

# Testing General Relativity with Gravitational Waves

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KICP

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Compton Lectures  
University of Chicago

<https://github.com/reedessick/compton-lectures-2019>

# Review

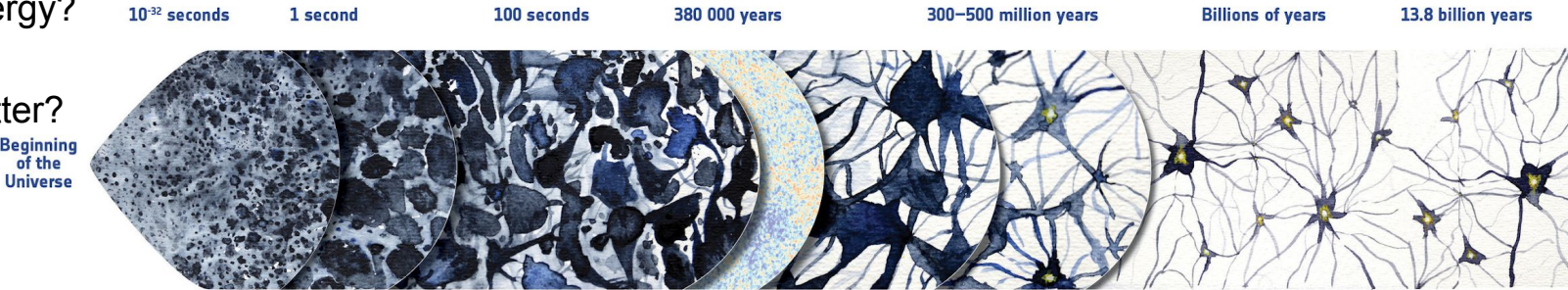
## General Relativity Basics

- Equivalence principle
- GWs travel at speed of light
- 2 polarizations

# Review

## Why test General Relativity?

- Dark Energy?
- Dark Matter?



### Inflation

Accelerated expansion of the Universe

### Formation of light and matter

### Light and matter are coupled

Dark matter evolves independently; it starts clumping and forming a web of structures

### Light and matter separate

- Protons and electrons form atoms
- Light starts travelling freely; it will become the Cosmic Microwave Background (CMB)

### Dark ages

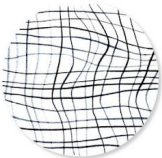
Atoms start feeling the gravity of the cosmic web of dark matter

### First stars

The first stars and galaxies form in the densest knots of the cosmic web

### Galaxy evolution

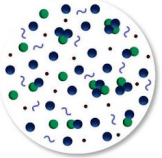
### The present Universe



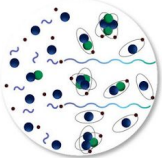
- Tiny fluctuations: the seeds of future structures
- Gravitational waves?



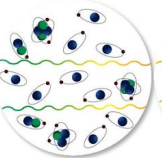
Frequent collisions between normal matter and light



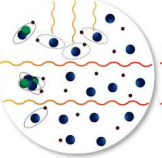
As the Universe expands, particles collide less frequently



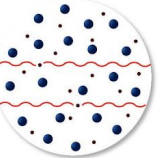
Last scattering of light off electrons  
→ **Polarisation**



The Universe is dark as stars and galaxies are yet to form



Light from first stars and galaxies breaks atoms apart and "reionises" the Universe



Light can interact again with electrons  
→ **Polarisation**

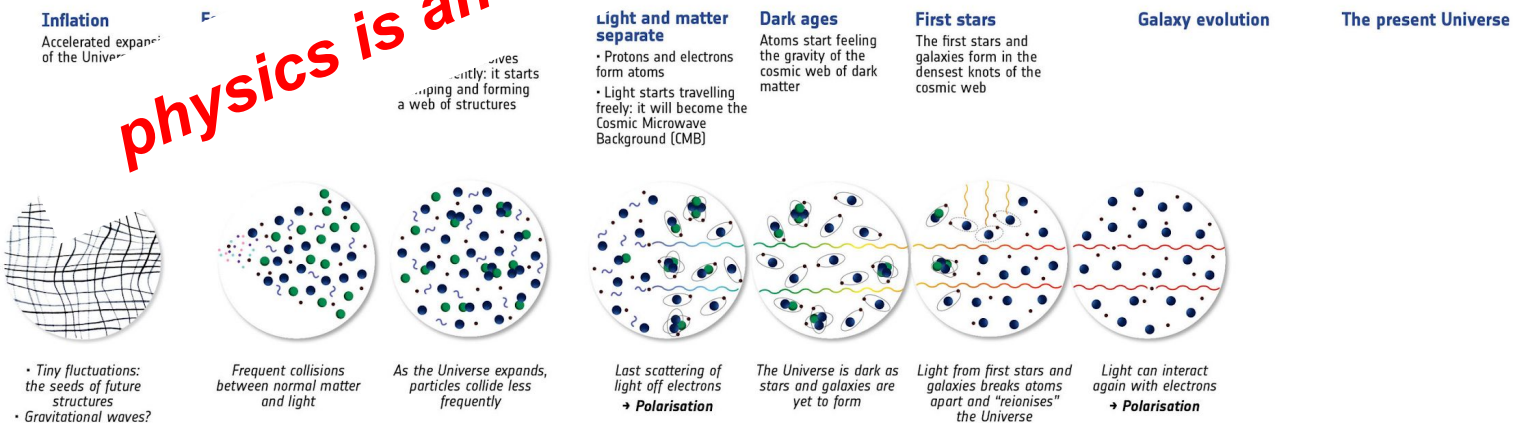
# Review

## Why test General Relativity?

- Dark Energy?
- Dark Matter?

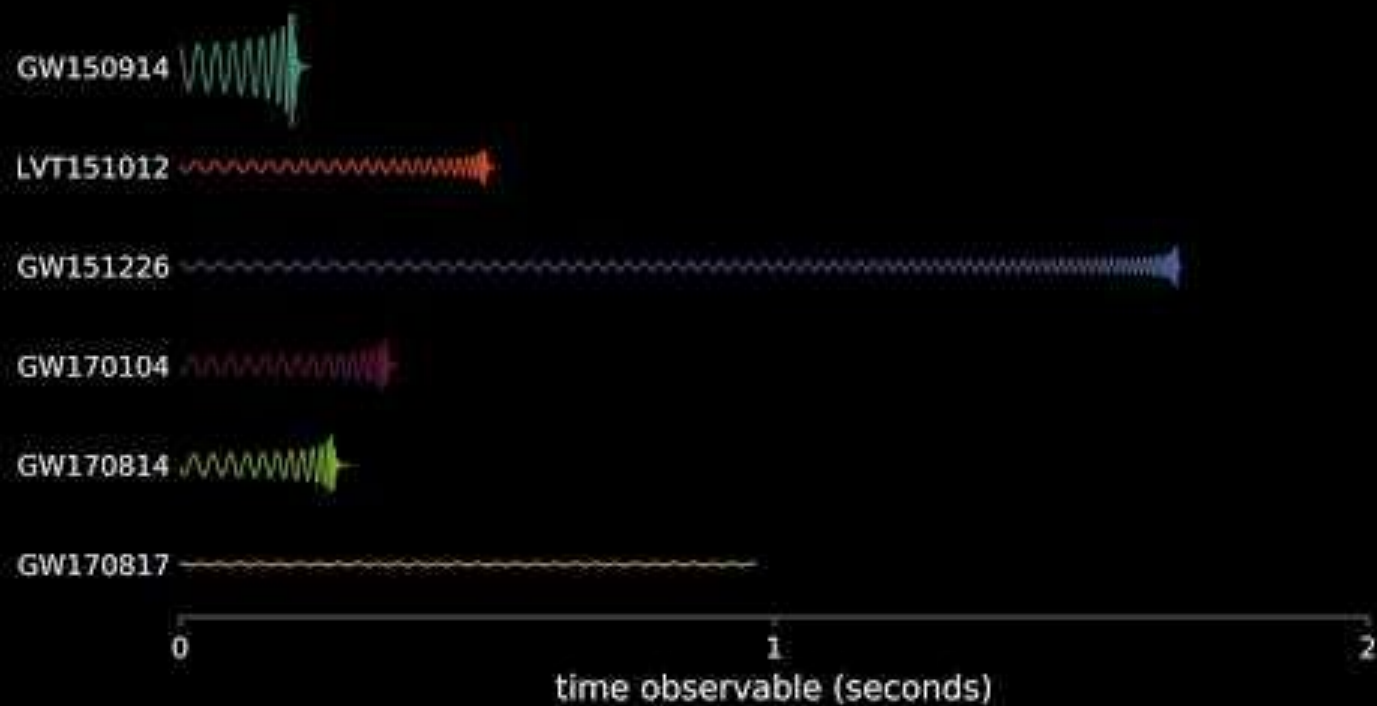


physics is an experimental science!

