Gravitational wave cosmology

Lecture 2

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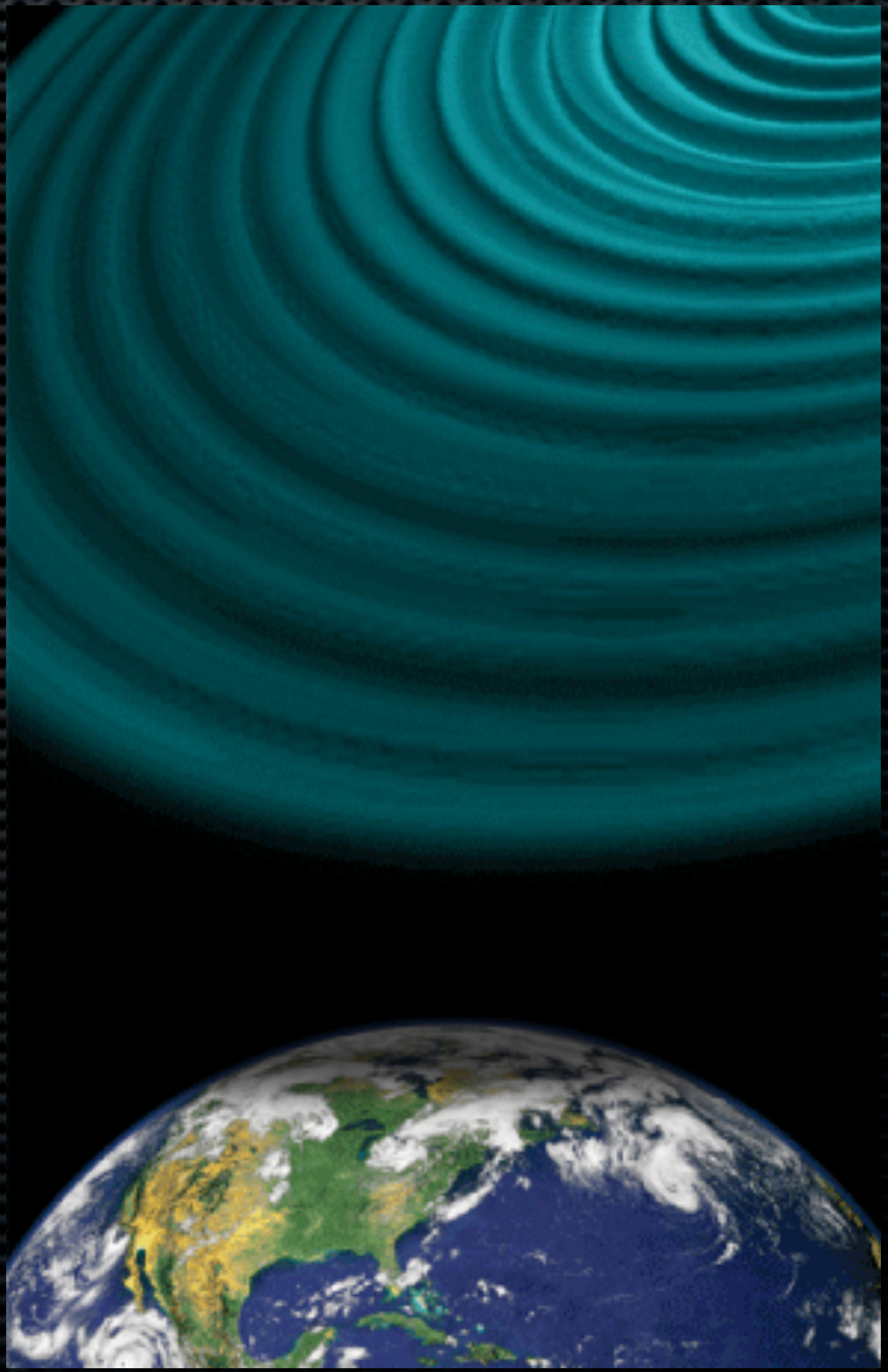
The University of Chicago



Thunder and lightning

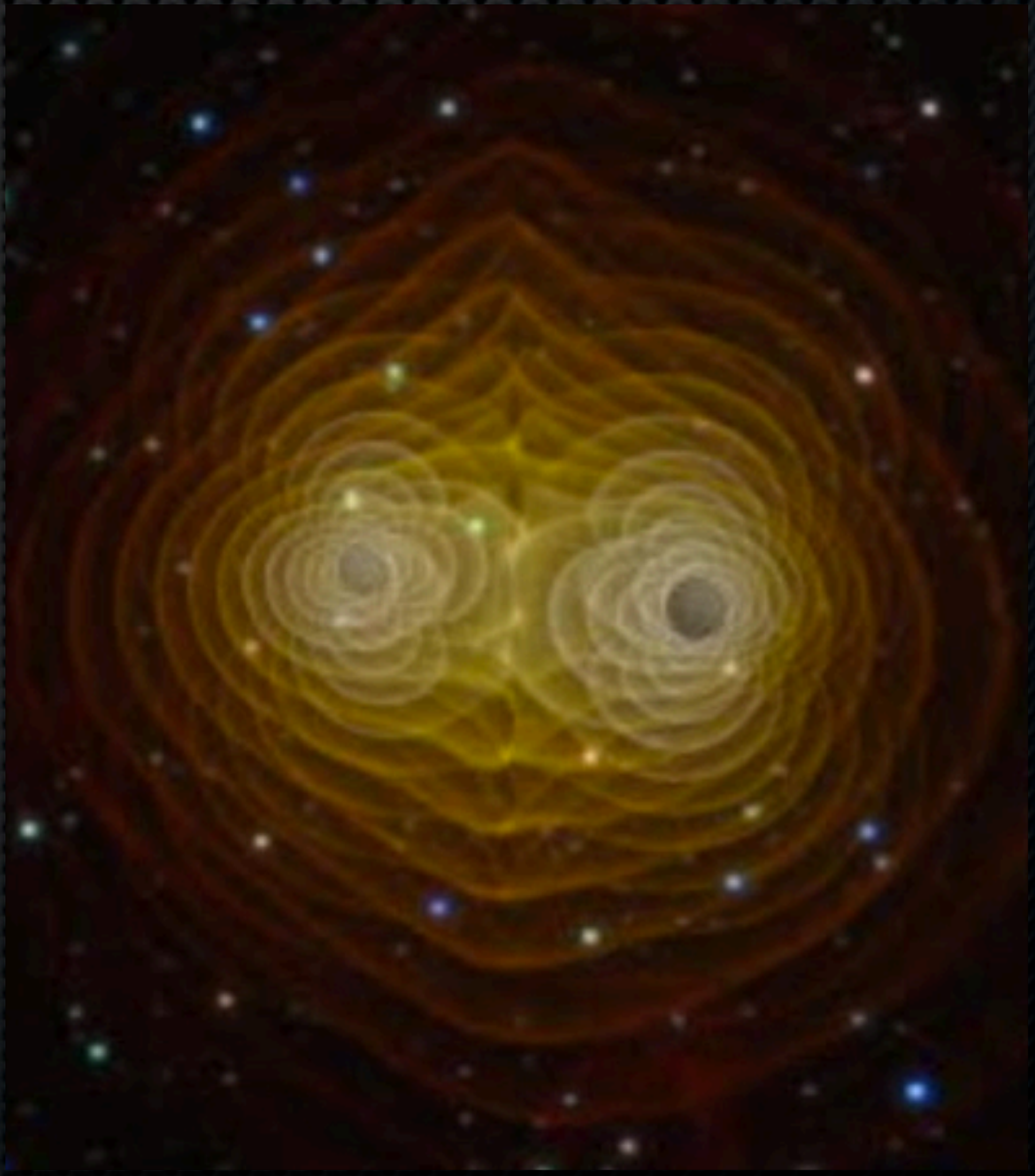
Thus far we've only seen the Universe (and 95% of it is dark: dark matter and dark energy).

In the the next few years we will finally be able to listen to the Universe.

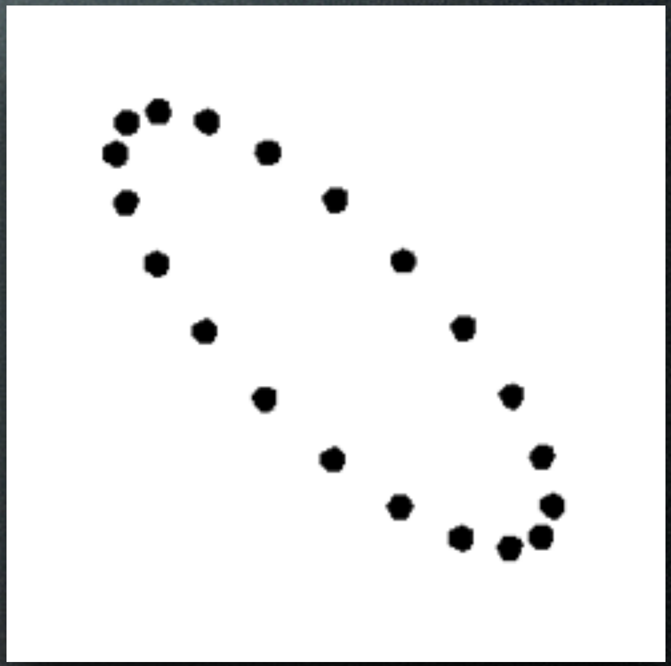
This will be revolutionary!

Outline

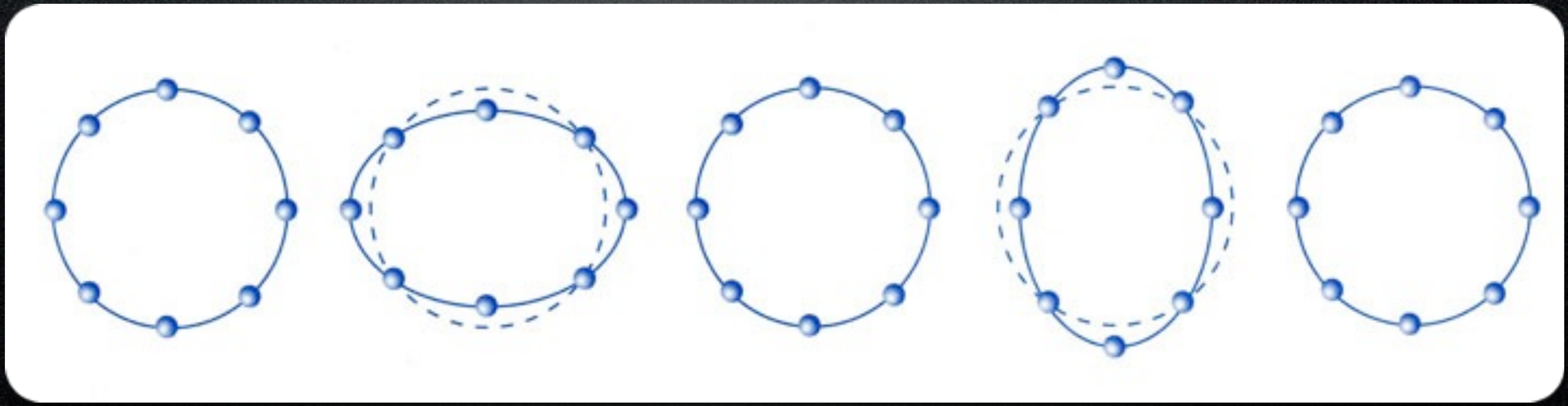
- Lecture 1: introduction to gravitational waves
- Lecture 2: detecting gravitational waves
- Lecture 3: what we might learn from gravitational waves



What do gravitational waves do?



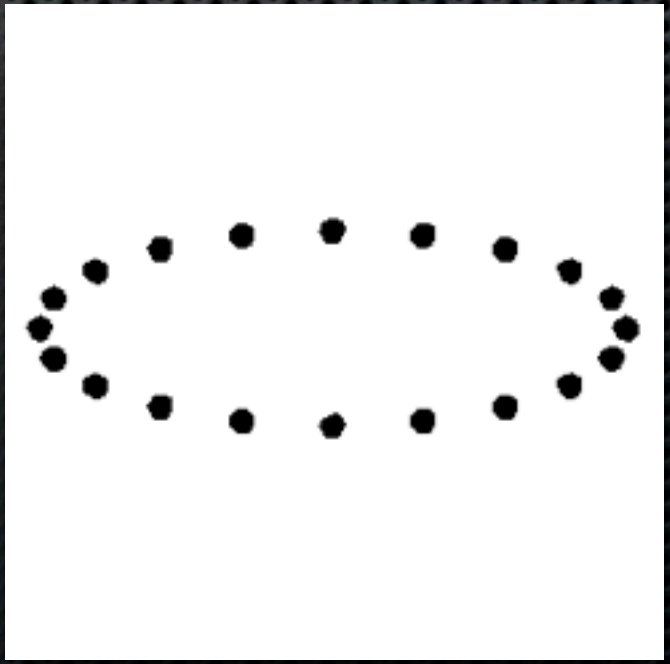
- Alternatively stretch and shrink the distance between points



Detecting gravitational waves

- Gravitational waves are very very very weak
- Fractional strain at Earth due to strong GWs:

$$h = \frac{\Delta L}{L} \sim 10^{-22}$$



Bar detectors

- Invented by Joe Weber
- Strain from GWs excites resonant modes of bar
- Cryogenically cooled, SQUID sensors
- Narrow band.
  Surpassed by LIGO

