
- Sky location

Gravitational waves



- Transverse distortions of the space-time itself ➔ ripples of space-time curvature
- Propagate at the speed of light
- Push on freely floating objects ➔ stretch and squeeze the space transverse to direction of propagation

$$h = \frac{\Delta L}{L}$$

- Energy and momentum conservation require that the waves are quadrupolar ➔ aspherical mass distribution

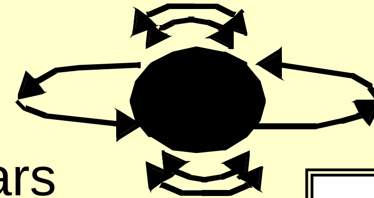
Astrophysics with GWs vs. E&M

E&M	GW
Accelerating charge	Accelerating aspherical mass
Wavelength small compared to sources ➔ images	Wavelength large compared to sources ➔ no spatial resolution
Absorbed, scattered, dispersed by matter	Very small interaction; matter is transparent
10 MHz and up	10 kHz and down

- Very different information, mostly mutually exclusive
- Difficult to predict GW sources based on EM observations

Astrophysical sources of GWs

- Periodic sources
  - Pulsars ➔ Spinning neutron stars
  - Low mass Xray binaries



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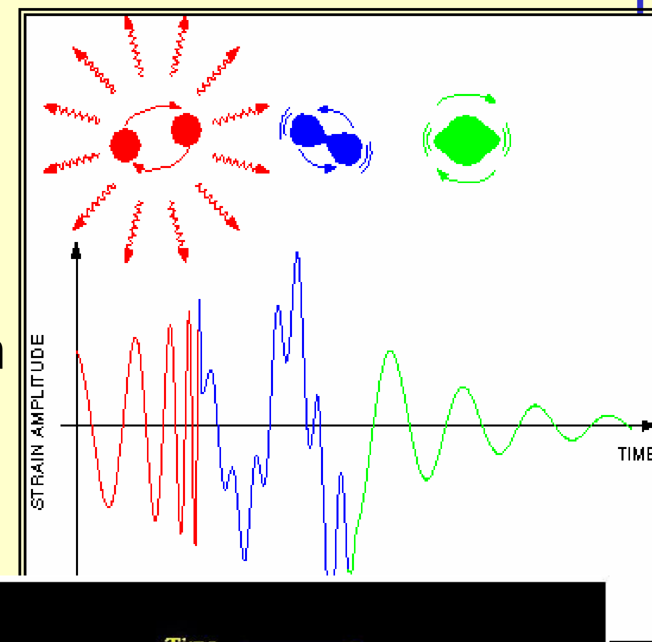
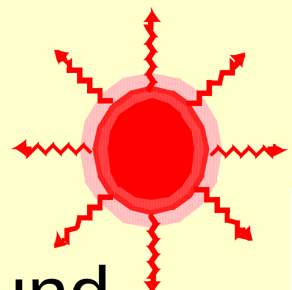
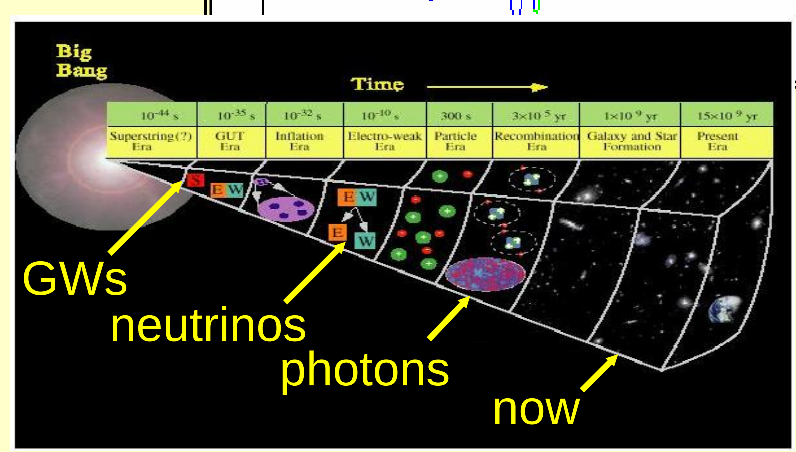
  - Classes of objects: NS-NS, NS-BH, BH-BH
  - Physics regimes: Inspiral, merger, ringdown



- Burst events
  - Supernovae with asymmetric collapse



- Stochastic background
  - Primordial Big Bang (t = 10-43 sec)
  - Continuum of sources



- The Unexpected

LIGO

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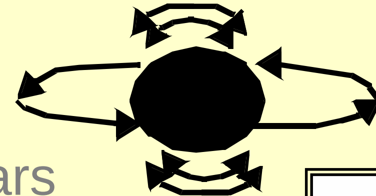

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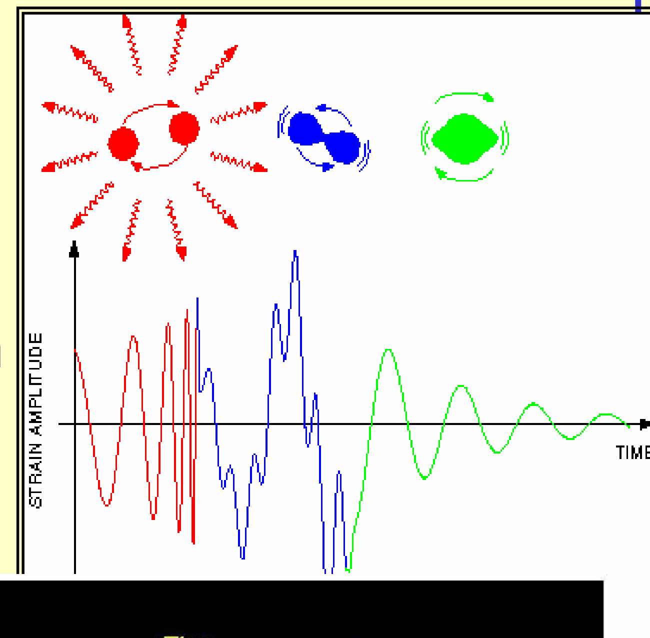

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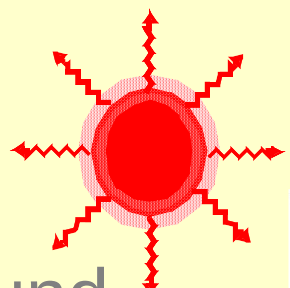

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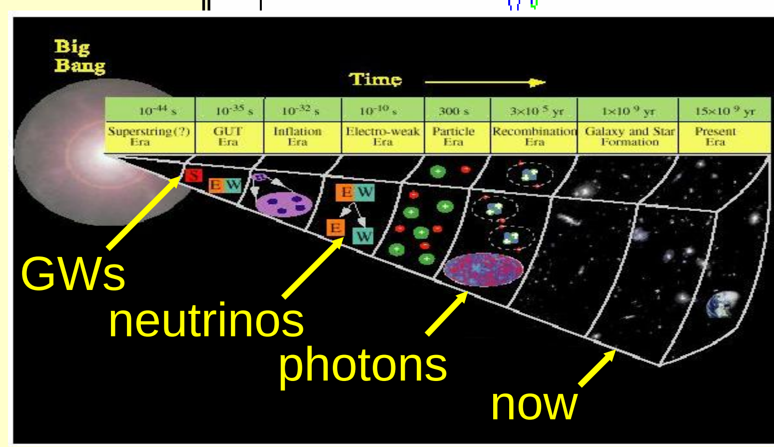

Pulsar born from a supernova

Courtesy of NASA (D. Berry)

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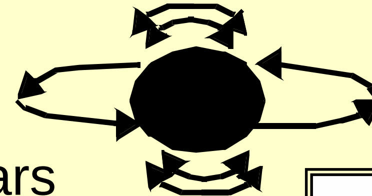

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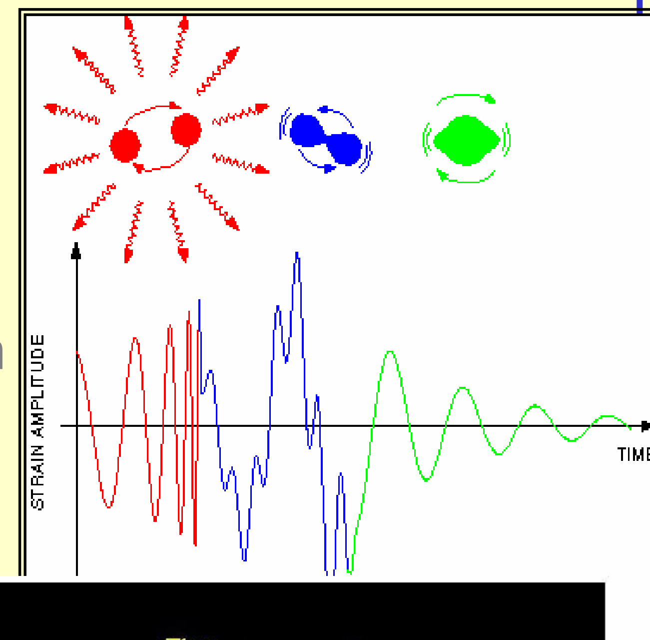

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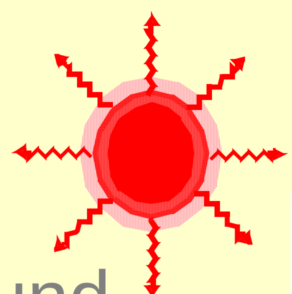

