mHz GW Science as a Function of Sensitivity

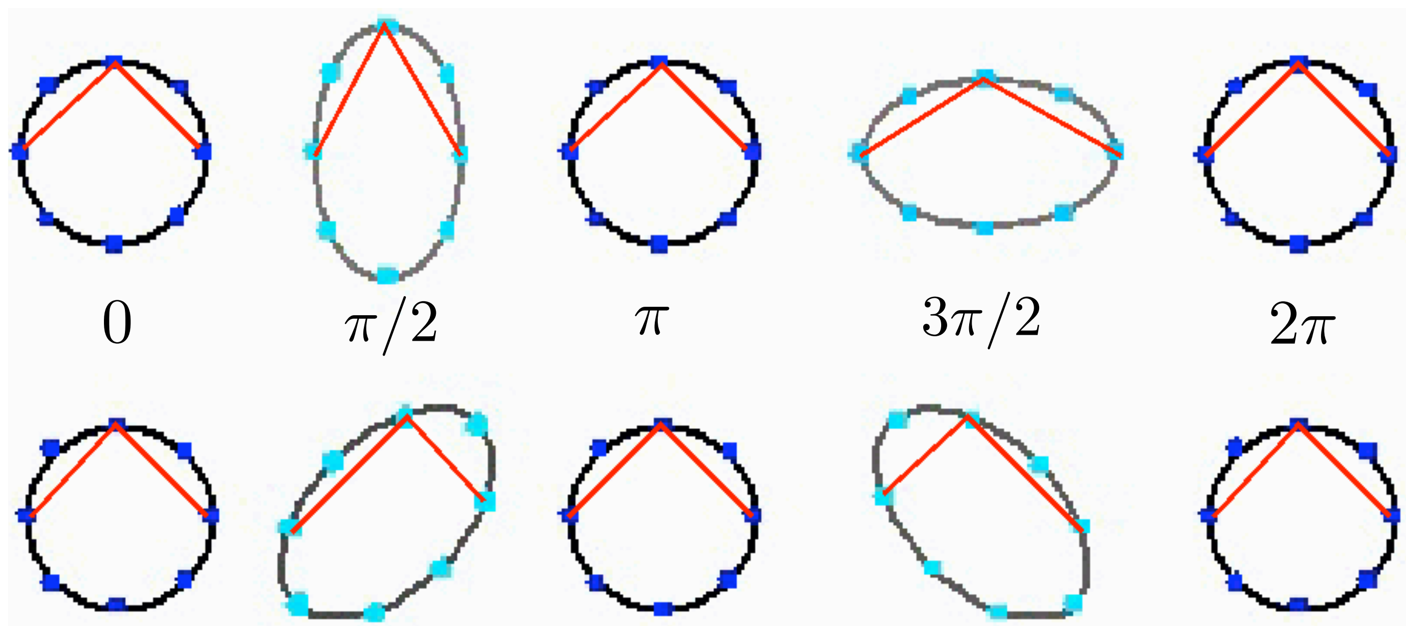
Tyson B. Littenberg
(UMD/GSFC)

Gravitational Waves 101

h_+

φ

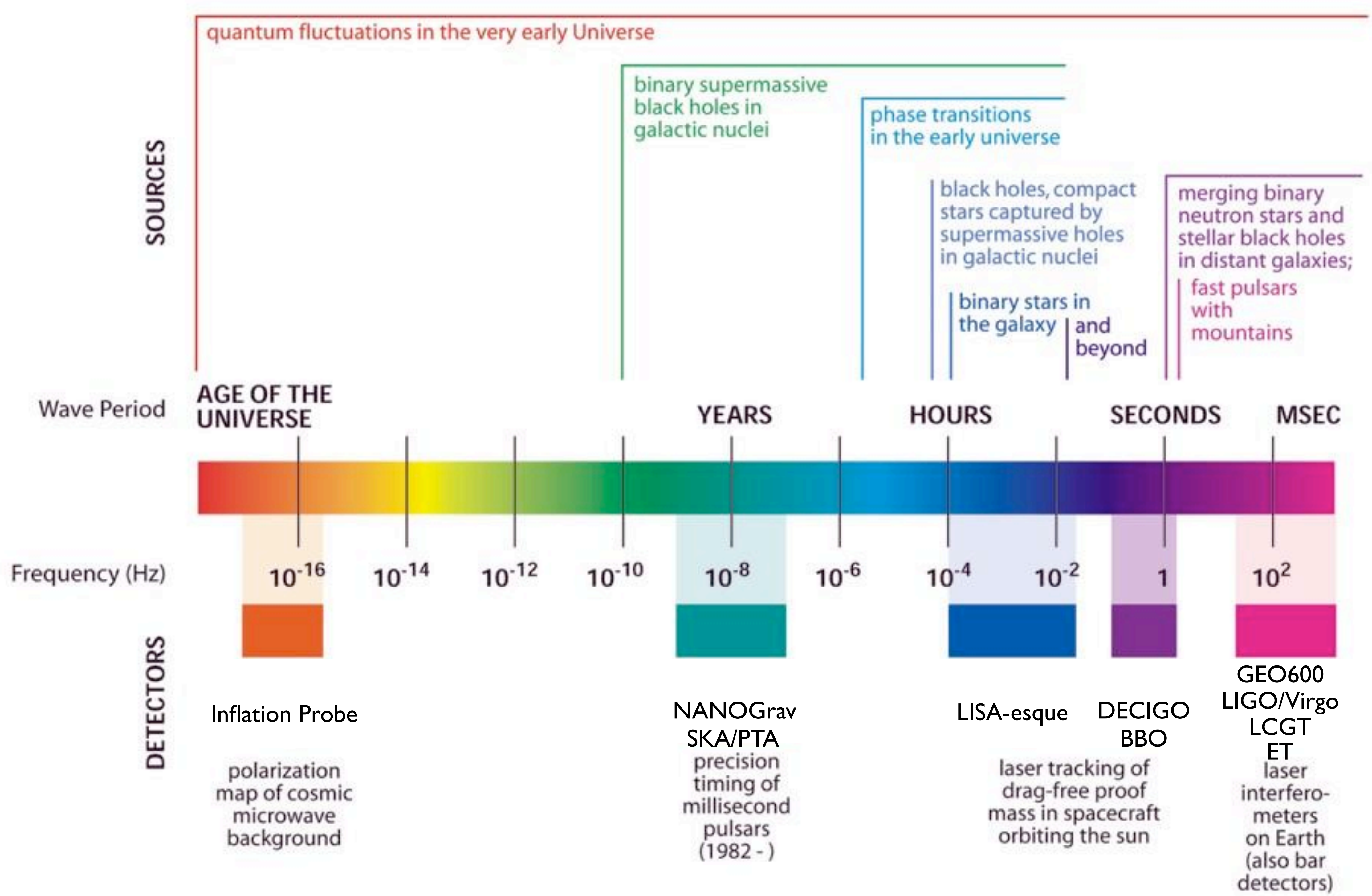
$h_\times$



$$\frac{\delta L}{L} \sim 10^{-21}$$

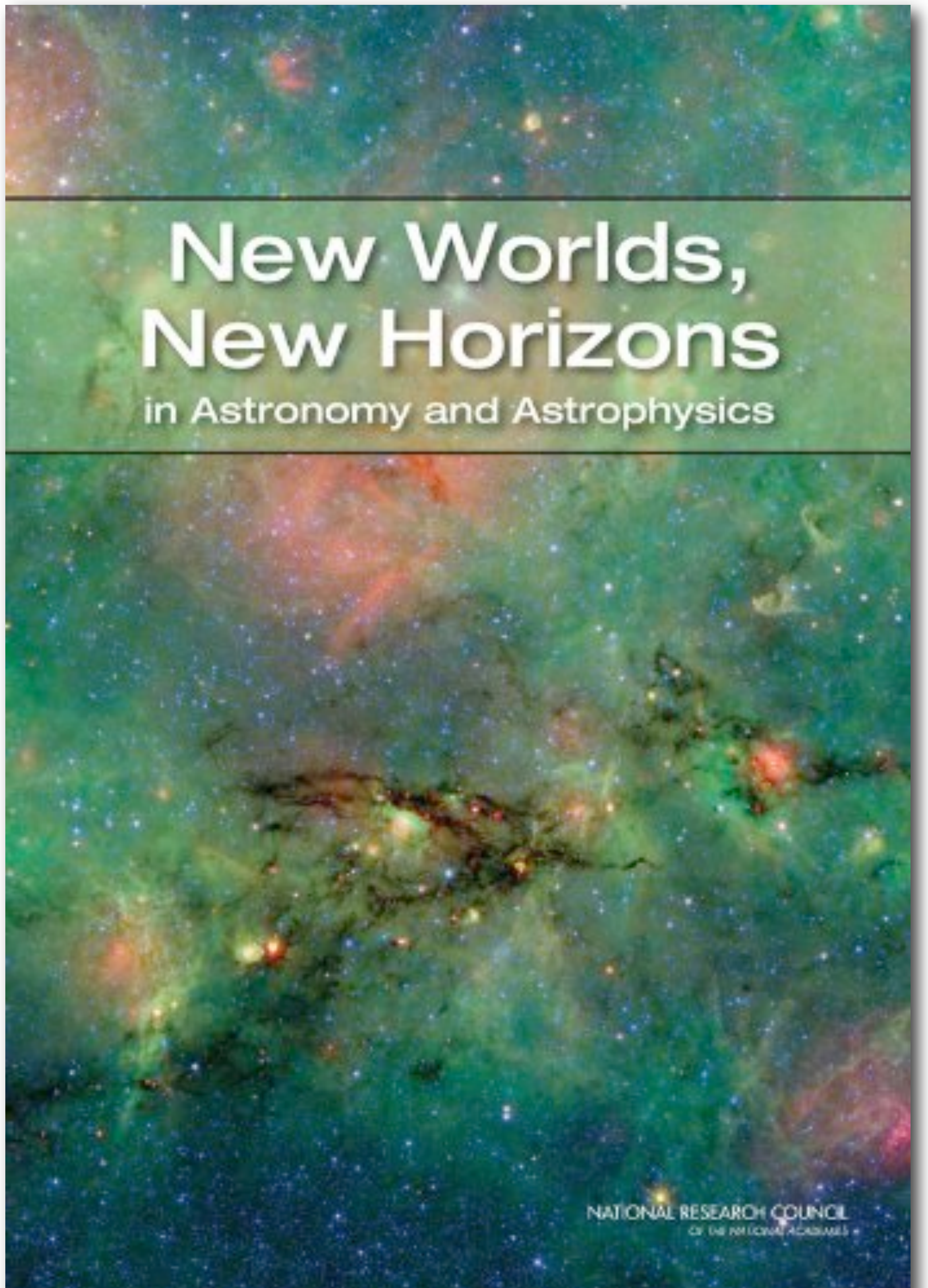
Gravitational wave detection is "big science"

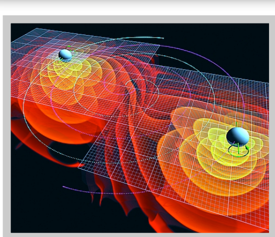
GW Sources

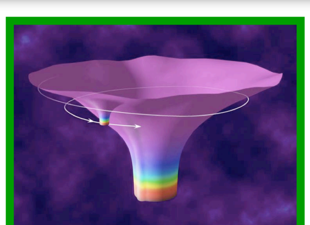


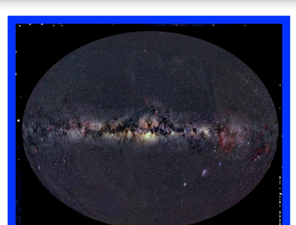
quantum fluctuations in the very early Universe
binary supermassive black holes in galactic nuclei
phase transitions in the early universe
black holes, compact stars captured by supermassive holes in galactic nuclei
binary stars in the galaxy
and beyond
merging binary neutron stars and stellar black holes in distant galaxies;
fast pulsars with mountains
SOURCES
Wave Period
AGE OF THE UNIVERSE
YEARS
HOURS
SECONDS
MSEC
Frequency (Hz)
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
1
10^{2}
DETECTORS
Inflation Probe
polarization map of cosmic microwave background
NANOGrav
SKA/PTA
precision timing of millisecond pulsars (1982 -)
LISA-esque
laser tracking of drag-free proof mass in spacecraft orbiting the sun
DECIGO
BBO
GEO600
LIGO/Virgo
LCGT
ET
laser interfero- meters on Earth (also bar detectors)

