Gravitational-wave constraints on an Effective-Field-Theory extension of GR

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EFT extension of GR

Endlich, Gorbenko, Huang & Senatore, JHEP 1709 (2017) 122

- Stellar-mass binaries probe curvature scales up to ~ km^{-2}.
- Extensions of GR at these energy scales **may be testable by LIGO/Virgo.**
- What is the most generic, and not yet constrained at those scales, EFT extension of the pure-gravity sector of GR (i.e. in vacuum and no extra DoF)?

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Locality+causality+diffeomorphism invariance + no new fields
$\Longrightarrow$ all operators can be constructed from $R_{\mu\nu\rho\sigma}$ (via field redefinitions)

$$S_{\rm eff} = 2M_{\rm pl}^2 \int d^4x\sqrt{-g}\left(-R + \frac{\mathcal{C}^2}{\Lambda^6} + \frac{\tilde{\mathcal{C}}^2}{\tilde{\Lambda}^6} + \frac{\tilde{\mathcal{C}}\mathcal{C}}{\Lambda_-^6} + \dots\right)$$

$$\mathcal{C} \equiv R_{\alpha\beta\gamma\delta}R^{\alpha\beta\gamma\delta}, \quad \tilde{\mathcal{C}} \equiv R_{\alpha\beta\gamma\delta}\,\epsilon^{\alpha\beta}{}_{\mu\nu}\,R^{\mu\nu\gamma\delta}$$

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Soft UV completion

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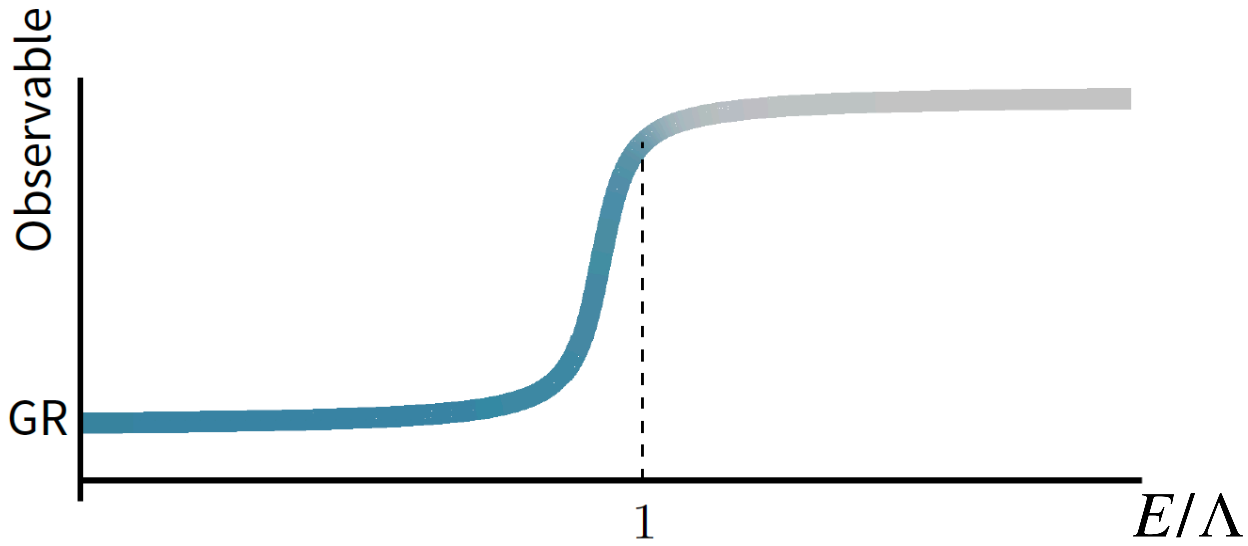
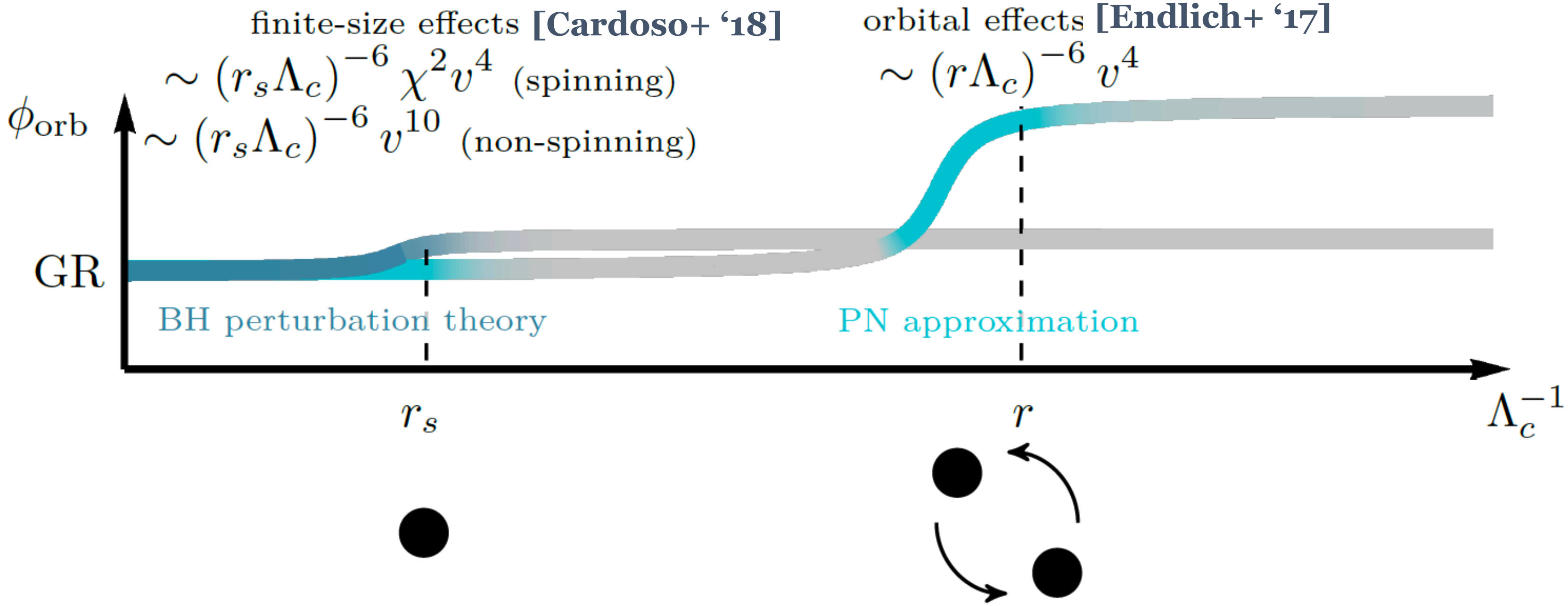
- No new physics seen at km scales… but EFT is still unconstrained if we assume a ***soft UV completion***: interactions suppressed by Λ stop growing with energy at energies above the cutoff scale

