Detecting gravitational waves with interferometers

Xavier Siemens

The Leonard E. Parker
Center for Gravitation, Cosmology & Astrophysics
at the University of Wisconsin–Milwaukee

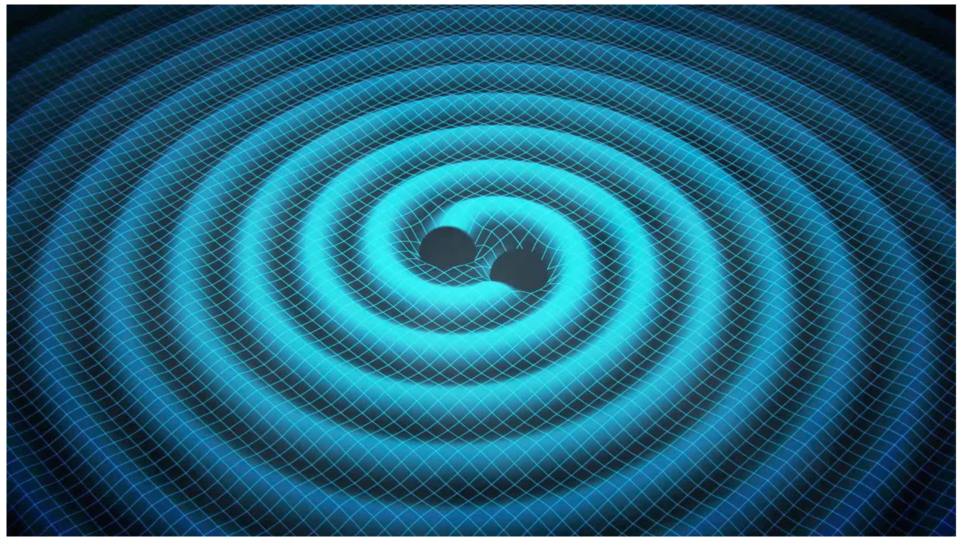
Summary

- Gravitational waves

- Interferometers

- Astrophysics

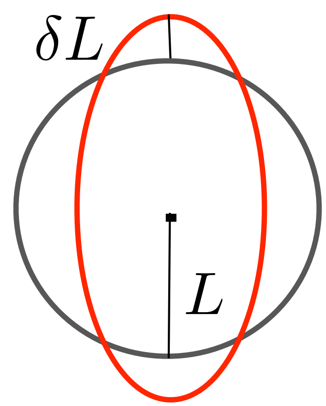
Gravitational waves (GWs)

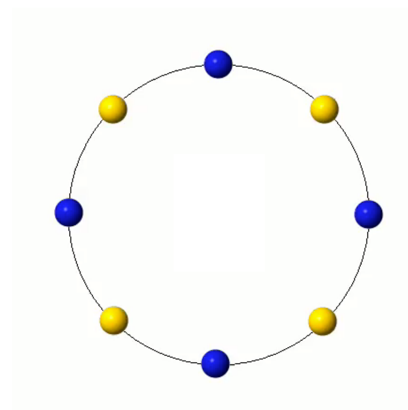


Gravitational waves are ripples in spacetime that propagate at the speed of light. They are a key prediction of general relativity.

They are produced by massive objects moving rapidly, and they change the distance between freely falling objects.

Their strength is measured by "strain".

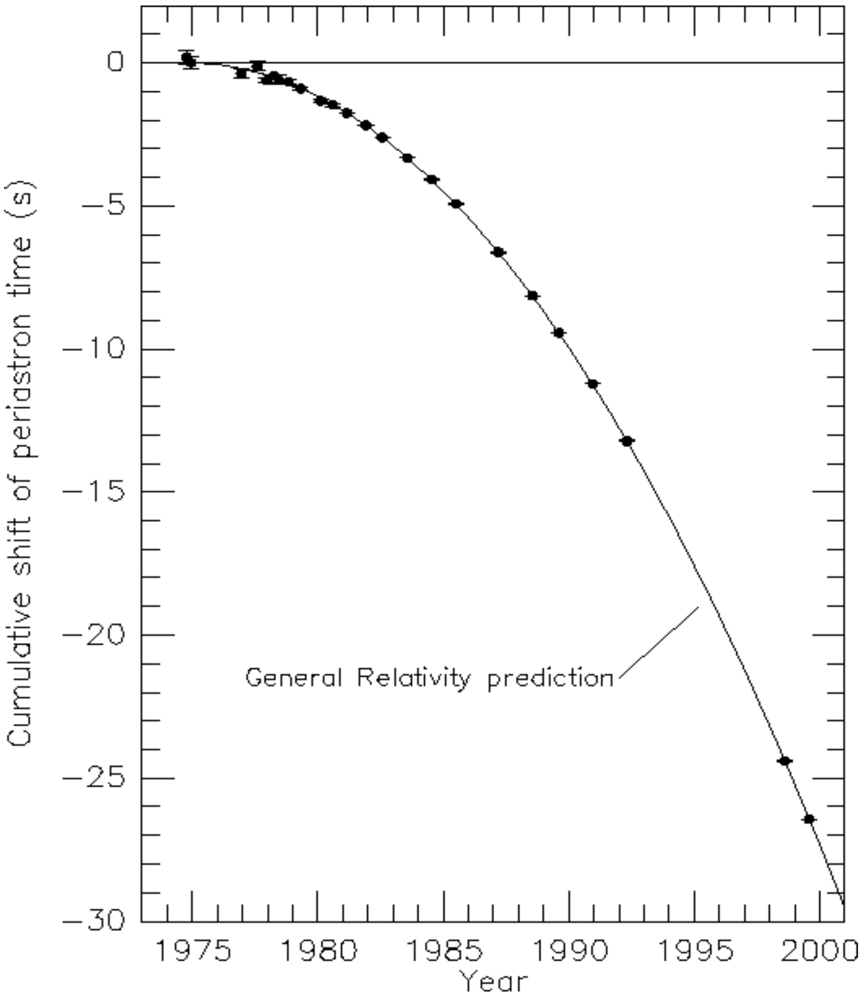




$$h = \frac{\delta L}{L}$$

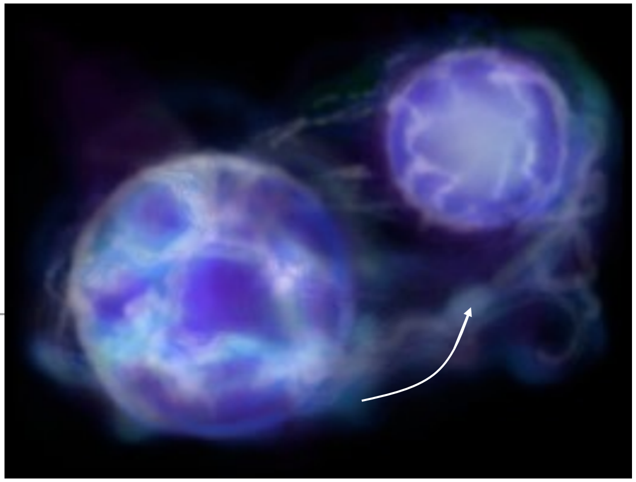
Gravitational wave observations will provide an entirely new means to study the universe.

