TIGER

A data analysis pipeline for testing general relativity using compact binary coalescence

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TIGER in short

- Test validity of GR using Bayesian model selection
  - Based on hypotheses instead of values of parameters
  - Make use of full information content
- Tailored to Advanced LIGO/Virgo
  - Suitable for low SNR
  - Moderate number of sources
- Quantify our belief in the validity of GR
  - Even in the presence of spurious effects (e.g. noise)
- Flexible in use
  - Independent of waveform family
  - Account for physical effects, e.g. spin, merger/ringdown, tidal deformation . . .

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Competing hypotheses: $\mathcal{H}_{\mathrm{GR}}$

- $\mathcal{H}_{\mathrm{GR}}$: Waveform has the form as predicted by GR
- E.g. Post-Newtonian (PN), effective one body (EOB)

Example: Testing the PN phase [1, 2]

- Phase coefficients, ψ_n, predicted by GR and depend on system's characteristics (masses, spins, …)

$$\Psi(v) = \sum_n \left[\psi_n + \psi_n^{(l)} \log\left(\frac{v}{c}\right)\right]\left(\frac{v}{c}\right)^{n-5}$$

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- Split $\mathcal{H}_{\text{modGR}}$ into testable sub-hypotheses

$$\mathcal{H}_{\text{modGR}} = \bigvee_{i_1 < i_2 < \ldots < i_k} H_{i_1 i_2 \ldots i_k} \quad (1)$$

- Define $H_{i_1 i_2 \ldots i_k}$: $\psi_{i_1}, \ldots, \psi_{i_k}$ do not have the functional dependence on the masses as predicted by GR, but all other $\psi_j, j \notin \{i_1, i_2, \ldots, i_k\}$ *do* have the dependence as in GR

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Odds ratio

- Analyse signal within stretch of data, d
- Construct the odds ratio as our figure of merit

$$O_{\rm GR}^{\rm modGR} = \frac{P(\mathcal{H}_{\rm modGR}|d,I)}{P(\mathcal{H}_{\rm GR}|d,I)} \qquad (2)$$

- $O_{\rm GR}^{\rm modGR} > 1$ favours $\mathcal{H}_{\rm modGR}$, $O_{\rm GR}^{\rm modGR} < 1$ favours $\mathcal{H}_{\rm GR}$
- Naturally allows for the combination of sources

$$\mathcal{O}_{\rm GR}^{\rm modGR} = \frac{P(\mathcal{H}_{\rm modGR}|d_1,\ldots,d_{\mathcal{N}},I)}{P(\mathcal{H}_{\rm GR}|d_1,\ldots,d_{\mathcal{N}},I)} \qquad (3)$$

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Constructing the background

- Noise can introduce false positives
- Construct a *background* by analysing GR signals in simulated noise
- Compare measured odds ratio to background to assess the *false alarm probability*

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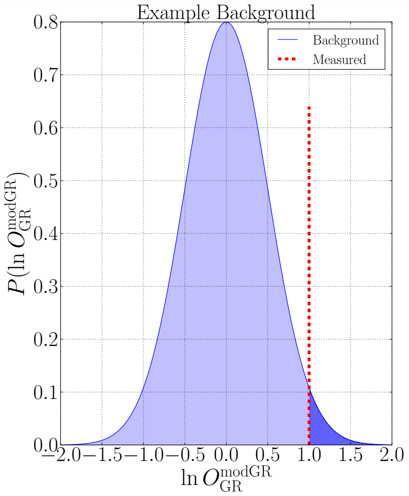
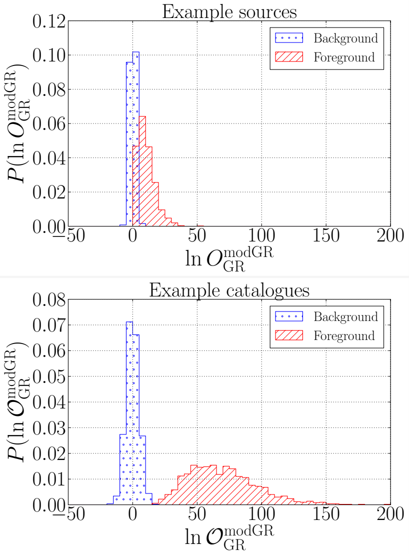


Testing TIGER (BNS)

Simulated deviations

- Test TIGER by introducing deviations to the waveforms
- Analyse many sources with the same type of deviation, *foreground*
- Compare background to foreground to asses how likely we can distinguish this type of deviation
- Combine sources to increase information



Simulation details

- Advanced LIGO/Virgo network [3, 4]
- BNS systems $M \in [1, 2]M_\odot$
- Realistic source distribution [5]
    - $D_L \in [100, 400]$Mpc
    - $SNR \in [8, 50]$
    - Uniform sky location/polarisation
- Construct background by analysing GR injections
- Construct foreground by analysing deviations

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10% deviation at 1.5PN

- `TaylorF2` templates [6]
- Introduce 10% shift at 1.5PN phase term [1]
- Top: single sources, moderate seperation
- Bottom: catalogues of 15 sources, complete seperation

