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Gravity has a story to tell: LISA and the search for low frequency gravitational waves

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Gravity has a story to tell:

LISA and the search for low frequency gravitational waves

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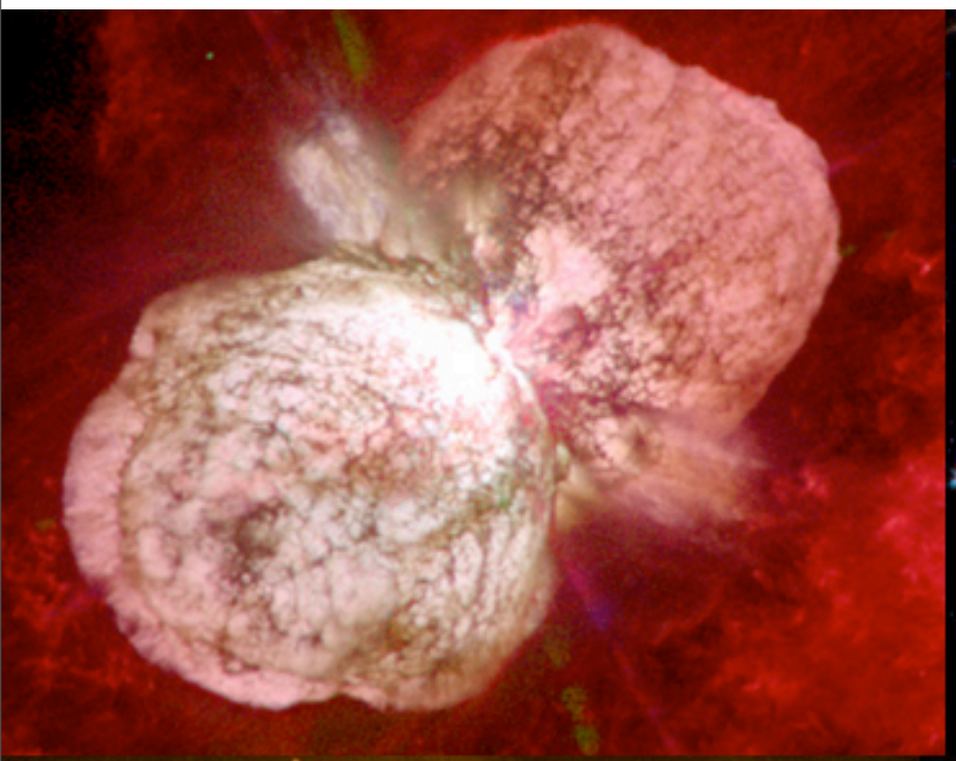
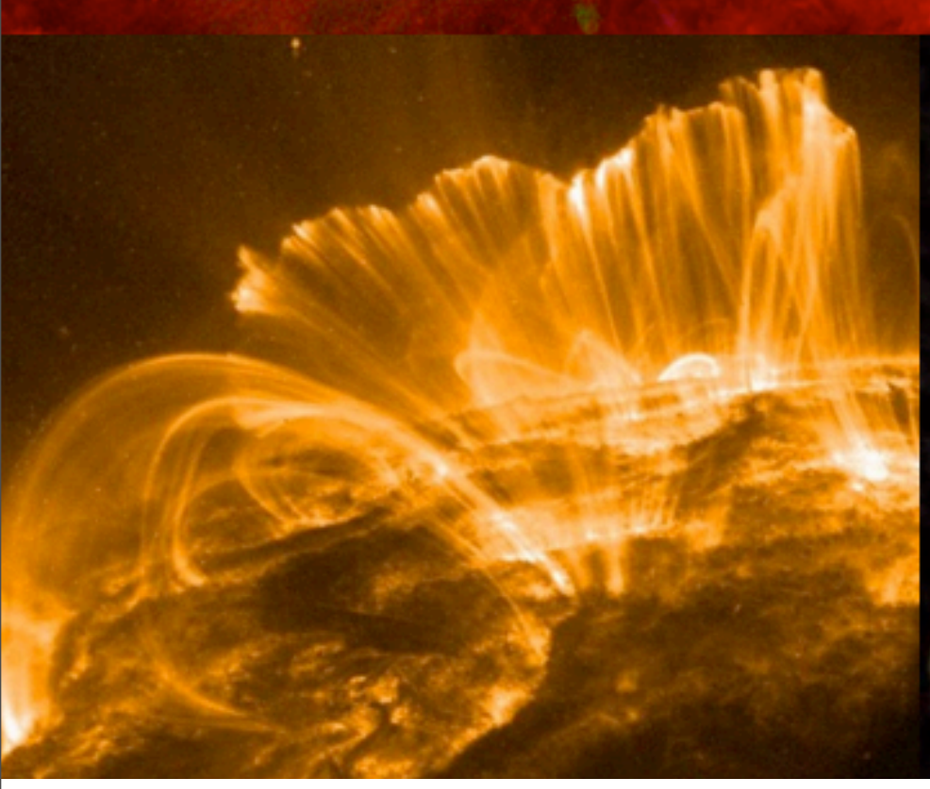
Colloquium
BYU – Physics
5 November 2008

Storyline

- Probing the Gravitational Wave Spectrum
- The LISA Mission
- Short Astrophysics Vignettes
  - Extreme mass ratio inspirals
  - Galactic Binary Stars
- The Future

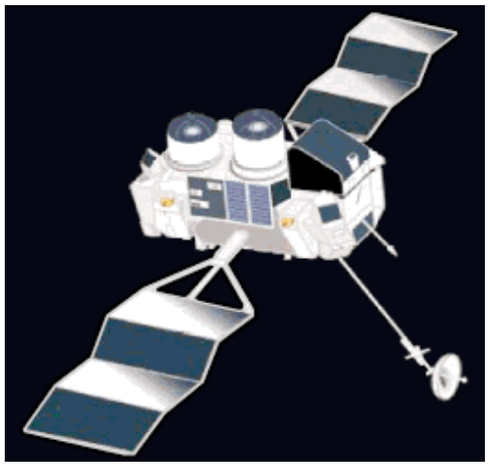
The Cosmos as we know it

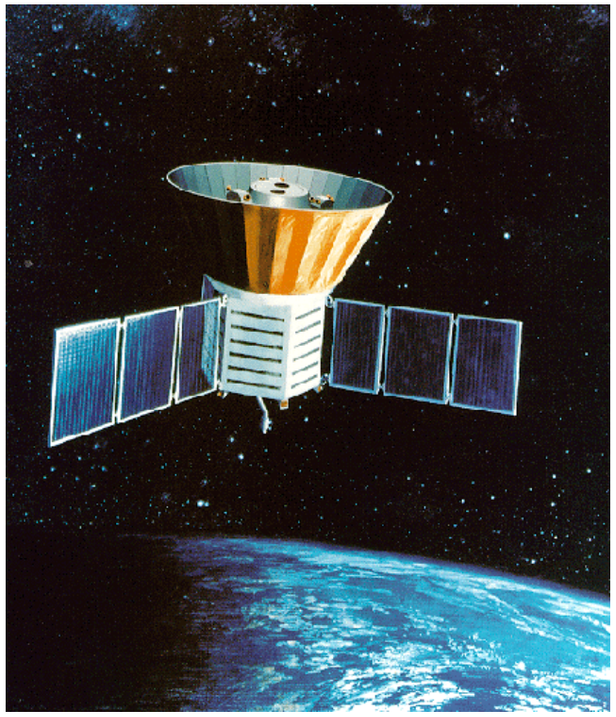




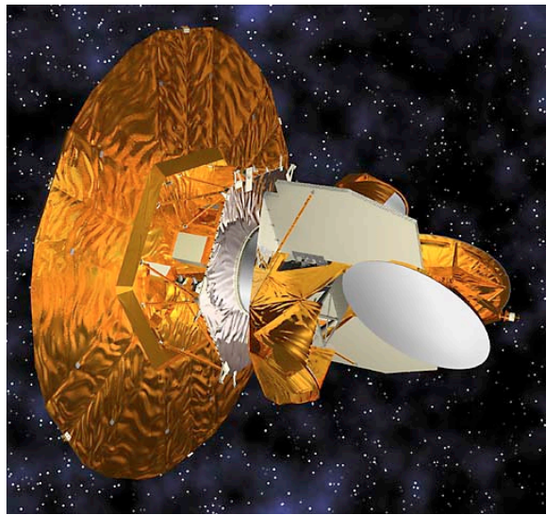
- **Light** has been our messenger from the Universe

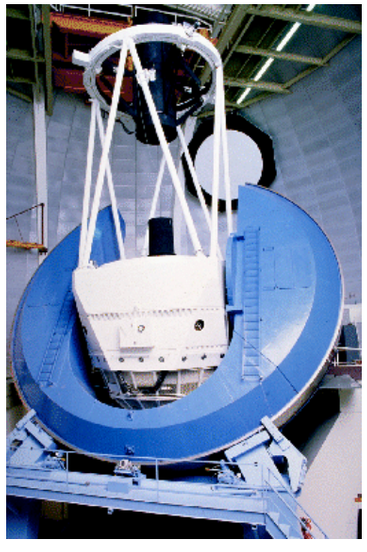
Photon eyes







- A myriad of instruments exist to detect photons, but photons are limited by the fact that they interact readily with matter.

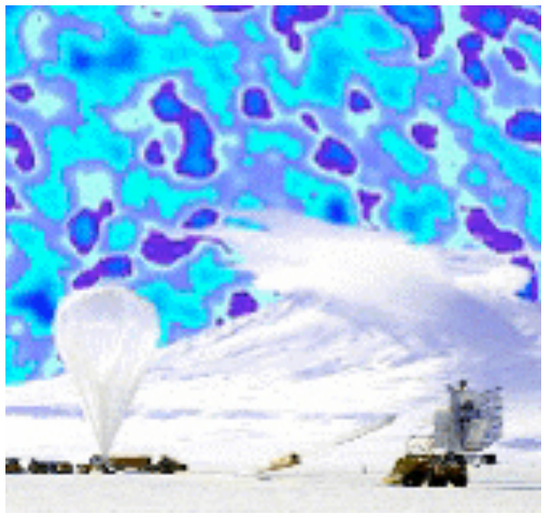
Frontiers of Astrophysics

- Don't look with **light**, look with **gravity**.
- Detect ripples in the fabric of spacetime generated by the **dynamic motion** of matter and energy in the Cosmos
- Gravitational waves travel unimpeded from source to observer

Gravitational wave Spectrum

Extremely Low Frequency

10^{-16}Hz



CMB Polarization

Very Low Frequency

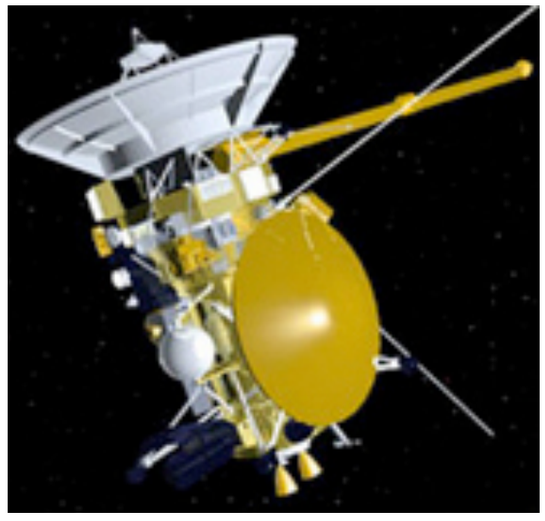
10^{-8}Hz

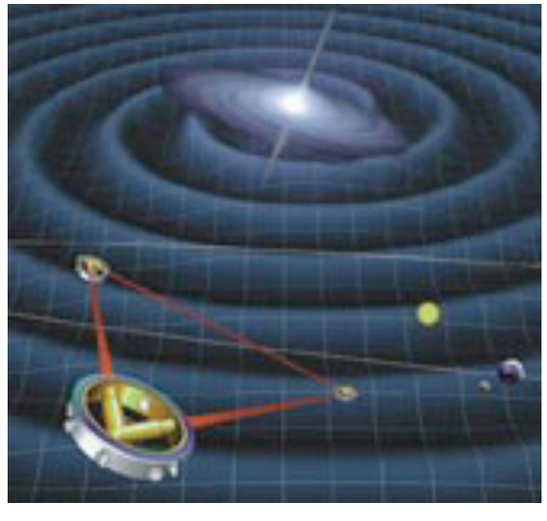
Pulsar Timing

Low Frequency

1Hz

Space



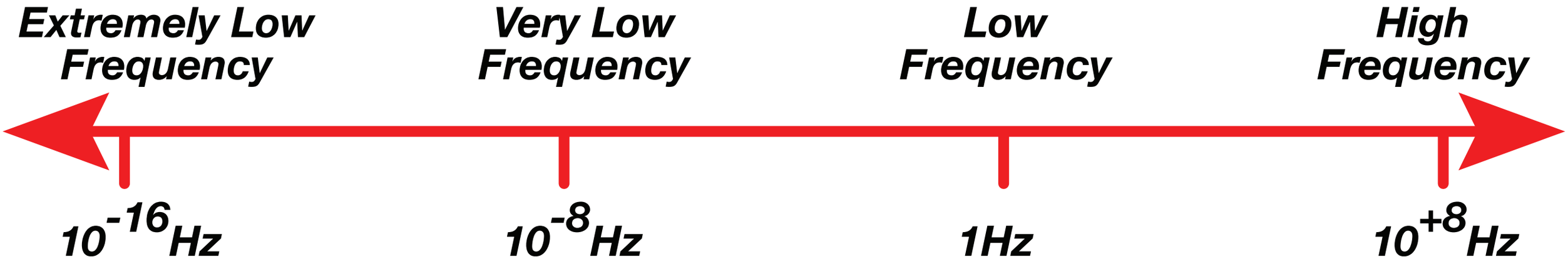


High Frequency

10^{+8}Hz

Ground

Gravitational wave Spectrum



Big Bang waves; inflationary epoch

Early Universe exotic physics
- phase transitions, cosmic strings, domain walls...

