Title: Advanced LIGO status and prospects to probe the strong gravity regime

Date: Nov 12, 2014 09:25 AM

URL: http://pirsa.org/14110088

Abstract: <span>Gravitational waves will allow scientists to test Einsteinâ€™s theory of General Relativity in the previously unexplored strong-field regime. Einsteinâ€™s theory of general relativity, as the most accepted theory of gravity, has been greatly constrained in the quasi-linear, quasi-stationary regime, where gravity is weak and velocities are small. Gravitational waves may carry information about highly dynamical and strong-field gravity that is required to generate measurable waves. Coalescing compact binaries are the most promising sources of gravitational waves accessible to ground-based interferometers, such as Advanced LIGO. Made of neutron stars and/or black holes that orbit each other hundreds of times a second just before they collide, the resulting waves are imprinted with information about the individual objects and the dynamical coalescence process. After reviewing the basic properties of gravitational waves, I will present an overview of the detector design and provide an update on the current status of Advanced LIGO and its ability to probe the strong gravity regime.</span>

# Advanced LIGO Status and Prospects to Probe the Strong Gravity Regime

Laleh Sadeghian
University of Wisconsin-Milwaukee

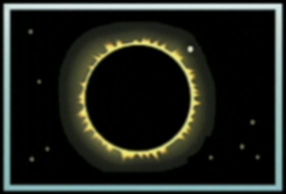
For LIGO scientific collaboration and
Virgo collaboration

LIGO-G1401303

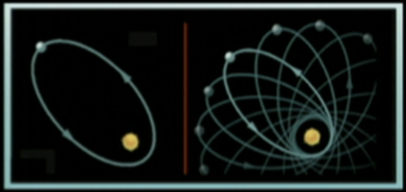
EHT2014, Perimeter Institute
Nov 12th, 2014

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

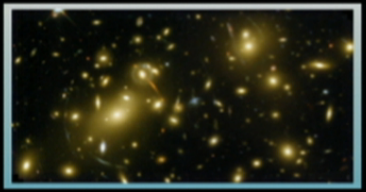
# Weak field regime tests of GR



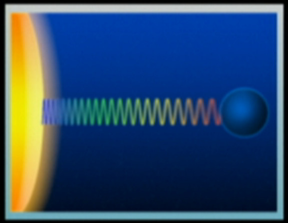
Bending Light



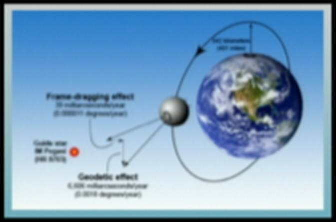
Mercury's Orbit



Gravitational Lensing



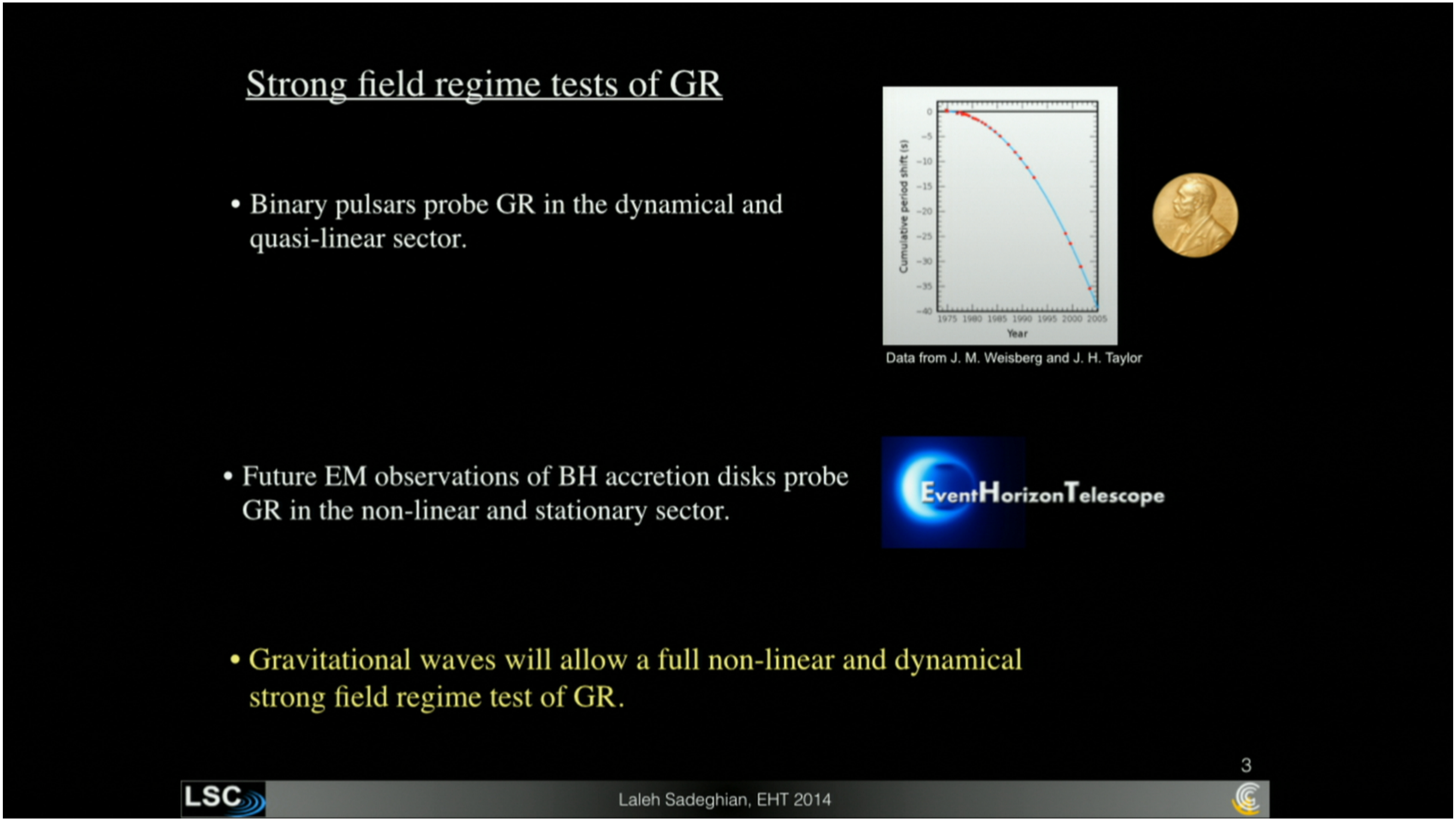
Gravitational redshift of light



Frame Dragging and Geodetic

• • •

Almost all of the previous experimental tests of GR are in the quasi-stationary, quasi-linear weak field regime.



# Strong field regime tests of GR

- Binary pulsars probe GR in the dynamical and quasi-linear sector.

Data from J. M. Weisberg and J. H. Taylor

- Future EM observations of BH accretion disks probe GR in the non-linear and stationary sector.

EventHorizonTelescope

- Gravitational waves will allow a full non-linear and dynamical strong field regime test of GR.

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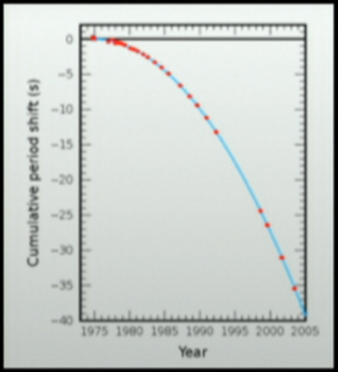

