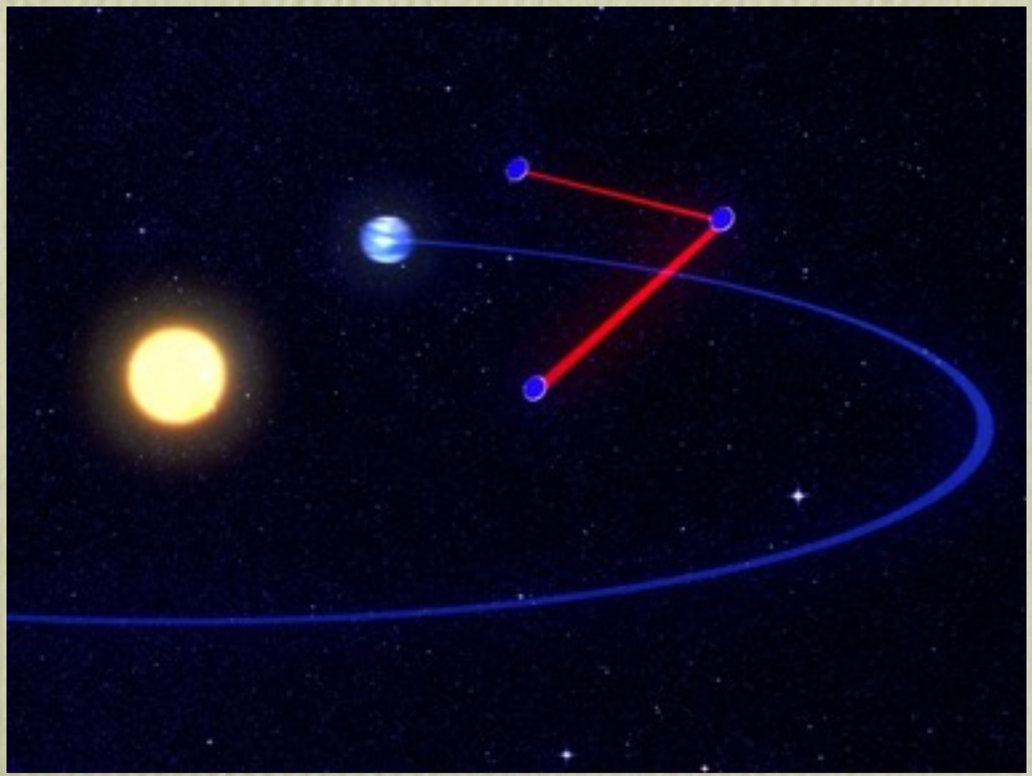
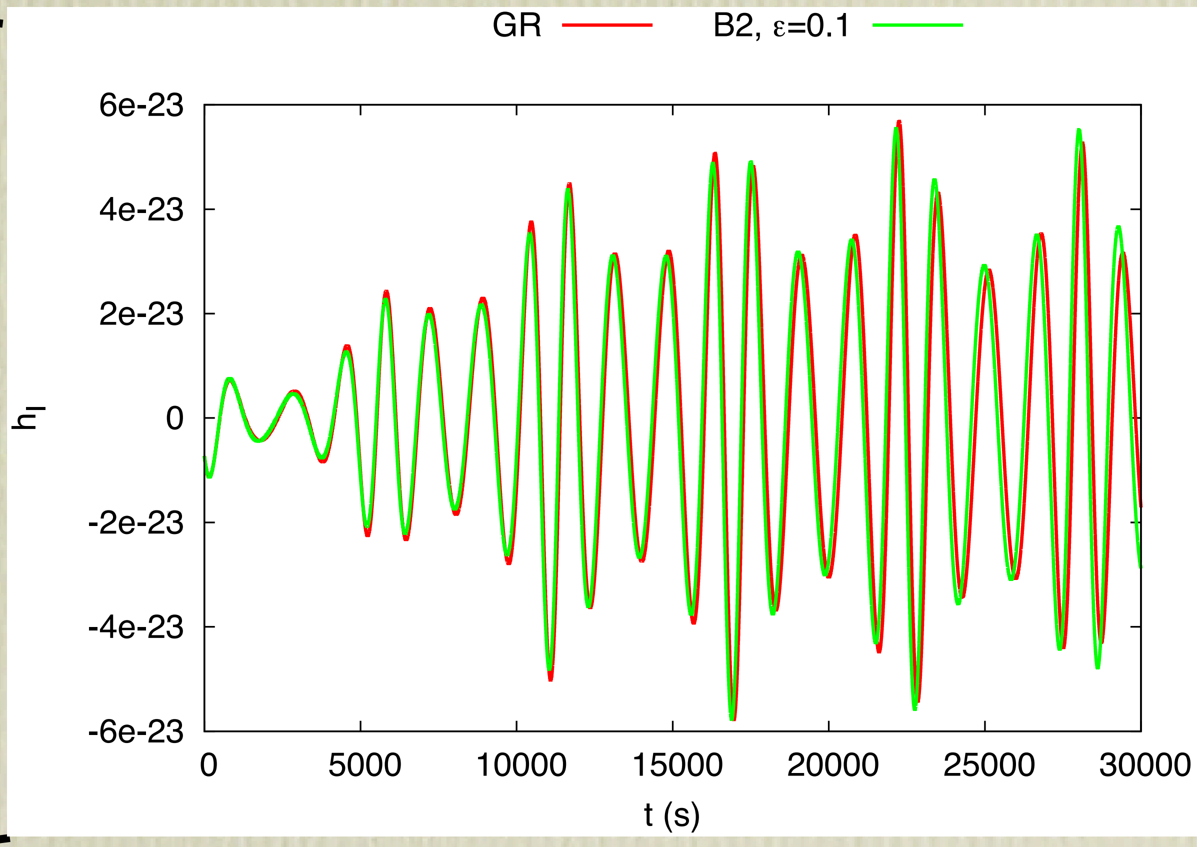
Working Group: Tests of Fundamental Laws