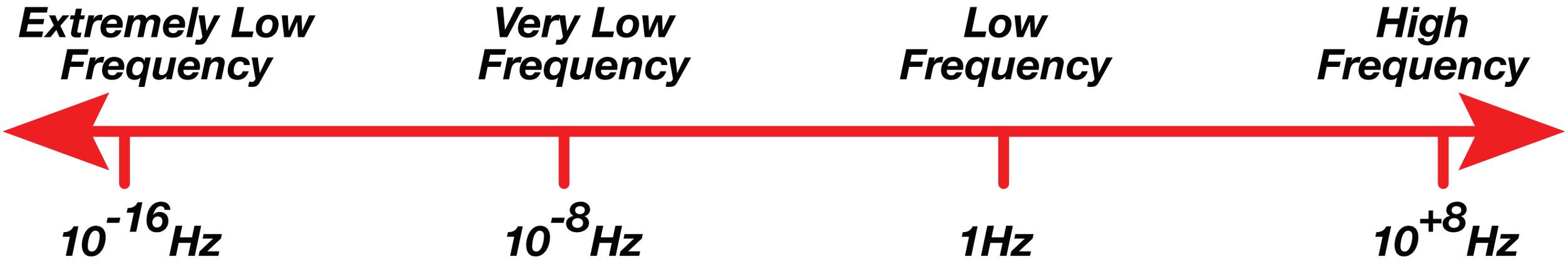
- Massive BH ~300 to 30 million solar masses
- Binary stars
- Galactic structure

- "Small" BH ~2 to 100 solar masses
- Neutron stars
- Supernovae

Singularities? Exotic stars?

? ? ?

Gravitational wave Spectrum



Big Bang waves; inflationary epoch

Early Universe exotic physics
- phase transitions, cosmic strings, domain walls...

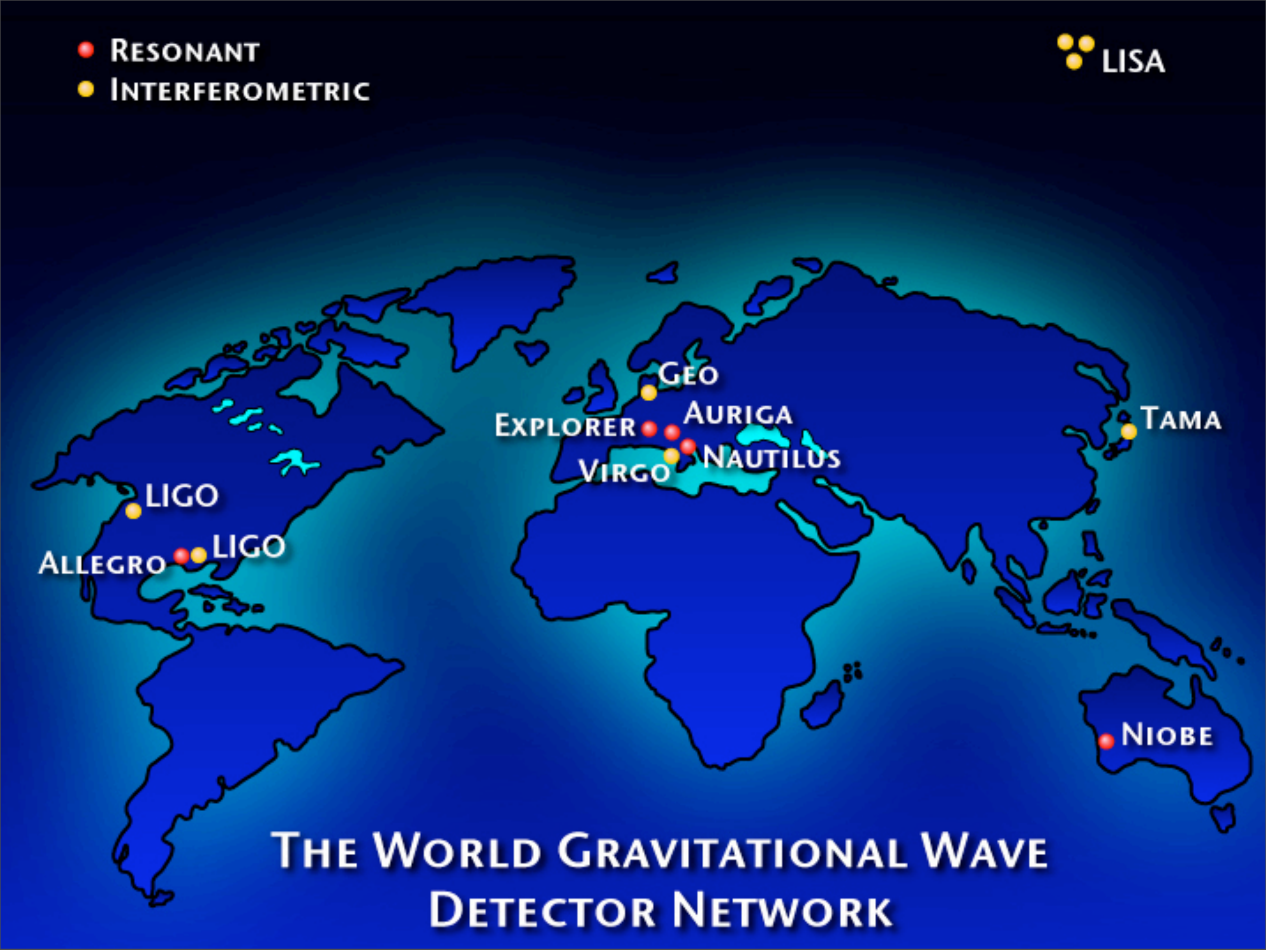
Pulsar timing search for G-waves rules out supermassive black hole binary in quasar 3C66b

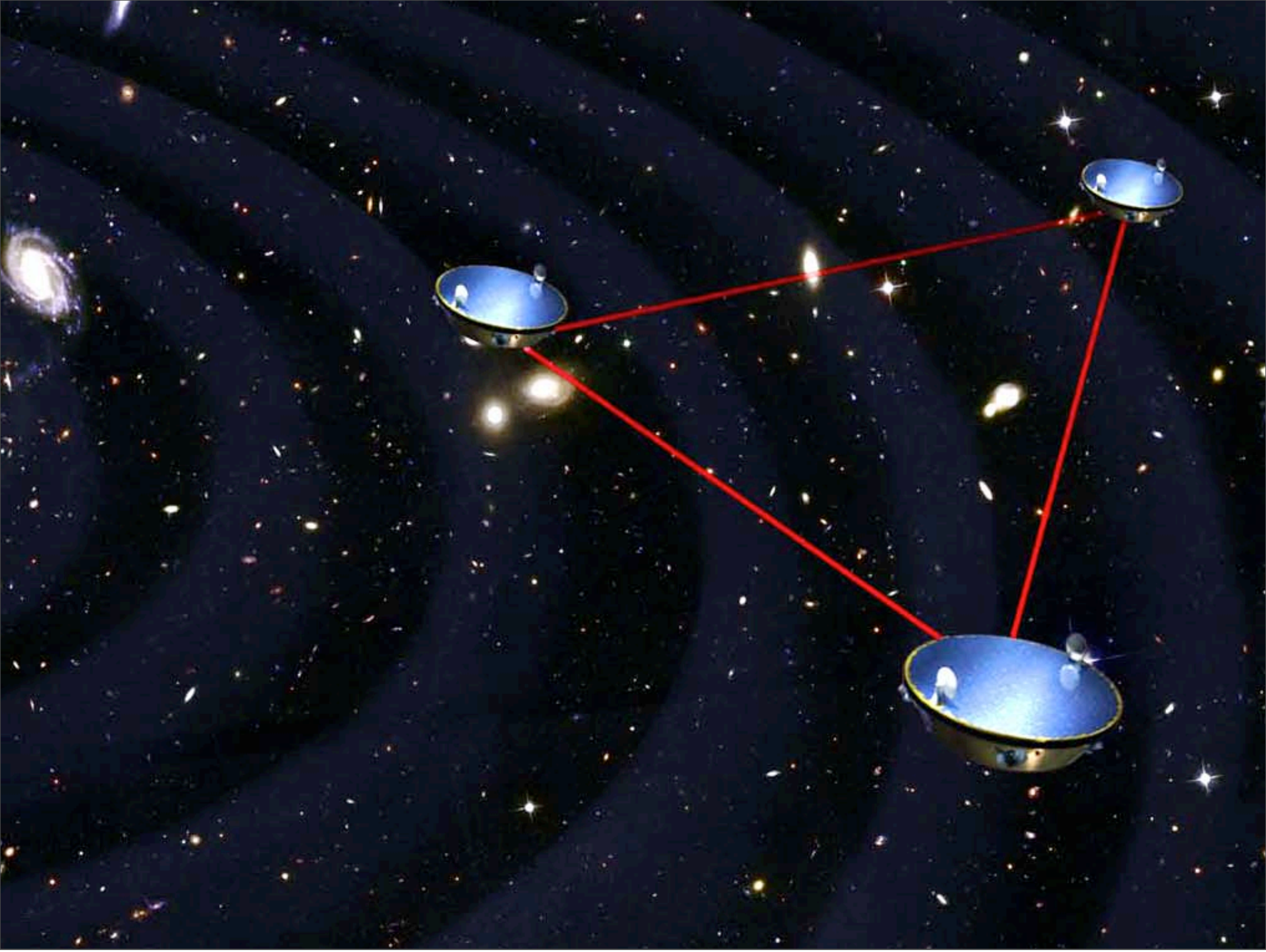
Jenet, Lommen, Larson, & Wen (ApJ 606, 2004)

LIGO limits on Crab pulsar
Abbott et al. (ApJL 683, 2005)
LIGO limits on Cosmic GW Background
Abbott et al. (PRD 76, 2007; ApJ 659, 2007)
LIGO limits on 78 Radio Pulsars
Abbott et al. (PRD 76, 2007)

Singularities? Exotic stars?