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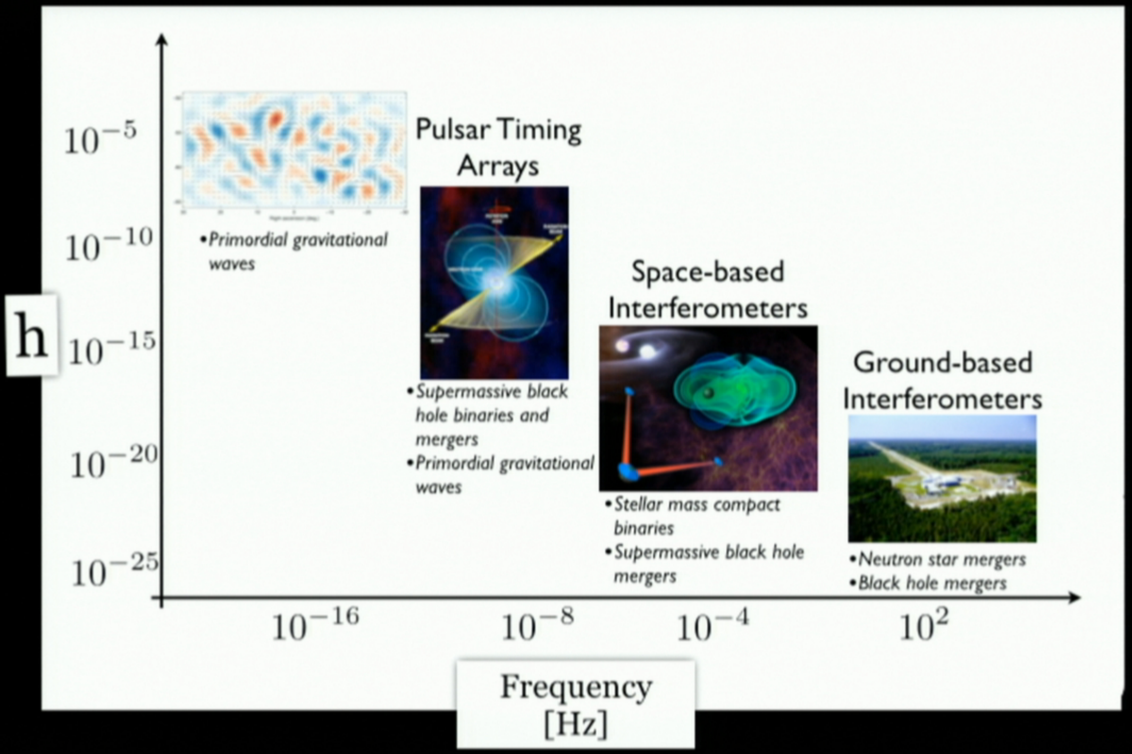
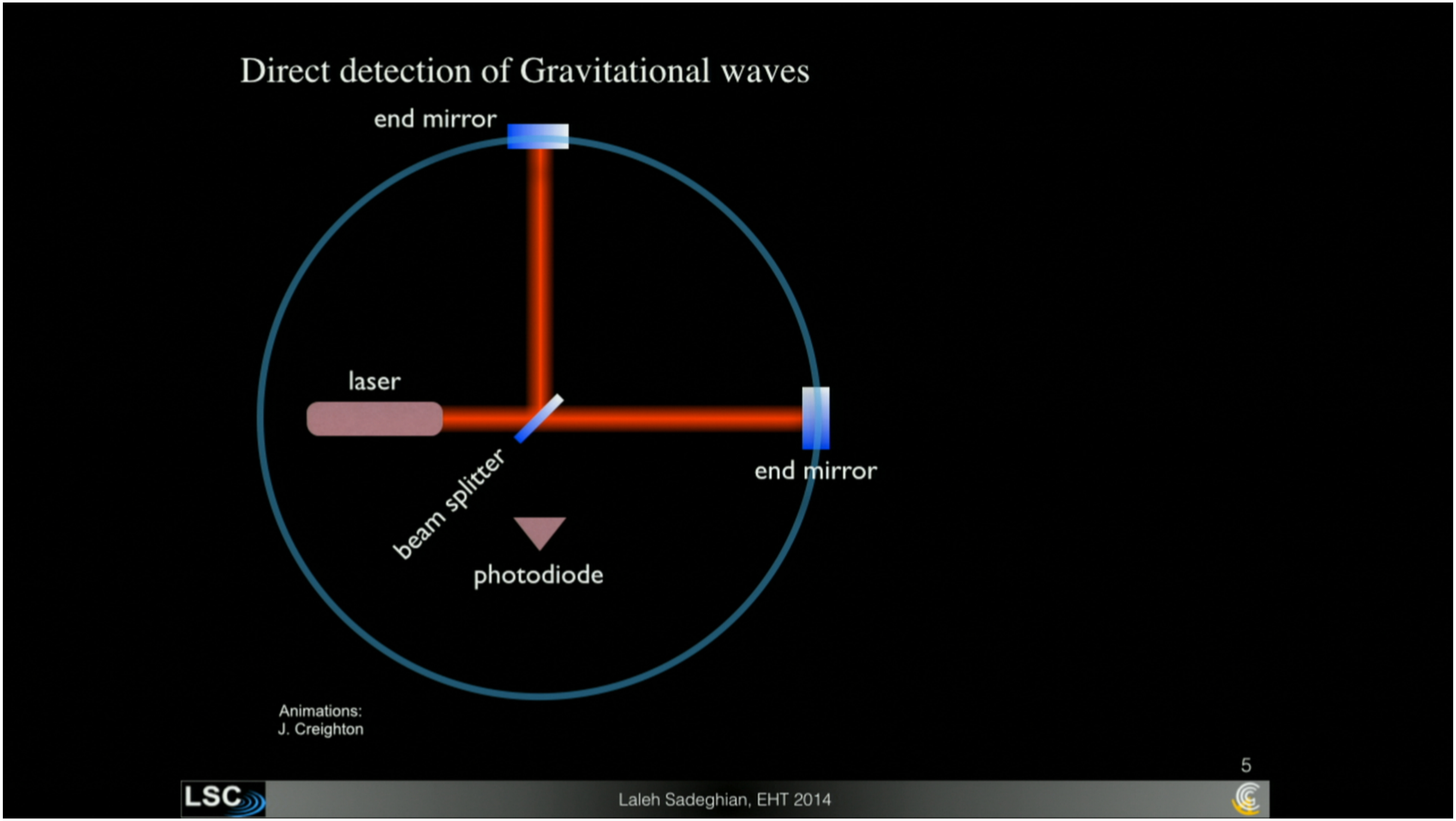
# Gravitational Waves

