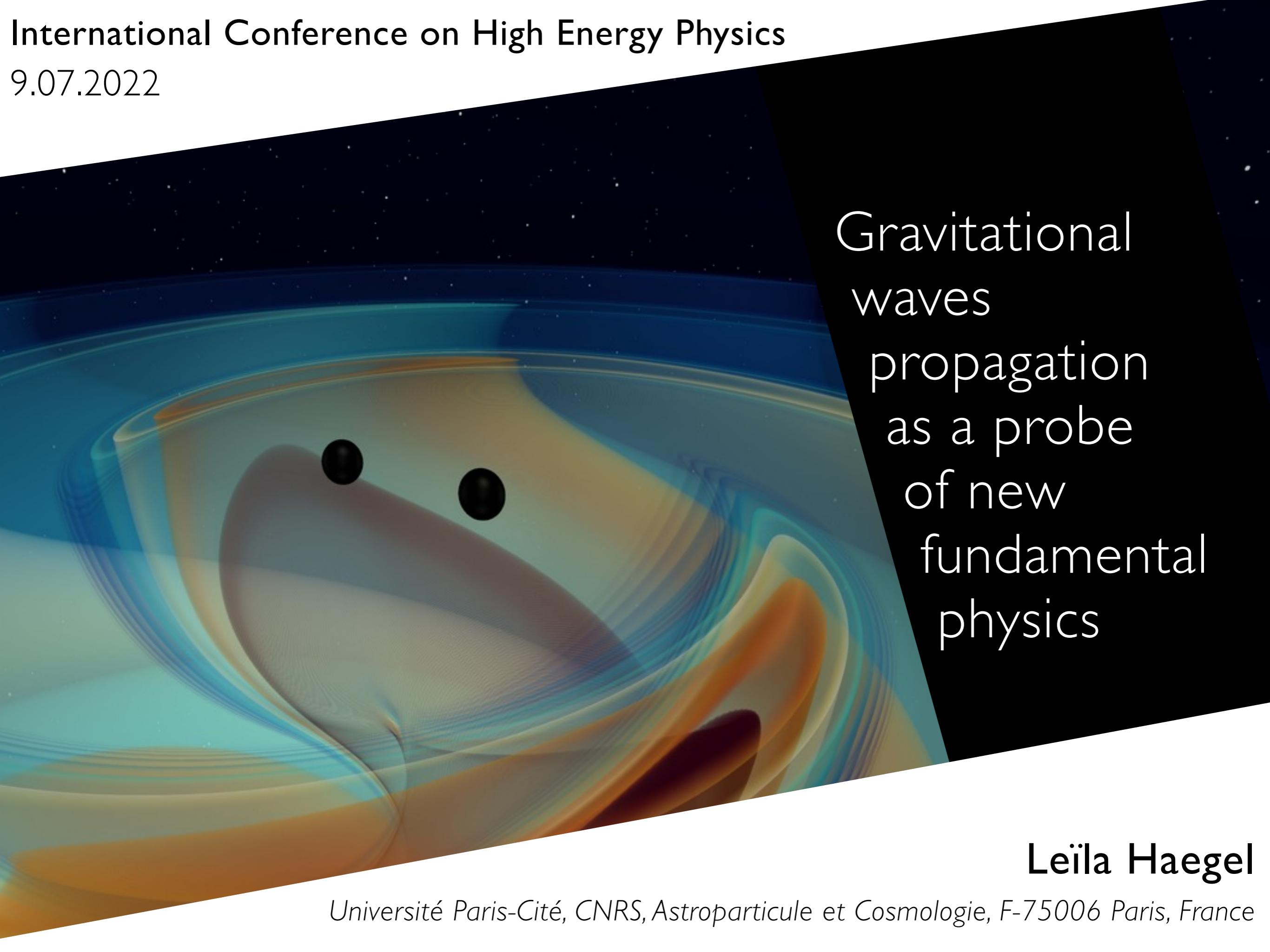


International Conference on High Energy Physics

9.07.2022



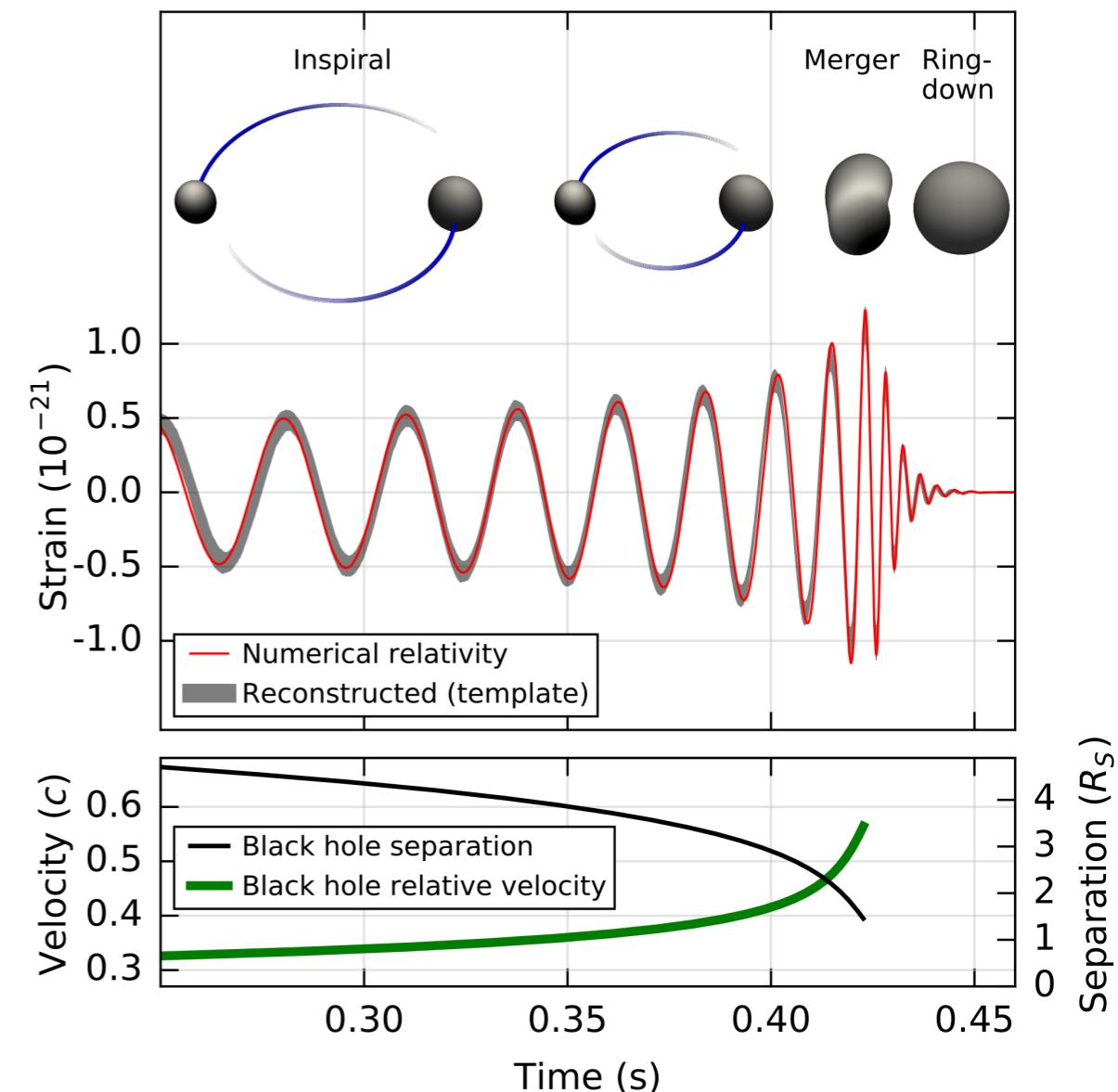
Gravitational
waves
propagation
as a probe
of new
fundamental
physics

Leïla Haegel

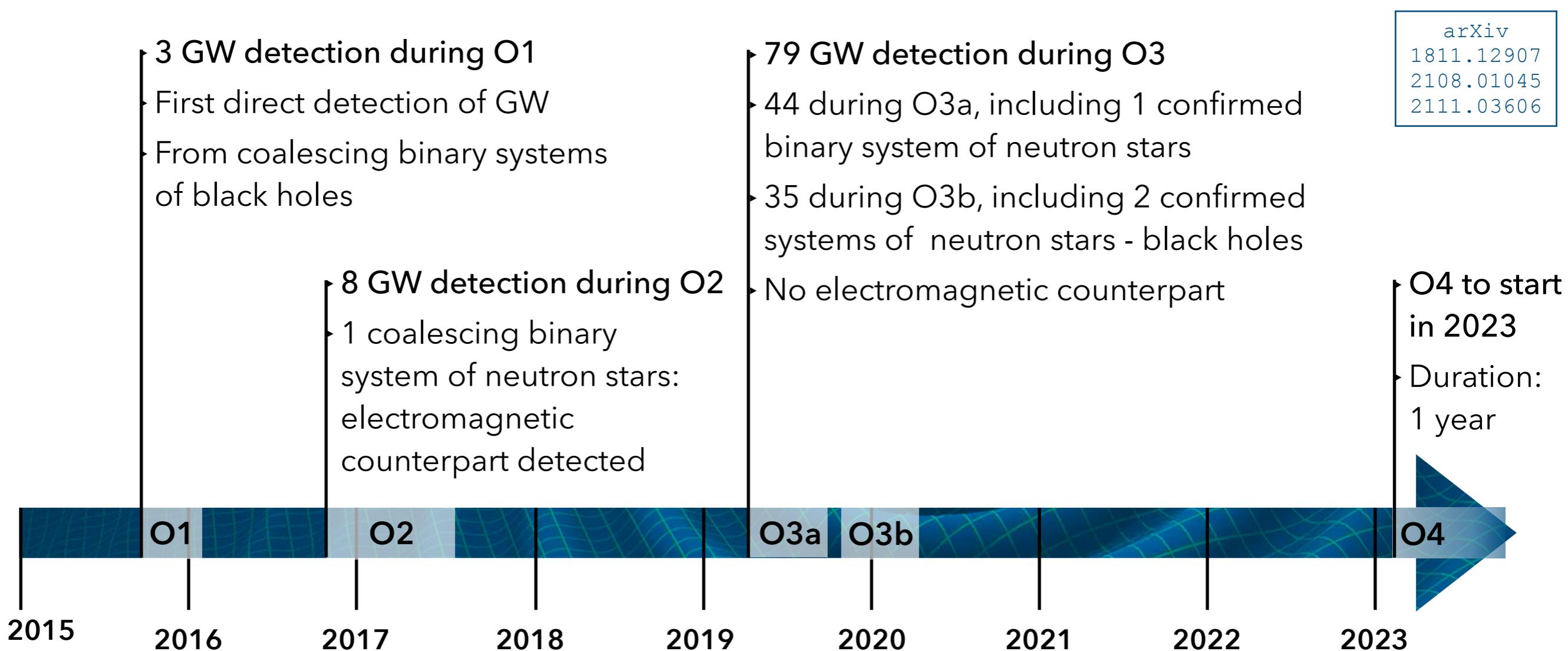
Université Paris-Cité, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France

