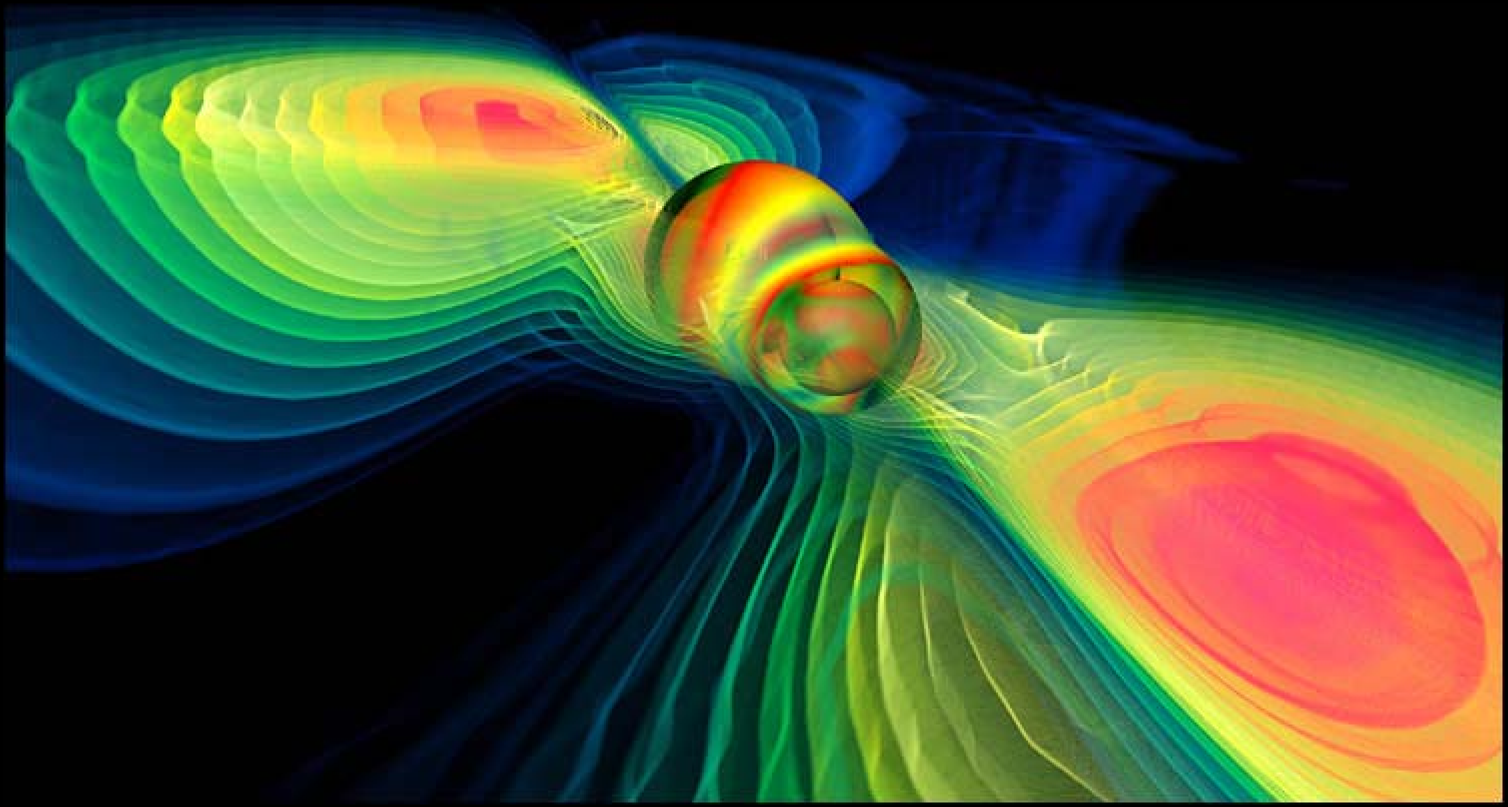
Gravitational waves:
the sound of the universe



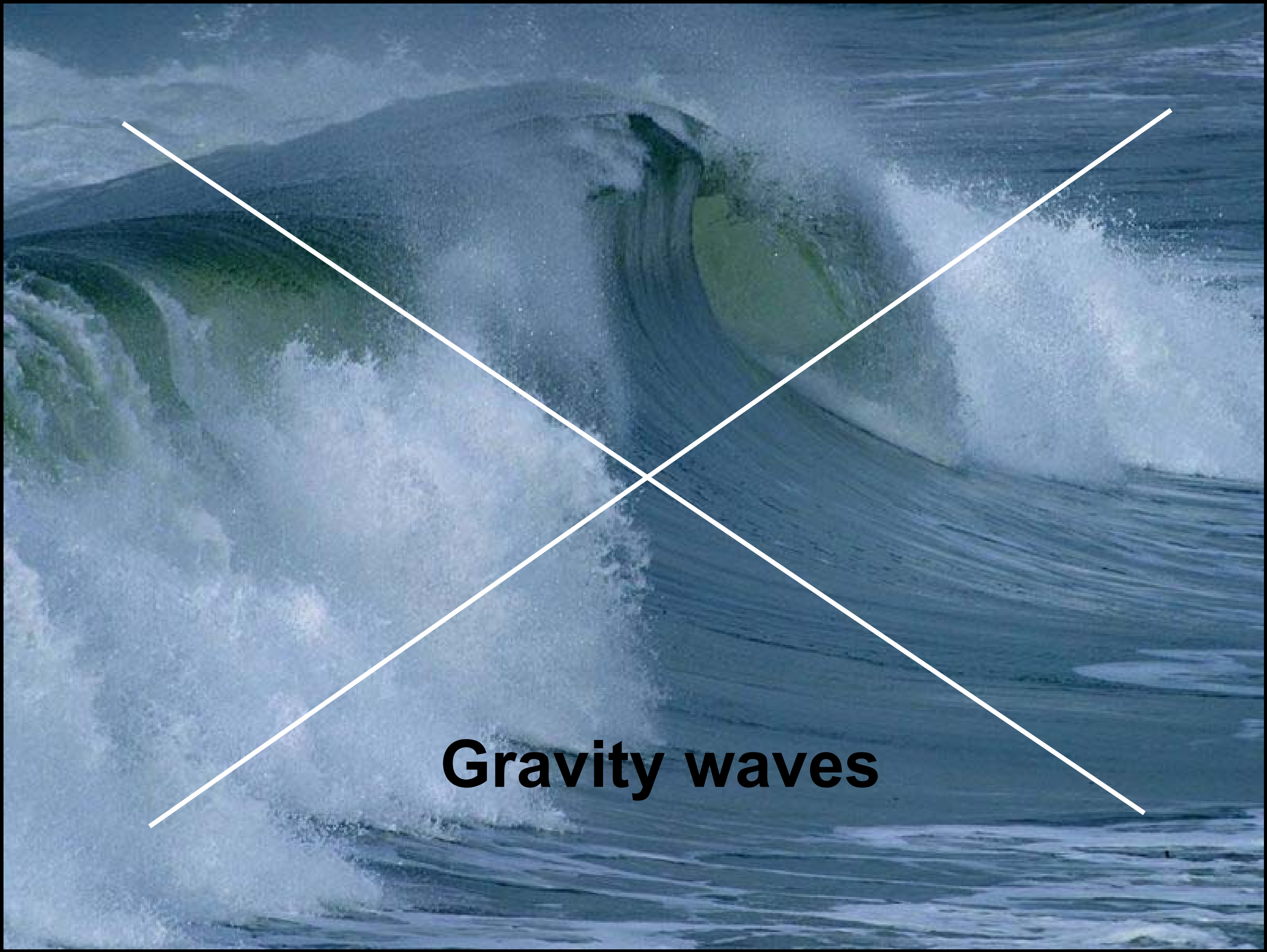
Vitor Cardoso
(CENTRA/IST & U. Mississippi)

24 April 2008

LIGO-G080249-00-Z

(Image: MPI for Gravitational Physics/W.Benger-Z)

What will NOT be discussed



Plan

Generalities

Properties of gws

GWs as the sound of the universe

Listening to the Universe

The instruments

The audience

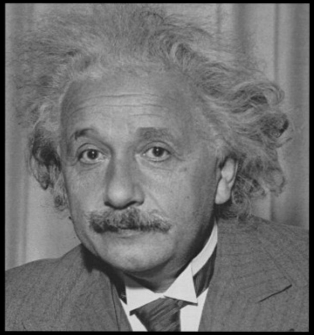
The sound

What's that playing?

Conclusions

A bit of history

- **In 1916, Einstein shows that gws are a consequence of the linearized theory**



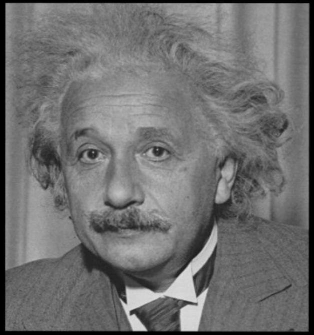
- **In 1936, with Nathan Rosen, Einstein derived an apparently contradictory result and submitted the paper** *Do gravitational waves exist?* **to Physical Review**

"Together with a young collaborator, I arrived at the interesting result that gravitational waves do not exist, though they had been assumed a certainty to the first approximation. This shows that the nonlinear field equations can show us more, or rather limit us more, than we have believed up till now"

Einstein in letter to Born, 1936

A bit of history

- **In 1916, Einstein shows that gws are a consequence of the linearized theory**



- **In 1936, with Nathan Rosen, Einstein derived an apparently contradictory result and submitted the paper** *Do gravitational waves exist?* **to Physical Review**

- **The paper was rejected (by Robertson), much to Einstein's annoyance**

"I see no reason to address the - in any case erroneous – opinion expressed by your referee"

Einstein response to Physical Review Editor

- **Confusion due to choice of coordinate choice. Einstein eventually understood his mistake**

A bit of history

Chapel Hill Conference, 1956

- ✓ **Feynman proposed "sticky bead" experiment to show gravitational waves carry energy**

- ✓ **Argument later formalized by Bondi, Weber and Wheeler**

A bit of history

First attempts at detection: Joseph Weber, 1960's

- ✓ **Aluminum resonant bar**
- ✓ **Reported coincident detection in two bars separated by 1000 Km**
- ✓ **1 event per day**

- × **Would require comparable rate of supernovae within 10 parsec**
- × **Results not reproduced in other detectors**
- × **Detector intrinsically too noisy**

What are gws?

$$g \subset ds^2 = -c^2dt^2 + (1+h_+)dx^2 + (1-h_+)dy^2 + 2\, h_x dxdy + dz^2$$

$$\Gamma^a{}_{bc} = 1/2\, g^{ad}\,(\partial_c g_{db} + \partial_b g_{dc} - \partial_d g_{bc})$$

$$R^a{}_{bcd} = \partial_c\, \Gamma^a{}_{bd} - \partial_d\, \Gamma^a{}_{bc} + \Gamma^a{}_{ce}\, \Gamma^e{}_{db} - \Gamma^a{}_{de}\, \Gamma^e{}_{cb}$$

$$R_{ab} = R^c{}_{acd}\ ;\quad R = R^a{}_a\ ;\quad G_{ab} = R_{ab} - 1/2\, g_{ab} R = 0$$

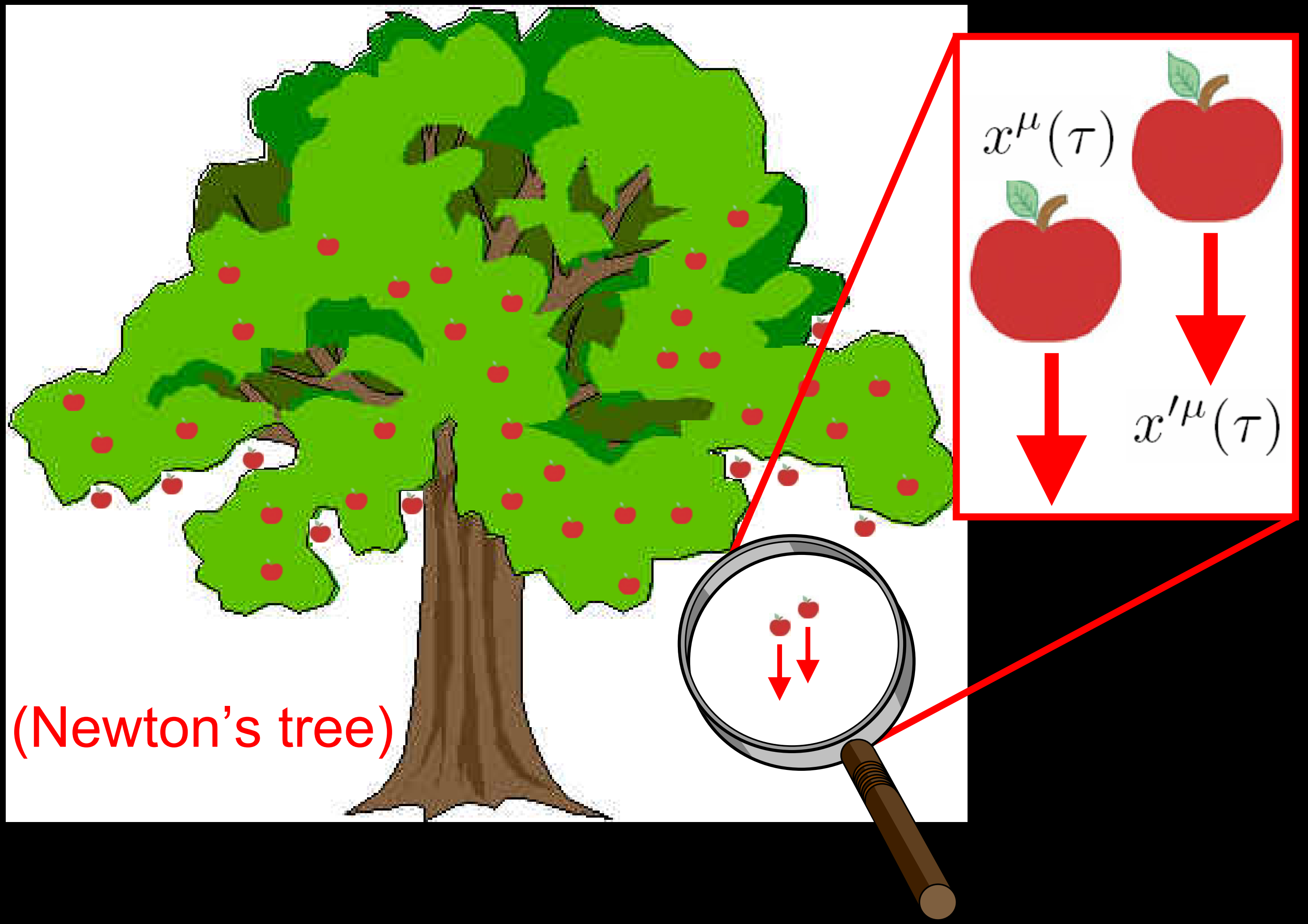
We get

$$\partial^2{}_z h_{+,x} - c^{-2}\, \partial^2{}_t h_{+,x} = 0$$

Wave equation: c!

