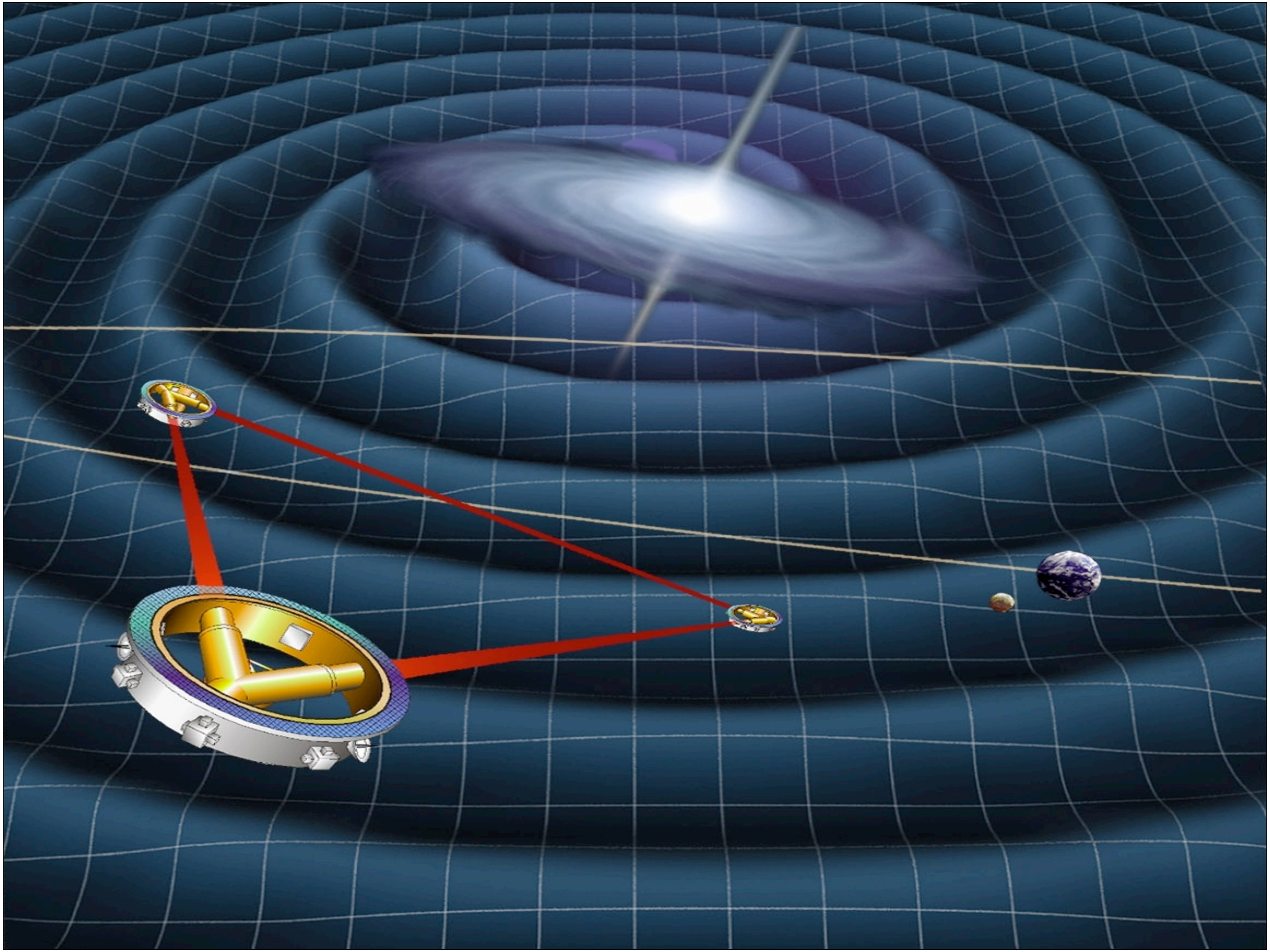


LISA and capture sources

O. Jennrich

LISA Project Scientist

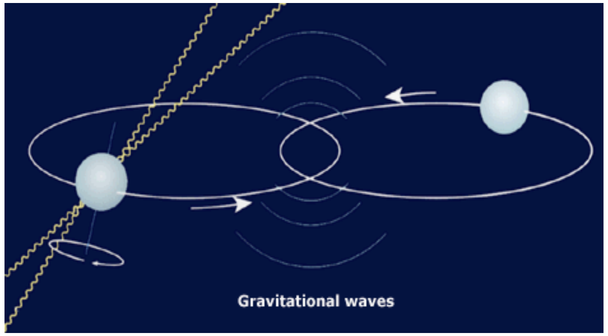
LISA

What are Gravitational Waves?

- Gravitational waves are predicted by GR (Einstein, 1918)
- Propagate with the speed of light
- Quadrupole waves, two polarisations
- Change distance between free-falling masses
- H. Bondi (1957): GW are physical: they carry energy, momentum and angular momentum
- Small coupling to matter, hence almost no absorption or scattering in the Universe
- Small amplitude, small effects
- Ideal tool to observe
  - distant objects
  - centre of galaxies
  - Black Holes
  - early Universe

Sources of gravitational waves

- **Any mass distribution that is accelerated in a non-spherically symmetric way (waving hands, running trains, planets in orbit, …)**
- **Large masses necessary to get any measurable signal**
  - Neutron star binary system
  - Supernovae
  - Black Holes



Crab nebula, HST

NGC 4261, HST

LISA

- **LISA is a space-borne interferometric gravitational-wave detector**
- **Designed to detect GW from**
  - coalescing massive black hole binaries
  - compact galactic binaries
  - capture events
- **Joint ESA/NASA mission**
- **Launch ~2018**

Science objectives of LISA

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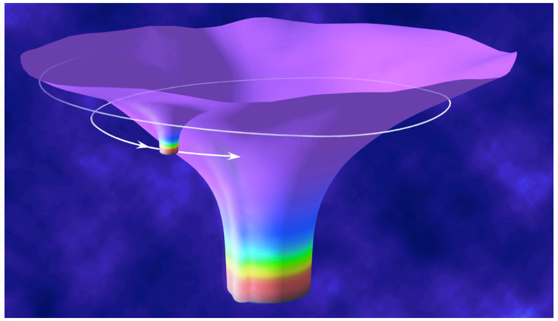
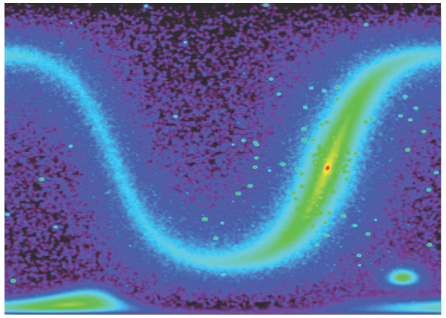
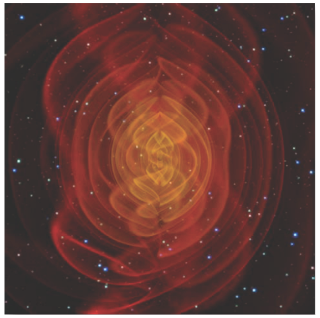
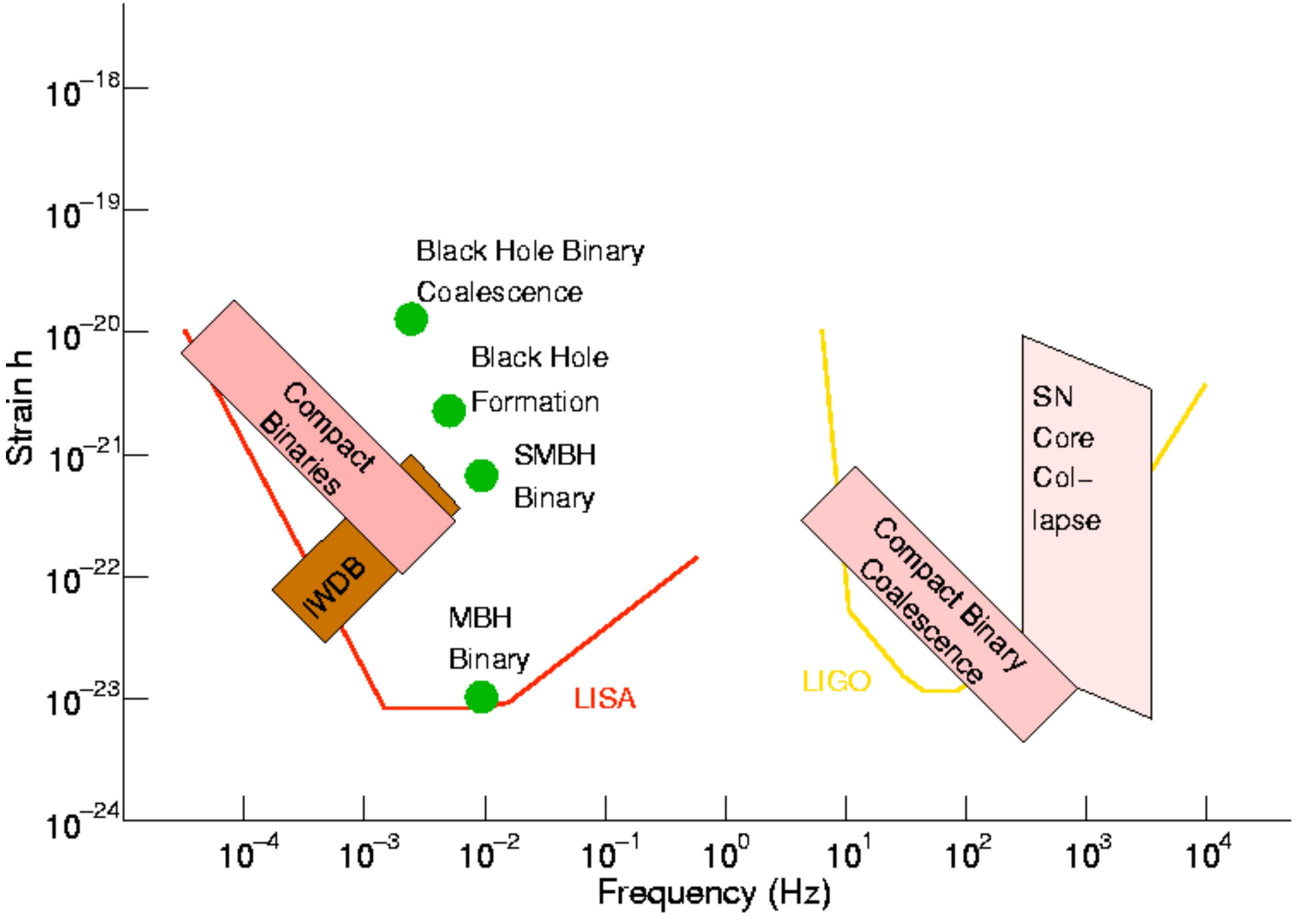






What are the sources?

