

The science of low-frequency gravitational waves

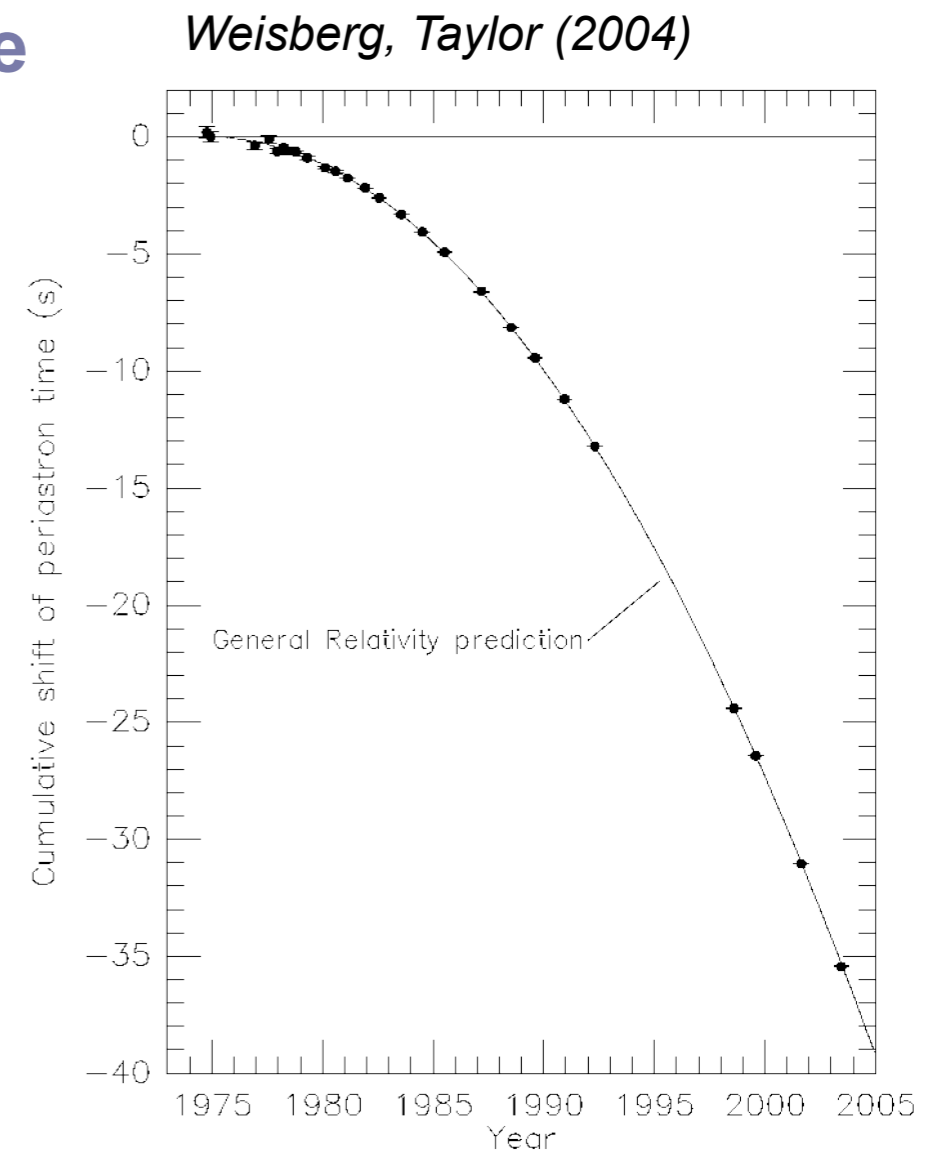
O. Jennrich
ESA

Overview

- **Introduction**
 - What are GW, how are they detected, what are their effects
- **Pulsar Timing Arrays**
- **Ground-based detectors**
- **Space borne detectors**
 - The Science
- **The future**

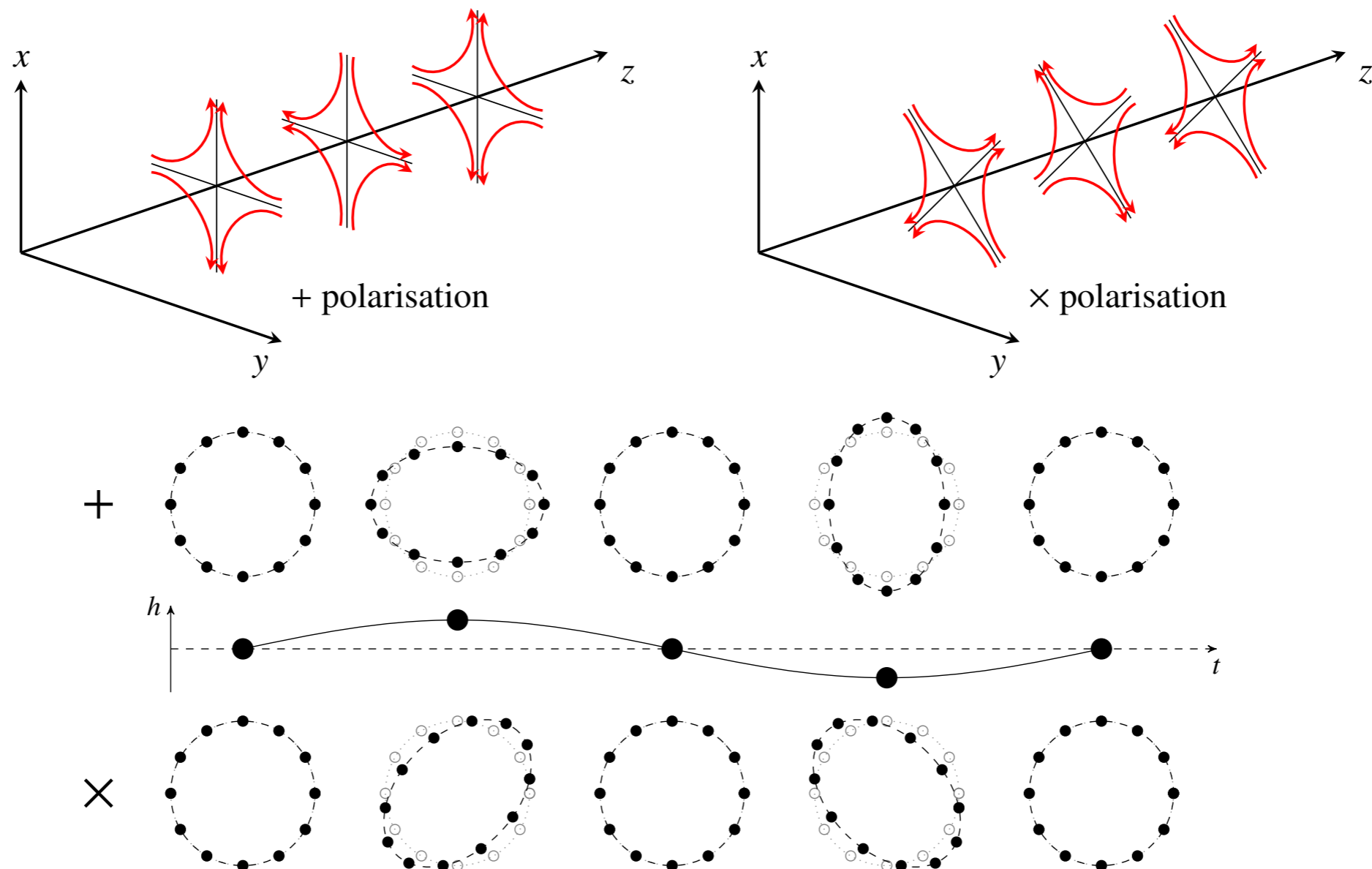
What are Gravitational Waves?

- **GW are a prediction of General Relativity**
 - first noticed by Einstein (1918), but dismissed as a mathematical curiosity
 - H. Bondi (1953): GW carry energy and momentum, so they are detectable
 - very small coupling to matter
- **GW cause a (periodic) strain in space-time**
 - Typical sources $dL/L \sim 10^{-21}$
- **Source: Suitably accelerated masses**
 - First observational evidence: Hulse-Taylor pulsar
 - Energy loss causes a spin-up of the pulsar
- **No direct detection of GW as of yet**
 - observational evidence in binary pulsars
 - PSR J0737-3039 binary double pulsar
 - Orbit shrinks by 7mm a day due to GW emission

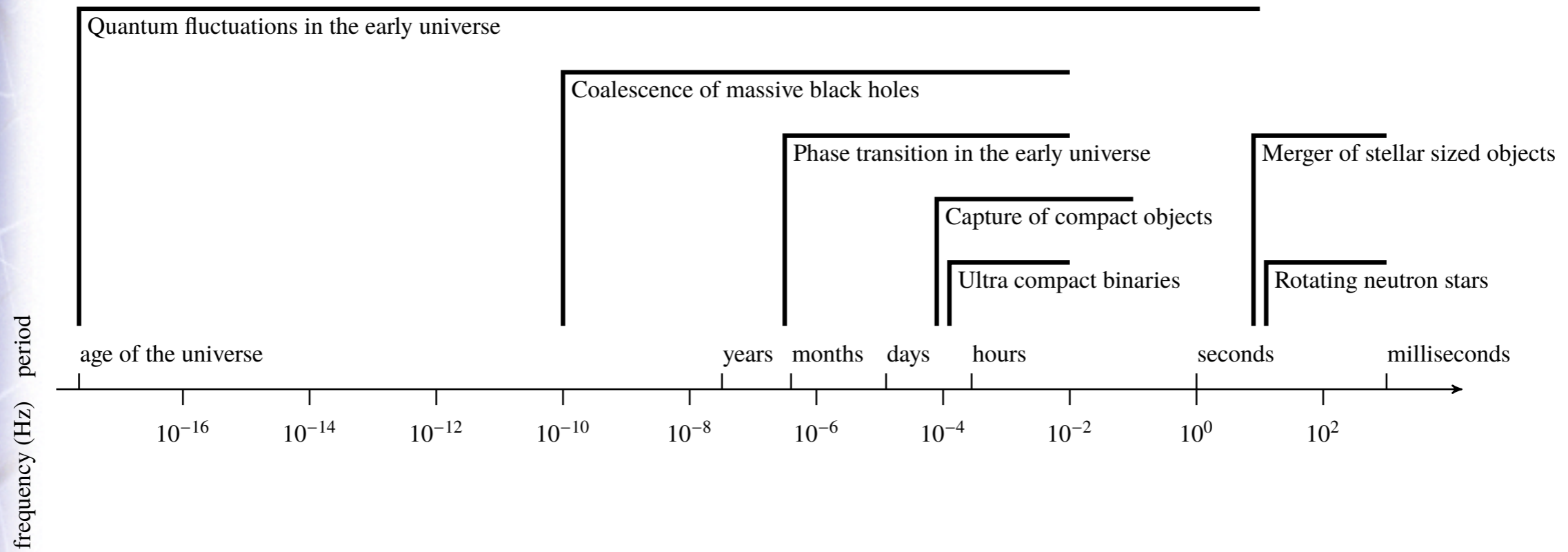


Properties of GW

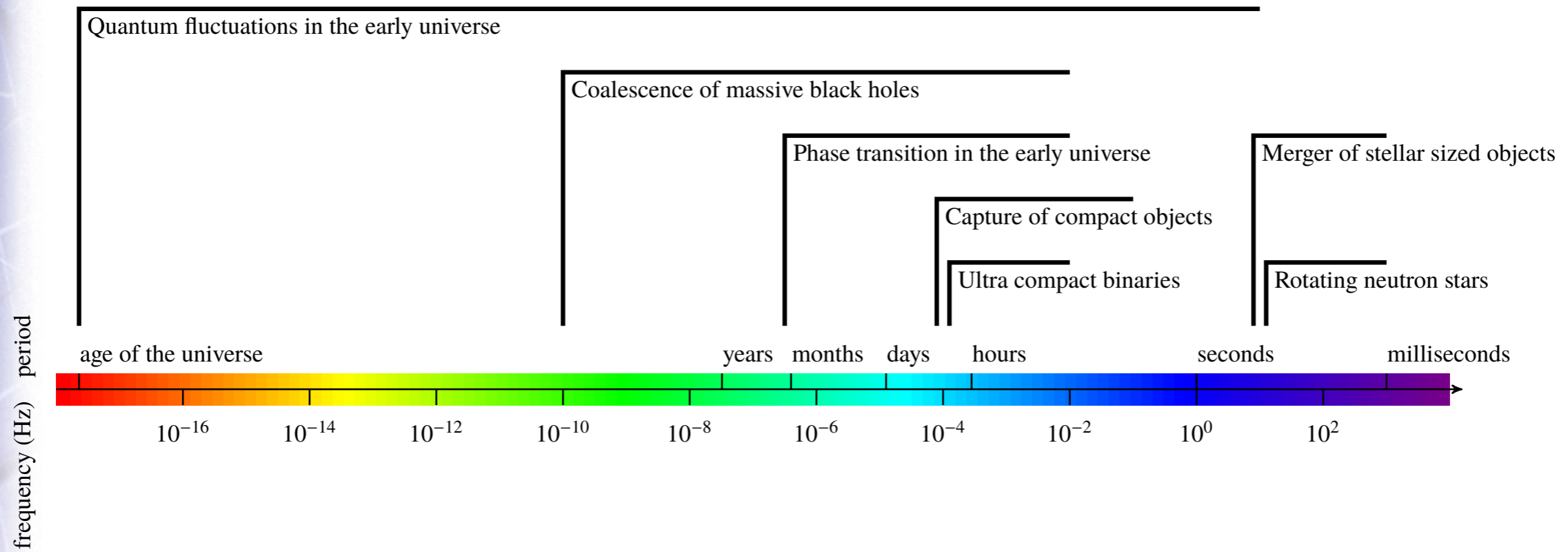
- Transversal waves
- Propagate with the speed of light
- Two polarisation states



