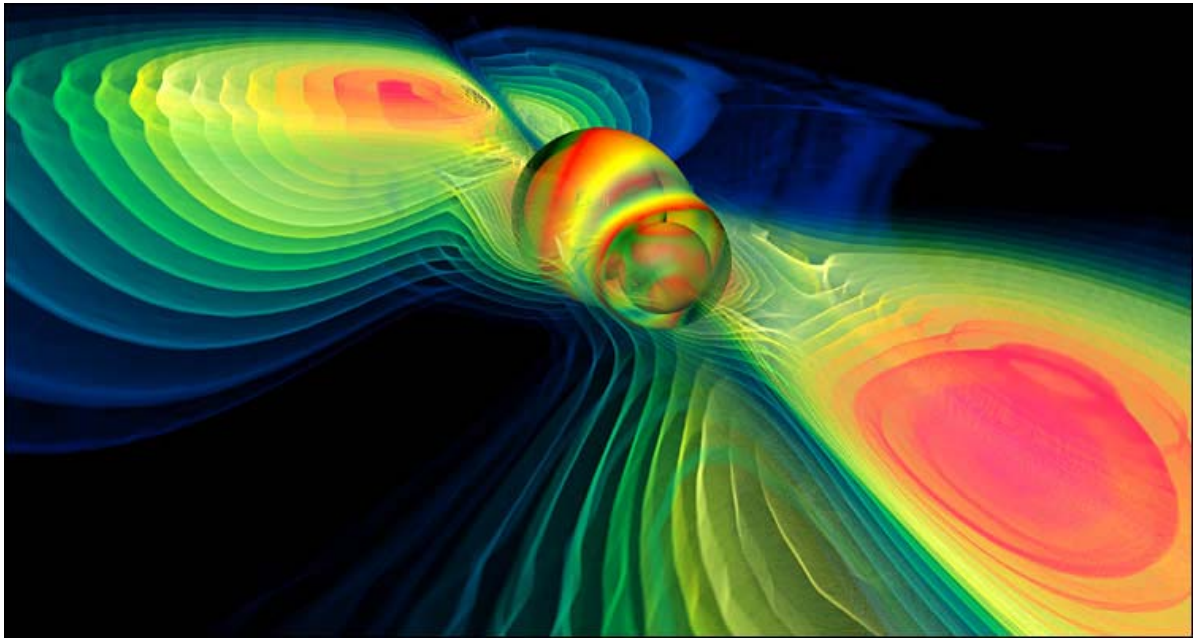
Gravitational waves: the sound of the universe



Vítor Cardoso
(CENTRA/Técnico & Perimeter)

TÉCNICO LISBOA centra blackholes.ist.utl.pt erc supports this project

Plan

Generalities

Properties of gws

GWs as the sound of the universe

Listening to the Universe

The instruments

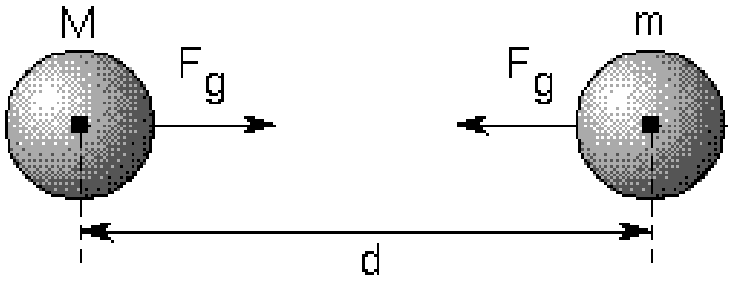
The audience

The sound

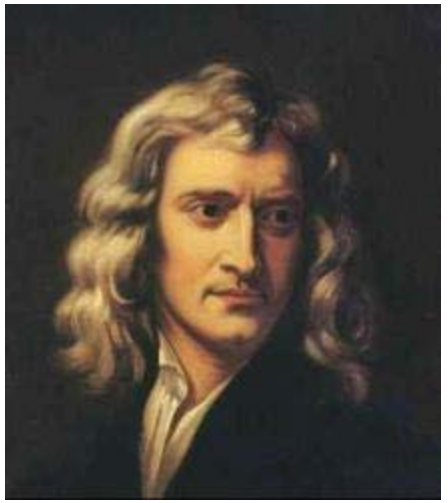
What's that playing?

Conclusions

Newton: “Action at a distance”



$$F_g = \frac{GMm}{d^2}$$



Action at a distance

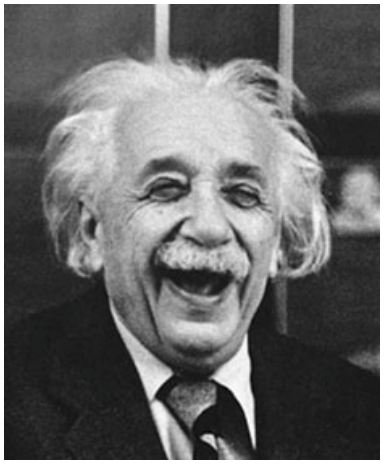
Instantaneous (contradicts SR)

All objects fall in same way

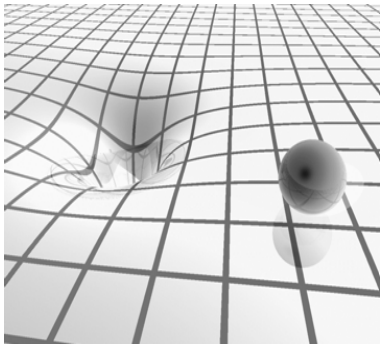
Einstein: Gravity is curvature

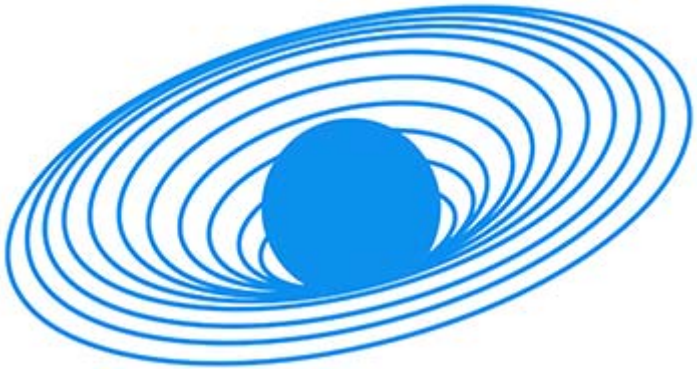
"Space-time tells mater how to move, matter tells spacetime how to curve"

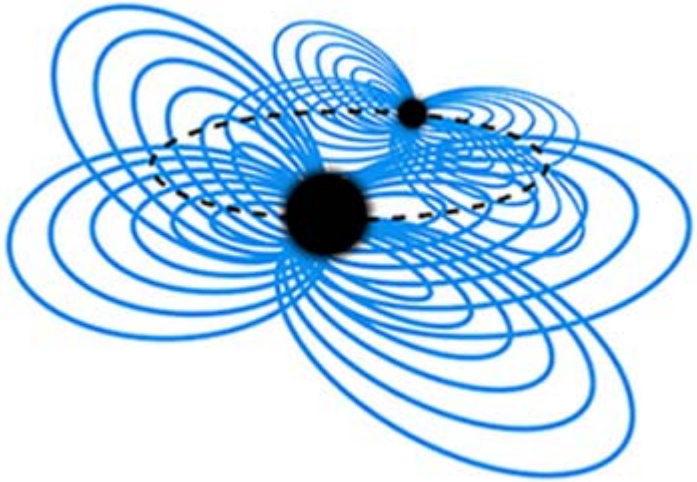
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$



Any mass-energy curves spacetime; free objects follow curvature







What are gws?