- Experiments in small curvature environments ($|R_{\mu\nu\rho\sigma}| \ll 1$) insensitive to deviations from GR within this assumption.



Impact on inspiraling binaries



- For $r_s \approx M \lesssim \Lambda_c^{-1}$ finite-size effects cannot be computed explicitly, but soft UV completion ensures that these effects saturate at $r_s \sim \Lambda_c$.
- Orbital effects can still be explicitly computed with post-Newtonian approximation ($M/r \sim v^2 \ll 1$) in the regime $r > \Lambda_c^{-1}$.
- At large orbital separations orbital effects give the most important corrections.

Restricting to the EFT regime

- EFT orbital correction is only computed in the perturbative regime ($r > d_\Lambda \equiv \Lambda^{-1}$).
- Extrapolating prediction outside of this regime can bias our analyses - *we restrict our attention to the parameter space in which the EFT calculations are valid*
- EFT orbital corrections expected to be valid up to:

$$f_{\rm high} \approx \# f_\Lambda \text{ equivalent to } r_{\rm min} \approx \# d_\Lambda \qquad (f_\Lambda \equiv M^{1/2} d_\Lambda^{-3/2} / \pi)$$

- Requiring EFT corrections to be at most of the order of the GR contribution gives $f_{\rm high} \approx 0.35 f_\Lambda$.
- Calculations only valid in the PN regime: use an inspiral-only waveform and focus on two low-mass signals from LIGO/Virgo's O1 and O2 run: **GW151226** and **GW170608**.