Introduction

- › Gravitational waves (GW) enable to test fundamental physics in the gravitational sector
 - ↳ complementary to tests with solar system, pulsars, gravitational lensing...
- › Several approaches to test for deviation from General Relativity
 - ↳ consistency tests
 - ↳ search for phenomena impacting GW generation
 - ↳ search for exotic compact objects...
- › New physics may affect the propagation of GW
 - ↳ gravitational coupling
 - ↳ overall effect on the signal (independent of the source)
 - ↳ cumulative effect
 - ↳ dynamical regime at large distance due to Universe expansion



Gravitational waves detection: a summary



90 GW
detections
reported



Coalescence
of black holes
and neutron stars



1 multimessenger
event (GW + EM
observation)



Mass range
 $1.2 \rightarrow 107 M_{\odot}$
(stellar)



Distance range
 $40 \text{ Mpc} \rightarrow 8 \text{ Gpc}$
($z \rightarrow 1.14$)

Gravitational waves propagation

General relativity (GR) case:

$$h_{ij}'' + 2 H h_{ij} + c^2 k^2 h_{ij} = 0$$



Nishizawa, Phys. Rev. D
97, 104037 (2018)

$$h_{ij}'' + (2 + \nu) H h_{ij} + (c_T^2 k^2 + a^2 \mu^2) h_{ij} = a^2 \Gamma \gamma_{ij}$$

GW friction

Amplitude
does not scale
as 1/distance

Speed of
gravity

Speed of
GW $\neq c$

Mass of
graviton

Non-0 graviton
mass

Polarisation
mixing

h_+ and h_\times

Can be probed with
multimessenger events

Can be probed from GW
signal (pattern & polarisation)

Gravitational waves propagation

General relativity (GR) case:

$$h_{ij}'' + 2 H h_{ij} + c^2 k^2 h_{ij} = 0$$



Nishizawa, Phys. Rev. D
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Mass of
graviton

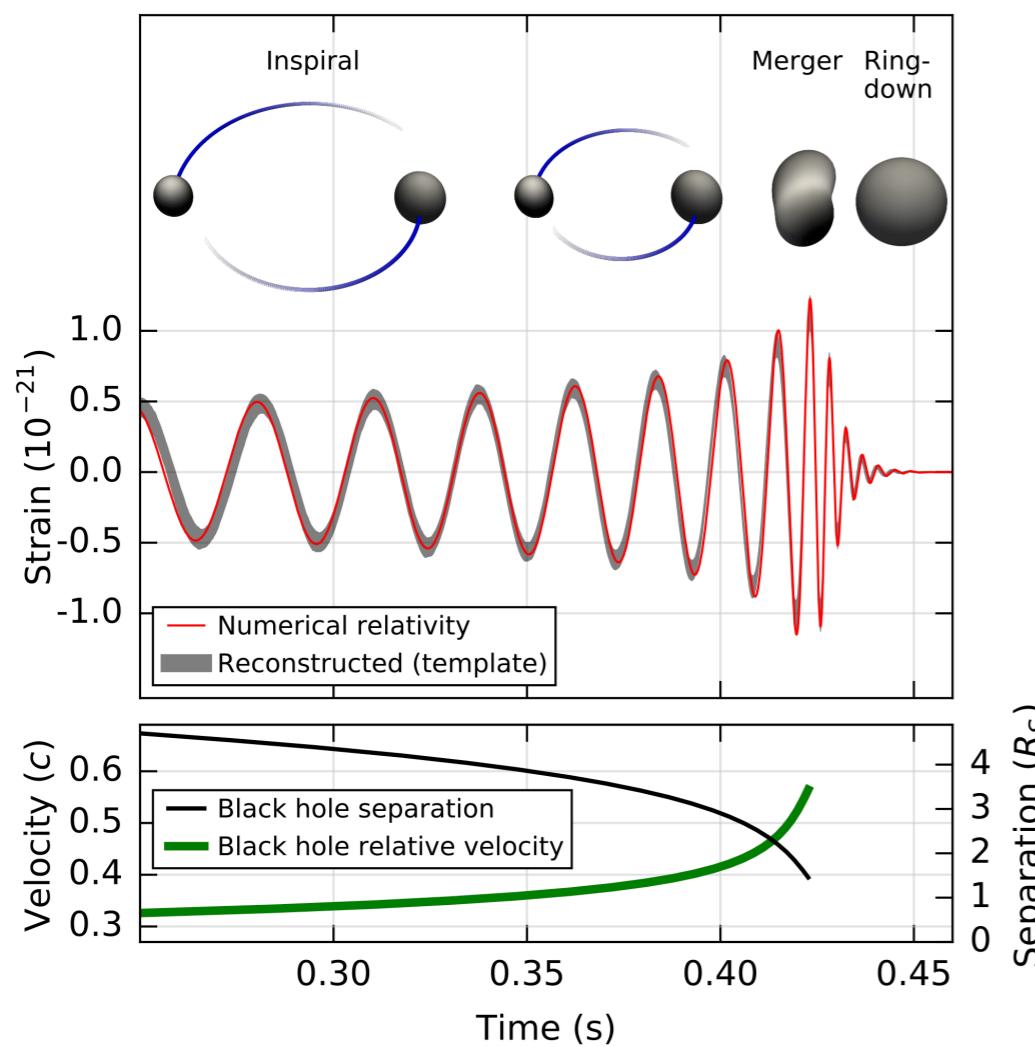
Non-0 graviton
mass

Lorentz invariance violation induced GW dispersion

- GW from the coalescence of compact binaries have a characteristic signal

$$h(t) = |h(t)| e^{-i(\omega(t) + \phi_c)}$$

with $|h(t)|, \omega(t)$ increasing until merger



- Breaking of Lorentz symmetry & massive graviton modify the energy relation:

$$E^2 = p^2 c^2 + m_g^2 c^4 + \mathbb{A} p^\alpha c^\alpha$$

- The extra term in \mathbb{A} creates a frequency-dependent dispersion of the GW

$$\tilde{h}(f) = |\tilde{h}(f)| e^{-i(\tilde{\phi}_{GR}(f) + \delta\tilde{\phi}(f))}$$

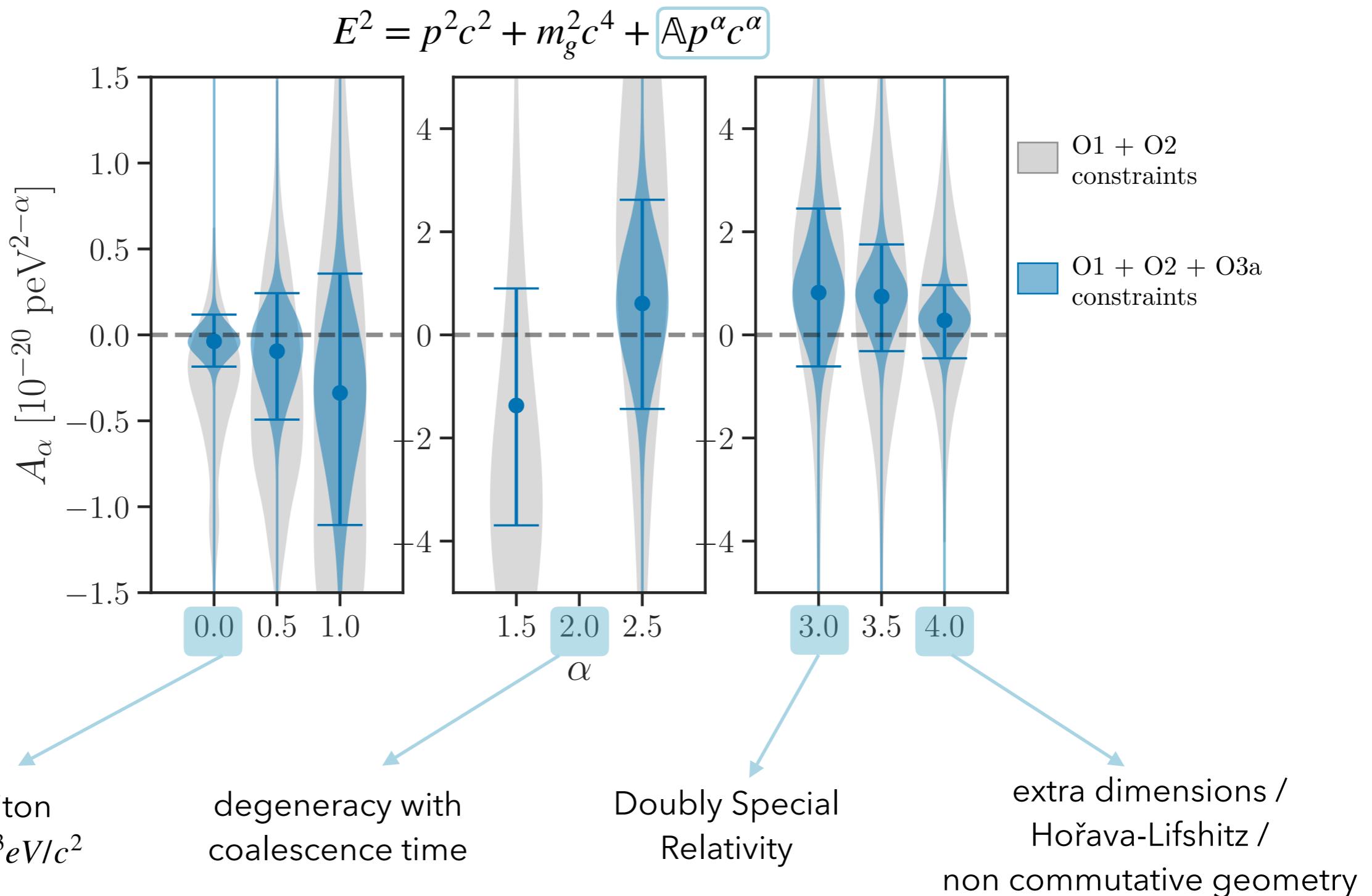
- The dispersion is:
 - isotropic
 - polarisation independent
 - possibly mapped to alternative theories of gravitation

