LISA
Opening New Horizons

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Greenbelt, MD USA

Building on New Worlds New Horizons

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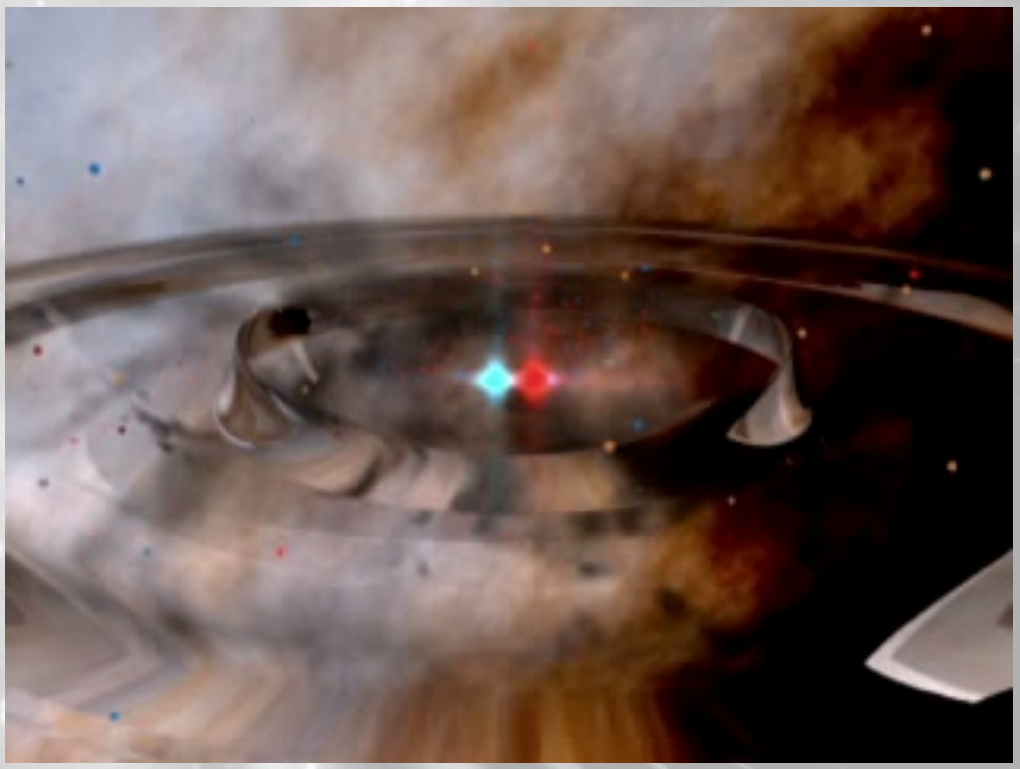
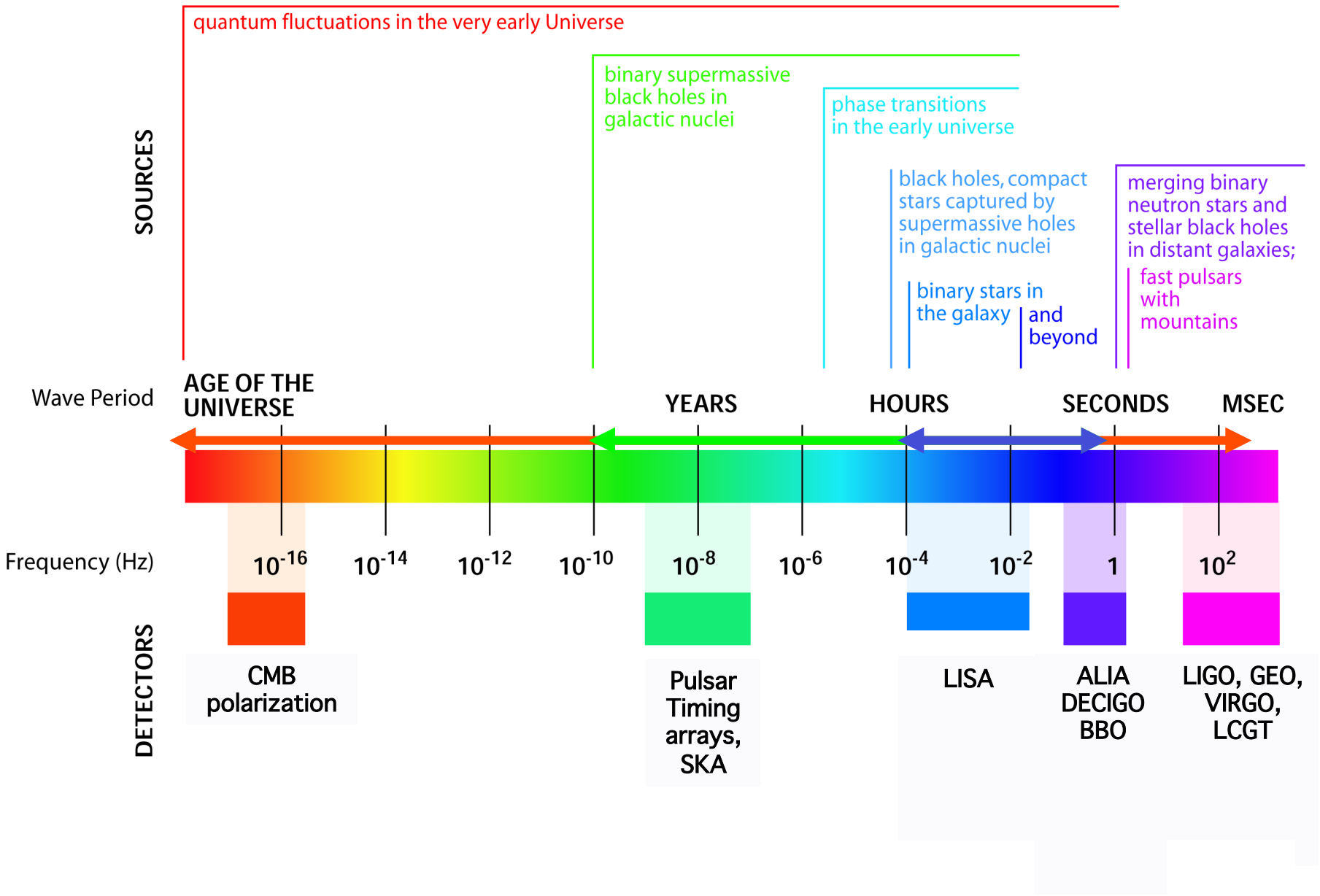
Gravitational Waves ….



- **Ripples in spacetime curvature**
- **Predicted by GR**
- **Travel at velocity *v = c***
- **Produced by masses w/ time-changing quadrupole moments**
  → *such as binary systems*
- **Carry energy & momentum**
  → *cause binary orbits to shrink*
- **Carry the direct signatures of the massive objects dynamics**
- **Interact weakly with matter**
  → *carry info about deep, hidden regions in the universe*
  → *direct detection is difficult…. precision measurements*
- ***New tool for observing the universe…..***

The Gravitational Wave Spectrum



GW amplitudes…. and GW detectors….

