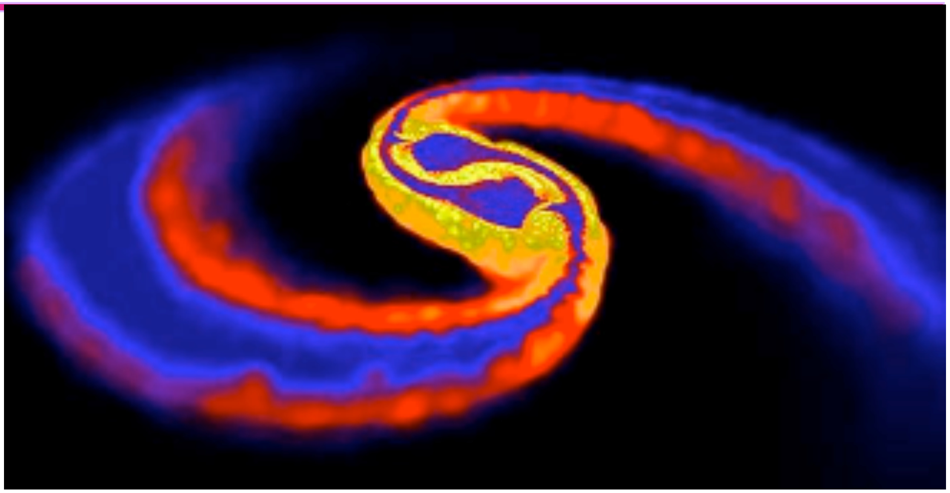
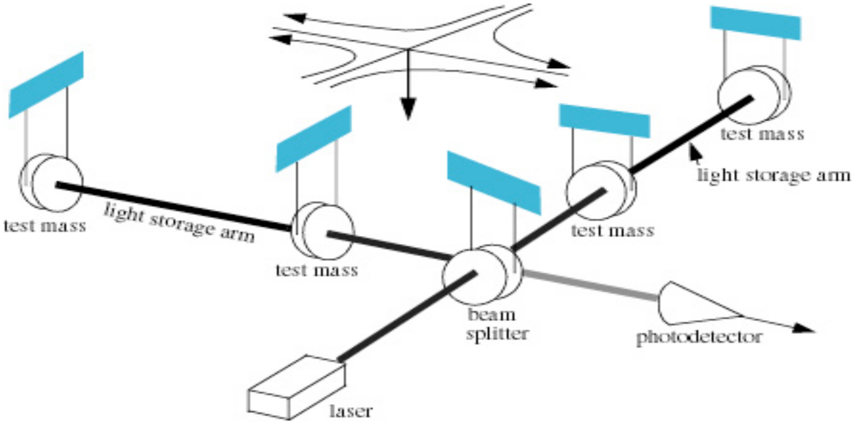
Status of the search for Gravitational Waves

- Gravitational waves
- Detection of GW's
- The LIGO project and its sister projects
- Astrophysical sources
- Recent results
- Conclusions



"Merging Neutron Stars" (Price & Rosswog)



No discovery to report here!

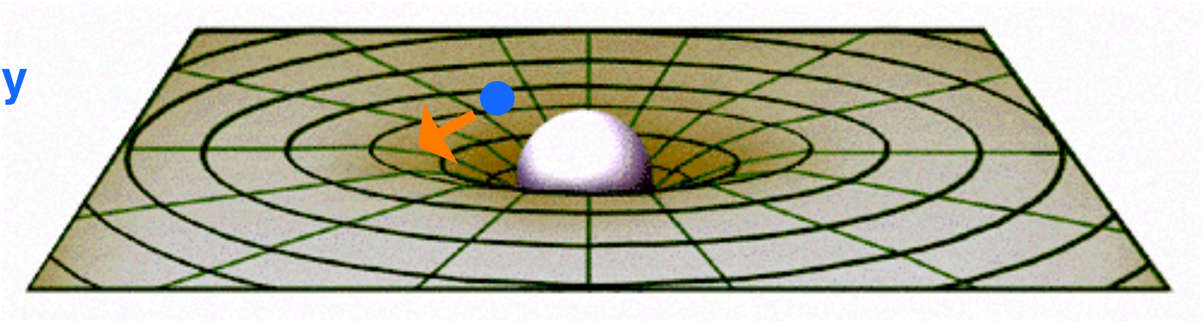
Alan Weinstein, Caltech

for the LIGO Scientific Collaboration

G0900070-v1

Gravitational Waves

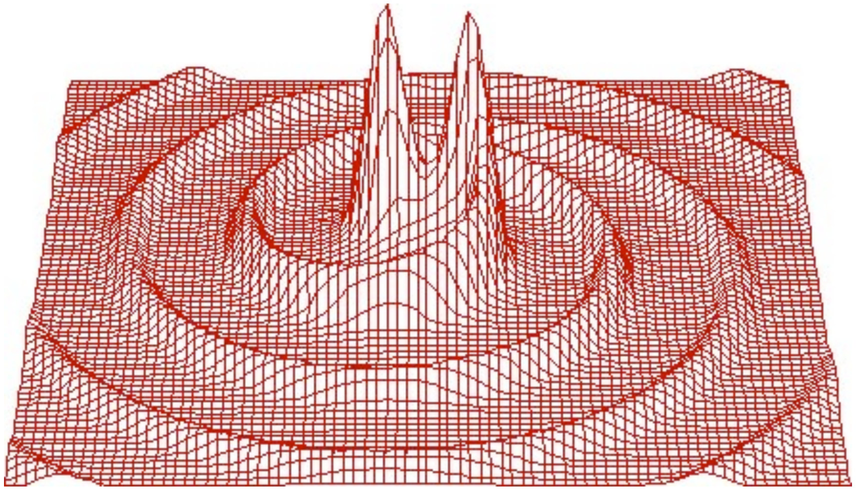
Static gravitational fields are described in General Relativity as a curvature or warpage of space-time, changing the distance between space-time events.



Shortest straight-line path of a nearby test-mass is a ~Keplerian orbit.

$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$

If the source is moving (at speeds close to c), *eg,* because it's orbiting a companion, the "news" of the changing gravitational field propagates outward as gravitational radiation – a wave of spacetime curvature



Nature of Gravitational Radiation

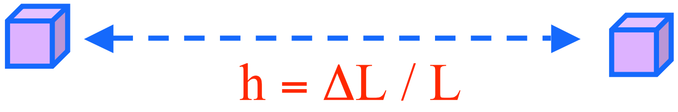
General Relativity predicts that rapidly changing gravitational fields produce ripples of curvature in fabric of spacetime

- Stretches and squeezes space between "test masses" – strain $h = \Delta L / L$
- propagating at speed of light
    - *mass of graviton = 0*
- space-time distortions are transverse to direction of propagation
- GW are tensor fields (EM: vector fields)

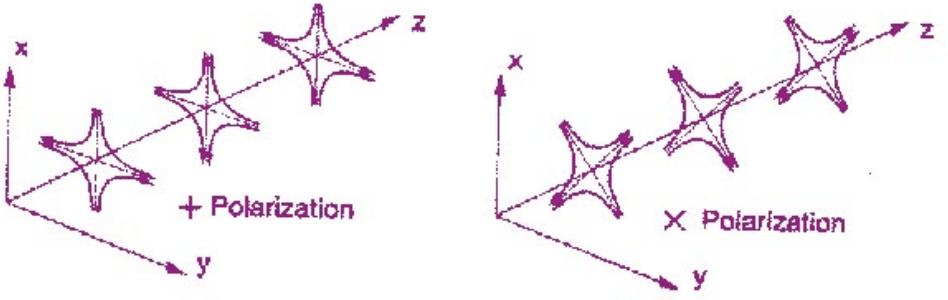
  two polarizations: plus (⊕) and cross (⊗)

  (EM: two polarizations, *x* and *y*)

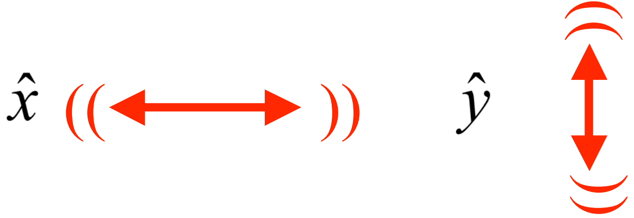
  Spin of graviton = 2

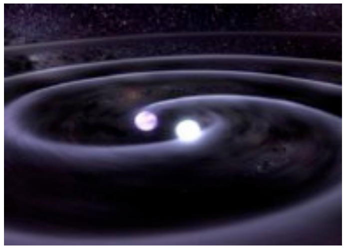


$h = \Delta L / L$



Contrast with EM dipole radiation:





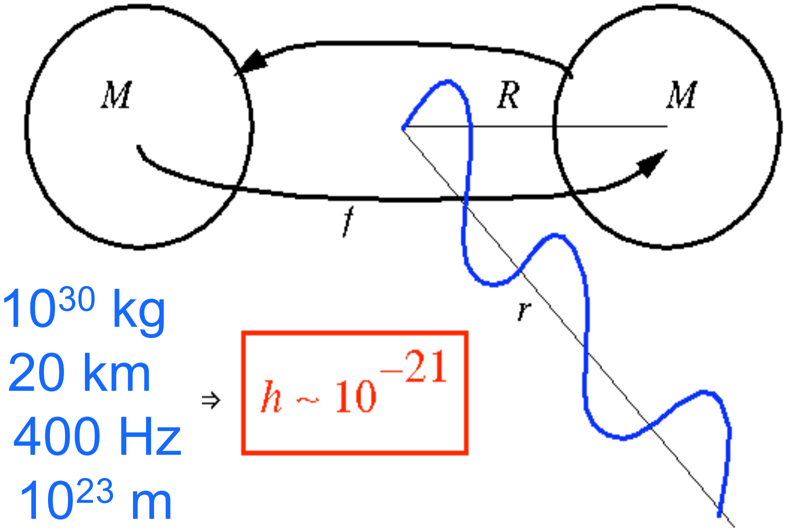
Sources of GWs

- Accelerating charge ⇒ electromagnetic radiation (dipole)
- Accelerating mass ⇒ gravitational radiation (quadrupole)
- Amplitude of the gravitational wave (dimensional analysis):

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

- $\ddot{I}_{\mu\nu}$ = second derivative of mass quadrupole moment (non-spherical part of kinetic energy – tumbling dumb-bell)
- *G* is a small number! (space-time is *stiff*).
- Waves can carry huge energy with minimal amplitude
- Need huge mass, relativistic velocities, nearby.
- For a binary neutron star pair, 10m light-years away, solar masses moving at 15% of speed of light:

Energy-momentum conservation:
energy cons ⇒ no monopole radiation
momentum cons ⇒ no dipole radiation
⇒ lowest multipole is quadrupole wave

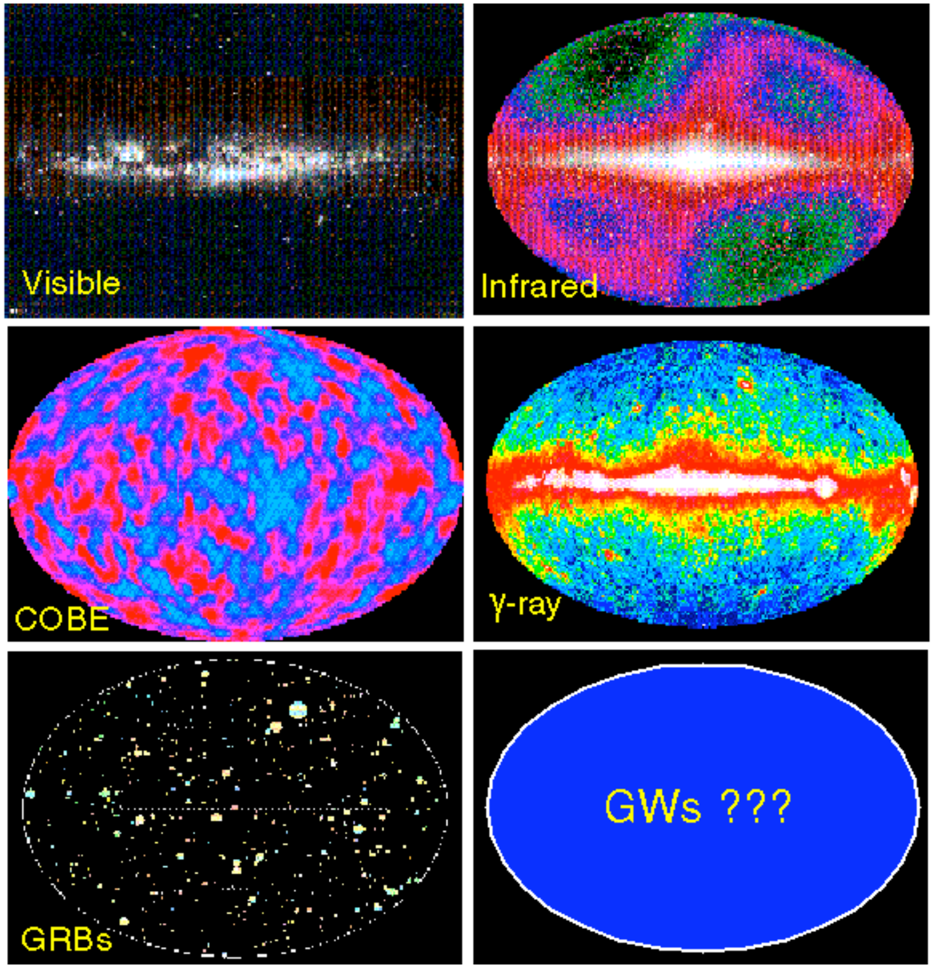


$M \sim 10^{30}$ kg
$R \sim 20$ km
$f \sim 400$ Hz
$r \sim 10^{23}$ m

⇒ $\boxed{h \sim 10^{-21}}$

Terrestrial sources *TOO WEAK*!

A NEW WINDOW ON THE UNIVERSE



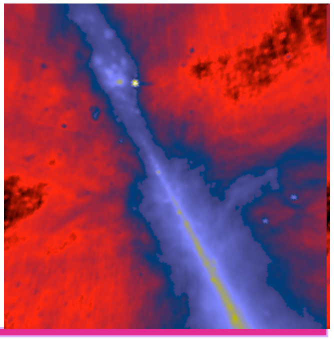
The history of Astronomy:
new bands of the EM spectrum
opened → major discoveries!

GWs aren't just a new band, they're a new spectrum, with very different and complementary properties to EM waves.

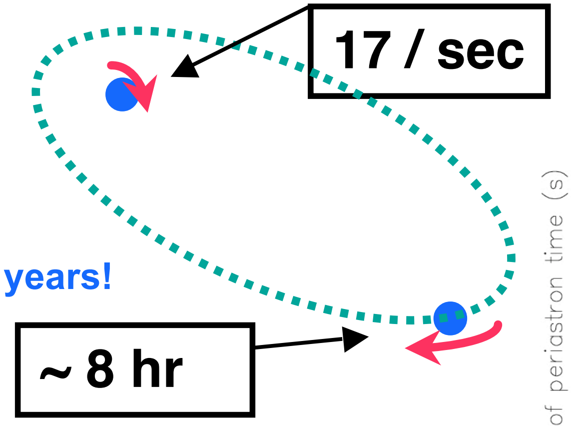
- Vibrations *of* space-time, not *in* space-time
- Emitted by coherent motion of huge masses moving at near light-speed; not vibrations of electrons in atoms
- Can't be absorbed, scattered, or shielded.

GW astronomy is a totally new, unique window on the universe

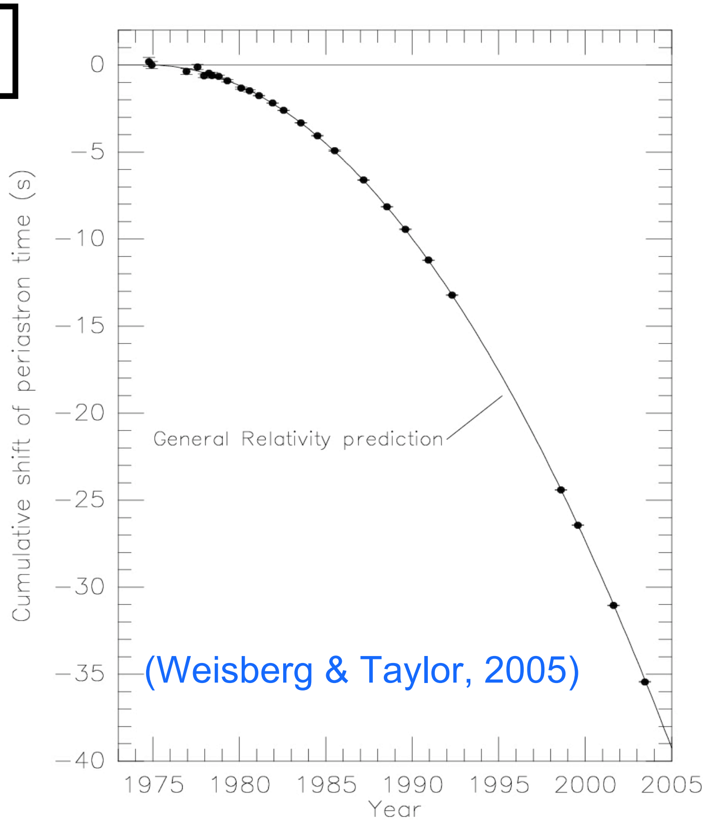
LIGO Indirect Evidence for GWs from Hulse-Taylor binary



emission of gravitational waves by compact binary system



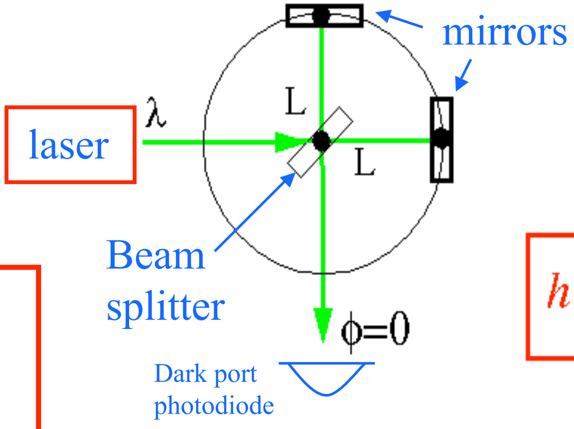
- Binary pulsar PSR 1913 + 16
- Discovered in 1974
- orbital parameters measured continuously measured over 30 years!
- Only 7 kpc away
- 8 hr period speeds up 35 sec from 1975-2005
- measured to ~50 msec accuracy
- deviation grows quadratically with time
- shortening of period ⇐ orbital energy loss
- Compact: negligible loss from friction, material flow
- beautiful agreement with GR prediction
- Apparently, loss is due to GWs!
- Nobel Prize, 1993
- Merger in about 300M years (<< age of universe!)
- GW emission will be strongest near the end – Coalescence of black holes!

