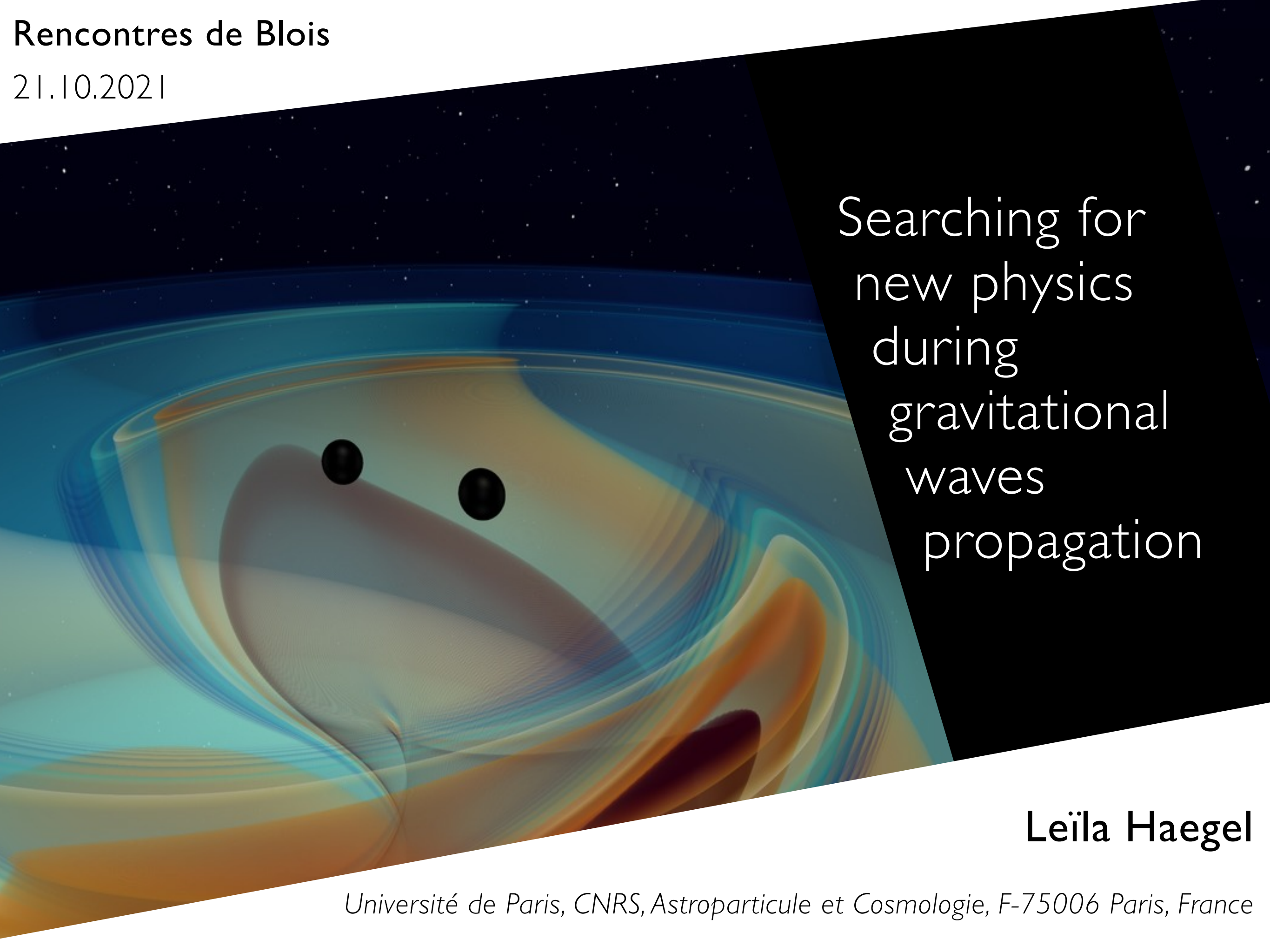


Rencontres de Blois

21.10.2021



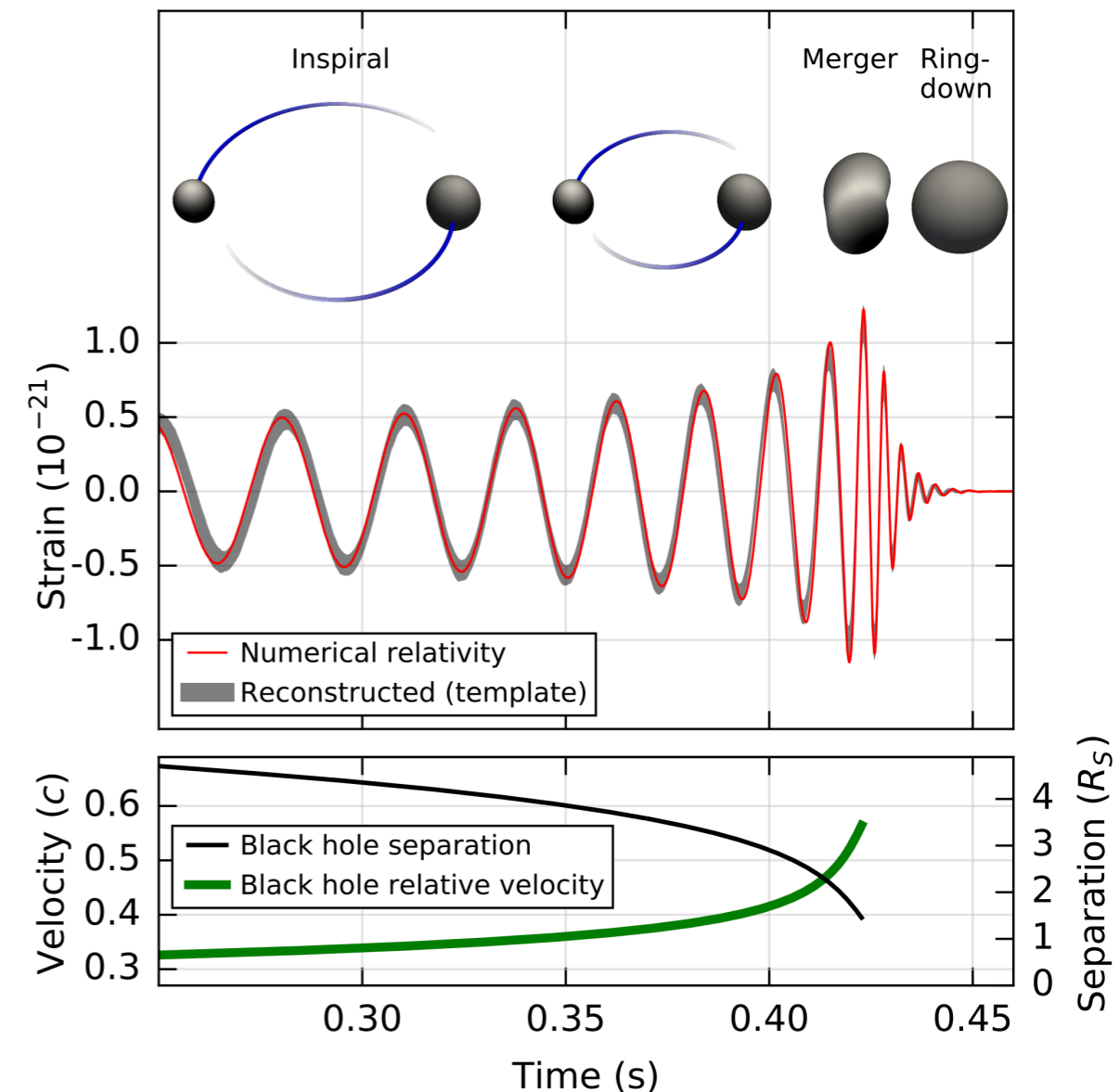
Searching for  
new physics  
during  
gravitational  
waves  
propagation