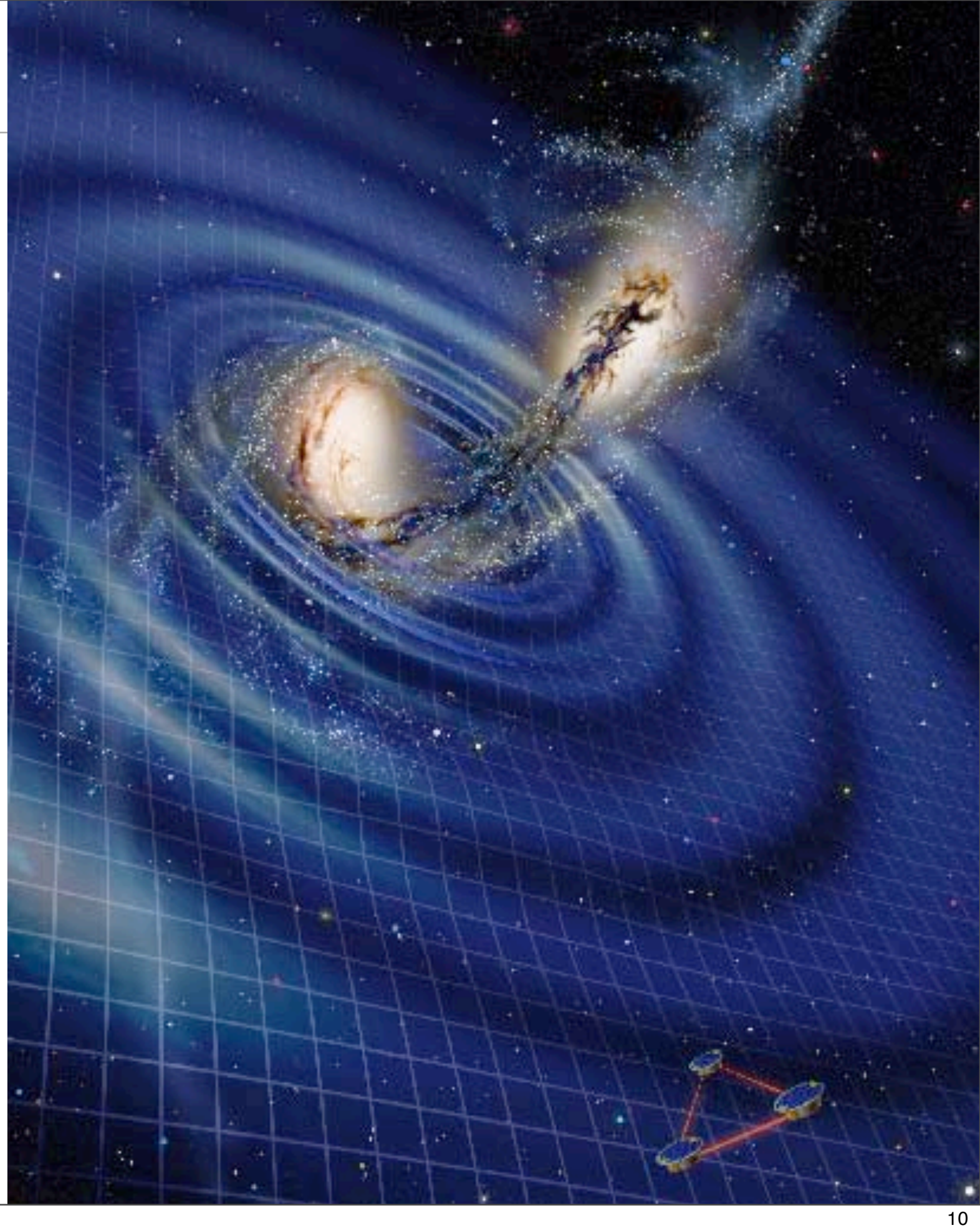
? ? ?


Resonant
Interferometric
LISA
Geo
Auriga
Explorer
Tama
Nautilus
Virgo
LIGO
LIGO
Allegro
Niobe
The World Gravitational Wave
Detector Network

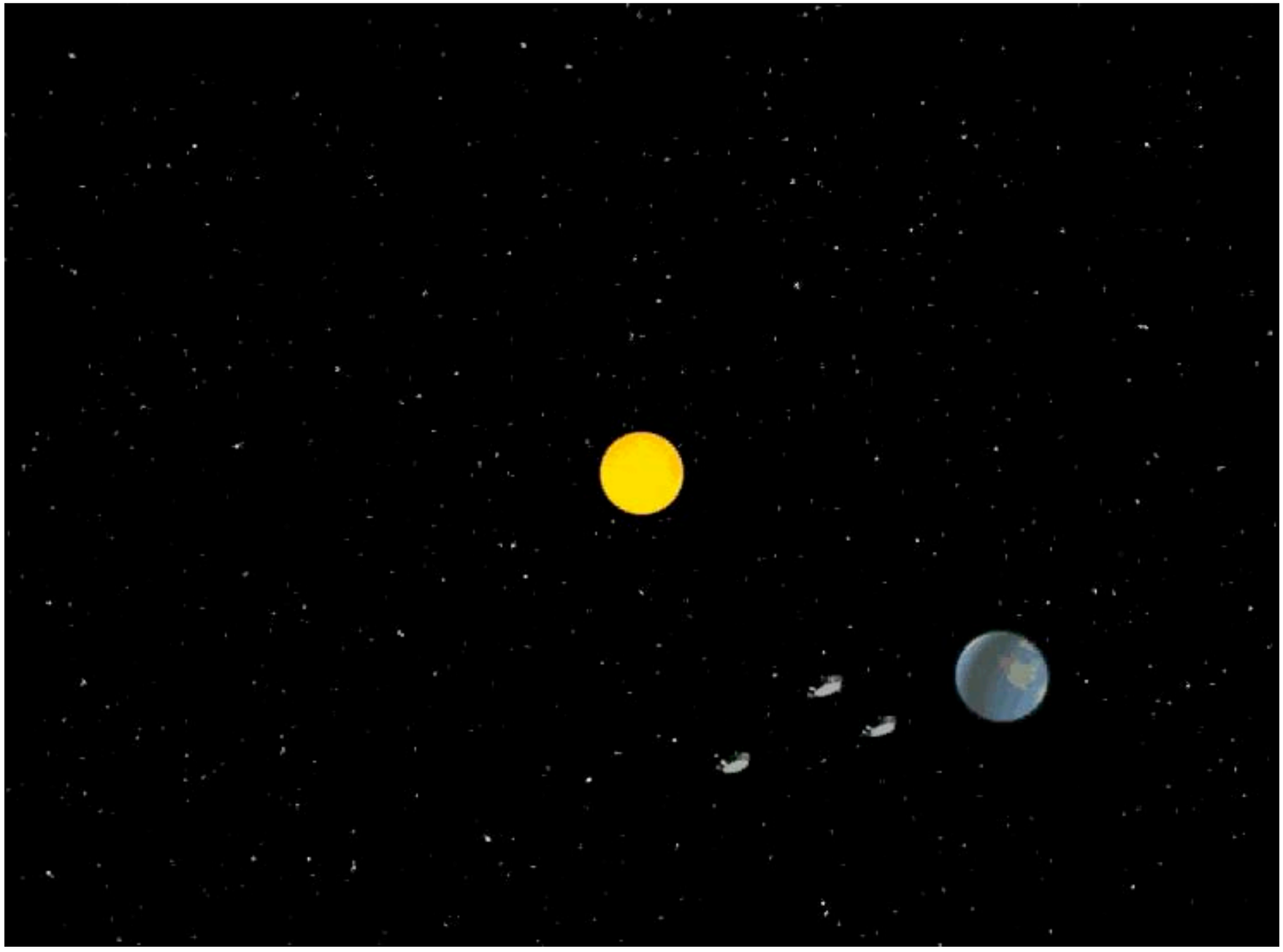


LISA

- Joint **NASA/ESA mission**, expected to launch in the mid-2010s
- Baseline 5 million kilometer armlength
- Sensitive to waves in the low frequency band, between ~ 10^{-5} Hz and 1 Hz

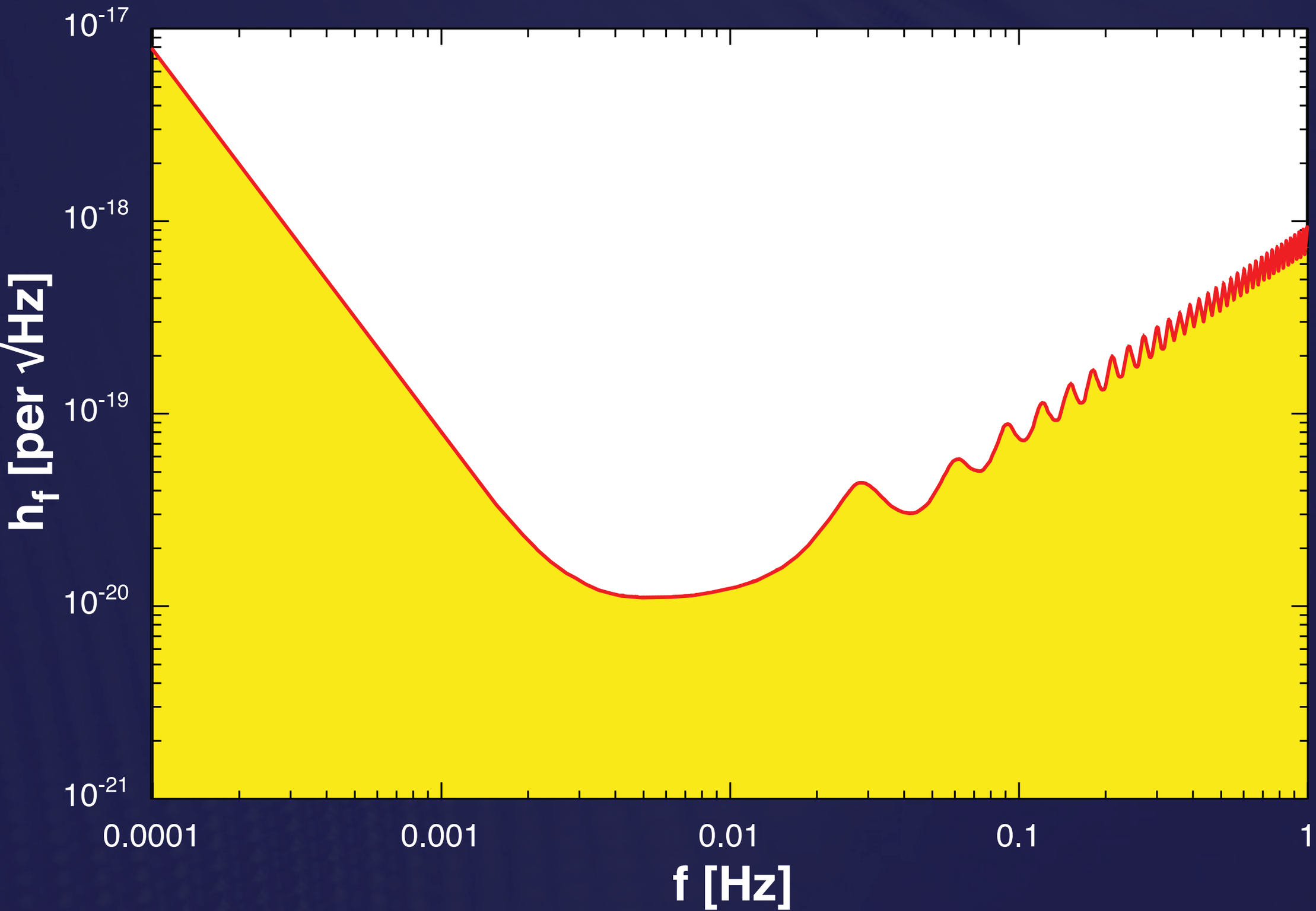


LISA Orbit



- LISA is in an Earth-trailing or Earth-leading orbit, 20° away from the Earth, inclined to the ecliptic by 60°
- The constellation motion modulates signals, giving pointing capability

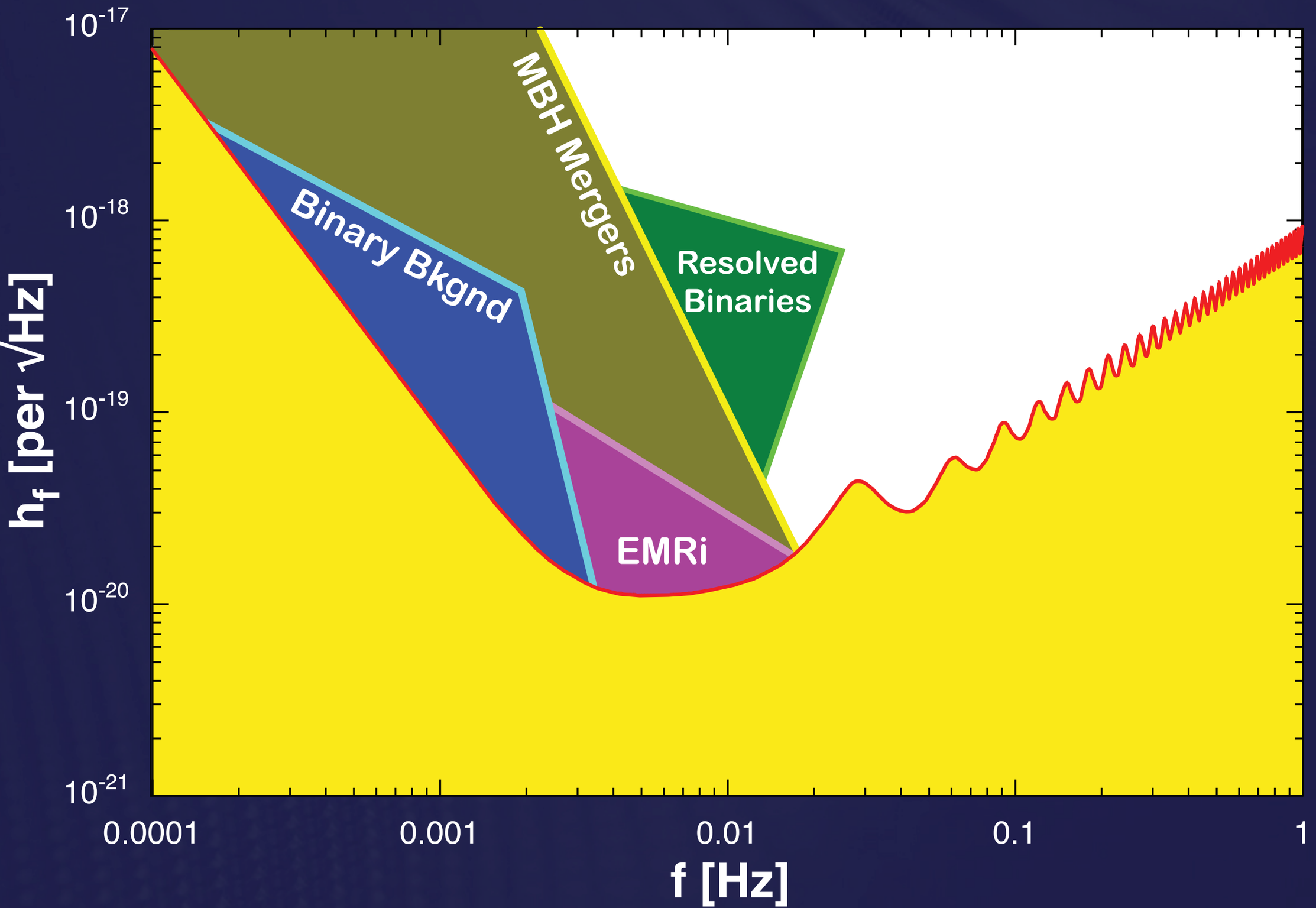
LISA Discovery Space



http://www.srl.caltech.edu/~shane/sensitivity/

Larson, Hiscock & Hellings (2000)