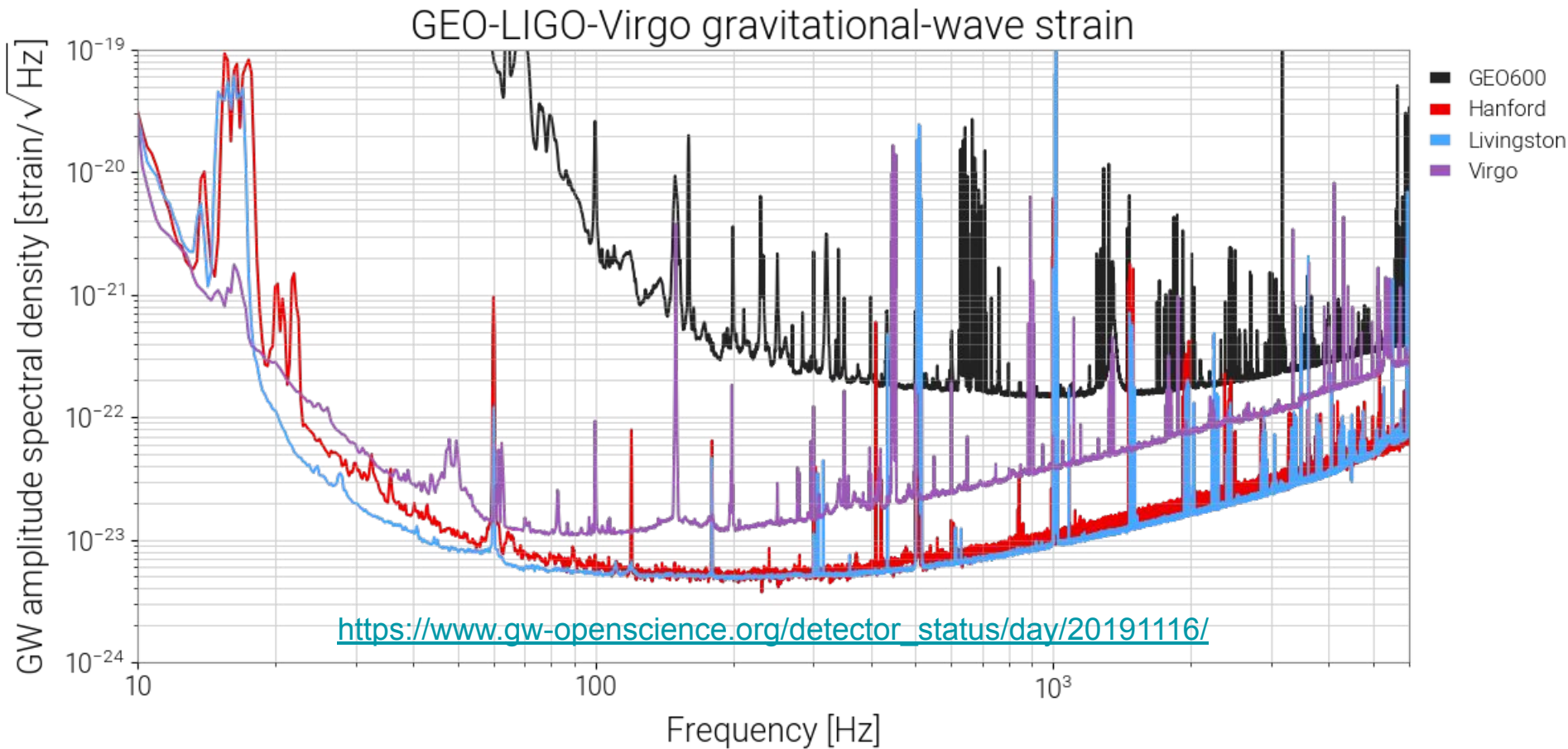


# Review

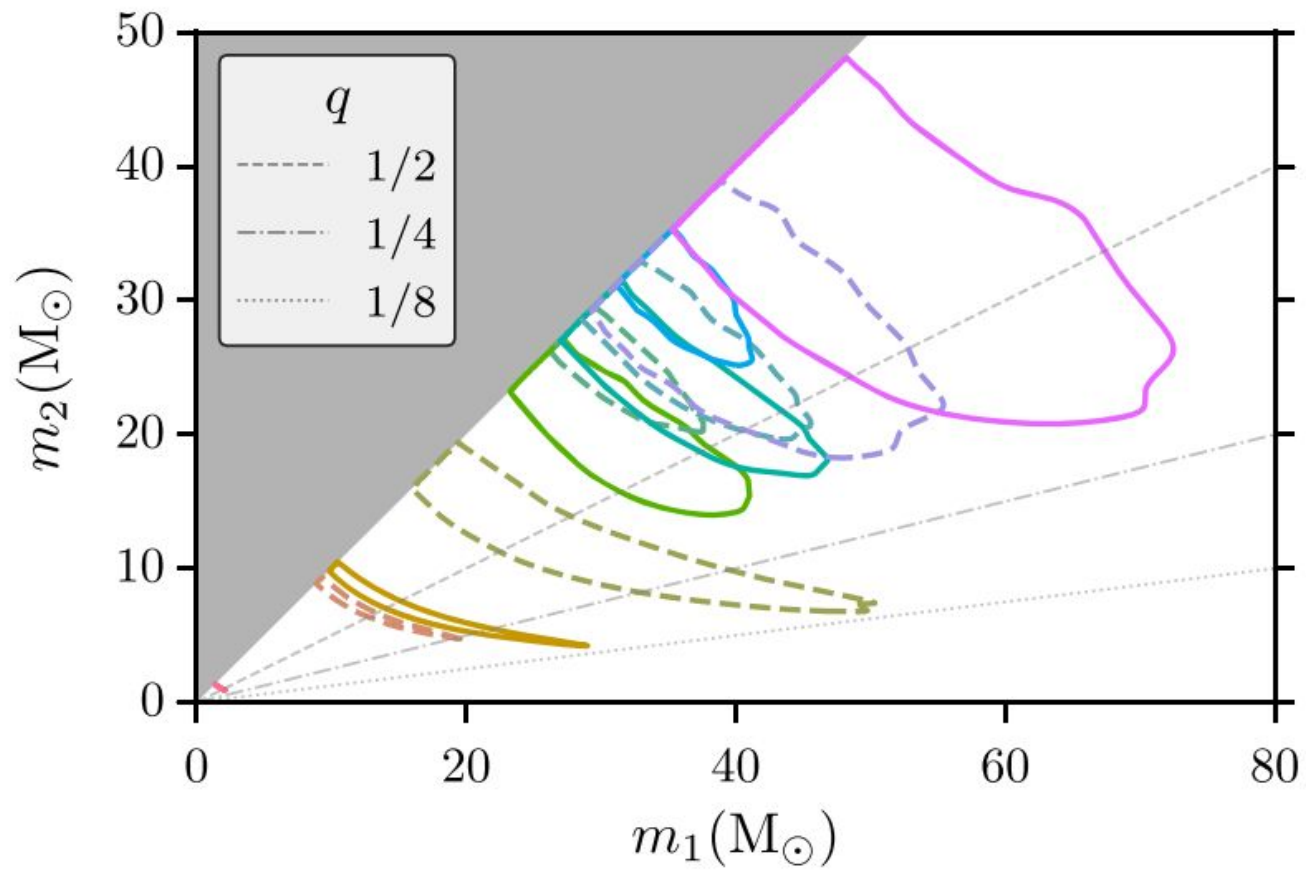
CBC signal types



# Review

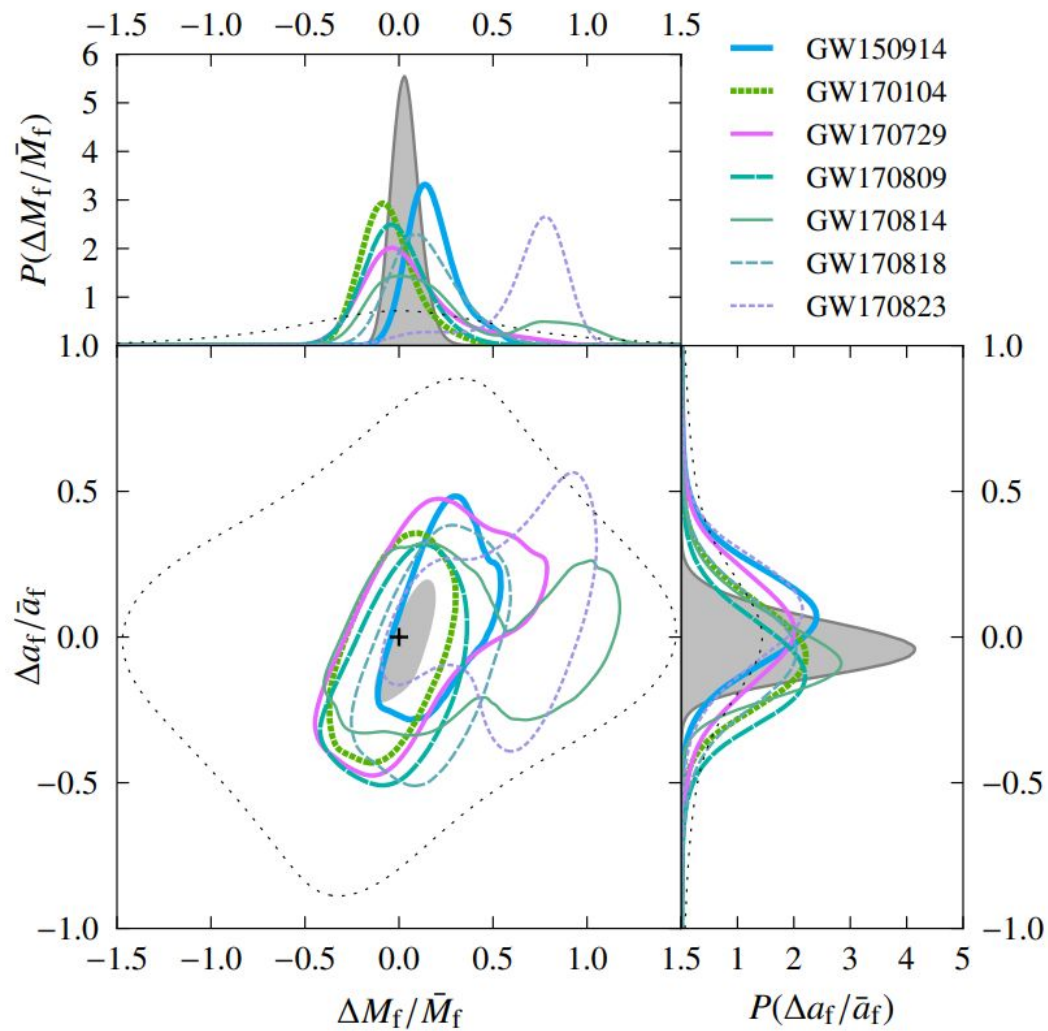


# Review





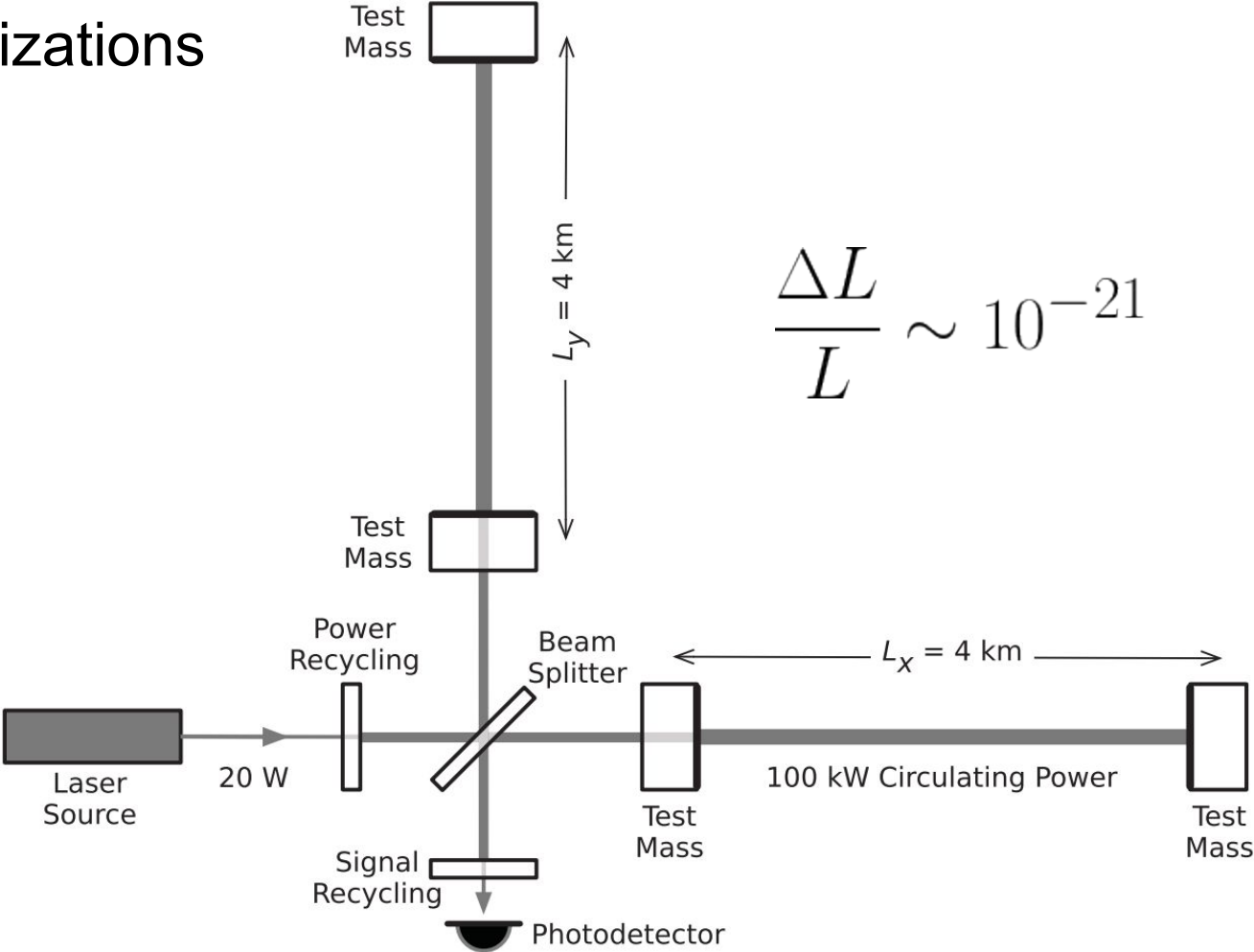