Jonathan Gair (IoA, Cambridge)

eLISA Consortium Meeting, Paris, October 23^{rd} 2012





Fundamental Laws

- First Fundamental Law that eLISA will test is
  - **a space-based gravitational wave detector is "about ten years in the future"**
- Observationally true since ~2002. Now receding......
- Hope we can prove this one wrong quickly!

Current Status

- eLISA provides an excellent laboratory for fundamental physics
  - **High signal-to-noise ratio** - SMBH binaries can have SNR in the thousands.
  - **Long duration signals** - EMRI systems generate ~10^5 cycles in strong field regime over the final few years of inspiral visible to eLISA.
  - **"Clean" systems** - main sources are black hole binaries. Waveforms expected to be minimally affected by matter.
- Various types of test have been proposed
  - **"No-hair theorem" tests of black hole structure.**
  - **Properties of gravitational waves** - polarisation, propagation.
  - **Tests of general relativity** against alternative theories, including Brans-Dicke, Chern-Simons or generic alternatives.
- Most studies for LISA. Difference for eLISA is mostly SNR.

Current Status

- Most literature on verification of the no-hair theorem. Idea is to measure spacetime multiple moments and check consistency with

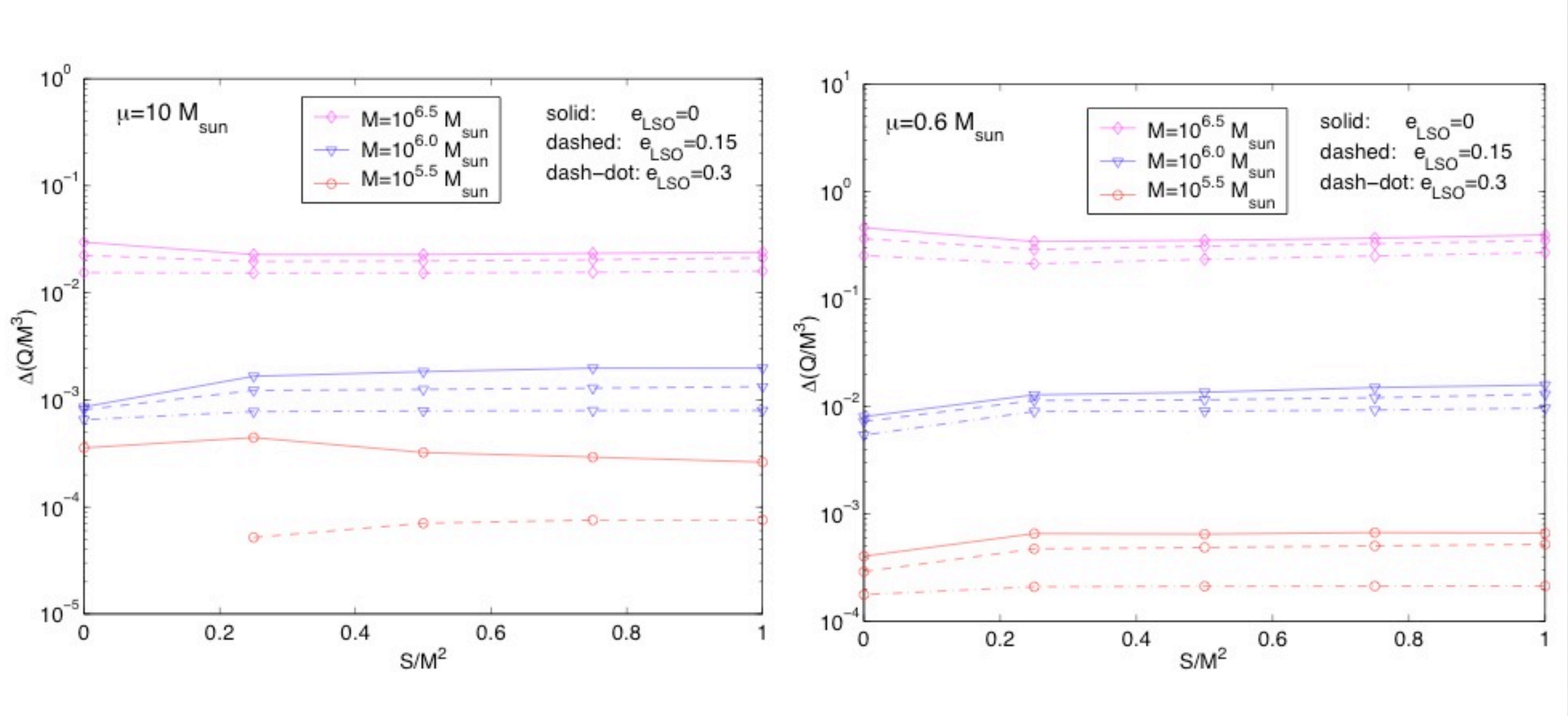
$$M_l + \mathrm{i}S_l = M(\mathrm{i}a)^l$$

- Moments are encoded in GW observables (Ryan 1995)

$$\frac{\Omega_p}{\Omega} = 3(M\Omega)^{\frac{2}{3}} - 4\frac{S_1}{M^2}(M\Omega) + \left(\frac{9}{2} - \frac{3}{2}\frac{M_2}{M^3}\right)(M\Omega)^{\frac{4}{3}}$$