Bar detectors

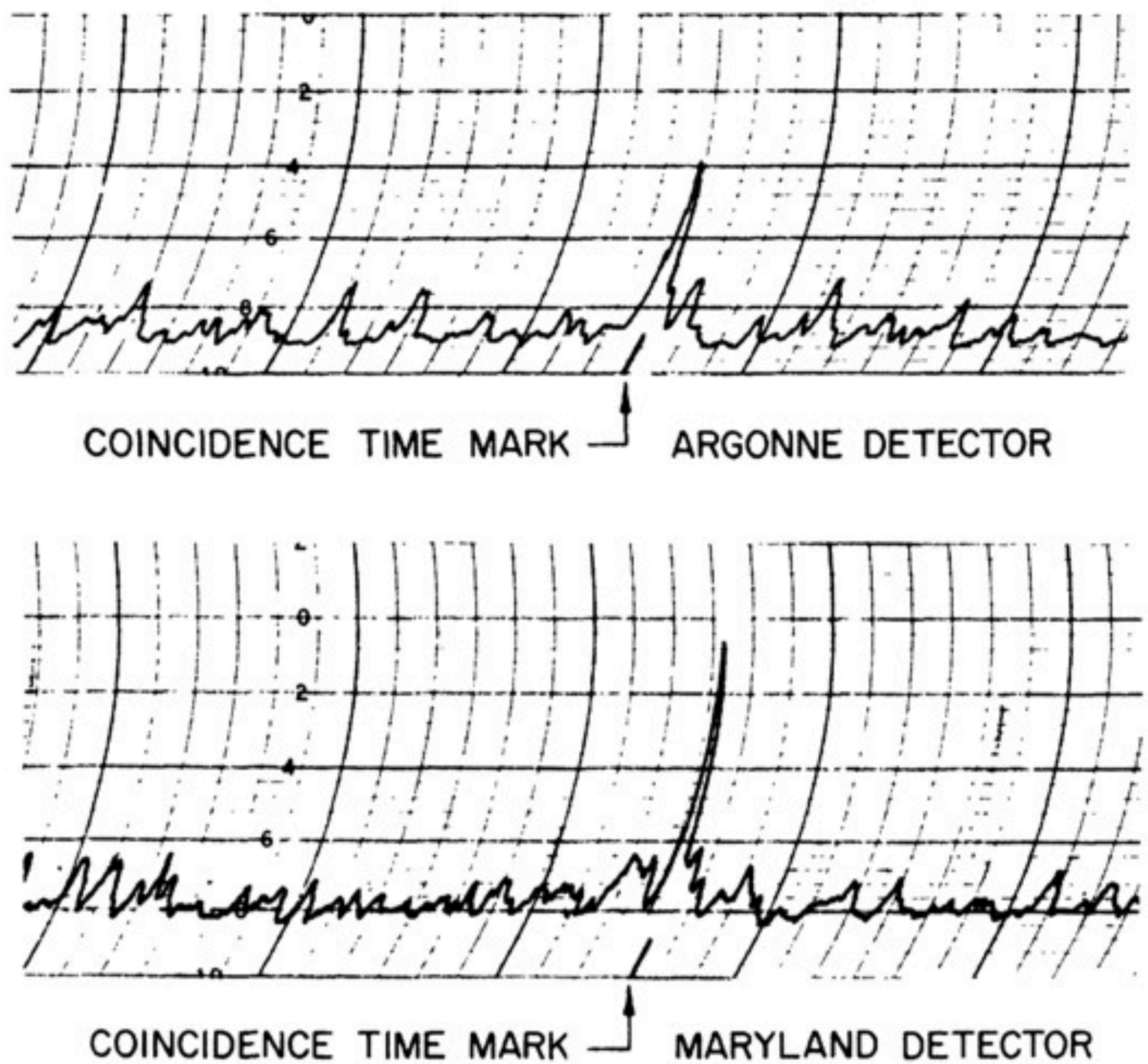
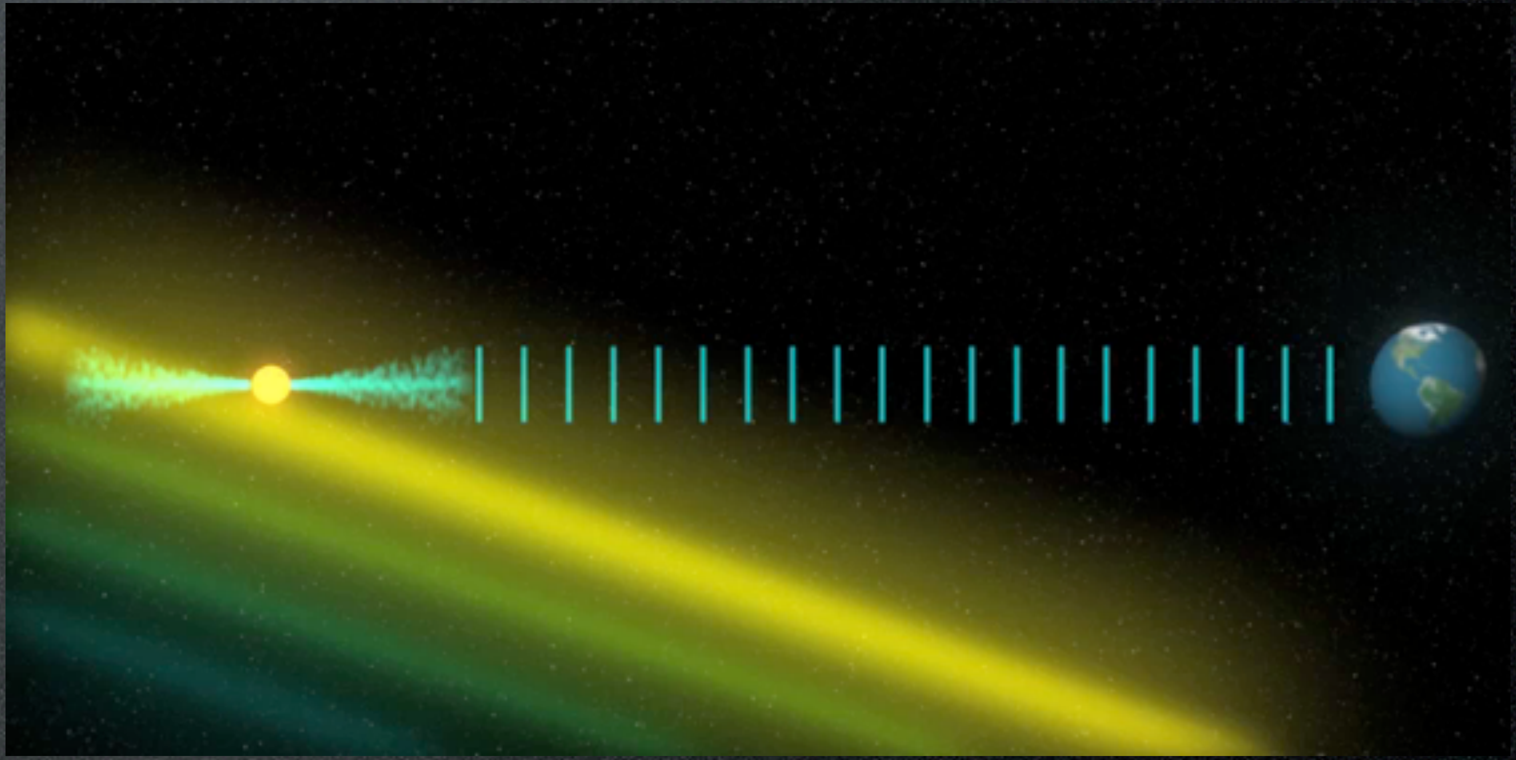


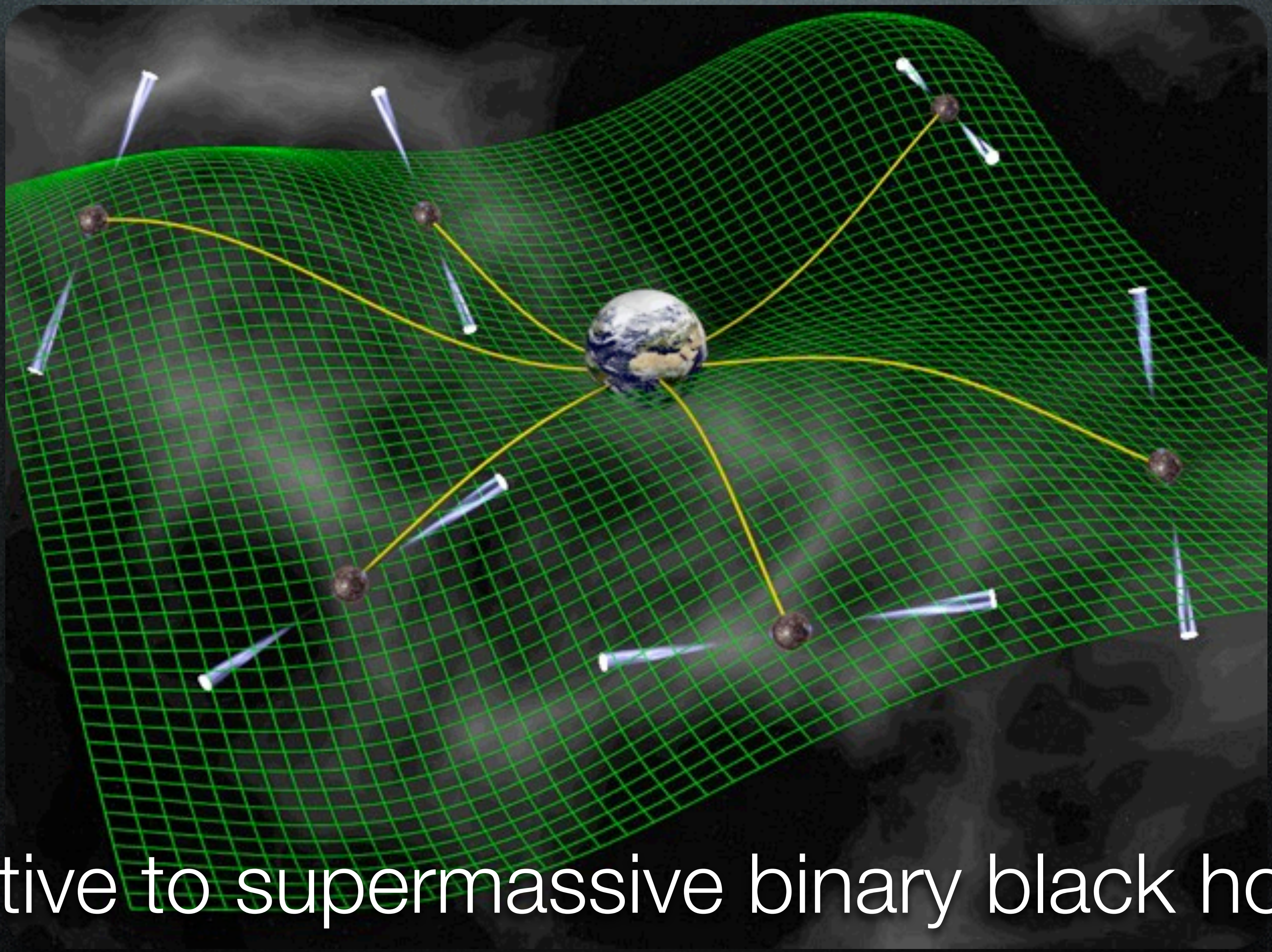
FIG. 2. Argonne National Laboratory and University of Maryland detector coincidence.

Pulsar timing arrays

- A millisecond pulsar is an exceedingly stable clock (better than best atomic clock)
- Observe many pulsars, and look for timing residuals (20 ns over a year)
- These come from GWs at source (uncorrelated) and at Earth (correlated)
- Can detect GW periods of ~year
- Band: 10^{-9}–10^{-6} Hz