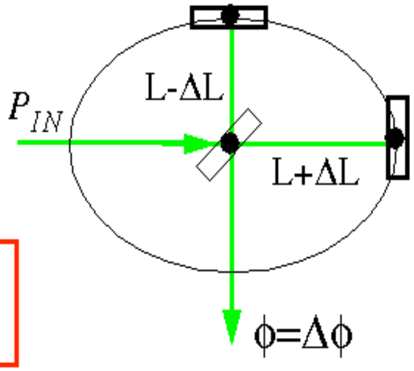


(Weisberg & Taylor, 2005)

Interferometric detection of GWs

GW acts on freely falling masses:



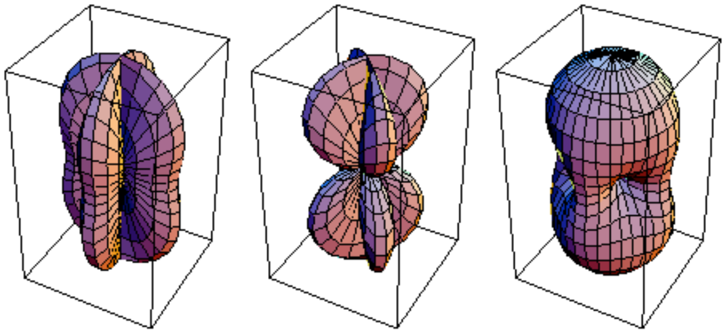


For fixed ability to measure *ΔL*, make *L* as big as possible!

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

$$P_{out} = P_{in} \sin^2(2k\Delta L)$$

Antenna pattern:
(not very directional!)



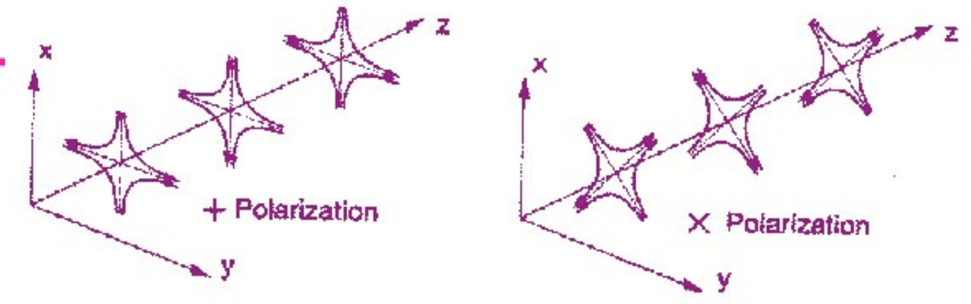
+ polarization × polarization unpolarized

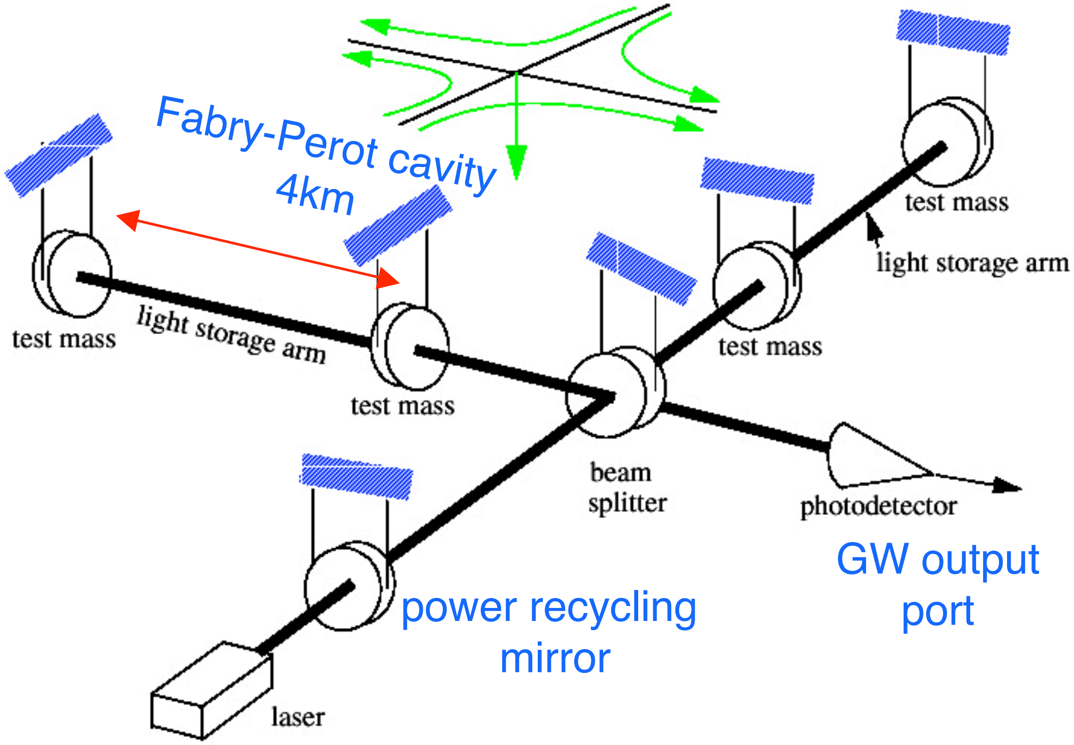
Interferometric GW detectors

- Quadrupolar radiation pattern

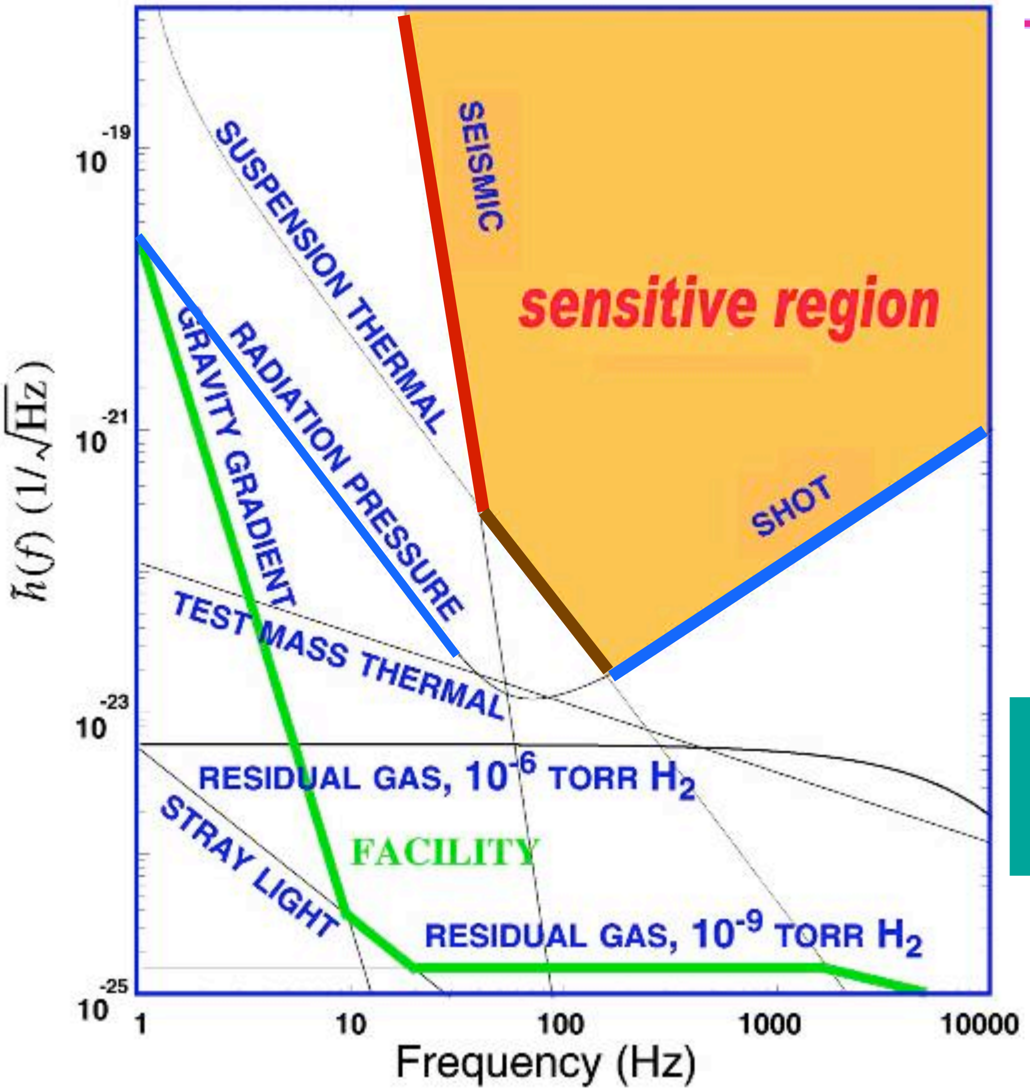
- Michelson interferometer
  "natural" GW detector
- Suspended mirrors
  in "free-fall"
- Broad-band response
  ~50 Hz to few kHz
- Waveform detector
  e.g., chirp reconstruction

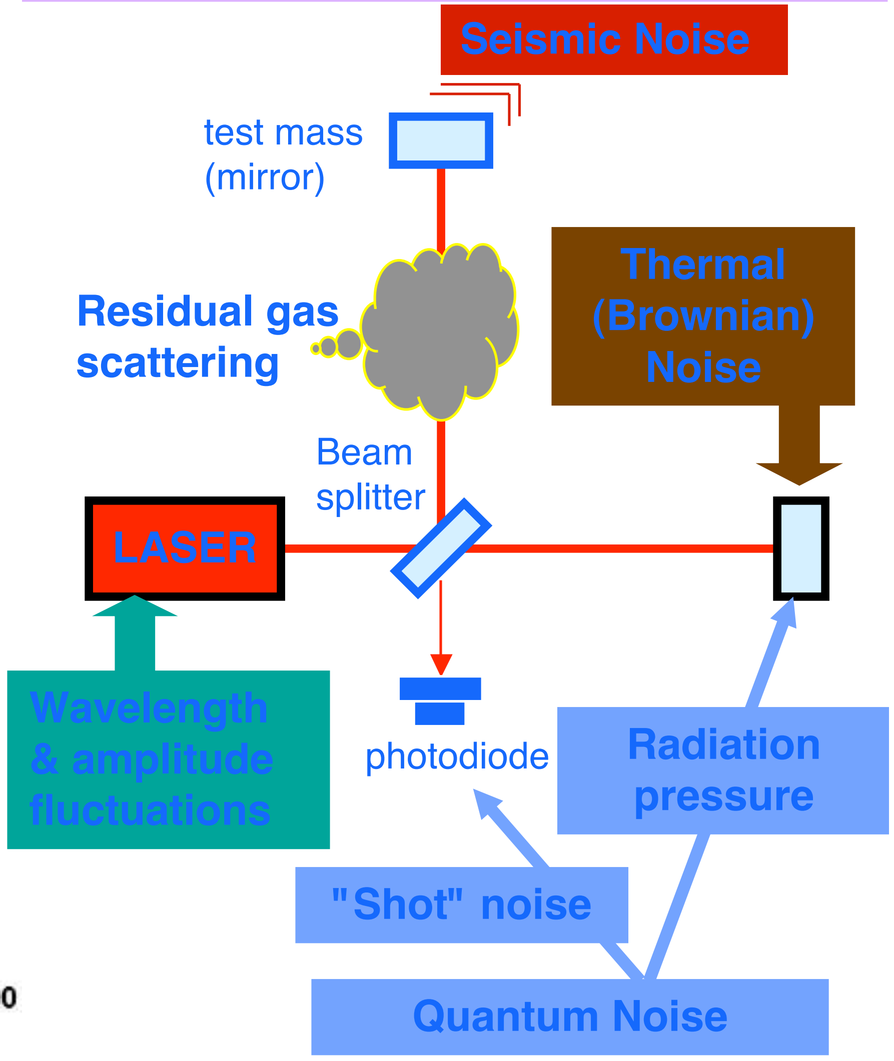
- $h = \Delta L / L$
  Goal: get $h \leq 10^{-22}$;
  can build $L = 4$ km;
  must measure
  $\Delta L = h\,L \leq 4\times10^{-19}$ m





Limits to Initial LIGO Sensitivity





Seismic Noise

test mass (mirror)

Residual gas scattering

Thermal (Brownian) Noise

Beam splitter

LASER

Wavelength & amplitude fluctuations

photodiode

Radiation pressure

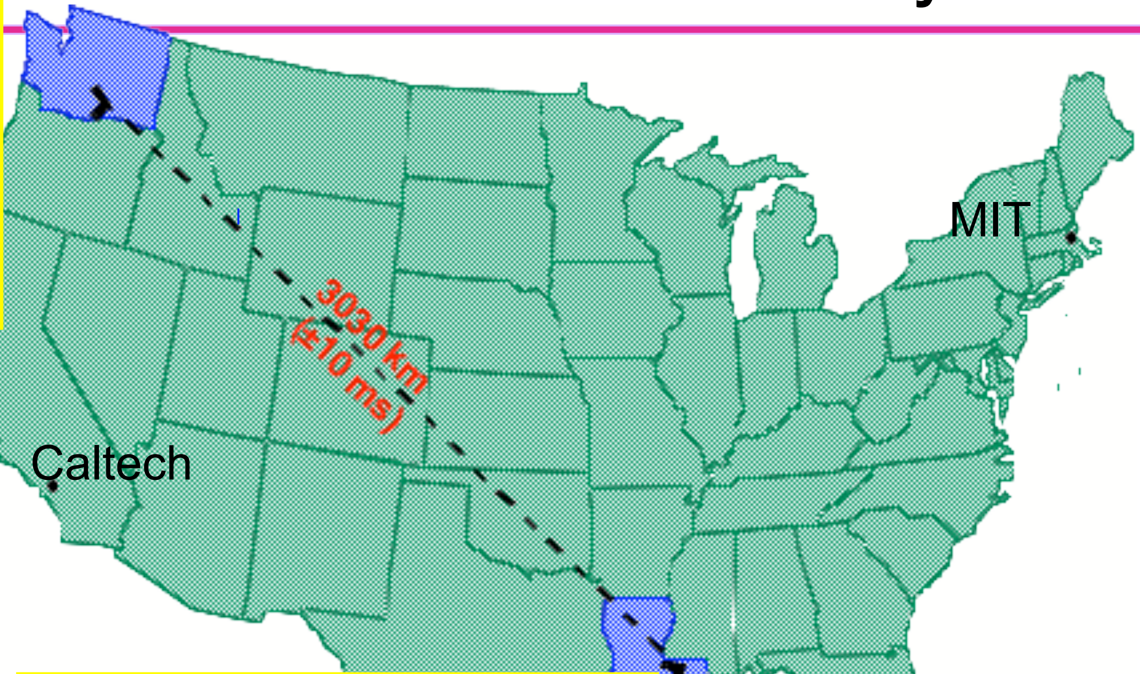
"Shot" noise

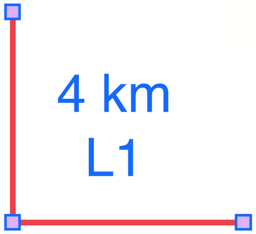
Quantum Noise

LIGO: Laser Interferometer Gravitational-wave Observatory

Hanford, WA

4 km (H1)
+ 2 km (H2)





4 km
L1

Livingston, LA

LIGO

LIGO Scientific Collaboration

LSC

University of Maryland 1856

MICHIGAN

University of Strathclyde

Loyola University New Orleans

Montana State University

PAH

University of Washington

University of Glasgow

Trinity University

San José State University

University of Wisconsin UWMilwaukee

ANU The Australian National University

Syracuse University Founded AD 1870 Suos Cultores Scientia Coronat

Università degli Studi del Sannio

LSU

UTB TSC

The University of Western Australia

1754

NASA

Goddard Space Flight Center

Per Ardua Alta

California Institute of Technology 1891

Northwestern University

Rochester Institute of Technology R·I·T 1829

Andrews University

Massachusetts Institute of Technology 1861

Southeastern Louisiana University

The University of Texas at Austin

Moscow State University

The University of Adelaide Australia

Sub Cruce Lumen

PAN

Sigill. Coll. Carleton Northfield, Minn. A.D. 1866

GEO 600

Embry-Riddle Aeronautical University

University of Massachusetts Amherst 1863

University of Southampton

PennState 1855

Cardiff University

Washington State University

Universitat de les Illes Balears

UF University of Florida

The University of Mississippi 1848

Charles Sturt University

University of Rochester

NAOJ

Southern University and Agricultural & Mechanical College

Hobart and William Smith Colleges

University of Minnesota

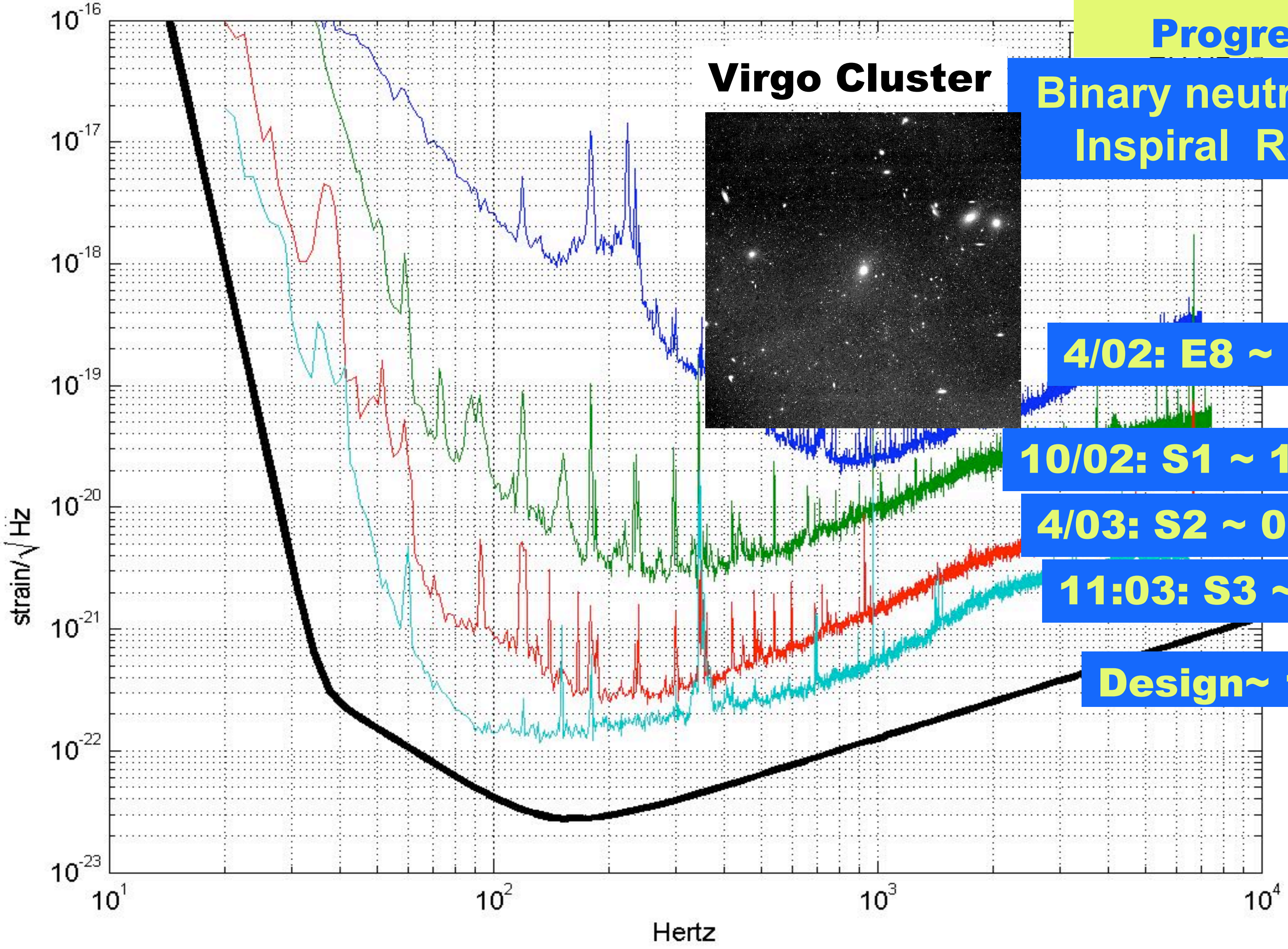
Universität Hannover

Science & Technology Facilities Council
Rutherford Appleton Laboratory

Despite a few difficulties, science runs started in 2002.