Detect deviations that are included in $\mathcal{H}_{\mathrm{modGR}}$

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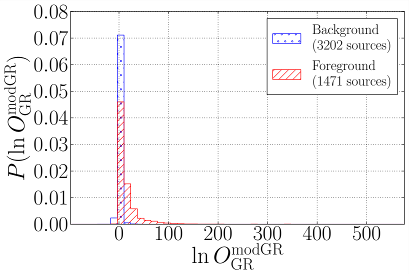

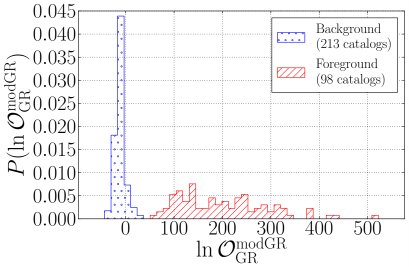

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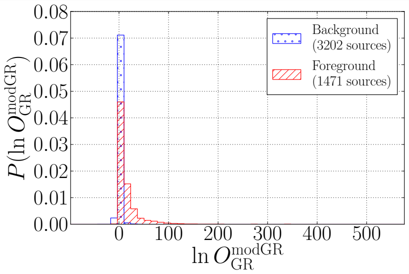

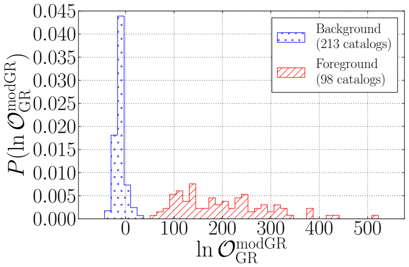

Mass dependent deviation

- `TaylorF2` templates
- Deviation of the form [2]

$$\frac{3}{128\eta}(v/c)^{-6+M/(M_{\odot})}$$

- Mass dependent power of velocity
- Fully generic, not included in $\mathcal{H}_{\mathrm{modGR}}$

Sensitive to generic deviations

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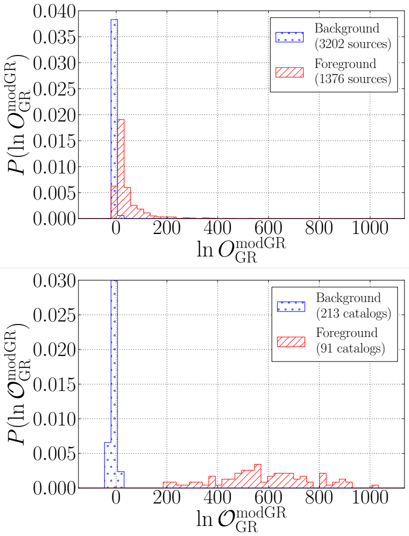

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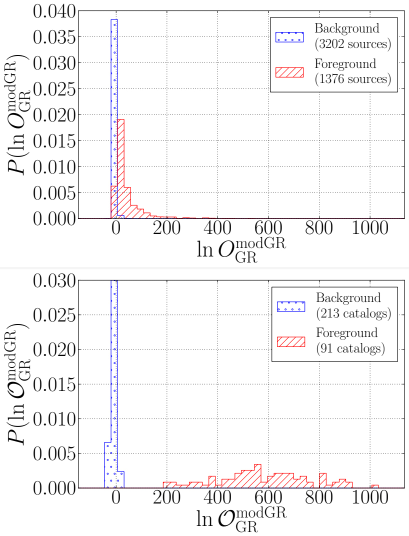

Other potential issues

Neglected physical effects can cause a perceived violation of GR

- Spin: major contributions expected from 1.5PN
  $\Rightarrow$ Include spin in the waveforms
- Tidal distortions: matter effects from 5PN, large pre-factor makes effect significant (BNS/BHNS)
- Merger/ringdown: effects beyond inspiral
  $\Rightarrow$ Introduce a frequency cut-off of 400Hz
- Calibration error: mischaracterisation of detector
  $\Rightarrow$ Construct the background with calibration errors

Spinning waveforms

- Include (anti-) aligned spins in `TaylorF2` [7]
- Dimensionless spin: Known spin frequencies, extreme assumptions on mass and radius [8] $\mathcal{N}(\mu = 0, \sigma = 0.05)$
- -10% deviation in 1.5PN

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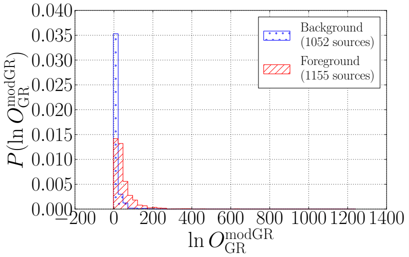