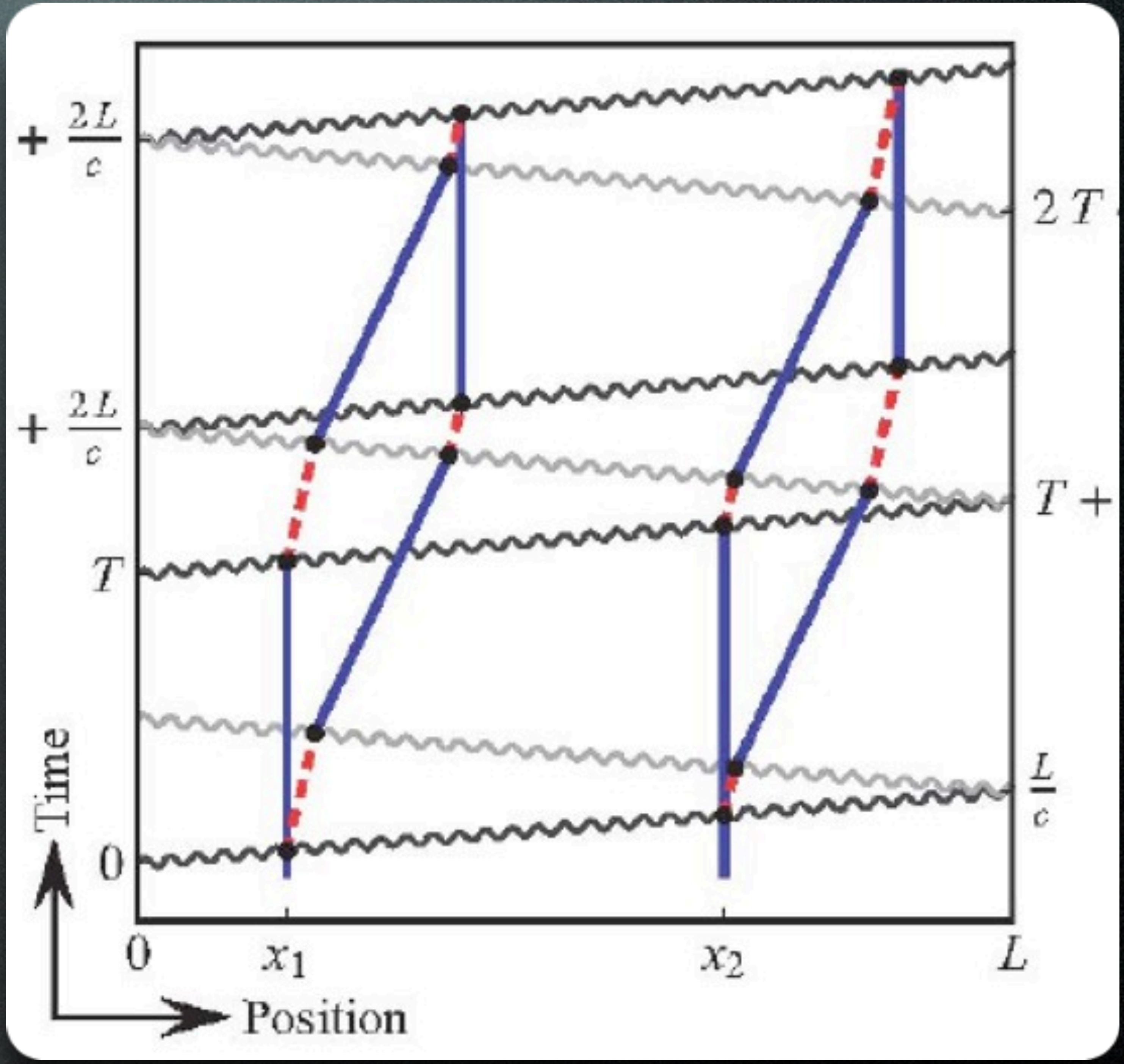
Pulsar timing arrays



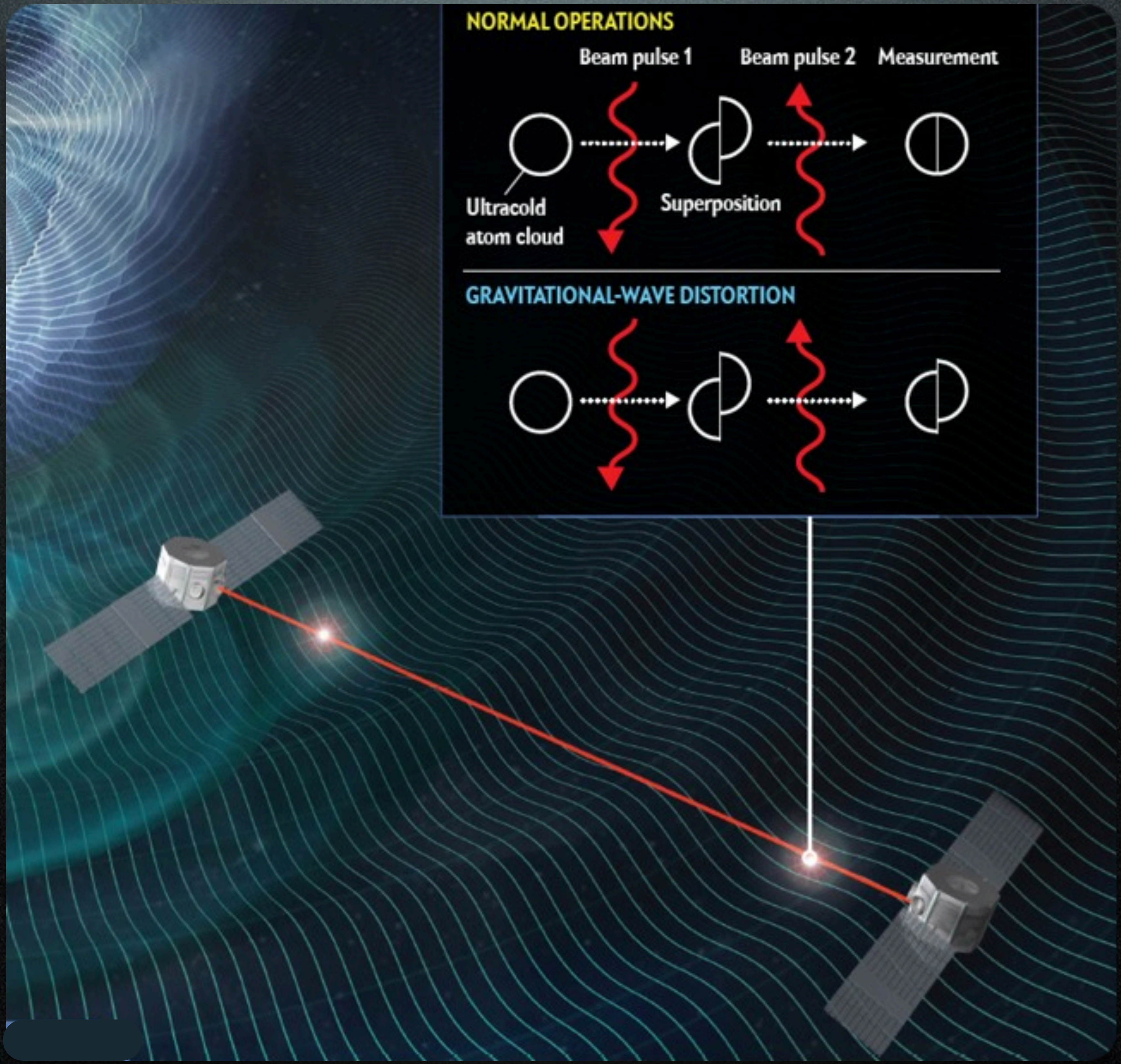
- Sensitive to supermassive binary black holes with orbital periods of months
- First detection possible in coming years
- Improve network by finding additional pulsars

Atom interferometry

- Use a cloud of cold atoms as an inteferometer
- Use two separated clouds: each one measures phase
- Probe both clouds with a single laser
- Measurement of phase differences detects GWs



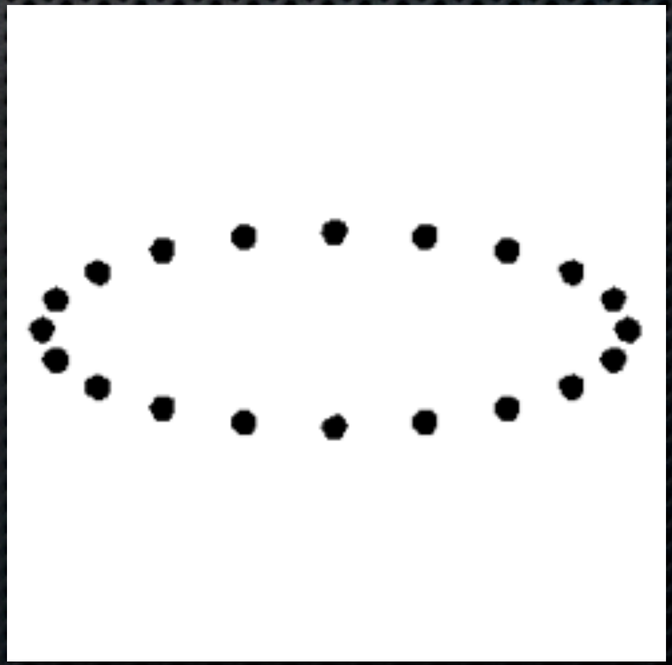
Atom interferometry



Laser interferometer

- Measures exactly what you want

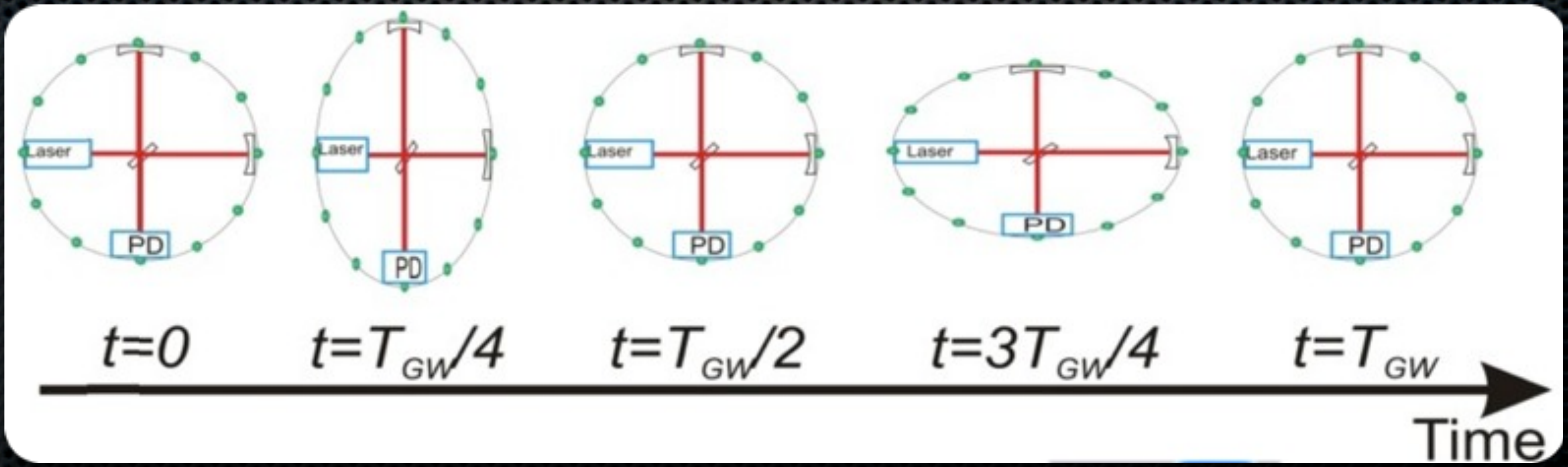
- Lots of sources of noise:
    - thermal
    - seismic
    - shotnoise
    - quantum



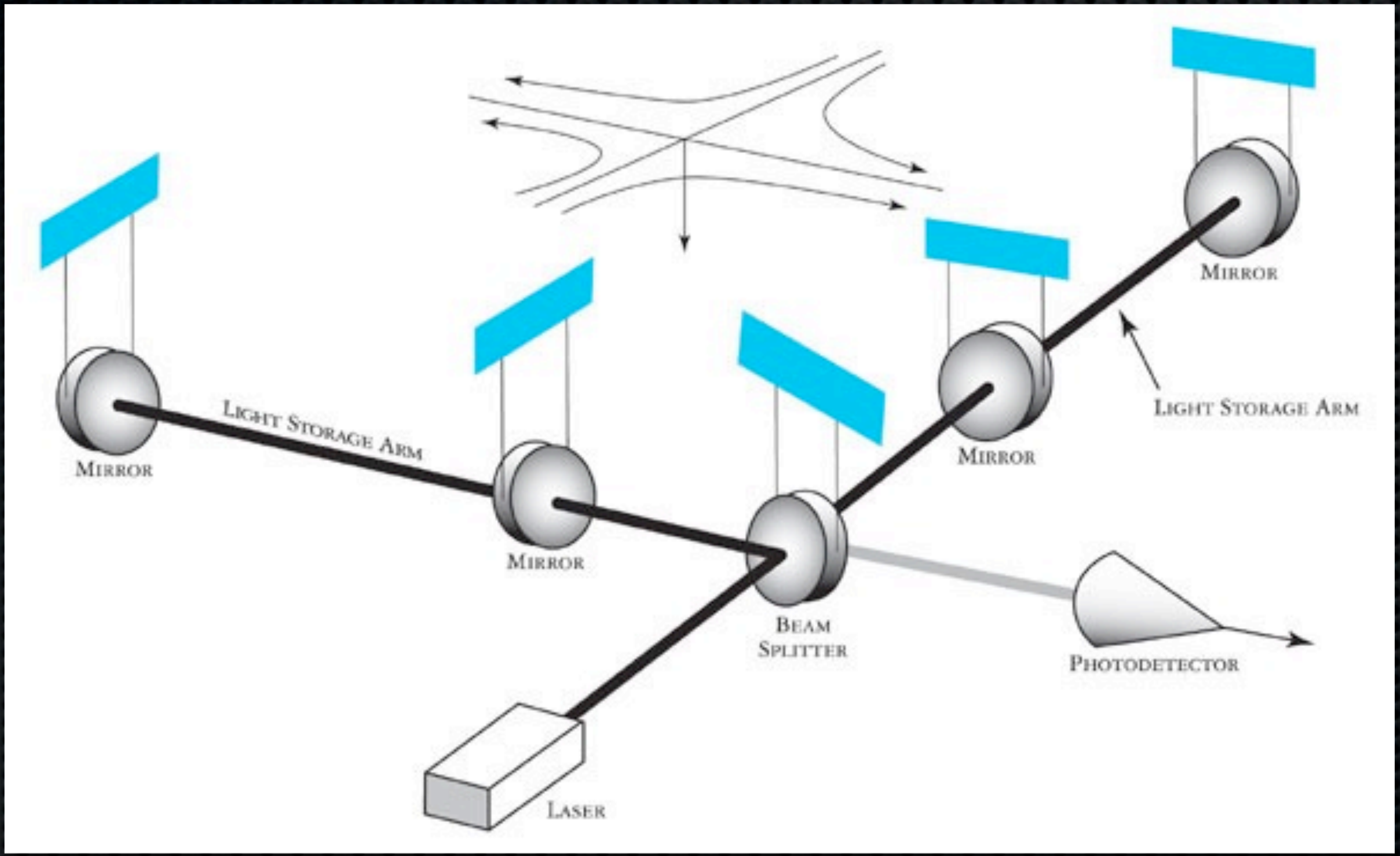
- Need a very very fancy interferometer!

