LISA: a modern astrophysical observatory

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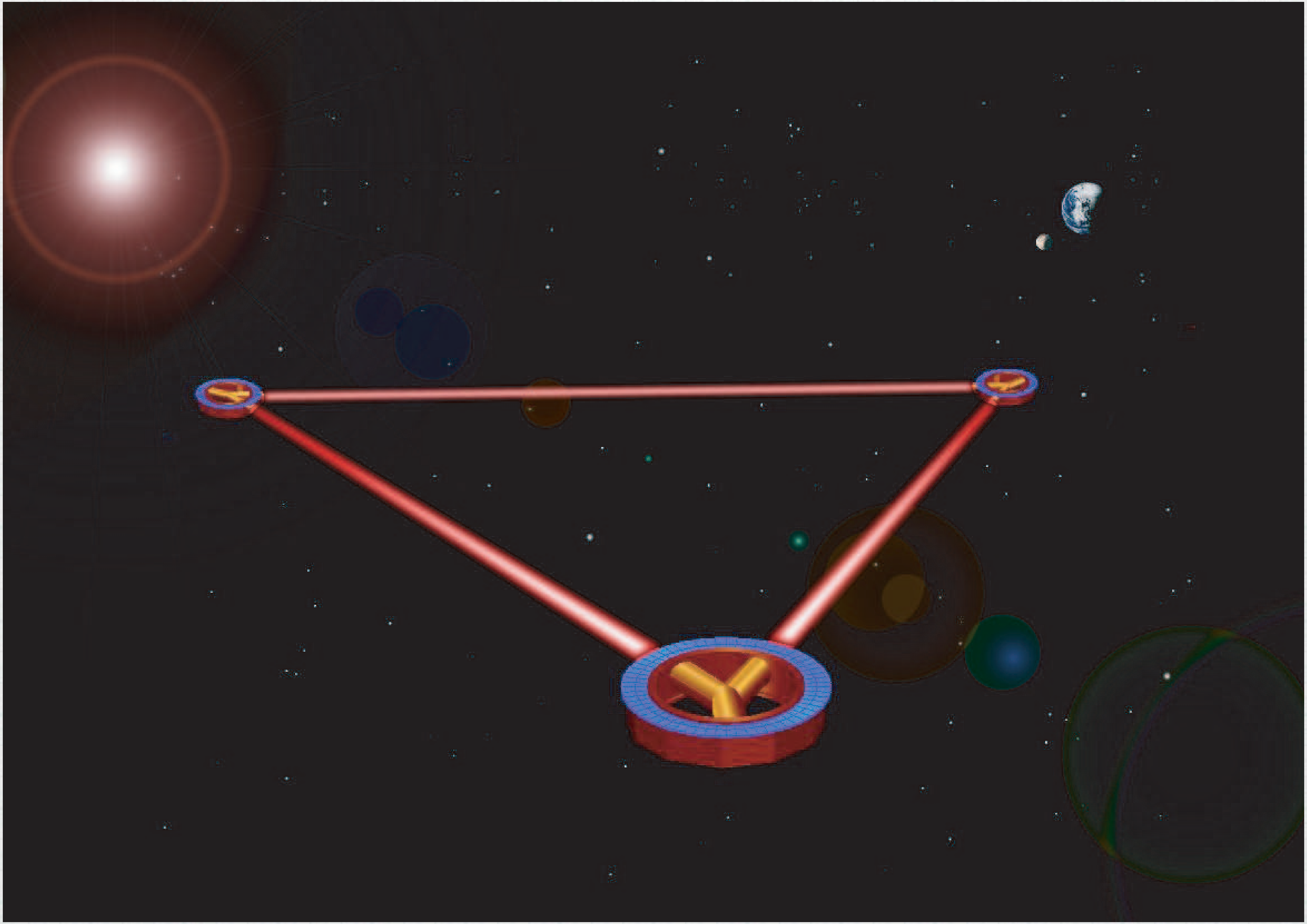
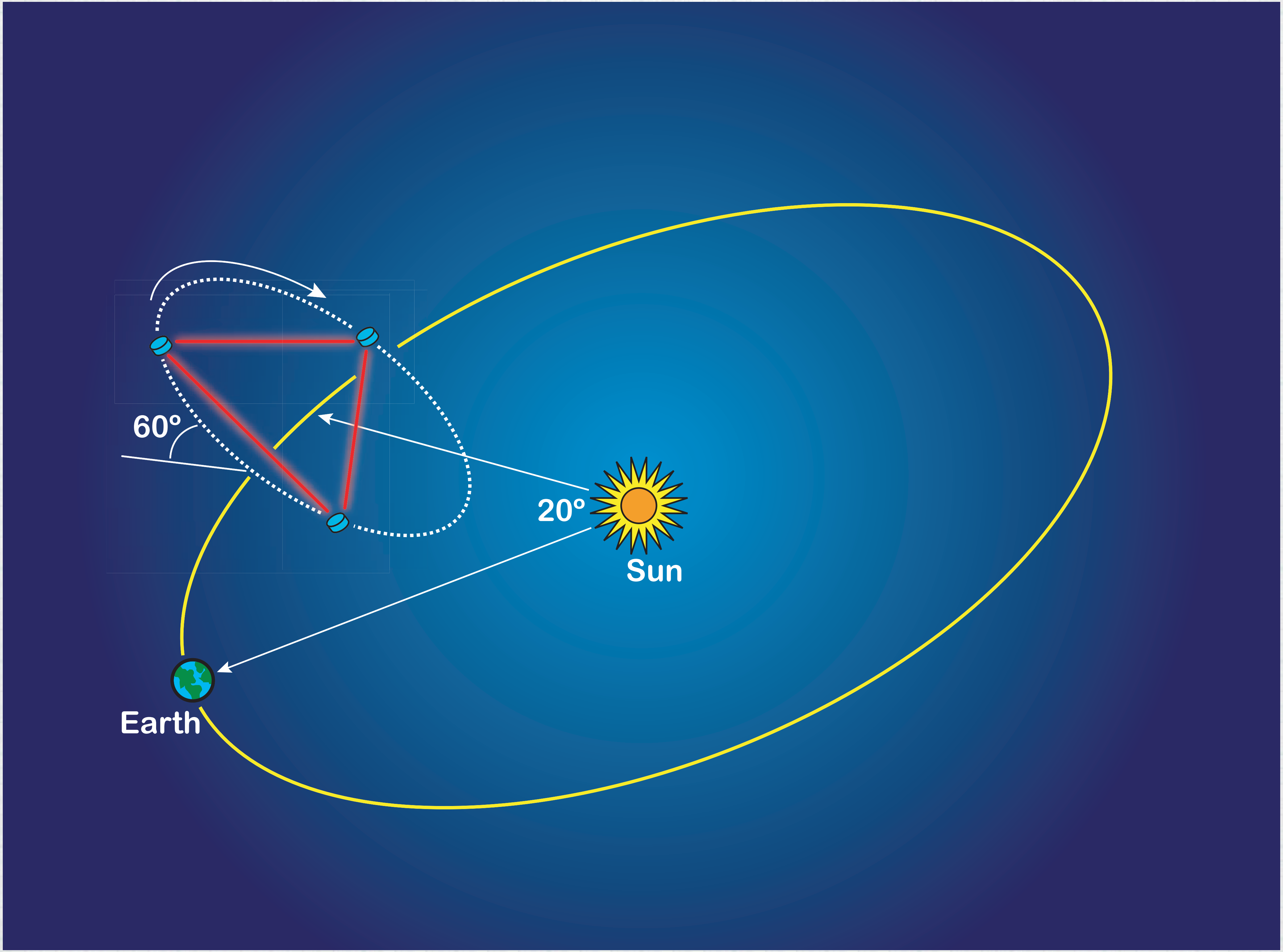
Storyline

