Gravitational Wave Astronomy with the ELISA(NGO) Detector.

Ed Porter (APC)

VIA Lecture

October 2011

Overview

- Gravitational Waves
- ELISA (NGO)
- Won’t LIGO, Virgo etc suffice?
- So why do we need ELISA?
- Astrophysics, cosmology & cosmography
- Fundamental physics & tests of GR
- Conclusion

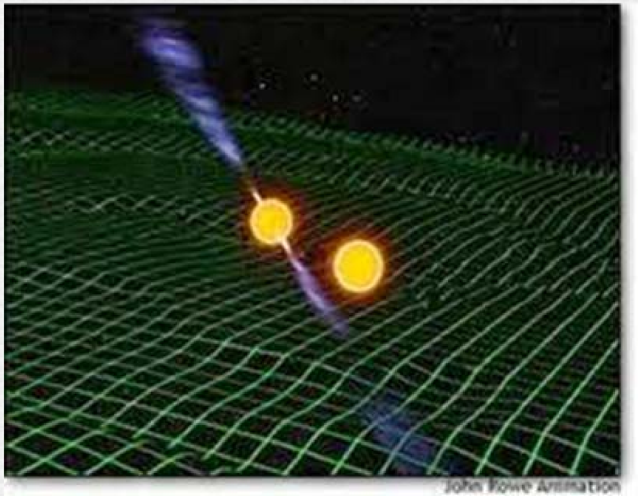
Gravitational Waves

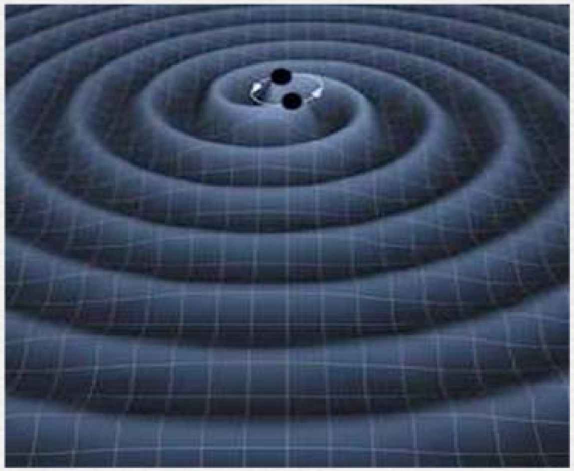
GWs

Prediction of GR & virtually all other theories of gravity.

Can be treated as a perturbation of the background metric

Oscillations in the curvature of spacetime

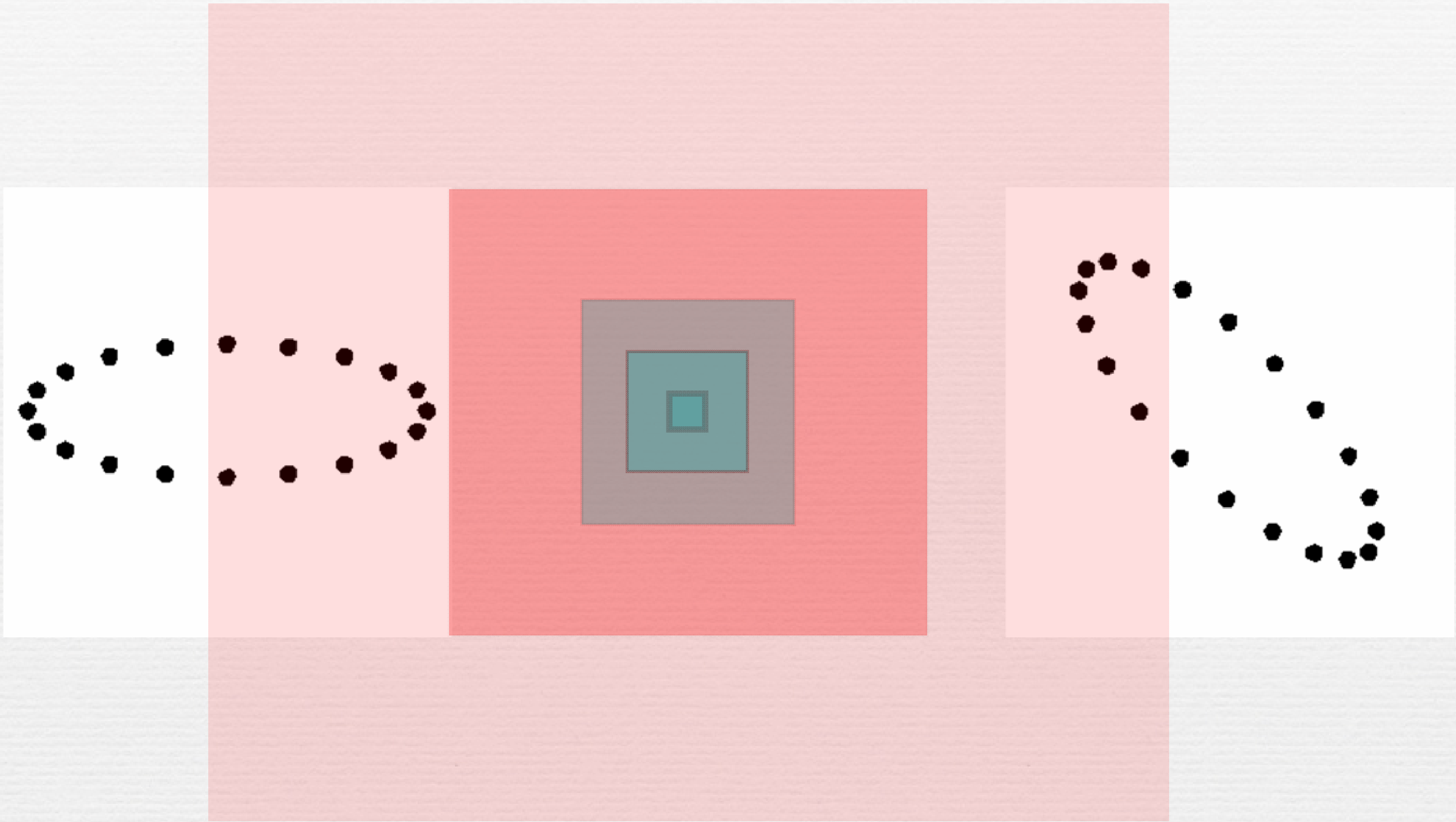




Sources of GW

- Big Bang
- Phase transitions - cosmic string kinks/cusps
- Coalescence of compact objects - SMBHBs, binary NSs, BHs, WDs etc.
- Supernovae
- Pulsars

GW Polarisations



Strength of GWs

Very weak,

For example : the earth-sun system GW amplitude is

$$A \sim \frac{(GM_c)^{5/3}}{c^4 D} \left(\frac{\pi}{P_{orb}}\right)^{2/3} \sim 10^{-19}$$

with a GW luminosity of

$$L_{GW} \leq \frac{c^5}{G} \left(\frac{GM}{Rc^2}\right)^5 \sim 10^{24}\, W \sim 10^{-3}\, L_{\odot}$$

with a maximum frequency of $f_{gw}(max) \sim 4.4\, kHz$

On the other hand, a SMBMB merger at z = 1 has

$$h \sim 10^{-21} \qquad L_{gw} \sim 10^{52}\, W \sim 10^{26}\, L_{\odot}$$

GW Detectors...Why so big?

Nature provides us with GW amplitudes of $h \sim 10^{-21}$

The strain at the detector is given by $h \sim \dfrac{\Delta L}{L}$

So, clearly we need a detector of the size

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

ELISA expects to measure phase differences on the order of ~ 20 pm, which means ELISA has to have