- Strongest constraints come from EMRIs,
  - **Many papers** - Ryan (1997), Collins & Hughes (2004), Kesden et al. (2004), Glampedakis & Babak (2006), Barack & Cutler (2007), Li & Lovelace (2007), Gair et al. (2008), Sopuerta & Yunes (2009), Berry & Gair (2011), Gair & Yunes (2011), Canizares et al. (2012) .....

Current Status



- Barack & Cutler estimated quadrupole moment measurement precision of 10^{-3} possible with simultaneous M, a measurements of 10^{-4} for LISA. Same precision at fixed SNR in eLISA, but SNRs typically ~2 lower.

Current Status

- Most literature on verification of the no-hair theorem. Idea is to measure spacetime multiple moments and check consistency with

$$M_l + \mathrm{i} S_l = M(\mathrm{i}a)^l$$

- Moments are encoded in GW observables (Ryan 1995)

$$\frac{\Omega_p}{\Omega} = 3(M\Omega)^{\frac{2}{3}} - 4\frac{S_1}{M^2}(M\Omega) + \left(\frac{9}{2} - \frac{3}{2}\frac{M_2}{M^3}\right)(M\Omega)^{\frac{4}{3}}$$

- Strongest constraints come from EMRIs,
    - **Many papers** - Ryan (1997), Collins & Hughes (2004), Kesden et al. (2004), Glampedakis & Babak (2006), Barack & Cutler (2007), Li & Lovelace (2007), Gair et al. (2008), Sopuerta & Yunes (2009), Berry & Gair (2011), Gair & Yunes (2011), Canizares et al. (2012) .....
    - Barack & Cutler estimated quadrupole moment measurement precision of 10^{-3} possible with simultaneous M, a measurements of 10^{-4} for LISA. Same precision at fixed SNR in eLISA, but SNRs typically ~2 lower.
    - Astrophysical perturbations could be present and measurable - Barausse et al. (2007, 2008), Yunes et al. (2011).