mHz GW Science Goals

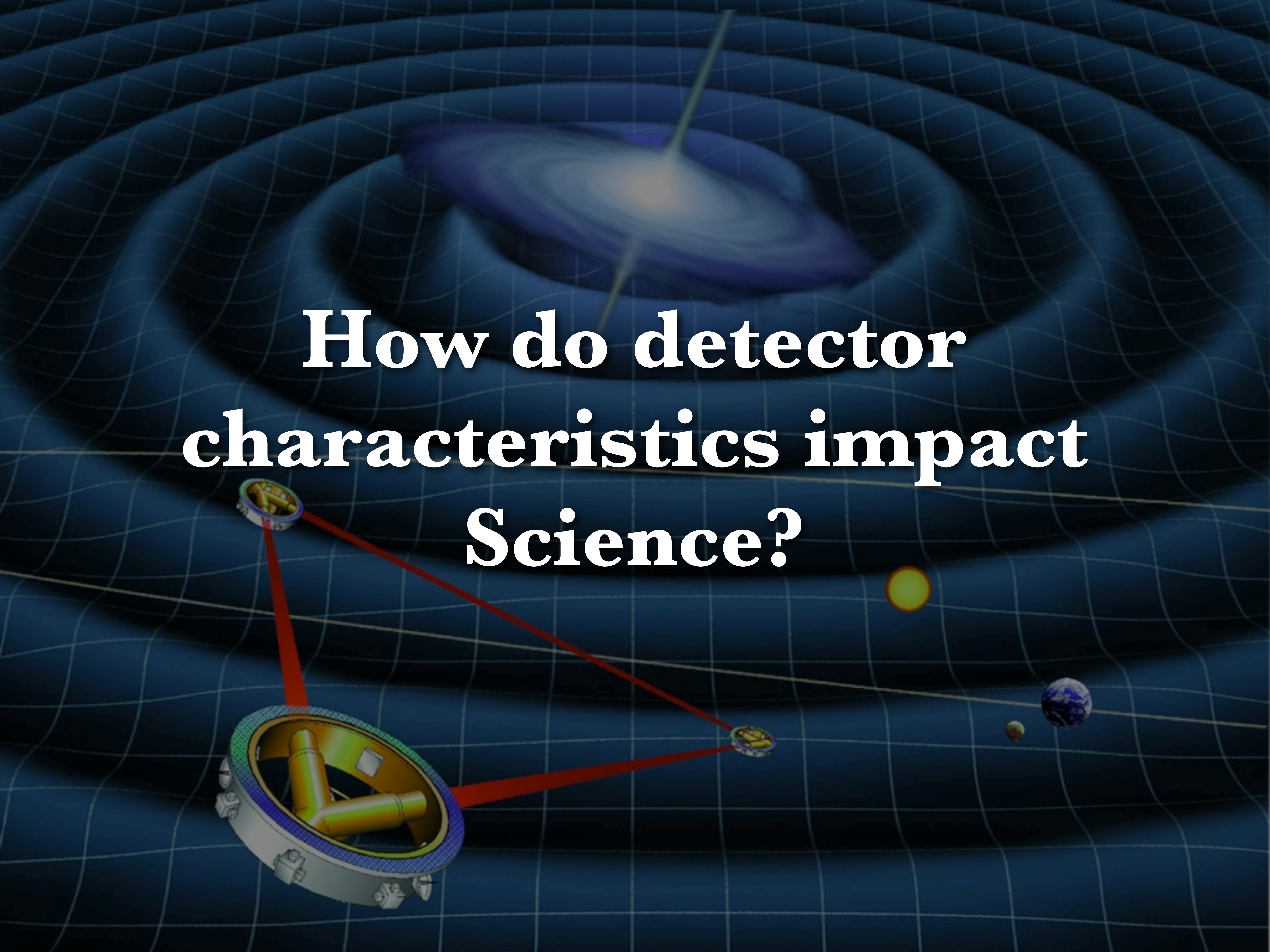






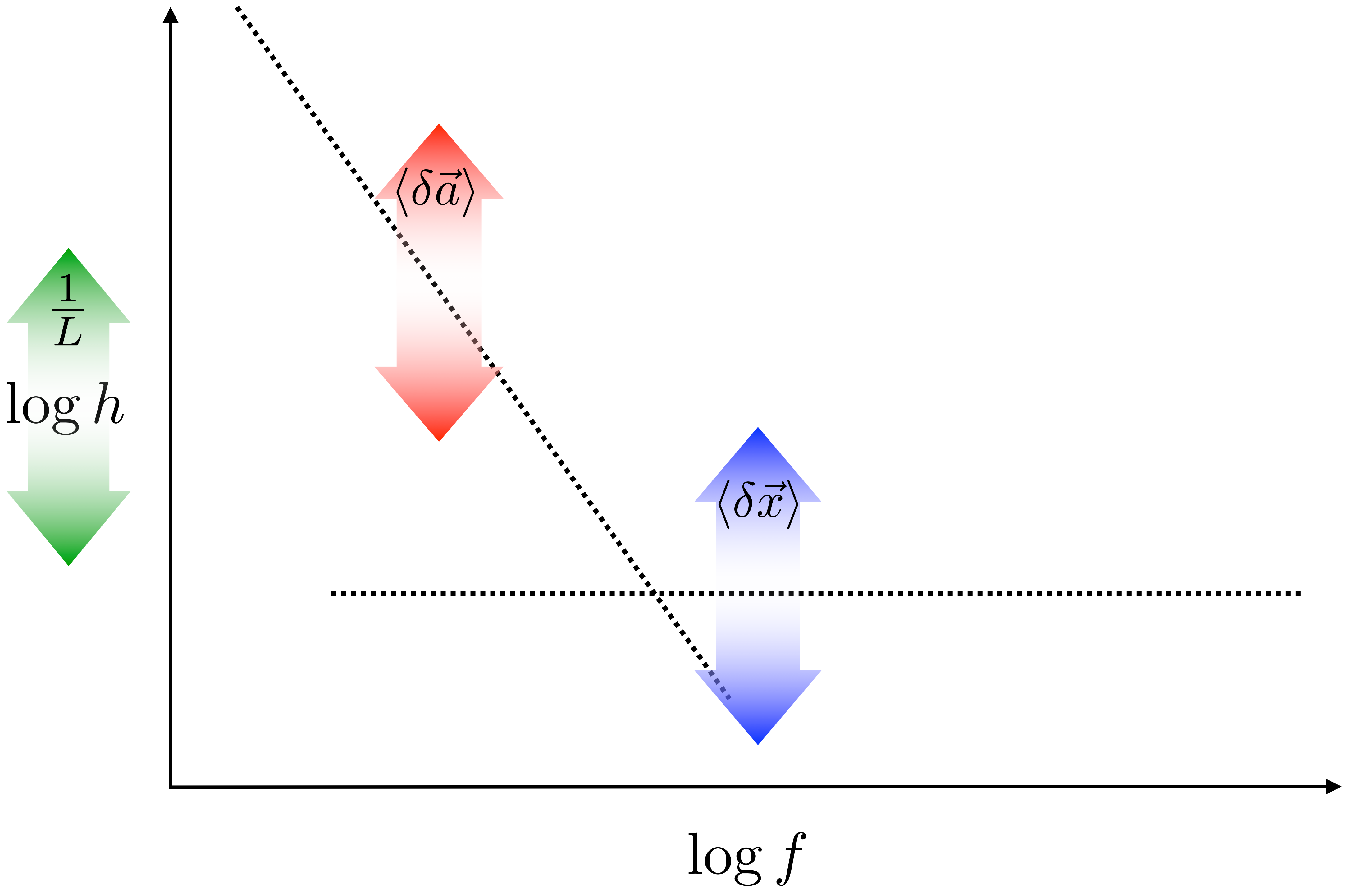


- Understanding the formation history of the Universe
  - Measure massive black hole *masses* and *spins* to constrain formation/growth models
- Confronting GR with measurement
  - Detecting EMRIs = measuring the BHs metric.
  - Does NR correctly predict the strong-field dynamics of BH-BH mergers?
  - Other (WDs, Additional polarization modes, ...)
- Opening unexplored Discovery space
  - GW themselves!
  - Stochastic background
  - Cosmic strings
  - etc...

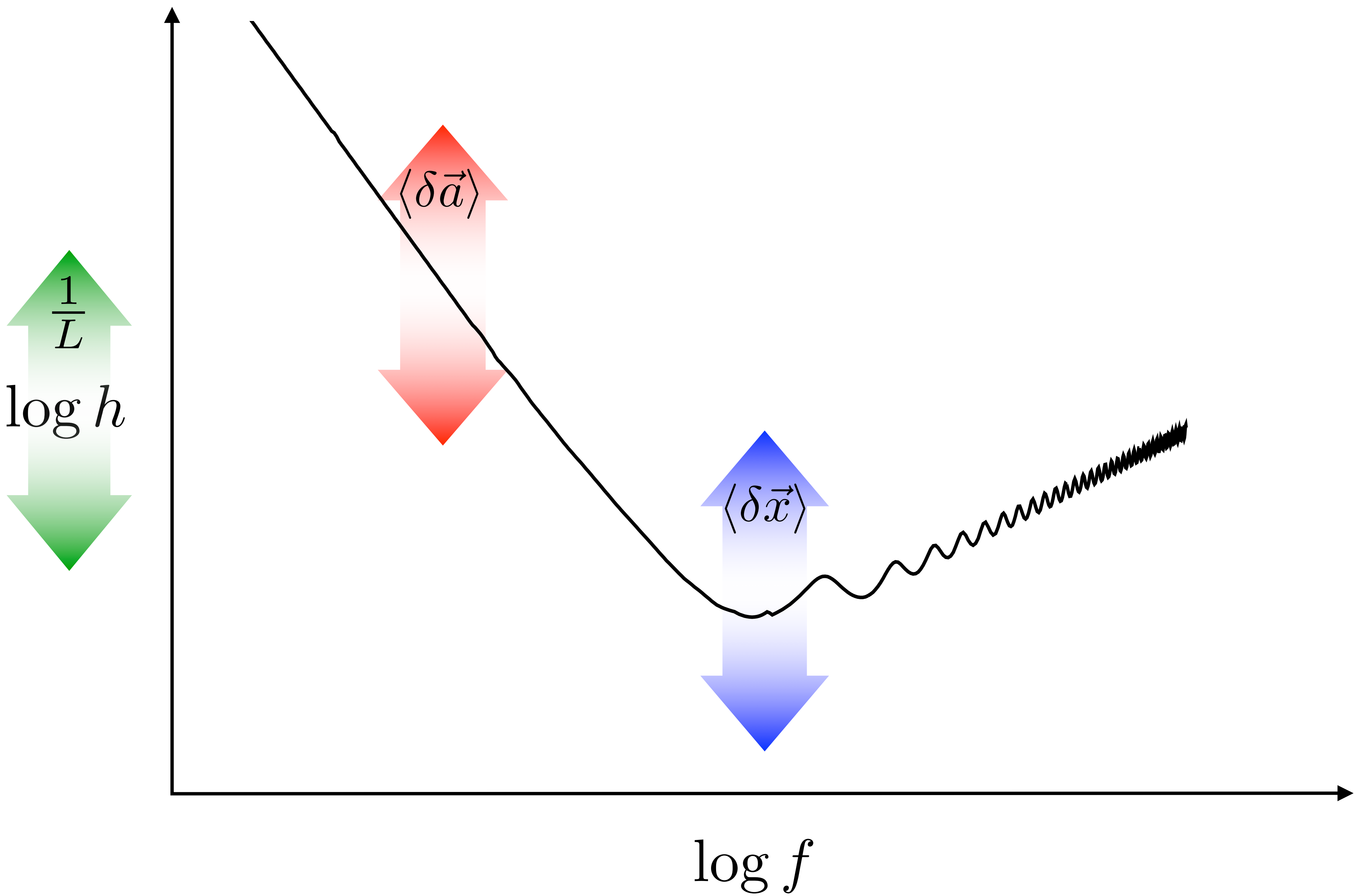


How do detector characteristics impact Science?

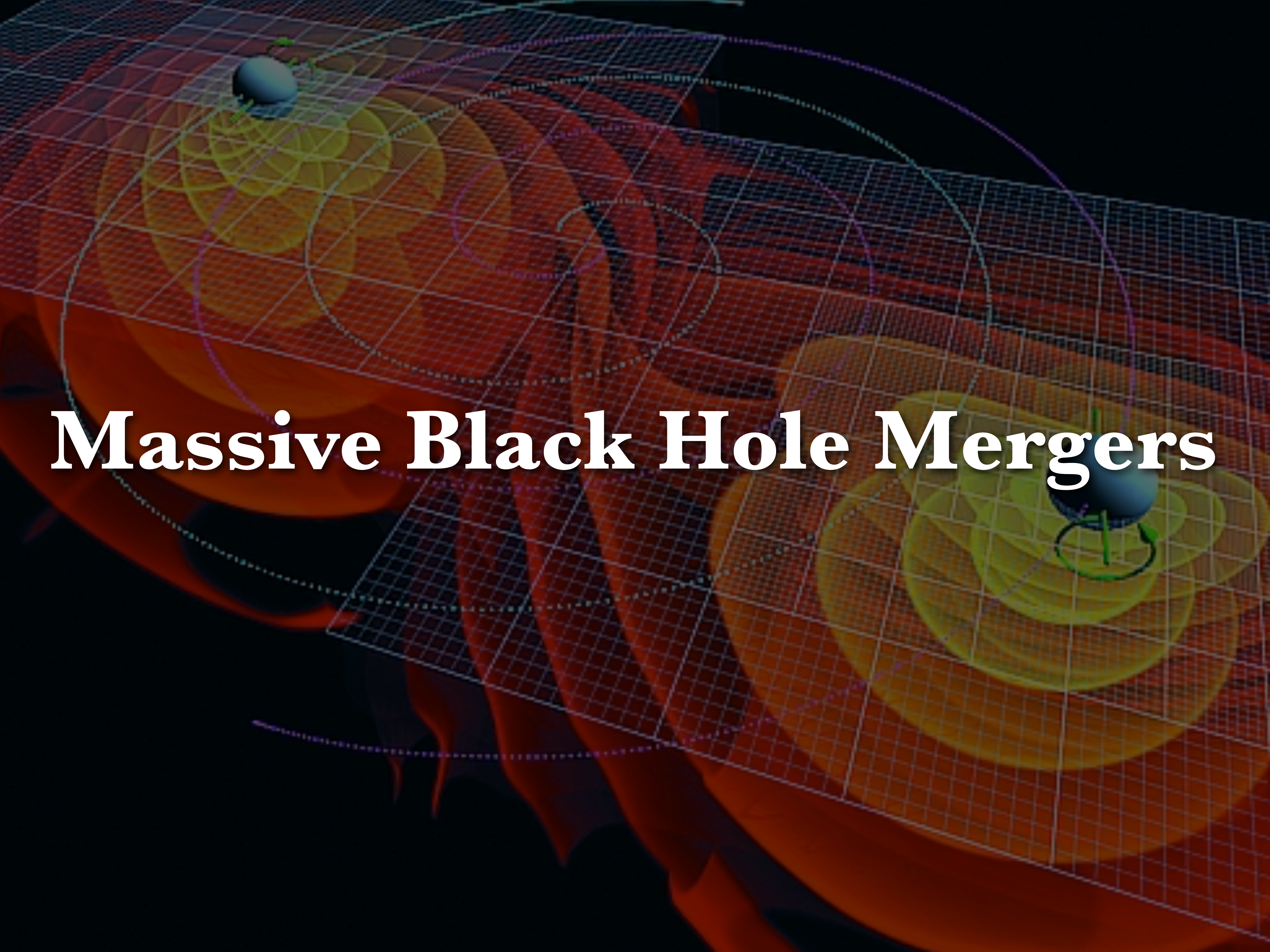
GW Detector Noise Curves



GW Detector ~~Noise~~ Sensitivity Curves

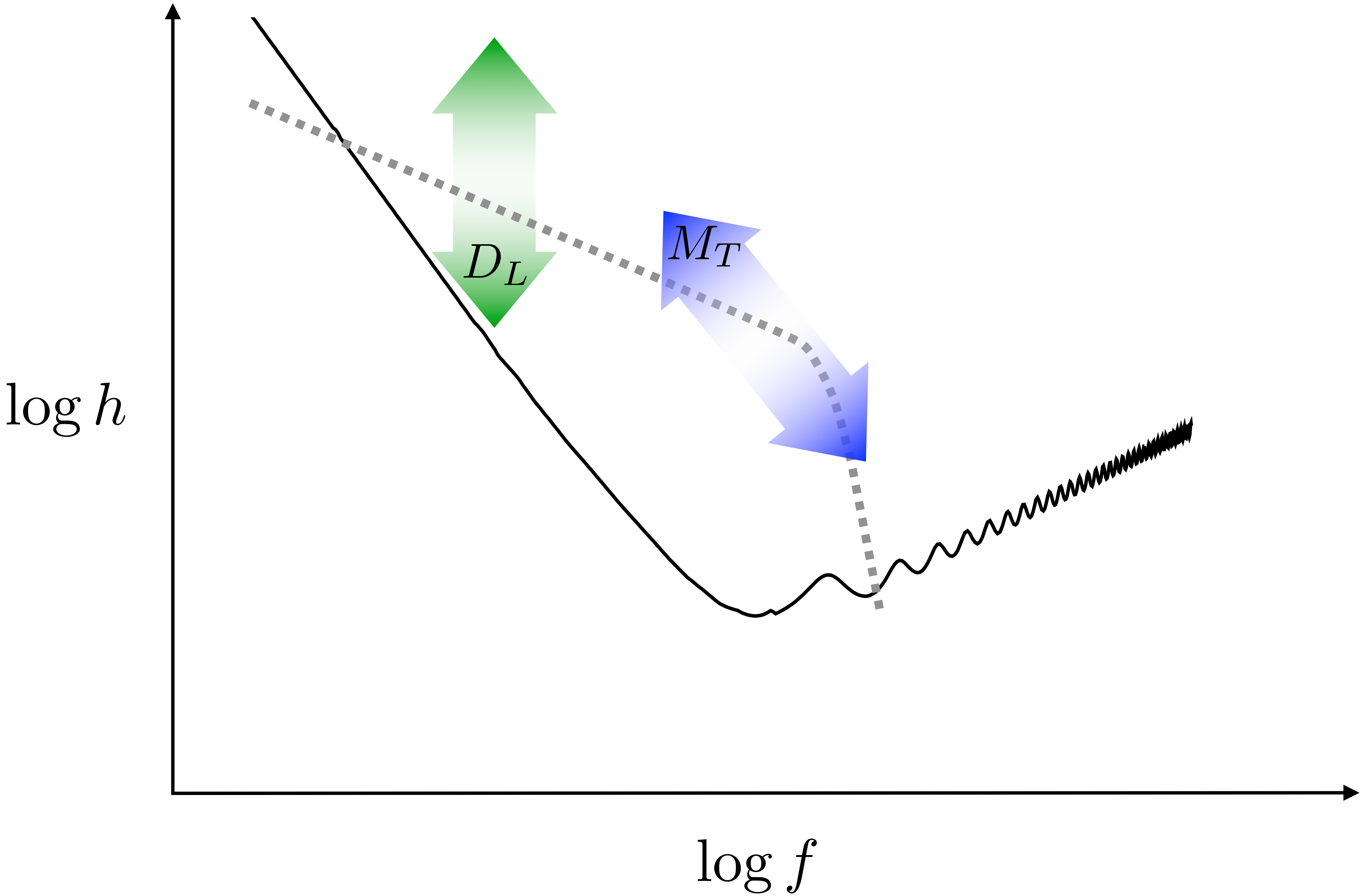


Massive Black Hole Mergers



Science: Massive Black Hole Mergers

NWNH: ***Measurements of BH mass and spin will be important for understanding the significance of mergers in the building of galaxies*.**



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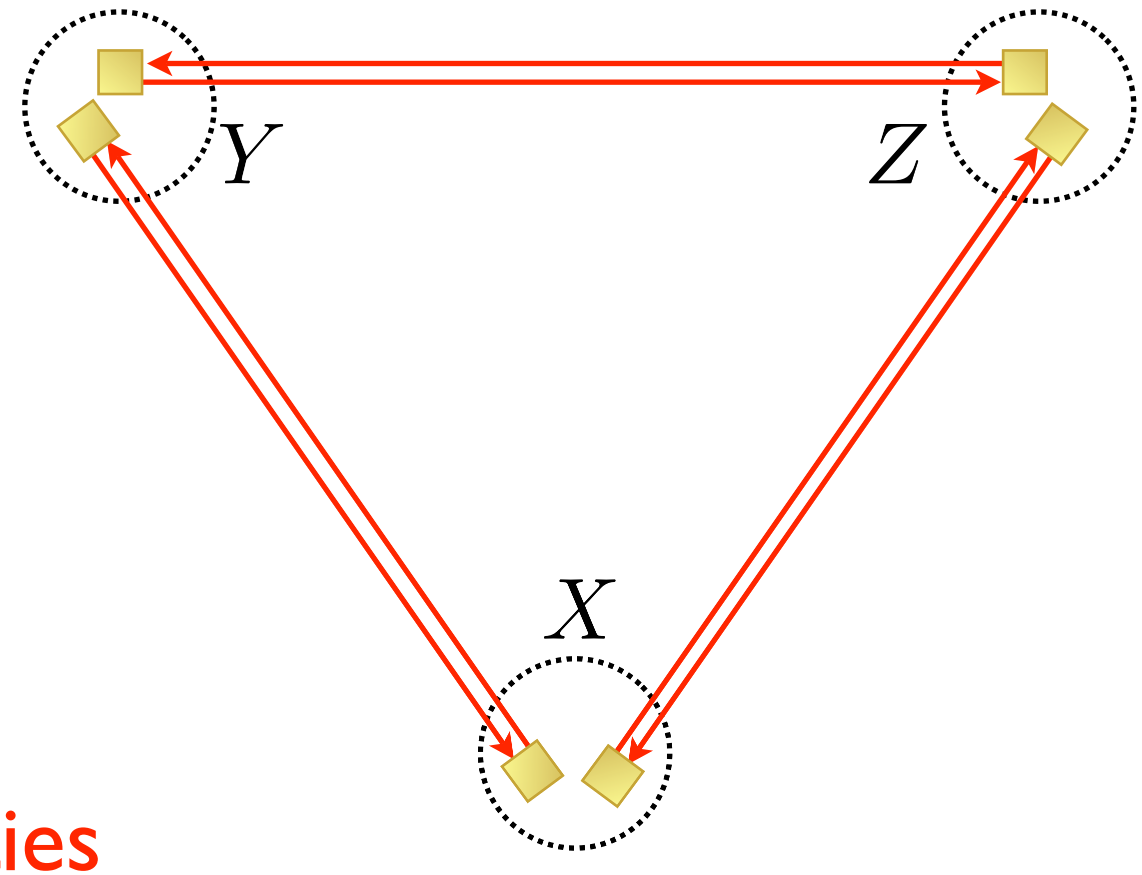
	LISA
Arm length (km)	**5×10^{6}**
Displacement (m $Hz^{-1/2}$)	**8×10^{-12}**
Acceleration (m/s^2 $Hz^{-1/2}$)	**3×10^{-15}**