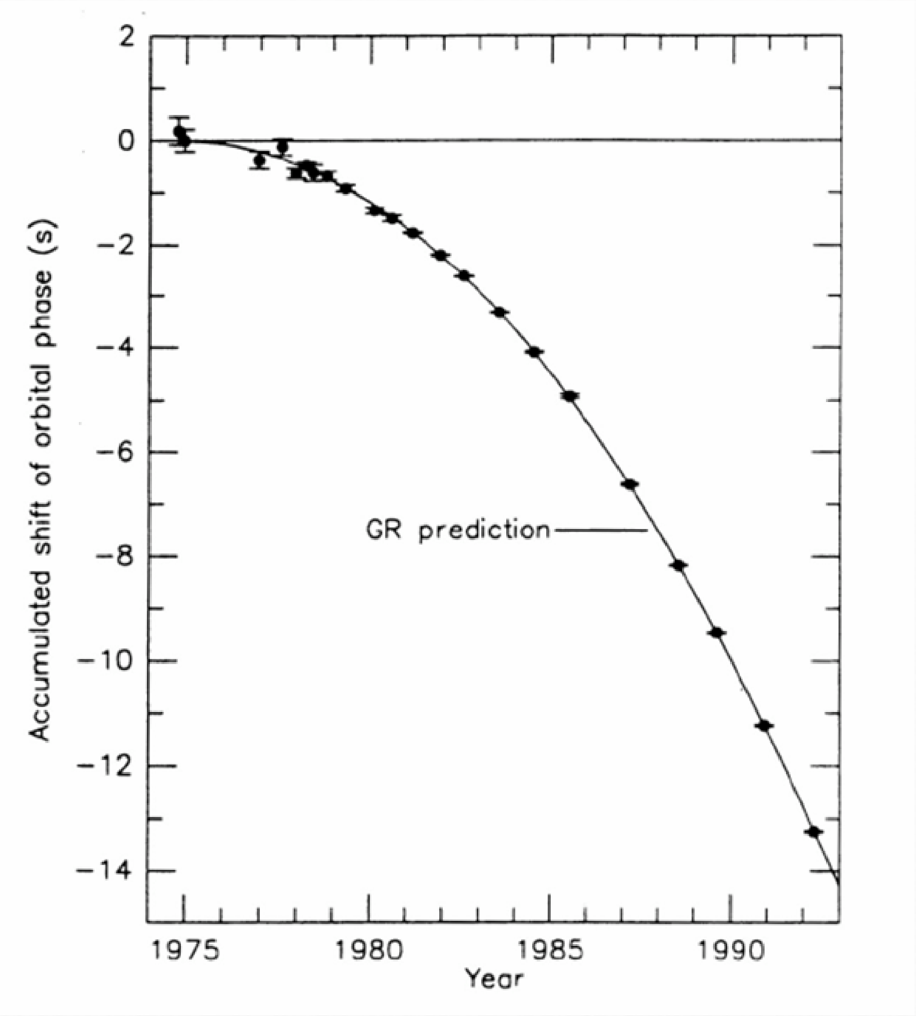
$$L \sim \frac{10^{-12}}{10^{-21}} \sim 10^9 m$$

Indirect Proof

Hulse-Taylor binary pulsar

dP/dt ~ GR prediction

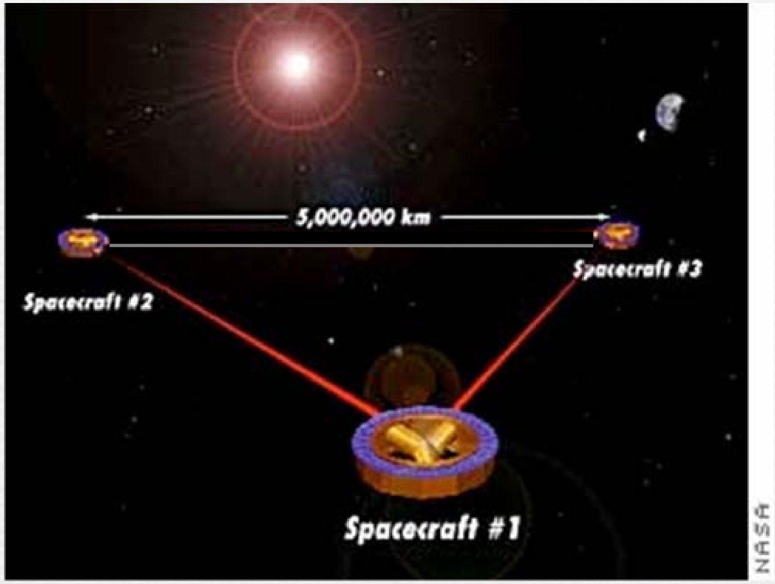
~15 other systems now known



ELISA(NGO)

ELISA

- 3 satellites in a triangular configuration separated by 1 million kms
- Earth orbit – (10-20)º behind
- Operating in the frequency range of 0.04 mHz to 0.1 Hz
- Main sources of interest : SMBHBs, EMRIs, galactic binaries, cosmic string kinks/cusps, stochastic background + unknown



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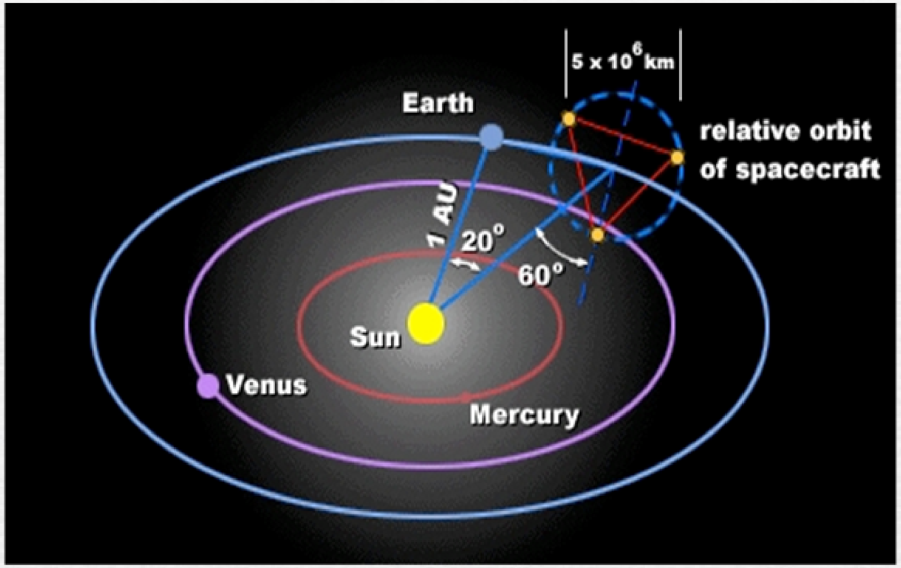

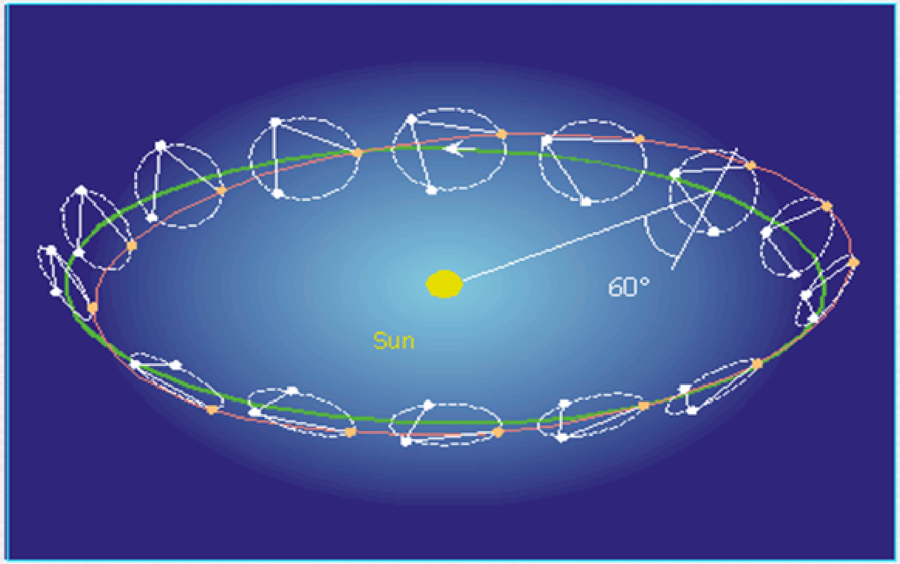

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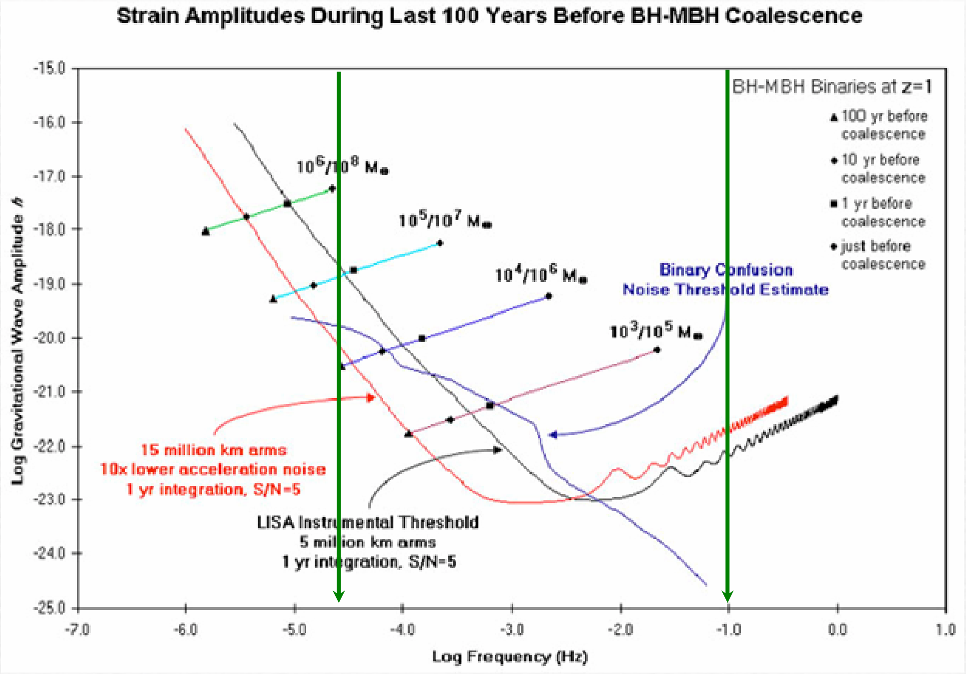