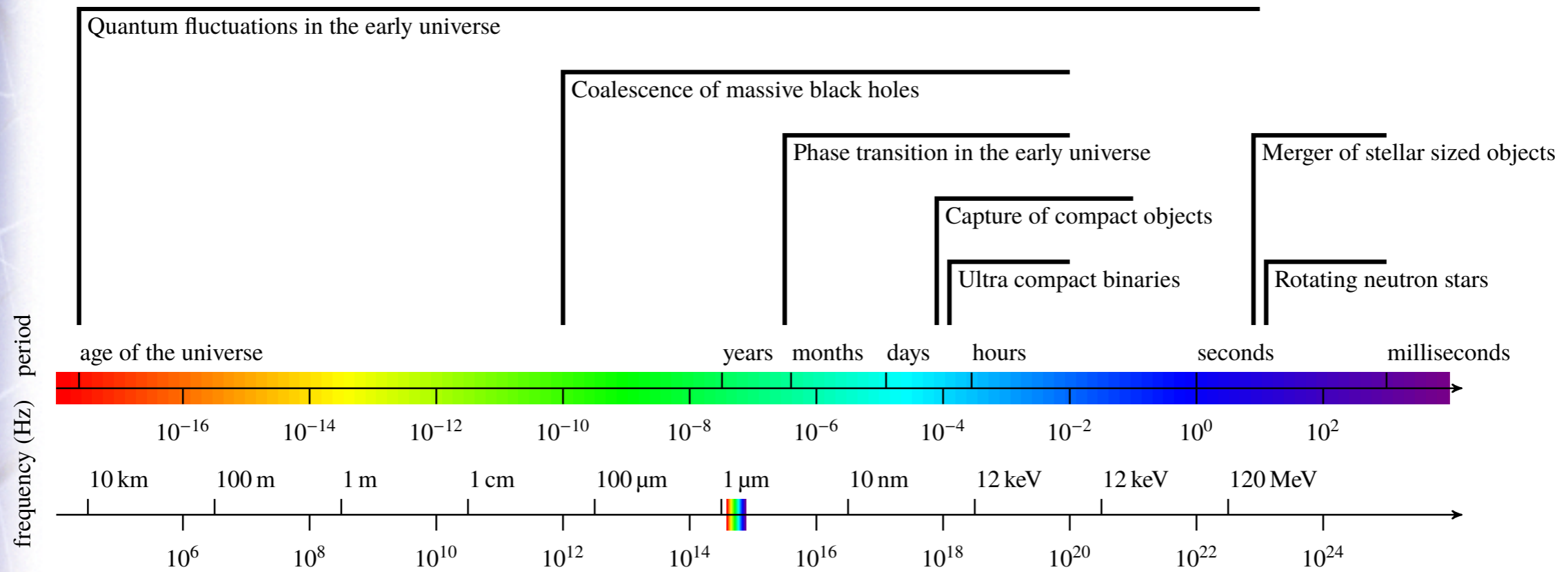
Frequency spectrum



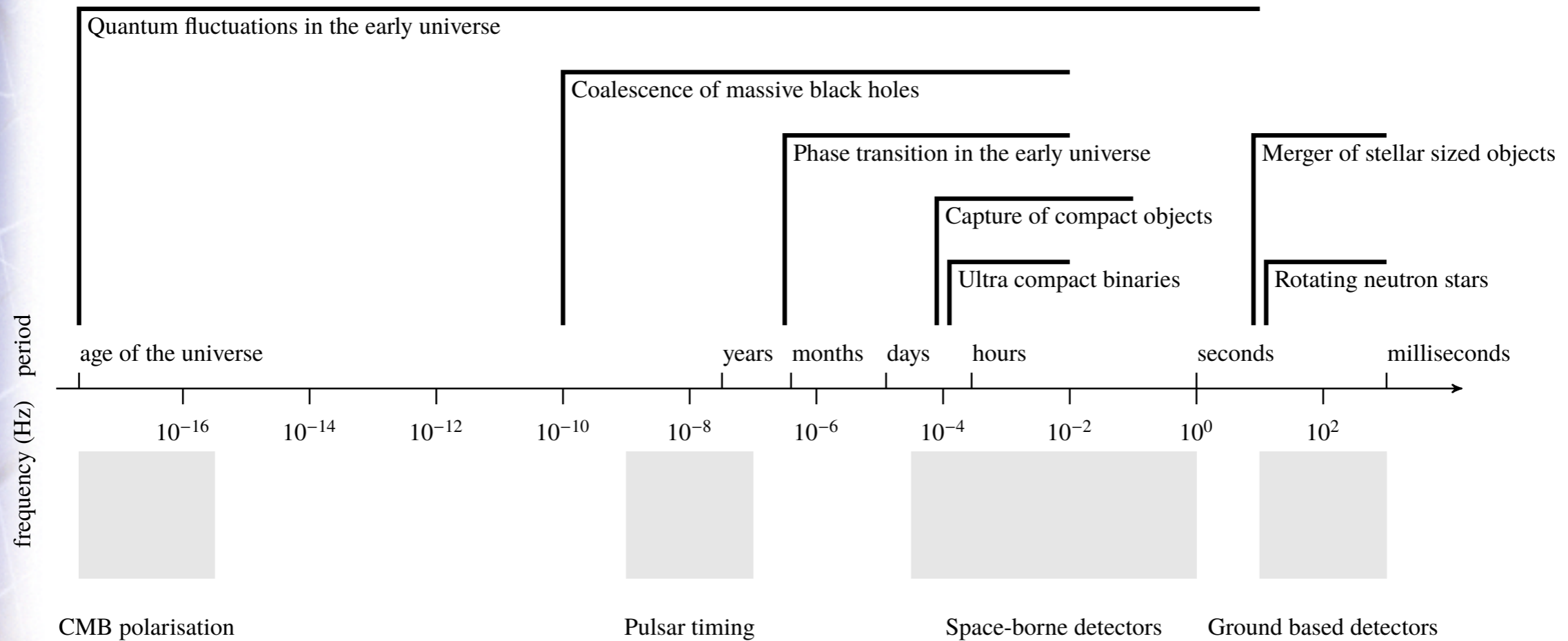
Frequency spectrum



Frequency spectrum

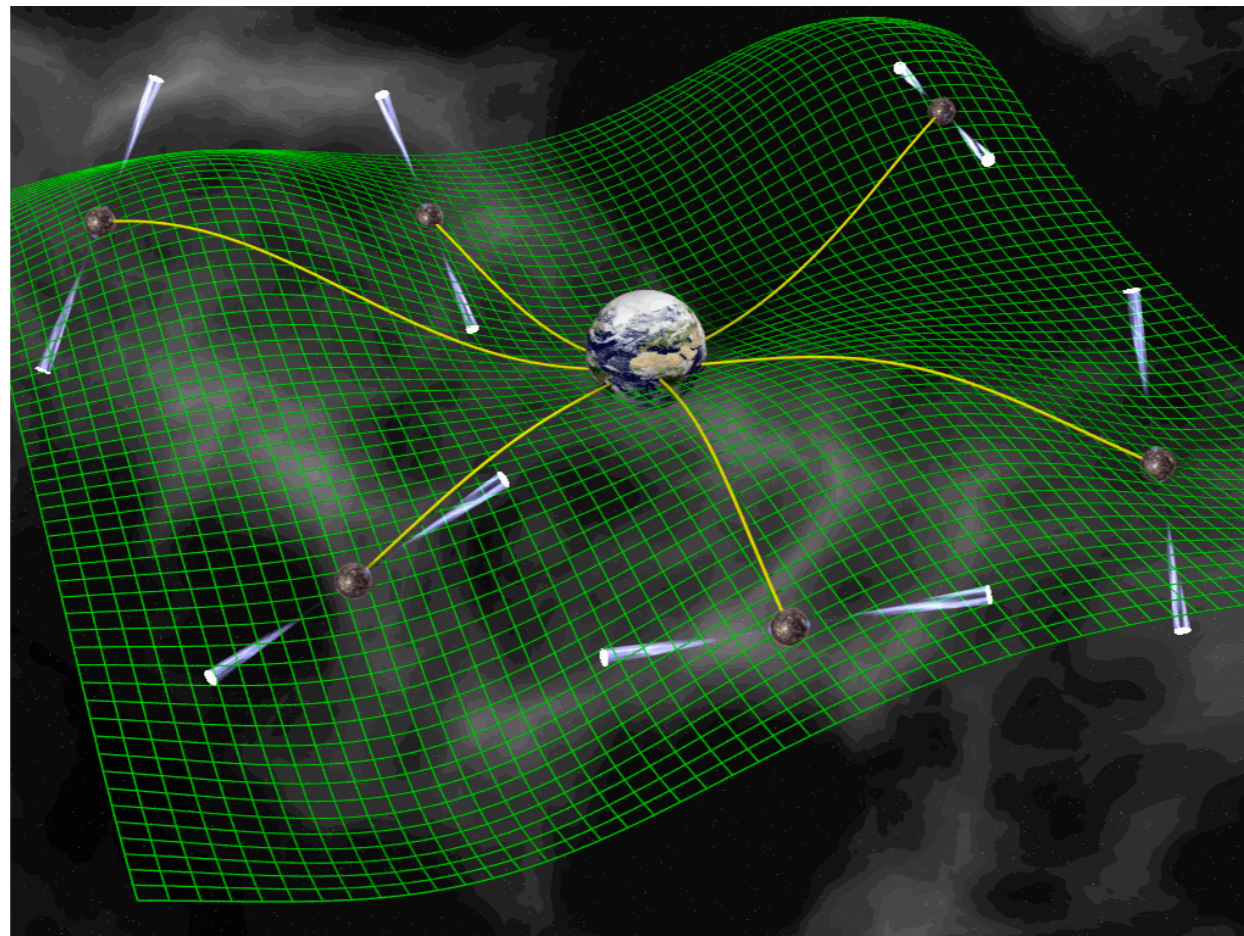


Frequency spectrum



Detecting GW with pulsars

- Millisecond pulsars are clocks of exquisite precision
 - Strain changes the arrival times of pulses
- Requires ~20 millisecond pulsars with ~ns timing accuracy
- Sensitive to gravitational waves ~ 0.1nHz ... 10 nHz
 - periods few years to many decades
- Sources: ultra-massive black holes coalescences ($10^9 M_{\text{sol}}$ and more)

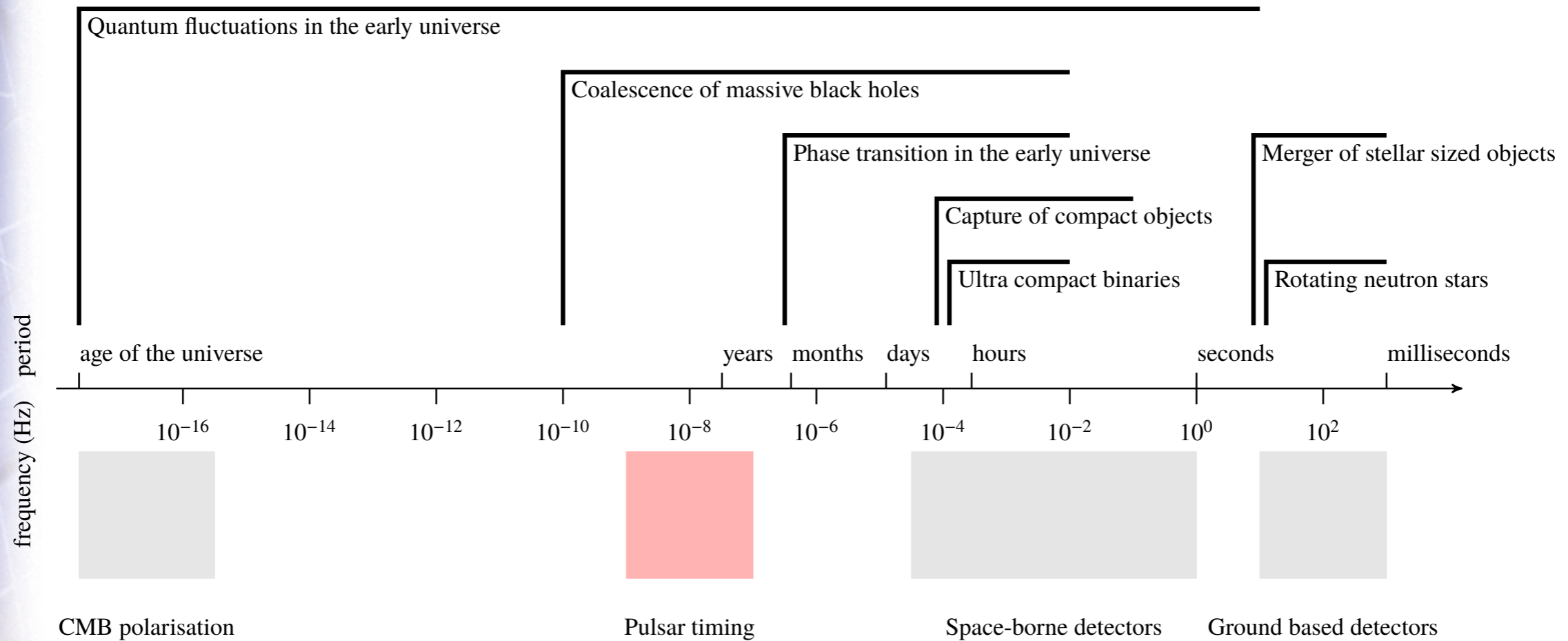


Pulsar timing array

- International Pulsar Timing Array
 - Europe: EPTA
 - North America: NANOGrav
 - Australia: Parks Pulsar Timing Array
 - In the future: SKA (SA, Australia)

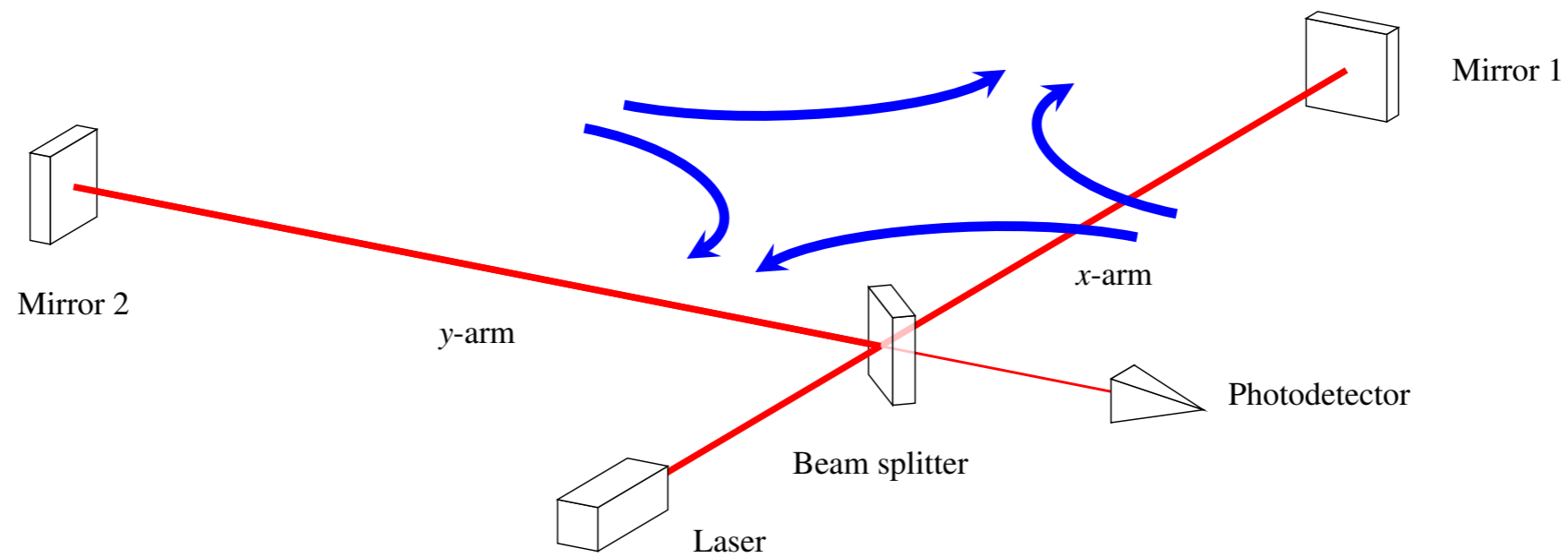
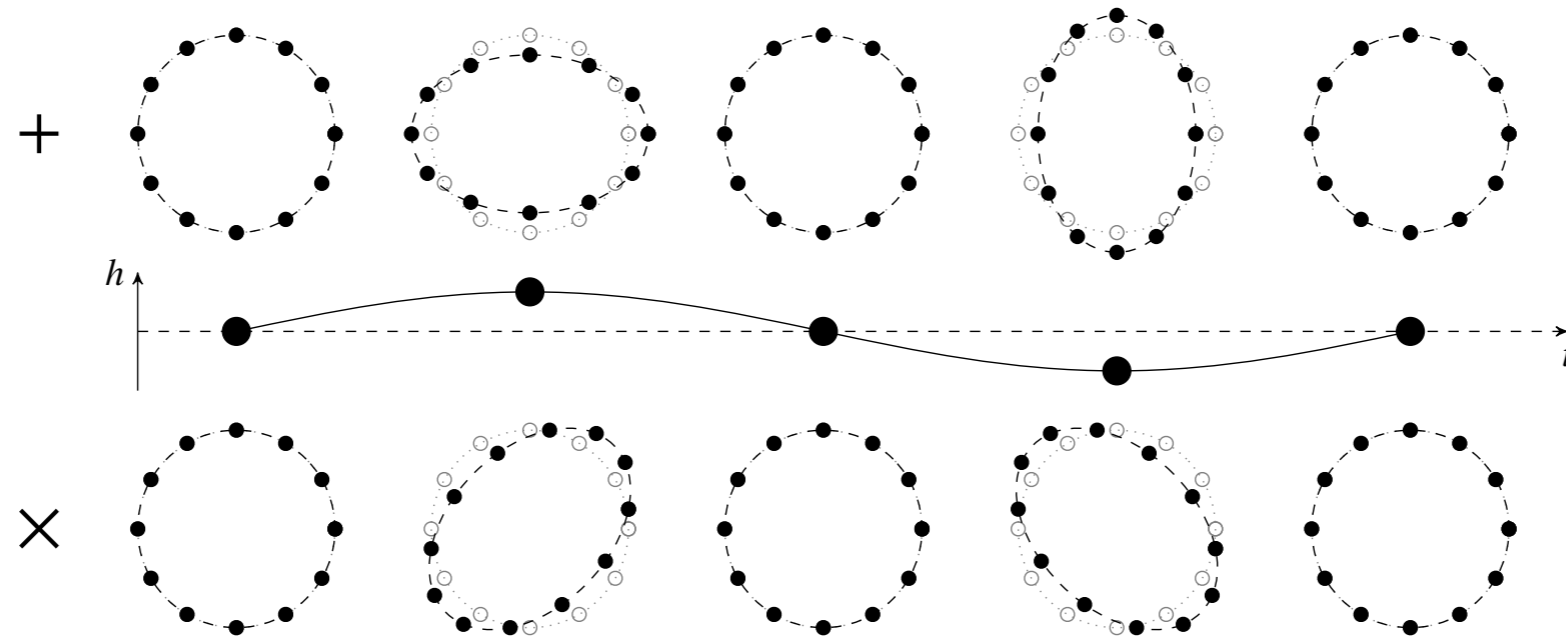


Frequency spectrum



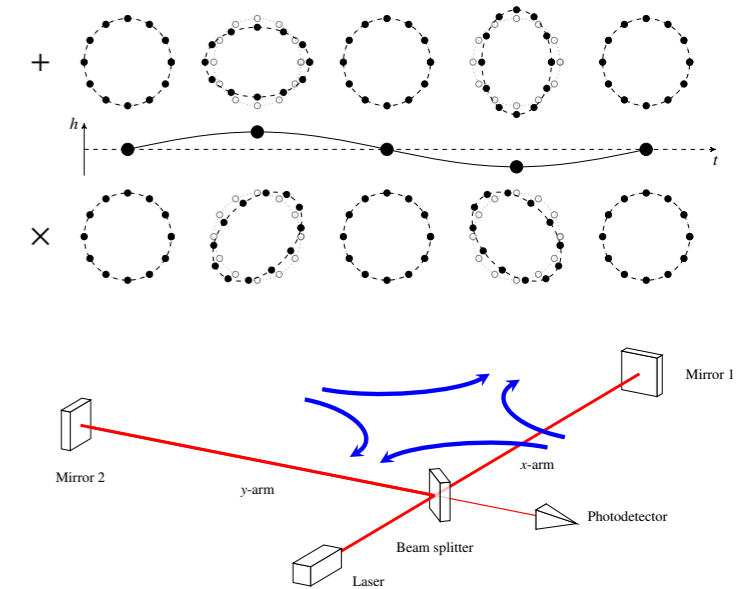
Interferometric detectors

- Exploit the tidal forces:



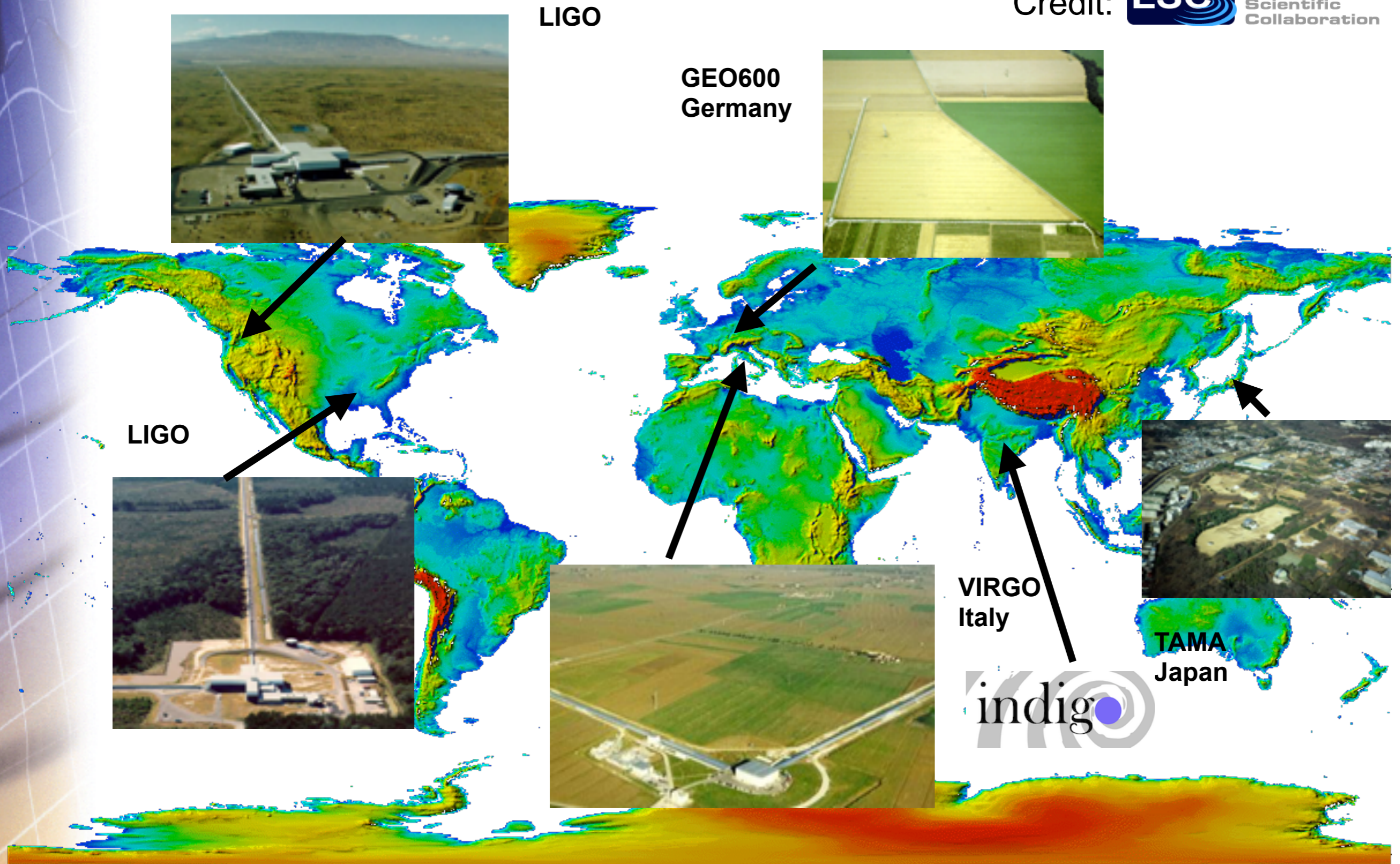
Interferometric detectors

- Exploit the tidal forces
- Effect of GW is a fractional change in length
 - the longer the baseline, the larger the effect
- Ground based detectors:
 - typical sizes ~km
 - required measurement sensitivity $\sim 10^{-19}$ m/ $\sqrt{\text{Hz}}$
- First prototypes ~ 1973
- Today a whole network of ground-based interferometric detectors