- **Binary orbital frequency**

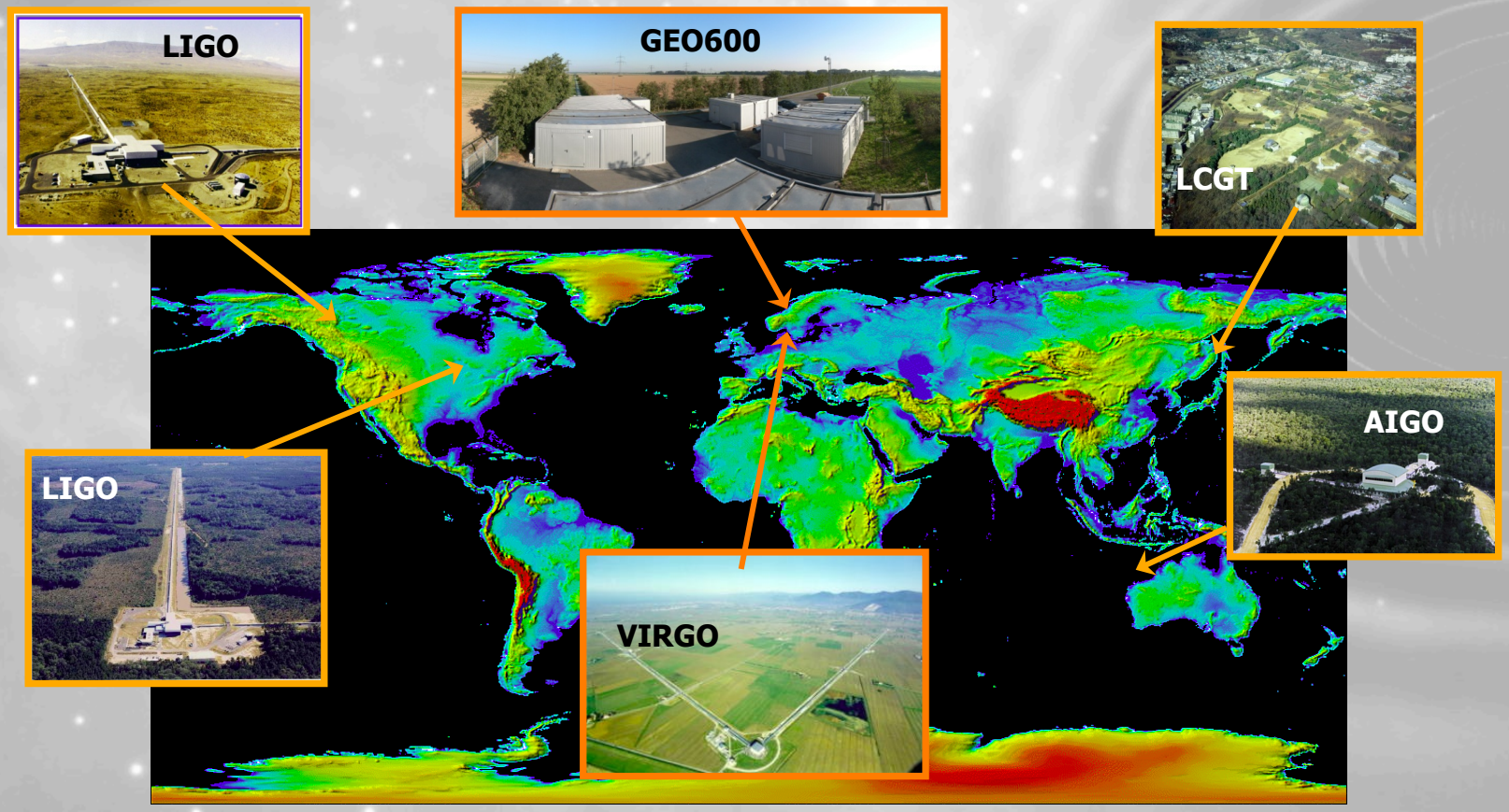
$$f_{\rm GW} \sim 2 f_{\rm orb} \sim \frac{1}{\pi}\left(\frac{GM}{a^3}\right)^{1/2}$$

- **BH/BH, $a \sim 5R_{\rm Sch}$**
  $f_{\rm GW} \sim 100$ Hz
- **MBH/MBH, $a \sim 5R_{\rm Sch}$**
  $f_{\rm GW} \sim 4 \times 10^{-4}$ Hz
- **MBH/MBH, $a \sim 5\times10^{4}\ R_{\rm Sch}$**
  $f_{\rm GW} \sim 4 \times 10^{-10}$ Hz

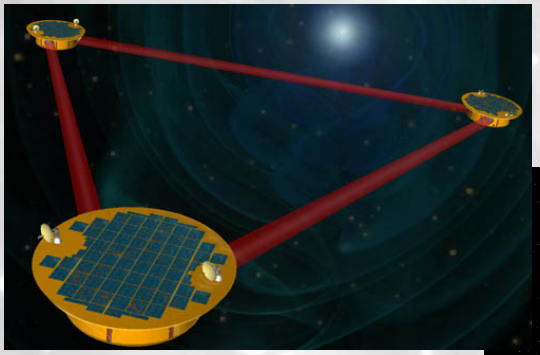
- **Ground-based: LIGO, VIRGO…**
  - Interferometers w/ km-scale arms
  - High freq, 10 Hz ≤ $f_{\rm GW} \le 10^{4}$ Hz
  - Mergers of stellar and IMBHs, BHs, NS/NS, NS/BHs…
- **Space-based: LISA**
  - Interferometer, arms ~ 5×10^{6} km
  - Low freq, 10^{-4} Hz ≤ $f_{\rm GW} \le 10^{-1}$ Hz
  - MBHs, Galactic compact binaries at wider separations
- **Pulsar Timing Arrays:**
  - GWs change pulsar TOA's
  - Very low freq, ~ 10^{-9} Hz
  - Widely separated MBH binaries, cosmic relic GW backgrounds

Ground-based detectors are opening the GW window…

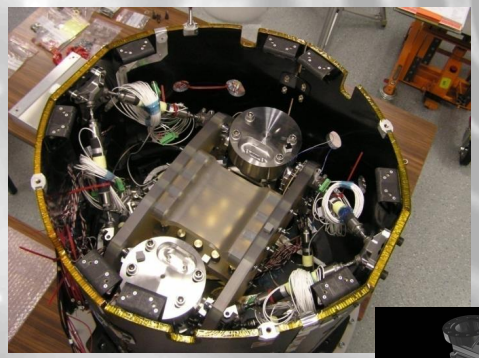
- Initial LIGO reached promised sensitivity in 2005-7 observing run (S5)
- Advanced LIGO, VIRGO expected to make *regular observations 2016+*
- Large Japanese detector (LCGT) funded, maybe another in Australia
- Sources are NS/NS mergers, etc ….*synergy w/ radio transients (Frail)*



LISA: Laser Interferometer Space Antenna

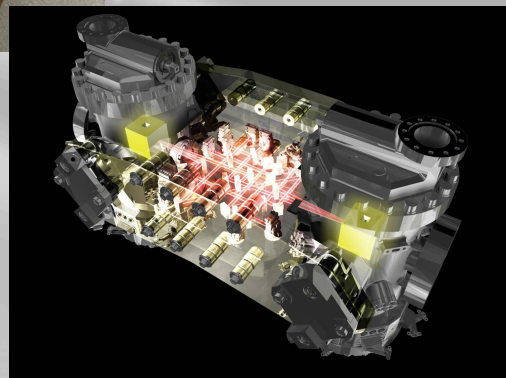


- Low frequency GWs:
  10^{-4} Hz ≤ f_{GW} ≤ 10^{-1} Hz
- NASA/ESA partnership
- 3 spacecraft, at vertices of equilateral triangle
- Interferometer $L \sim 5 \times 10^6$ km
- Heliocentric orbit, 20° behind Earth