**Leila Haegel**

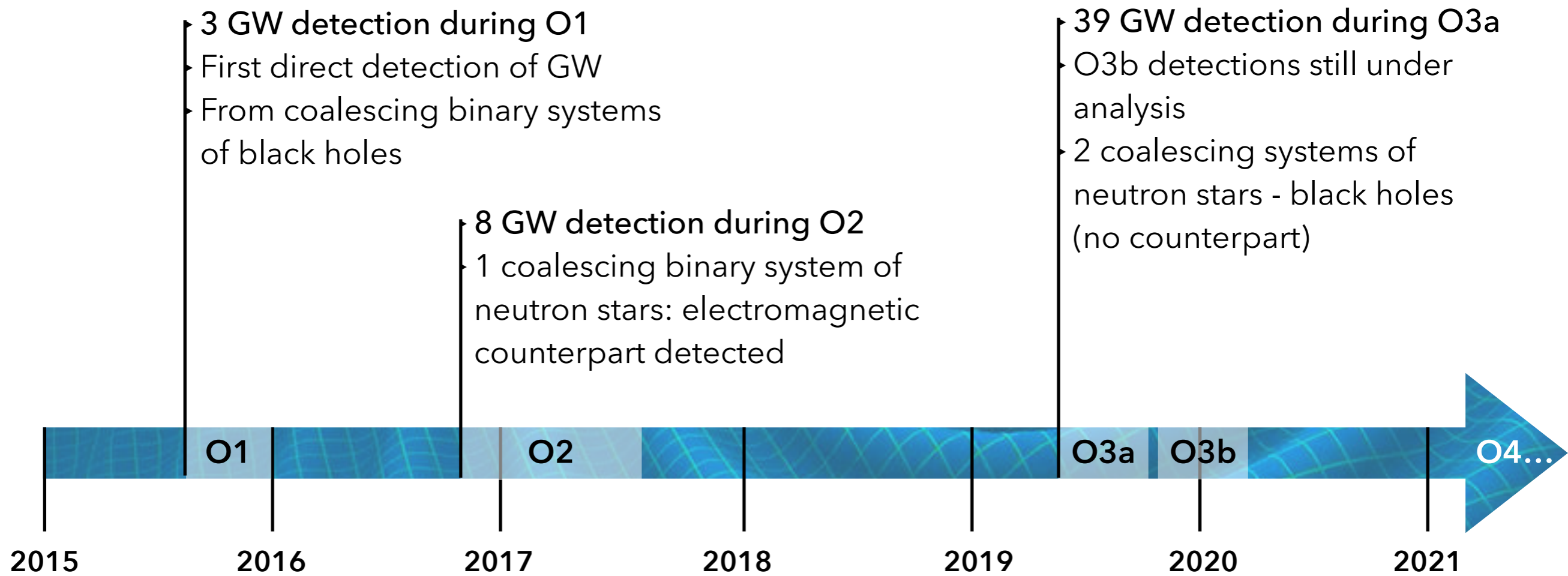
*Université de Paris, CNRS, Astroparticule et Cosmologie, F-75006 Paris, France*

# Introduction

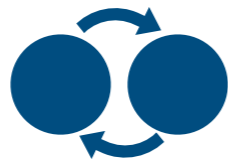
- Gravitational waves (GW) enable to test fundamental physics in the gravitational sector
  - ↳ complementary to tests with solar system, pulsars, gravitational lensing...
- Several approaches to test for deviation from General Relativity
  - ↳ consistency tests
  - ↳ search for phenomena impacting GW 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



**52 GW**  
detections  
reported



**Coalescence of  
compact objects**  
(black holes,  
neutron stars)



**1 multimessenger**  
event (GW + EM  
observation)



**Mass range**  
1.4 → 95  $M_{\odot}$   
(stellar)



**Distance range**  
40 Mpc → 4.4 Gpc  
( $z \rightarrow 0.45$ )

# Gravitational waves propagation

General relativity (GR) case:

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

Modified GR

[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  $h_x$

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  
97, 104037 \(2018\)](#)

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

Mass of  
graviton

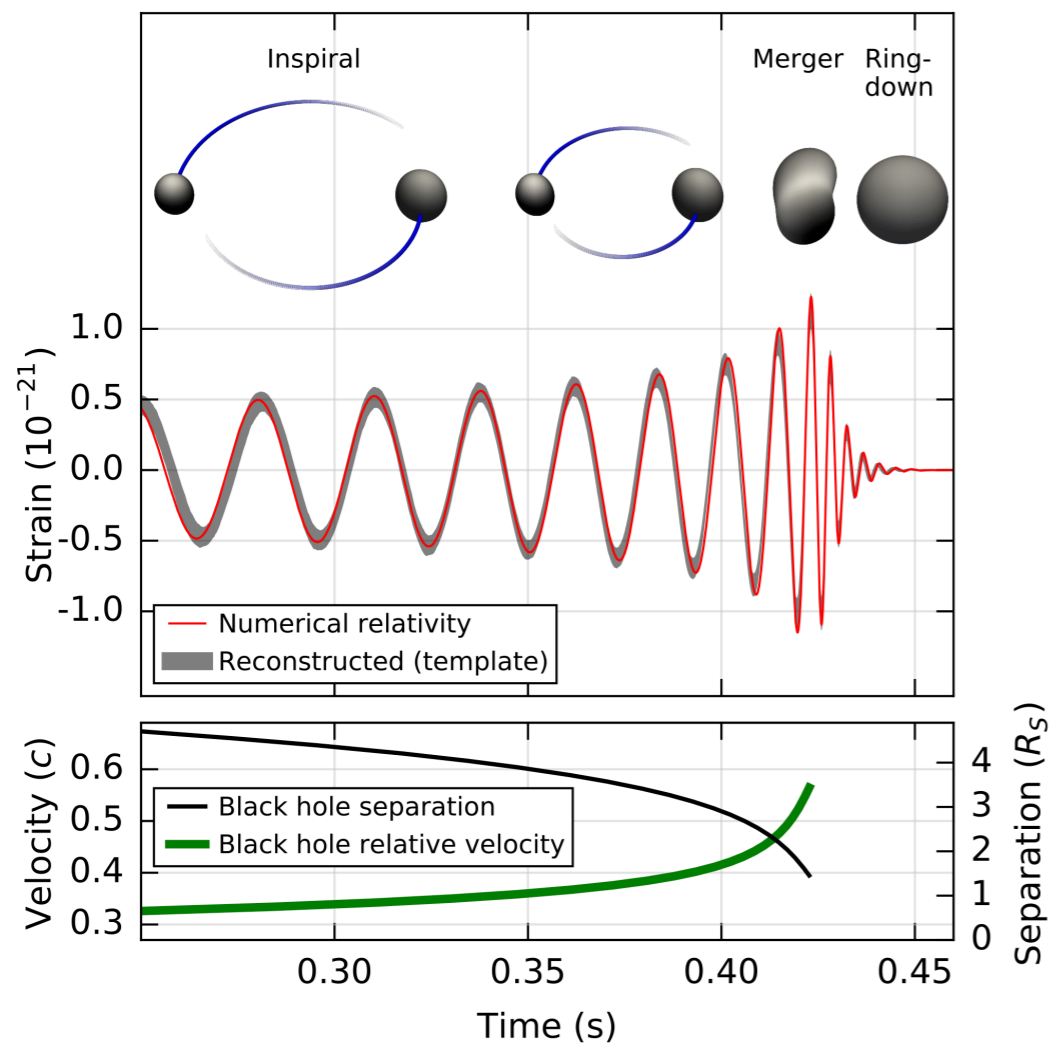
Non-0 graviton  
mass

# 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:
  - anisotropic
  - polarisation independent
  - possibly mapped to alternative theories of gravitation