- LISA: Observatory Design
- LISA Interferometry (TDI)
- Observatory sensitivity
- Sources and astronomy

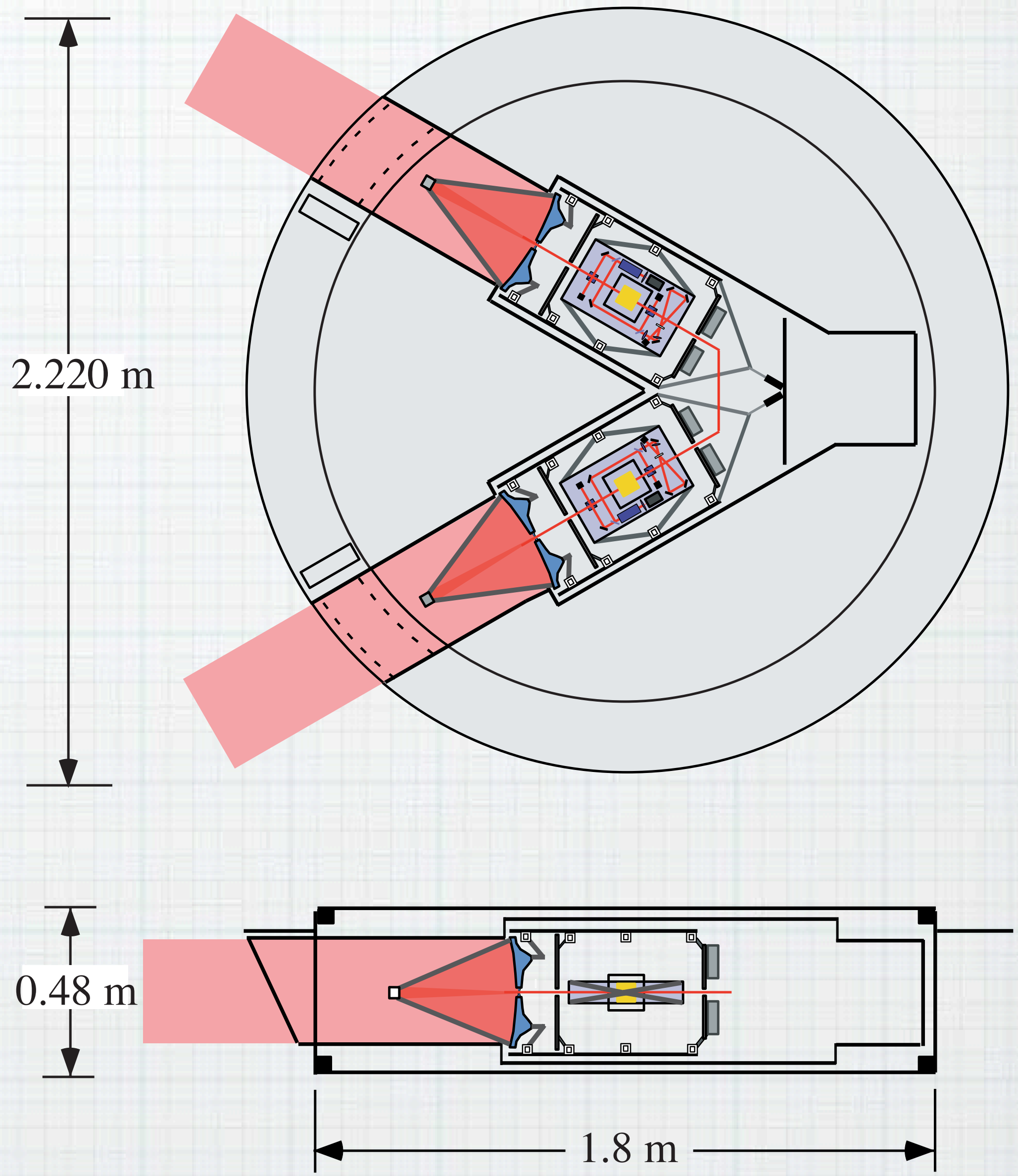
LISA: Laser Interferometer Space Antenna