- Only a space borne detector can overcome the seismic barrier

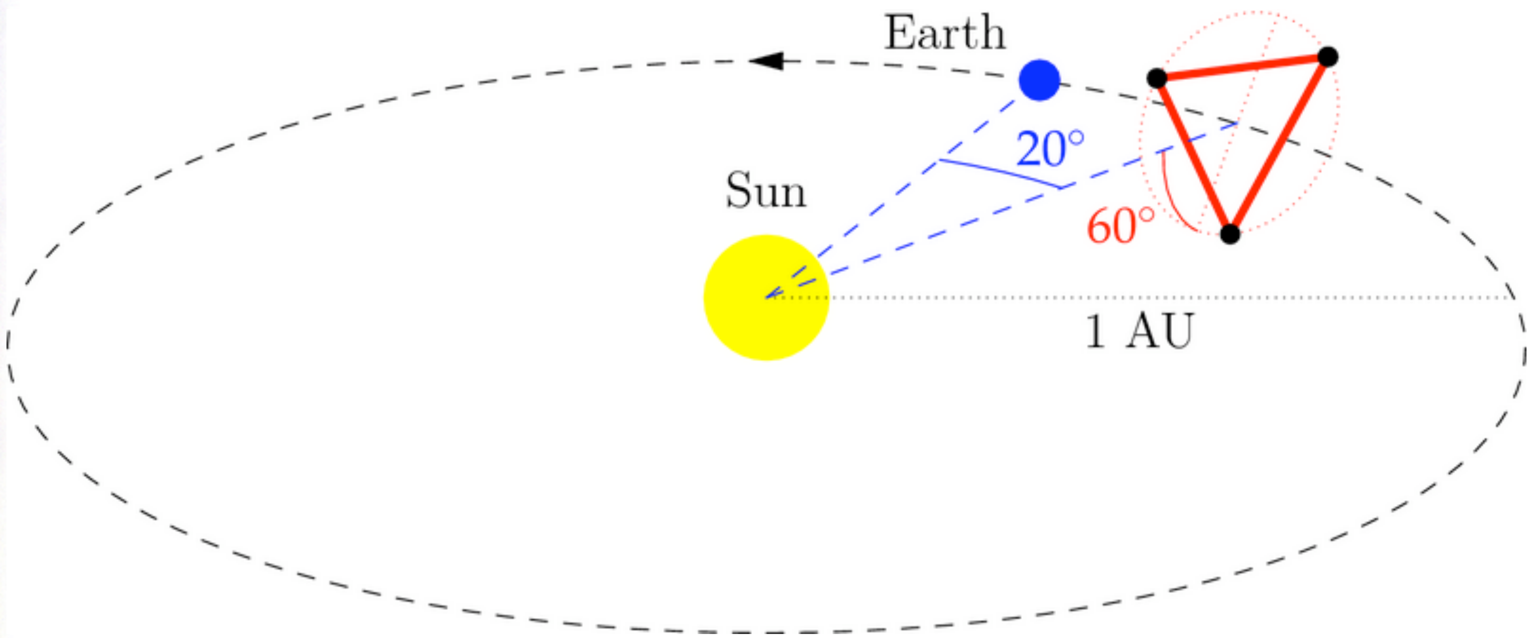


LISA Mission Concept

- **Measure the change of distance between free falling proof masses**
- **Interferometric distance measurement**
  - Use lasers
  - Use large distances to enhance the effect of the GW
- **Ensure that proof masses follow gravitational orbits**
  - Avoid orbit control
  - Suppress non-gravitational forces (electrostatic, magnetic, …)

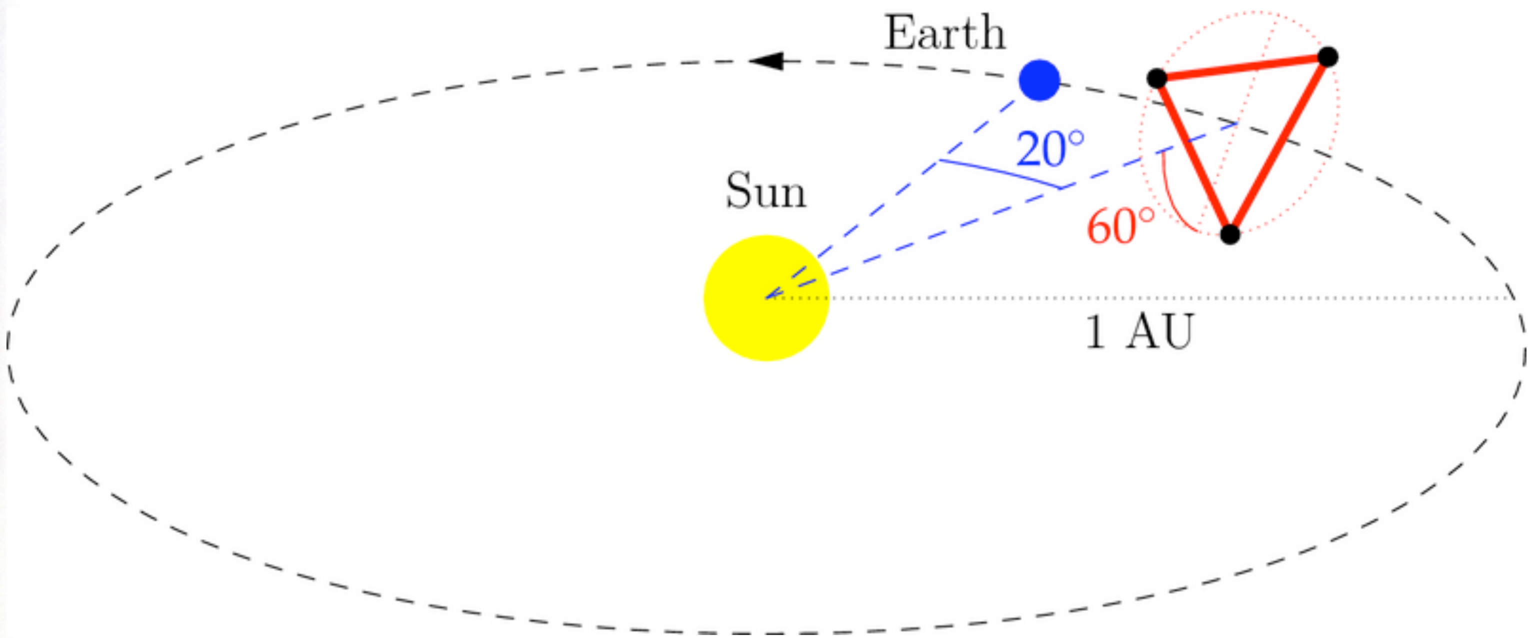
LISA Mission Concept

- **Cluster of 3 spacecraft in a heliocentric orbit**
  - Spacecraft shield the test masses from external forces (solar wind, radiation pressure)
  - Allows measurement of amplitude and polarisation of GW