# Masses+Spins





# Number of Polarizations

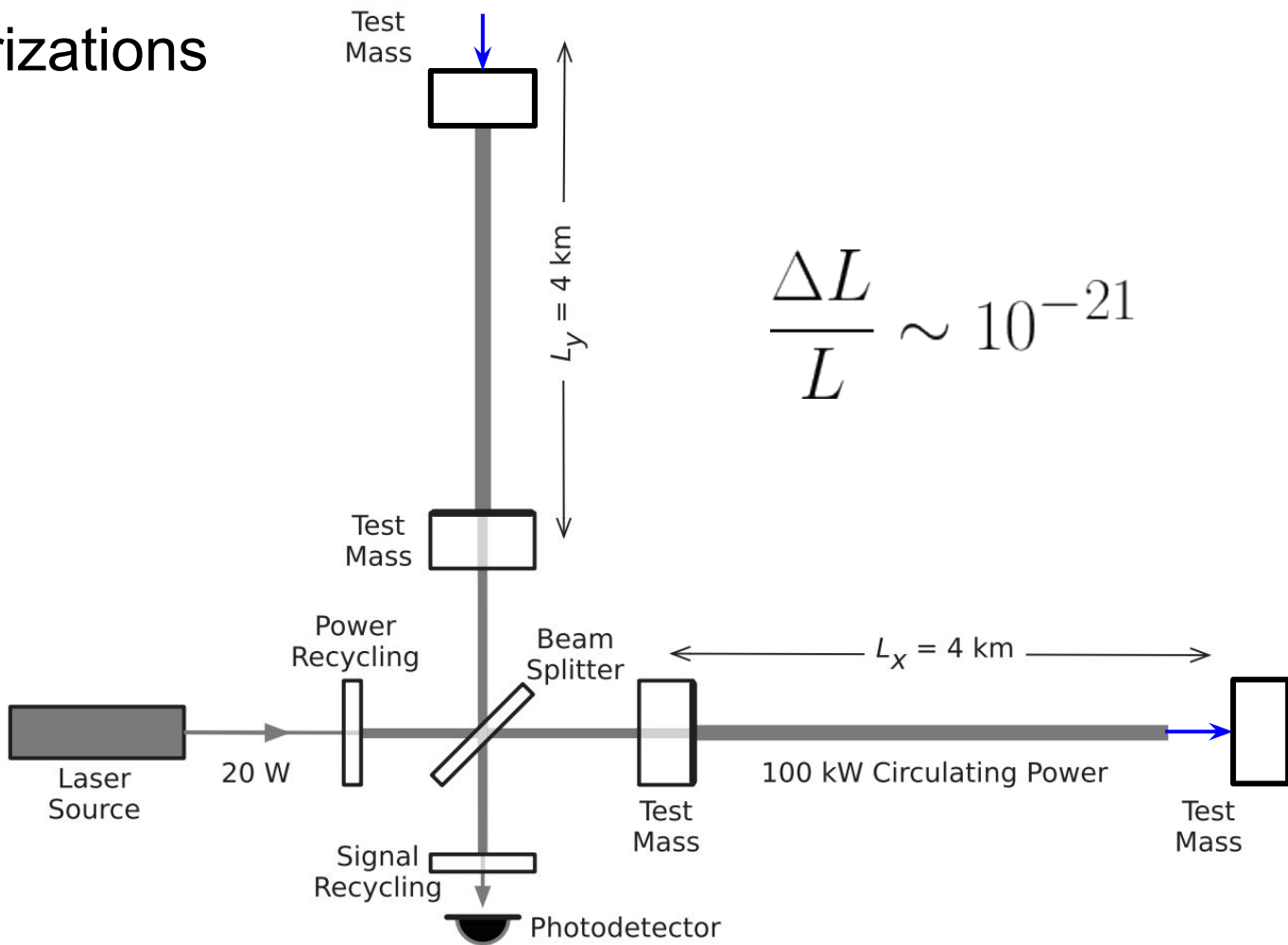
*Tensor* Modes



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

# Number of Polarizations

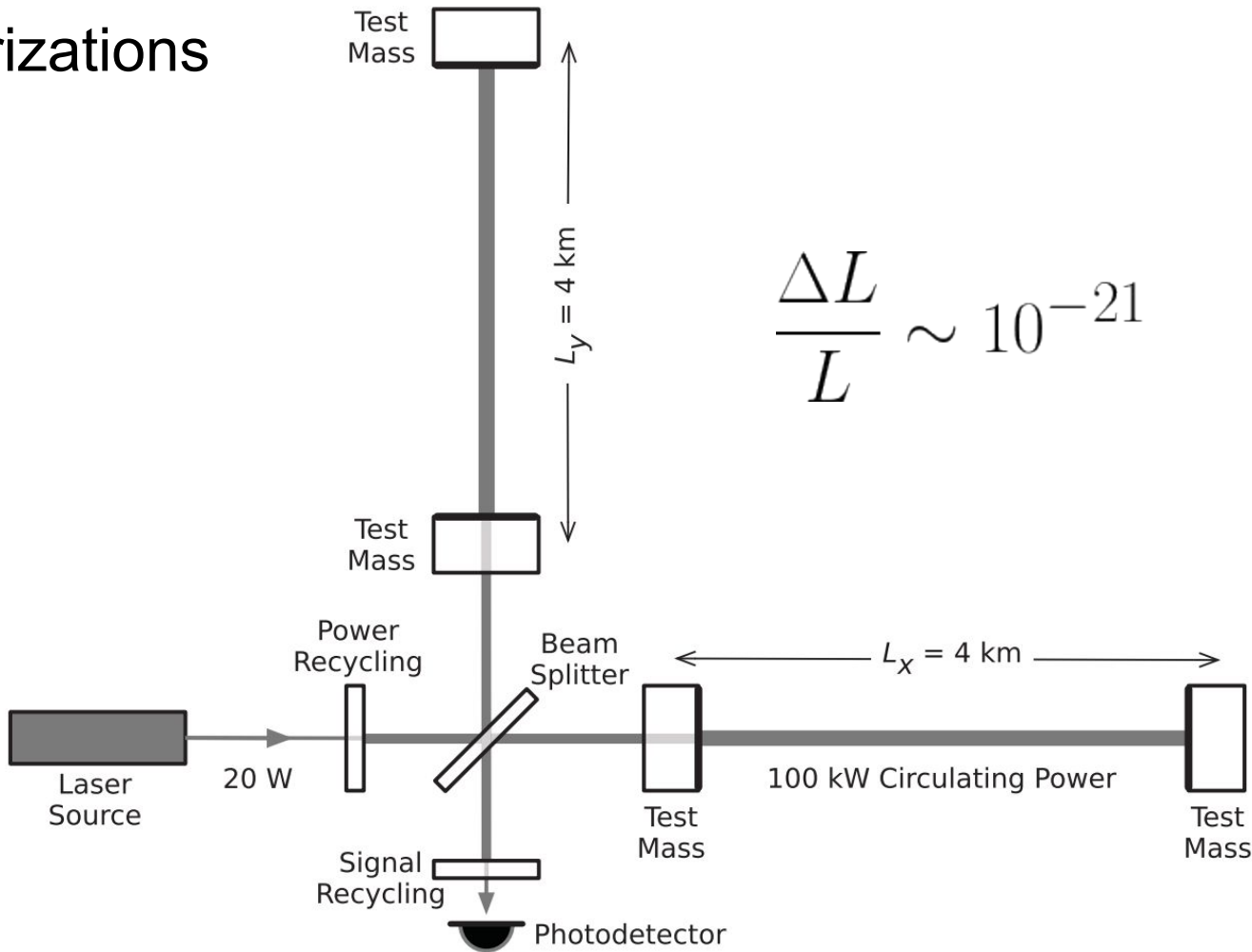
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