60º
20º
Sun
Earth

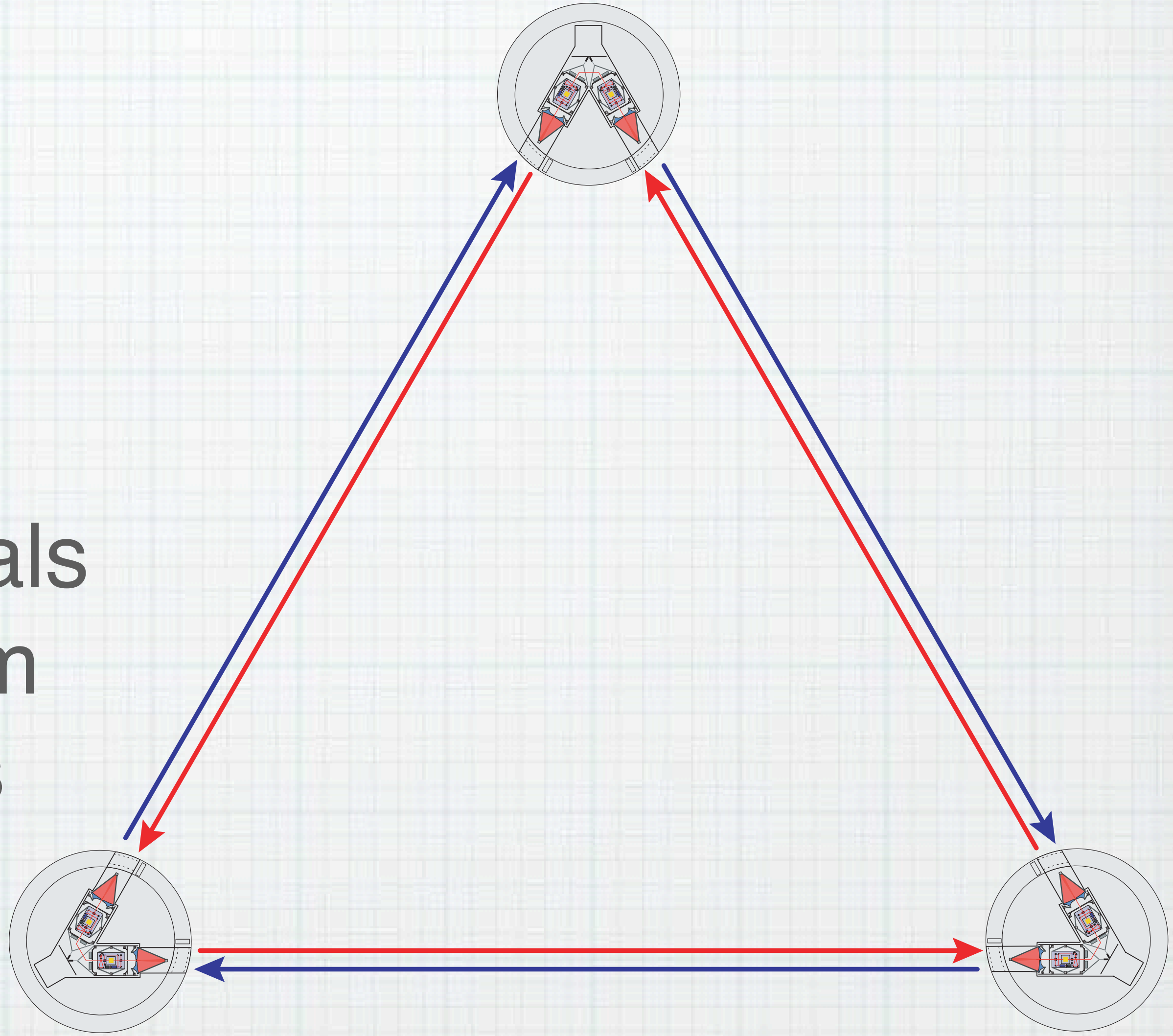
Spacecraft Configuration

- Three identical spacecraft, six independent lasers
- Free-flying, following individual “test-masses”
- Spacecraft protects test-masses from external forces except gravity -- the test-masses are “geodesic”

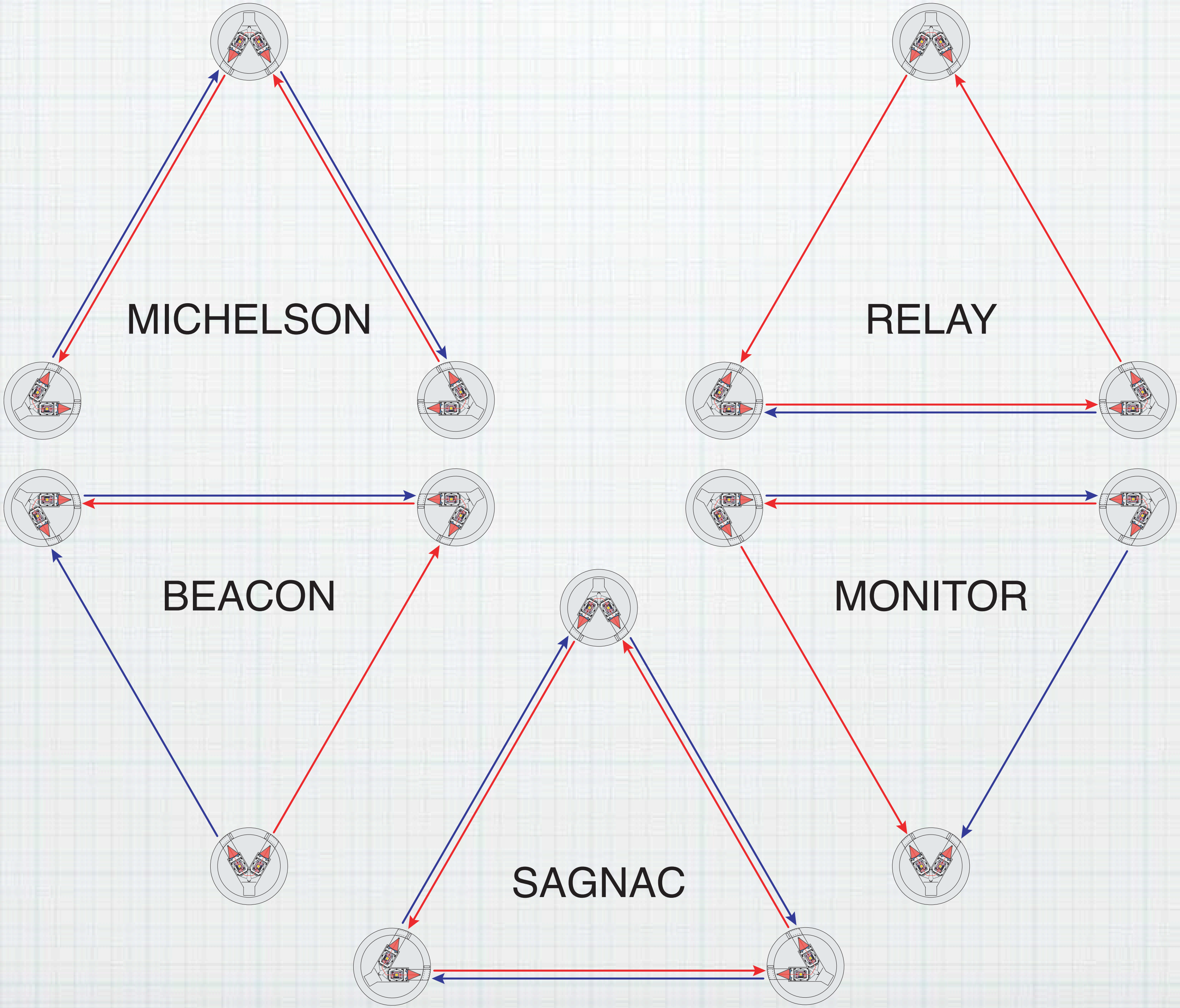


Laser Links & Interferometry

- True interferometry (comparing arm signals) is not done on orbit
- Interferometric signals are synthesized from individual laser links
- Time Delay Interferometry (TDI)
  {AET1, AET2, PTLA}



TDI Laser Topologies



Time Delay Interferometry (TDI)

- Premise is to delay individual laser signals to make light travel time in arms geometrically equal
- Necessary to remove certain kinds of noise (e.g. phase fluctuations in the lasers)
- Example: Unequal-arm Michelson

$$
\begin{aligned}
X(t) &= s_1(t) - s_2(t) - [s_1(t - 2\tau_2) - s_2(t - 2\tau_1)] \\
&= [s_1(t) - s_1(t - 2\tau_2)] - [s_2(t) - s_2(t - 2\tau_1)]
\end{aligned}
$$