Evidence for GWs



- Hulse and Taylor observed a rotating neutron star in a binary for 25 years

- Found orbit decay consistent with gravitational wave emission (Nobel prize 1993)

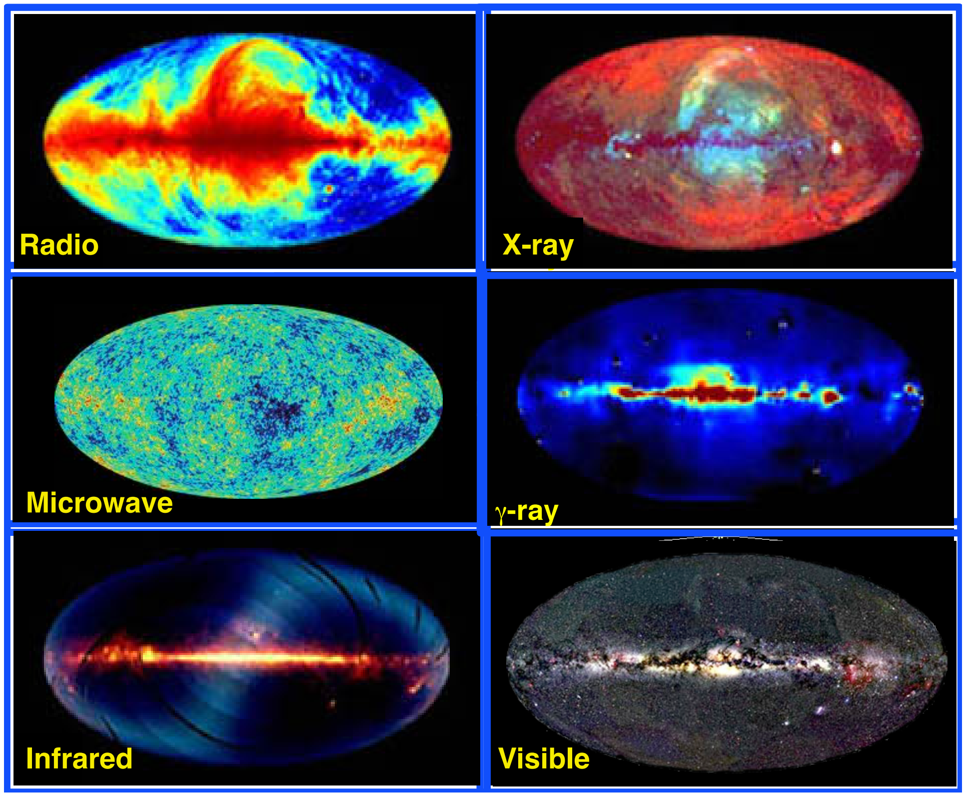


So aren't we done then?

No.

We want to observe gravitational waves directly by measuring changes in the light travel time between objects. This will allow us to "see" the universe in a completely new way, observe phenomena that cannot be seen electromagnetically, and test gravity.

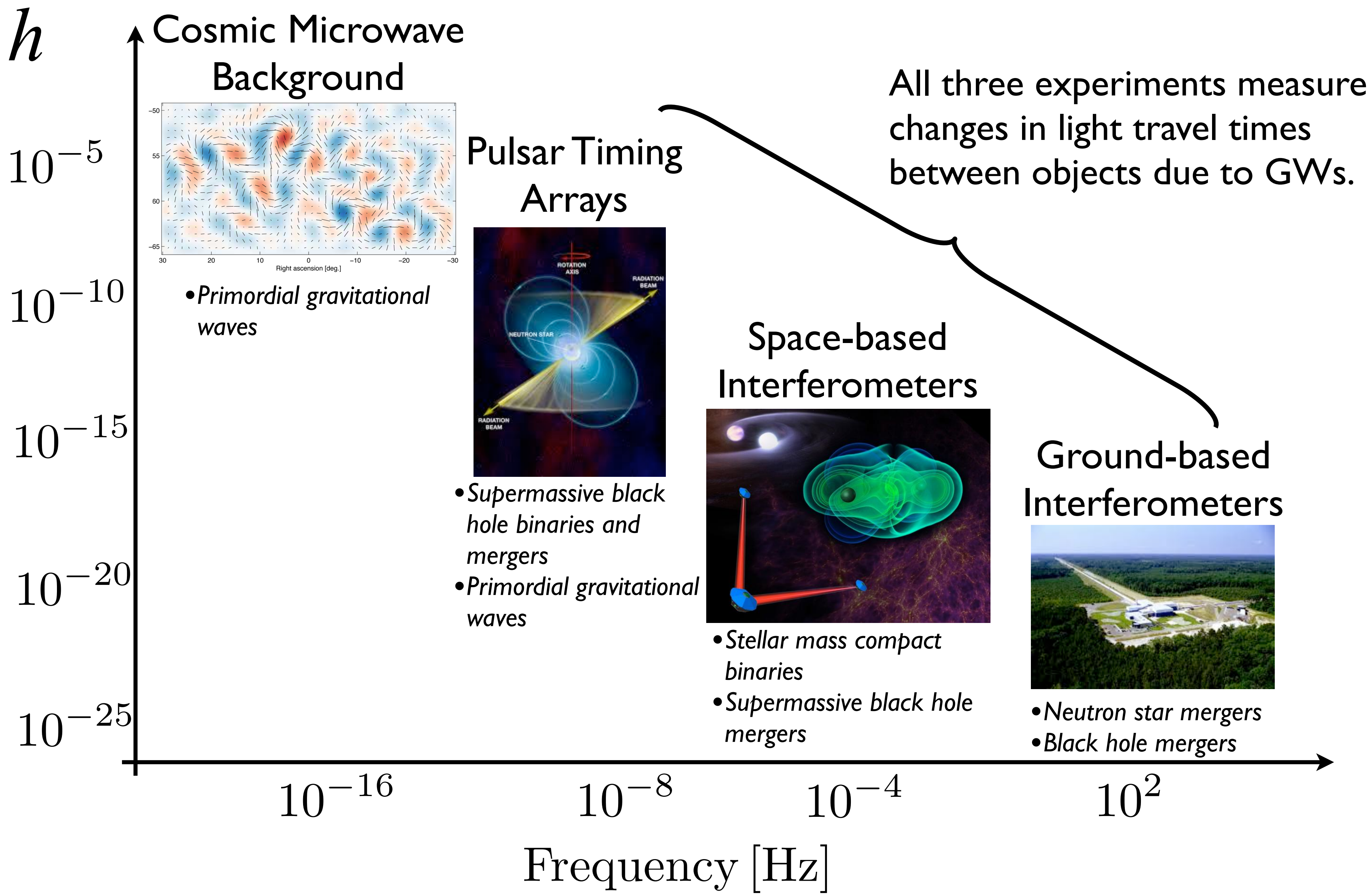
Analogy with electromagnetic observations



Observations in different parts of the EM spectrum have provided us with invaluable complementary insights and knowledge about our universe.