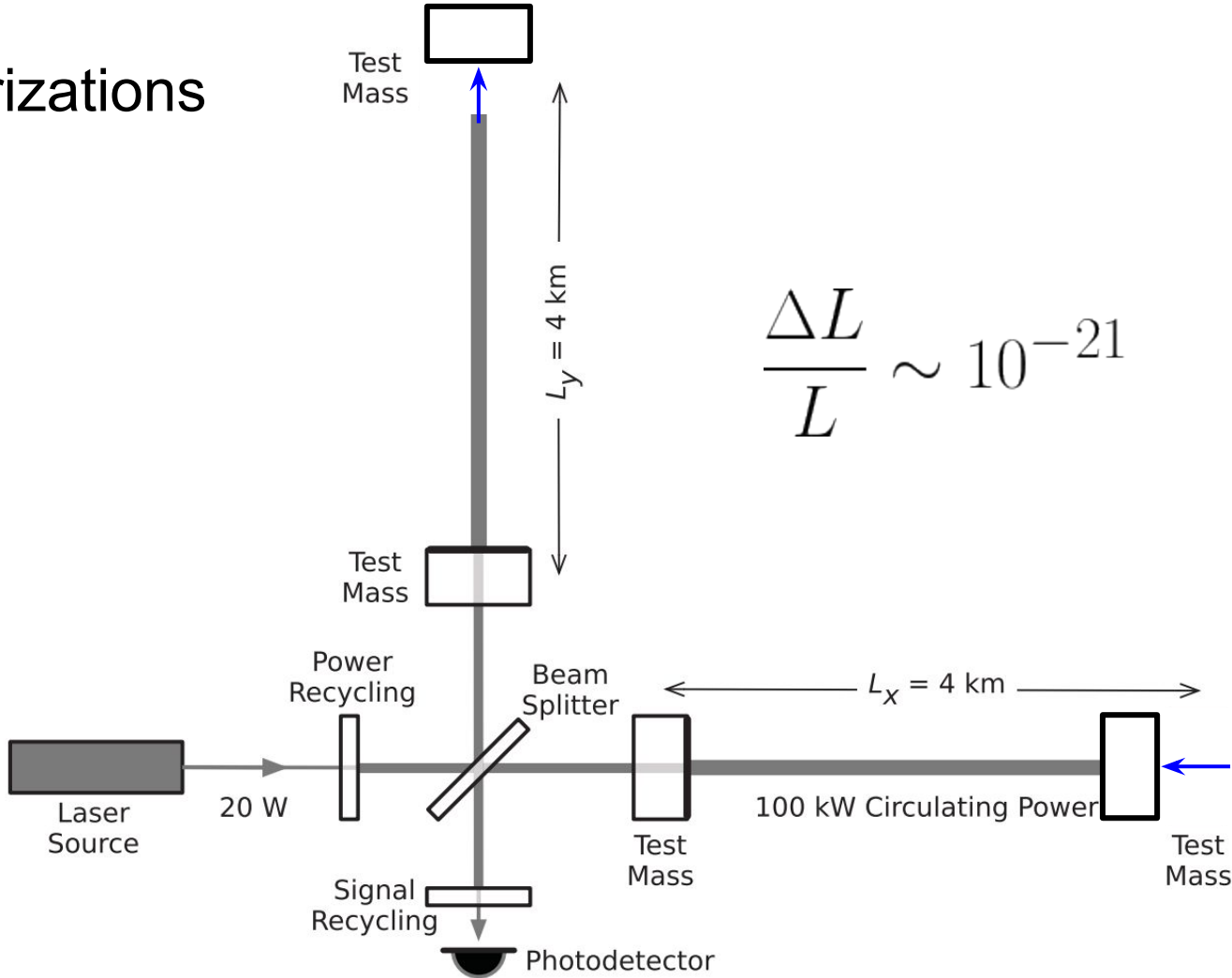
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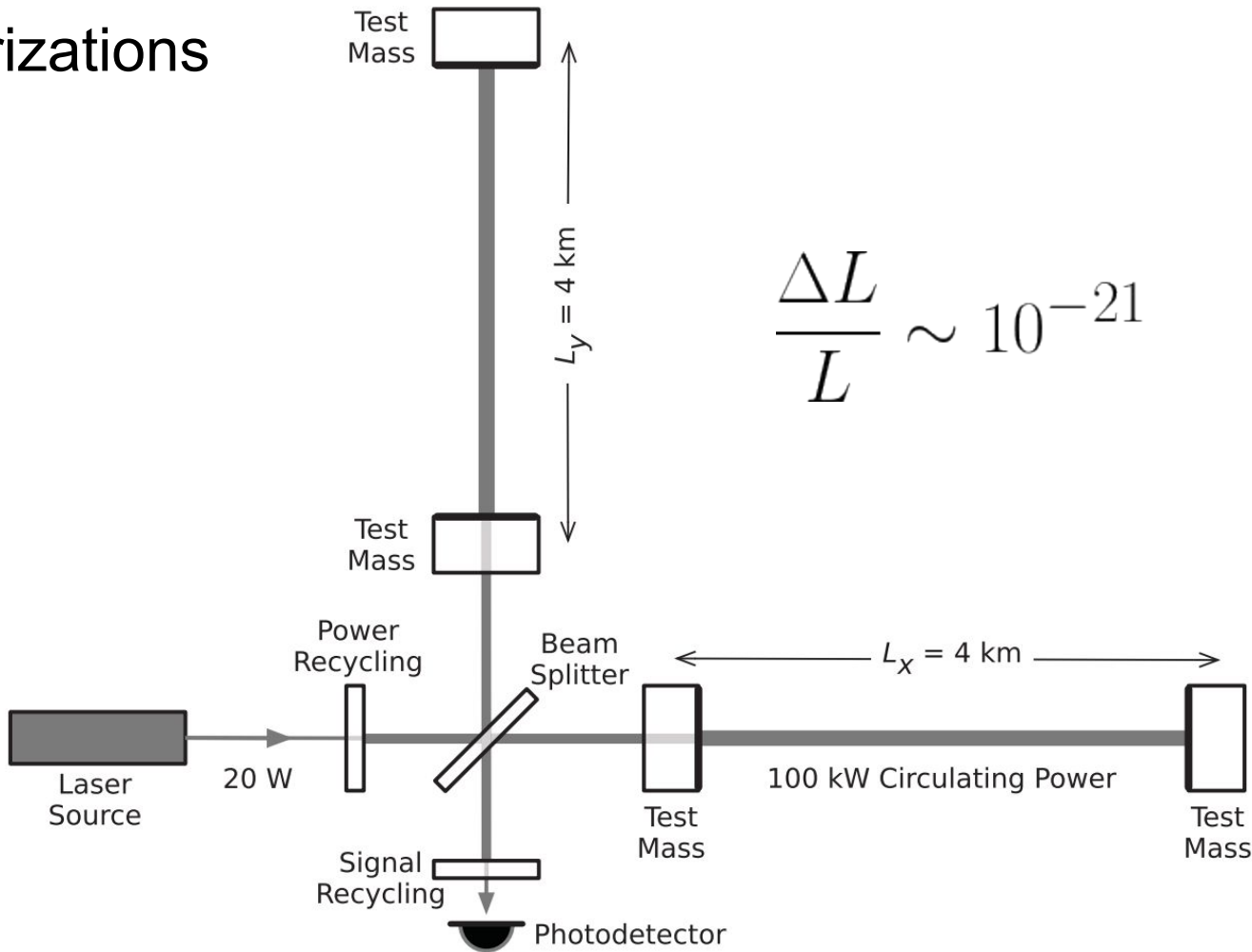
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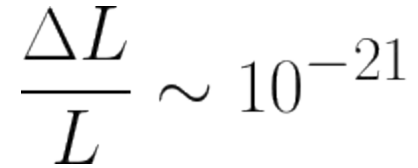
# Number of Polarizations