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

$$\Gamma^\mu_{\nu\rho} = \frac{1}{2}g^{\mu\alpha}\left(\partial_\rho g_{\alpha\nu} + \partial_\nu g_{\alpha\rho} - \partial_\alpha g_{\nu\rho}\right)$$

$$R^\mu_{\nu\alpha\beta} = \partial_\alpha\Gamma^\mu_{\nu\beta} - \partial_\beta\Gamma^\mu_{\nu\alpha} + \Gamma^\mu_{\alpha\eta}\Gamma^\eta_{\beta\nu} - \Gamma^\mu_{\beta\eta}\Gamma^\eta_{\alpha\nu}$$

$$R_{\mu\nu} = R^\eta_{\mu\eta\nu}$$

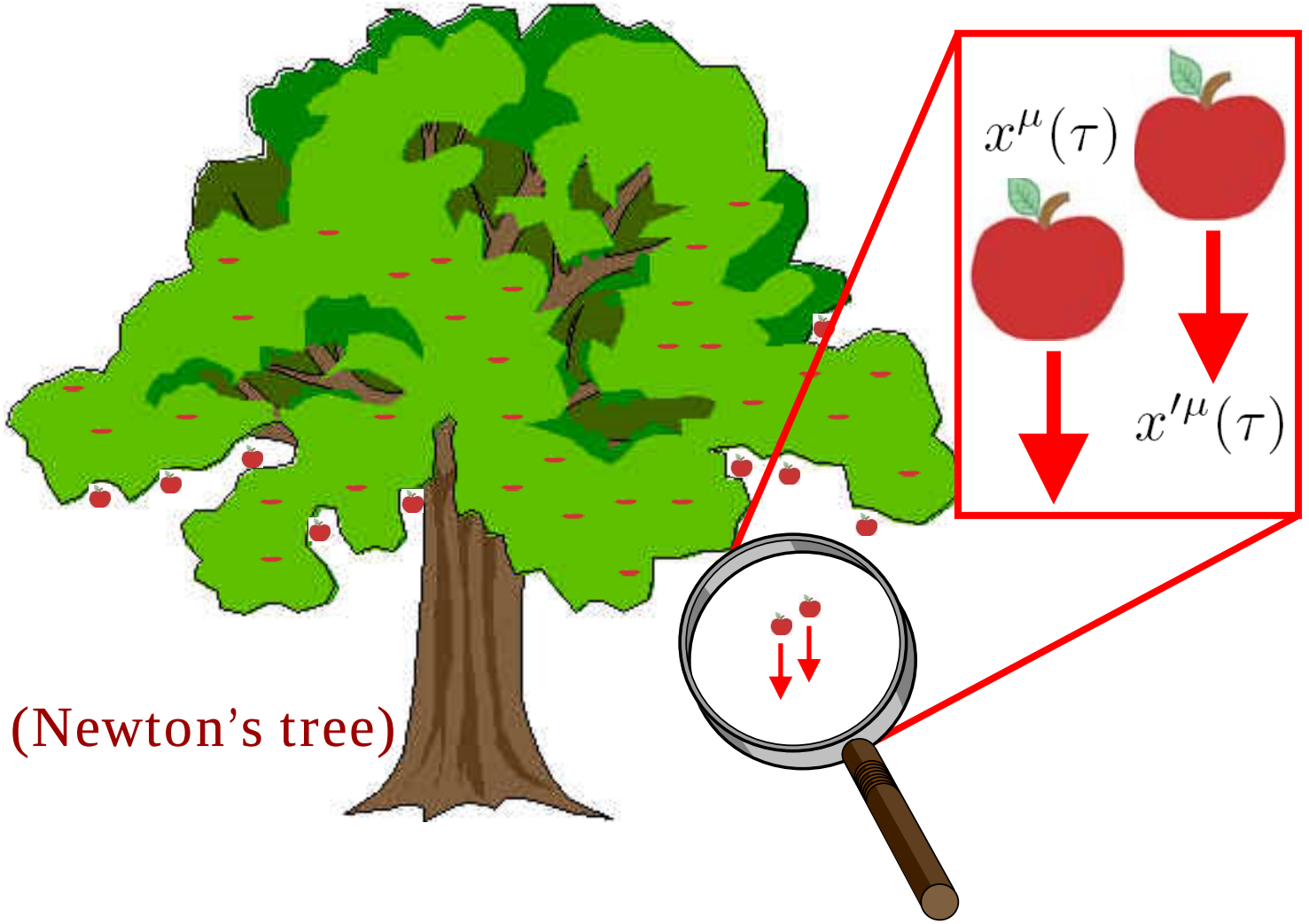
$$R = R^\mu_\mu$$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R = 0$$

Get $$\partial_z^2 h_{+,\times} - \frac{1}{c^2}\partial_t^2 h_{+,\times} = 0$$

Wave equation: c!

Geometry of detection: gws are tidal forces

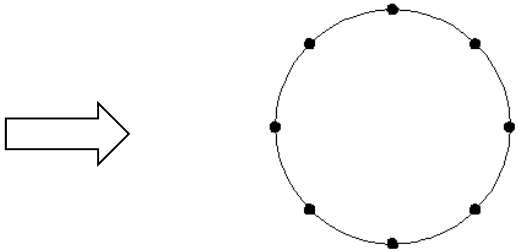


(Newton's tree)

$$\delta L = h_+ \, L$$

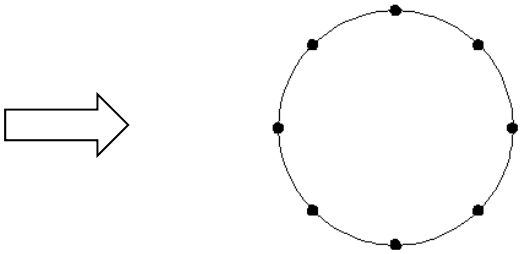
Polarization “+” :

h_+

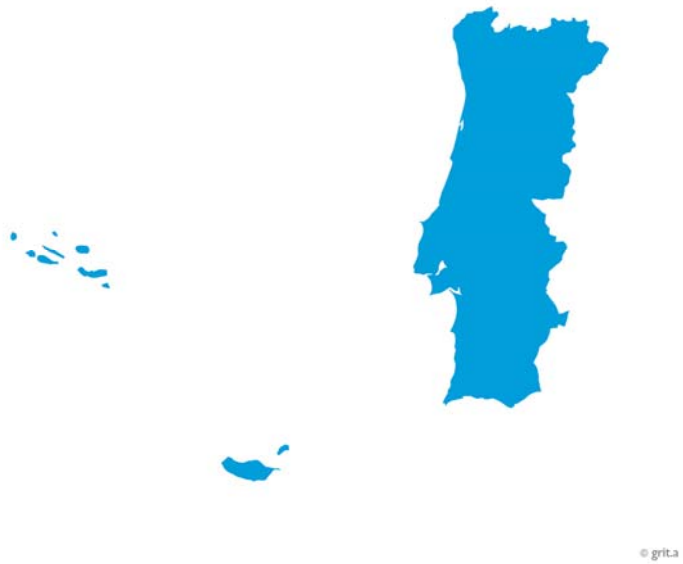


Polarization “x”:

$h_\times$

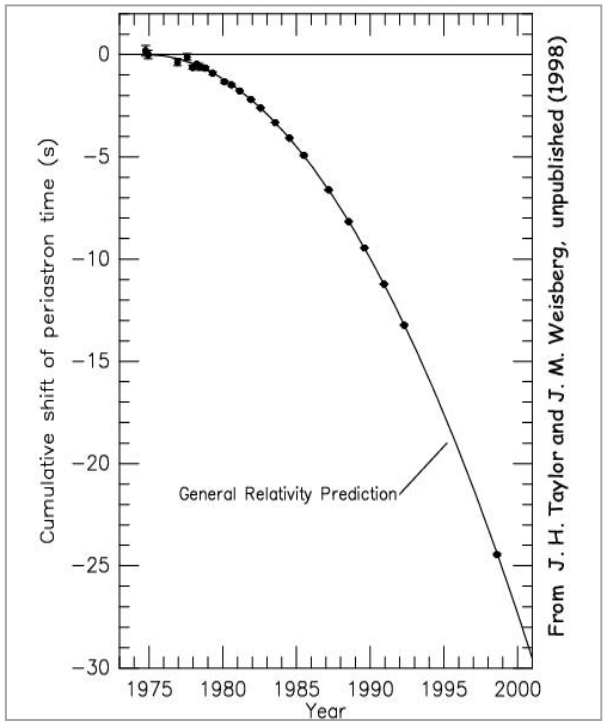


Polarization “+” : h_+ $\delta L = h_+ L$



Polarization “x”: $h_\times$

Do they exist?



Pulsar slowdown $-2.4085(52) \times 10^{-12}$ s/s

GWs exist!!

GWs: properties

Interact weakly – Both blessing and a curse

λ ~ Size of source – Not good to form images, as EM. More like sound: 2 polarizations carry stereophonic description of source.