Goal of GW community is to see what the universe looks like across the GW spectrum

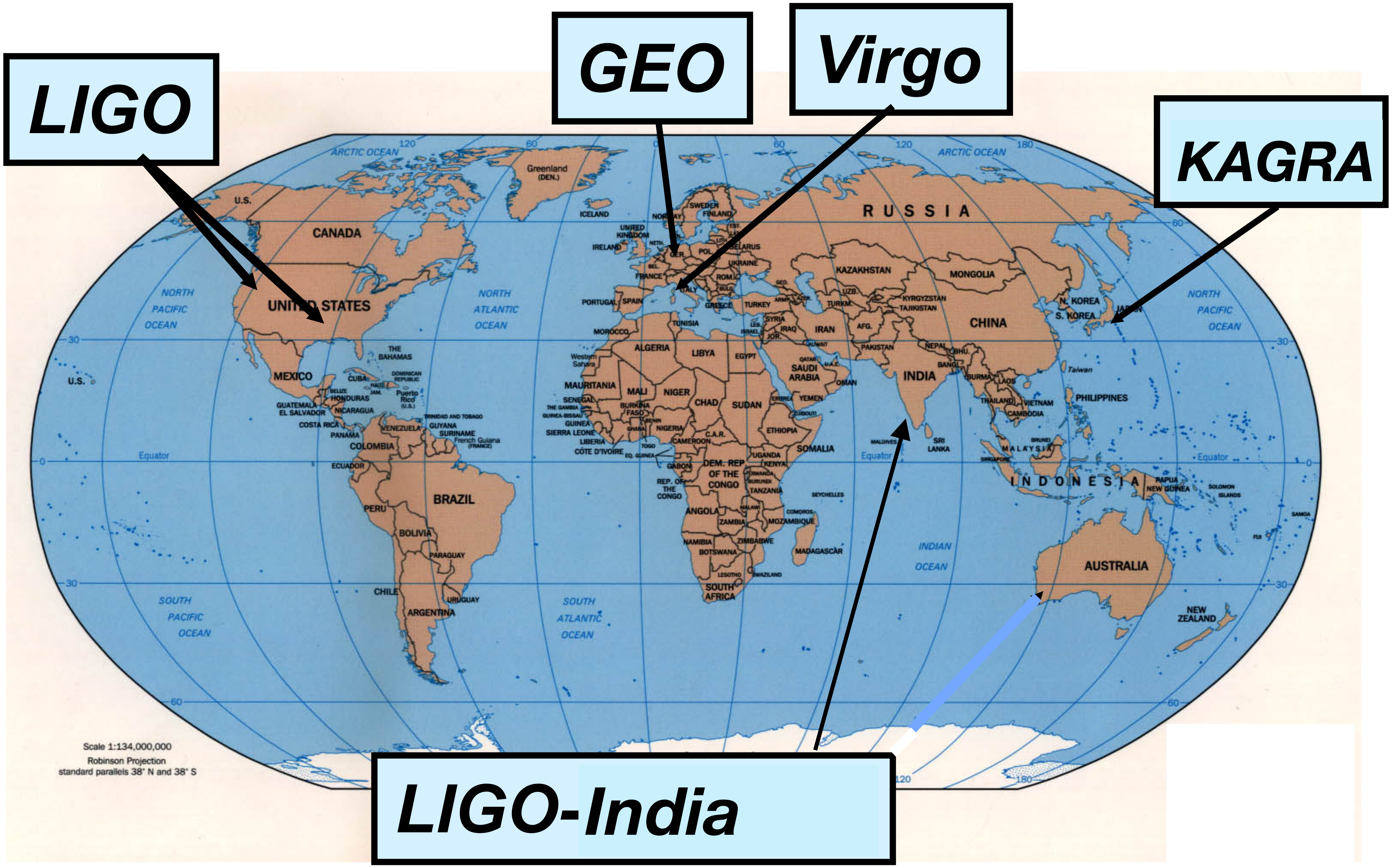
Gravitational wave experiments



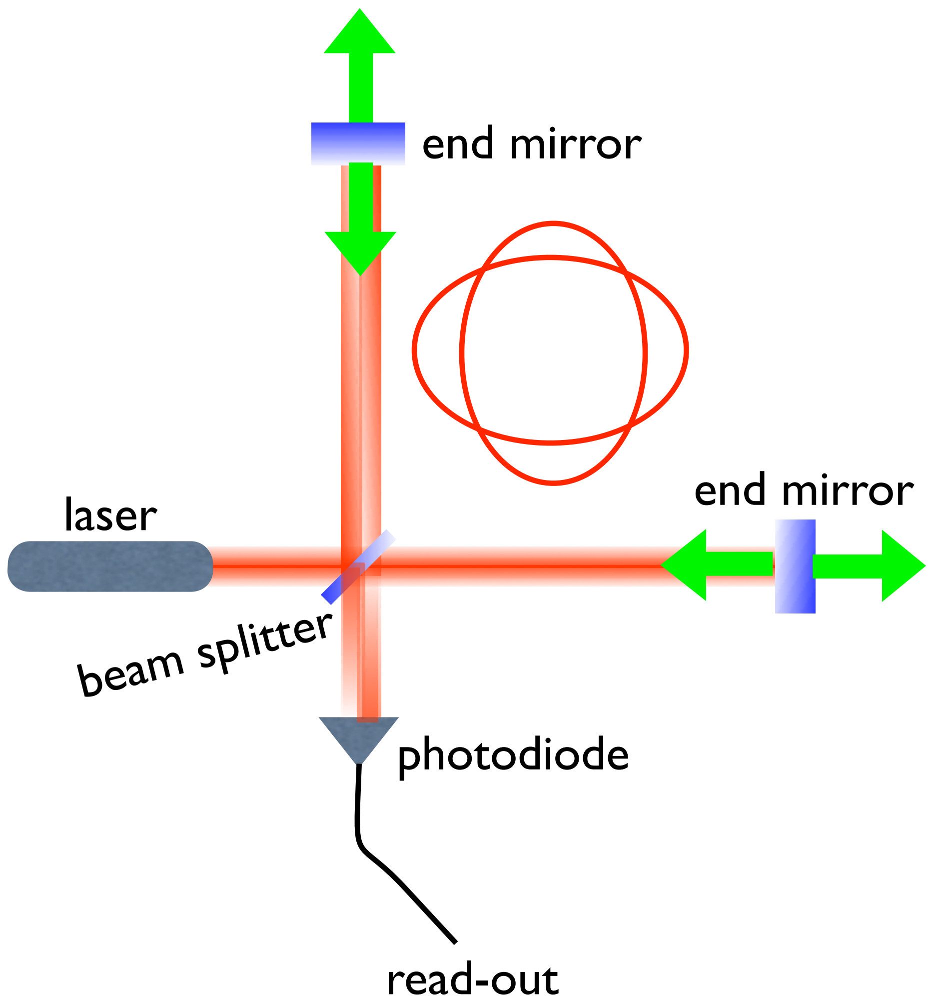
Direct vs. indirect

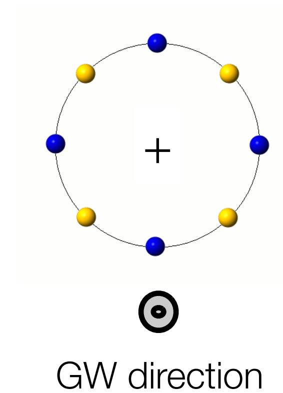
Ground base interferometers

Global network of detectors



How do interferometers for GW detection work?