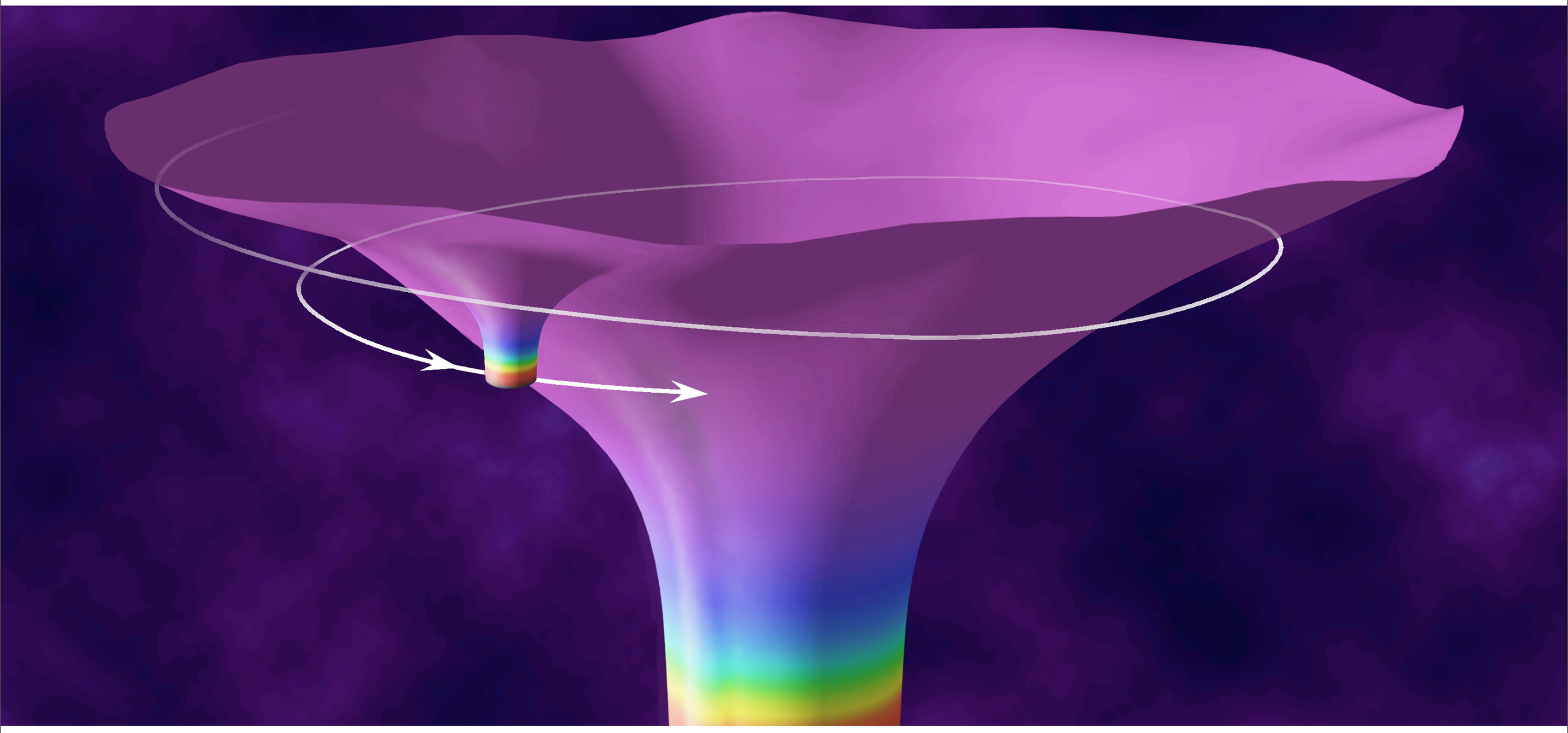
LISA Discovery Space



http://www.srl.caltech.edu/~shane/sensitivity/

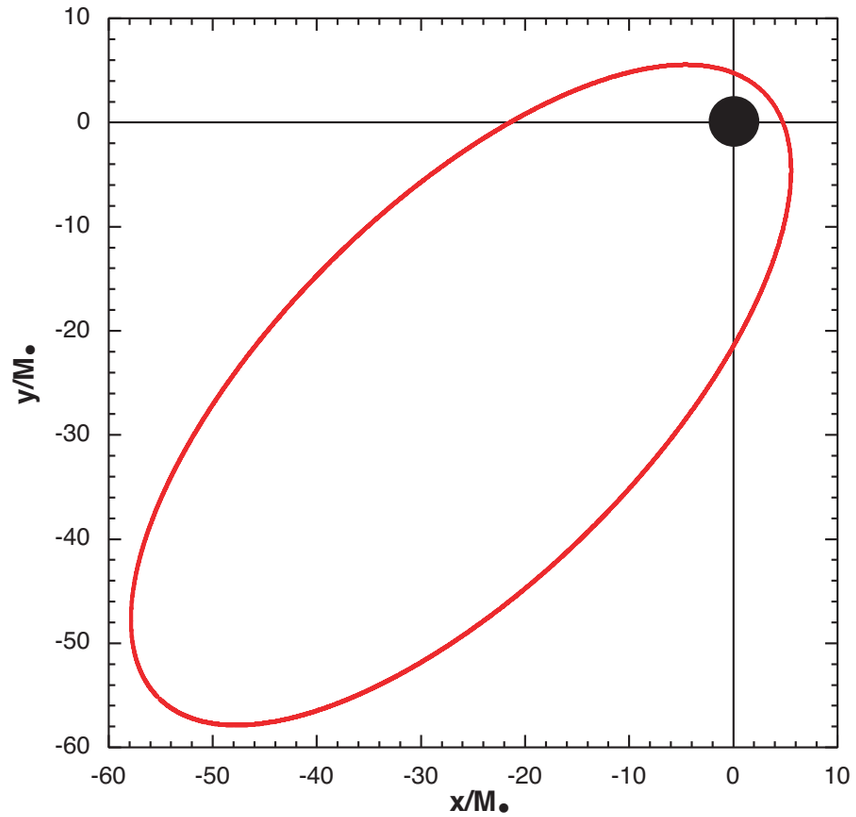
Larson, Hiscock & Hellings (2000)