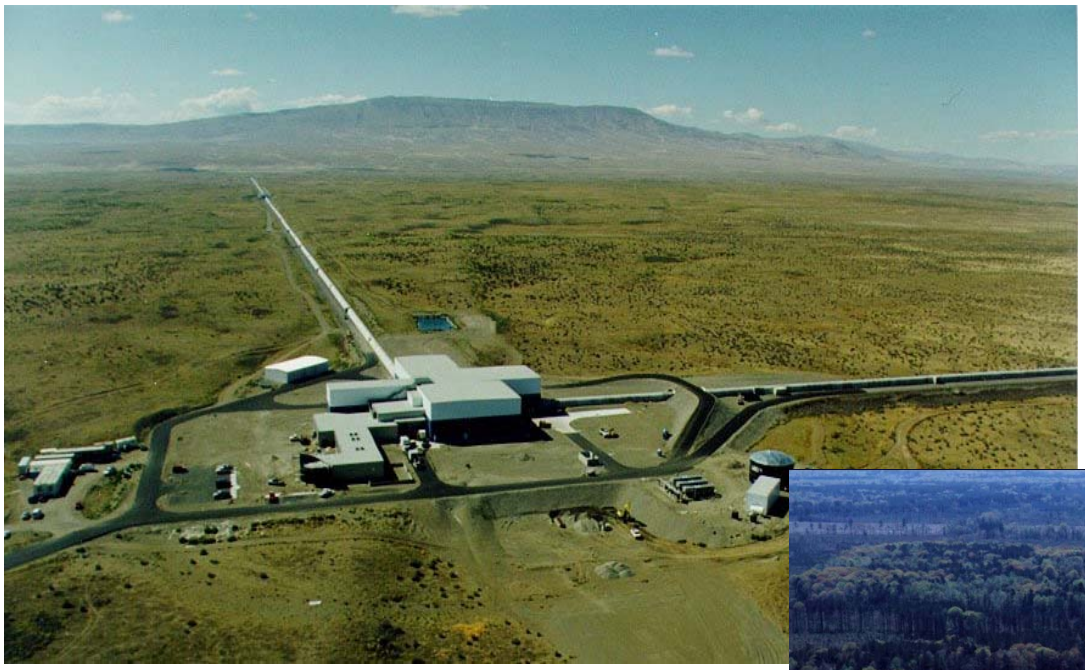
Gravitons are coherent - produced by source motion as a whole (photons are incoherent)

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.