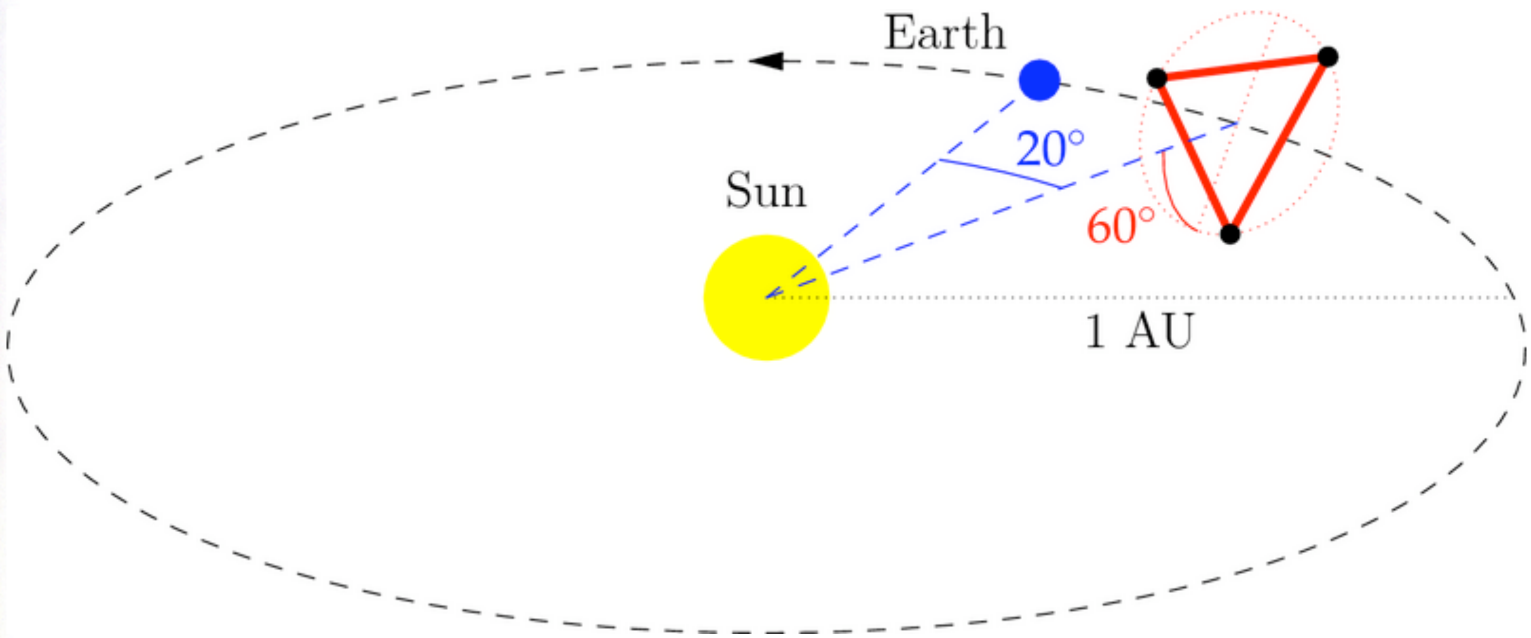
LISA Mission Concept

- **Cluster of 3 spacecraft in a heliocentric orbit**
- **Trailing the Earth by 20° (50 million kilometres)**
  - Reducing the influence of the Earth-Moon system on the orbits
  - Keeping the communication requirements (relatively) standard



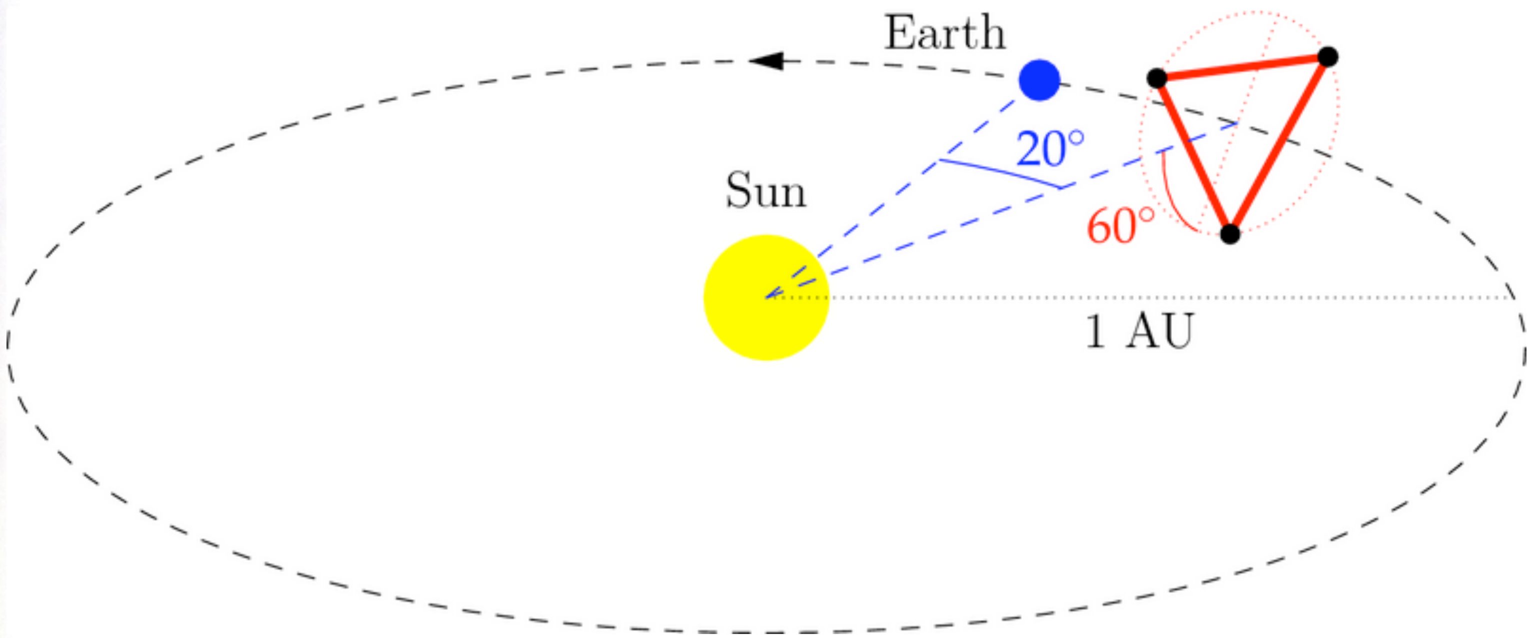
LISA Mission Concept

- **Cluster of 3 spacecraft in a heliocentric orbit**
- **Trailing the Earth by 20° (50 million kilometres)**
- **Equilateral triangle with 5 million kilometres arm length**
  - Results in easily measurable pathlength variations
  - Orbit is still stable enough to allow for mission duration >5years



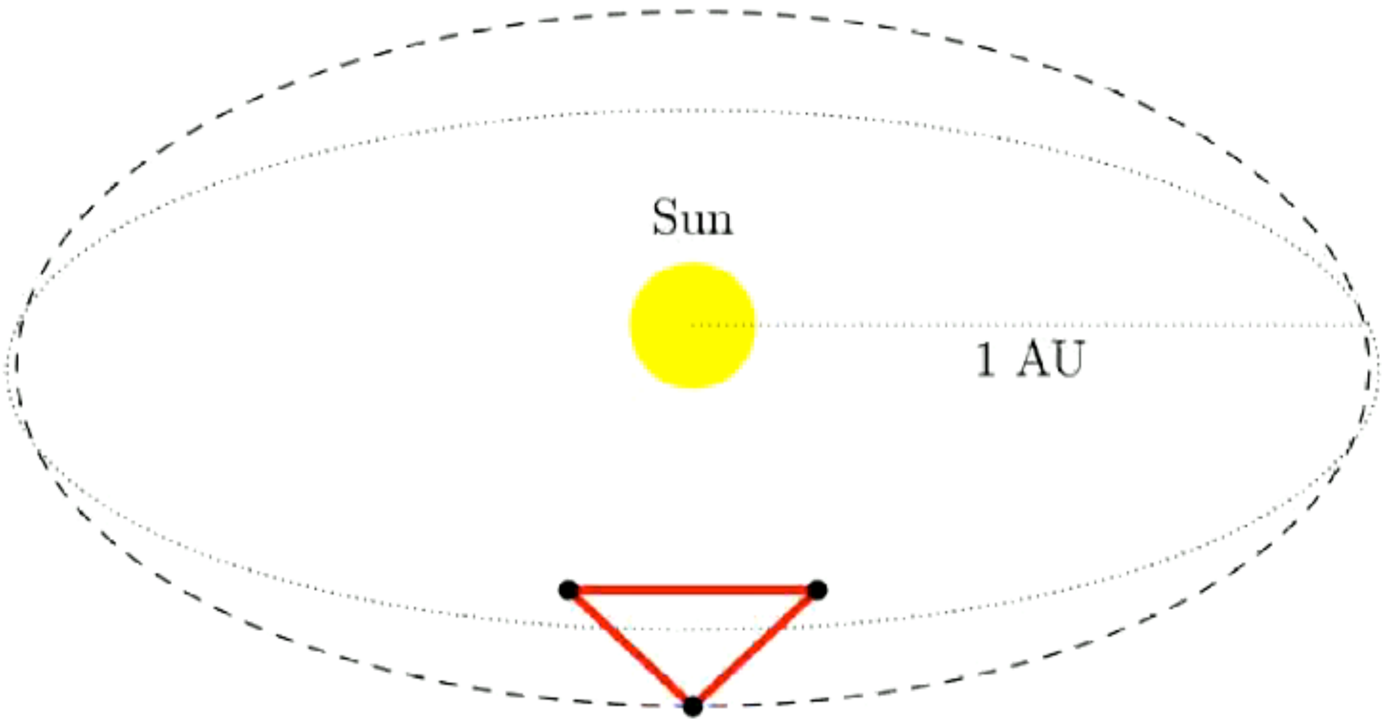
LISA Mission Concept

- Cluster of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by 20° (50 million kilometres)
- Equilateral triangle with 5 million kilometres arm length
- Inclined with respect to the ecliptic by 60°
  - Required by orbital mechanics



The LISA Orbit

- Constellation counter-rotates during the course of one year.
- No additional orbit control necessary.
- Constellation forms an “almost rigid” triangle.