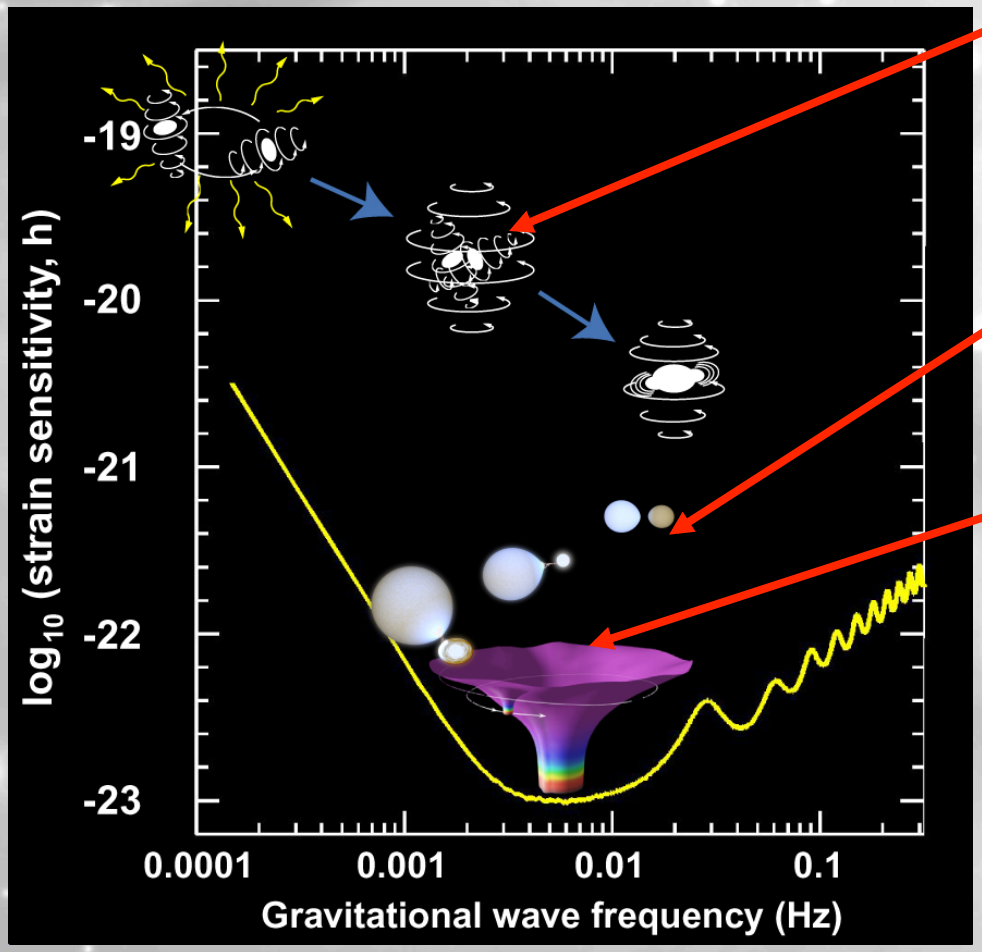
LISA Pathfinder

- ESA mission (NASA participation)
- Single interferometer, $L \sim$ 30cm
- Will test LISA hardware in a space environment
  → "drag free" flying
- Launch ~ 2013



LISA has many strong GW sources….

The low frequency GW window is richly populated with strong sources



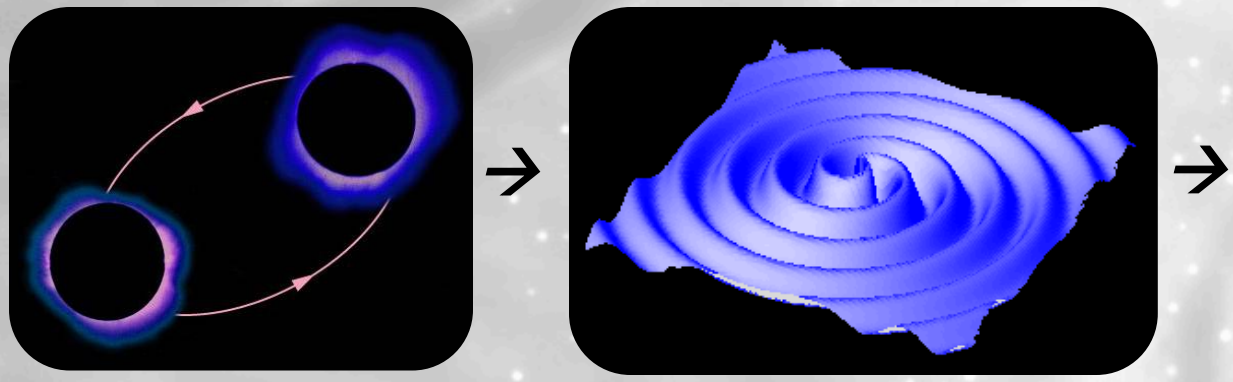
Massive Black Hole binary inspirals and mergers (to z~20) (~ tens to hundreds)

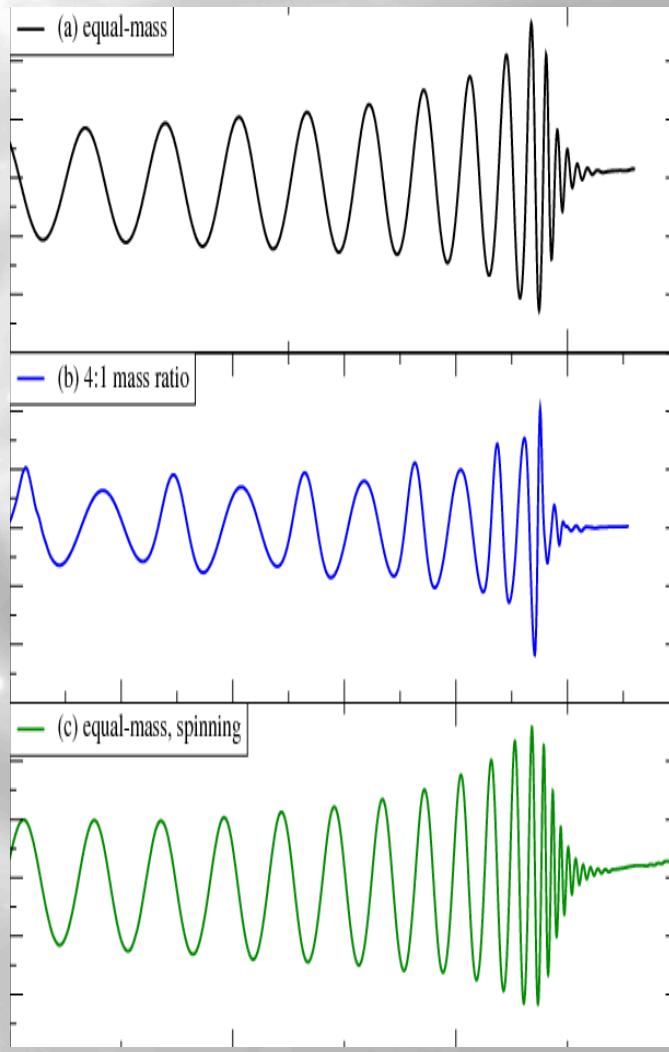
Ultra-compact binaries, mostly in Galaxy (~ thousands)

Capture of stellar-mass Black Holes by massive BHs in normal galactic nuclei to z ~ 1 (~hundreds)

Cosmic backgrounds, superstring bursts, …?