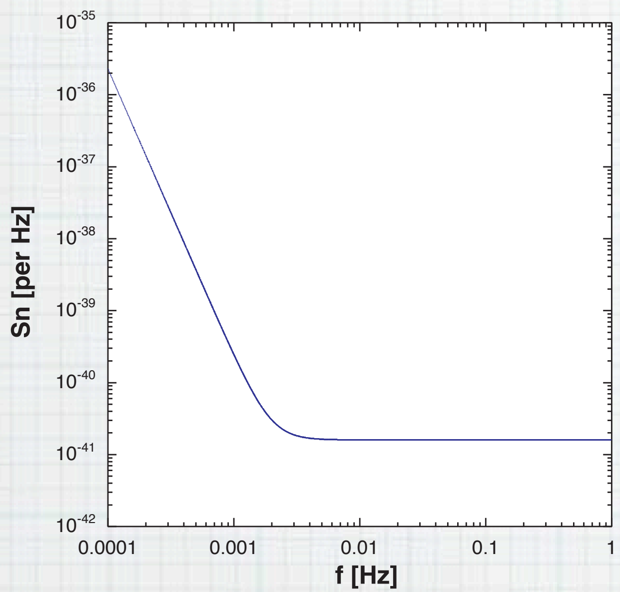
$$
\begin{aligned}
s_i(t) &= \text{laser phase in arm } i \\
\tau_i &= \text{one way light travel time down arm } i
\end{aligned}
$$

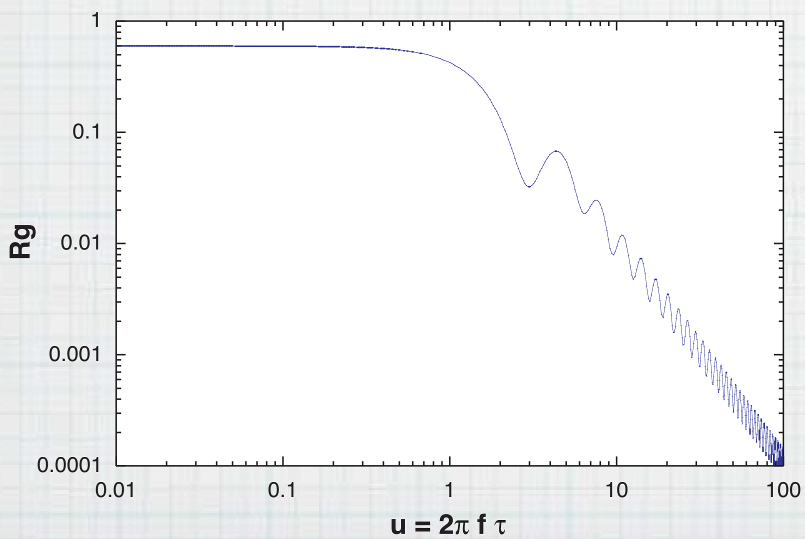
LISA Sensitivity

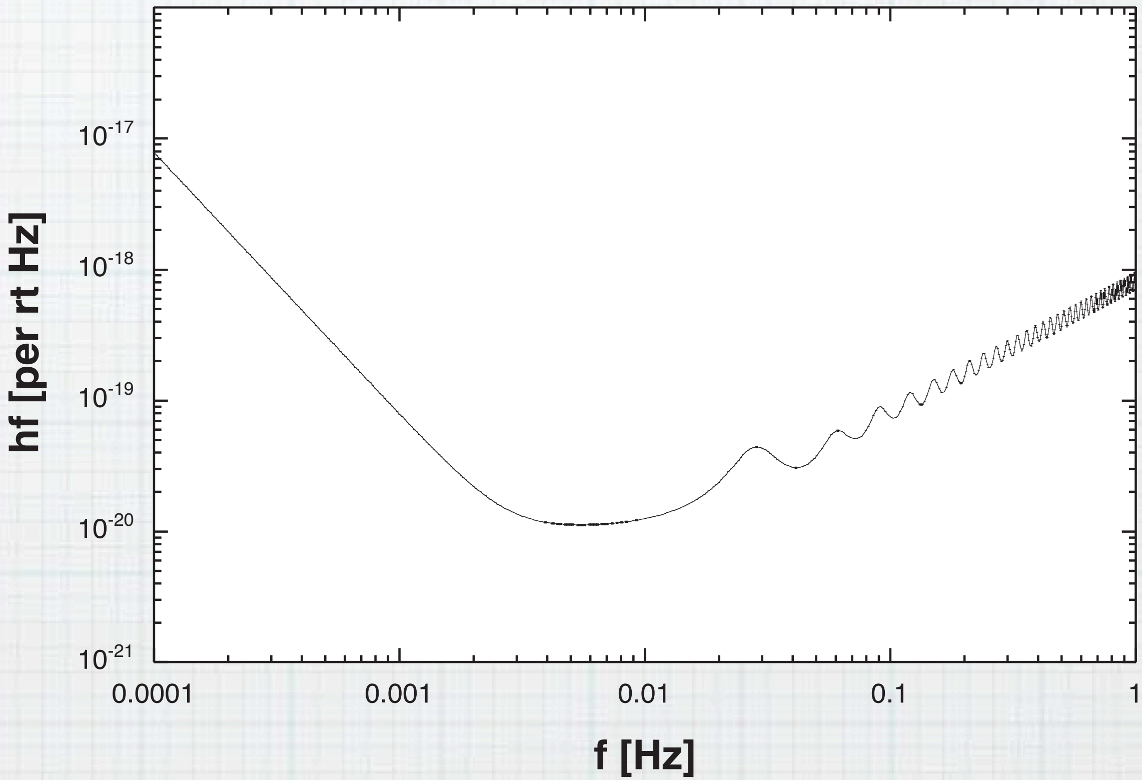
- Sensitivity is a combination of the TDI variable of interest and specifying instrumental noise
- The TDI variable has a *response function* (or *transfer function*) that shapes the sensitivity when combined with a noise curve
- For LISA, the response function depends on frequency. This is not true for LIGO, where the response function is roughly constant
- As normally plotted, LISA sensitivity curves are averaged over sky locations and source orientation (related to polarization)

LISA Sensitivity (2)

$$h_f = \sqrt{\frac{S_N}{\mathcal{R}_g}} = \sqrt{\frac{\mathcal{R}_n \cdot S_n}{\mathcal{R}_g}}$$