$$h_{ij} = \frac{2G}{c^4}\frac{1}{r}\frac{d^2Q_{ij}}{dt^2}$$

metric perturbation

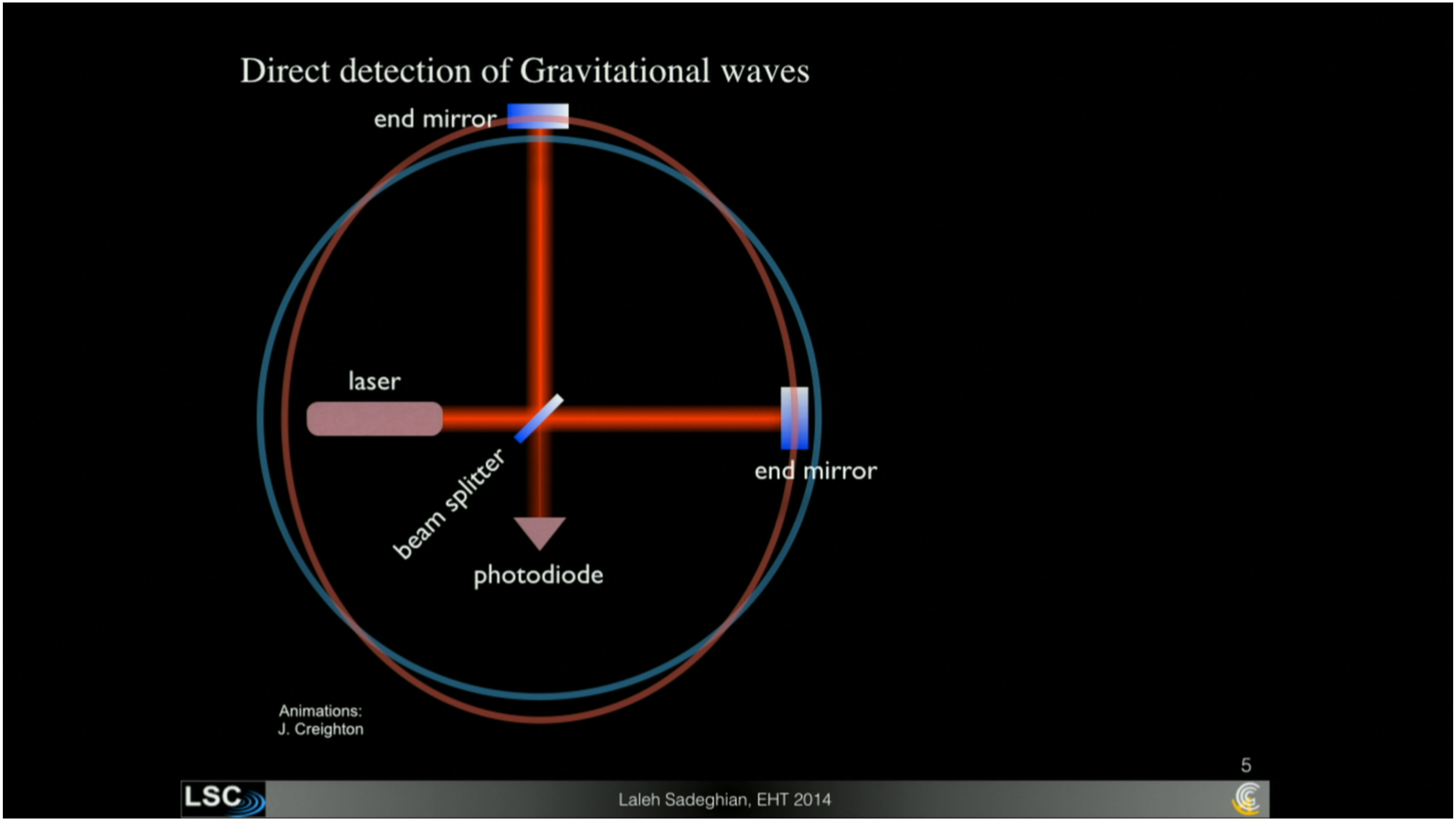
quadrupole moment





# Direct detection of Gravitational waves

Animations:
J. Creighton



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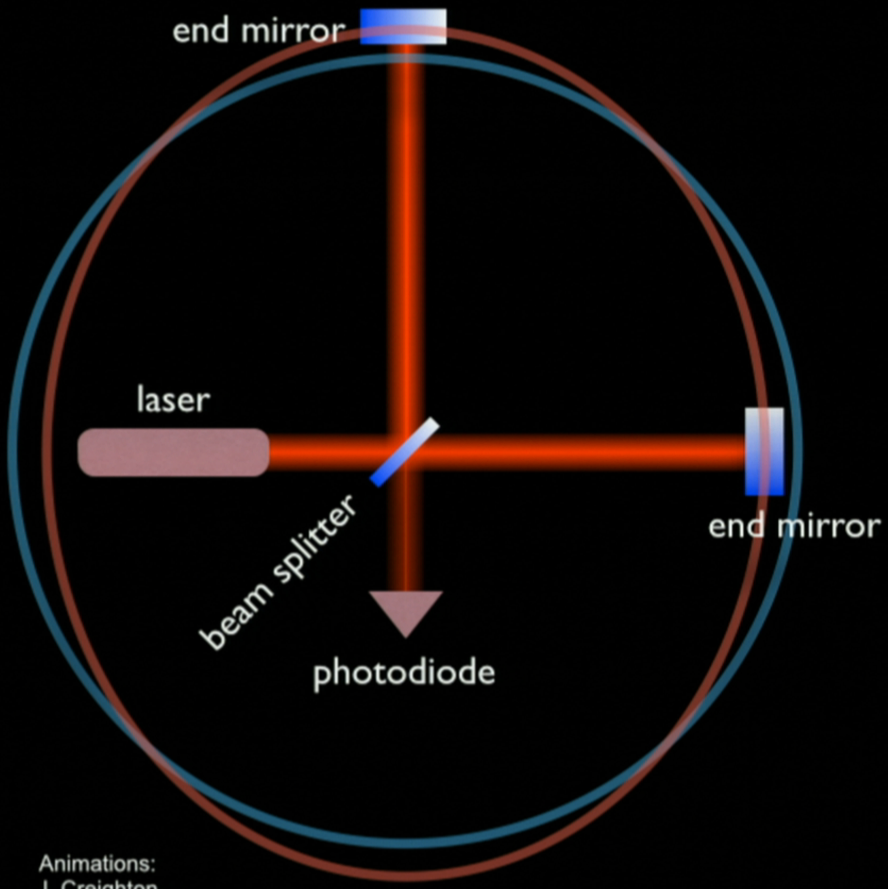

predicted polarizations by GR

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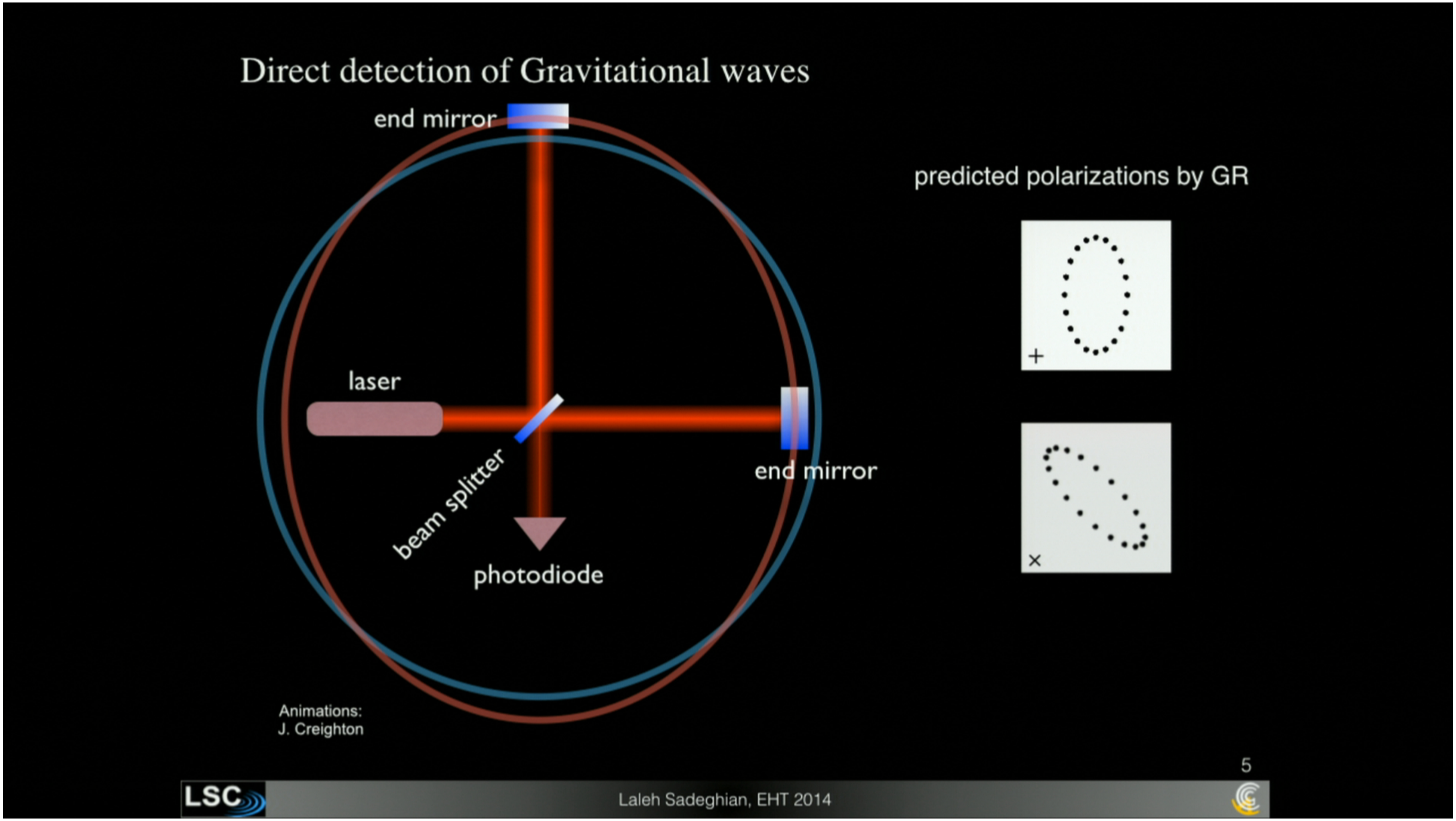
J. Creighton

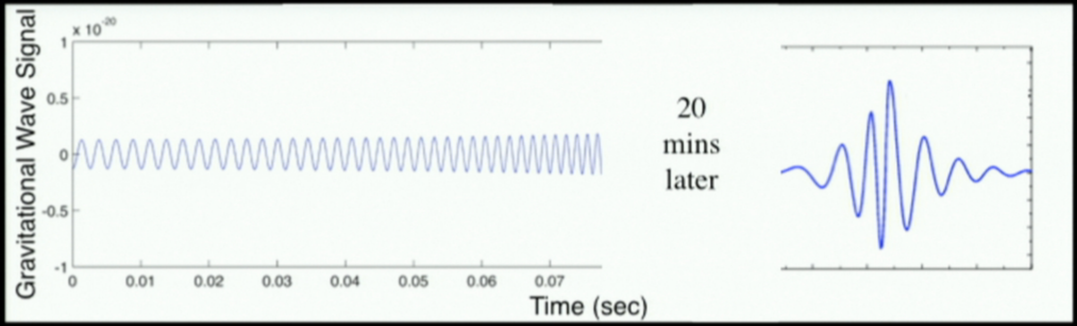


# Direct detection of Gravitational waves

predicted polarizations by GR

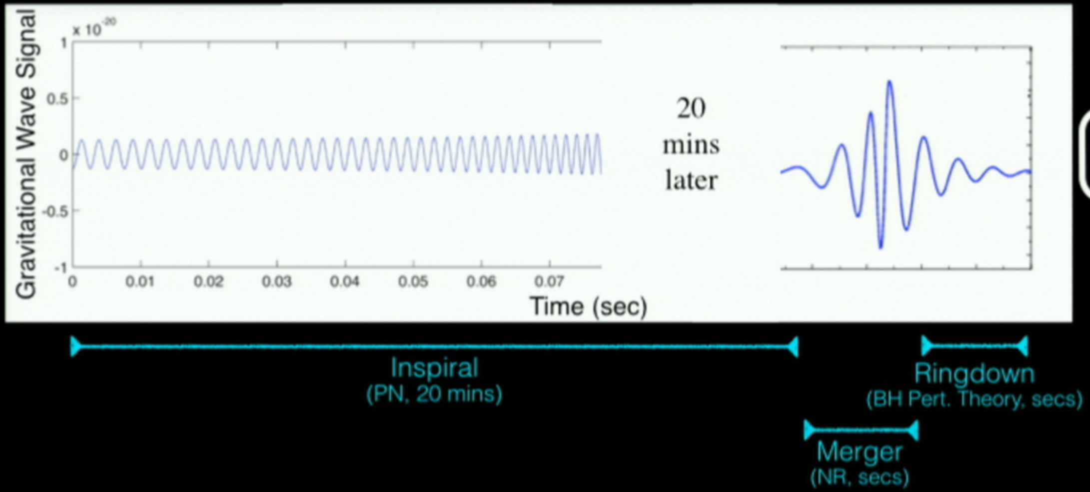
Animations:
J. Creighton

signal for a binary NS in circular orbit:



$$\boxed{\tilde{h}(f) = A(f;\vec{\theta})e^{i\Psi(f,\vec{\theta})}}$$

signal for a binary NS in circular orbit:



Inspiral
(PN, 20 mins)

Ringdown
(BH Pert. Theory, secs)

Merger
(NR, secs)

$$\boxed{\tilde{h}(f) = A(f;\vec{\theta})e^{i\Psi(f,\vec{\theta})}}$$

template (projection of metric perturbation)