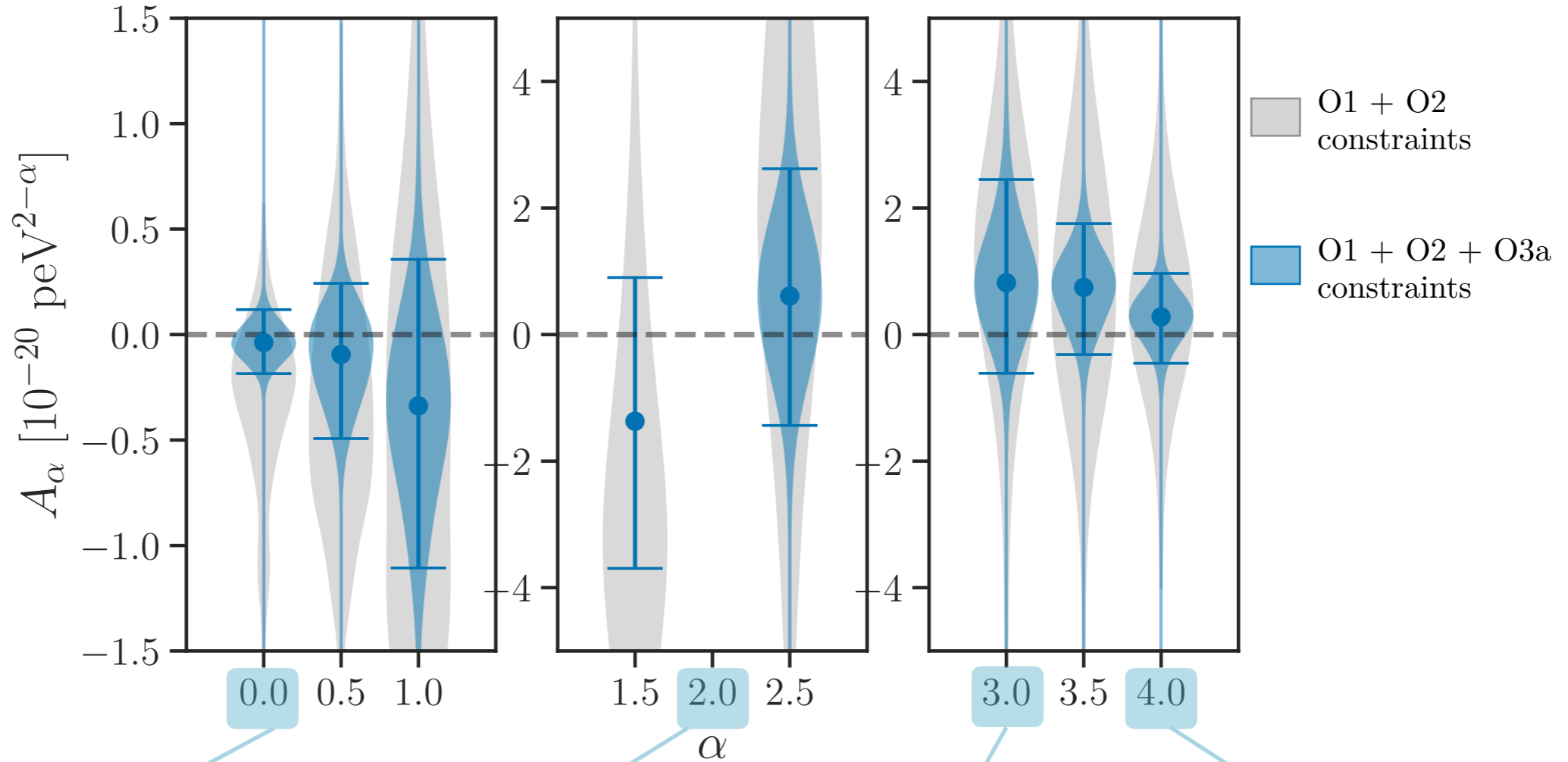
[Mirshekari, Yunes & Will  
Phys. Rev. D85: 024041 \(2012\)](#)

# 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 \(2021\)](#)

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



massive graviton  
 $m_g < 1.76 \cdot 10^{-23} \text{ eV}/c^2$

degeneracy with  
 coalescence time

Doubly Special  
 Relativity

extra dimensions /  
 Hořava-Lifshitz /  
 non commutative geometry

# 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 \(2018\)](#)

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

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
$\begin{array}{ c c c } \hline \mu & \nu & \dots \\ \hline \rho & \sigma & \\ \hline \circ & \circ & \\ \hline \end{array}$	$s^{(d)\mu\rho\nu\sigma\circ\circ\circ^{d-4}}$	even	even, $\geq 4$	$(d-3)(d-2)(d+1)$
$\begin{array}{ c c c c } \hline \mu & \nu & \sigma & \dots \\ \hline \rho & \circ & \circ & \\ \hline \circ & & & \\ \hline \end{array}$	$q^{(d)\mu\rho\nu\sigma\circ\circ\circ^{d-5}}$	odd	odd, $\geq 5$	$\frac{5}{2}(d-4)(d-1)(d+1)$
$\begin{array}{ c c c c c } \hline \mu & \nu & \rho & \sigma & \dots \\ \hline \circ & \circ & \circ & \circ & \\ \hline \end{array}$	$k^{(d)\mu\nu\sigma\rho\circ\circ\circ\circ^{d-6}}$	even	even, $\geq 6$	$\frac{5}{2}(d-5)d(d+1)$