Science Runs

A Measure of Progress



Virgo Cluster

Binary neutron star Inspiral Range

4/02: E8 ~ 5 kpc

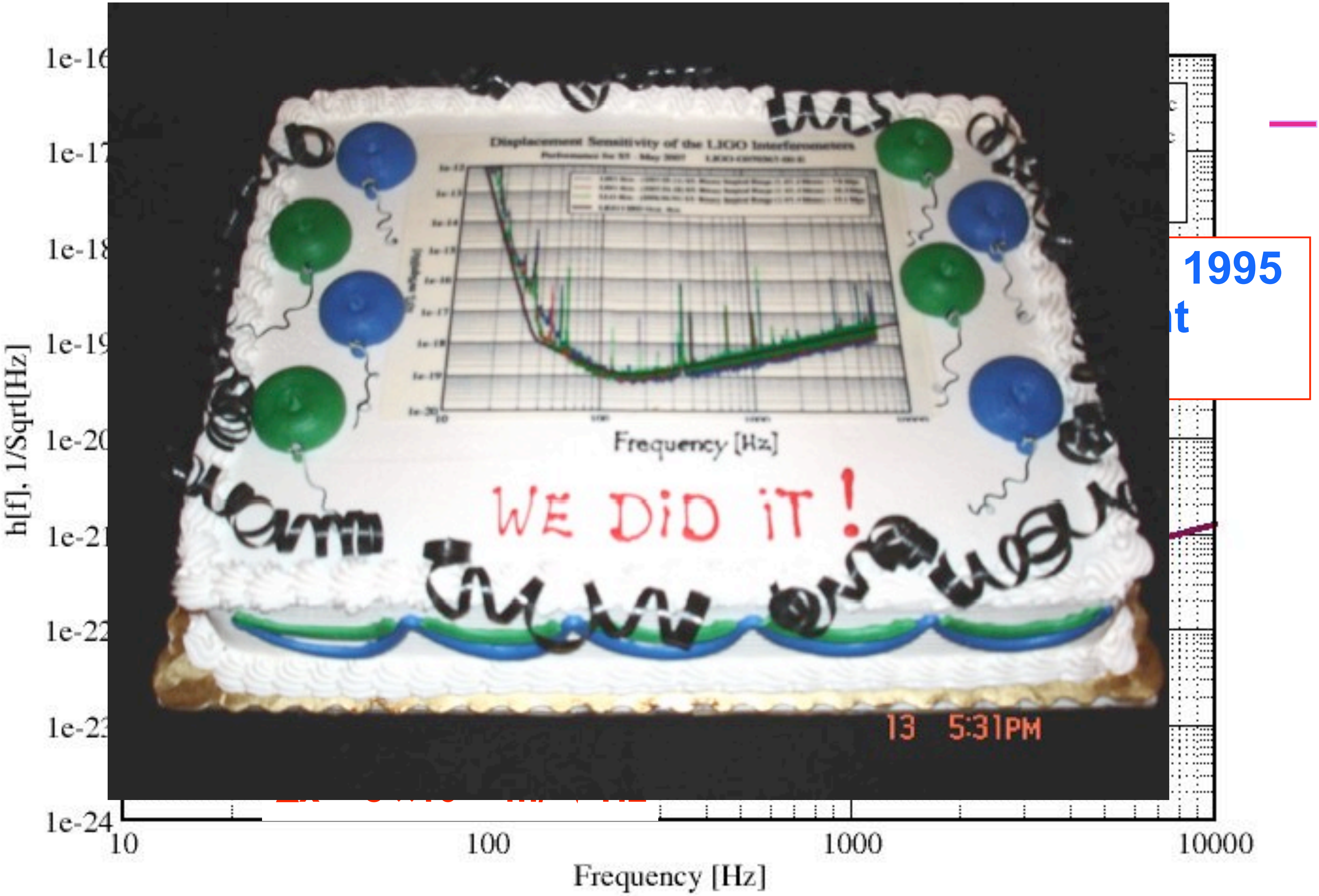
10/02: S1 ~ 100 kpc

4/03: S2 ~ 0.9Mpc

11:03: S3 ~ 3 Mpc

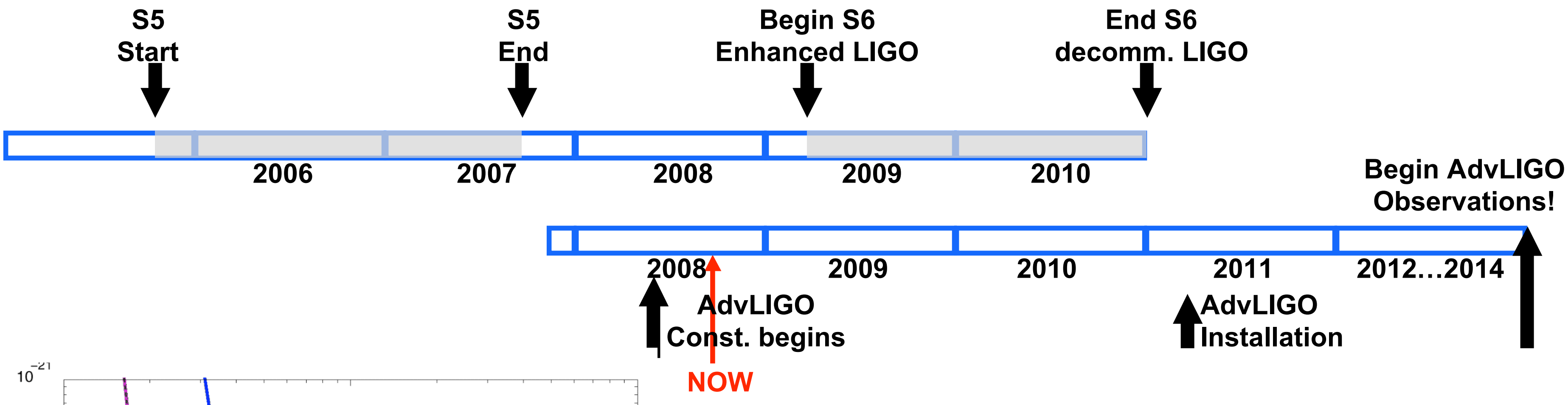
Design~ 18 Mpc

Strain Sensitivity for the LIGO 4km Interferometers



1995
t

LIGO → eLIGO → AdvLIGO



S5 Start

S5 End

Begin S6 Enhanced LIGO

End S6 decomm. LIGO

2006 2007 2008 2009 2010

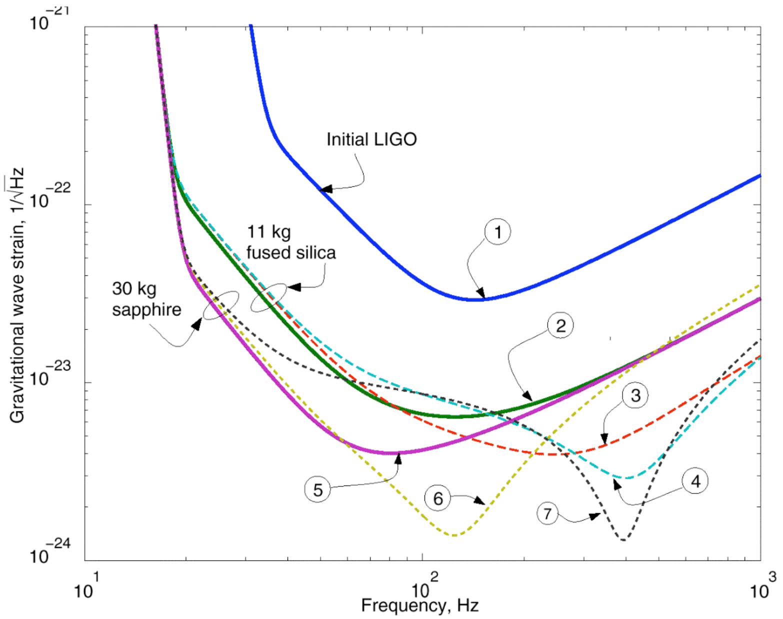
Begin AdvLIGO Observations!

2008 2009 2010 2011 2012…2014

AdvLIGO Const. begins

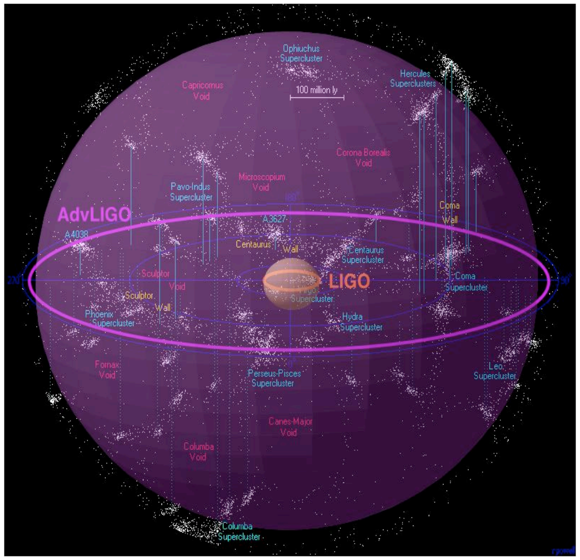
NOW

AdvLIGO Installation

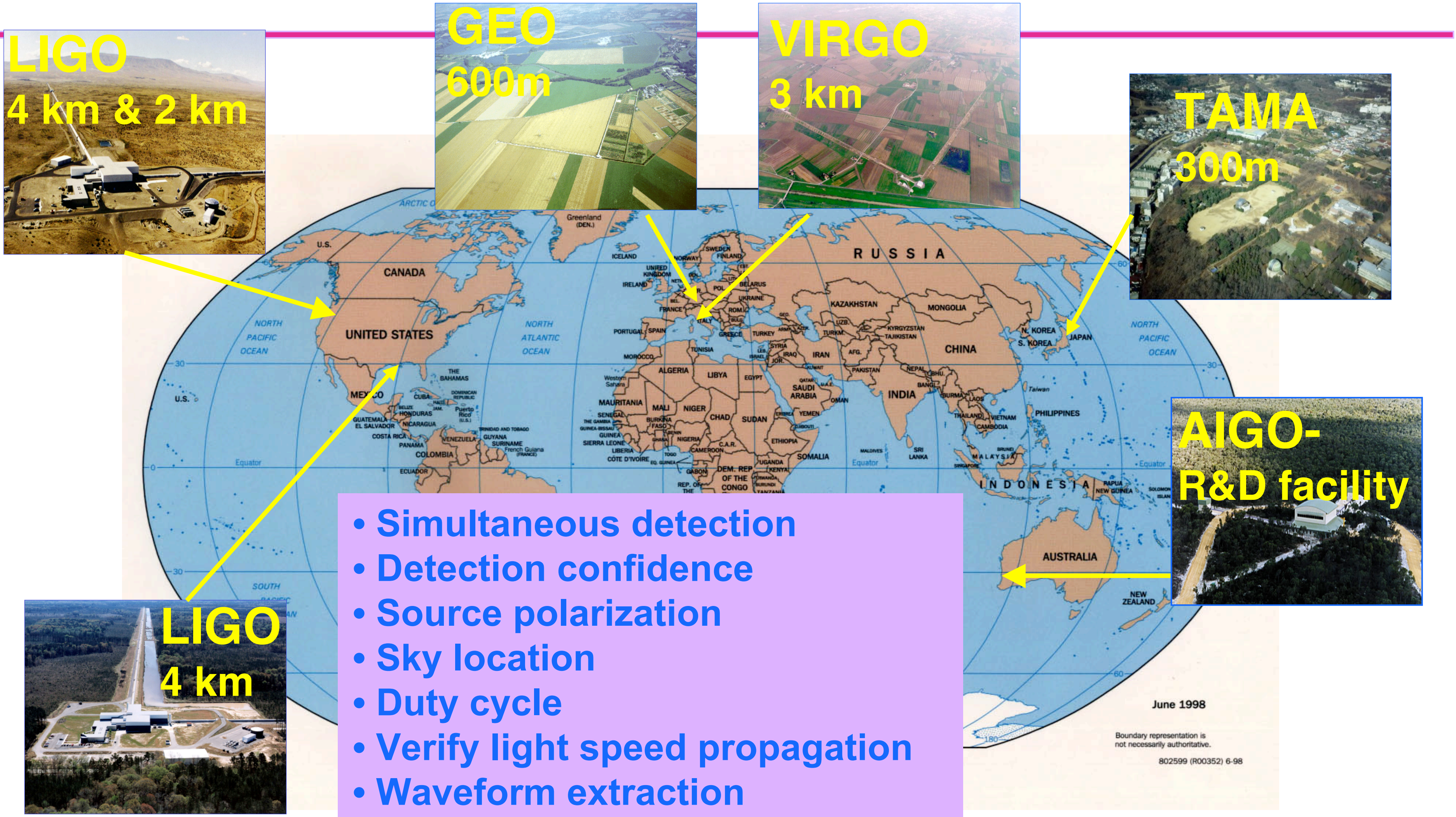


Improve amplitude sensitivity by a factor of 10x, and…

⇒ Number of sources goes up 1000x!



Global network of interferometers

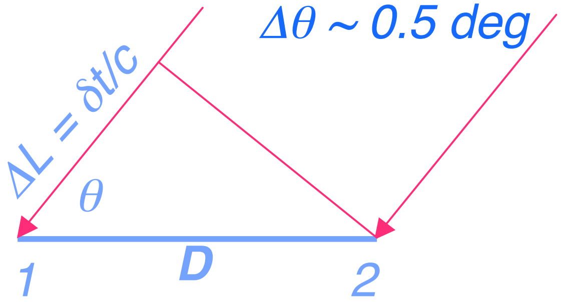


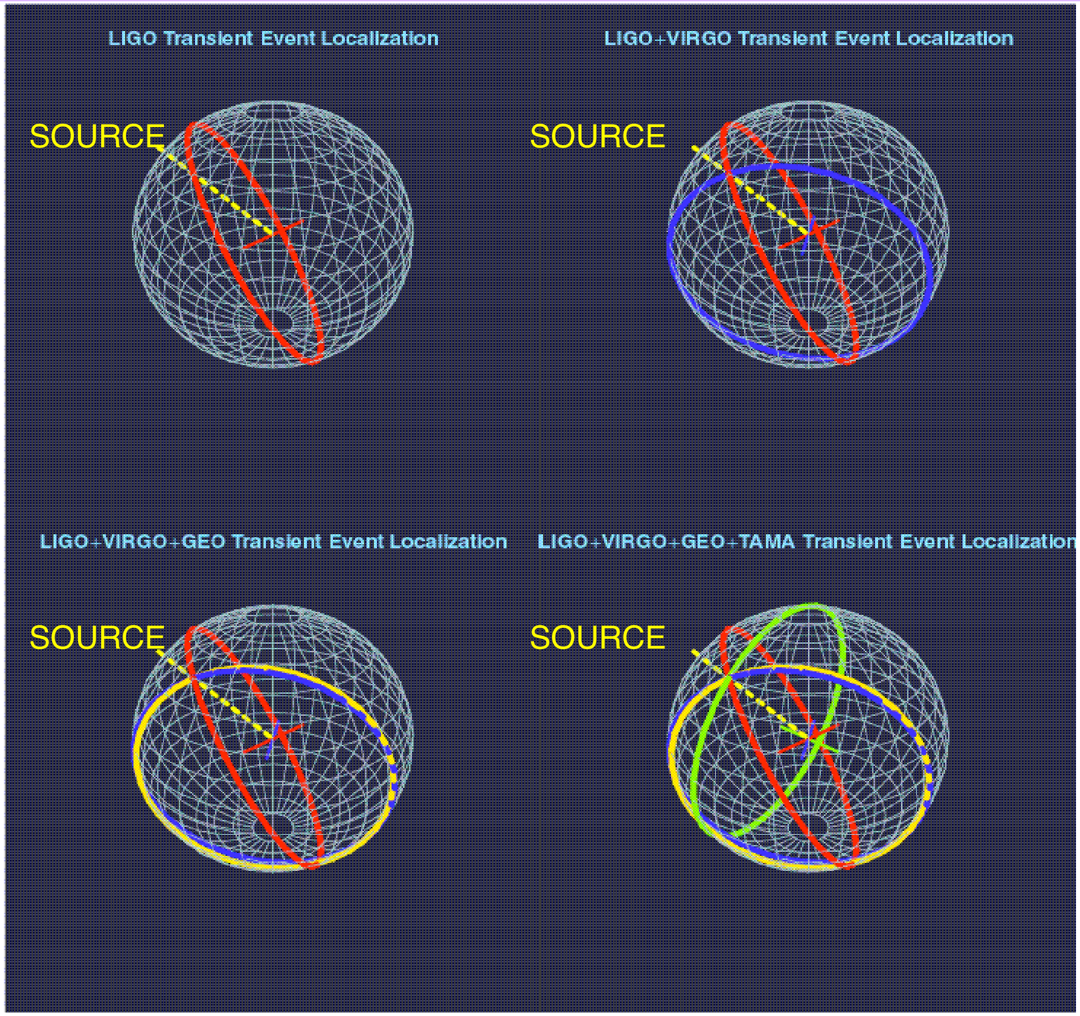
- Simultaneous detection
- Detection confidence
- Source polarization
- Sky location
- Duty cycle
- Verify light speed propagation
- Waveform extraction

