

<https://bit.ly/3vdLF8D>



# Intersections with ~~Astrophysics~~ Gravitational Wave Astronomy

Will M. Farr (Stony Brook / CCA)  
25 July 2022



# Intersections

1. QCD at T=0 and high density.
2. Tests of General Relativity at high curvature.
3. Propagation tests of gravity.
4. Calibrated cosmological distances.

# Intersections

1. QCD at T=0 and high density.
2. Tests of General Relativity at high curvature.
3. Propagation tests of gravity.
4. Calibrated cosmological distances.

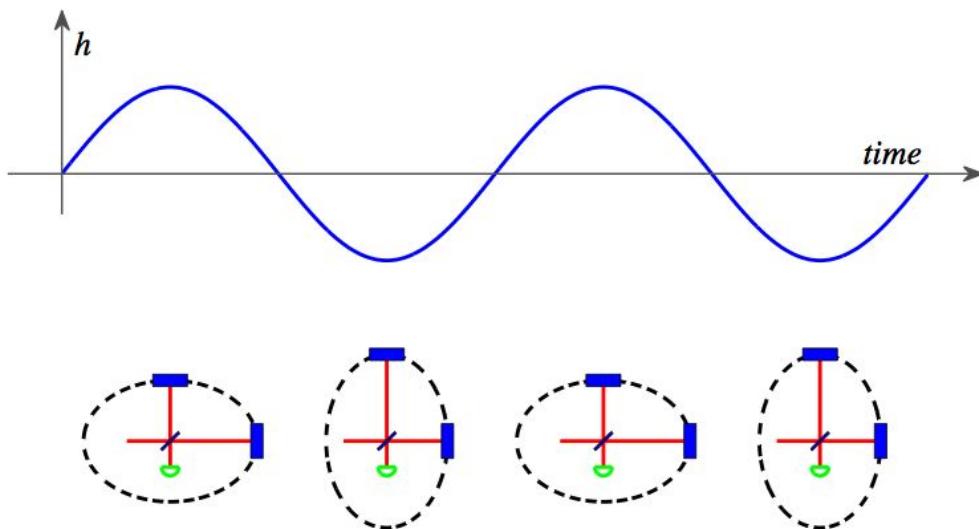
TODAY

# Intersections

1. QCD at T=0 and high density.
2. Tests of General Relativity at high curvature.
3. Propagation tests of gravity.
4. Calibrated cosmological distances.

