

GdR Ondes Gravitationnelles - AG 2020

Testing spacetime birefringence with gravitational waves

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The Standard Model Extension (SME) framework

► A framework to probe new physics:

- The SME contains a Lagrangian description of new physics
- Effective field theory originally developed to extend the Standard Model
- New physics are new fields added to the Lagrangian
- Extensive constraints on new fields from the particle physics sector

Colladay &
Kostelecky
[arxiv:9809521](https://arxiv.org/abs/9809521)

Kostelecky
& Russell
[arxiv:0801.0287](https://arxiv.org/abs/0801.0287)

$$\mathcal{L}_{SME} = \mathcal{L}_{SM} + \mathcal{L}_{GR} + \mathcal{L}_{LI} + \mathcal{L}_{LV} + \mathcal{L}_{CPT-C} + \mathcal{L}_{CPT-V} + \dots$$

New terms
Lorentz invariant / Lorentz Violating New terms
CPT Conserving / CPT Violating

The SME in the gravitation sector

► For gravitation:

- Tests of General Relativity in the SME already performed with post-Newtonian test in the solar system, clock comparisons, etc
- Recent development to perform tests with gravitational waves (GW)
- New fields are probed during the propagation of the GW

► Generic SME term for GW:

$$\begin{aligned} \circ \mathcal{L}_{K^{(d)}} &= \frac{1}{4} h_{\mu\nu} \hat{K}^{(d)\mu\nu\rho\sigma} h_{\rho\sigma} \\ &= \frac{1}{4} h_{\mu\nu} (\hat{S}^{\mu\nu\rho\sigma} + \hat{q}^{\mu\nu\rho\sigma} + \hat{k}^{\mu\nu\rho\sigma}) h_{\rho\sigma} \end{aligned}$$

- d = mass dimension, starts at $d = 4$

Kostelecky & Mewes
[arxiv:1602.04782](https://arxiv.org/abs/1602.04782)

The SME operators in the gravitation sector

$$\mathcal{L}_{K^{(d)}} = \frac{1}{4} h_{\mu\nu} (\hat{s}^{\mu\nu\rho\sigma} + \hat{q}^{\mu\nu\rho\sigma} + \hat{k}^{\mu\nu\rho\sigma}) h_{\rho\sigma}$$

Tableau	Operator $\hat{\mathcal{K}}^{(d)\mu\nu\rho\sigma}$	CPT	d	Number	
	$s^{(d)\mu\rho\circ\nu\sigma\circ\circ^{d-4}}$	even	even, ≥ 4	$(d-3)(d-2)(d+1)$	
	$q^{(d)\mu\rho\circ\nu\circ\sigma\circ\circ^{d-5}}$	odd	odd, ≥ 5	$\frac{5}{2}(d-4)(d-1)(d+1)$	
	$k^{(d)\mu\circ\nu\circ\rho\circ\sigma\circ\circ^{d-6}}$	even	even, ≥ 6	$\frac{5}{2}(d-5)d(d+1)$	

Currently probed in LVC dispersion analysis

Corresponds to spacetime birefringence

Not tackled yet, smaller effects

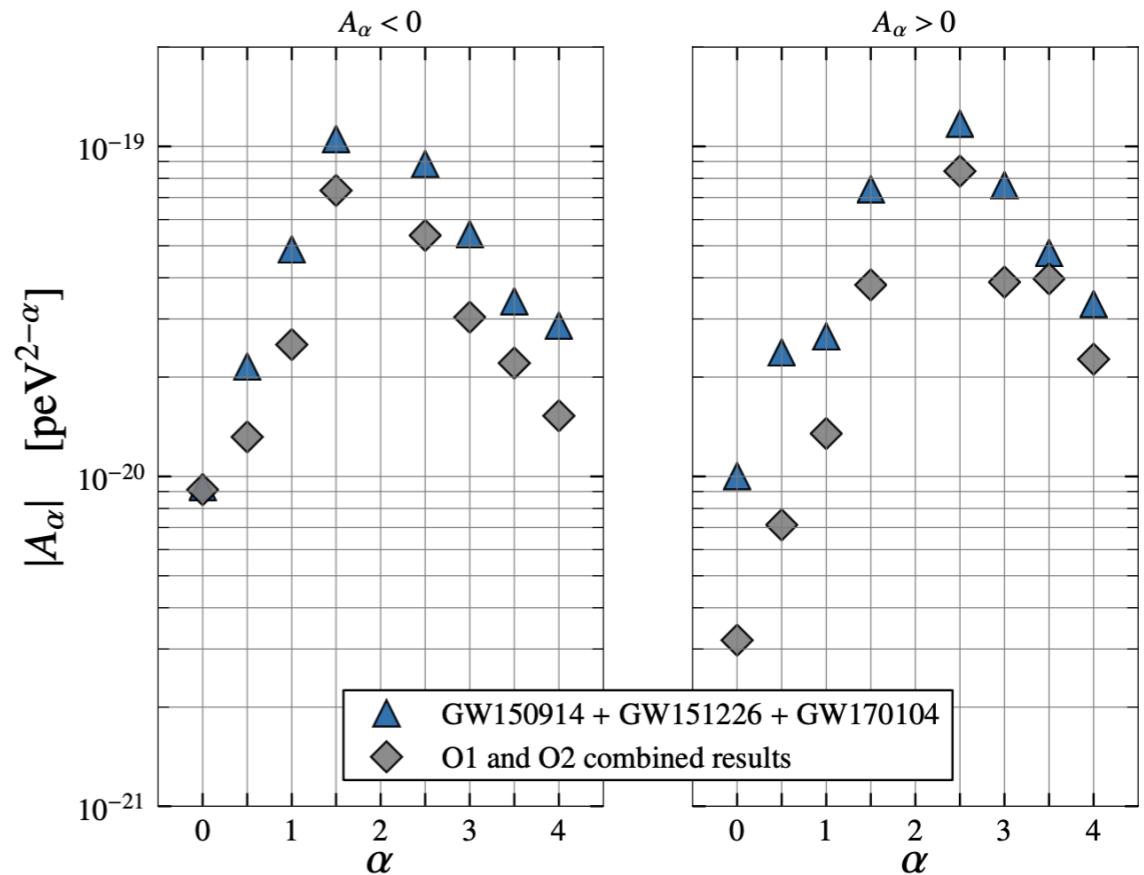
TABLE I: Gauge-invariant operators in the quadratic gravitational action.