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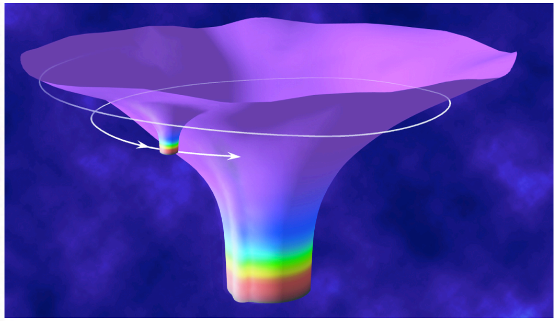
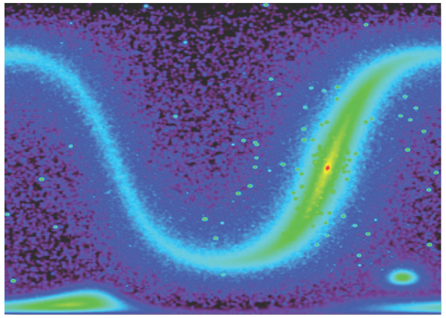
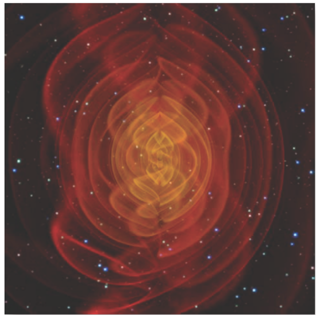
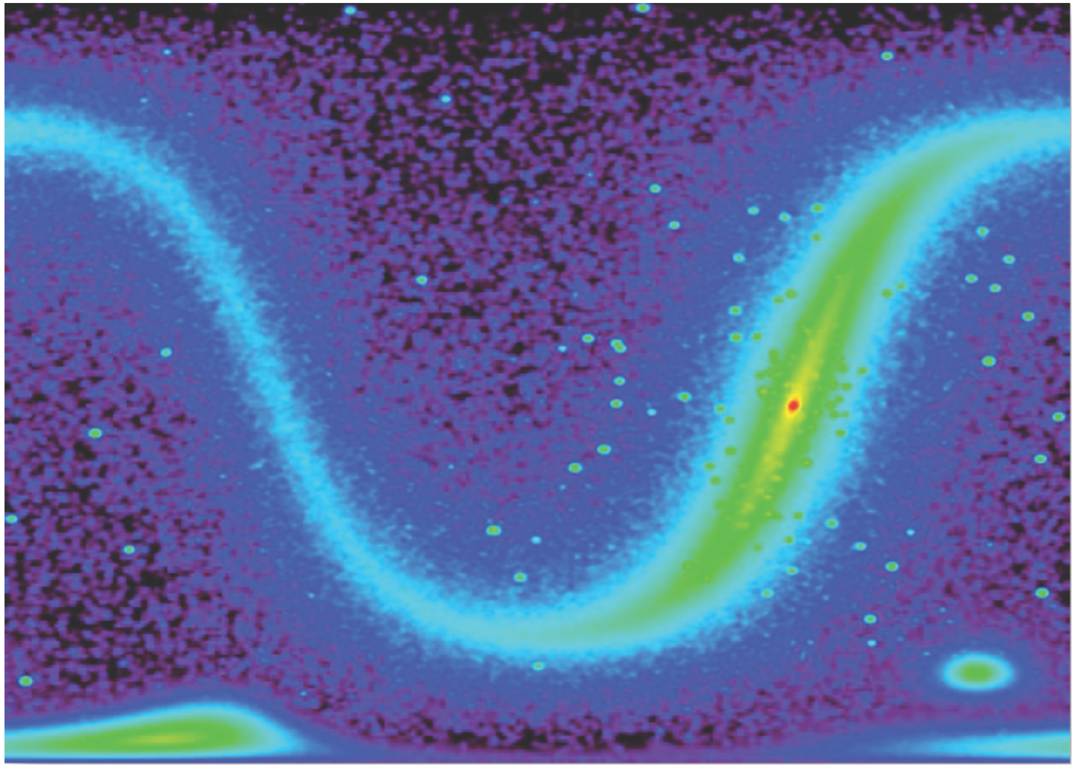






Galactic binaries

- **Over 30 Million compact binaries in our galaxy**
  - Learning about the structure of our Galaxy
- **Extra-galactic sources (equivalent to Olbers' paradox)**

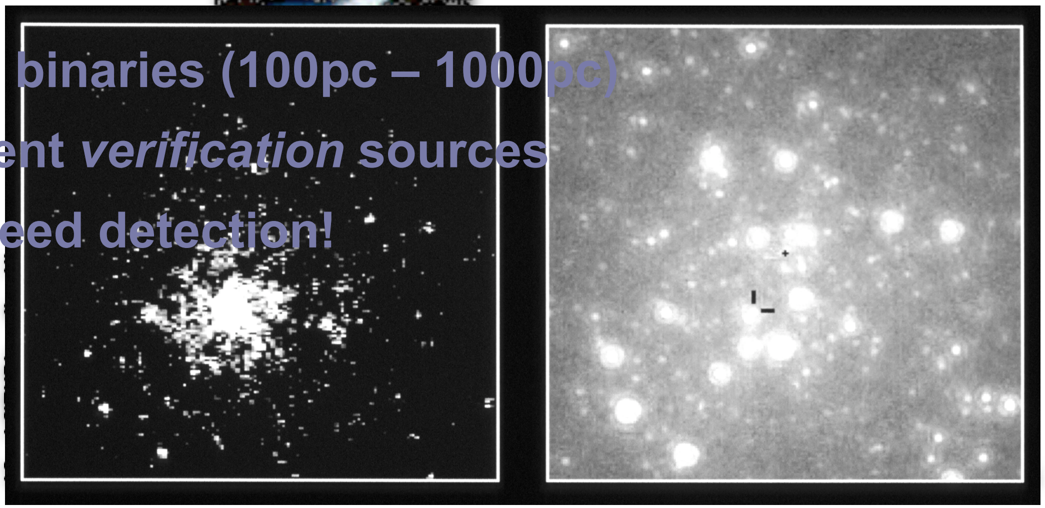


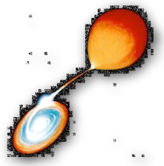
LISA Verification Binaries

Class	Source	*f* (mHz)	Strain *h* (10^{-23})
WD+WD	WD 0957-666	0.38	40
	WD 1101+364	0.16	20
	WD 1704+481	0.14	40
	WD 2331+290	0.14	> 20
WD+sdB	KPD 0422+4521	0.26	60
	KPD 1930+2752	0.24	100
LMXB	4U1820-30	3.0	2
	4U1626-67	0.79	0.6
W Uma	CC Com	0.105	60

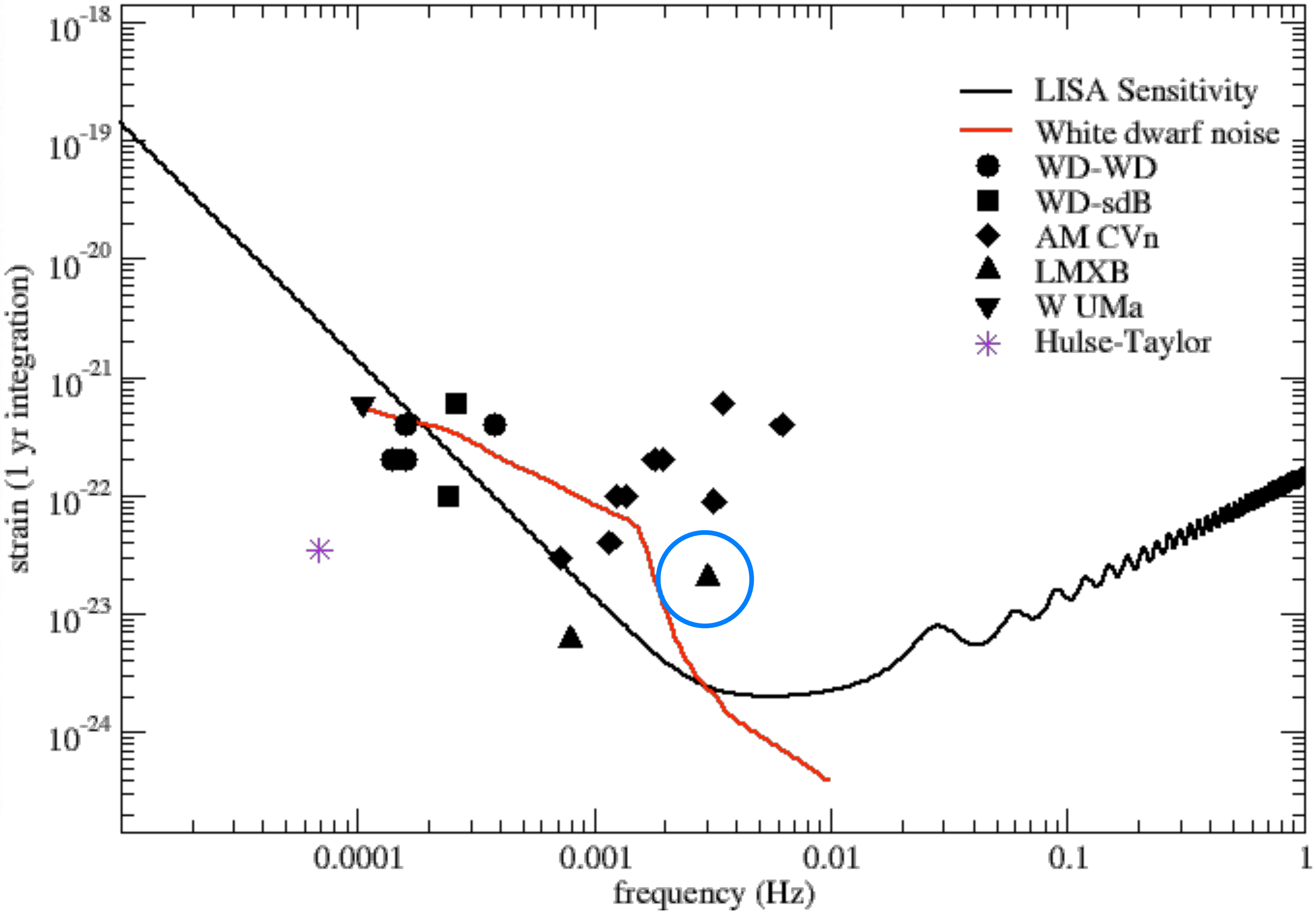
Class	Source	*f* (mHz)	Strain *h* (10^{-23})
AM CVn	RXJ0806.3+1527	6.2	40
	RXJ1914+245	3.5	60
	KUV05184-0939	3.2	9
	AM CVn	1.94	20
	HP Lib	1.79	20
	CR Boo	1.36	10
	V803 Cen	1.24	10
	CP Eri	1.16	4
	GP Com	0.72	3