ELISA

- LFA response to a GW

$$h_i(t) = h_+(\xi(t))F^+(t) + h_\times(\xi(t))F^\times(t)$$

- BPFs give overall amplitude modulation

$$F^{+,\times}(t) = F^{+,\times}(t;\theta,\phi,\psi)$$

- System information contained in polarisations

$$h_{+,\times}(t) = h_{+,\times}(t;\lambda^\mu,\theta,\phi)$$

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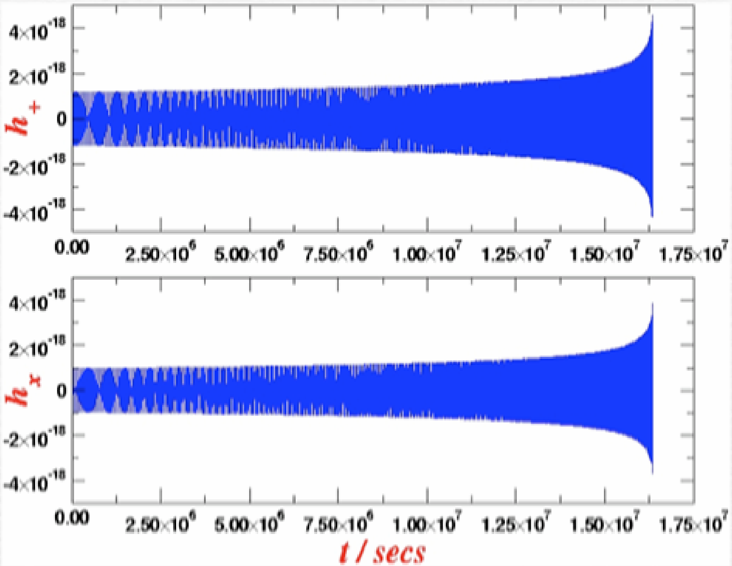

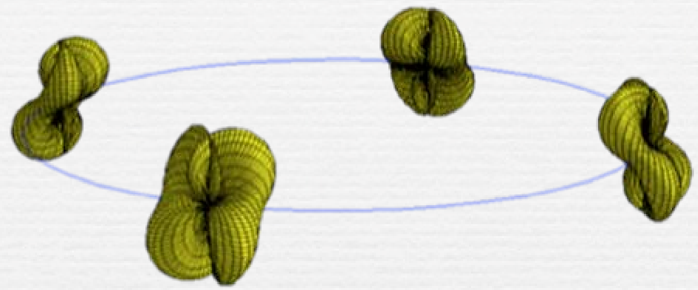

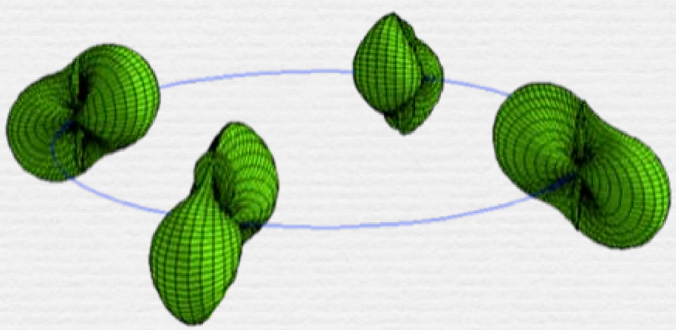

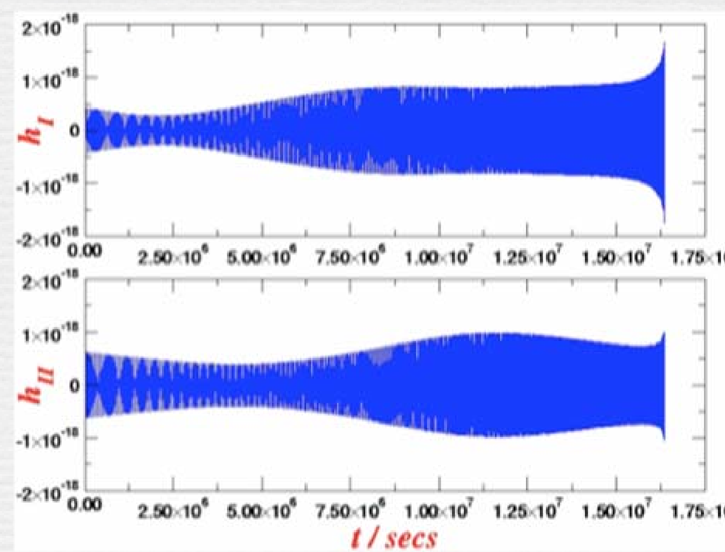

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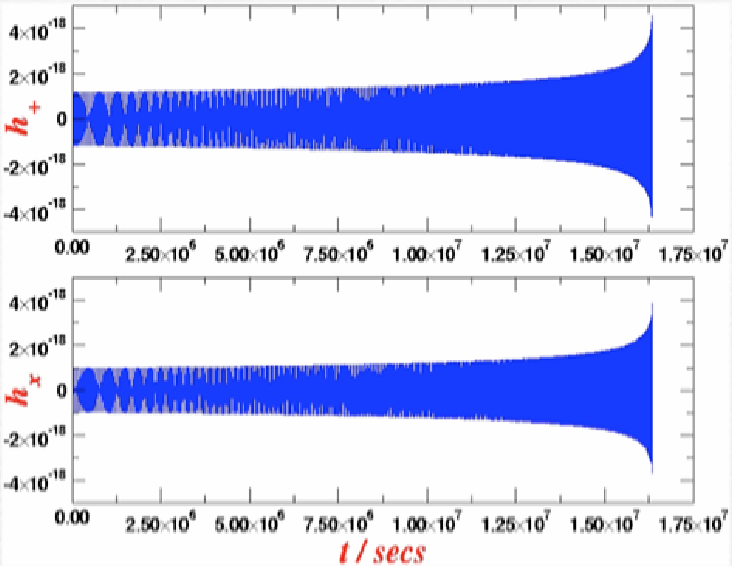
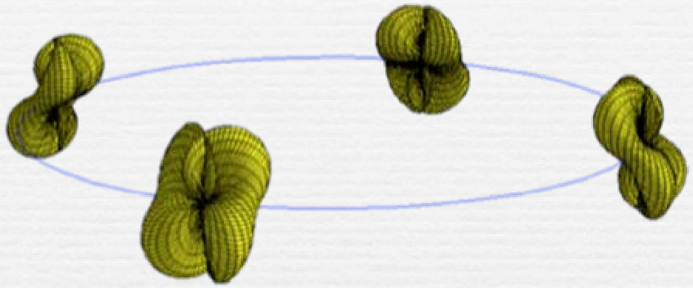
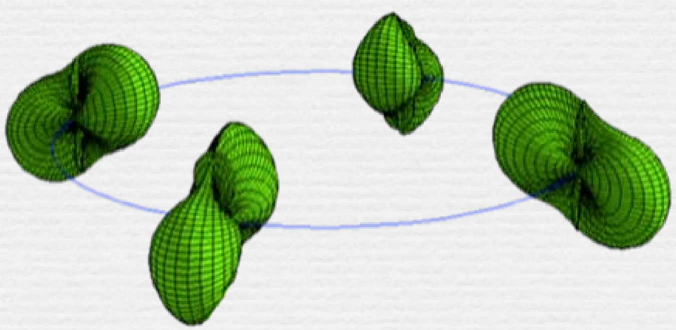
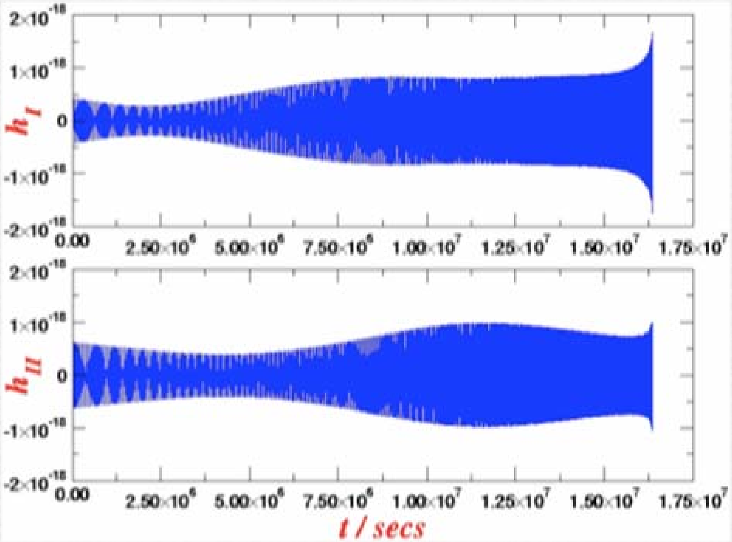