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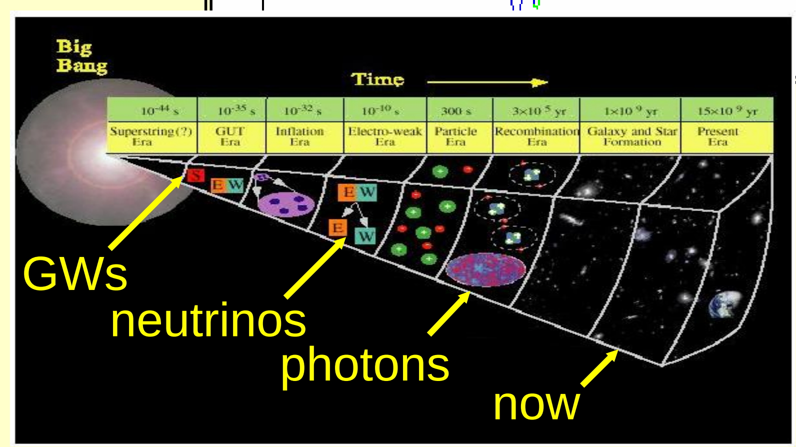

Millisecond pulsar accretion

Courtesy of NASA (D. Berry)

Astrophysical sources of GWs

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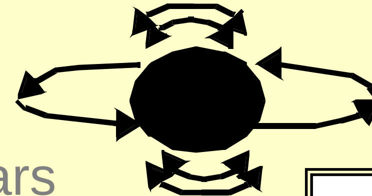

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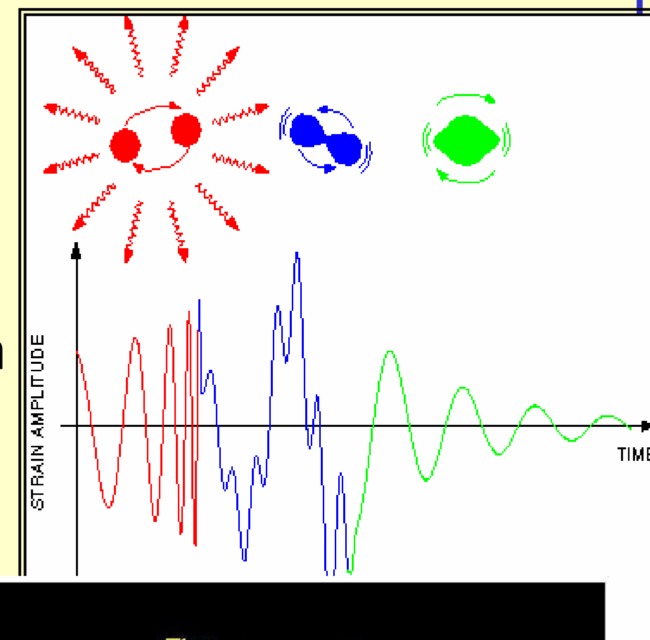

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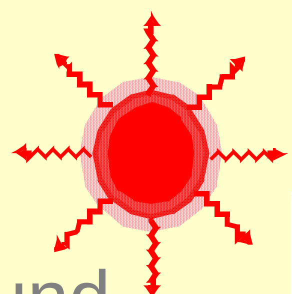

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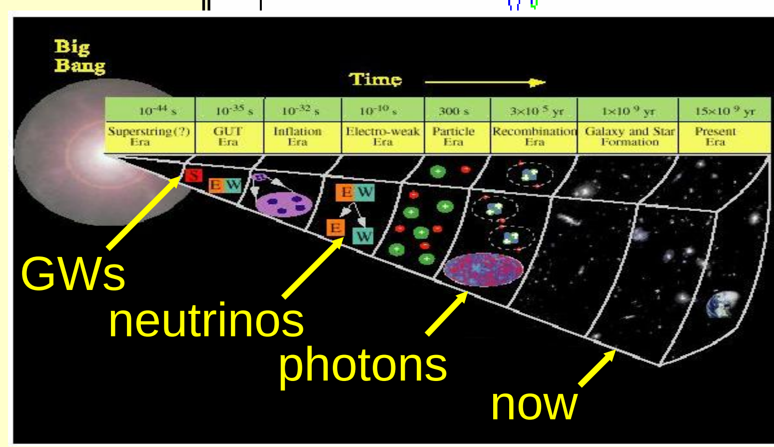
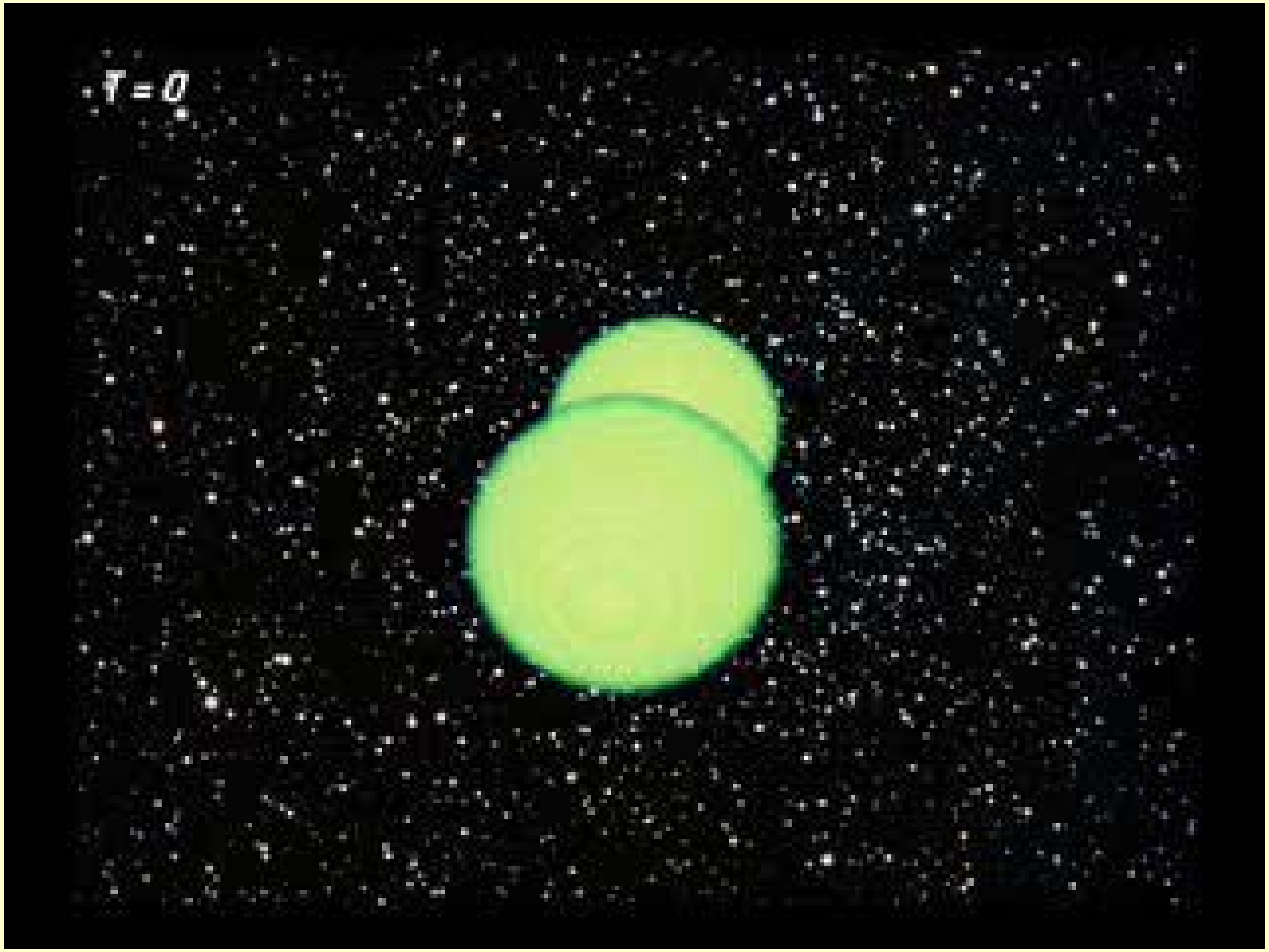


Neutron Stars
spiraling toward each other



Courtesy of WUStL GR group

Strength of GWs: e.g. Neutron Star Binary

- Gravitational wave amplitude (strain)

$$h_{\mu\nu} = \frac{2G}{c^4 r}\ddot{I}_{\mu\nu} \Rightarrow h \approx \frac{4\pi^2 GMR^2 f_{orb}^2}{c^4 r}$$