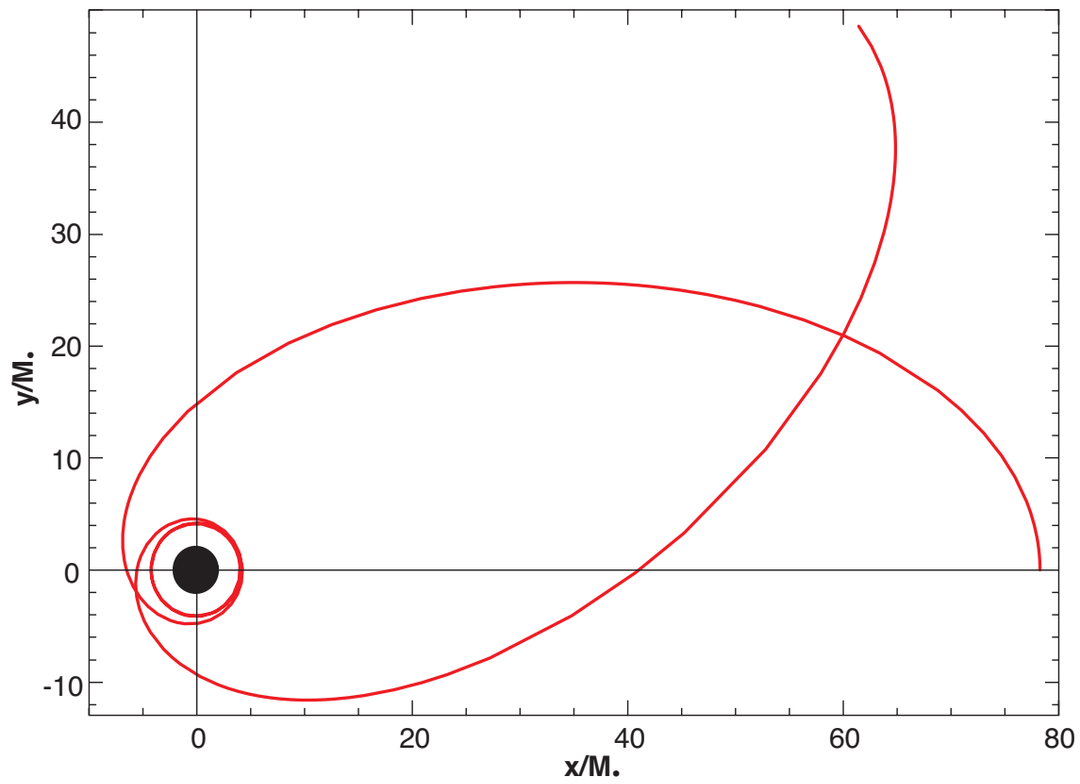
Extreme Mass Ratio Inspirals

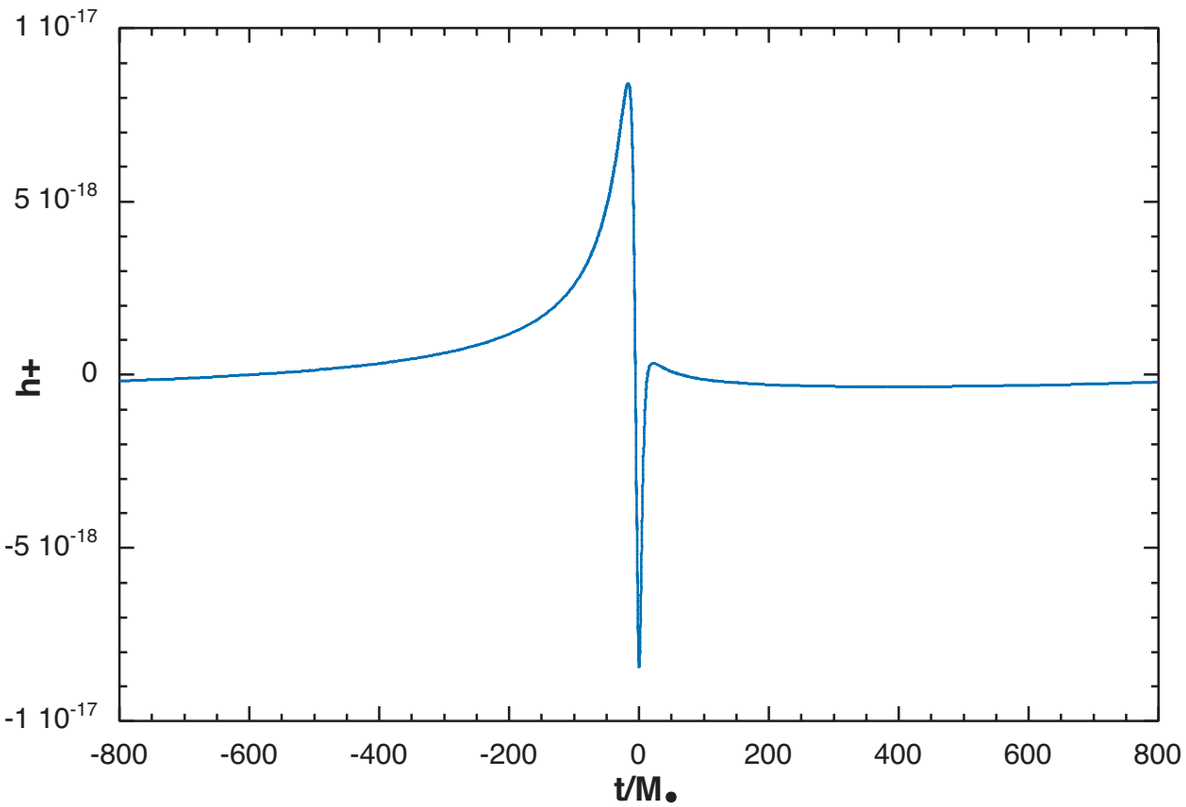


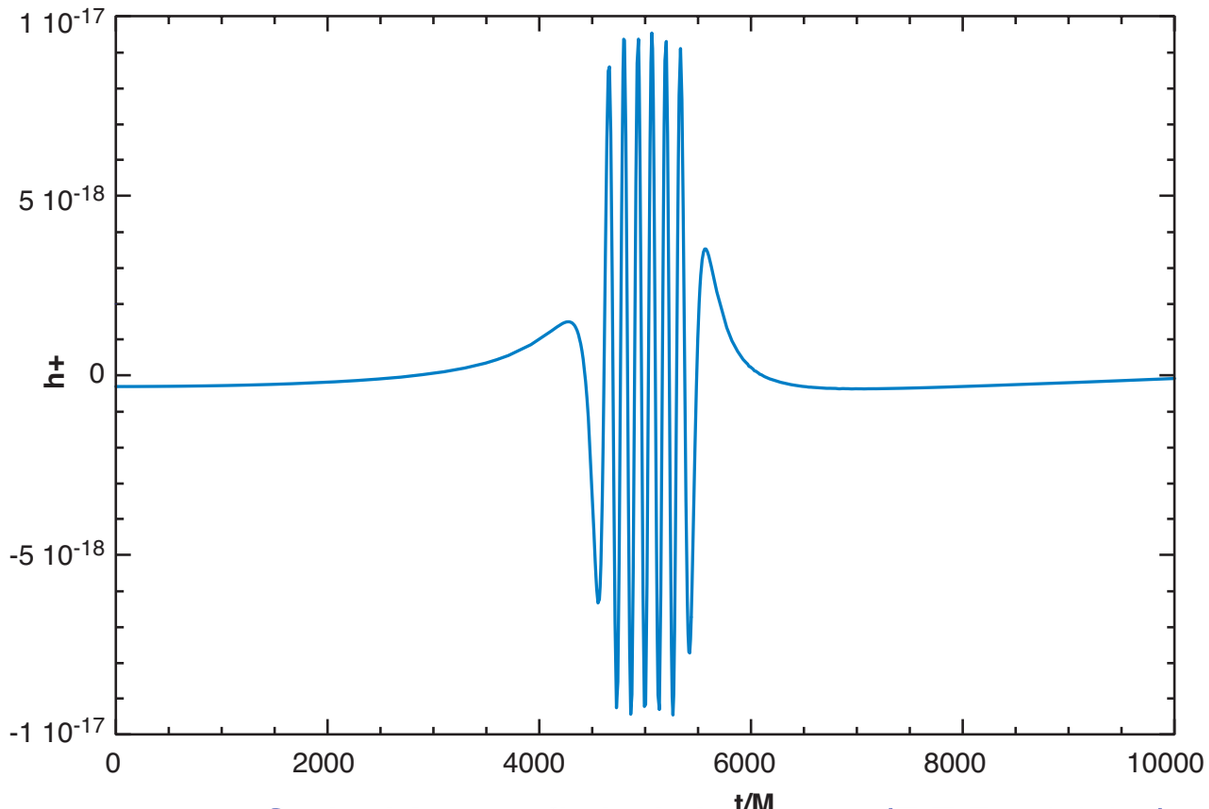
- **EMRIs**: little stars & big black holes, $(m^*/m\bullet) \sim 10^{-5}$ to 10^{-8}
- **CAPTURE CONTENT**: what are the constituents of nuclear star clusters? What is the growth history of galactic black holes?
- **HOLIODESEY**: the mapping of black hole spacetimes

Zoom whirl orbits



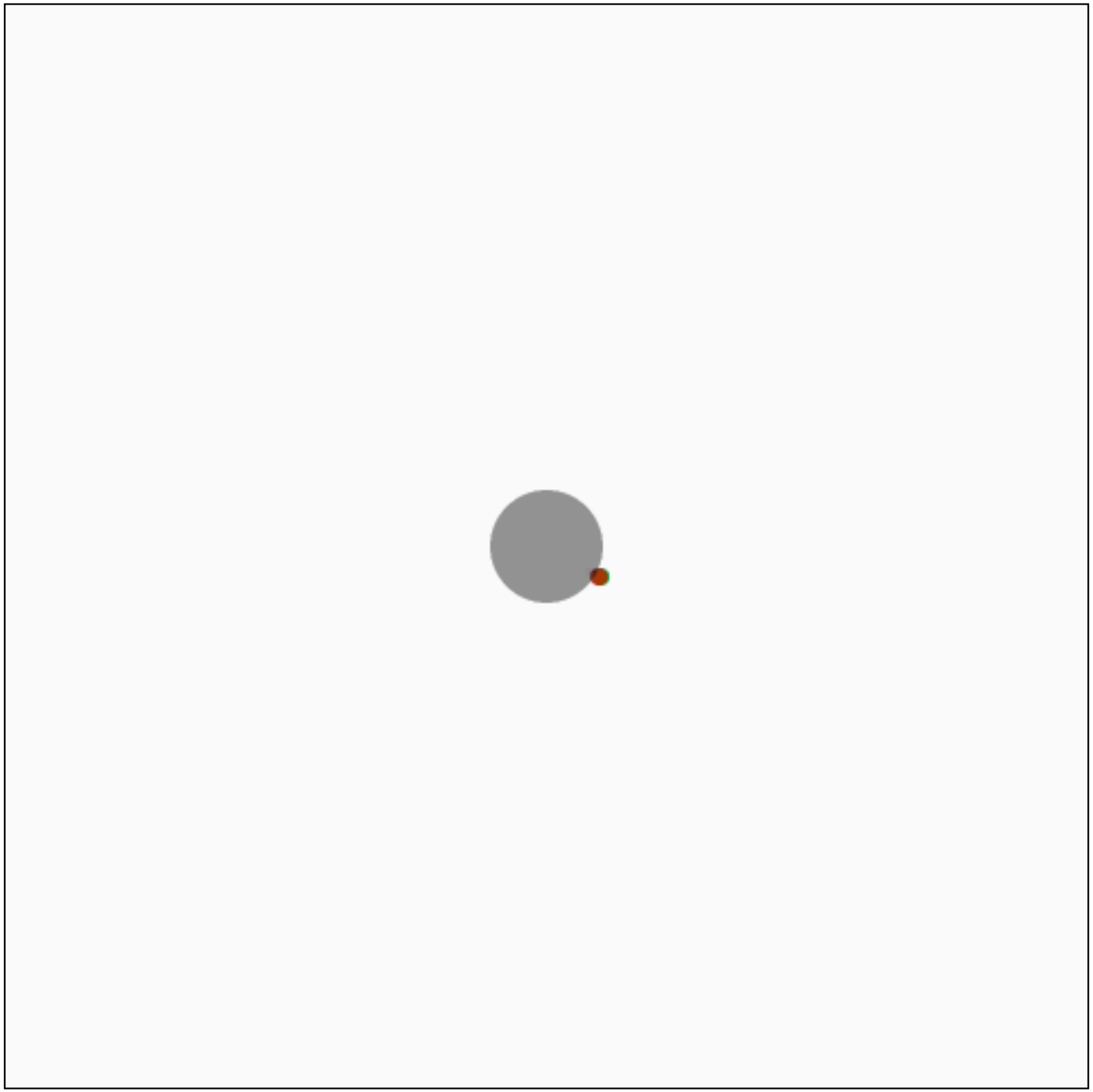






Gair, Kennefick & Larson (PRD, 2005)

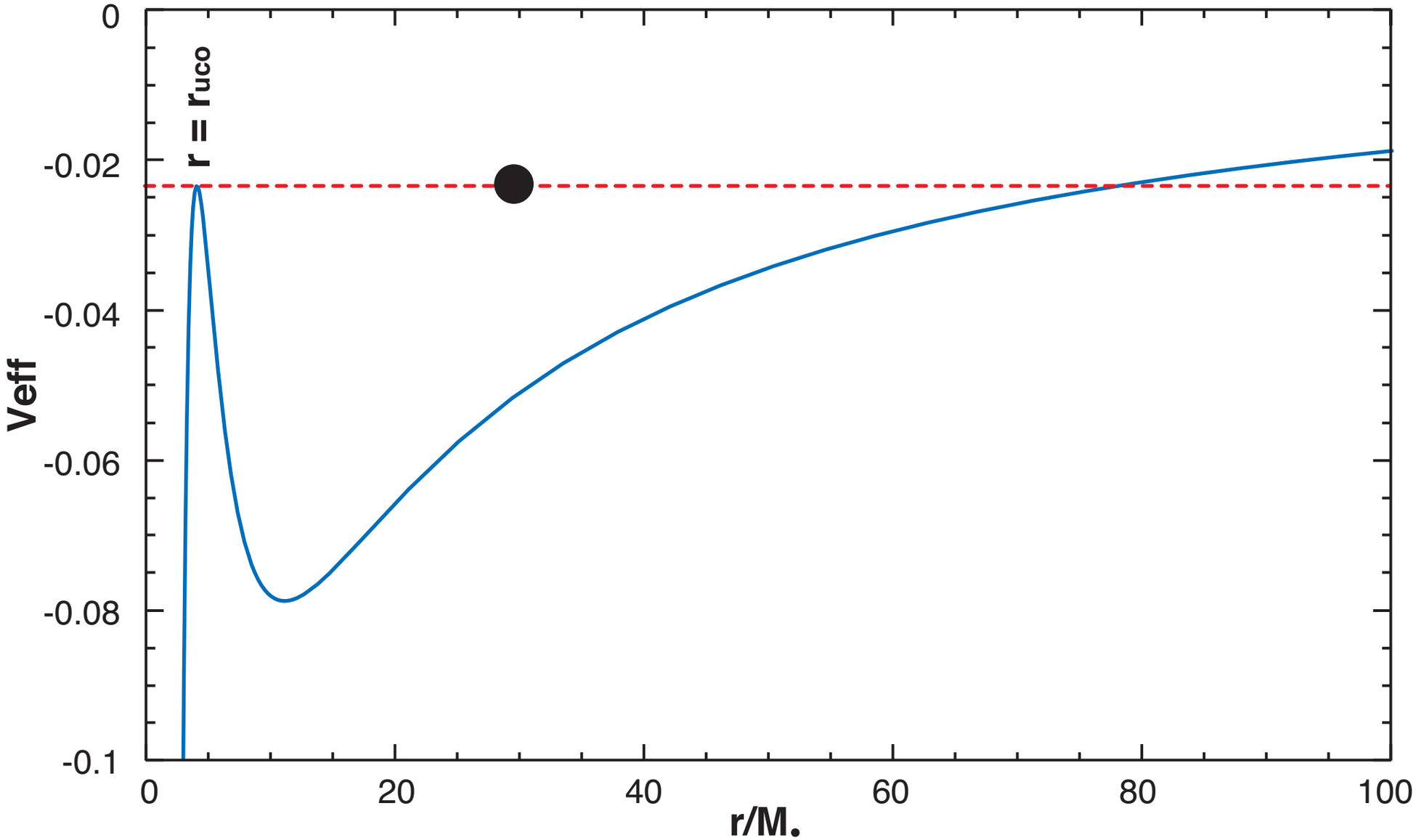
Zoom whirl orbits



Movie by
T. Creighton
UT-Brownsville

Why do the orbits whirl?

- The extreme whirling behaviour is perihelion precession gone wild
- Happens when particle probes effective potential near the inner peak, near the black hole!