4×10^{-18}
2×10^{-18}
h_+
0
-2×10^{-18}
-4×10^{-18}
0.00
2.50×10^6
5.00×10^6
7.50×10^6
1.00×10^7
1.25×10^7
1.50×10^7
1.75×10^7
$h_\times$
t / secs

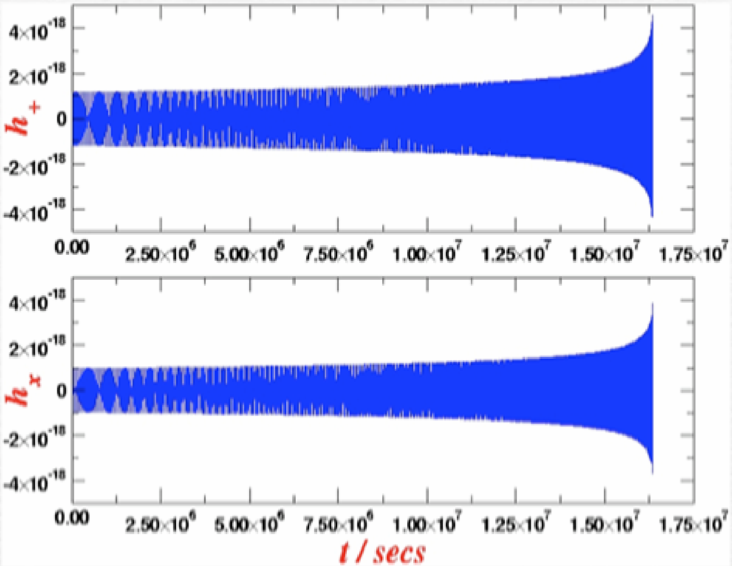




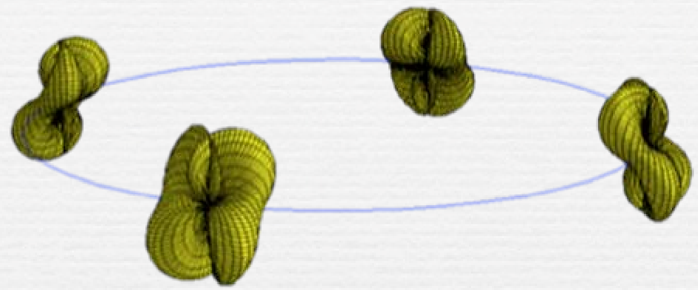


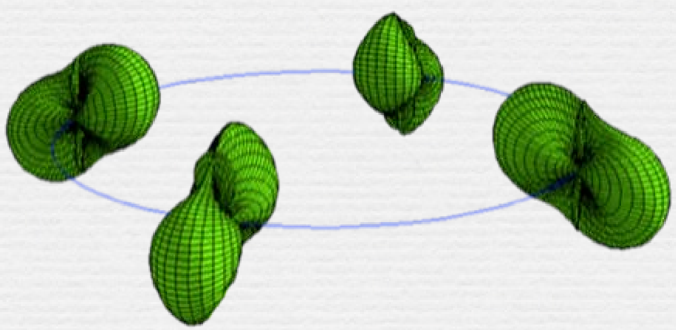
2×10^{-18}
1×10^{-18}
h_I
0
-1×10^{-18}
-2×10^{-18}
0.00
2.50×10^6
5.00×10^6
7.50×10^6
1.00×10^7
1.25×10^7
1.50×10^7
1.75×10^7
h_{II}
t / secs

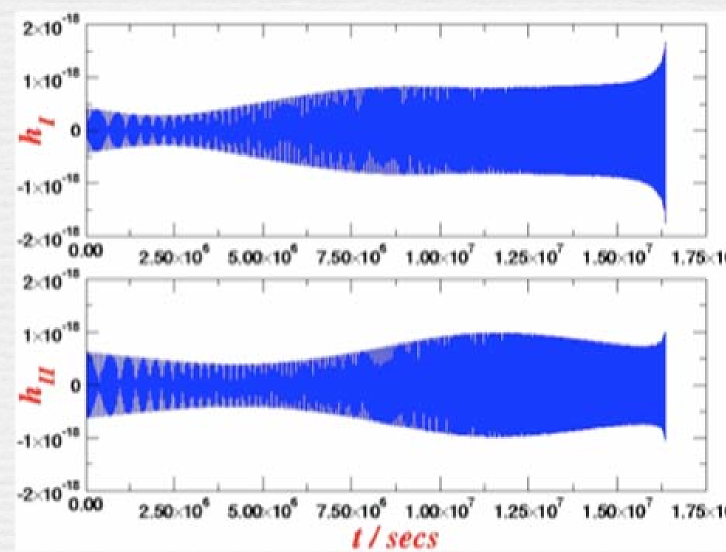
ELISA



h_+
$h_\times$
4×10^{-18}
2×10^{-18}
0
-2×10^{-18}
-4×10^{-18}
0.00
2.50×10^6
5.00×10^6
7.50×10^6
1.00×10^7
1.25×10^7
1.50×10^7
1.75×10^7
t / secs







h_I
h_{II}
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t / secs

ELISA

Detector	ELISA	LIGO/VIRGO
Frequencies	0.04mHz - 0.1 Hz	20 Hz - 2 kHz
Sources	SMBHBs, EMRIs, GBs, CSs, SB	BH-BH, BH-NS, NS-NS, SN
Source Duration	weeks - years	0.5 - 40 secs
Main Difficulty	Source dominated, source confusion	Noise dominated, glitches mimic GWs

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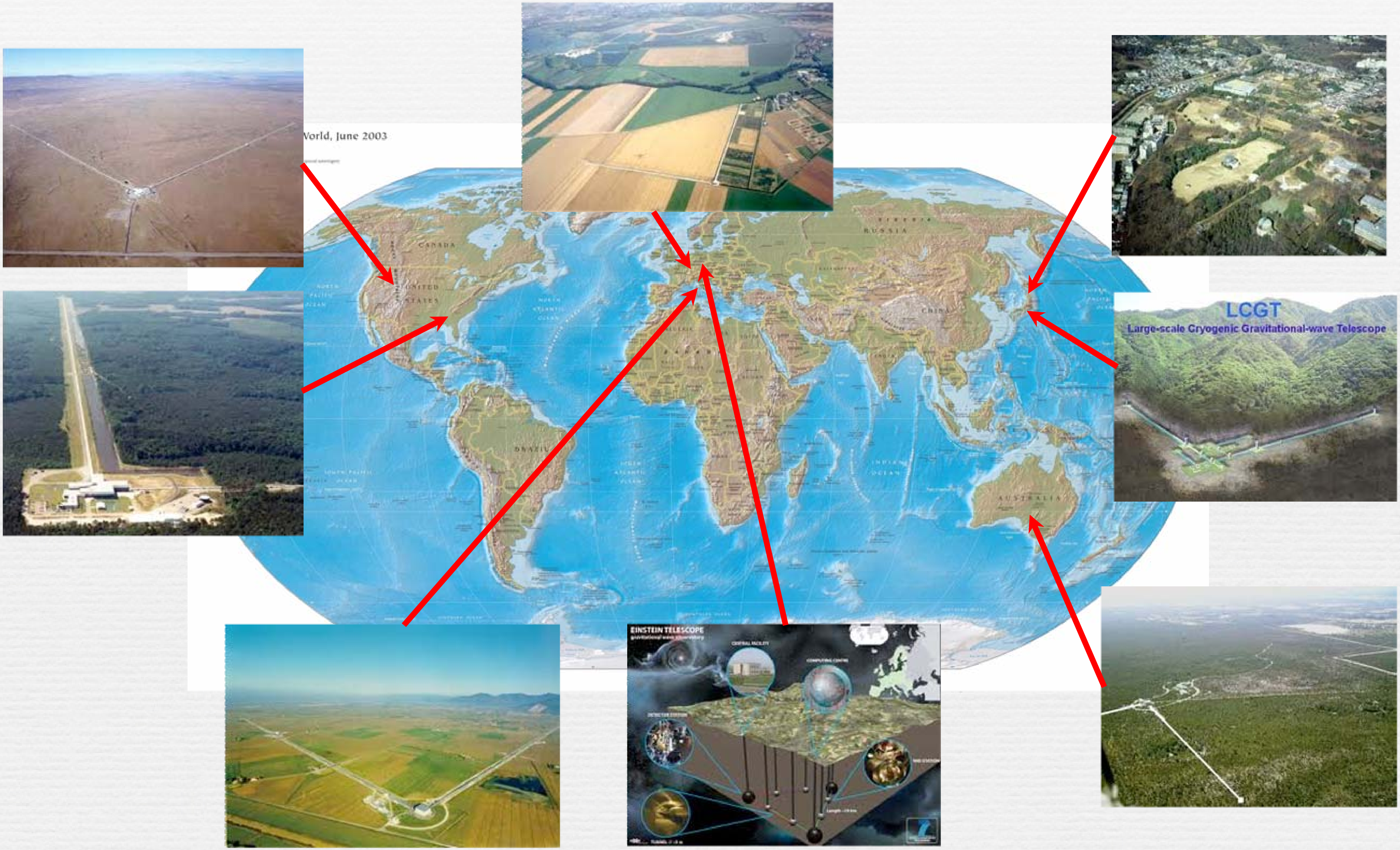
Won't LIGO, Virgo, GEO etc. suffice??