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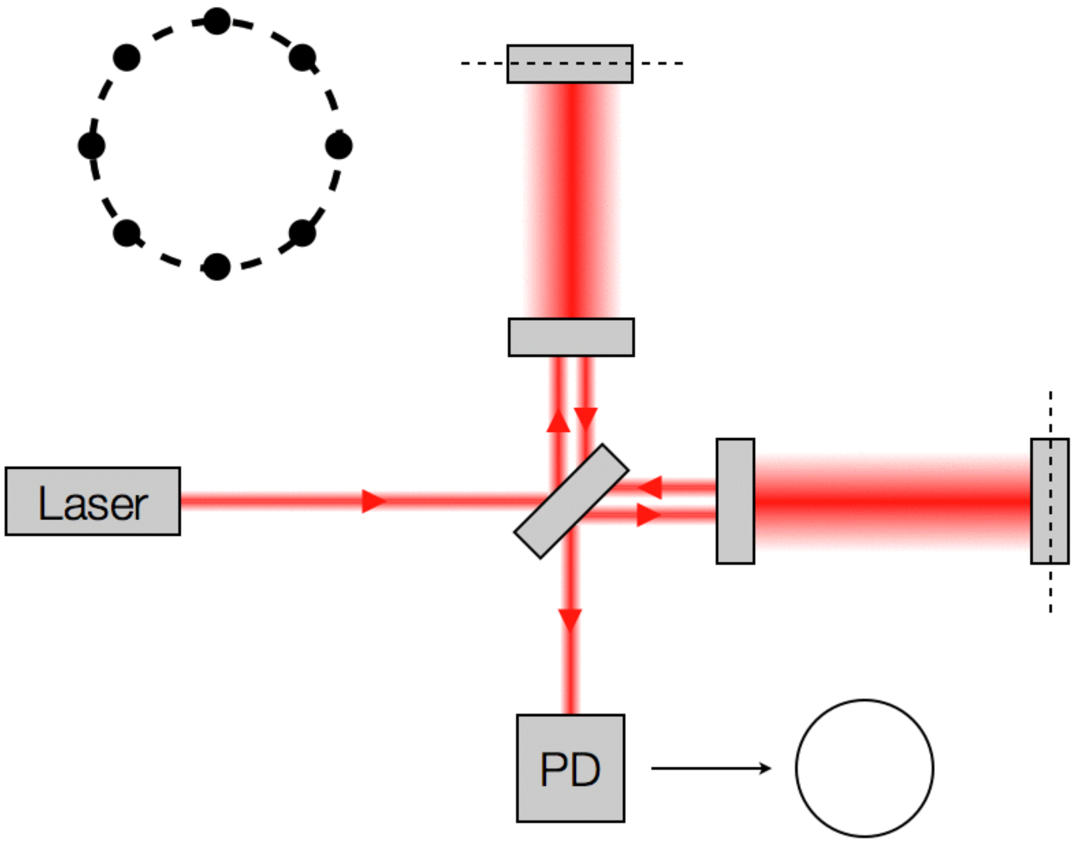


credit: L. Wade

We can look for patterns in the light that we see in our photodiode by matching them to signals we expect

Or, if we have more than one instrument, we can look for signals that match between instruments

Why is LIGO so sensitive?

- Interferometers measure $h = \dfrac{\Delta L}{L}$, $\Delta L = L_x - L_y$

- Can easily measure changes in length on the order of a fringe

$$h \sim \frac{\lambda}{L} \sim 3 \times 10^{-10}, \;\; \lambda \sim 1\,\mu\mathrm{m},\, L = 4\,\mathrm{km}$$

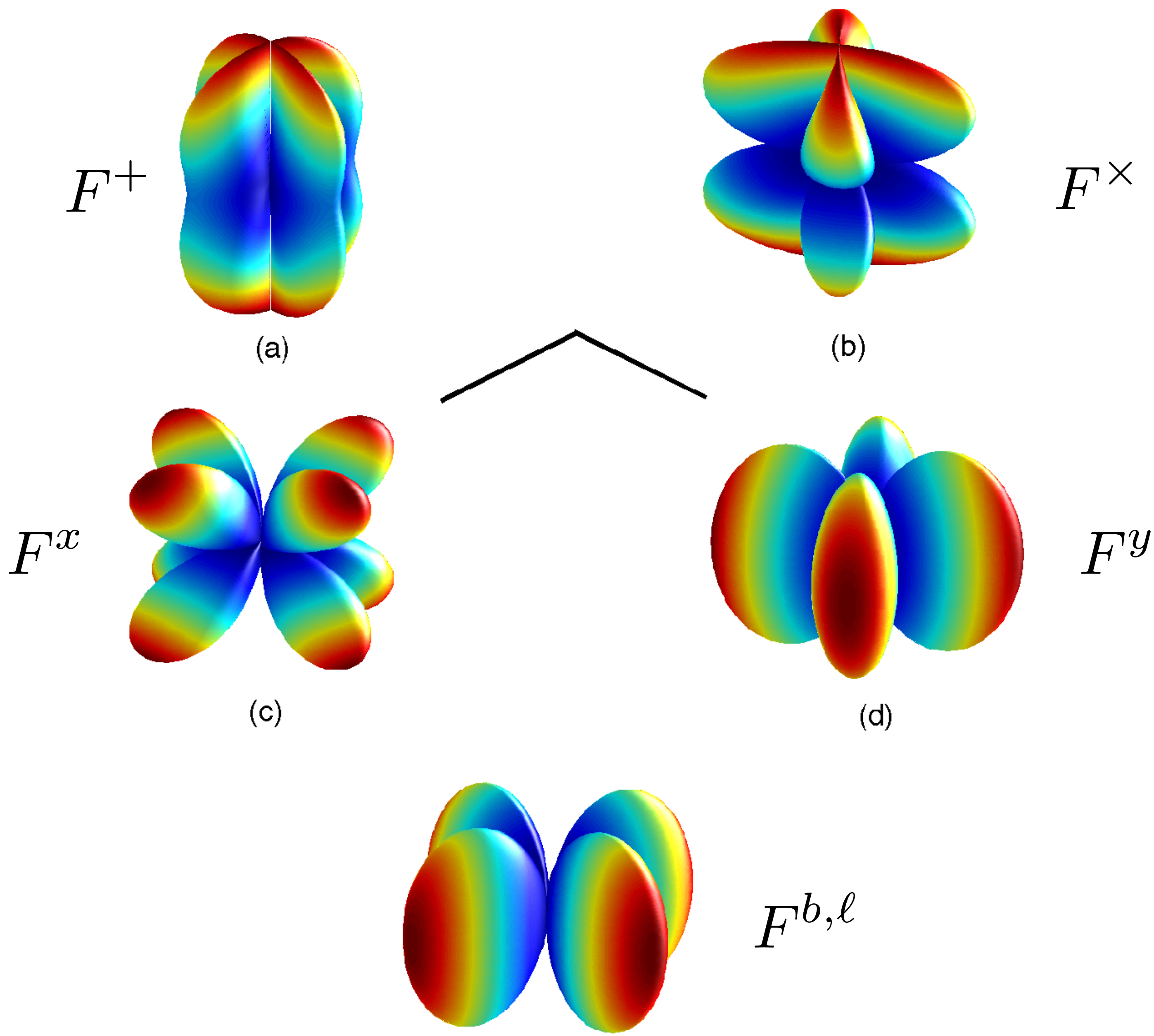
- Can measure fractions of a fringe if we have enough photons

$$\Delta L \sim \frac{\lambda}{N^{1/2}} \qquad N \sim \frac{P}{f h_p \nu} \sim 10^{16} \qquad h \sim 10^{-18}$$