*Review of LISA's capabilities

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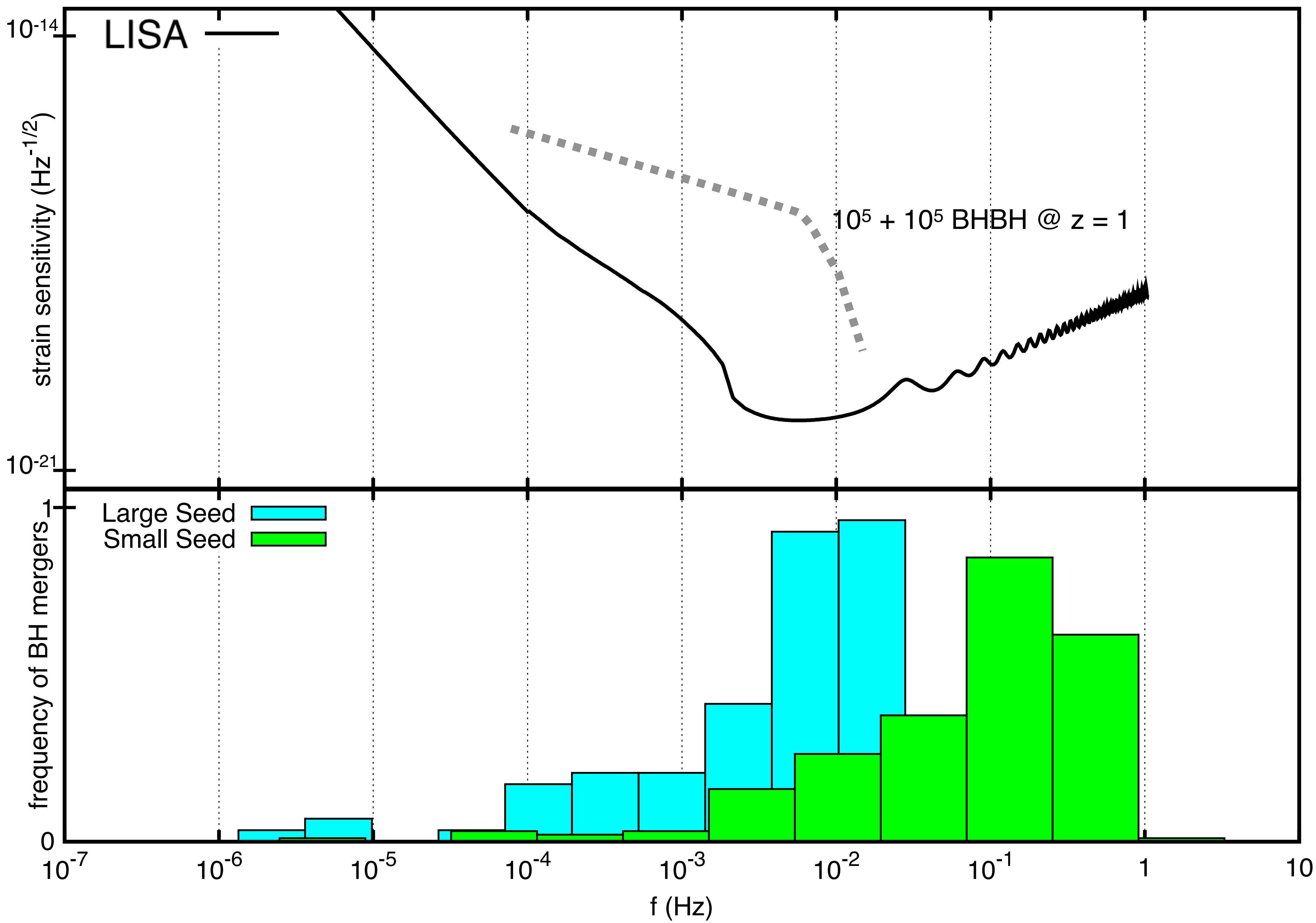

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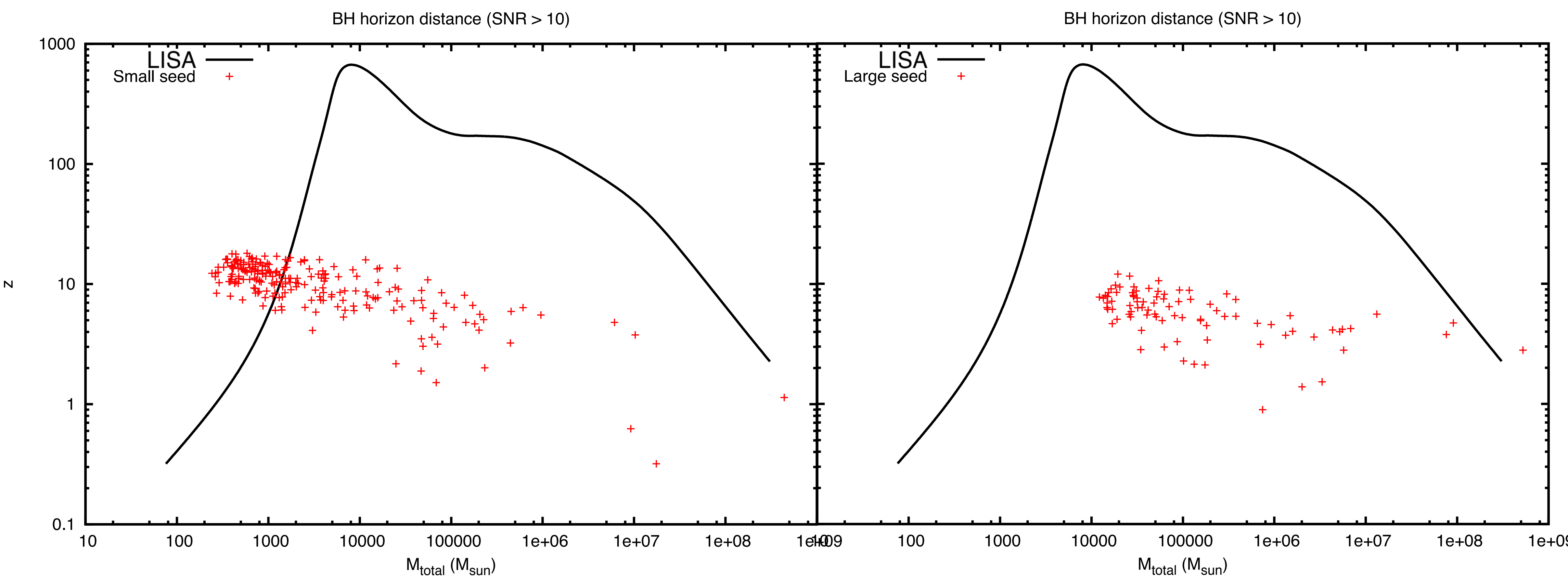

Science: Massive Black Hole Mergers

NWNH: ***Measurements of BH mass and spin will be important for understanding the significance of mergers in the building of galaxies*.**

	LISA	Minimum MBH Sensitivity
Arm length (km)	5×10^{6}	**5×10^{4}**
Displacement (m $Hz^{-1/2}$)	8×10^{-12}	**8×10^{-11}**
Acceleration (m/s^2 $Hz^{-1/2}$)	3×10^{-15}	**3×10^{-14}**

*Relax each of the key requirements to locate the minimum BH science

Science: Massive Black Hole Mergers

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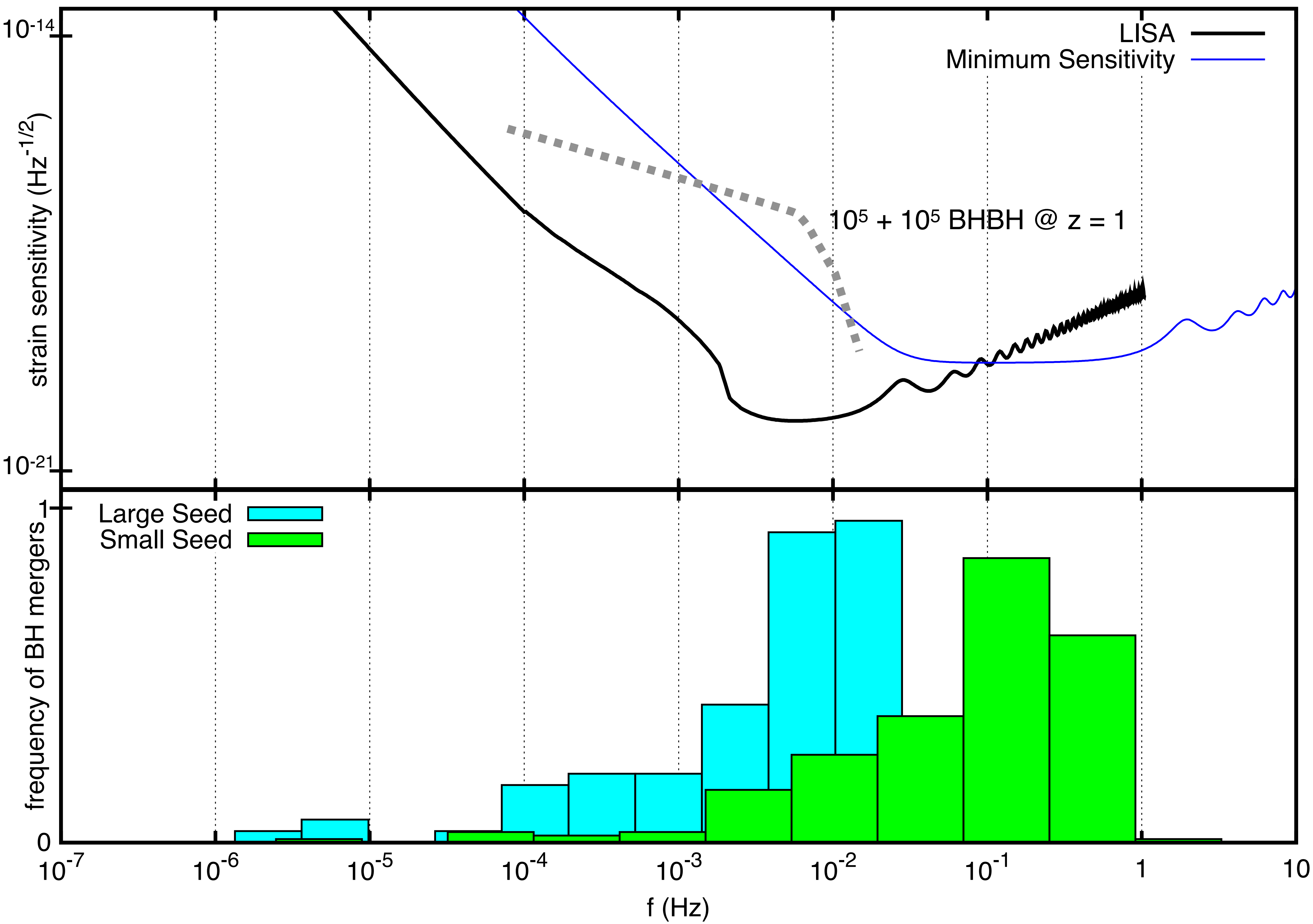

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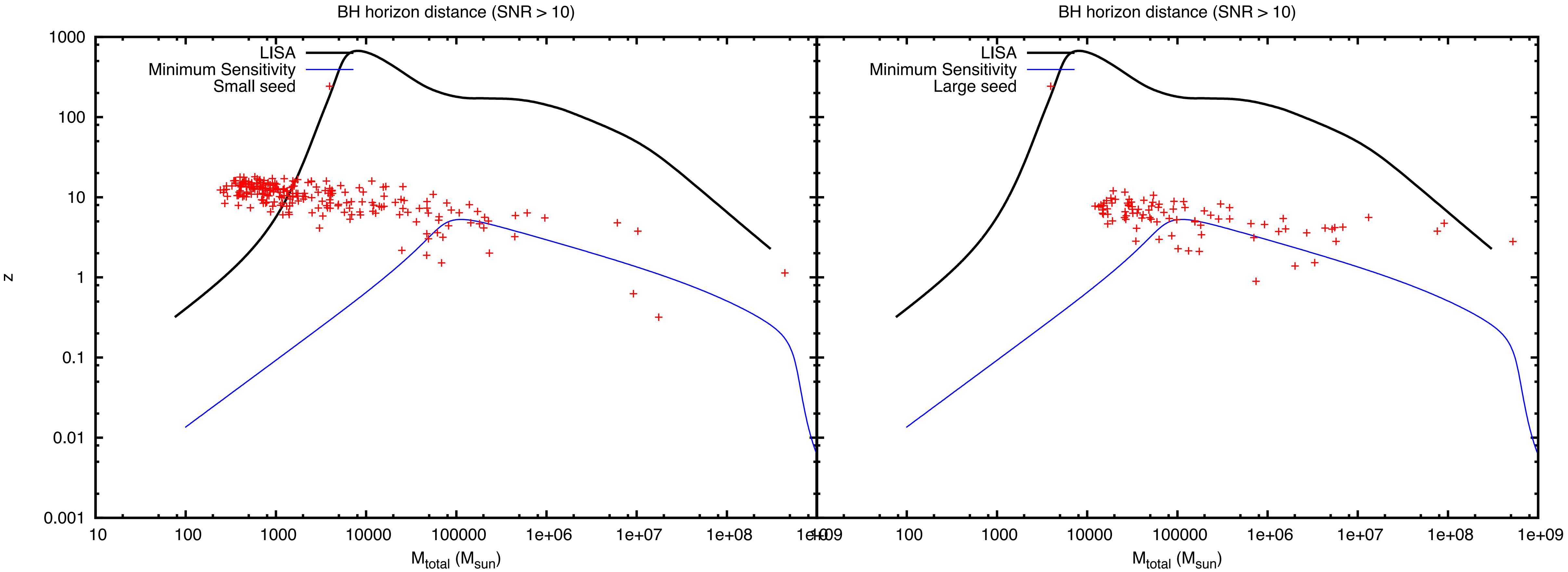

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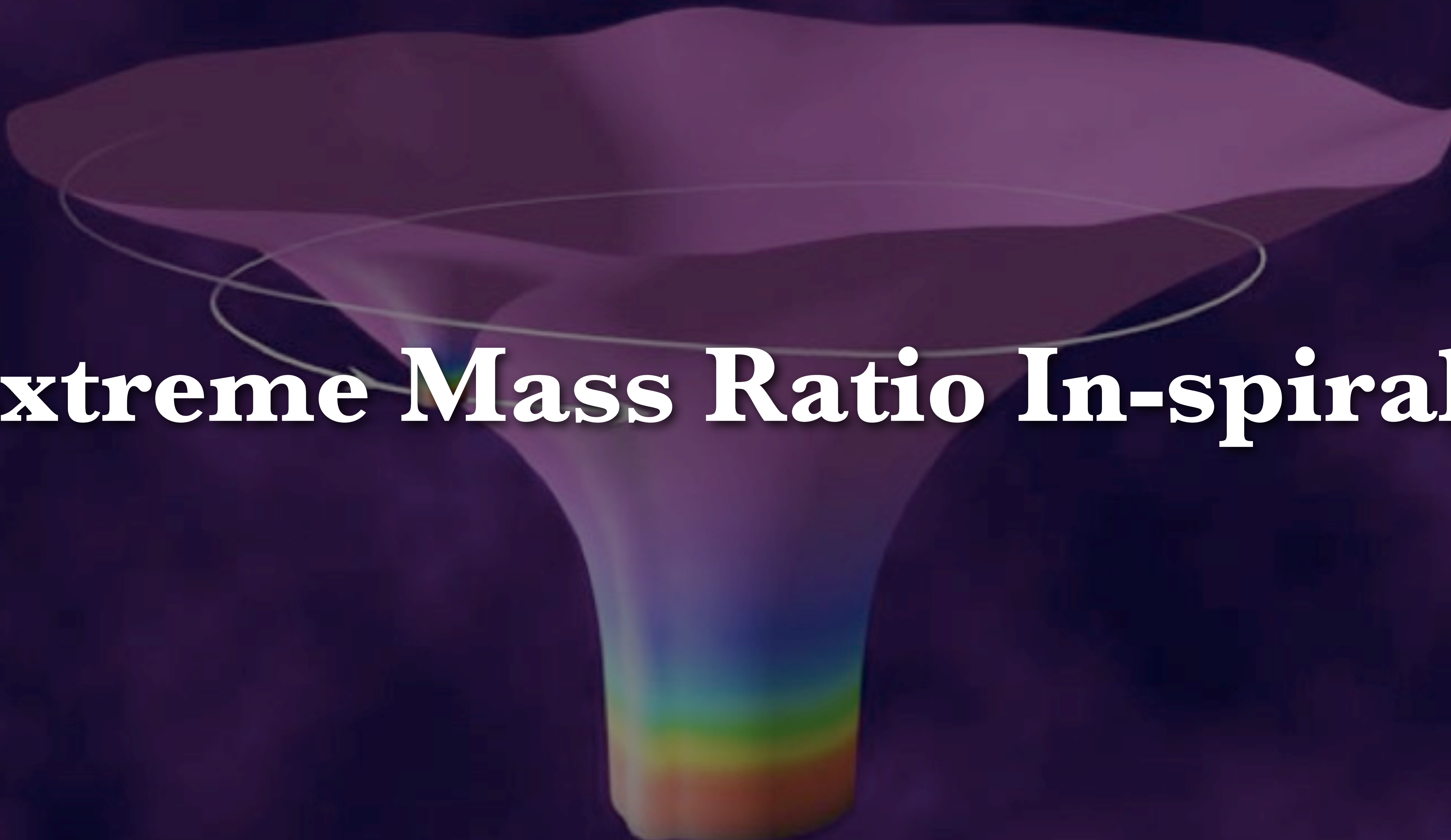
Displacement (m $Hz^{-1/2}$)	8×10^{-12}	8×10^{-11}
Acceleration (m/s^2 $Hz^{-1/2}$)	3×10^{-15}	3×10^{-14}
MBH Rates (yr^{-1})	**40/20**	**5/5**