Event Localization With An Array of GW Interferometers

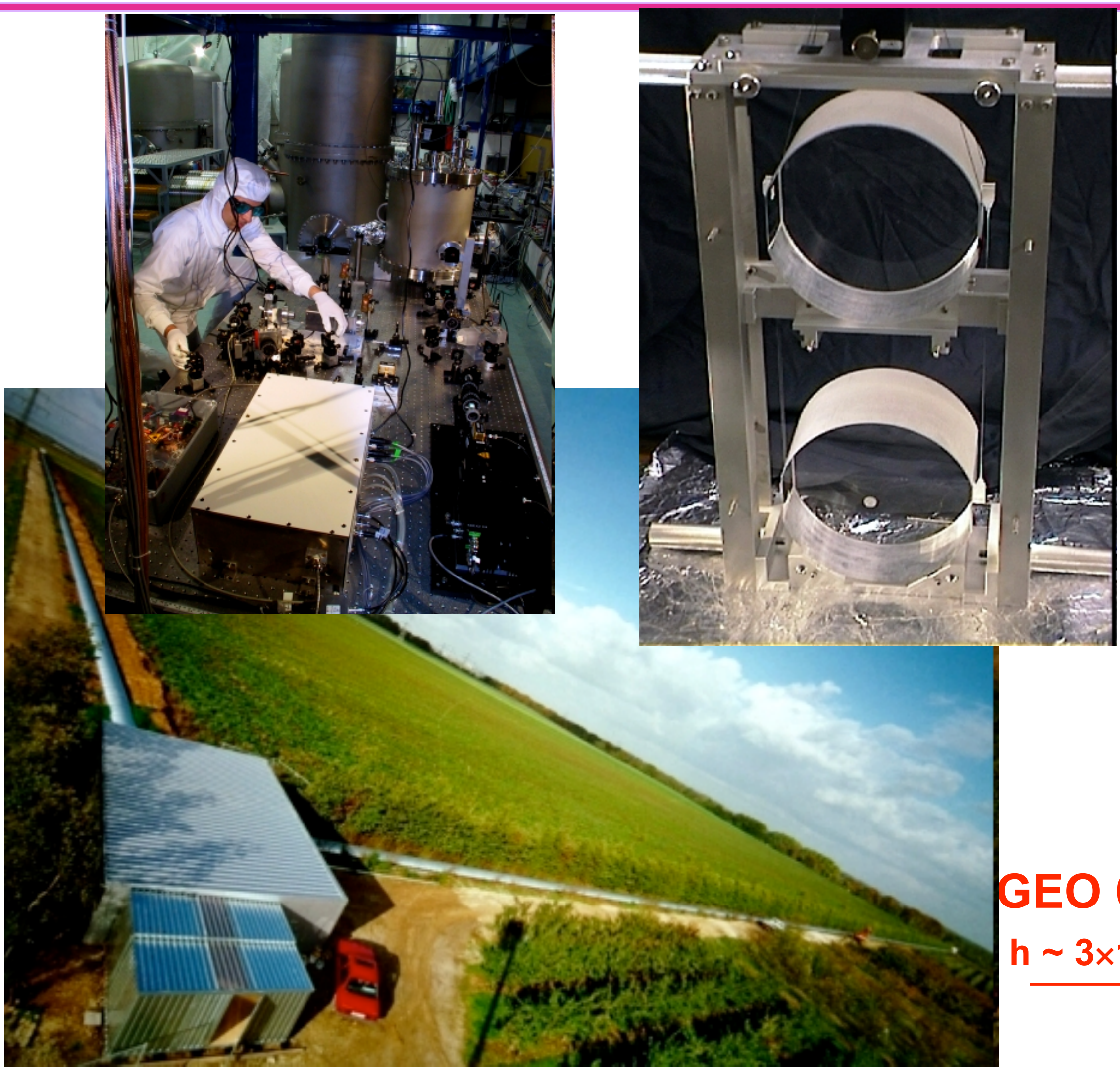
$\cos\theta = \delta t / (c\, D_{12})$

$\Delta\theta \sim 0.5$ deg



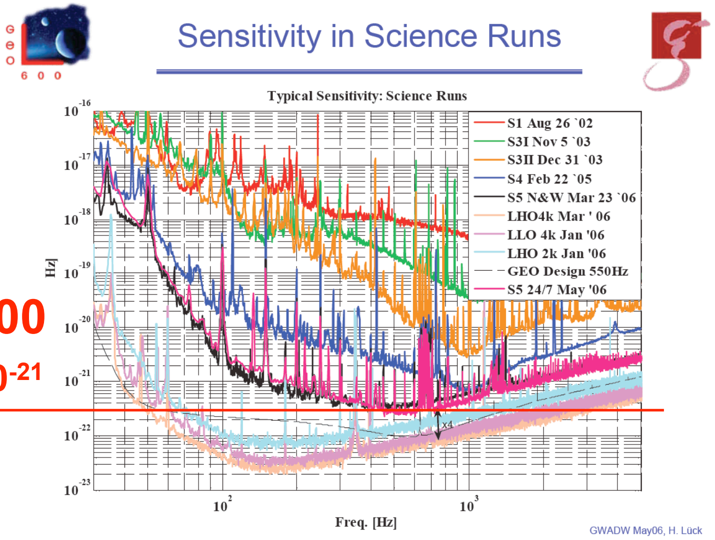


GEO 600 (Hannover, Germany)



GEO 600

h ~ 3×10^{-21}

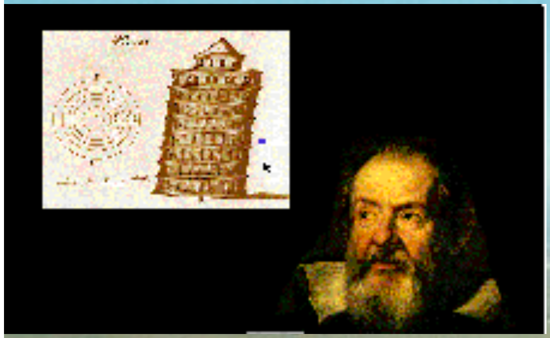


Sensitivity in Science Runs

GWADW May06, H. Lück

VIRGO

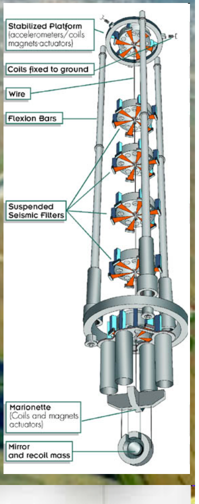
EGO

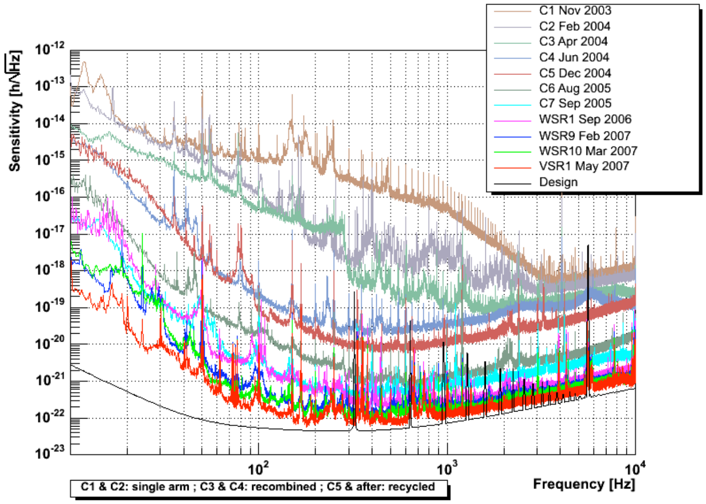


- LAPP - Annecy
- INFN - Firenze/Urbino
- INFN - Frascati
- IPN - Lyon
- INFN - Napoli
- OCA - Nice
- ESPCI - Paris
- LAL - Orsay
- INFN - Perugia
- INFN - Pisa
- INFN - Roma

NIKHEF - Amsterdam (joining)

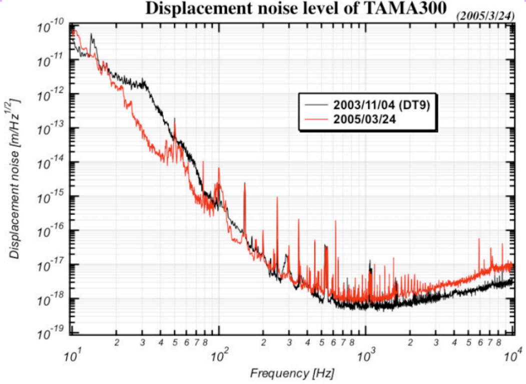
Inaugurated July 2003

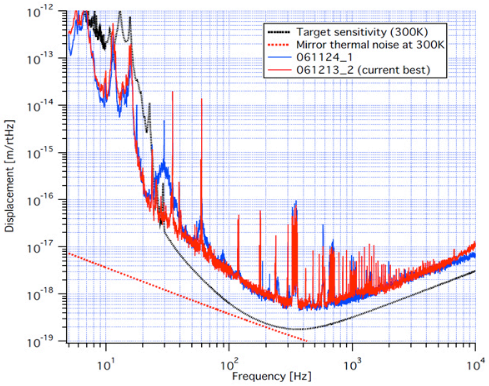


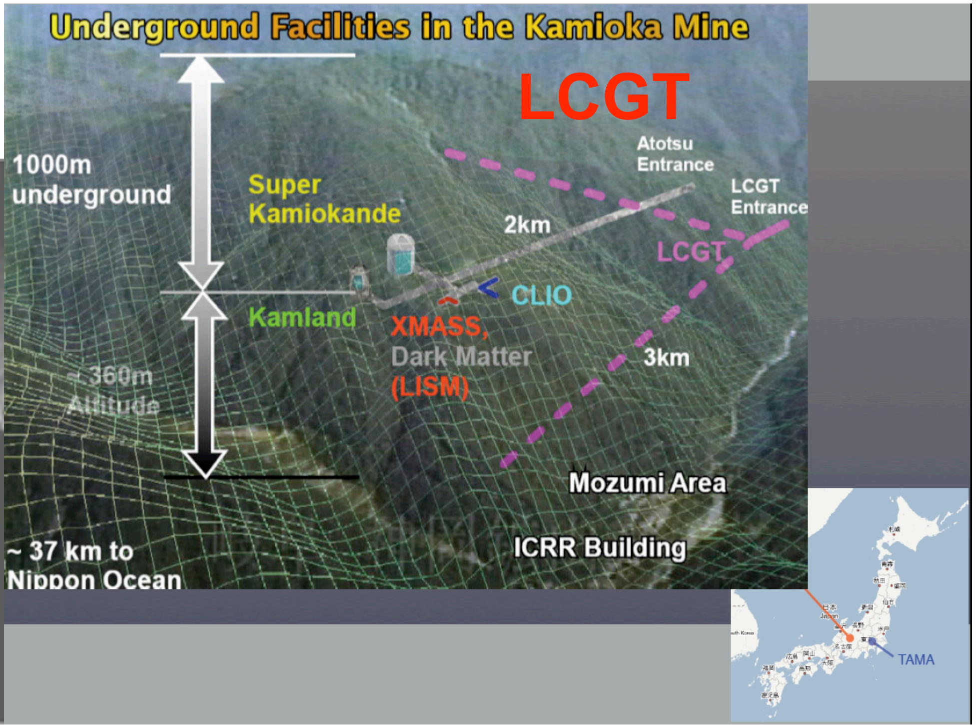


C1 & C2: single arm ; C3 & C4: recombined ; C5 & after: recycled

Detectors in Japan: TAMA 300, CLIO 100, LCGT

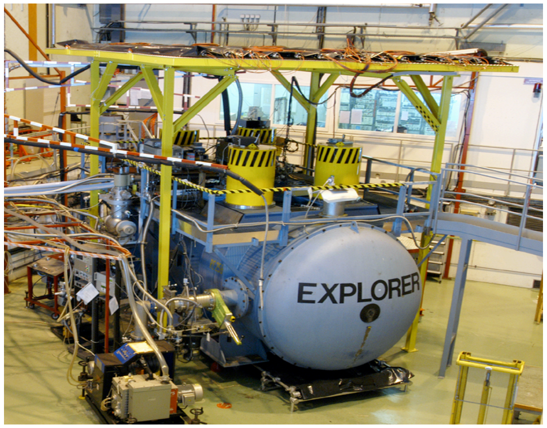




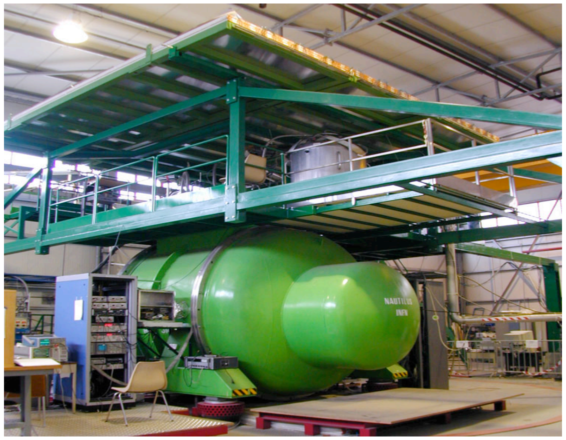


Cryogenic Resonant detectors

Explorer (at CERN)
Univ. of ROME ROG group

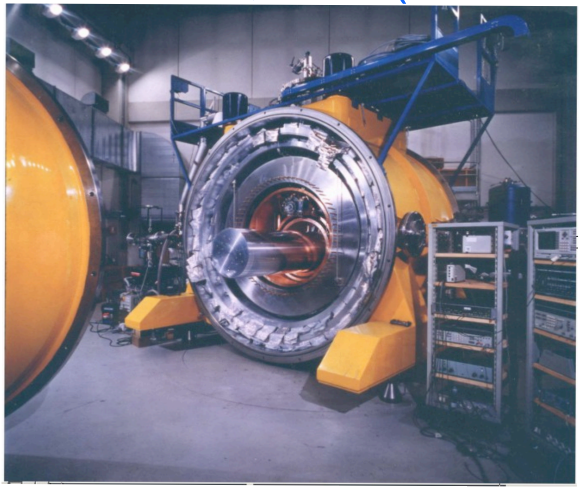


Nautilus (at Frascati)
Univ. of ROME ROG group

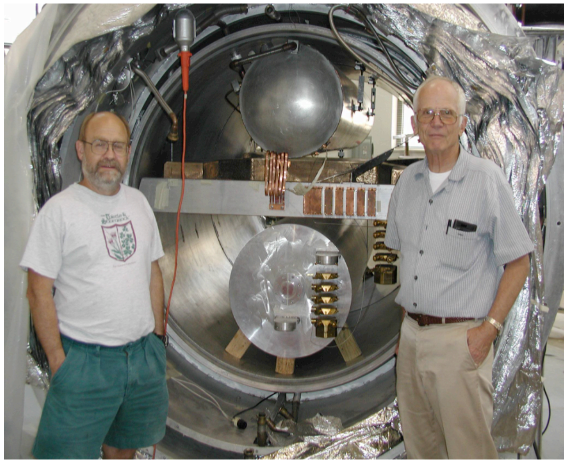


sensitivity:
$h_{rms} \sim 10^{-19}$;
excellent duty cycle

AURIGA, LNL (Padova)



ALLEGRO, LSU (Baton Rouge)



IGEC
International Gravitational Event Collaboration
To proceed to the IGEC public Web space,
ENTER HERE

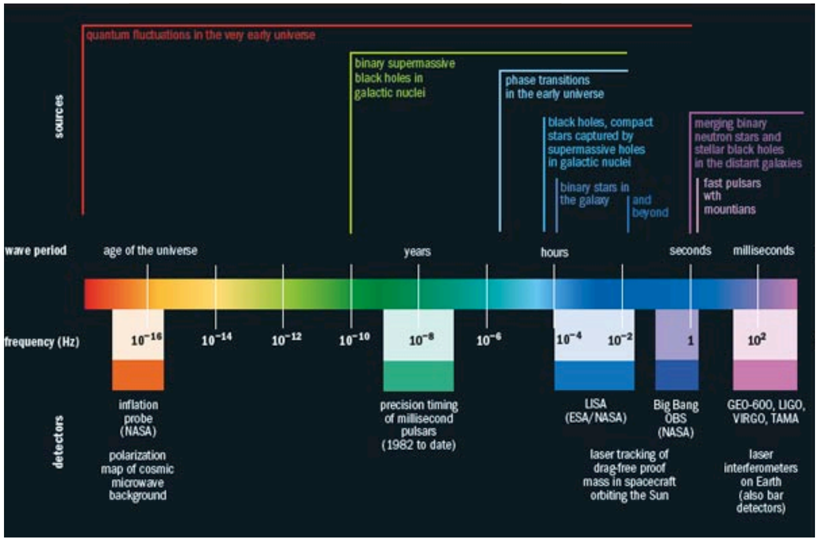
Frequency range of GW Astronomy

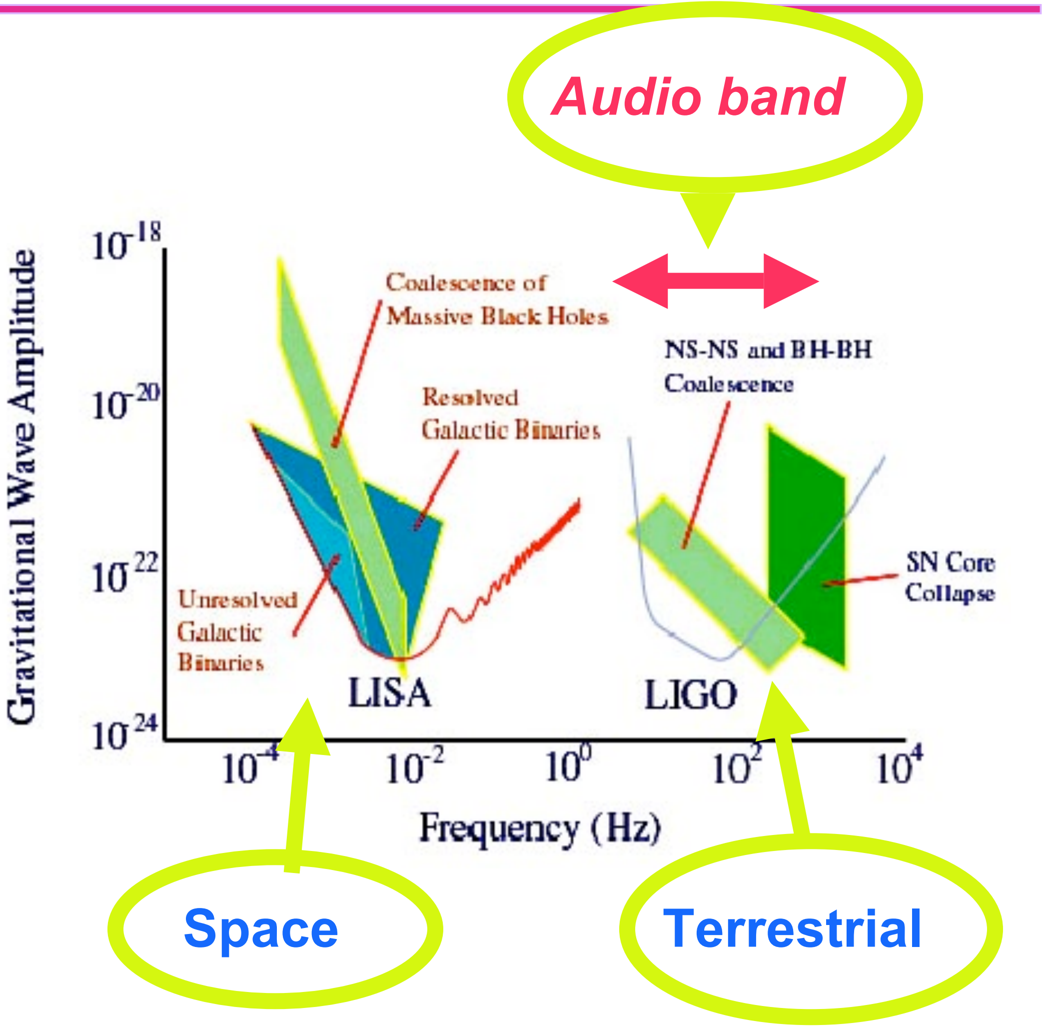
Electromagnetic waves

- over ~16 orders of magnitude
- Ultra Low Frequency radio waves to high energy gamma rays

Gravitational waves

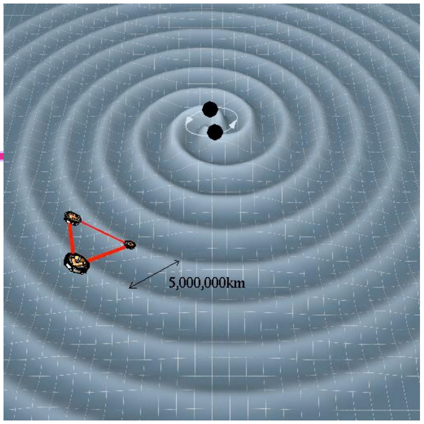
- over ~8 orders of magnitude
- Terrestrial + space detectors





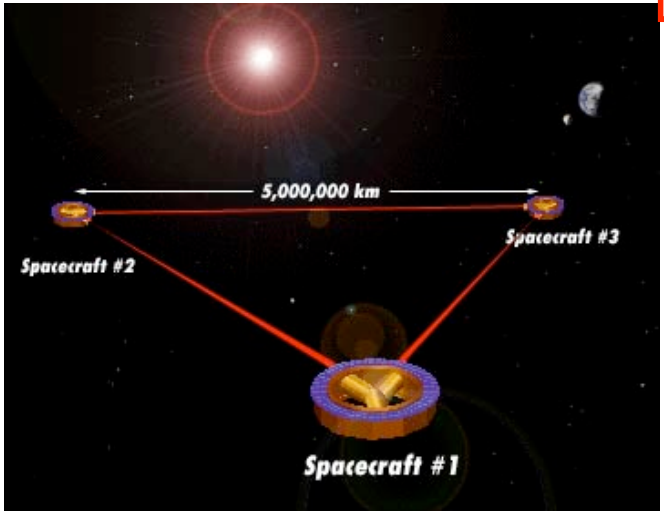
The Laser Interferometer Space Antenna

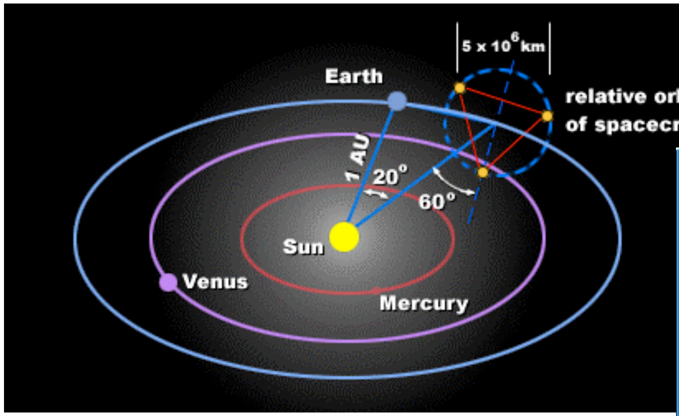
LISA

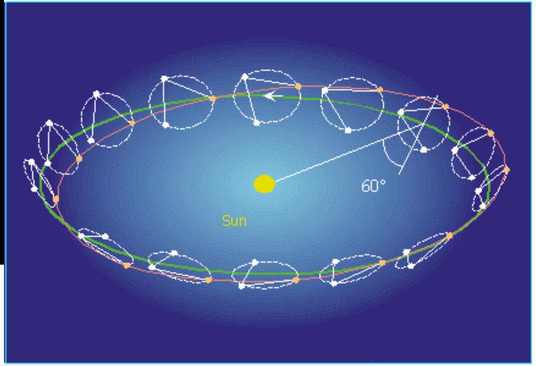


Three spacecraft in orbit
about the sun,
with 5 million km baseline

The center of the triangle formation
will be in the ecliptic plane
1 AU from the Sun and 20 degrees
behind the Earth.