- **Galactic binaries (100pc – 1000pc)**
- **Instrument *verification* sources**
- **Guaranteed detection!**





LISA Verification Binaries



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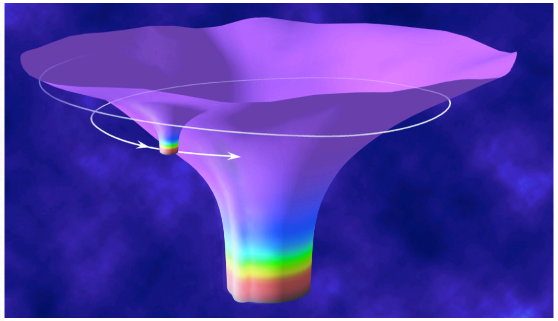
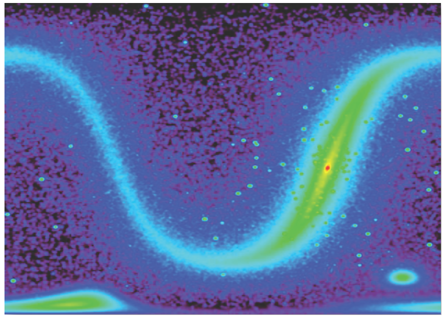
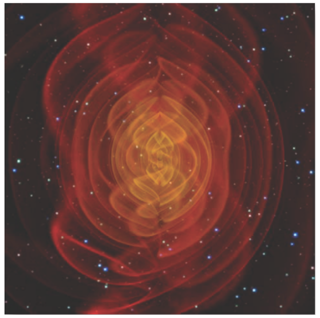
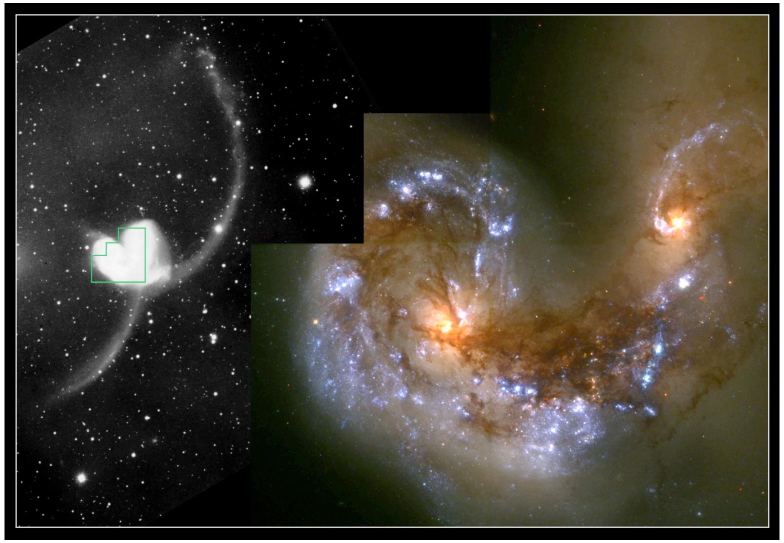






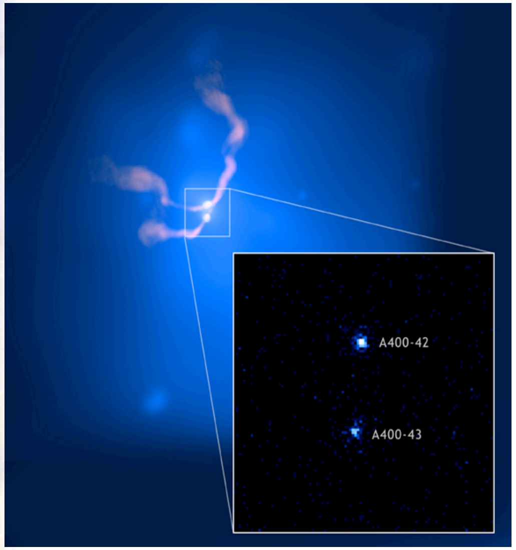
Massive black hole (MBH) binaries



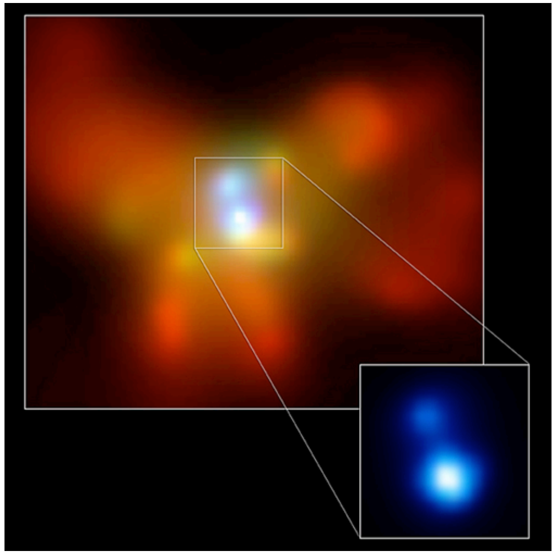
- MBH found at centre of most galaxies
- Most galaxies merge one or more times
  → MBH binaries
- MBH mergers trace galaxy mergers
- MBH mergers are strong sources of gravitational waves
- These GWs are detectable by LISA to z ~ 30 or more
  – Most signals will occur around z~10
- Expect to see 10s – 100s of events per year
- Observing these gravitational waves gives the masses and spins of the MBHs to high precision and probes the early stages of structure formation

Evidence for MBH Binaries

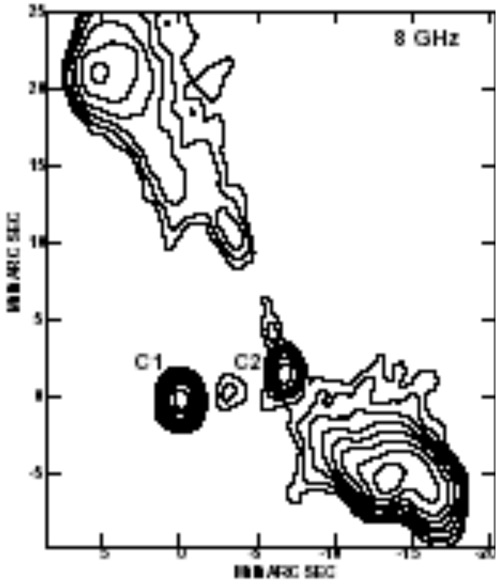
- **Abell 400**
  - Separation ~ 7600 pc
- **NGC 6240**
  - Separation ~ 1000 pc
- **0402+379**
  - Separation ~ 7.3 pc



(X-ray: NASA/CXC/AIfA/D.Hudson & T.Reiprich et al; Radio:NRAO/VLA/NRL)



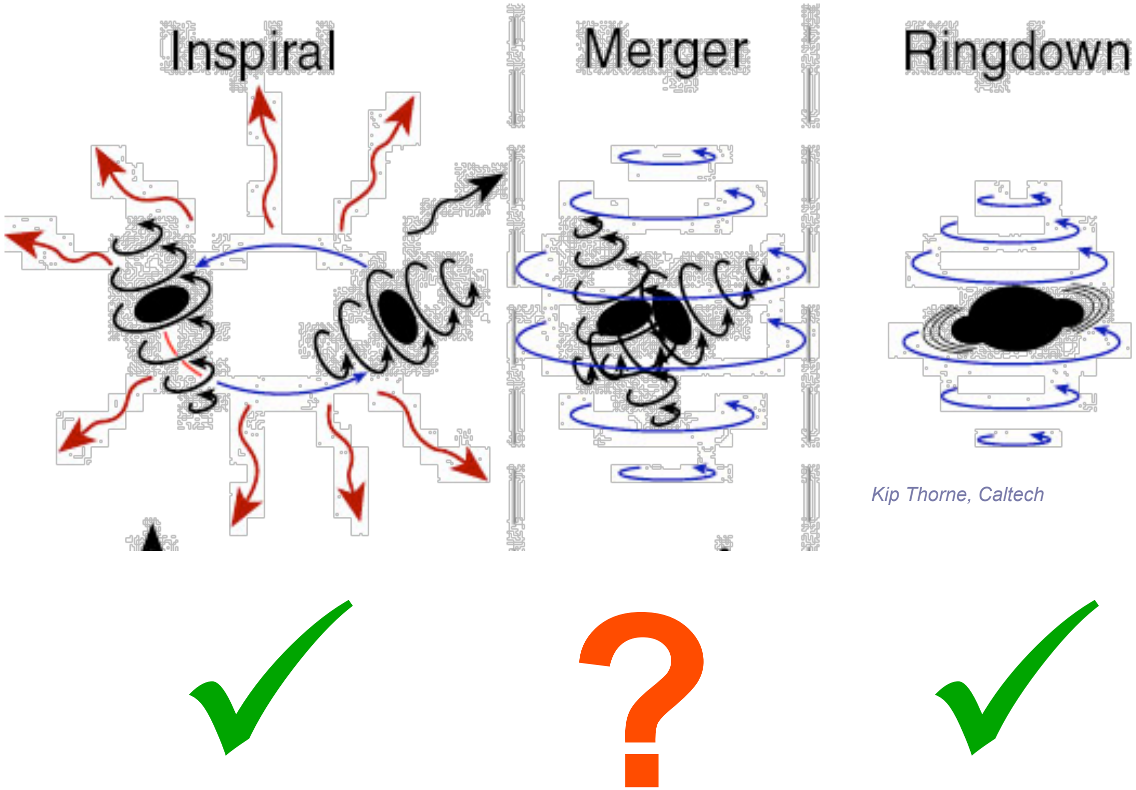
(NASA/CXC/MPE/S.Komossa et al.)