The audience

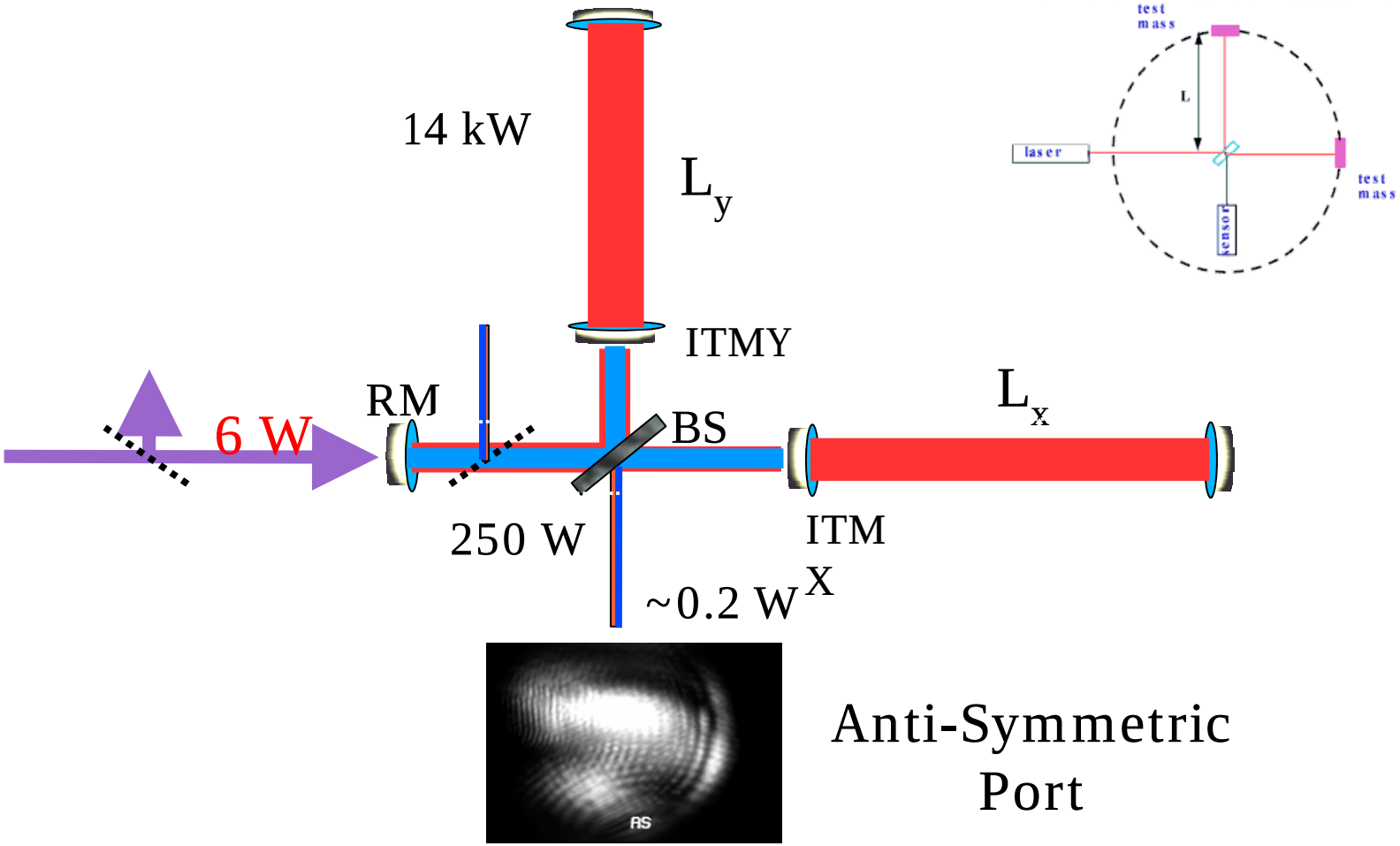
LIGO instrument



Hanford, WA

Livingston, LA

LIGO instrument

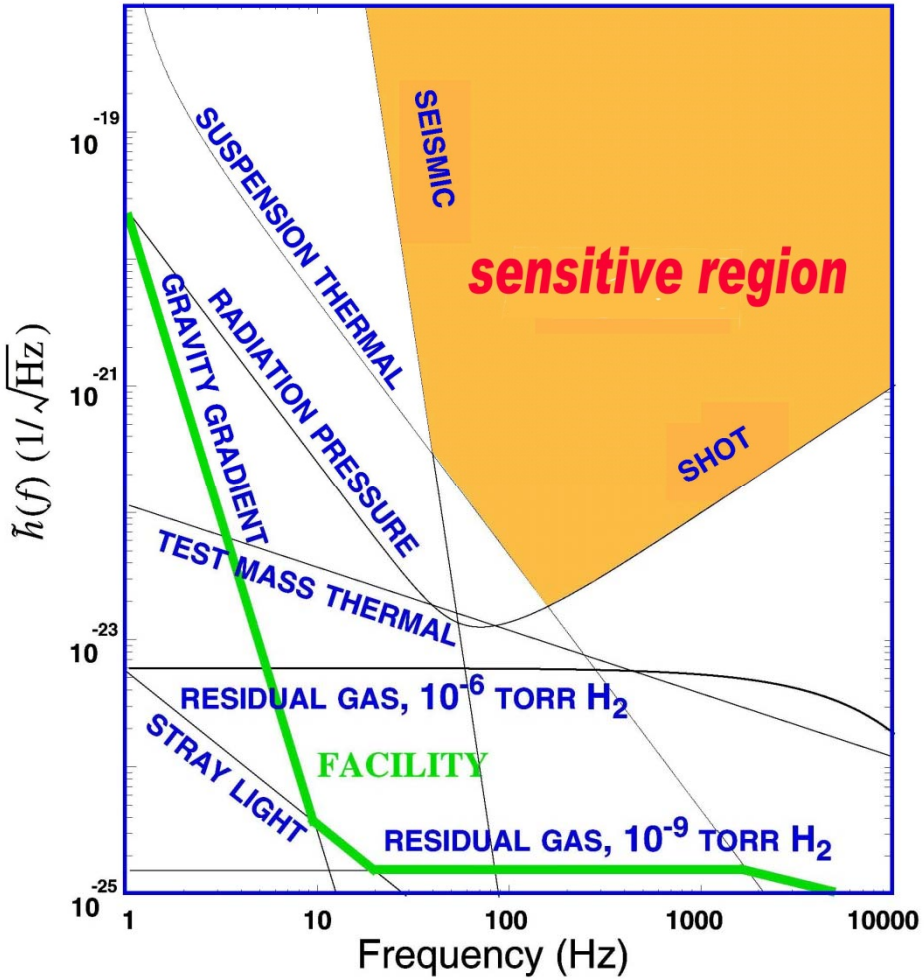


Anti-Symmetric
Port

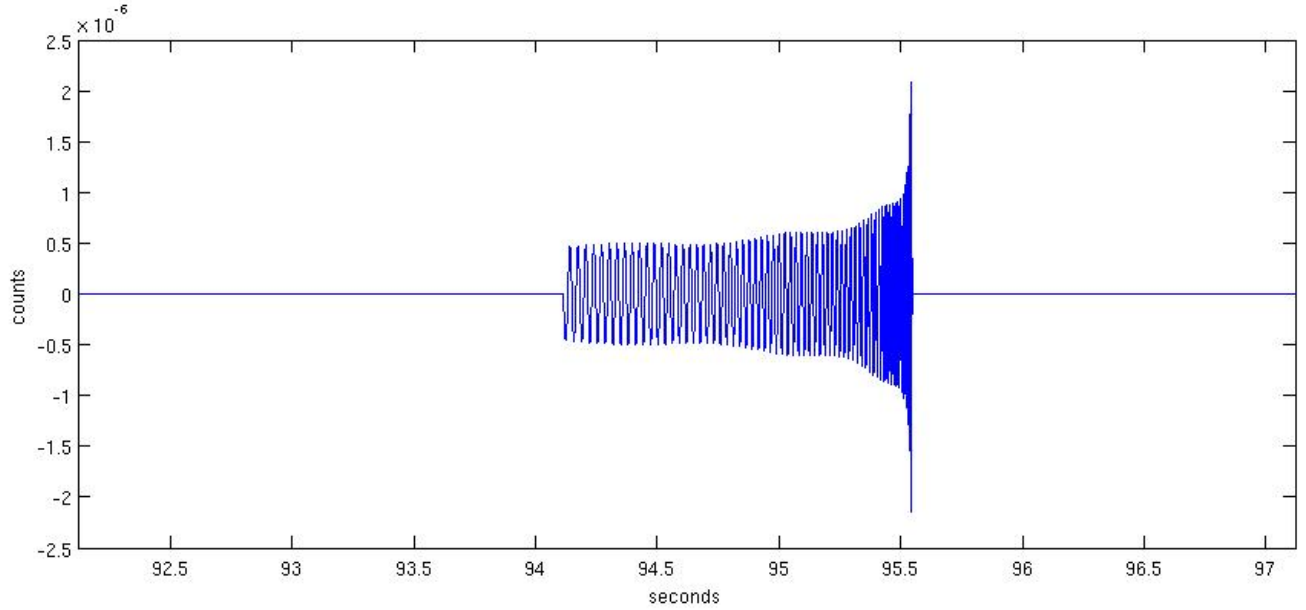
LIGO design sensitivity

Noise sources:

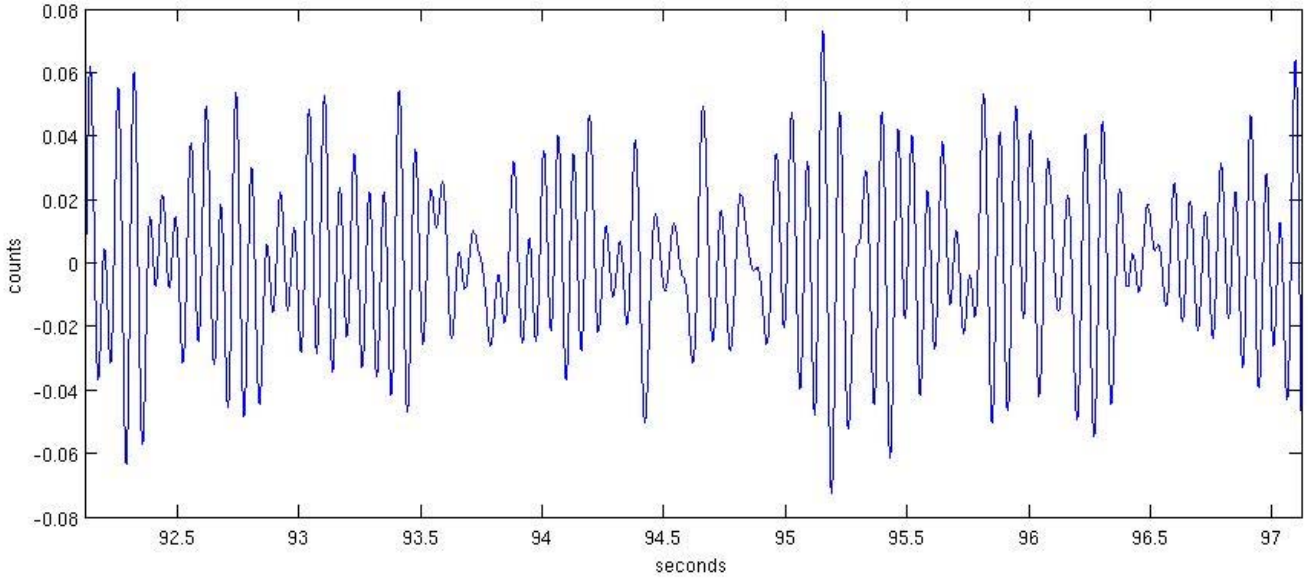
- seismic
- thermal
- shot
- etc...