Solution: $h_{+,x} = h \sin(kz - \omega t)$

Geometry of detection

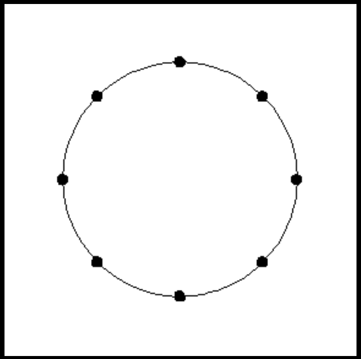


Gws are tidal forces

$$\delta x^i = \frac{1}{2} h_{ij}^{TT} x^j$$

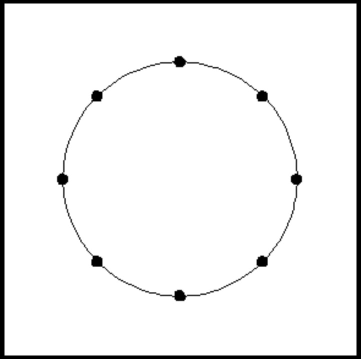
"+" polarization:

$$h_+(t-z) = h_{xx}^{TT} = -h_{yy}^{TT}$$



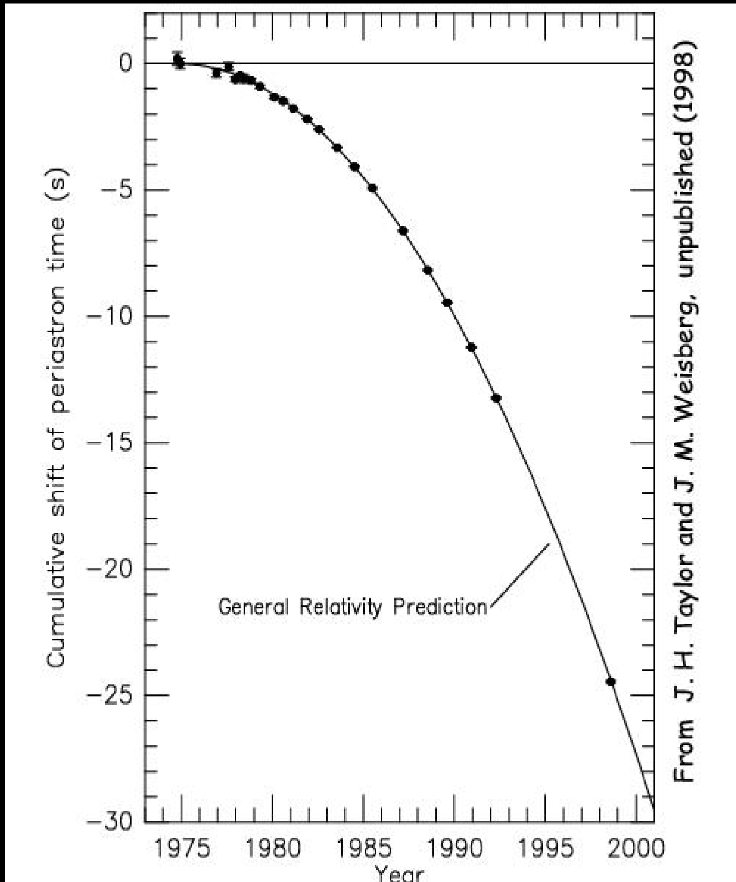
"x" polarization:

$$h_\times(t-z) = h_{xy}^{TT} = h_{yx}^{TT}$$



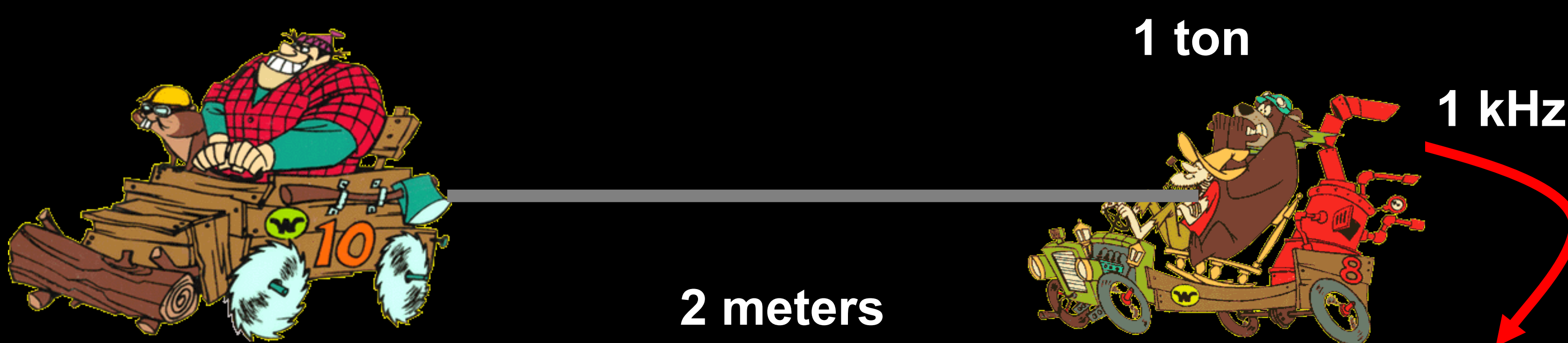
Do they exist?

slow down of a binary pulsar



GWs: properties

- **Interact very weakly**



$h_{lab}=2.6 \times 10^{-33}$ meters/r

$h_{lab}=9 \times 10^{-39}$, $r > \lambda \sim 300$ Km

too weak by 16 orders of magnitude!

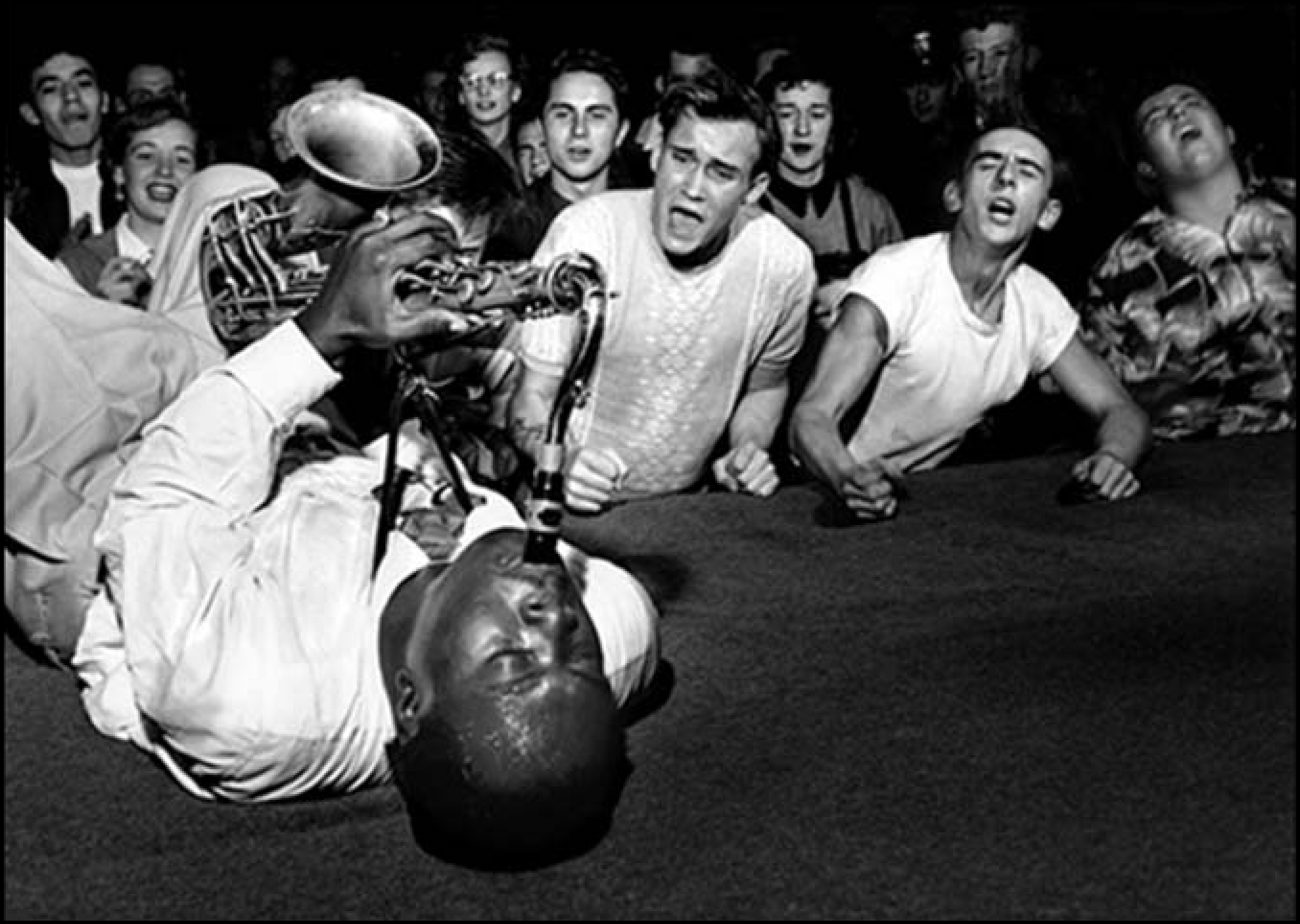
GWs: properties

- **Interact weakly –** Both blessing and a curse
- λ ~ **Size of source** – Not good to form images, as EW. More like sound: 2 polarizations carry stereophonic description of source.
- **Gravitons are coherent** - produced by source motion as a whole (photons are incoherent)
- **Observable h ~1/r**. Consequence of coherence. If sensitivity doubles, visible universe increases 8 x!
- **Detectors have 4π sensitivity**. All sky! Poor resolution, but access to all sky. Again, just like sound.

“Imagine being able to see the world but you are deaf, and then suddenly someone gives you the ability to hear things as well - you get an extra dimension of perception”

B. Schutz, BBC

Listening to the Universe

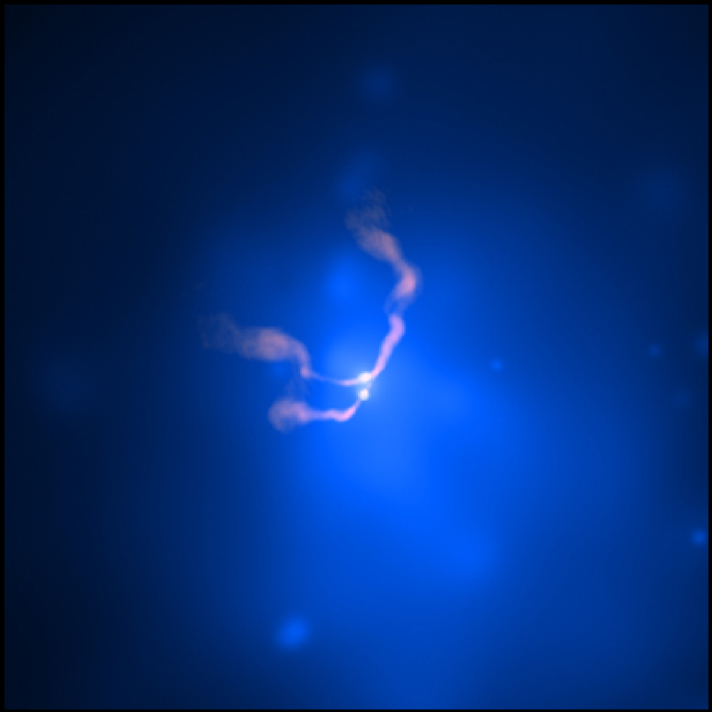


Big Jay Mc Neely, Photograph by Bob Willoughby

The instruments

Sources of gravitational waves

- ♦ Coalescing binary neutron stars or black holes
- ♦ Spinning neutron stars
- ♦ Gravitational bursts (e.g. supernovae)
- ♦ Big bang gravitational echo



Picture credit: NASA/CXC/AIfA; NRAO/VLA/NRL

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Picture credit: NASA/HST/STScI

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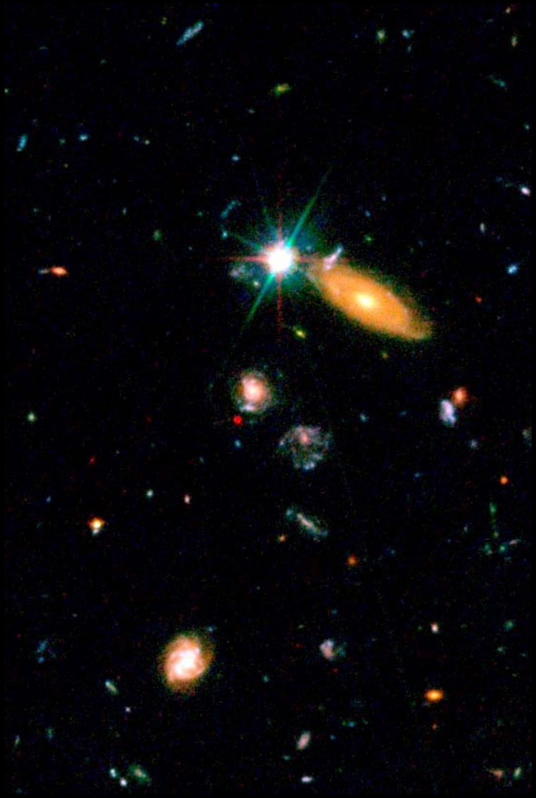