[Mirshekari, Yunes & Will](#)
[Phys. Rev. D85: 024041 \(2012\)](#)

Constraints on Lorentz invariance violation

- Constraints on \mathbb{A} from 31 GW events detected during O1 + O2 + O3a (GWTC-2 catalog)

[LVC, Phys. Rev. D 103, 122002 \(2021\)](#)



Gravitational waves propagation

General relativity (GR) case:

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Polarisation
mixing

h_+ and h_\times

EFT for spacetime symmetry breaking

- Breaking of spacetime symmetries (CPT, Lorentz) can be studied with an effective field theory (EFT) formalism (Standard Model Extension, or SME):

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

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

Impact GW momentum:
dispersion effect,
this study

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

[Kostelecky & Mewes, Phys. Lett. B757:510–514 \(2016\)](#)

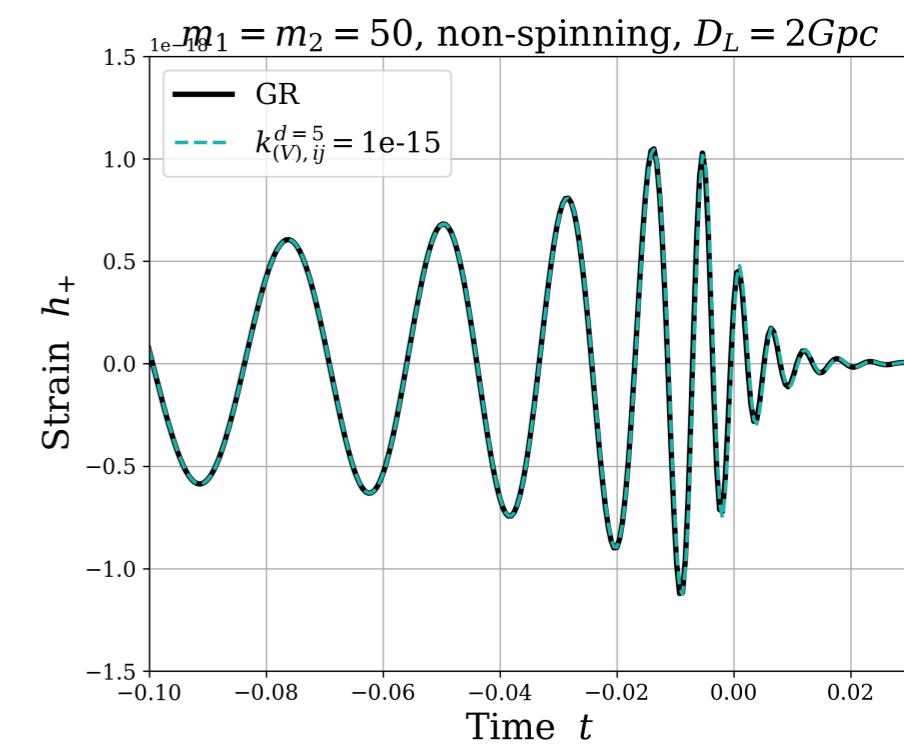
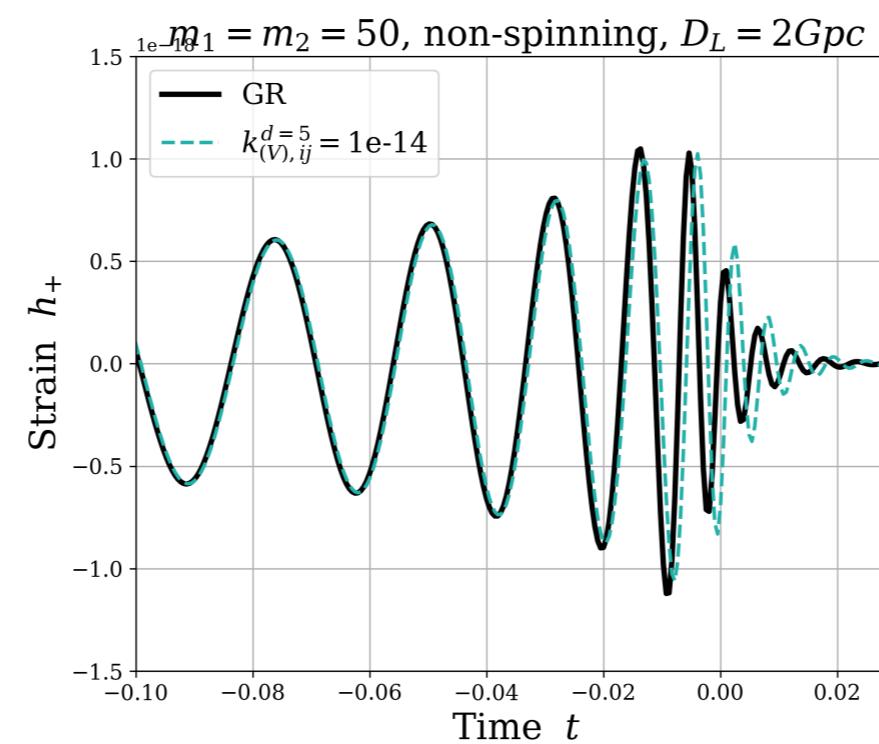
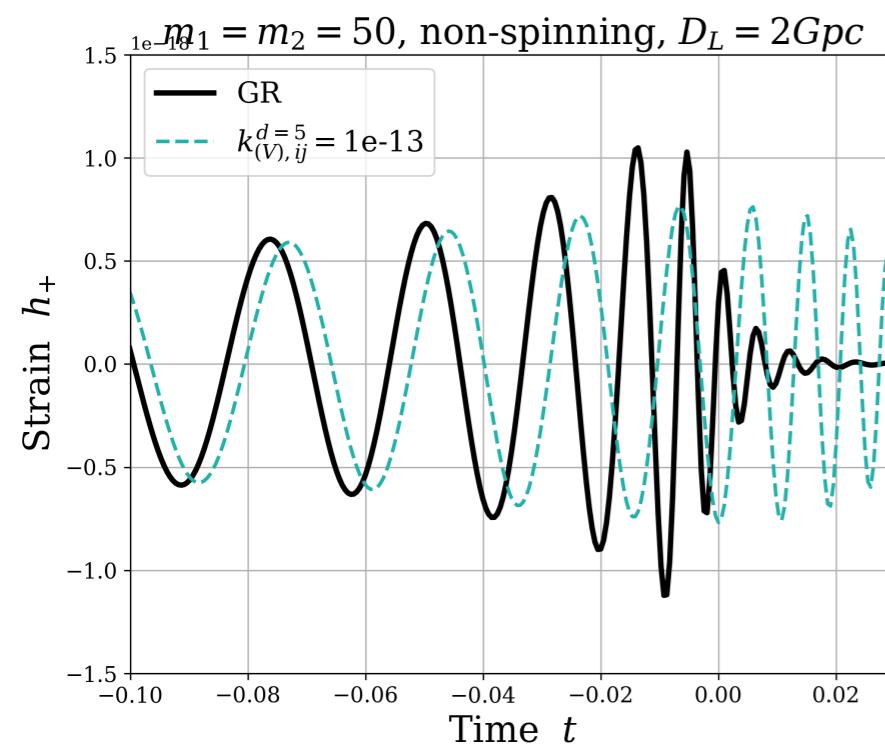
Polarisation-dependent, anisotropic dispersion

- The coupling of new fields with the metric modified the GW propagation in a frequency-dependent, polarisation-dependent, anisotropic way:

$$h_{+,x}^{SME} = e^{i\delta}(\cos \beta \mp i \sin \vartheta \cos \varphi \sin \beta) h_{+,x}^{GR} - e^{i\delta}(\cos \vartheta \pm i \sin \vartheta \sin \varphi) \sin \beta h_{x,+}^{GR}$$

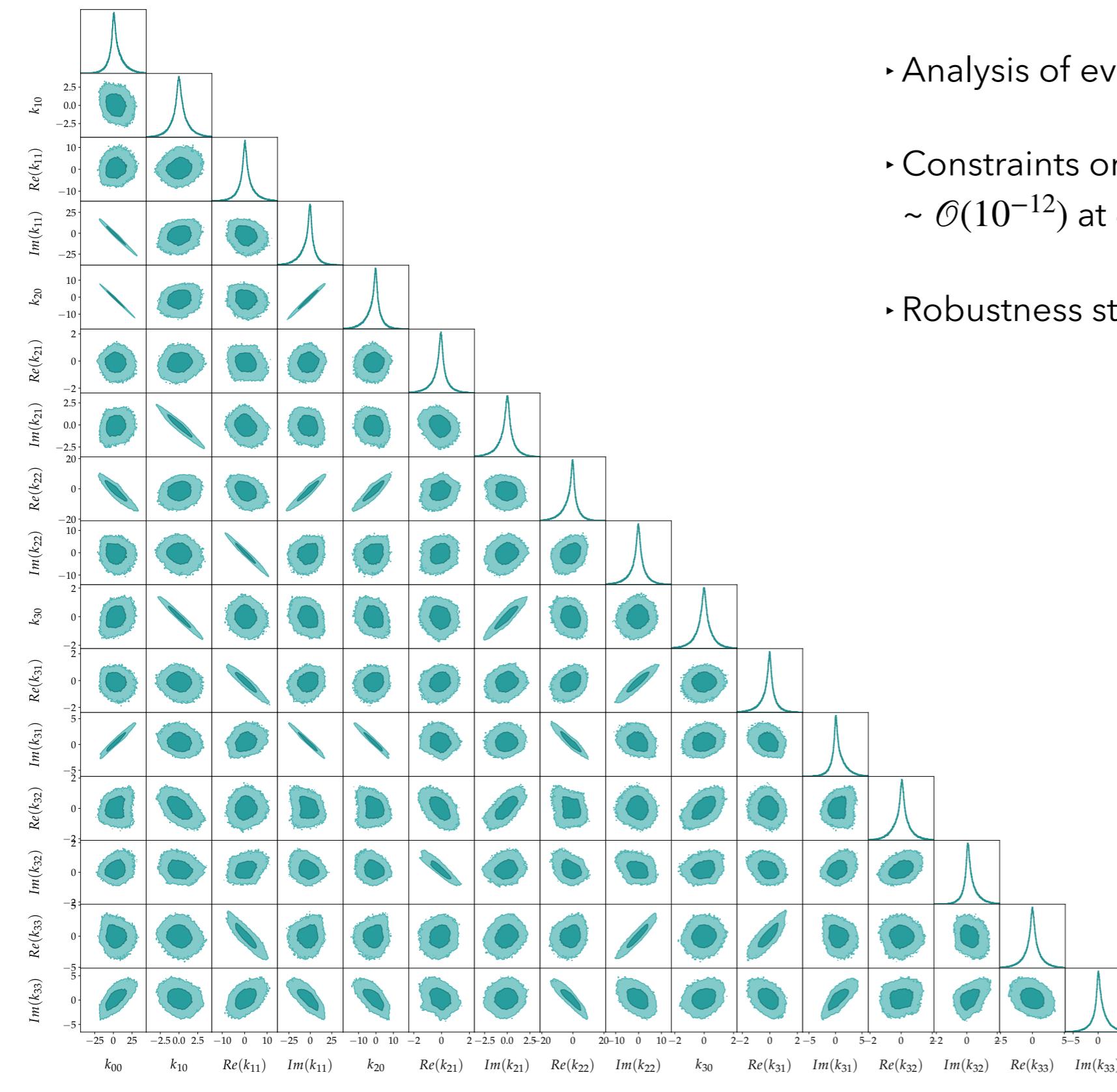
$$\delta, \beta, \vartheta, \varphi \propto \zeta^{1,2,3} \simeq \sum_{djm} \omega^{d-4} Y_{jm}(\theta, \phi) k_{(I,E,B,V)jm}^{(d)}$$