Kostelecky & Mewes
[arxiv:1602.04782](https://arxiv.org/abs/1602.04782)

GW dispersion during propagation

- ▶ Currently, only dispersion from $d=4$ operator is probed:
 - C the generic equation:
$$E = p^2 c^2 + m^2 c^4 + \mathbb{A} p^\alpha c^\alpha$$
 - \mathbb{A} is constrained for several values of α from the GW emitted by coalescing BBH

LVC
[arxiv:1903.04467](https://arxiv.org/abs/1903.04467)



- ▶ Search for $d=5$ dispersion in GW propagation:
 - Spacetime birefringence can impact the propagation of GW
 - Frequency dependent change in the GW polarisation

Spacetime birefringence in the SME

- ▶ **Propagation of the GW:** $\omega = (1 - \varsigma^0 \pm \sqrt{(\varsigma^1)^2 + (\varsigma^2)^2 + (\varsigma^3)^2}) |\vec{p}|$
 (ω, \vec{p}) is the GW 4-momentum

- ▶ **Spacetime birefringence:**

Enters the term: $\varsigma^3 = \sum_{djm} \omega^{d-4} Y_{jm}(\hat{n}) k_{(V)jm}^{(d)}$

Mewes
[arxiv:1905.00409](https://arxiv.org/abs/1905.00409)

$j = 0$: isotropic birefringence

$j \neq 0$: anisotropic birefringence

- ▶ **Analysis:**

The goal is to constraint the $k_{(V)jm}^{(d)}$ tensor components for $d = 5$

Constraints from time delay

- ▶ **Birefringence and GW time delay :**

Measuring birefringence consists in comparing if the speed of the GW polarisations are different

Tasson, Haegel & Ault-O'Neal
Snowmass 2021 LOI

- ▶ **Birefringence as a time delay measurement**

If spacetime birefringence is large, the peak of the GW would be dissociated because h_+ and h_\times would not arrive at the same time

In practise, constraint arise from the width of the peak as no double structure is apparent

$$\text{GW150914: } \left| \sum_{jm} Y_{jm}(160^\circ, 120^\circ) k_{(V)jm}^{(5)} \right| < 2 \cdot 10^{-14} \text{ m}$$

Kostelecky & Mewes
[arxiv:1602.04782](https://arxiv.org/abs/1602.04782)

- ▶ **This analysis:**

Constraint the $k_{(V)jm}^{(d)}$ tensor components individually

Birefringence modification on the GW

- ▶ **Birefringence impacts on the GW:**

$$h_{+,x}^{SME} = e^{i\delta}(\cos \beta \mp i \sin \theta \cos \varphi \sin \beta) h_{+,x}^{GR} - e^{i\delta}(\cos \theta \pm i \sin \theta \sin \varphi) \sin \beta h_{x,+}^{GR}$$
$$\beta = \omega^{(d-3)} \tau |\vec{\zeta}^{(d)}|$$

- ▶ **Implementation on the LVC software:**

We start with the isotropic component $k_{(V)00}^{(5)}$

Modification of the LALSimulation template waveform:

$$\beta = 2 \pi^{3/2} f^2 \frac{r}{c^2} |k_{(V)00}^{(5)}| \int_c^r \frac{1+z}{H(z)} dz$$



