Title: Binary Black Hole Mergers beyond General Relativity - Part 2

Speakers: Maria Okounkova

Series: Strong Gravity

Date: September 30, 2021 - 1:00 PM

URL: https://pirsa.org/21090026

Abstract: At some length scale, Einstein's theory of general relativity (GR) must break down and be reconciled with quantum mechanics in a quantum theory of gravity. Binary black hole mergers probe the strong field, non-linear, highly dynamical regime of gravity, and thus gravitational waves from these systems could contain beyond-GR signatures. While LIGO presently performs model-independent and parametrized tests of GR, in order to perform model-dependent tests, we must have access to numerical relativity binary black hole waveform predictions in beyond-GR theories through full inspiral, merger, and ringdown. In this talk, I will discuss our results in producing full numerical relativity waveforms in beyond-GR theories, including dynamical Chern-Simons gravity and Einstein dilaton Gauss-Bonnet gravity, and performing gravitational wave data analysis on these waveforms.

Zoom Link: https://pitp.zoom.us/j/91782607606?pwd=SkpaYlF6a04zVDNXS2ZlWjJwdUpkQT09


BINARY BLACK HOLES
BEYOND GENERAL RELATIVITY
Dr. Maria [Masha] Okounkova
FLATIRON
INSTITUTE

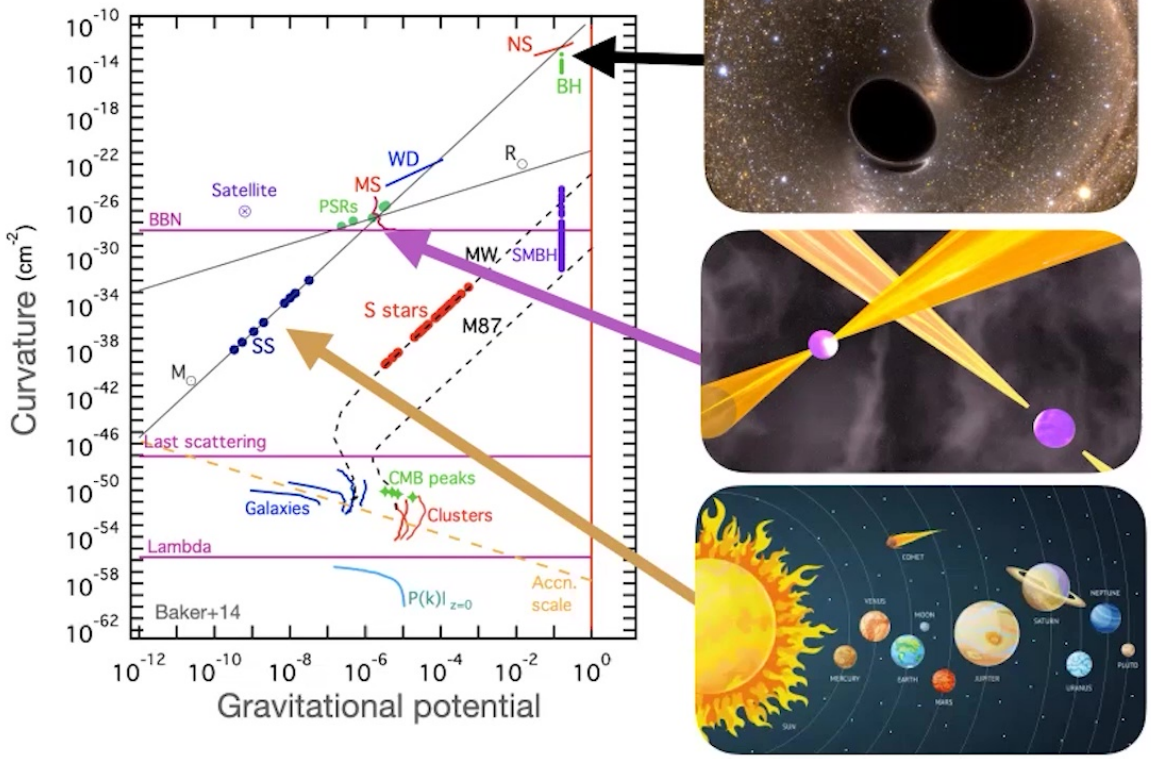

Maria (Masha) Okoun...

$G_{ab} = 8\pi T_{ab}$

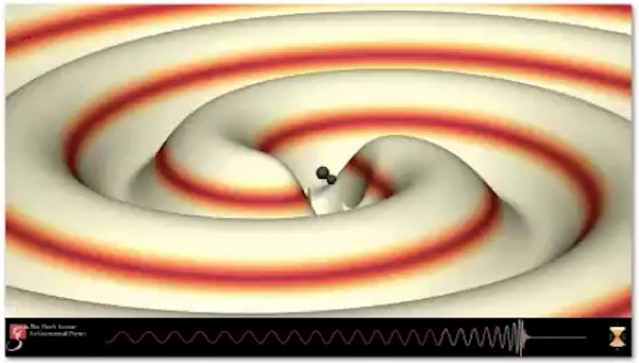
Why do you spend so much time testing GR?
We *know* that the theory is right.

Nature isn't classical

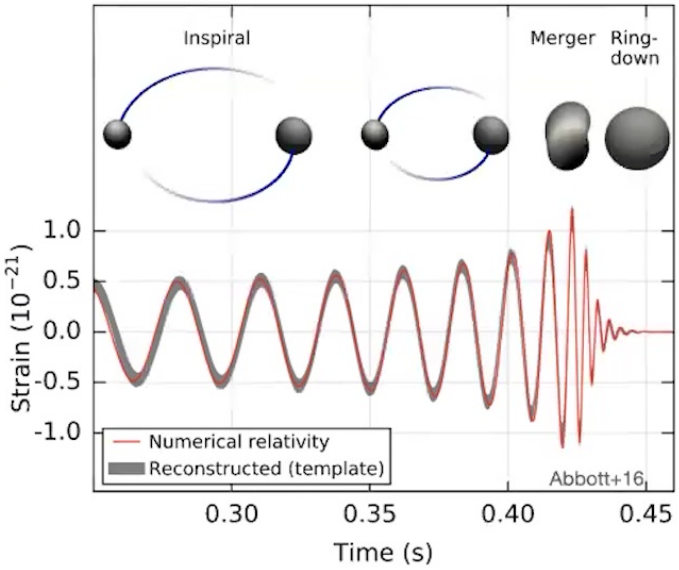
Looking for extreme gravity



Binary black hole mergers:

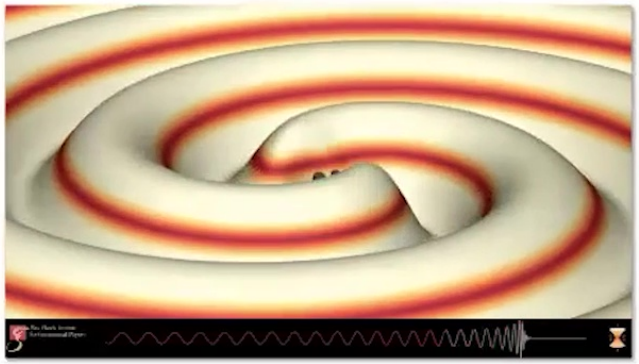


Gravitational waves:



Probe the non-linear,
highly dynamical,
strong-field regime of gravity

Binary black hole mergers:



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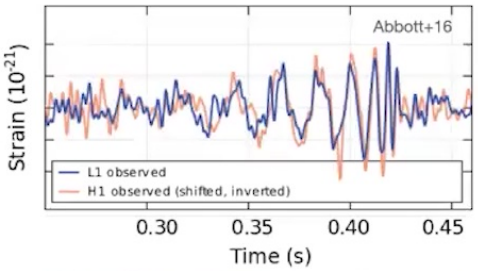
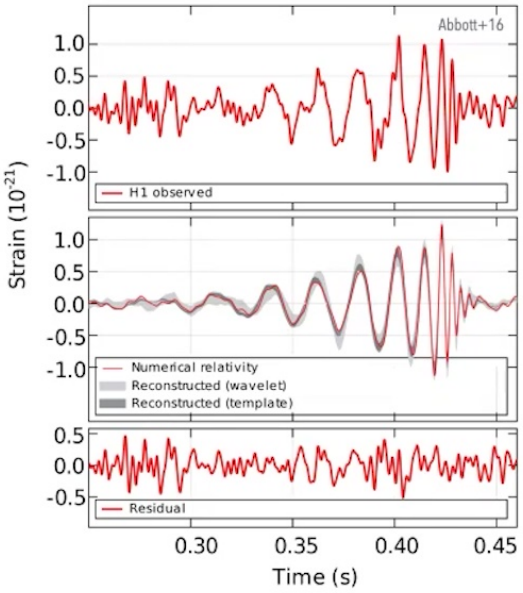