Laser interferometer

- Mirrors are “freely falling” test masses
- Interferometer is a transducer: GWs are turned into photocurrent



LIGO: Laser Interferometer Gravitational wave Observatory



- Michelson interferometer:
  - quadruple pendulum; 40 kg end masses
  - dual-recycled Fabry-Perot; 4 km arms
  - 180 W laser (>700 kW per arm)
  - active isolation (f_{low}~12 Hz)

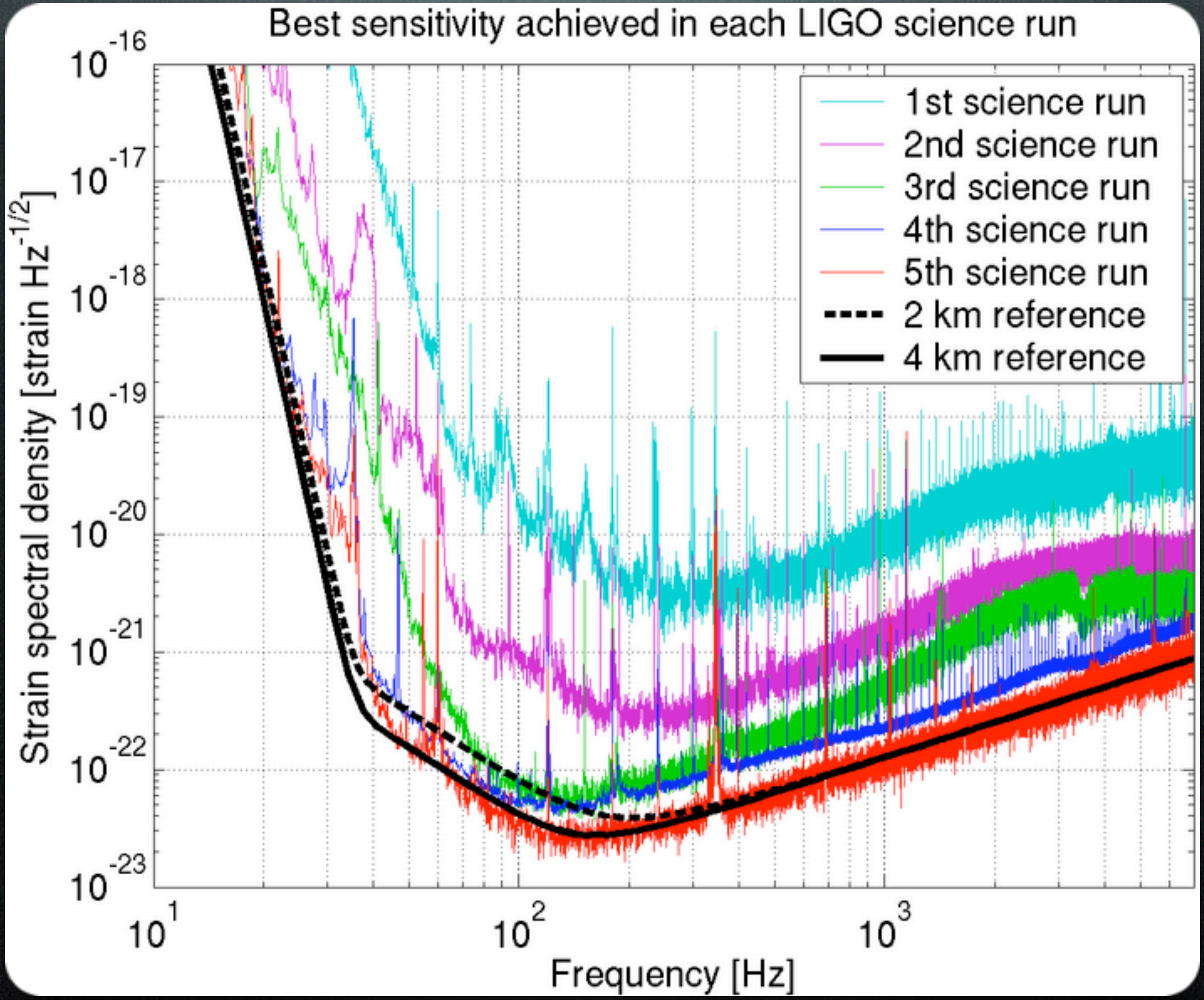
We will detect gravitational waves soon!

- Detectors are currently being significantly upgraded

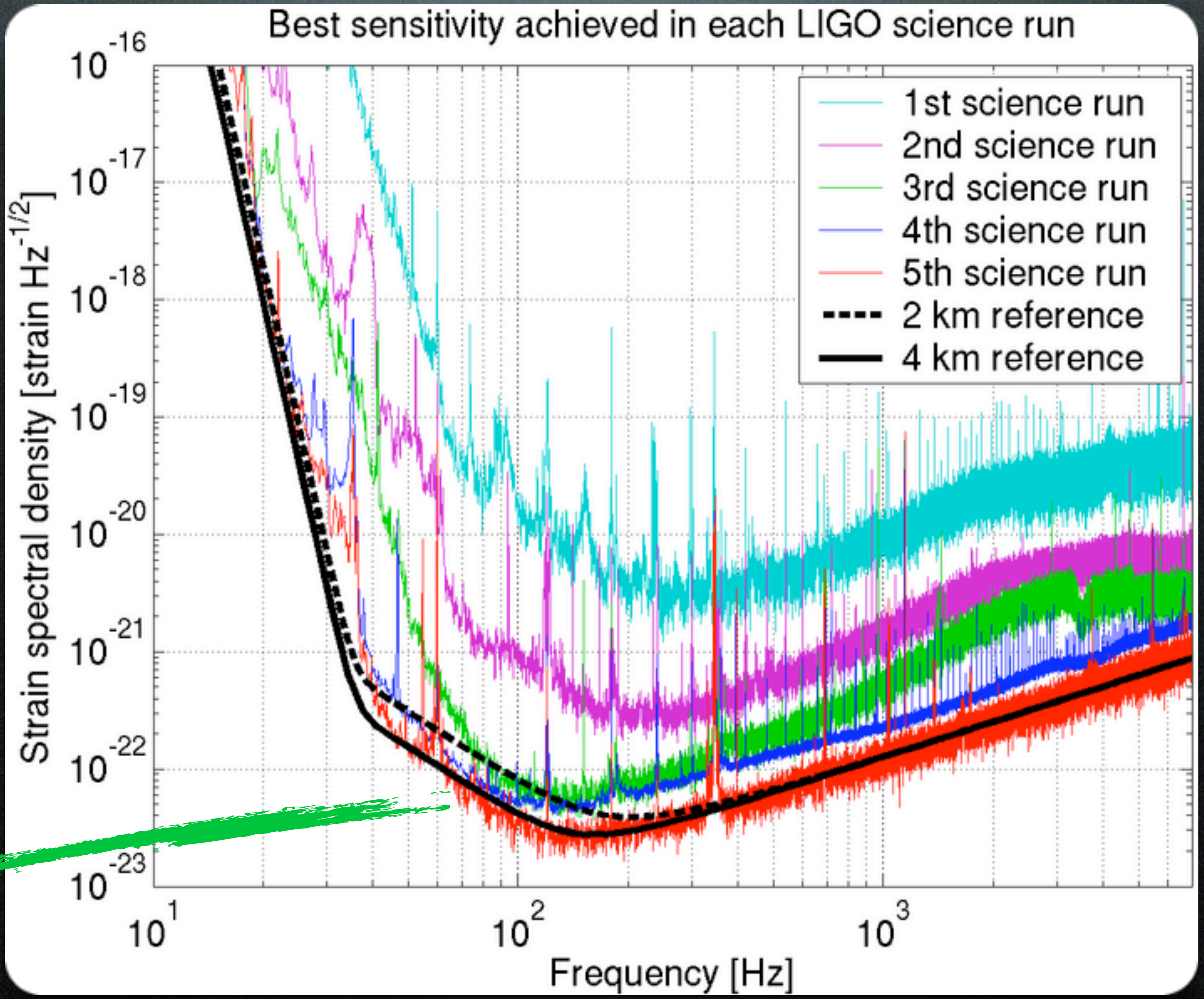
- Will be operating at advanced sensitivity in about 3 years

- Coming generation of instruments expected to make the first detections!

LIGO sensitivity

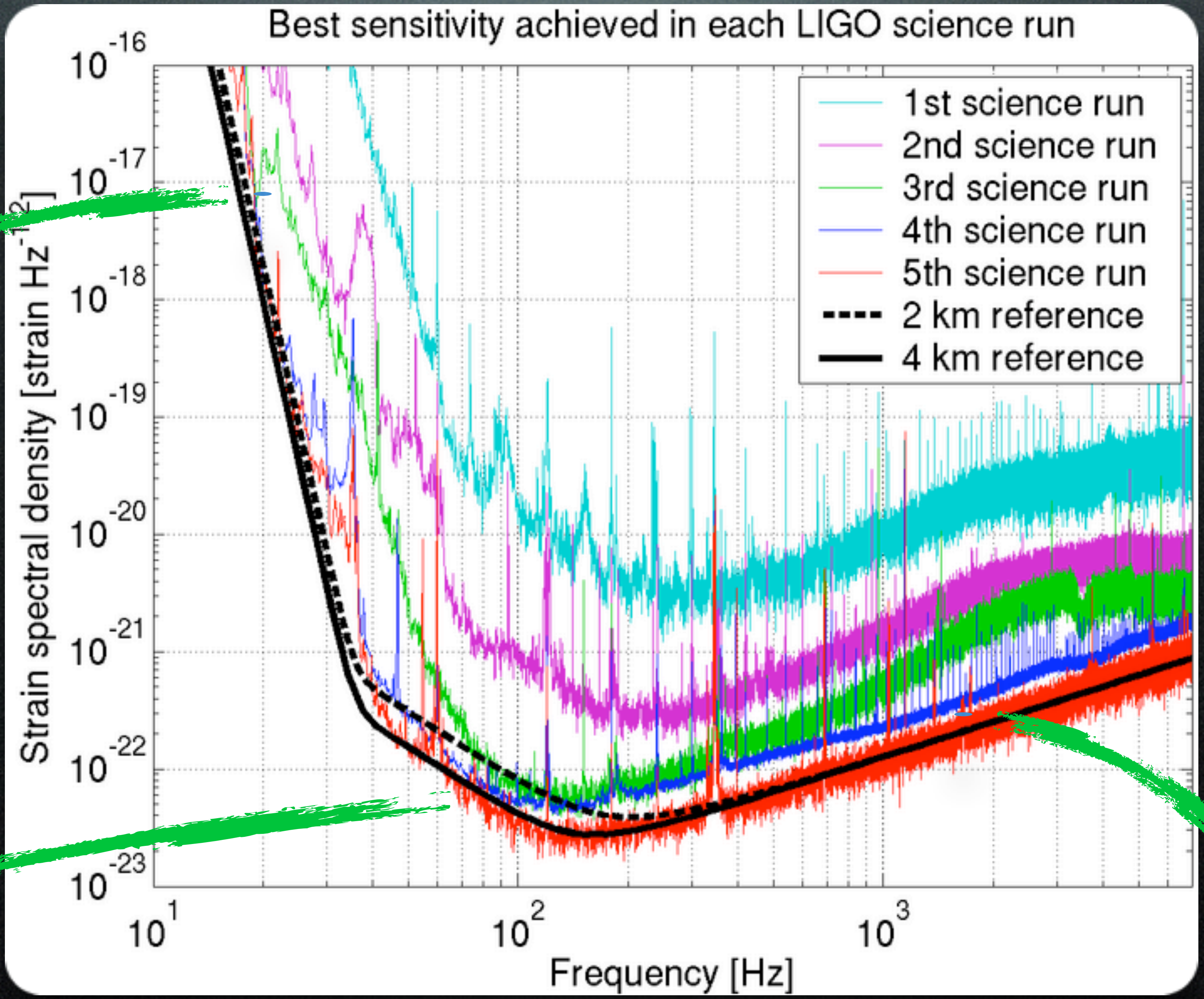


LIGO should blow your mind!



Sensing changes over 4 km
to a thousandth the size of a proton

LIGO measures noise



Seismic noise

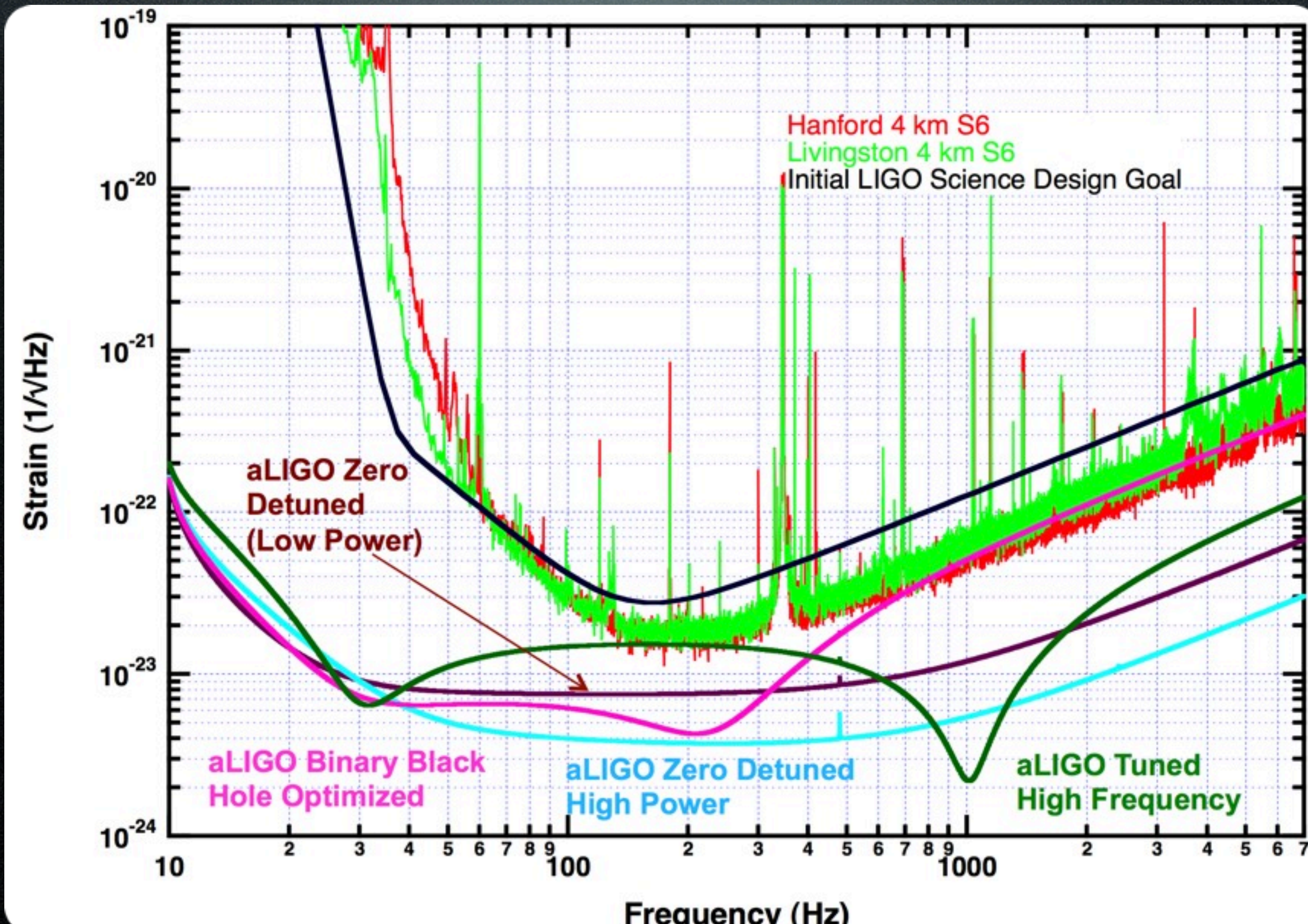
Thermal noise

Photon shot noise

What is advanced?