- For a binary neutron star pair

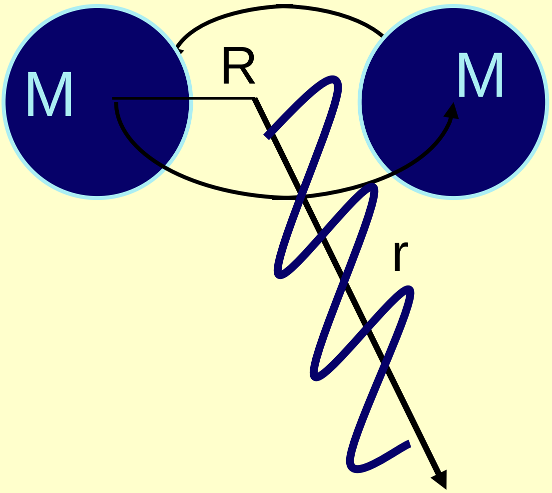
$M \approx 10^{30}$ kg

$R \approx 20$ km

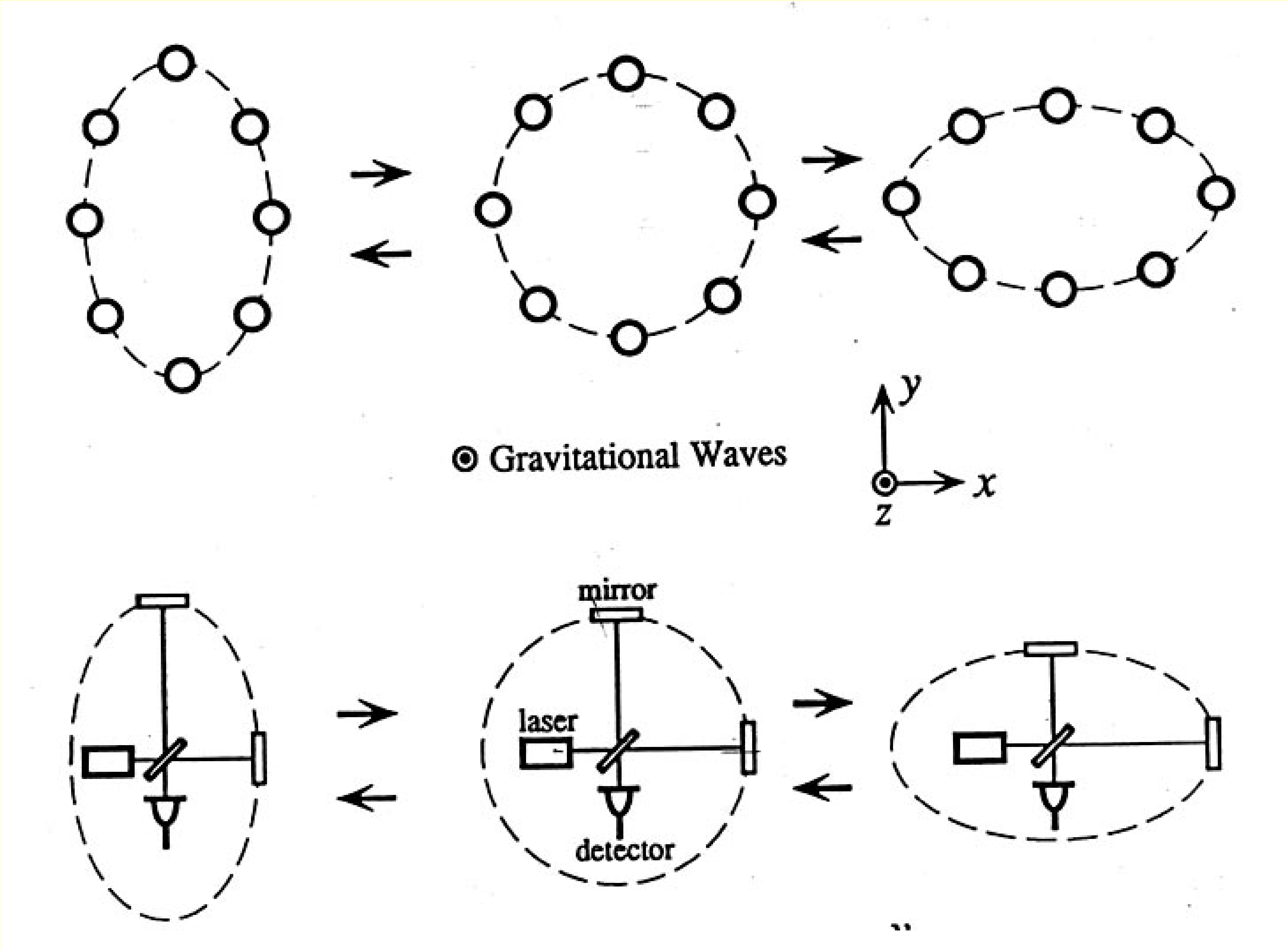
$f \approx 400$ Hz

$r \approx 10^{23}$ m

⇨ $h \sim 10^{-21}$



Effect of a GW on matter



Measurement and the real world

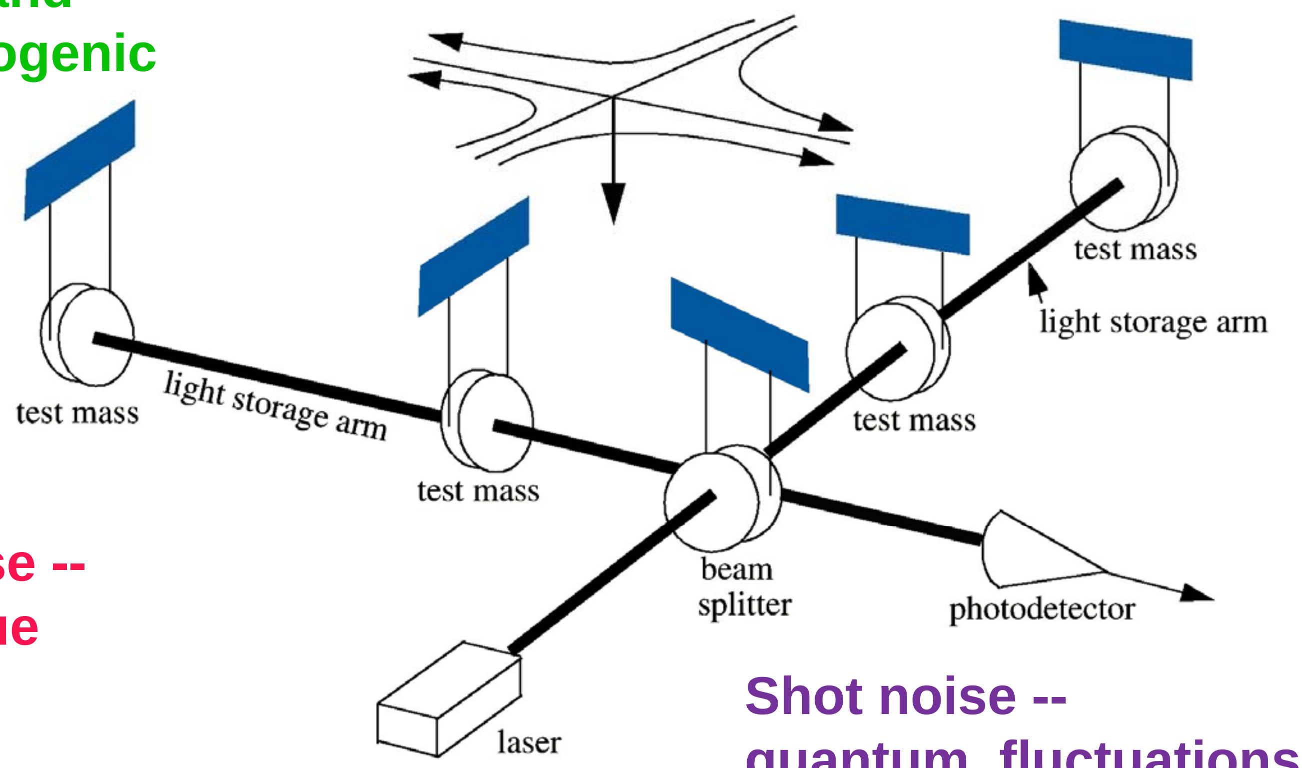
- How to measure the gravitational-wave?
  - Measure the displacements of the mirrors of the interferometer by measuring the phase shifts of the light
- What makes it hard?
  - GW amplitude is small
  - External forces also push the mirrors around
  - Laser light has fluctuations in its phase and amplitude