[Mewes, Phys. Rev. D 99, 104062 \(2019\)](#)

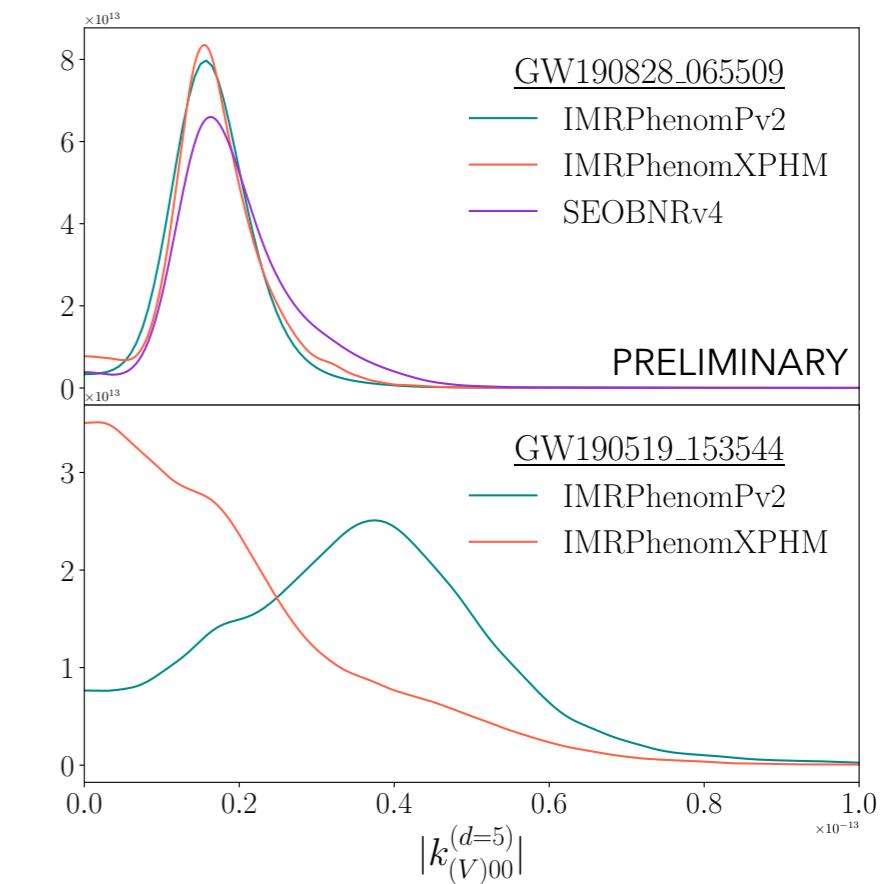


[Ault-O'Neal, Bailey, Dumerchat, Haegel, Tasson, Universe 2021, 7\(10\), 380 \(2021\)](#)

Polarisation-dependent, anisotropic dispersion



- Analysis of events from O1 + O2 + O3 events
- Constraints on 16 dispersion parameters at $\sim \mathcal{O}(10^{-12})$ at 68.3% CI
- Robustness study: impact of waveform model



Gravitational waves propagation

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Nishizawa, Phys. Rev. D
97, 104037 (2018)

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	$k^{(d)\mu\nu\rho\sigma} \circ \circ \circ \circ^{d-6}$	even	even, ≥ 6	$\frac{5}{2}(d-5)d(d+1)$

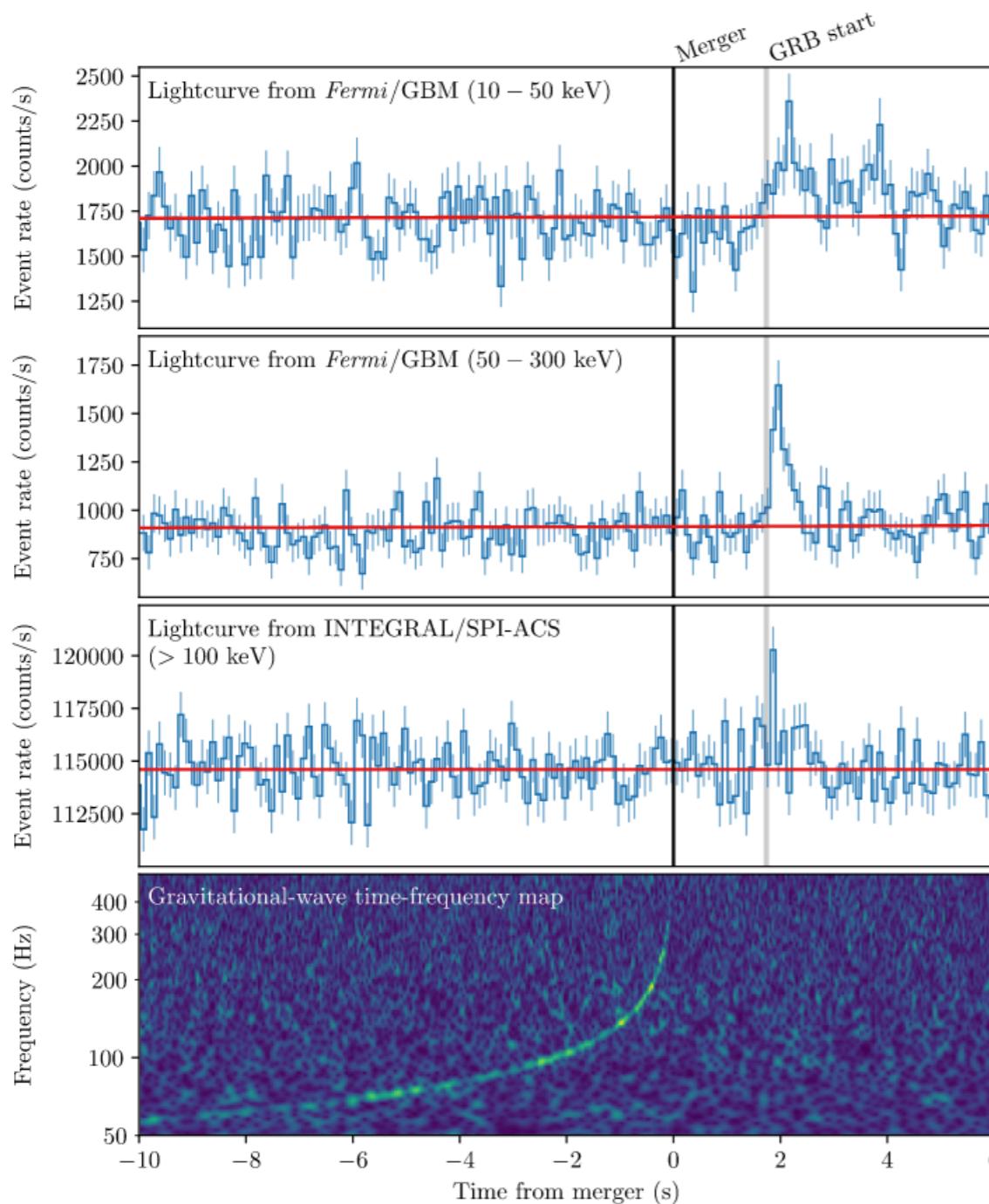
Impact GW velocity:
constrained with the
BNS event GW170817

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

[Kostelecky & Mewes, Phys. Lett. B757:510–514 \(2016\)](#)

Multimessenger event: GW170817

- GW170817: binary neutron star merger



- Difference in time of arrival between electromagnetic and gravitational radiation enables to constrain the speed of gravity:

$$-3 \times 10^{-15} \leq \frac{\Delta v}{v_{\text{EM}}} \leq +7 \times 10^{-16}$$

- As well as Lorentz-violating parameters in the SME:

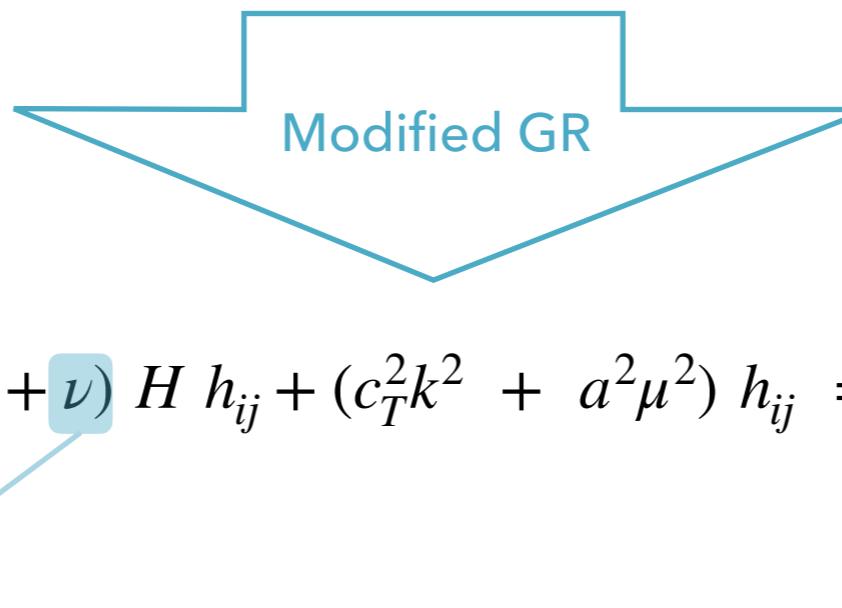
$$\Delta v = - \sum_{\ell m} Y_{\ell m}(\hat{n}) \left(\frac{1}{2} (-1)^{1+\ell} \bar{s}_{\ell m}^{(4)} - c_{(I)\ell m}^{(4)} \right)_{\ell \leq 2}$$

Coefficient	This Work Upper	Previous Upper
$\bar{s}_{00}^{(4)}$	5×10^{-15}	8×10^{-5}
$\bar{s}_{10}^{(4)}$	7×10^{-15}	7×10^{-14}
$-\text{Re } \bar{s}_{11}^{(4)}$	2×10^{-15}	8×10^{-14}
$\text{Im } \bar{s}_{11}^{(4)}$	7×10^{-15}	9×10^{-14}
$-\bar{s}_{20}^{(4)}$	8×10^{-15}	7×10^{-14}
$-\text{Re } \bar{s}_{21}^{(4)}$	2×10^{-15}	7×10^{-14}
$\text{Im } \bar{s}_{21}^{(4)}$	8×10^{-15}	8×10^{-14}
$\text{Re } \bar{s}_{22}^{(4)}$	3×10^{-15}	8×10^{-14}
$-\text{Im } \bar{s}_{22}^{(4)}$	4×10^{-15}	7×10^{-14}

Gravitational waves propagation

General relativity (GR) case:

$$h_{ij}'' + 2 H h_{ij} + c^2 k^2 h_{ij} = 0$$



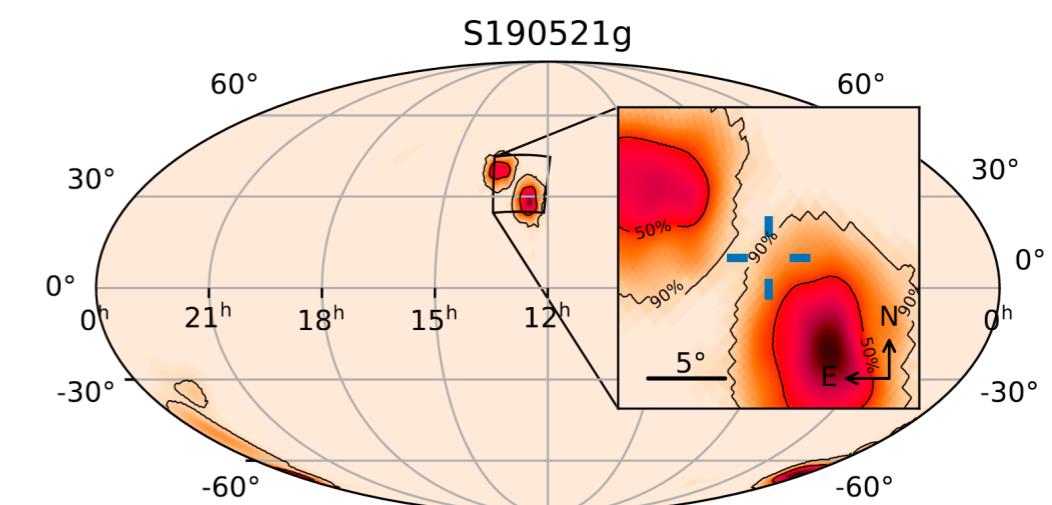
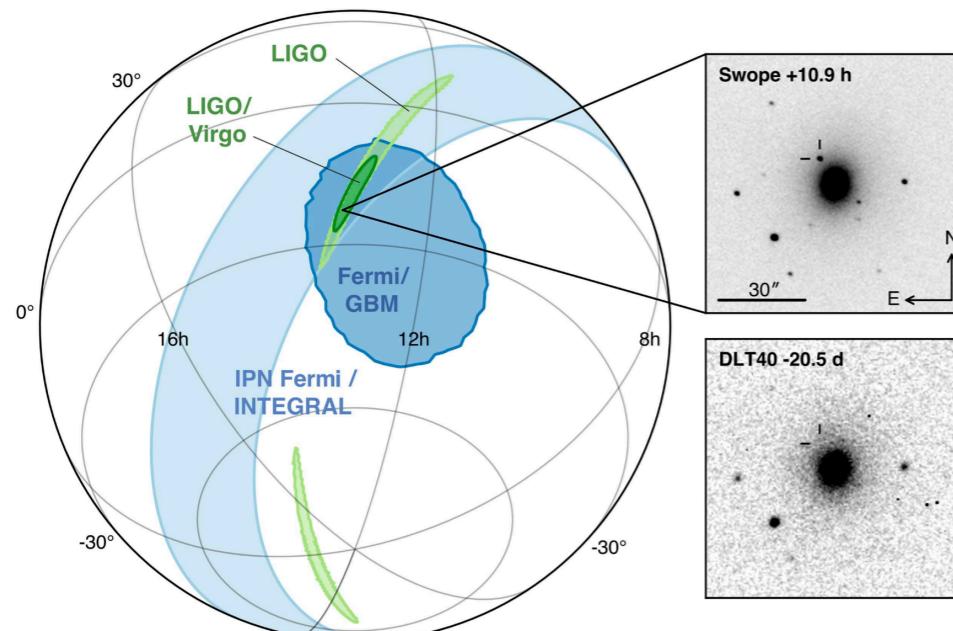
[Nishizawa, Phys. Rev. D
97, 104037 \(2018\)](#)

Amplitude
does not scale
as 1/distance

Standard sirens

- Standard siren = simultaneous observation of electromagnetic and gravitational radiation from the same event
- The distance (luminosity distance & redshift) can be separately inferred from the two signals, enabling to measure cosmological and GW friction parameters

- **GW170817:**
 - binary neutron star merger
 - $z \approx 0.01$
- **GW190521:**
 - binary black holes merger
 - potential location in AGN disk creating electromagnetic signal (not confirmed)
 - $z \approx 0.44$



[LVC, Phys. Rev. Lett. 125, 101102 \(2020\)](#)

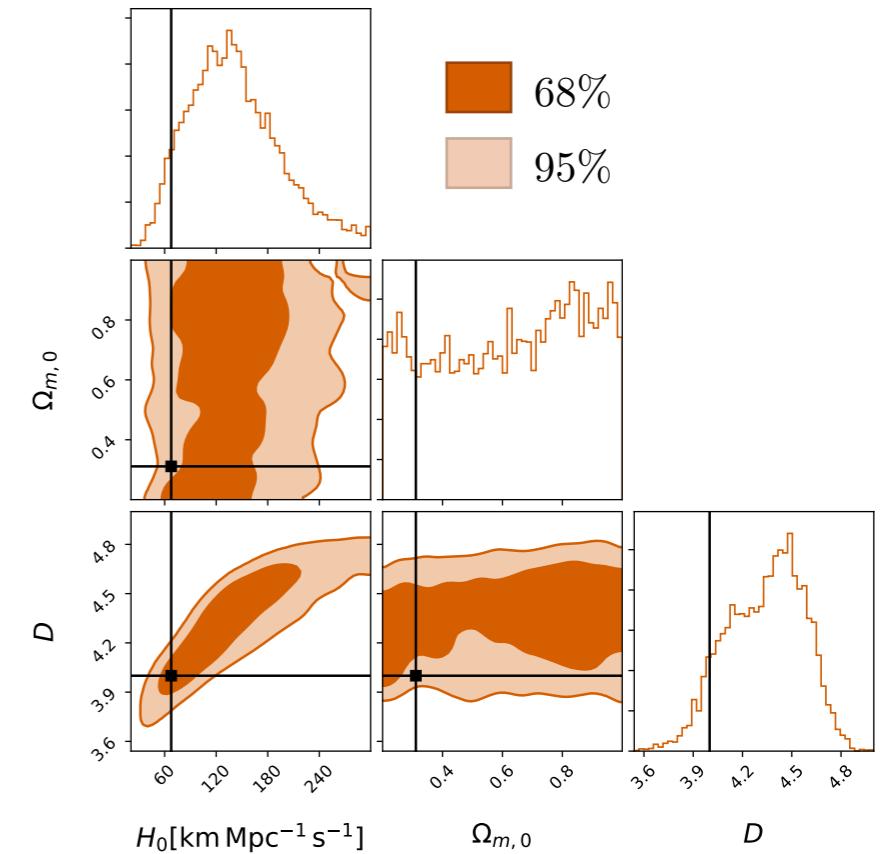
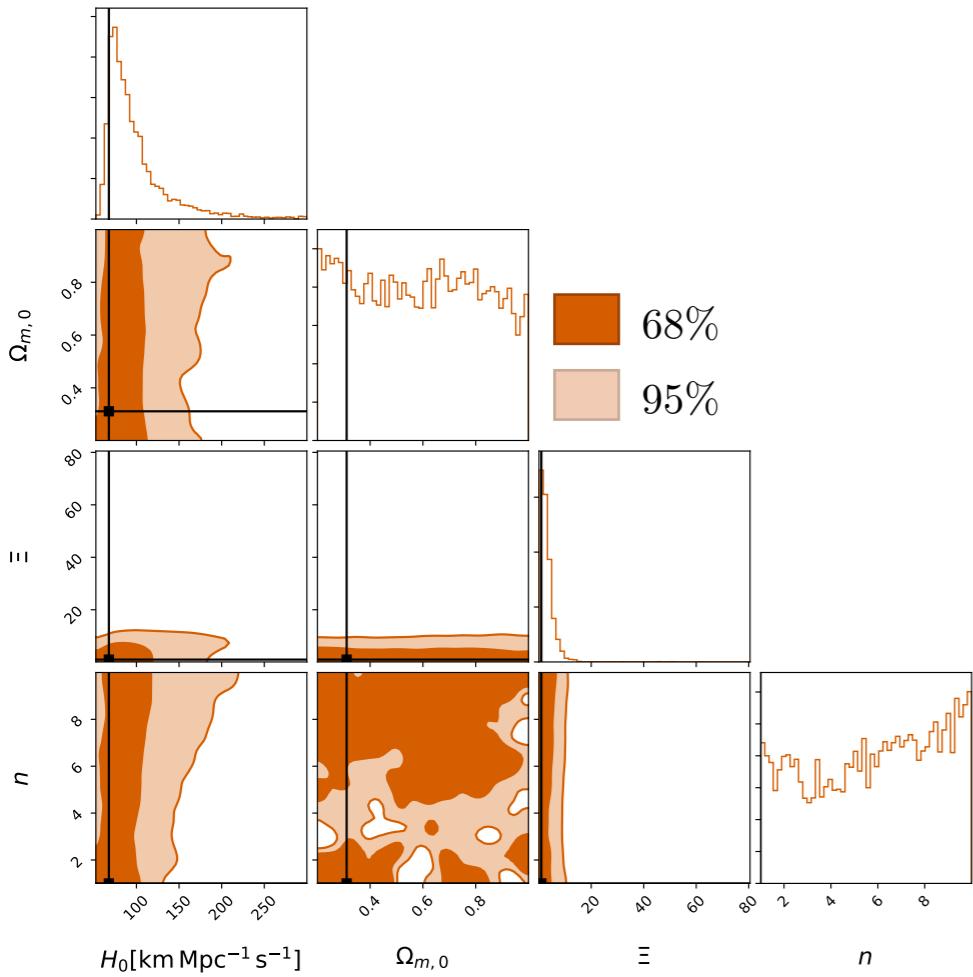
[Graham et al, Phys. Rev. Lett. 124, 251102 \(2020\)](#)