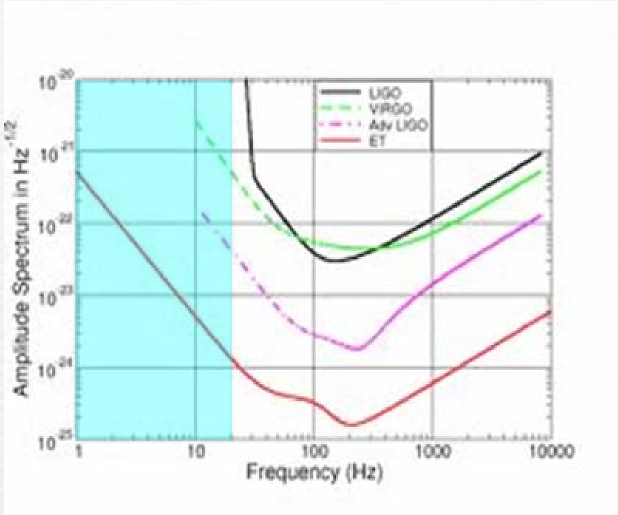
GW Map of the World

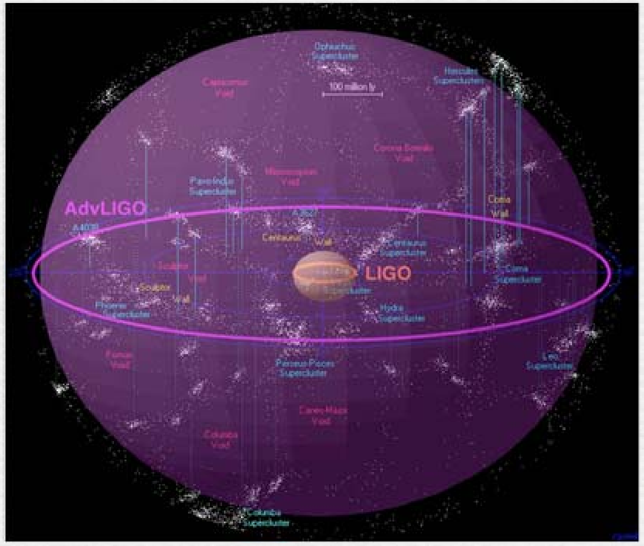


Detector Capabilities

Ground based detectors limited by :

1) Thermal noise
2) Photon shot noise
3) Tectonic plate movement
4) Local noise - people, transport
5) Weather patterns
6) Changes in local Newtonian potential - gravitational gradient noise





So, why do we need ELISA?

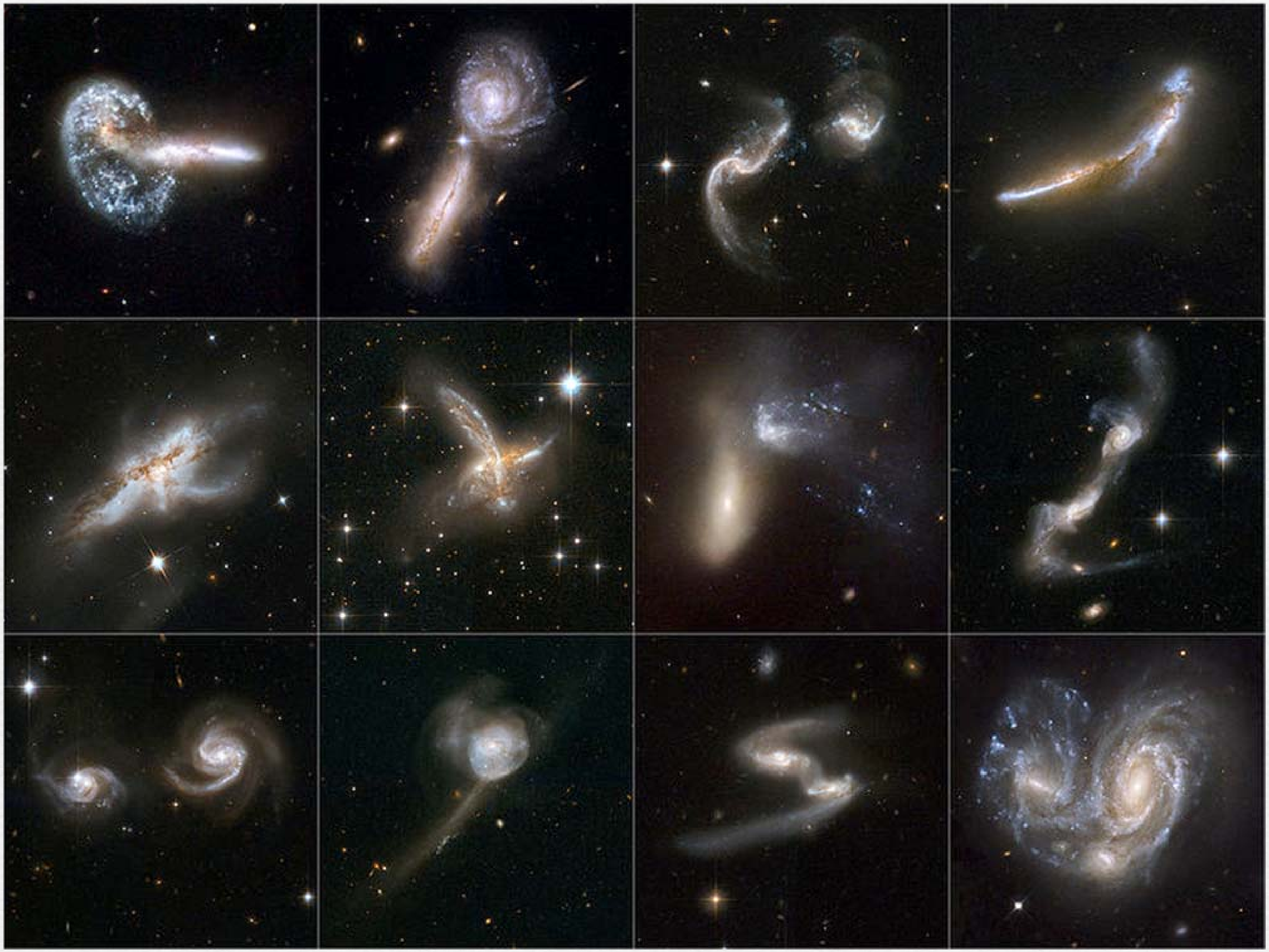
Low Frequency Sources

ELISA sources appear at much lower frequencies

All stellar mass sources are restricted to frequencies about 10 Hz.

Ground based detectors cannot see the massive universe

Galactic Mergers



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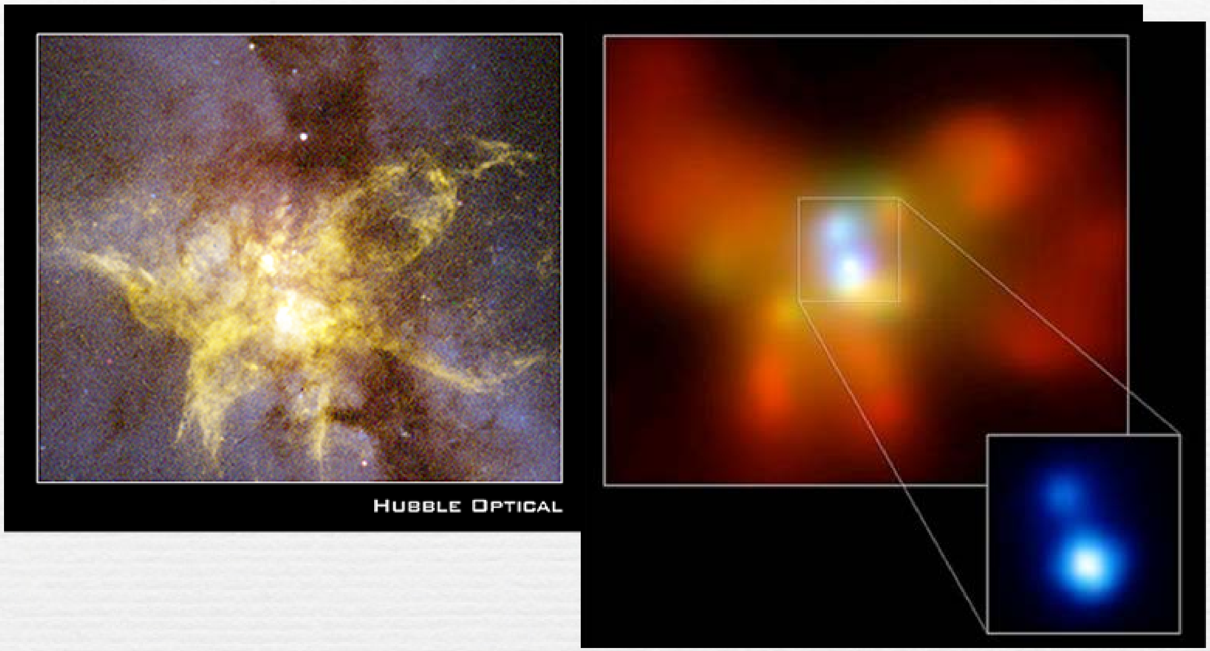