The Global Network

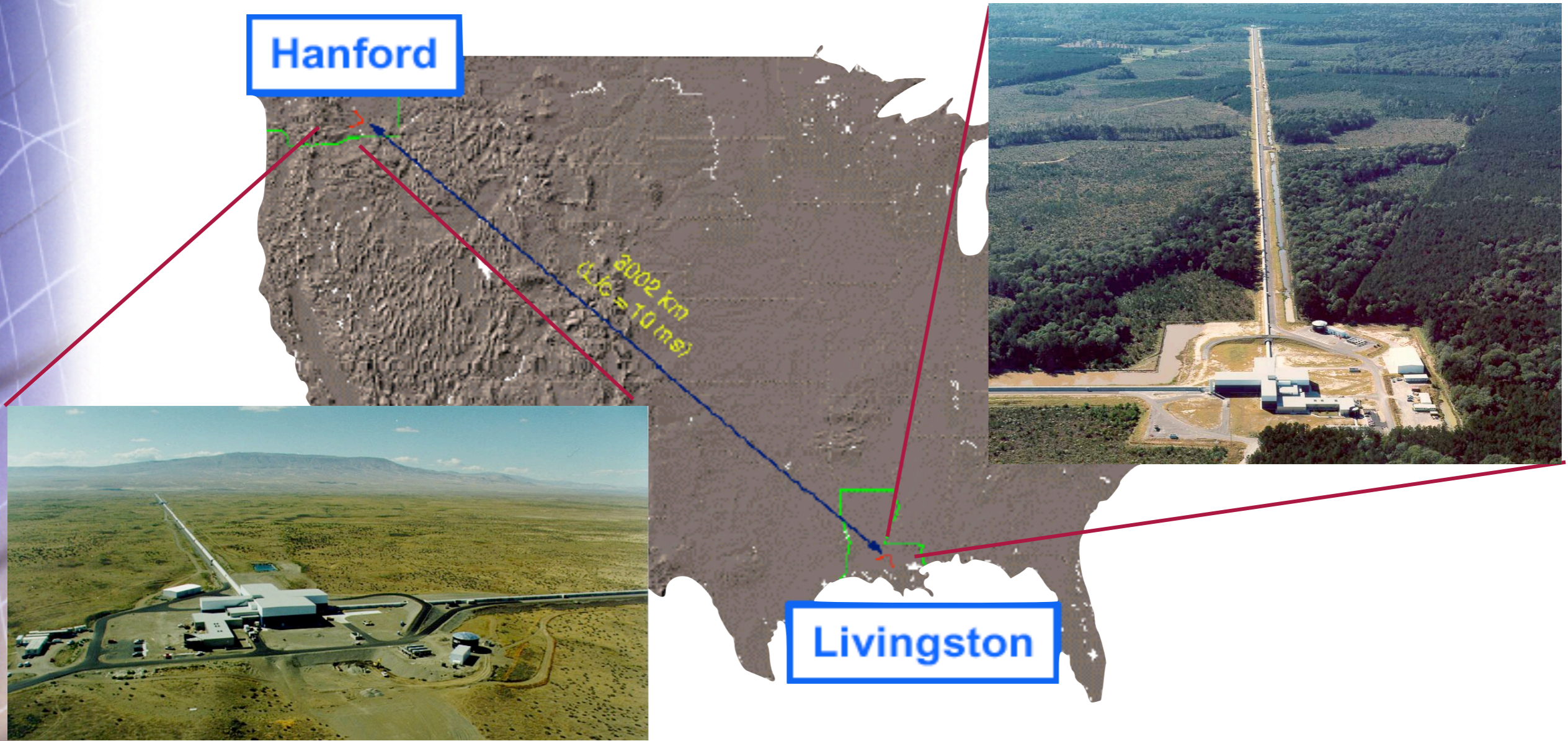
Credit:  LIGO Scientific Collaboration



LIGO

LIGO Observatories are operated by Caltech and MIT

Credit: LIGO Scientific Collaboration



LIGO Hanford Observatory

LIGO Livingston Observatory

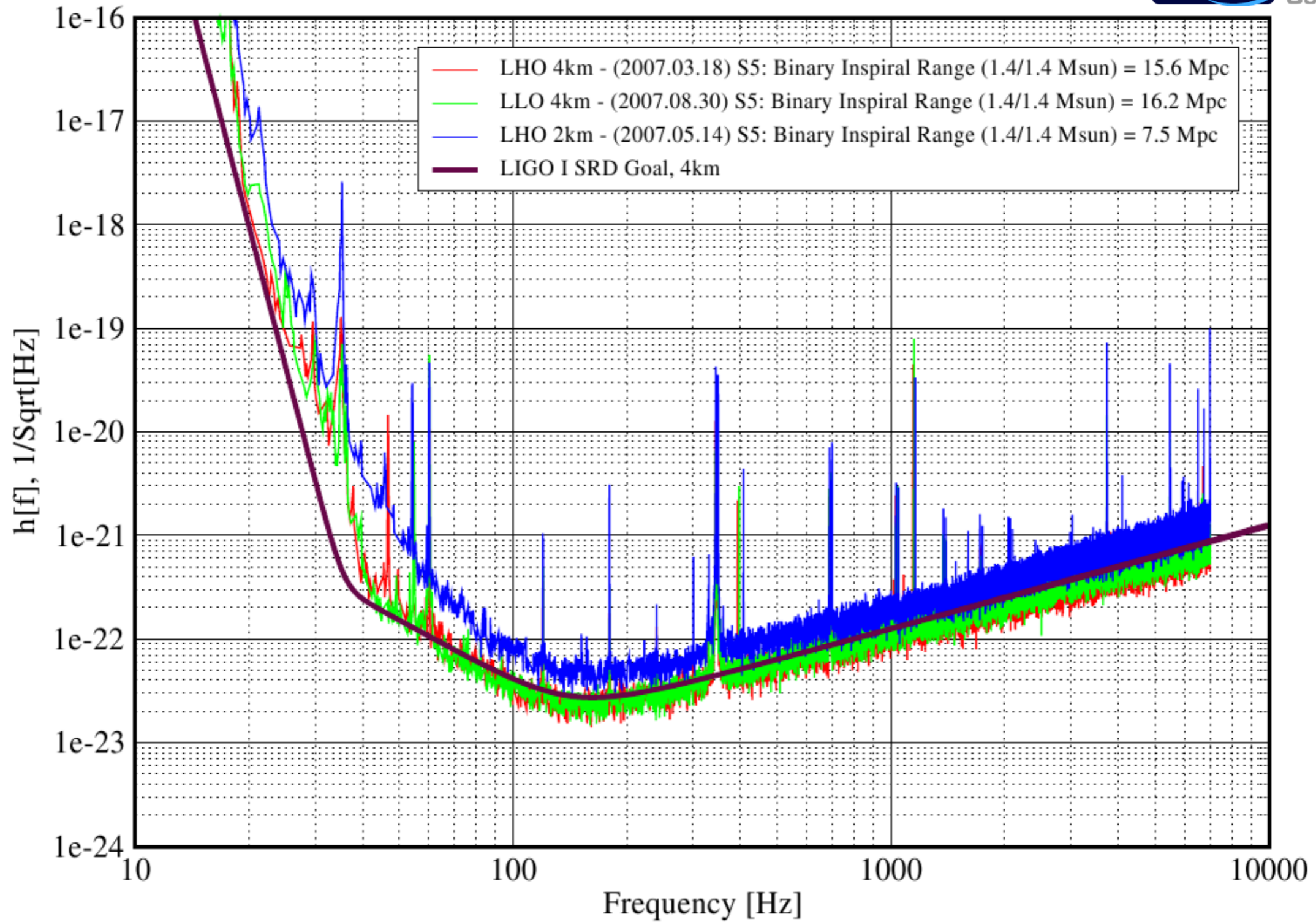
Virgo

Credit:  LIGO Scientific Collaboration



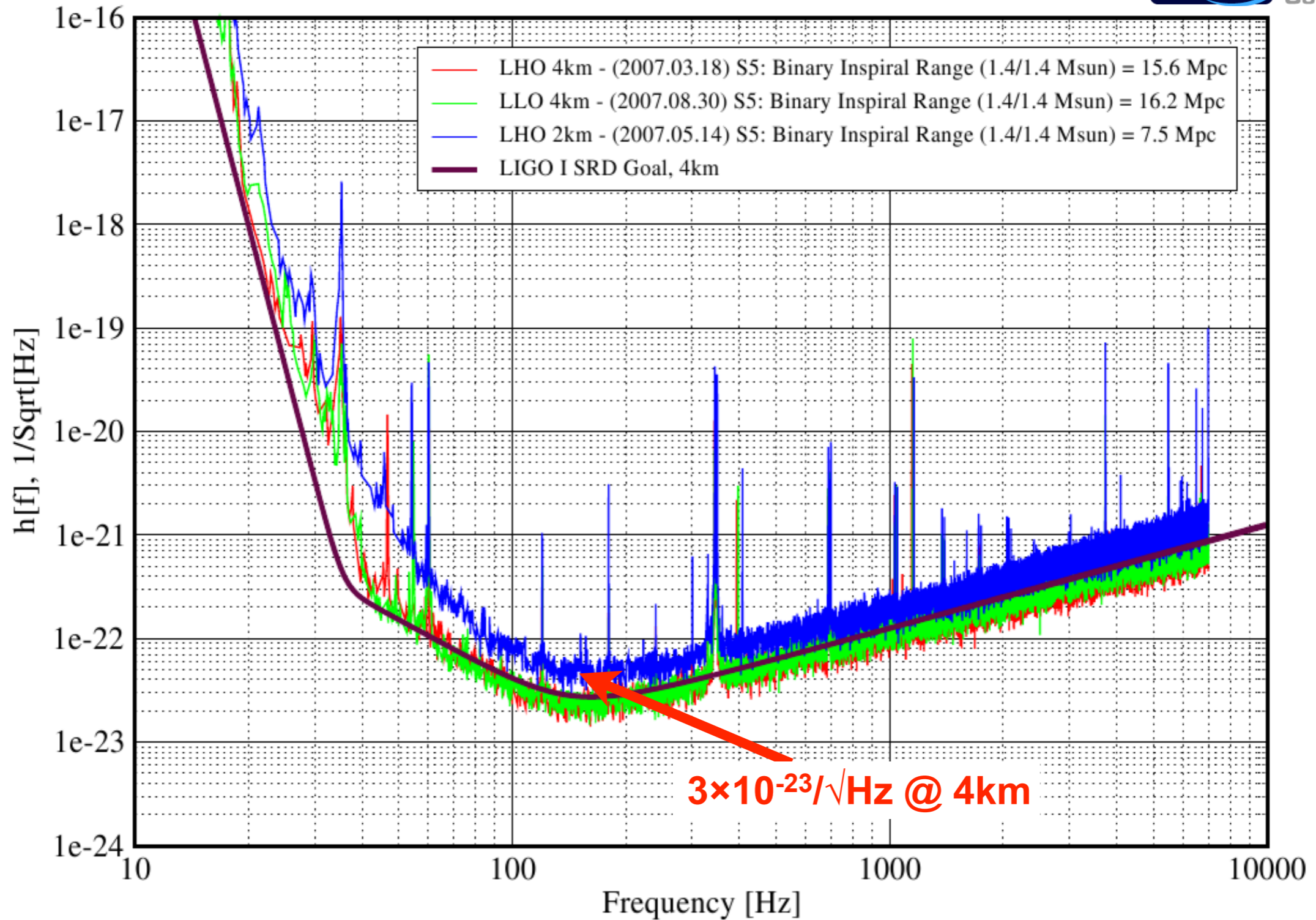
LIGO sensitivity

Credit:  LIGO Scientific Collaboration

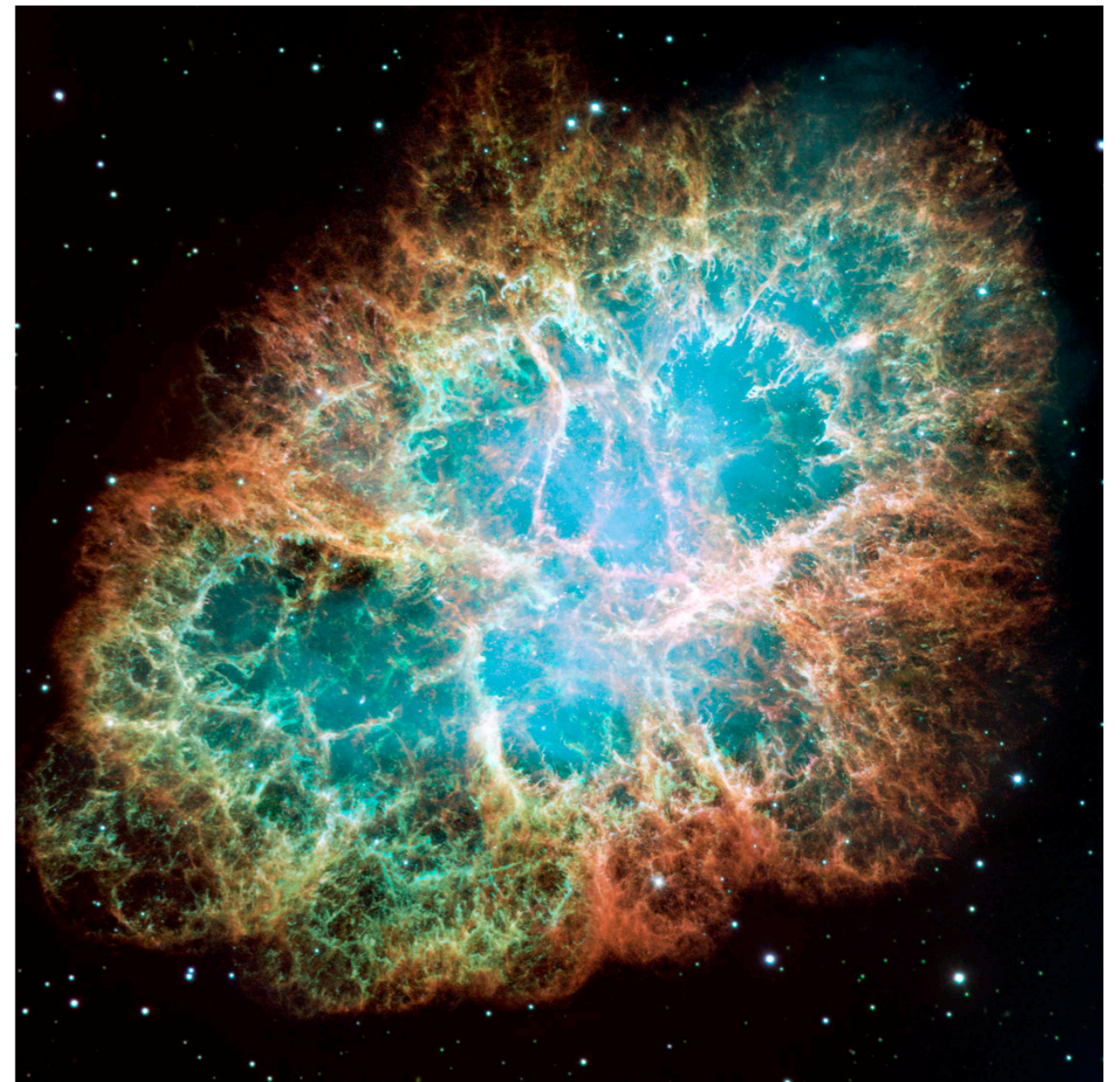


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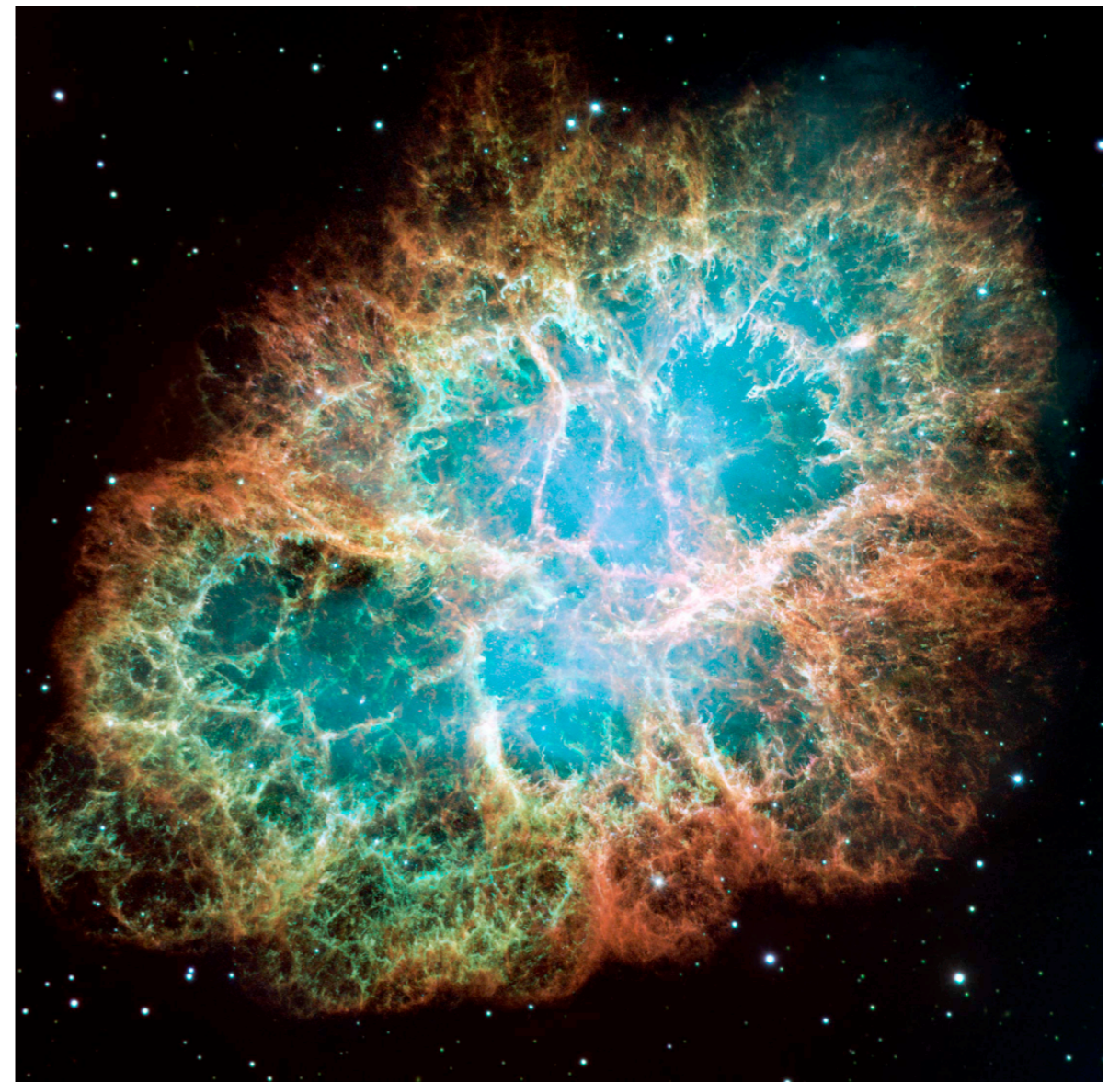


The Crab pulsar



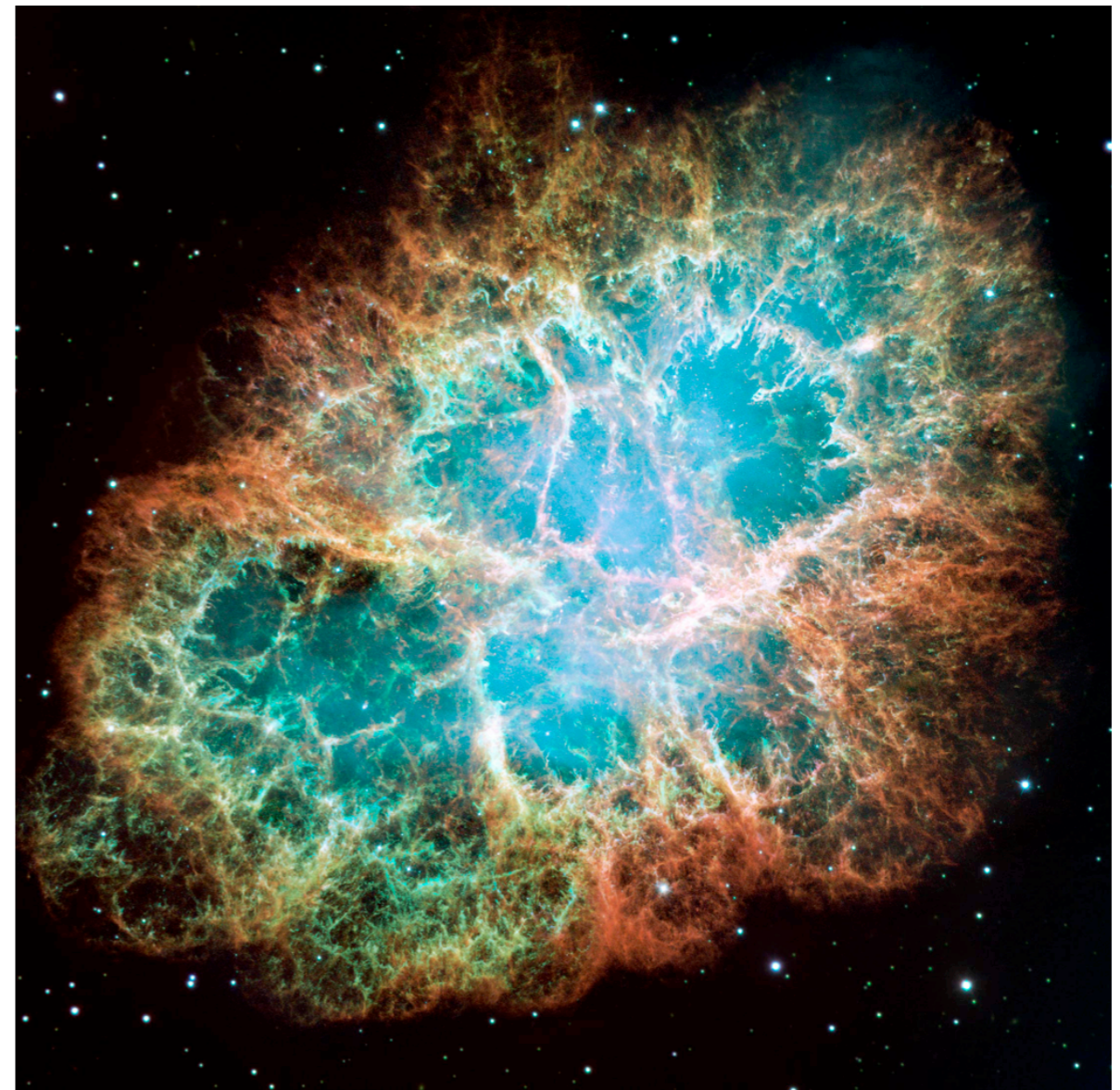
The Crab pulsar

- Crab pulsar rotates with $f \approx 30$ Hz



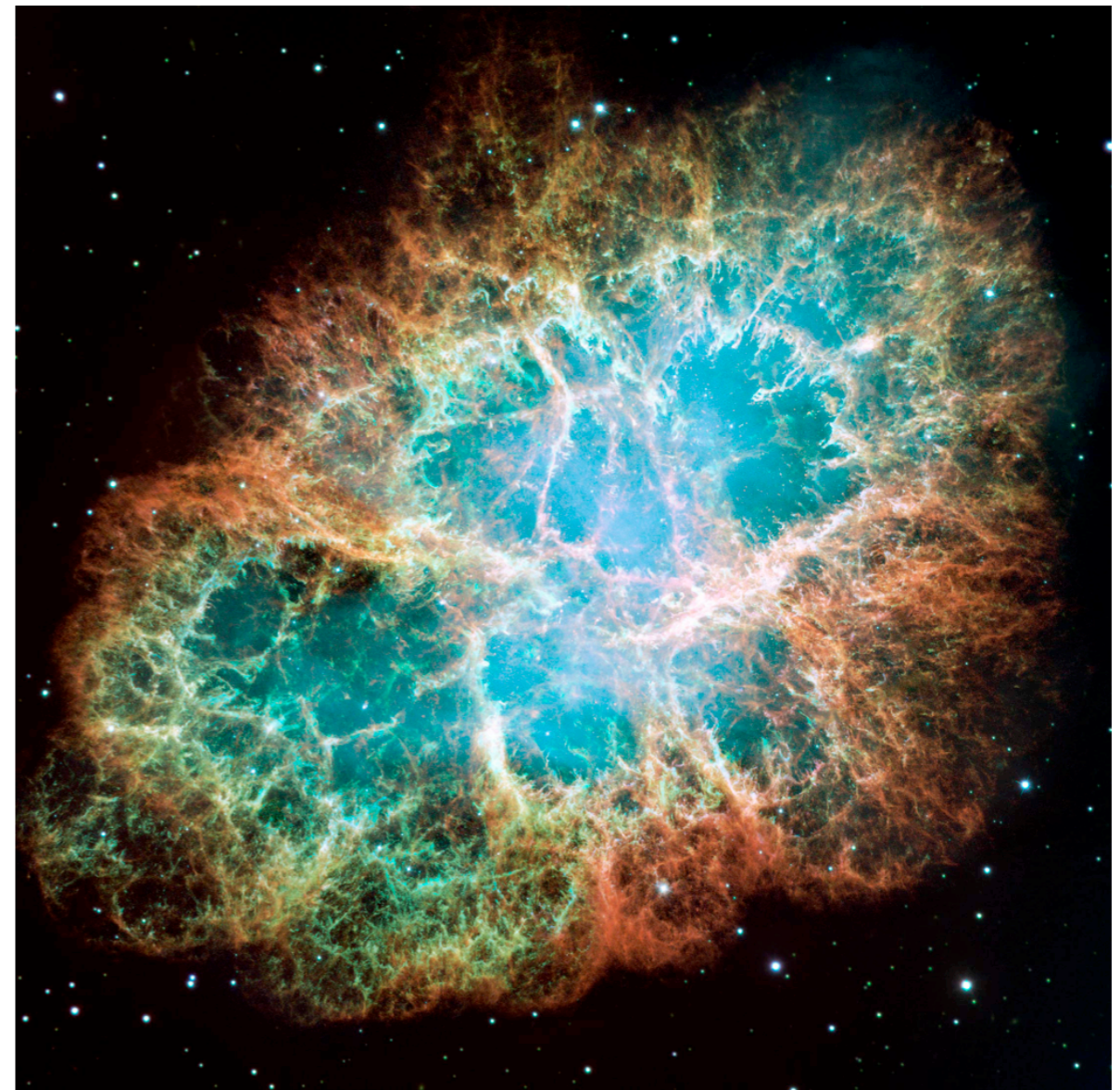
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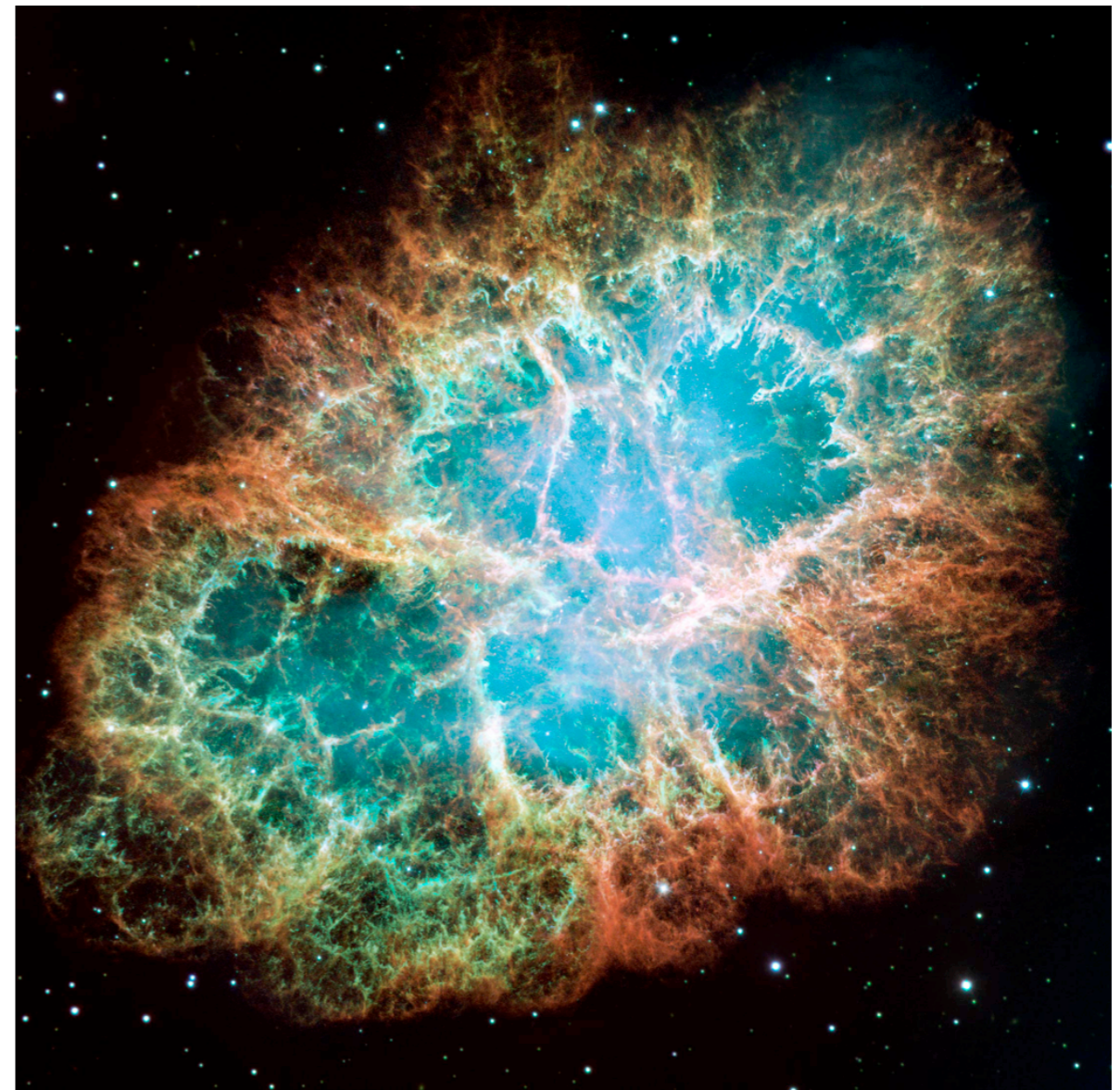
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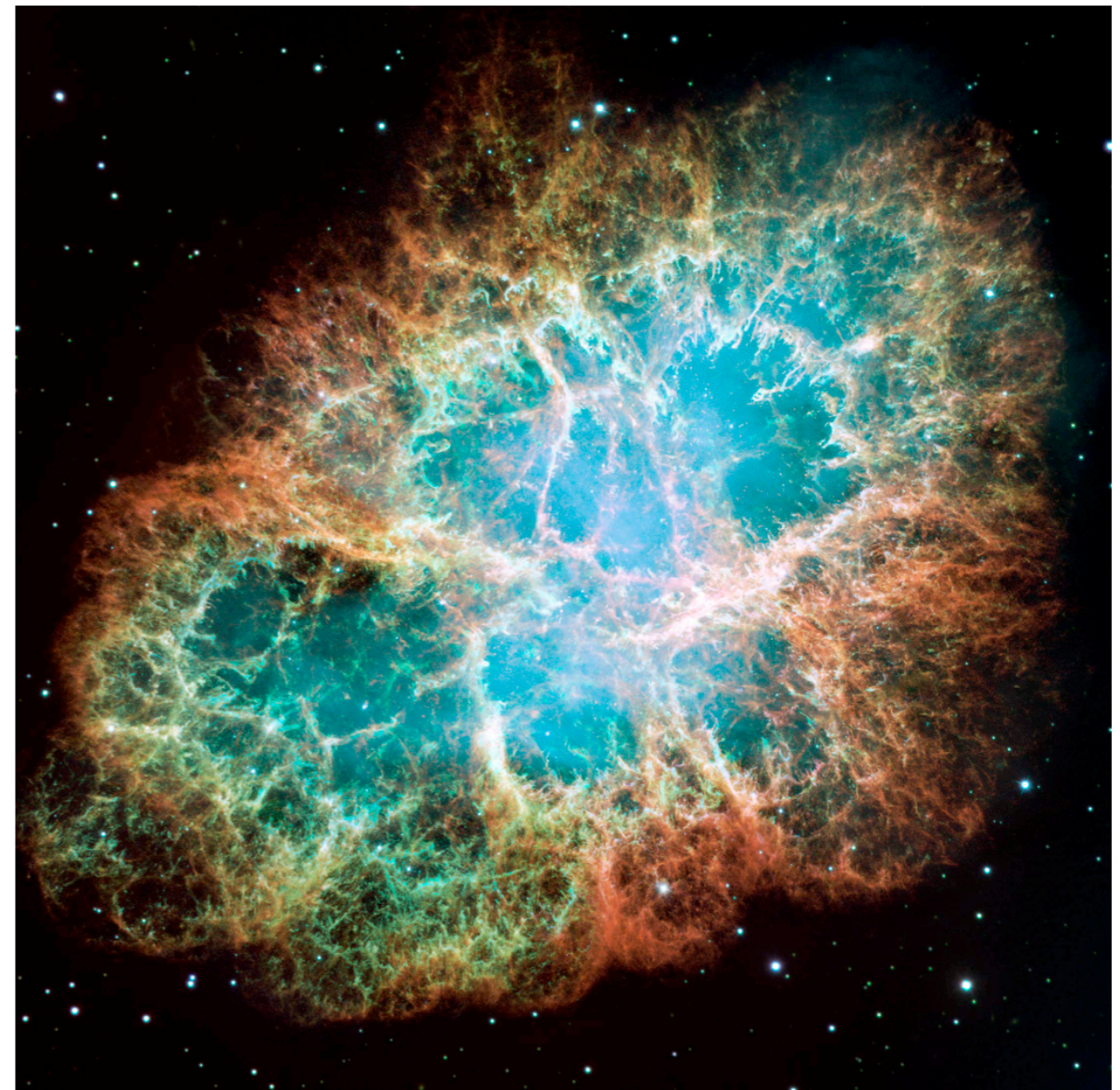
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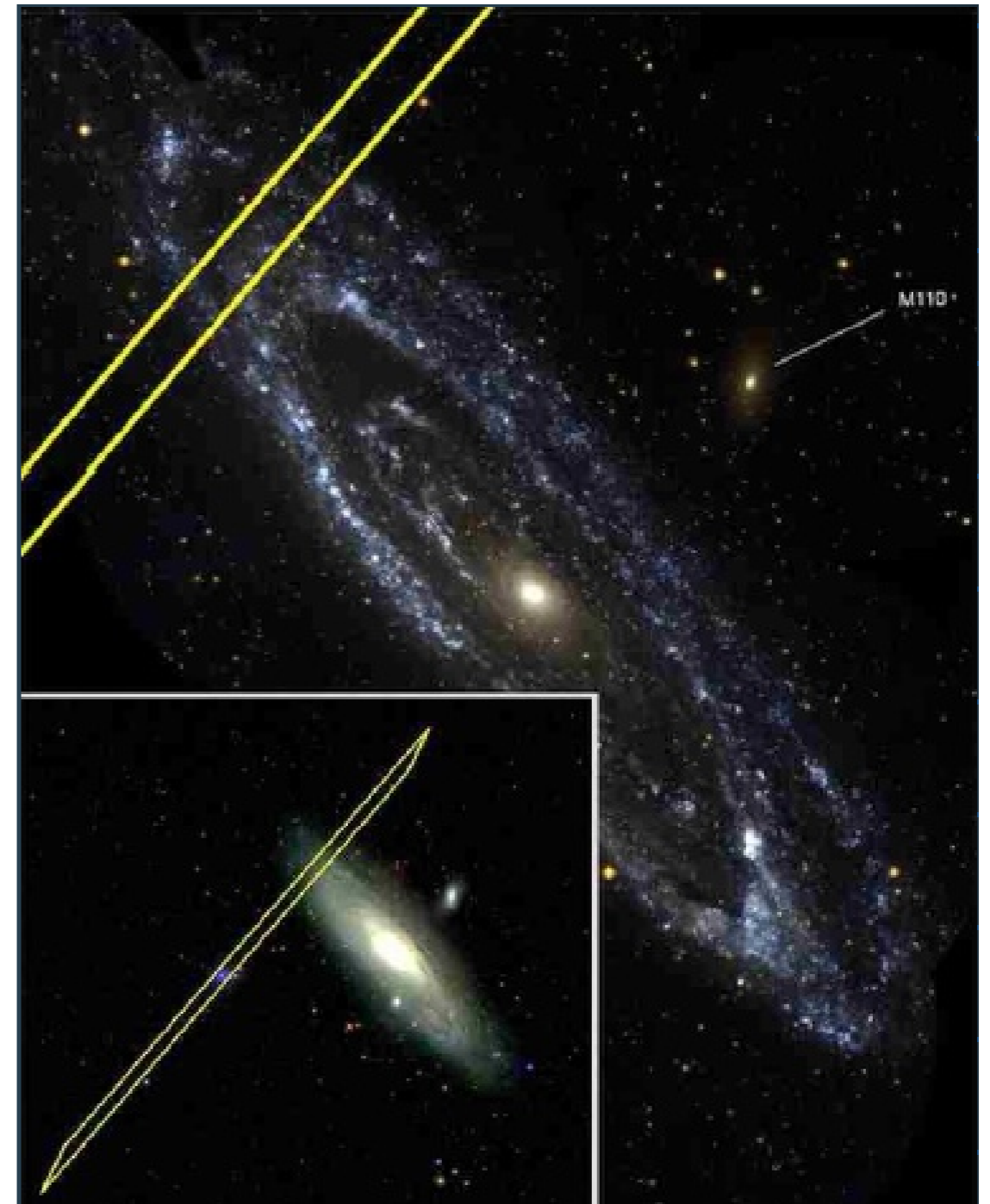
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- If mass quadrupole exists, GW expected at 60Hz
- Observed $df/dt \approx 0.37$ nHz/s gives limit on energy loss
 - up to 15% of energy loss due to GW plausible
- Result of GW search: <2% energy loss due to GW emission