Gravitational waveforms encode the dynamics of massive objects…





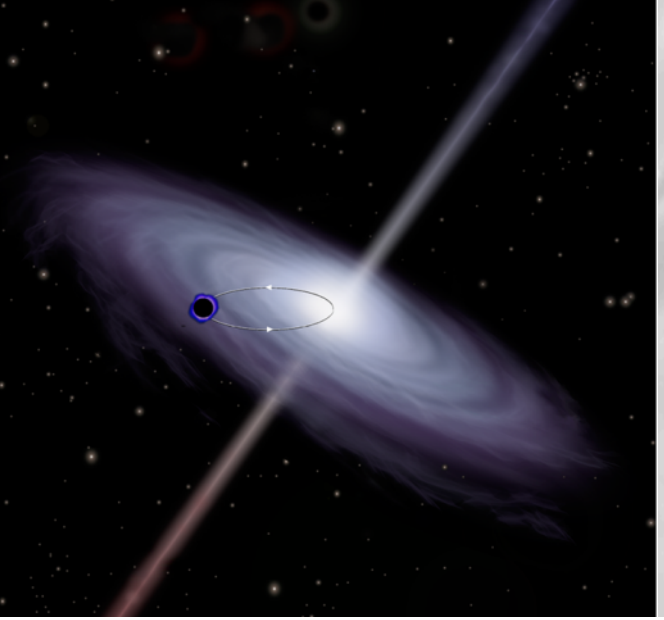
Analysis of the waveforms gives direct measurements of

- masses,

- spin vectors,

- luminosity distance,

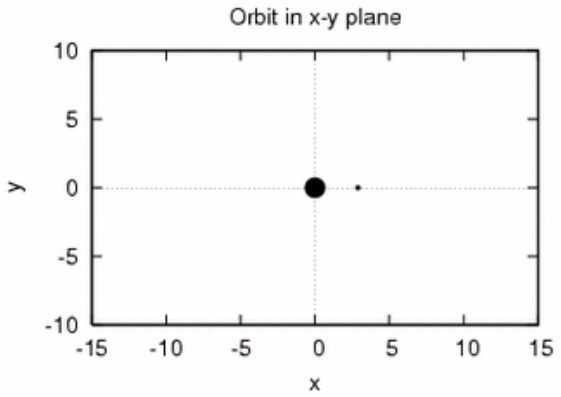
- orbital inclination…..

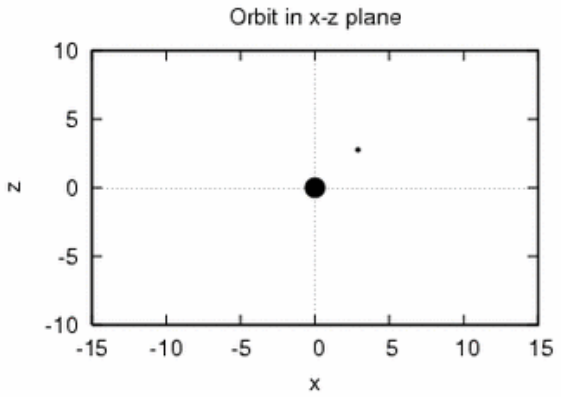


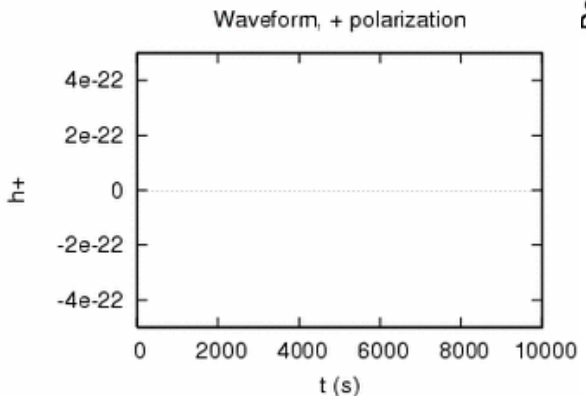
Black Hole Captures….

- Compact object spirals into a massive BH
- Map of curved space geometry near BH horizon → *is it a Kerr black hole?*
- Study populations in normal galaxies

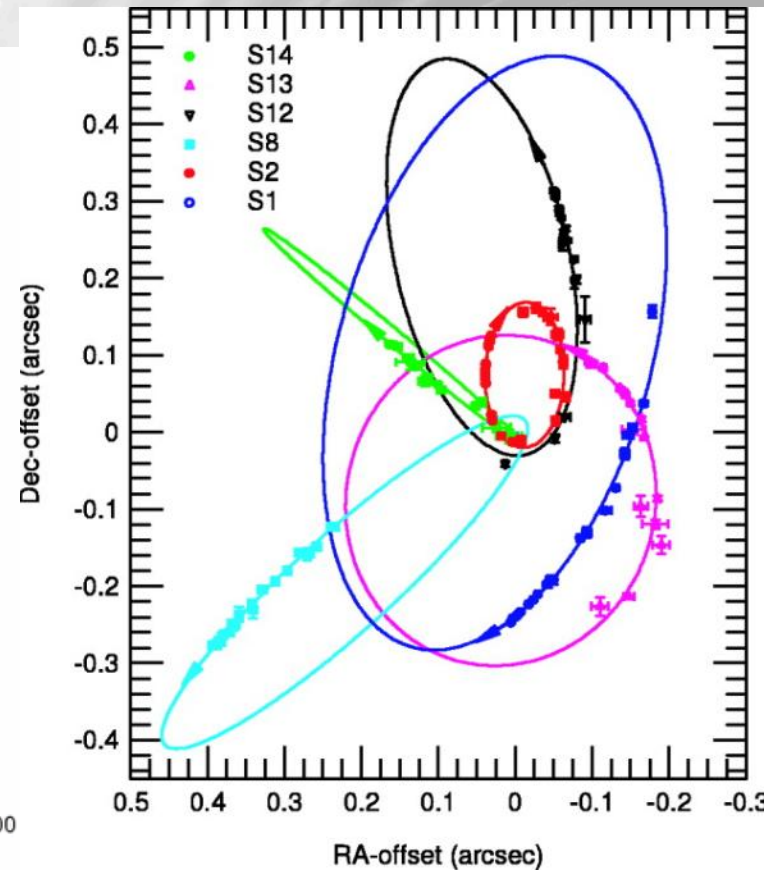
J. Gair





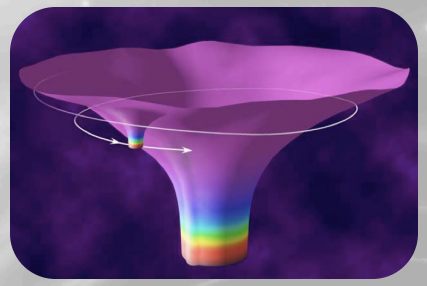


LISA will observe ~10^5 orbits in a year

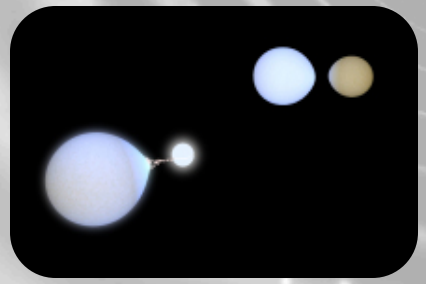


UNDERSTANDING THE COSMIC ORDER

- *How do black holes grow, radiate, & influence their surroundings?*
  - *Mergers of BHs out to z > 15*
  - *Captures of stellar compact objects by central massive BHs out to z ~ 1*