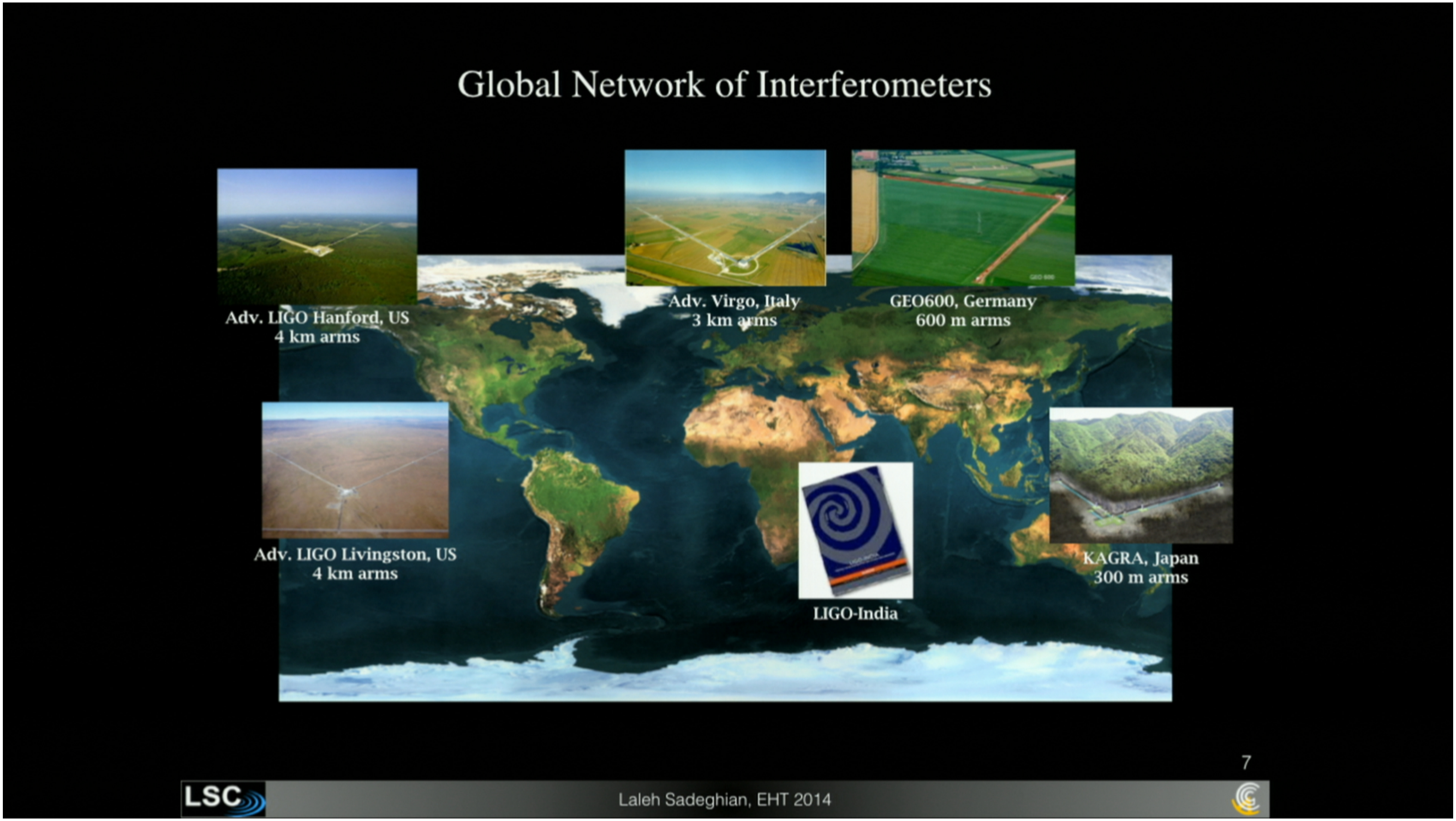
data

params of the system

$$\rho^2 \sim \int \frac{\tilde{s}(f)\tilde{h}(f,\vec{\theta})}{S_n(f)}df$$

signal-to-noise ratio (SNR)

detector noise (spectral noise density)