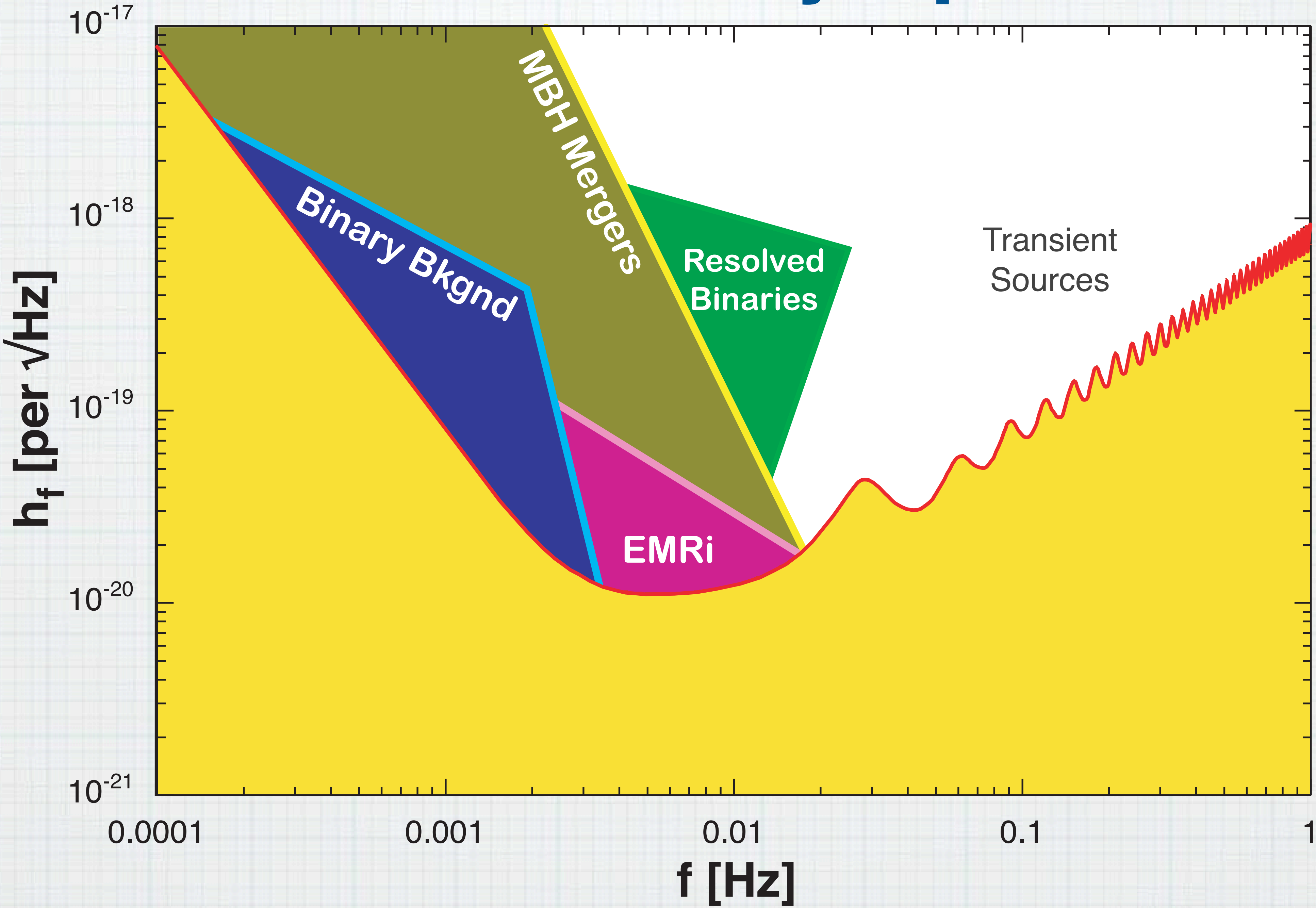






{LHH1, LHH2, AET1}

LISA Discovery Space



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

Pocket Estimators

Chirp Mass

$$\mathcal{M}_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

Scale Amplitude

$$h_o = \frac{\mathcal{M}_c}{D}(\pi f \mathcal{M}_c)^{2/3}$$

$$h_f = \frac{h_o}{\sqrt{\Delta f}} = h_o \sqrt{T_{obs}}$$

Chirp

$$\dot{f} = \frac{96}{5}\frac{f}{\mathcal{M}_c}(\pi f \mathcal{M}_c)^{8/3}$$

Merger Frequency

$$f_{merge} \simeq 205\text{Hz}\left(\frac{20 M_\odot}{m_1 + m_2}\right)$$

Massive Black Hole Mergers

- The LISA band is 10^{-4} Hz < f < 0.1 Hz
- Black hole binaries merging in band have total masses ~ 4 x 10^7 Mo to ~ 4 x 10^4 Mo
- LISA will be sensitive to last year of inspiral and merger
- Visible to cosmological horizon