(Rodriguez, et al. ApJ, in press, astro-ph/0604042)

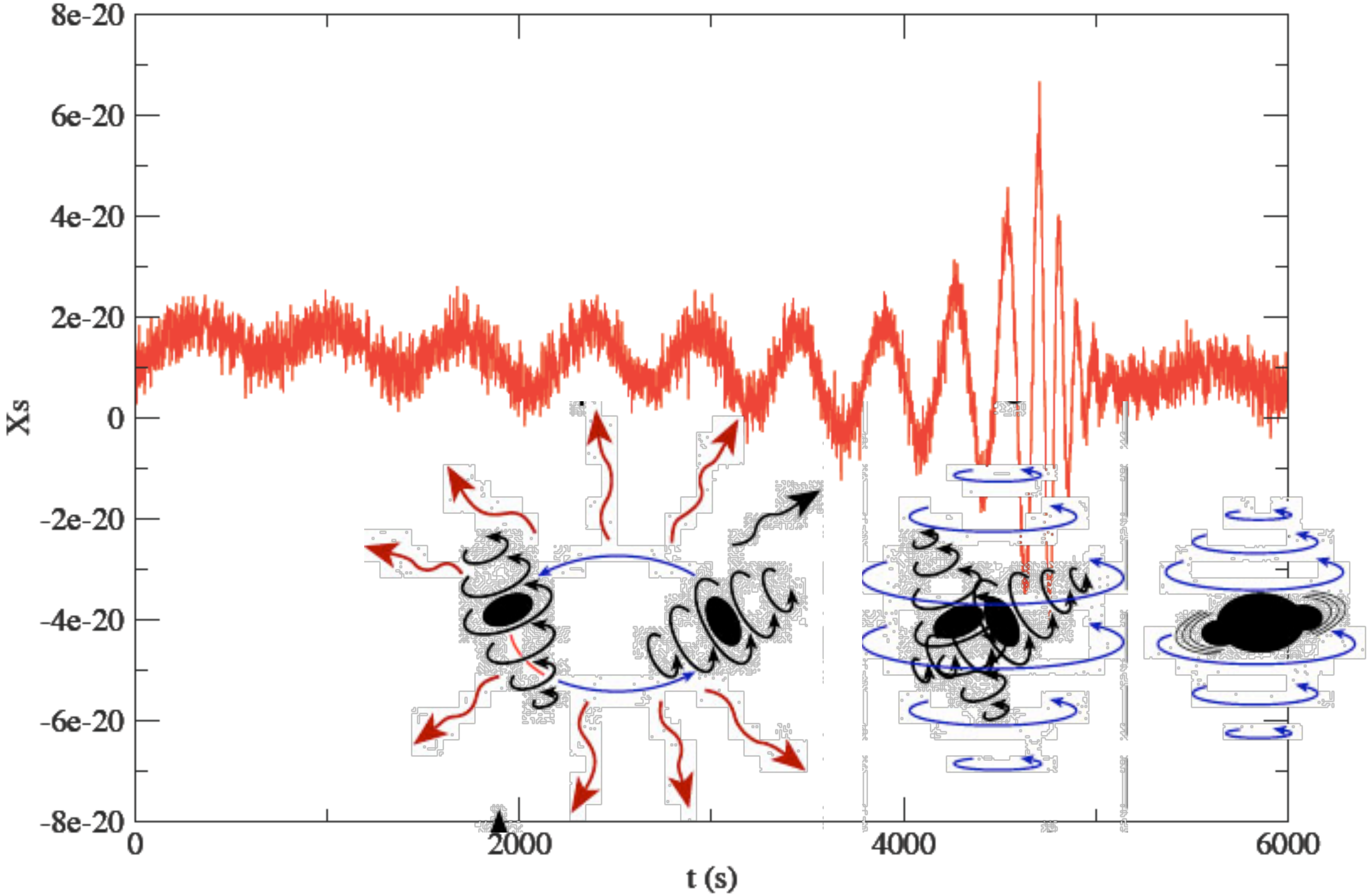
MBH mergers

- MBH waveforms constitute a numerical challenge
- Unsolved for over 40 years



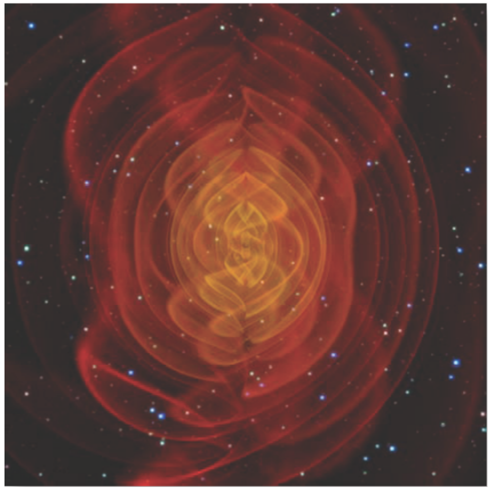
MBH signals

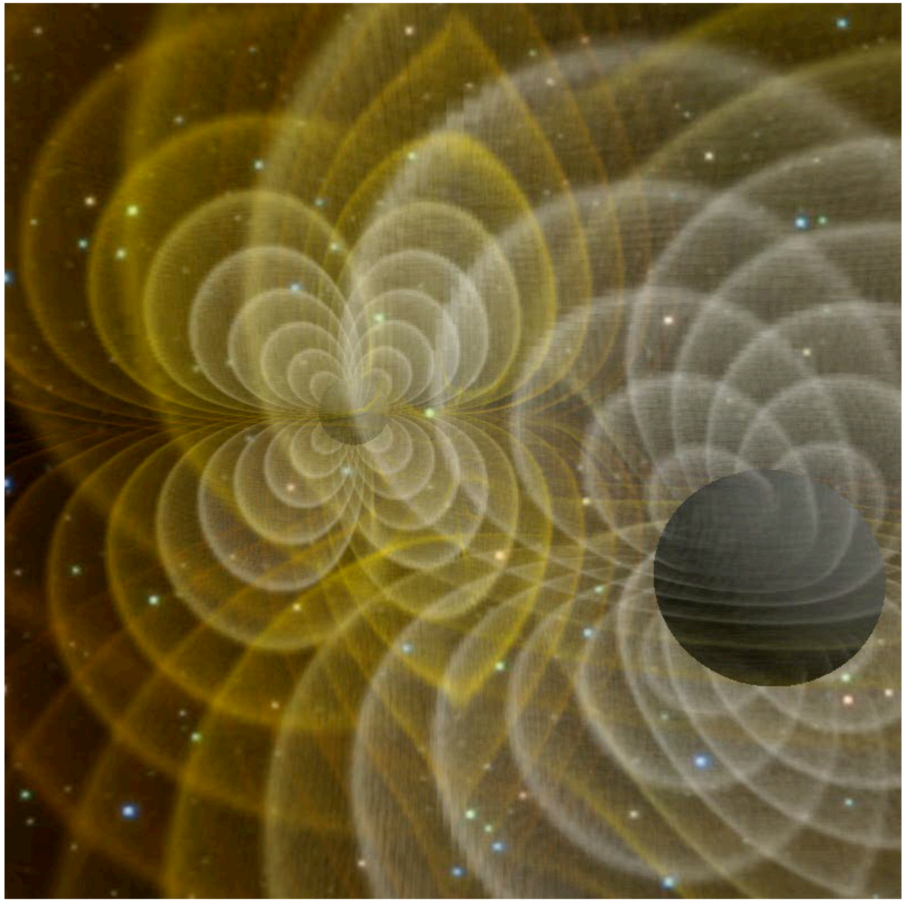
- Recent progress in numerical relativity allows to accurately assess the waveforms in all three phases



GW Signals from MBH mergers

- MBH mergers emit ~4% percent of their rest mass in GW.
- Very strong signals: $10^{23}L_{sun}$
- LISA will observe MBH mergers out to z~30.