Picture credit: NASA/HST/STScI

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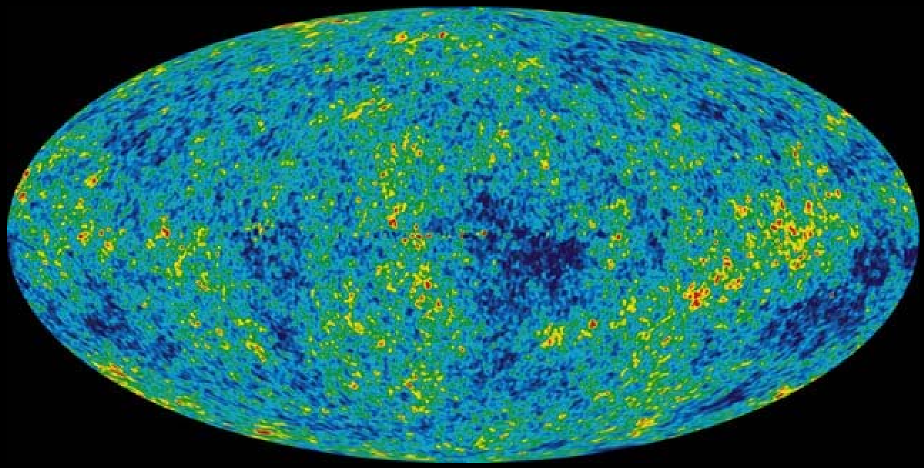
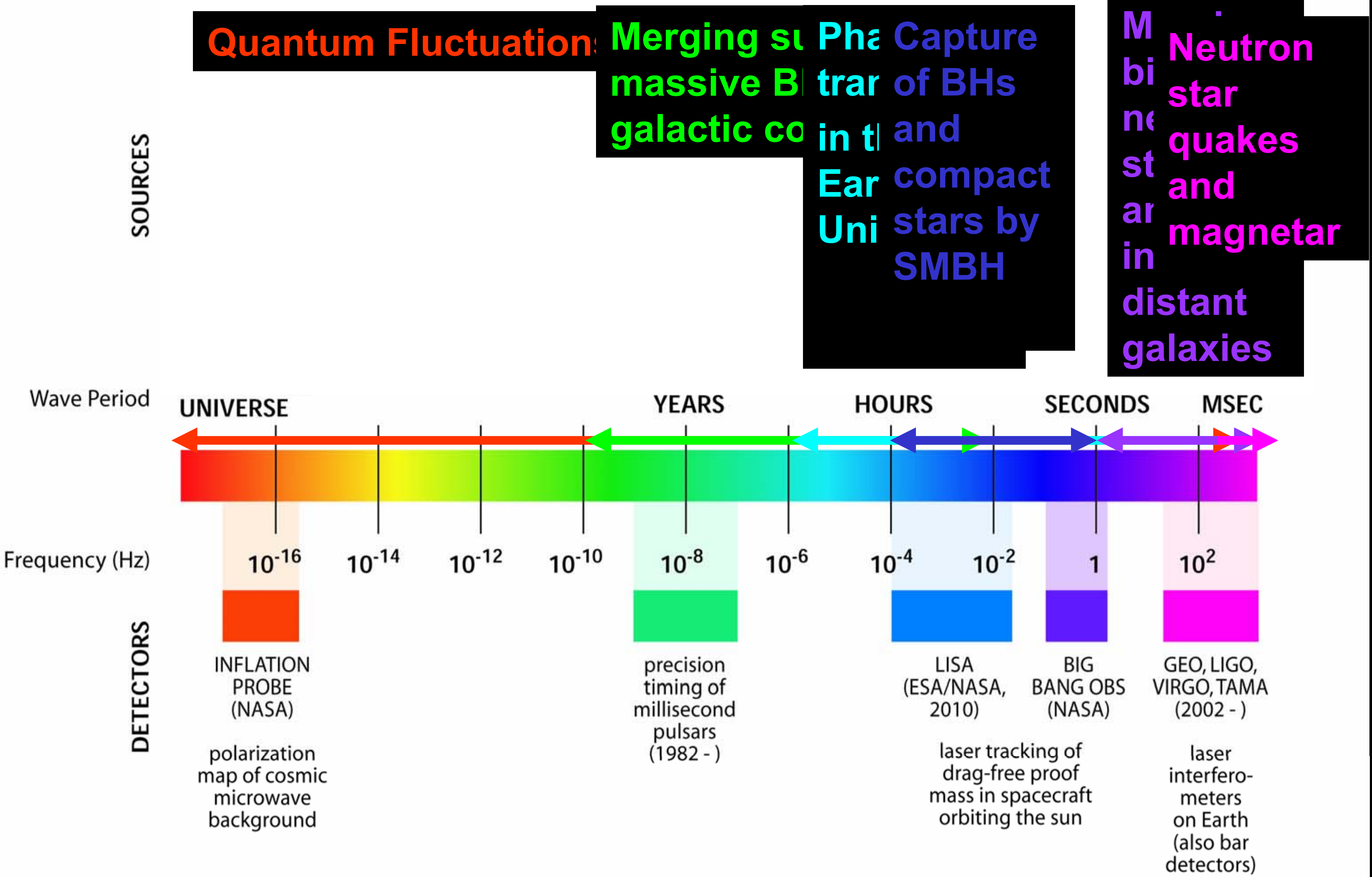


Picture credit: **NASA/WMAP**

Gravitational Wave Spectrum



Order of magnitude estimate

For a coalescing compact object into a black hole:

$$f \sim \frac{1}{M} \sim 10^4 \text{ Hz} \left(\frac{M_\odot}{M}\right)$$

$$h \sim \epsilon^{1/2} \frac{M}{r} \sim 10^{-21} \left(\frac{\epsilon}{0.01}\right)^{1/2} \left(\frac{M}{M_\odot}\right) \left(\frac{10 \text{ Mpc}}{r}\right)$$

Distance Earth-Sun (1.5 x 10^7 km)….

…stretches by a fraction of an atom!

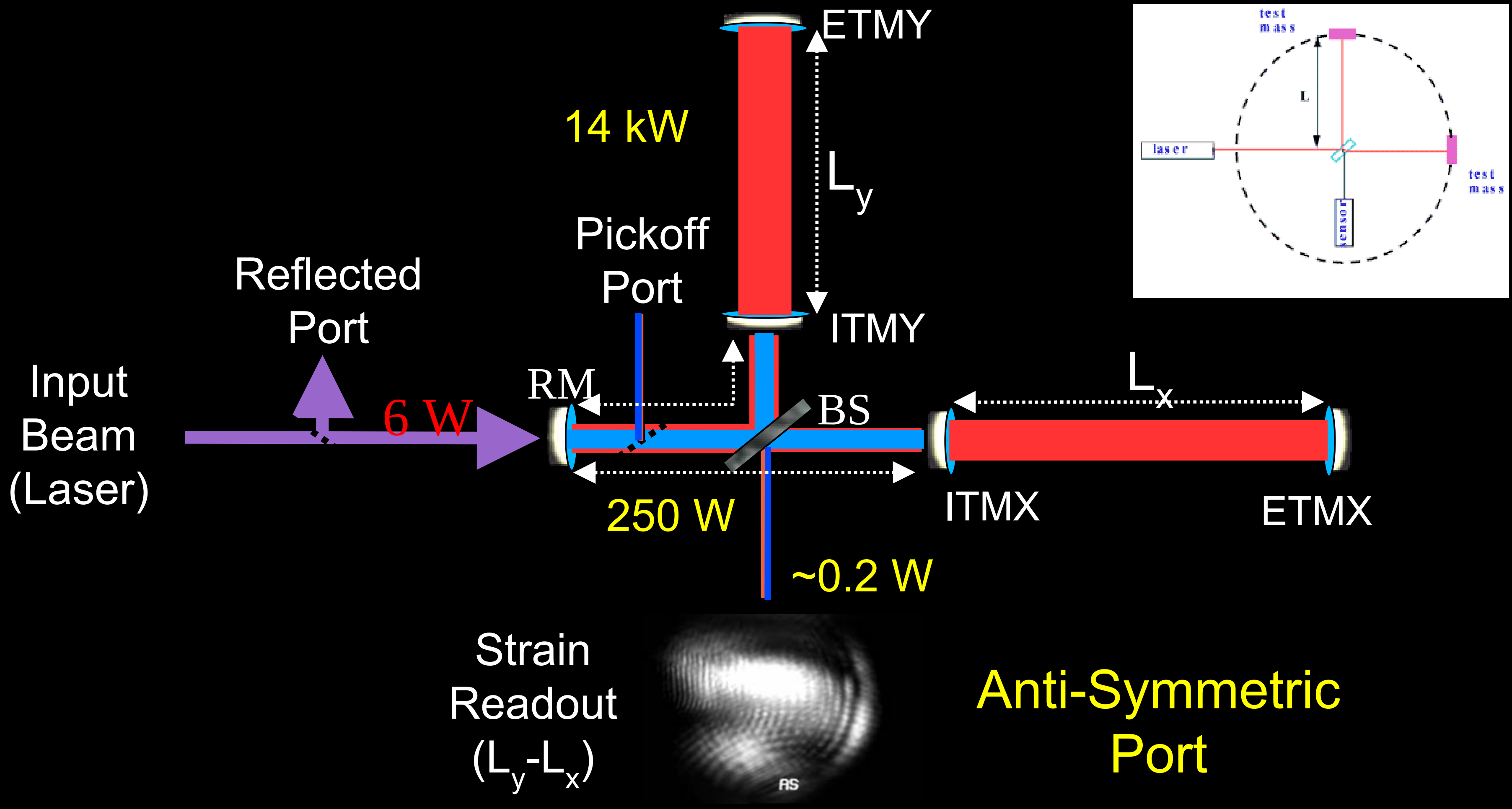
Order of magnitude estimate

But remember, the human ear can detect 10^{-11}m!

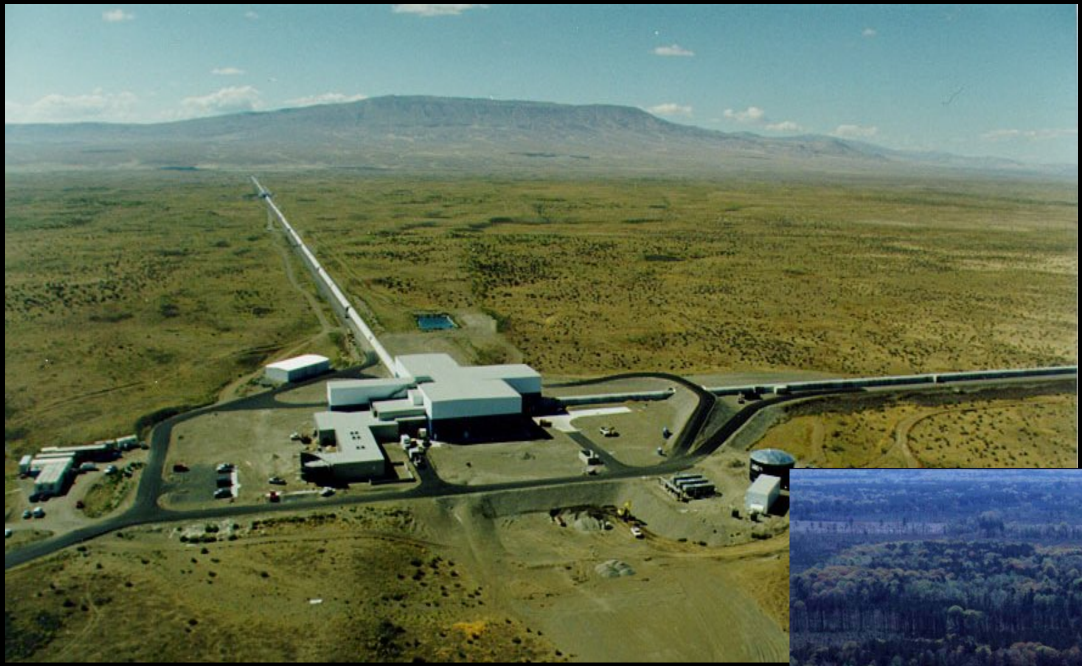
(R. Serway "Physics for Scientists and Engineers"; Ana Mourão)