# Global Network of Interferometers

**Adv. LIGO Hanford, US**
**4 km arms**

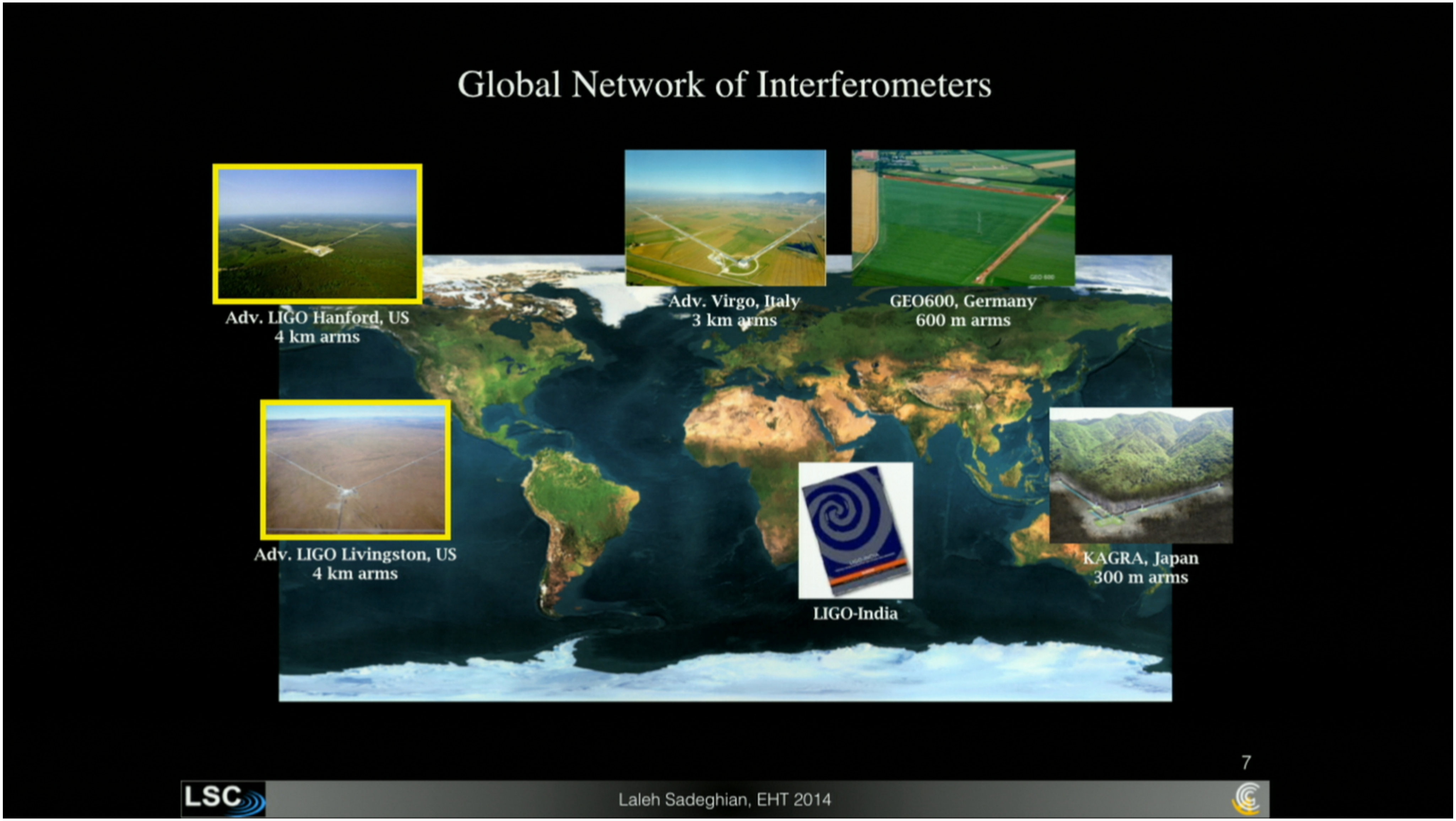
**Adv. Virgo, Italy**
**3 km arms**

**GEO600, Germany**
**600 m arms**

**Adv. LIGO Livingston, US**
**4 km arms**

**LIGO-India**

**KAGRA, Japan**
**300 m arms**



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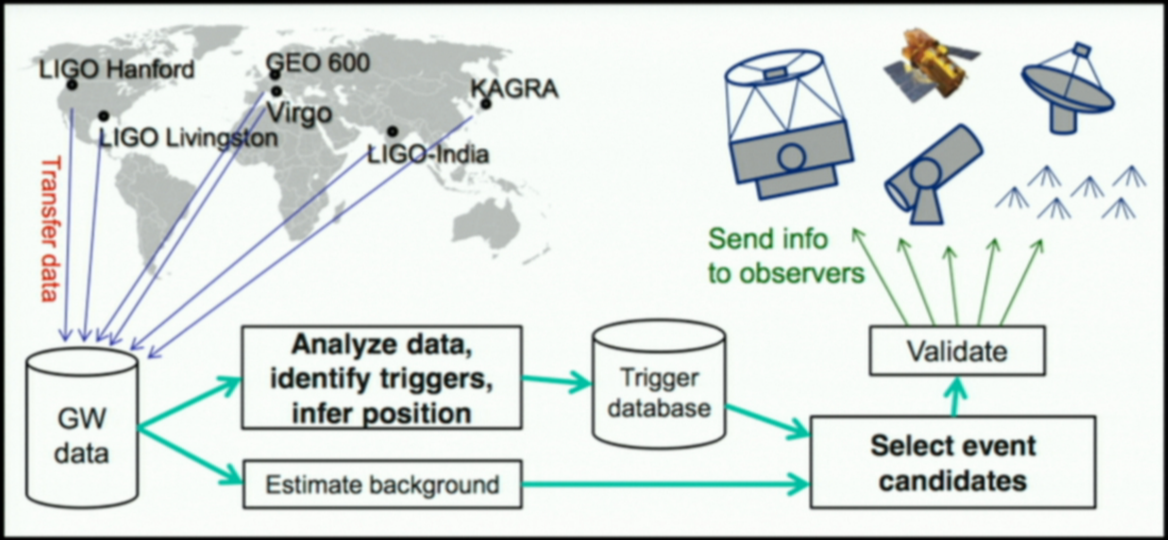
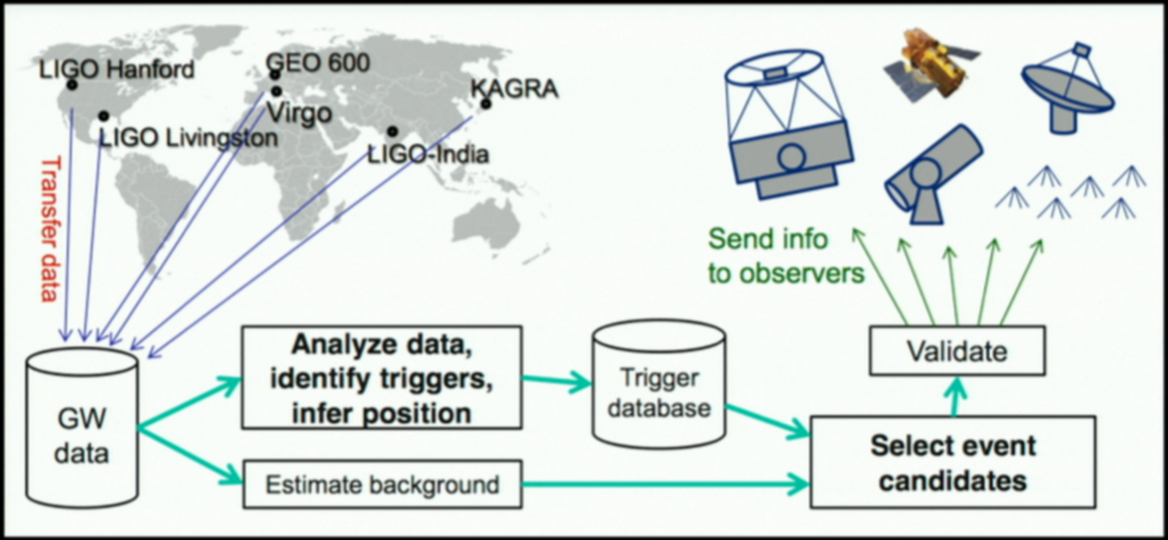
# Multi-messenger Astronomy



- Science return from Gravitational Wave detection will be strongly enhanced if there are simultaneous EM observations.
- EM counterparts to GW events will result in better localization of GW events.
- After the first four published GW events, LSC and Virgo will promptly release public triggers to be followed up.

# Multi-messenger Astronomy



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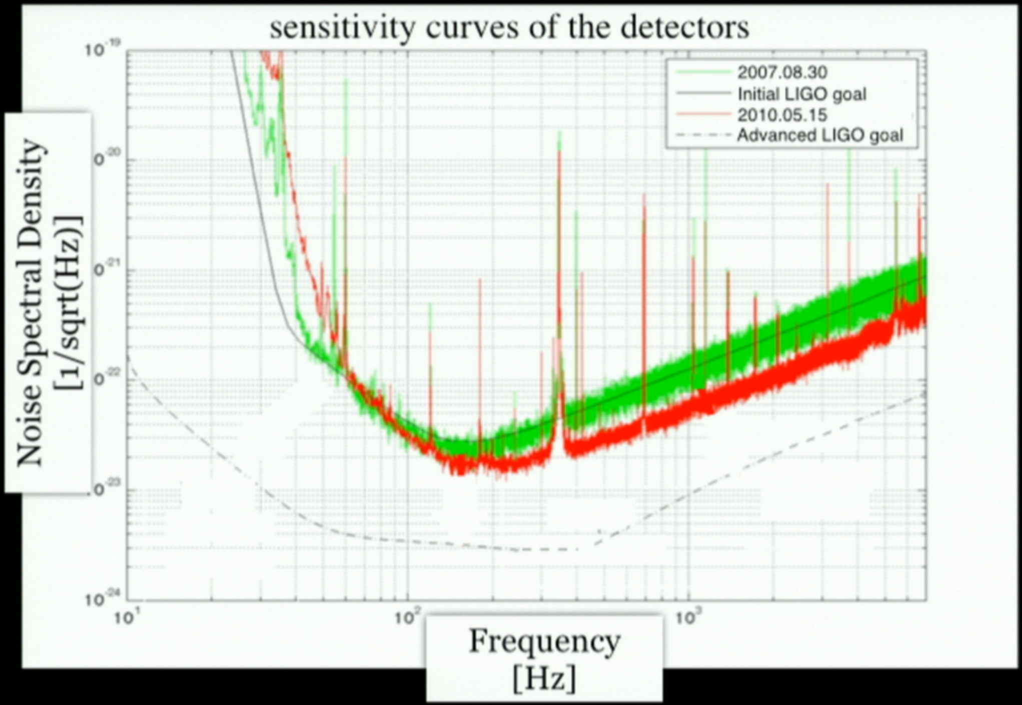
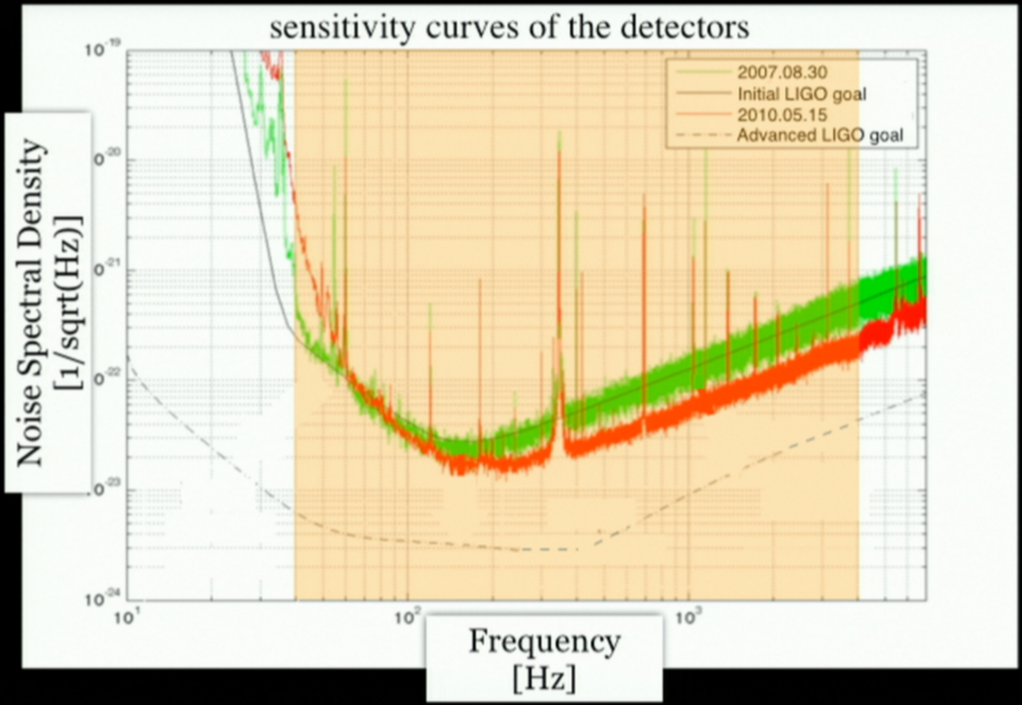
# Initial LIGO



$$\underset{\substack{\downarrow \\ \text{signal-to-noise ratio} \\ \text{(SNR)}}}{\rho^2} \sim \int \frac{\overset{\substack{\text{data} \\ \searrow}}{\tilde{s}(f)}\,\overset{\substack{\text{template} \\ \downarrow}}{\tilde{h}}(f,\overset{\substack{\text{params of the system} \\ \swarrow}}{\vec{\theta}})}{\underset{\substack{\searrow \\ \text{detector noise} \\ \text{(spectral noise density)}}}{S_n(f)}}\,df$$