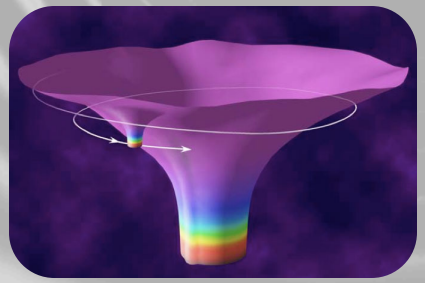
- *How do the lives of massive stars end?*
- *What are the progenitors of Type Ia supernovae and how do they explode?*
  - *LISA will find ~ 20,000 compact binaries, mostly in the Galaxy*
  - *At least ~ 100 will also be observed optically*



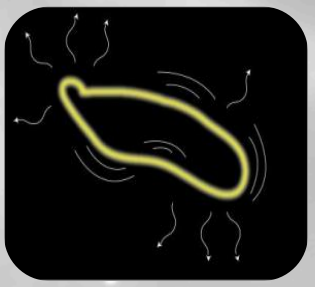
ORIGINS

- *What were the first objects to light up the universe, and when did they do it?*
  - *MBH megers at high redshifts z > 15*

- *What is the fossil record of galaxy assembly from the first stars to the present?*
- *How do cosmic structures form and evolve?*
  - *MBH megers at high redshifts z > 15*
  - *Captures of compact objects by central MBHs → study central MBH environments in normal galaxies in local universe*



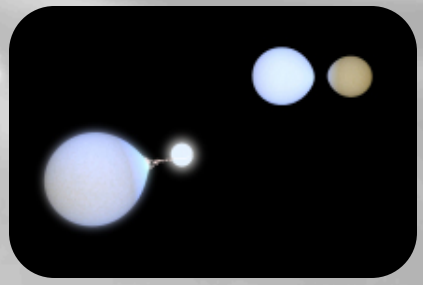
- *How did the universe begin?*
  - *Cosmic strings, relic GWs…..*



FRONTIERS OF KNOWLEDGE

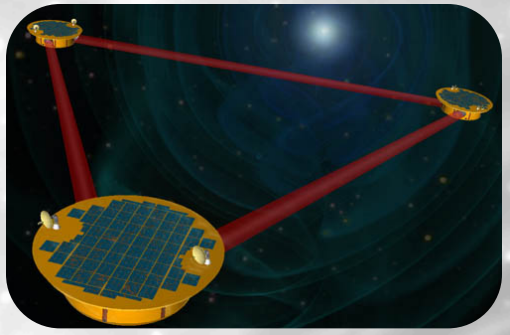
- *Why is the universe accelerating?*
  - *Using MBH mergers out to z = 3, in 3 years LISA can determine dark energy parameter "w" to ±(2 -4)% using statistical methods and without EM counterparts (Petiteau, Babak, Sesana 2011)*

- *What controls the mass, radius, and spin of compact stellar remnants?*
  - *LISA will find ~ 20,000 compact binaries, mostly in the Galaxy*
  - *At least ~ 100 will also be observed optically*



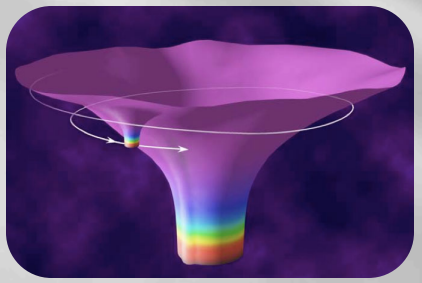
DISCOVERY

- *Gravitational wave astronomy*
  - *LISA will open an exceptionally rich portion of the GW spectrum*



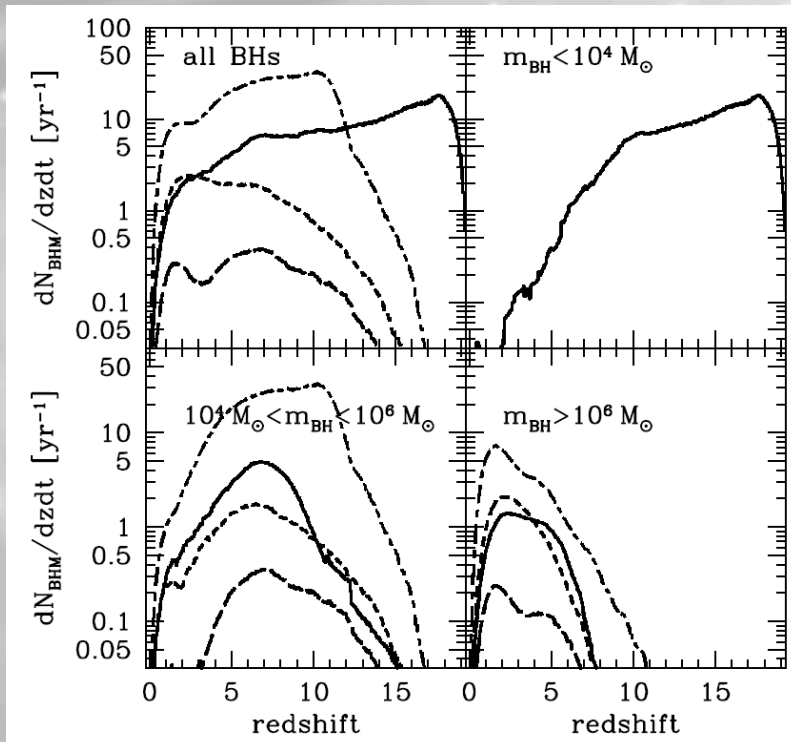
- *The epoch of reionization*
  - *MBH mergers in the high redshift universe*

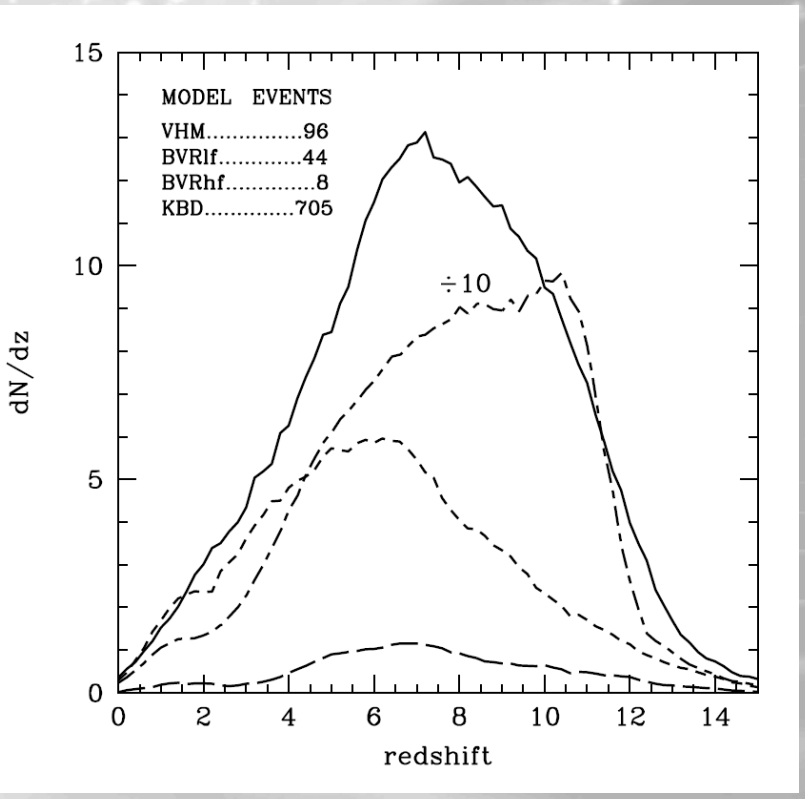
- *Time-domain astronomy*
  - *Long-lived GW signals*
  - *Advance notice of mergers*