The audience

LIGO instrument



LIGO instrument

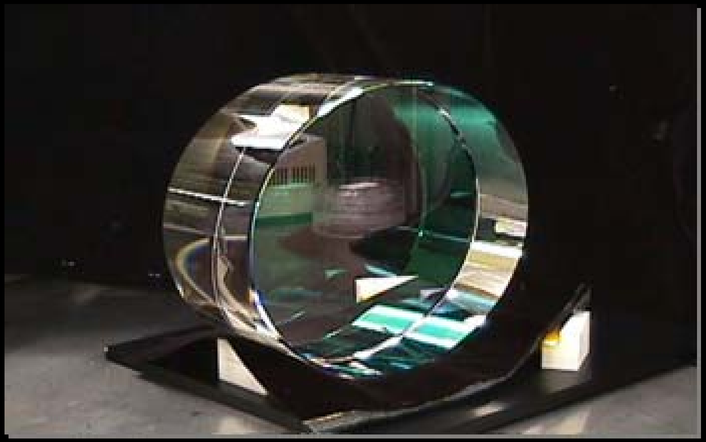


Hanford, WA

Livingston, LA

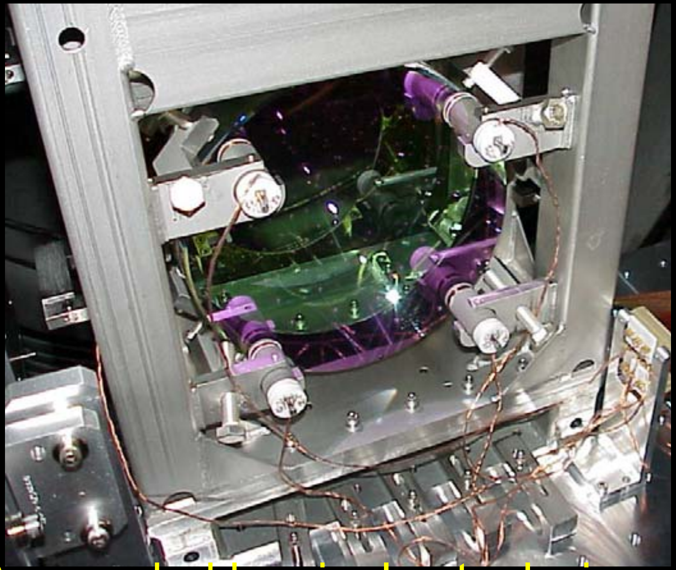
Vacuum equipment

Core optics



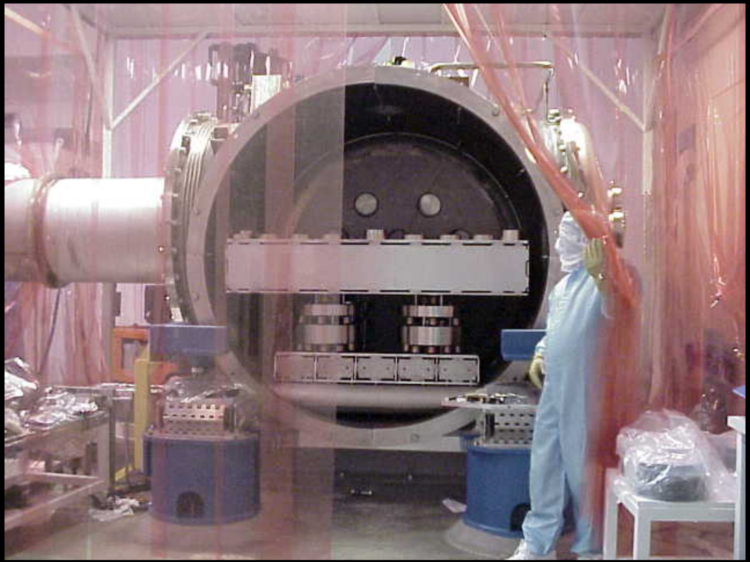
Fused silica (high-Q, low-absorption, 1 nm surface rms, 25-cm diameter)

Optics suspension



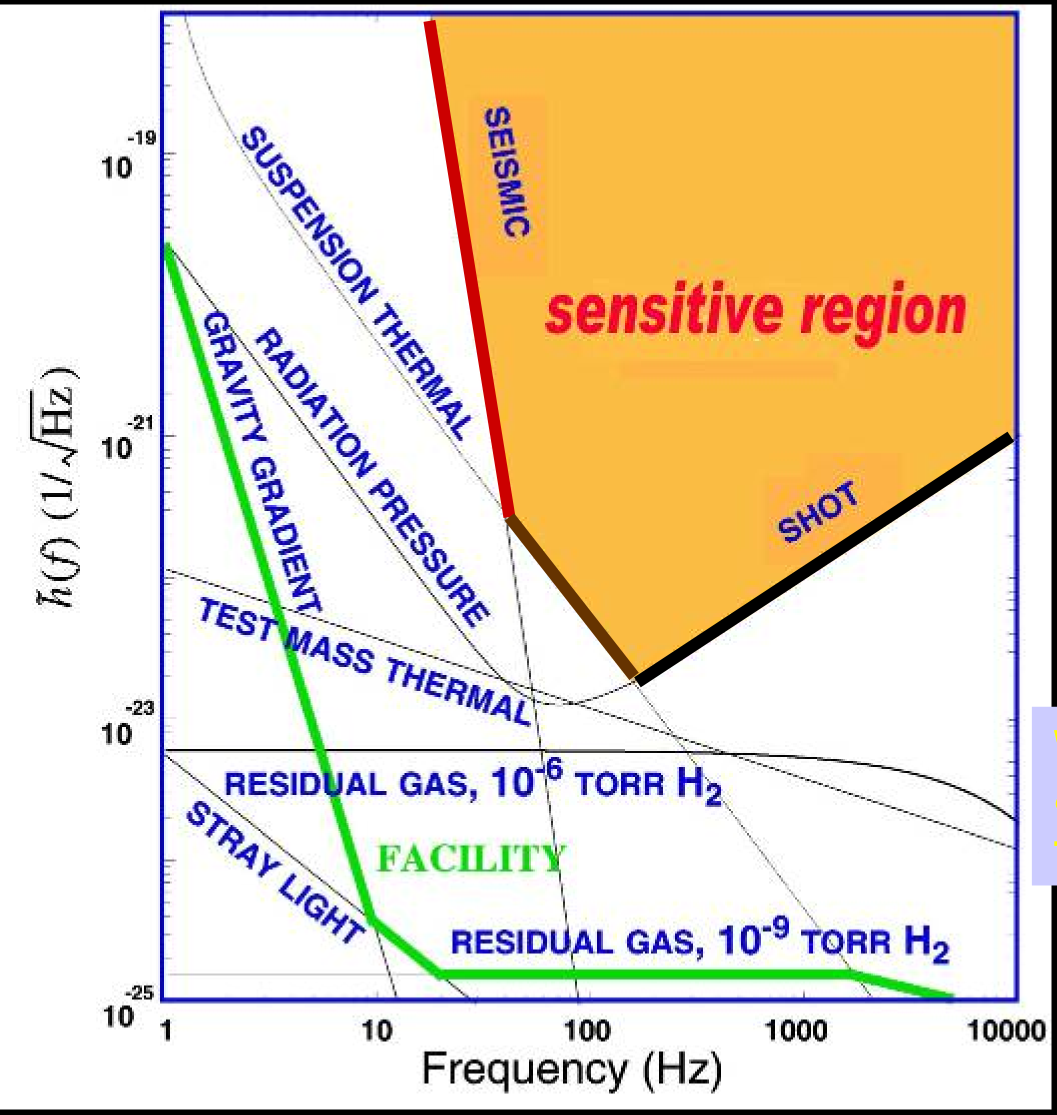
Suspended by single steel wire alignment with magnets and coils

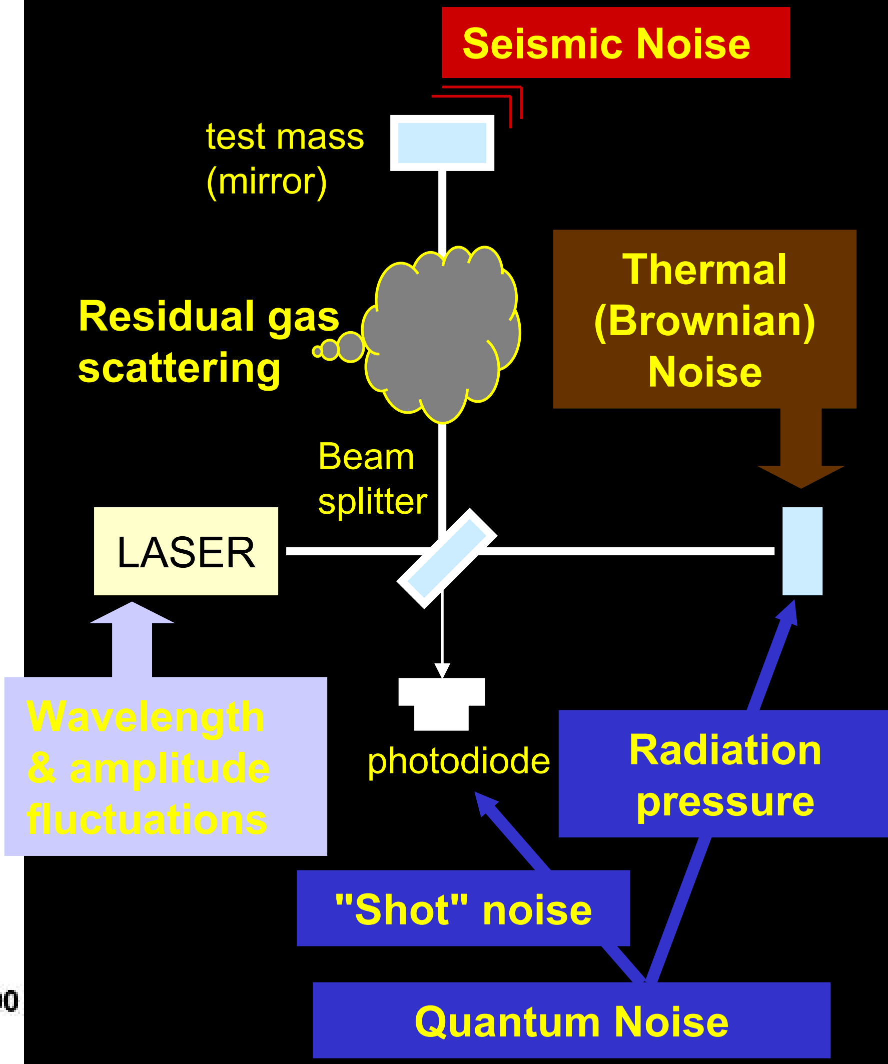
Seismic suspension



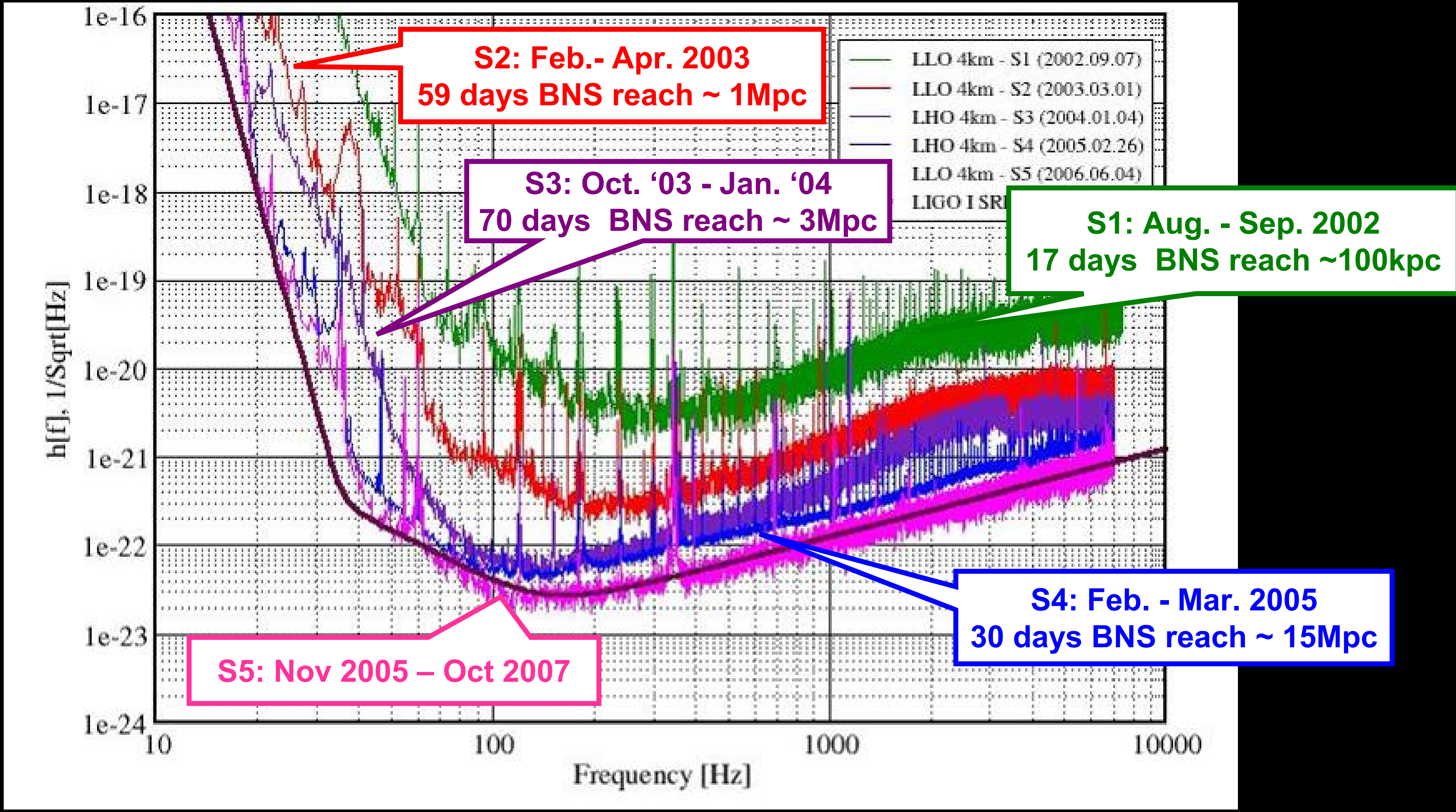
Optical table support gives 10^6 suppression