GW detector at a glance

L ~ 4 km
For $h \sim 10^{-21}$
$\Delta L \sim 10^{-18}$ m

Seismic motion -- ground motion due to natural and anthropogenic sources

$$h = \Delta L / L$$



Thermal noise -- vibrations due to finite temperature

Shot noise -- quantum fluctuations in the number of photons detected

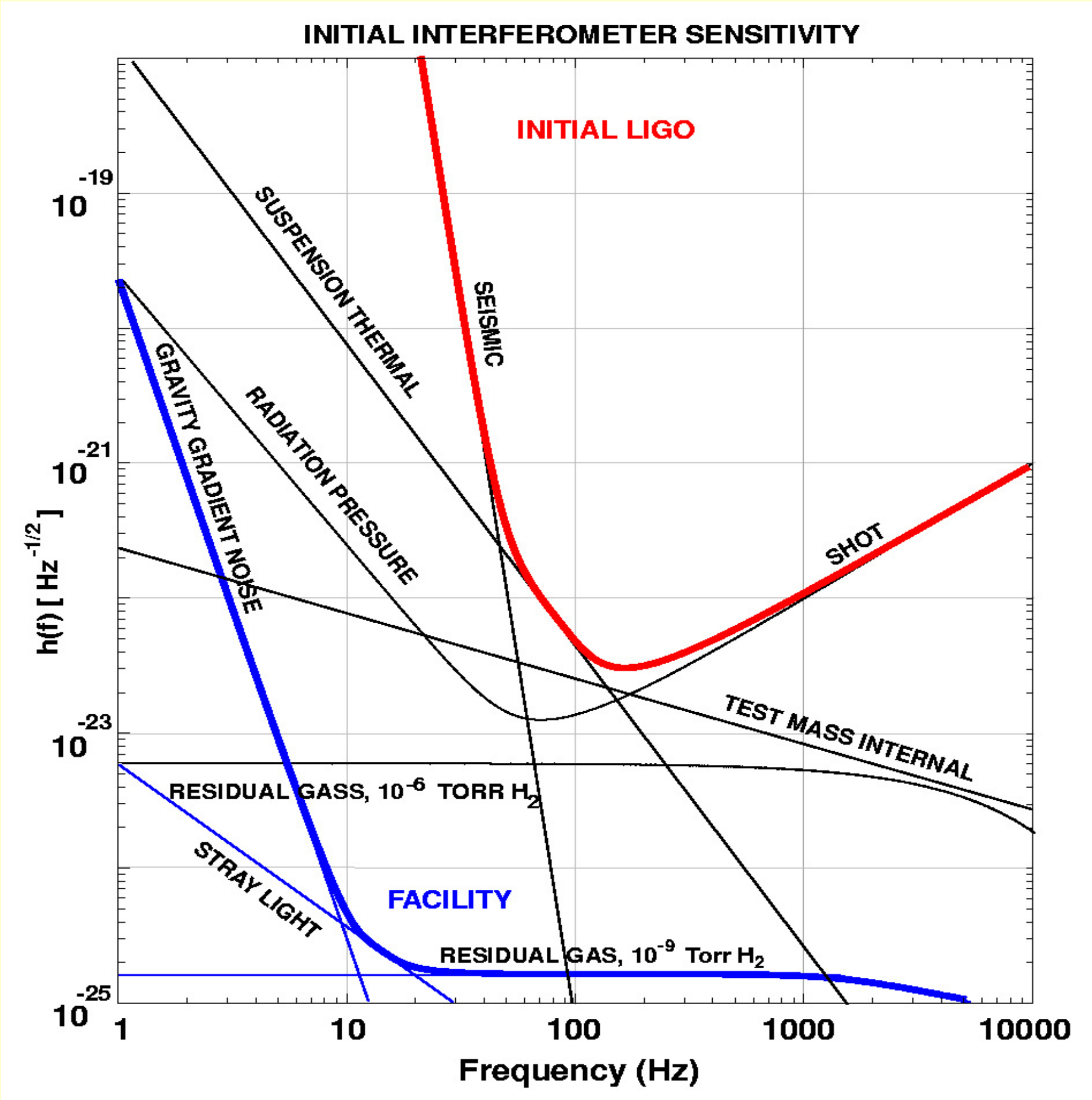
LIGO: Laser Interferometer Gravitational-wave Observatory

4 km

2 km

4 km

Initial LIGO Sensitivity Goal



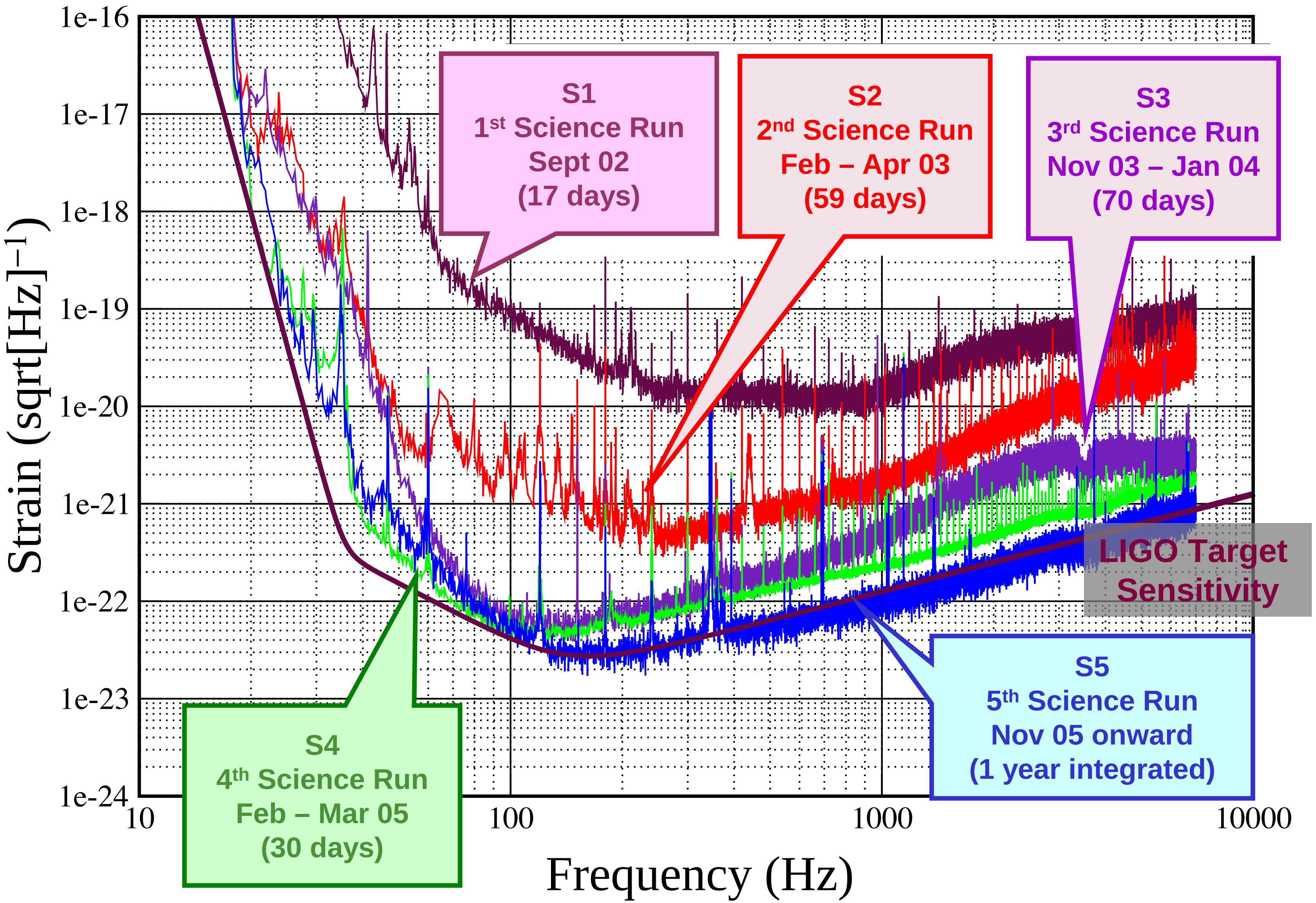
- Strain sensitivity $< 3\times10^{-23}$ $1/Hz^{1/2}$ at 200 Hz
- Displacement Noise
  - Seismic motion
  - Thermal Noise
  - Radiation Pressure
- Sensing Noise
  - Photon Shot Noise
  - Residual Gas
- Facilities limits much lower

Gravitational-wave searches

Reaching LIGO's Science Goals

- **Interferometer commissioning**
  - Intersperse commissioning and data taking consistent with obtaining one year of integrated data at $h = 10^{-21}$ by end of 2006
- **Science runs and astrophysical searches**
  - Science data collection and intense data mining interleaved with commissioning
    - **S1 Aug 2002 – Sep 2002 duration: 2 weeks**
    - **S2 Feb 2003 – Apr 2003 duration: 8 weeks**
    - **S3 Oct 2003 – Jan 2004 duration: 10 weeks**
    - **S4 Feb 2005 – Mar 2005 duration: 4 weeks**
    - **S5 Nov 2005 – ... duration: 1 yr integrated**
- **Advanced LIGO**

Science runs and sensitivity



Science Run 5 (S5) begins

- Schedule
  - Started in November, 2005
  - Get 1 year of data at design sensitivity
  - Small enhancements over next 3 years
- Typical sensitivity (in terms of inspiral distance)
  - H1 10 to 12 Mpc (33 to 39 million light years)
  - H2 5 Mpc (16 million light years)
  - L1 8 to 10 Mpc (26 to 33 million light years)
- Sample duty cycle (12/13/05 to 12/26/05)
  - 68% (L1), 83% (H1), 88% (H2) individual
  - 58% triple coincidence

New rate predictions from SHBs?

- 4 Short Hard gamma ray Bursts since May 2005
  - Detected by Swift and HETE-2, with rapid follow-up using Hubble, Chandra, and look-back at BATSE
  - Find that SHB progenitors are too old (>5 Gyr) to be supernova explosions (cause of long GRBs)
  - Remaining candidates for progenitors of SHBs: old double neutron star (DNS) or neutron star-black hole (NS-BH) coalescences
  - Predicted rates for Initial LIGO (S5) could be as high as

$$R_{\text{NS-BH}} \approx 30\ \text{yr}^{-1} \qquad R_{\text{DNS}} \approx 3\ \text{yr}^{-1}$$

Nakar, Gal-Yam, Fox, astro-ph/0511254

  - But great uncertainty in rate estimates

An exciting time in gravitational wave detection

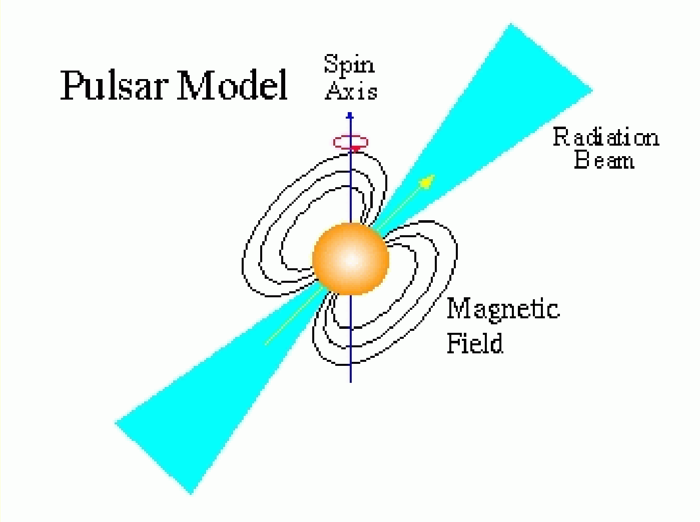
- The initial LIGO detectors have reached their target sensitivity
  - Incredibly small motion of mirrors → 10^{-19} m (less than 1/1000 the size of a proton)
- LIGO has begun its biggest and most sensitive science data run
- Unprecedented sensitivity → prospects for new science are very promising
  - On *Science* magazine's list of things to watch out for in 2006
- Design of an even more sensitive next generation instrument is progressing rapidly