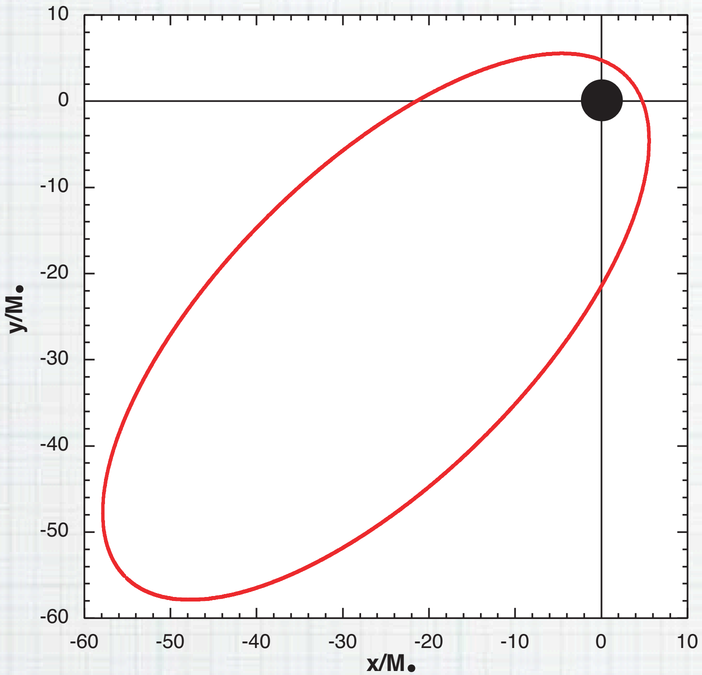
{Hughes}

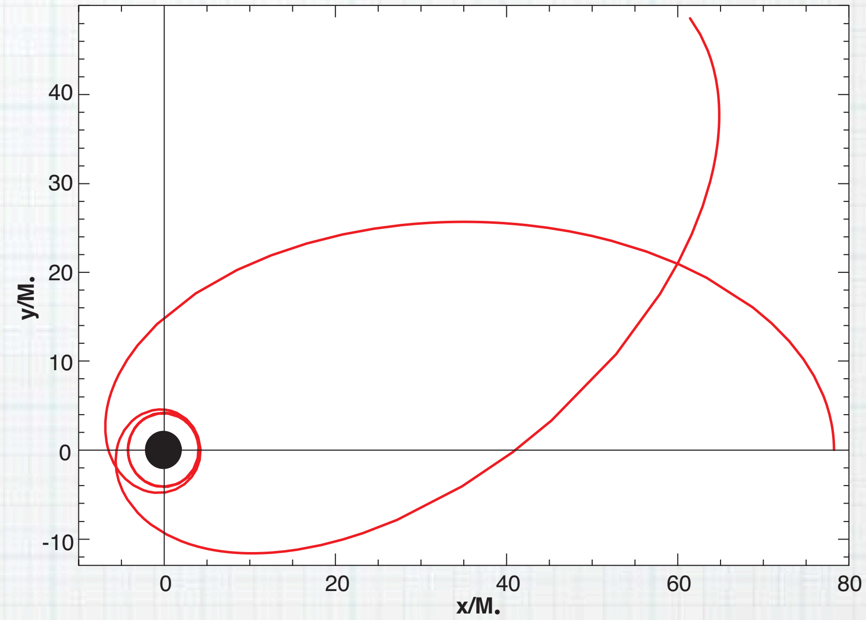
EMRIs: Mapping Black Holes

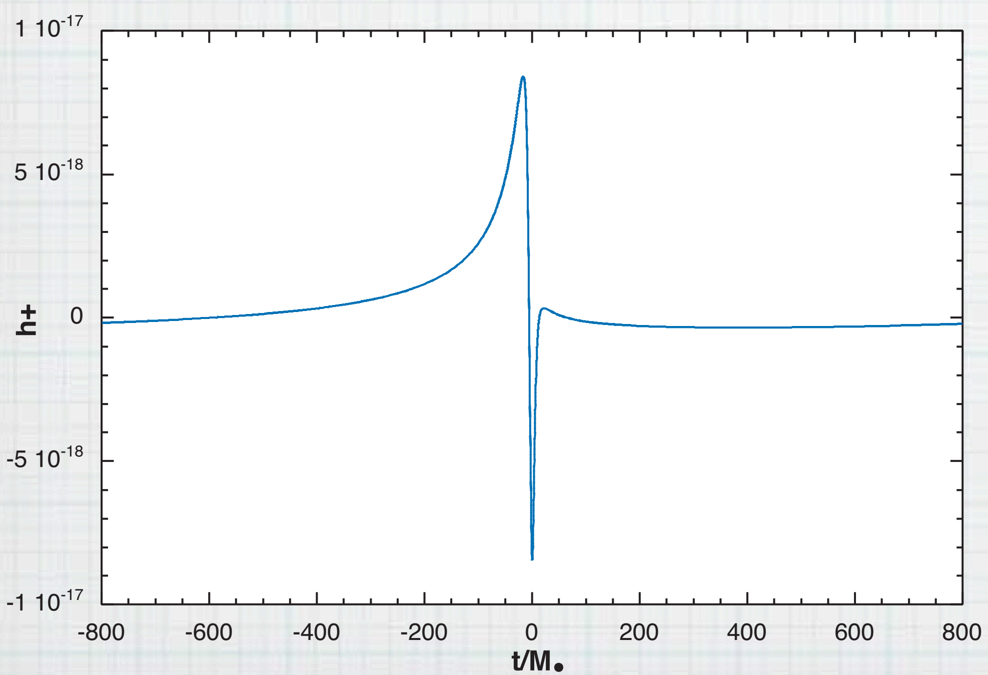
- Stellar mass black holes will probe the strongly curved spacetime near supermassive black holes and encode the map in the radiation
- Analogous to geodesey, where monitor the location of a small satellite as it moves through the Earth's gravitational potential
- Very difficult to effectively characterize from data because orbits can be complex