Parameter	*Initial LIGO*	*Advanced LIGO*
Input Laser Power	10 W (10 kW arm)	180 W (>700 kW arm)
Mirror Mass	10 kg	40 kg
Interferometer Topology	Power-recycled Fabry-Perot arm cavity Michelson	Dual-recycled Fabry-Perot arm cavity Michelson (stable RC)
GW Readout Method	RF heterodyne	DC homodyne
Optimal Strain Sensitivity	3×10^{-23} / rHz	Tunable, better than 5×10^{-24} / rHz in broadband
Seismic Isolation Performance	$f_{low} \sim 50$ Hz	$f_{low} \sim 12$ Hz
Mirror Suspensions	Single Pendulum	Quadruple pendulum

Advanced LIGO sensitivity



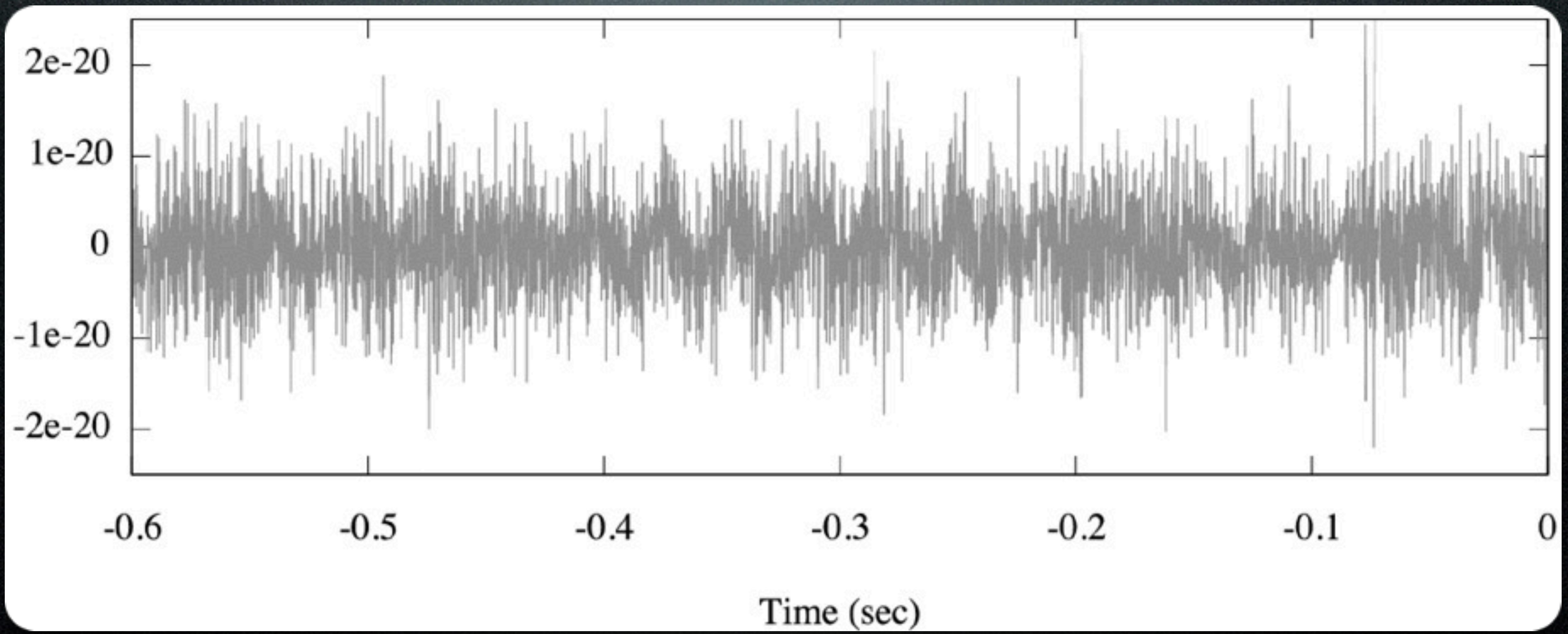
How well does LIGO do?

- Encapsulated in the signal-to-noise ratio (SNR)
- SNR in a detector is a function of the noise curve of the detector as well as the waveform (amplitude and frequency) of the source

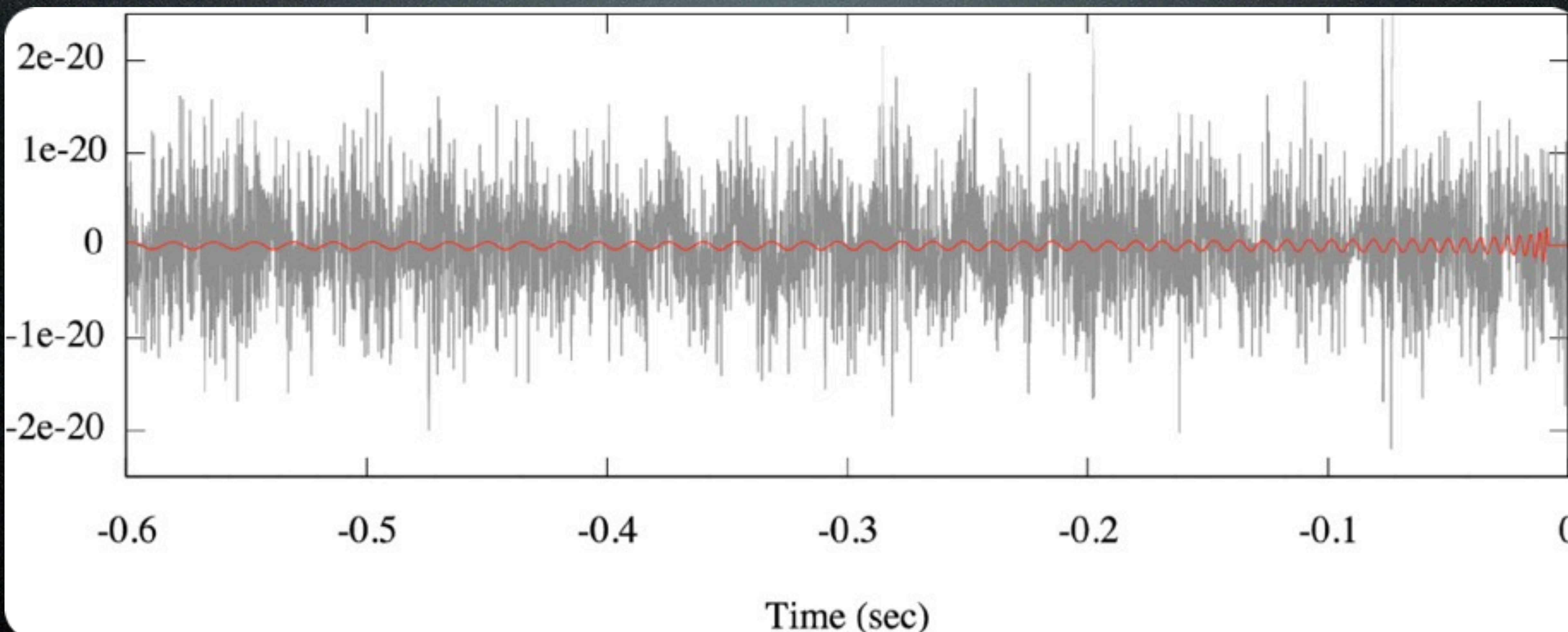
$$\mathrm{SNR} = 4 \int_{f_{\mathrm{min}}}^{f_{\mathrm{max}}} df' \, \frac{\left|\tilde{h}(f')\right|^2}{S_n(f')}$$

- $\tilde{h}(f')$ is the source GW waveform (Fourier)
- $S_n(f')$ is the spectral strain noise density

LIGO detects noise!



Can extract signal from noise

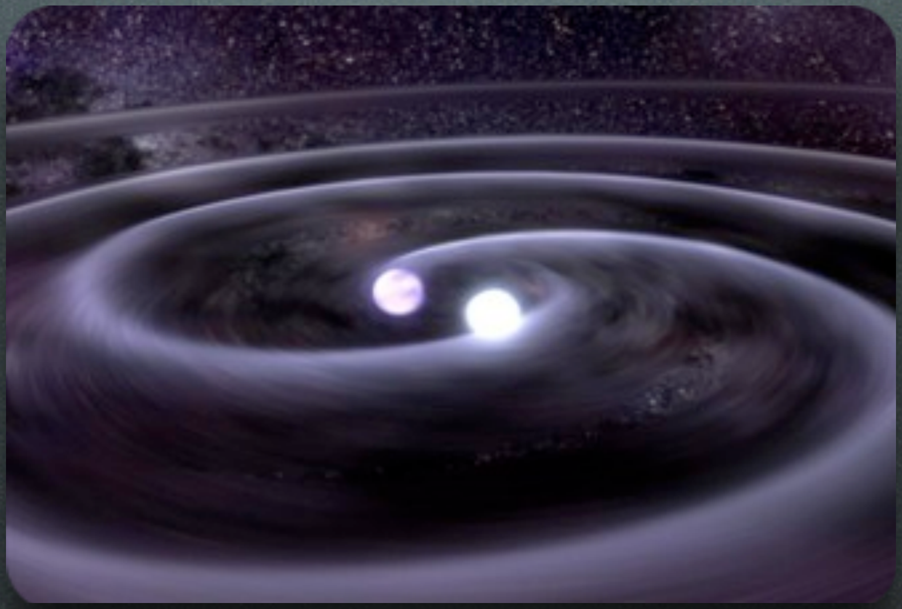


- Red: binary black hole merger at 100 Mpc
- Data analysis challenge

Only find what you look for

- Matched filter search has greatest reach
- Need excellent waveform templates to analyze data
- Huge numerical and analytic effort to determine waveforms from supernovae and compact object binaries
- Problem is solved for equal-mass, circular, slowly spinning binaries
- Problem is not yet solved for larger mass ratio or highly spinning/eccentric binaries

GWs from binary black holes



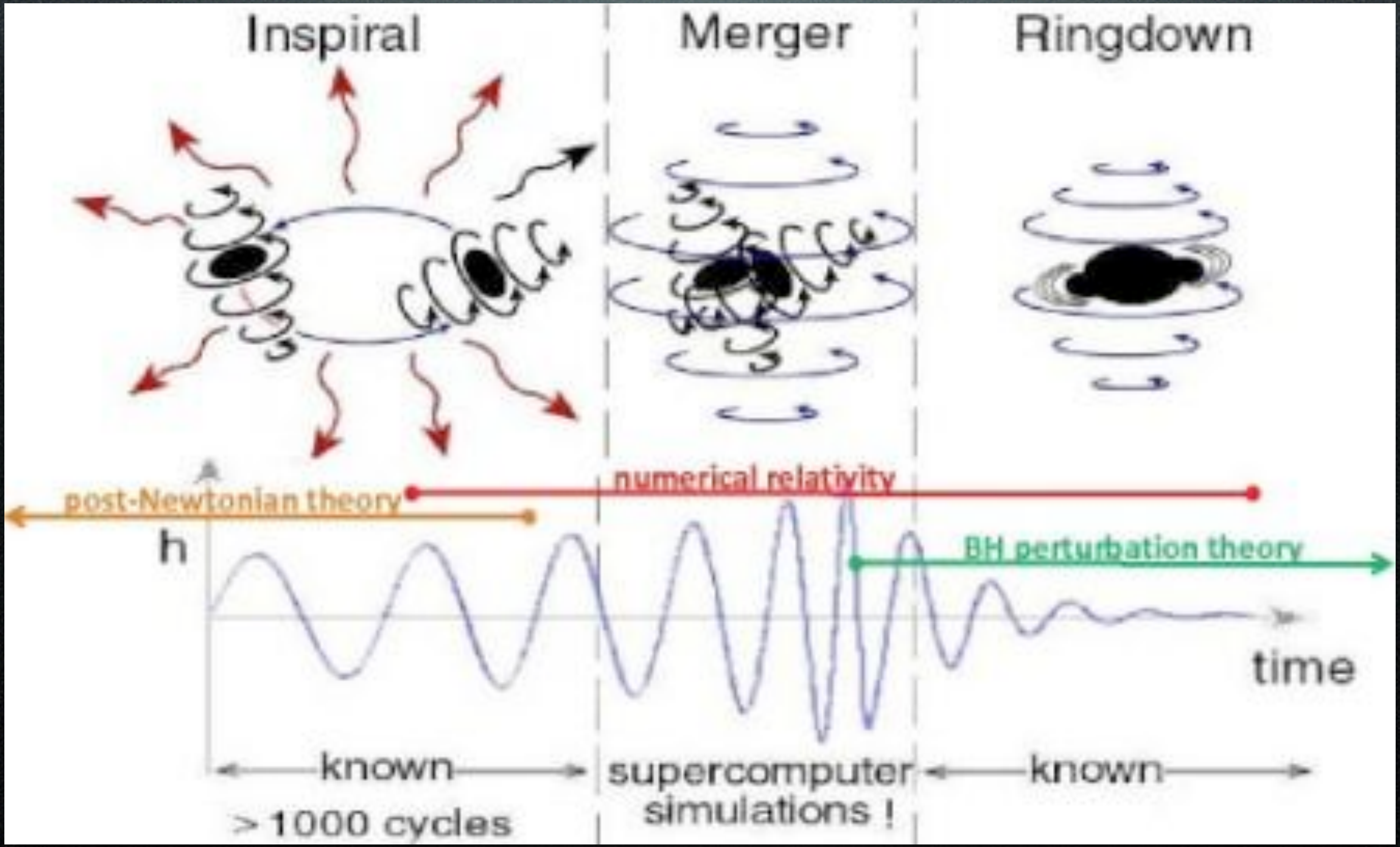
- Assume GW emission plus Kepler's laws:

$$\frac{dP}{dt} = -\frac{96}{5}\pi 4^{1/3}\left(\frac{2\pi M}{P}\right)^{5/3}$$

$$= -3.4 \times 10^{-12}\left(\frac{M}{M_\odot}\frac{1\,\mathrm{hour}}{P}\right)^{5/3}$$