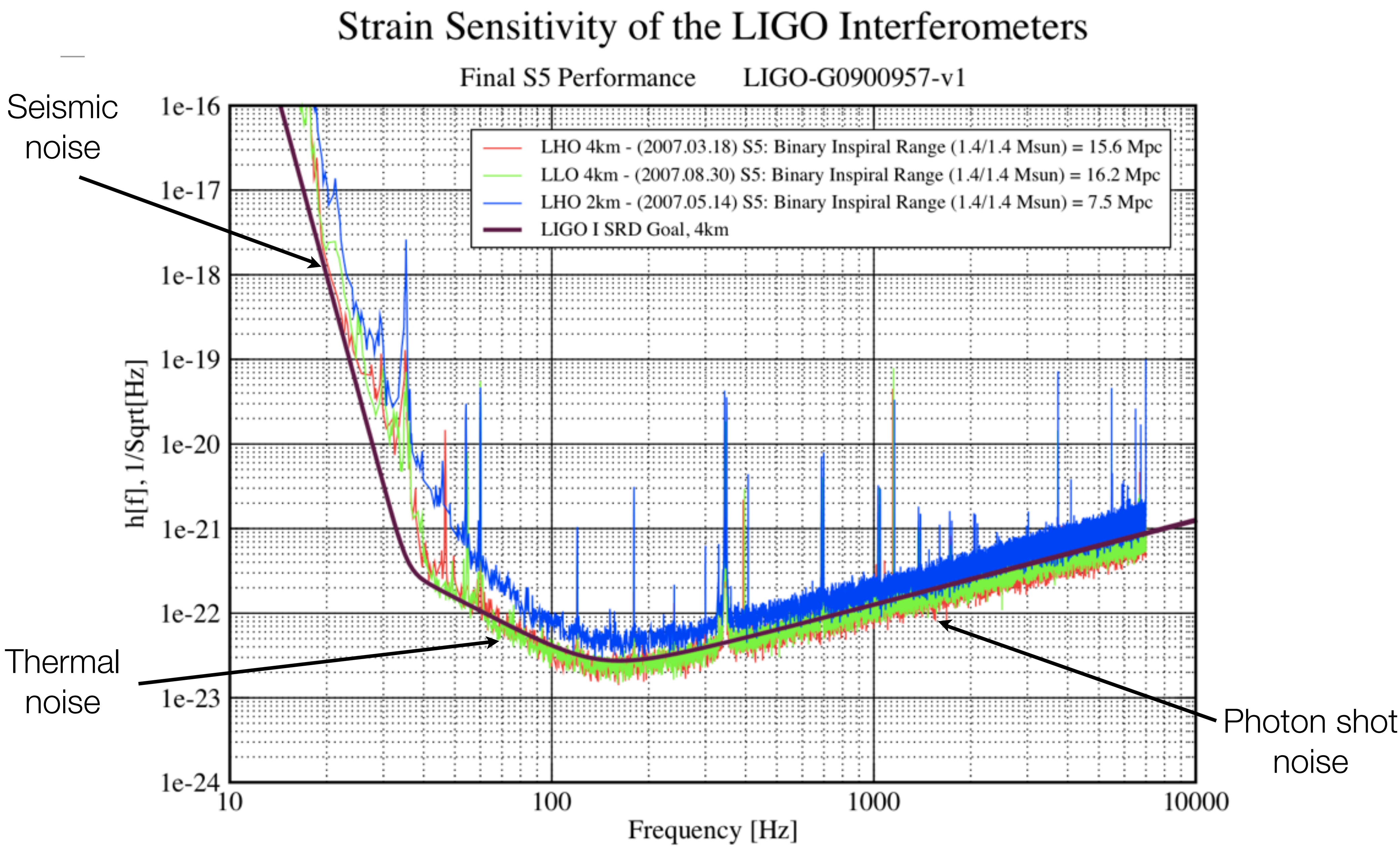
- Can make arms longer by putting Fabry-Perot cavities in the arms. For GW frequencies of ~100 Hz and below, light travels back and forth in the arms ~1000 times

$$\rightarrow h \sim 10^{-21}$$

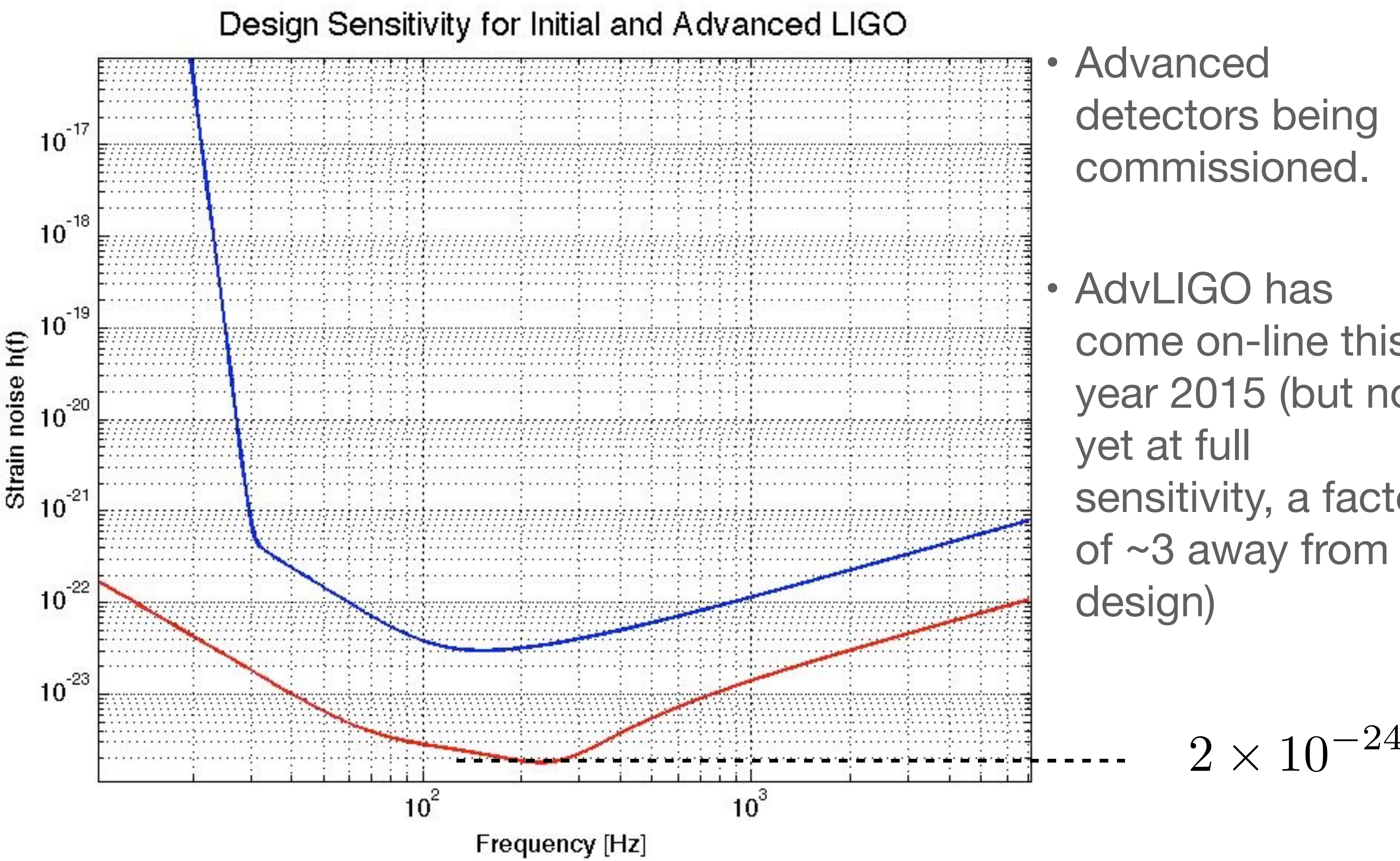
Antenna pattern response functions for LIGO/Virgo