TODAY      ... and in the FUTURE

# Gravitational Waves



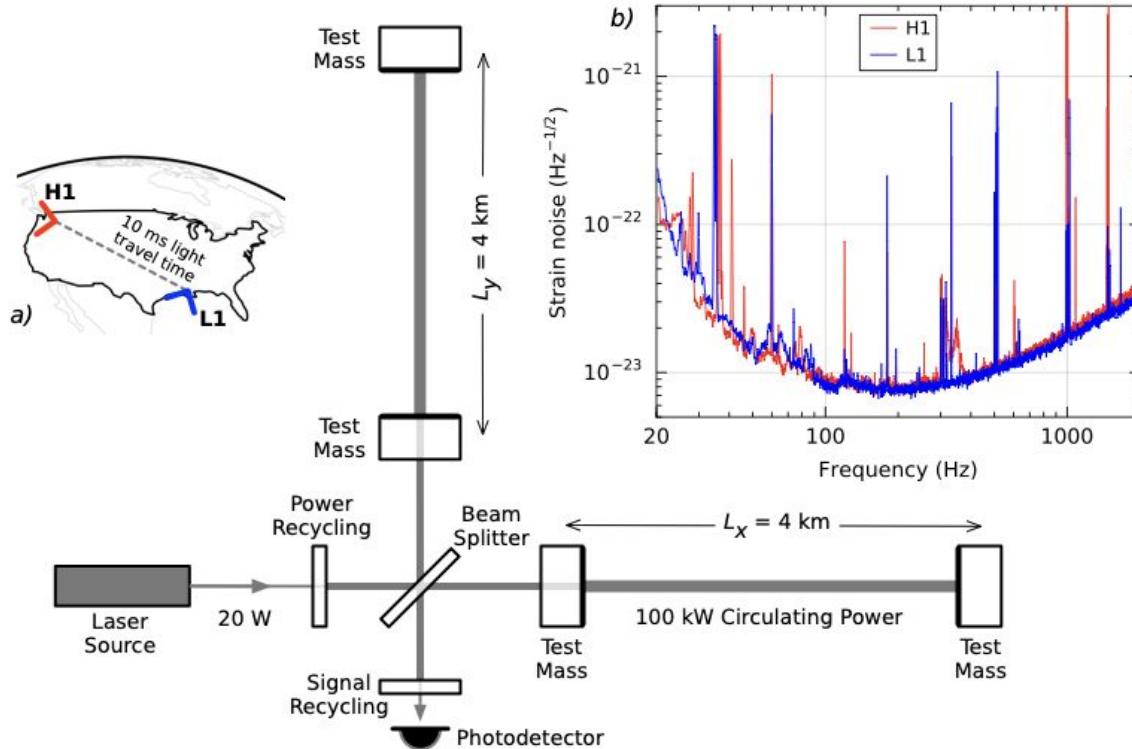
# LIGO



Astrophysics

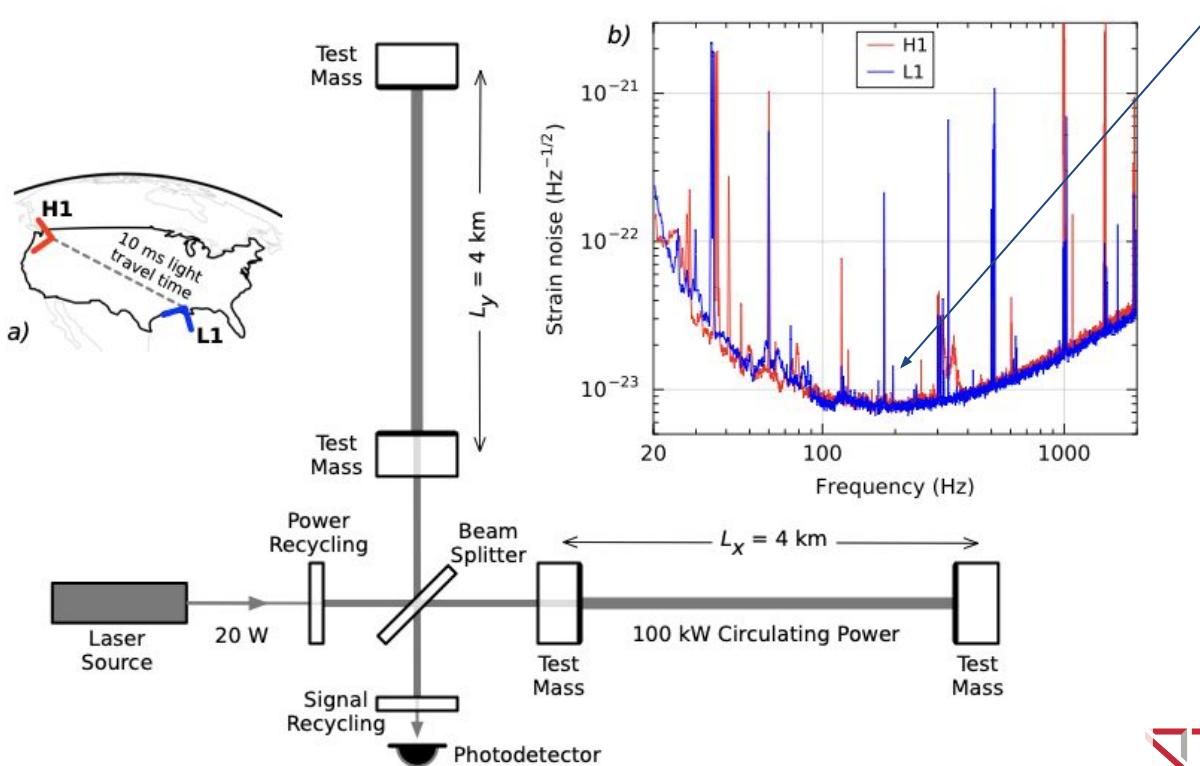
ON  
THE  
LIGO

# LIGO



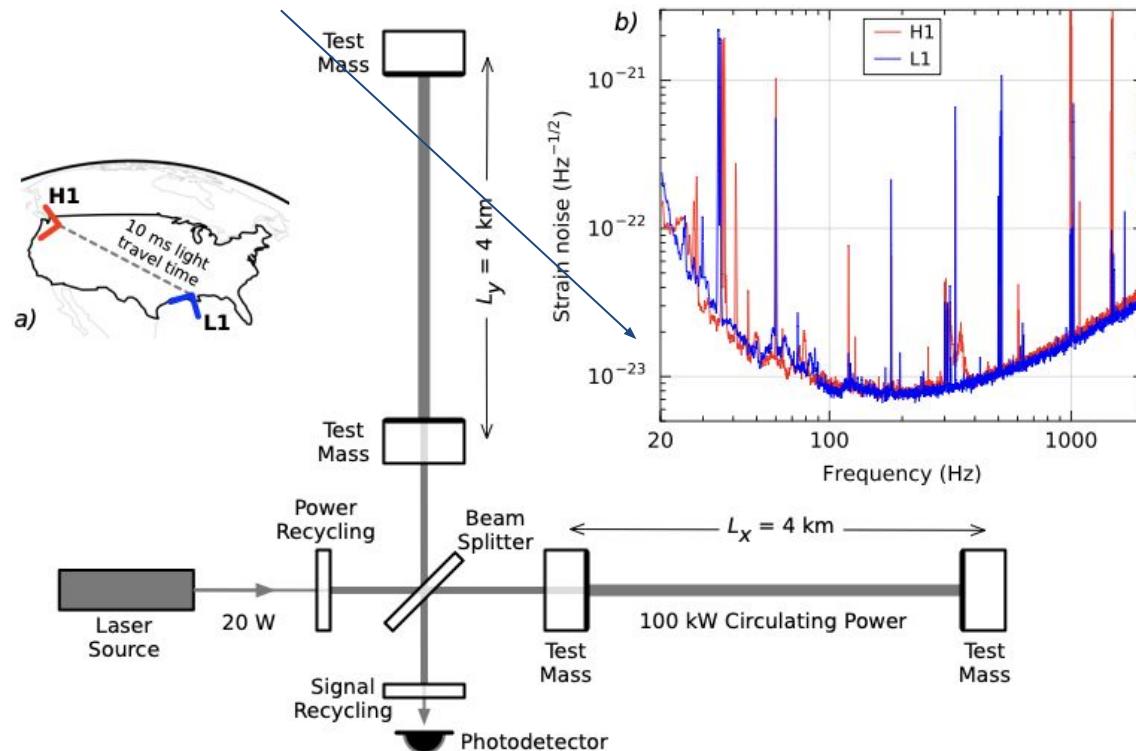
# LIGO

$$f_{\text{ISCO}} = 200 \text{ Hz} \frac{10M_{\odot}}{M}$$

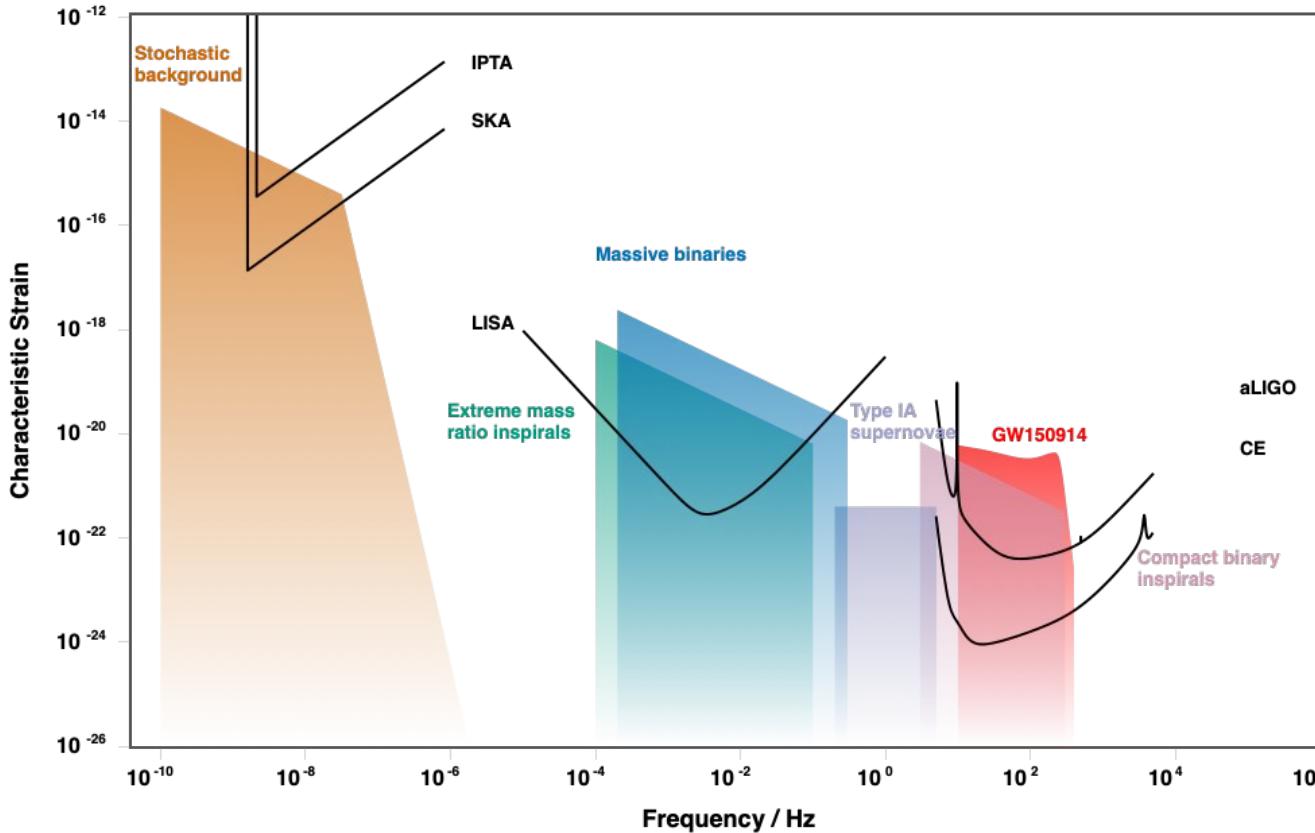


[Abbott, et al. \(2016\)](#)

$$h = \mathcal{O}(1) \times \frac{R_{\text{Schw}}}{r} \simeq 10^{-23} \frac{M}{10 M_\odot} \frac{1 \text{ Gpc}}{r}$$