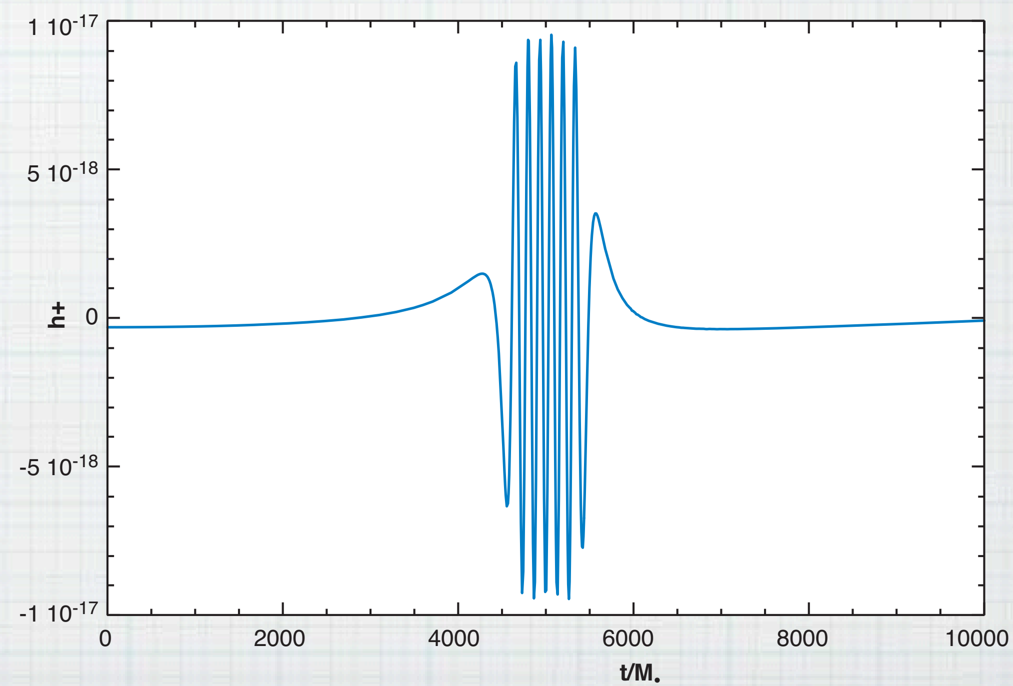
{Freitag, Gair et al.}

Zoom Whirl Orbits



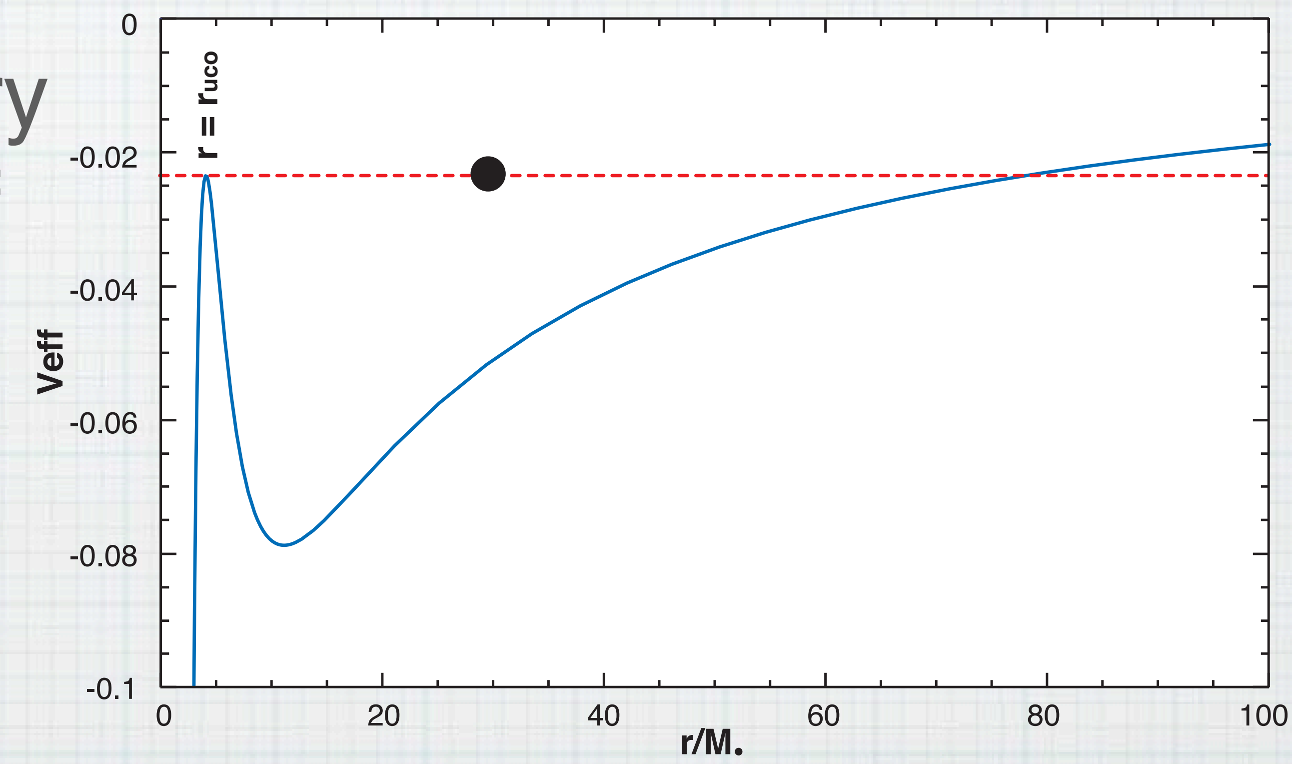




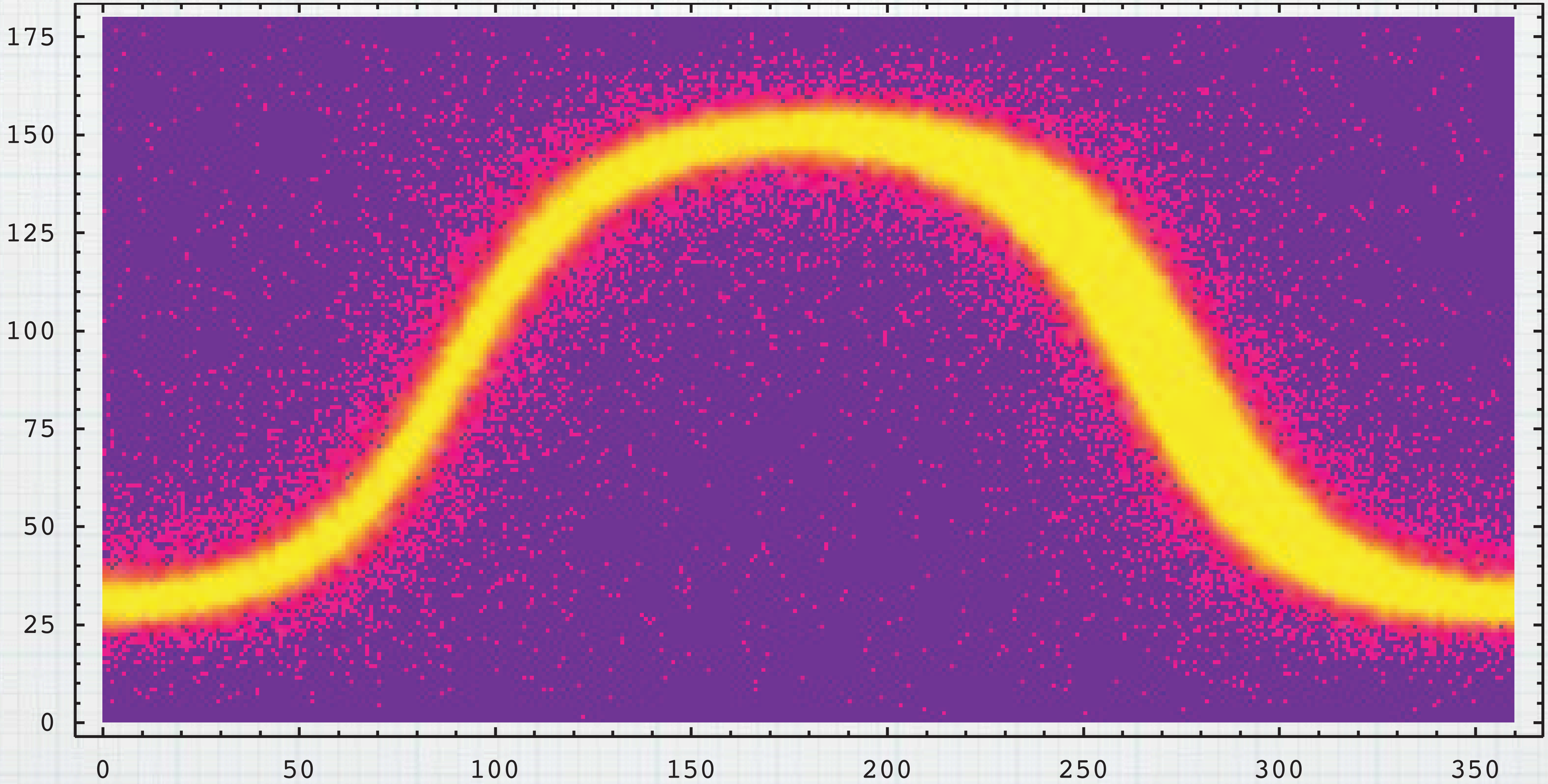


Why the orbits whirl

- The extreme whirling behaviour is perihelion precession gone wild
- Happens when particle probes effective potential near the inner peak
- Trajectory is very similar to that of a circular orbit