→ Impact GW momentum: dispersion effect, this study

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

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



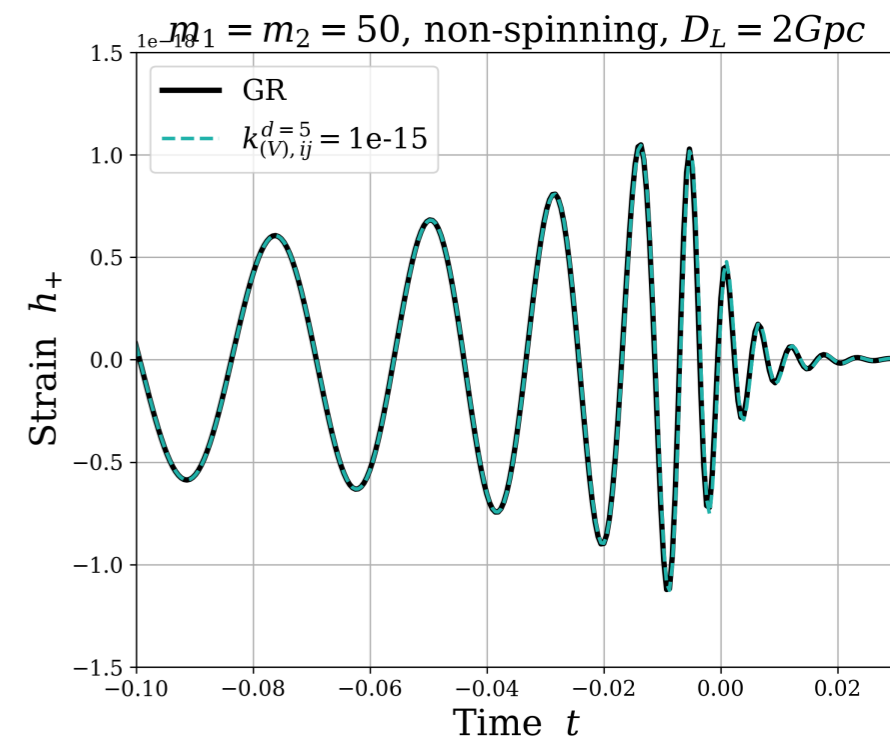
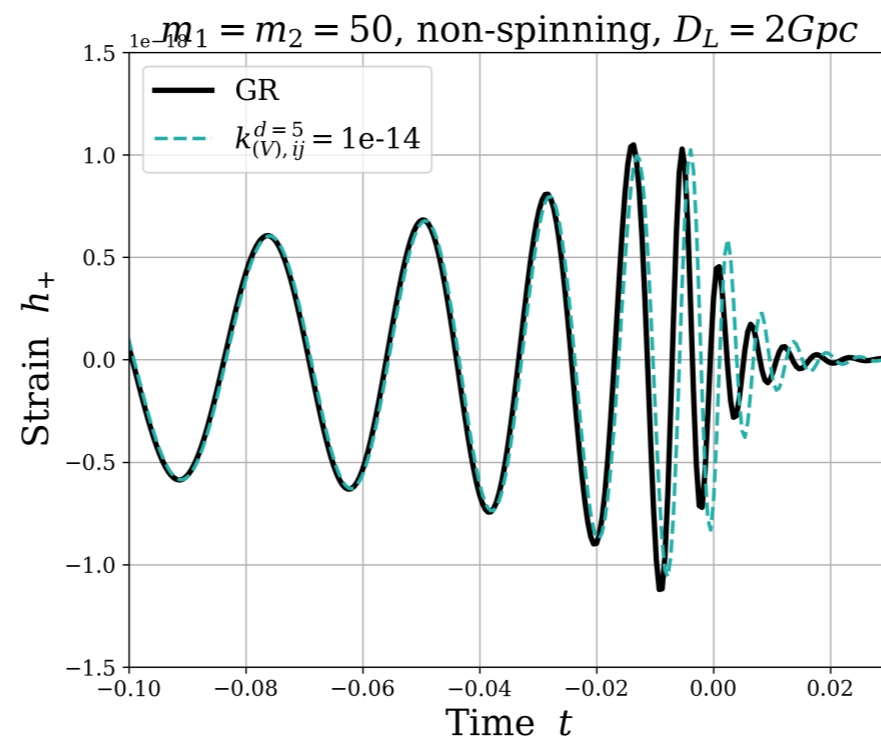
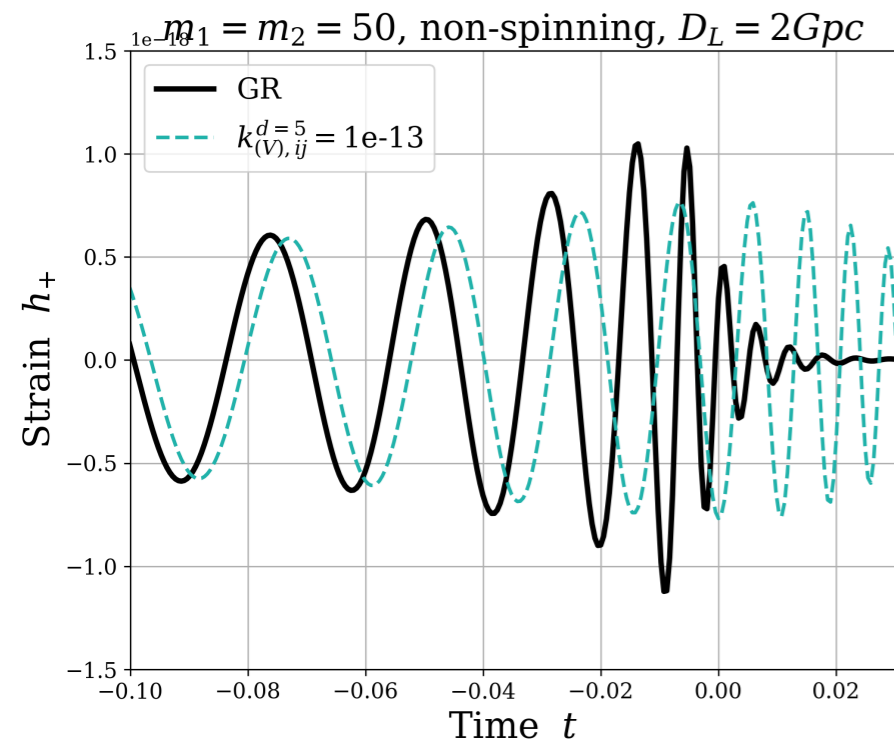
# Polarisation-dependent, anisotropic dispersion

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

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

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

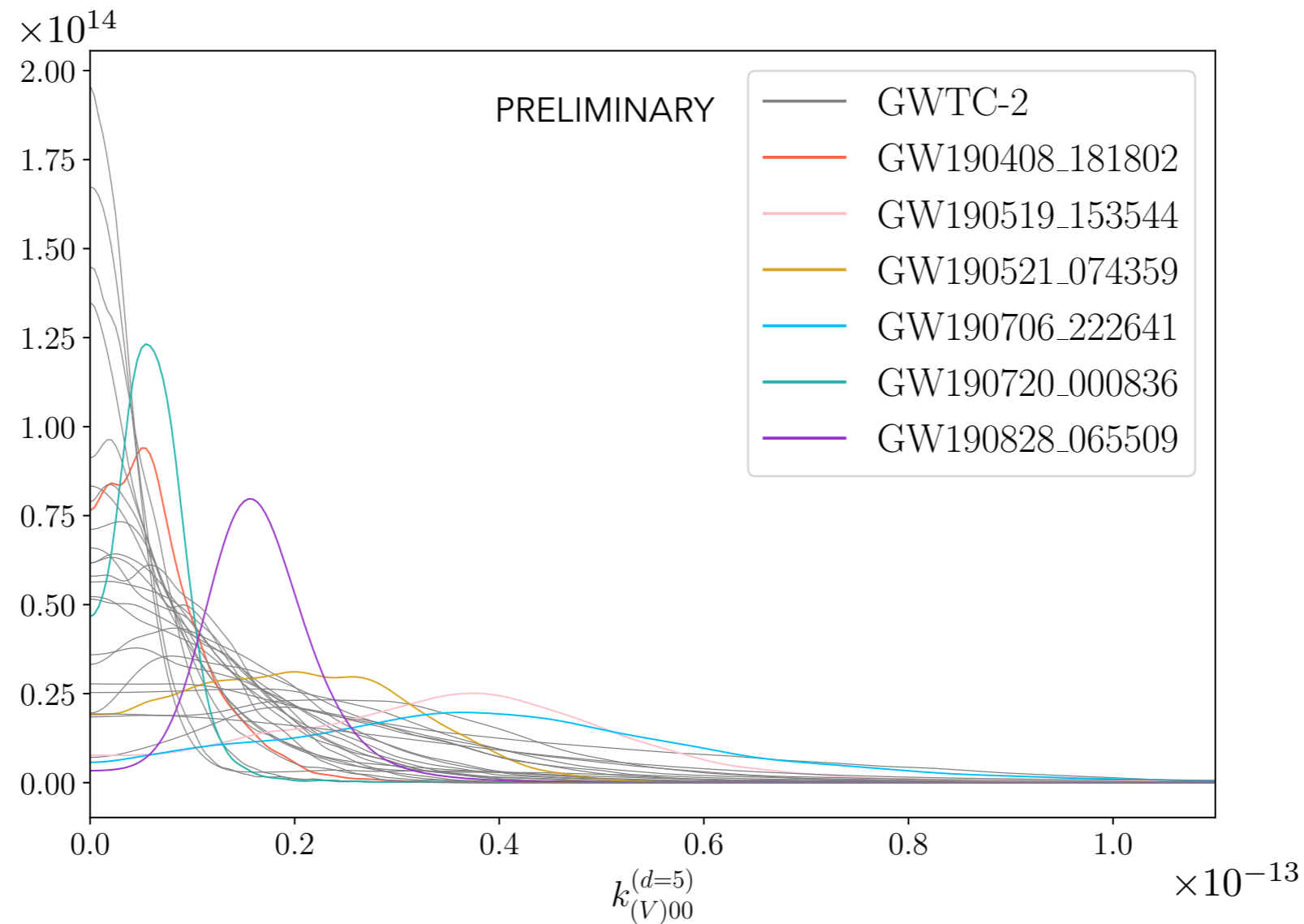
[Mewes, Phys. Rev. D 99, 104062 \(2019\)](#)



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

# Polarisation-dependent, anisotropic dispersion

- Analysis of events from O1 + O2 + O3a ongoing
- Preliminary results with 28 events shows individual limit  $\sim \mathcal{O}(10^{-13})$ , joined limit  $\sim \mathcal{O}(10^{-15})$  at 90% CI



# 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 \(2018\)](#)

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

Speed of  
gravity

Speed of  
GW  $\neq c$

# 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
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$\begin{array}{ c c c c c } \hline \mu & \nu & \rho & \sigma & \dots \\ \hline \circ & \circ & \circ & \circ & \\ \hline \end{array}$	$k^{(d)\mu\nu\sigma\rho\circ\circ\circ\circ^{d-6}}$	even	even, $\geq 6$	$\frac{5}{2}(d-5)d(d+1)$