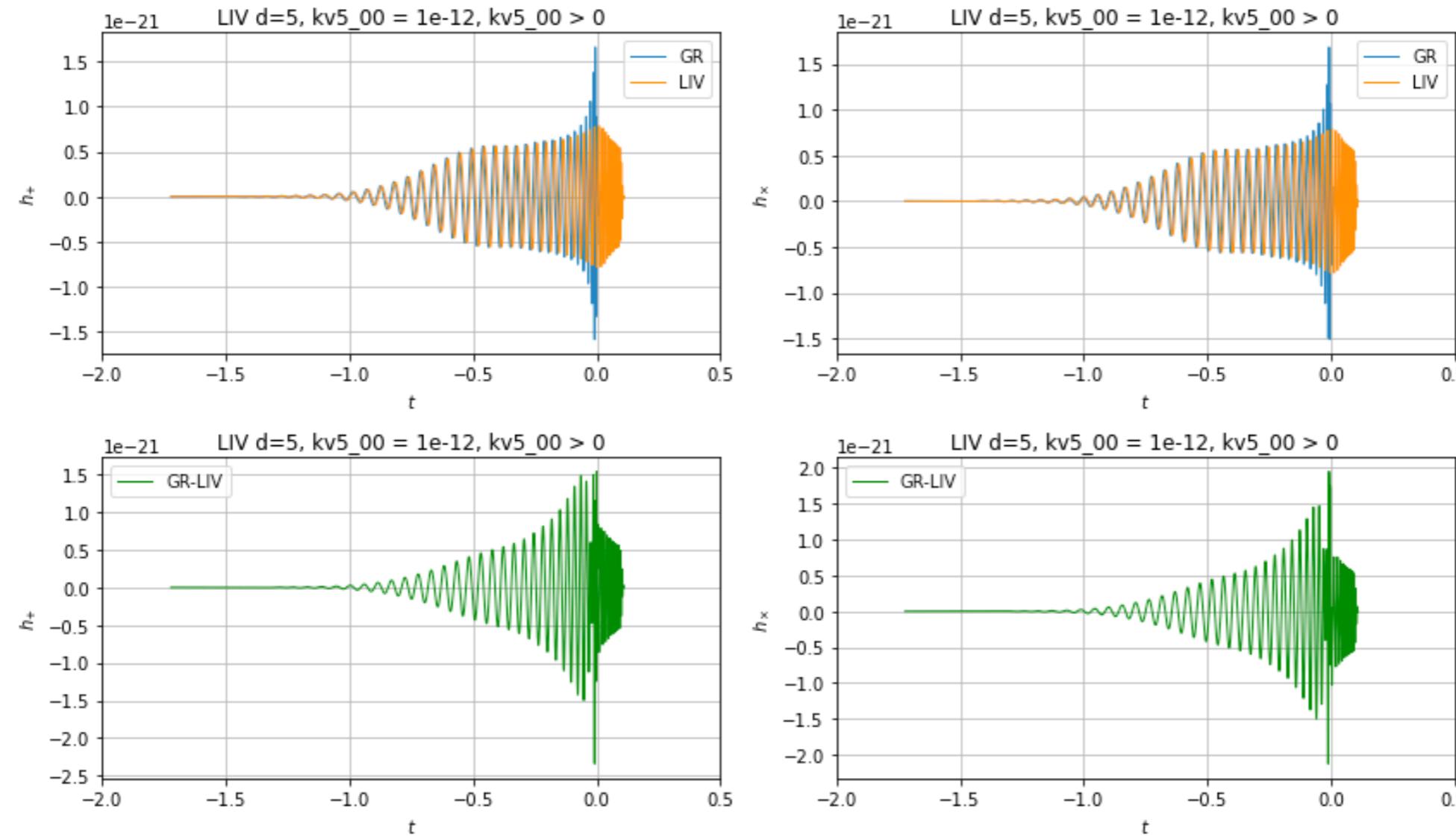
$$k_{(V)00}^{(5), eff}$$

The integral cannot be computed during the Markov chain sampling, so we define this effective parameter and recover $k_{(V)00}^{(5)}$ from the posteriors

Birefringence modification on the GW

► LALSimulation example:

```
--m1 40.834 --m2 33.263 --spin1x 0.092 --spin1y 0.038 --spin1z 0.326  
--spin2x 0.215 --spin2y 0.301 --spin2z -0.558 --D = 500 Mpc -kv5_00 = 1E-12
```



Next steps

- ▶ **Injection studies:**

- Inject fake data signals with birefringence to study the degeneracy between GR (e.g. precession) and birefringence effects
- Perform a sensitivity study of birefringence measurements v.s. distance, amplitude

- ▶ **Real data measurement:**

- First perform a measurement of isotropic birefringence with GWTC-2
- Extend to anisotropic birefringence