Initial LIGO sensitivity

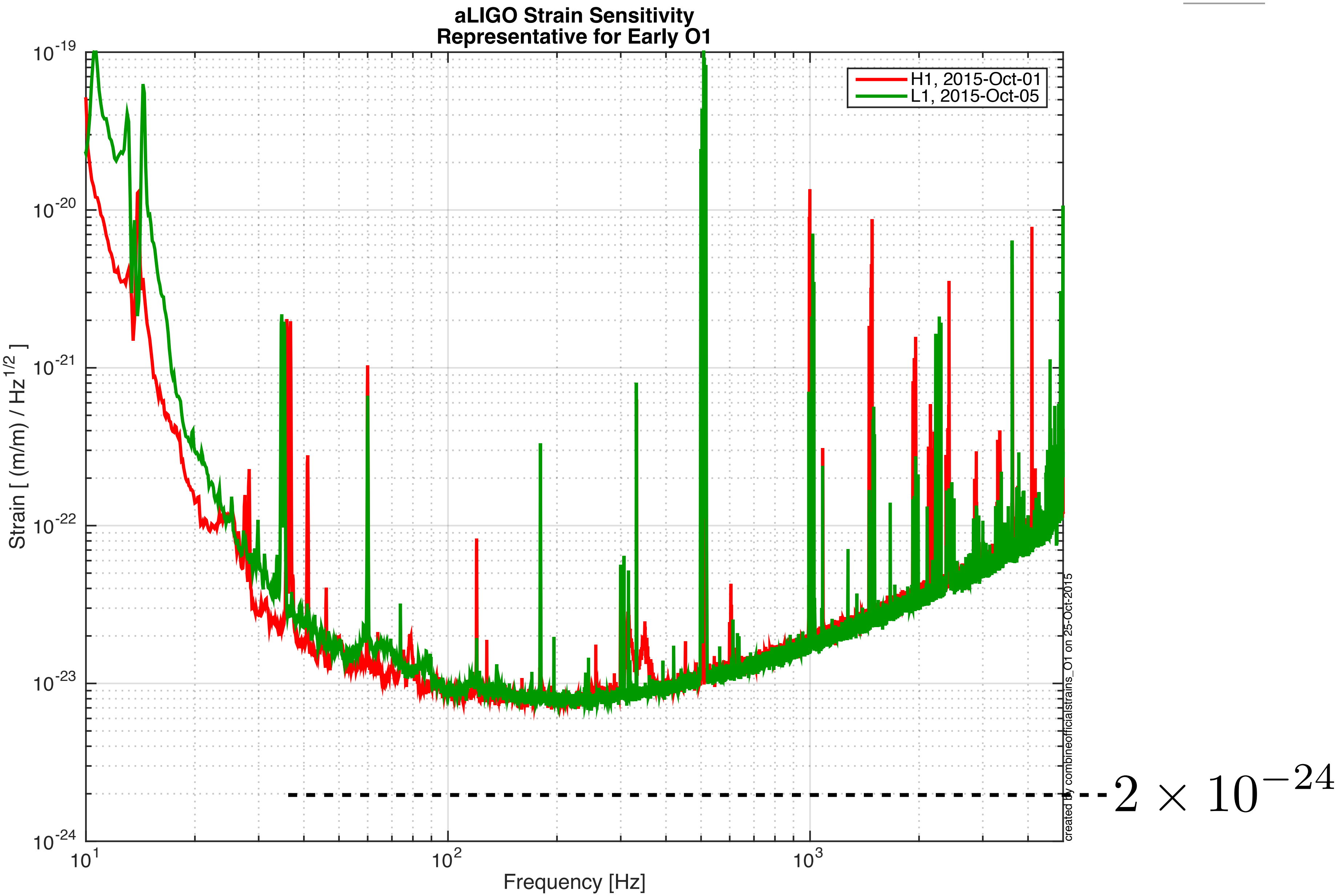


Advanced detectors



- Advanced detectors being commissioned.
- AdvLIGO has come on-line this year 2015 (but not yet at full sensitivity, a factor of ~3 away from design)

Current state

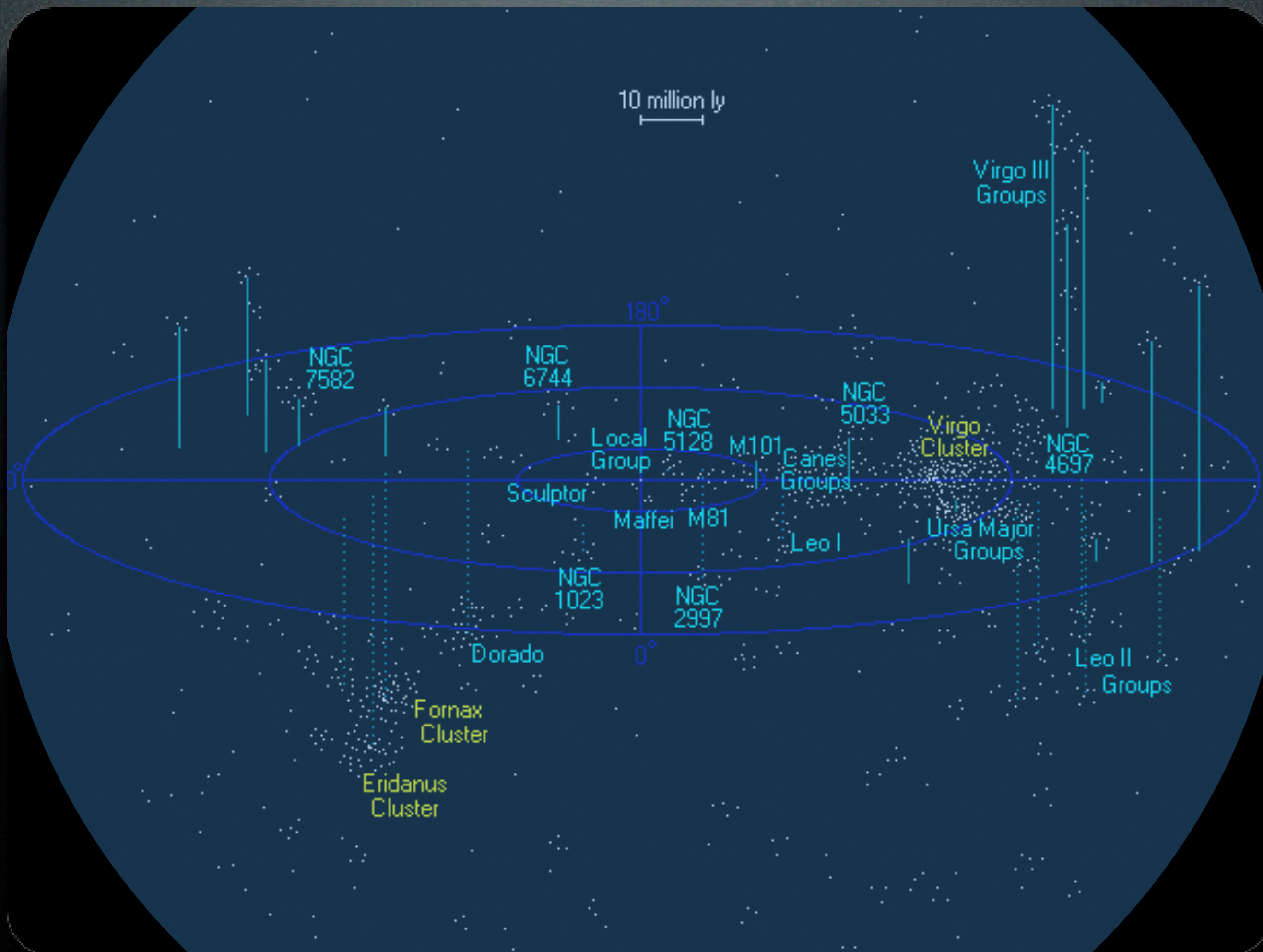


Timeline

Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		$5\,\mathrm{deg}^2$	$20\,\mathrm{deg}^2$
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