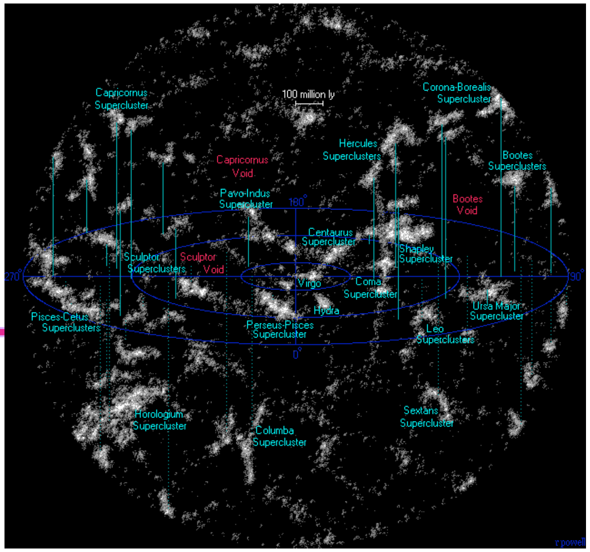


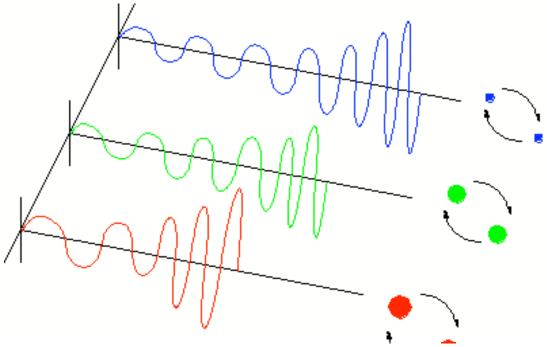


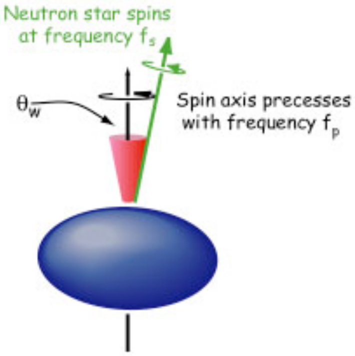


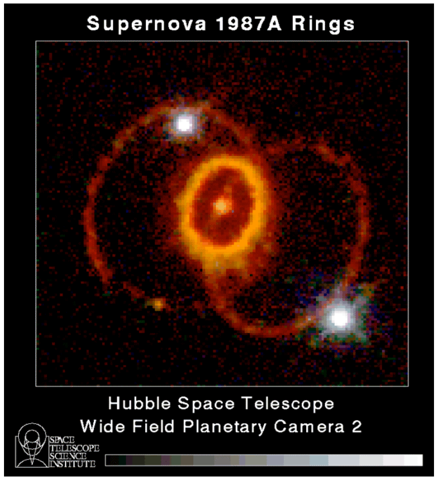
LISA (NASA/JPL, ESA) may fly in the next 10 years!

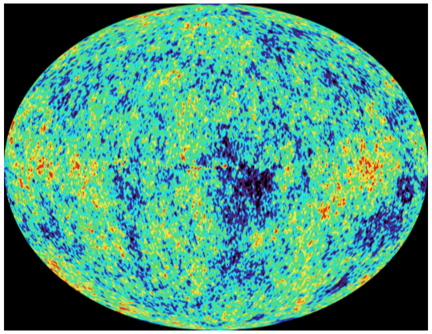
What will we see?











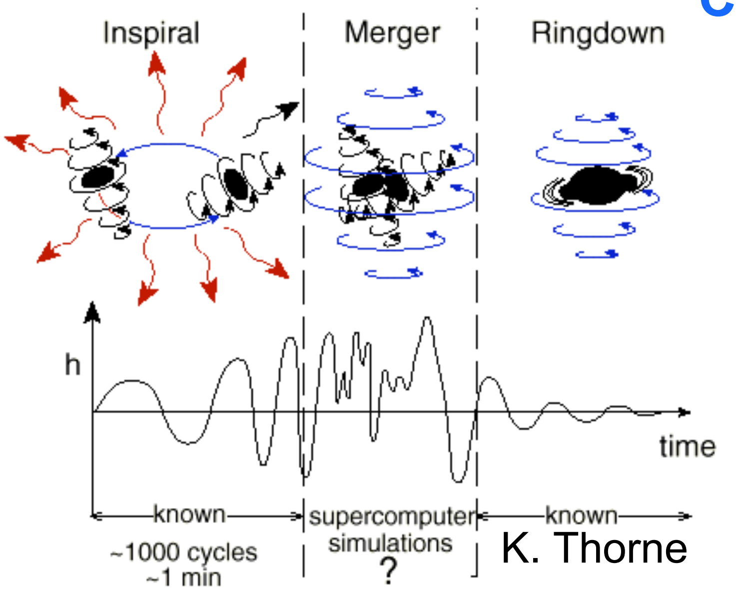
Analog from cosmic microwave background -- WMAP 2003

GWs from the most energetic processes in the universe!

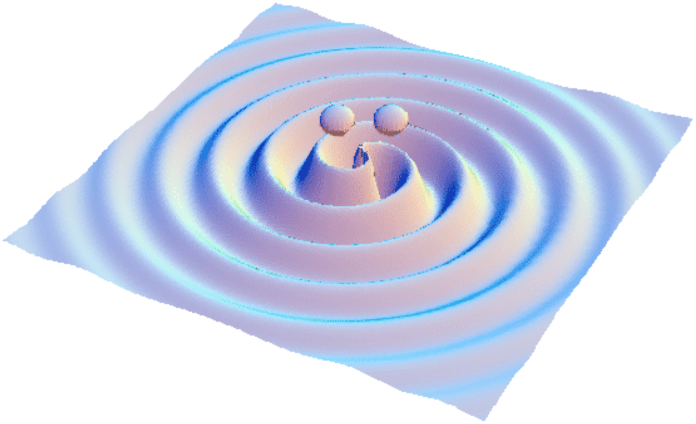
- Compact Binary Coalescences: black holes orbiting each other and then merging together
- GW bursts of unknown waveform: Supernovas, GRB engines
- Continuous waves from pulsars, rapidly spinning neutron stars
- Stochastic GW background from vibrations from the Big Bang

GWs from coalescing compact binaries (NS/NS, BH/BH, NS/BH)

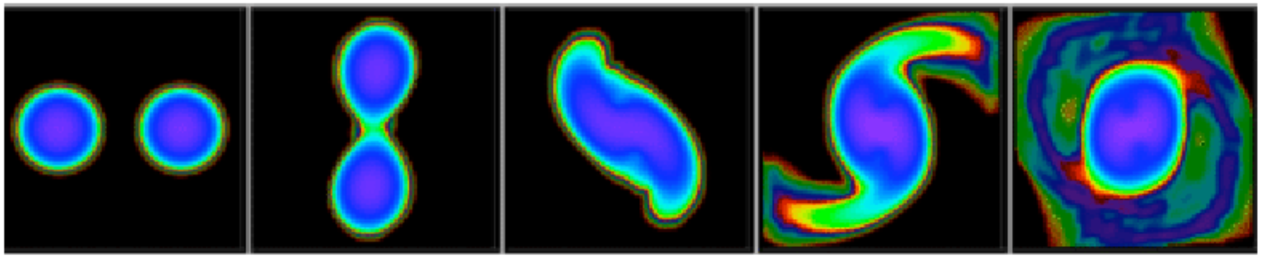
Compact binary mergers



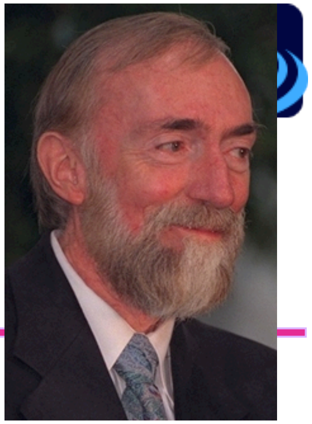
K. Thorne



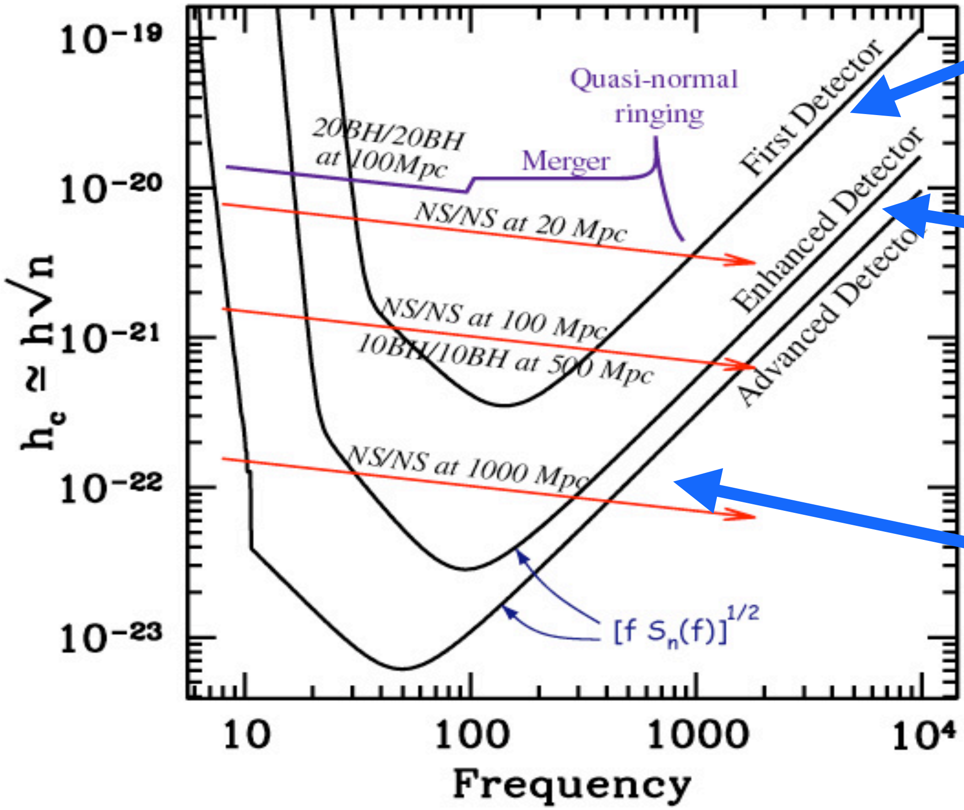
- Neutron star – neutron star (Centrella et al.)



Astrophysical sources: Thorne diagrams



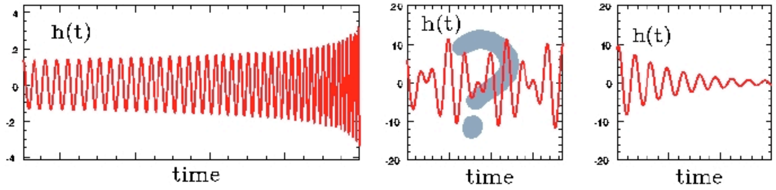
Sensitivity of LIGO to coalescing binaries



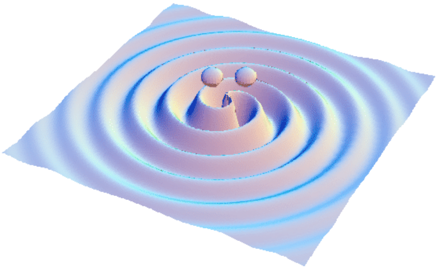
Initial LIGO (2002-2008)

Advanced LIGO (2012-)

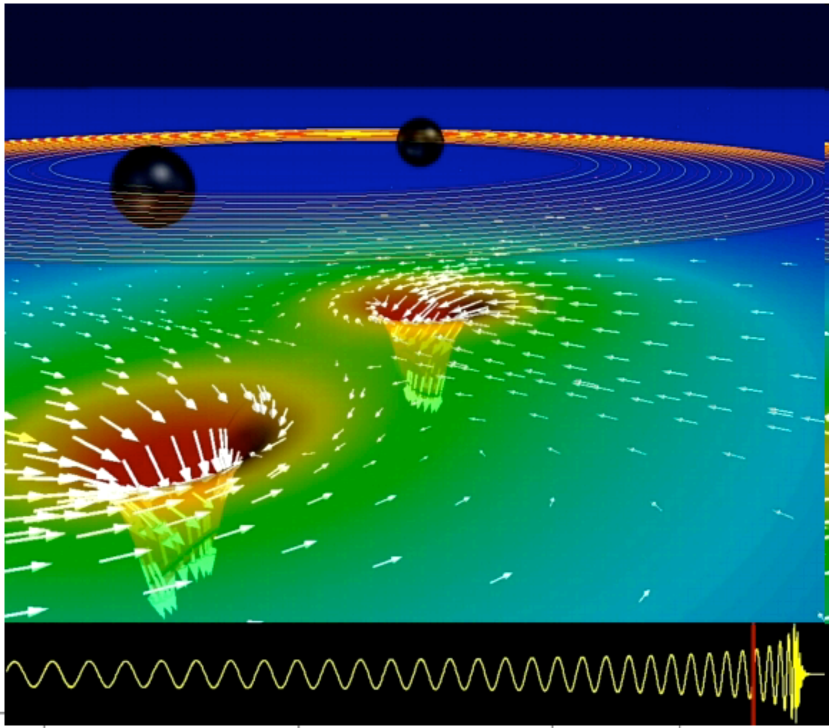
Beyond Advanced LIGO

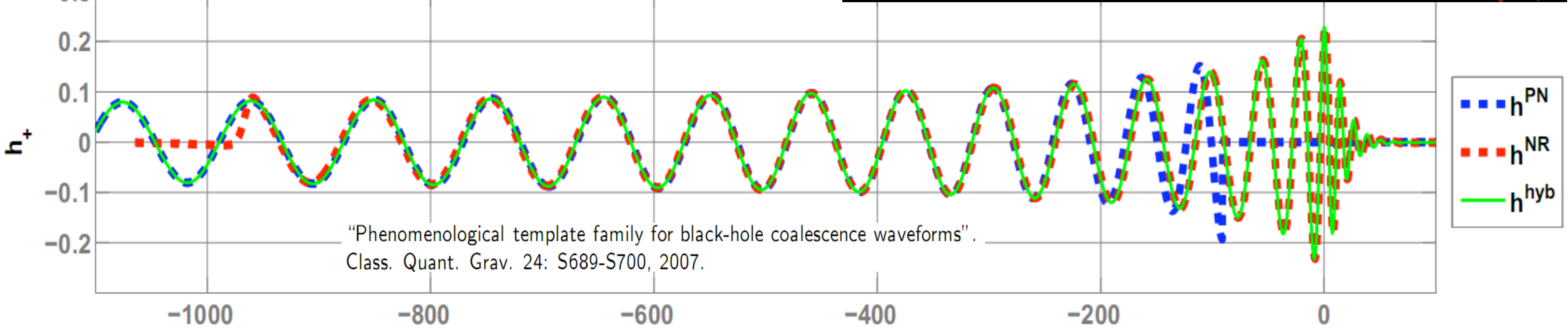


Understanding Inspiral-Merger-Ringdown



- The key to optimal detection is a well-modeled waveform, especially the phase evolution
- Low-mass systems (BNS) merge above ~1500 Hz, where LIGO noise is high - we see the inspiral
- Higher-mass systems (BBH) merge or ring down in-band.
- These systems are unique: highly relativistic, dynamical, strong-field gravity – exactly where Einstein's equations are most non-linear, intractable, interesting, and poorly-tested.
- Numerical relativity is devoted to deriving waveforms for such systems, to aid in detection and to test our understanding of strong-field gravity.
- HUGE progress in the last few years!

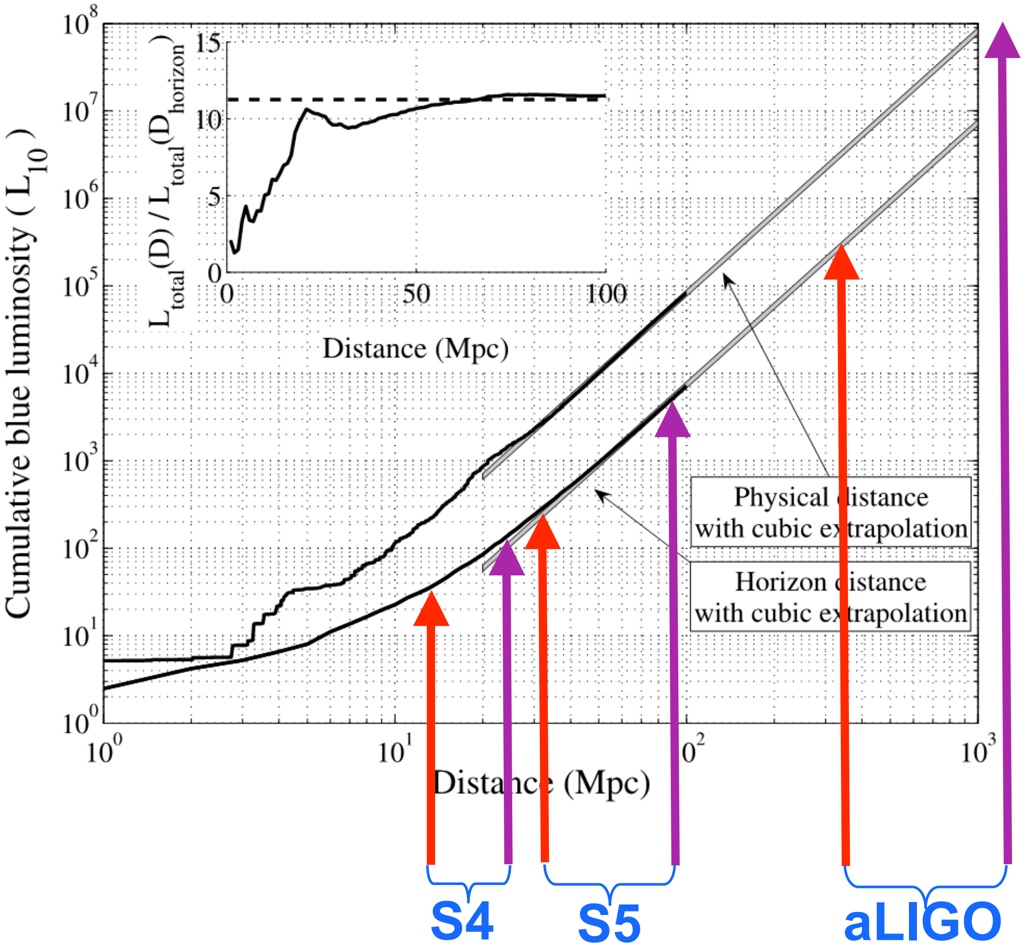




"Phenomenological template family for black-hole coalescence waveforms". Class. Quant. Grav. 24: S689-S700, 2007.