- This gives the full time evolution/waveform

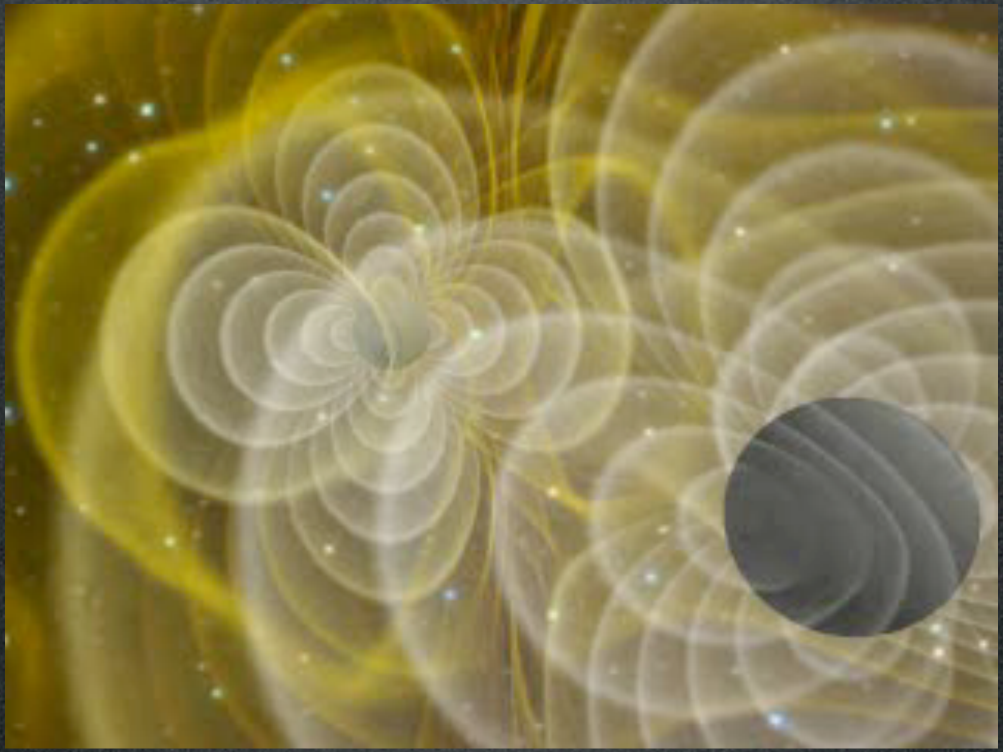
Only find what you look for



- Three phases of binary evolution

Only find what you look for

- Analytic methods:
  - post-Newtonian expansions
  - effective one-body formalism
- Gold standard: numerical relativity



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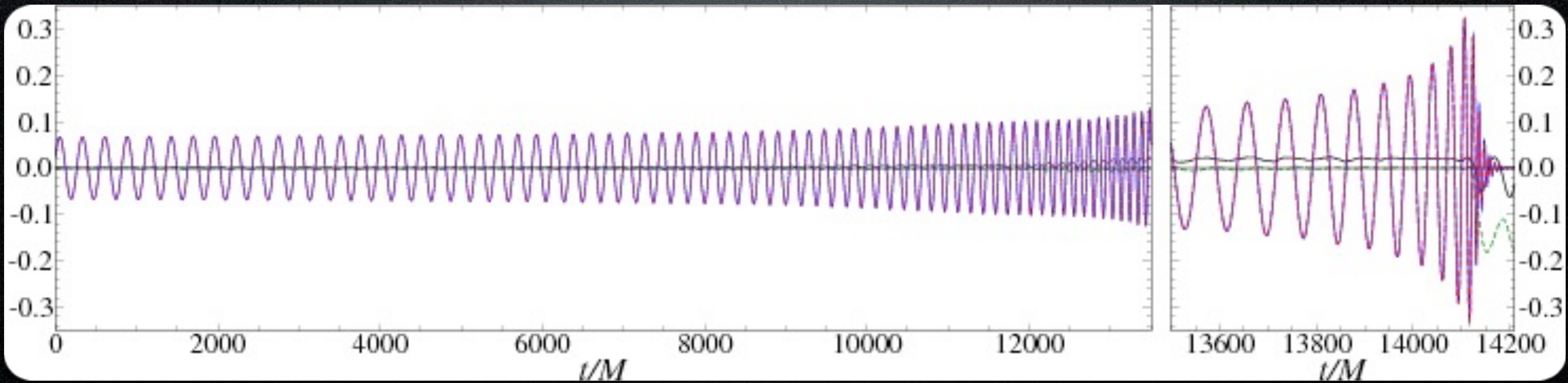
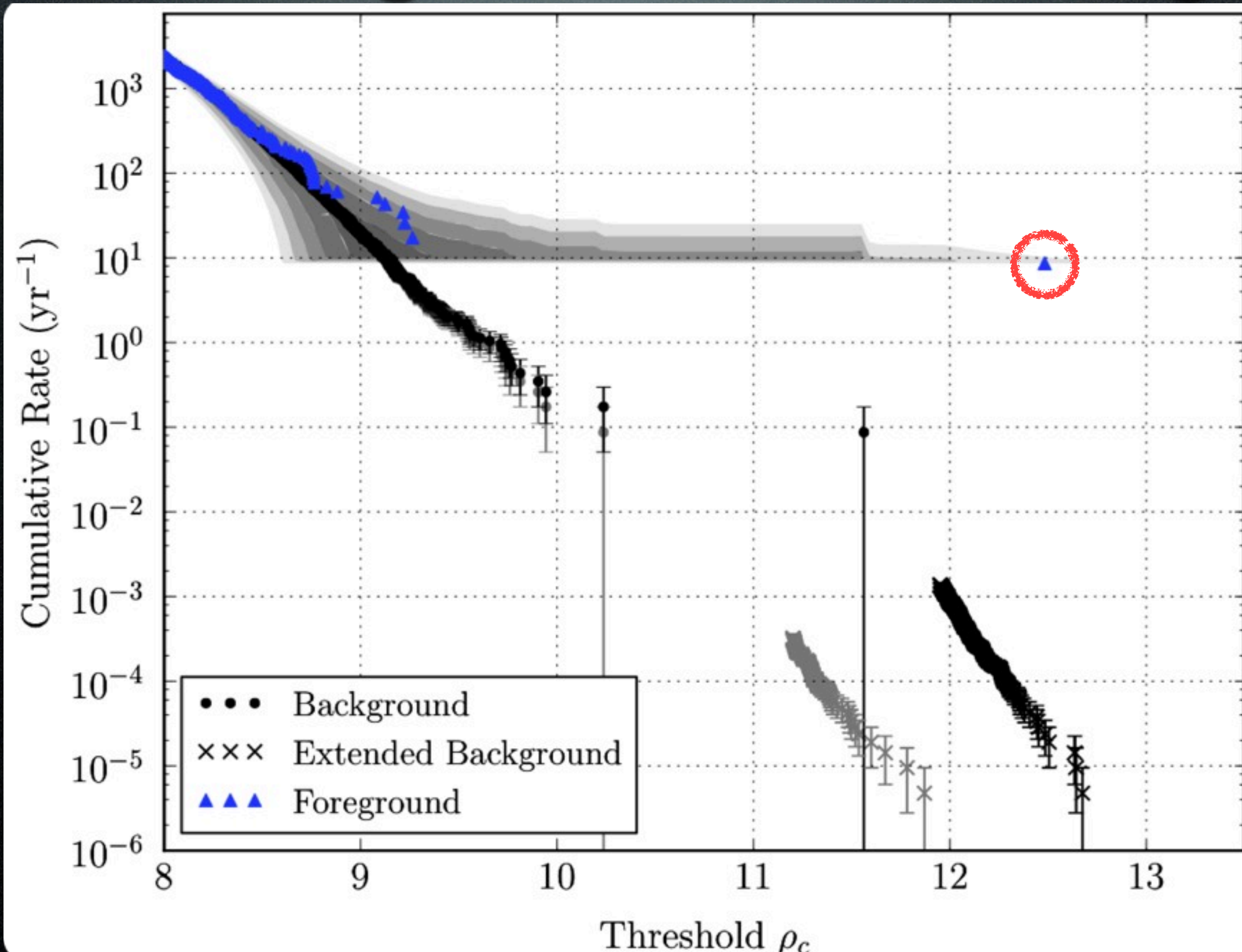
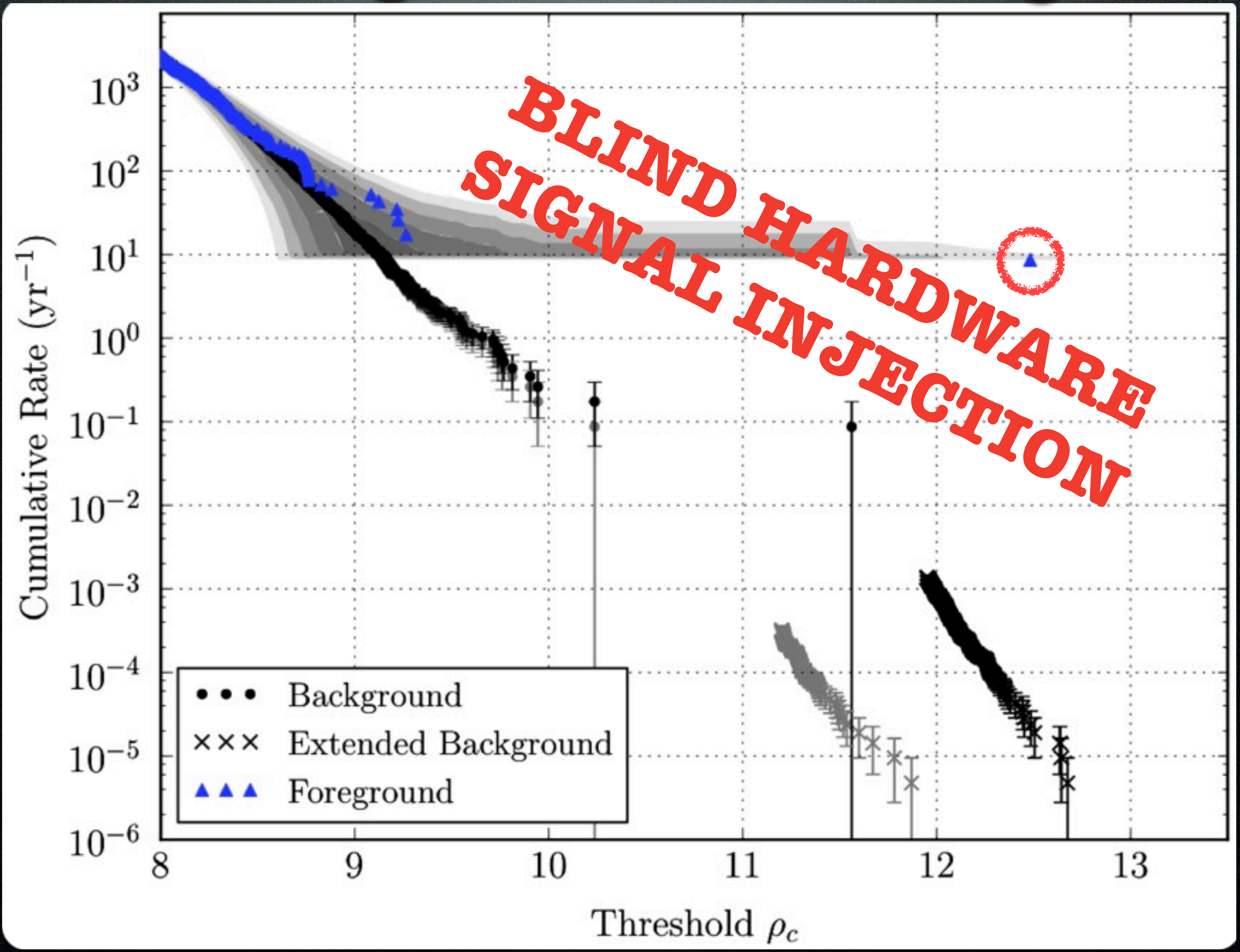


LIGO/Virgo finds something!