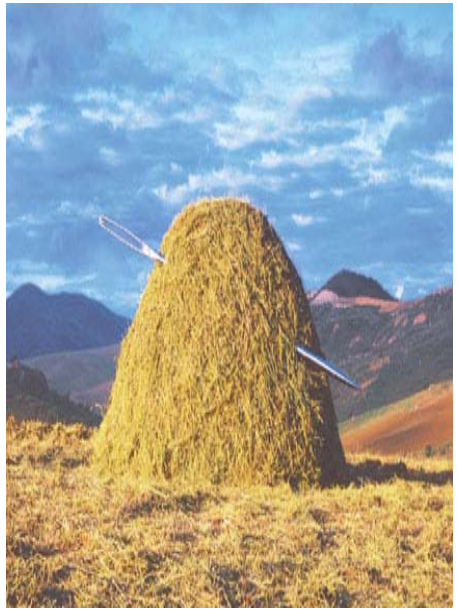


Typical signal for coalescing binaries

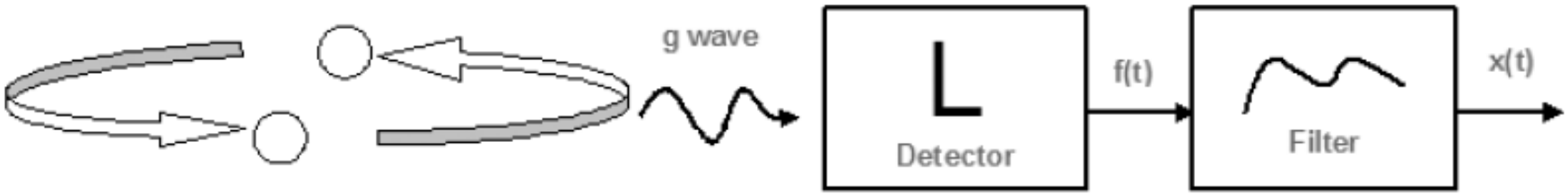


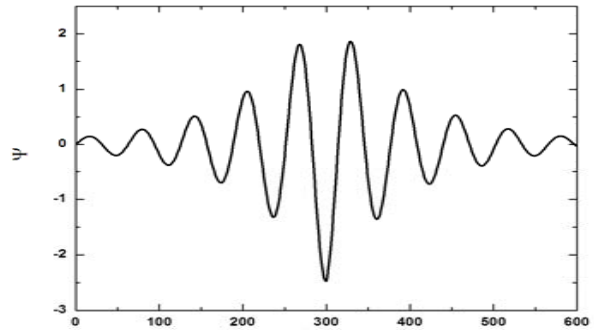
Typical stretch of data

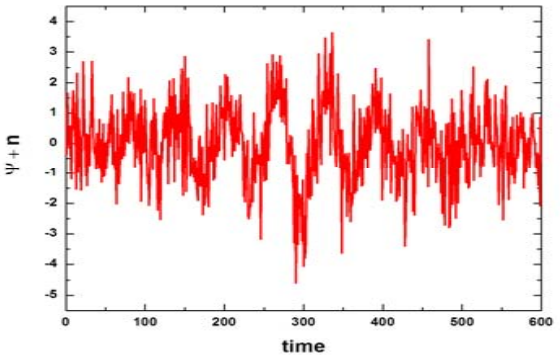


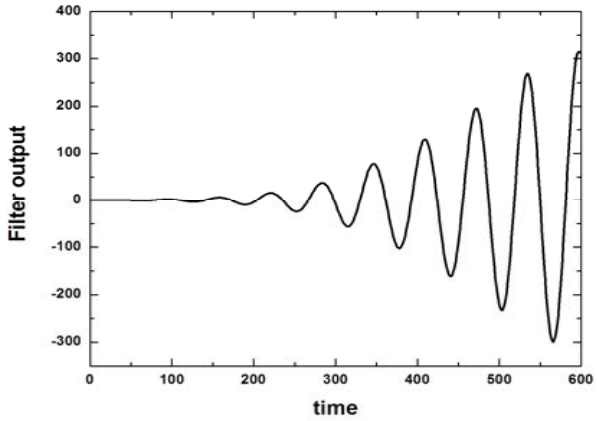


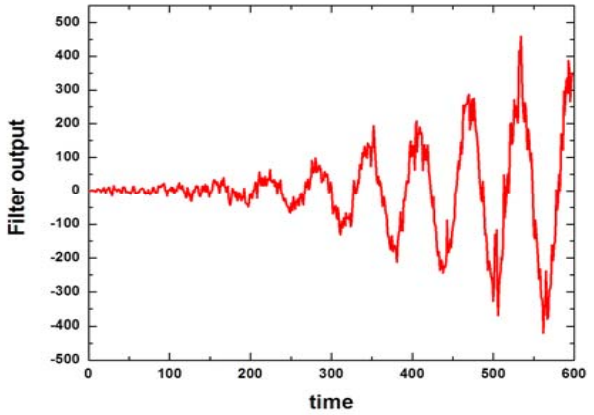
Matched-Filtering



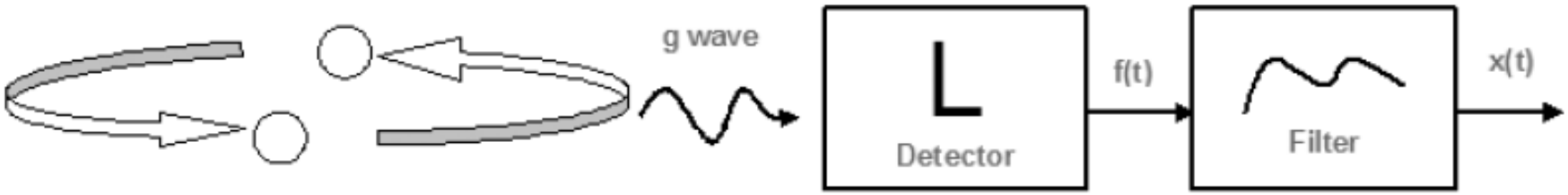








Matched-Filtering



Lack of knowledge ⟶ 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

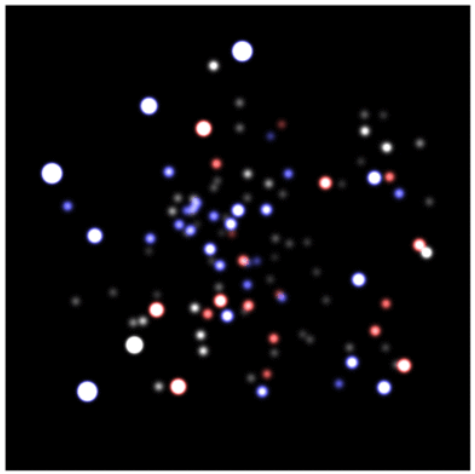
↳ Triggers – level II

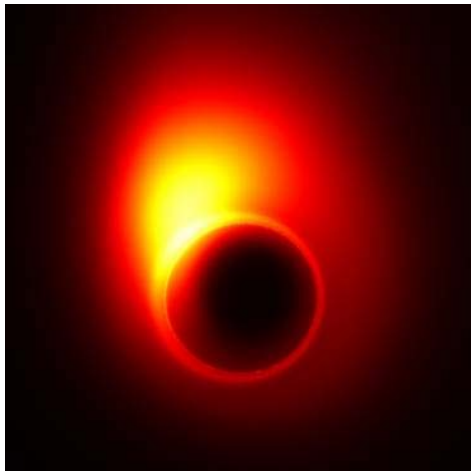
Coherent SNR for multiple detectors ⇨ Final triggers

Careful follow-up of single candidates

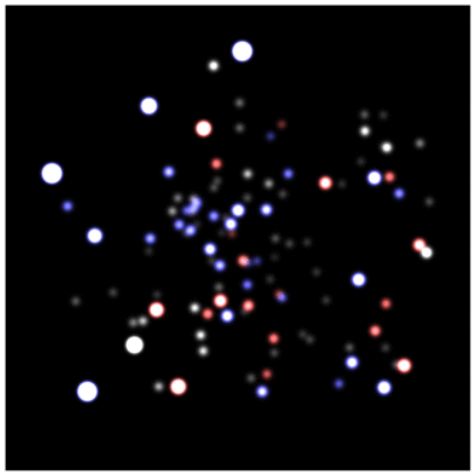
The instruments

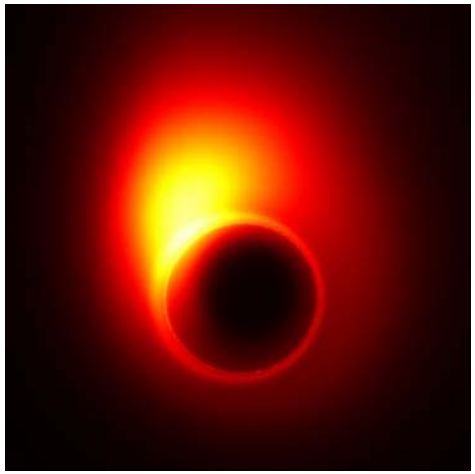
Black holes...they exist!





Black holes...they exist!



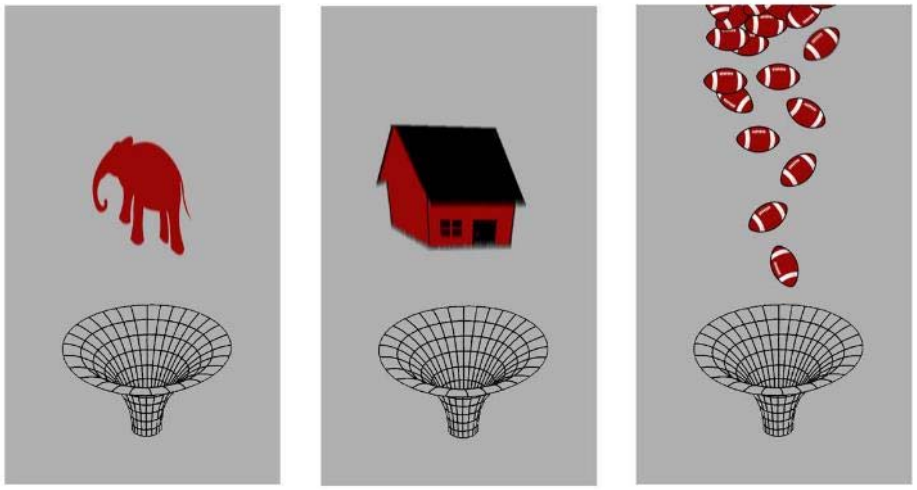


Black holes have no hair

One star made of matter and other of antimatter, produce identical BHs.