Expected detection rate: How many sources can we see?

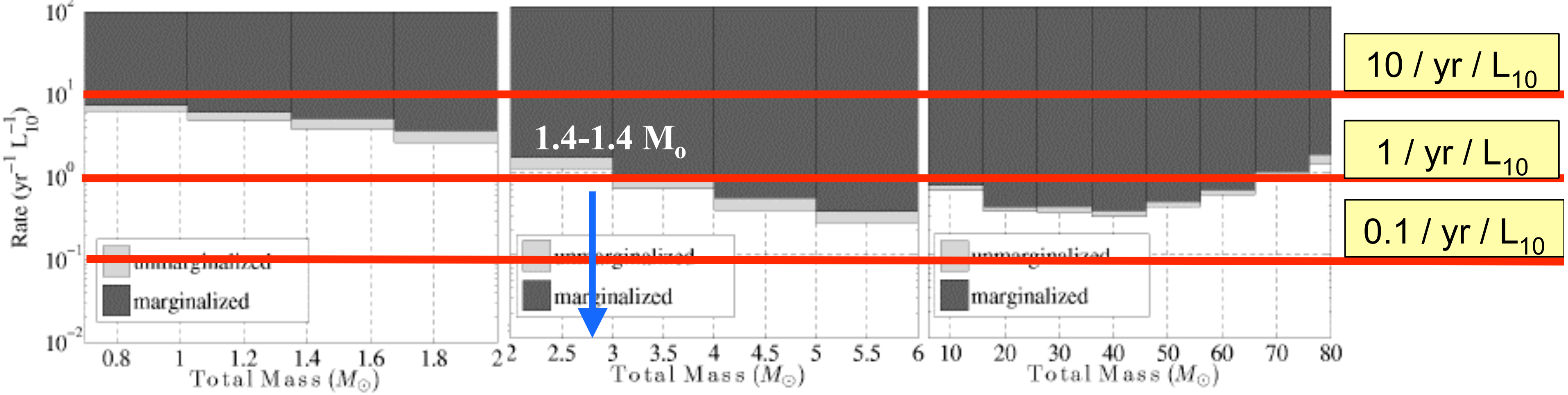
- CBC waveforms have known amplitude
  $h \sim (GM/c^2 r) \times F(\alpha,\delta,\iota)$
- Measured detector sensitivity defines a *horizon distance*
- This encloses a known number of sources:
  MWEG = 1.7×10^{10} L_s = 1.7 L_{10}
- From galactic binary pulsars:
  R(BNSC) ~10-170 /Myr/L_{10}
- From population synthesis:
  R(BBHC) ~0.1 - 15 /Myr/L_{10}
- To see more than 10 events/yr, we need to be sensitive to
  10^5 - 10^7 galaxies!



S4 upper limits-compact binary coalescence

- Rate/year/L_{10} vs. binary total mass
  $L_{10} = 10^{10}\ L_{sun,B}$ (1 Milky Way = 1.7 L_{10})
- Dark region excluded at 90% confidence.

Primordial BH binaries NS-NS BH-BHs



10 / yr / L_{10}

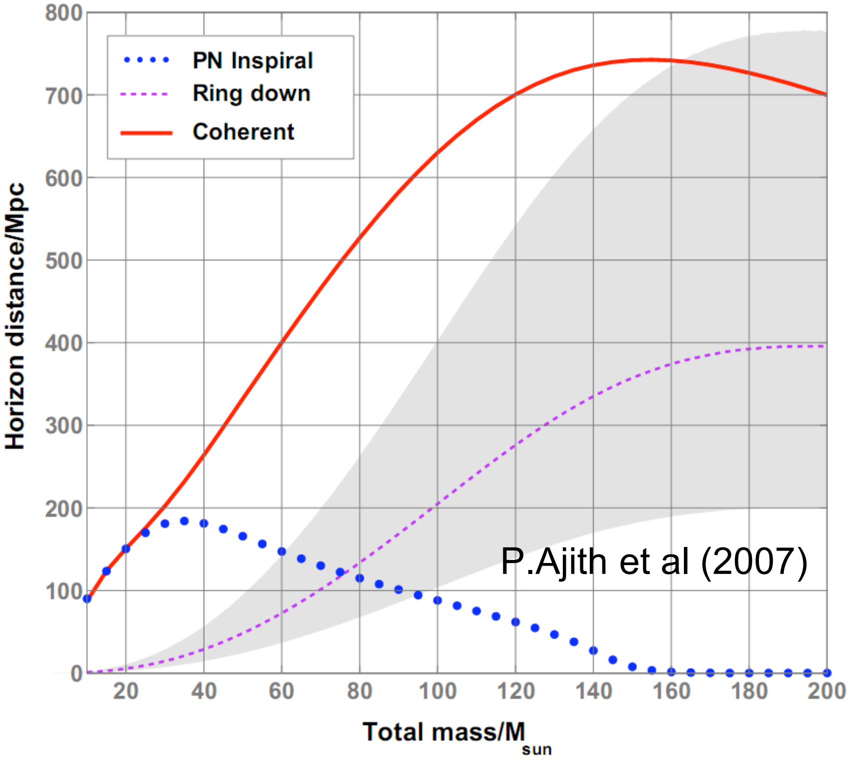
1 / yr / L_{10}

0.1 / yr / L_{10}

0.8-80 M_{sun}

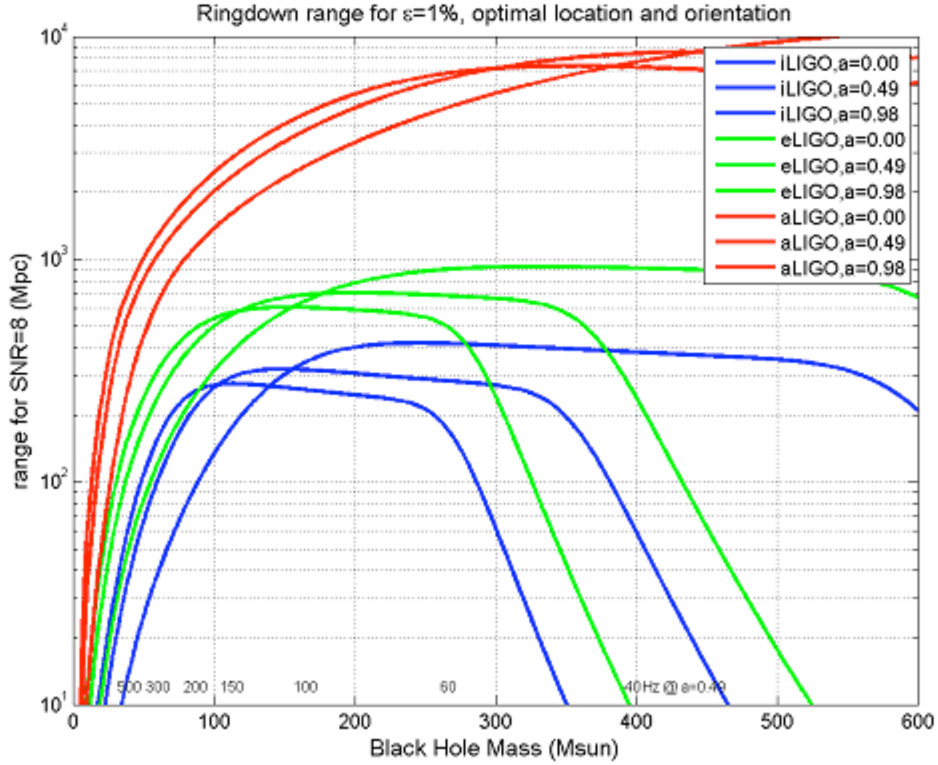
Horizon distance is a strong function of mass

Horizon distance (Mpc)
versus mass (M_{sun})
Inspiral-Merger-Ringdown
Initial LIGO



P.Ajith et al (2007)

Horizon distance (Mpc)
versus mass (M_{sun})
for ringdowns
iLIGO ⇒ eLIGO ⇒ aLIGO


Ringdown range for ε=1%, optimal location and orientation

Triggered searches: GRB 070201

- **Feb 1, 2007: short hard γ burst (T_{90}=0.15 s)**
- **Observed by five spacecraft**
- **Location consistent with M31 (Andromeda) spiral arms (0.77 Mpc)**
- **At the time of the event,
both Hanford instruments were recording data (H1, H2),
while others were not (L1, V1, G1)**
- **Short GRB: could be inspiral of compact binary system (NS/BH), or perhaps soft gamma repeater**

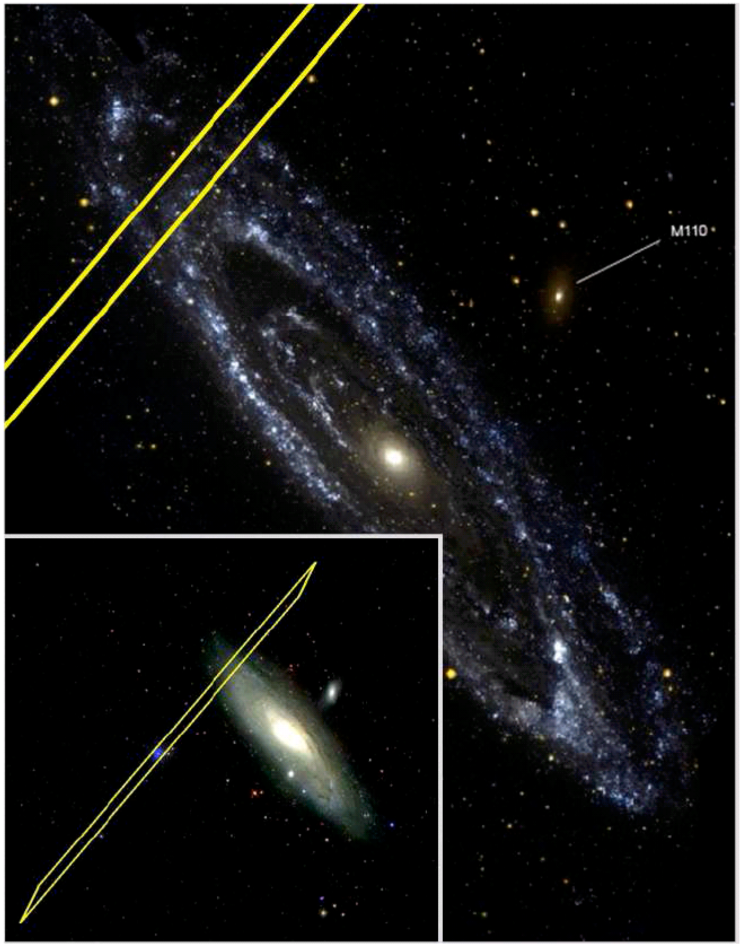


FIG. 1.— The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et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

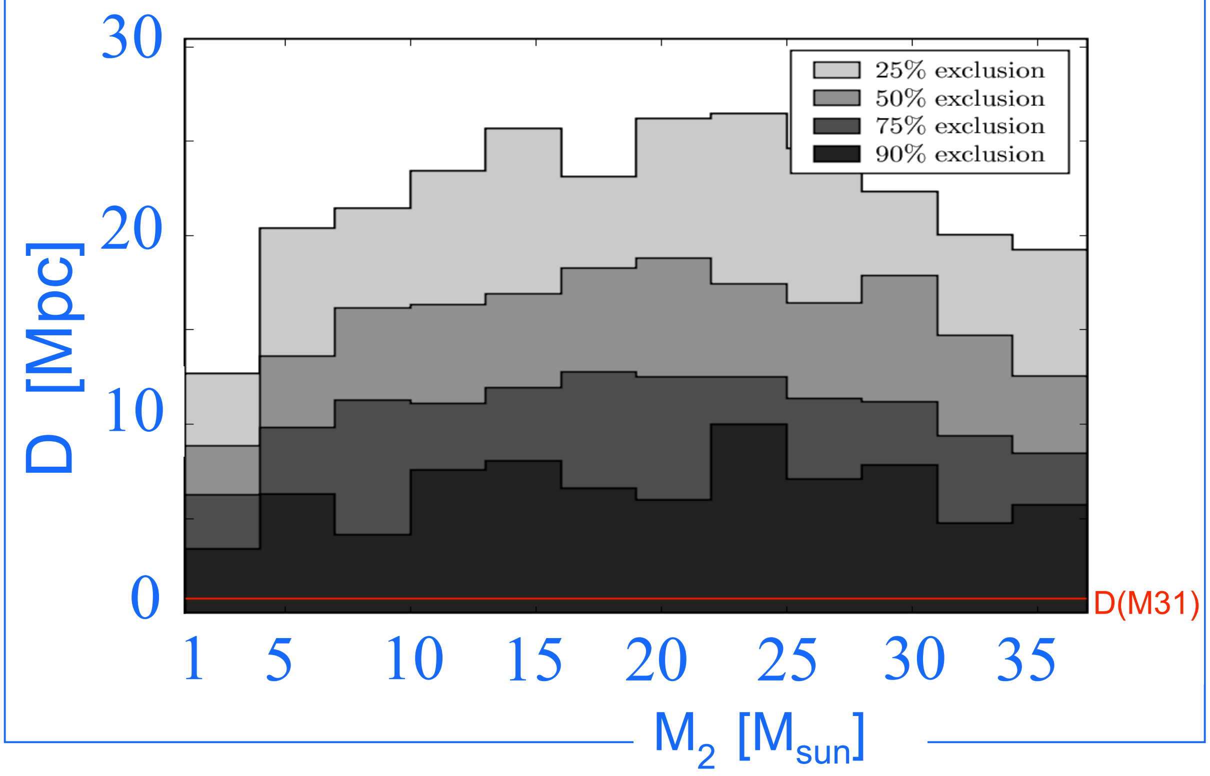
Inspiral search - GRB 070201

- Matched template analysis, $1M_\odot < m_1 < 3M_\odot$, $1M_\odot < m_2 < 40M_\odot$
- H1 ~ 7200 templates, H2 ~ 5400 templates, obtain filter SNR
- Require consistent timing and mass parameters between H1, H2
- Additional signal-based vetos

No gravitational wave candidates found

Compact binary in M31 with
$1M_\odot < m_1 < 3M_\odot$
$1M_\odot < m_2 < 40M_\odot$
excluded at 99% confidence

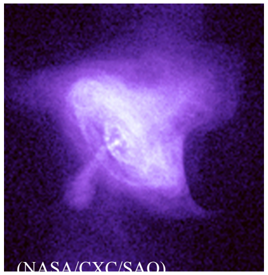
Astrophys.J 681, 1419 (2008)



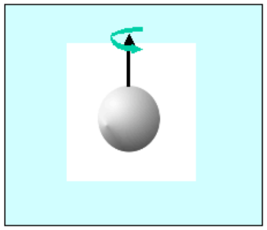
Pulsars and continuous wave sources

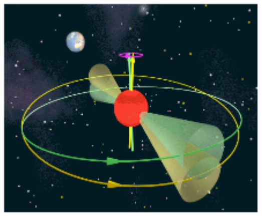
- **Pulsars in our galaxy**
  - »non axisymmetric: 10-4 < ε < 10-6
  - »science: EOS; precession; interiors
  - »"R-mode" instabilities
  - »narrow band searches best

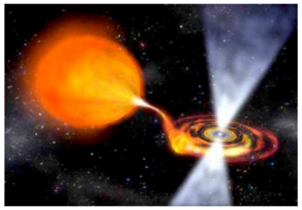
$$h = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f_{GW}^2}{r} \varepsilon$$

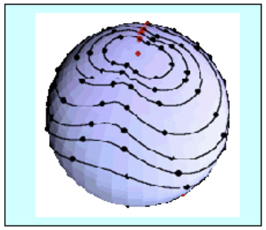

(NASA/CXC/SAO)

$$f_{GW} = 2 f_{ROT}$$

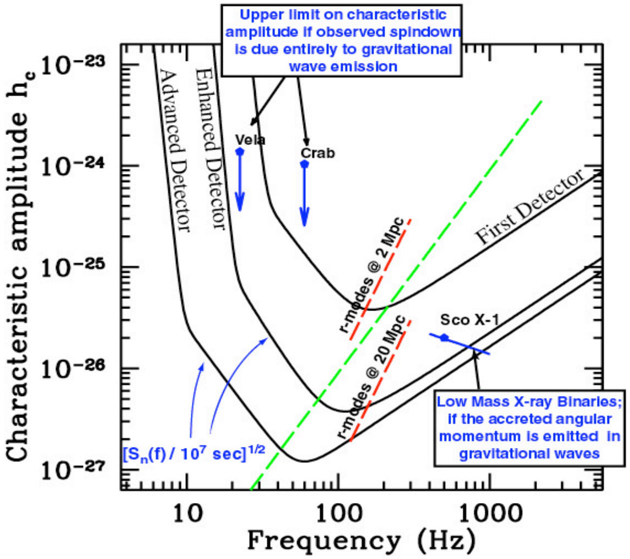

Mountain on a star

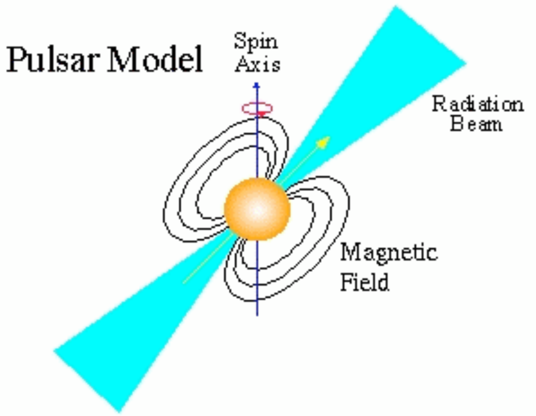

Wobbling star


Accreting star


Oscillating star

Sensitivity of LIGO to continuous wave sources





Search for known pulsars- preliminary

Joint 95% upper limits for 97 pulsars using ~13 months of the LIGO S5 run. Results are overlaid on the estimated median sensitivity of this search.