Gravitational-wave searches

Pulsars

Continuous Wave Sources

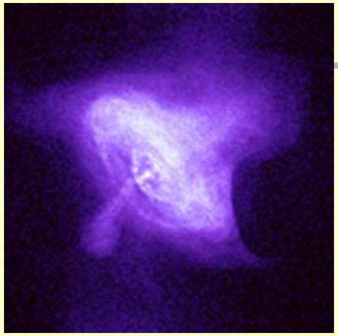
- Nearly-monochromatic continuous GW radiation, e.g. neutron stars with
  - Spin precession at f_{rot}
  - Excited modes of oscillation, e.g. r-modes at $\frac{4}{3} f_{rot}$
  - Non-axisymmetric distortion of shape at $2 f_{rot}$
- Signal frequency modulated by relative motion of detector and source
- Amplitude modulated by the motion of the antenna pattern of the detector
- Search for gravitational waves from a triaxial neutron star emitted at $2 f_{rot}$

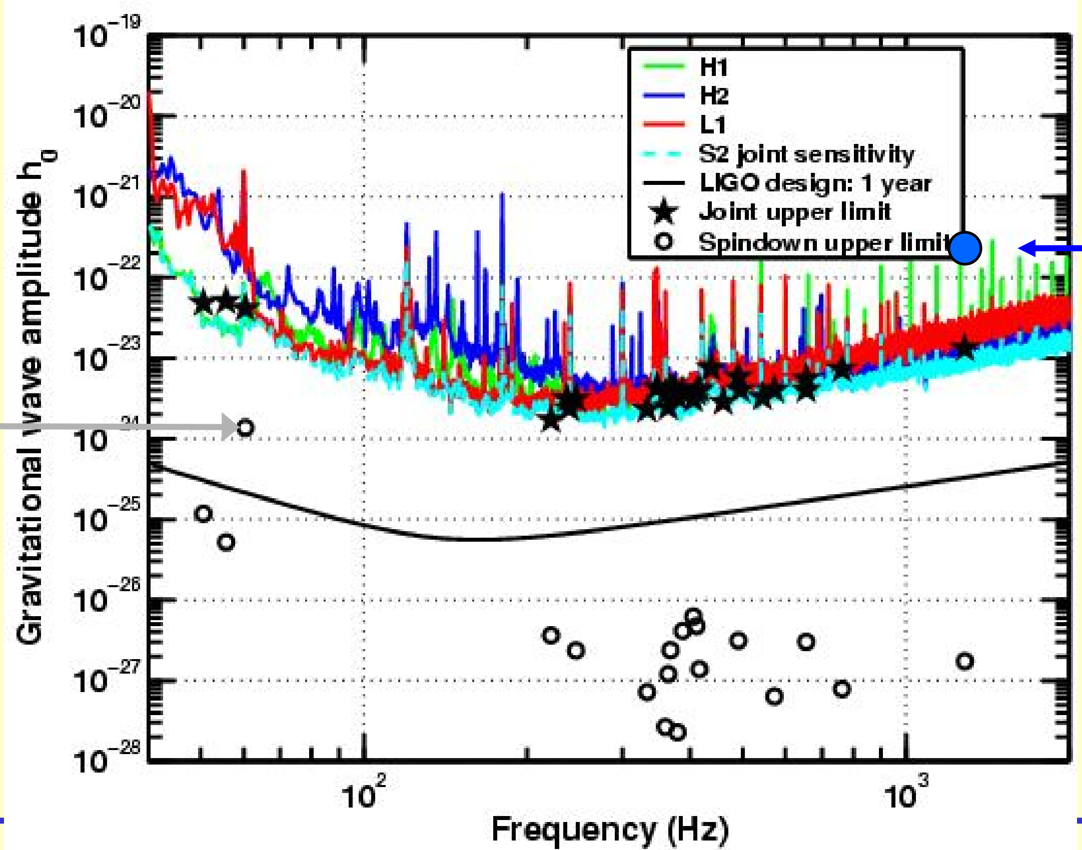


Summary of pulsar searches

- **S1** → Setting upper limits on the strength of periodic gravitational waves from PSR J1939 2134 using GEO600 and LIGO data
  - Phys. Rev. D **69** (2004) 082004
- **S2** → Limits on GW emission from 28 selected pulsars using LIGO data
  - Phys. Rev. Lett. **94** (2005) 181103

Crab pulsar



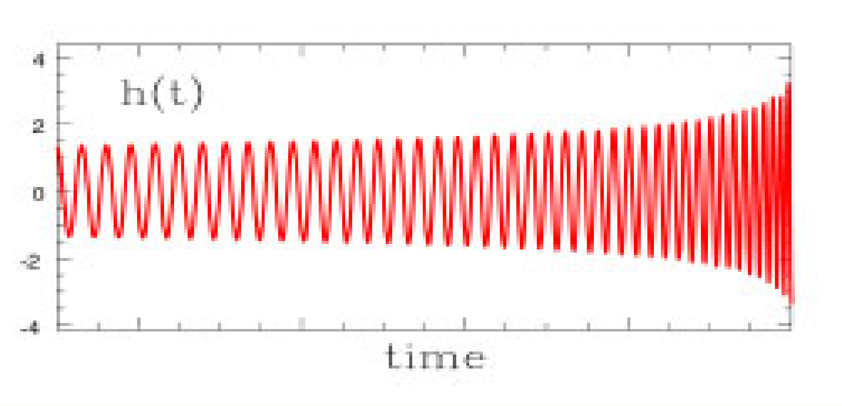


Gravitational-wave Searches

Binary Inspirals

Search for Inspirals

- **Sources**
  - Orbital-decaying neutron star binaries
  - Black hole binaries
  - MACHOs
- **Search method**
  - Waveforms calculable
  - Use optimal matched filtering
    → correlate detector output
    with template waveform
  - Template inputs from population synthesis



Binary Neutron Star Inspiral (S2)

- Upper limit on binary neutron star coalescence rate
  - Express the rate as a rate per **Milky-Way Equivalent Galaxies** (MWEG)

$$R_{90\%} = \frac{2.3}{T_{obs} N_G} = \frac{2.3}{355 \text{ hrs } \times 1.14} < 50 \text{ /year/MWEG}$$

Theoretical prediction: R < 2 x 10^{-5} / yr /MWEG

  - Express as the **distance** to which radiation from a 1.4 M_{sun} pair would be detectable with a SNR of 5

$$D = 2 \text{ Mpc} \approx 10^{22} \text{ m}$$

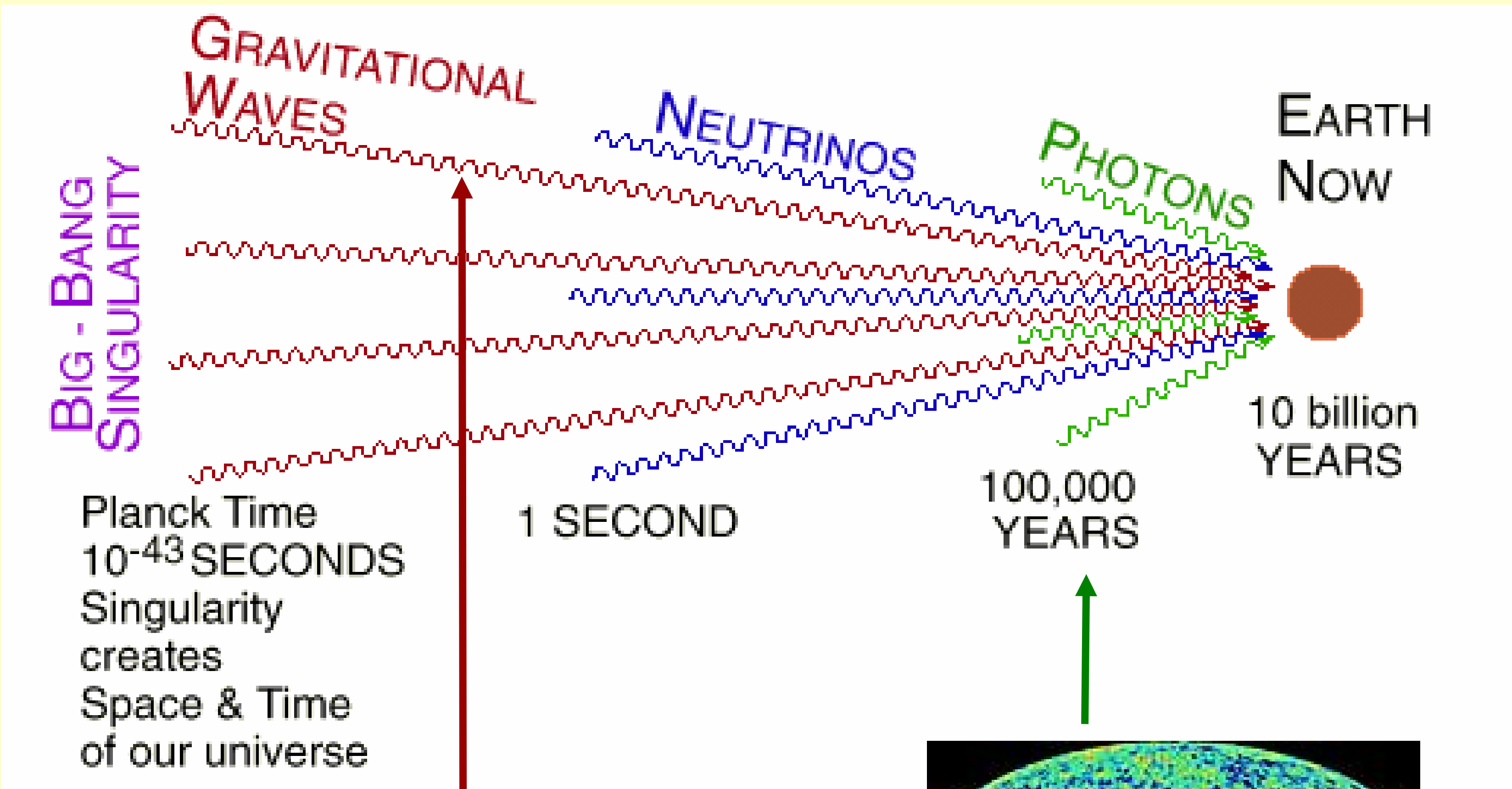
  - Important to look out further, so more galaxies can contribute to population of NS