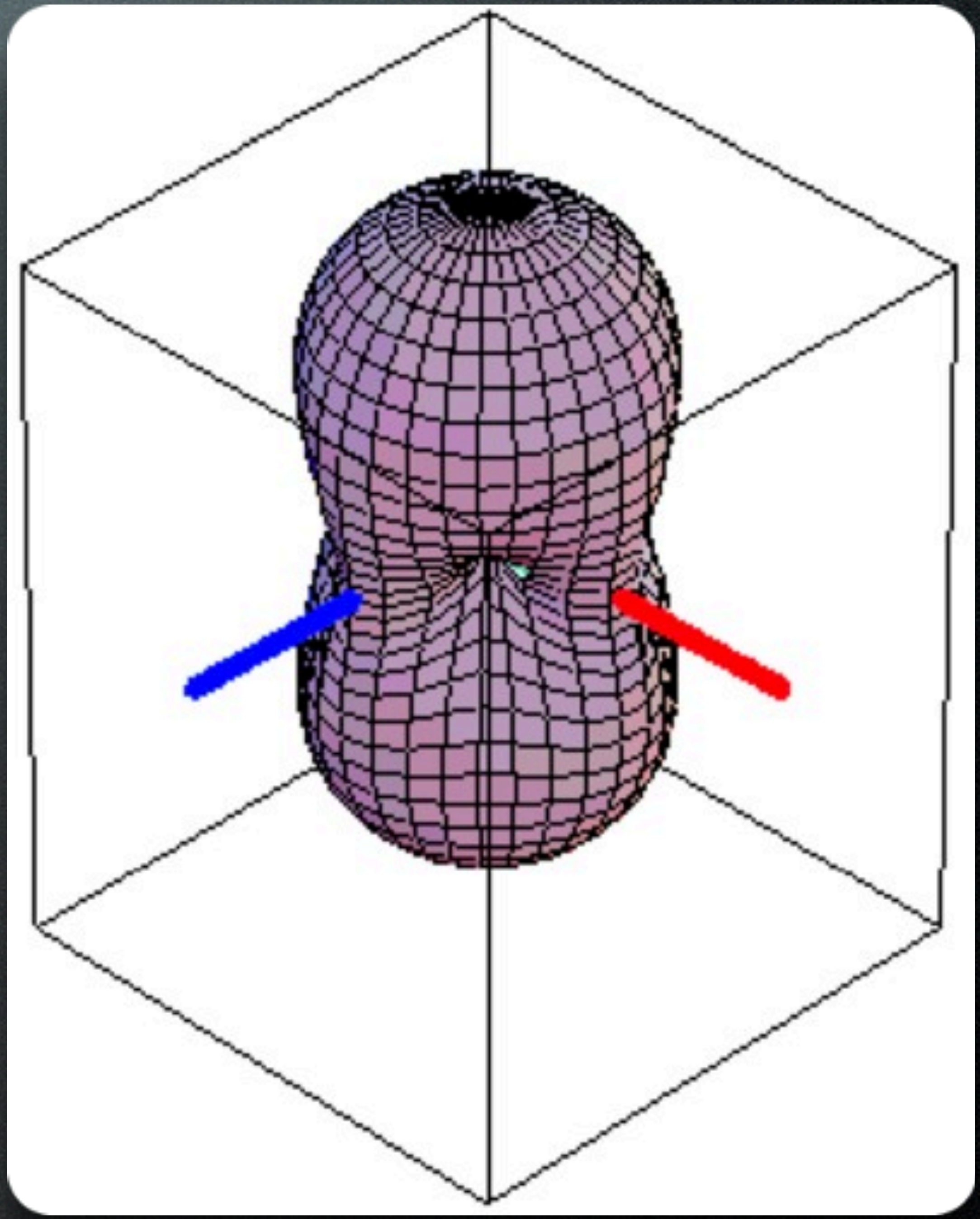


LIGO/Virgo finds nothing

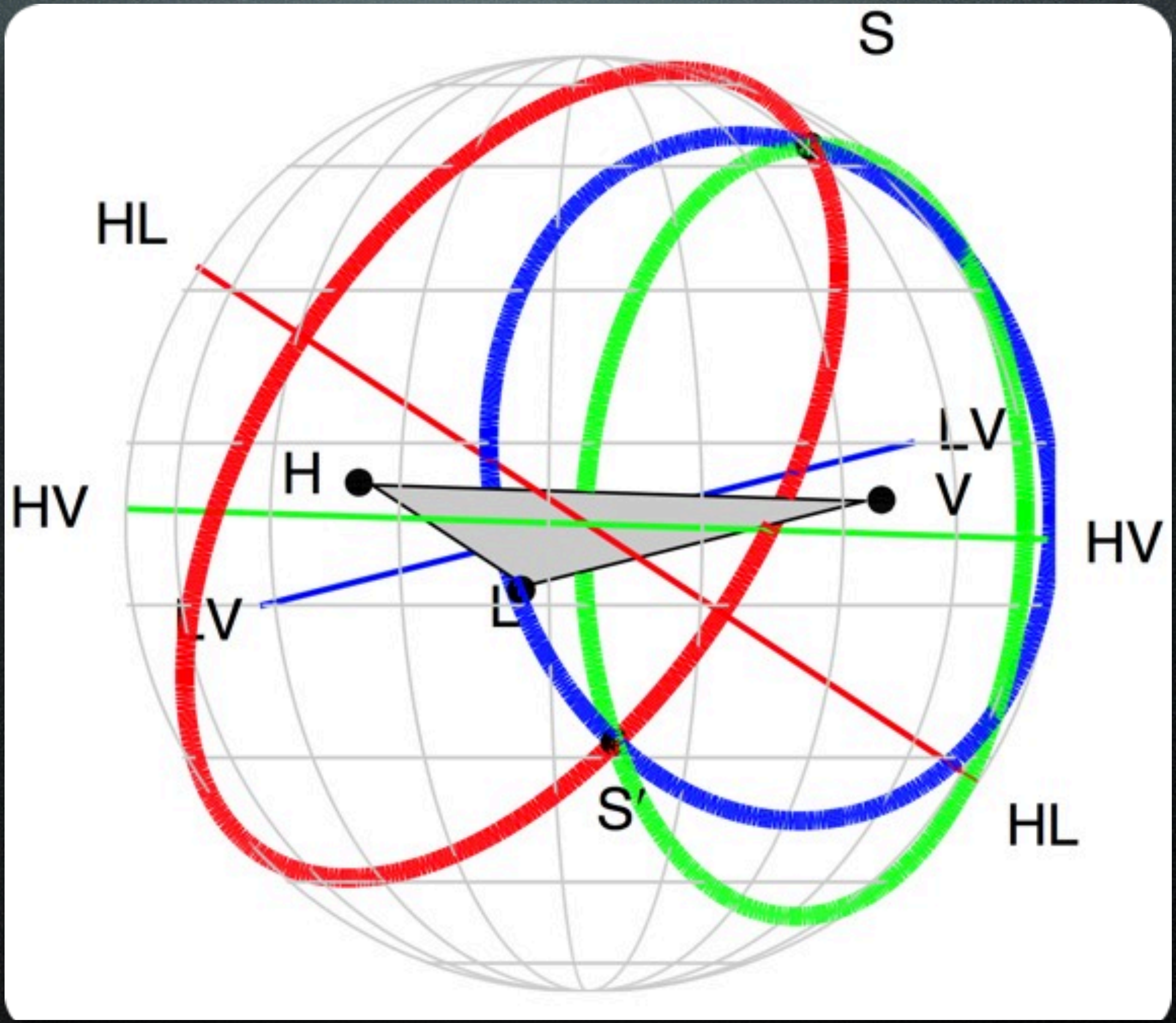


Sky sensitivity

- Sensitivity of a single interferometer
- Livingston and Hanford are closely aligned, so as to see same polarization
- LIGO sees a peanut on the sky
- Need a network to see the full sky



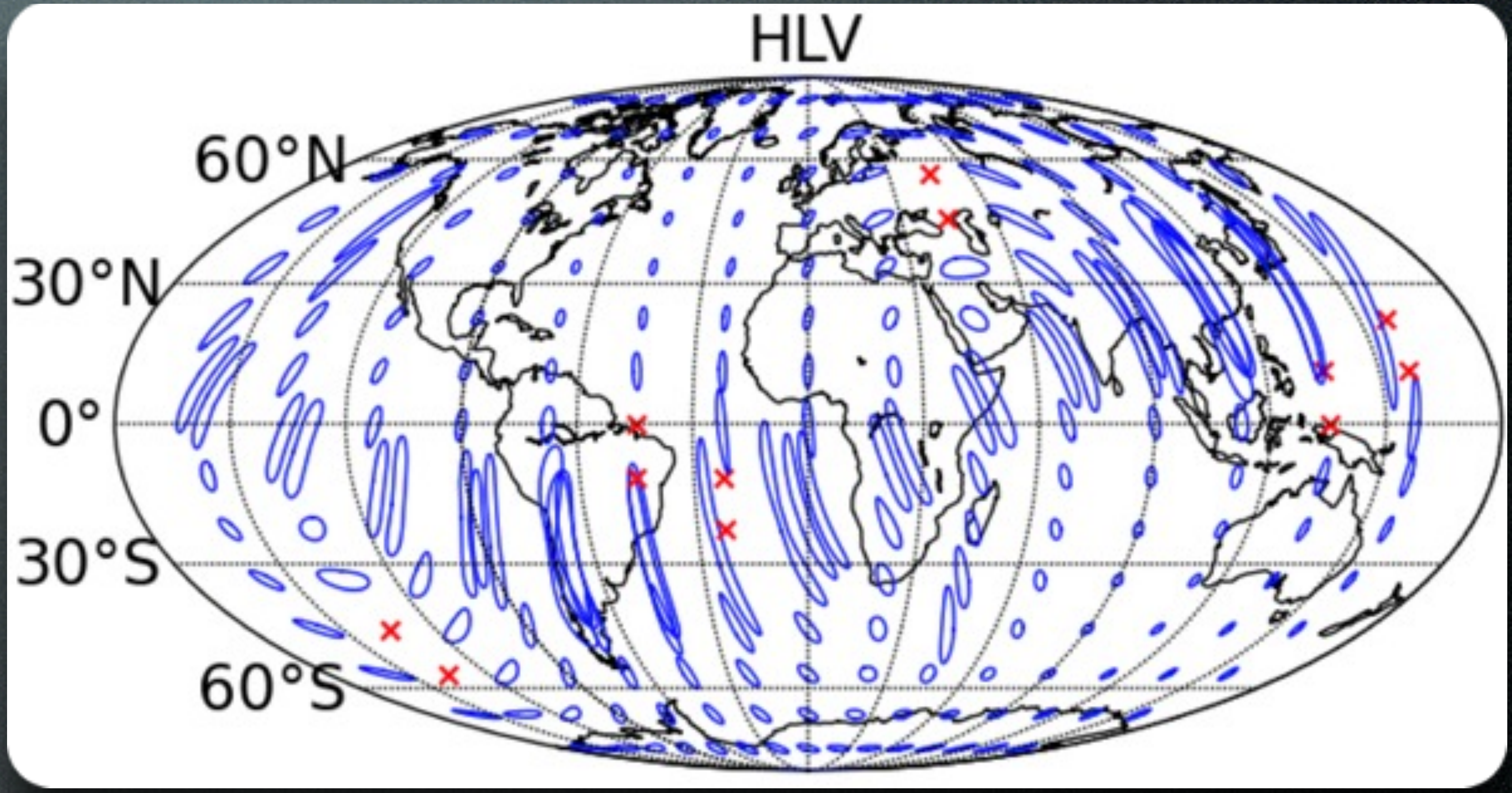
Sky localization

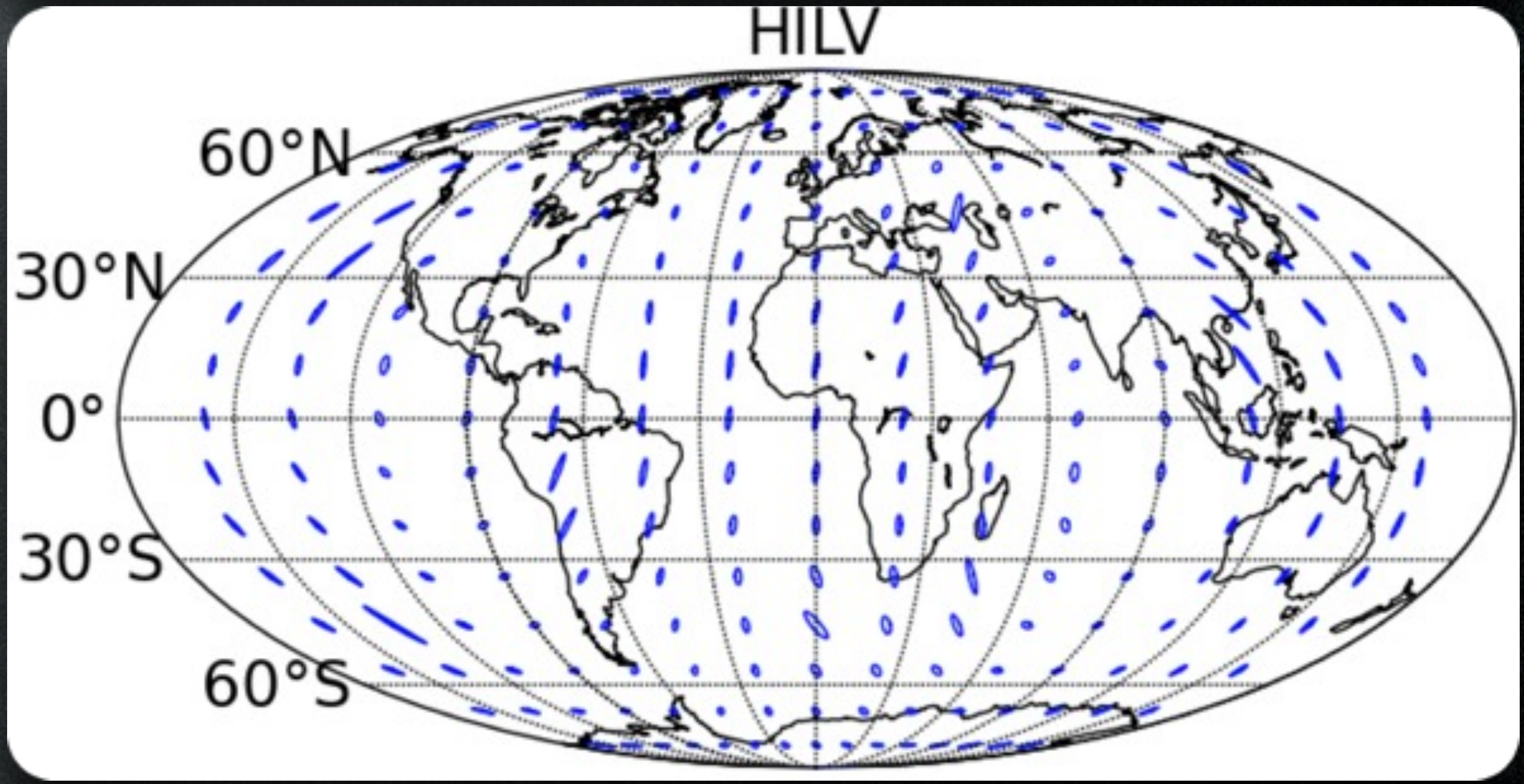


- Localization comes primarily from timing
- Two detectors produces an annulus on the sky