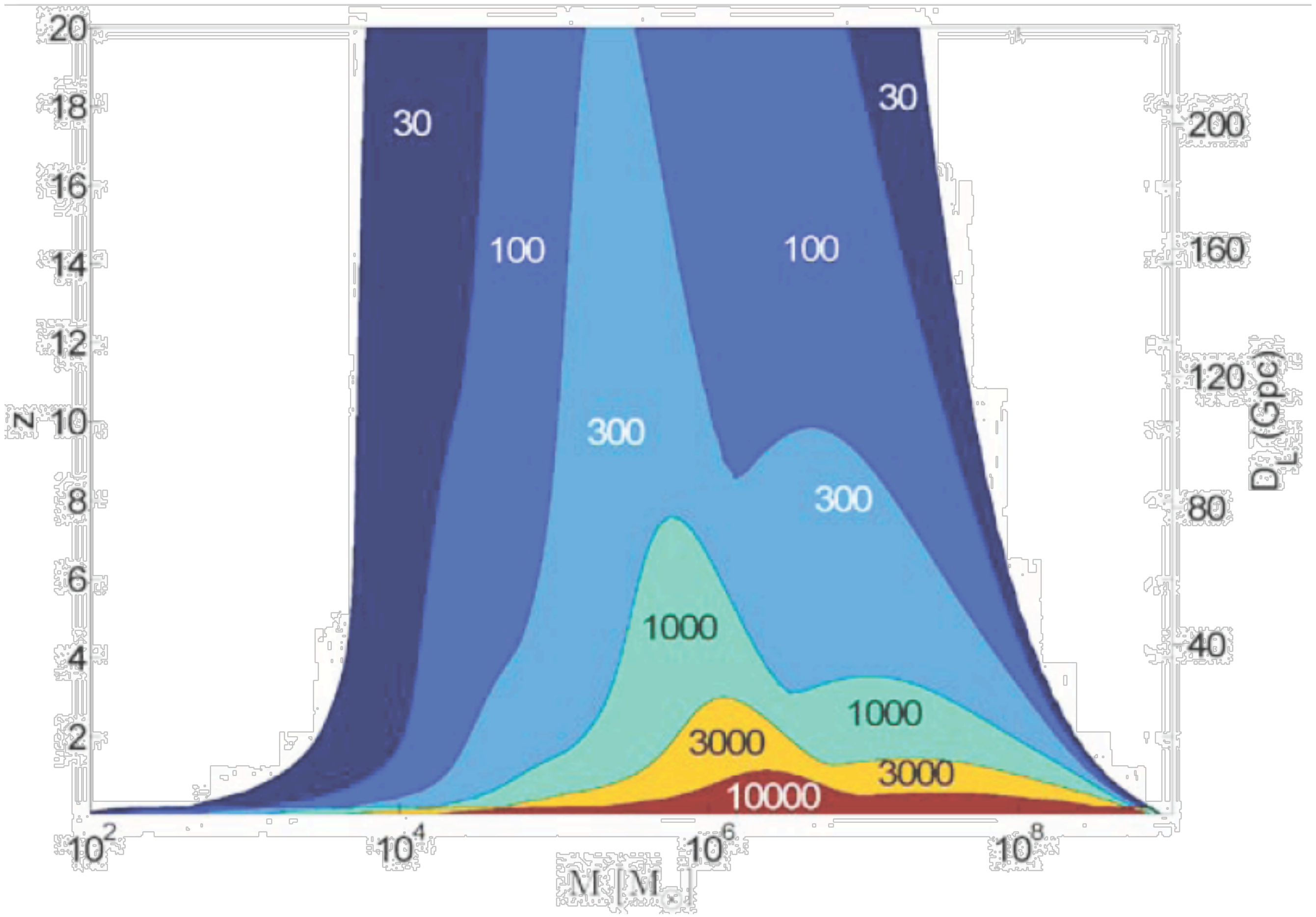




Baker, NASA GSFC, ***(Visualizations by Chris Henze, NASA/Ames)***

Mergers of Massive Black Holes

- Signal-to-noise of 1000 or more allows LISA to perform precision tests of General Relativity at ultra-high field strengths



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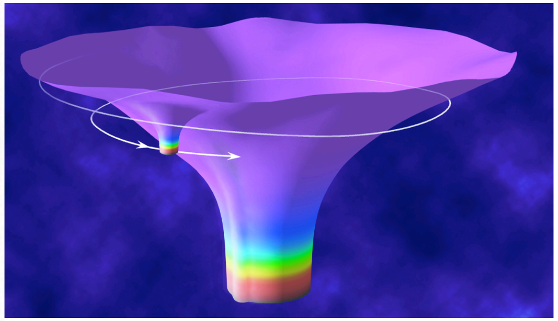
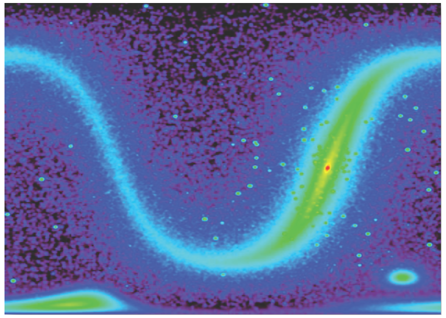
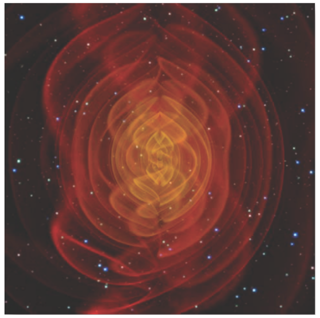
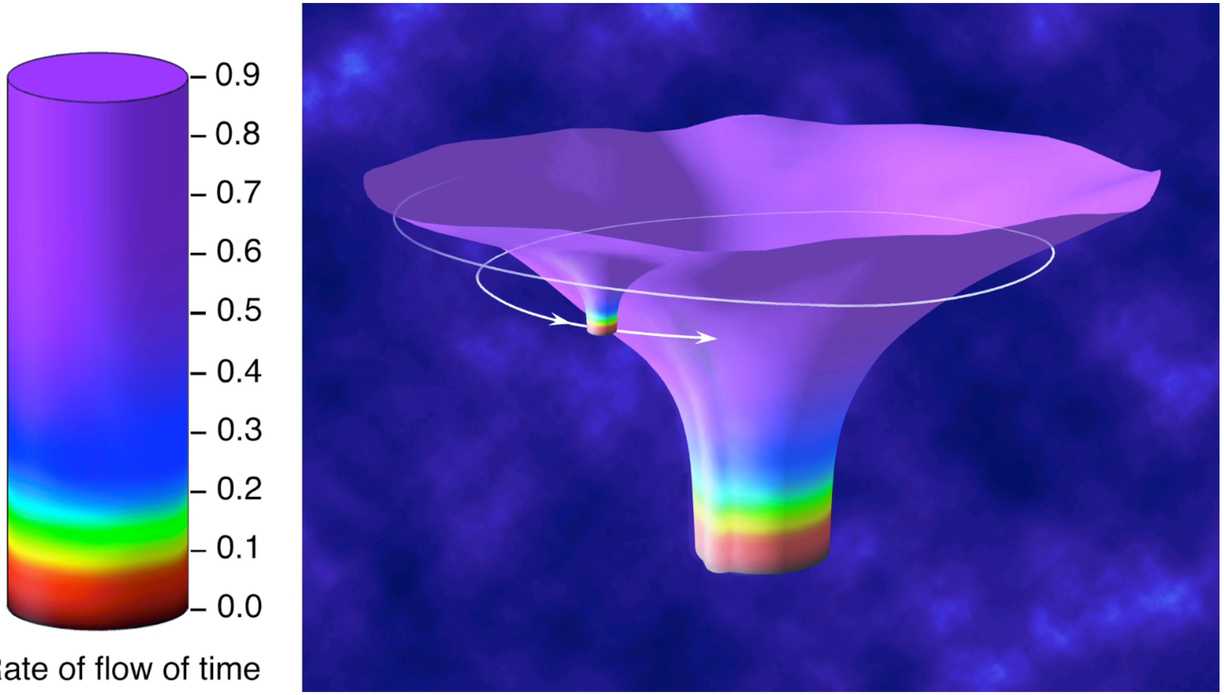






At the Edge of a Black Hole

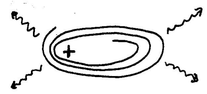
- By observing 10,000 or more orbits of a compact object as it inspirals into a massive black hole (MBH), LISA can map with superb precision the space-time geometry near the black hole.
- Allows tests of many predictions of General Relativity including the “no hair” theorem.



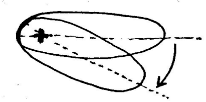
Extreme mass-ratio sources

G. Woan

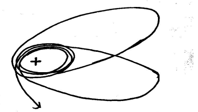
Quasi-periodic orbits showing a complex “zoom-whirl” structure