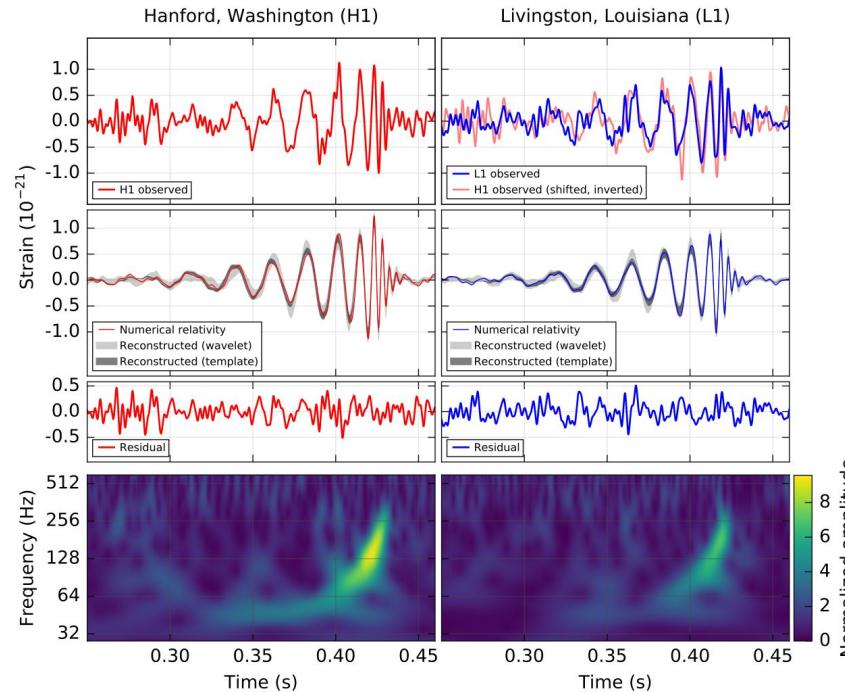


# GW Landscape

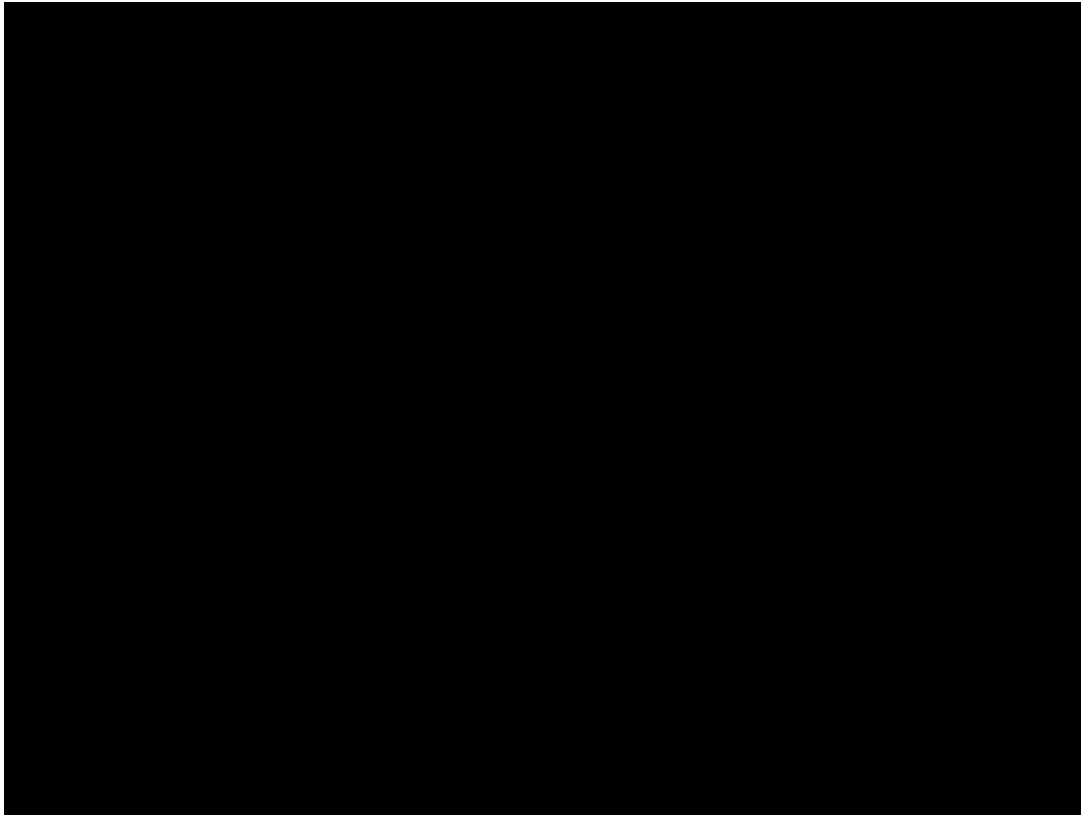


<http://gwplotter.com>  
Moore, Cole, & Berry (2014)

# GW150914



# GW170817



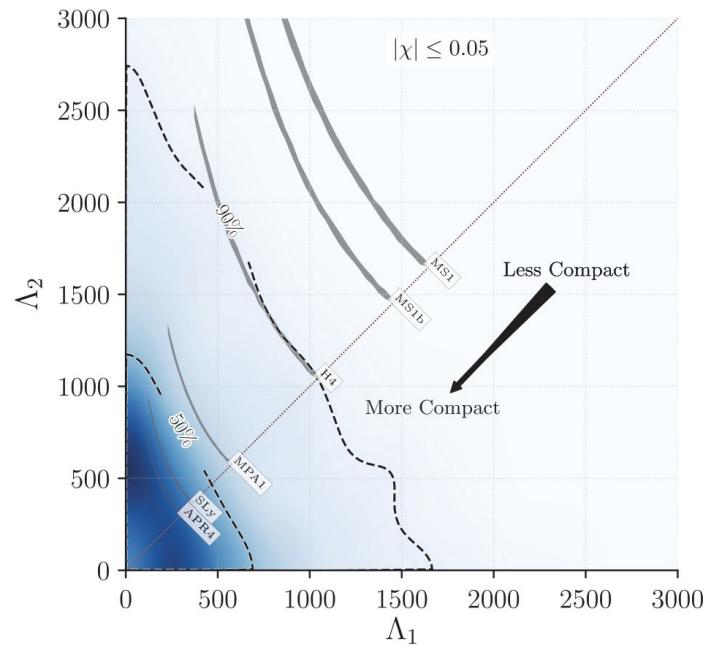
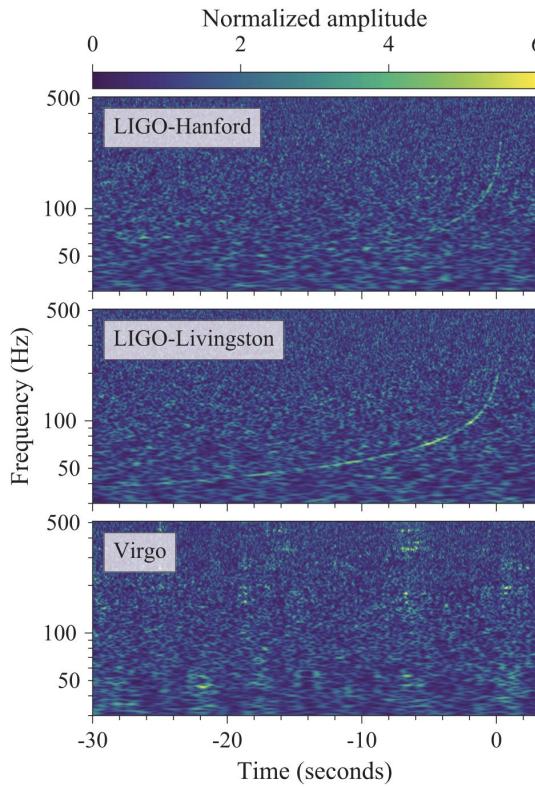
$1-c_g/c_\gamma \sim 2 \text{ sec} / 120 \text{ Myr} \sim 1\text{e}-15$