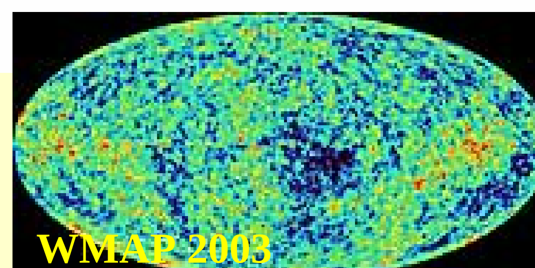
Phys.Rev. D72 (2005) 082001

Gravitational-wave searches

Stochastic Background

Stochastic Background





Waves now in the LIGO band were produced 10^{-22} sec after the Big Bang

Stochastic Background of GWs

- Given an energy density spectrum $\Omega_{gw}(f)$, there is a GW strain power spectrum

$$\Omega_{GW}(f) = \frac{1}{\rho_{critical}} \frac{d\rho_{GW}}{d(\ln f)} \rightarrow S_{gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{gw}(f)$$

- For standard inflation (ρ_c depends on present day Hubble constant)

$$h(f) = S_{gw}^{1/2}(f) = 5.6\times 10^{-22}\, h_{100} \sqrt{\Omega_0} \left(\frac{100\text{Hz}}{f}\right)^{3/2} \text{Hz}^{1/2}$$

- Search by cross-correlating output of two GW detectors: L1-H1, H1-H2, L1-ALLEGRO
  - The closer the detectors, the lower the frequencies that can be searched (due to overlap reduction function)

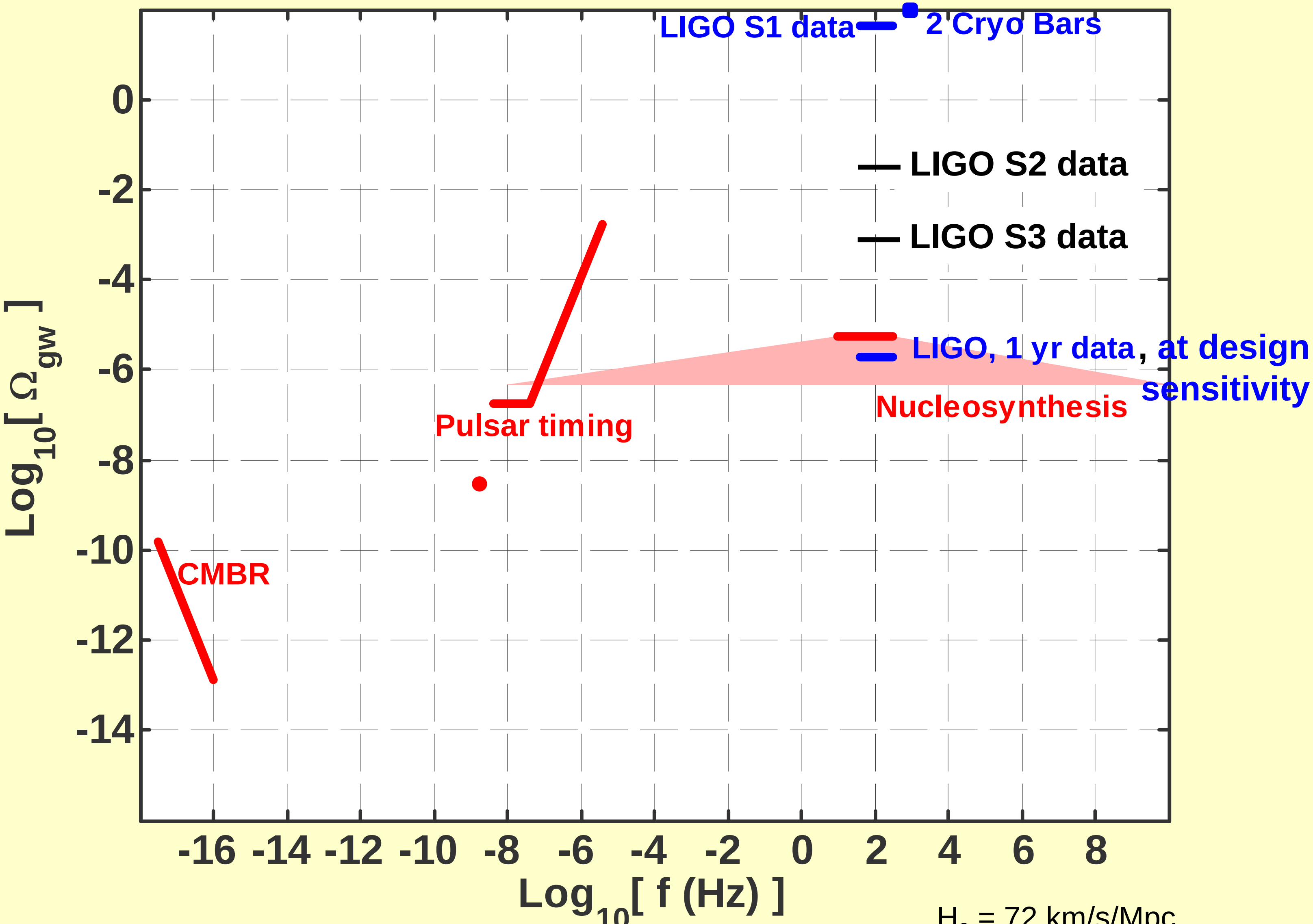
LIGO results for $\Omega_0 h_{100}^2$

LIGO run	$\Omega_0 h_{100}^2$	Comments	Frequency Range	Observation Time
S1 PRD **69** (2004)	**< 23 ± 4.6** **(H2-L1)**	**Cross-correlated instrumental noise found**	**40 to 314 Hz**	**64 hours** **(08/02 – 09/02)**
S2	**< 0.018** **(H1-L1)**		**50 to 300 H**[illegible]	[illegible] **hours** [illegible] **04/03)**
S3 PRL **95** (2005)	**< 8** [illegible]	$\Omega_{gw} = \Omega_\alpha \left(f / 1 \right.$[illegible] **α = 0** [illegible] [illegible] **→ rotating NS** **α = 2 → pre-BB cosmology**	**70 to 160 Hz** **(H1-L1)**	**200 hrs (H1-L1)** **(10/03 – 01/04)**
S4		**Analysis underway**		**447 hrs (H1-L1)** **510 hrs (H1-H2)** **(02/05 – 03/05)**