Constraints on GW friction

- Large extra dimensions (DGP gravity and other non-compactified extra dimensions quantum gravity theories)

$$d_L^{GW}(z) = \left[1 + \left(\frac{d_L^{EM}(z)}{R_c} \right)^n \right]^{\frac{D-2}{2n}}$$

[Mastrogiovanni, Haegel, Karathanasis, Magana-Hernandez, Steer, JCAP 02 \(2021\) 043](#)



- Scalar-tensor theories of gravitation parameterisation (Brans-Dicke, Horndeski, beyond-Horndeski, DHOST)

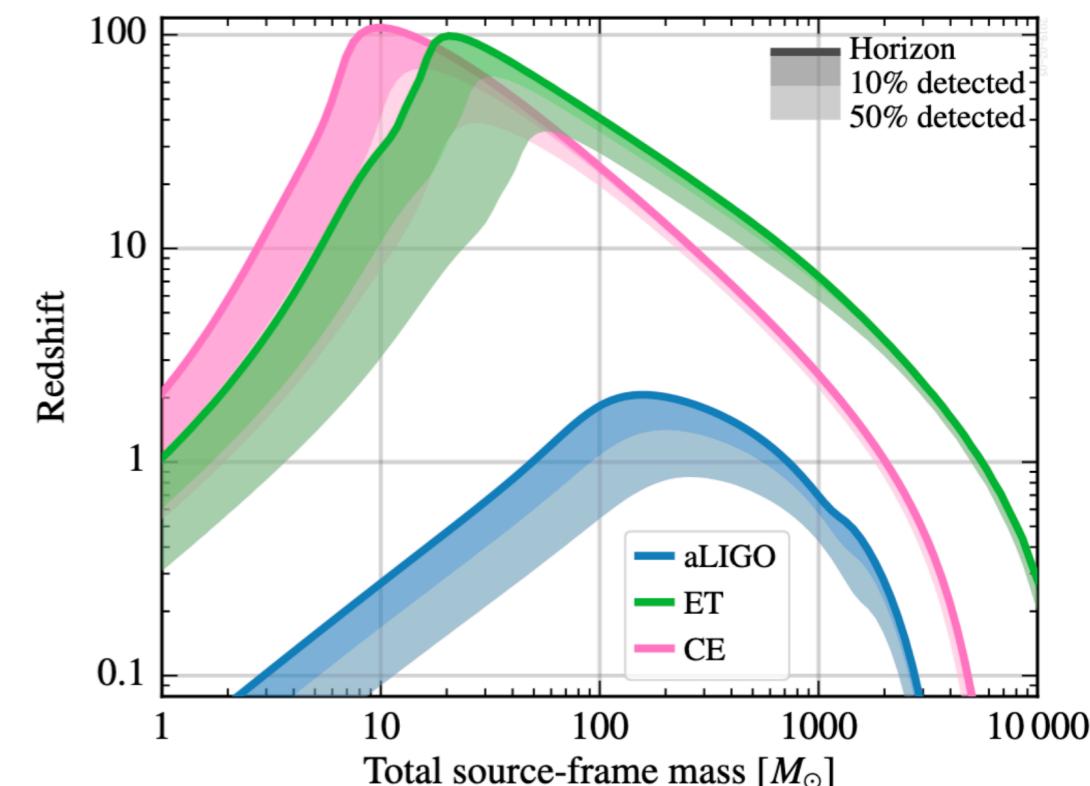
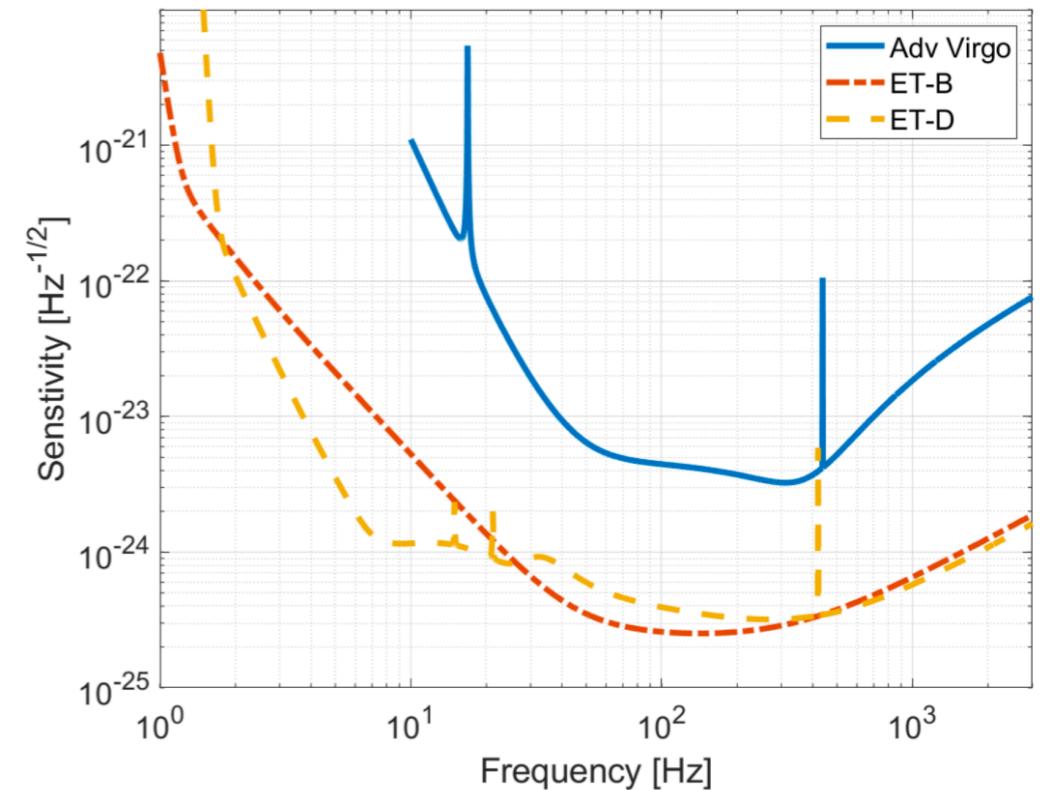
$$d_L^{GW}(z) = d_L^{EM}(z) \left[\Xi + \frac{1 - \Xi}{(1+z)^n} \right]$$

- Constraints can be improved in case of detection of a lensed event (current study, [H. Narola talk at GR23 \[C3\]](#))

Conclusion

[Maggiore et al, JCAP 03 \(2020\) 050](#)