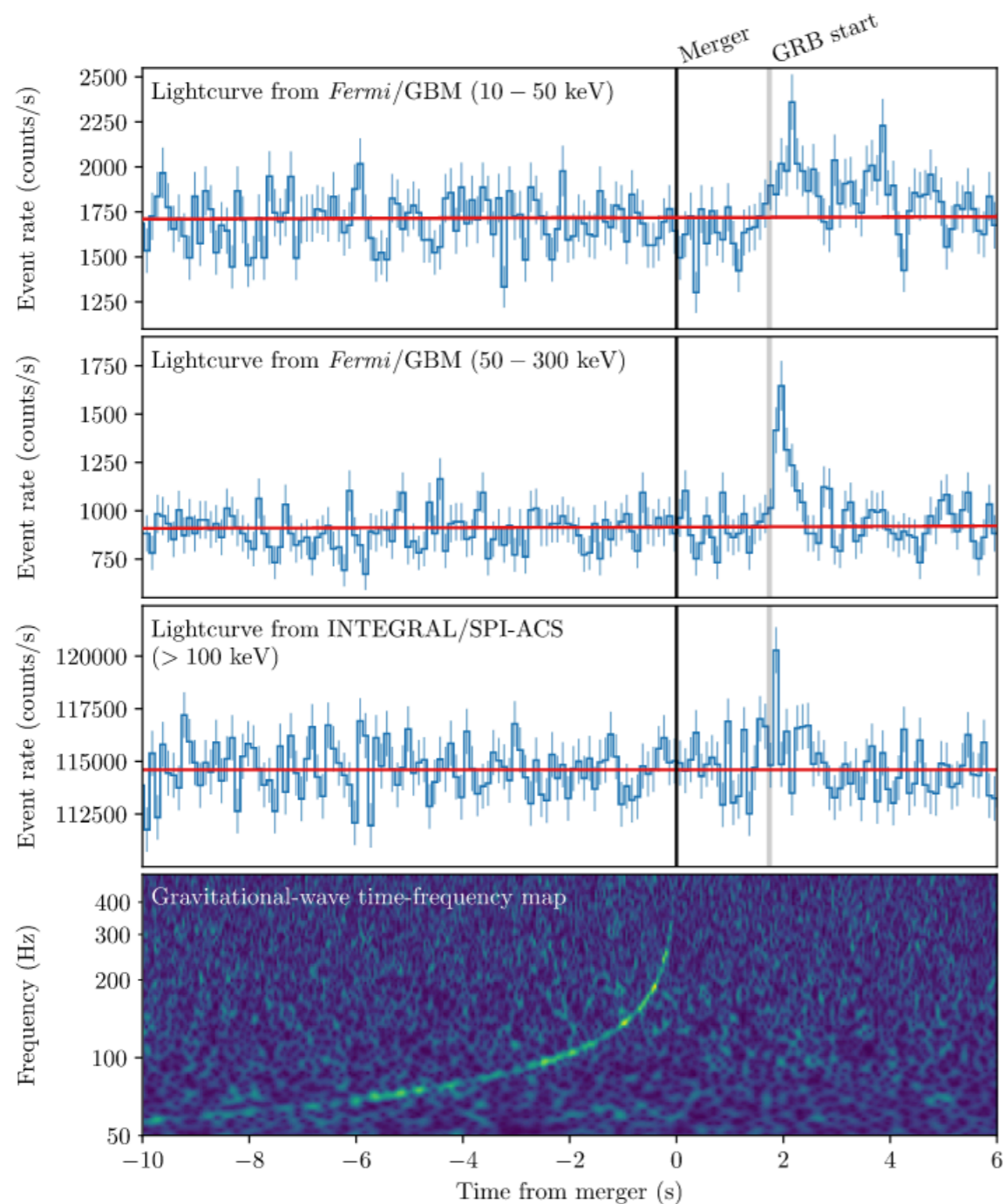
Impact GW velocity:  
constrained with the  
BNS event GW170817

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:

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

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



# 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 \(2018\)](#)

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

GW friction

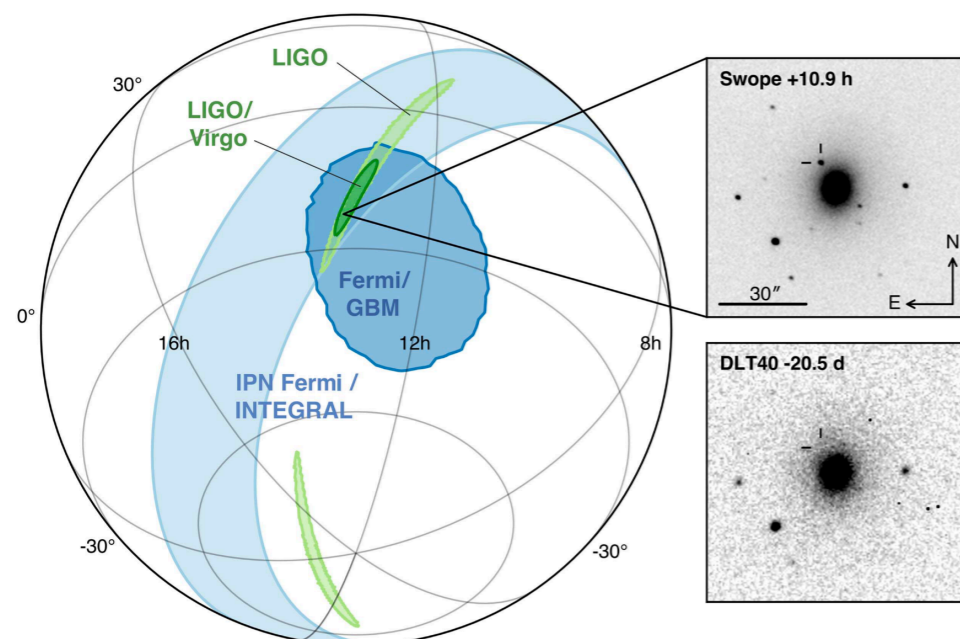
Amplitude  
does not scale  
as 1/distance

# 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

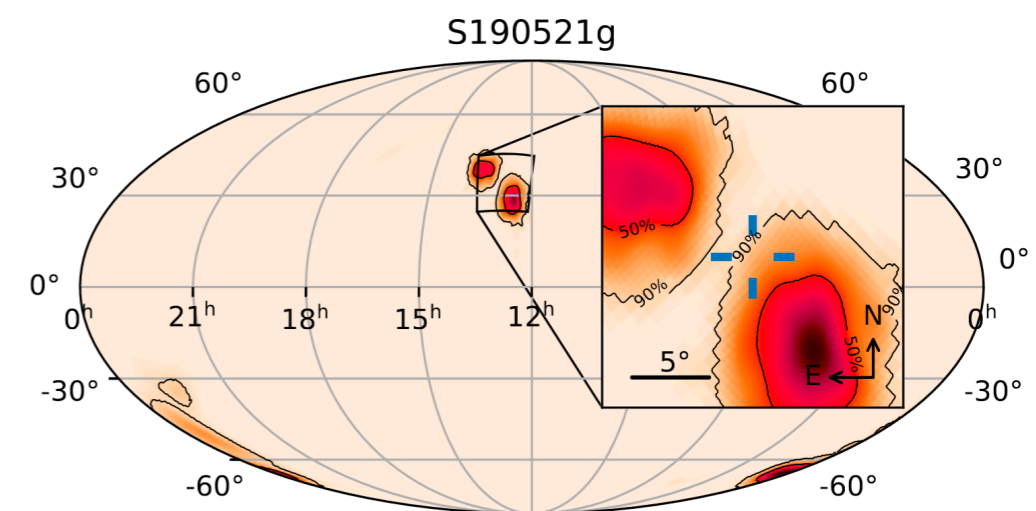
- ▶ **GW170817:**

- binary neutron star merger
- $z \approx 0.01$



- ▶ **GW190521:**

- binary black holes merger
- potential location in AGN disk creating electromagnetic signal (not confirmed)
- $z \approx 0.44$