Songs of the black holes

- The waveforms encode information about the black hole system, which I can demonstrate by converting into sound
- Consider black hole + black hole with ~10^{-5} mass ratio
  - **Sound 1**: Non-spinning big black hole, circular orbits
  - **Sound 2**: Spinning big black hole, circular orbits
  - **Sound 3**: Spinning big black hole, eccentric orbits

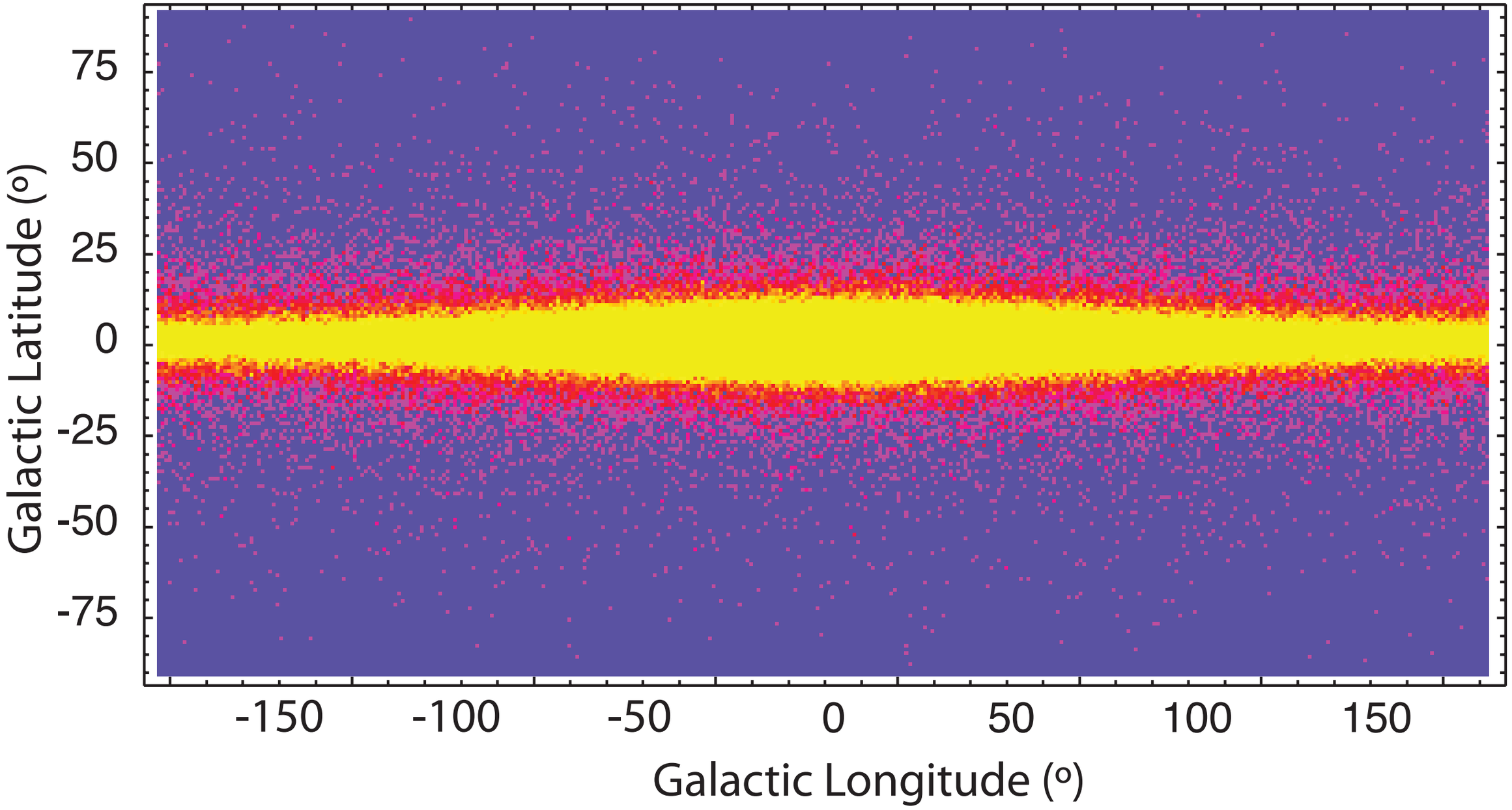


Sounds by
Scott Hughes, MIT

The Close Binaries

- There are so many binaries, their signals overlap, and it is difficult to tell them apart
- This is called the "**confusion limit**", and is analogous to a party
- You can hear people **nearby**
- You can hear **loud people**
- Alll else is a **dull noise**

The Low Frequency Galaxy

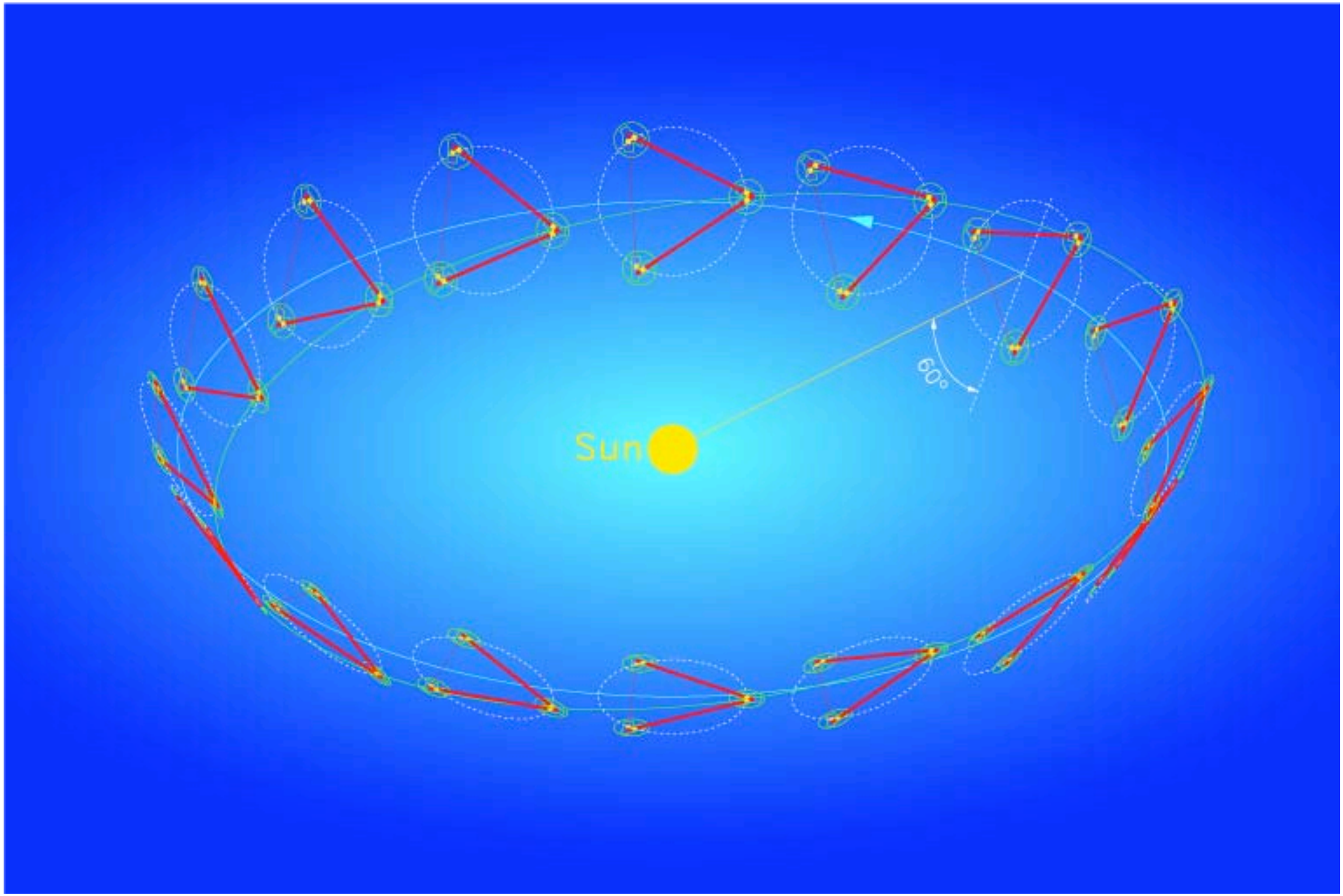


- There are 30 million close galactic binaries in the Milky Way. As probes of the galaxy, they can all be seen by LISA.
- These binaries encode the physical structure of the Milky Way

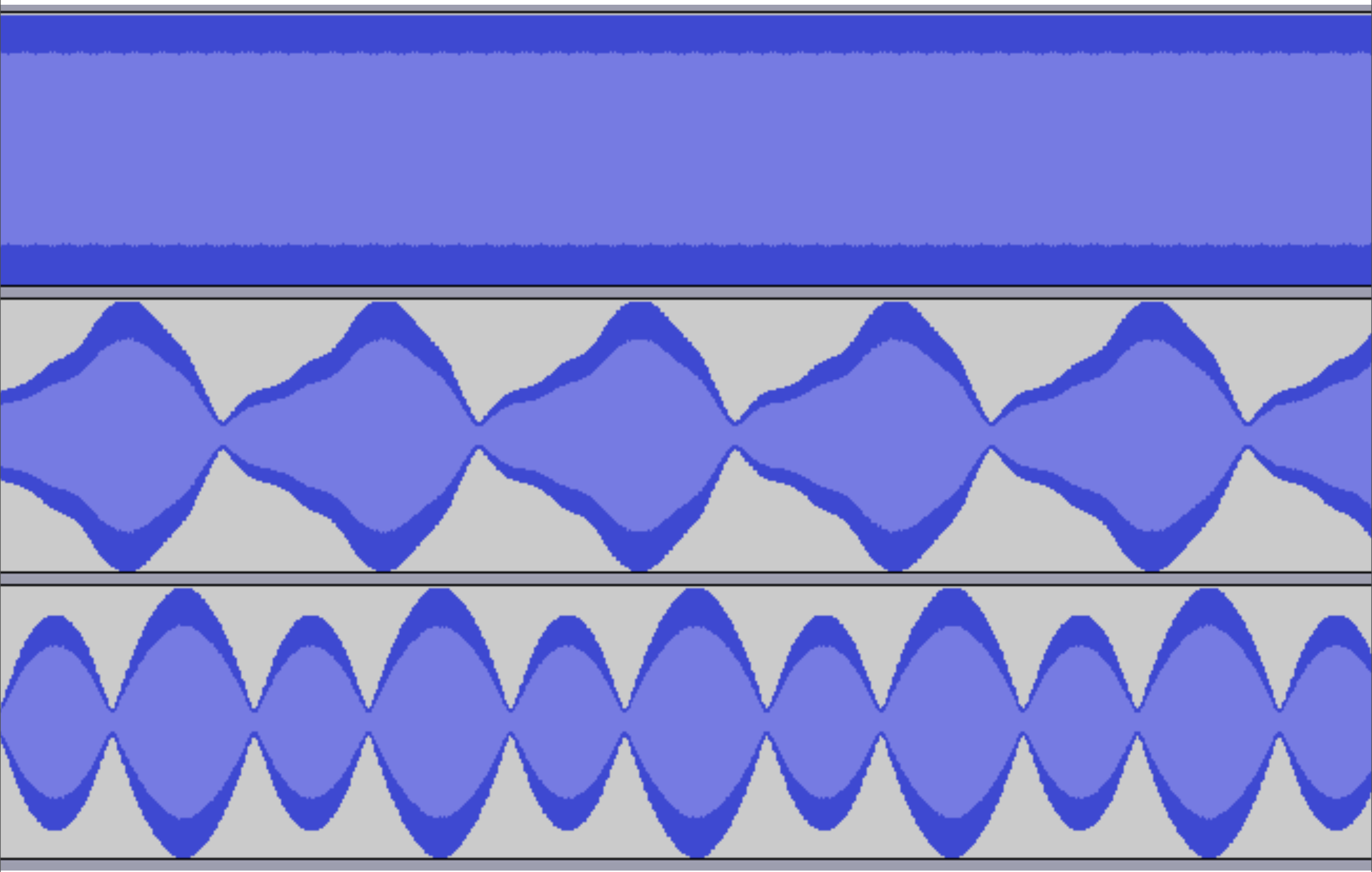
Songs of the Binaries

- LISA's motion also complicates the received signals
- LISA is **omnidirectional**, so it **points** everywhere!
- Motion of LISA **modulates** signals!