Constraining Λ with LIGO/Virgo

❖ Apply Bayesian methods to discriminate between two hypotheses:

1. EFTGR: $\Lambda = \Lambda_* \quad (d_\Lambda = d_{\Lambda *})$
2. GR: $\Lambda \to \infty \quad (d_\Lambda = 0)$

Bayes Factor

Prior odds

$$\mathcal{O}^{\rm EFTGR}_{\rm GR} = \frac{P(d\,|\,{\rm EFTGR})}{P(d\,|\,{\rm GR})}\frac{P({\rm EFTGR})}{P({\rm GR})} = {\rm BF}^{\rm EFTGR}_{\rm GR} \times \frac{P({\rm EFTGR})}{P({\rm GR})} \approx {\rm BF}^{\rm EFTGR}_{\rm GR}$$

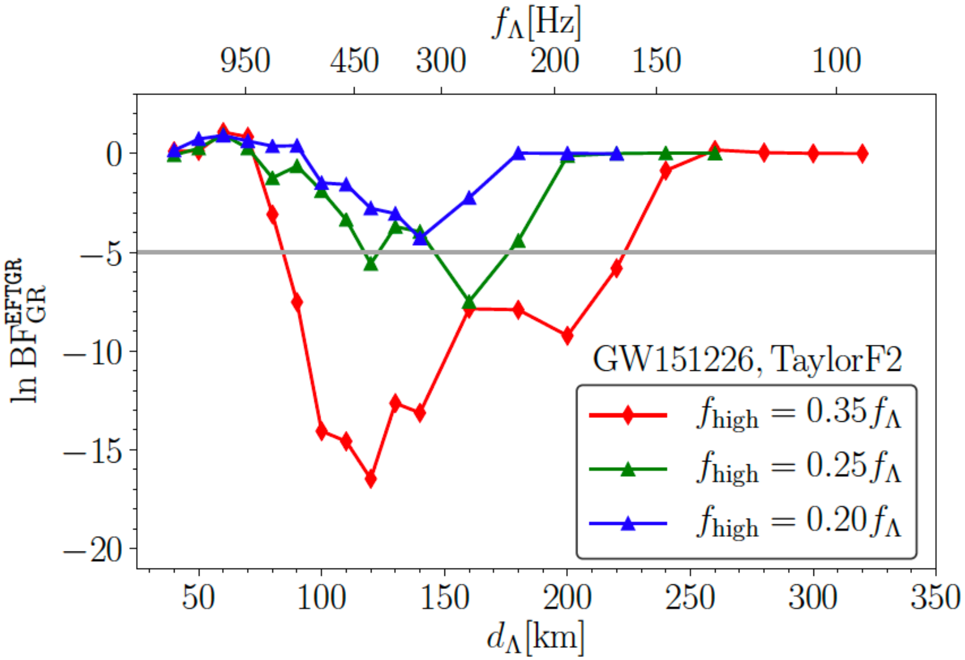
${\rm BF}^{\rm EFTGR}_{\rm GR} < 1 \implies$ GR preferred over EFTGR

${\rm BF}^{\rm EFTGR}_{\rm GR} \lesssim 1/100 \implies$ decisive "preference" of GR over EFTGR

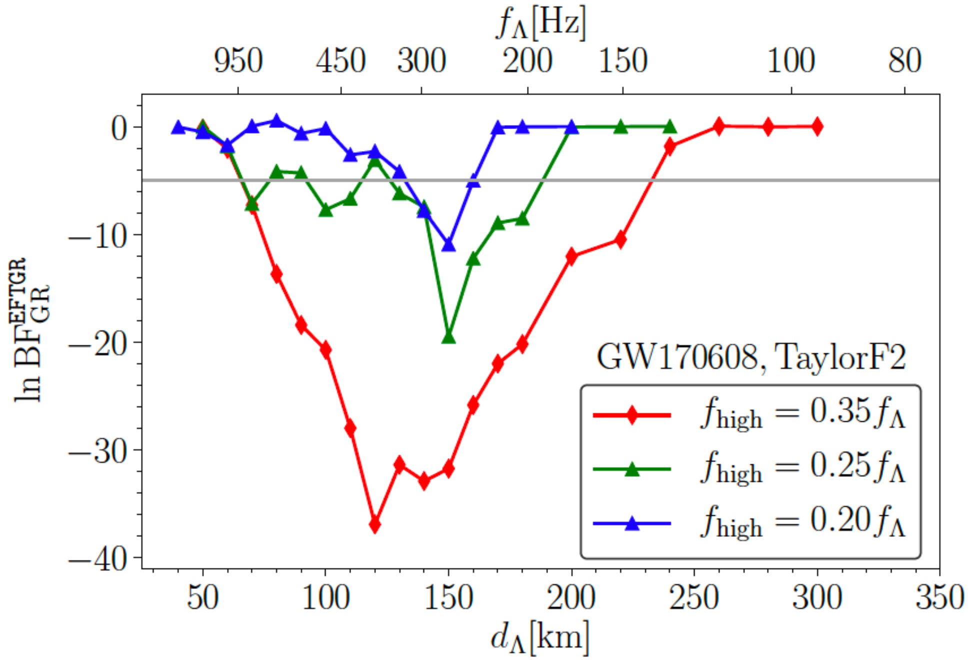
[Jeffreys, '39]