Spin-down limit:

$$h_{\rm sd} = \left(\frac{5}{2}\frac{G I_{zz}|\dot{\nu}|}{c^3 r^2 \nu}\right)^{1/2}$$

Pulsar timings provided by the
Jodrell Bank pulsar group

Lowest GW strain upper limit:

PSR J1435-6100

(f_{gw} = 214.0 Hz, r = 3.3 kpc)

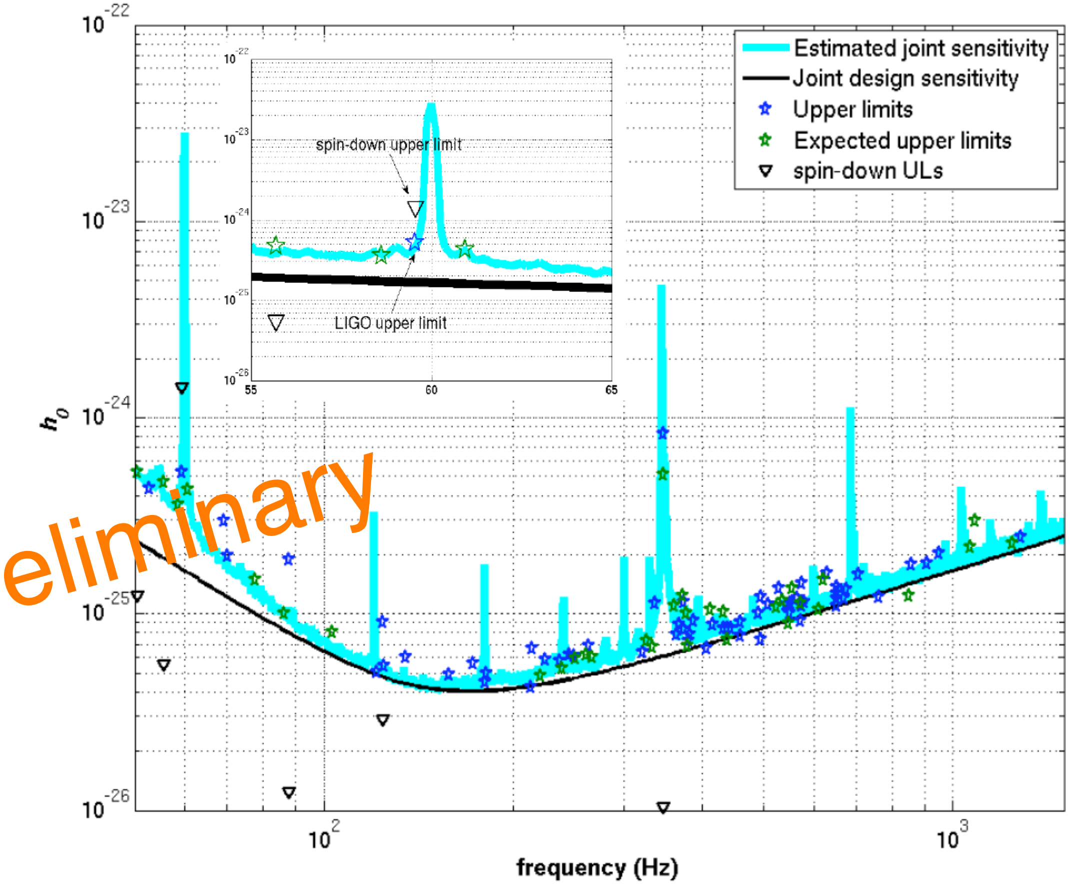
$h_0 < 4.2\times10^{-26}$

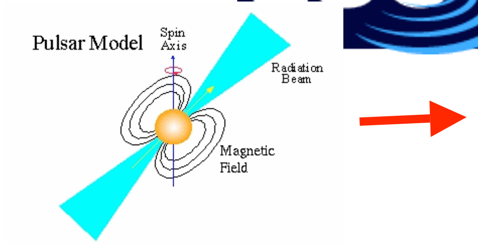
Lowest ellipticity upper limit:

PSR J2124-3358

(f_{gw} = 405.6 Hz, r = 0.25 kpc)

$\varepsilon < 9.6\times10^{-8}$



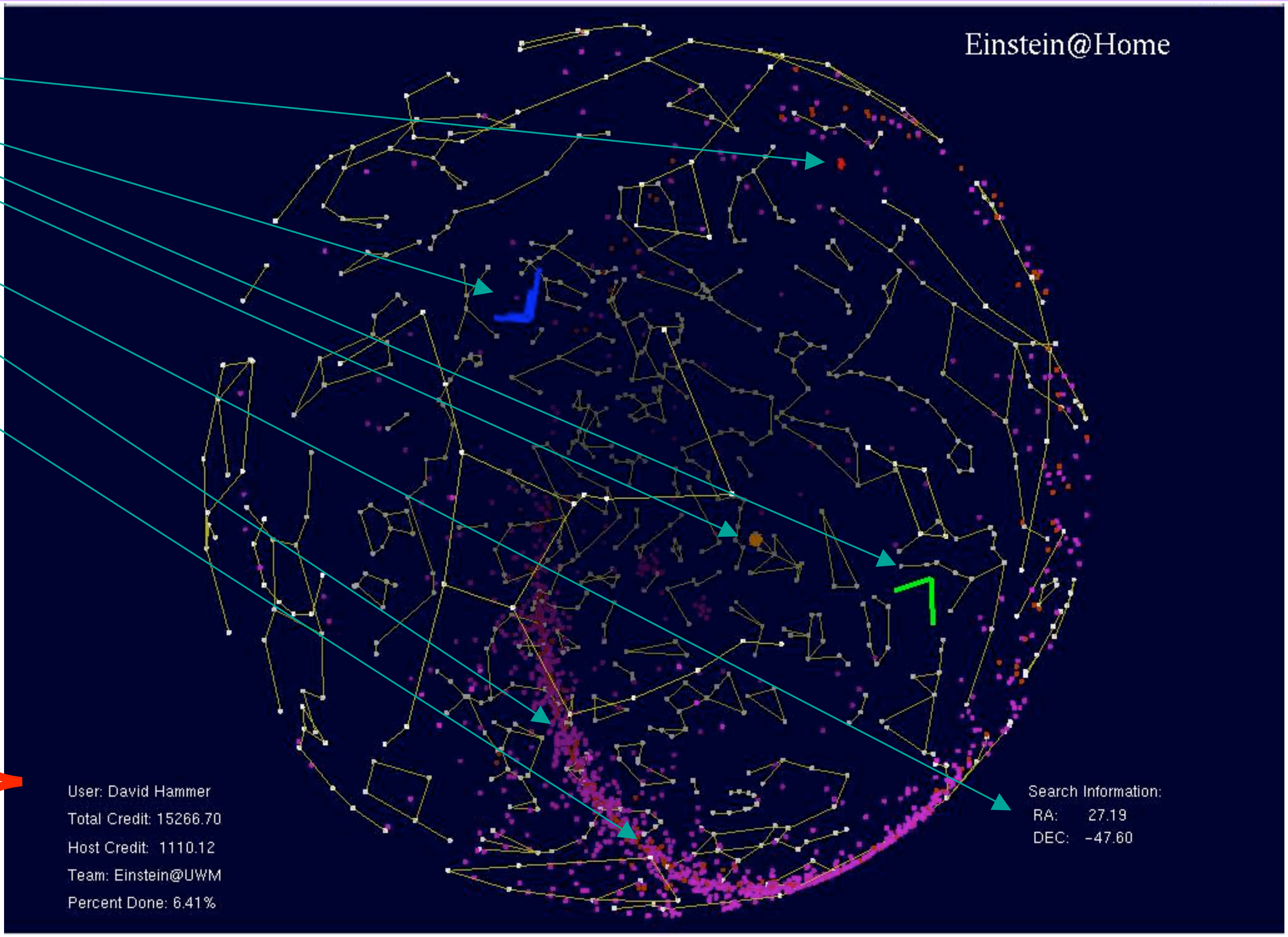


All sky searches

- Most spinning neutron stars are not observed pulsars; EM dim and hard to find.
- But they all emit GWs in all directions (at some level)
- Some might be very close and GW-loud!
- Must search over huge parameter space:
  - sky position: 150,000 points @ 300 Hz, more at higher frequency or longer integration times
  - frequency bins: 0.5 mHz over hundreds of Hertz band, more for longer integration times
  - df/dt: tens(s) of bins
- Computationally limited! Full coherent approach requires ~100,000 computers (Einstein@Home)

Einstein@Home: the Screensaver

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants

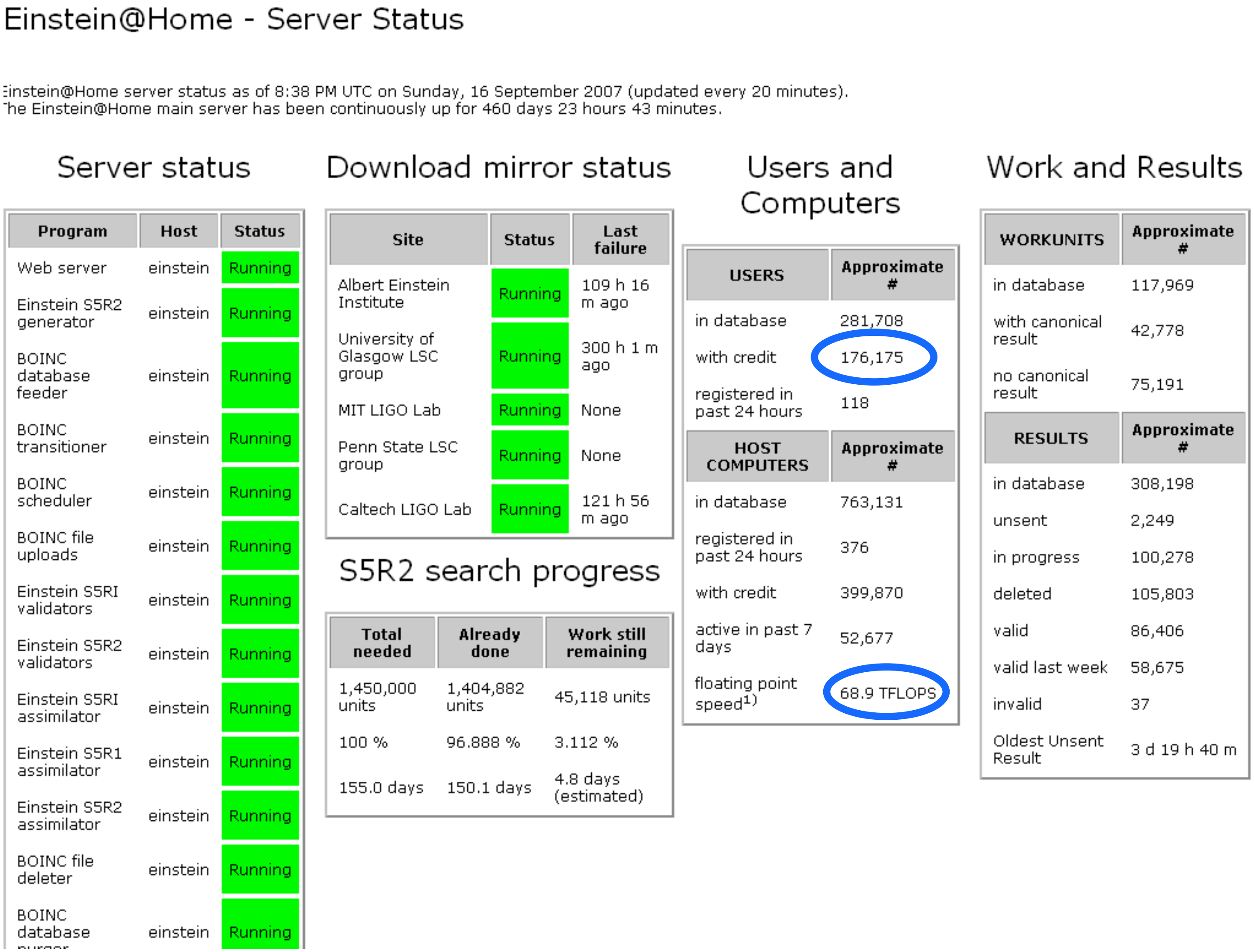


User: David Hammer
Total Credit: 15266.70
Host Credit: 1110.12
Team: Einstein@UWM
Percent Done: 6.41%

Search Information:
RA: 27.19
DEC: -47.60

- User name
- User's total credits
- Machine's total credits
- Team name
- Current work % complete

The second-largest distributed computing project in the world!



Einstein@Home - Server Status

instein@Home server status as of 8:38 PM UTC on Sunday, 16 September 2007 (updated every 20 minutes).
he Einstein@Home main server has been continuously up for 460 days 23 hours 43 minutes.

Server status

Program	Host	Status
Web server	einstein	Running
Einstein S5R2 generator	einstein	Running
BOINC database feeder	einstein	Running
BOINC transitioner	einstein	Running
BOINC scheduler	einstein	Running
BOINC file uploads	einstein	Running
Einstein S5RI validators	einstein	Running
Einstein S5R2 validators	einstein	Running
Einstein S5RI assimilator	einstein	Running
Einstein S5R1 assimilator	einstein	Running
Einstein S5R2 assimilator	einstein	Running
BOINC file deleter	einstein	Running
BOINC database	einstein	Running

Download mirror status

Site	Status	Last failure
Albert Einstein Institute	Running	109 h 16 m ago
University of Glasgow LSC group	Running	300 h 1 m ago
MIT LIGO Lab	Running	None
Penn State LSC group	Running	None
Caltech LIGO Lab	Running	121 h 56 m ago

S5R2 search progress

Total needed	Already done	Work still remaining
1,450,000 units	1,404,882 units	45,118 units
100 %	96.888 %	3.112 %
155.0 days	150.1 days	4.8 days (estimated)

Users and Computers

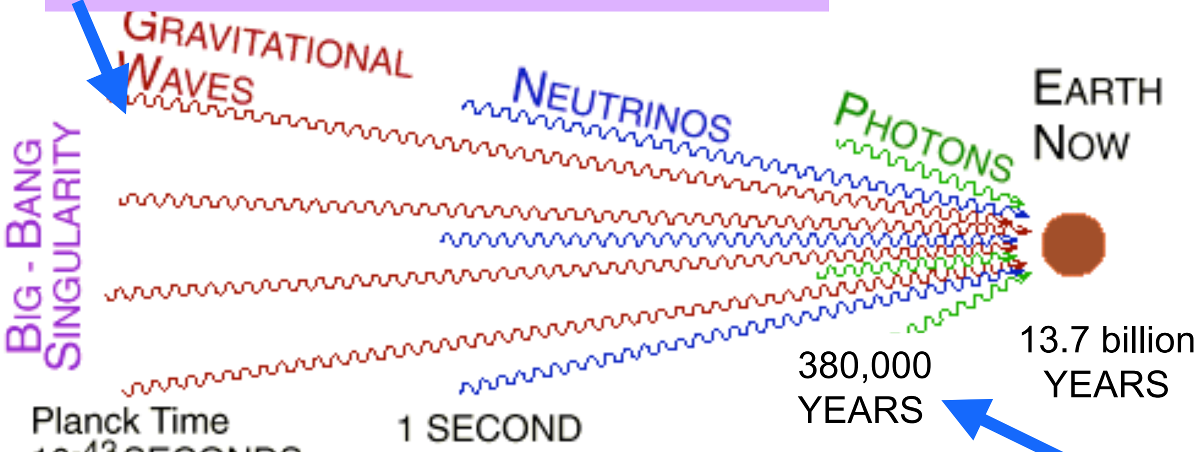
USERS	Approximate #
in database	281,708
with credit	176,175
registered in past 24 hours	118
HOST COMPUTERS	**Approximate #**
in database	763,131
registered in past 24 hours	376
with credit	399,870
active in past 7 days	52,677
floating point speed[1)	68.9 TFLOPS

Work and Results

WORKUNITS	Approximate #
in database	117,969
with canonical result	42,778
no canonical result	75,191
RESULTS	**Approximate #**
in database	308,198
unsent	2,249
in progress	100,278
deleted	105,803
valid	86,406
valid last week	58,675
invalid	37
Oldest Unsent Result	3 d 19 h 40 m

Gravitational waves from Big Bang

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

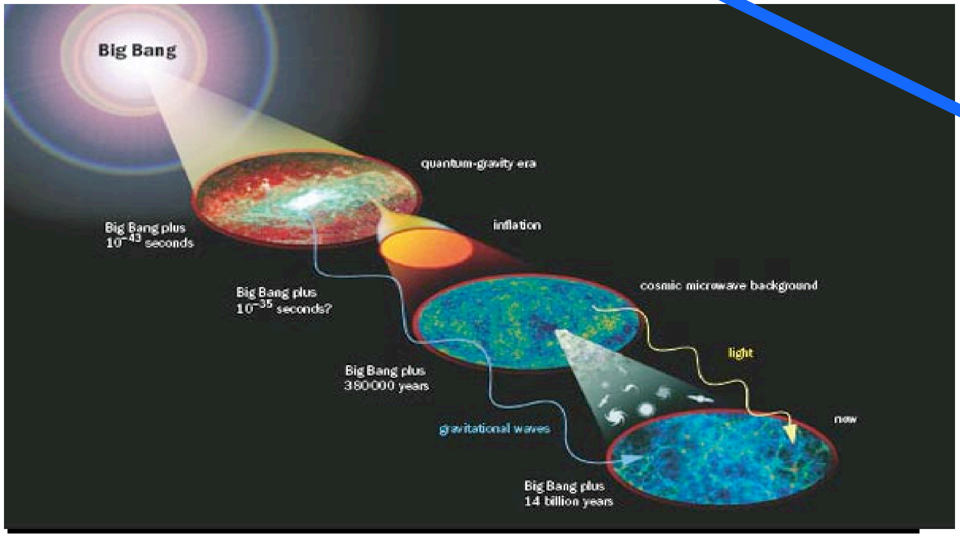


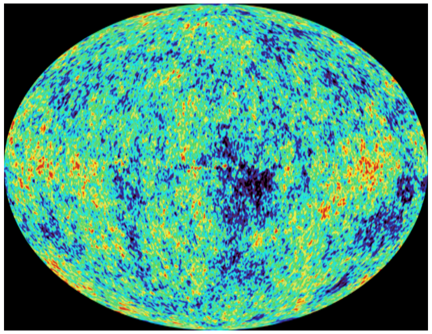
Planck Time
10^{-43} SECONDS
Singularity
creates
Space & Time
of our universe