Galactic Close Binary Foreground

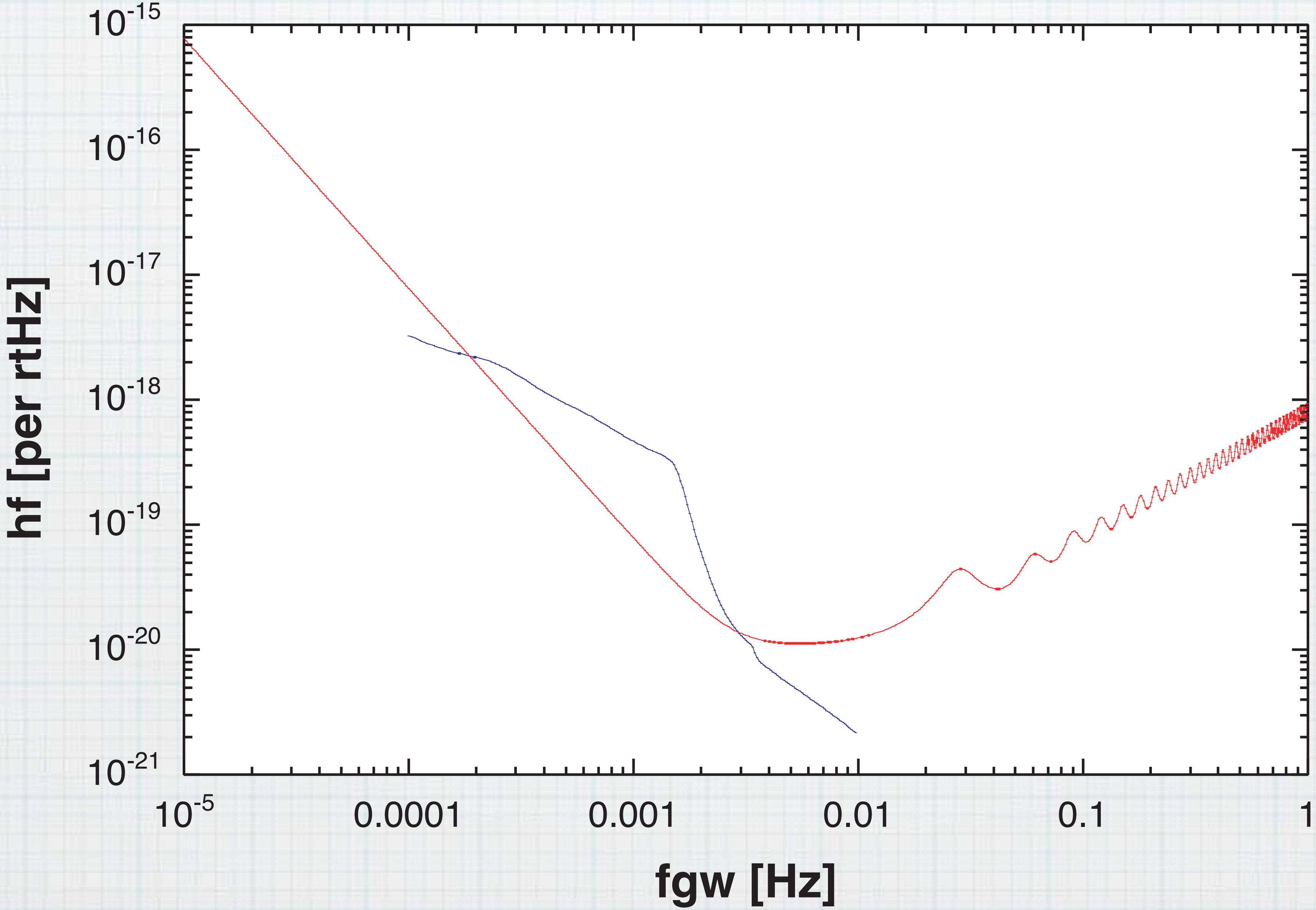


{Benacquista et al., Nelemans et al.}

Galactic Foreground (2)

- About 10 million+ close binaries in the Milky Way
- Most are too far away to see with photons; LISA can see them across the entire galaxy
- Only 5000-10,000 will be individually resolvable
  - Identify parameters and "subtract" from data {eg Cornish & Larson}
- Remaining stars merge to form a confusion foreground
  - Effectively a source of irreducible noise, astrophysical in origin
  - Affects other data analysis (particularly EMRIs)

LISA Sensitivity with Close Binaries



End Notes...

- LISA is due to launch in ~2013
- Technology demonstration (LISA Pathfinder in ~2008)
- Guaranteed astrophysical sources!
- Wide range of activities which need attention: instrumentation, data analysis, astrophysics

LISA Literature Resources 1

- LISA: GENERAL INFO & MISSION SPECIFICATIONS
  - LISA Symposia in Classical & Quantum Gravity
    - LISA I: CQG **14** (No6) [1997]
    - LISA III: CQG **18** (No19) [2001]
    - LISA IV: CQG **20** (No10) [2003]
    - LISA V: CQG **22** (No10) [2005]
  - LISA Final Technical Report (FTR), available at http://www.srl.caltech.edu/lisa/documents.html
  - LISA Pre-Phase A Report (LPPA), available at http://www.srl.caltech.edu/lisa/documents.html

LISA Literature Resources 2

- LISA Sensitivity
  - {AET1} Armstrong, Estabrook & Tinto: ApJ **527**, 814 [1999]
  - {AET2} Estabrook, Tinto & Armstrong: PRD **62**, 042002 [2000]
  - {LHH1} Larson, Hiscock & Hellings: PRD **62**, 062001 [2000]
  - {LHH2} Larson, Hellings & Hiscock: PRD **66**, 062001 [2002]
  - {PTLA} Prince, Tinto, Larson & Armstrong: PRD **66**, 122002 [2002]
- LISA Data Analysis
  - Cutler: PRD **57**, 7089 [1998] (LISA Angular Resolution & parameter estimation)
  - Moore & Hellings: PRD **65**, 062001 [2002] (LISA Angular Resolution & parameter estimation)
  - Cornish & Larson: CQG **20**, 163 [2003] (Source demodulation)
  - Cornish & Larson: PRD **67**, 103001 [2003] (Source Subtraction)

LISA Literature Resources 3

- LISA Sources
  - Gair et al., CQG **21**, 1595 [2004] (EMRI Event Rates)
  - Freitag, ApJ **583**, L21 [2003] (Milky Way EMRIs)
  - Hughes, MNRAS **331**, 805 [2002] (SMBH & cosmology)
  - Meliani, de Araujo & Aguiar, A+A **358**, 417 [2000] (CVs as resolvable binary sources)
- Binary Foreground
  - Benacquista, Degoes & Lunder, CQG **21**, S509 [2004] (Simulation of foreground)
  - Nelemans, Yungelson & PortegiesZwart, A+A **375**, 890 [2001] (Simulation of foreground)
  - Farmer & Phinney, MNRAS **346**, 1197 [2003] (extragalactic close binary background)