MBH mergers at high redshifts…

- **MBH mergers are proxies for galaxy mergers, trace structure formation**
- **LISA detections of MBH mergers will discriminate between models of structure formation *(Sesana, Volonteri, Haardt 2009)***





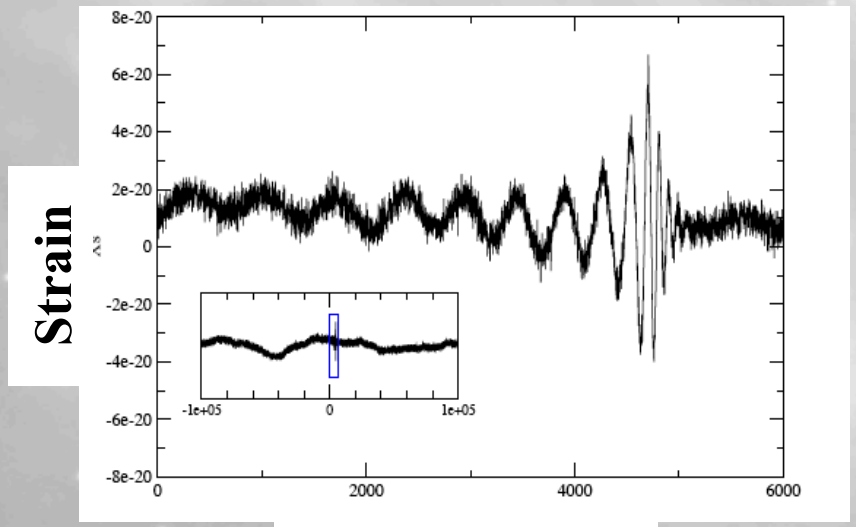
# of mergers observed per year by LISA, for various $m_{BH} = m_1 + m_2$, for different stucture formation models

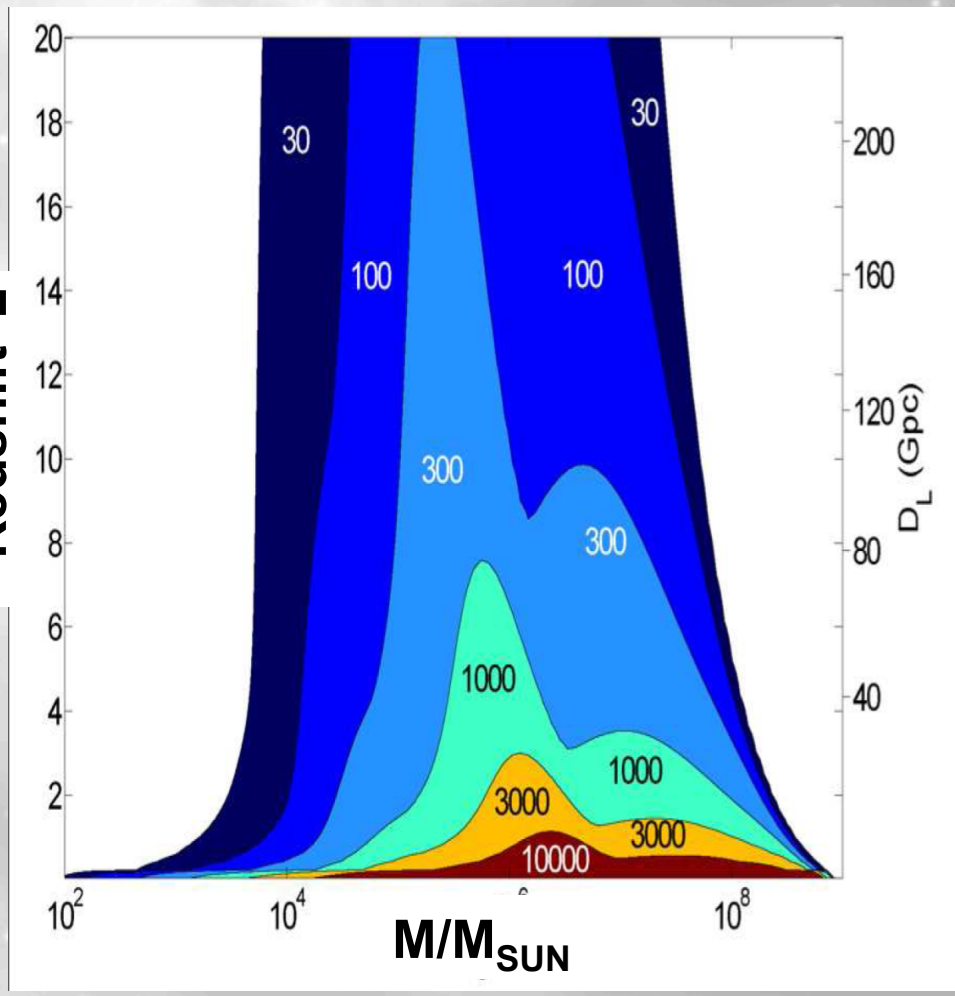
Redshift distribution of MBH mergers observed in 3 years with S/N > 5 for various struc formation models

LISA will detect MBH mergers at high SNR…..

- Masses & spins to very high precision < 1%
- Luminosity distances to good precision ~ 10%

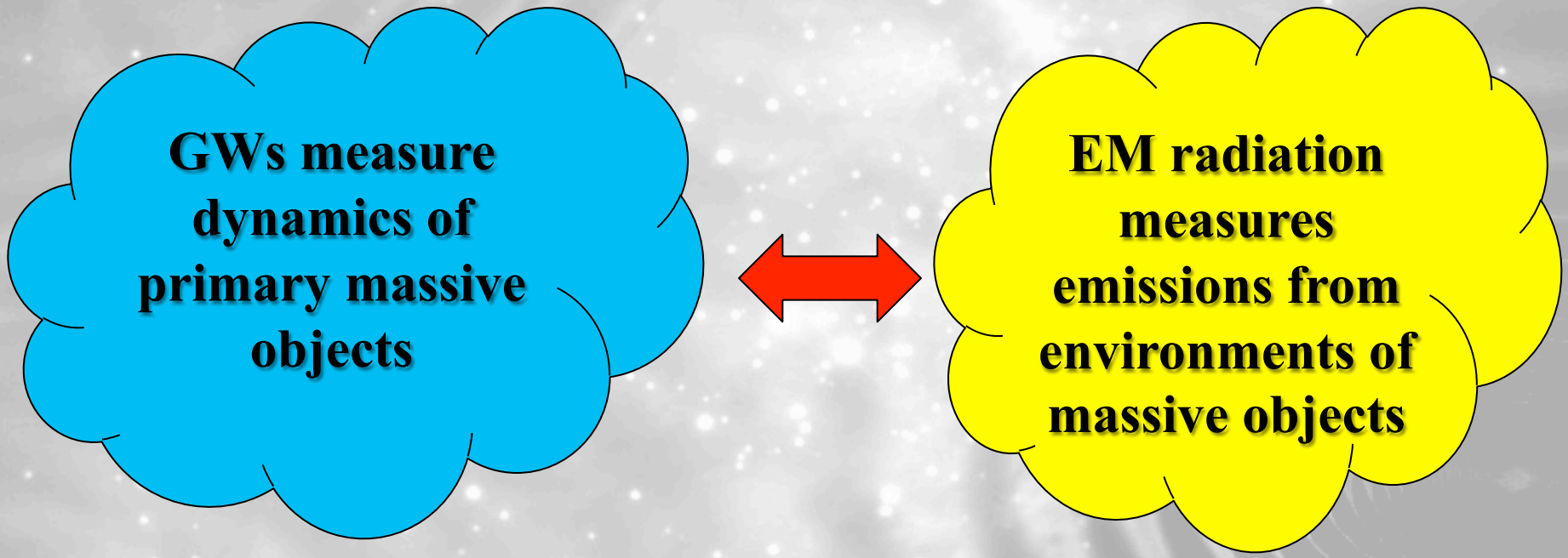
Simulated LISA data stream from merger of two $10^5 M_\odot$ BHs, *with instrument noise*





Amplitude S/N Contours (optimal case)

Complementary observations….