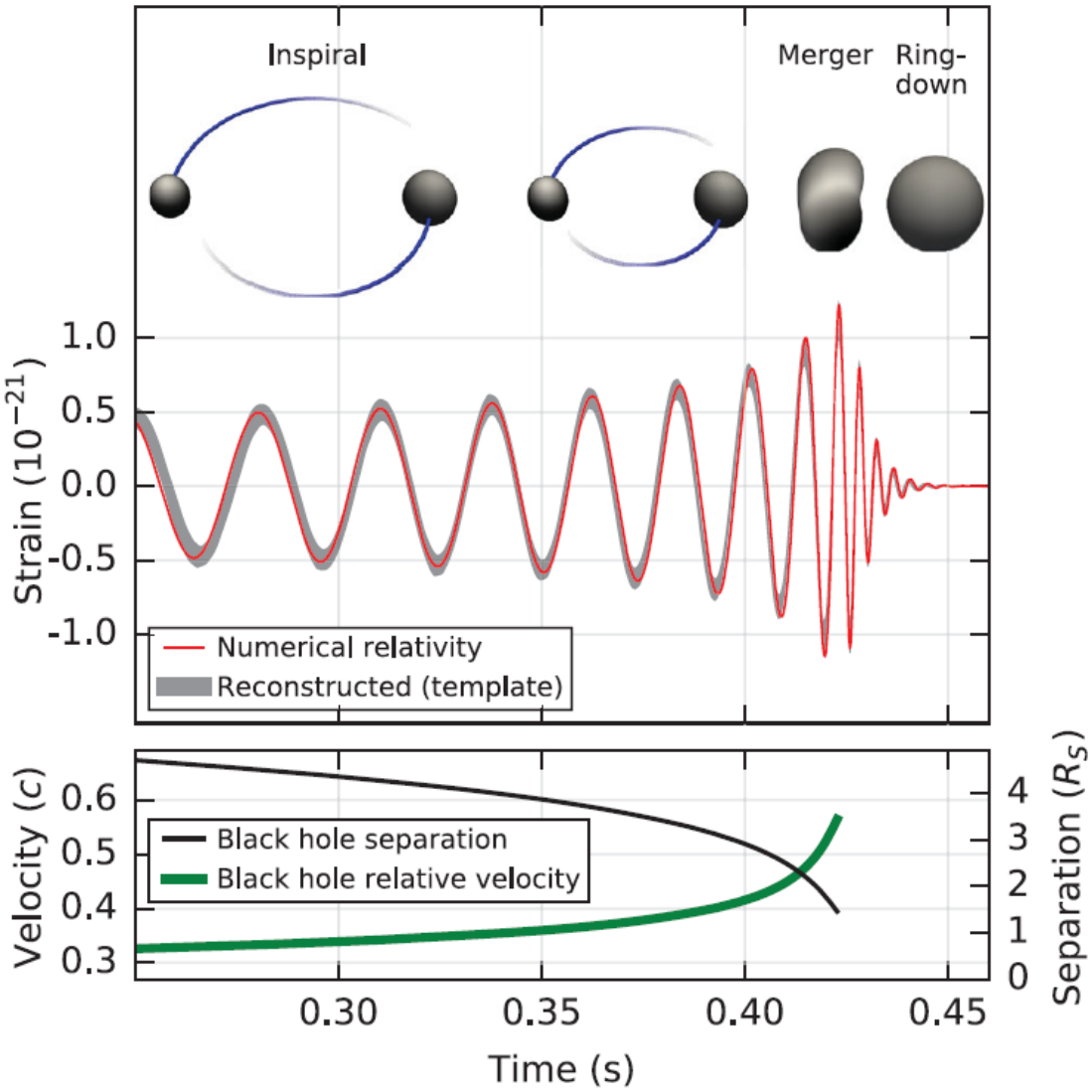
A stationary BH is characterized by only three quantities:

mass, spin and electric charge



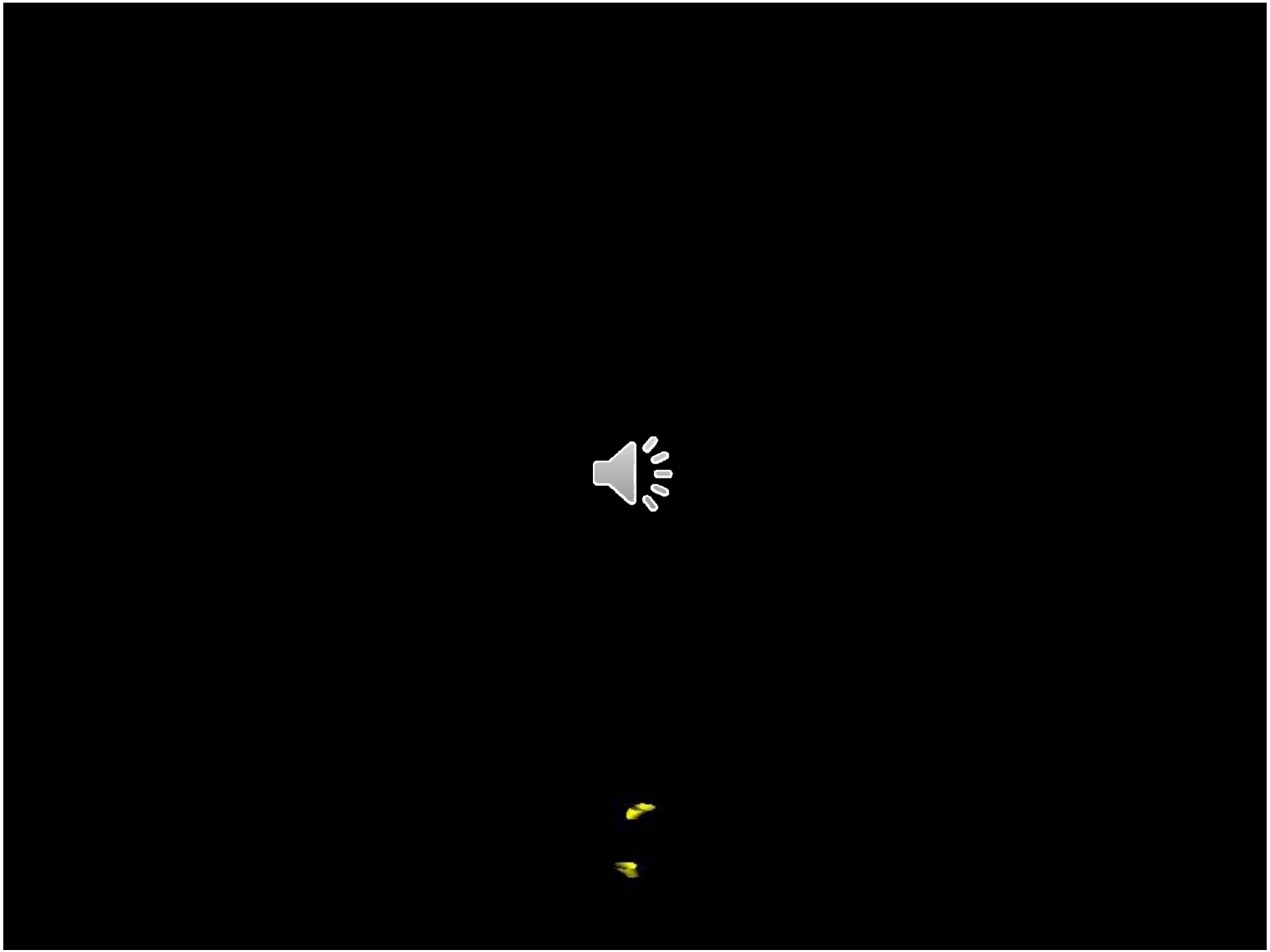
Note: B & L numbers are also non-conserved in black hole physics