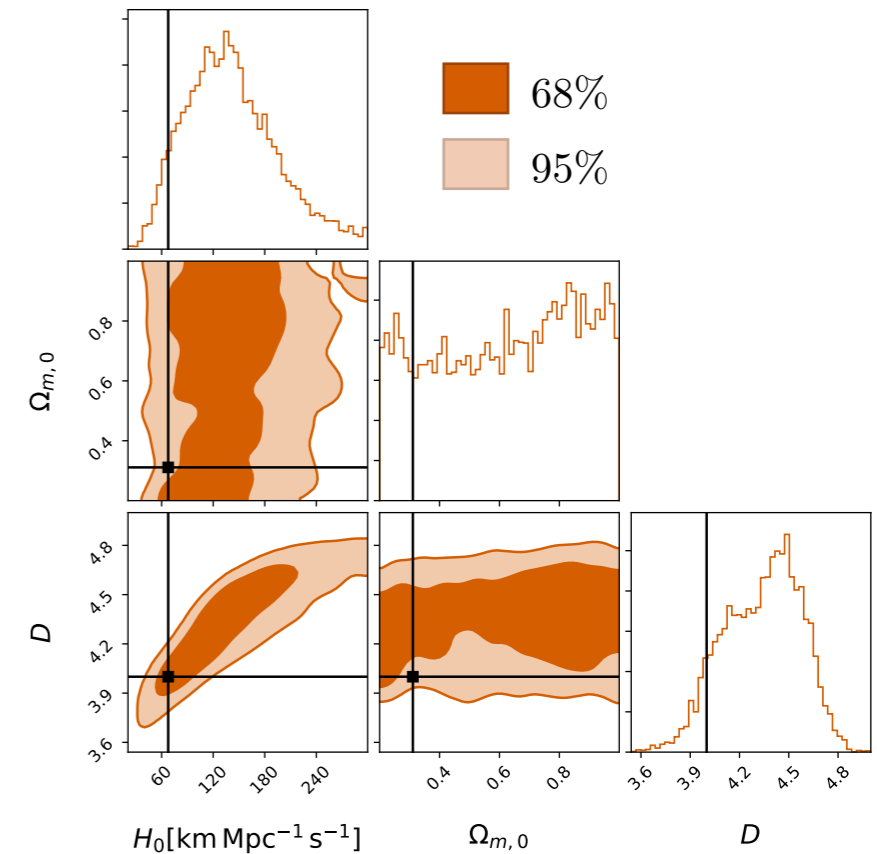
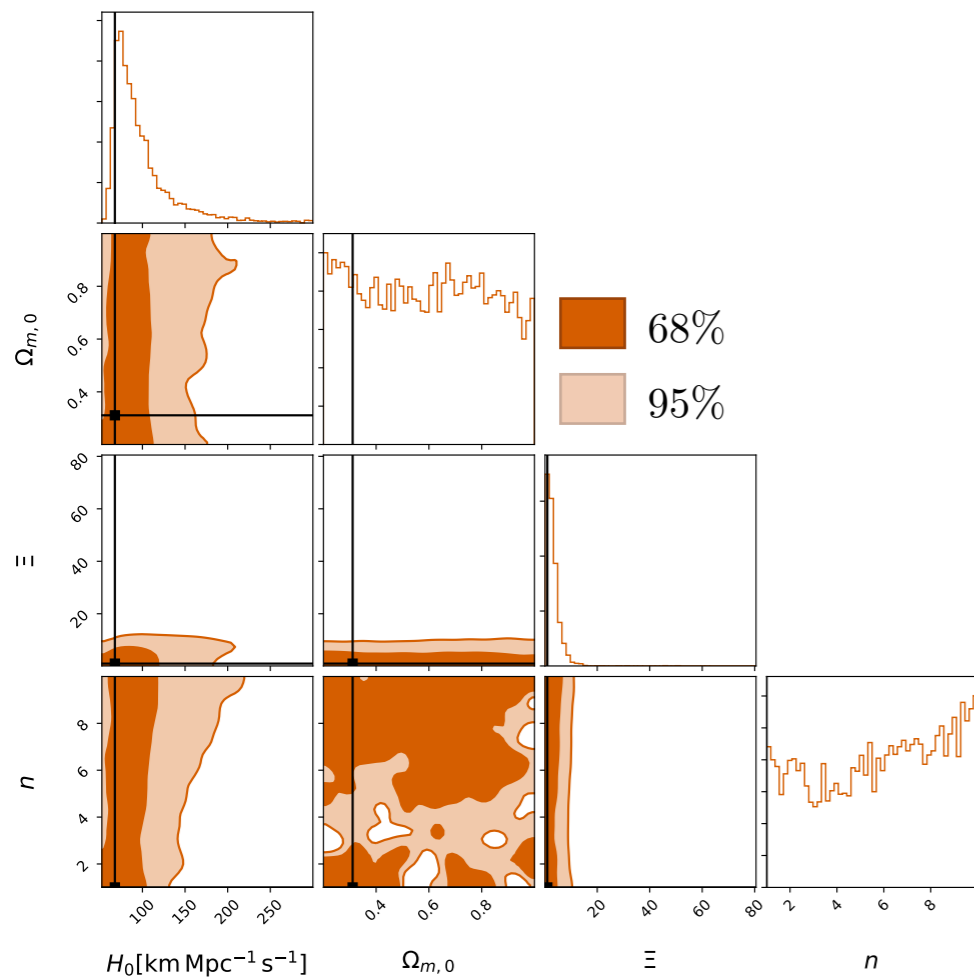
[LVC, Phys. Rev. Lett. 125, 101102 \(2020\)](#)

[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)