**Vector** Modes



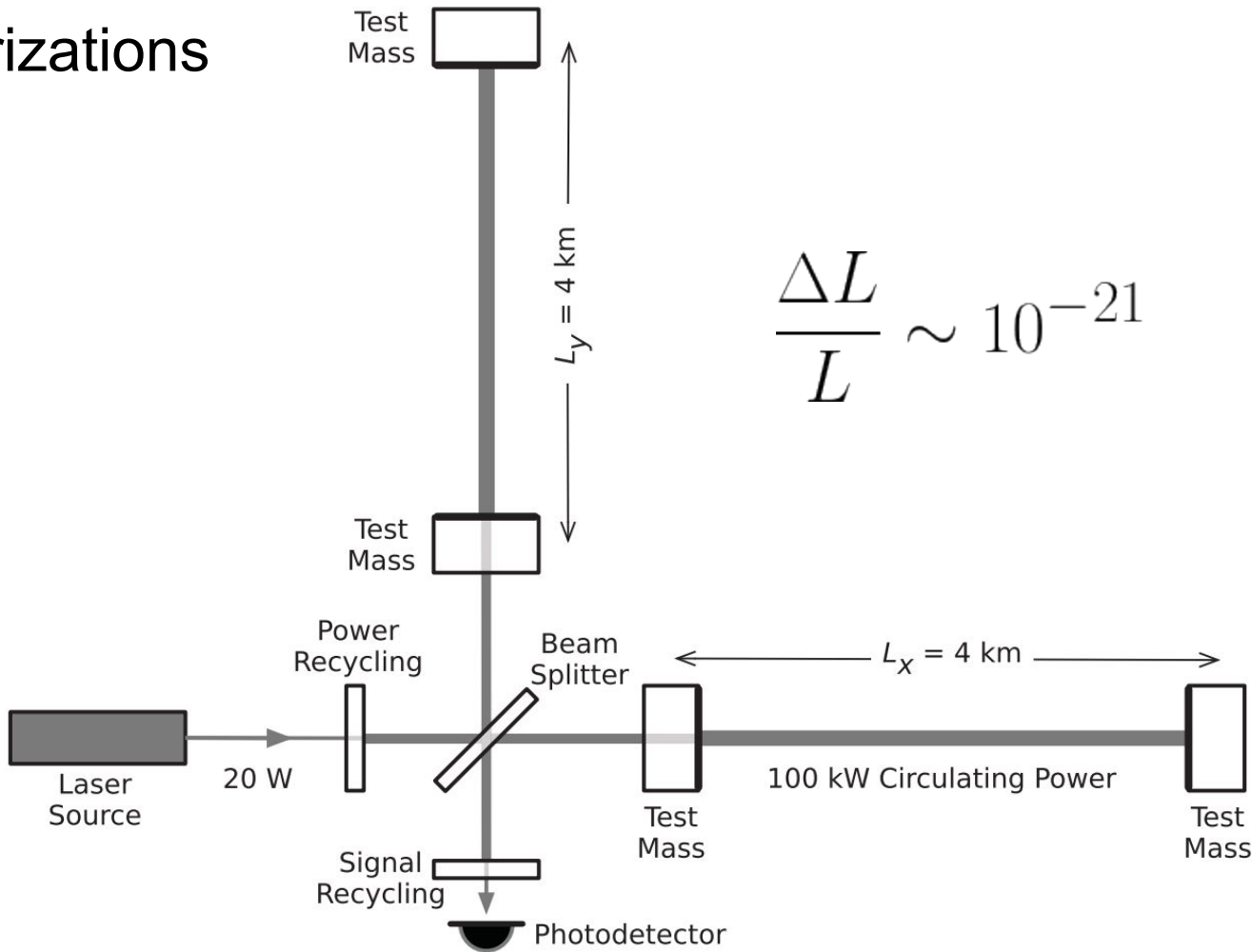
$$\frac{\Delta L}{L} \sim 10^{-21}$$

## Vector Modes



# Number of Polarizations

**Vector** Modes

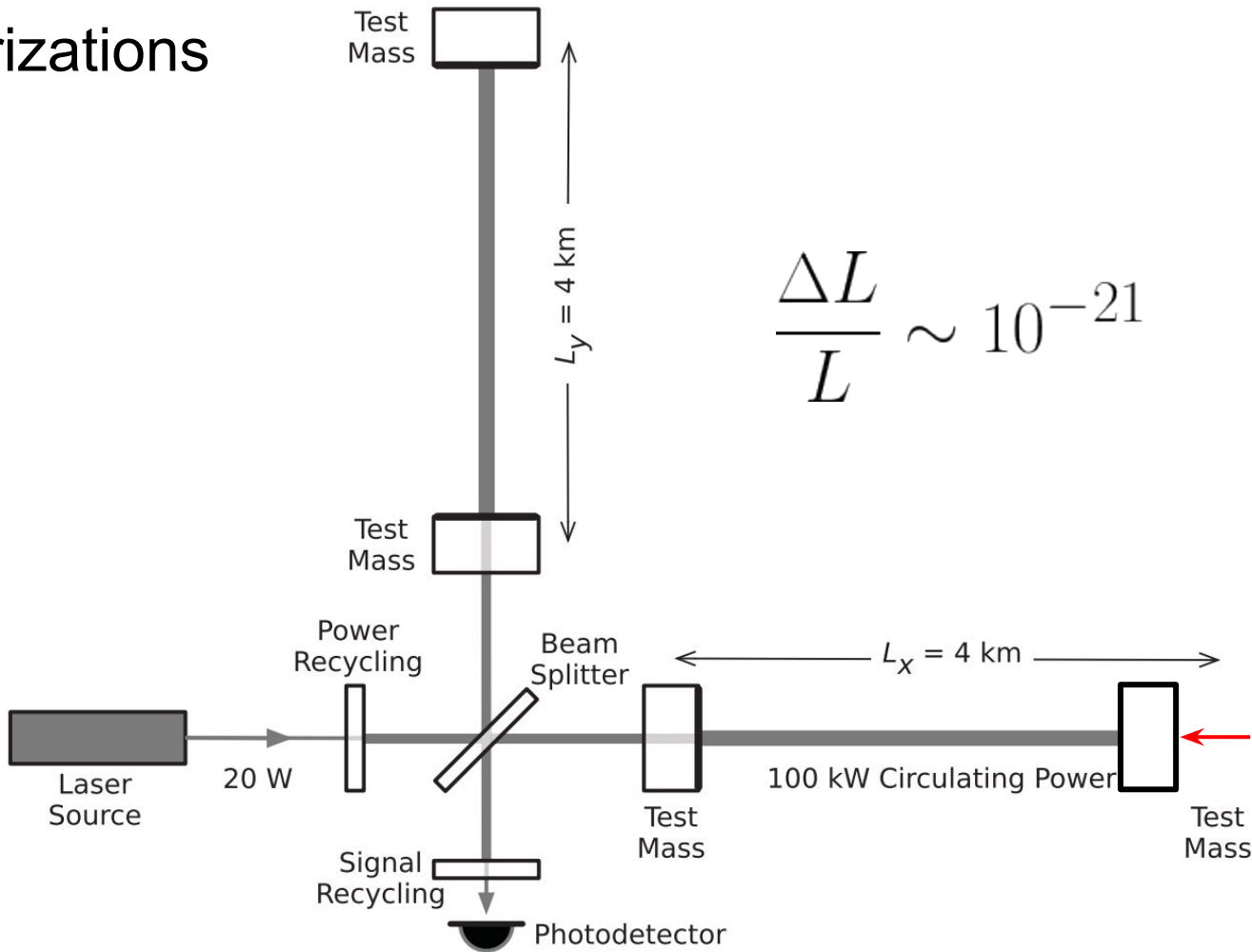


$$\frac{\Delta L}{L} \sim 10^{-21}$$



# Number of Polarizations

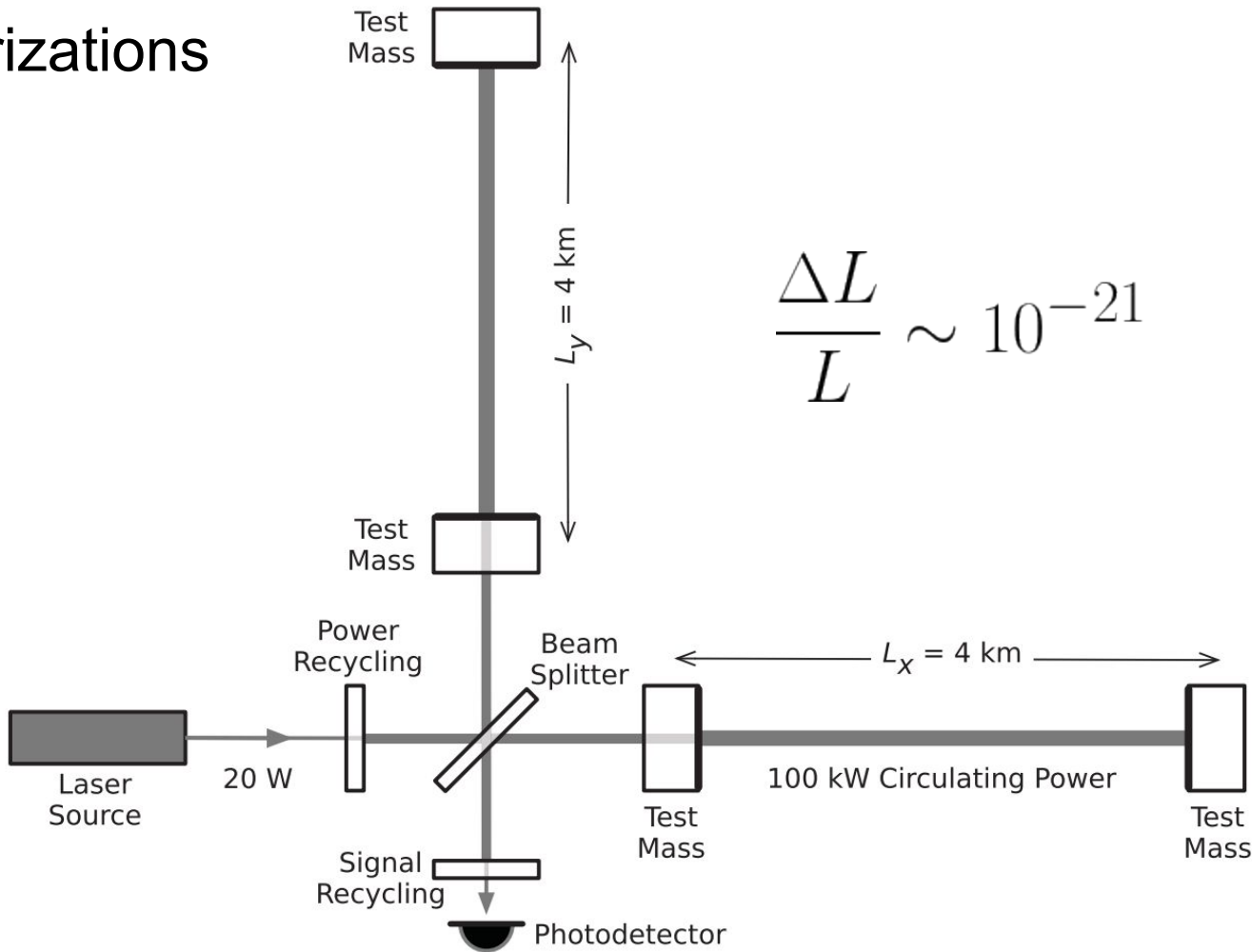
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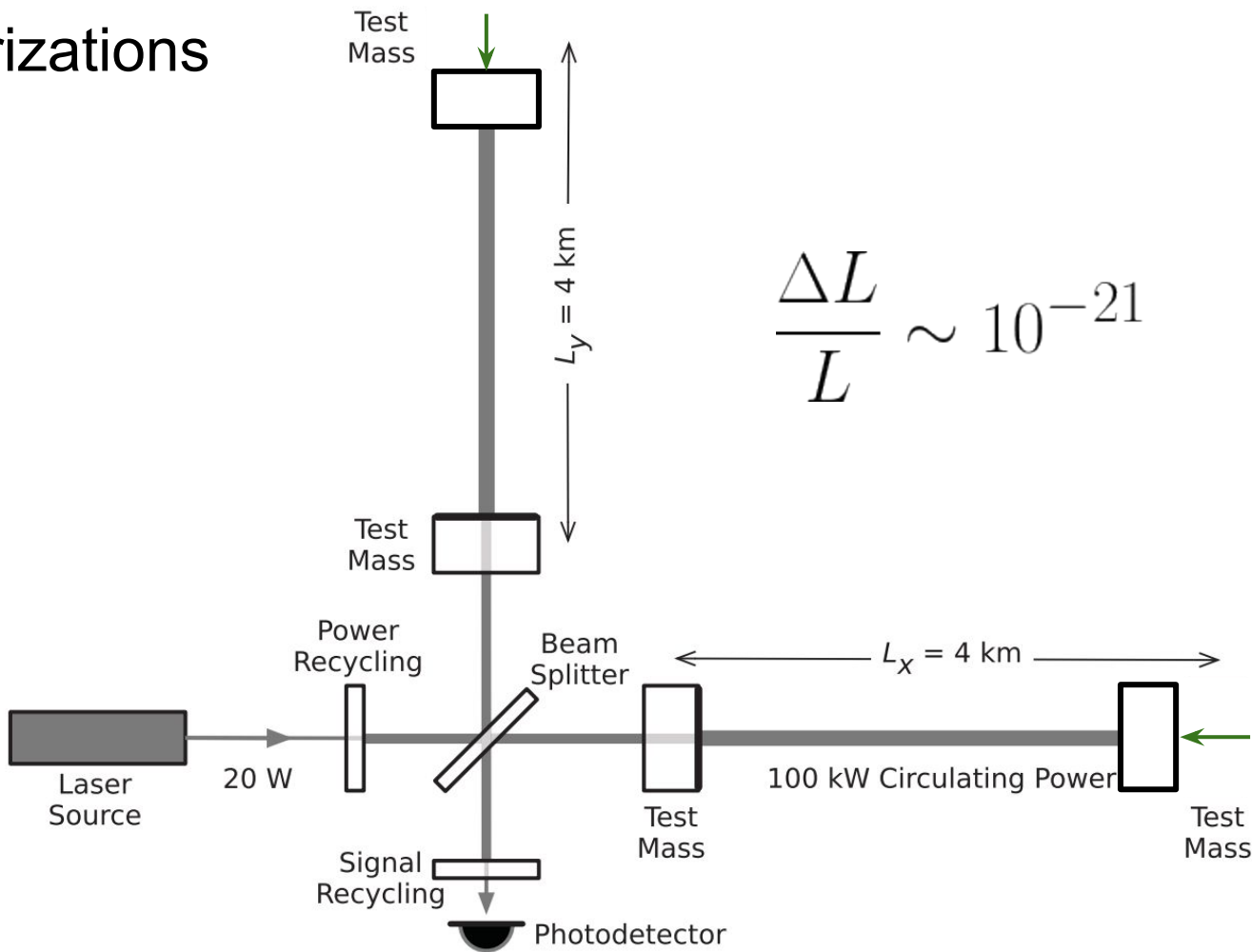
Scalar Modes