$$\Omega_{GW}(f) = \frac{1}{\rho_c}\,\frac{d\rho_{GW}(f)}{d\ln f}$$

$$\rho_{GW} = \frac{c^2}{32\pi G} < \dot{h}_{ab}\,\dot{h}^{ab} >$$

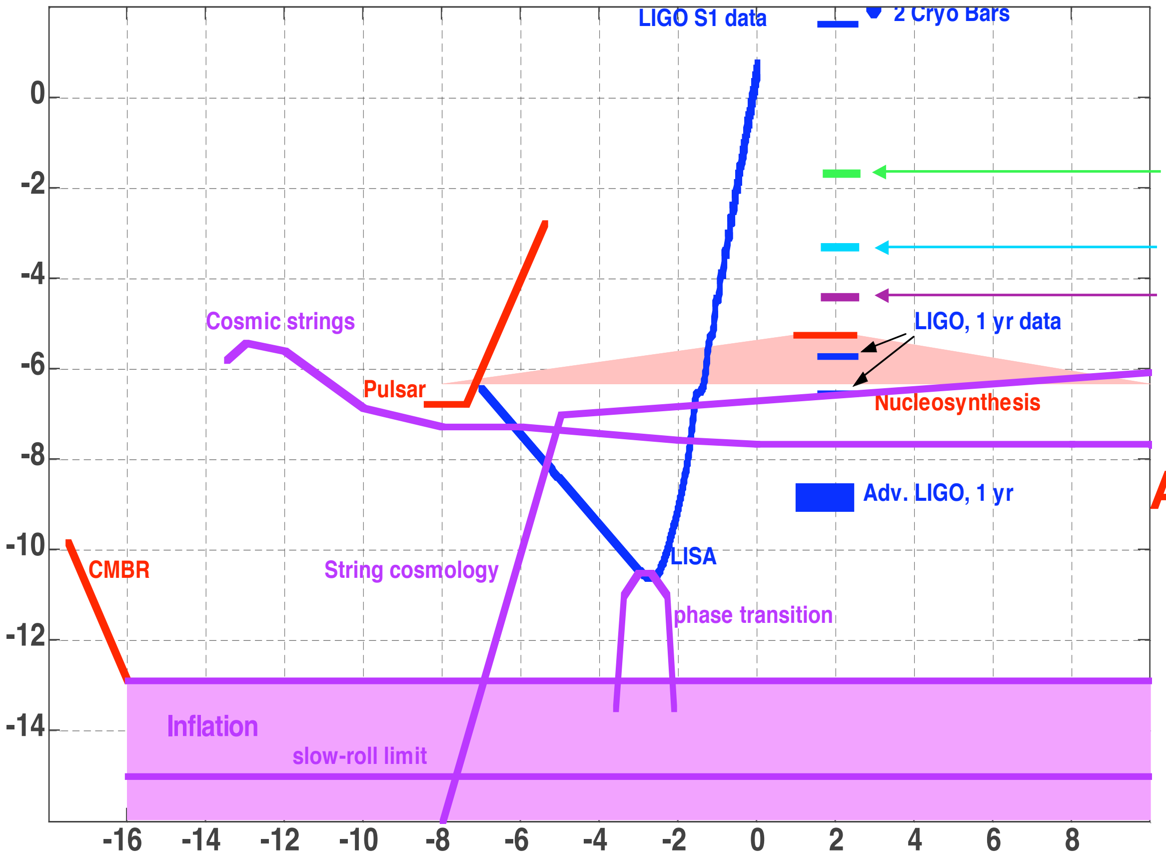
$$h(f) = 6.3\times 10^{-22}\sqrt{\Omega_{GW}(f)}\left(\frac{100\text{ Hz}}{f}\right)^{3/2}\text{Hz}^{-1/2}$$





cosmic microwave background -- WMAP 2003

LIGO limits and expectations on Ω_{GW}



S1 result: $\Omega_{GW} < 23$

S2 result: $\Omega_{GW} < 0.02$

S3 result: $\Omega_{GW} < 8\times10^{-4}$

S4 result: $\Omega_{GW} < 6.5\times10^{-5}$

LIGO design, 1 year:
Ω_{GW} <~ 10^{-5} - 10^{-6}

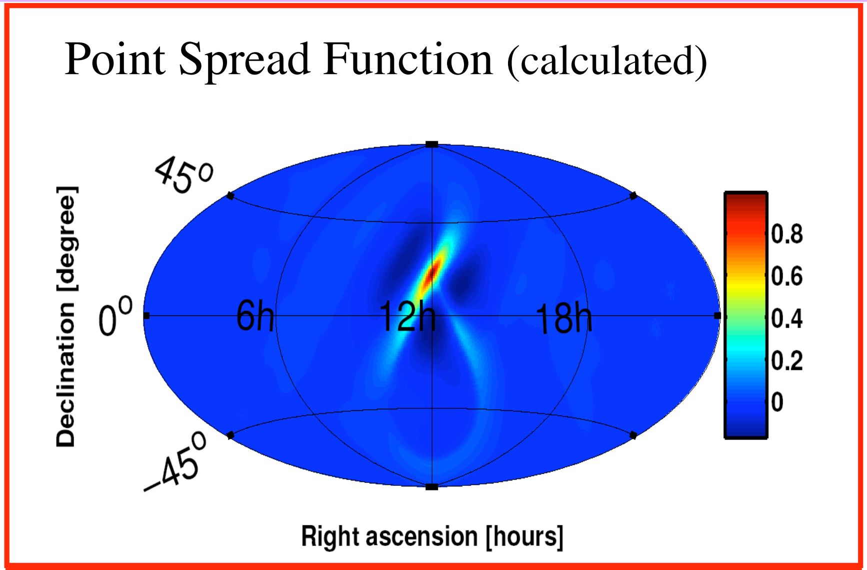
Advanced LIGO, 1 year:
Ω_{GW} <~ 10^{-9}

Challenge is to identify and eliminate noise correlations between H1 and H2!

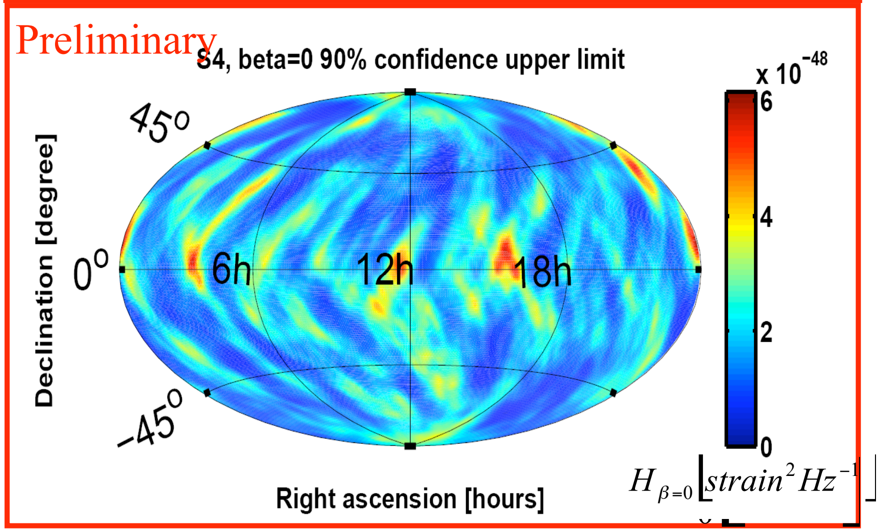
Upper limit map of a stochastic GW background

- S4 data- 16 days of 2 site coincidence data
- Get positional information from sidereal modulation in antenna pattern and time shift between signals at 2 separated sites
- **No signal was seen**.
- Upper limits on broadband radiation source strain power originating from any direction.

  (0.85-6.1 x 10^{-48} (Hz^{-1}) for min-max on sky map; flat source power spectrum)



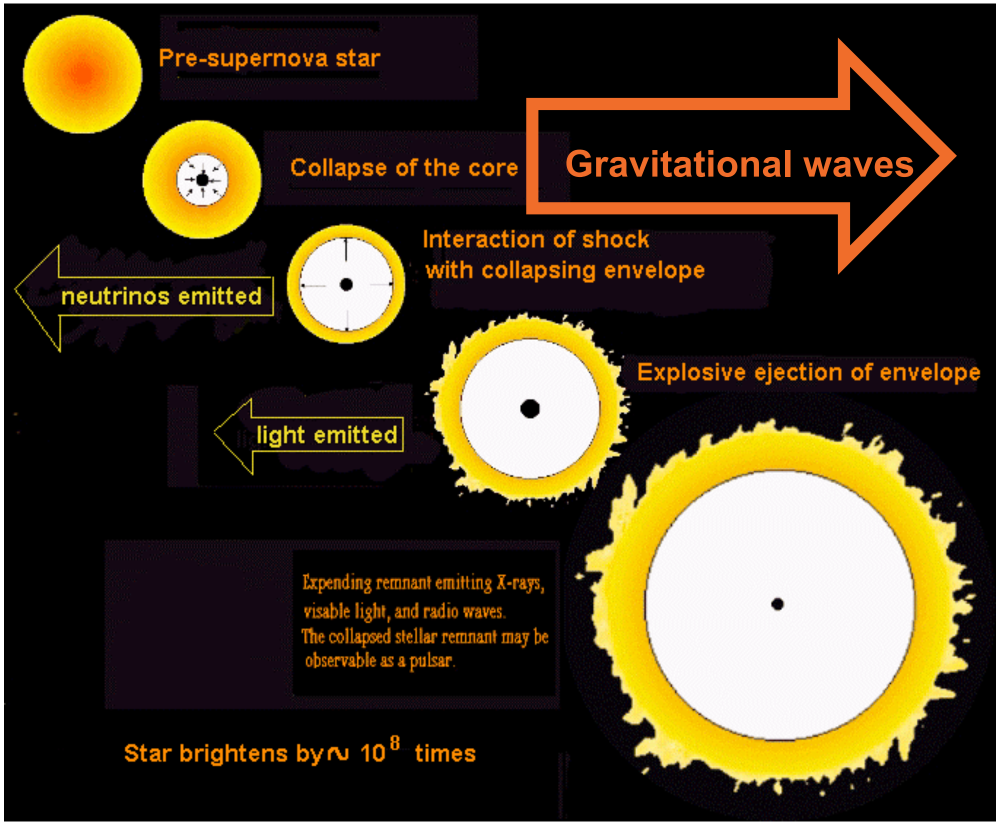
Point Spread Function (calculated)



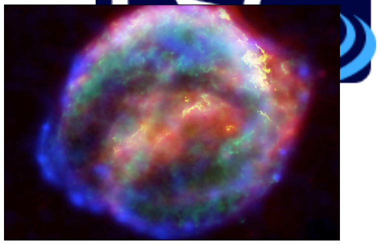
Preliminary

S4, beta=0 90% confidence upper limit

GW Bursts from core collapse supernova



- Within about 0.1 second, the core collapses and gravitational waves are emitted.
- After about 0.5 second, the collapsing envelope interacts with the outward shock. Neutrinos are emitted.
- Within 2 hours, the envelope of the star is explosively ejected. When the photons reach the surface of the star, it brightens by a factor of 100 million.
- Over a period of months, the expanding remnant emits X-rays, visible light and radio waves in a decreasing fashion.



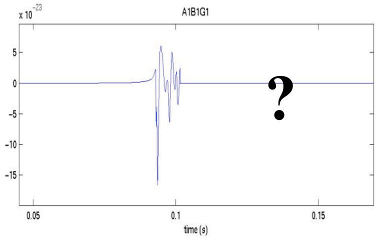
Untriggered GW burst search

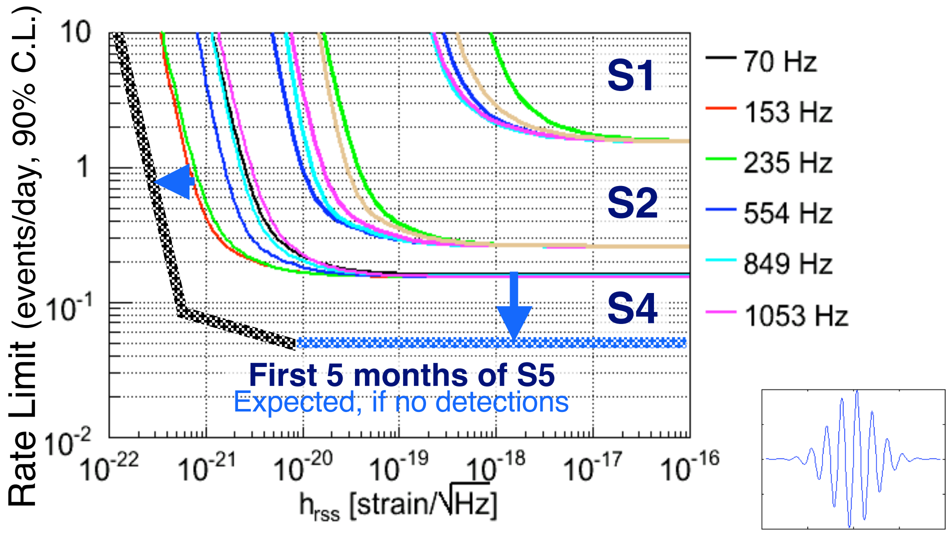
- Look for short, unmodeled GW signals in LIGO’s frequency band
  - –From stellar core collapse, compact binary merger, etc. — or unexpected source
- Look for excess signal power and/or cross-correlation among data streams from different detectors

- No GW bursts detected in S1/S2/S3/S4; preliminary results from 1st 5 months of S5

Limit on GWB rate vs. GW signal strength sensitivity

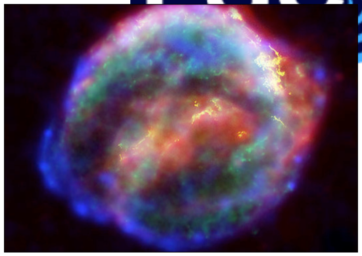
- Detection algorithms tuned for 64–1600 Hz, duration << 1 sec
- Veto thresholds pre-established before looking at data
- Corresponding energy emission sensitivity **$E_{GW} \sim 10^{-1}$ M_{sun} at 20 Mpc** (153 Hz case)





h_{rss} (root-sum-squared strain amplitude)

Triggered Searches for GW Bursts



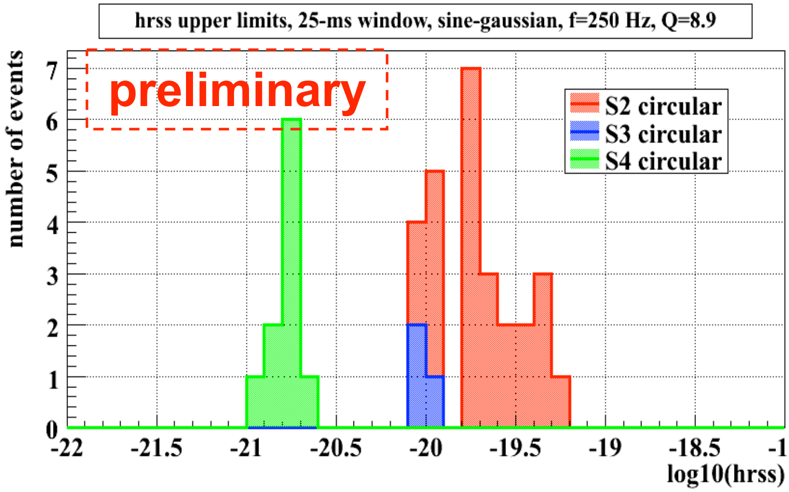
Soft Gamma Repeater 1806-20

- galactic neutron star (10-15 kpc) with intense magnetic field (~1015 G)
- source of record gamma-ray flare on December 27, 2004
- quasi-periodic oscillations found in RHESSI and RXTE x-ray data
- search LIGO data for GW signal associated with quasi-periodic oscillations-- no GW signal found
- sensitivity: E_{GW} ~ 10–7 to 10–8 Msun for the 92.5 Hz QPO
- this is the same order of magnitude as the EM energy emitted in the flare

preliminary

Gamma-Ray Bursts

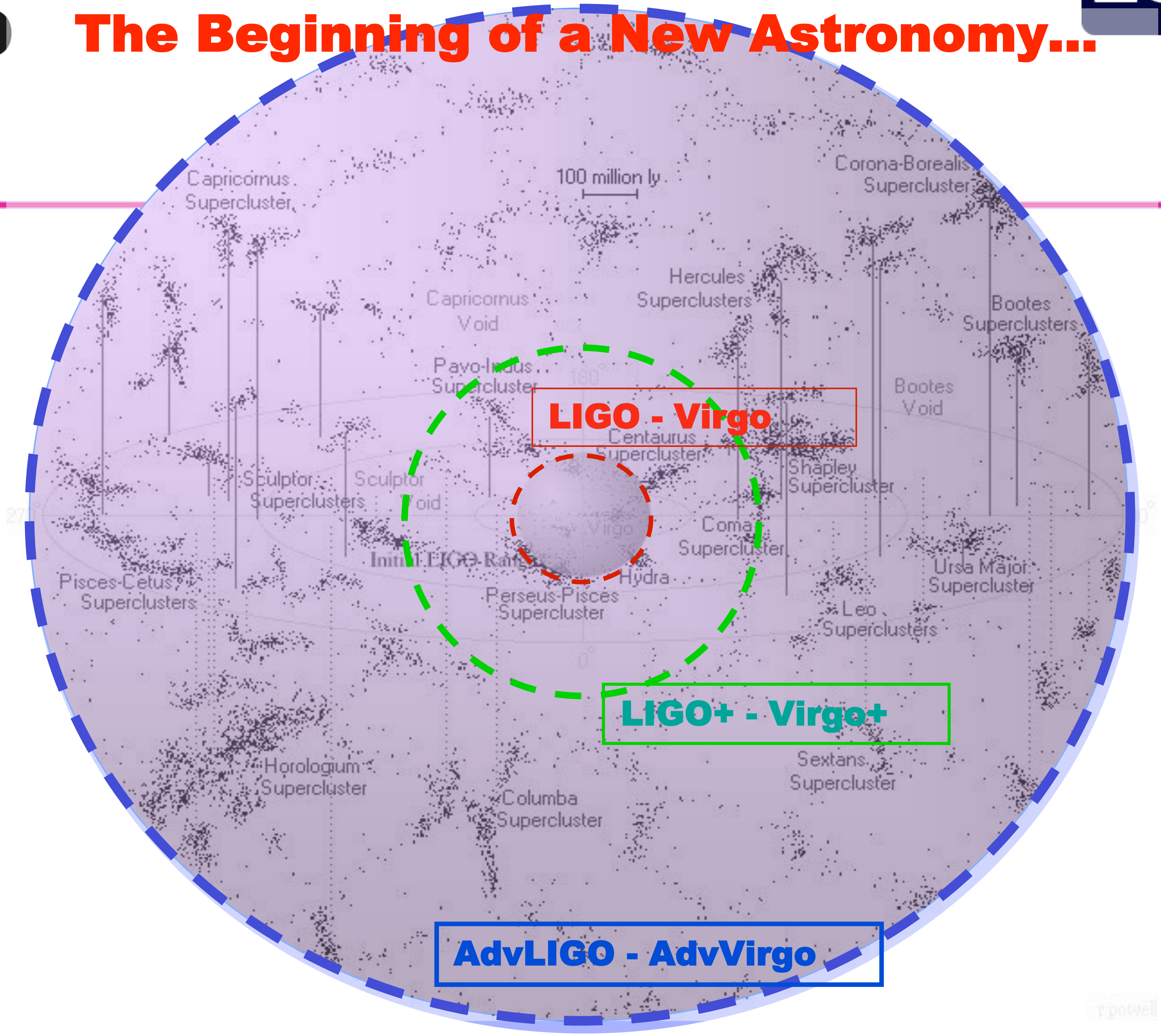
- search LIGO data surrounding GRB trigger using cross-correlation method
- no GW signal found associated with 39 GRBs in S2, S3, S4 runs
- set limits on GW signal amplitude
- 53 GRB triggers for the first five months of LIGO S5 run
- typical S5 sensitivity at 250 Hz: **E_{GW} ~ 0.3 M_{sun}** at 20 Mpc



Summary

- LIGO is operating in science mode at design sensitivity
  - first long science run (S5) is now complete
  - No detections to report yet – but there may be some in the can!
- VIRGO, GEO, TAMA and CLIO approaching design sensitivity
- LIGO Sensitivity/range will be increased by ~ 2 in 2009 and a factor of 10-15 in ~2014 with Advanced LIGO
  - We expect to found the field of GW astrophysics with Advanced LIGO
- LIGO searches producing some interesting upper limits
- An international network of ground-based GW detectors is taking shape.
- Detections, and the exploration of the universe with GWs, will begin over the next decade!

The Beginning of a New Astronomy…



LIGO - Virgo

LIGO+ - Virgo+

AdvLIGO - AdvVirgo