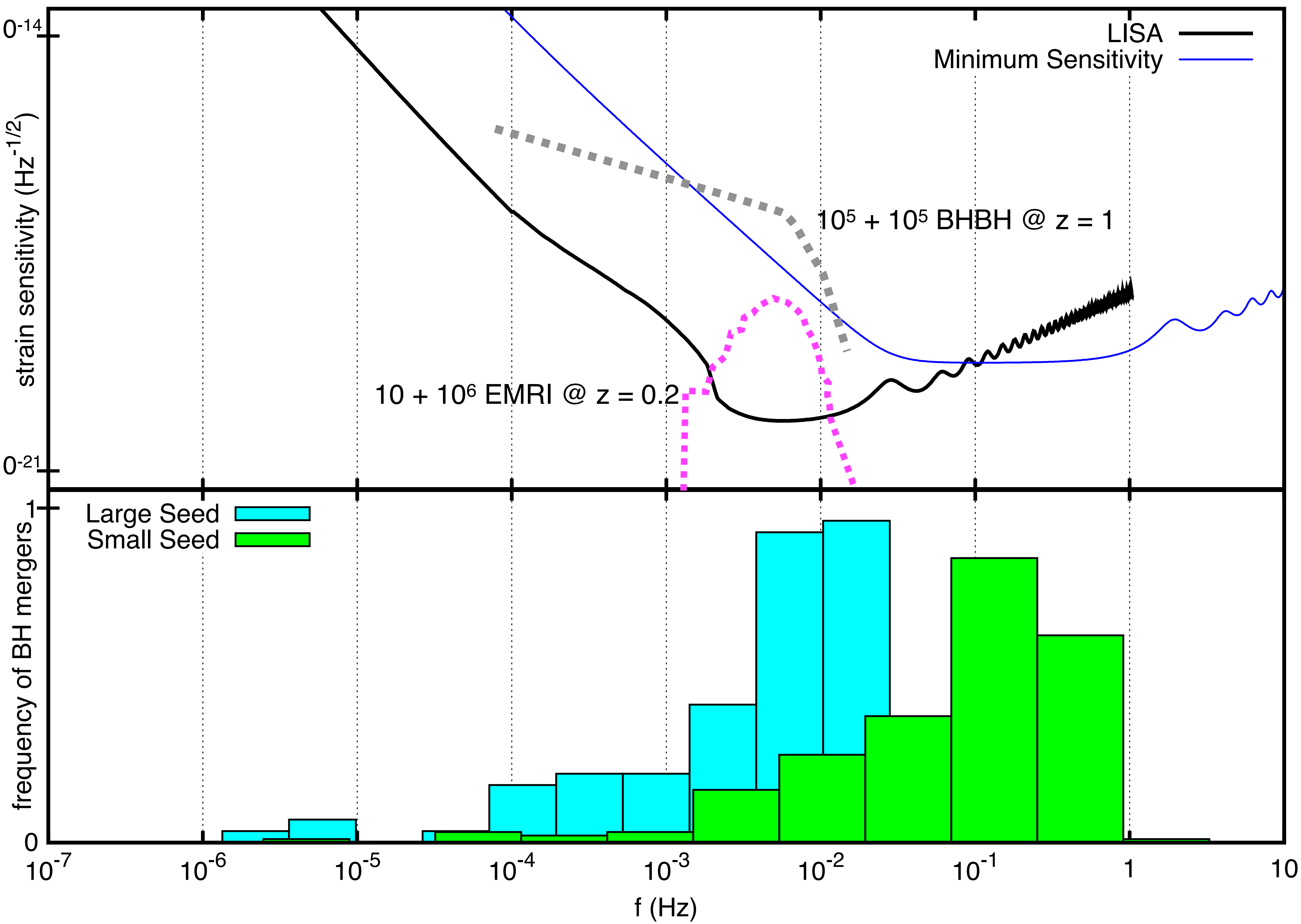
*Span of possible event rates
Quoted results are for (small/large) seeds

Extreme Mass Ratio In-spirals



Science: Extreme Mass Ratio Inspirals

NWNH: ***Detections of signals from EMRIs would provide exquisitely precise tests of Einstein's theory of gravity.***



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MBH Rates (yr^{-1})	40/20	5/5
EMRI Detections	**300**	**0**

-EMRI rates are *very* uncertain -- Factors of 10x are in play.
-# of detections assumes 2-year integration time.

Science: Extreme Mass Ratio Inspirals

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	LISA	Minimum MBH Sensitivity	Minimum EMRI Sensitivity
Arm length (km)	5×10^{6}	5×10^{4}	**1×10^{6}**
Displacement (m $Hz^{-1/2}$)	8×10^{-12}	8×10^{-11}	**8×10^{-12}**
Acceleration (m/s^2 $Hz^{-1/2}$)	3×10^{-15}	3×10^{-14}	**3×10^{-15}**
MBH Rates (yr^{-1})	40/20	5/5	
EMRI Detections	**300**	**0**	

-EMRI rates are *very* uncertain -- Factors of 10x are in play.
*Individual results may vary.
-# of detections assumes 2-year integration time.

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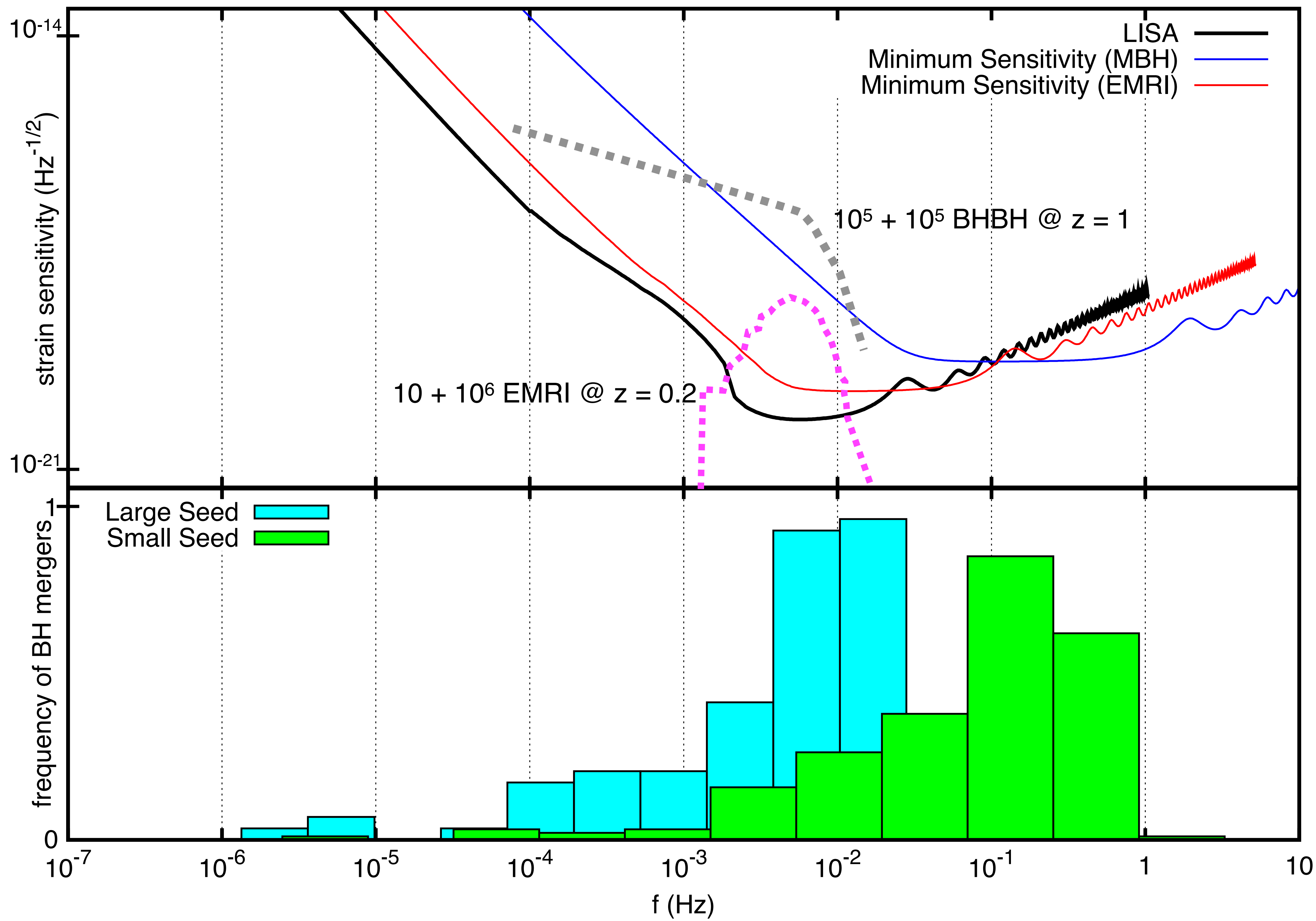

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Arm length (km)	5×10^6	5×10^4	1×10^6
Displacement (m $Hz^{-1/2}$)	8×10^{-12}	8×10^{-11}	8×10^{-12}
Acceleration (m/s^2 $Hz^{-1/2}$)	3×10^{-15}	3×10^{-14}	3×10^{-15}
MBH Rates (yr^{-1})	40/20	5/5	**20/20**
EMRI Detections	300	0	**10**

*Shrinking LISA by 5x puts us right on the edge of delivering EMRI science.

Galactic Binaries

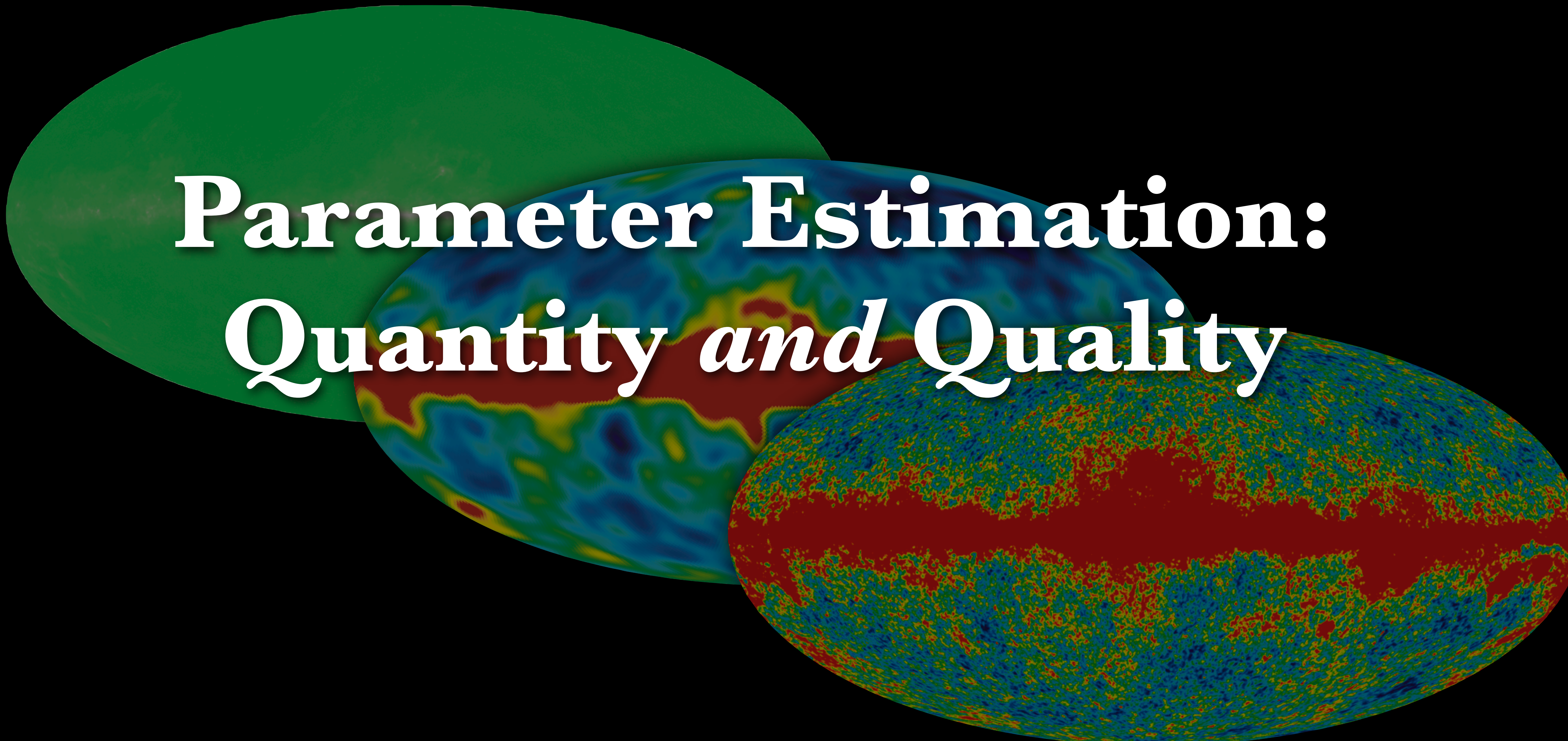
Science: Galactic Binaries

Unique probe of galactic astronomy & stellar evolution.
Multimessenger astronomy -- long term tests of GR.