- **Bulk motion dynamics**
- **Luminosity distance**
- **Progenitor masses, spins…...**

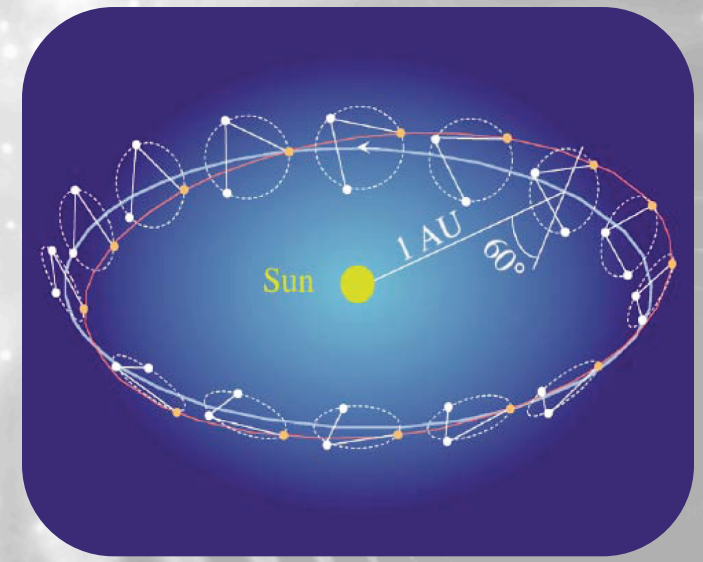
- **Host galaxy**
- **Gas environment**
- **Red shift…..**

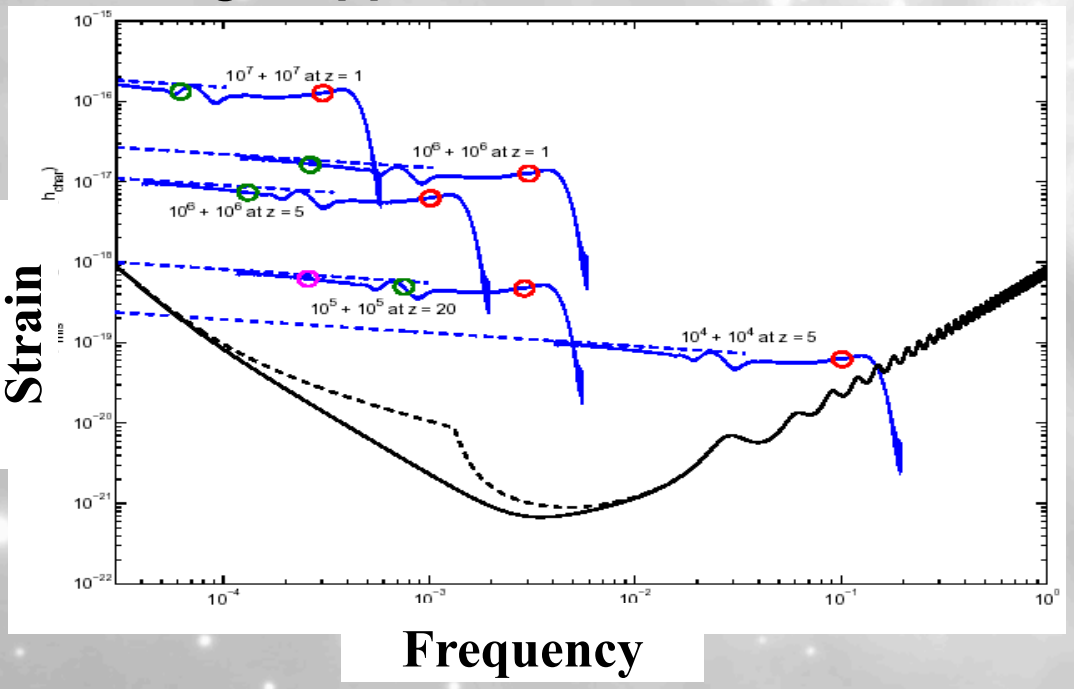
Multi-messenger astronomy

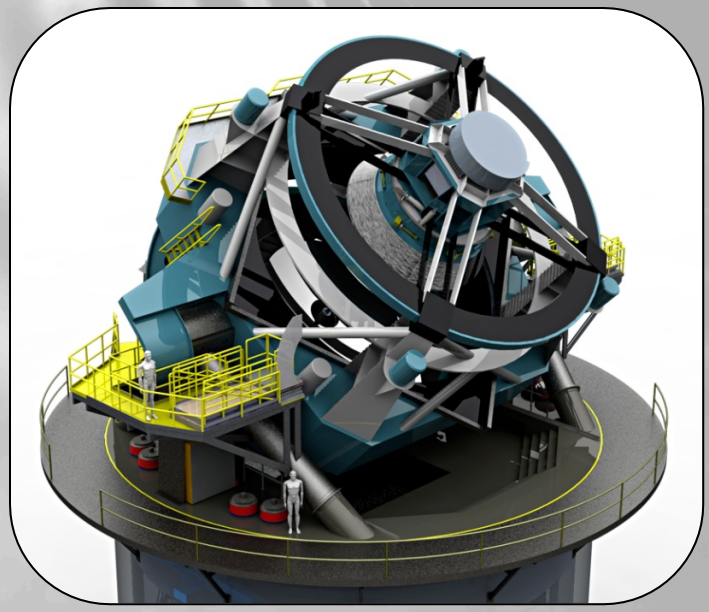
opens exciting new possibilities for discovery….

Multi-messenger observations of MBH mergers

- Coalescing MBH binaries evolve upwards in frequency ("chirp") through LISA band over ~months – year(s)
- LISA will give ~few-degree error boxes and time of merger ***months*** in advance
- Error box dimensions shrink to ~ 10s of arcmin or smaller as S/N increases and merger approaches