[Ezquiaga & Zumalacárregui \(2017\)](#)

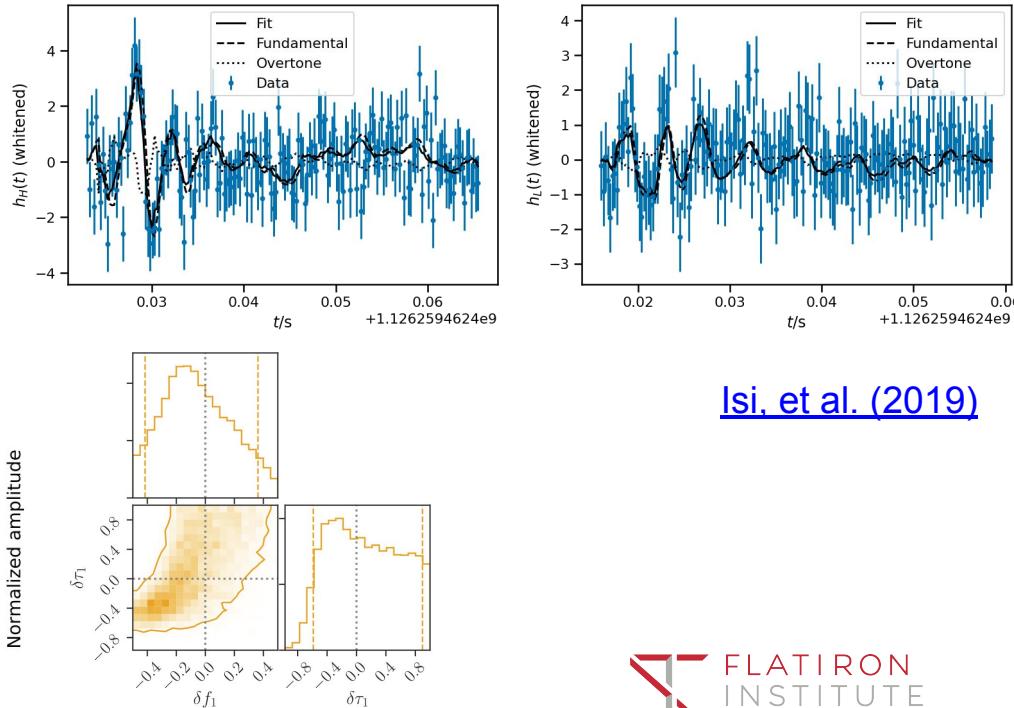
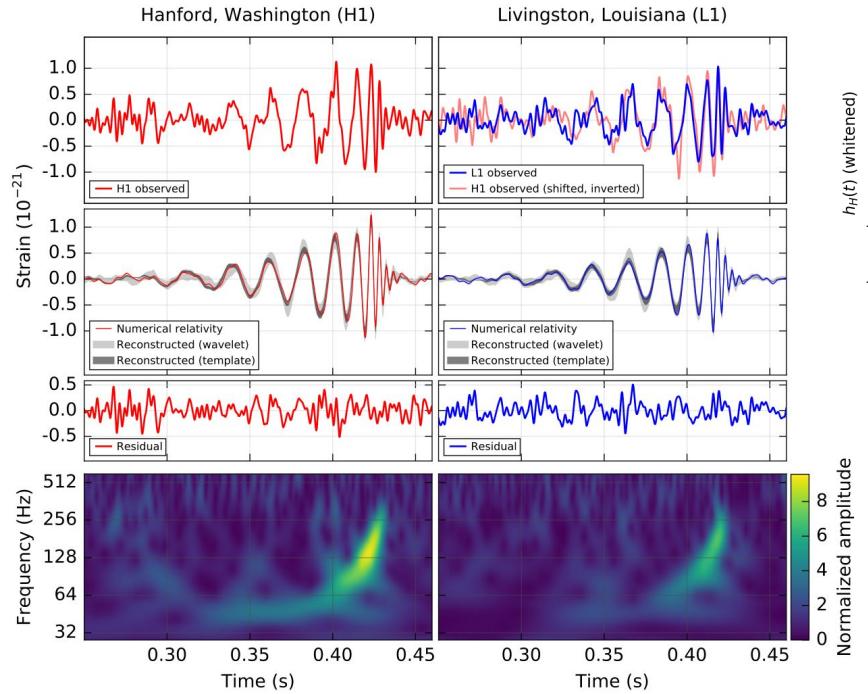


[Abbott, et al. \(2017\)](#)

# GW170817: QCD at high density.



# GW150914: Tests of GR in strong field



[Isi, et al. \(2019\)](#)

[Abbott, et al. \(2016\)](#)

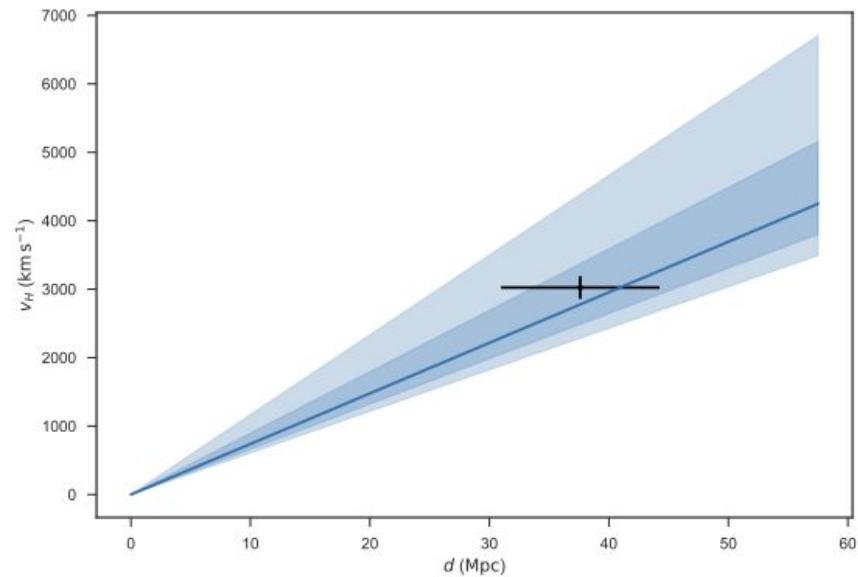
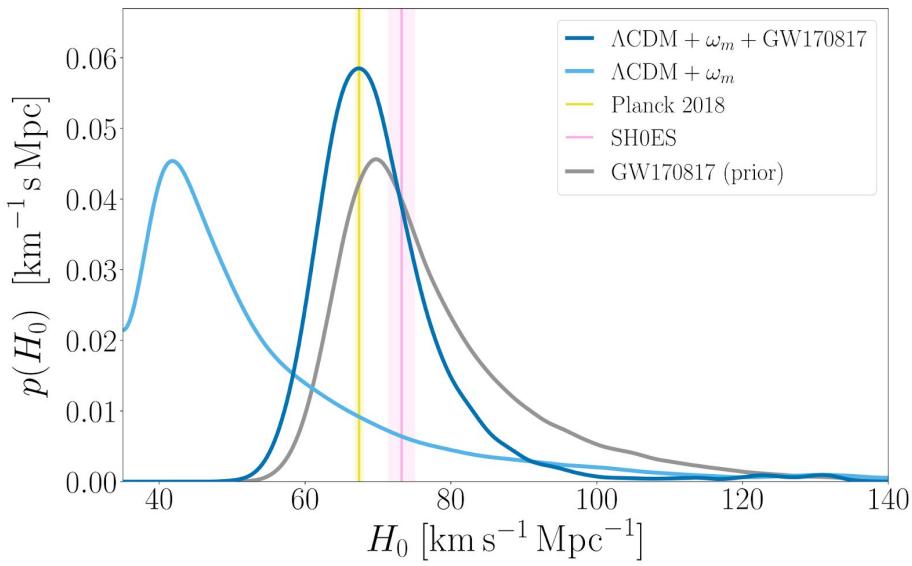
# Distances

$$\frac{c^5}{G} \simeq 3 \times 10^{59} \text{ erg s}^{-1} \simeq 10^6 \text{ SNe}$$