arxiv:1304.0670

Initial LIGO (S5)
Advanced LIGO

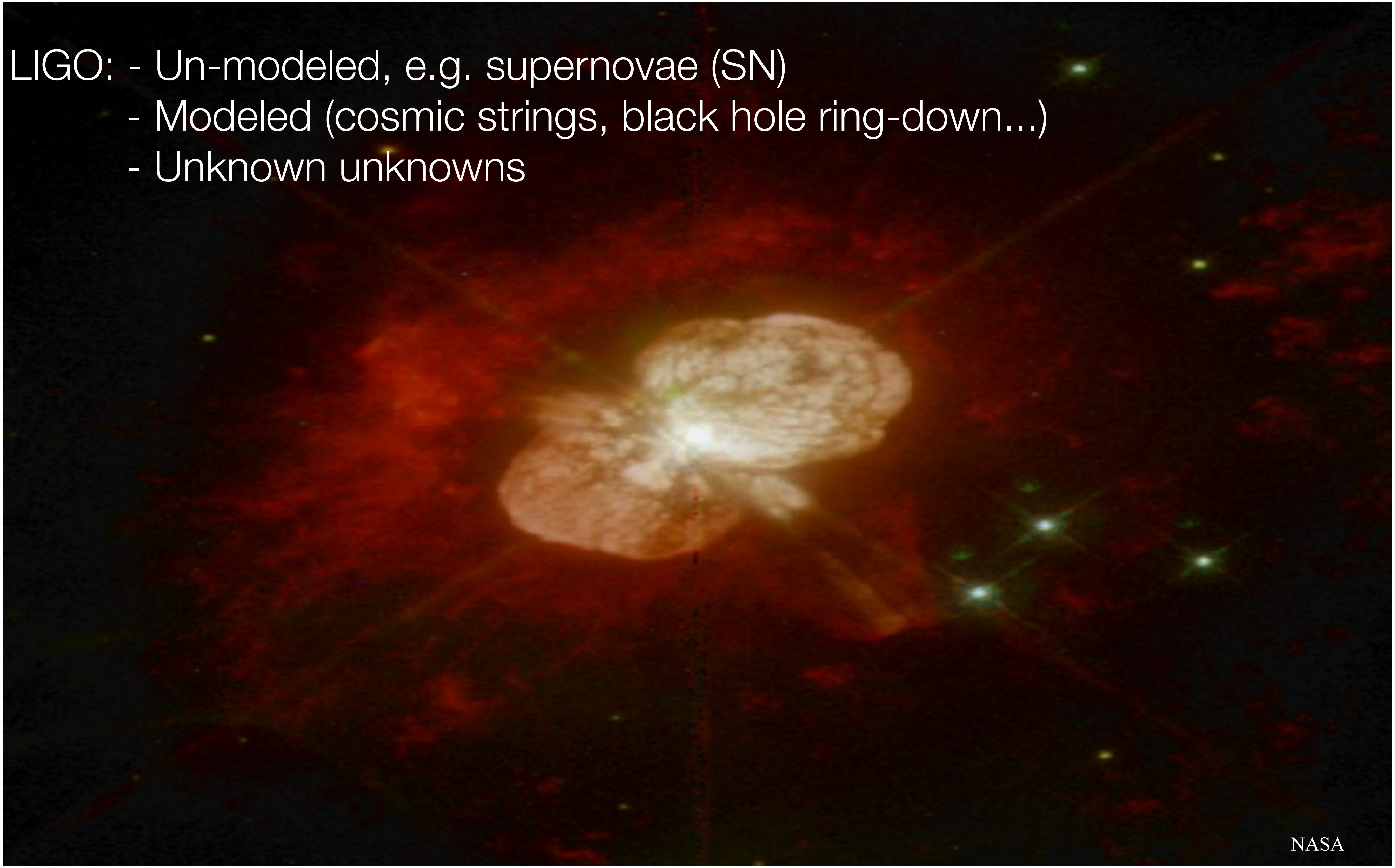


Binary Neutron Star Range

Credit: Jolien Creighton

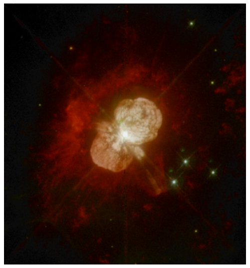
Sources: Bursts

LIGO: - Un-modeled, e.g. supernovae (SN)
- Modeled (cosmic strings, black hole ring-down...)
- Unknown unknowns

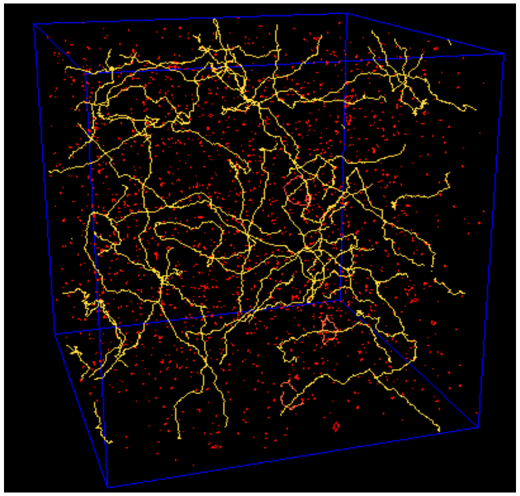


Sensitivity: Bursts

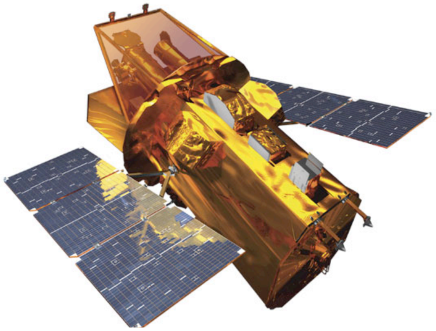
- w/. AdvLIGO we will only detect a SN if it occurs in the galaxy. We could learn about SN engine



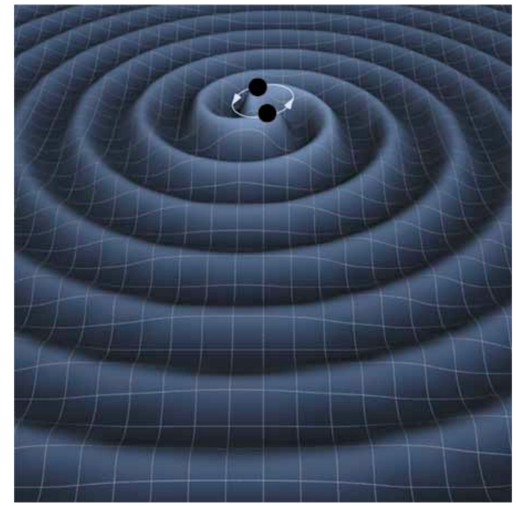
- Cosmic strings can exist in a vast range of energy scales (search using Initial LIGO/Virgo and more recent data set underway)



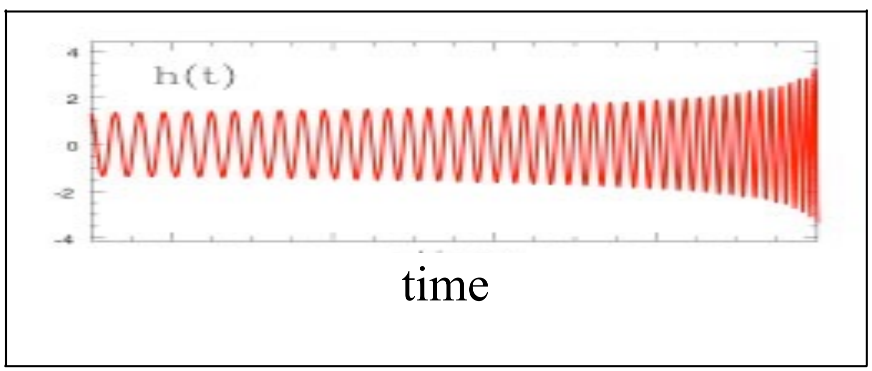
- A lot of effort is going into setting up combined multi-messenger astronomy campaigns (GW-optical, GW-radio, GW-gamma ray, GW-neutrino, ...)