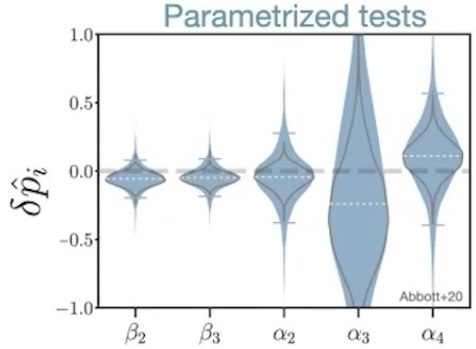
Could contain beyond-GR signatures

Looking for beyond-GR physics with GWs

Null tests



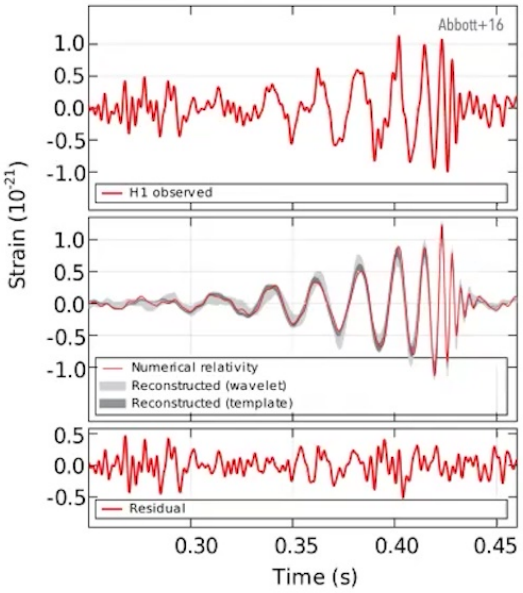
Parametrized tests



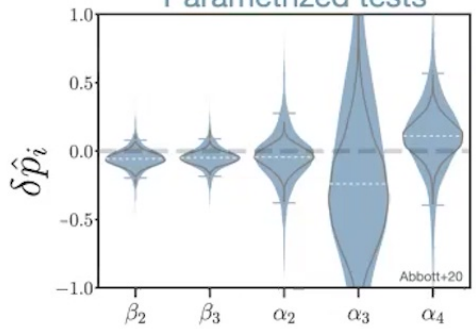
Missing model-dependent tests

Looking for beyond-GR physics with GWs

Null tests



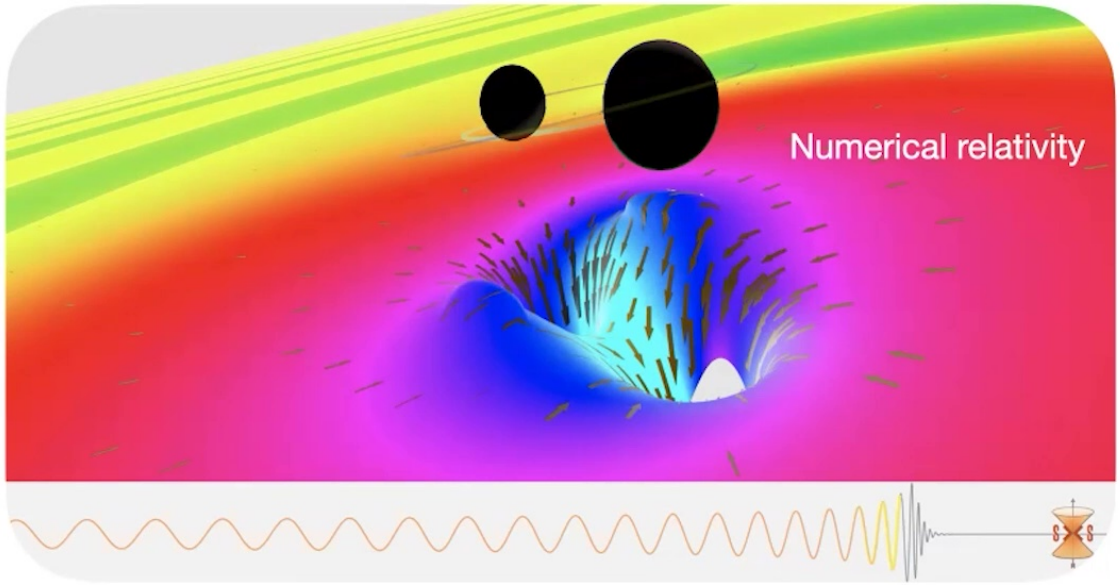
Parametrized tests



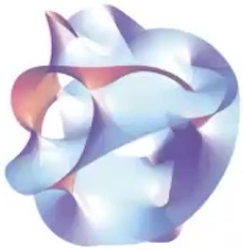
Missing model-dependent tests

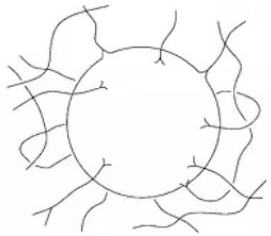
Missing beyond-GR waveforms

Missing beyond-GR gravitational waveforms → Let's make them!



Choosing beyond-GR theories



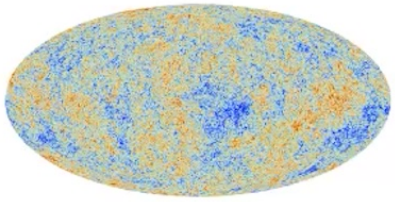


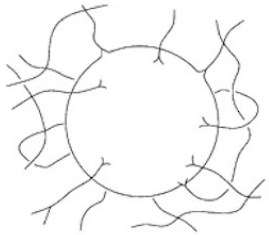
Beyond-GR effective field theories

$$\int d^4x\sqrt{-g}\,\left(R+\varepsilon^2\mathcal{R}^2+\varepsilon^4\mathcal{R}^3+\ldots\right)$$

Dynamical Chern-Simons gravity

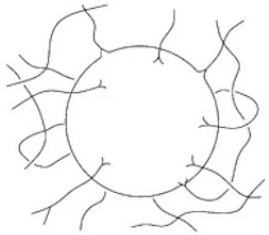
$$S = \int d^4x\sqrt{-g}\left(R - \ell^2\vartheta\ ({}^*R_{abcd}R^{abcd}) - \frac{1}{2}\partial_a\vartheta\partial^a\vartheta\right)$$





Einstein dilaton Gauss-Bonnet gravity

$$S = \int d^4x\sqrt{-g}\left(R + \alpha e^{\vartheta}(R_{abcd}R^{abcd} - 4R_{ab}R^{ab} + R^2) - \frac{1}{2}\partial_a\vartheta\partial^a\vartheta\right)$$



Dynamical Chern-Simons gravity

$$\ell^2 \vartheta \, ({}^*R_{abcd} R^{abcd})$$

Schwarzschild ✓ Kerr ✘

Einstein dilaton Gauss-Bonnet gravity

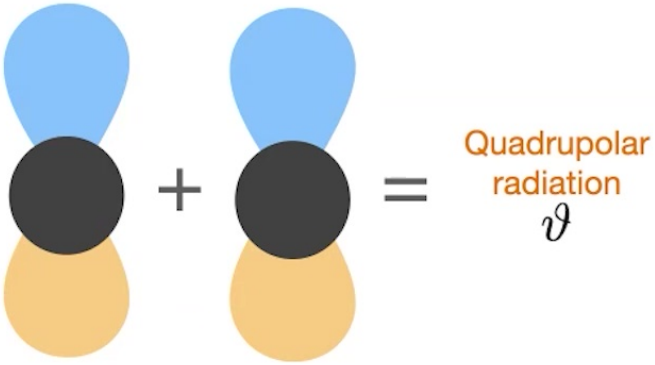
$$\alpha e^{\vartheta} (R_{abcd} R^{abcd} - 4 R_{ab} R^{ab} + R^2)$$

Schwarzschild ✘ Kerr ✘

Dynamical Chern-Simons gravity

$$\ell^2 \vartheta \, ({}^*R_{abcd}R^{abcd})$$

Schwarzschild ✓ Kerr ✘



Quadrupolar radiation ϑ

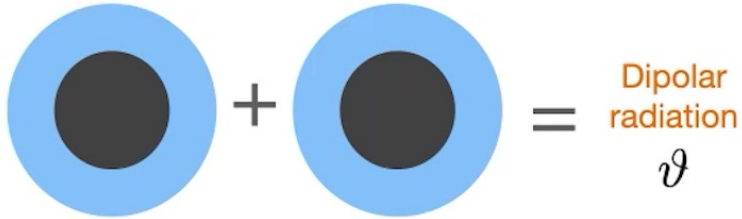
ϑ Dipole

+2 PN order correction

Einstein dilaton Gauss-Bonnet gravity

$$\alpha e^{\vartheta}(R_{abcd}R^{abcd} - 4R_{ab}R^{ab} + R^2)$$

Schwarzschild ✘ Kerr ✘



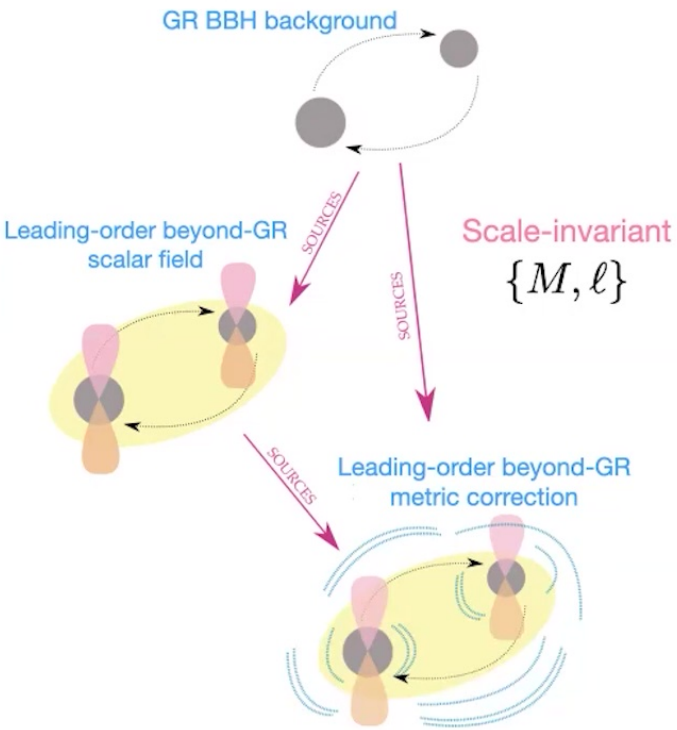
Dipolar radiation ϑ

ϑ Monopole

-1 PN order correction

What we've done: The first BBH merger waveforms in higher-curvature theories of gravity

Our method: order reduction-scheme



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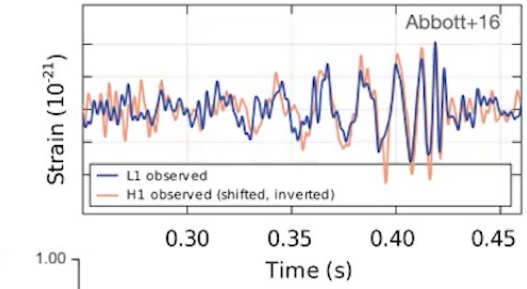
2. What we've learned
3. What we're going to do in the coming decades

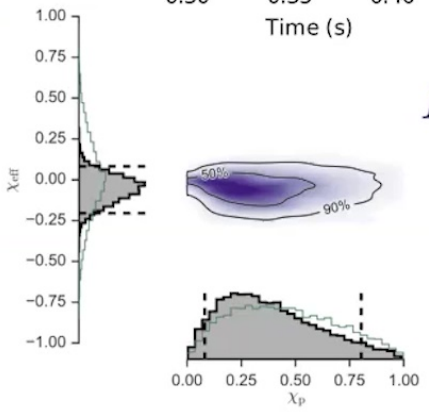
Choosing BBH parameters to simulate

Scale-invariant

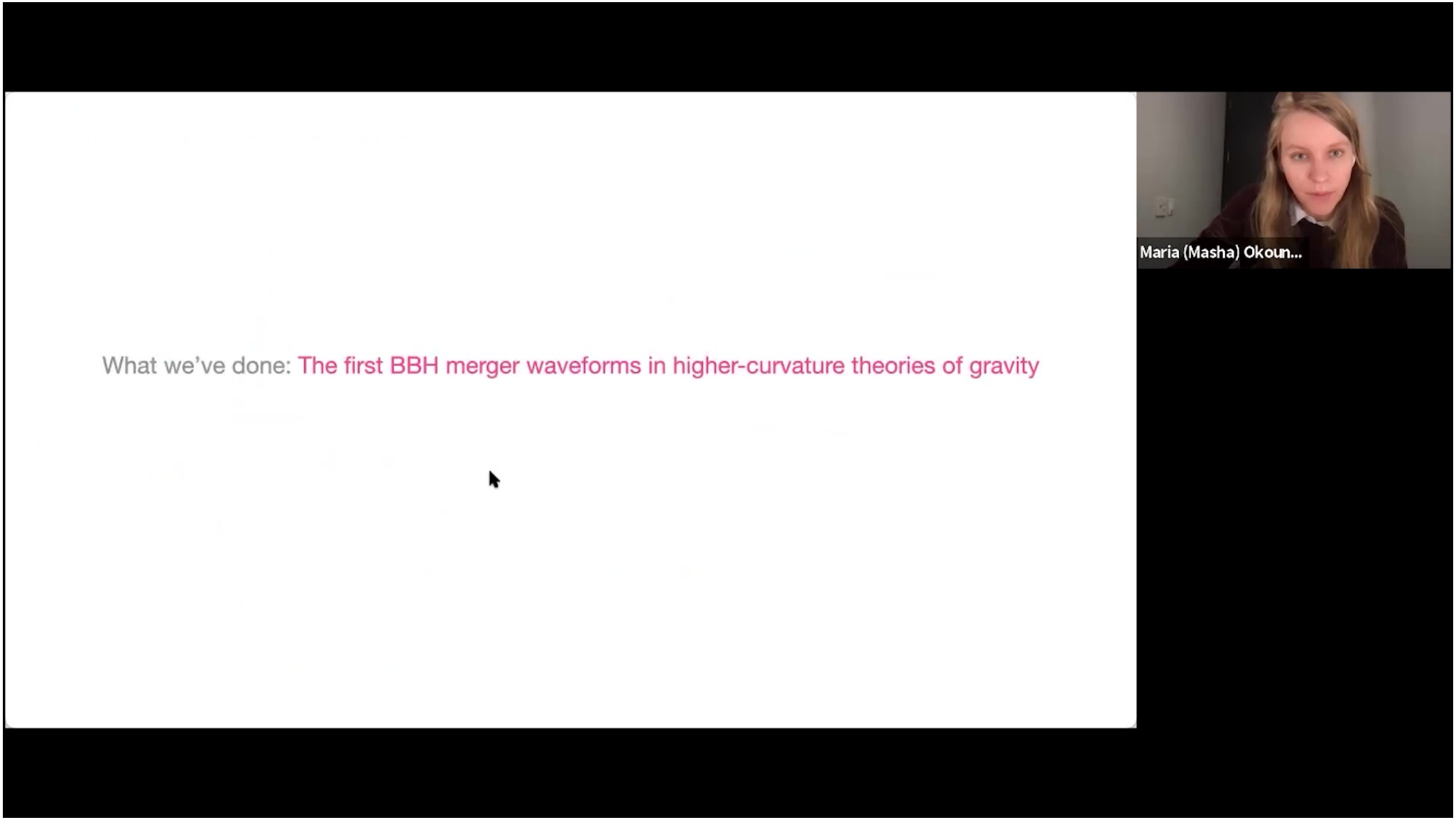
$\{M, \ell\}$

GW150914 parameters





$M = 68M_\odot$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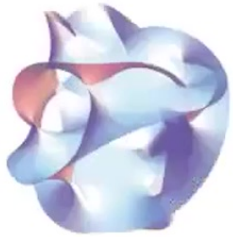