# Redshifts are Hard

$$m_{\text{obs}} = m(1 + z)$$

# Easy Mode: GW + EM Measurements



[Abbott, et al. \(2017\)](#)  
[Chen, et al. \(2020\)](#)

# Redshifts Without EM Observations

$$m_{\text{obs}} = m(1 + z)$$

# Redshifts Without EM Observations

If I know this

$$m_{\text{obs}} = m(1 + z)$$

# Redshifts Without EM Observations

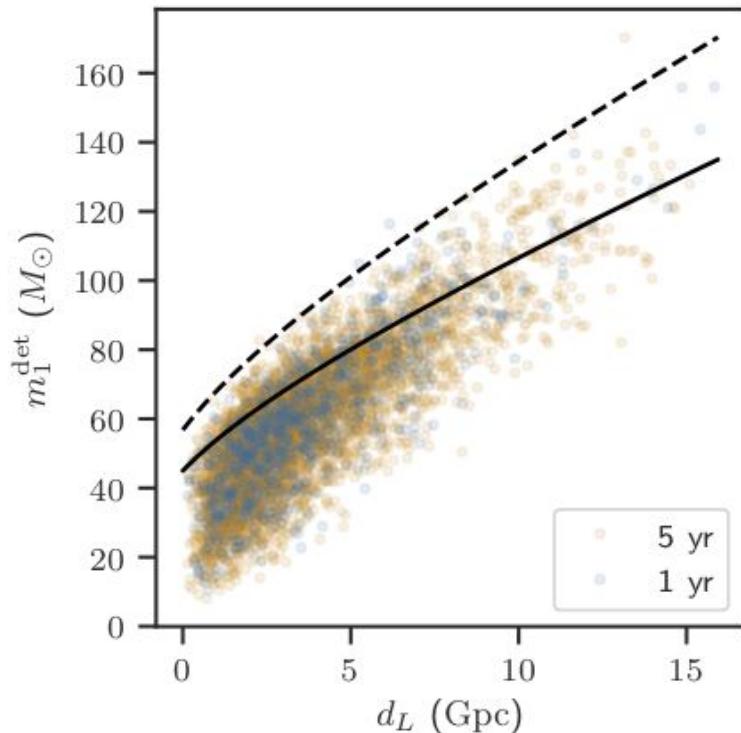
If I know this

$$m_{\text{obs}} = m(1 + z)$$

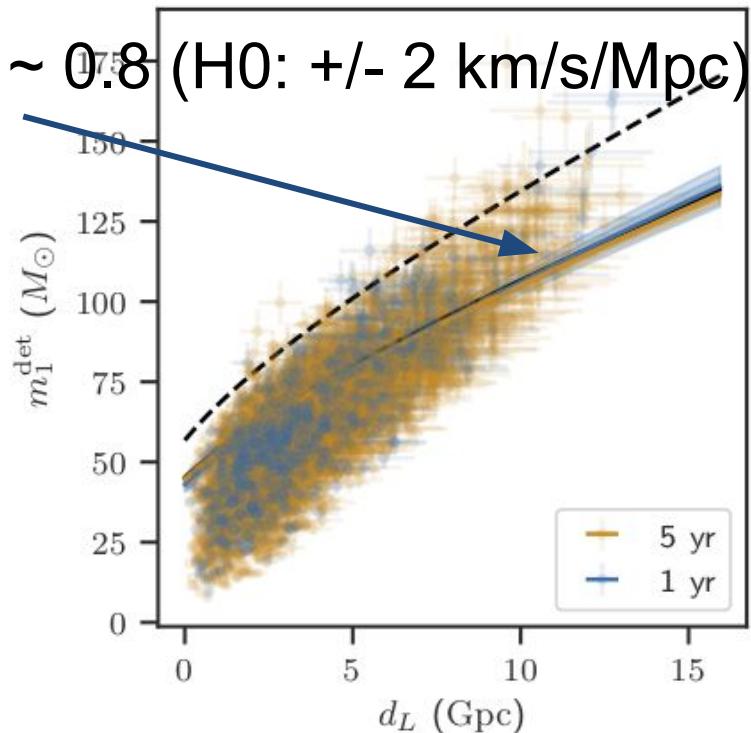
Then I can measure this.

[Chernoff & Finn \(1993\)](#)  
[Taylor & Gair \(2012\)](#)