Results from individual events

GW151226



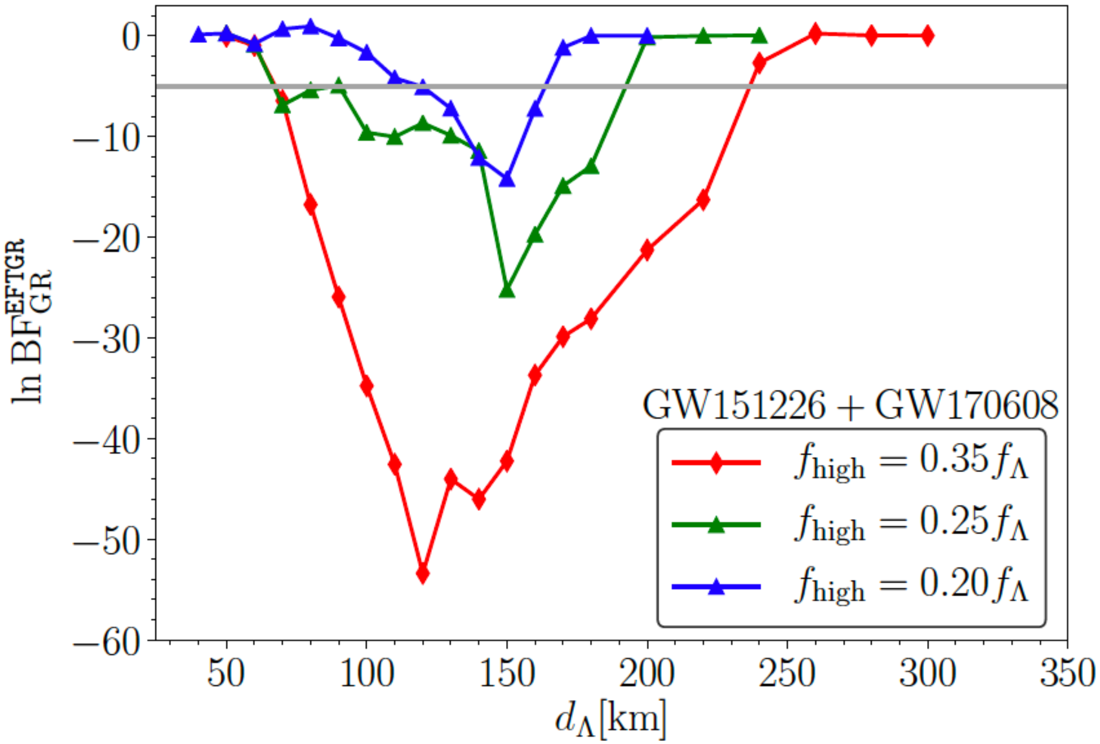
GW170608



Event	d_Λ [km]		
	$f_{\mathrm{high}} = 0.2 f_\Lambda$	$f_{\mathrm{high}} = 0.25 f_\Lambda$	$f_{\mathrm{high}} = 0.35 f_\Lambda$
GW151226	–	$\sim [125, 175]$	$\sim [85, 225]$
GW170608	$\sim [135, 160]$	$\sim [65, 190]$	$\sim [65, 230]$

Combining events

For N independent events with unrelated parameters: $\mathrm{BF}^{\mathrm{EFT}}_{\mathrm{GR}} = \prod_{k=1}^{N} {}^{(k)}\mathrm{BF}^{\mathrm{EFT}}_{\mathrm{GR}}$



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GW170608	$\sim [135, 160]$	$\sim [65, 190]$	$\sim [65, 230]$
Combined	$\sim [120, 165]$	$\sim [65, 190]$	$\sim [65, 235]$

Conclusions

- Current gravitational-wave observations can constrain higher-order curvature terms entering on scales $\sim [70, 200]$ km.
- Bounds from multiple events can be combined straightforwardly; future detections will continue to improve constraints.

Thank you!

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MARIE CURIE ACTIONS