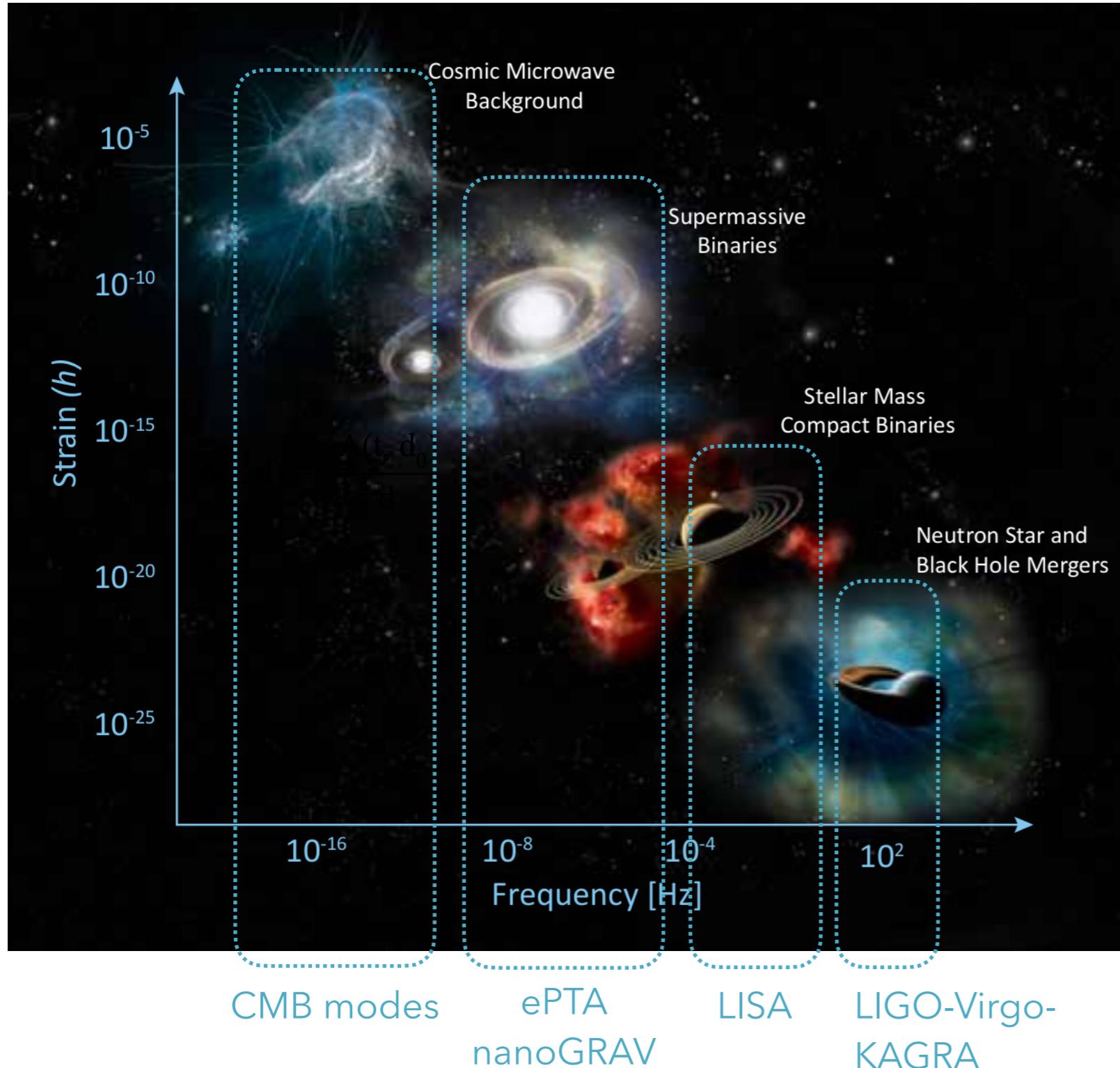
- GW enable to test several beyond-GR phenomenology:
 - speed of gravity
 - graviton mass
 - spacetime symmetry breaking
 - scalar-tensor theories of gravitation
 - "agnostic" deviations
- Multimessenger studies are complementary to GW-only tests
a collaborative effort from the community
- The best is yet to come
towards the advanced Virgo / Einstein Telescope era



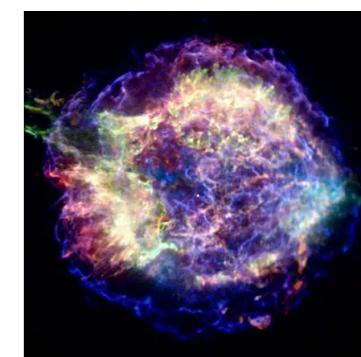
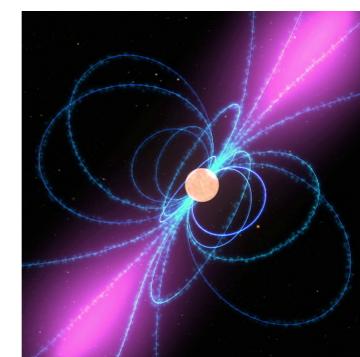
Bonus

Gravitational waves sources

Credit: SSU EPO/Aurore Simonnet



+ pulsars + supernovae



Measuring SME coefficients for d=5

- ▶ In practice: look at each mass dimension separately
- ▶ Dispersion starts for mass dimension $d = 5$
- ▶ It is controlled by 16 coefficients $k_{(V),ij}^{(d=5)}$
- ▶ The modified GW signal is:

$$h_+ = \cos \beta \ h_+^{GR} - \sin \beta \ h_\times^{GR}$$

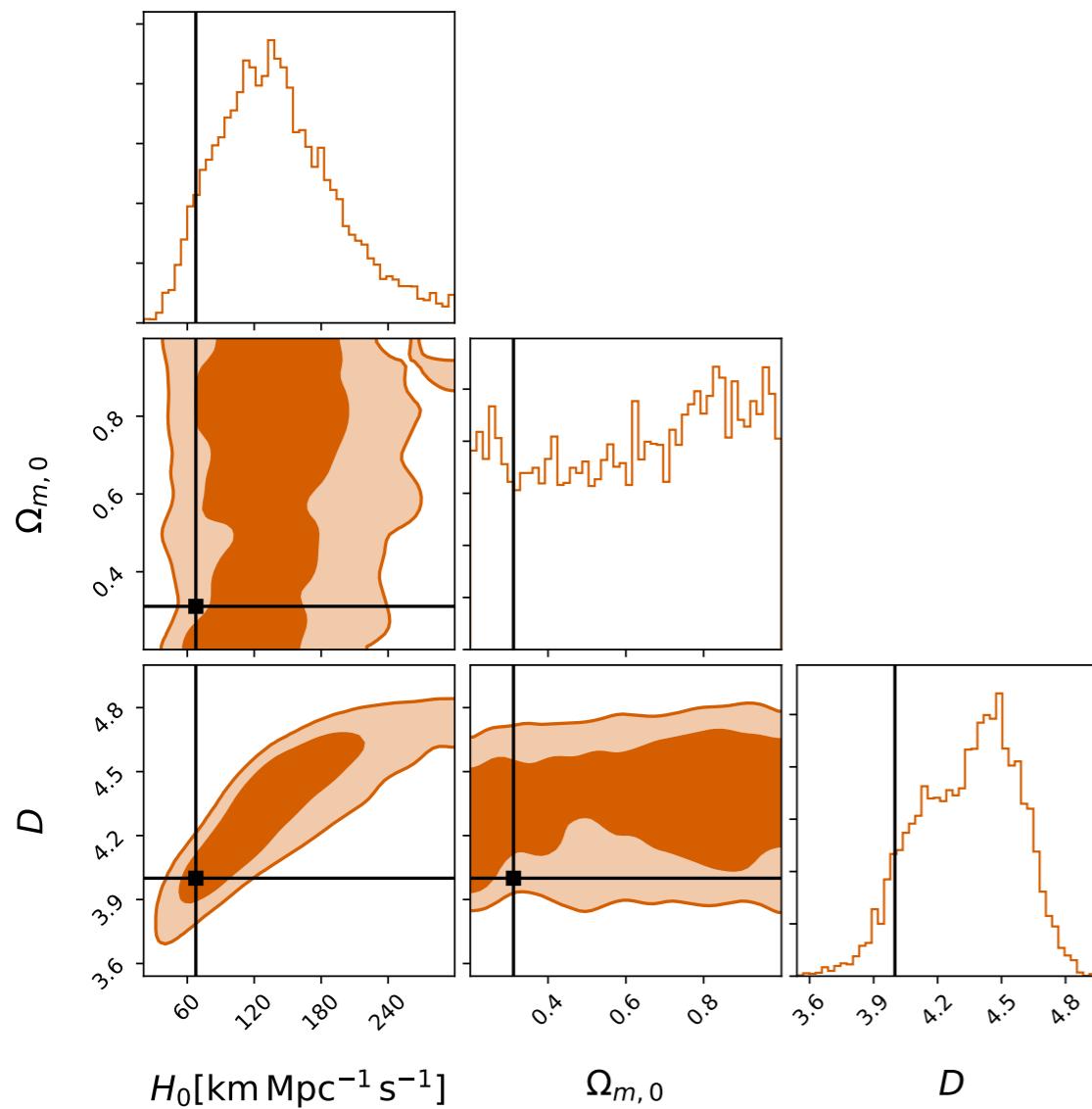
- ▶ Constrain $k_{(V),eff}^{(d=5)}$ with individual events, then reinterpret the constraint as a single coefficient / all coefficients constraint

$$k_{(V),eff}^{(d=5)}$$

$$\begin{aligned} \beta = \omega^2 \tau & \left| \begin{array}{l} \frac{1}{2} \frac{1}{\sqrt{\pi}} k_{00} \\ + \frac{1}{2} \sqrt{\frac{3}{\pi}} \cos \theta k_{10} \\ - \sqrt{\frac{3}{2\pi}} \sin \theta (\cos \phi \operatorname{Re}(k_{11}) - \sin \phi \operatorname{Im}(k_{11})) \\ + \frac{1}{4} \sqrt{\frac{5}{\pi}} (3 \cos^2 \theta - 1) k_{20} \\ - \sqrt{\frac{15}{2\pi}} \sin \theta \cos \theta (\cos \phi \operatorname{Re}(k_{21}) - \sin \phi \operatorname{Im}(k_{21})) \\ + \frac{1}{2} \sqrt{\frac{15}{2\pi}} \sin^2 \theta (\cos 2\phi \operatorname{Re}(k_{22}) - \sin 2\phi \operatorname{Im}(k_{22})) \\ + \frac{1}{4} \sqrt{\frac{7}{\pi}} (5 \cos^3 \theta - 3 \cos \theta) k_{30} \\ - \frac{1}{4} \sqrt{\frac{21}{\pi}} \sin \theta (5 \cos^2 \theta - 1) (\cos \phi \operatorname{Re}(k_{31}) - \sin \phi \operatorname{Im}(k_{31})) \\ + \frac{1}{2} \sqrt{\frac{105}{2\pi}} \sin^2 \theta \cos \theta (\cos 2\phi \operatorname{Re}(k_{32}) - \sin 2\phi \operatorname{Im}(k_{32})) \\ - \frac{1}{4} \sqrt{\frac{35}{\pi}} \sin^3 \theta (\cos 3\phi \operatorname{Re}(k_{33}) - \sin 3\phi \operatorname{Im}(k_{33})) \end{array} \right. \end{aligned}$$