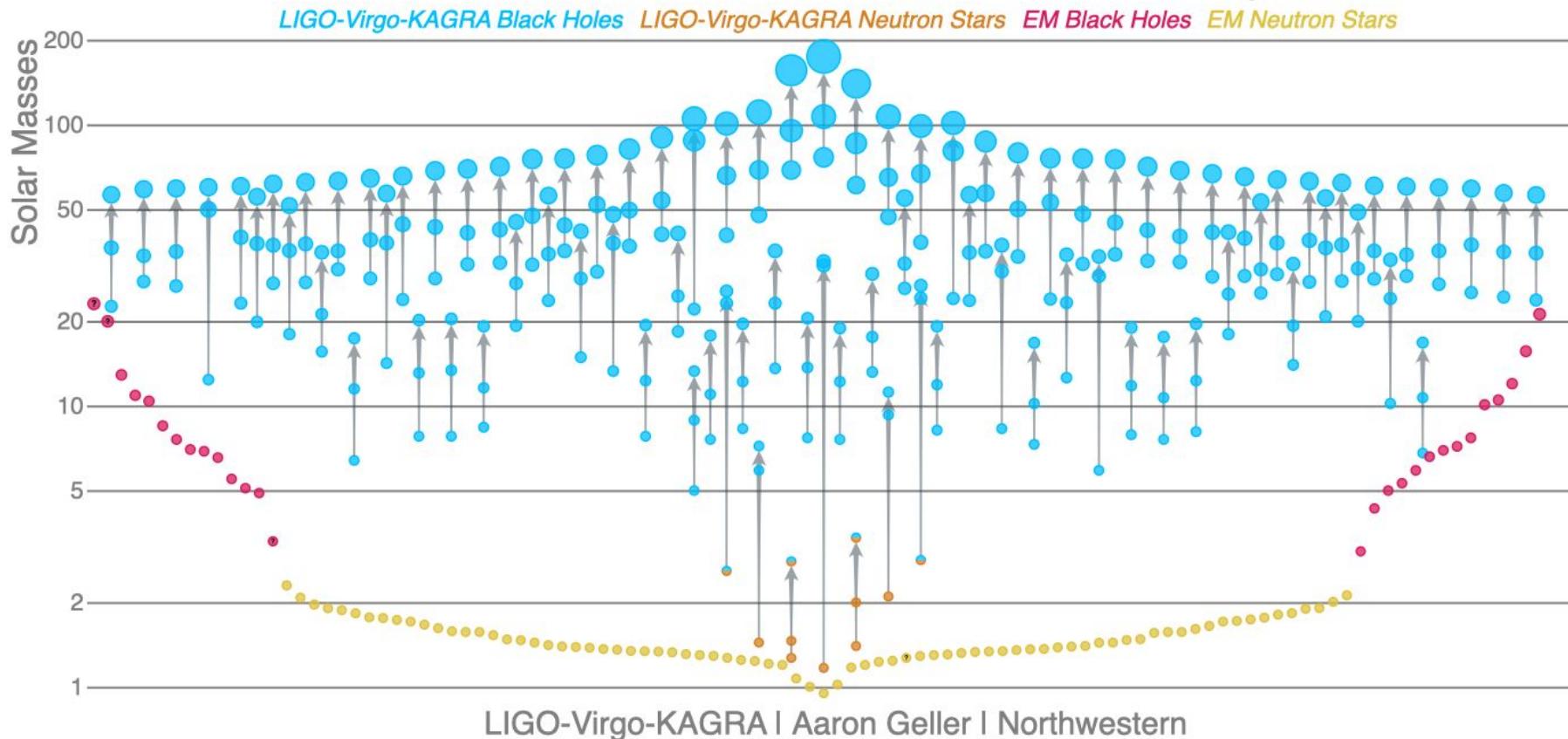
# What It Might Look Like This Decade



3% at  $z \sim 0.8$  ( $H_0: +/- 2 \text{ km/s/Mpc}$ )!

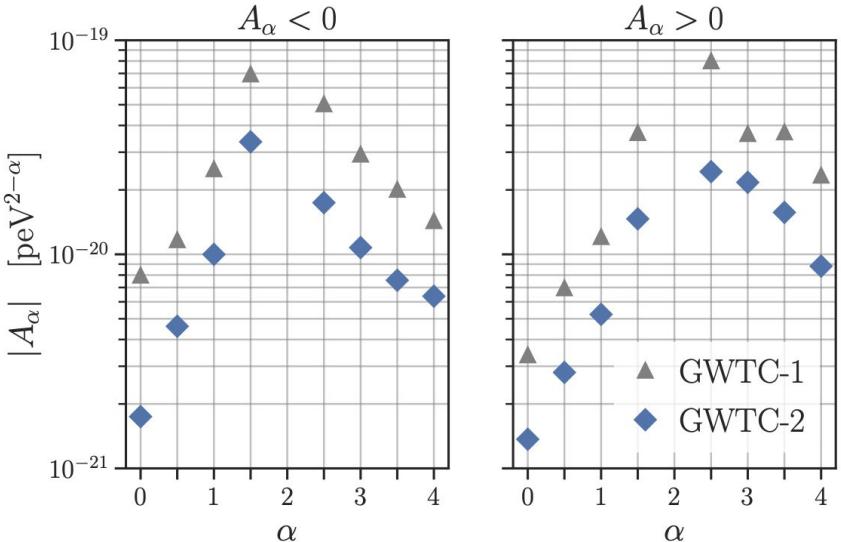


# Masses in the Stellar Graveyard

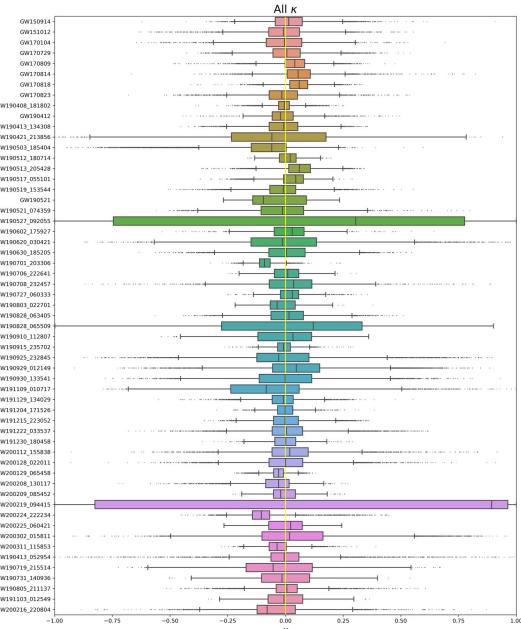


# Propagation Tests

$$E^2 = p^2 c^2 + A_\alpha p^\alpha c^\alpha$$



Abbott, et al. (2020)

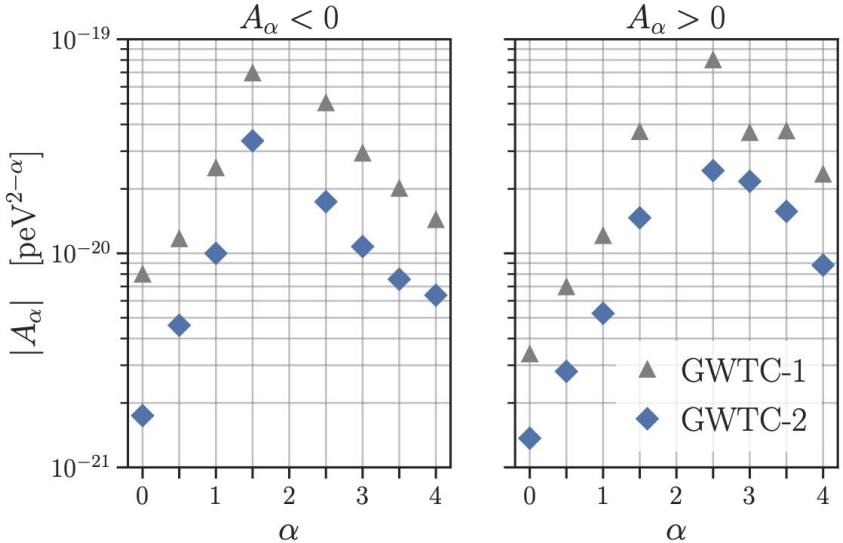


CCA GW Group, in prep.



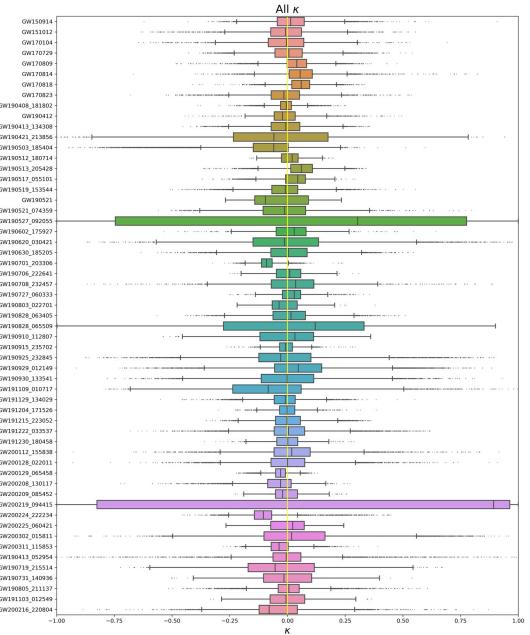
# Propagation Tests

$$E^2 = p^2 c^2 + A_\alpha p^\alpha c^\alpha$$



[Abbott, et al. \(2020\)](#)

Birefringent Opacity:



CCA GW Group, in prep.