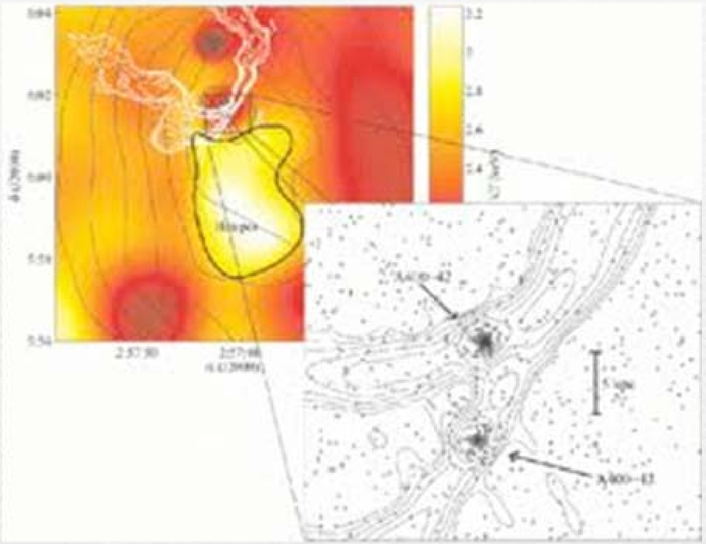

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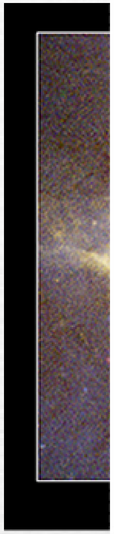

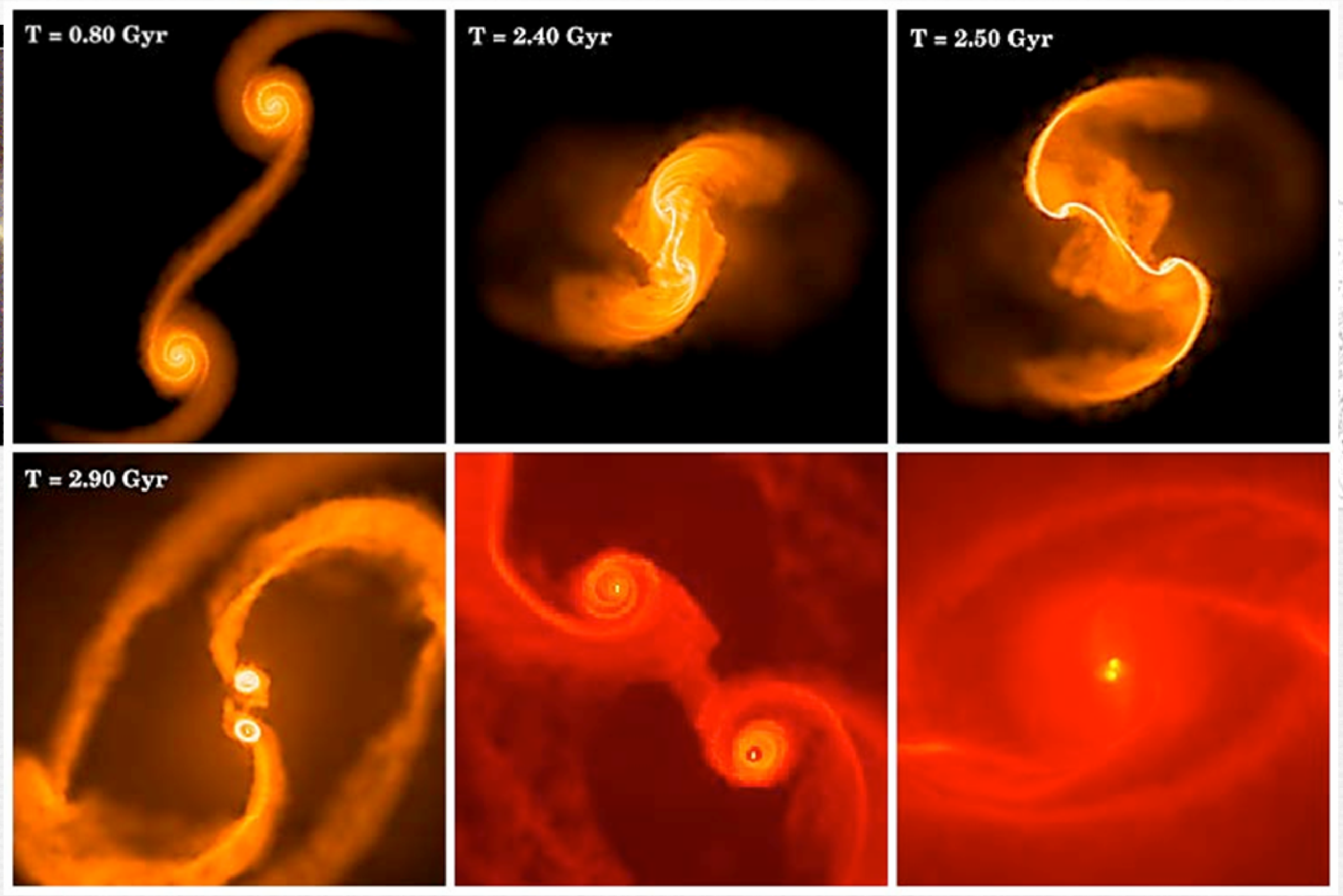

Galactic Mergers

A candidate sub-parsec supermassive binary black hole system

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Abstract

The role of mergers in producing galaxies, together with the finding that most large galaxies harbour black holes in their nuclei[1], implies that binary supermassive black hole systems should be common. Here we report that the quasar SDSS J153636.22+044127.0 is a plausible example of such a system. This quasar shows two broad-line emission systems, separated in velocity by 3,500 km s^{-1}. A third system of unresolved absorption lines has an intermediate velocity. These characteristics are unique among known quasars. We interpret this object as a binary system of two black holes, having masses of $10^{7.3}$ and $10^{8.9}$ solar masses separated by ~0.1 parsec with an orbital period of ~100 years.