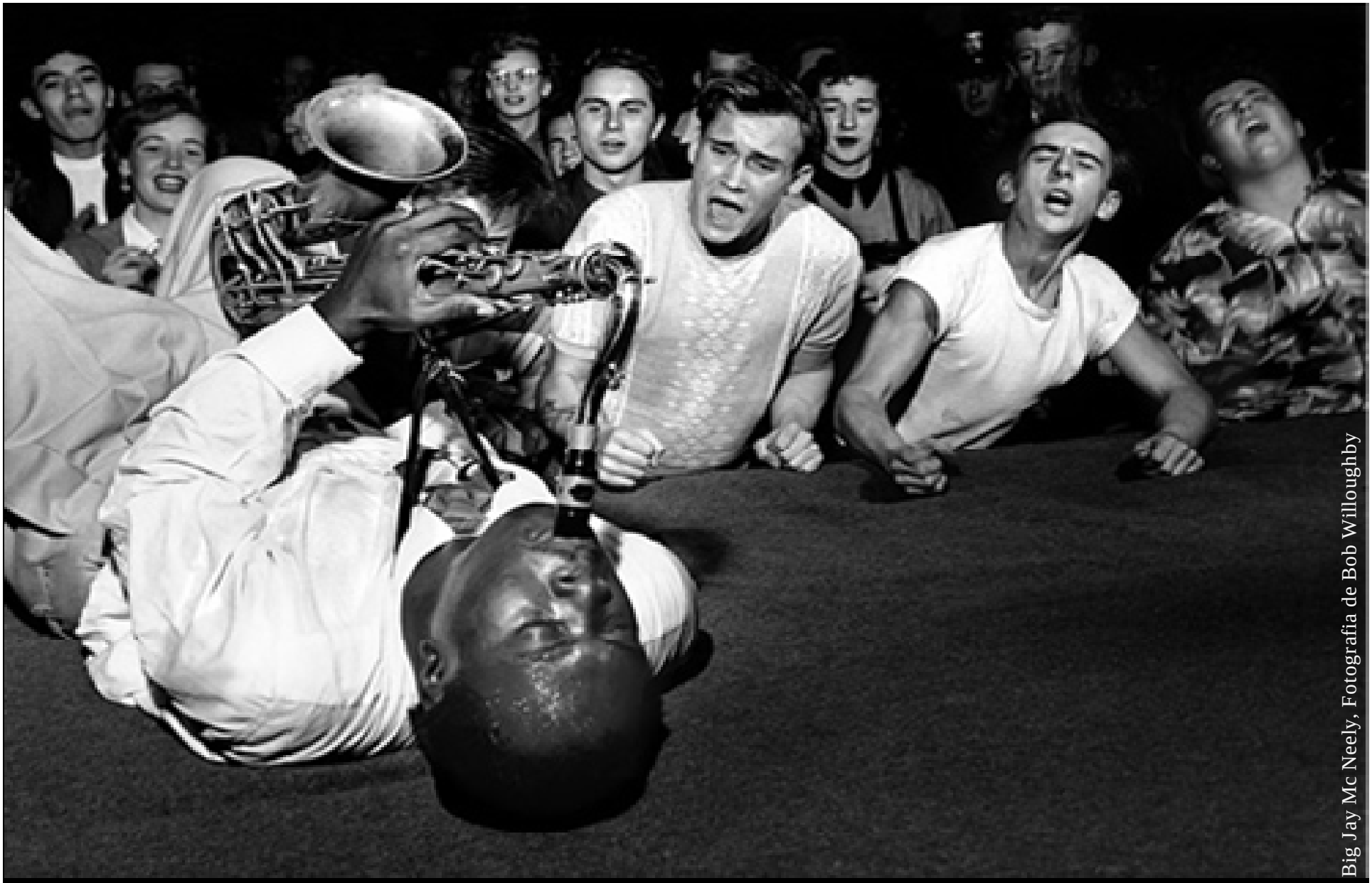
The sound


Inspiral
Merger
Ring-down
Strain (10^{-21})
1.0
0.5
0.0
-0.5
-1.0
Numerical relativity
Reconstructed (template)
Velocity (c)
0.6
0.5
0.4
0.3
Black hole separation
Black hole relative velocity
Separation (R_S)
4
3
2
1
0
0.30
0.35
0.40
0.45
Time (s)

BH coalescence

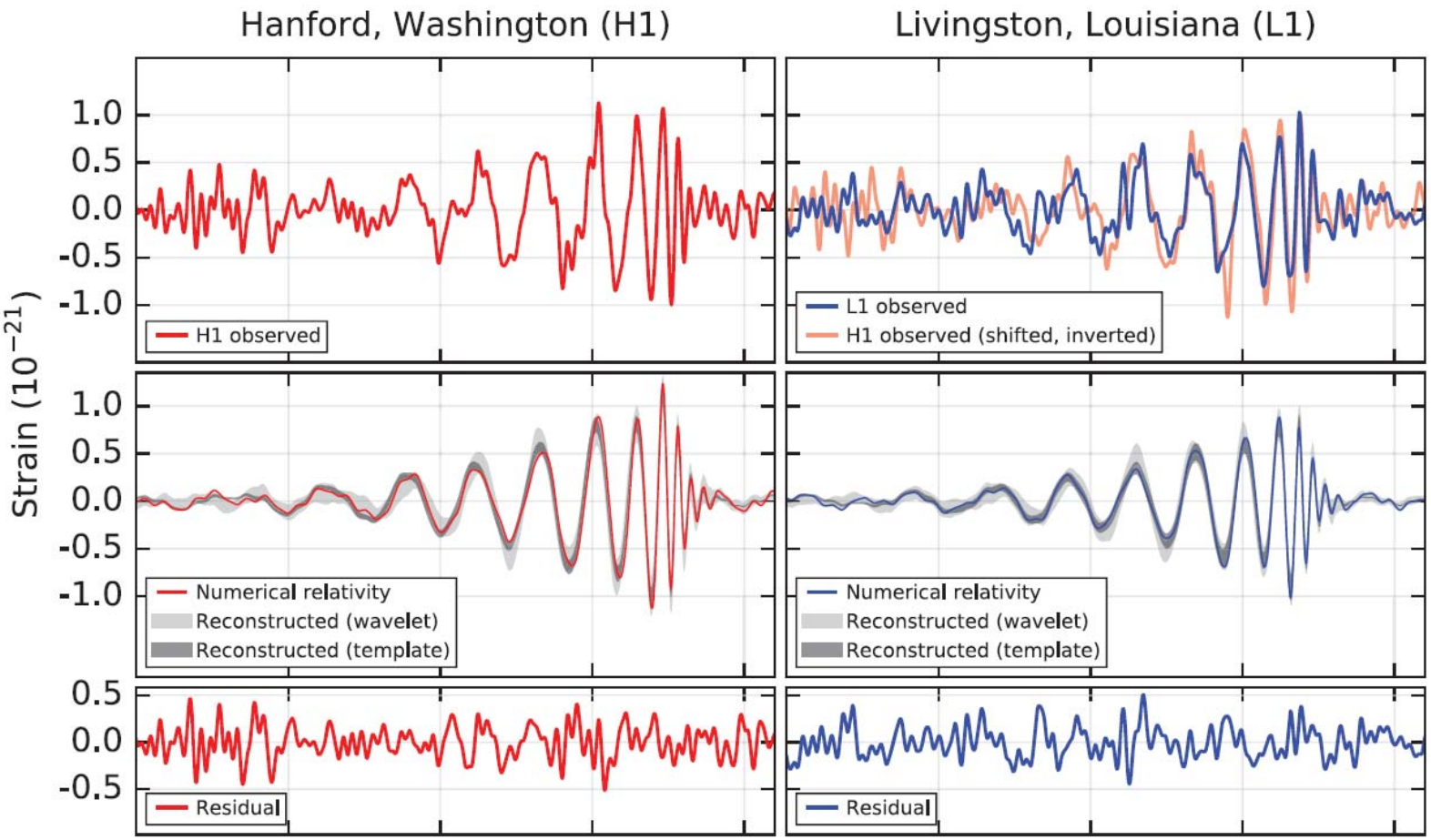
Courtesy Marcus Thierfelder and Bernd Bruegmann



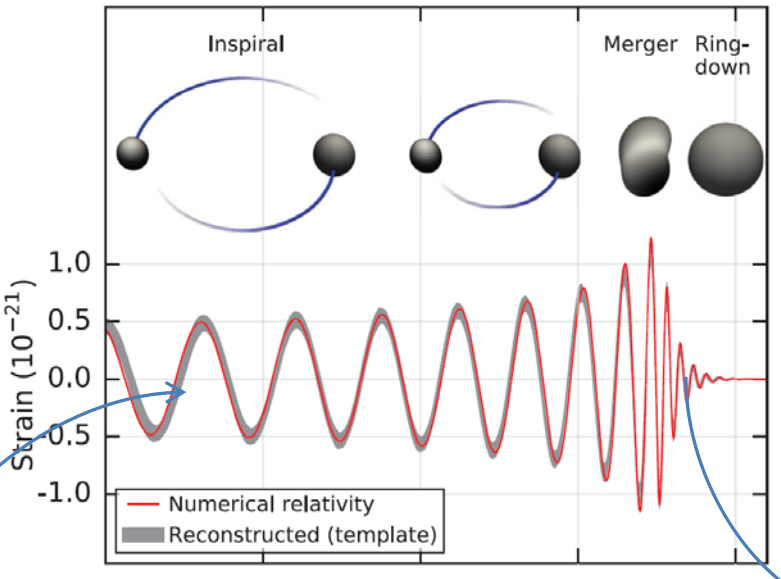


Big Jay Mc Neely, Fotografia de Bob Willoughby

“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



(Abbott et al, Phys.Rev.Lett.116:061102 (2016)



Time-of-arrival: sky position and speed of waves
(Blas et al 2016, Ellis et al 2016)

Future: timing with EM

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

Inspiral stage, quasi-Newtonian:

Determine individual masses and spins

Is there dipolar rad (Barausse et al 2016)?

Other signs of modified gravity?

DM imprints (Silk & Eda 2013, Macedo et al 2013)?