LIGO design sensitivity

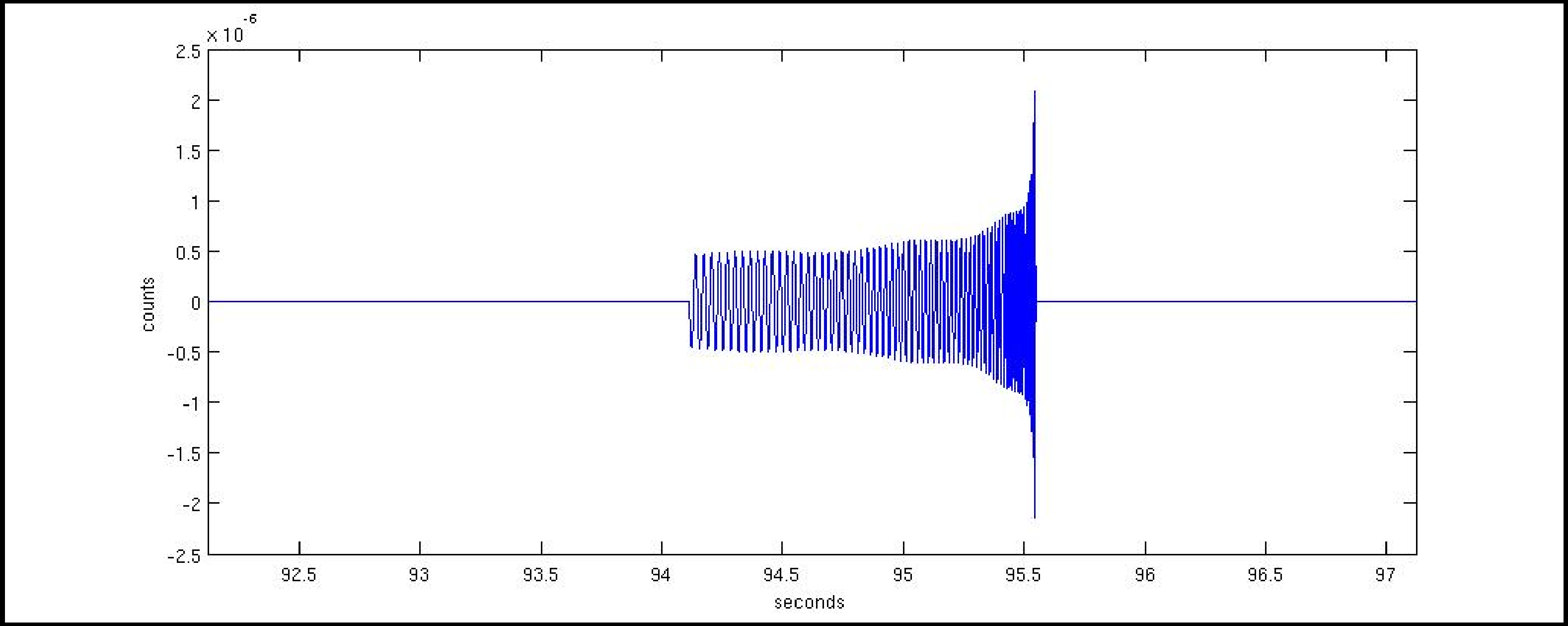




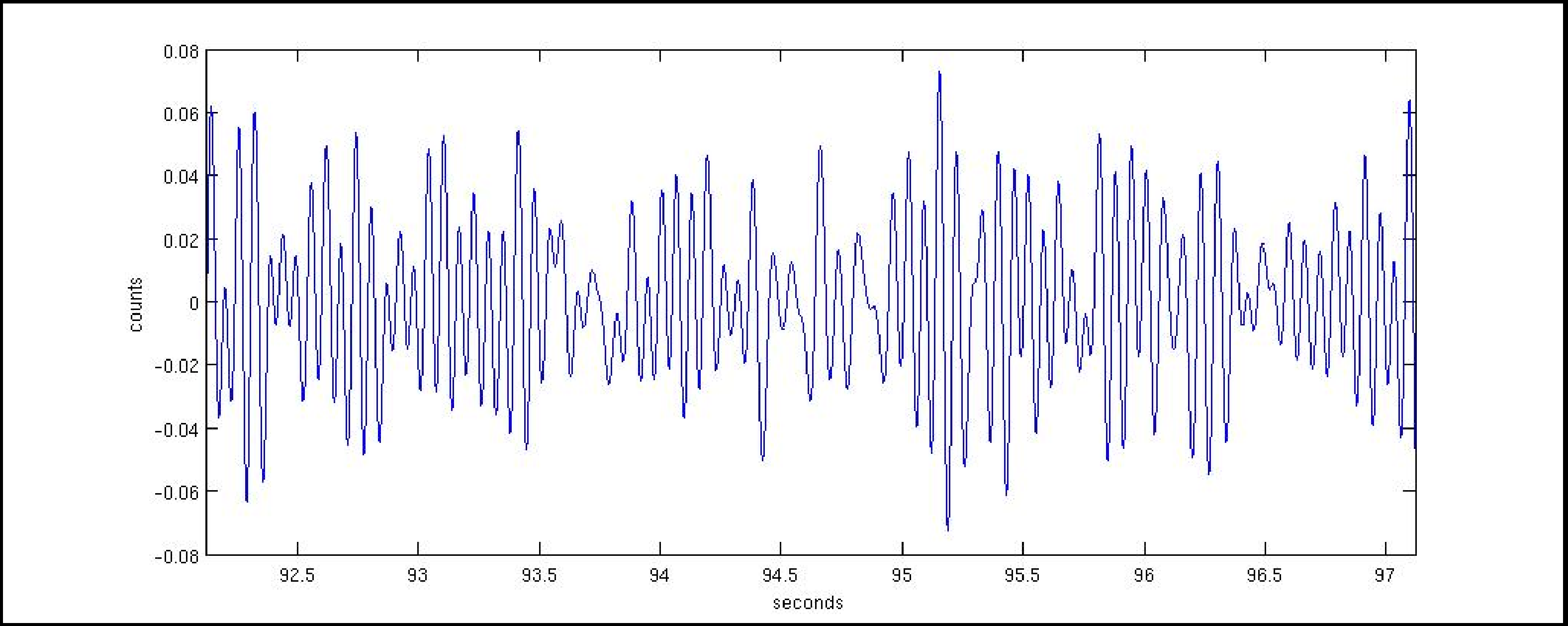
LIGO actual sensitivity



Typical signal for coalescing binaries



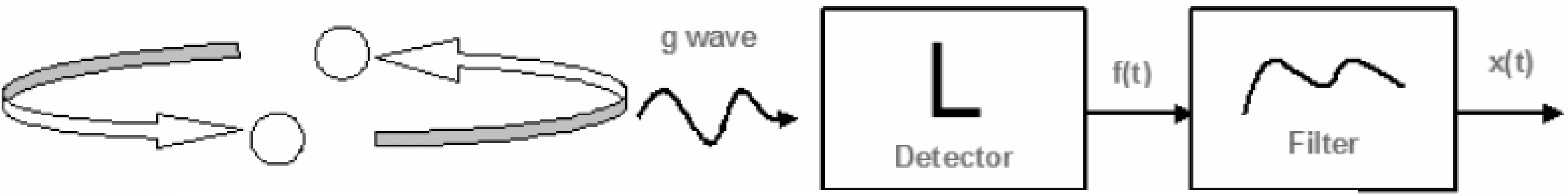
Typical stretch of data

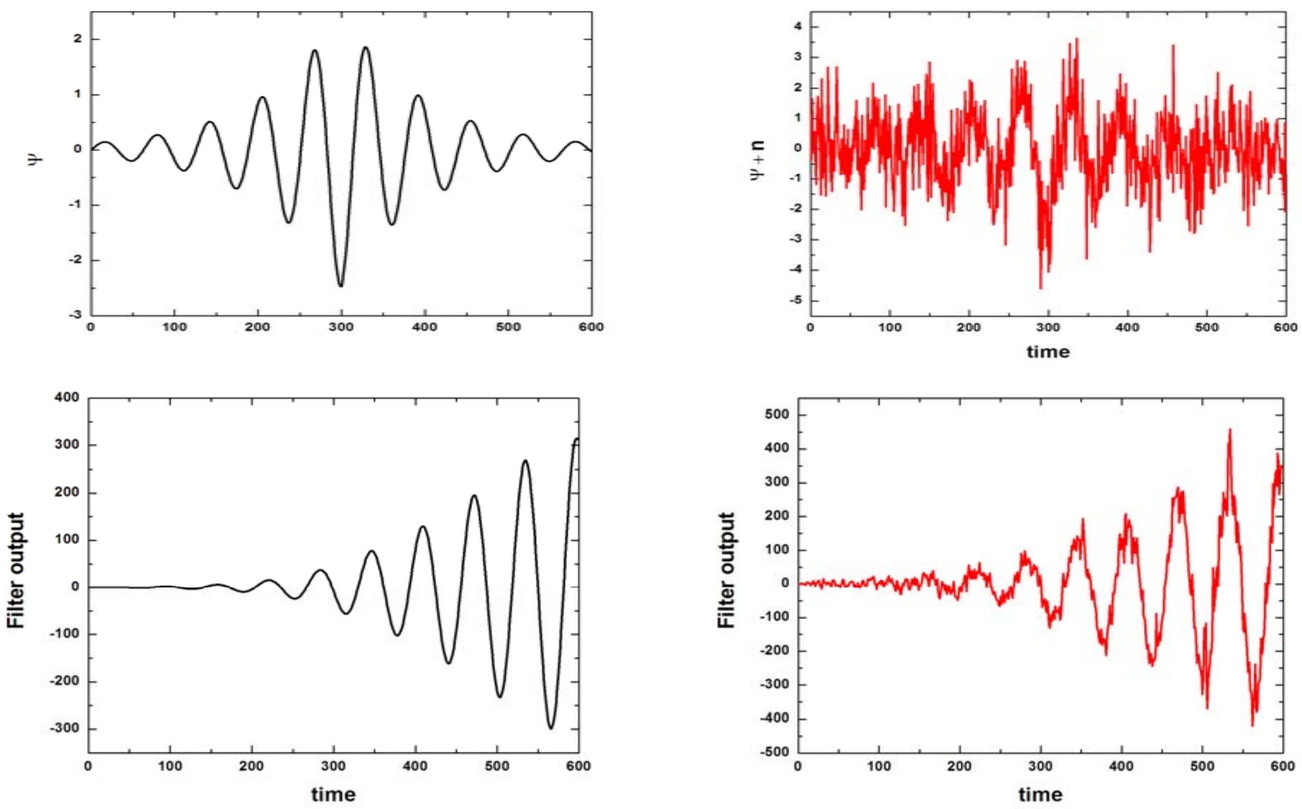


A typical  problem!

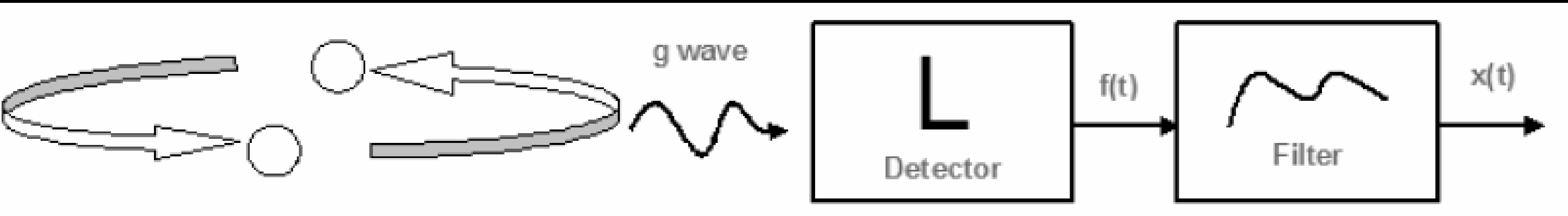
(but with a smaller needle)

Matched-Filtering





Matched Filtering



- Wrong filter
- Mismatch
- Decreased SNR

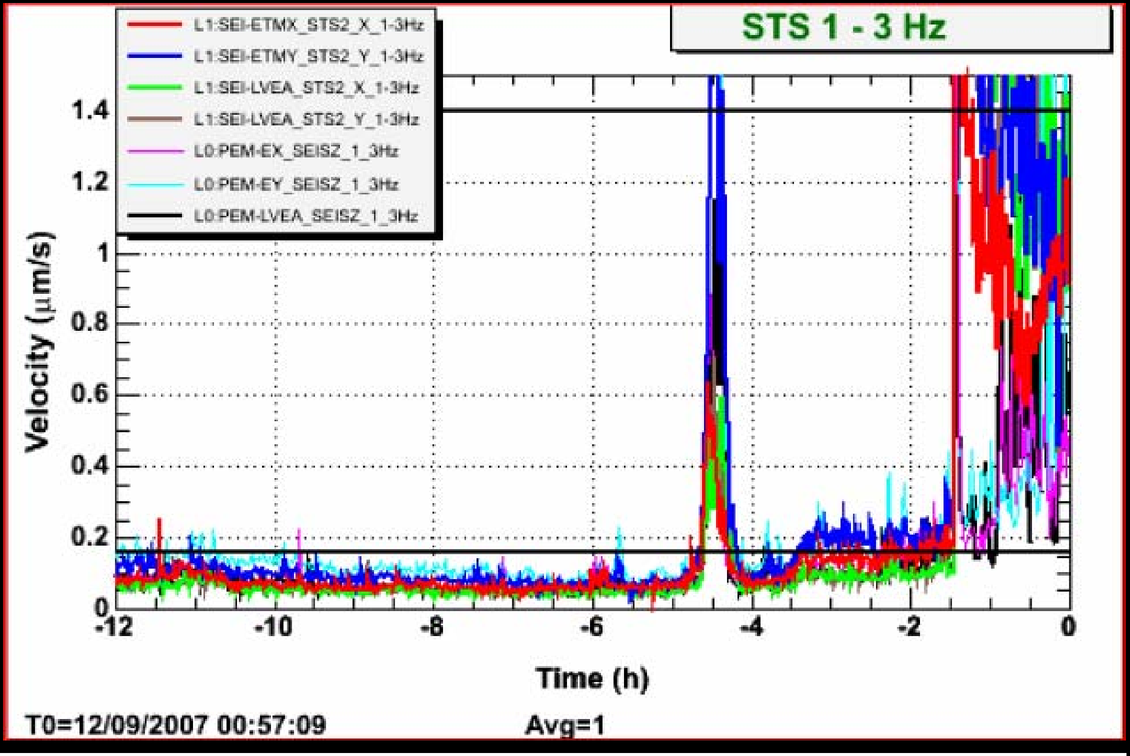
3% Mismatch: 10% lost events!