Astrophysics, Cosmology and Cosmography

Galactic Binaries

Expect 60 million WDBs in our own galaxy

This includes a number of verification binaries

We expect to be able to individually resolve ~3000 WDBs

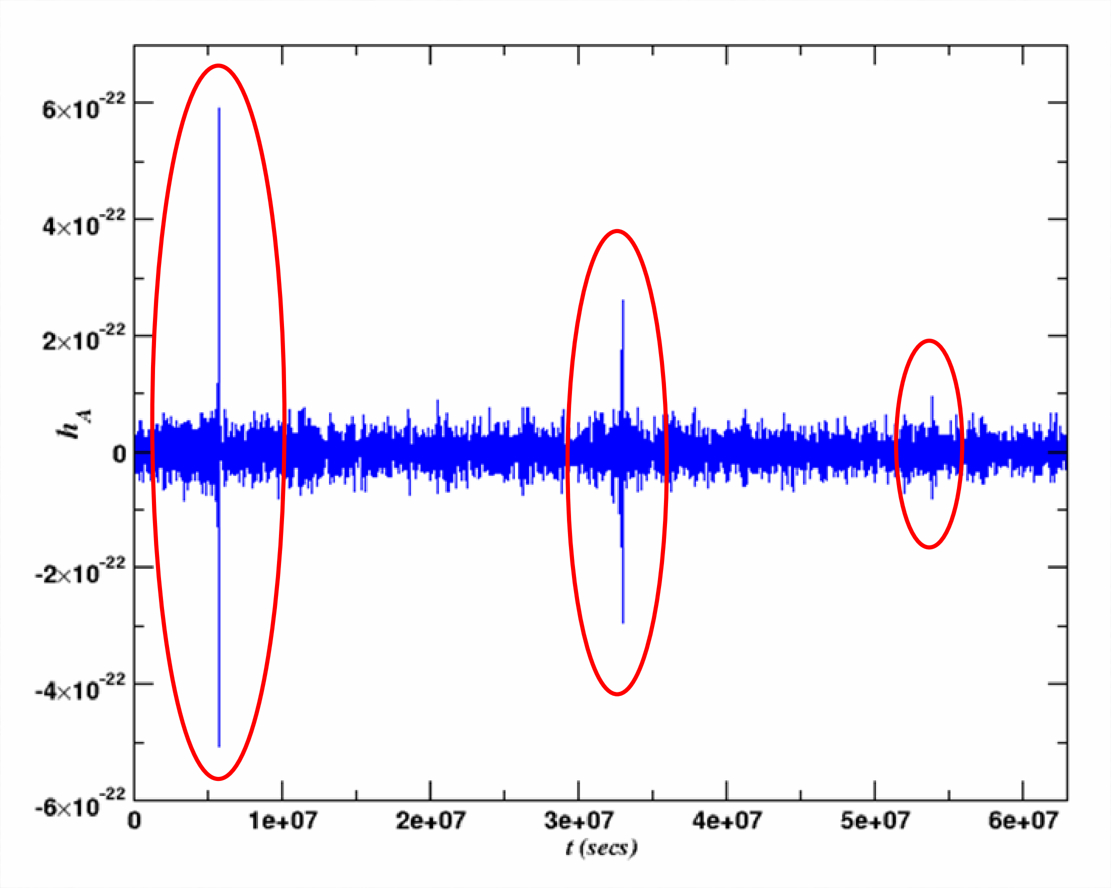
NS/NS and NS/BH binaries may also be possible

SMBHBs

Brightest GW events

10’s < SNR < 100’s

Event rates : 1-100s/yr



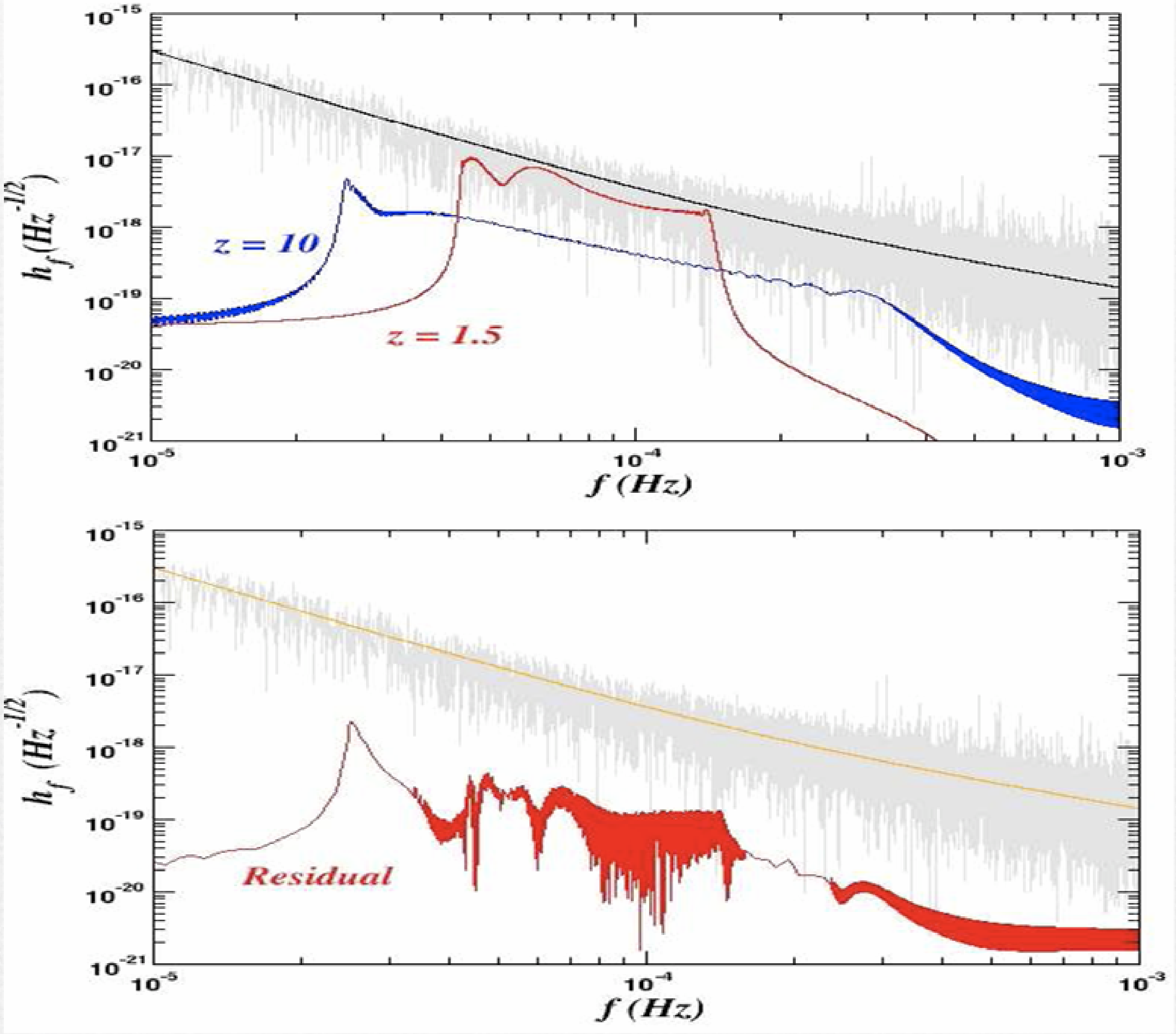
SMBHBs

Cornish & Porter, 2006

Expected range
of detection : z~10-15

Need detection
confidence level of
99.99%

Otherwise, other
sources are disturbed



Black Hole Seeds

- Scenario 1 : Light mass seeds
- Merger of Pop III remnants
- Masses of > 100 solar masses
- Scenario 2 : High mass seeds
- Direct collapse of protogalactic clouds
- Masses of > 10^4 solar masses