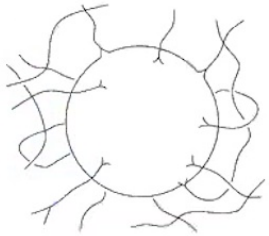

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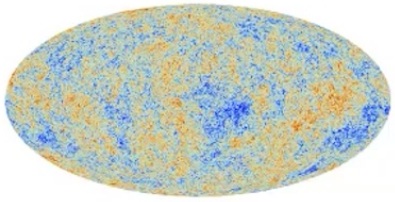

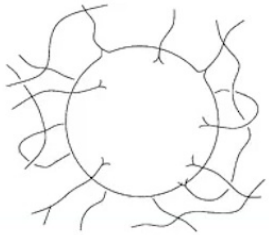

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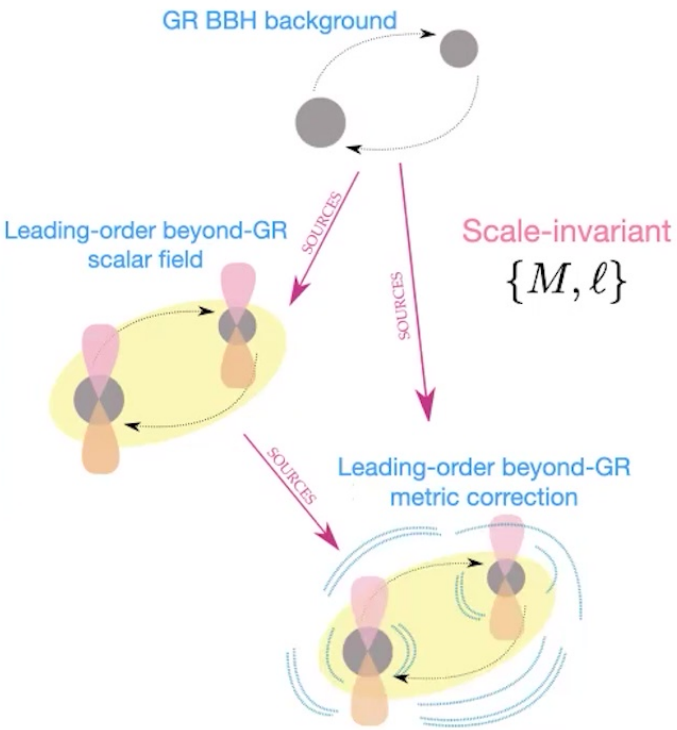

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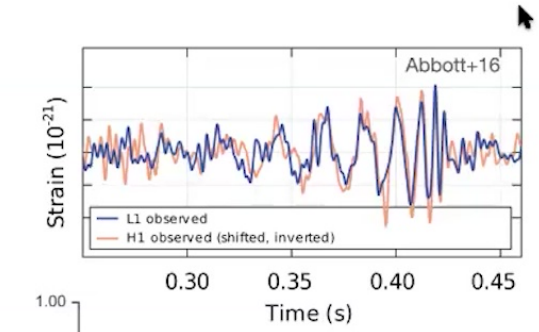
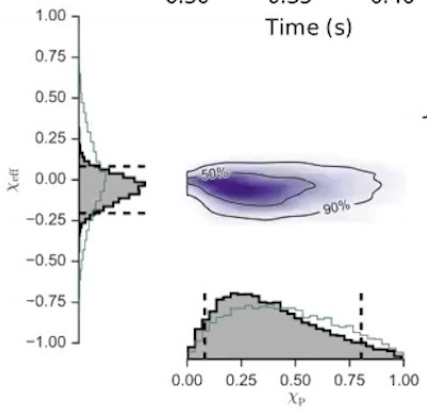
$\{M, \ell\}$

GW150914 parameters





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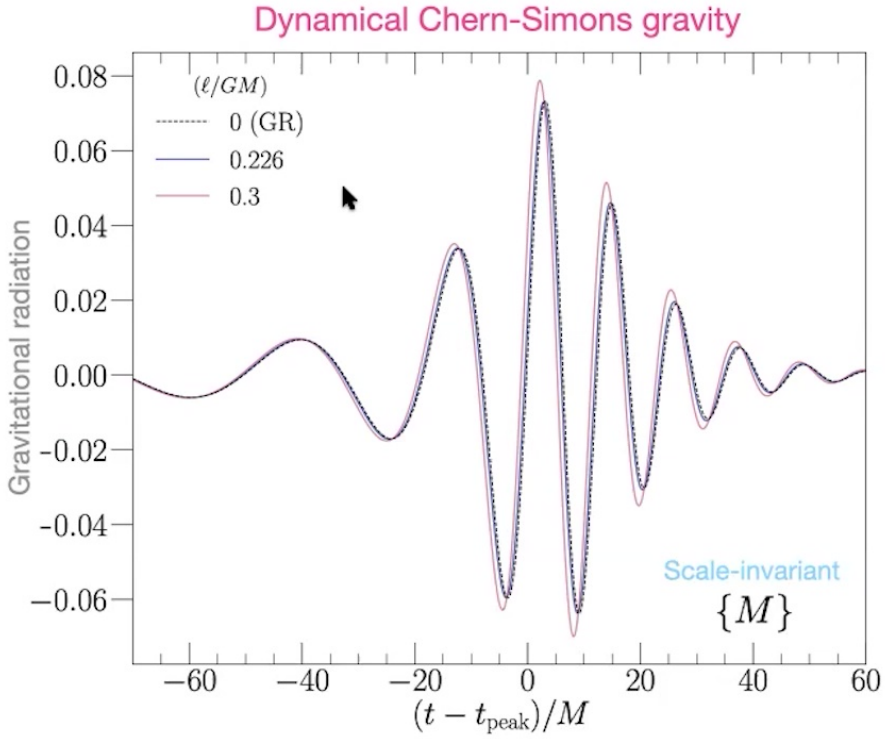
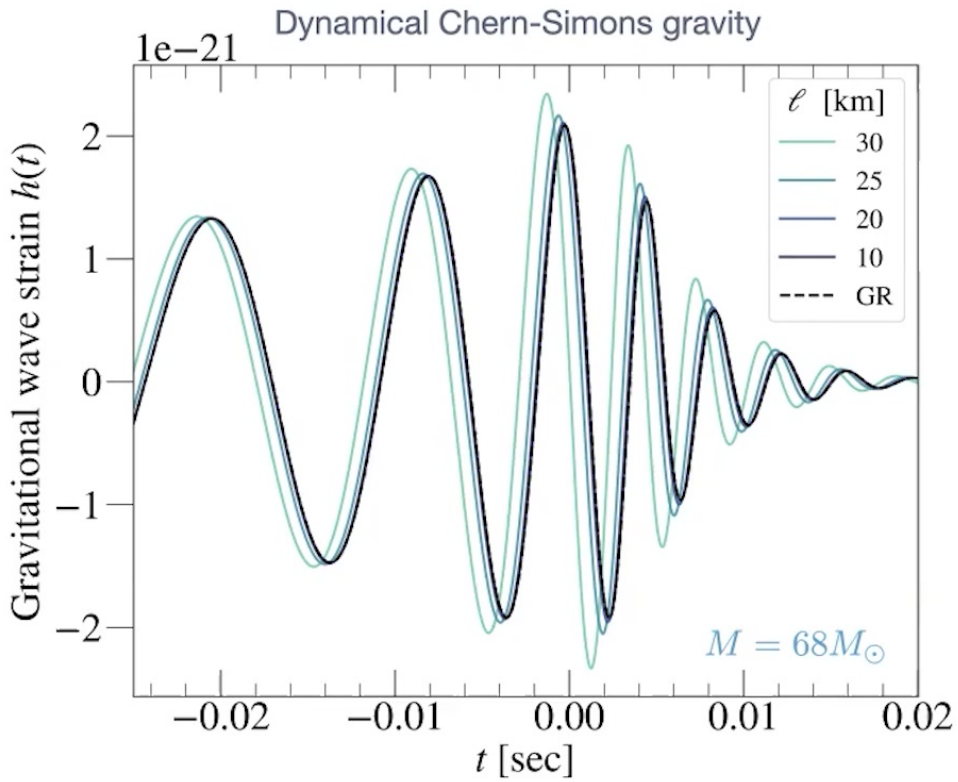
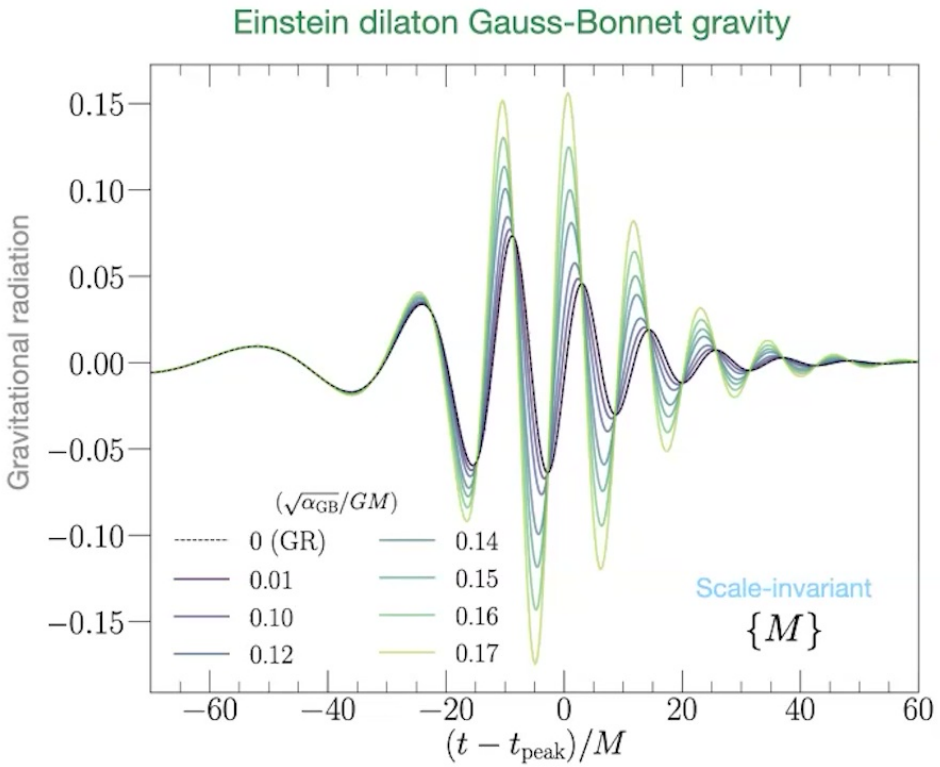
The first BBH merger waveforms in higher-curvature theories of gravity