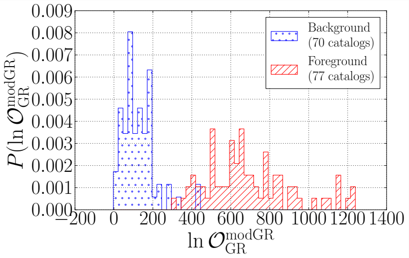

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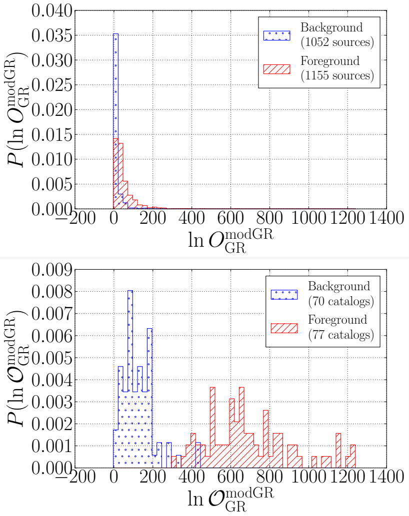

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Upper frequency cut-off

- `TaylorF2` templates
- Upper cut-off $f = 400\text{Hz}$
  - Merger/ringdown
  - Matter effects [9]
- Bulk SNR from $< 400\text{Hz}$
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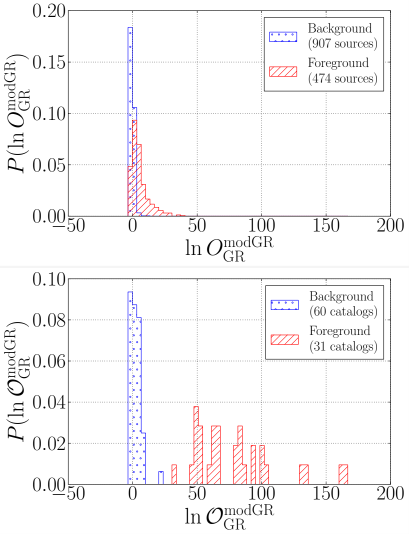

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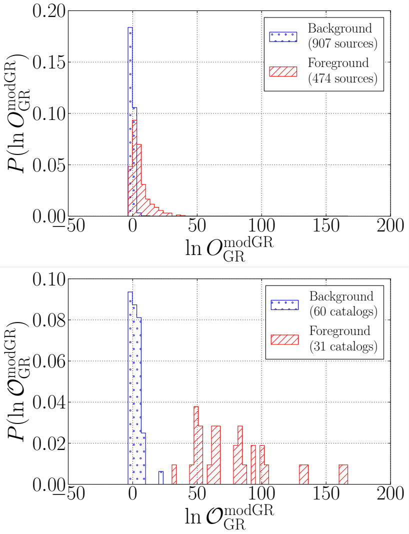

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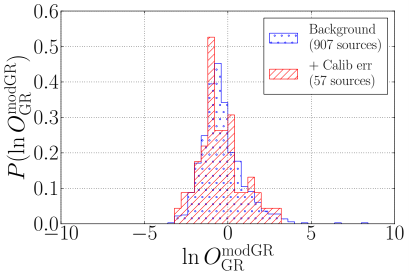

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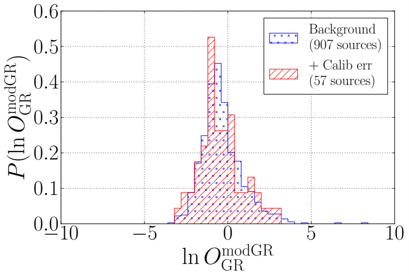

Testing TIGER (BBH)

Merger/ringdown

- `IMRPhenomB` templates [13]
- BBH, $M \in [5, 15] M_\odot$
- $D_L \in [300, 1250]$
- 0.5% deviation in 3PN
- Merger/ringdown provides better precision

Merger/ringdown potential region for additional tests

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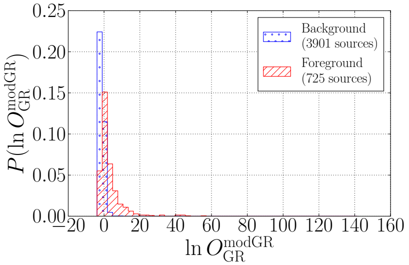

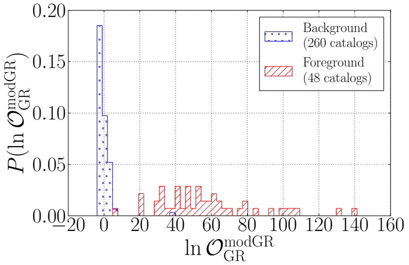

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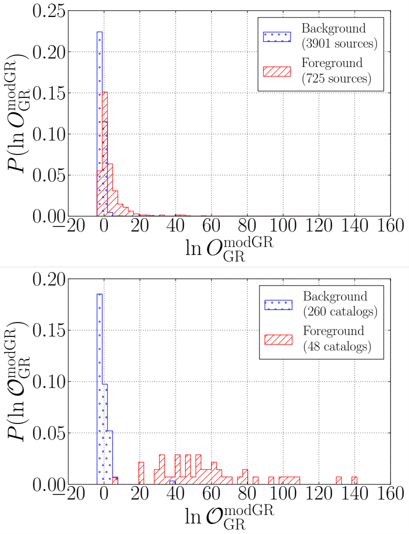

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Join the effort!

Weekly telecons - Thursday
5pm CET / 11am EST / 8am PST