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



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

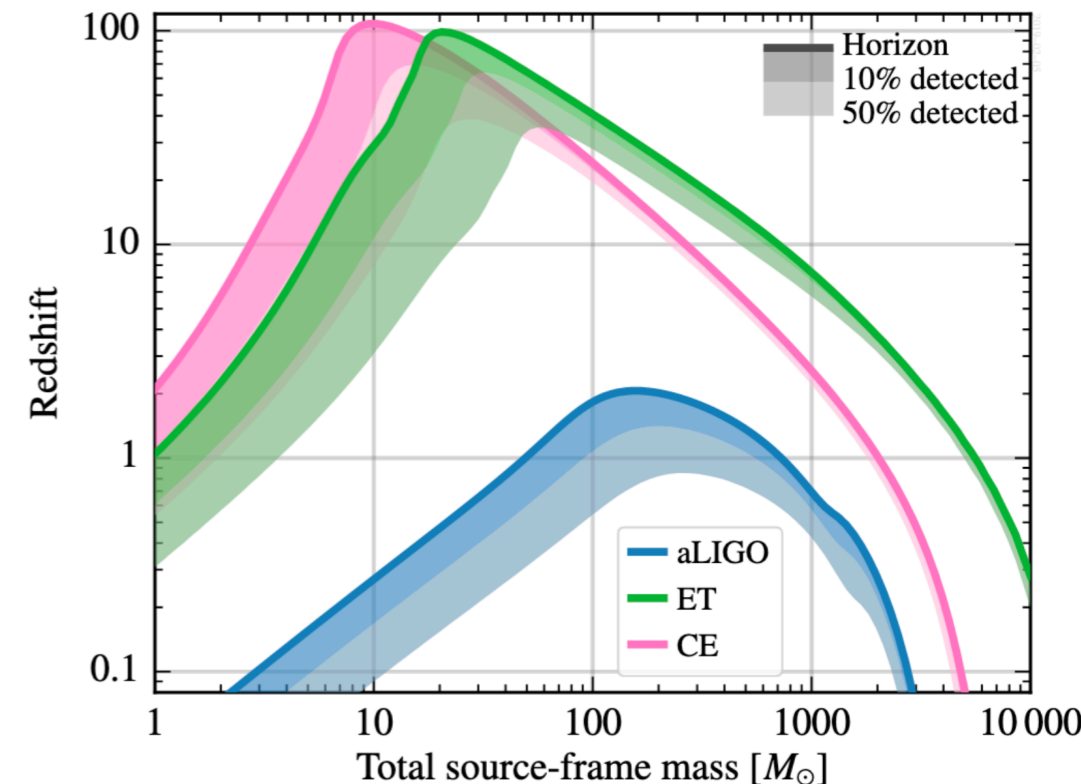
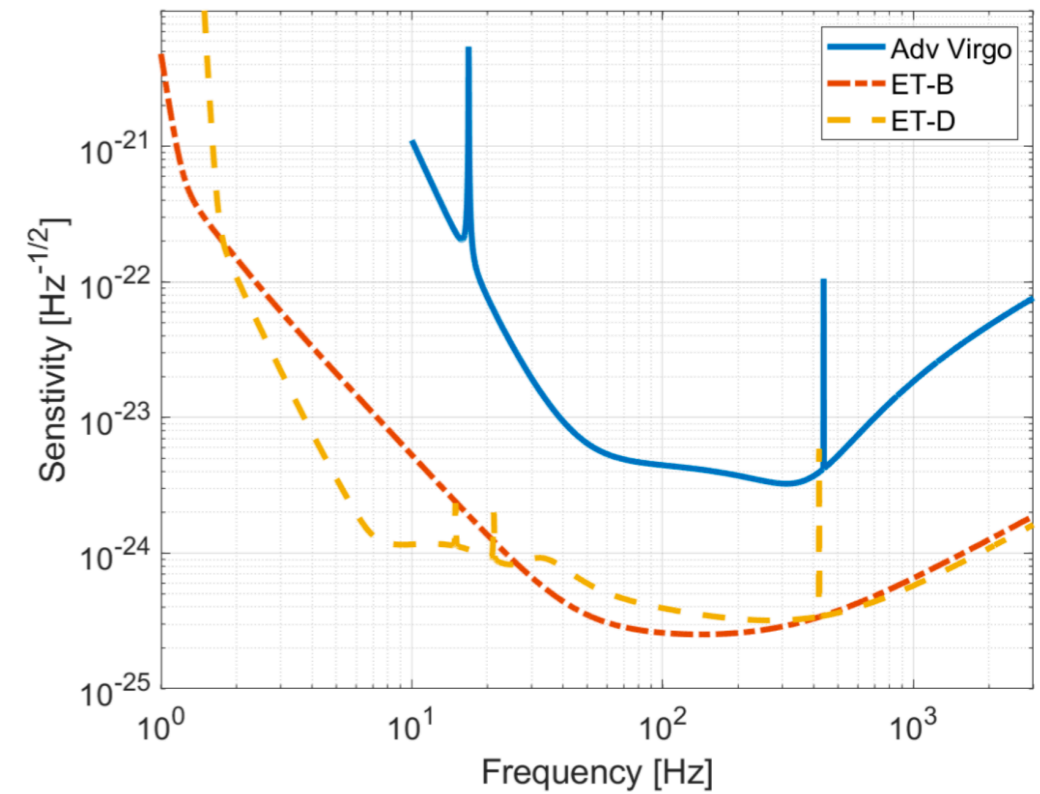
$$d_L^{GW}(z) = d_L^{EM}(z) \left[ \Xi + \frac{1 - \Xi}{(1+z)^n} \right]$$