	LISA	Minimum MBH Sensitivity	Minimum EMRI Sensitivity
Arm length (km)	5×10^{6}	5×10^{4}	1×10^{6}
Displacement (m $Hz^{-1/2}$)	8×10^{-12}	8×10^{-11}	8×10^{-12}
Acceleration (m/s^2 $Hz^{-1/2}$)	3×10^{-15}	3×10^{-14}	3×10^{-15}
MBH Rates (yr^{-1})	40/20	5/5	20/20
EMRI Detections	300	0	10
WDWD Detections	**2×10^{4} (10)**	**20 (0)**	**1×10^{4} (8)**

*Estimates for 2-year integration times.
Number of verification binaries in parentheses

Parameter Estimation: Quantity *and* Quality



Parameter Estimation: Wringing Science from GW detections.

$$\underbrace{d}_{\text{Data}} = \underbrace{R}_{\text{Instrument Response}} * \underbrace{h}_{\text{Gravitational Wave}} + \underbrace{n}_{\text{Noise}}$$

$$R \longrightarrow R(t; \underbrace{\vec{k}}_{\text{Line of sight}}, \underbrace{\Omega}_{\text{Sky-location}}, \underbrace{\psi}_{\text{Polarization}})$$

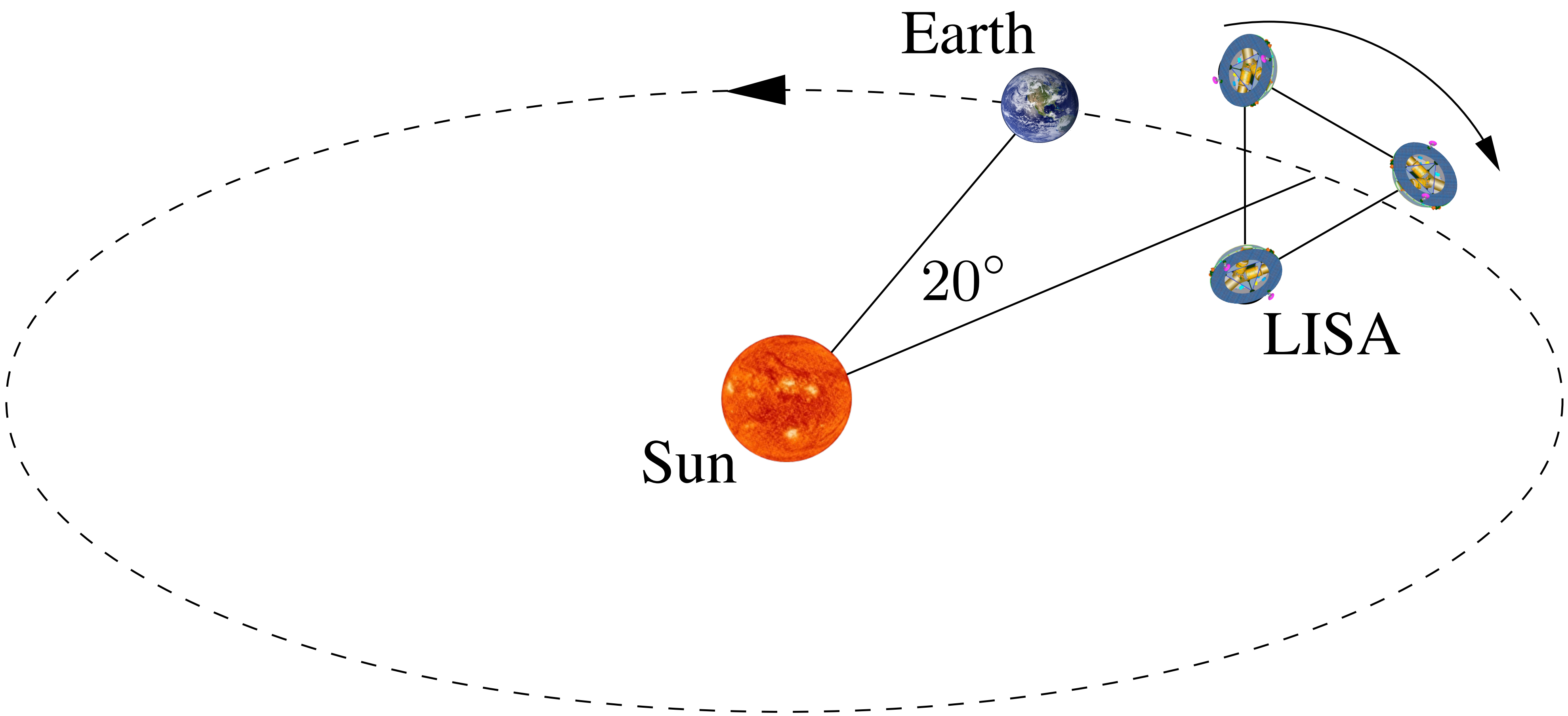
$$h \longrightarrow h(t; \underbrace{M}_{\text{Masses}}, \underbrace{\vec{S}}_{\text{Spins}}, \underbrace{\vec{L}}_{\text{Orientation}})$$

$$\text{guess} : \theta' \longrightarrow \left\{ \Omega, M, \vec{S}, \vec{L}, t_{\text{ref}}, \phi_{\text{ref}} \right\}$$

$$\text{minimize} : \int (d - R' * h')^2$$

Parameter Estimation: Orbits & R

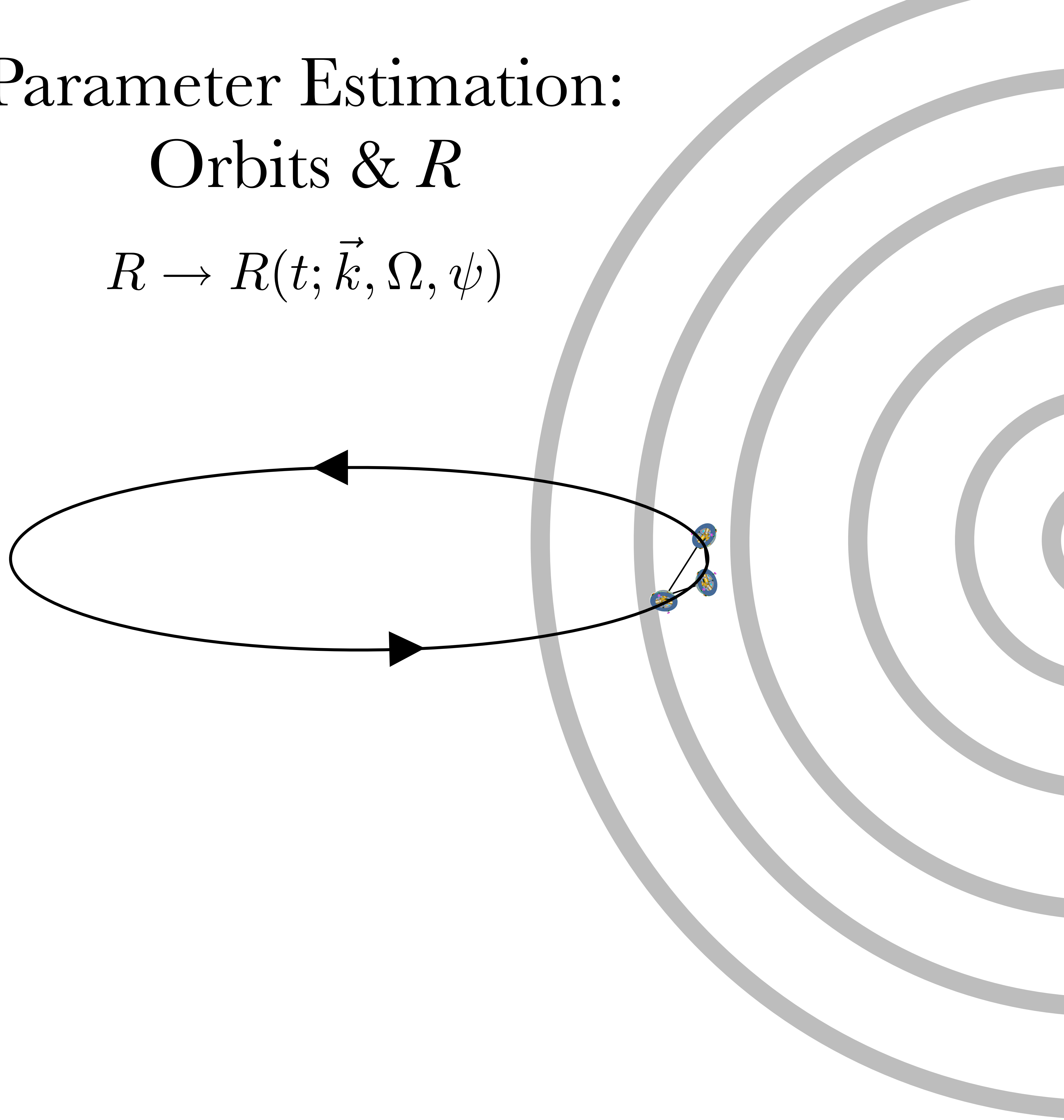
$$R \rightarrow R(t; \vec{k}, \Omega, \psi)$$



Parameter Estimation: Orbits & R

$$R \rightarrow R(t; \vec{k}, \Omega, \psi)$$

Doppler Modulation:

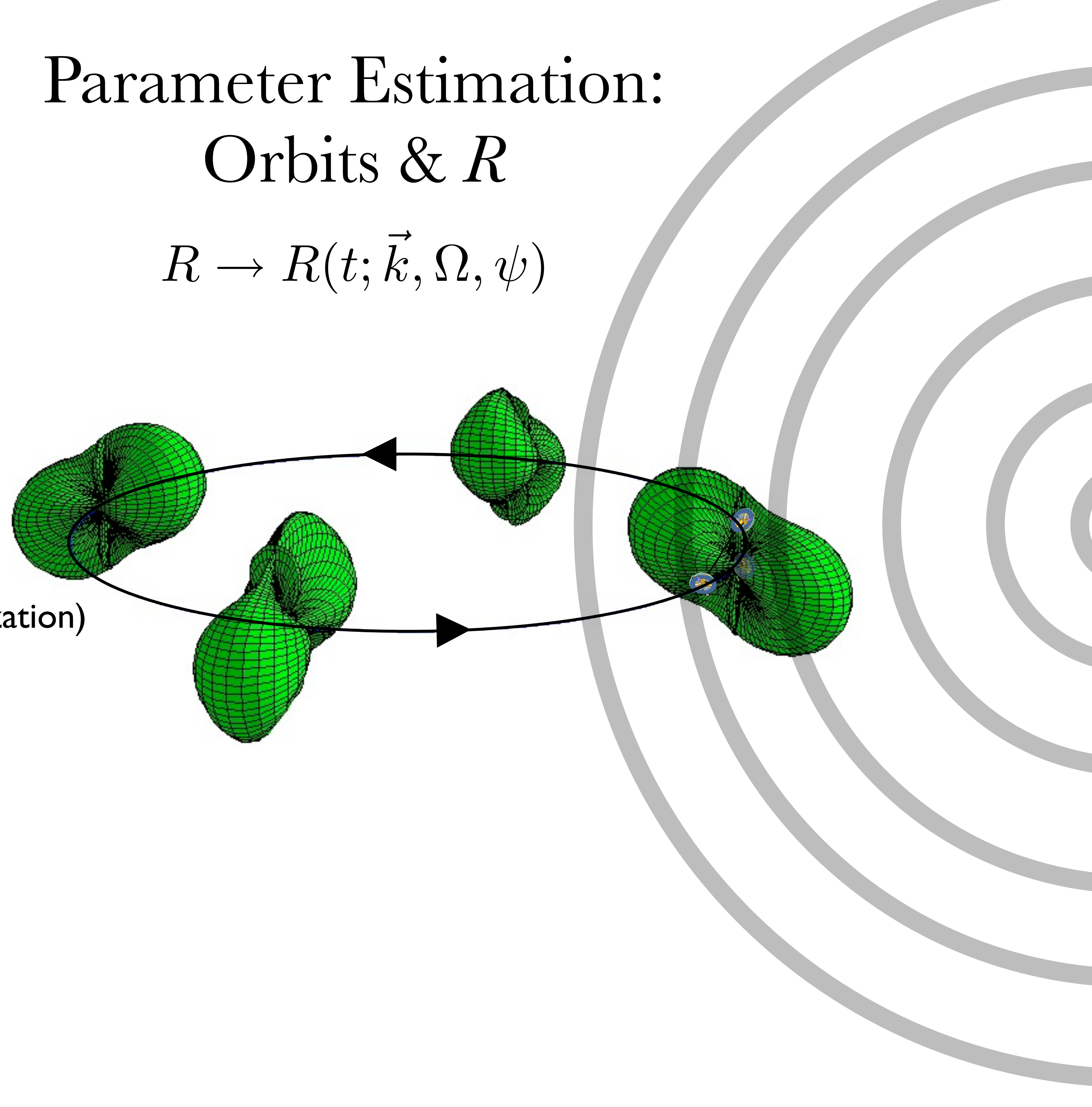


Parameter Estimation: Orbits & R

$$R \to R(t; \vec{k}, \Omega, \psi)$$

Doppler Modulation:

Amplitude (and Polarization) Modulation:



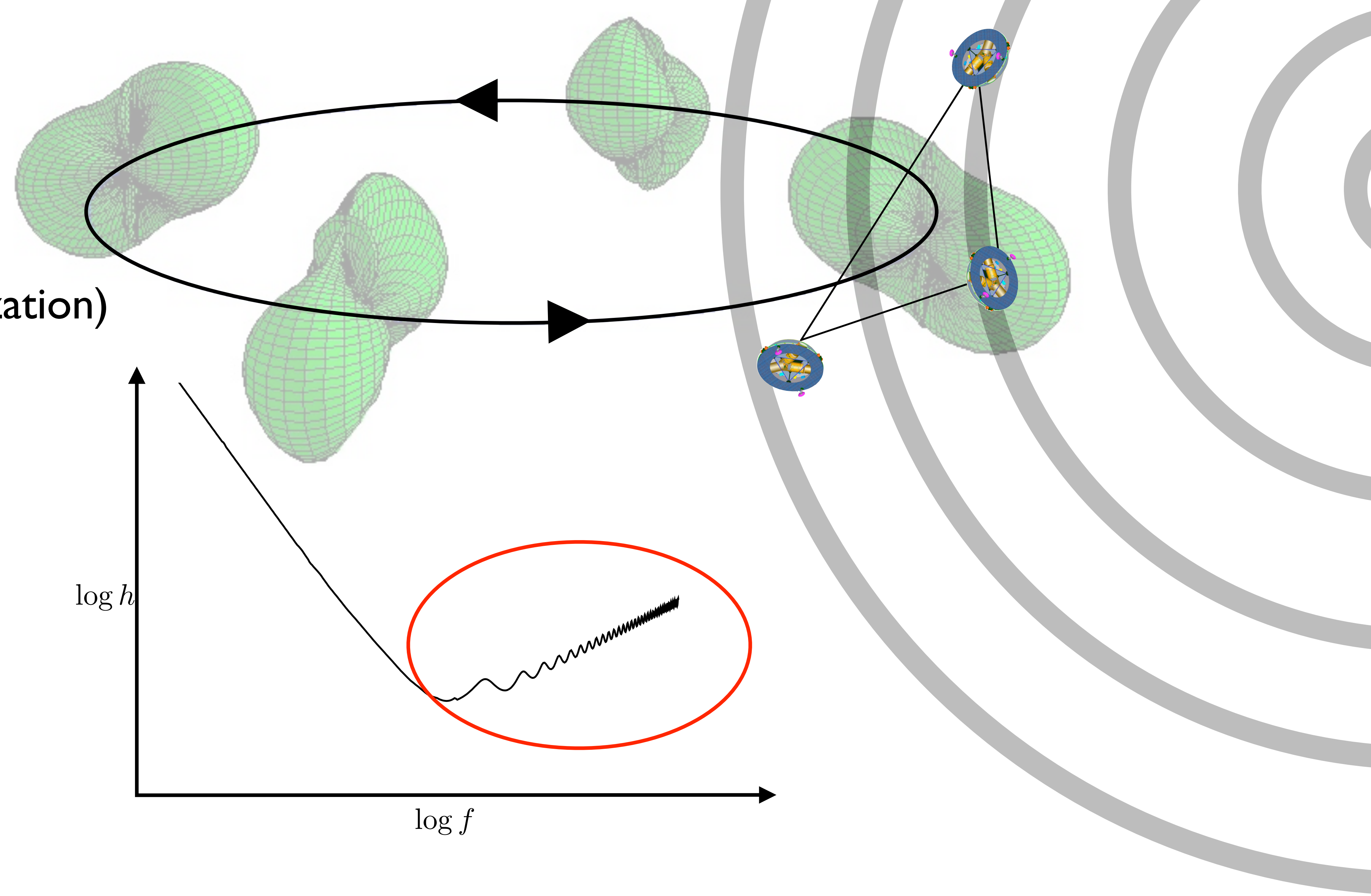
Parameter Estimation: Orbits & R

$$R \rightarrow R(t; \vec{k}, \Omega, \psi)$$

Doppler Modulation:

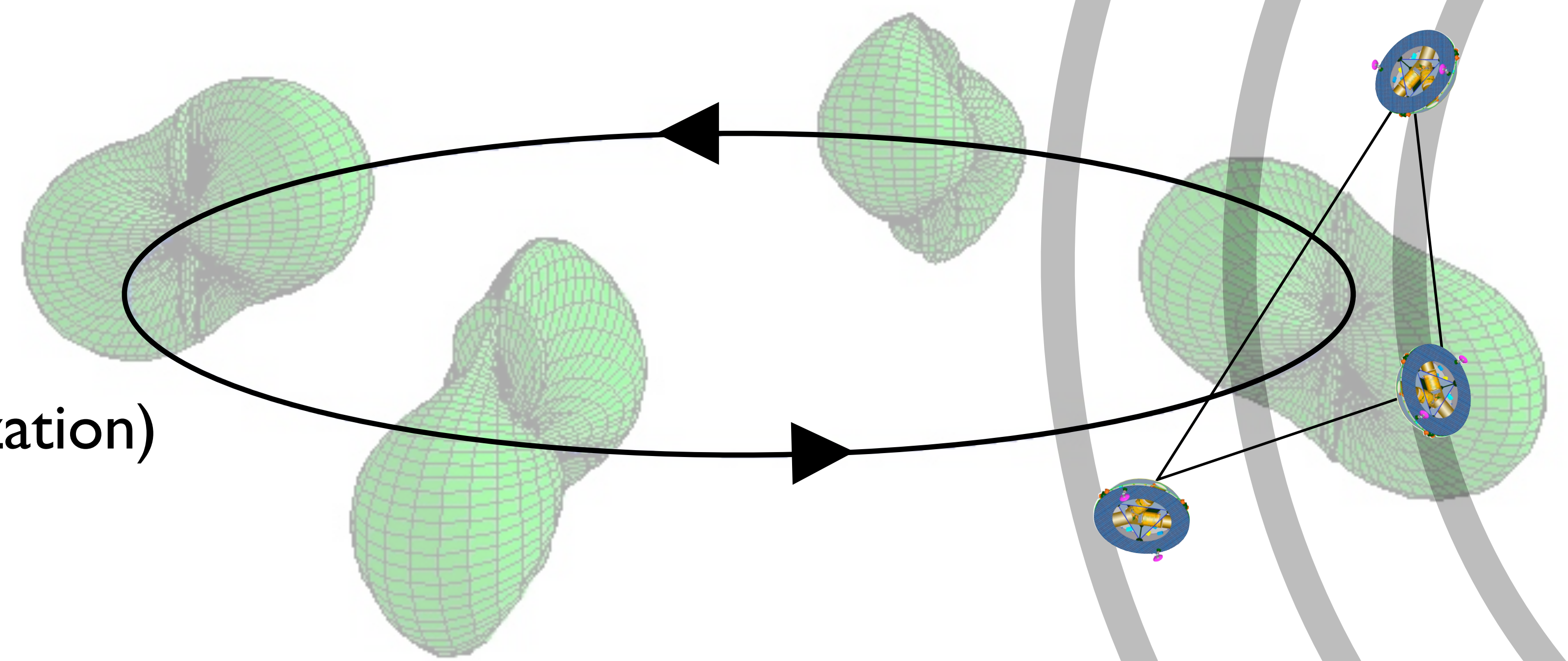
Amplitude (and Polarization) Modulation:

Arm-length:



Parameter Estimation: Orbits & R

$$R \to R(t; \vec{k}, \Omega, \psi)$$



Doppler Modulation:

Amplitude (and Polarization) Modulation:

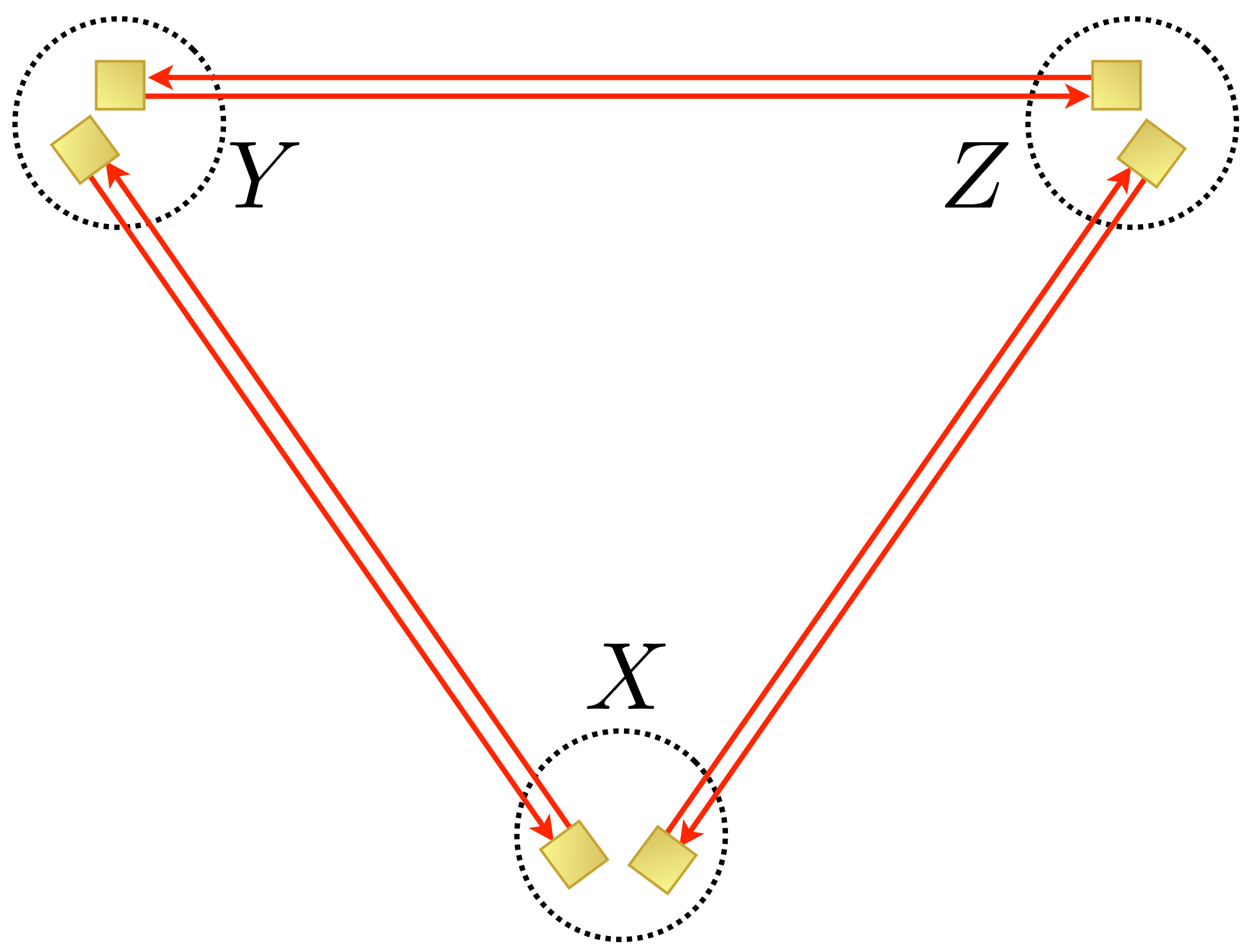
Arm-length:

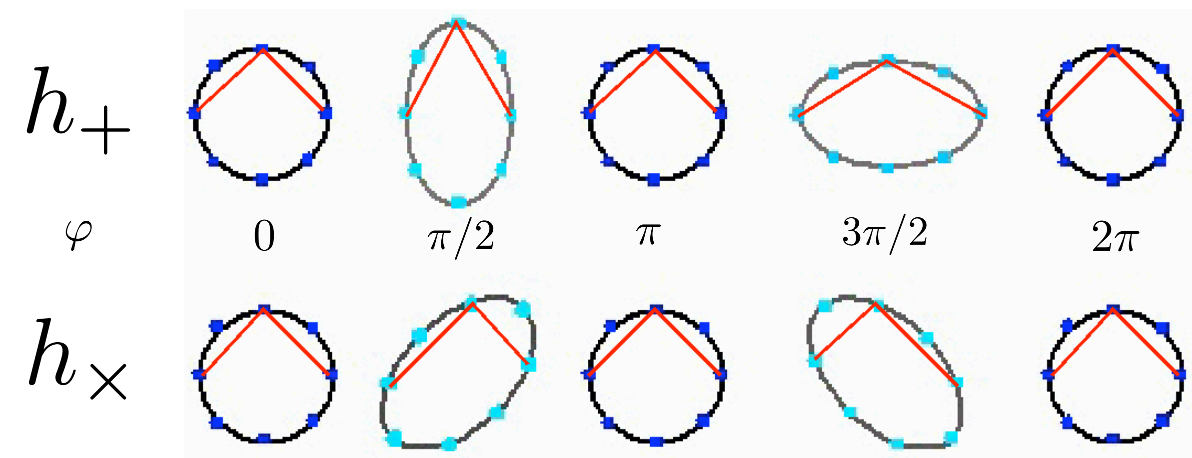
$$N_{\rm BH} = {\rm rate}_{\rm BH} \times T_{\rm obs}$$

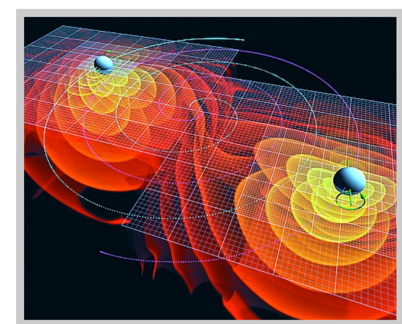
Mission lifetime:

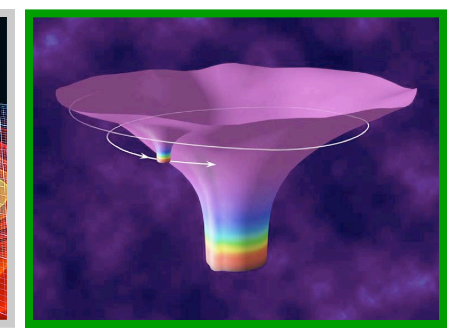
$$\mathrm{SNR}_{\rm EMRI,GB} \propto \sqrt{T_{\rm obs}}$$