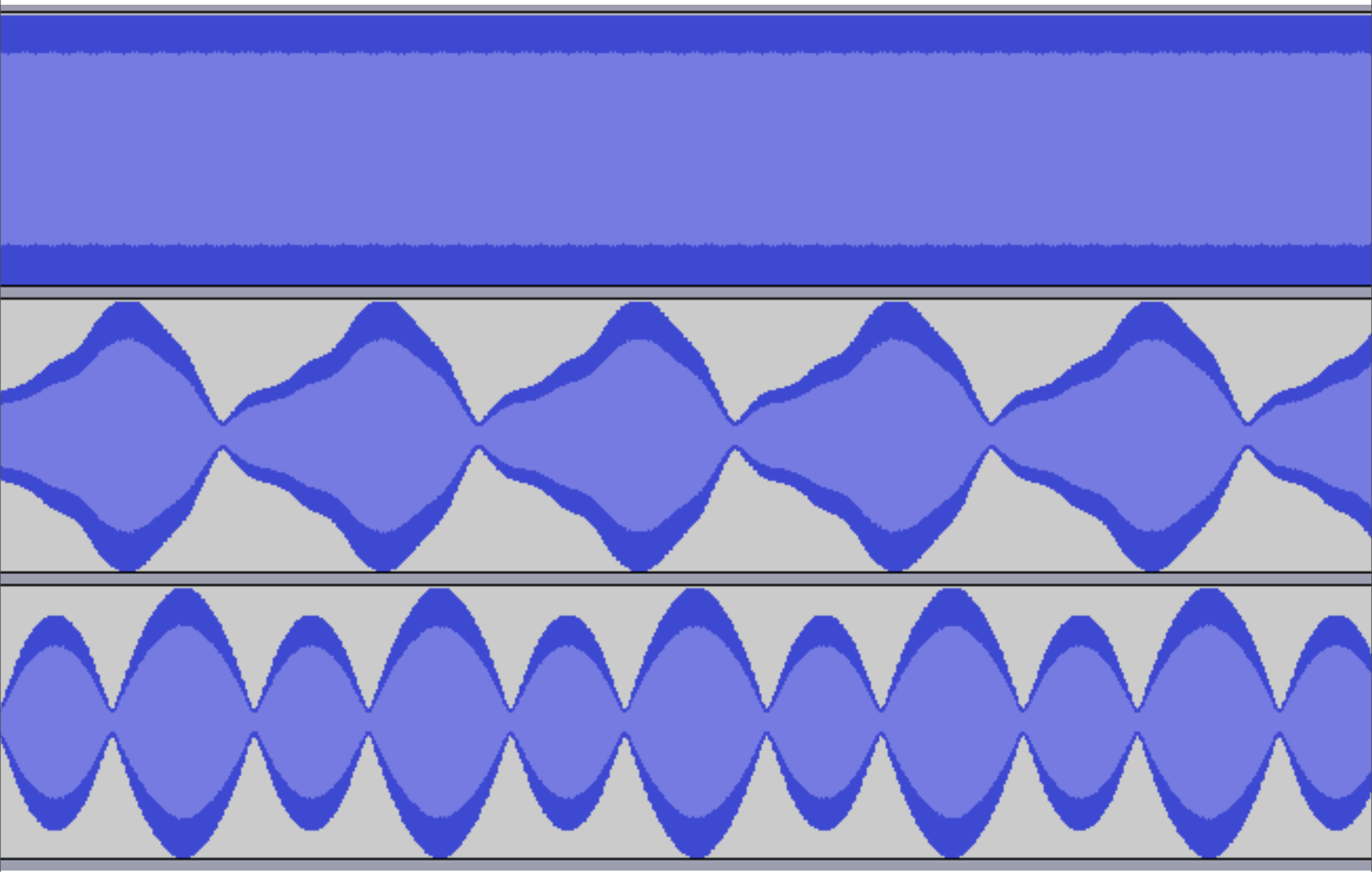
Songs of the Binaries



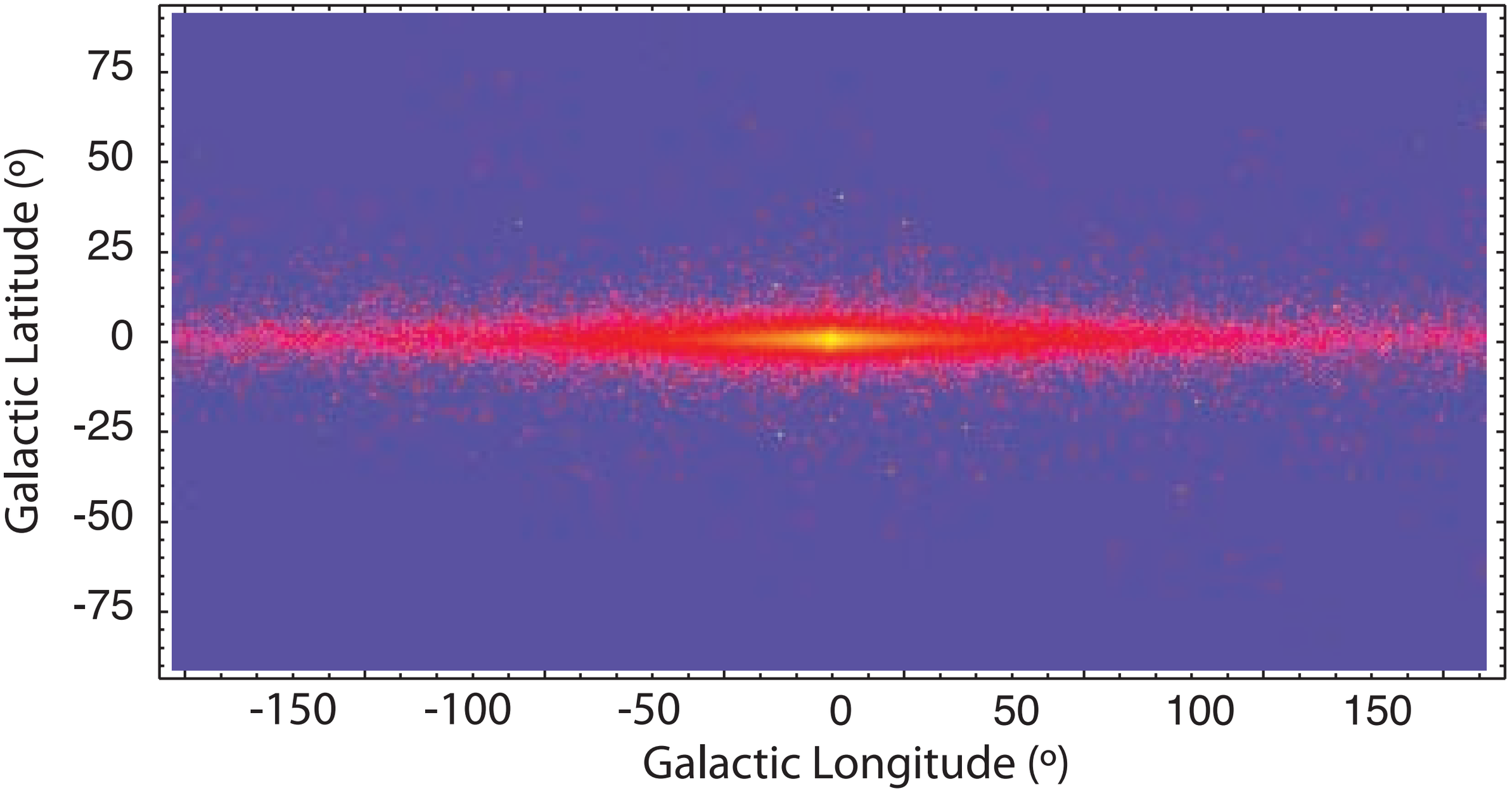
Songs of the Binaries



Songs of the Binaries



The Low Frequency Galaxy



- ~10,000 binaries will be separable from the confusion
- You can still recover the structure of the galaxy!

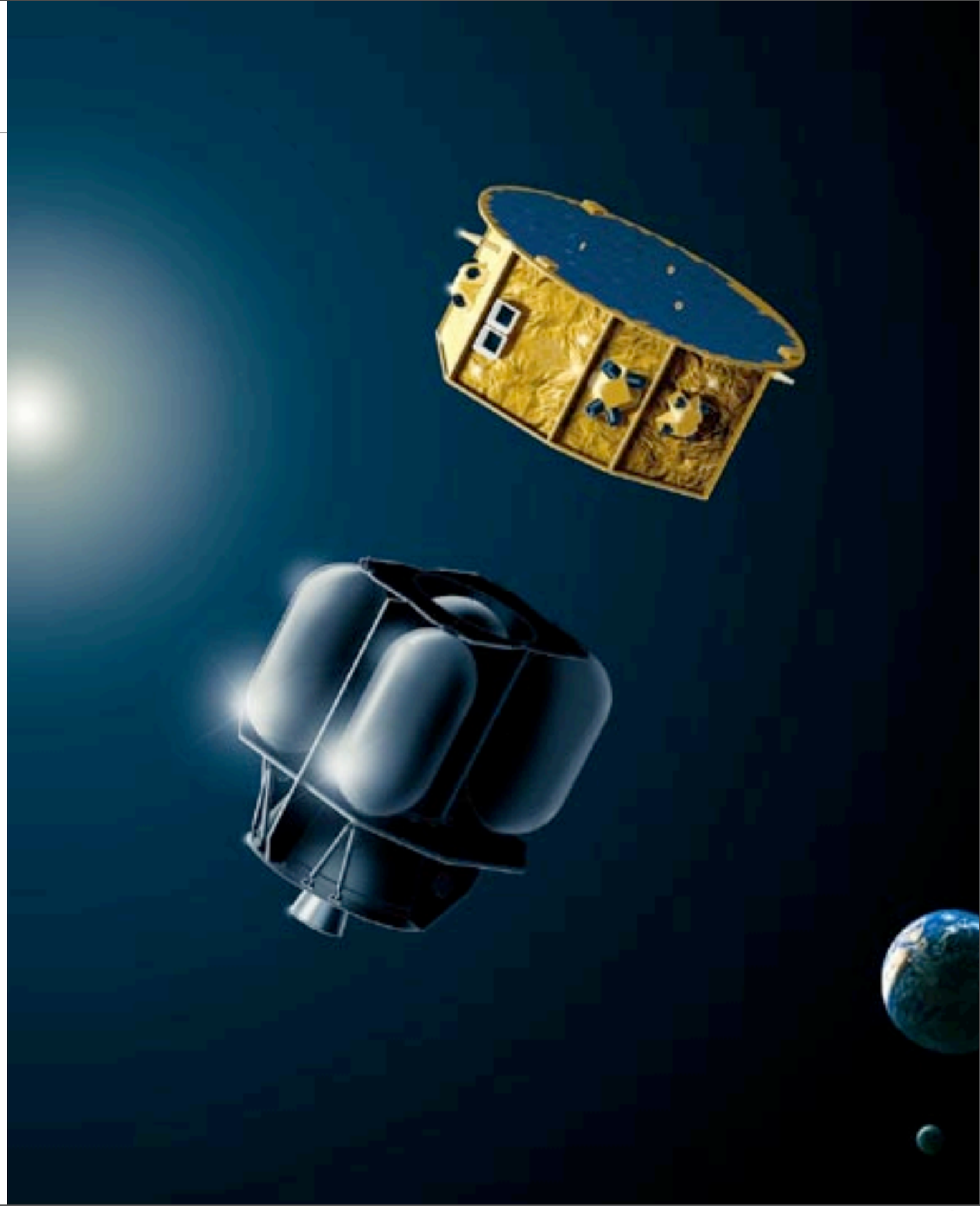
Larson, Benacquista & Taylor (in prep)

The Future of Gravitational Wave Astronomy

- **LIGO**
  - Currently upgrading to **Enhanced LIGO**, with science runs beginning next year, expanding reach in volume by 8x
  - Upgrades to **Advanced LIGO** have been funded, and slated for operation in 2014, expanding reach in volume by 1000x
- **LISA**
  - 2007 National Academy BEPAC Report gave LISA it's highest scientific ranking: "*LISA, in the committee's view, should be the flagship mission of a long-term program addressing Beyond Einstein goals.*"
  - Decadal Survey in Astronomy & Astrophysics is beginning
  - **LISA Pathfinder** in 2011

LISA Pathfinder

- The LISA Technology Development Mission
- Launch in late 2011
- Core instrument is the **LISA Technology Package**