Putting in a mass scale

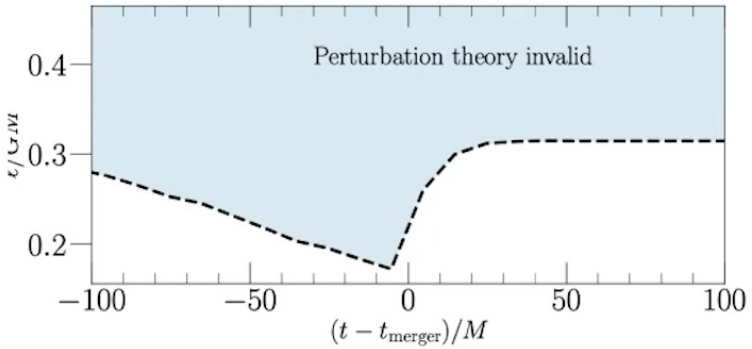


The first BBH merger waveforms in higher-curvature theories of gravity

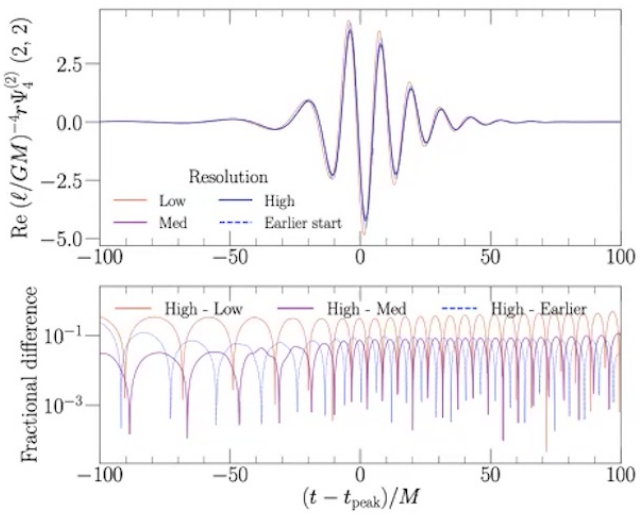


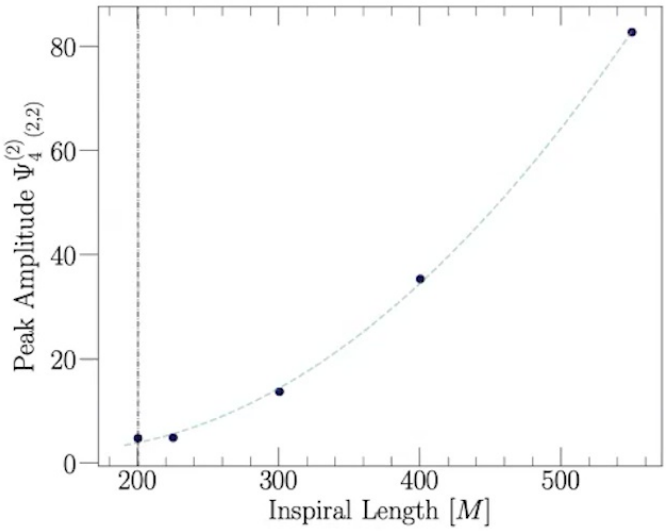
Instantaneous regime of validity

$$\left|\frac{\ell}{GM}\right|_{\max} \lesssim C^{1/4}\left(\frac{8\,\|g_{ab}\|}{\|\Delta g_{ab}\|}\right)^{1/4}_{\min}$$

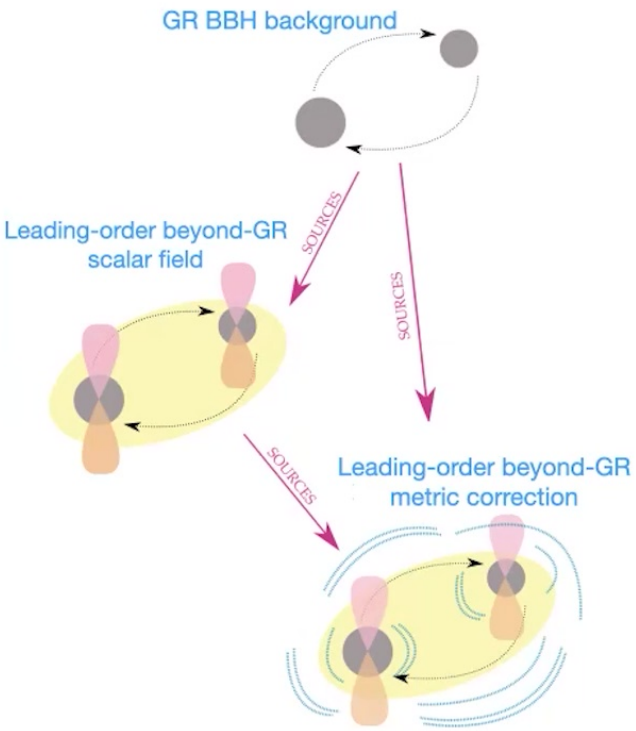


Secular regime of validity





Our method: order reduction-scheme



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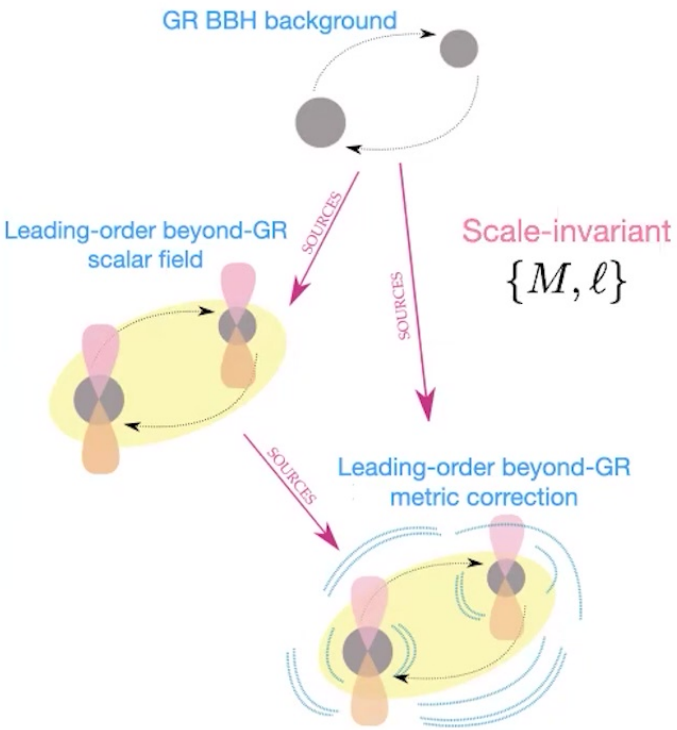

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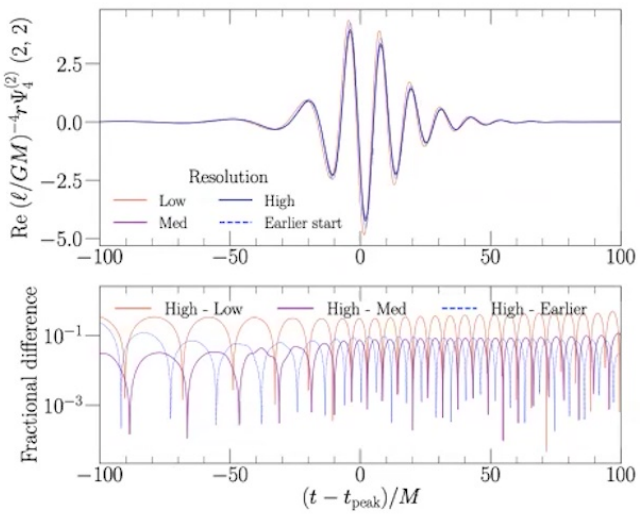
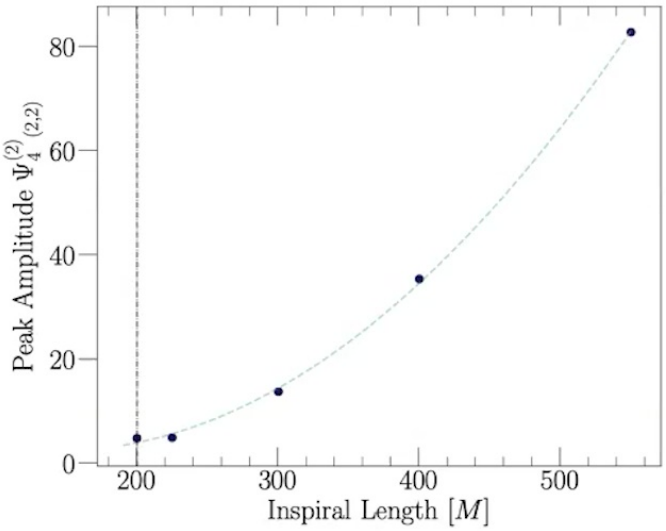
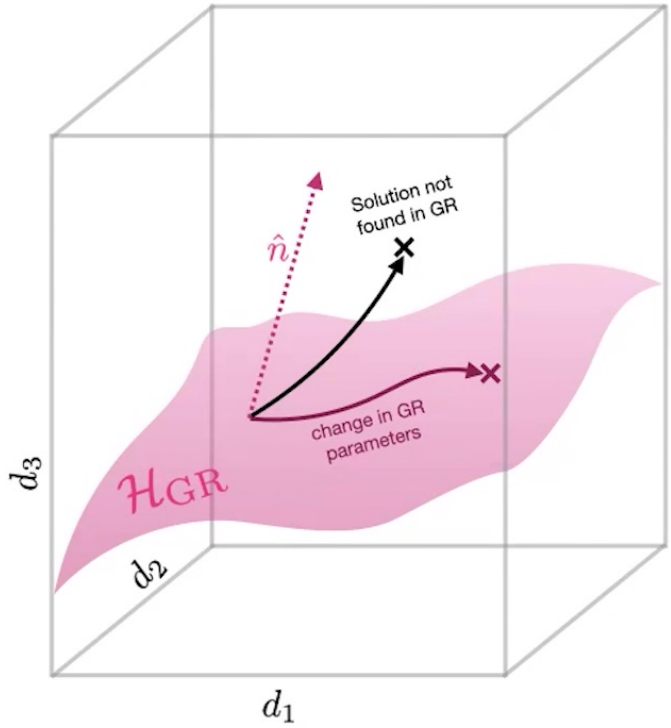
Secular regime of validity