GRB 070201

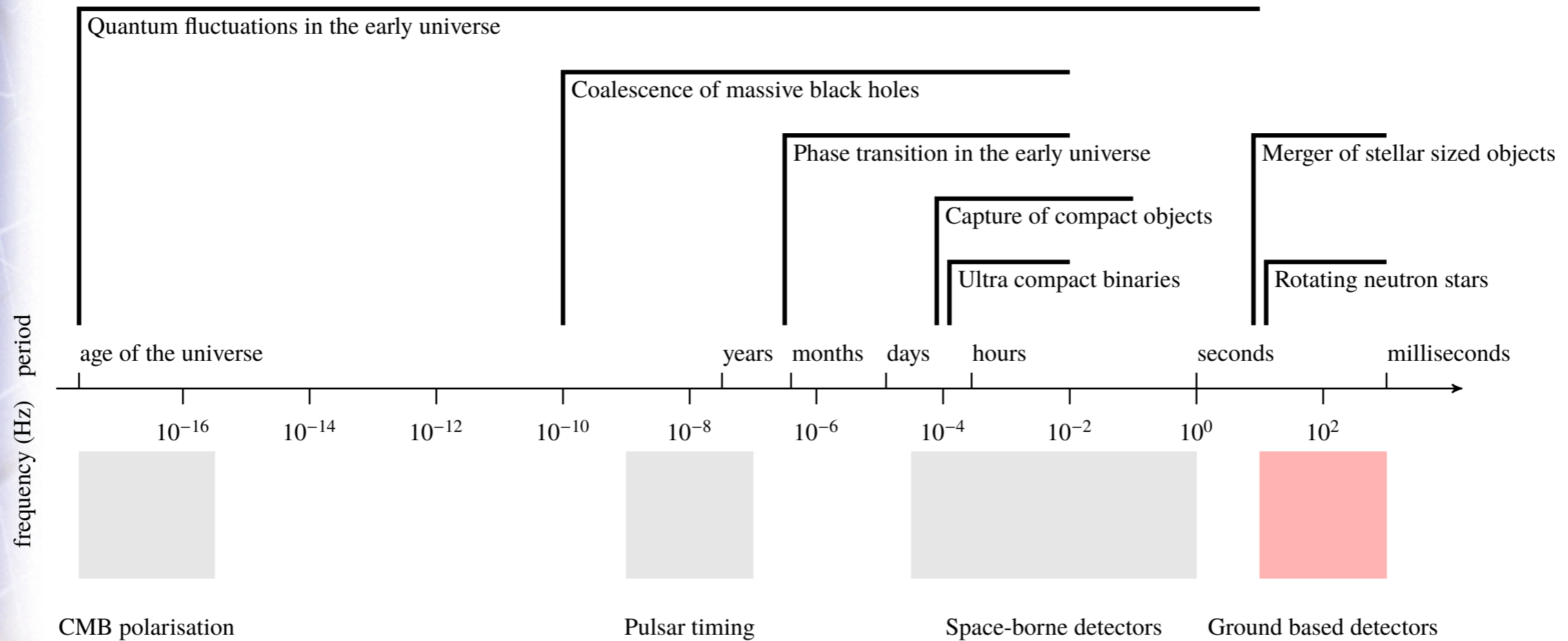
- GRB 070201 direction compatible with source in M31
- GW search: $P > 99\%$ that signal does not originate from a coalescing binary in M31



Ground based detectors

- **No direct detection (yet).**
- **Rate problem:**
 - LIGO “reach” currently about (max) 30 Mpc, 15 Mpc for typical NS-NS binary
 - expected rate of events few/century
- **aLIGO will have 10 times the reach, hence about 1000 times the rate!**
 - 10s of signal per year
 - routine operation expected by 2016

Frequency spectrum



Space borne GW detectors

- **Reminder:**

- the longer the baseline, the larger the effect
- the longer the baseline, the lower the frequency band

- **Advantage of space:**

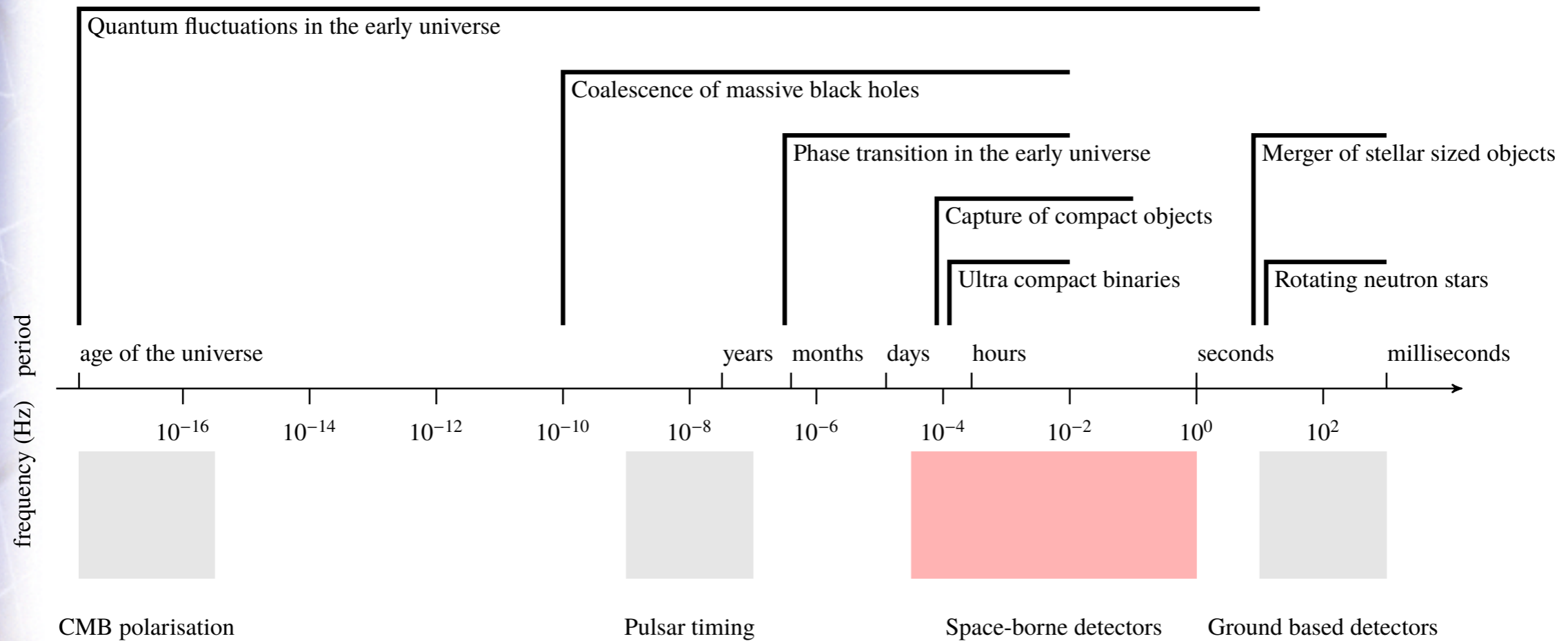
- baseline comes (almost) for free
- Vacuum is for free
- Anthropogenic noise sources are limited
- Very quiet environment possible

- **Disadvantage of space**

- Expensive
- Long planning cycles

- **Baseline of some million km opens an unexplored window**

Frequency spectrum

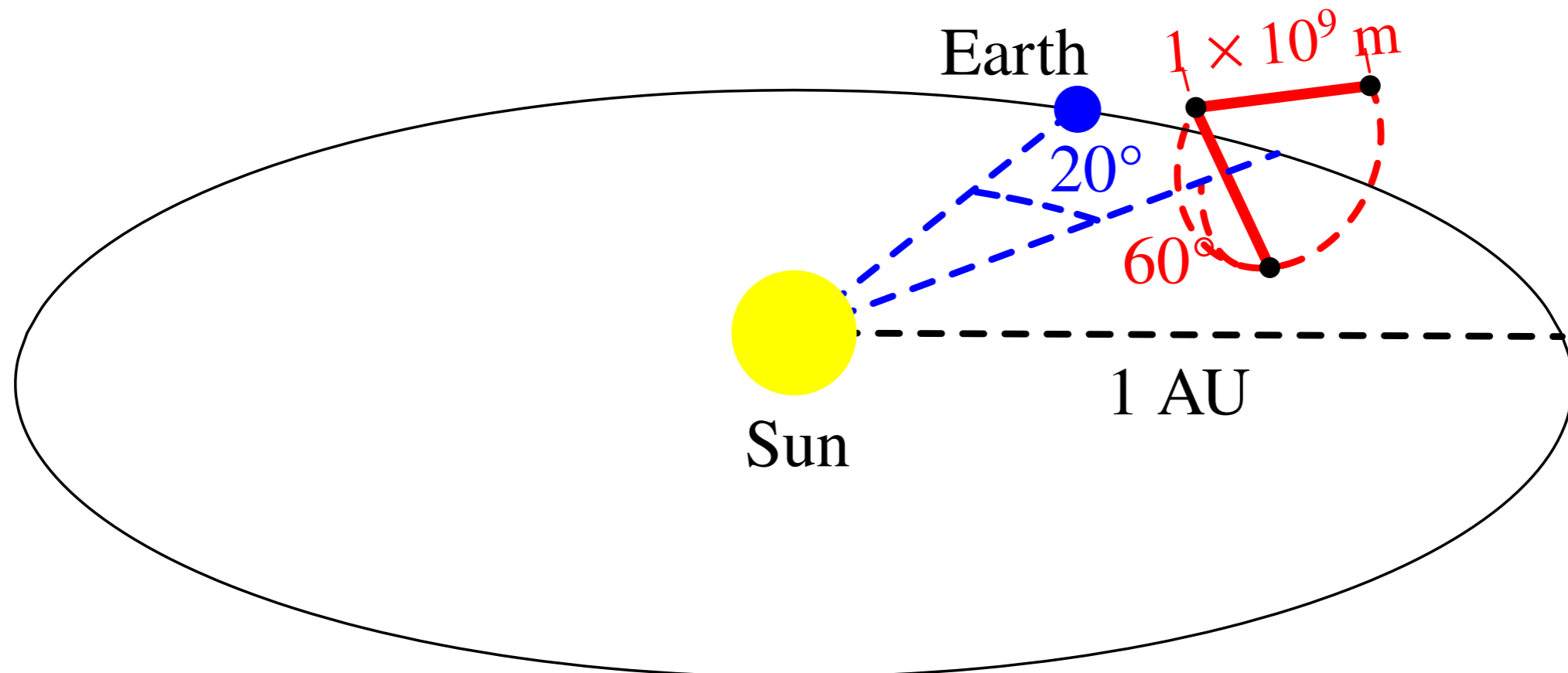


eLISA/NGO Mission Concept

- **Measure the change of distance between free falling proof masses**
- **Interferometric distance measurement**
 - Ensure picometer accuracy
 - 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, ...)