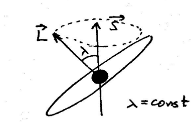
inspiral



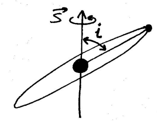
Periastron precession



“Zoom-Whirl” effect

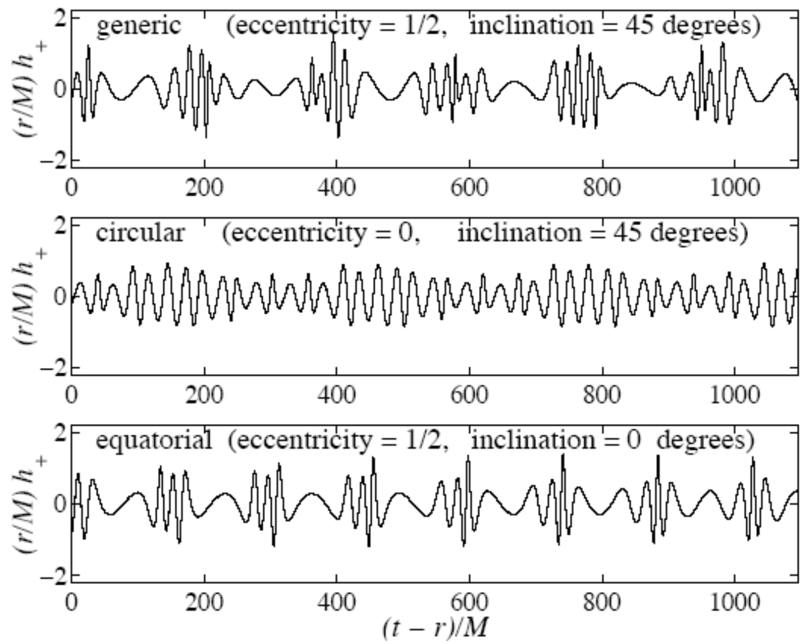


Spin-Orbit coupling

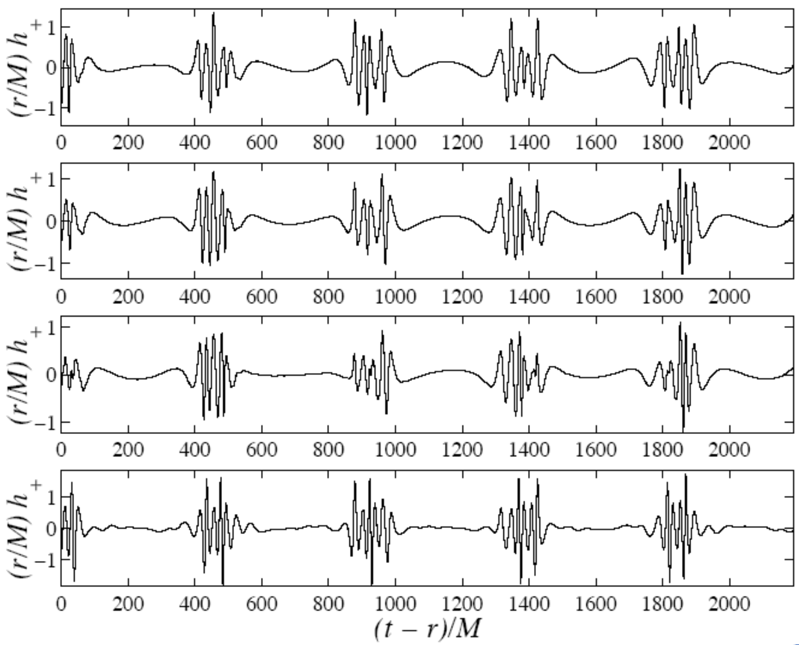


Evolution of inclination angle

L. Barack



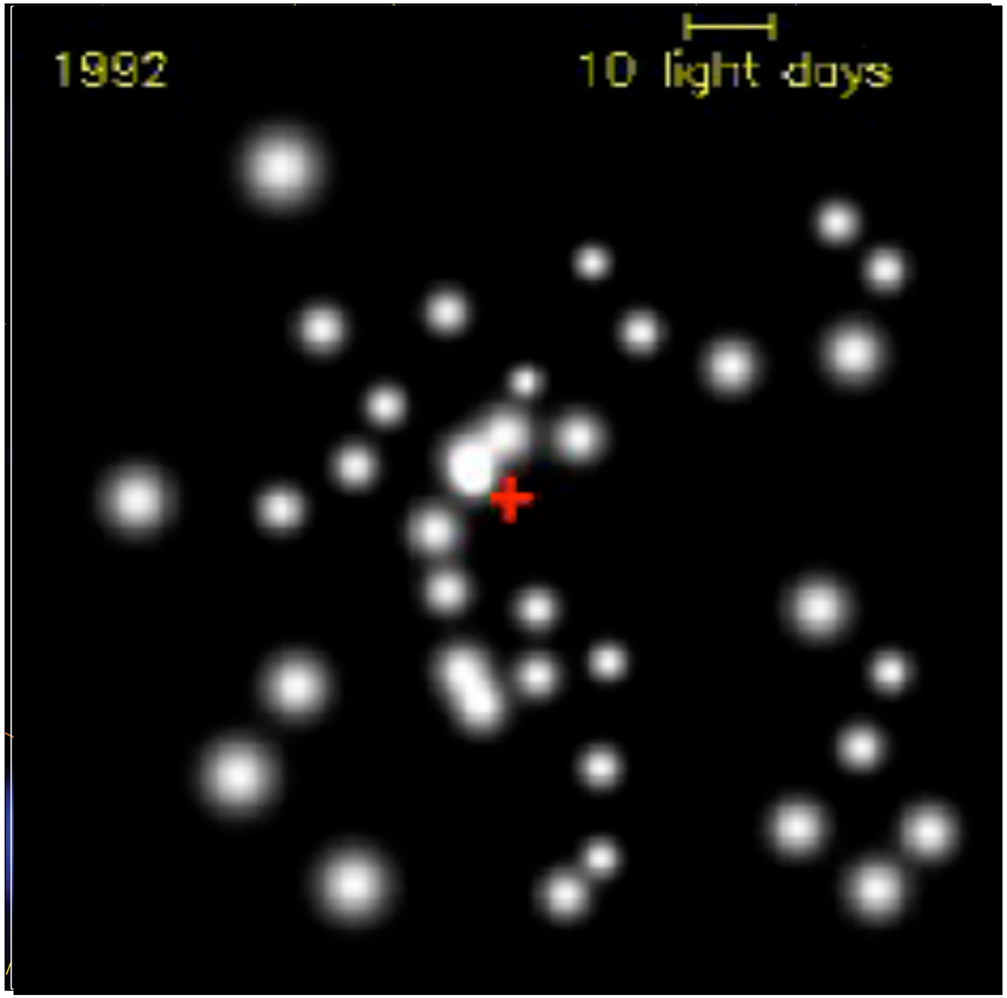
eccentricity = 0.7, viewed from θ = 90° (top), 60°, 30°, 0° (bottom)



Drasco & Hughes

Direct Evidence for EMRI?

- Stellar motions in the vicinity of Sgr A*.
- The orbital accelerations of stars close to the Galactic centre allow placing constraints on the position and mass of the central super-massive black hole.
- EMRI are not observable directly, but statistics and physics allow for inspirals.



UCLA Galactic Center Group

Probing Strong Curvature with EMRIs

B. Schutz

- **EMRIs are one of LISA's strongest tools for studying fundamental physics, and they set the LISA noise requirement at mid-range frequencies.**
- **Very sensitive because of large number of cycles: chirp time**

$$t_{\rm chirp} \sim \frac{5}{96}\frac{M}{\eta}\left(\frac{M}{R}\right)^{-4} \quad \text{with} \quad \eta = m/M$$

- **Null test of uniqueness of Kerr metric: fit EMRI waveforms to signal, determine if errors are consistent with noise/confusion background.**
- **Testing for non-Kerr metric: existing studies (Glampedakis & Babak 2005, Barak & Cutler 2007, Barausse et al 2007) examine how EMRIs could test if metric is non-Kerr but still GR: eg due to accretion disk or tidally distorting nearby body.**
  - They do not look for evidence for non-GR theories, because they assume GR to generate waveforms in the distorted metric.

Using EMRIs to Test Gravity Theory

B. Schutz

- **To compare GR with an alternative theory, need to compute EMRI waveforms self-consistently in the other theory, including EOM.**
  - For Hulse-Taylor Binary Pulsar, the limits on Brans-Dicke ω come from a calculation that includes scalar radiation and its back-reaction (Will).
  - In Hulse-Taylor system, scalar effects are anomalously small (test anomalously weak) because stars have nearly equal mass, reducing scalar dipole radiation.
- **Black holes radiate away massless fields when formed, so in Brans-Dicke, BHs are the same as in GR.**
  - EMRI signals from stellar-mass BHs falling into SMBHs will *not* test such theories. Weaker EMRI signals from NS's or WD cores of giant stars will provide tests.
- **We lack a "Parametrized Post Kerr" framework that includes other theories – hard to quantify the meaning of a null result when looking for violations of GR.**
- **Dispersion**
  - Fitting inspiral signal to PN model, with high SNR, may reveal unexpected phasing if higher frequencies travel faster than lower (graviton mass).
  - For inspirals or EMRIs, orbital plane might show anomalous precession due to parity failure (right- and left-hand polarizations propagate differently in some string theory models).

Measuring Hubble Relation

B. Schutz

- Any binary system that chirps during observation has intrinsic distance information in signal. Chirp time measures chirp mass $M = (m_1 m_2)^{3/5} / (m_1+m_2)^{1/5}$. Amplitude depends just on M/D_L, where D_L is the luminosity distance, so measuring it gives D_L.
- Converting detector response into signal amplitude requires measurement of polarization, sky position. Strong covariance of errors among these and the chirp mass.
- Getting the redshift normally requires identifying the host galaxy or cluster and obtaining an optical redshift. Small error box is key to this.
- Identification reduces error in D_L.
- Weak lensing produces random errors in D_L. Not clear how much can be removed by lensing studies of signal field.
- Using EMRI spirals, Hogan & McLeod (2007) show that LISA can measure H_0 to 1% accuracy (needs 20 events to $z = 0.5$).

Conclusions

- **LISA is a mission to detect and observe gravitational waves**
  - Gravitational waves are predicted by any "reasonable" theory of gravity, yet not directly detected.
  - Gravitational waves are a tool for astronomers, astrophysicists and cosmologists
- **LISA will address important questions in fundamental physics, astrophysics and cosmology.**
  - Precision tests of GR
  - Nature of objects in the center of galaxies
  - History and evolution of galaxies
  - Structure formation in the Universe

Conclusions

- **LISA is a mission to detect and observe gravitational waves**
- **LISA will address important questions in fundamental physics, astrophysics and cosmology.**
- **Joint mission, equally shared between ESA and NASA**
  - Technology development ongoing
  - LISA Pathfinder as a technology demonstrator will launch in 2010
  - LISA will launch in the timeframe of 2018
- **By 2020, we will be able to look at…**

Gravitational Wave Sky