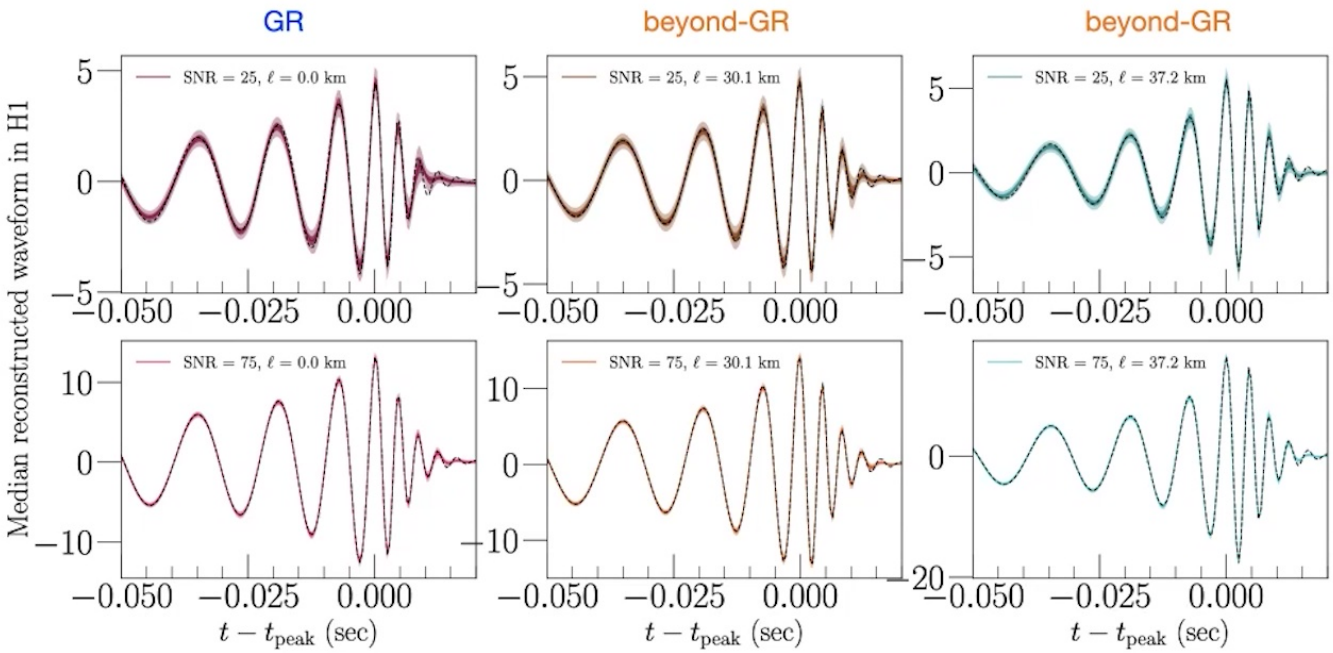


What we've learned: Degeneracy and seeing these signals in GW detectors

GR and Beyond-GR Degeneracy



Model-independent searches



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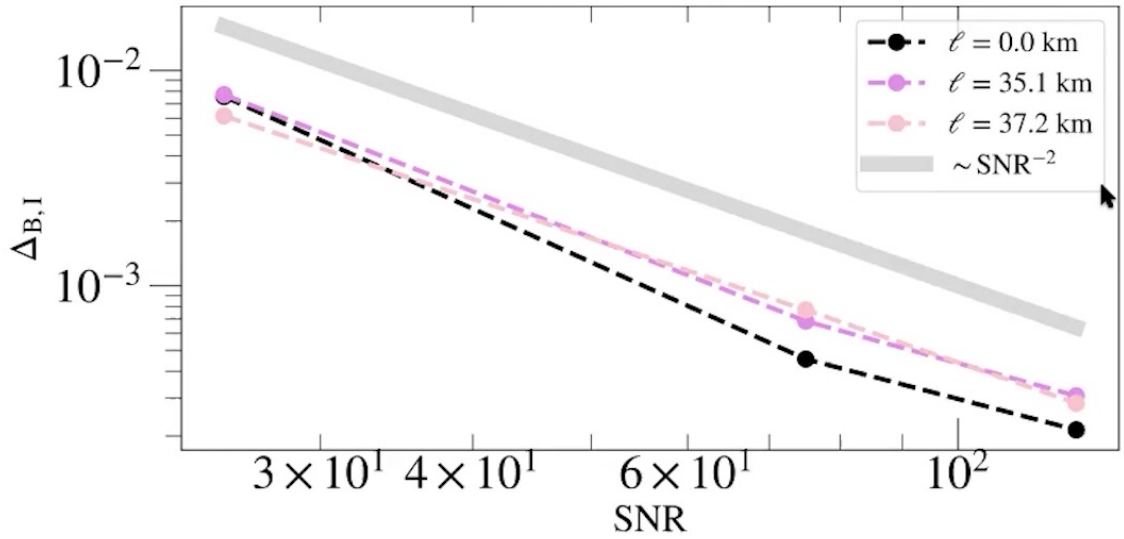
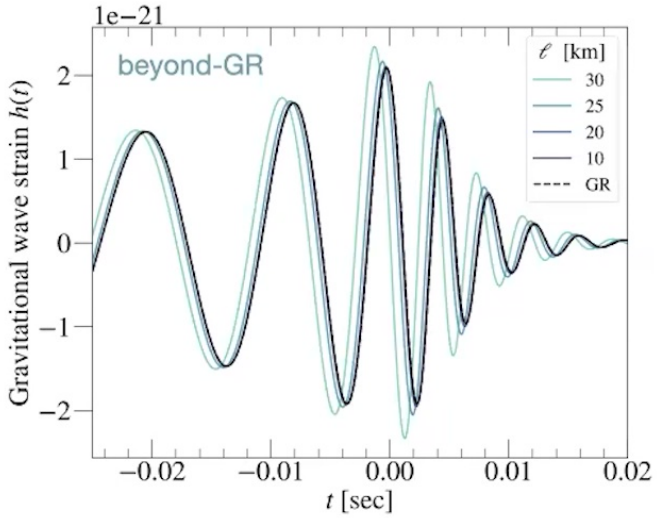


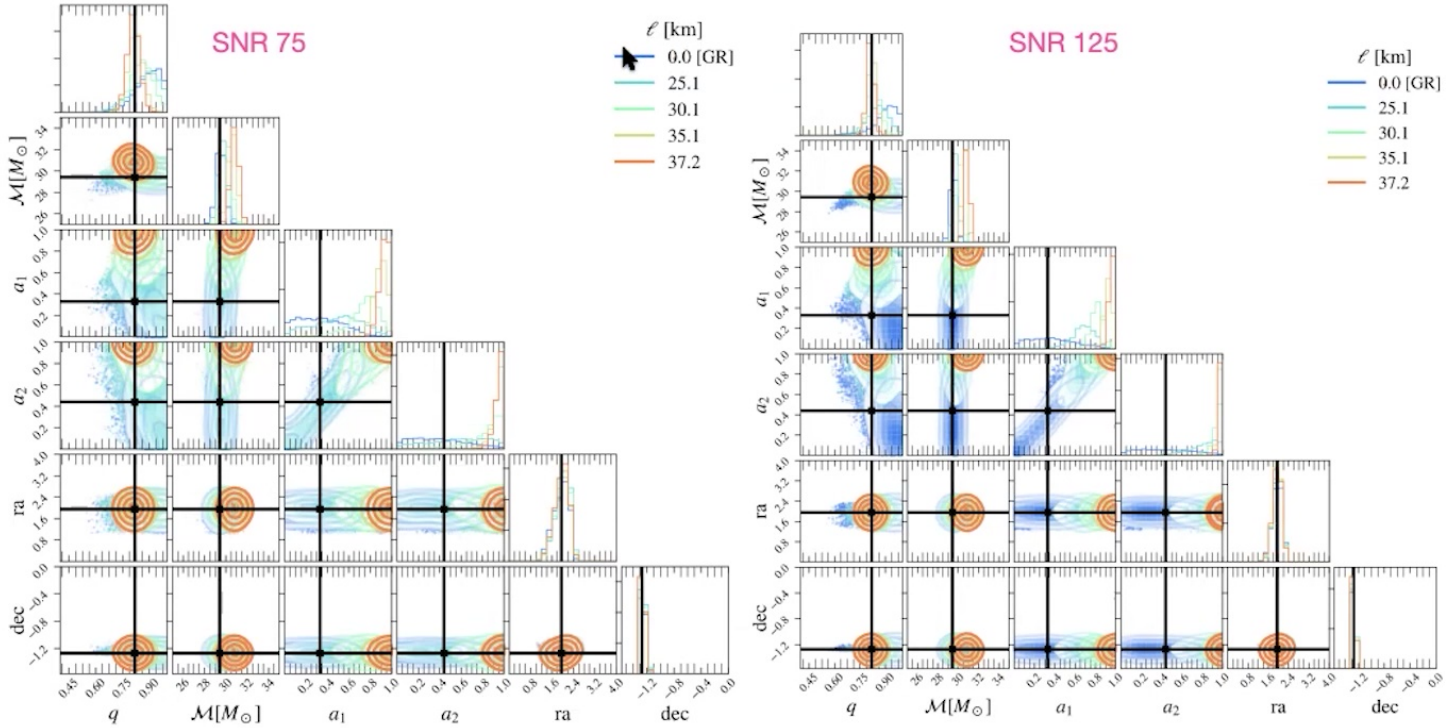
LIGO can detect and reconstruct beyond-GR signals

Model-dependent searches: Assuming GR



Parameter estimation assuming GR

Model-dependent searches: Assuming GR



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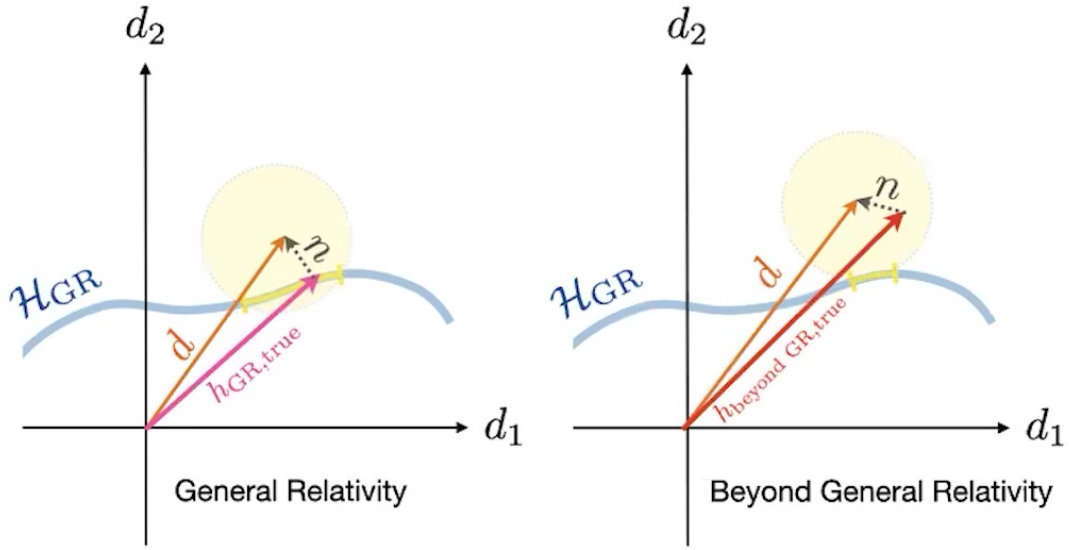