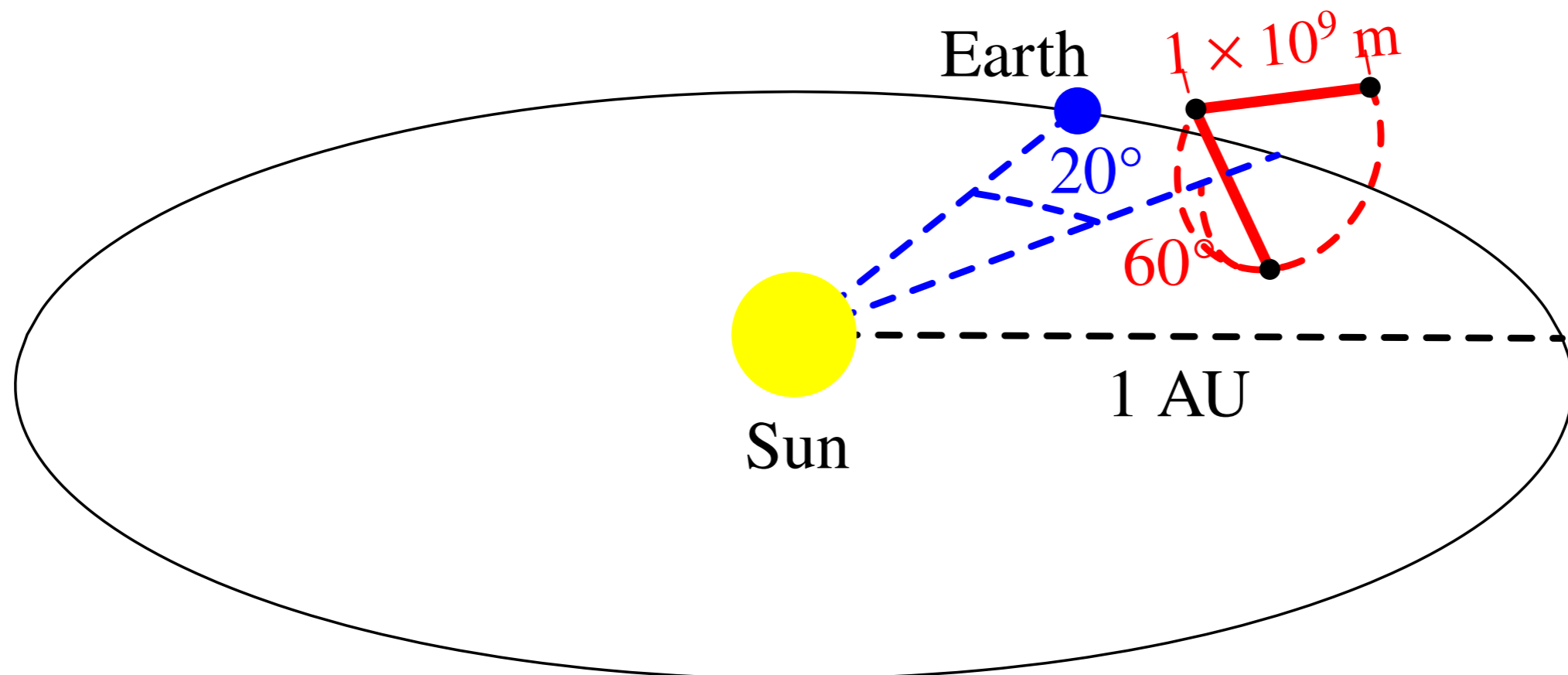
eLISA/NGO Mission Concept

- Constellation 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



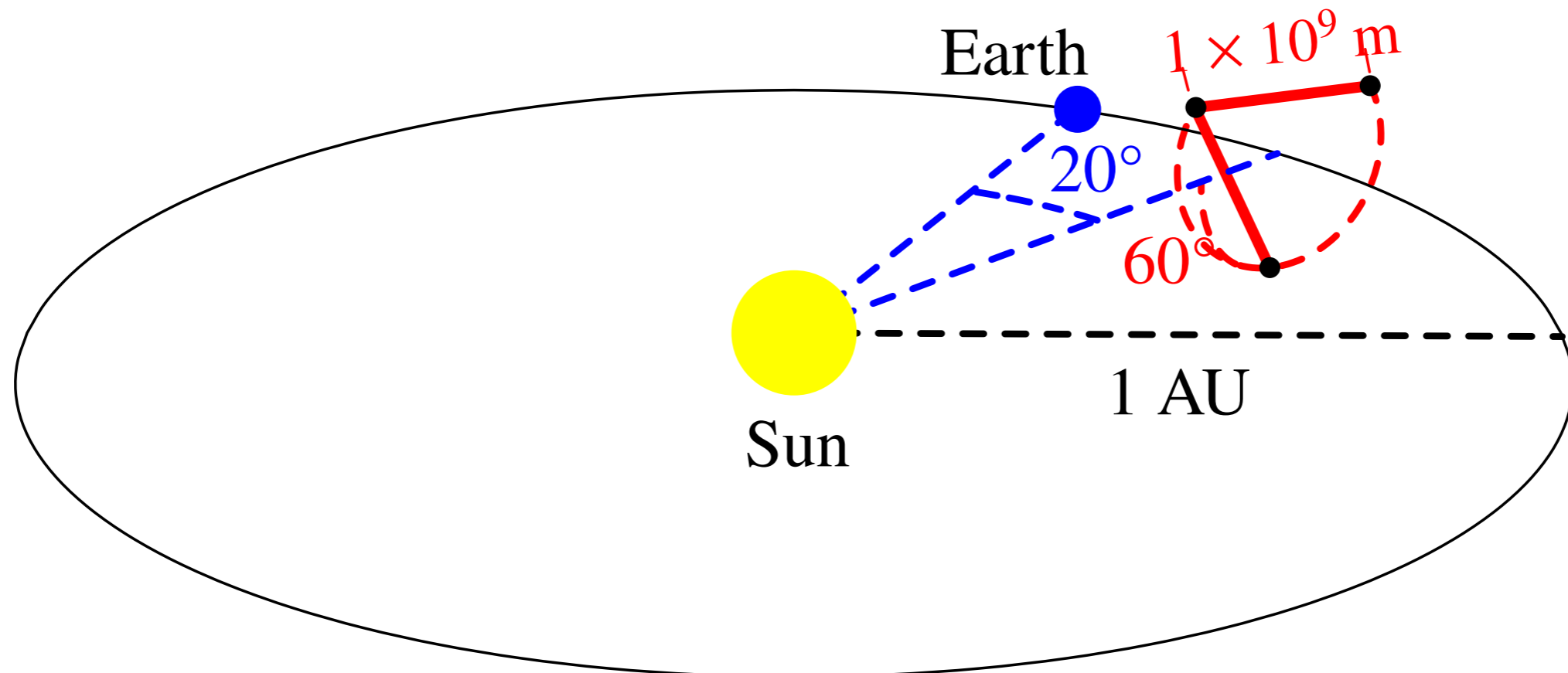
eLISA/NGO Mission Concept

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



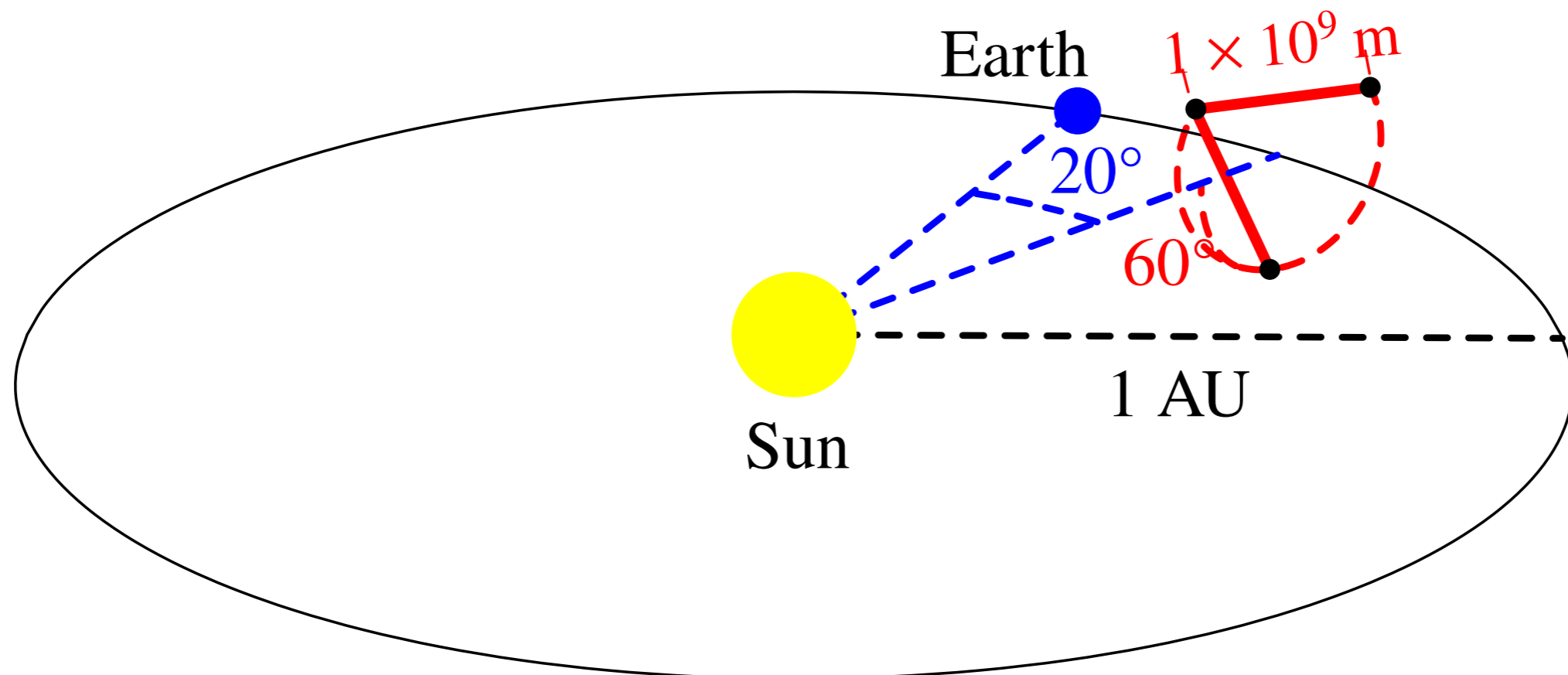
eLISA/NGO Mission Concept

- Constellation of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by $\sim 20^\circ$ (50 million kilometers)
- Equilateral triangle with 1 million kilometers arm length
 - Results in easily measurable pathlength variations
 - Orbit is still stable enough to allow for mission duration up to 5 years



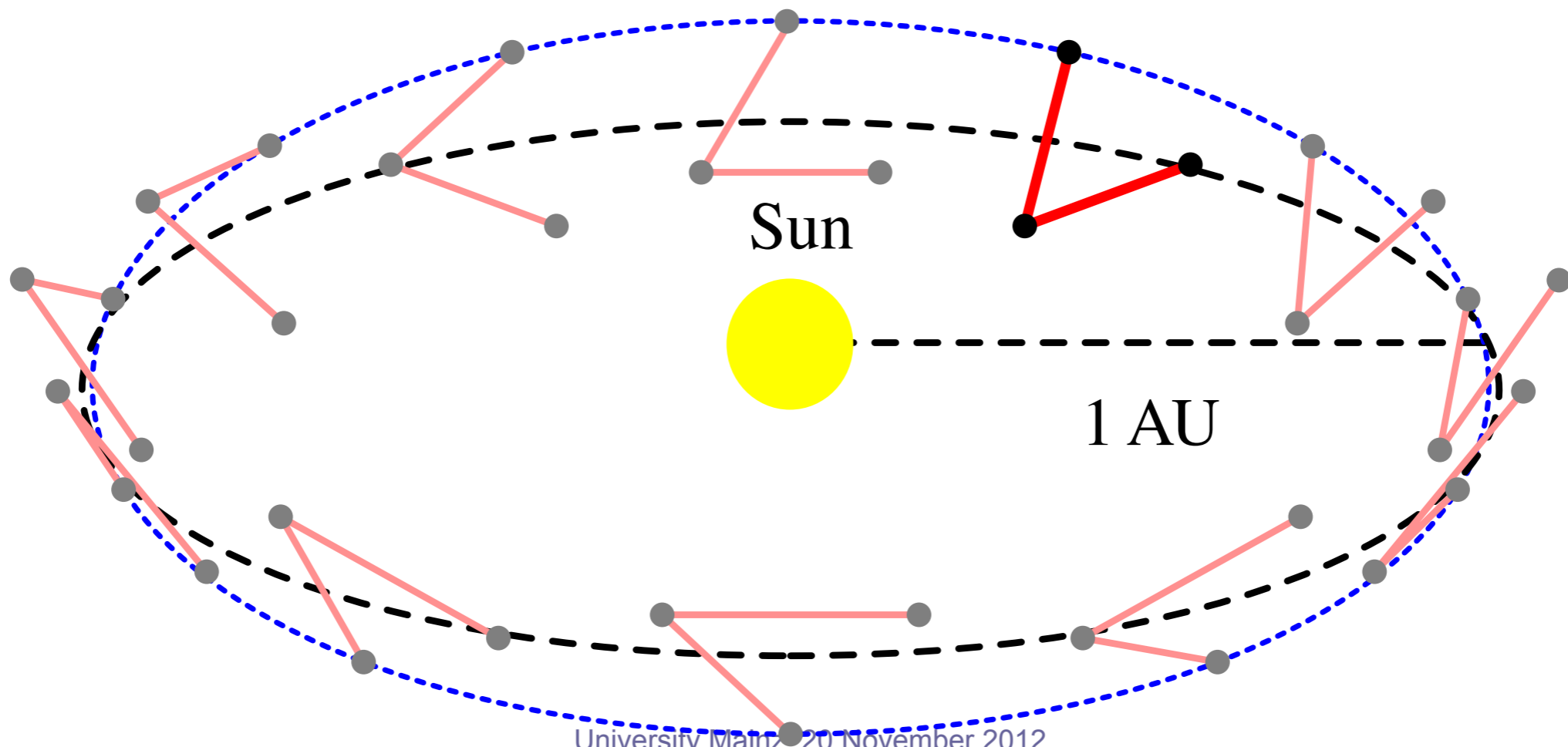
eLISA/NGO Mission Concept

- Constellation of 3 spacecraft in a heliocentric orbit
- Trailing the Earth by 20° (50 million kilometers)
- Equilateral triangle with 1 million kilometers arm length
- Inclined with respect to the ecliptic by 60°
 - Required by orbital mechanics



eLISA/NGO Mission Concept

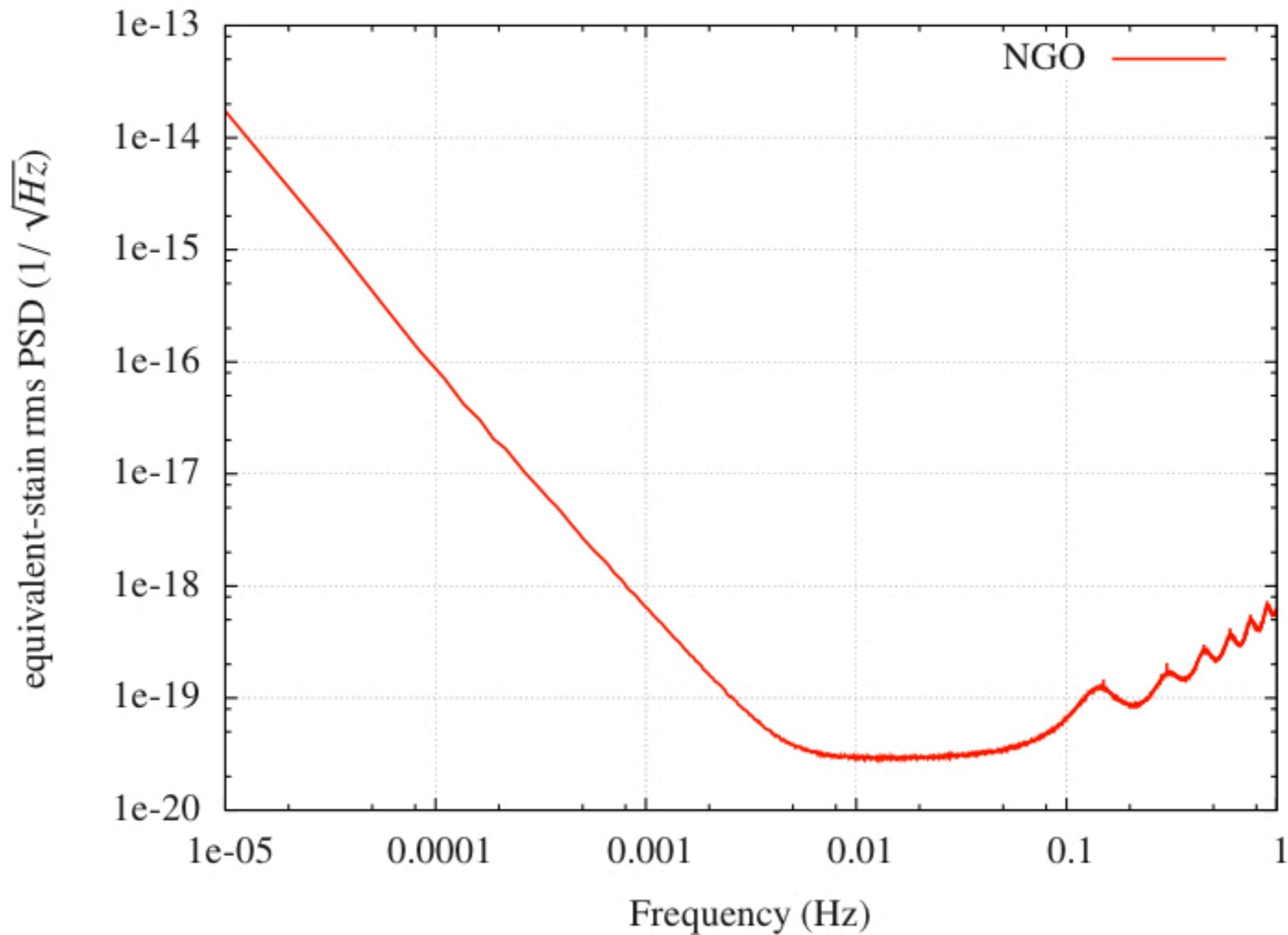
- Constellation counter-rotates during the course of one year.
- No additional orbit control necessary.
- Constellation forms an “almost rigid” triangle.