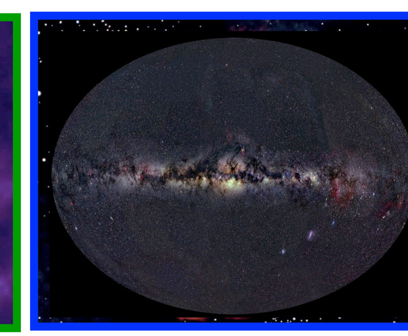
Parameter Estimation: 4 vs. 6 links

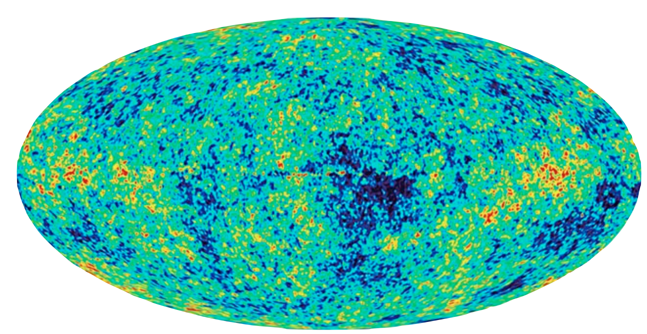


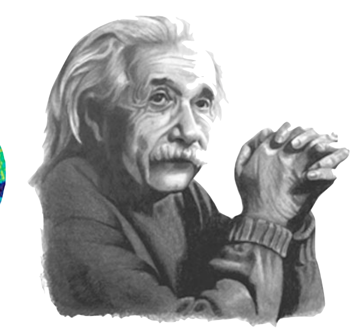




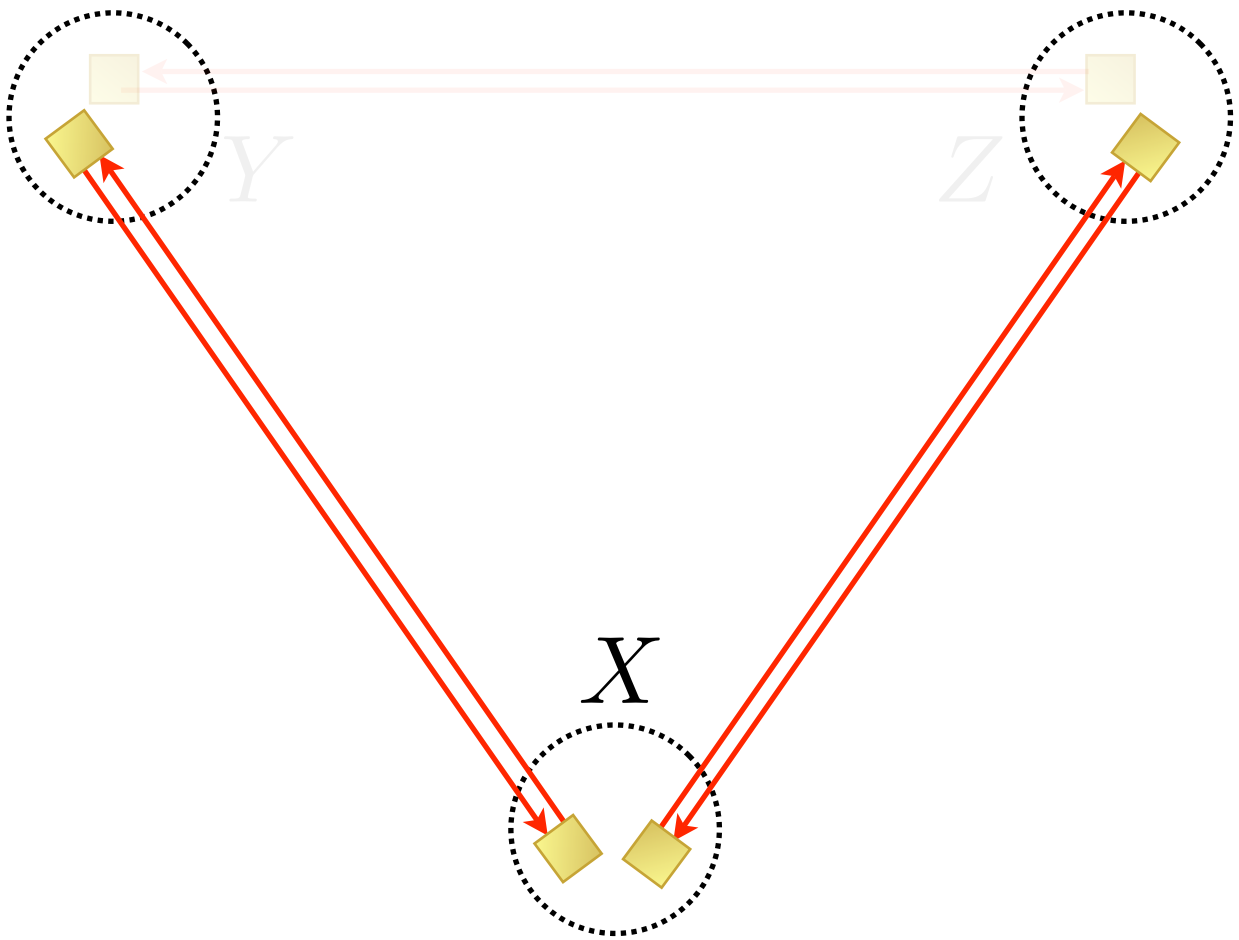


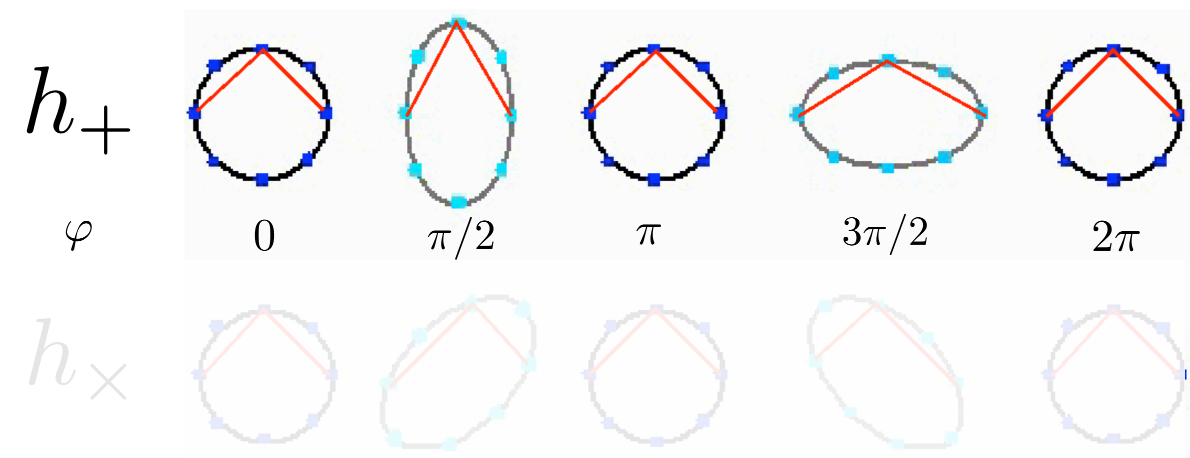


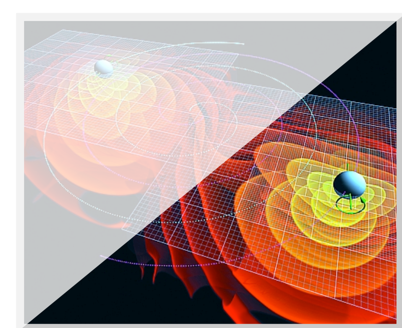


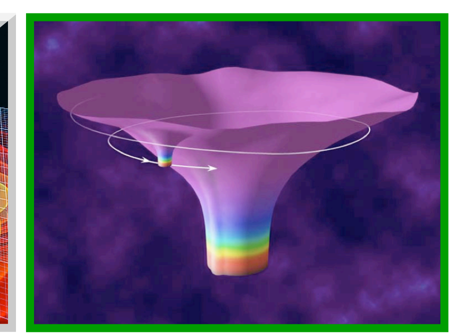


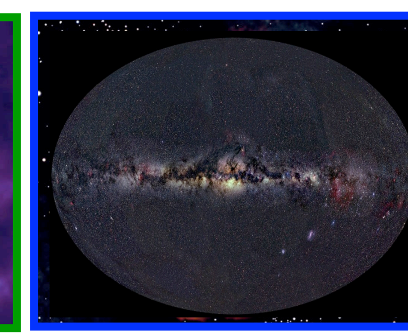
Parameter Estimation:
4 vs. 6 links

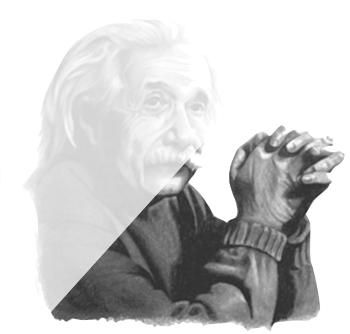




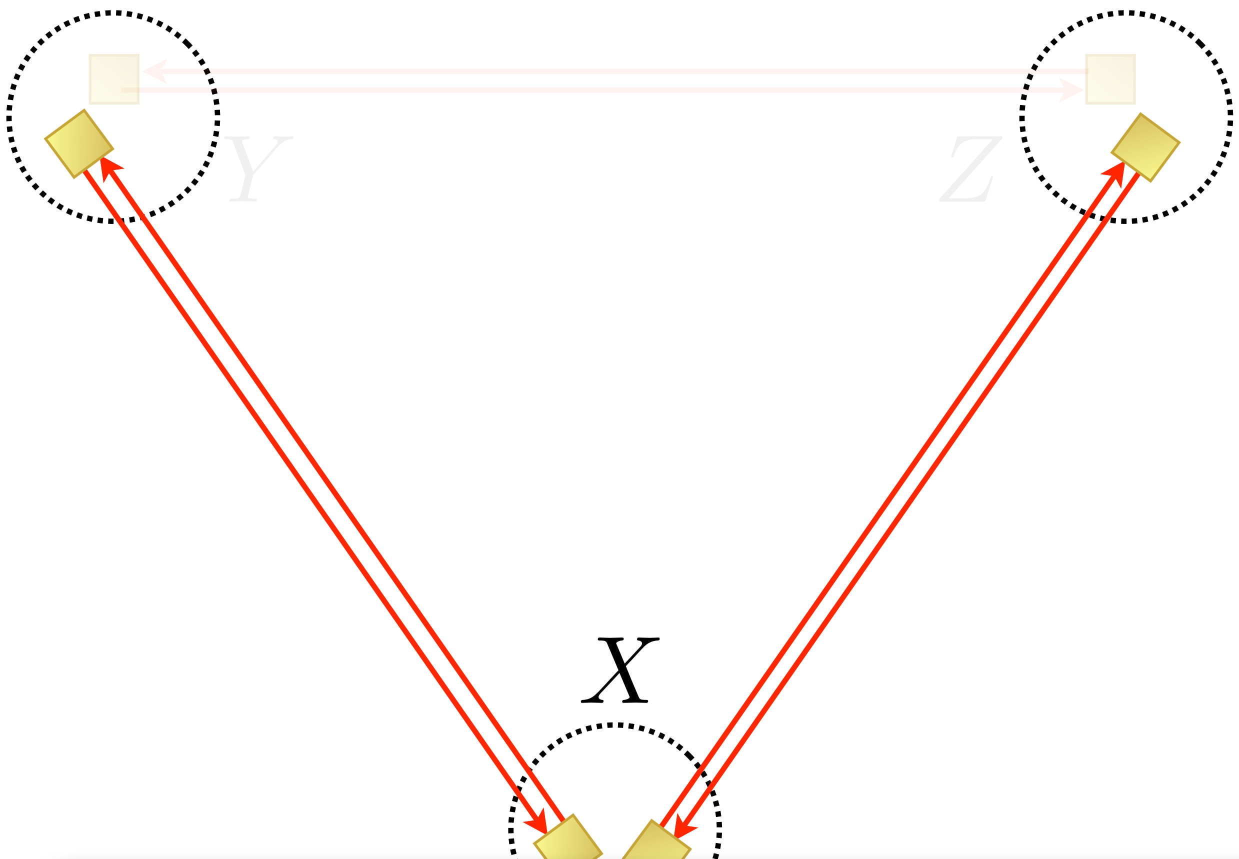


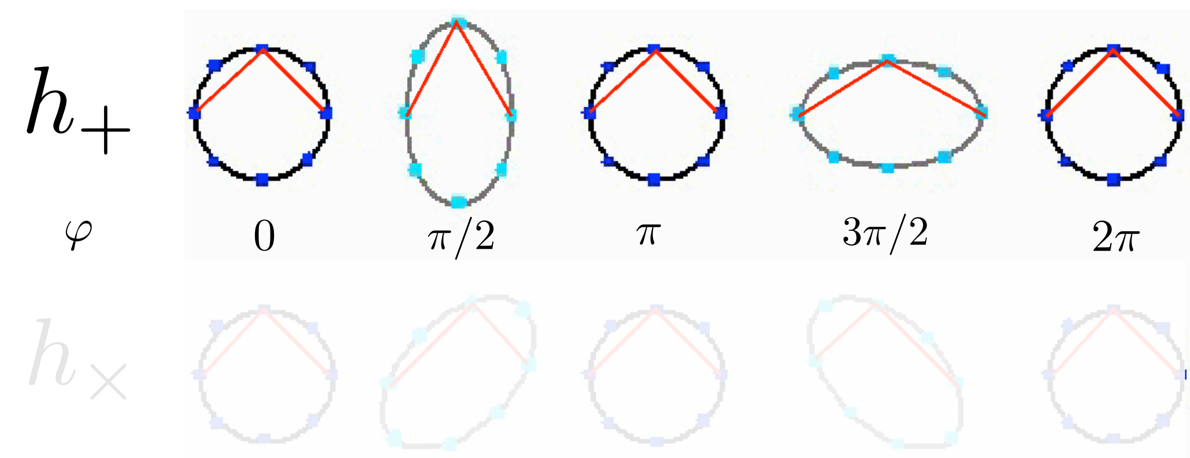


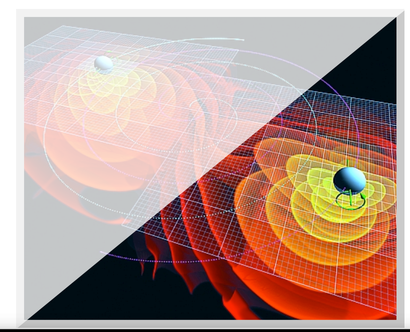


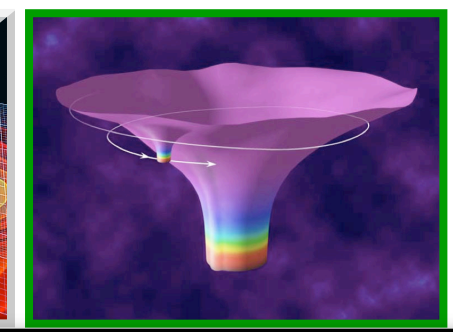


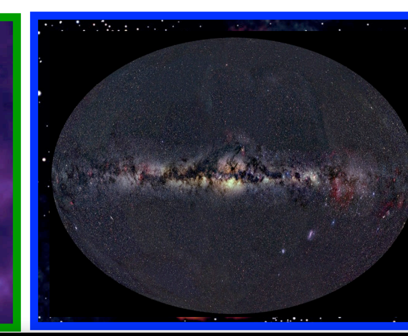
Parameter Estimation: 4 vs. 6 links





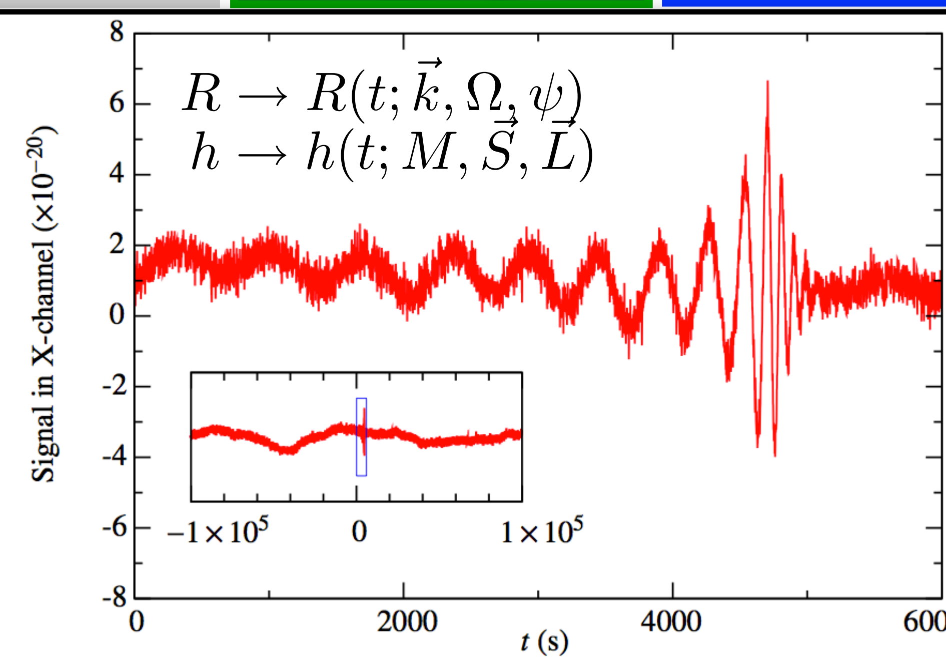






For MBH mergers, lose:

- -factor of <2 in SNR
- -factor of ~10 in distance determination.
- -factor of ~100 in angular resolution!
- -mass & spin errors change by < 10x
  - -and they're already really precise.



In Summary:

- **To do NWNH science, we have some margin around the original LISA design.**
    - But it doesn't take much to ruin the sensitivity curve -- factors of a few equate to orders of magnitude degradation in science.
- MBH mergers have the most wiggle room
    - Keep the arms w/in a factor of 10ish, and the noise performance w/in a factor of a few-ish.
    - **Precision measurement of Mass & Spin come with good SNR.**
        - Mass and Spin distributions go a long way toward constraining MBH formation scenarios (z>few).
        - But, **simultaneously measuring both polarizations is *critical*** for:
            - Sky-localization (optical counterparts)
            - Distance determination (optical counterparts + *better* constraints on formation scenarios)
- EMRI detection rates are highly uncertain. Consequently there is less margin for the detectors.
    - But, **if you can detect an EMRI, you can precisely measure its parameters**.
- Galactic Binary science for "free."

mHz GW Science as a Function of Sensitivity

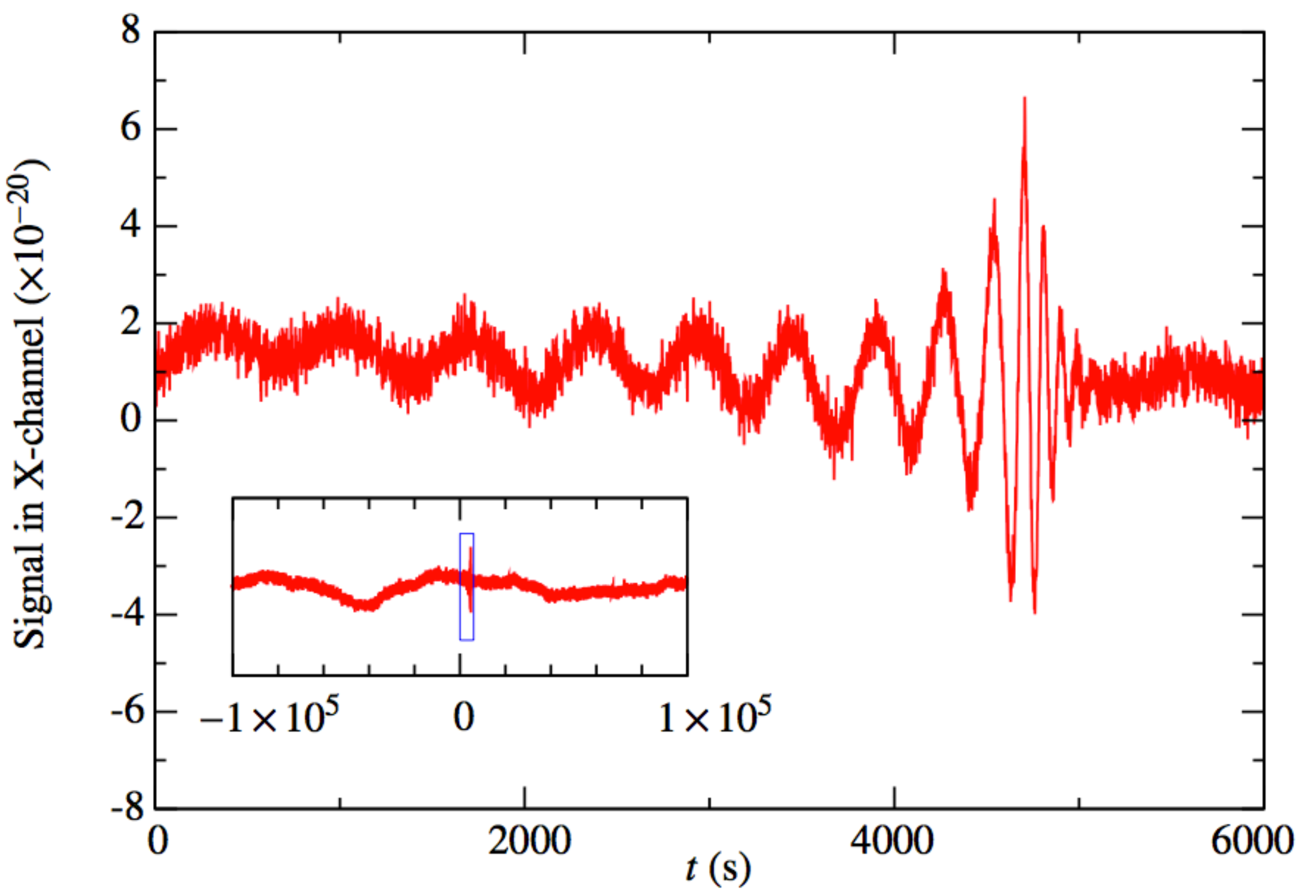
Tyson B. Littenberg
(UMD/GSFC)

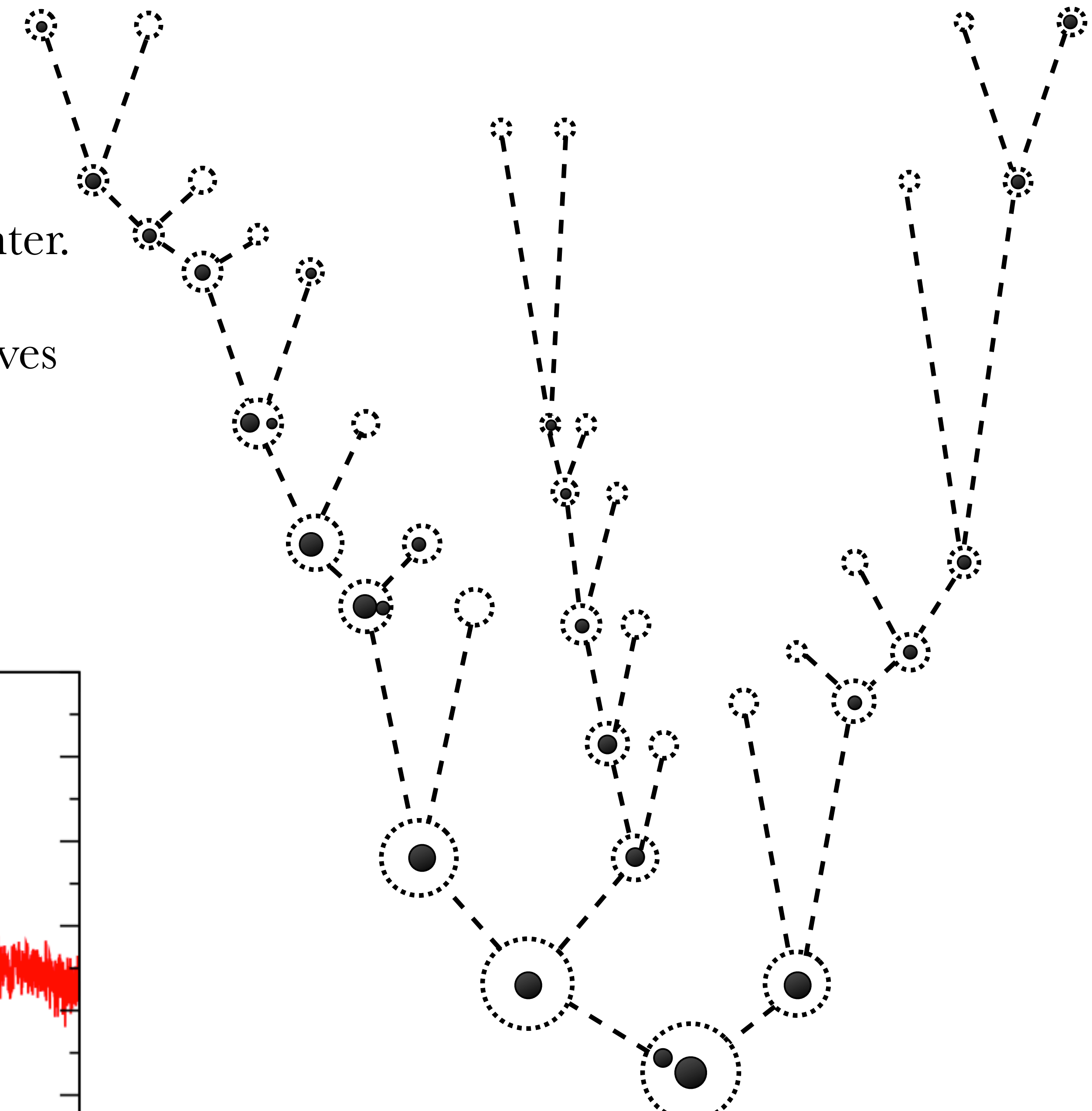
Extra Slides

mHz Gravitational Wave Astronomy

Supermassive Black Hole Mergers:

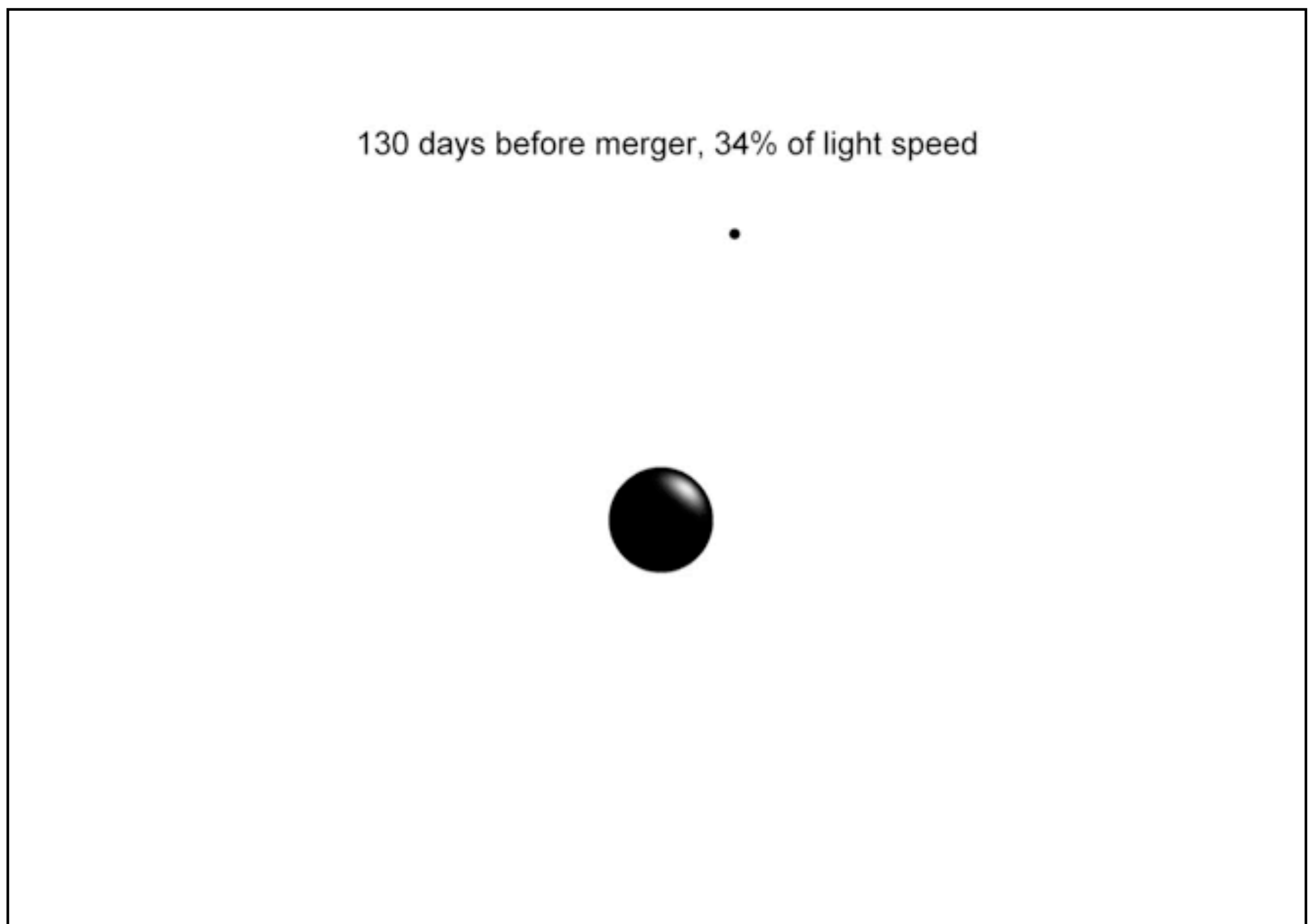
- Large-scale structure formation requires major mergers between galaxies.
- Supermassive black holes at the cores of merging galaxies dynamically sink to the center.
- Once close enough, the emission of GW drives the black holes to merge.
- Ridiculously energetic: 10^{56} erg/s (c.f., 10^{43} erg/s for Sn Ia)!





mHz Gravitational Wave Astronomy
Extreme Mass Ratio In-spirals (EMRIs)

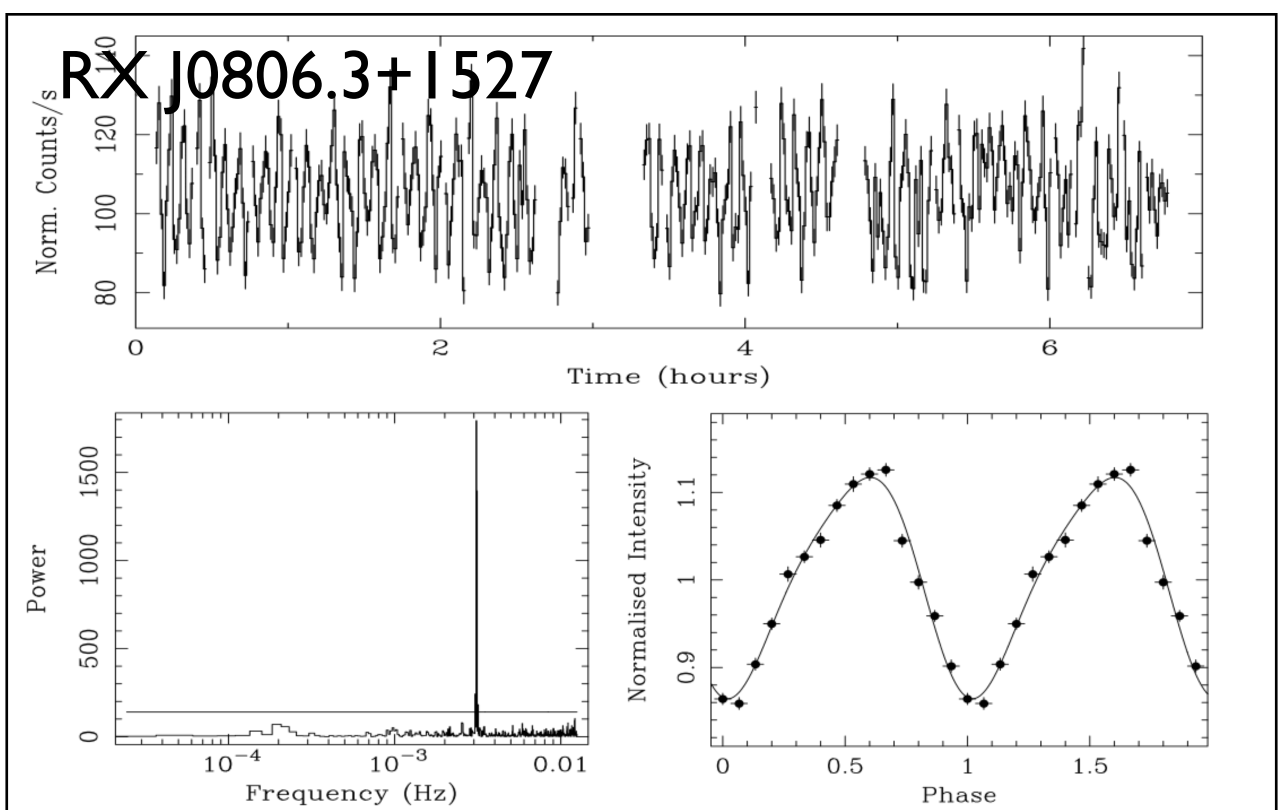
- Compact objects which form near SMBHs can be scattered into capture orbits.
- The compact object makes *numerous* orbits before plunging into the central BH.
- The orbit of the compact object provides a detailed trace of the space-time around the central black hole.



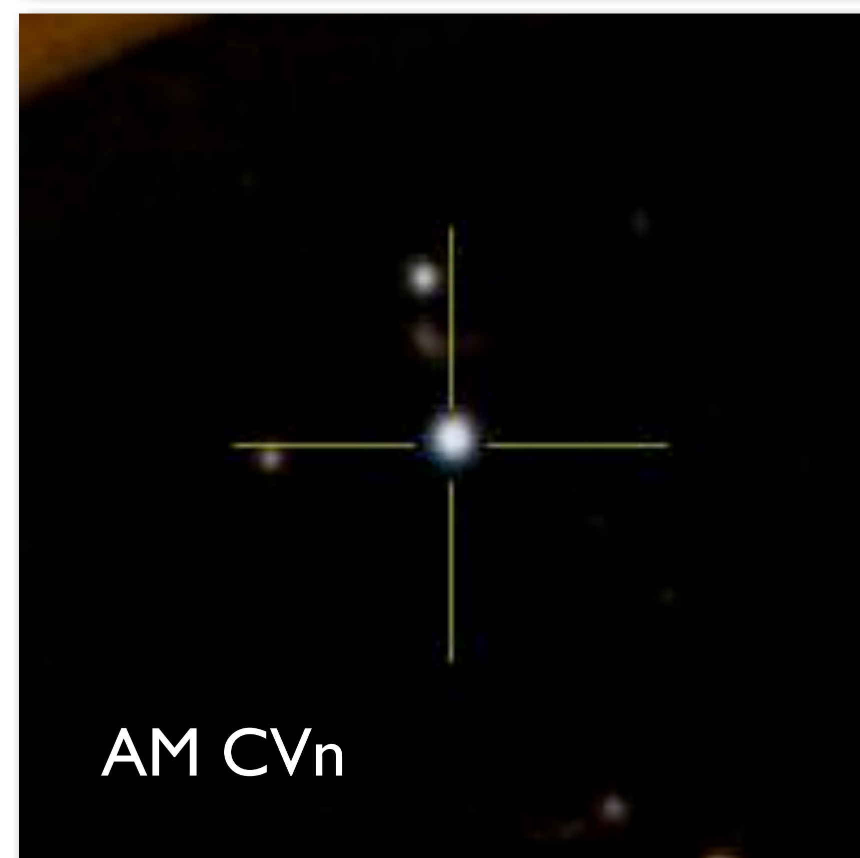
Credit: S. Drasco
<http://www.tapir.caltech.edu/~sdrasco/animations/index.html>

mHz Gravitational Wave Astronomy
White Dwarf Binaries

- Around 30 known mass transferring systems (of which AM CVn is the archetype).
- A handful of detached white dwarf binaries from SDSS
- ~60 million of their friends, waiting to be discovered

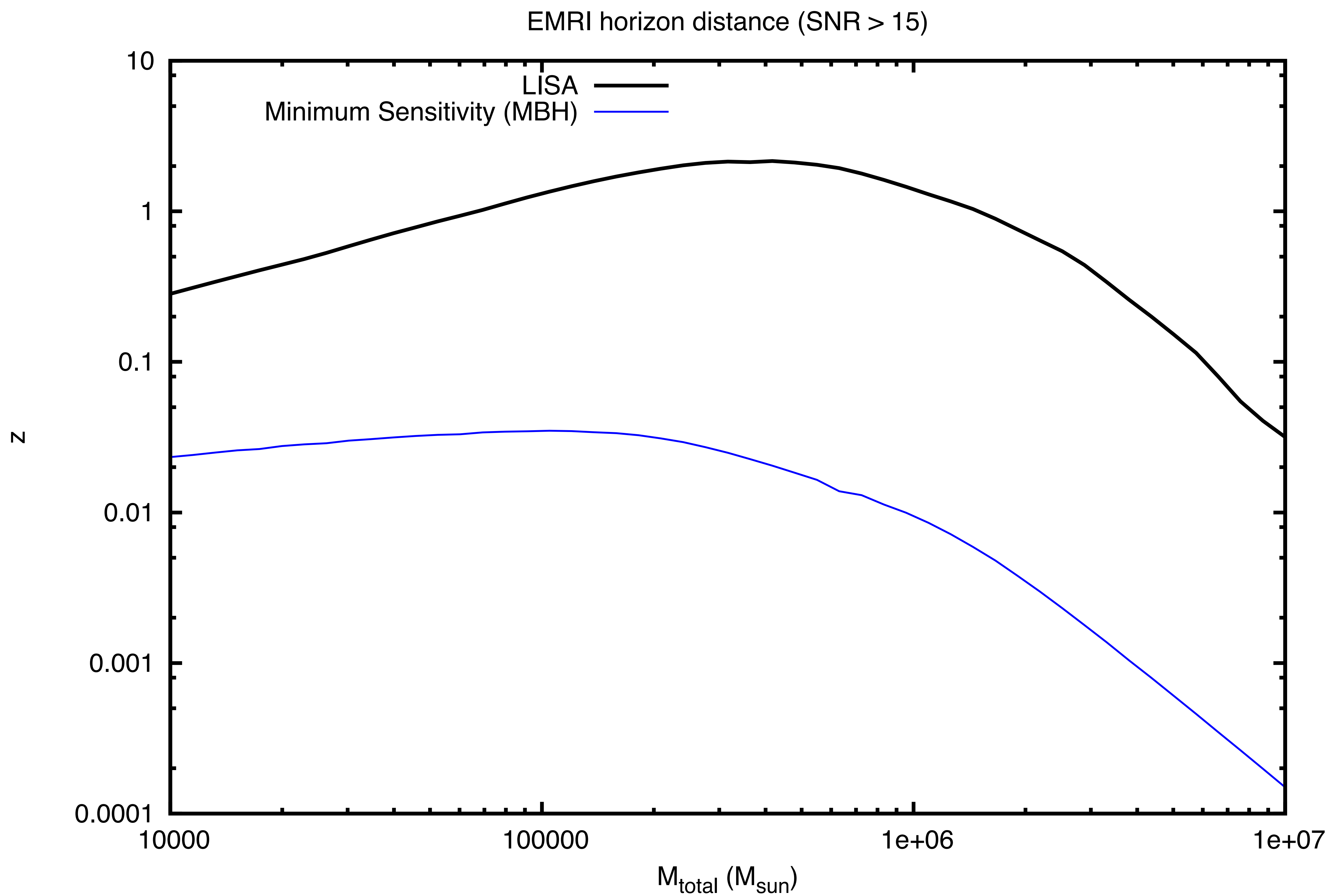


From Israel et al (2002)



Science: Extreme Mass Ratio Inspirals

NWNH: ***Detections of signals from EMRIs would provide exquisitely precise tests of Einstein's theory of gravity*****.**



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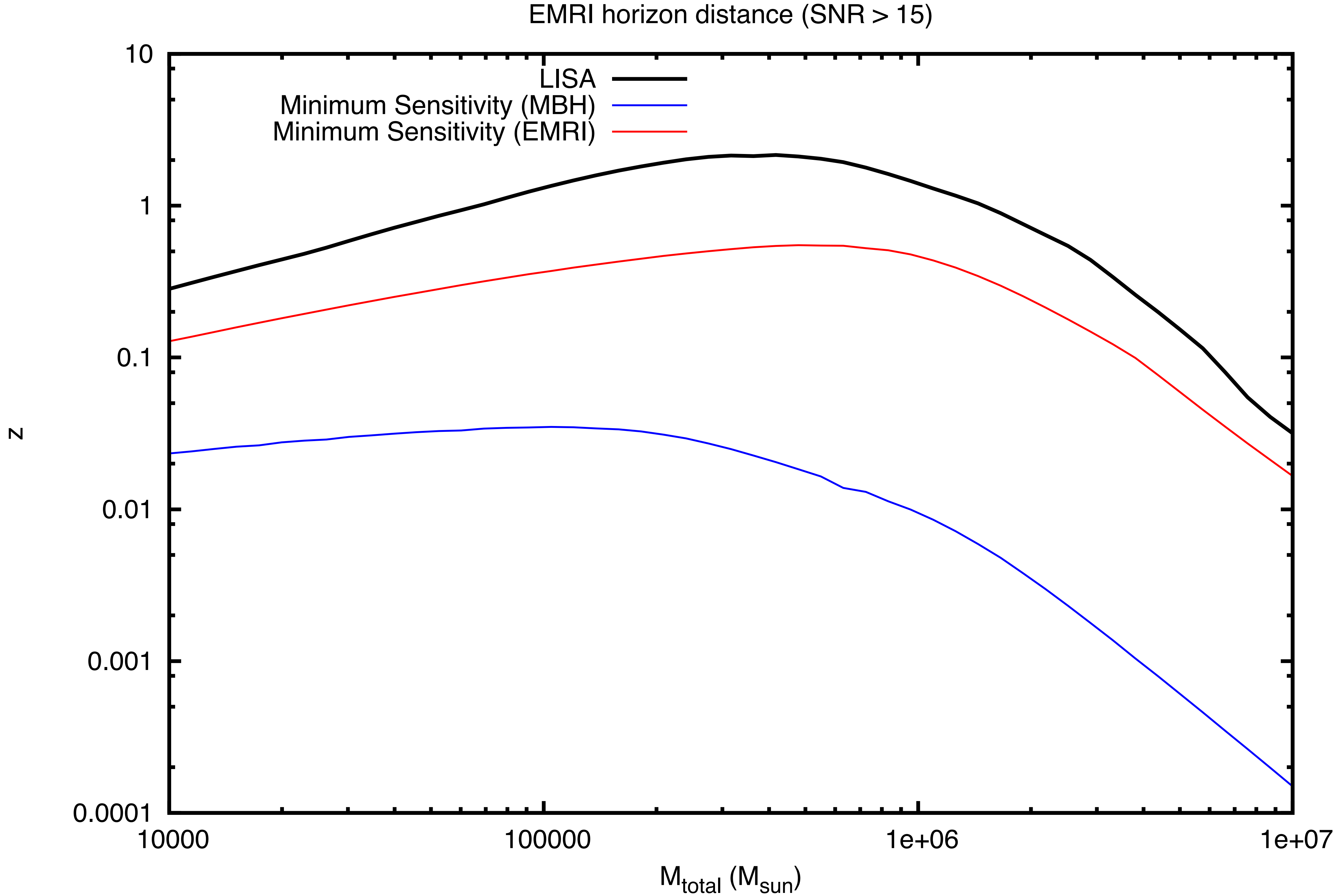

Parameter Estimation: Keep going, theorists!

$$\sigma_{\vec{\theta}}^{2\mathrm{PN}}/10/10/10$$