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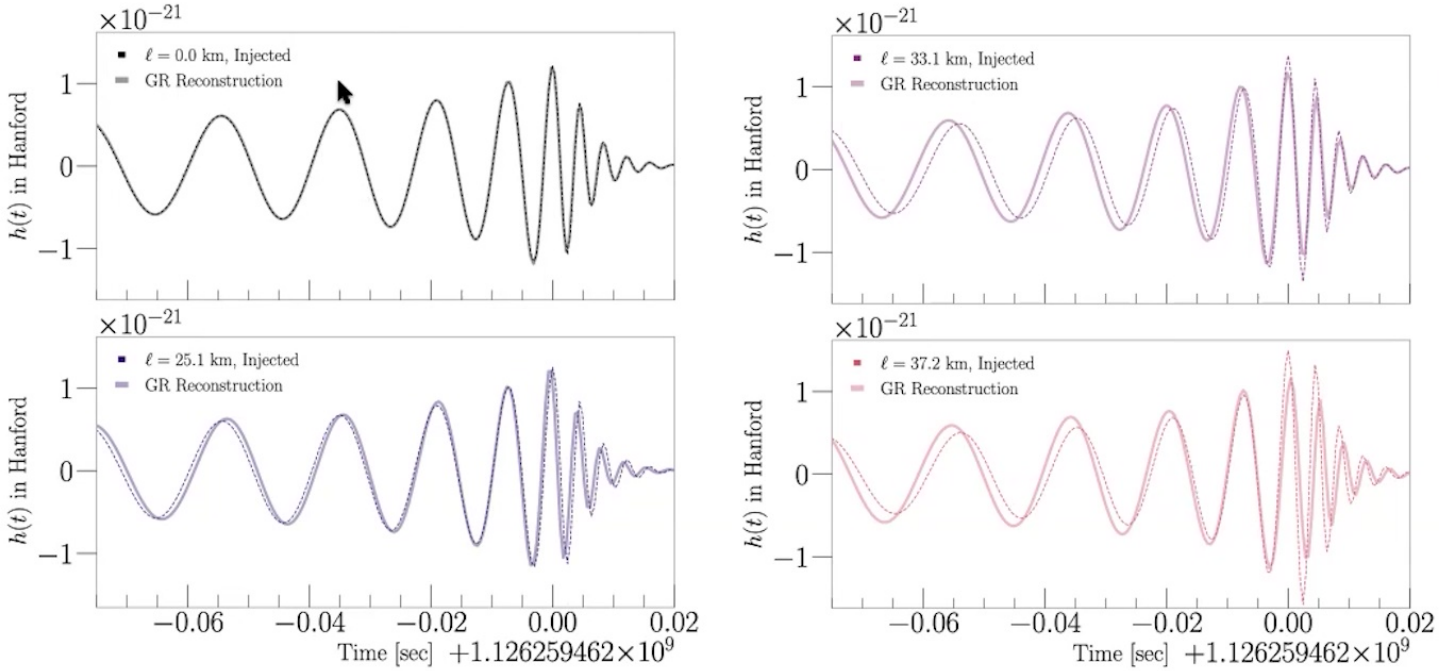
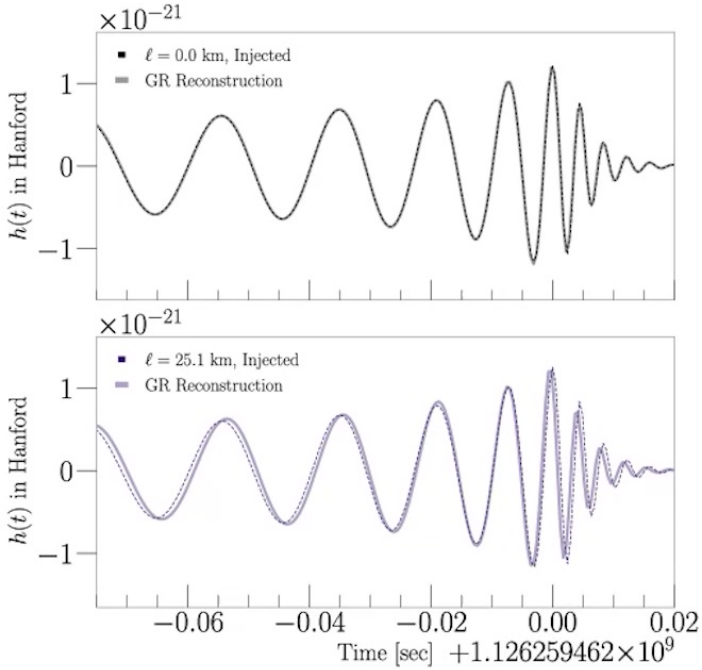
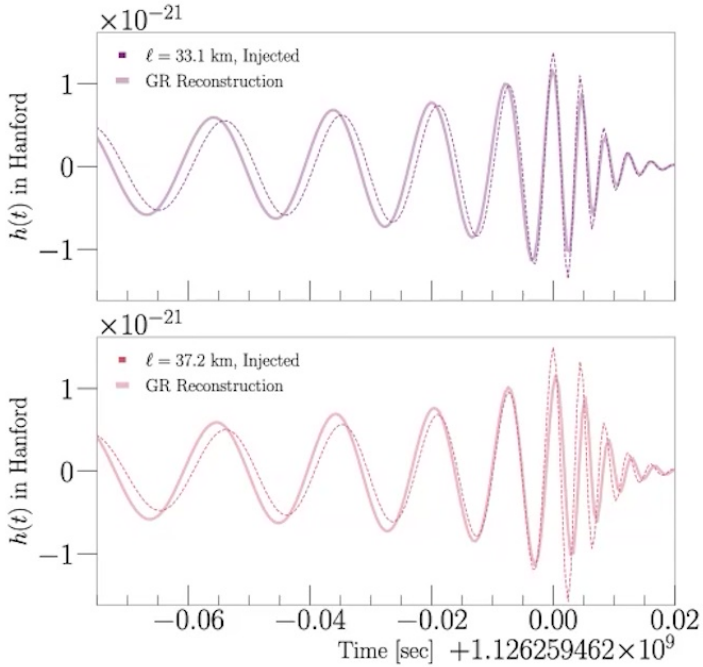
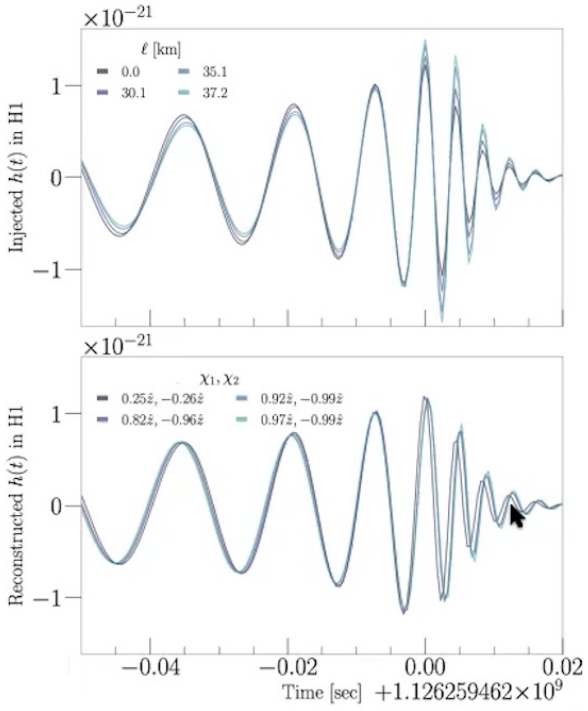


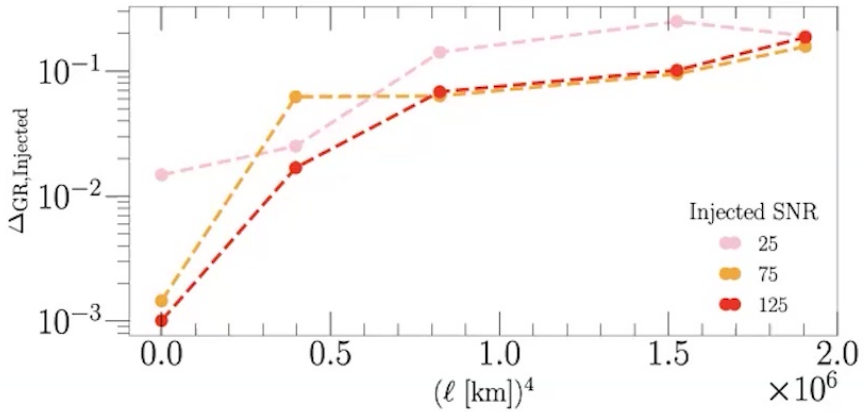
Model-dependent searches: Assuming GR

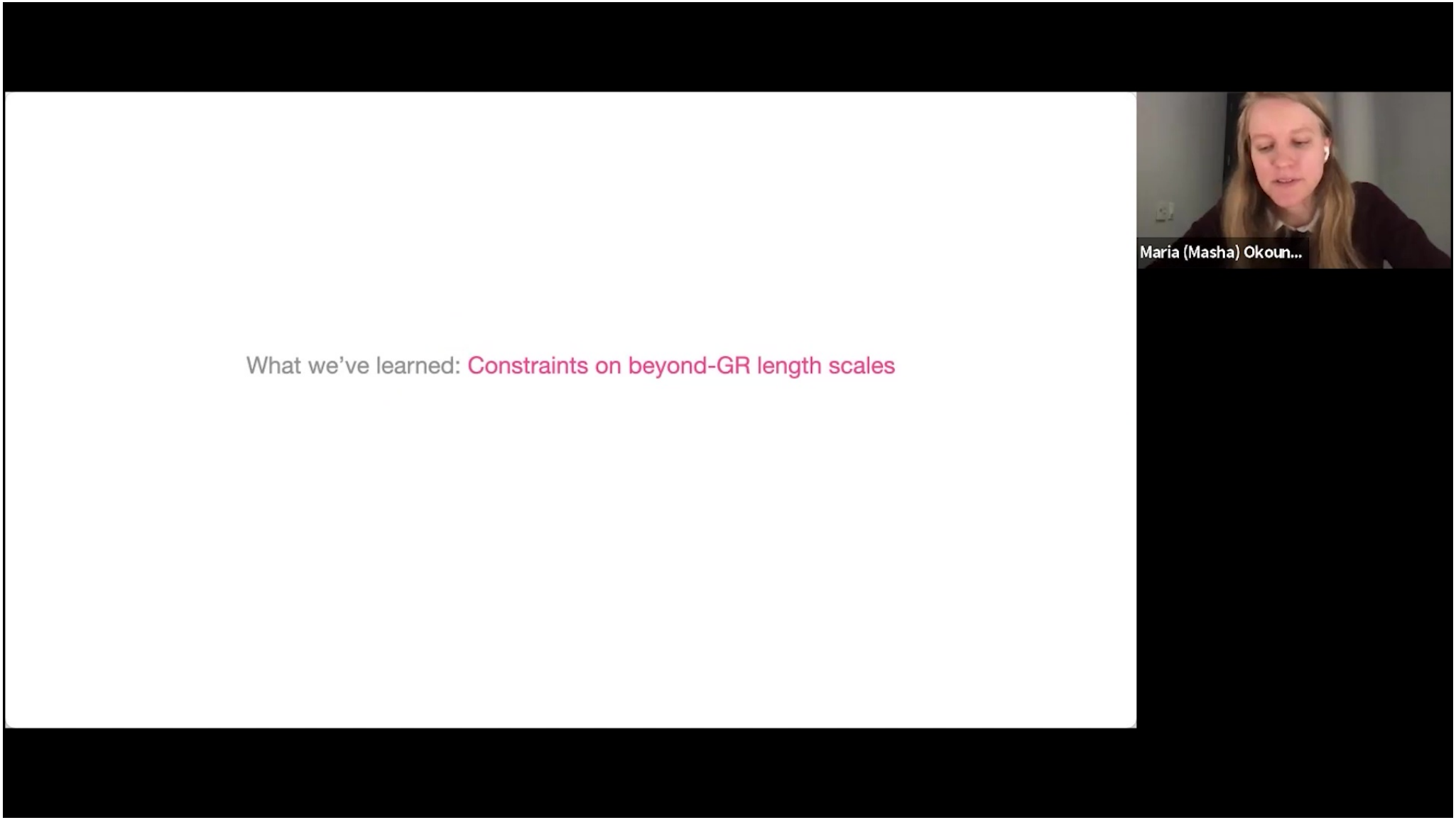




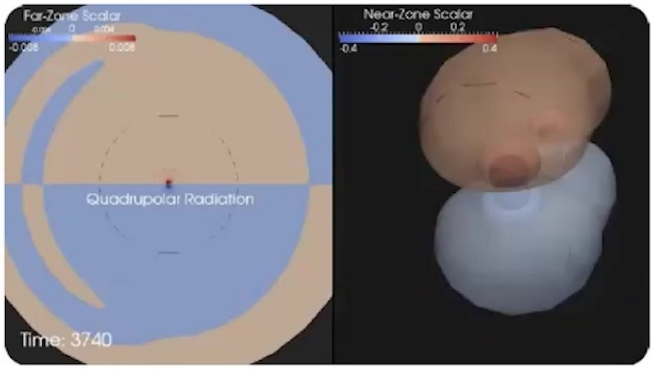
Model-dependent searches: Assuming GR






What we've learned: Constraints on beyond-GR length scales
Maria (Masha) Okoun...