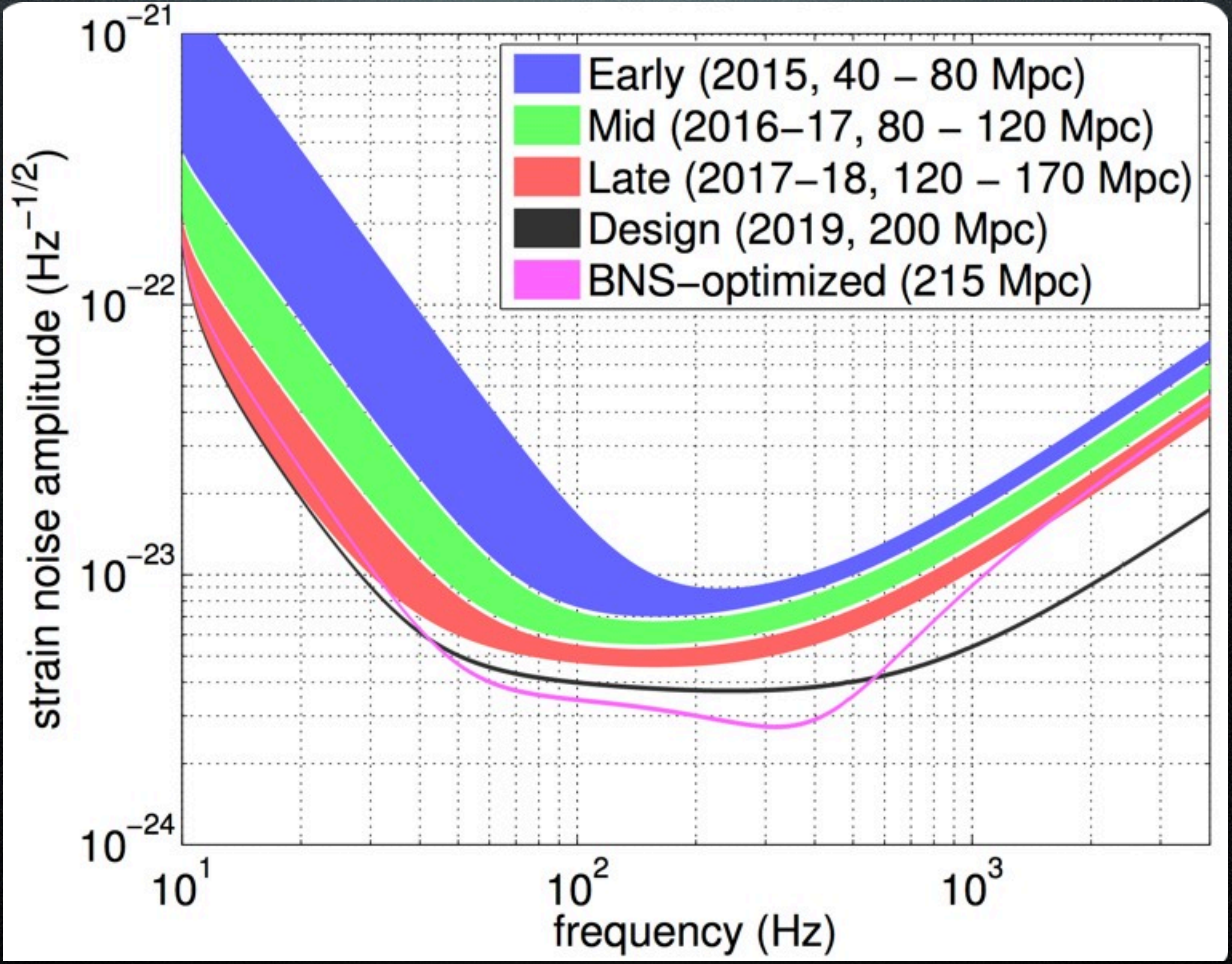
Sensitivity & Localization

- More detectors is better
- A detector in India is essential to cover the sky





Advanced LIGO timetable



Advanced LIGO/Virgo timetable

Epoch	Estimated Run Duration	$E_{\mathrm{GW}} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within $5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

Worldwide GW network

Detecting gravitational waves in space!

Laser Interferometer Space Antenna (LISA)

CANCELED DUE TO FUNDING ISSUES

Detects supermassive black hole mergers anywhere in the Universe

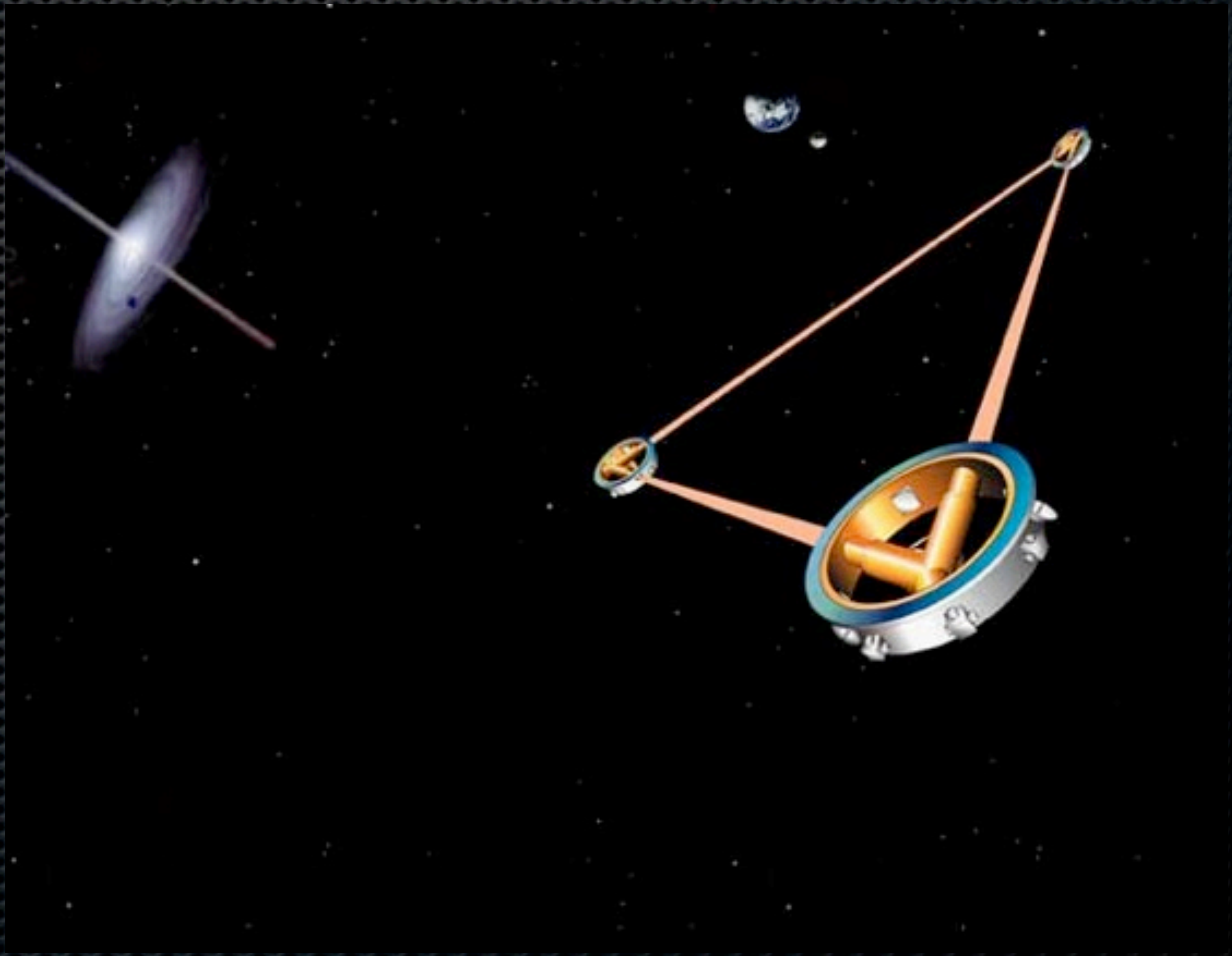
Also Space!

~~Laser Interferometer Space Antenna~~

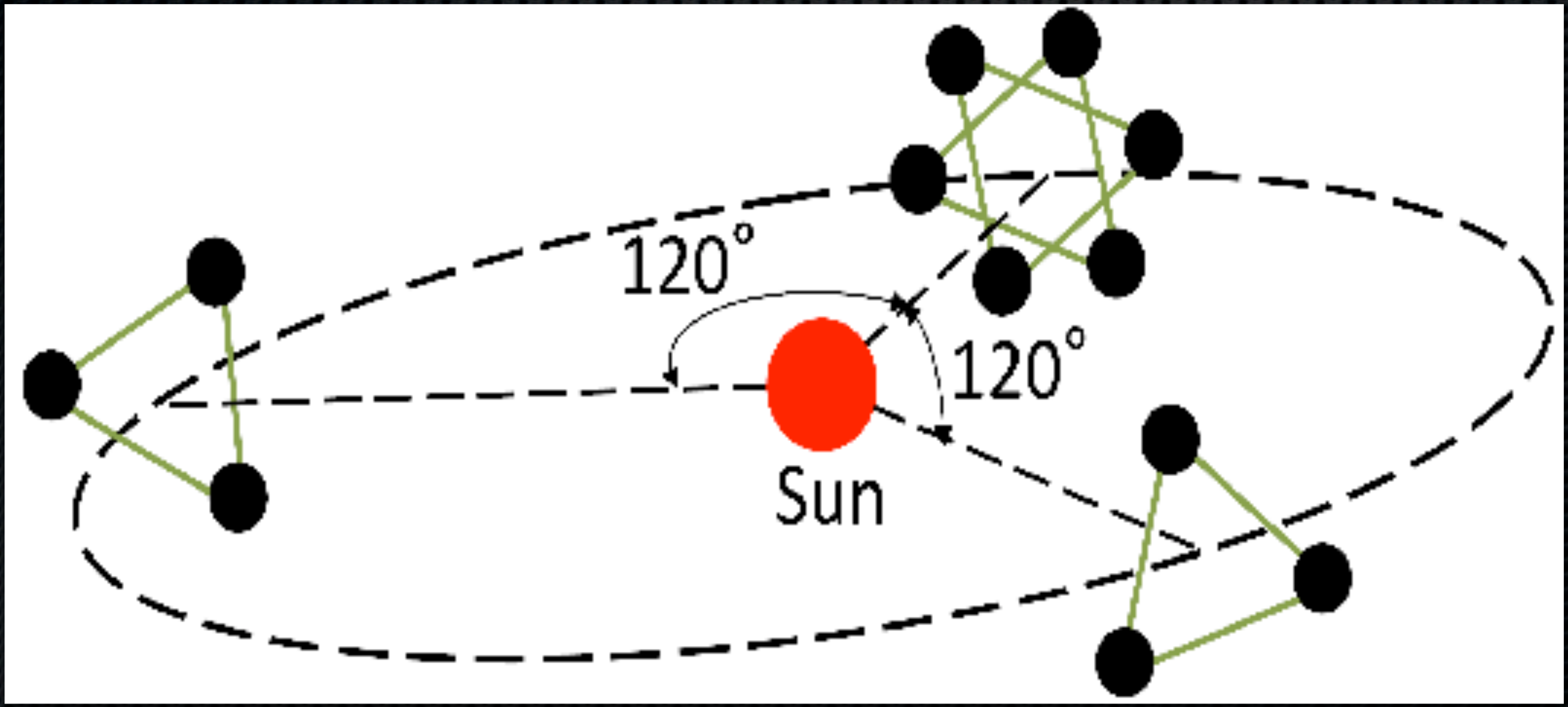
eLISA → 2034

DECIGO

Big Bang Observer

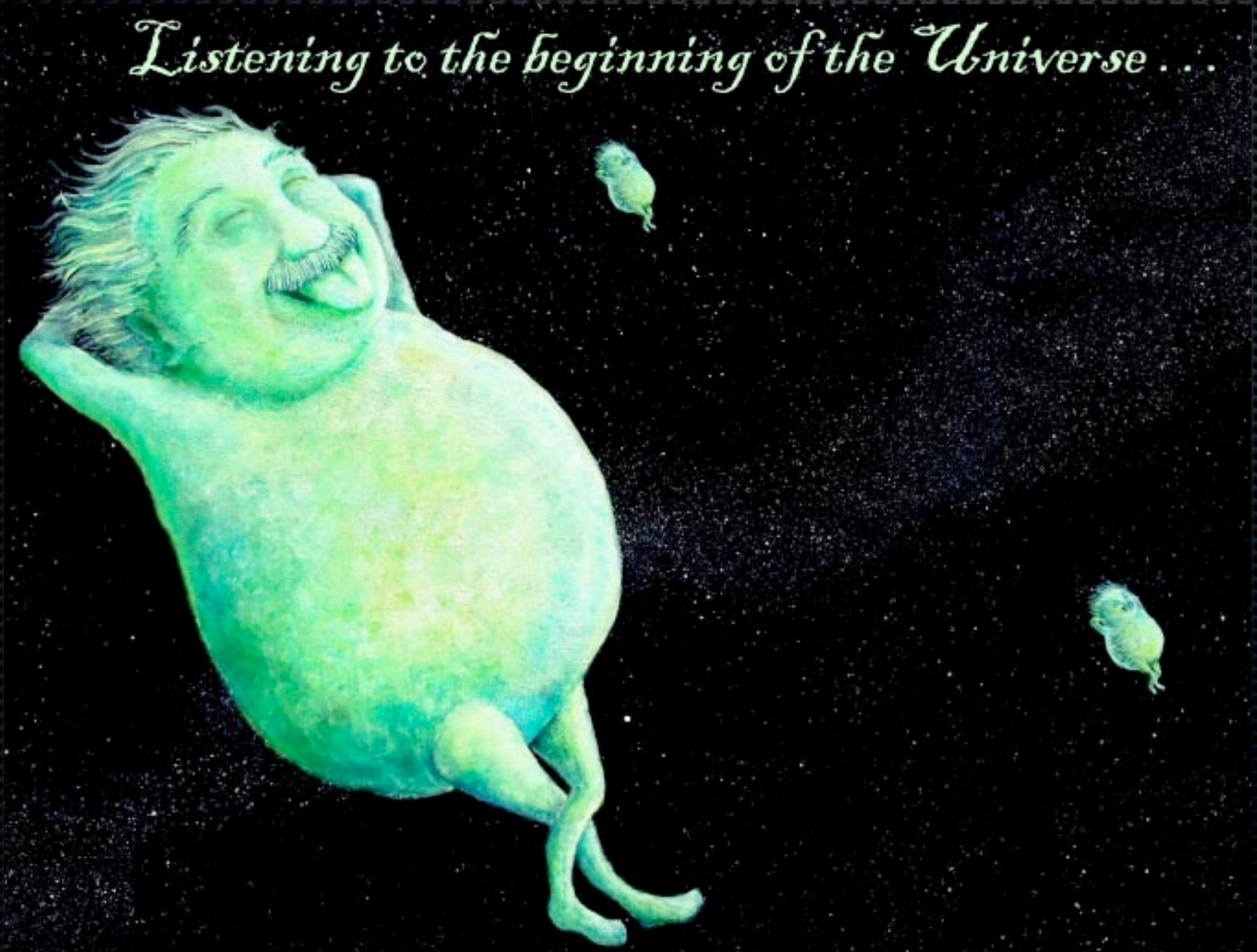


Far, far away



- Big Bang Observer (BBO)

Far, far away



- DeciHertz Gravitational wave observatory (DECIGO)

GW science reach