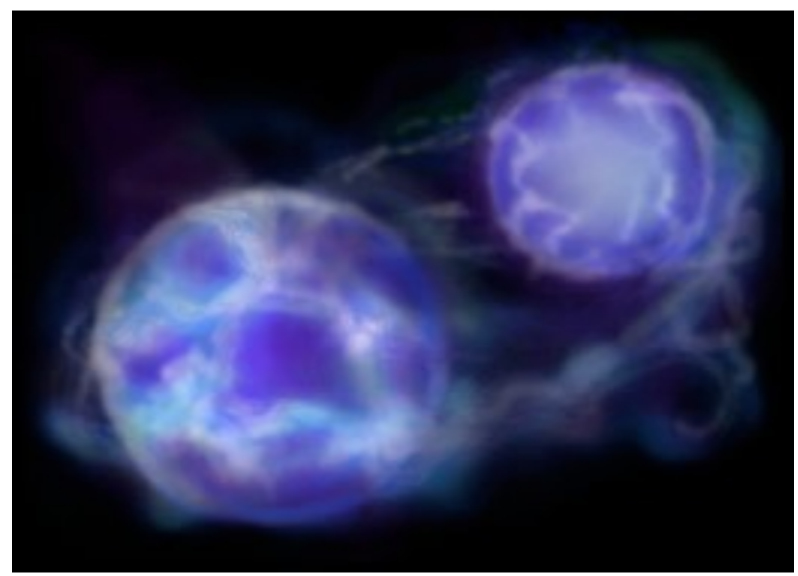


Sources: Compact binary coalescence



- LIGO's most promising source
- Neutron star-Neutron star (NS), NS-Black hole (BH), BH-BH binaries
- Chirp waveform



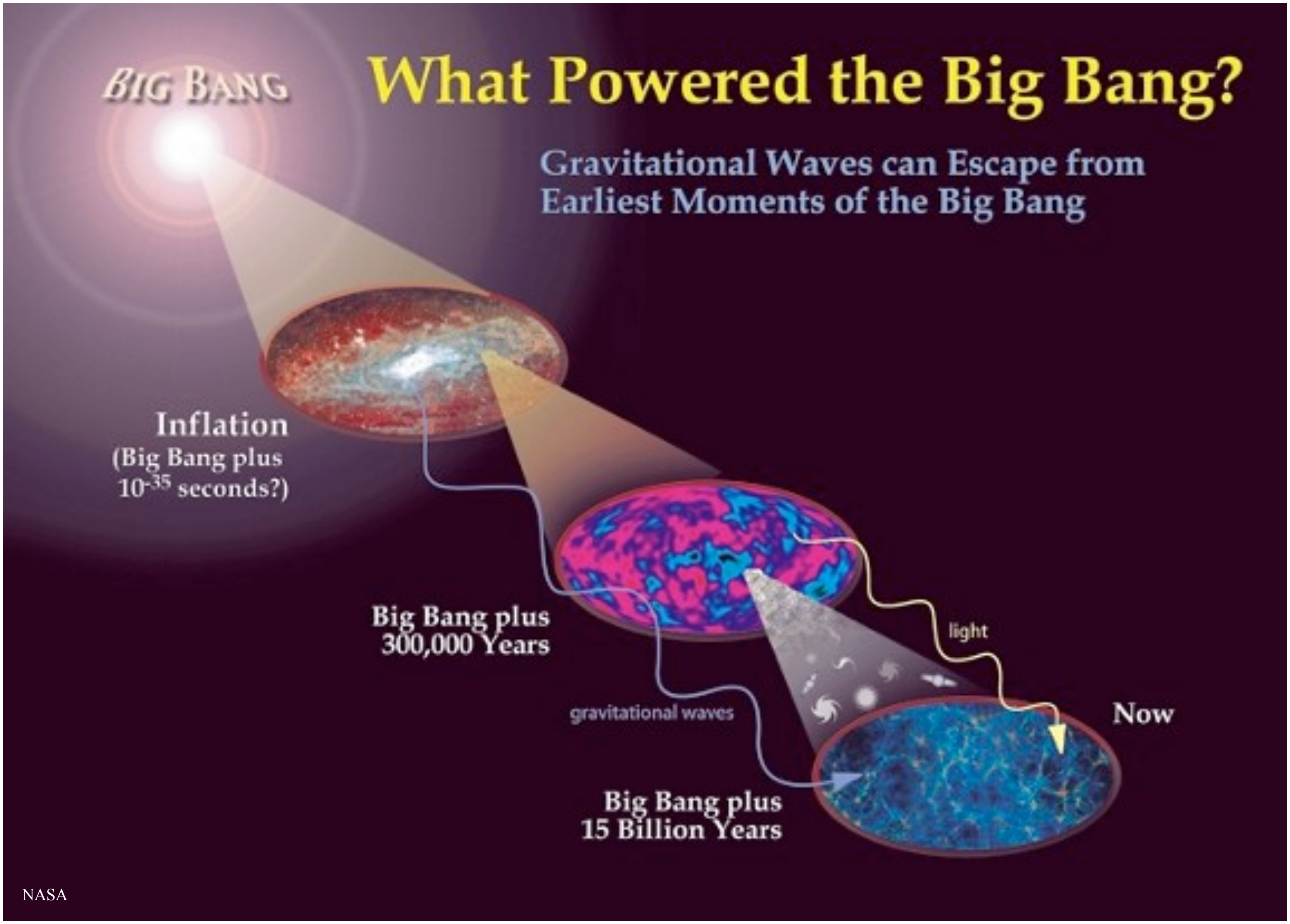


Sensitivity: CBCs

IFO	Source[a]	$\dot{N}_{\mathrm{low}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{re}}\ \mathrm{yr}^{-1}$	$\dot{N}_{\mathrm{high}}\ \mathrm{yr}^{-1}$
	NS–NS	2×10^{-4}	0.02	0.2
	NS–BH	7×10^{-5}	0.004	0.1
Initial	BH–BH	2×10^{-4}	0.007	0.5
	NS–NS	0.4	40	400
	NS–BH	0.2	10	300
Advanced	BH–BH	0.4	20	1000

- Initial LIGO didn't see anything (searched up to 35 solar mass BH) -- as expected
- Advanced LIGO will likely see ~1 event/week
- Will learn about stellar evolution, galactic evolution, ... NS-NS binaries are thought to be GRB progenitors so good opportunities for multi-messenger astronomy

Source: Stochastic background



Gravitational analog of cosmic microwave background

Stochastic Backgrounds

Gravitational radiation produced by an extremely large number of weak, independent and unresolved gravity-wave sources.

Credit: Jolien Creighton

- Astrophysical Sources: Black Hole Binaries, NS Binaries, White Dwarf Binaries, Supernovae...
- Cosmological Sources: Inflation, Cosmic Strings, Preheating, Phase Transitions...
- LIGO/AdvLIGO: Cosmic strings, astrophysical sources, phase transitions
- Background from inflation not detectable perhaps accessible via CMB)

Conclusions

- Gravitational wave astronomy around 100Hz is happening now

- Many exciting astrophysics possibilities