Compute energy in scalar field



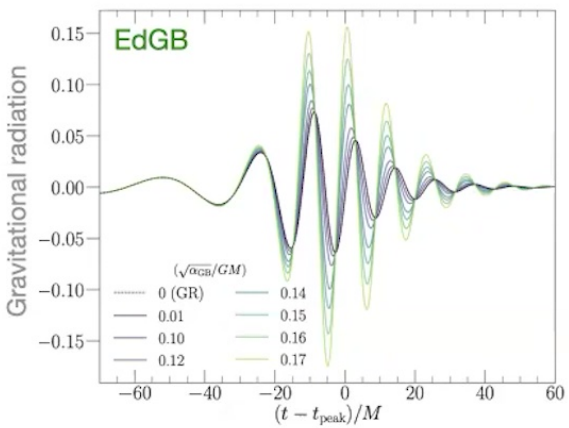
Projected bound for GW150914 parameters:

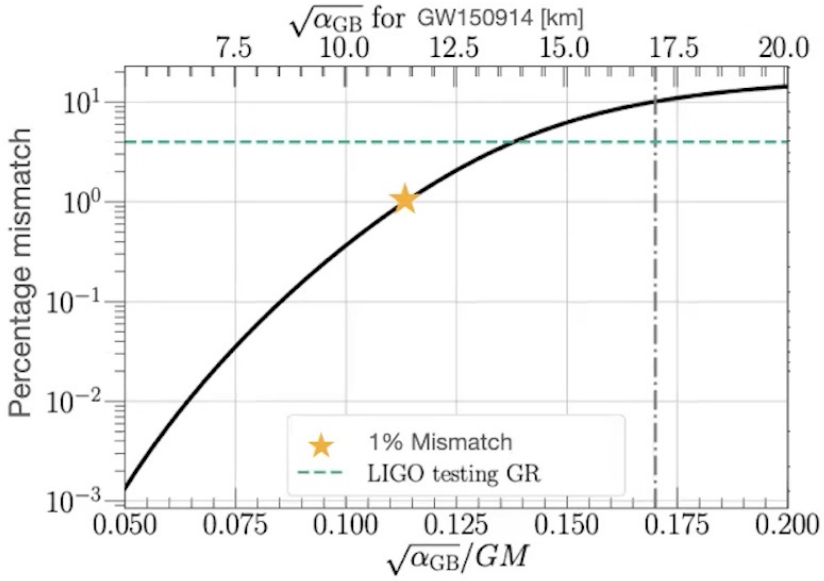
$$\ell \lesssim 11\,\mathrm{km}\left(\frac{\sigma_\phi}{0.1}\right)^{1/4}$$

Black hole horizon scale

$$\ell \lesssim 10^8\ \mathrm{km}$$

Compute mismatches

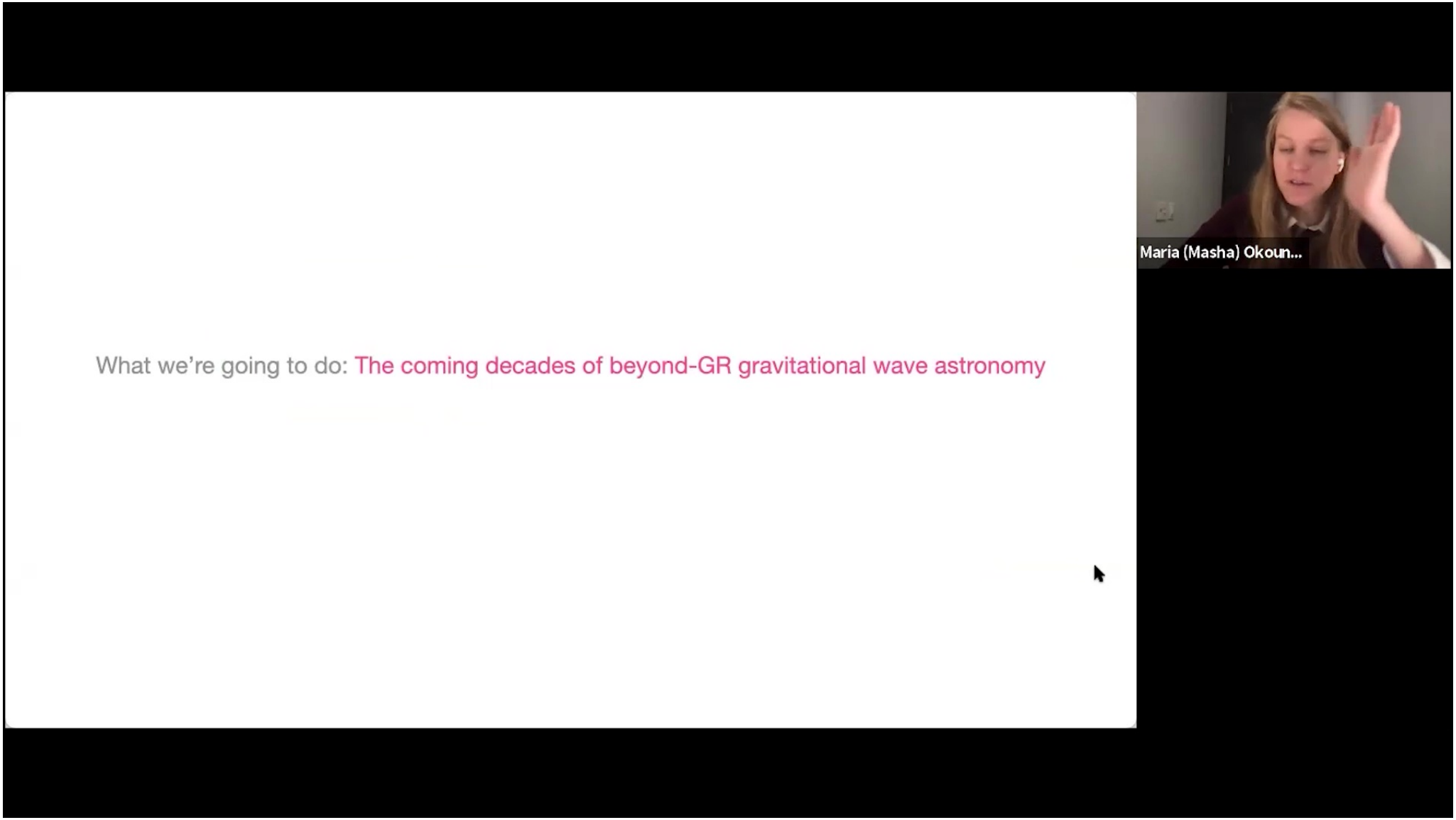




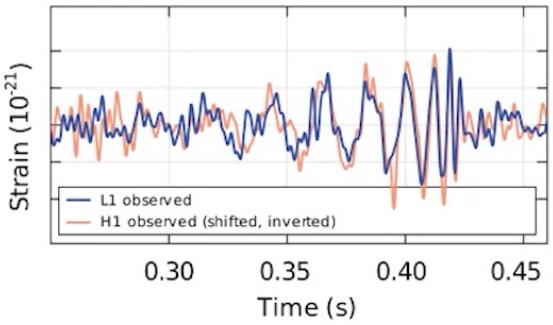
Projected bound for GW150914 parameters:

$$\sqrt{\alpha_{\rm GB}} \lesssim 11 \text{ km}$$

X-ray binary orbital decay: 10 km

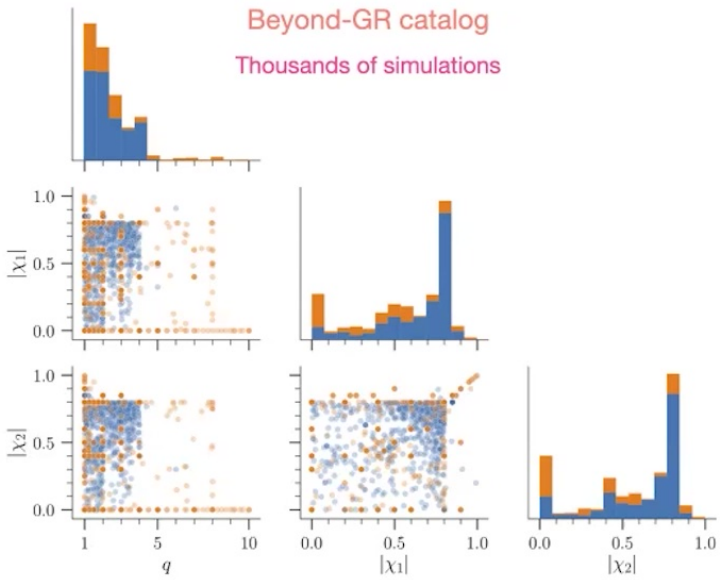

What we’re going to do: The coming decades of beyond-GR gravitational wave astronomy
Maria (Masha) Okoun...

Model-dependent tests of GR



$$\{m_1, m_2, \chi_1, \chi_2, \ell, \sqrt{a_{\rm GB}}\}$$

1. Cover BBH parameter space with simulations



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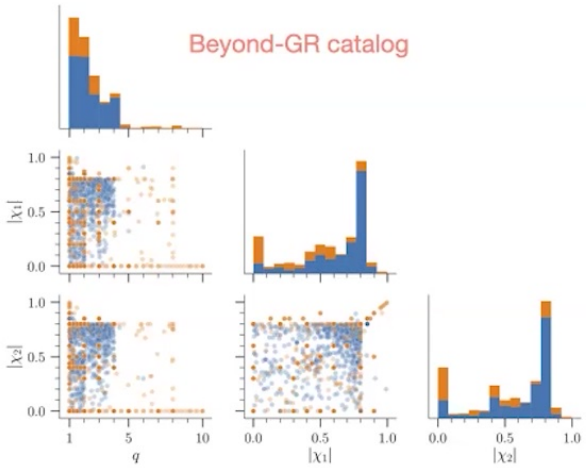
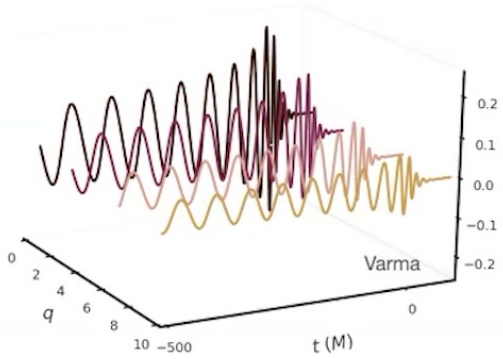