# Initial LIGO



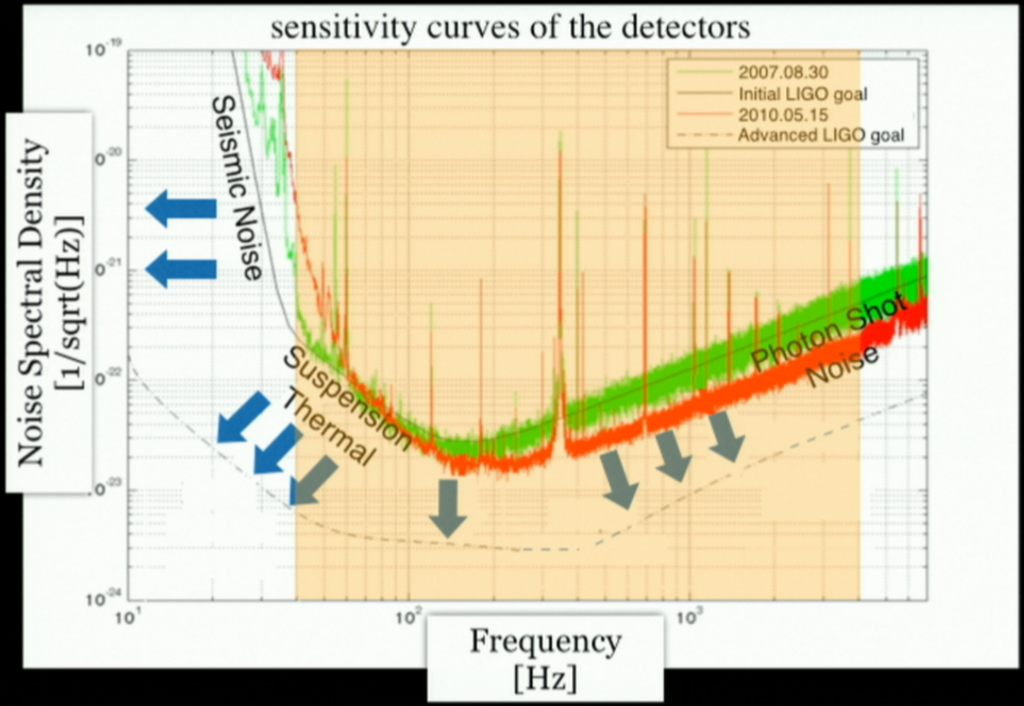
data　template　params of the system

$$\rho^2 \sim \int \frac{\tilde{s}(f)\tilde{h}(f,\vec{\theta})}{S_n(f)} df$$

signal-to-noise ratio (SNR)

detector noise (spectral noise density)

# Initial LIGO



data

template

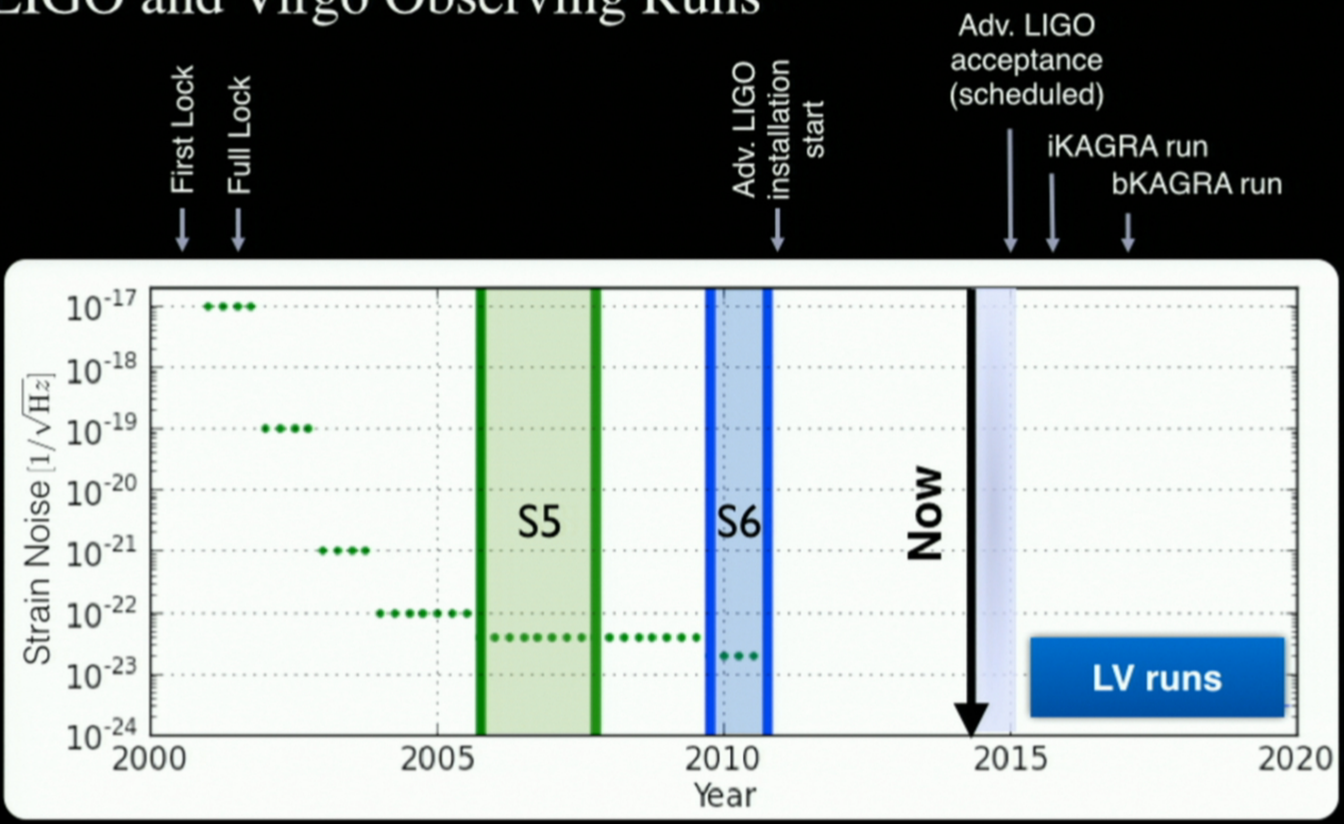
params of the system

$$\rho^2 \sim \int \frac{\tilde{s}(f)\tilde{\vec{h}}(f,\vec{\theta})}{S_n(f)}\,df$$

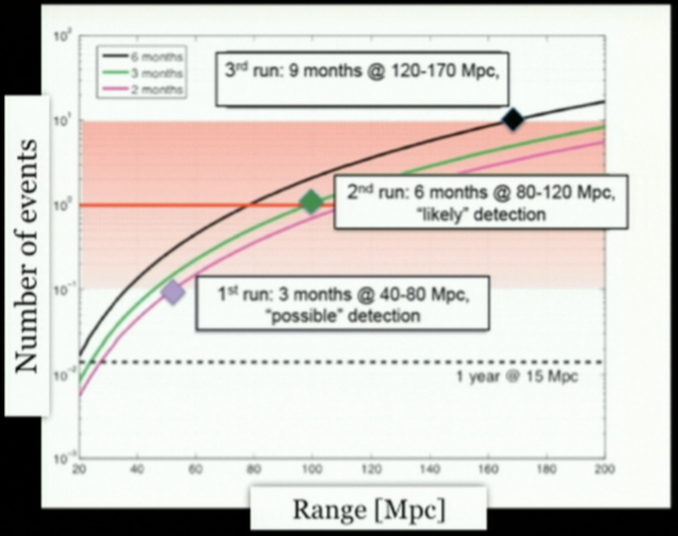
signal-to-noise ratio (SNR)

detector noise (spectral noise density)

# LIGO and Virgo Observing Runs



Fifth science run (S5) data and all Fifth and Sixth science runs results can be found in ligo.org

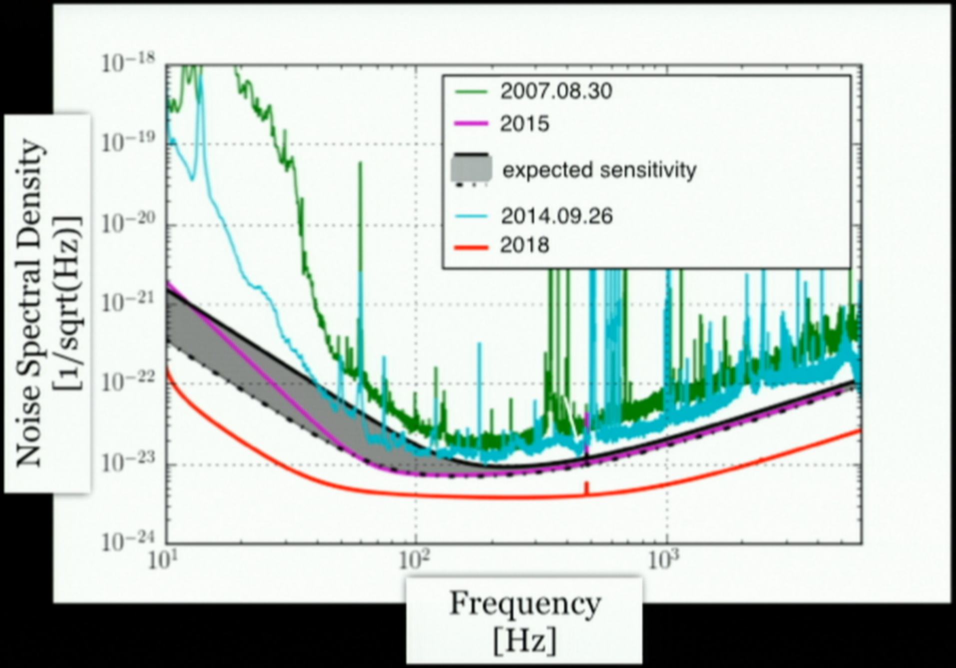


| Epoch | Estimated Run Duration | BNS Range (Mpc) LIGO | BNS Range (Mpc) Virgo | Number of BNS Detections | % BNS Localized within 5 $\deg^2$ | % BNS Localized within 20 $\deg^2$ |
|---|---|---|---|---|---|---|
| 2015 | 3 months | 40 – 80 | – | 0.0004 – 3 | – | – |
| 2016–17 | 6 months | 80 – 120 | 20 – 60 | 0.006 – 20 | 2 | 5 – 12 |
| 2017–18 | 9 months | 120 – 170 | 60 – 85 | 0.04 – 100 | 1 – 2 | 10 – 12 |
| 2019+ | (per year) | 200 | 65 – 130 | 0.2 – 200 | 3 – 8 | 8 – 28 |
| 2022+ (India) | (per year) | 200 | 130 | 0.4 – 400 | 17 | 48 |