# The Future (Ground-Based, 2035)

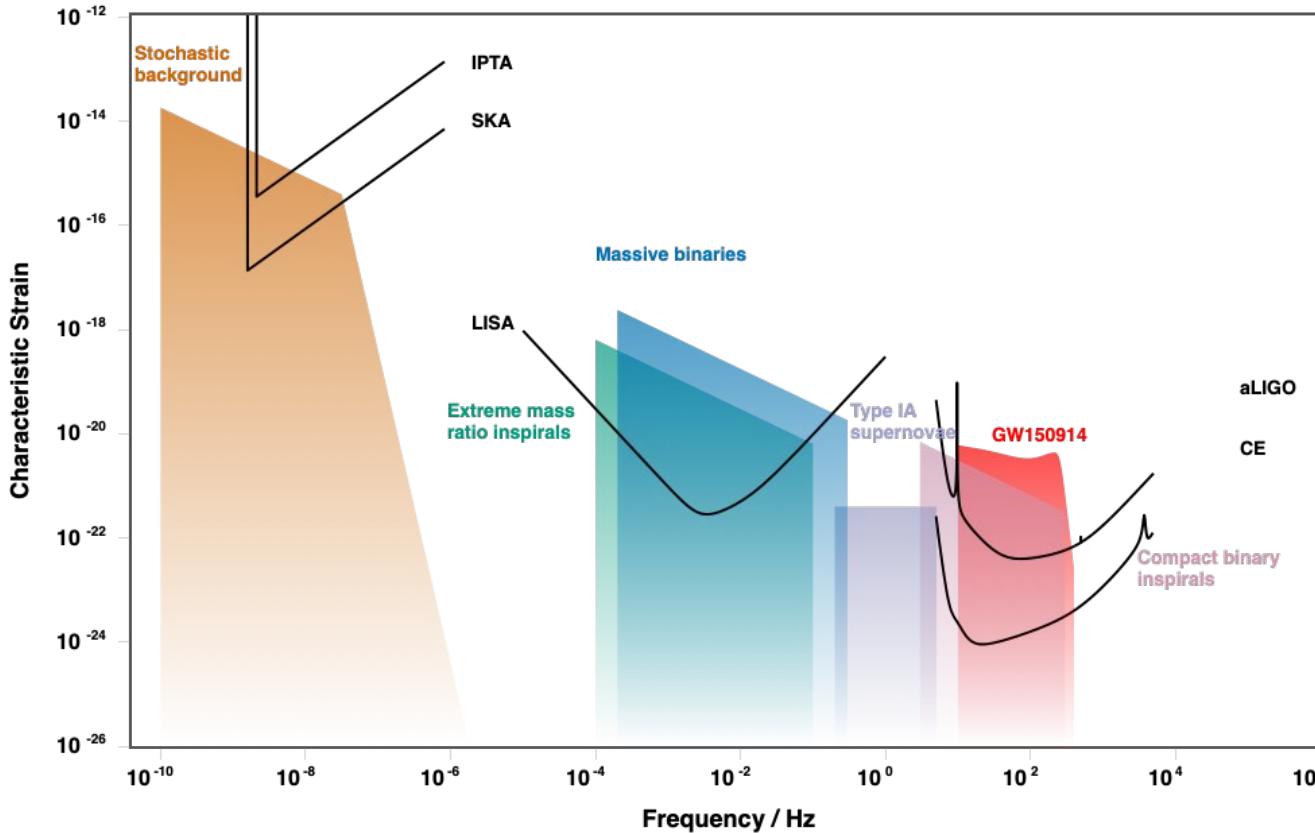
Cosmic Explorer



LIGO

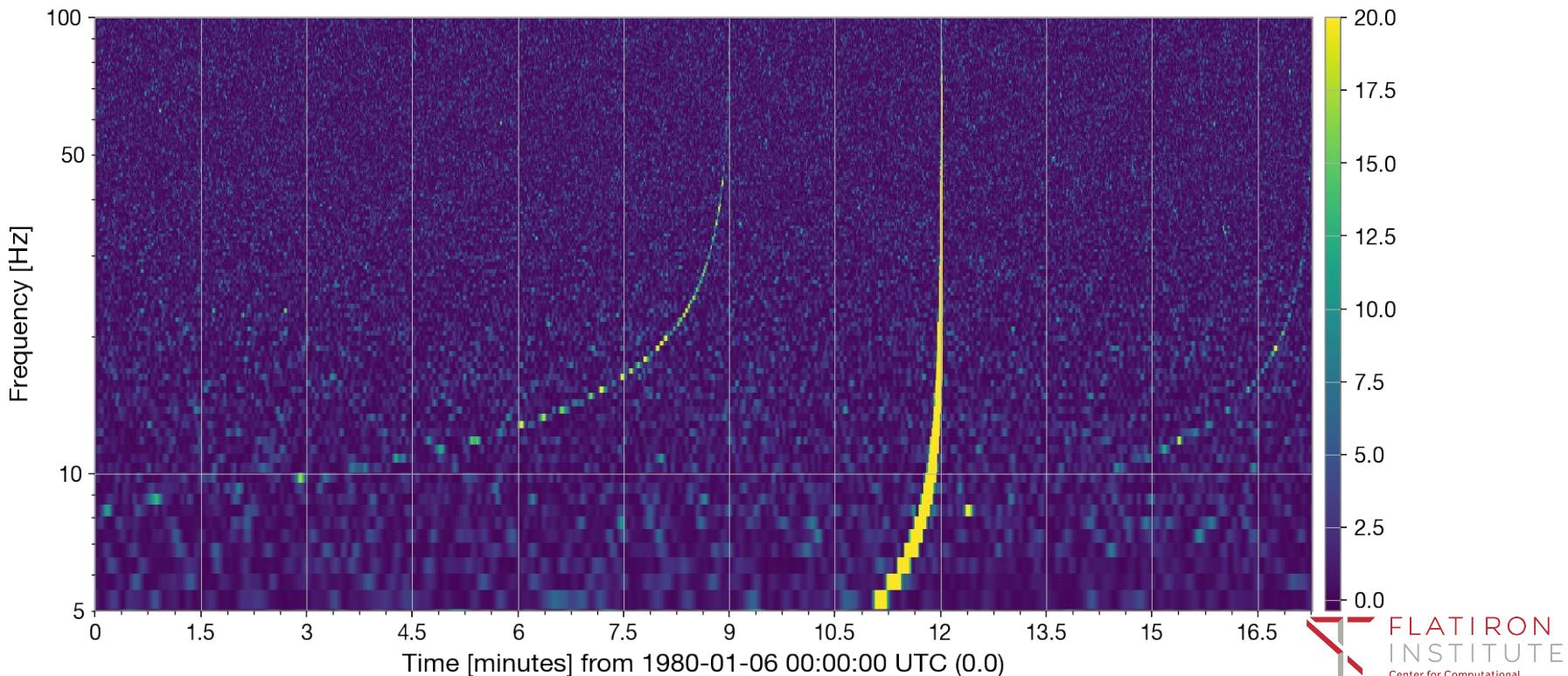


# GW Landscape



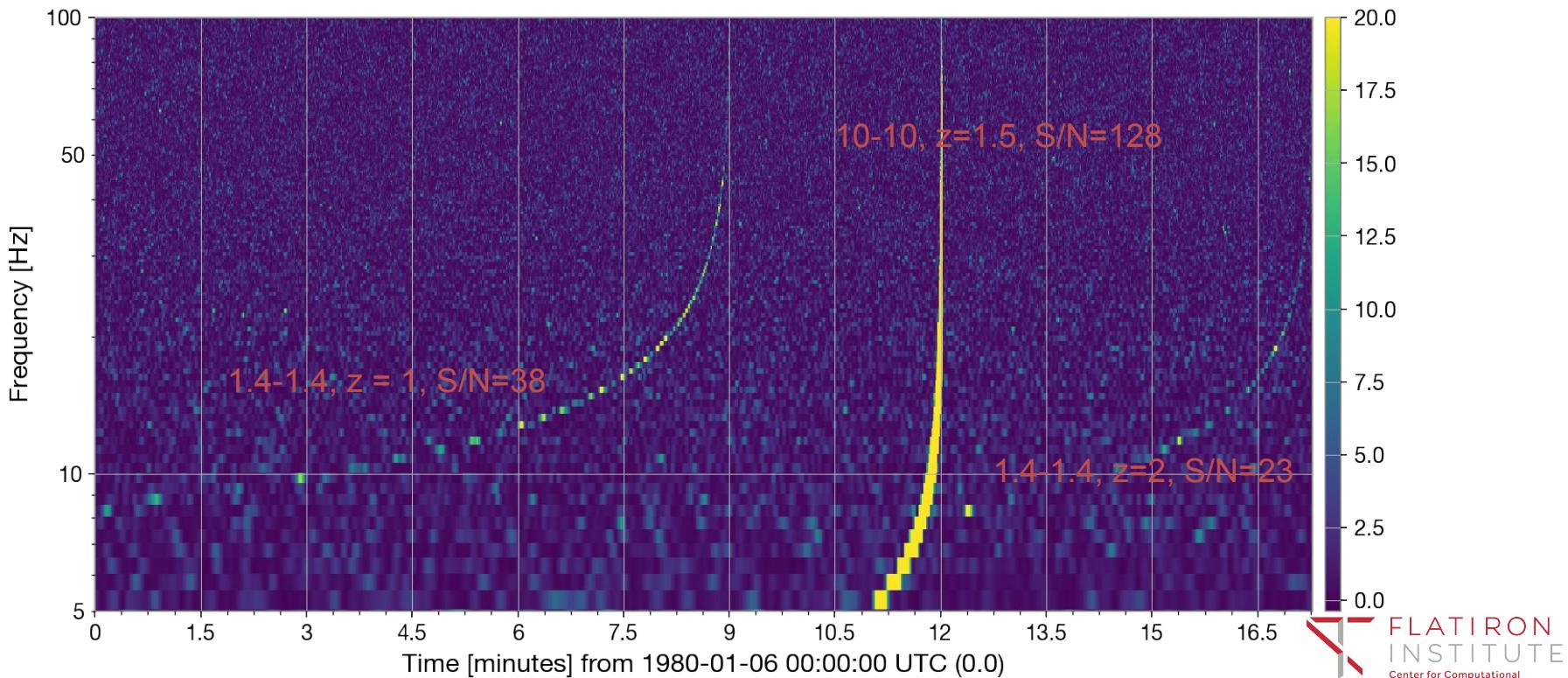
<http://gwplotter.com>  
Moore, Cole, & Berry (2014)

# A Lazy Tuesday Afternoon at Cosmic Explorer...



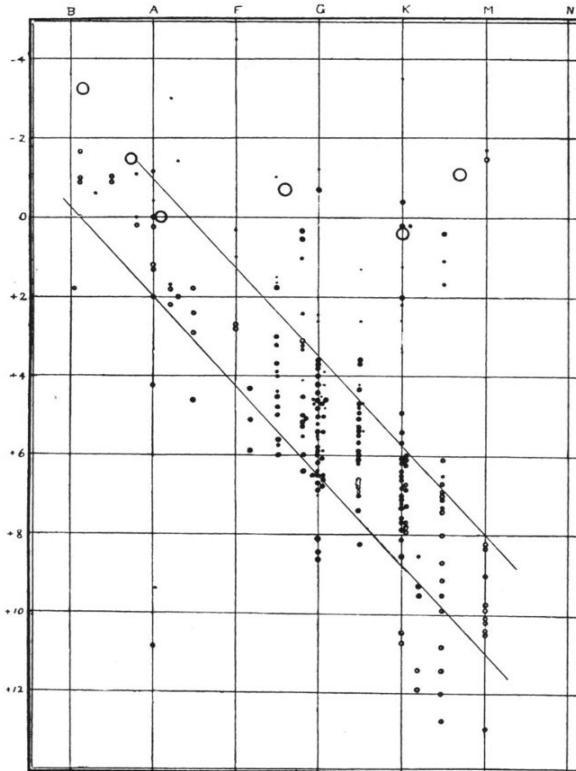
Farr, W. M. & [Farr, B.](#)

# A Lazy Tuesday Afternoon at Cosmic Explorer...



Farr, W. M. & [Farr, B.](#)

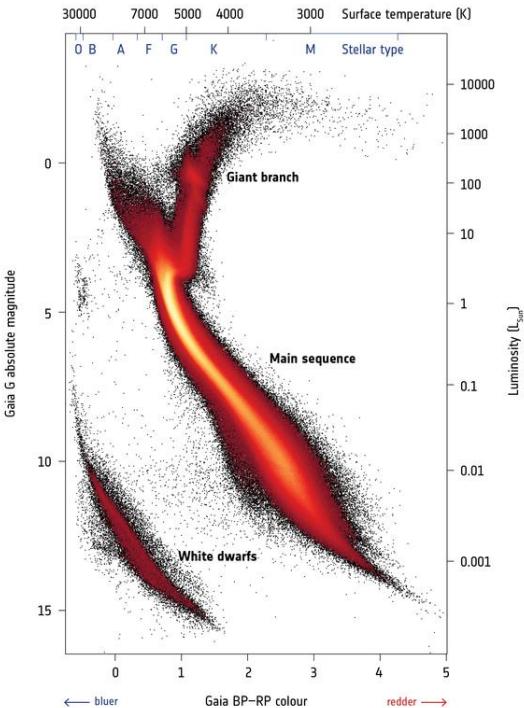
# Analogy: The Present



Russell (1914)