LISA Pathfinder

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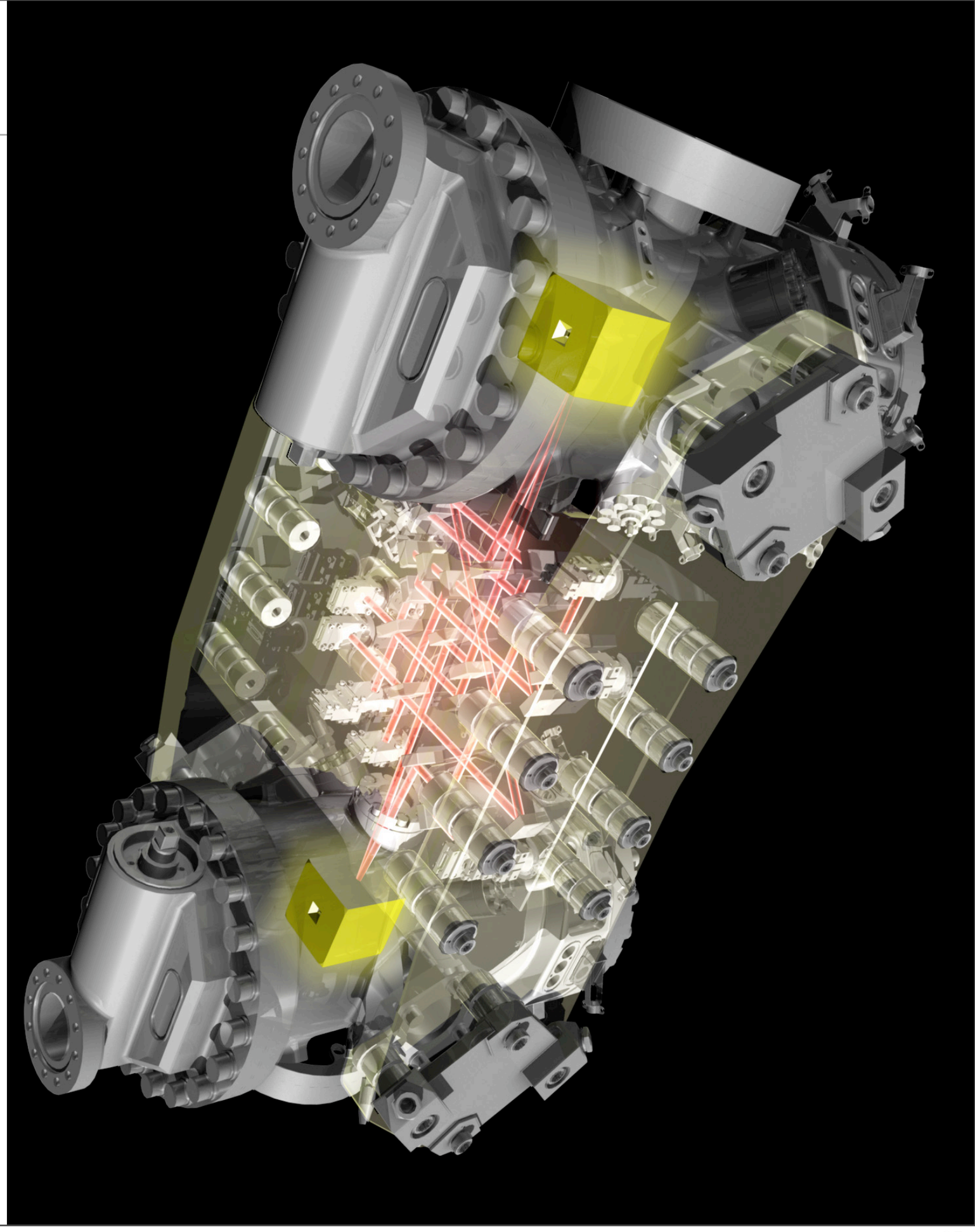
LISA Pathfinder

- LTP is the basic LISA sensing instruments on the scale of 35cm, not 5 million km!
- Coupled to the Disturbance Reduction System
- Micro-Newton thrusters control the spacecraft position to a millionth of a millimeter



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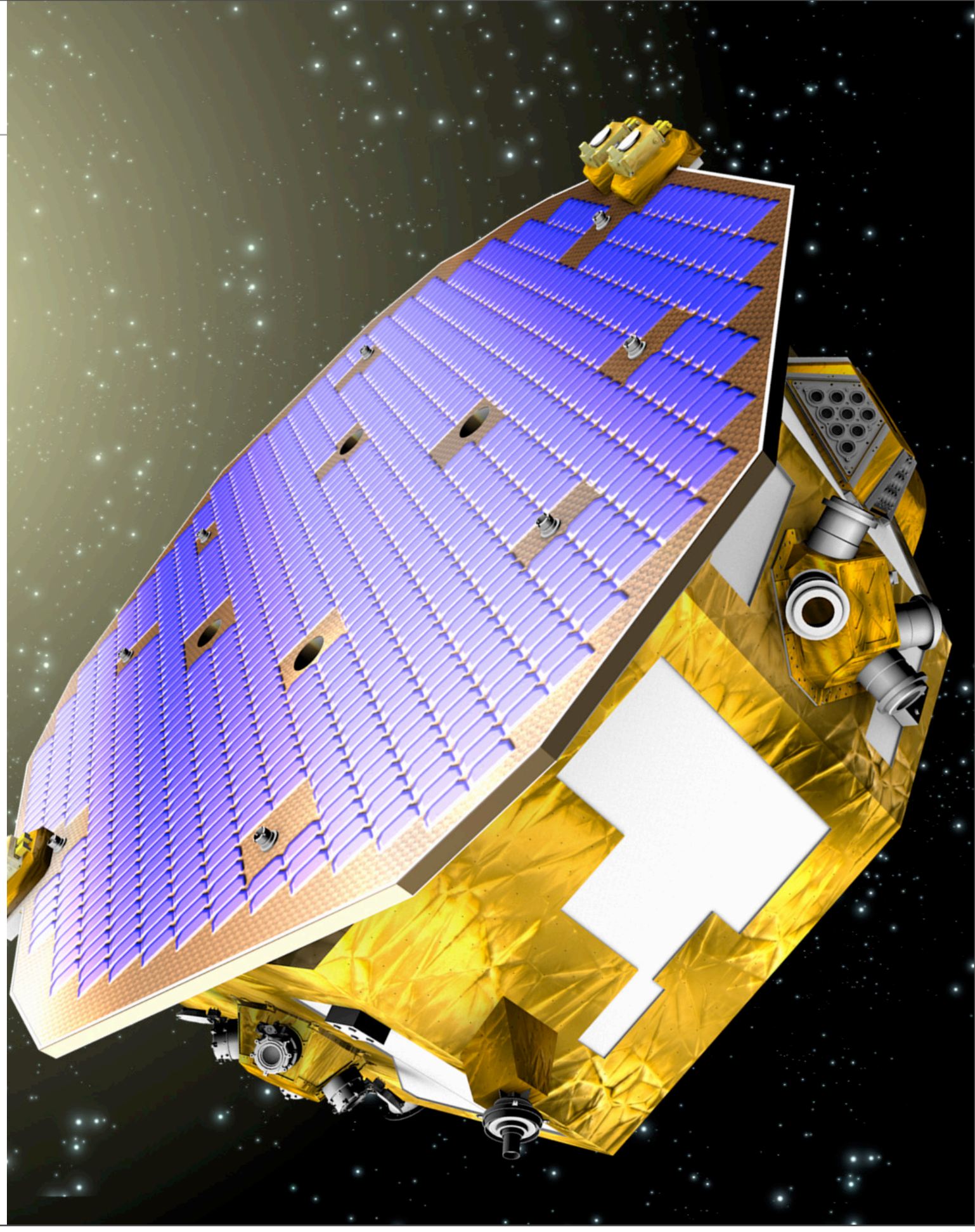
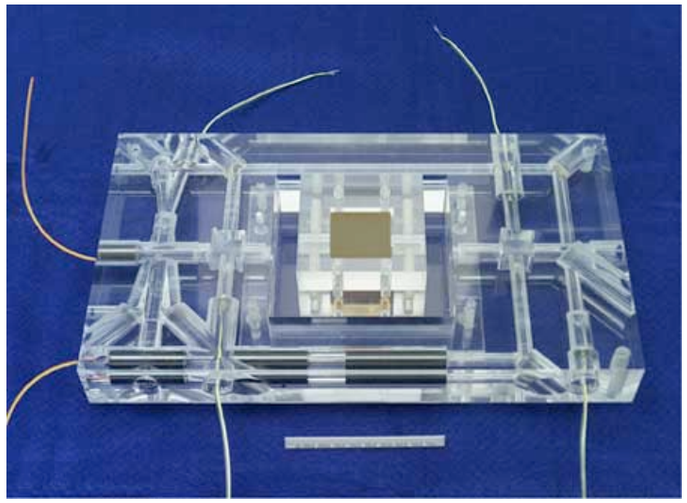
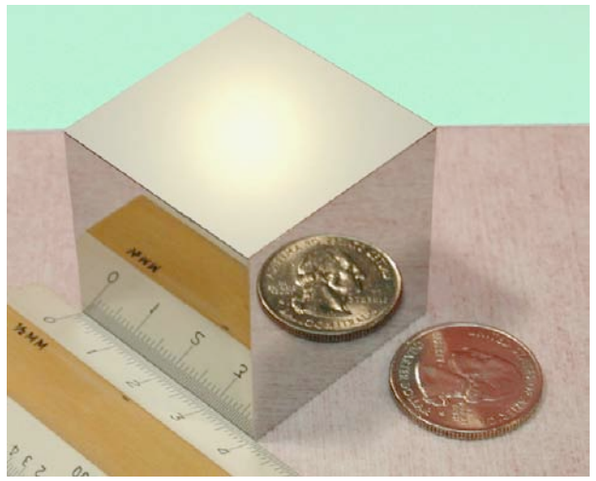


The Future of Gravitational Wave Astronomy

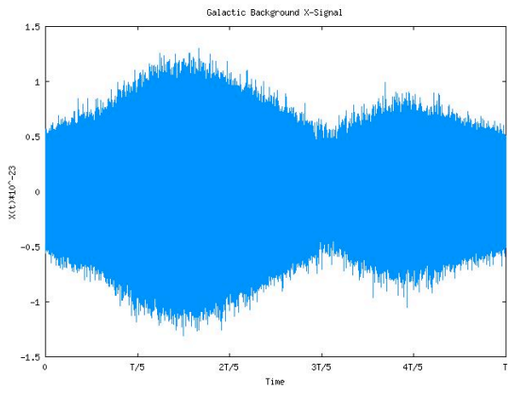
- Gravitational wave astronomy, like most of modern astronomy, is highly **interdisciplinary**. There are several main thrusts:

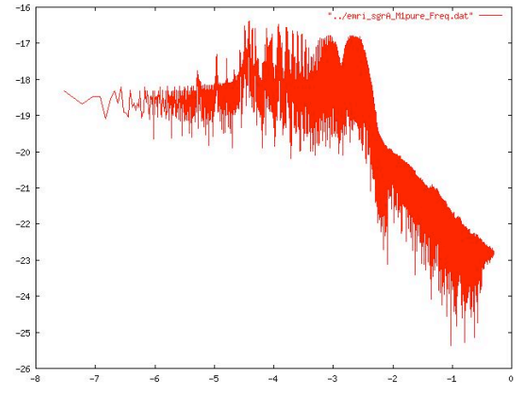
Technology

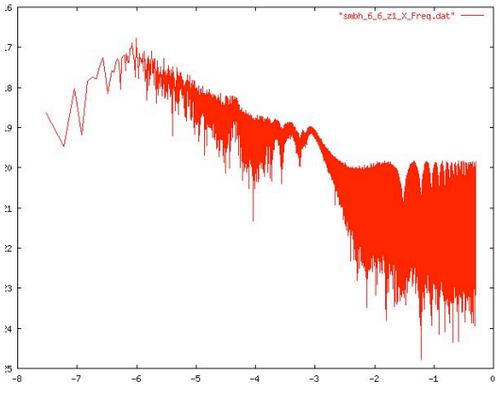




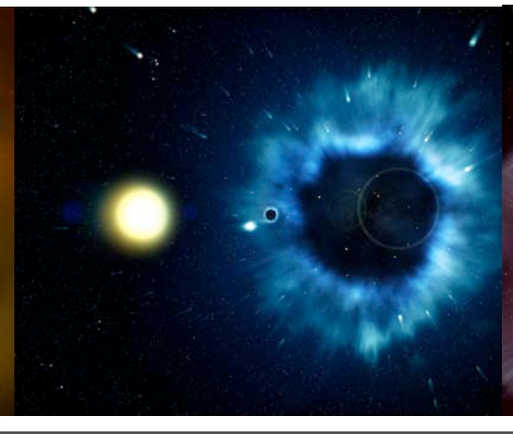
Science Analysis







Astrophysics & Gravitational Science



Summary

- The Gravitational Wave Enterprise is progressing rapidly, with LISA as a major component
- LISA will be a new tool for probing the Cosmos that complements other astronomical tools and enhances our science capabilities
- Because of the nature of the enterprise, broadly trained people able to communicate across discipline boundaries are highly valued
- Come visit us at the *American Astronomical Society Meeting* in Long Beach this January (mission booth, posters, evening splinter session, special invited session on gravitational waves)