Sources

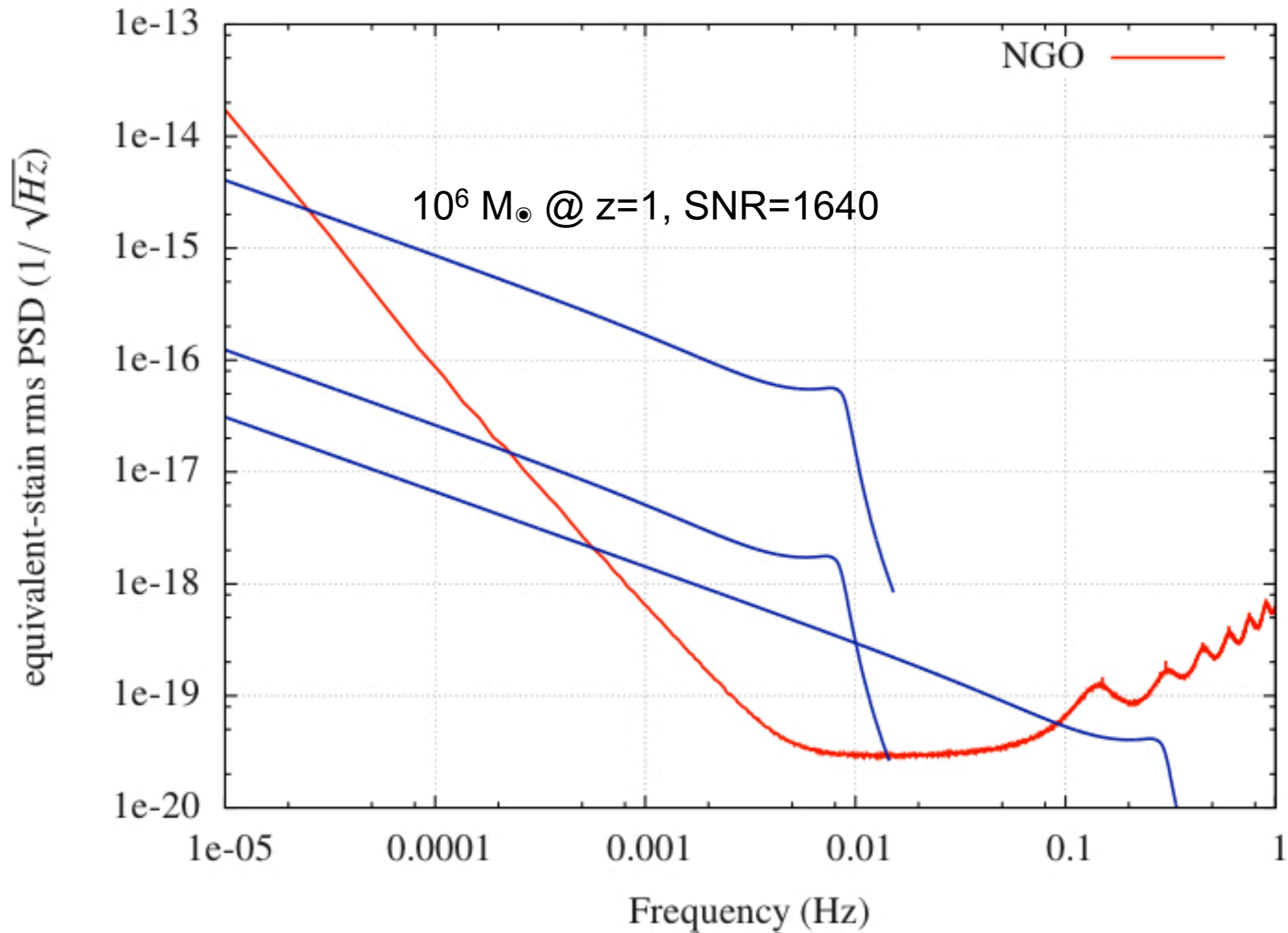
- **Massive Black hole coalescences**
 - Structure formation
 - Test of General relativity
- **Extreme mass ratio inspiral (“Test particle”)**
 - Testing GR with very high precision
 - Population studies around central Black Holes
- **Ultra-compact binaries**
 - Morphology of the galaxy
 - Binary evolution, stellar evolution

Sensitivity and BH Science



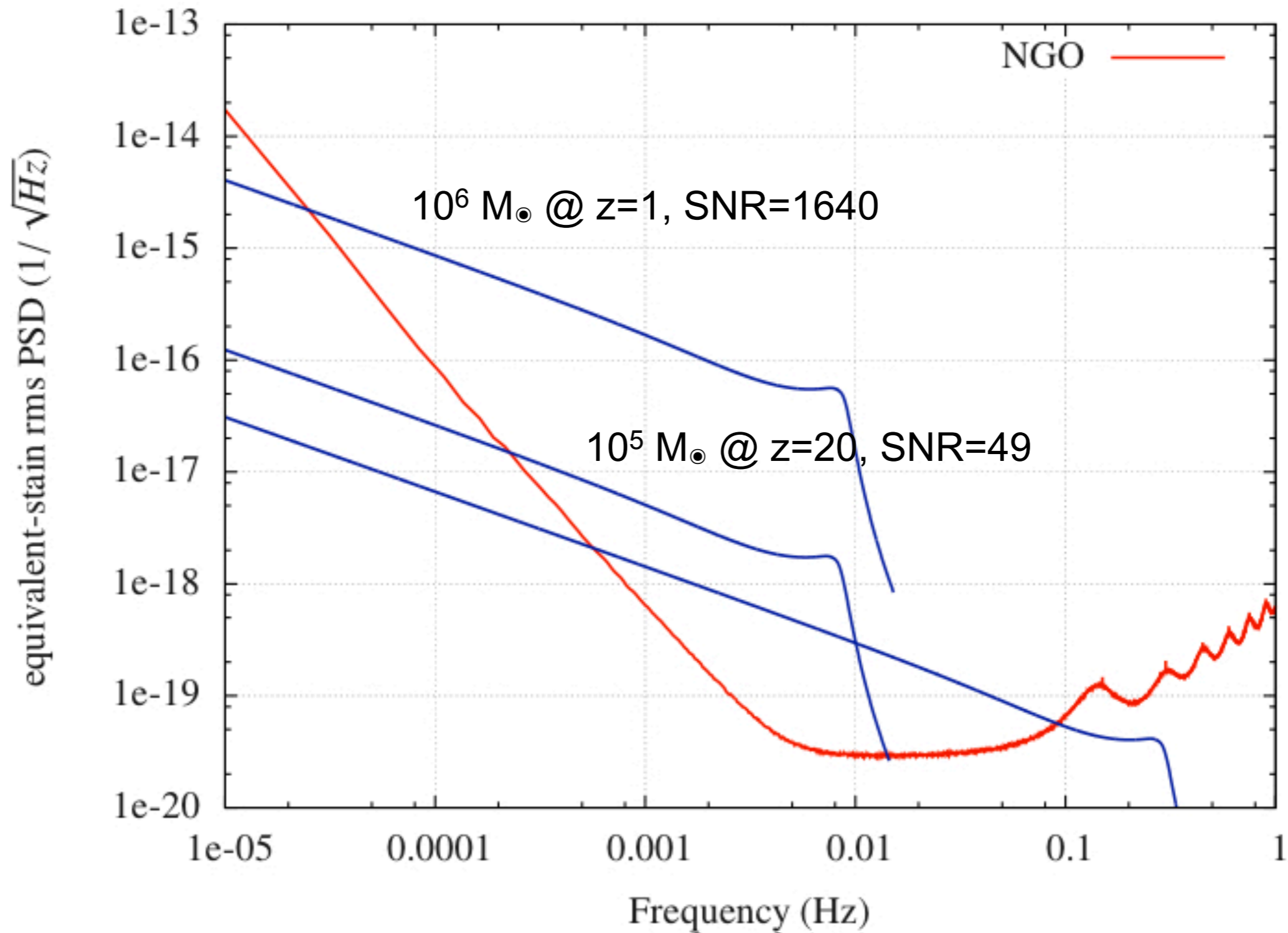
Slide: B. Schutz

Sensitivity and BH Science



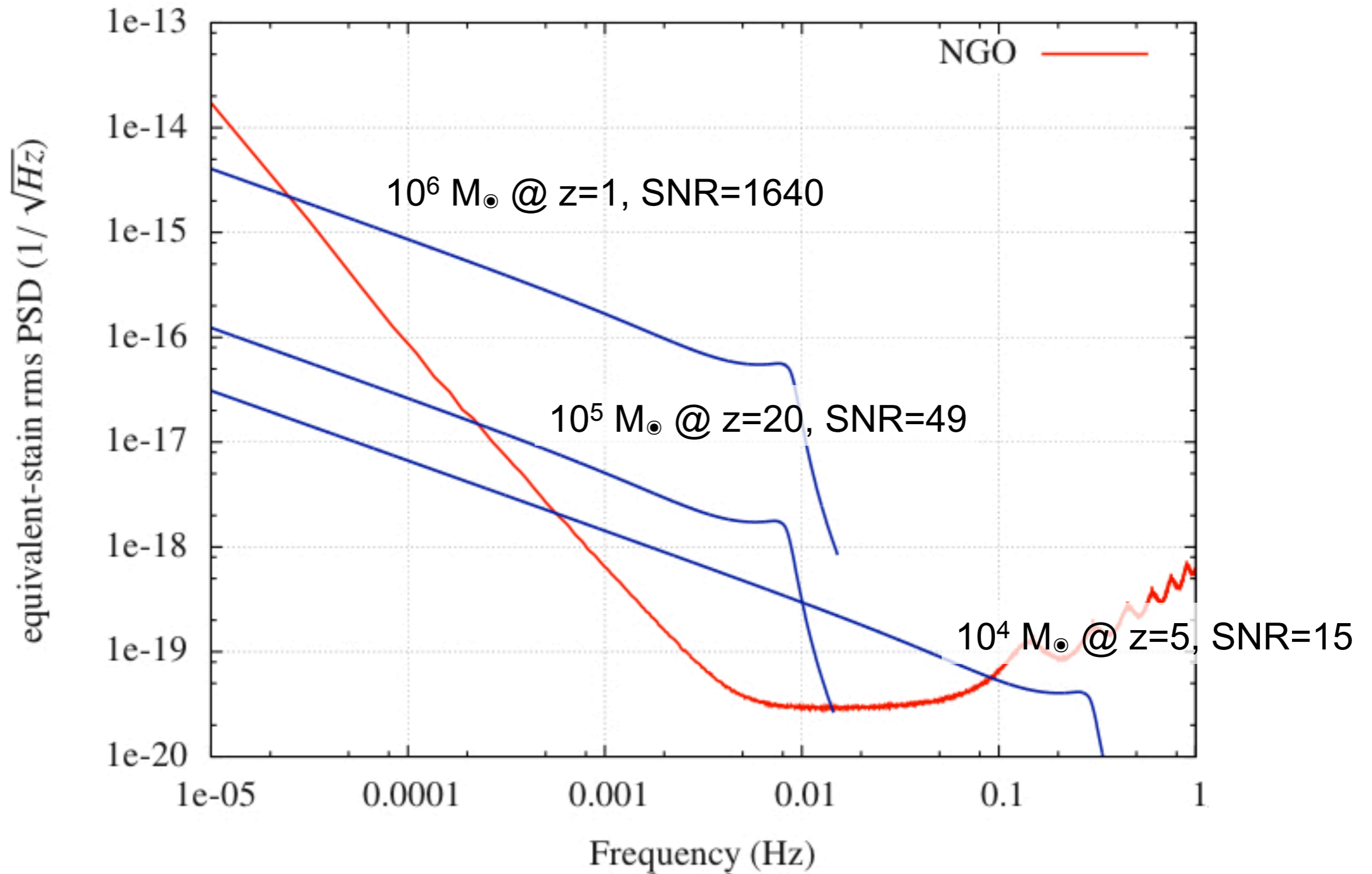
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Sensitivity and BH Science



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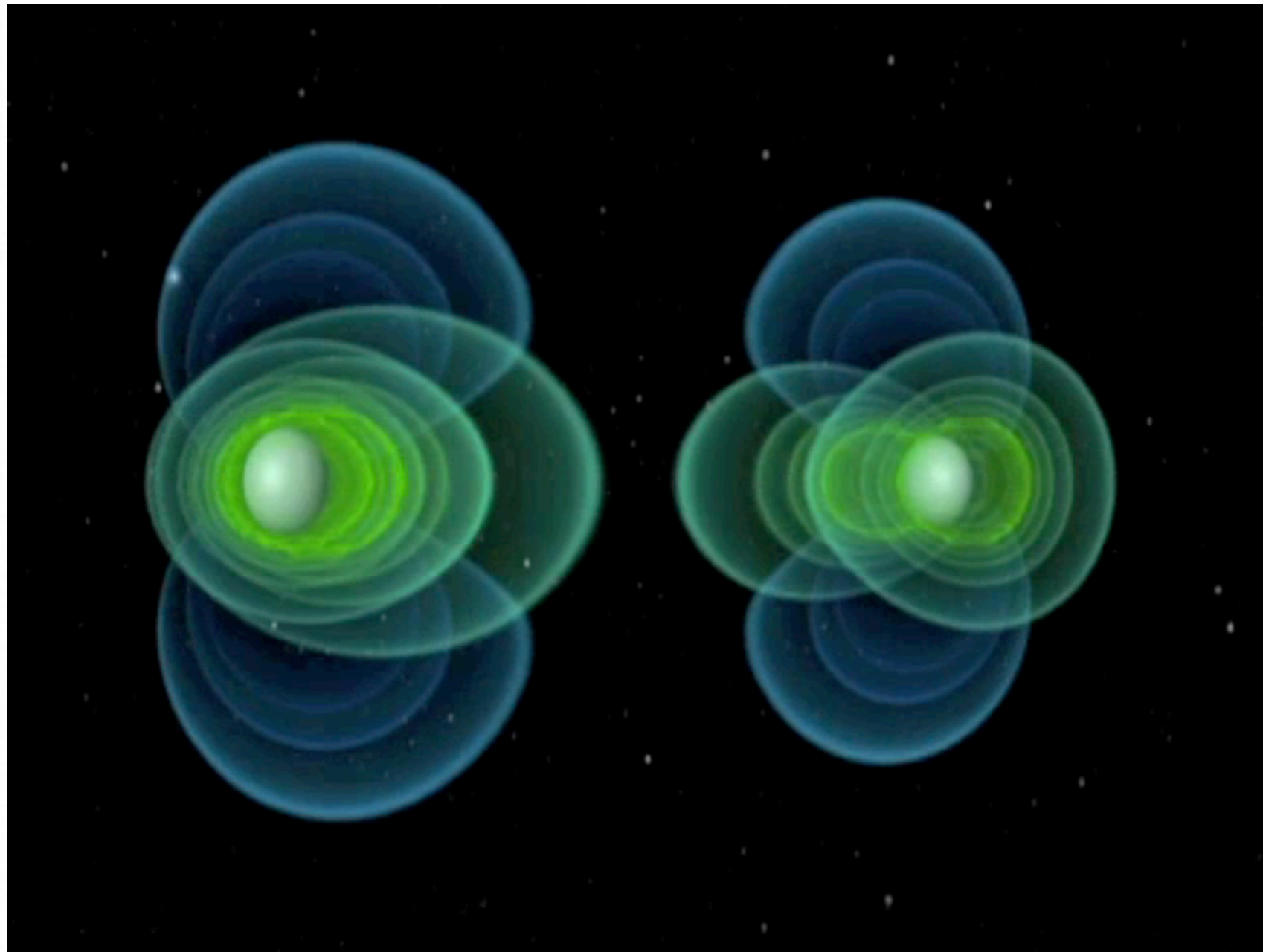
Black hole mergers

- eLISA should detect 10-200 BH-BH binary mergers in 2 years.
- **Direct measurement:**
 - masses to $\pm 0.5\%$, spin magnitudes to ± 0.01 .
 -

*Numerical relativity
simulation by AEI;
viz by M Koppitz,
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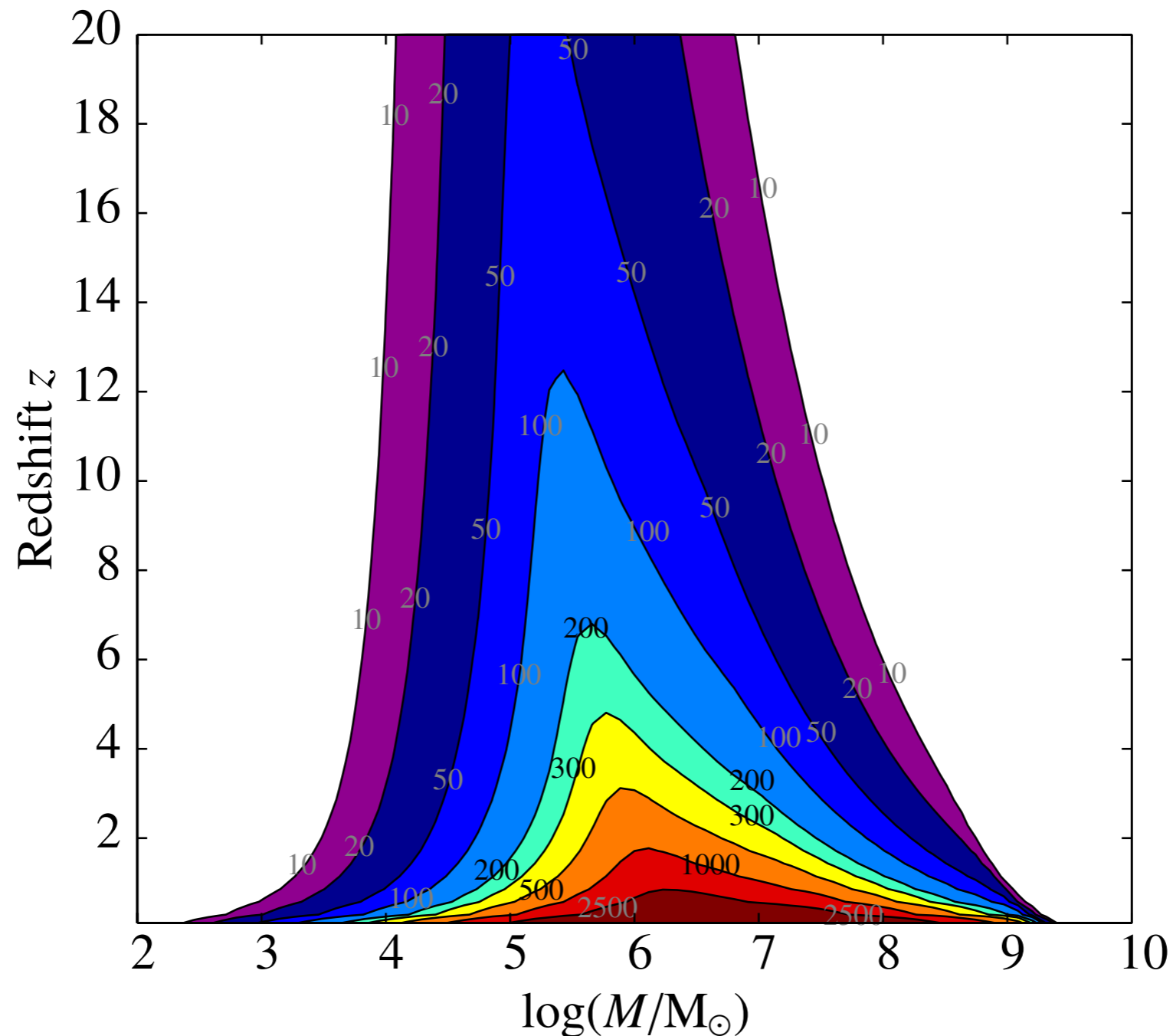
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Up close to BH mergers

- **eLISA should detect 10-200 BH-BH binary mergers in 2 years.**
- **Direct measurement:**
 - masses to $\pm 0.5\%$, spin magnitudes to ± 0.01 .
- **Spin alignments**
 - wet (gas rich) or dry merger.
- **Test GR in strong gravity at the edge of a black hole.**
 - Signal vs numerical simulations in GR (and if needed, in other theories).
 - Violations of cosmic censorship?
 - Other gravitational degrees of freedom?
 - ...