Analysis pipeline (CBC search)

- Data quality cuts
- Matched filtering → **Triggers – level I**
- Time+parameter coincidence
- Refined MF+ signal based vetoes+coincidence
  → **Triggers – level II**
- Coherent SNR for multiple detectors → **Final triggers**
- Careful follow-up of single candidates

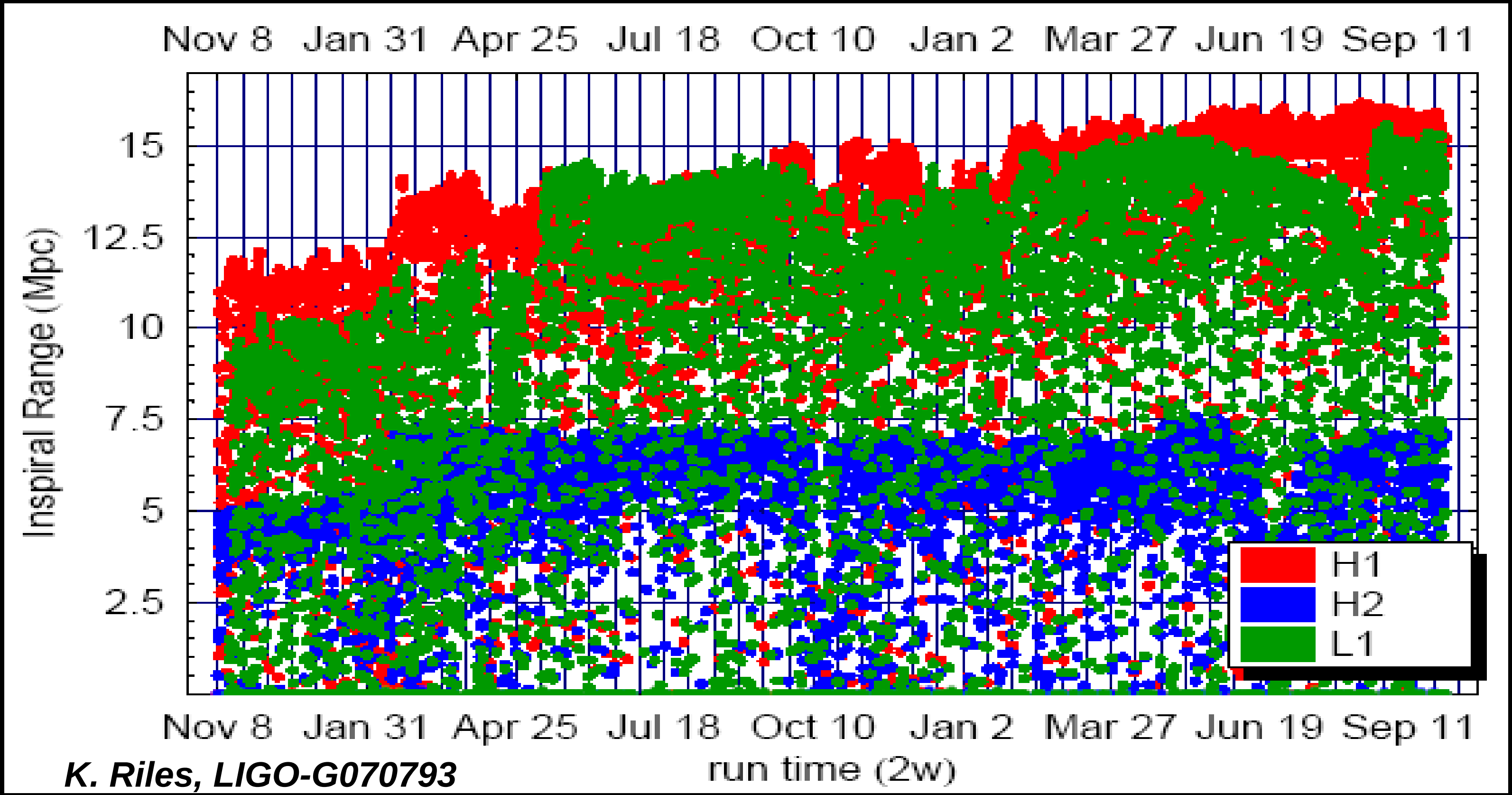
LIGO is so sensitive that it feels

- ♦ Cars and trucks
- ♦ Airplanes
- ♦ Sea waves
- ♦ Earthquakes…



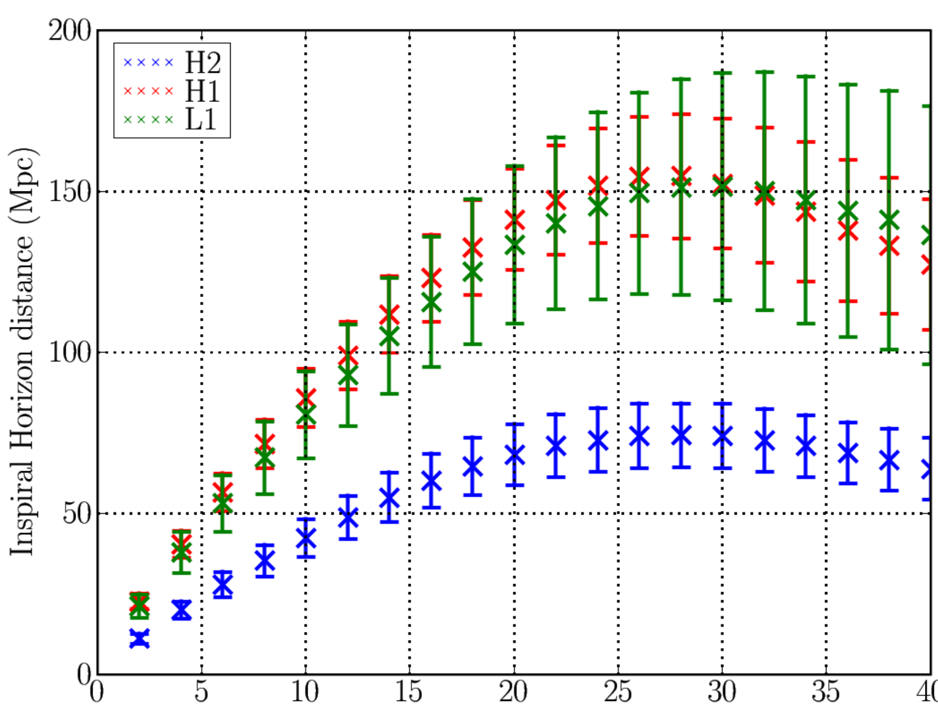
MAP	5.2	2007/09/12 12:21:44	-2.667	100.318	10.0	KEPULAUAN MENTAWAI REGION, INDONESIA
MAP	8.4	2007/09/12 11:10:26	-4.517	101.382	30.0	SOUTHERN SUMATRA, INDONESIA

BNS horizon distance



Distance to which an interferometer can detect an inspiral NS-NS system, averaged over all sky positions and orientations with snr=8

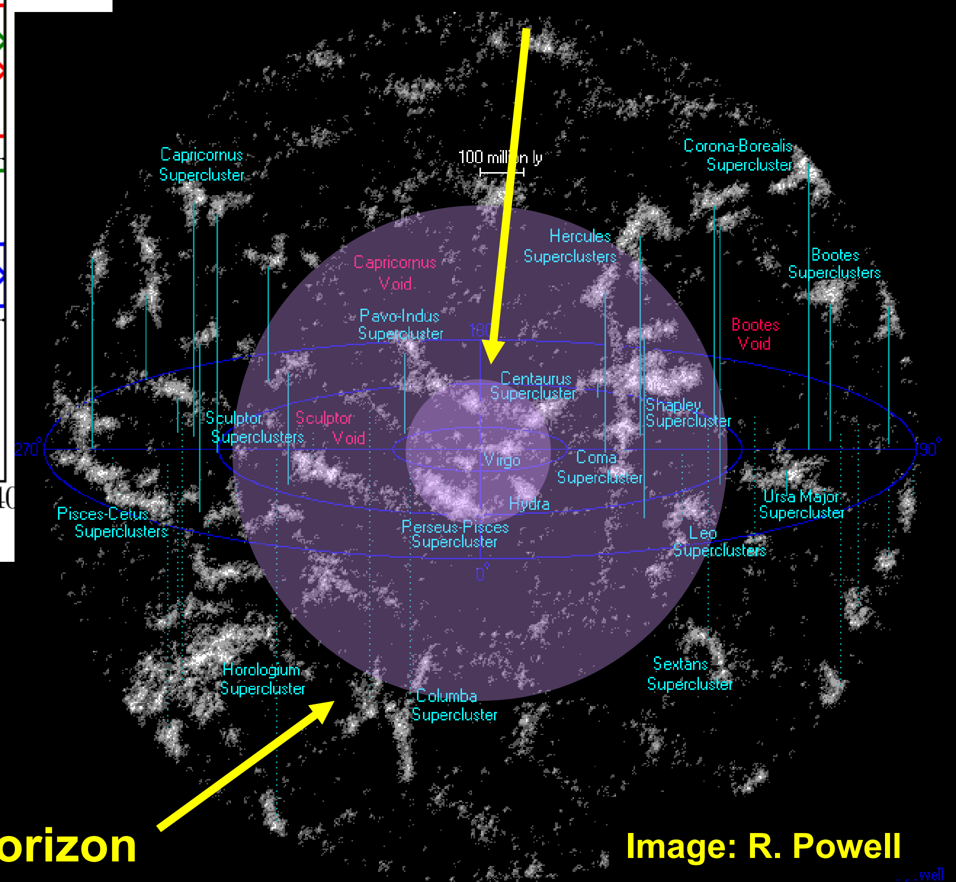
LIGO instrument



D. Brown, G070800-00

Mass dependence

S5 BNS horizon = 30Mpc



S5 BBH horizon

Image: R. Powell

GRB070201

[arXiv:0711.1163]

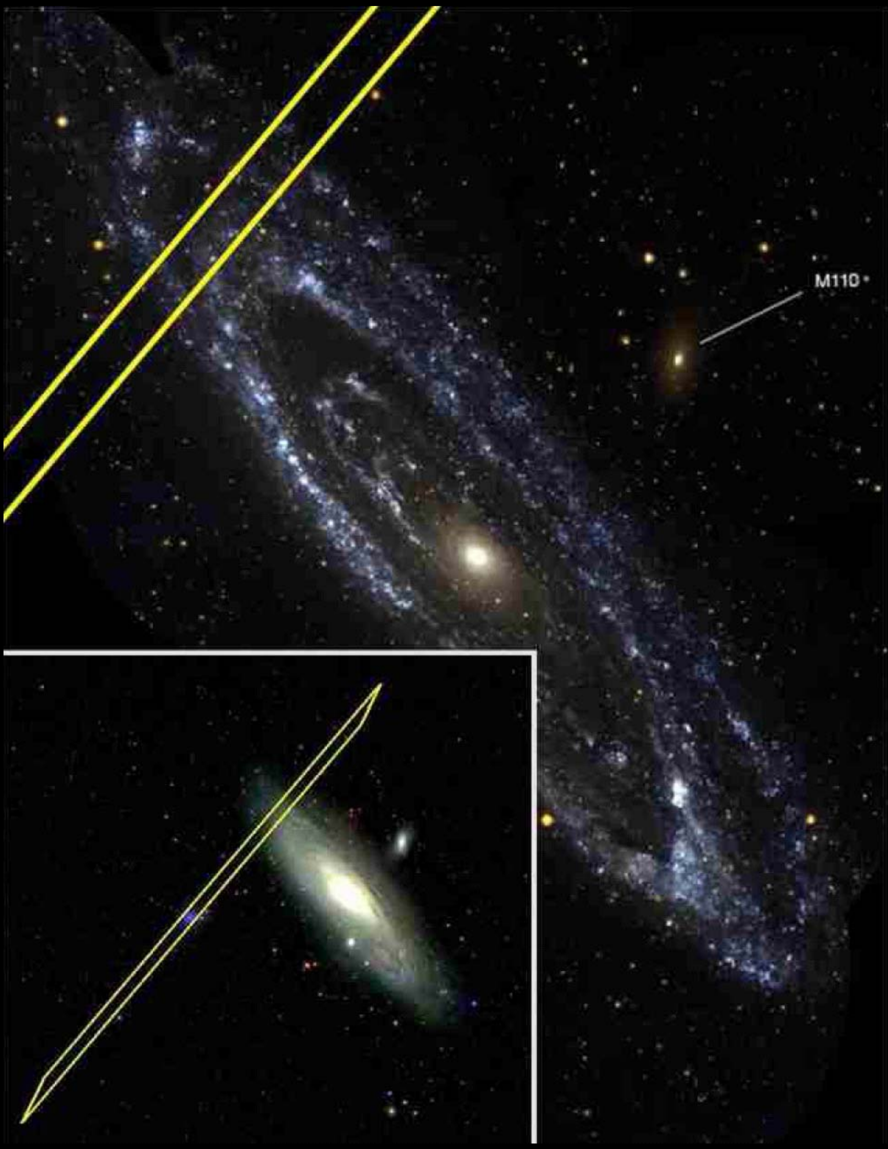
Intense, short-duration hard GRB

Flux: $1.57^{-0.21}_{+0.06} \times 10^{-5}\ \mathrm{erg \cdot cm^{-2}}$

Frequency: 20 keV – 1 MeV

Sky position compatible with Andromeda (770 kpc)

↳ **$E \sim 10^{45}$ erg**



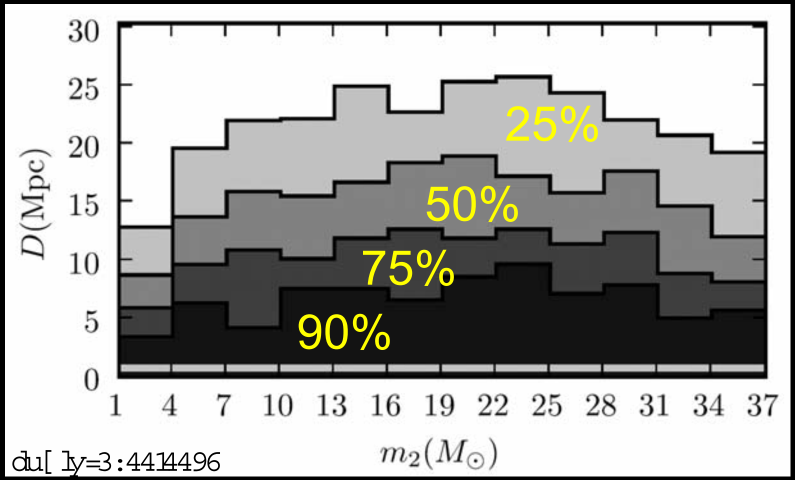
CBC search

35.7 Mpc (H1)

15.3 Mpc (H2)

x 43%

No event observed



LIGO in the future

Enhanced LIGO:

- ♦ Factor of **2** improvement in sensitivity (**event rate x 8**)
- ♦ Install in 2008 - online in 2009 for one yr

Advanced LIGO:

- ♦ Factor of **10** improvement in sensitivity (**event rate x 1000**)
- ♦ Install starting in 2011 - online in 2014

BNS range:

Initial LIGO - Hundreds of galaxies

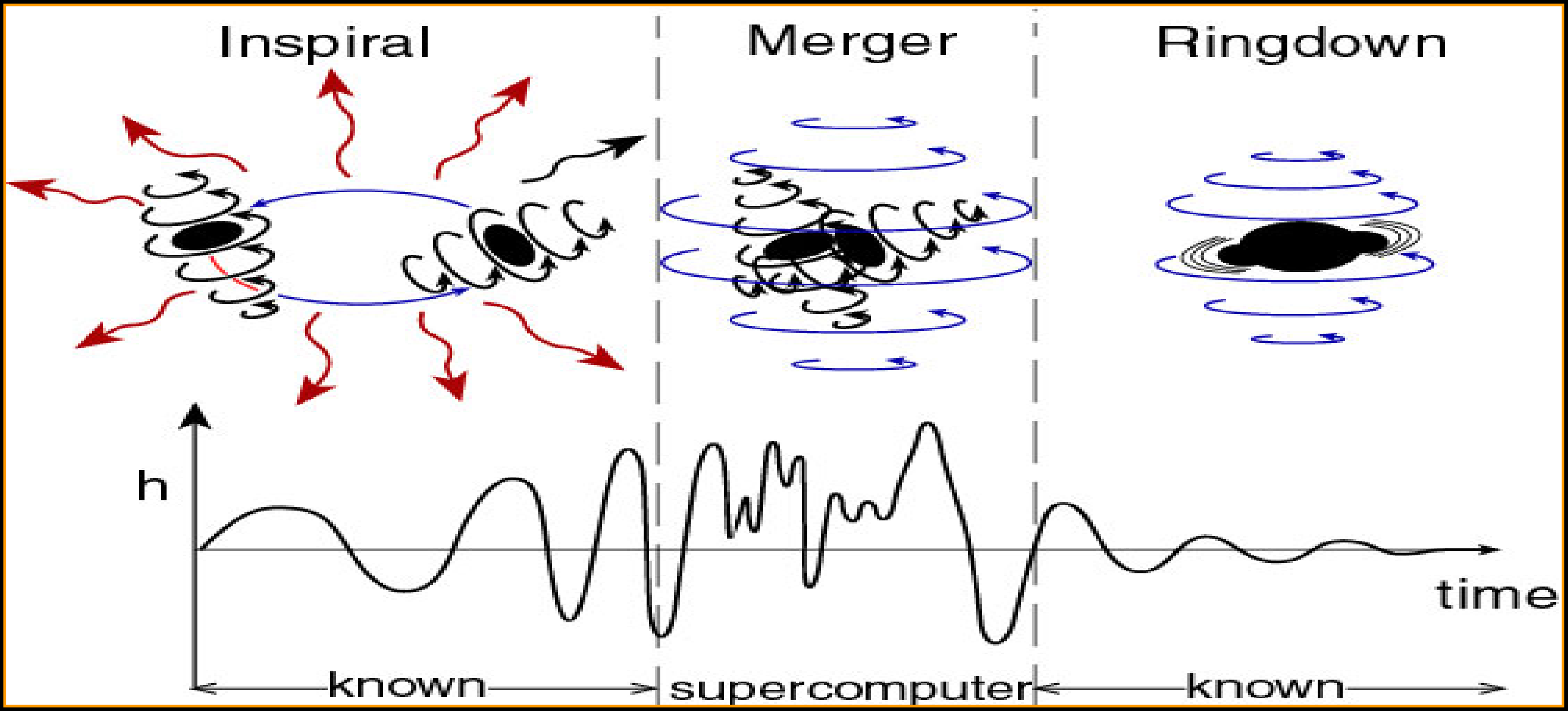
ELI - Thousands of galaxies

AdL - Millions of galaxies!

3 hrs of AdL ~ 1 yr of initial LIGO

The sound

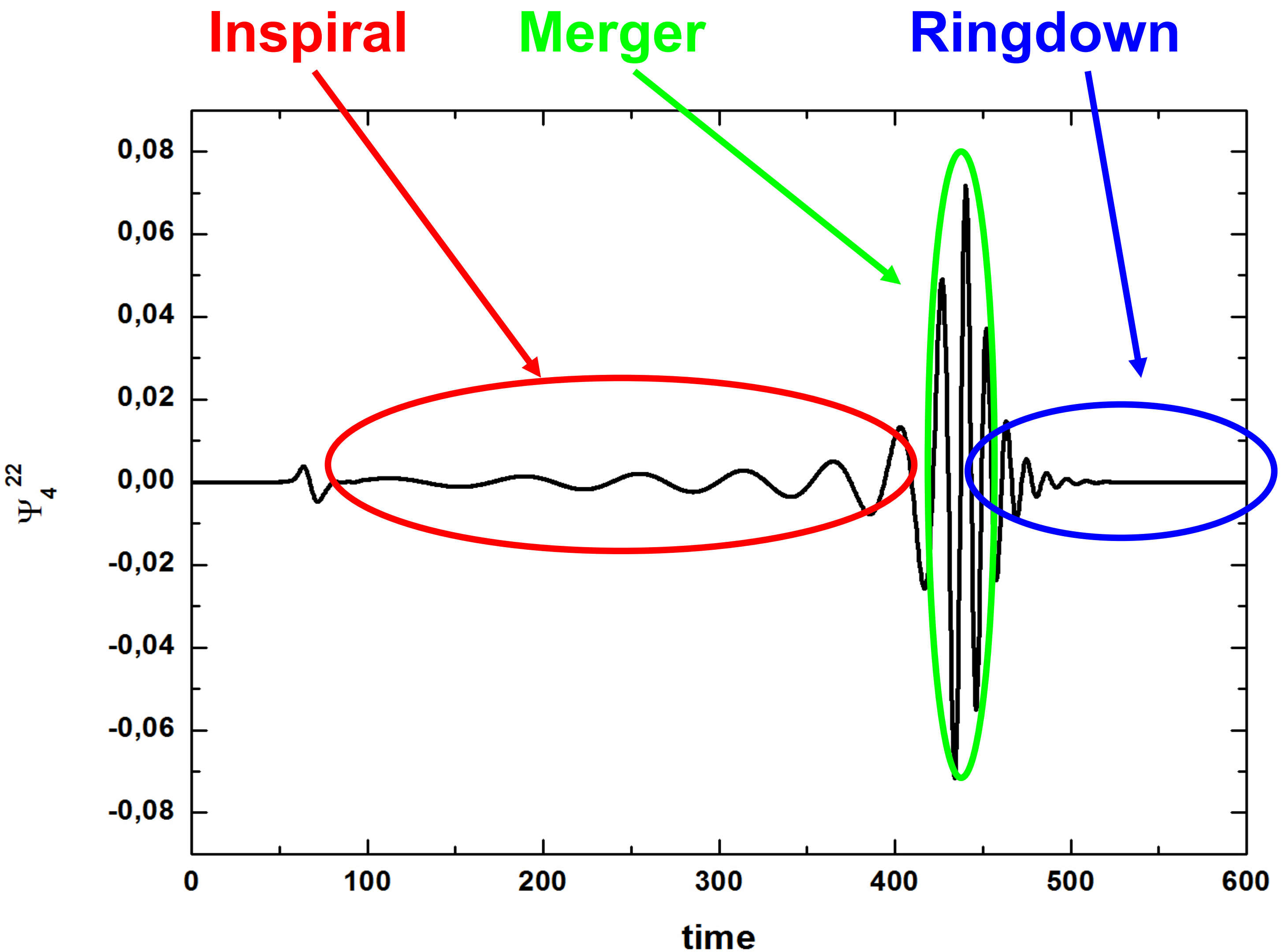
BH coalescence



BH coalescence

Courtesy Marcus Thierfelder and Bernd Bruegmann

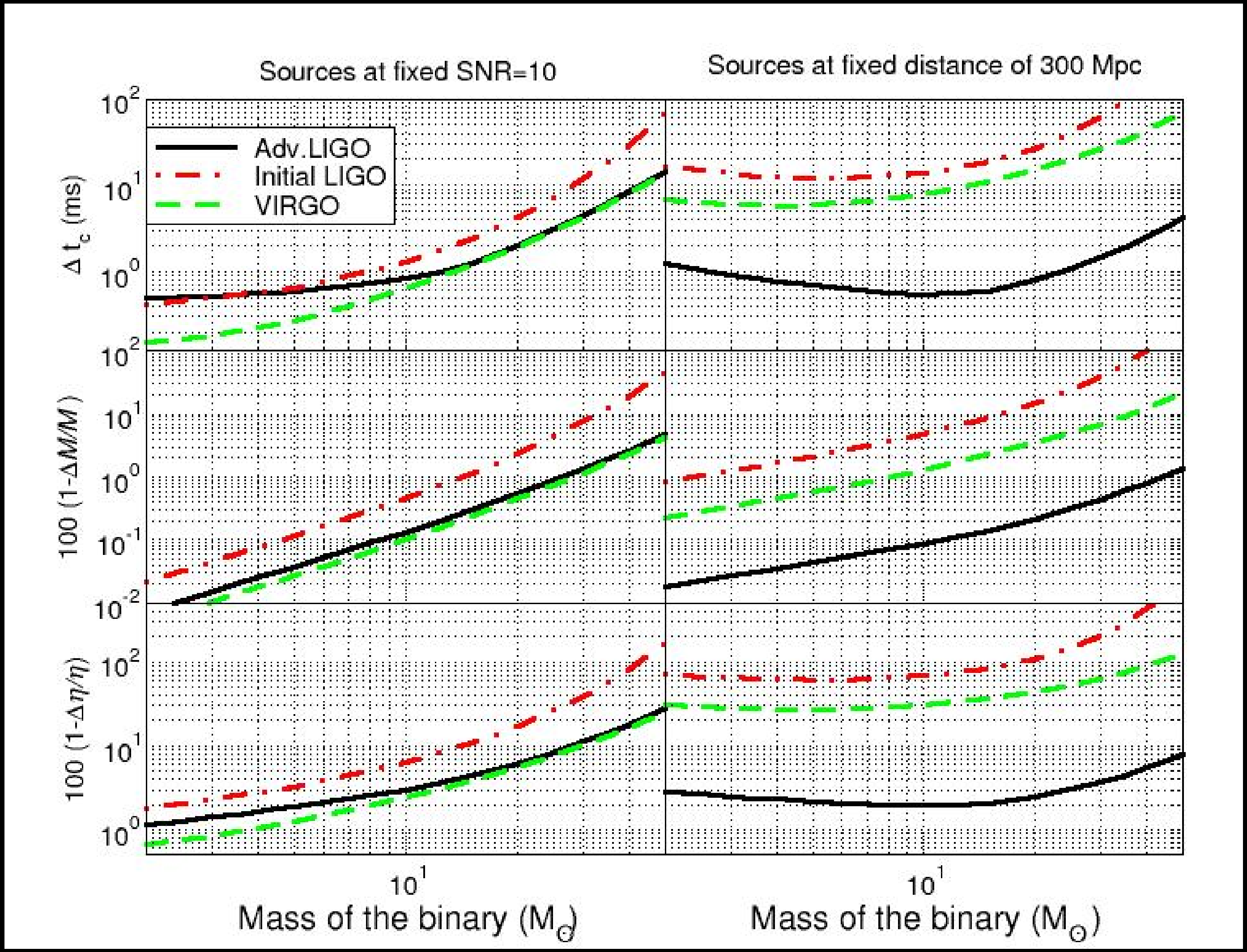
Typical signal for BH binaries



(Berti, Cardoso, Sperhake, Gonzalez, Brugmann, Hannam & Husa,PRD76:064034,2007)

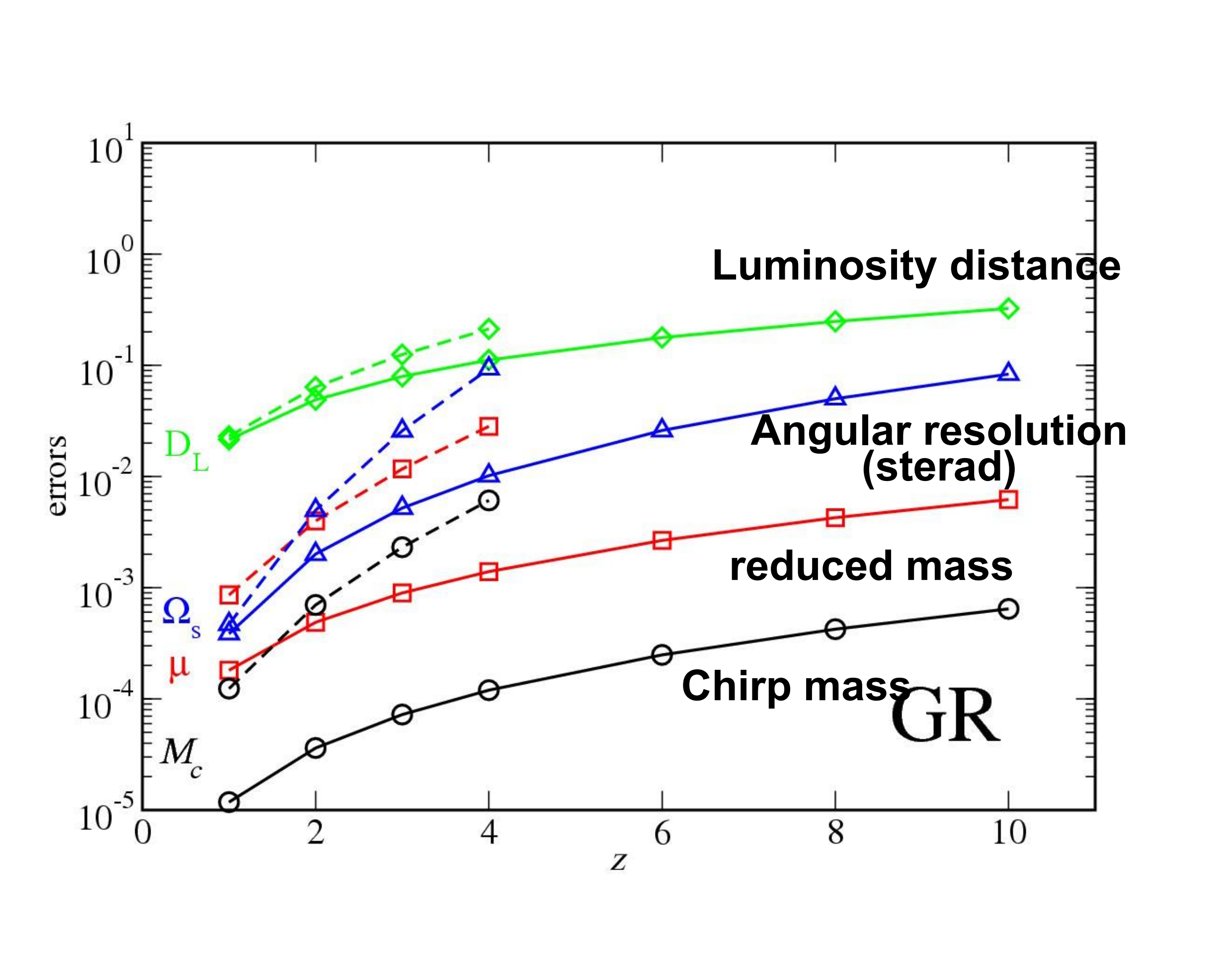
Can the audience guess the instrument from the sound?