arXiv:1304.0670

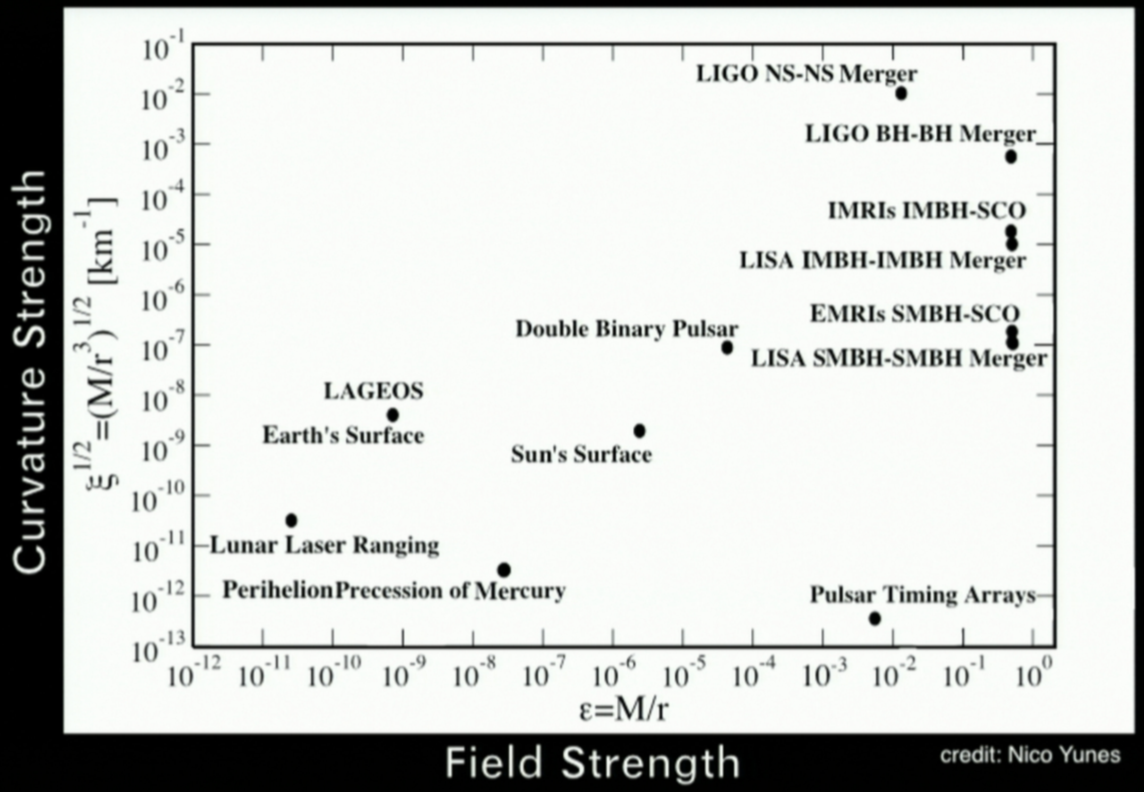
# Recent News

(September 26, 2014)



Preliminary Calibration!

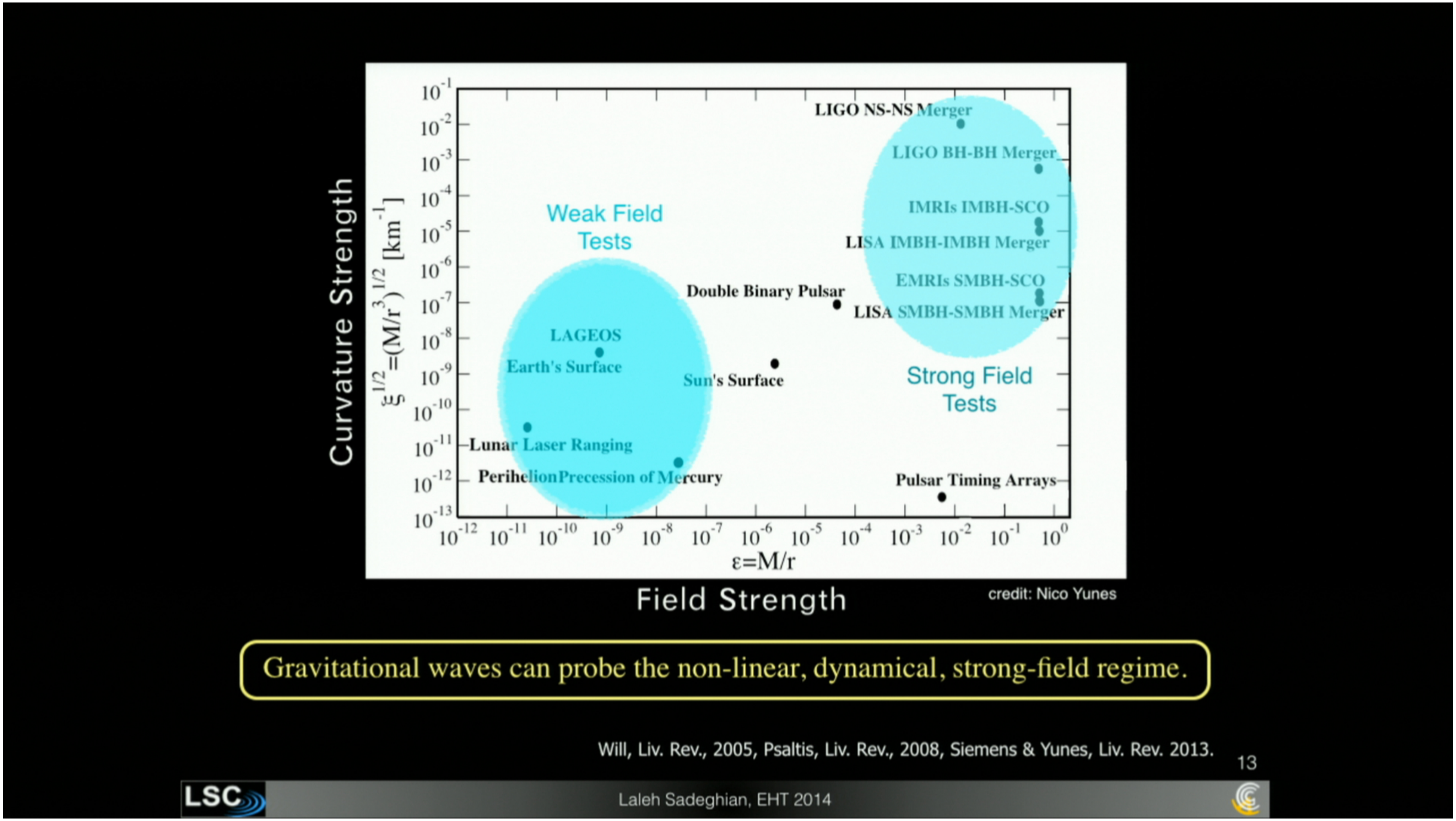
https://alog.ligo-la.caltech.edu/aLOG/index.php?callRep=14821



credit: Nico Yunes

Gravitational waves can probe the non-linear, dynamical, strong-field regime.

Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2013.