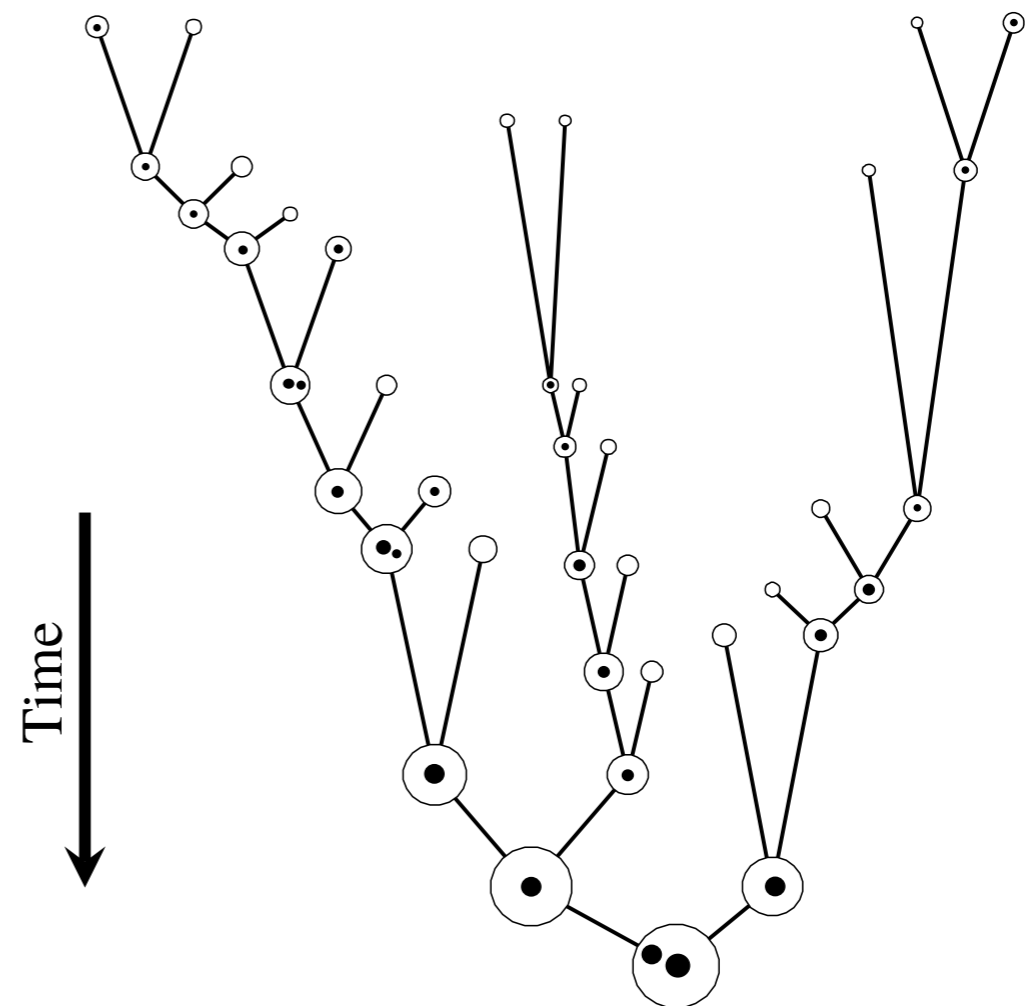
Observing the entire universe

- eLISA will detect ALL the mergers in the universe in its frequency band, even out to $z=15$ and beyond if they are happening.



How did SMBHs form and grow?

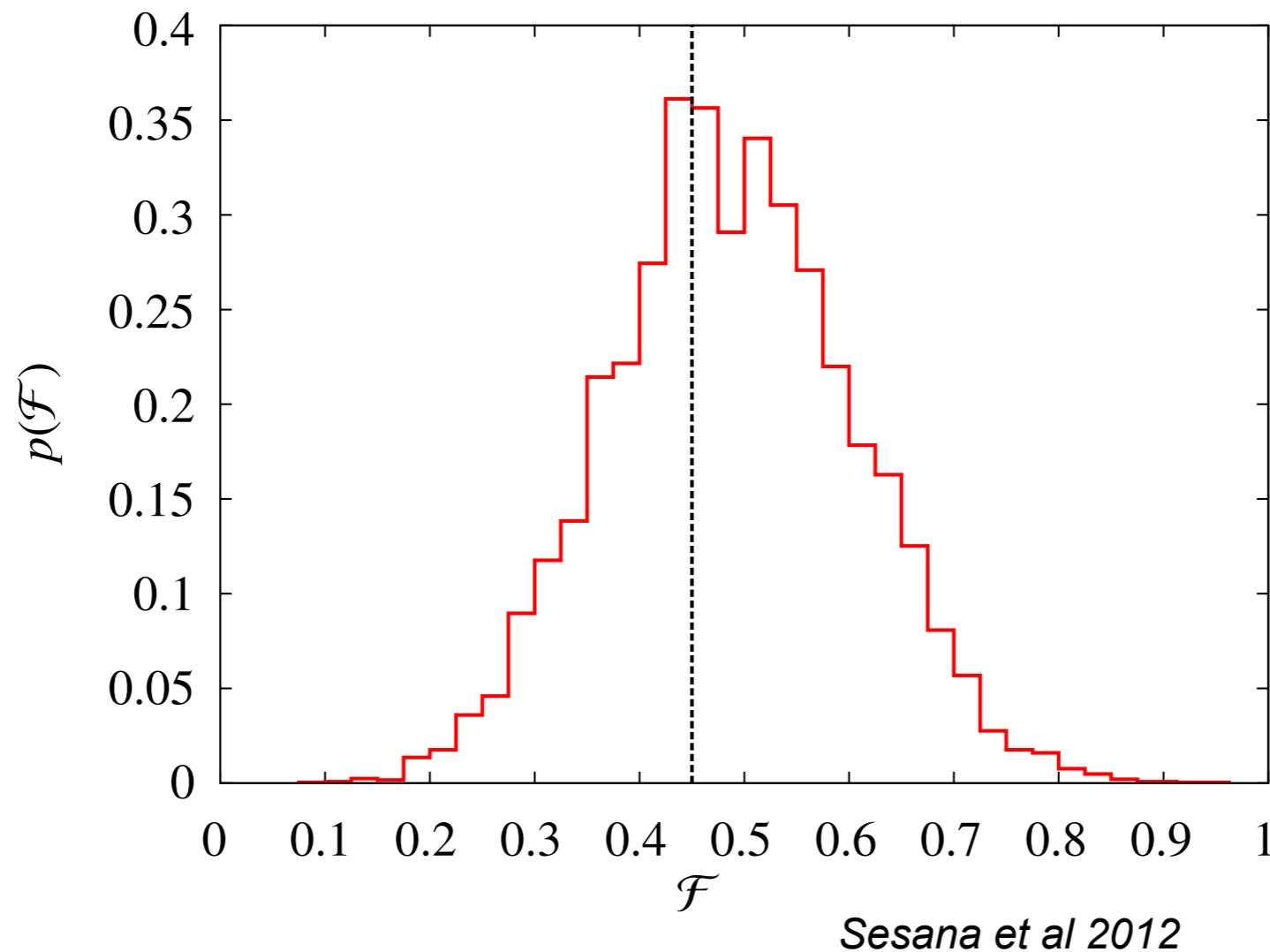
- NGO will detect enough mergers to $z = 15$ to discriminate among different seed models (early or late), accretion models, metallicities.
- Most if not all massive black holes are in the LISA band at some point in their cosmic evolution.



Volonteri 2010

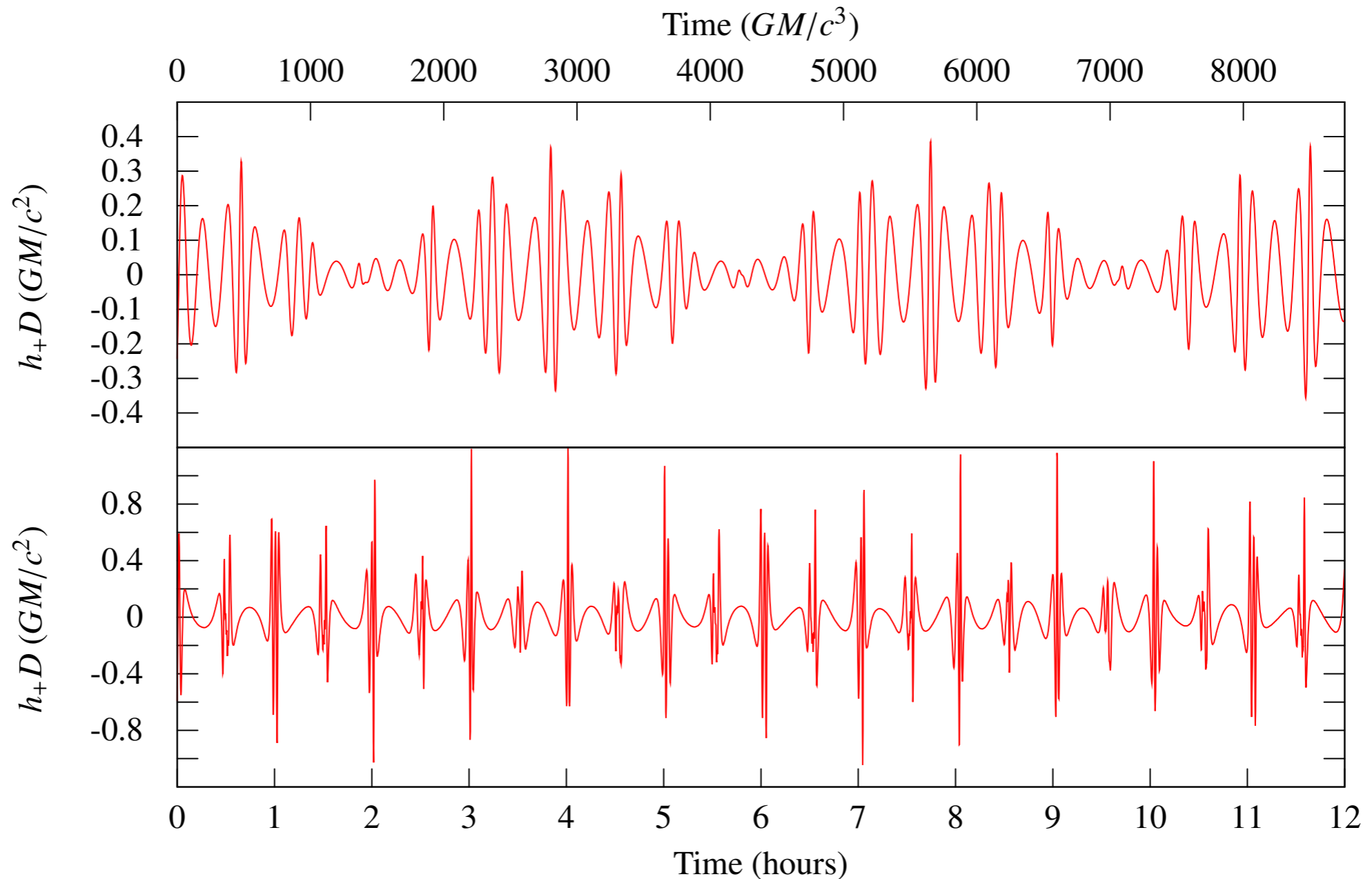
How did SMBHs form and grow?

- “Hybrid” seed model:
 - fraction \mathcal{F} of BHs originates from small early seeds (Pop III BHs)
 - $(1-\mathcal{F})$ originates from later large seeds (more recent gas cloud collapse).



Extreme Mass-Ratio Inspirals: EMRIs

- Stellar-mass BH capture by a massive BH: dozens per year to $z \sim 0.7$.
 - Very complex and rich signal



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Large black hole:
 shown to scale
 3,000,000 solar masses
 90% maximal spin

Small black hole:
 shown enlarged
 270 solar masses
 negligible spin

Trace duration:
 1 day

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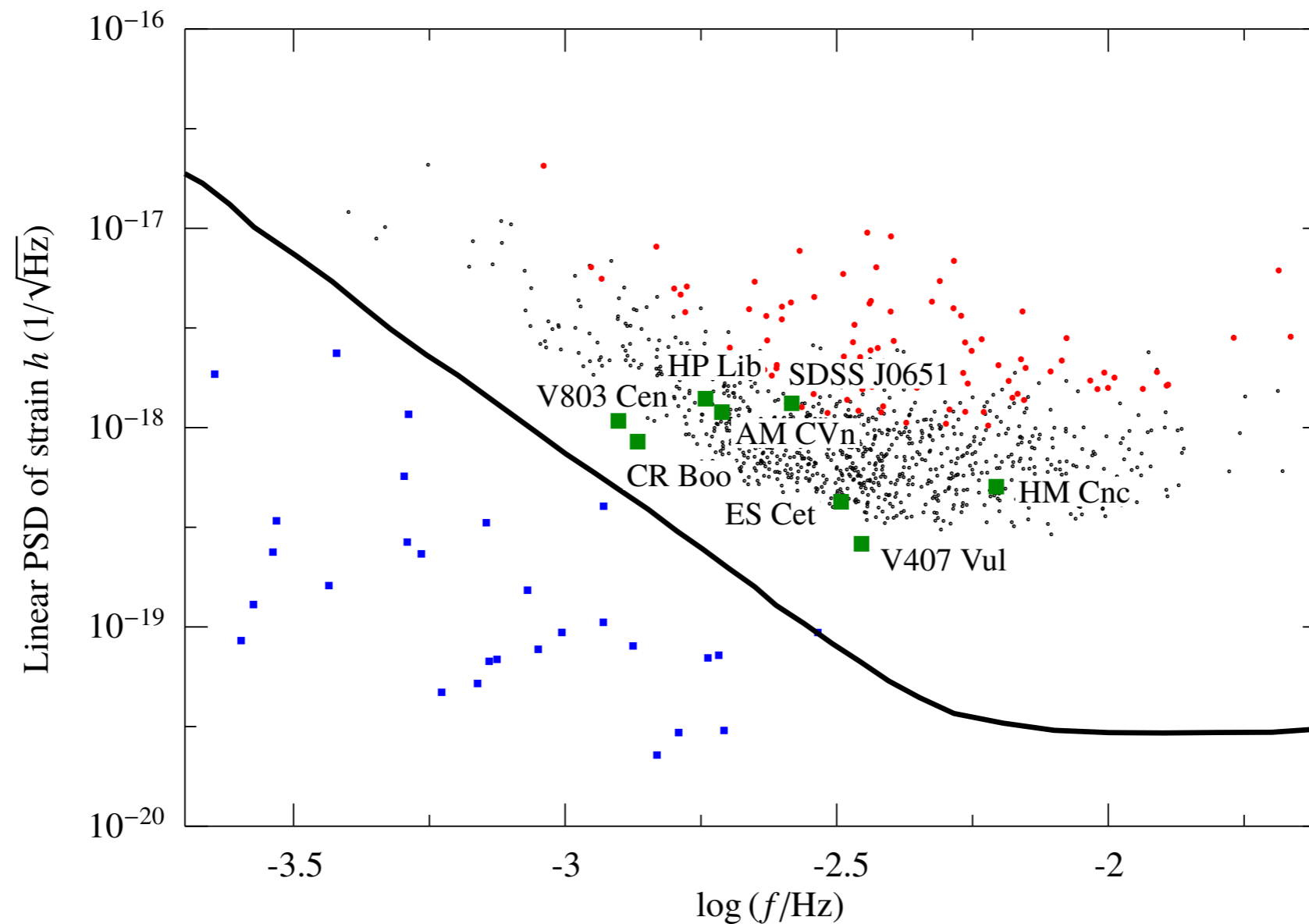


Extreme Mass-Ratio Inspirals: EMRIs

- **Stellar-mass BH capture by a massive BH: dozens per year to $z \sim 0.7$.**
 - Very complex and rich signal
- **High precision probe of the metric around a BH:**
 - Prove horizon exists.
 - Test the no-hair theorem to 1%.
 - Measure masses of holes to 0.1%, spin of central BH to 0.001%.
 - EMRI rate: Population studies of central and cluster BHs.
- **Probe of the neighbourhood of the BH:**
 - other masses, massive accretion disk etc.

Compact binaries

- Study of binary evolution and the endpoint of stellar evolution.
 - Guaranteed (known) sources: verification binaries



Programmatics

- **eLISA/NGO not selected for ESA L1 launch (~2020)**
- **Call for L2/L3 launch TBD**
 - expected Q1 2013
 - possible launch date 2024/26
- **Strong science case**
- **Proven technology**
- **Cost**
 - ~ 1B€ for ESA,
 - about 250 M€ for the member states (payload)
- **Strong contender for the next launch opportunity**

Conclusion

- **Gravitational waves populate a very large frequency range**
- **Sources exist on all distance scales**
- **Rich science to be expected**
- **Various efforts underway**
 - Pulsar Timing
 - Ground-based detectors
 - Space-borne detectors (eventually)
- **Direct detection of GW will happen within the next 10 years**

Gravitational Wave Sky