Inspiral: Earth-based



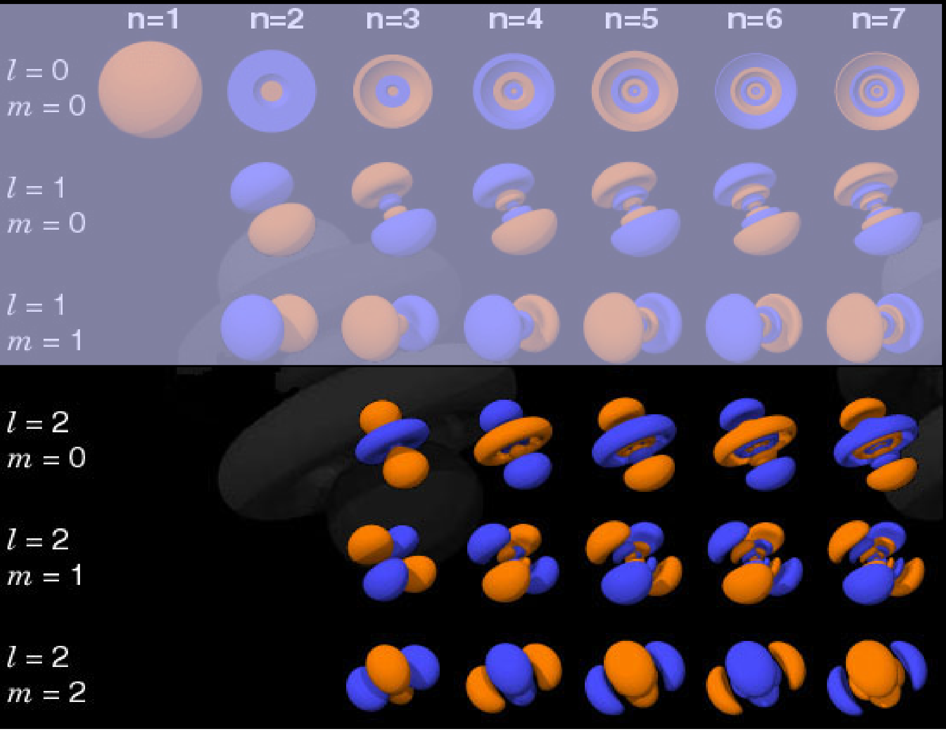
(Arun et al, PRD71:084008,2005)

Inspiral:LISA



2x10^{6}M (solid) and 2x10^{7}M (dashed)

(Berti, Buonanno & Will, PRD71:084025,2005)



BH spectrosocpy

$$10M\omega_{\ell\,\ell\,0} \approx 7.4 + 3.9\ell - (7.8 + 1.8\ell)\left(1 - \frac{J}{M^2}\right)^{\frac{3.2+4.9\ell}{100}}$$

$$10Q_{\ell\,\ell\,0} \approx 2.6 + 2.2\ell + (-3.6 + 8.8\ell)\left(1 - \frac{J}{M^2}\right)^{-0.49}$$

(Cardoso, 2007)

Ringdown

✓ **One mode detection:**

- *Suppose* we know which mode we are detecting (eg. **l=m=2**); then

$$\mathbf{f(M,j),\ t(M,j) \longrightarrow M(f,t),\ j(f,t)}$$

- Measure of black hole's mass and angular momentum

(Echeverria, PRD40:3194-3203,1989; Finn, PRD46:5236-5249,1992)

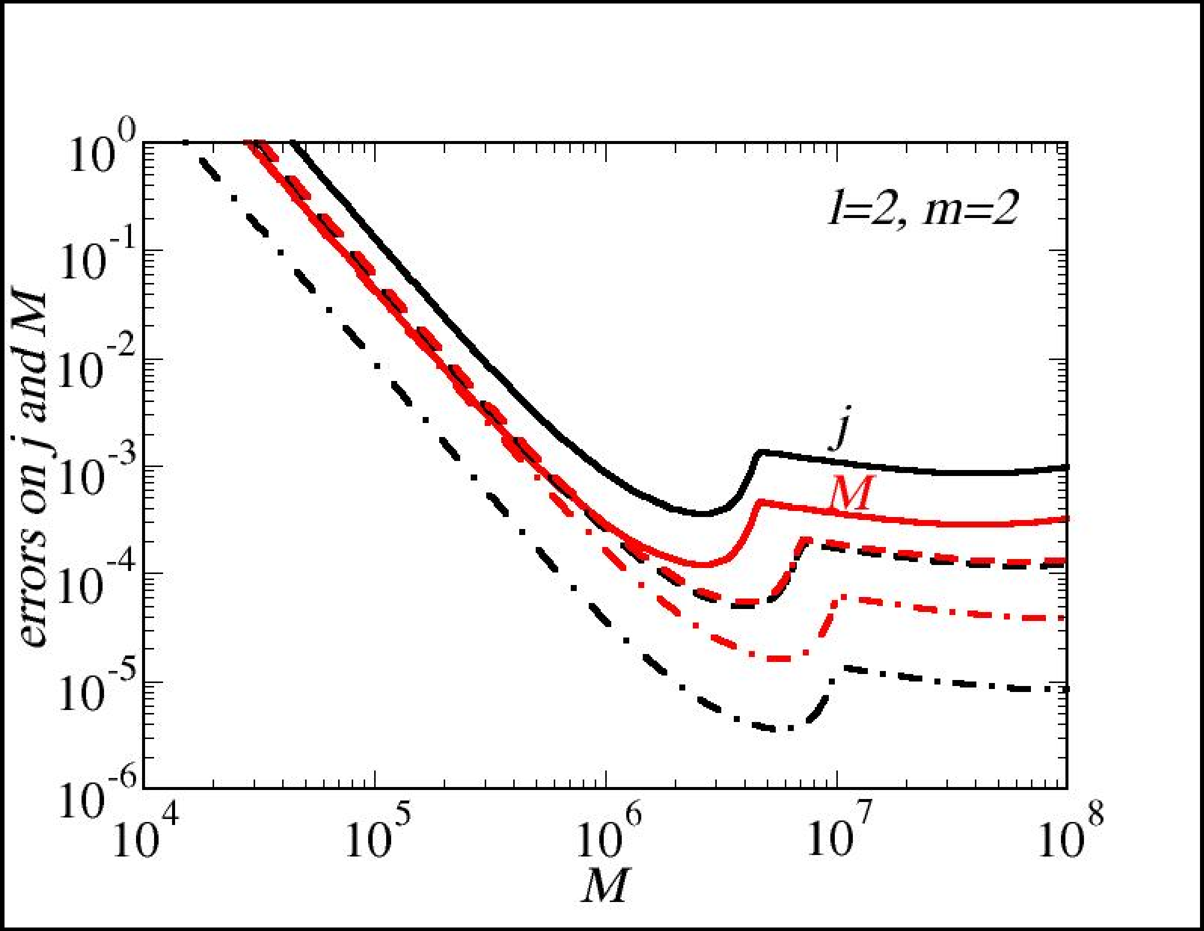
✓ **Multi-mode detection:**

- First mode yields **(M,j)**
- In GR, Kerr modes depend ***only*** on **M** and j:

second mode yields test that we are observing a Kerr black hole, if we can resolve the modes

(Berti, Cardoso & Will, PRD71:084025,2005)

Ringdown: LISA



j=0,0.8,0.98

(Berti, Cardoso & Will, PRD71:084025,2005)

And now what? Physics

Velocity of propagation: timing with EM observations

Angular resolution 10^{-5}: needs three or more detectors

(Redshifted) Mass and Angular momentum to levels of 1%

Distance to 10%

Standard candles to measure the Hubble constant:

(i) (Schutz, Nature, 1986)

a) Determine distance to source

b) Identify host galaxy and measure its redshift

(ii) (Markovic, PRD 1993)

Assume neutron stars have 1.4 . Determine z

Conclusions

Exciting times for gravitational-wave research!

- ♦ Advances in theory and numerical relativity
- ♦ LIGO has reached design sensitivity. Being upgraded
- ♦ A network of gravitational-wave observatories
- ♦ GRB070201: Birth of gravitational-wave astrophysics
- ♦ Birth of a new science: Gravitational wave astronomy

Conclusions

Gravitational wave astronomy:

✓ Birth and interaction of massive objects, specially BHS

✓Central engine for GRBs

✓ Demographics of very compact objects (gws determine mass and spin to better than 1%!)

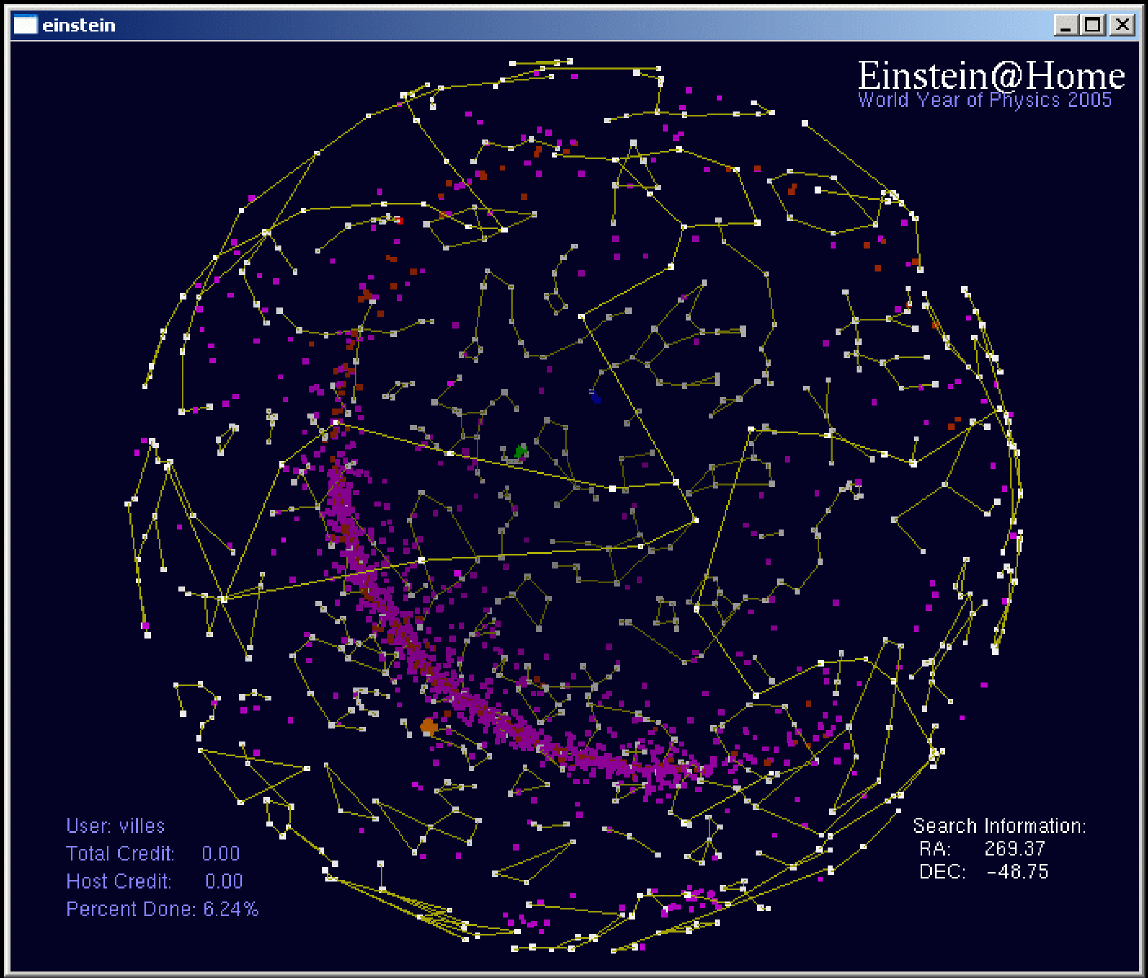
✓ Formation of proto-galactic structure and dark matter halos. Galaxy coalescence

✓Does GR describe strong field regime?

✓?

You can contribute too

Einstein@home project



USERS	Approximate #
Fri Mar 28 2008 01:07 UTC	
in database	317,699
with credit	193,994
registered in past 24 hours	187

HOST COMPUTERS	Approximate #
in database	926,386
registered in past 24 hours	3,163
with credit	472,438
active in past 7 days	78,102
floating point speed[1)]	117.4 TFLOPS

http://www.einsteinathome.org

Thank you