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

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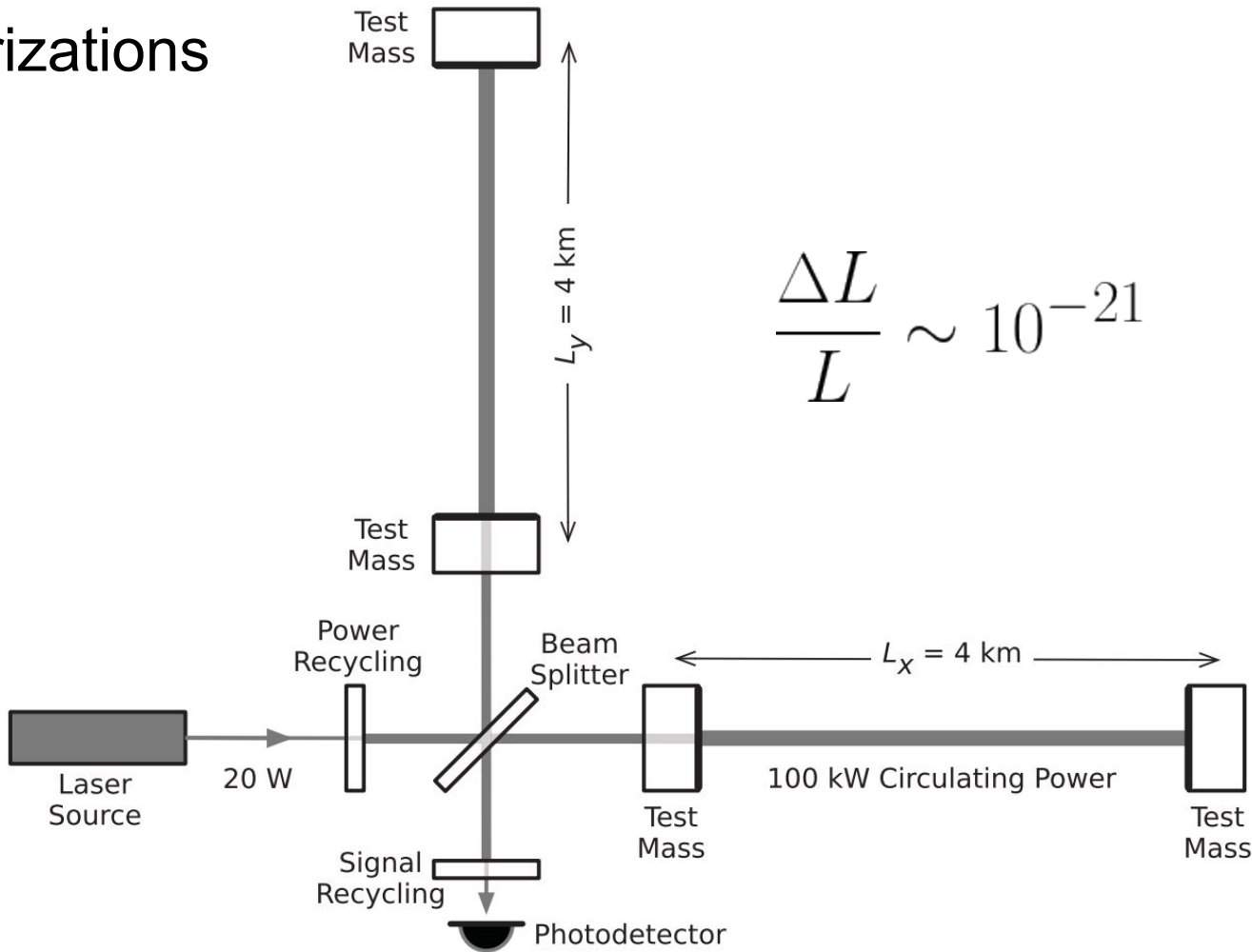
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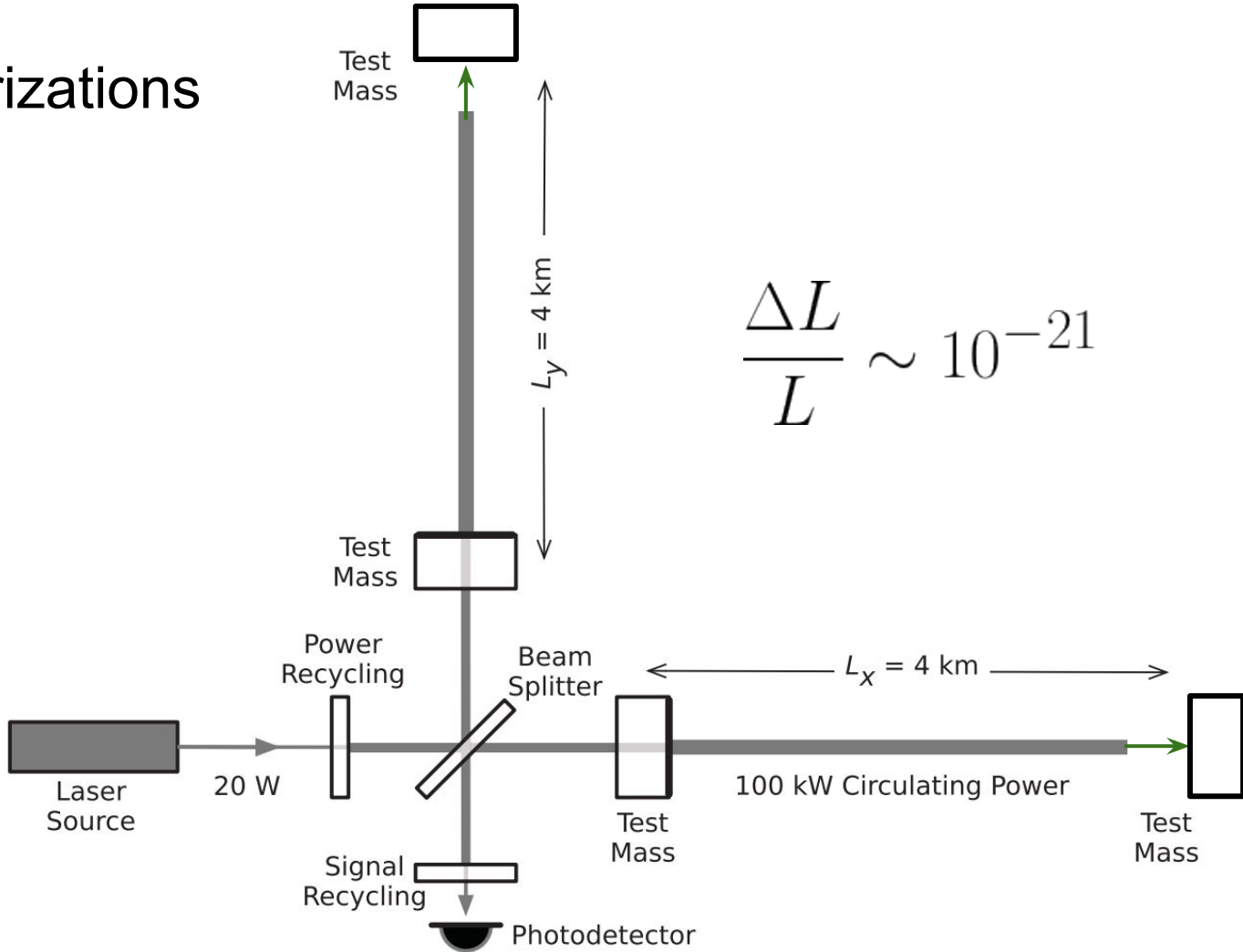
Scalar Modes