2. Beyond-GR surrogate model



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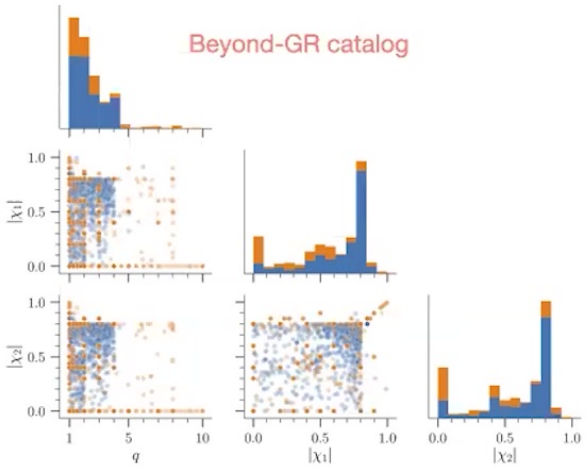

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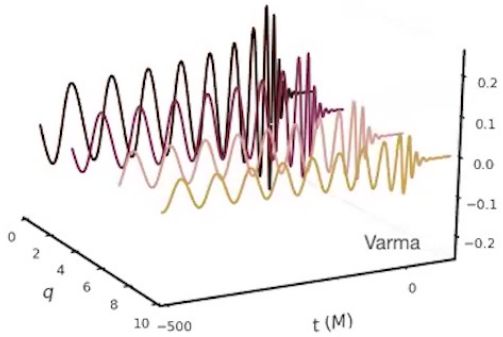
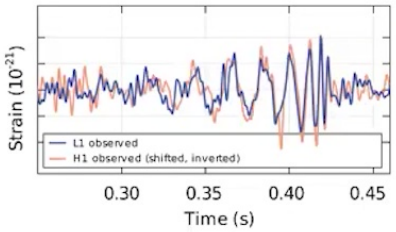
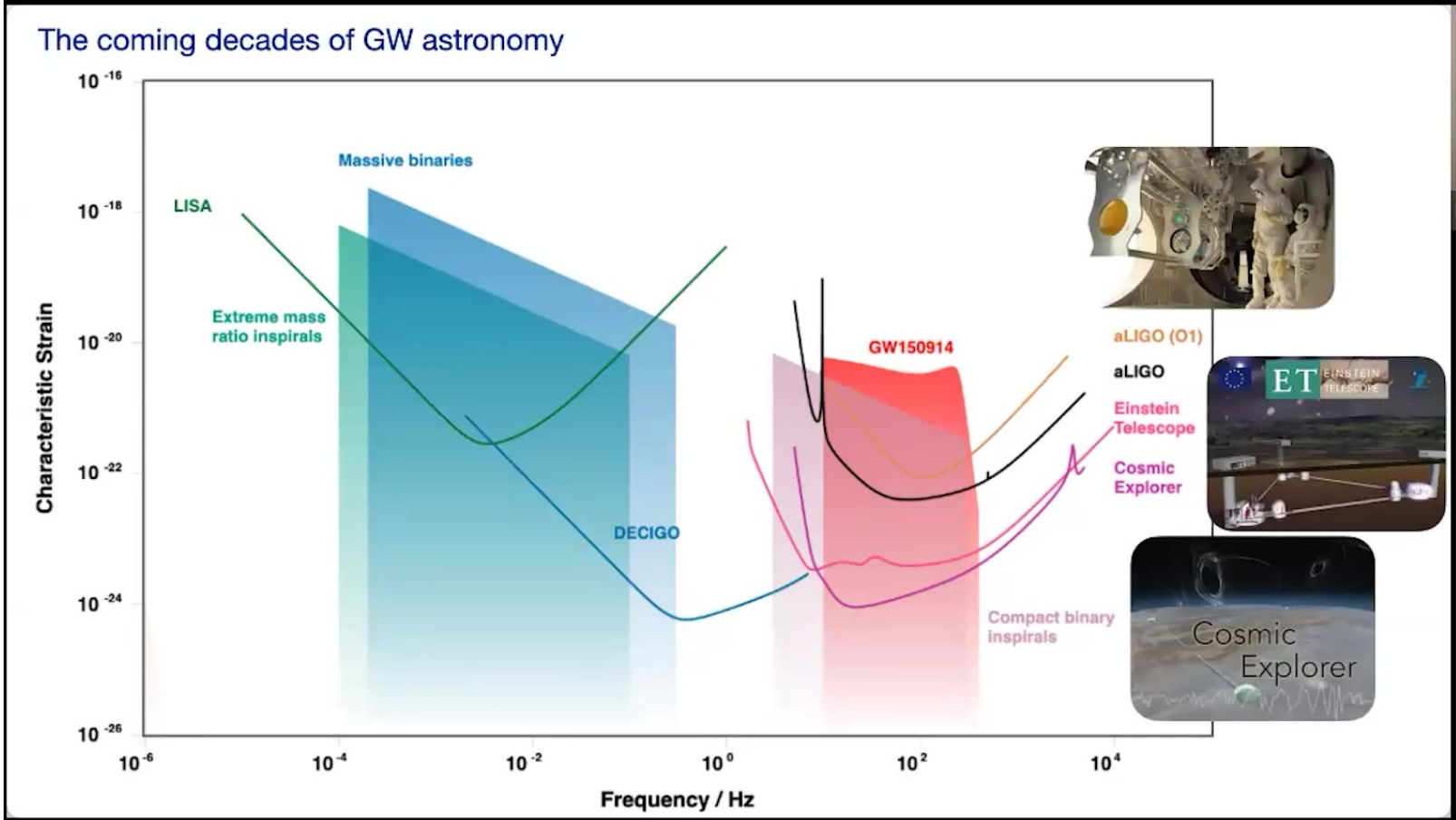


3. Beyond-GR data analysis pipeline



$$\{m_1, m_2, \chi_1, \chi_2, \ell, \sqrt{a_{\rm GB}}\}$$


The coming decades of GW astronomy
Characteristic Strain
Frequency / Hz
Massive binaries
LISA
Extreme mass ratio inspirals
DECIGO
GW150914
Compact binary inspirals
aLIGO (O1)
aLIGO
Einstein Telescope
Cosmic Explorer
ET
EINSTEIN TELESCOPE
Cosmic Explorer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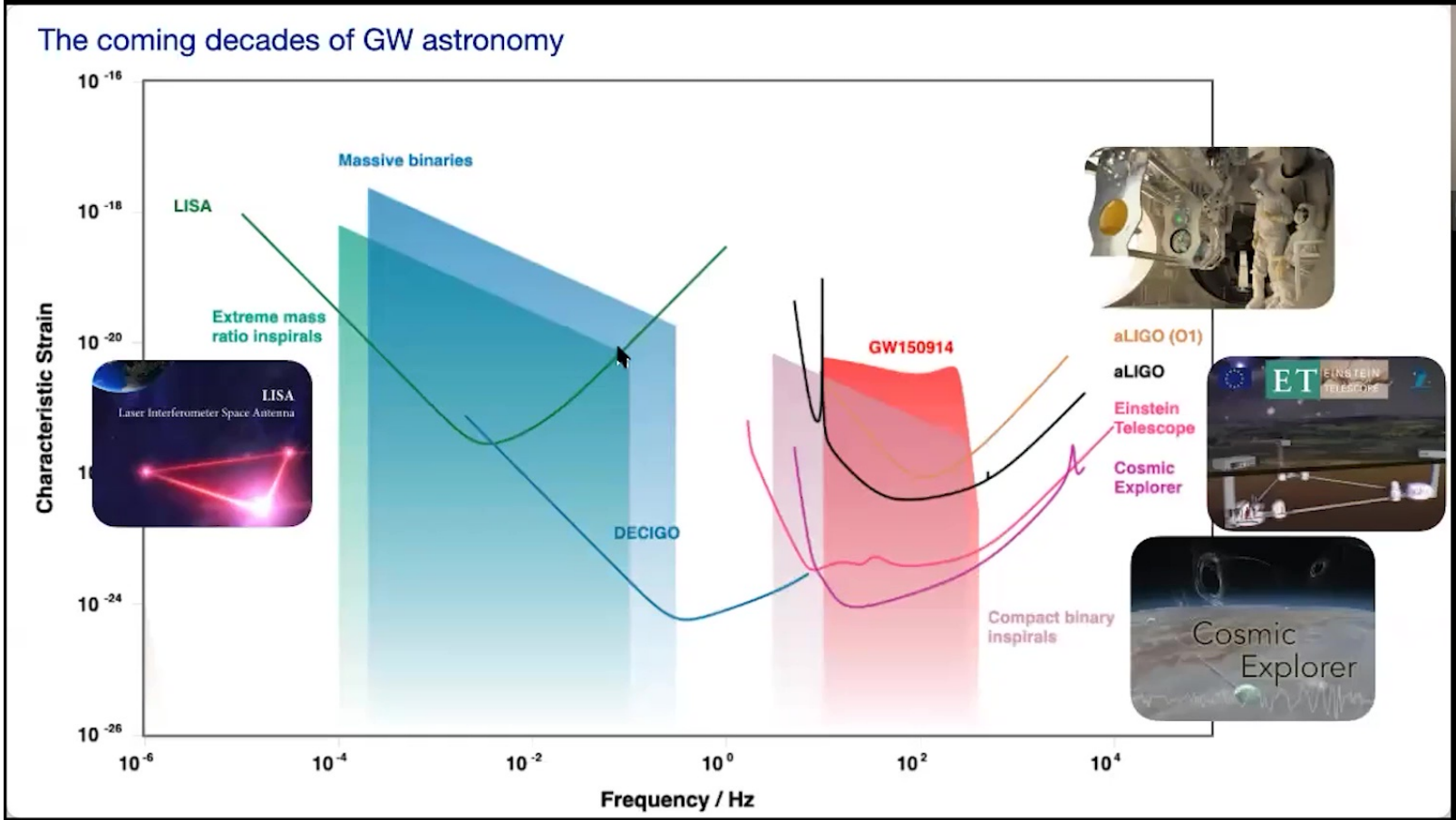
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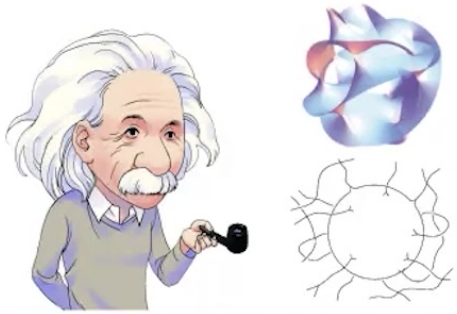
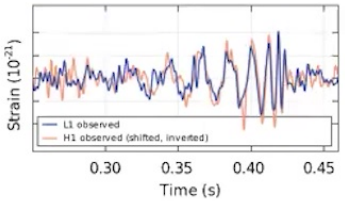
To summarize:

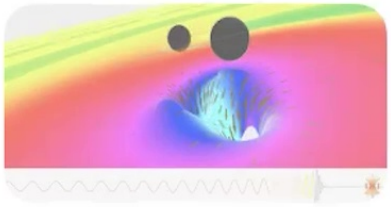


GR must break down at some scale

non-linear, dynamical,
strong-field regime of gravity

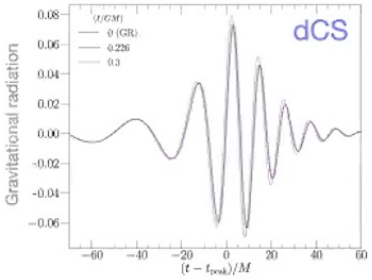


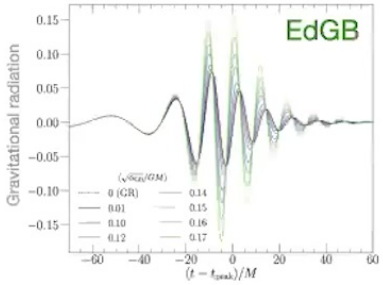
Model-dependent tests of GR



Numerical relativity
beyond general relativity

First beyond-GR merger gravitational waveforms





Coauthors + collaborators on this research effort