Initial LIGO (1 yr) $\Omega_0 h_{100}^2 < 2 \times 10^{-6}$

Advanced LIGO (1 yr) $\Omega_0 h_{100}^2 < 7 \times 10^{-10}$

Limits on Ω_{gw} from astrophysical observations

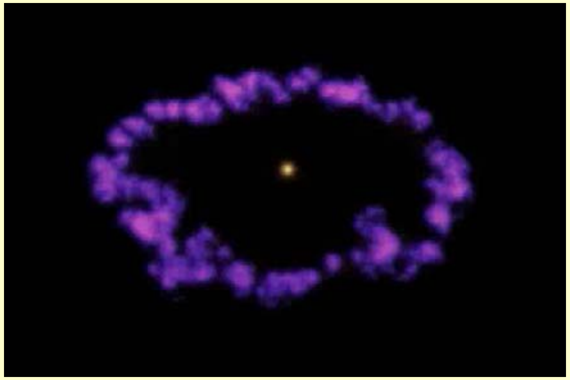


Gravitational-wave Searches

Transient or “burst” events

GWs from burst sources

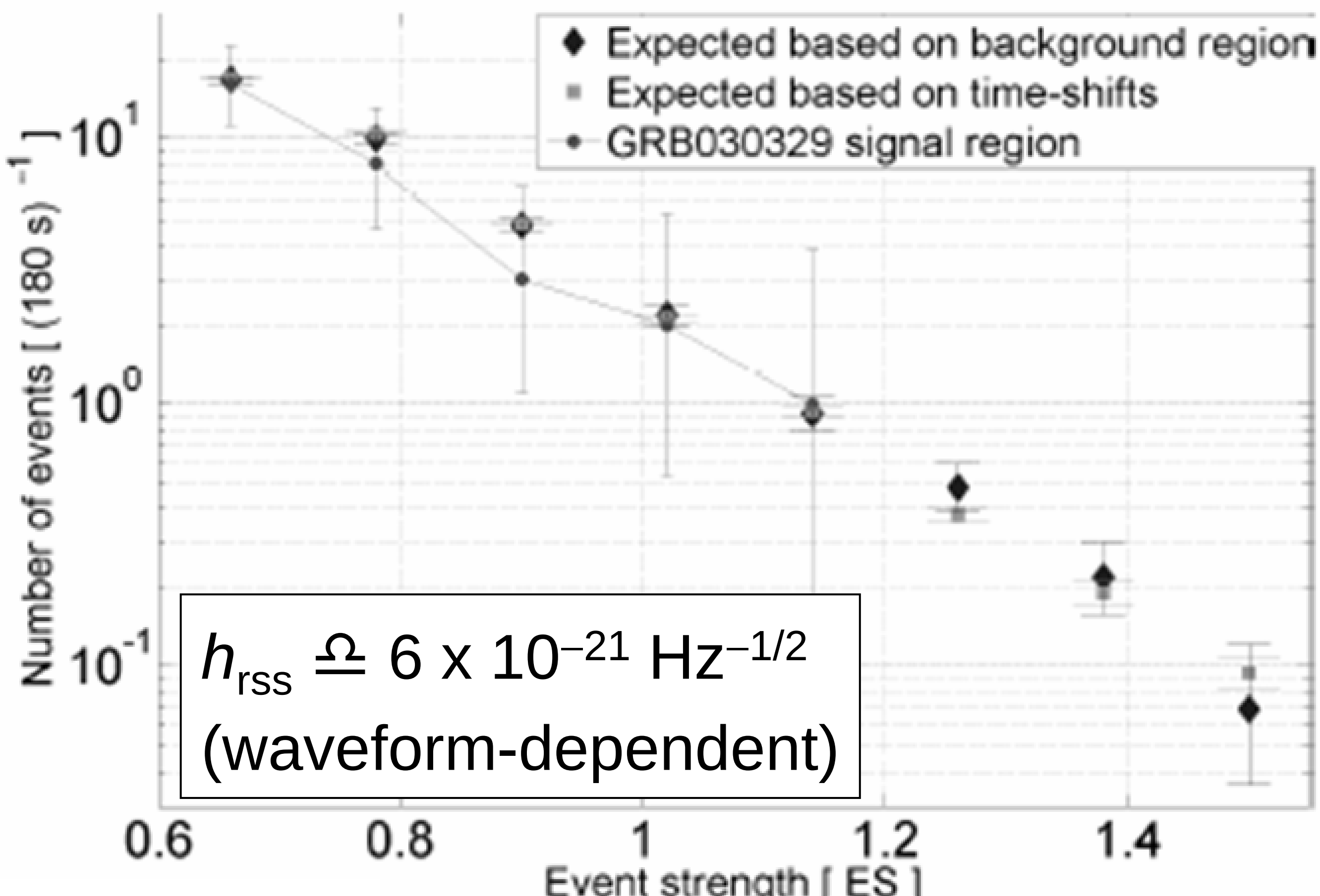
- Brief transients: unmodelled waveforms
- Time-frequency search methods
- Upper limit on rate, and rate as a function of amplitude for specific shapes
- Triggered searches
  - Use external triggers (GRBs, supernovae)
- Untriggered searches
  - compact binary system coalescences…



(SN1987A Animation: NASA/CXC/D.Berry)

Gamma Ray Burst: GRB030329

- A supernova at z ~ 0.17 ~ 800 Mpc
- H1 and H2 operational during S2
- Targeted search
  ➔ NO detection



$h_{rss} \simeq 6 \times 10^{-21}$ Hz$^{-1/2}$
(waveform-dependent)

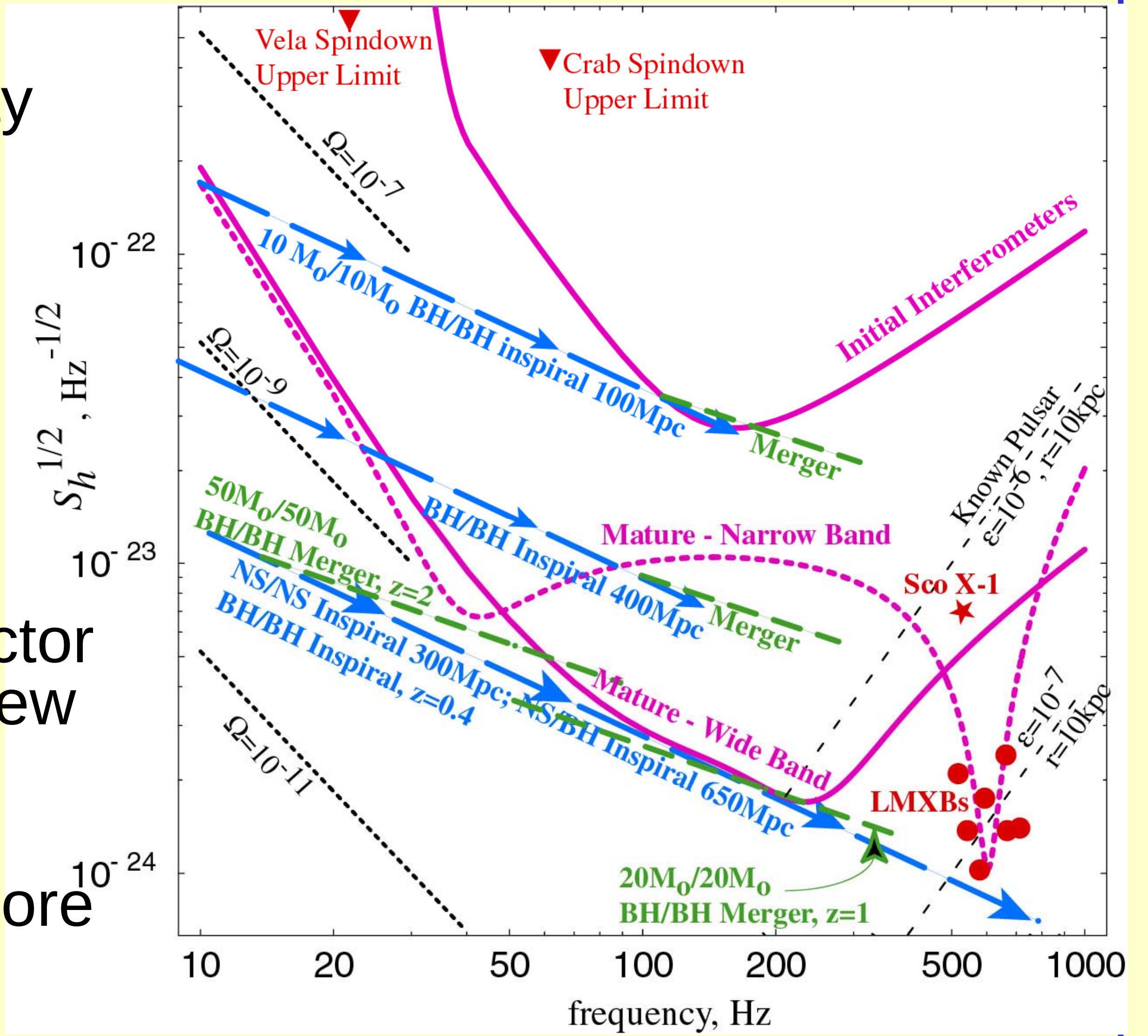
Phys. Rev. D **72** (2005) 042002

Advanced LIGO

LIGO

Why a better detector? Astrophysics

- Factor 10 better amplitude sensitivity
  - $(\text{Reach})^3$ = rate
- Factor 4 lower frequency bound
- Hope for NSF funding in FY08
- Infrastructure of initial LIGO but replace many detector components with new designs
- Expect to be observing 1000x more galaxies by 2013