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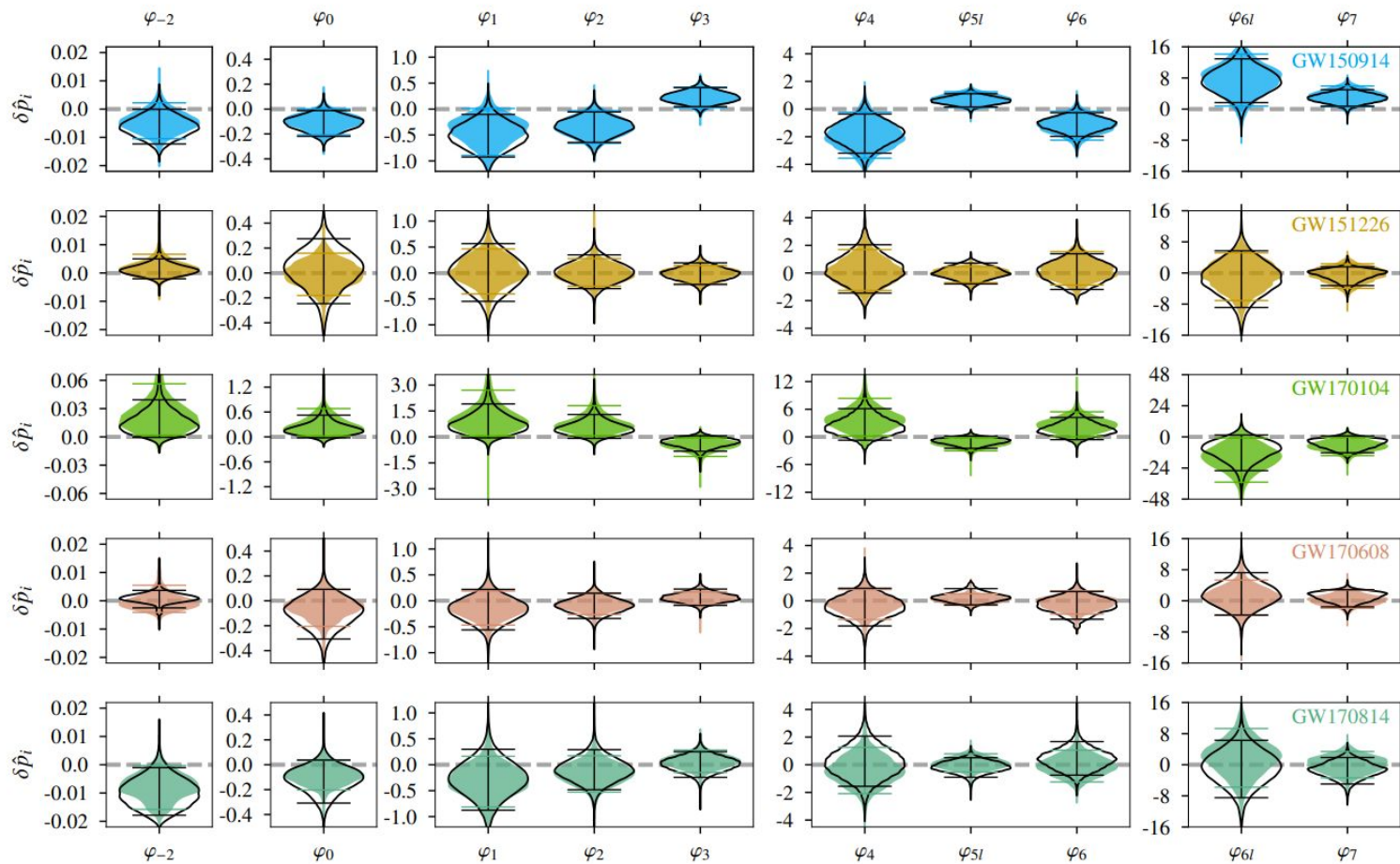
# Number of Polarizations

*Scalar* Modes

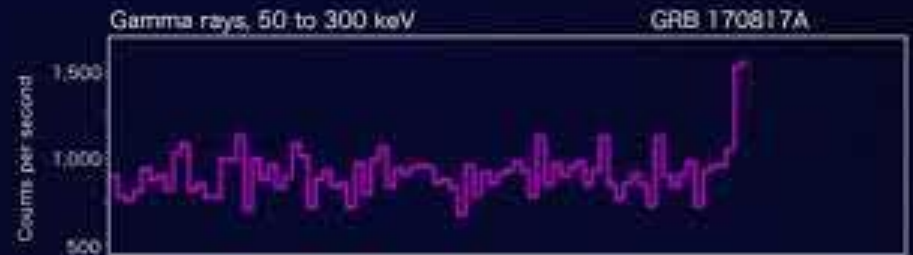


# Orbital Evolution

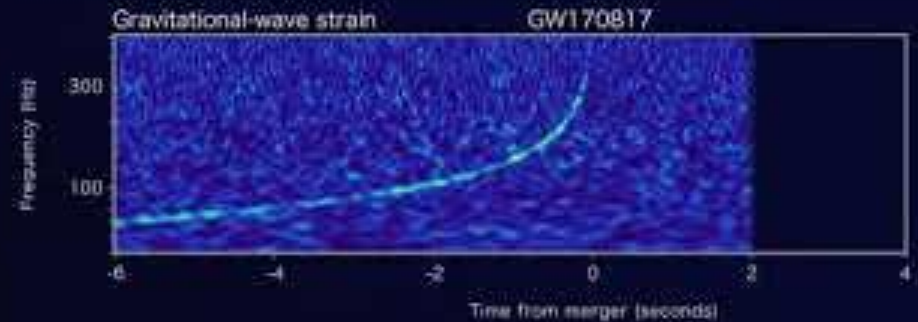
Parameterized tests  
come up with an  
alternative model  
and see if the data  
matches it better



# Speed of Gravity



LIGO





Speed of Gravity

$$\Delta t = \frac{D}{c} - \frac{D}{c_{\text{GW}}} \approx \frac{D}{c} \left( \frac{c_{\text{GW}} - c}{c} \right)$$

# Speed of Gravity

Speed of gravity

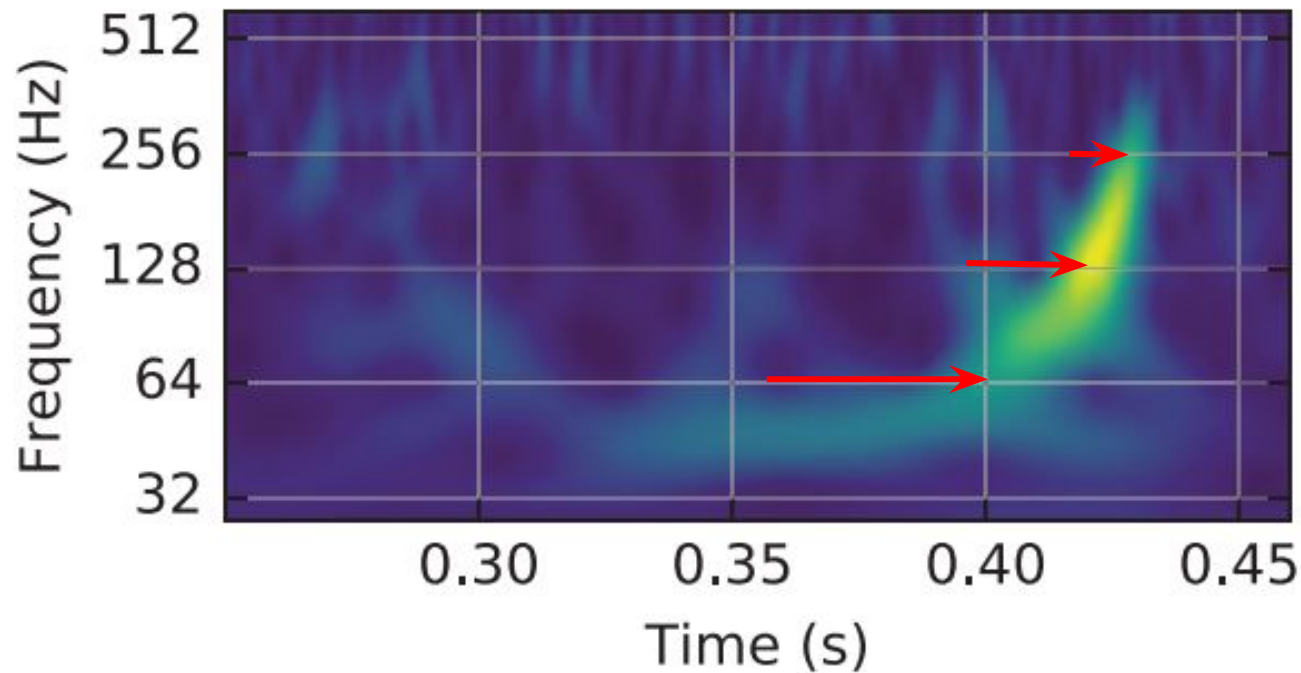
Mass of the graviton

$$E^2 = m^2 c^4 + c^2 p^2$$
$$\left(\frac{\nu}{c}\right)^2 = \left(\frac{mc}{h}\right)^2 + \frac{1}{\lambda^2}$$
$$v_{\text{group}} \approx c - \frac{1}{2} \left( \frac{mc^2}{h\nu} \right)$$

# Speed of Gravity

Speed of gravity

Mass of the graviton



$$m_g \leq 4.7 \times 10^{-23} \text{ eV}/c^2$$
$$\lambda_g \geq 1.64 \times 10^{13} \text{ mi}$$