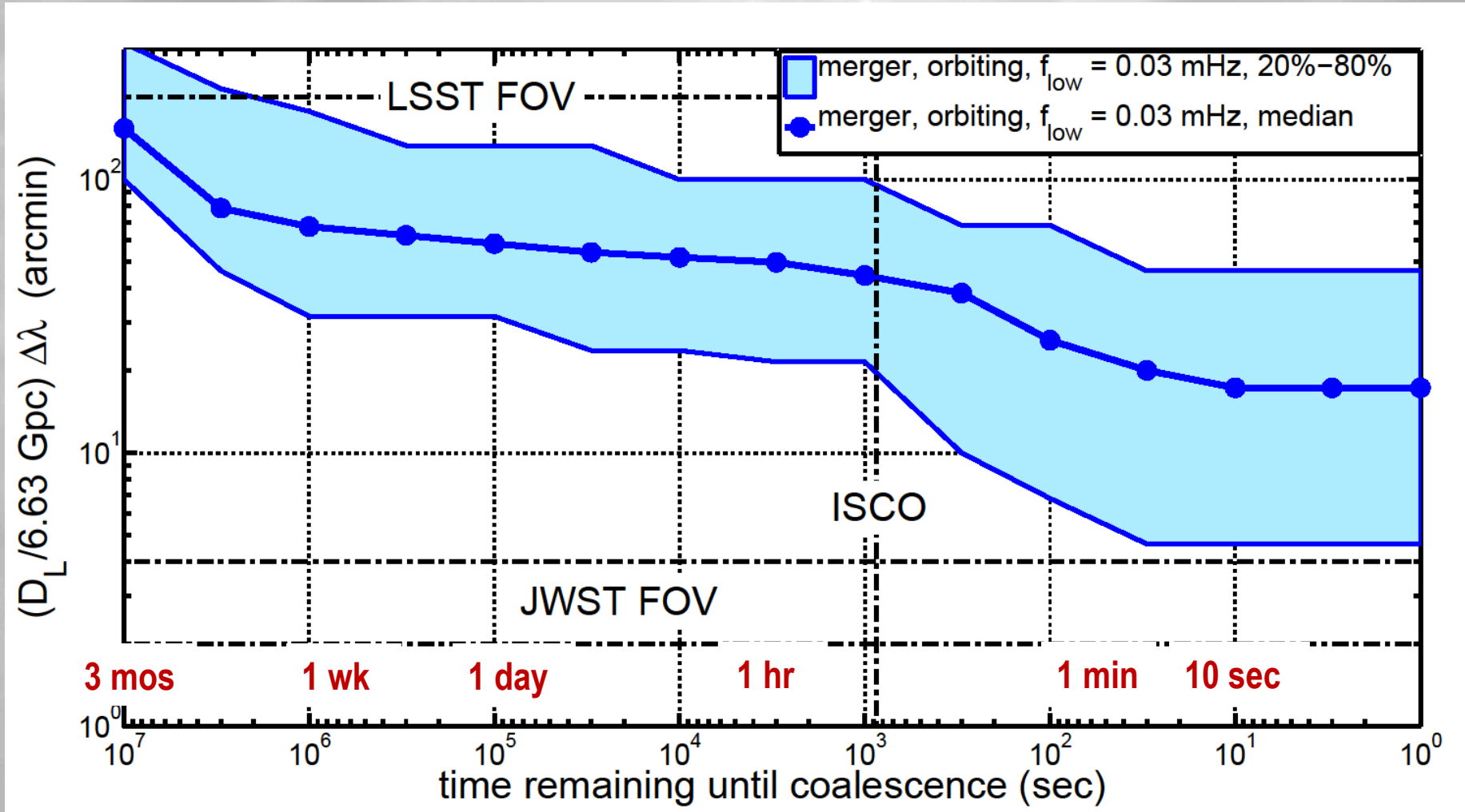




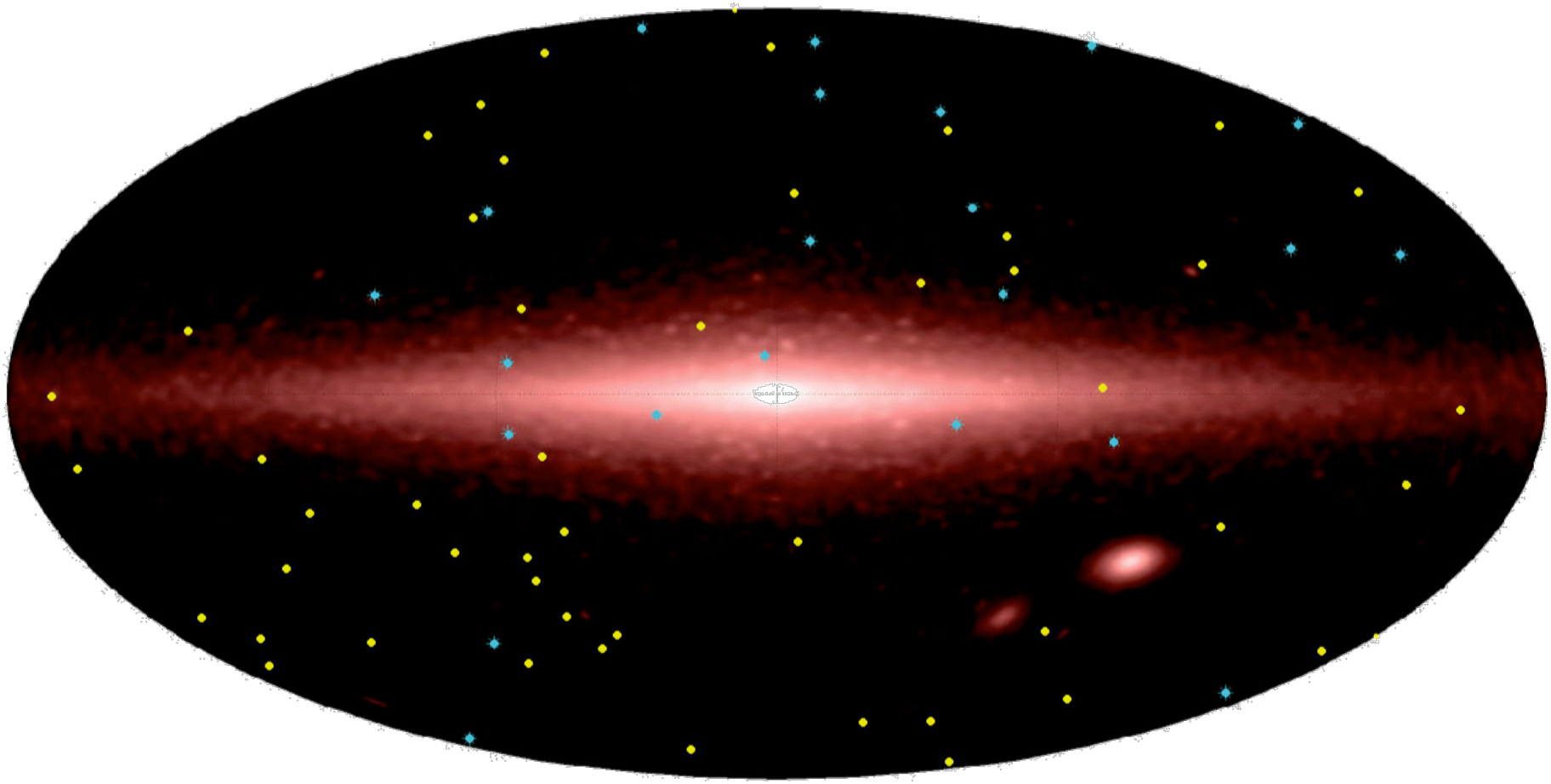
Area between signal (blue) & noise (black) gives SNR

Observing a MBH merger with LISA…

- **2 x 10^6 M_{SUN} MBH binary at z = 1**
- **Full waveform including merger, with LISA's motion**



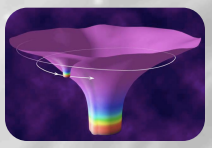
Simulation of the Gravitational Wave Sky….

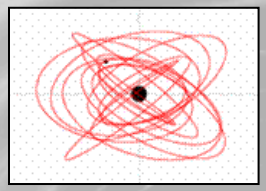


- ***LISA**: Compact binaries, MBH mergers, BH captures…*
- ***Ground-based**: BH & NS mergers, supernovae…*
- ***Pulsar Timing** (not shown): GW backgrounds (MBH binaries, cosmological….*

GWs add a new dimension to studying the universe…

- GWs have many analogies to sound: waves of spacetime
- Detectors are our "microphones"
  - 1D response, not an image.
  - Convert to sound → *you can listen to GWs*





- LISA will add the audio dimension to our ability to monitor the dynamical universe:
  the soundtrack of the cosmos
- So…*imagine*….

(AEI/Milde Science Comm/getye1/Novak/ Willmann)