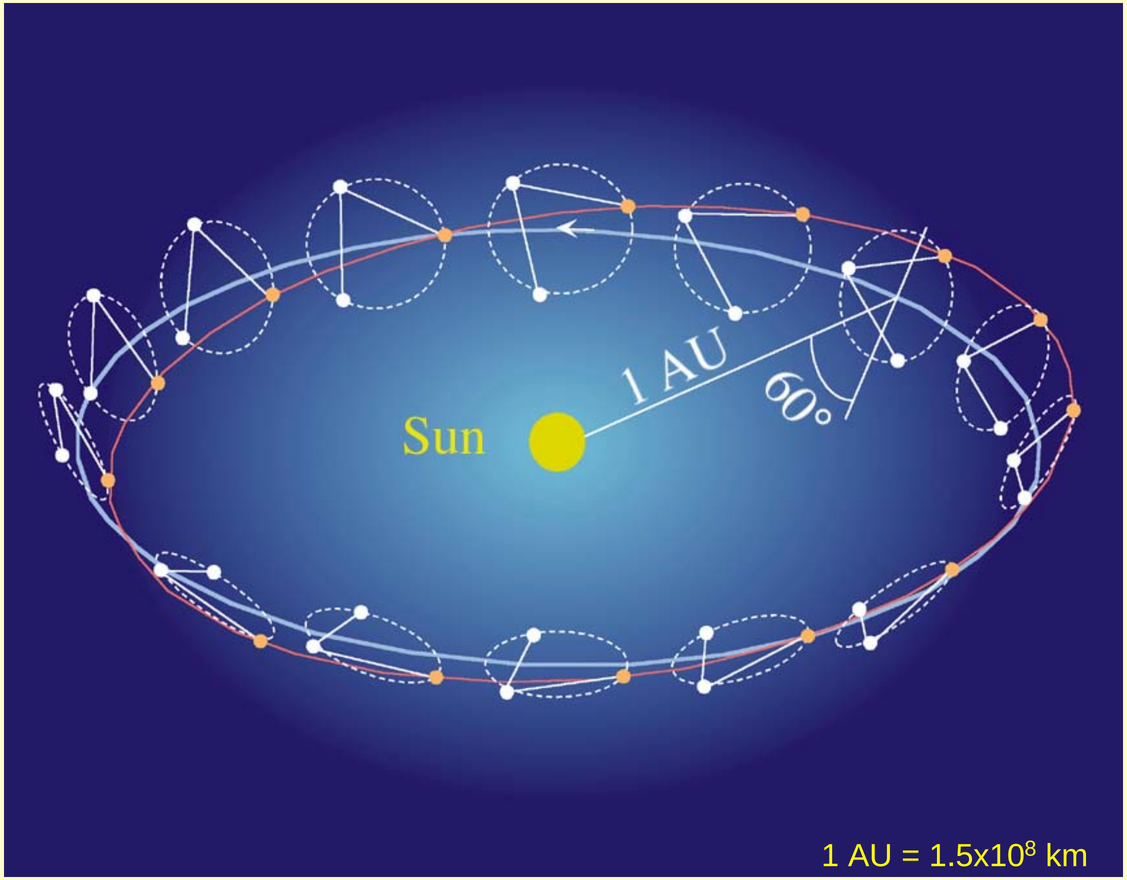


LISA

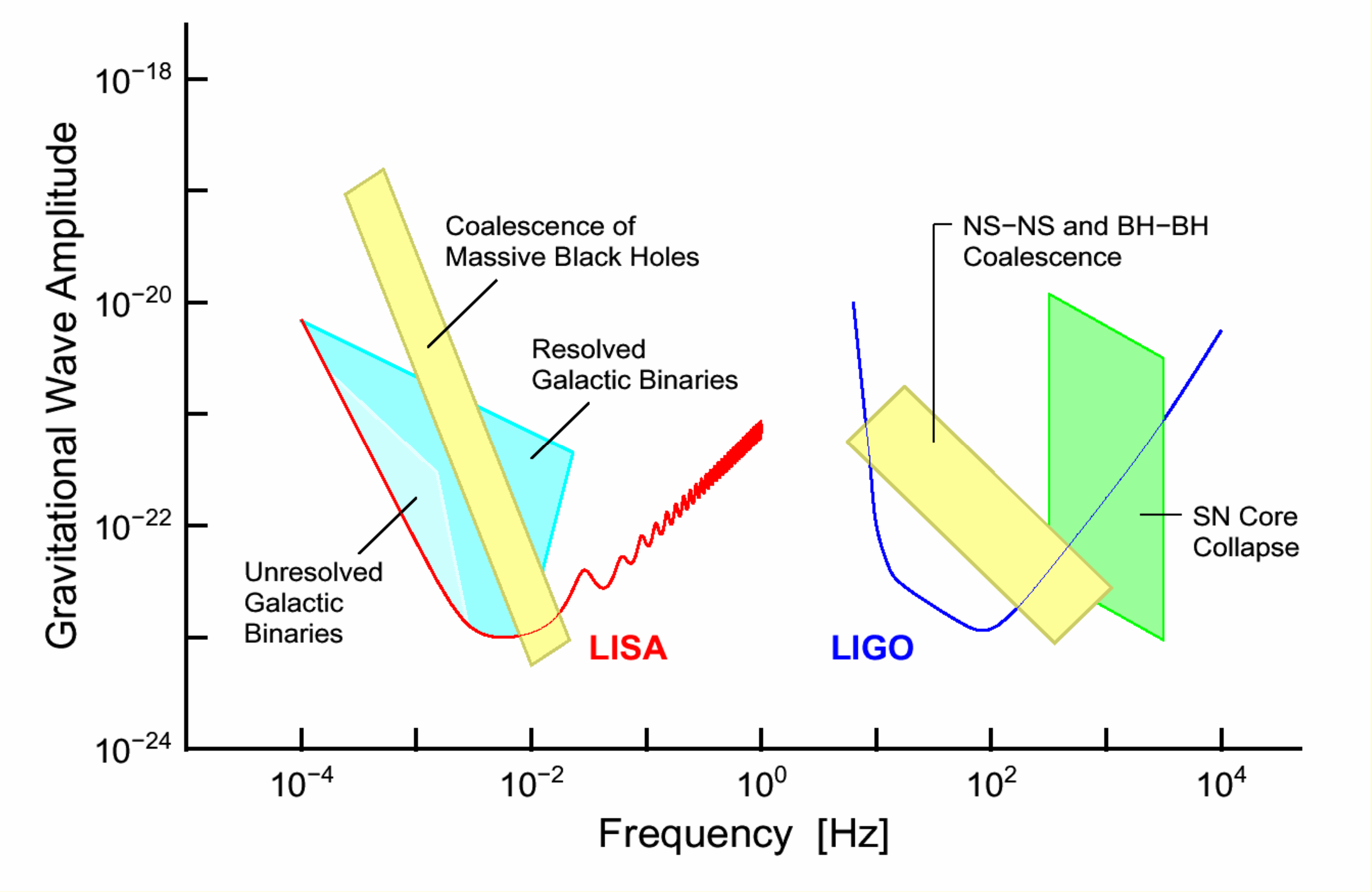
Laser Interferometer Space Antenna

Laser Interferometer Space Antenna (LISA)

- ❑ **Three spacecraft**
  - ❑ **triangular formation**
  - ❑ **separated by 5 million km**
- ❑ **Formation trails Earth by 20°**
- ❑ **Approx. constant arm-lengths**
- ❑ **Constant solar illumination**



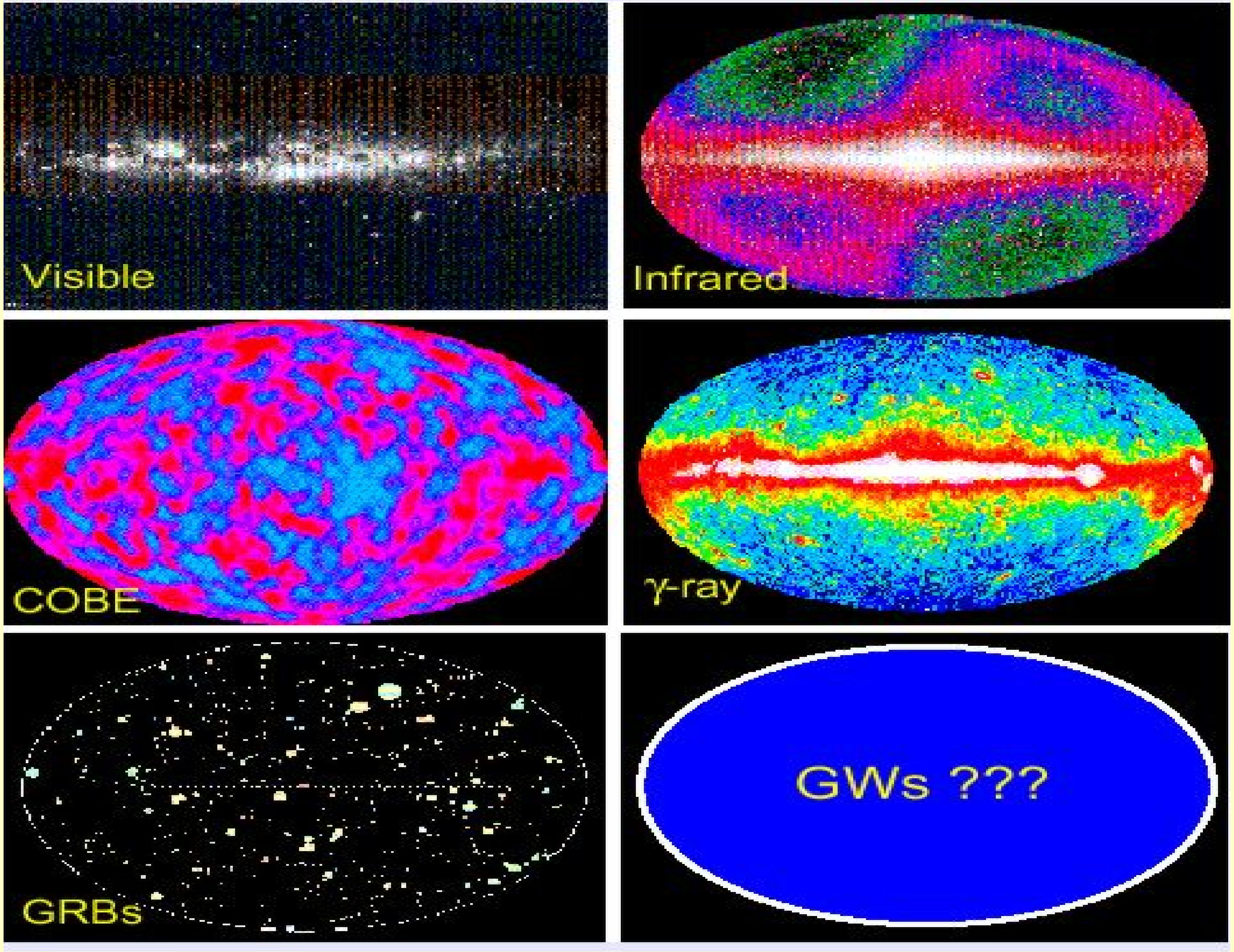
LISA and LIGO



In closing...

- Astrophysical searches from early science data runs completed
- The most sensitive search yet (S5) begun with plan to get 1 year of data at initial LIGO sensitivity
- Advanced LIGO approved by the NSB
  - Construction funding expected (hoped?) to begin in FY2008
- Joint searches with partner observatories in Europe and Japan

Ultimate success...
New Instruments, New Field, the Unexpected...



The End