# Number of Spatial Dimensions

Number of spatial dimensions

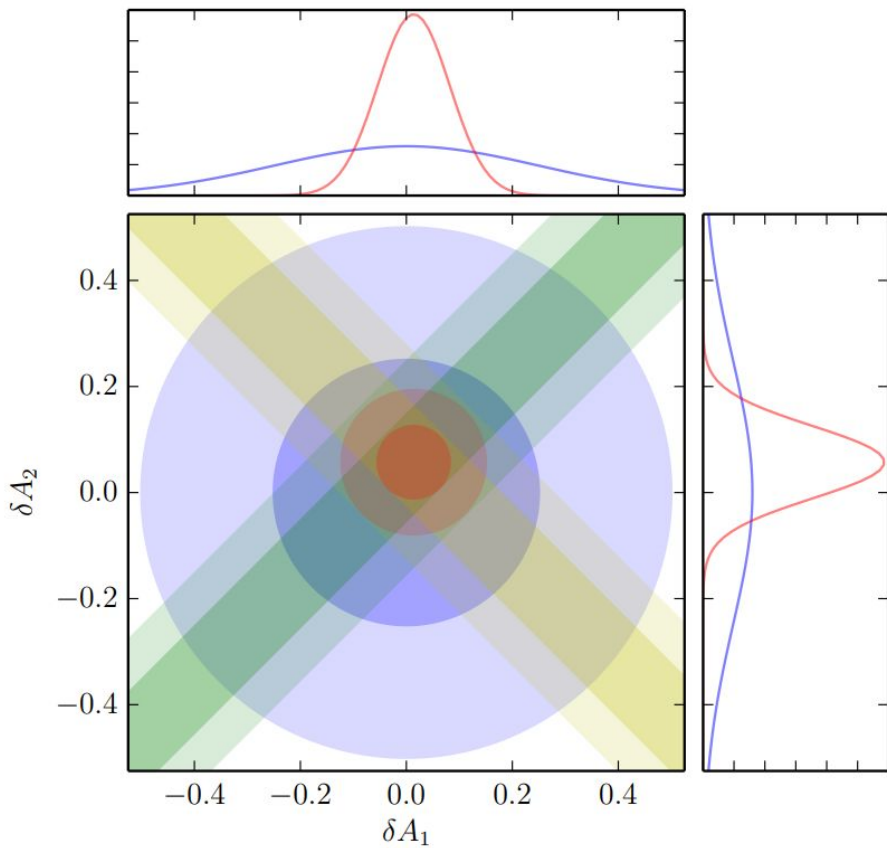
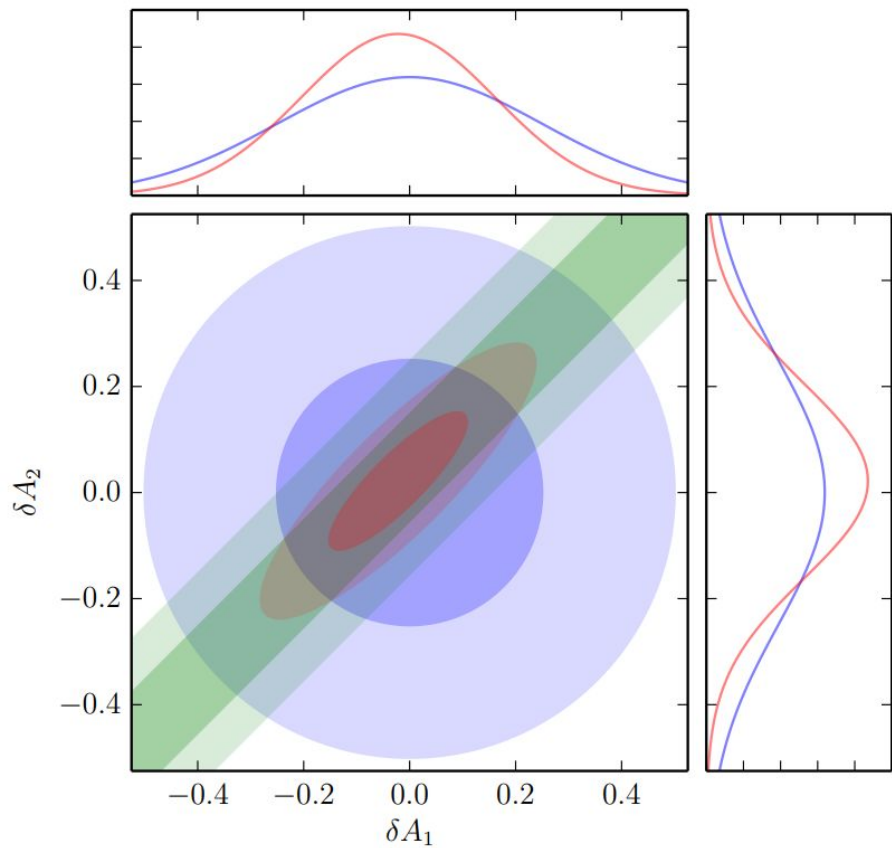
$$h \sim \frac{h_0}{D^{(n-1)/2}}$$

# Astrophysical Calibration

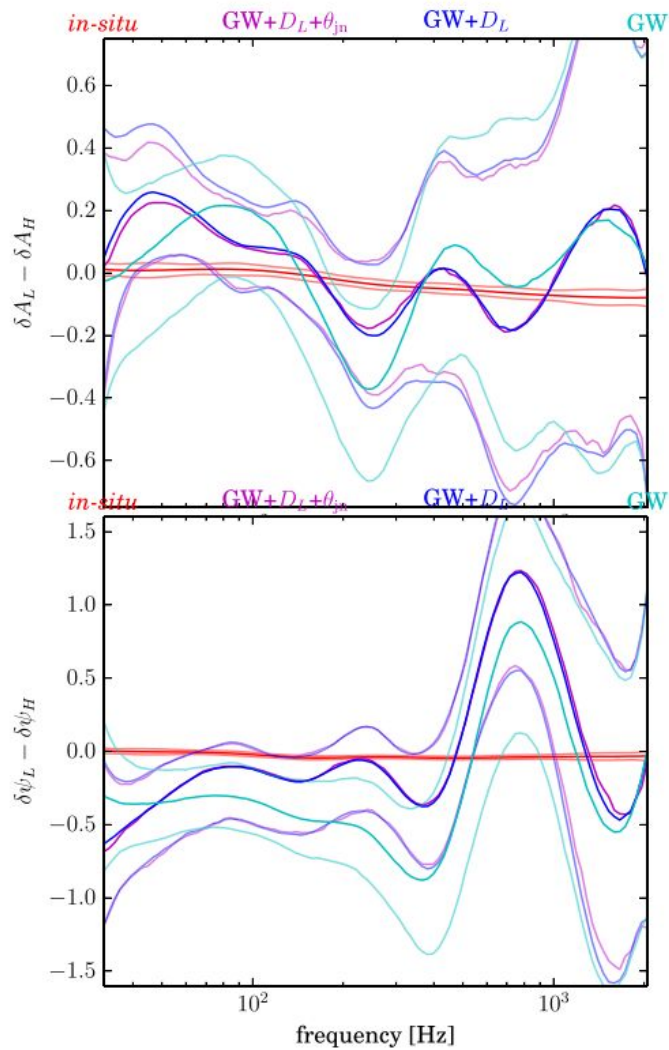
What if GR is perfect?

Can we learn about our detectors?

# Astrophysical Calibration

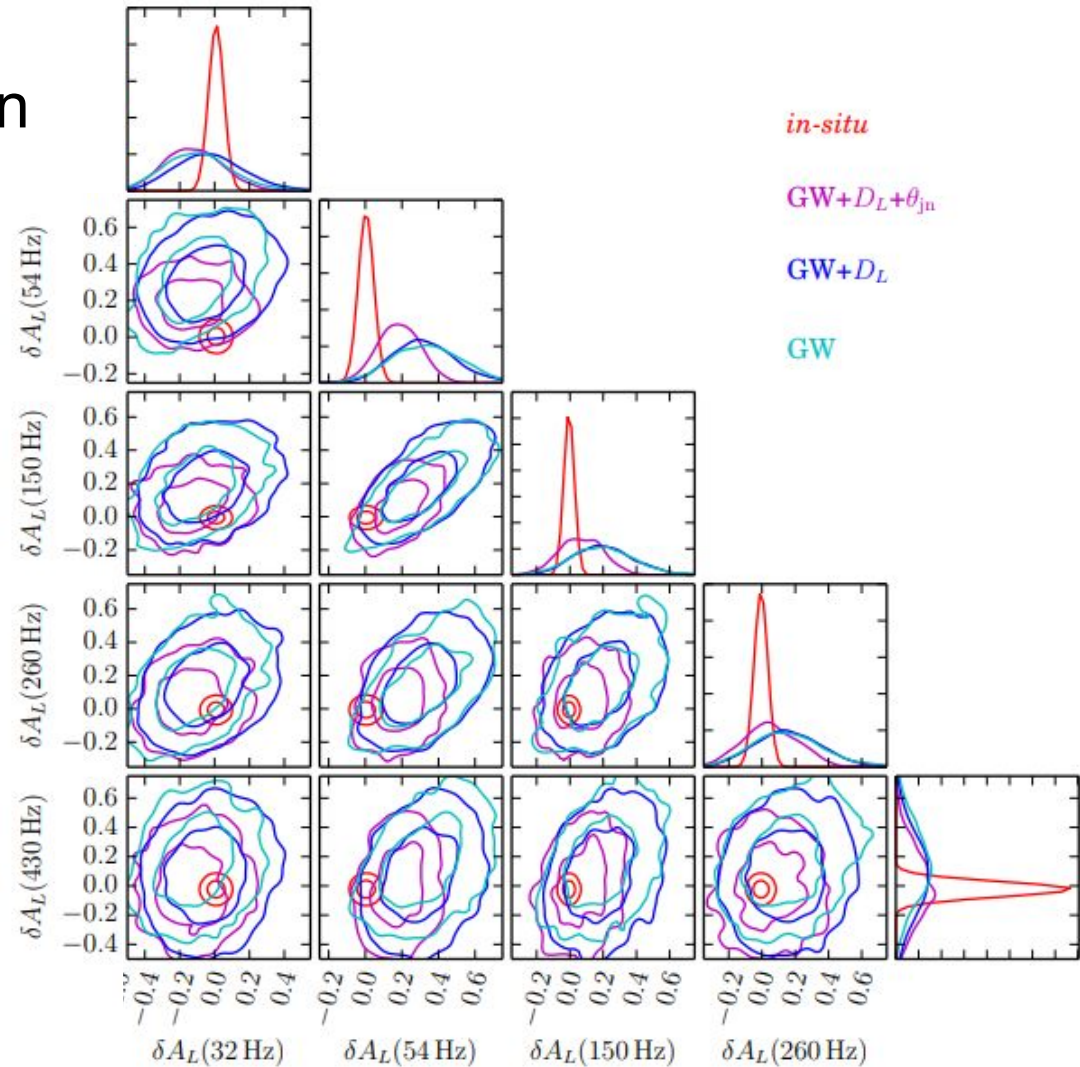


# Astrophysical Calibration





# Astrophysical Calibration



# Next time

## Gravitational Waves Over the Next 40 Years

- (Current) advanced detectors
- 3G detectors
- Space-based detectors, pulsar timing, and other missions

# Suggested Reading

- Clifford Will. *Was Einstein Right? Putting General Relativity to the Test*. Basic Books (1993).
- <https://www.ligo.org/science/Publication-GW170817TGR/index.php>
- <https://www.ligo.org/science/Publication-O2TGR/index.php>