Current Status

- No-hair theorem tests also possible using SMBH ringdown radiation - "black hole spectroscopy" (Berti et al. 2006).
- Tests based on gravitational wave propagation include
  - **Polarisation** - four additional polarisation states exist in general metric theories of gravity which eLISA can constrain (Tinto & Alves 2010).
  - **Propagation speed:** graviton mass bounds of $m_g \lesssim 4 \times 10^{-26}$eV (Berti et al. 2005a, 2012); parity violation detectable by comparing propagation speeds of left/right polarised GWs (Alexander et al. 2009).
- Tests of alternative theories
  - **Brans-Dicke** - bounds on $\omega_{\rm BD}$ possible if observe NS + low mass MBH inspiral. In general worse than Cassini bound (Berti et al. 2005a,b).
  - **Chern-Simons modified gravity** - various studies suggest eLISA can place bounds several orders of magnitude better than existing constraints (e.g., Canizares et al. 2012), but uncertainties remain.

(Some) Outstanding Issues

- Update many published LISA results for alternative detector configurations, in particular eLISA.
- Framework for approaching fundamental physics tests not yet developed. Various suggestions have been made, but work needed
  - **pN phase coefficient fitting** - Arun et al. (2006).
  - **ppE framework** - Yunes & Pretorius (2009), Gair & Yunes (2011).
  - **Null test** - look for GR and translate results to bounds on deviations.
- Very little work on constraints from the merger phase of SMBH binaries - opportunity to test GR in a highly dynamical regime.
- Need to model GR waveforms extremely precisely in order to place robust constraints. Previously unanticipated features, e.g, resonances in EMRIs, impact tests of fundamental laws.
- Data analysis implications - must test ideas in MeLDC.

Ongoing Activities

- Work on fundamental physics tests of gravity is continuing
  - **Theory**: e.g., compact objects in alternative theories - Pani et al. (1109.0928), Yagi et al. (1206.6130); GW inspirals - Yagi et al. (1208.5102),
  - **GW constraints:** e.g., Brans-Dicke - Berti et al. (1204.4340); massive scalars - Cardoso et al. (1109.6021); CS gravity - Canizares et al. (1206.0322)
  - **Other constraints:** e.g., binary-pulsar - Alsing et al. (1112.4903), X-rays - Bambi (1210.5679).
- Focus on GW constraints is shifting to Adv. LIGO
  - Adv. LIGO Science is not as interesting - low SNR, fewer waveform cycles. However, they have data, so funding is easier to come by!
  - LIGO studies have value for eLISA. Often straightforward to extend analysis to another detector, e.g., Cornish et al. (1105.2088).
  - Need eLISA specific work too - EMRIs are not LIGO sources, SMBH binaries have much higher SNRs, eLISA waveforms are longer.
- High value of eLISA is clearly and widely recognised, but interest will wane if it is too long before there is an "official" mission again.

Community Involvement

- Other eLISA working groups
  - **Astrophysical source groups** - close interaction with BH and EMRI working groups for modelling, event rates etc.
  - **Cosmology** - detection of a cosmic GW background or cosmic strings or cosmological parameter measurement is fundamental physics.
  - **Data analysis** - need to understand how to carry out fundamental physics tests in practice; include in MLDCs at some point.
- Waveform developers - self-force models; numerical relativity; pN, especially NRAR programme. Needed to understand GR waveforms fully and explore dynamical regime for possible fundamental physics tests.
- "Photonic" astronomers - there are ongoing efforts to constrain fundamental physics using observations of CMB, clusters etc. Must maintain contact in order to ensure we react to progress in those areas and take advantage of theoretical work.

Discussion

- Some possible discussion points
  - Second convenor - from mathematical or numerical side? One suggestion: Philippe Grandclement.
  - Organisation - what is expected? teleconferences? meetings? how often?
  - Membership - within our community and wider.
  - Advertising our activities - to attract broader interest, propagate idea that eLISA is alive and well.
  - Funding opportunities - do any exist? European network on modified gravity - not motivated by GWs, but involving them.
  - Name - NGO was the L1 proposal. Do we use eLISA to refer to every possible future mission, or the specific NGO design?