credit: Nico Yunes

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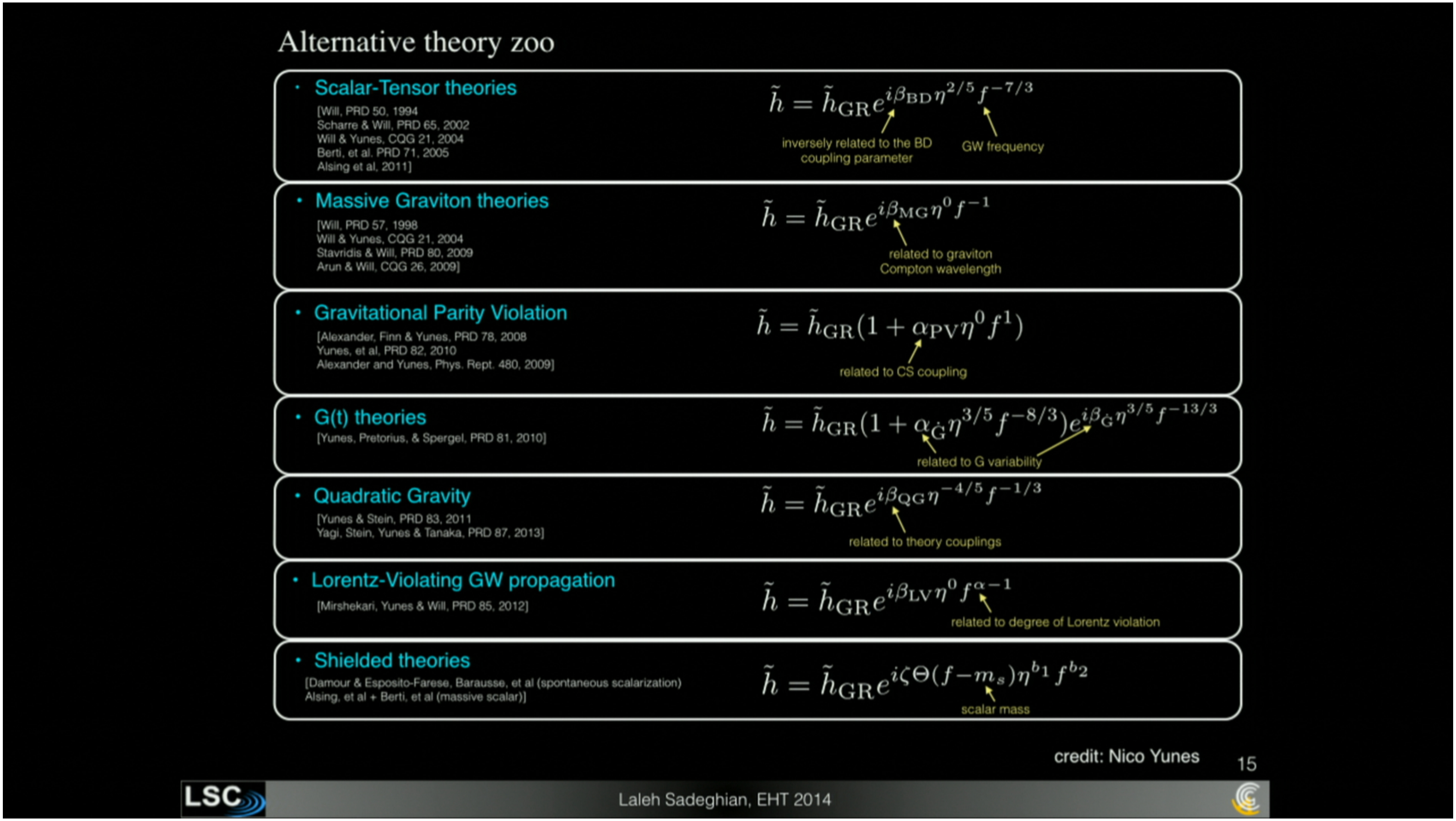
Will, Liv. Rev., 2005, Psaltis, Liv. Rev., 2008, Siemens & Yunes, Liv. Rev. 2013.

# Feasible GR tests using Gravitational Wave detection

- Do Gravitational waves travel at the speed of light? Is Graviton massless?
- Do Gravitational waves have only plus and cross polarizations or are there more?
- Does Kerr solution explain the exterior geometry of a BH? (no-hair theorem test)



# Alternative theory zoo

- Scalar-Tensor theories

[Will, PRD 50, 1994
Scharre & Will, PRD 65, 2002
Will & Yunes, CQG 21, 2004
Berti, et al. PRD 71, 2005
Alsing et al, 2011]

$$\tilde{h} = \tilde{h}_{\rm GR} e^{i\beta_{\rm BD}\eta^{2/5} f^{-7/3}}$$

inversely related to the BD coupling parameter

GW frequency

- Massive Graviton theories

[Will, PRD 57, 1998
Will & Yunes, CQG 21, 2004
Stavridis & Will, PRD 80, 2009
Arun & Will, CQG 26, 2009]

$$\tilde{h} = \tilde{h}_{\rm GR} e^{i\beta_{\rm MG}\eta^{0} f^{-1}}$$

related to graviton Compton wavelength

- Gravitational Parity Violation

[Alexander, Finn & Yunes, PRD 78, 2008
Yunes, et al, PRD 82, 2010
Alexander and Yunes, Phys. Rept. 480, 2009]

$$\tilde{h} = \tilde{h}_{\rm GR}(1 + \alpha_{\rm PV}\eta^{0} f^{1})$$

related to CS coupling

- G(t) theories

[Yunes, Pretorius, & Spergel, PRD 81, 2010]

$$\tilde{h} = \tilde{h}_{\rm GR}(1 + \alpha_{\dot{G}}\eta^{3/5} f^{-8/3}) e^{i\beta_{\dot{G}}\eta^{3/5} f^{-13/3}}$$

related to G variability

- Quadratic Gravity

[Yunes & Stein, PRD 83, 2011
Yagi, Stein, Yunes & Tanaka, PRD 87, 2013]

$$\tilde{h} = \tilde{h}_{\rm GR} e^{i\beta_{\rm QG}\eta^{-4/5} f^{-1/3}}$$

related to theory couplings

- Lorentz-Violating GW propagation

[Mirshekari, Yunes & Will, PRD 85, 2012]

$$\tilde{h} = \tilde{h}_{\rm GR} e^{i\beta_{\rm LV}\eta^{0} f^{\alpha-1}}$$

related to degree of Lorentz violation

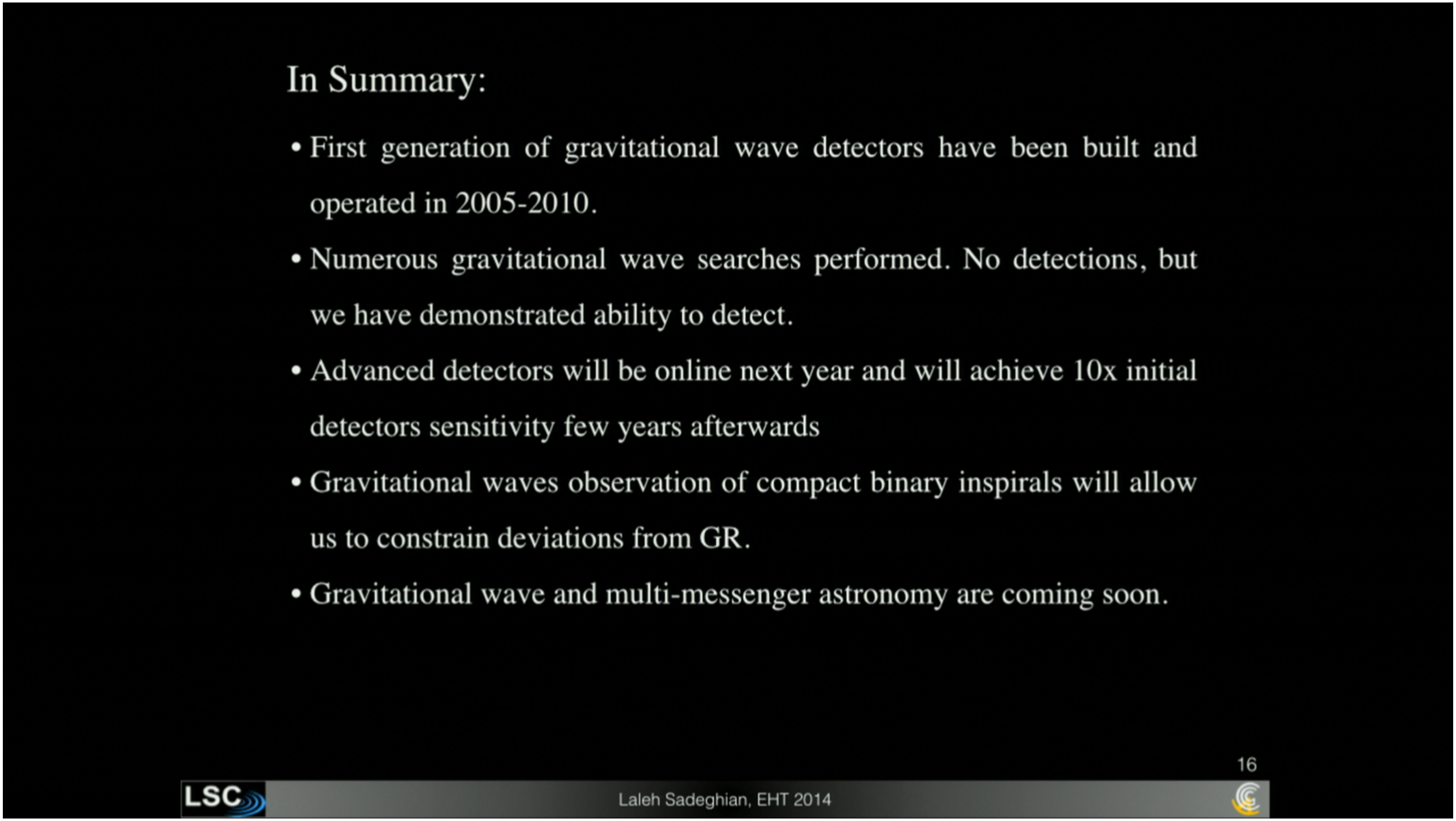
- Shielded theories

[Damour & Esposito-Farese, Barausse, et al (spontaneous scalarization)
Alsing, et al + Berti, et al (massive scalar)]

$$\tilde{h} = \tilde{h}_{\rm GR} e^{i\zeta\Theta(f-m_s)\eta^{b_1} f^{b_2}}$$

scalar mass

credit: Nico Yunes



## In Summary:

- First generation of gravitational wave detectors have been built and operated in 2005-2010.
- Numerous gravitational wave searches performed. No detections, but we have demonstrated ability to detect.
- Advanced detectors will be online next year and will achieve 10x initial detectors sensitivity few years afterwards
- Gravitational waves observation of compact binary inspirals will allow us to constrain deviations from GR.
- Gravitational wave and multi-messenger astronomy are coming soon.