# Analogy: The Future

→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM



[ESA/Gaia/DPAC](#)

# Intersections

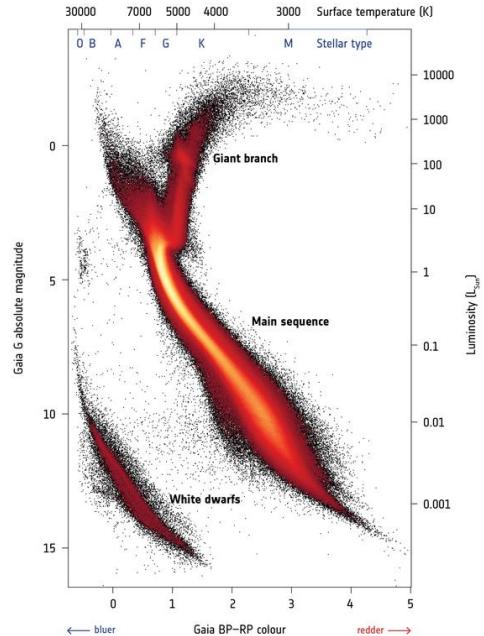
→ GAIA'S HERTZSPRUNG-RUSSELL DIAGRAM

1. QCD at T=0 and high density.
2. Tests of General Relativity at high curvature.
3. Propagation tests of gravity.
4. Calibrated cosmological distances.

These all get better with:

1. 250k sources / yr (!)
2. S/N >> 100 sources

The future is BRIGHT!



ESA/Gaia/DPAC  
FLATIRON  
INSTITUTE

Center for Computational  
Astrophysics