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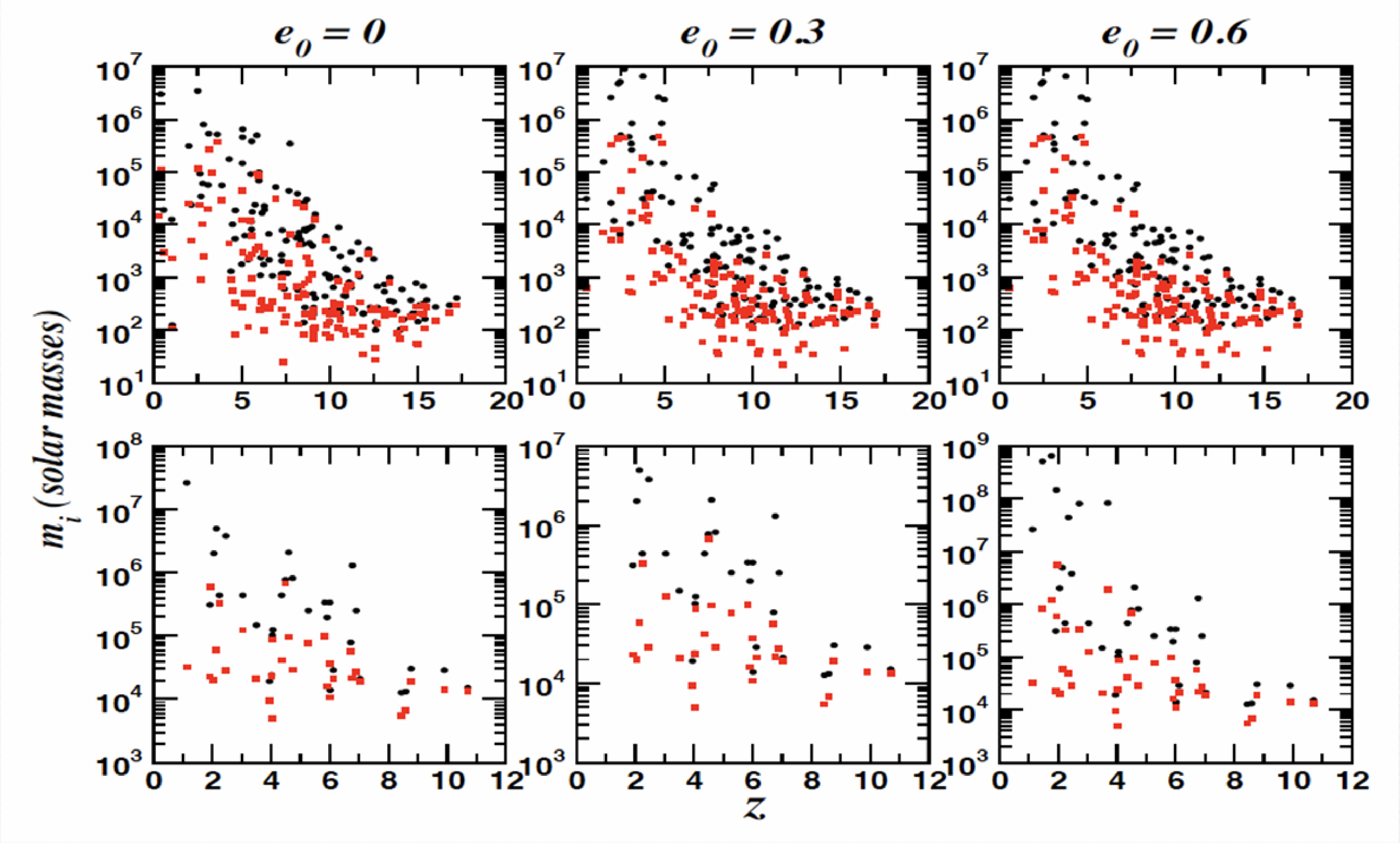
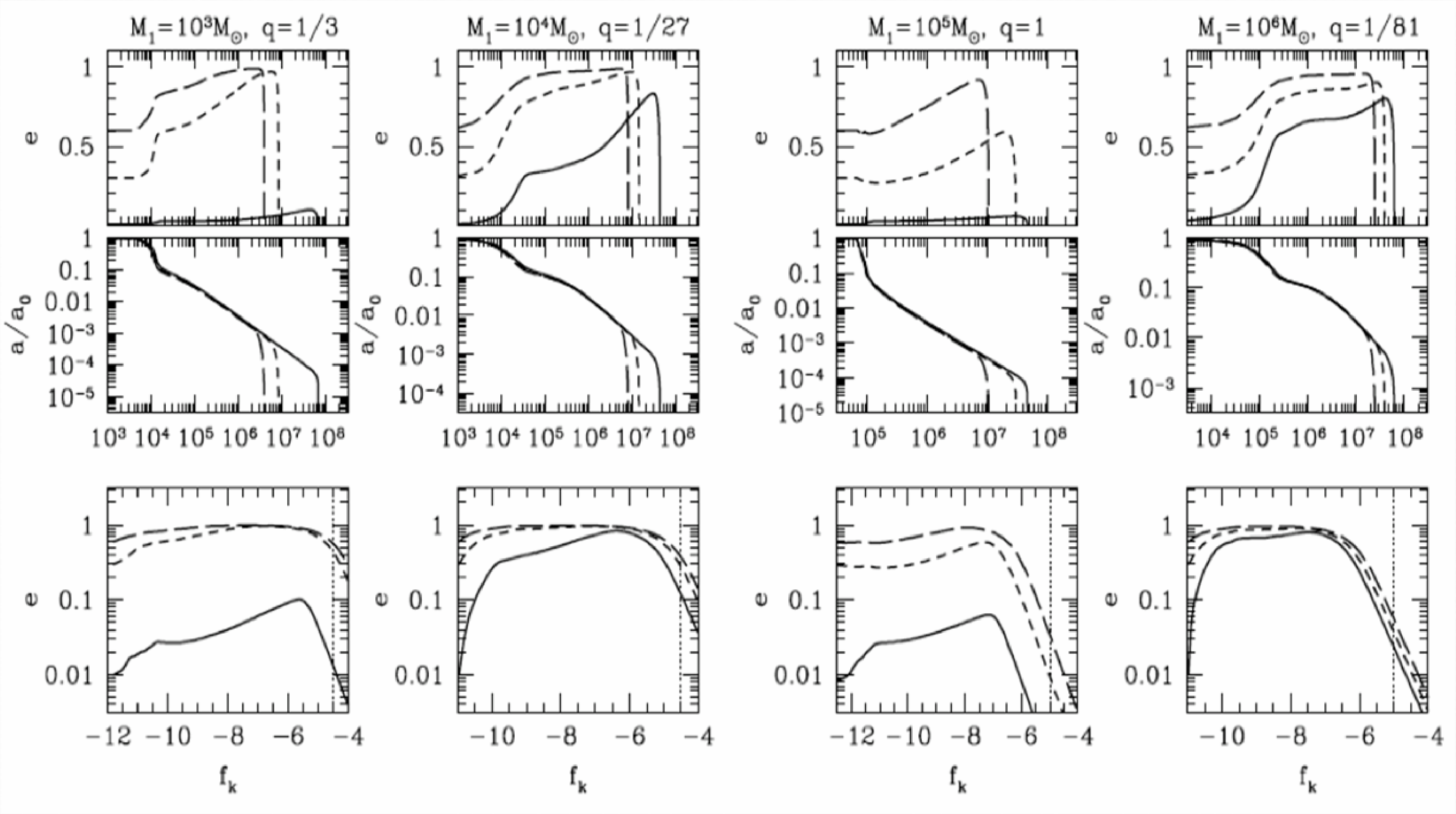
Masses vs. Redshift



Porter & Sesana, 2010

Eccentricity Evolution



Porter & Sesana, 2010

Parameter Estimation

For sources at $z < 7$

We would expect to be able to measure :

The masses of the binary to < 1%
The spin of the largest object to < 0.1
The luminosity distance to < 50% and in some cases to < 10%
The sky position to 1-100 square degrees

Parameter Estimation

With this level of accuracy, we would be able to trace the formation history of galaxies to a redshift of 7

It would also allow us to say something about black hole seed formation

Eccentricity Evolution

GWs very efficient at circularising a binary

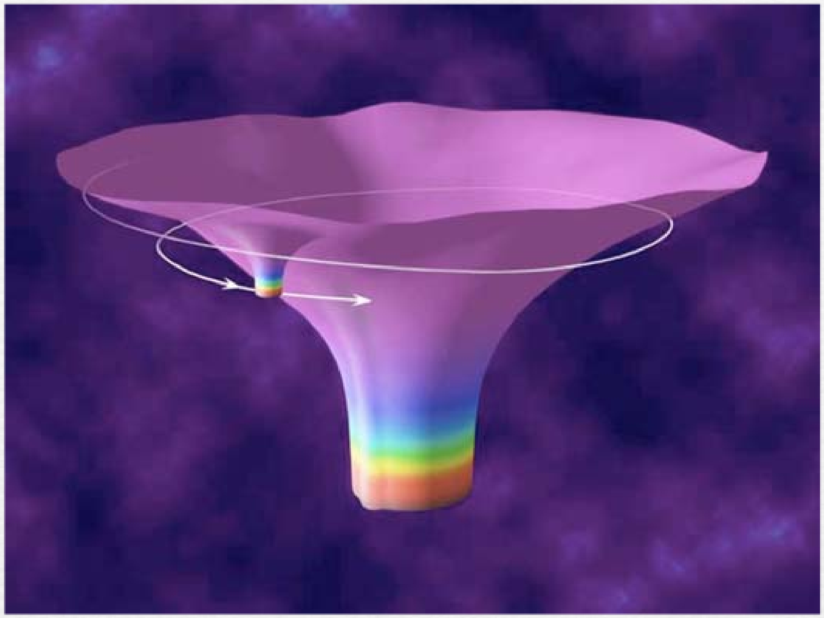
Should be able to detect eccentricity to 1:1000
(*Amaro-Seoane, Eichhorn, Porter & Spurzem, 2009 - Porter & Sesana, 2010 - Key & Cornish, 2010*)

Can give valuable information for BH seed formation

EMRIs

EMRIs

Describes the inspiral of a stellar mass compact object into a SMBH



Extremely low chance of EM counterpart

Complex sources to model

$$x^\nu = (\ln M, \ln \mu, S/M^2, \cos\theta_S, \phi_S, \cos\theta_K, \phi_K, \nu_0, e_0, \alpha_0, \tilde{\gamma}_0, \lambda, \phi_0, D_L)$$

Parameter Estimation

EMRIs spend most of their detector lifetime in the strong field regime : $r/M < 10$

We can track approximately 100,000 GW cycles

This allows us to measure the mass of both bodies to $< 1\%$, the luminosity distance to the source to $< 10\%$ and the spin and eccentricity of the central black hole to < 0.01

Testing GR

Kerr BH in GR is fully described by the mass and current multipole moments (M_l, S_l)

where $M_0 = M_{BH}$ and $S_1 = M_0 a$

All other multipoles are related by

$$M_l + iS_l = M_{BH}(ia)^l$$

Therefore, once two are known, we have all others

Fundamental Physics

Cosmic String Cusps

Short bursts of GWs

ELISA effectively stationary

No Doppler information

Sky comes from spacecraft triangulation

Search needed with other sources included

Conclusion

Conclusion

- Can explore low frequency sources with ELISA
- Can see SMBHBs, EMRIs etc
- Expect to test GR
- Can carry out high precision astrophysics, cosmology and cosmography
- If lucky, can test fundamental physics
- ELISA will open up a new window on the universe and be complementary to other fields of astronomy.

Conclusion

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