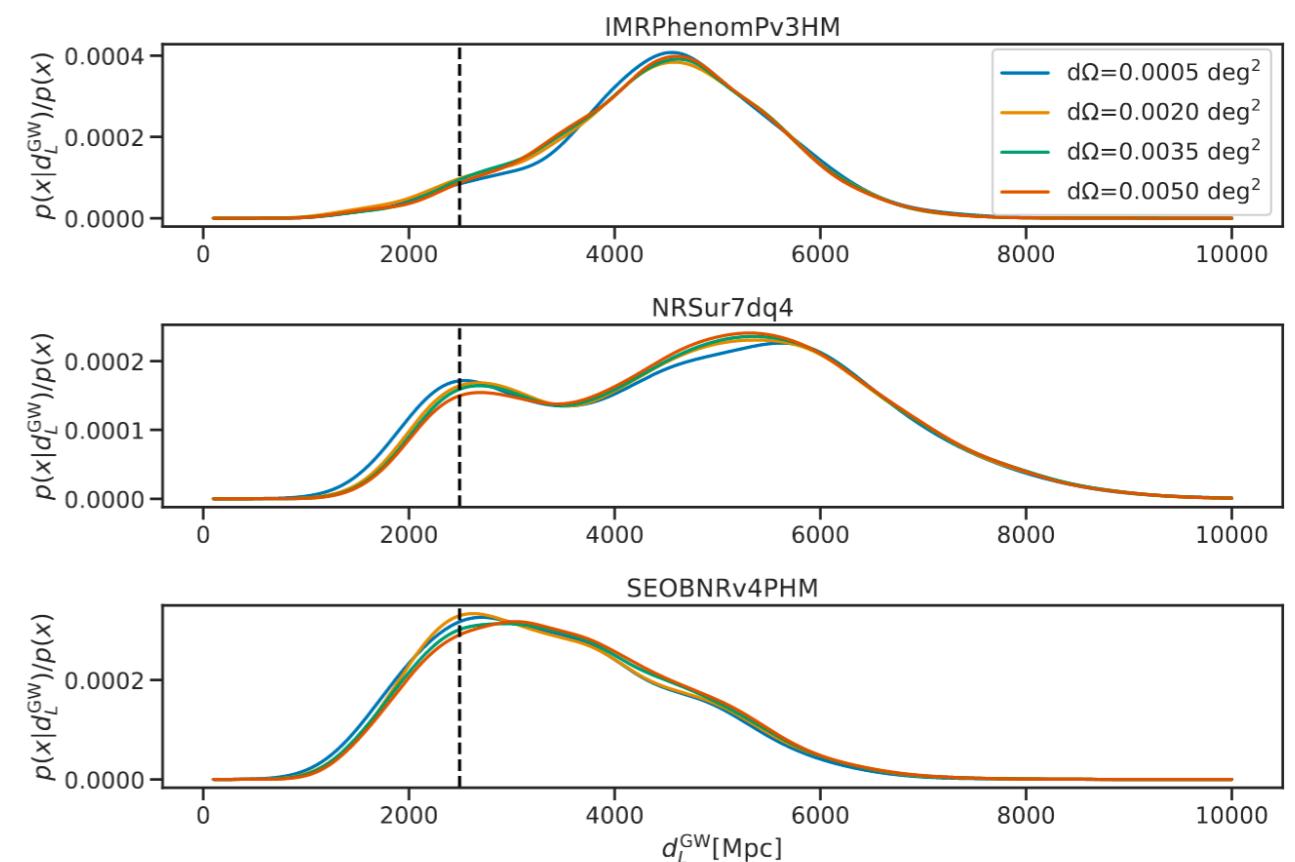
GW friction and extra dimensions

- D=4 is on the edge on the contour due to the luminosity distance posterior skewed towards large values



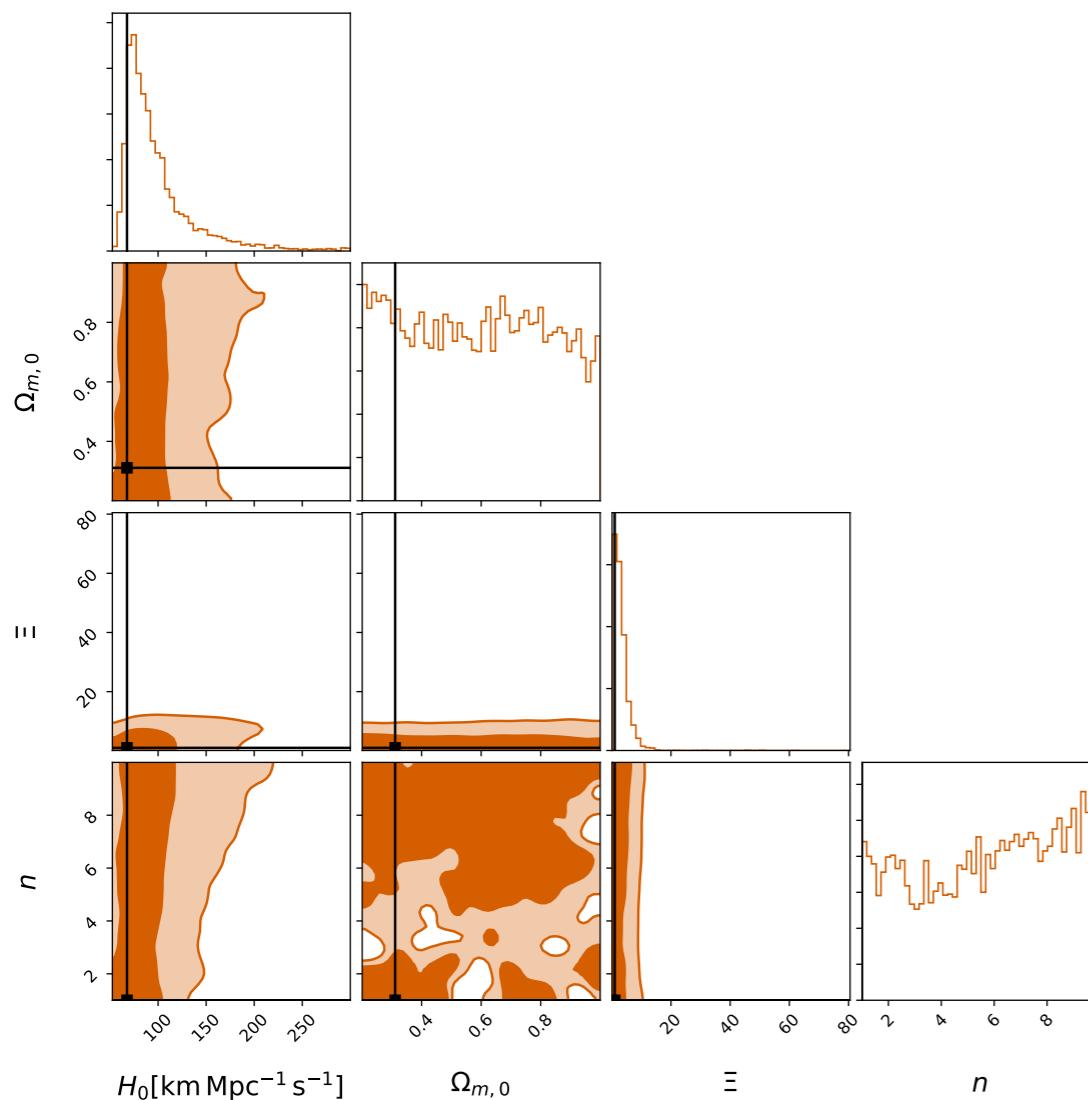
[Mastrogiovanni, Haegel, Karathanasis, Magana-Hernandez, Steer, JCAP 02 \(2021\) 043](#)

$$d_L^{GW}(z) = \left[1 + \left(\frac{d_L^{EM}(z)}{R_c} \right)^n \right]^{\frac{D-2}{2n}}$$



From GW friction to scalar-tensor theories

- Scalar-tensor theories of gravitation parameterisation
(Brans-Dicke, Horndeski, beyond-Horndeski, DHOST)



$$d_L^{GW}(z) = d_L^{EM}(z) \left[\Xi + \frac{1 - \Xi}{(1 + z)^n} \right]$$

Model	$\Xi_0 - 1$	n	Refs.
HS $f(R)$ gravity	$\frac{1}{2}f_{R0}$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$	[68]
Designer $f(R)$ gravity	$-0.24\Omega_m^{0.76}B_0$	$3.1\Omega_m^{0.24}$	[69]
Jordan–Brans–Dicke	$\frac{1}{2}\delta\phi_0$	$\frac{3(\tilde{n}+1)\Omega_m}{4-3\Omega_m}$	[70]
Galileon cosmology	$\frac{\beta\phi_0}{2M_{\text{Pl}}}$	$\frac{\dot{\phi}_0}{H_0\phi}$	[71]
$\alpha_M = \alpha_{M0}a^{\tilde{n}}$	$\frac{\alpha_{M0}}{2\tilde{n}}$	\tilde{n}	[67]
$\alpha_M = \alpha_{M0}\frac{\Omega_\Lambda(a)}{\Omega_\Lambda}$	$-\frac{\alpha_{M0}}{6\Omega_\Lambda}\ln\Omega_m$	$-\frac{3\Omega_\Lambda}{\ln\Omega_m}$	[67, 72]
$\Omega = 1 + \Omega_+a^{\tilde{n}}$	$\frac{1}{2}\Omega_+$	\tilde{n}	[6]
Minimal self-acceleration	$\lambda \left(\ln a_{\text{acc}} + \frac{C}{2}\chi_{\text{acc}} \right)$	$\frac{C/H_0-2}{\ln a_{\text{acc}}^2-C\chi_{\text{acc}}}$	[66]

Alternatives theories of gravity

- **Doubly special relativity:**

Modification of special relativity with the addition of an observer-independent maximum energy ; length scale (Planck length / energy). Motivation: same scale of quantum gravity effects for all observers

[Amelino-Camelia, Symmetry 2 \(2010\) 230–271](#)

- **Hořava-Lifshitz gravity:**

Quantisation of gravitation with a QFT approach, where ghosts are avoided by introducing anisotropic scaling between space and time at high energies

[Wang, Int. J. Mod. Phys. D26 \(2017\) 1730014](#)

- **DGP gravity:**

Extension of the Einstein-Hilbert action to a 4+1 Minkowski space. Motivation: acceleration of the Universe expansion without Λ .

[Dvali, Gabadadze, Porrati. Phys. Lett. B 485:208–214 \(2000\)](#)

- **Horndeski (and beyond) gravity:**

General formulation of scalar-tensor theory of gravitation (includes Brans-Dicke, DHOST, linked to Gauss-Bonet). Particularly used to study inflation, metric perturbation, cosmological effects.

[Kobayashi. Rept. Prog. Phys. 82 \(2019\) no.8, 086901](#)

- **f(R) gravity:**

Class of beyond-GR theory where the Ricci scalar R follows an arbitrary function. Presence of equivalence with scalar-tensor theories for GW.

[Sotiriou, Faraoni. Rev. Mod. Phys. 82:451–497 \(2010\)](#)