Tidal effects

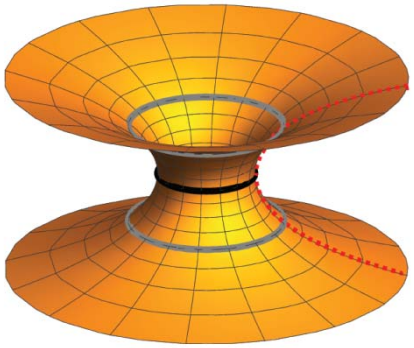
Breathing of final object:

Relativistic regime: CCC!!! (light travel)

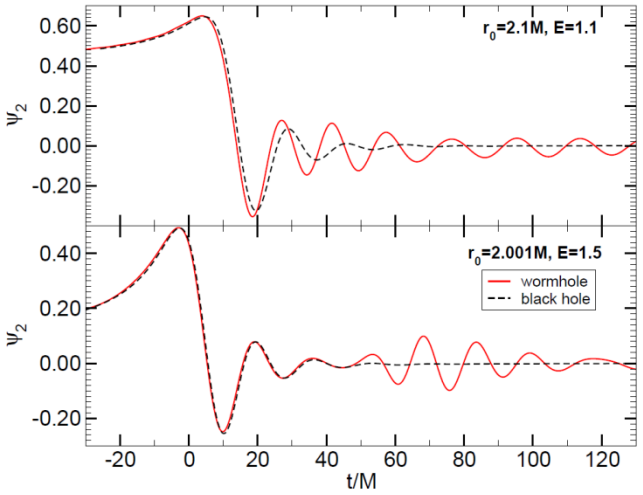
BH spectroscopy: measure mass and spin to 1% (Berti, Cardoso, Will 2006)

Test GR (Berti et al 2015)

Are there event horizons?
(Cardoso, Franzin, Pani 2016)



(Cardoso, Franzin and Pani, 2016)



Distance to 10%

Standard candles to measure the Hubble constant (Schutz, Nature, 1986)

a) Determine distance to source

b) Identify host galaxy and measure its redshift

(ii) Assume neutron stars have 1.4 . Determine z (Markovic, PRD 1993)

Conclusions I

Exciting times for gravitational-wave research!

Advances in theory and numerical relativity

LIGO has reached design sensitivity. Being upgraded...

A network of GW observatories

GRB070201: Birth of GW astrophysics

GW150914...birth of a new science: GW astronomy

Conclusions II

Gravitational wave astronomy:

Evidence for black holes

Birth and interaction of massive objects, specially BHs

Central engine for GRBs

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

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

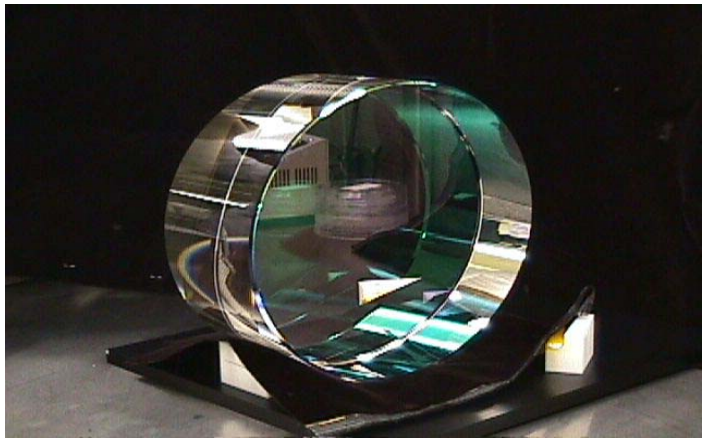
Does GR describe strong field regime?

?

Thank you

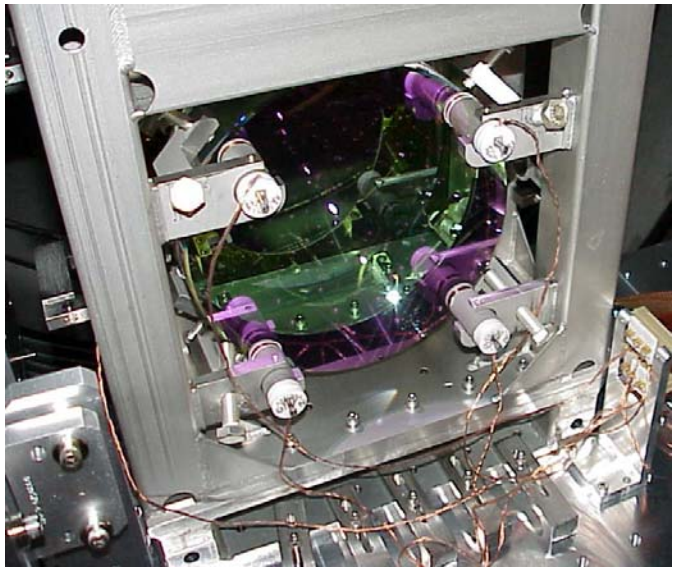
Vacuum equipment

Core optics



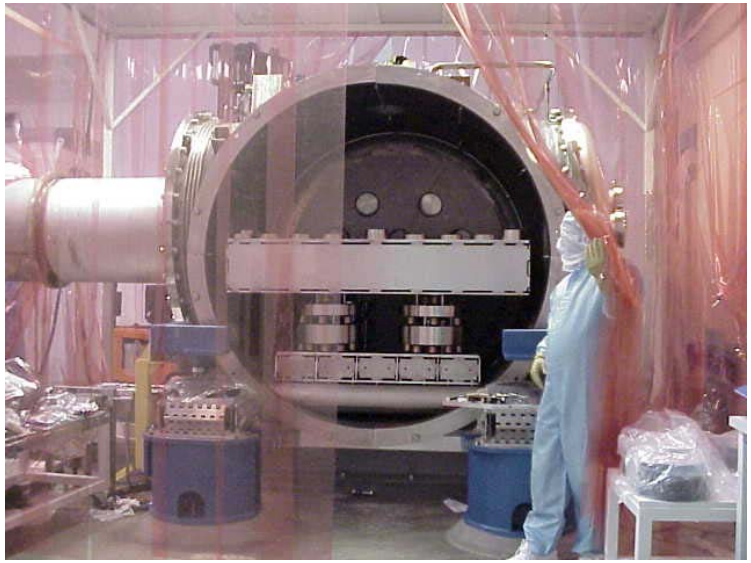
Fused silica (high-Q, low-absorption,
1 nm surface rms, 25-cm diameter)

Optics suspension



Suspended by single steel wire
alignment with magnets and coils

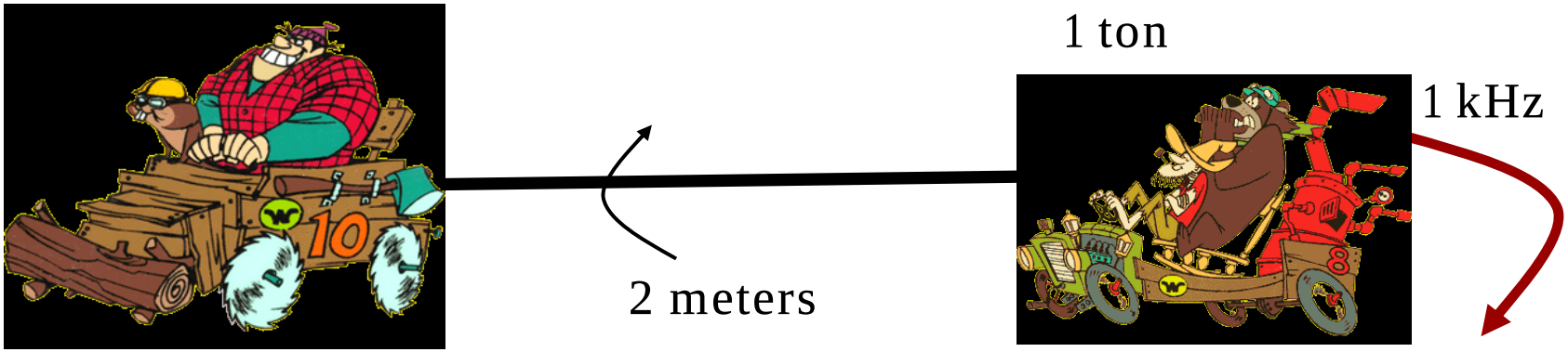
Seismic suspension



Optical table support gives 10^6 suppression

GWs: properties

- Interact very weakly



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

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

too weak by 16 orders of magnitude!