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

# Conclusion

- 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

Maggiore et al, JCAP 03 (2020) 050

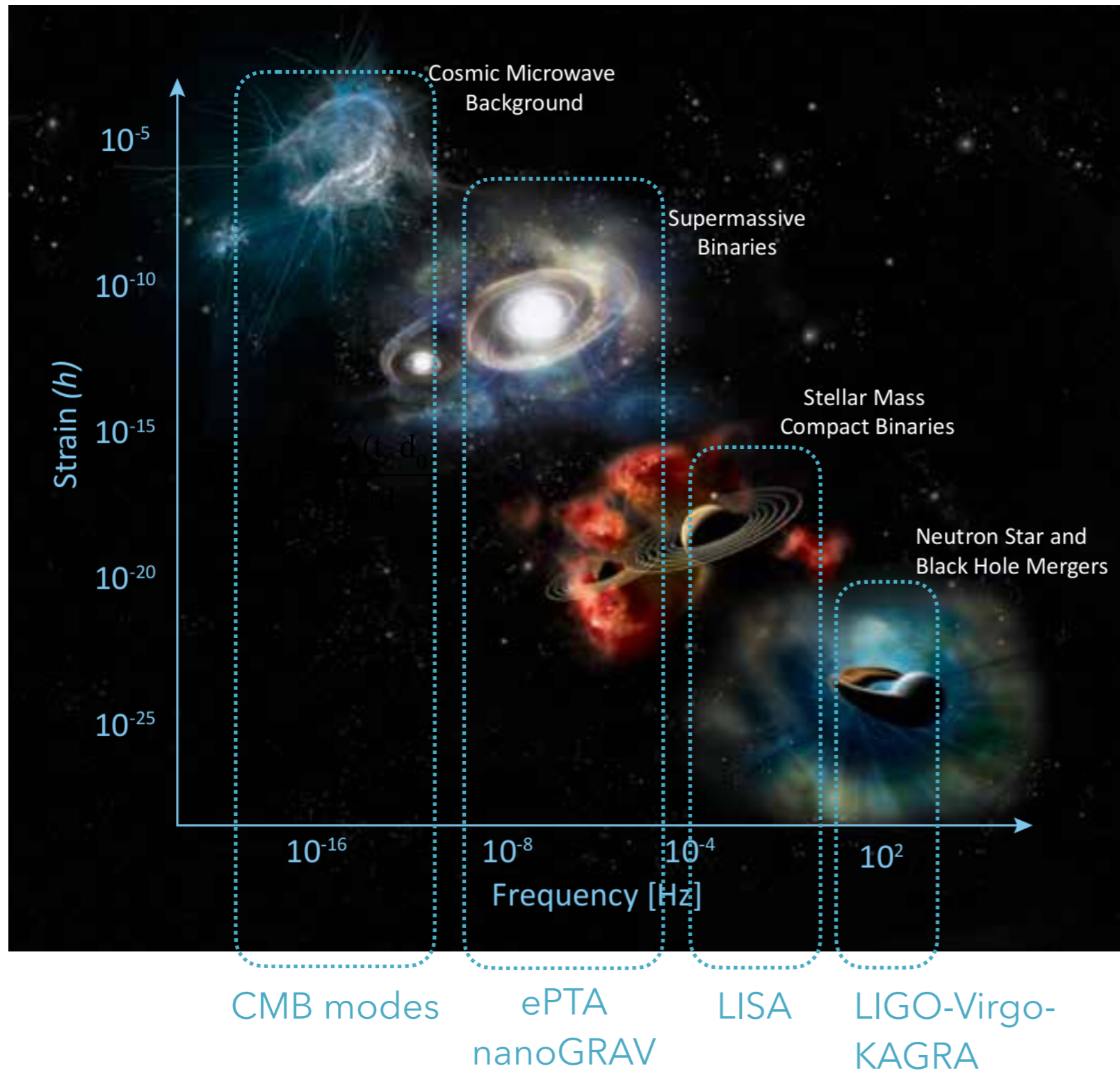


# Bonus

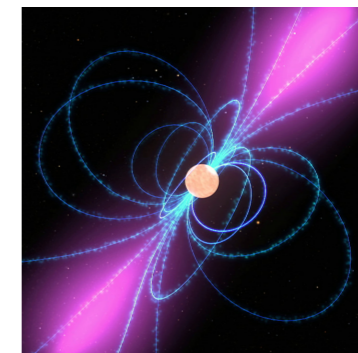


# Gravitational waves sources

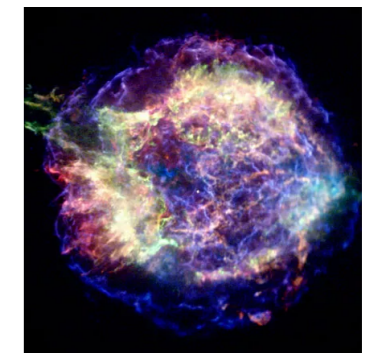
Credit: SSU EPO/Aurore Simonnet



+ 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

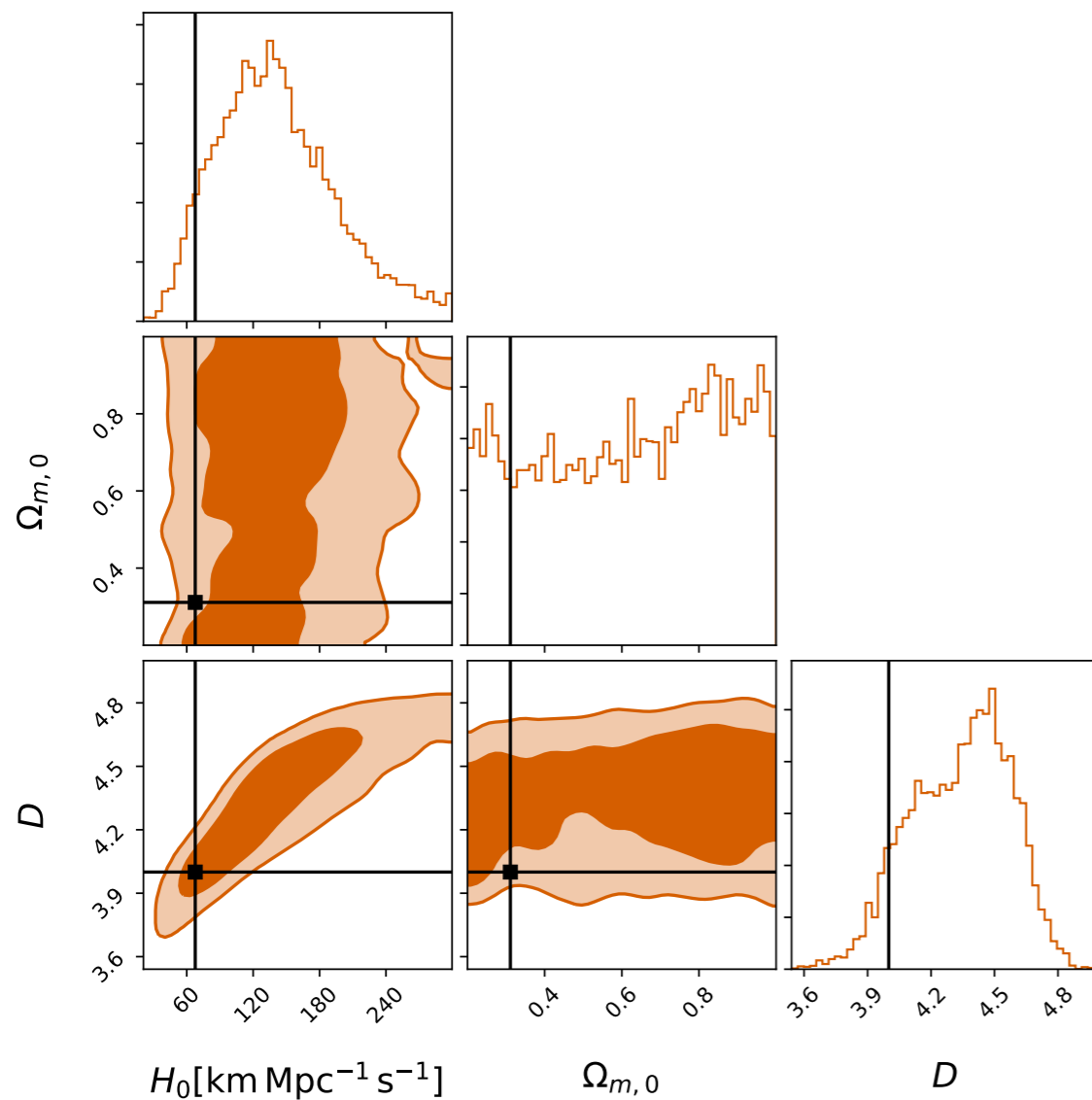
$$\beta = \omega^2 \tau \left| \begin{aligned} & \frac{1}{2} \frac{1}{\sqrt{\pi}} k_{00} \\ & + \frac{1}{2} \sqrt{\frac{3}{\pi}} \cos \theta k_{10} \\ & - \sqrt{\frac{3}{2\pi}} \sin \theta (\cos \phi \operatorname{Re}(k_{11}) - \sin \phi \operatorname{Im}(k_{11})) \\ & + \frac{1}{4} \sqrt{\frac{5}{\pi}}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

$k_{(V),eff}^{(d=5)}$  ←

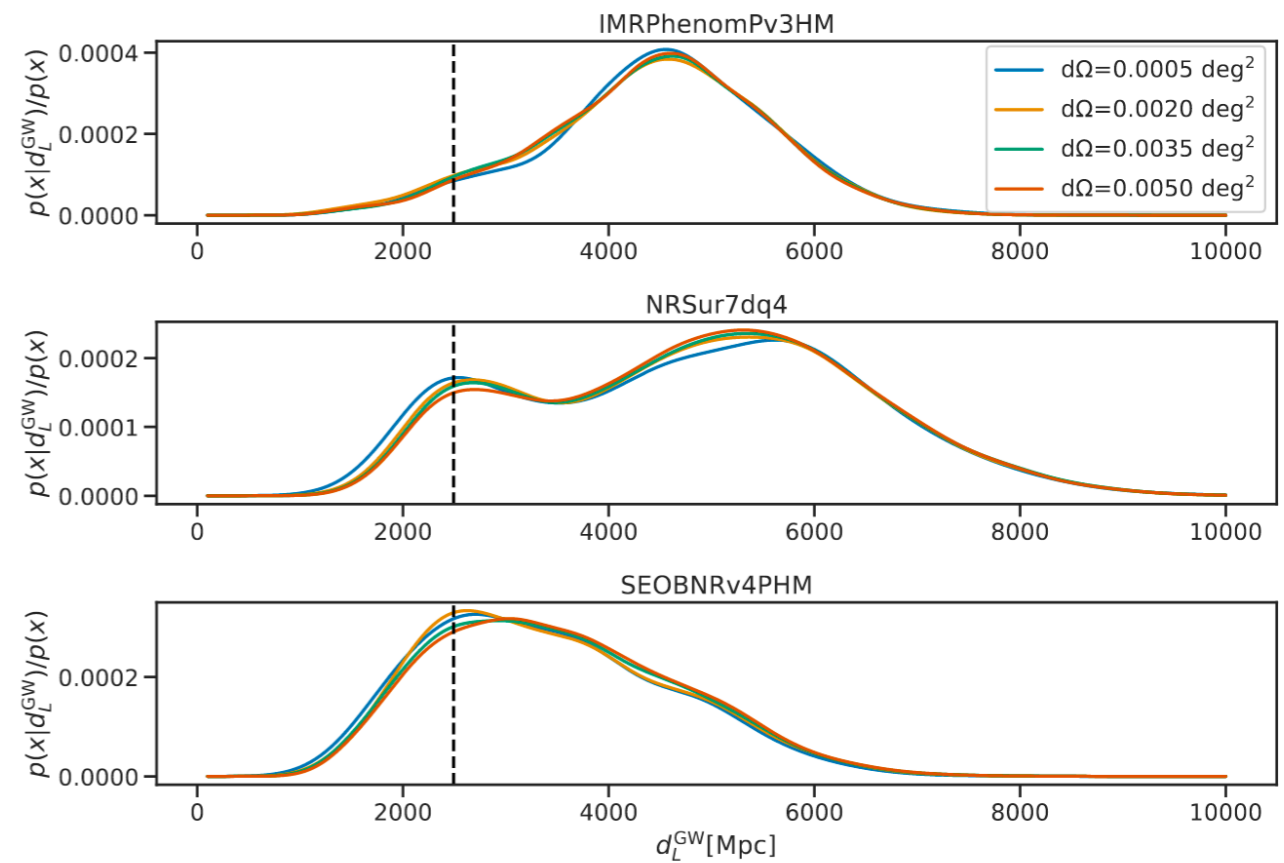
# GW friction and extra dimensions

- 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](#)



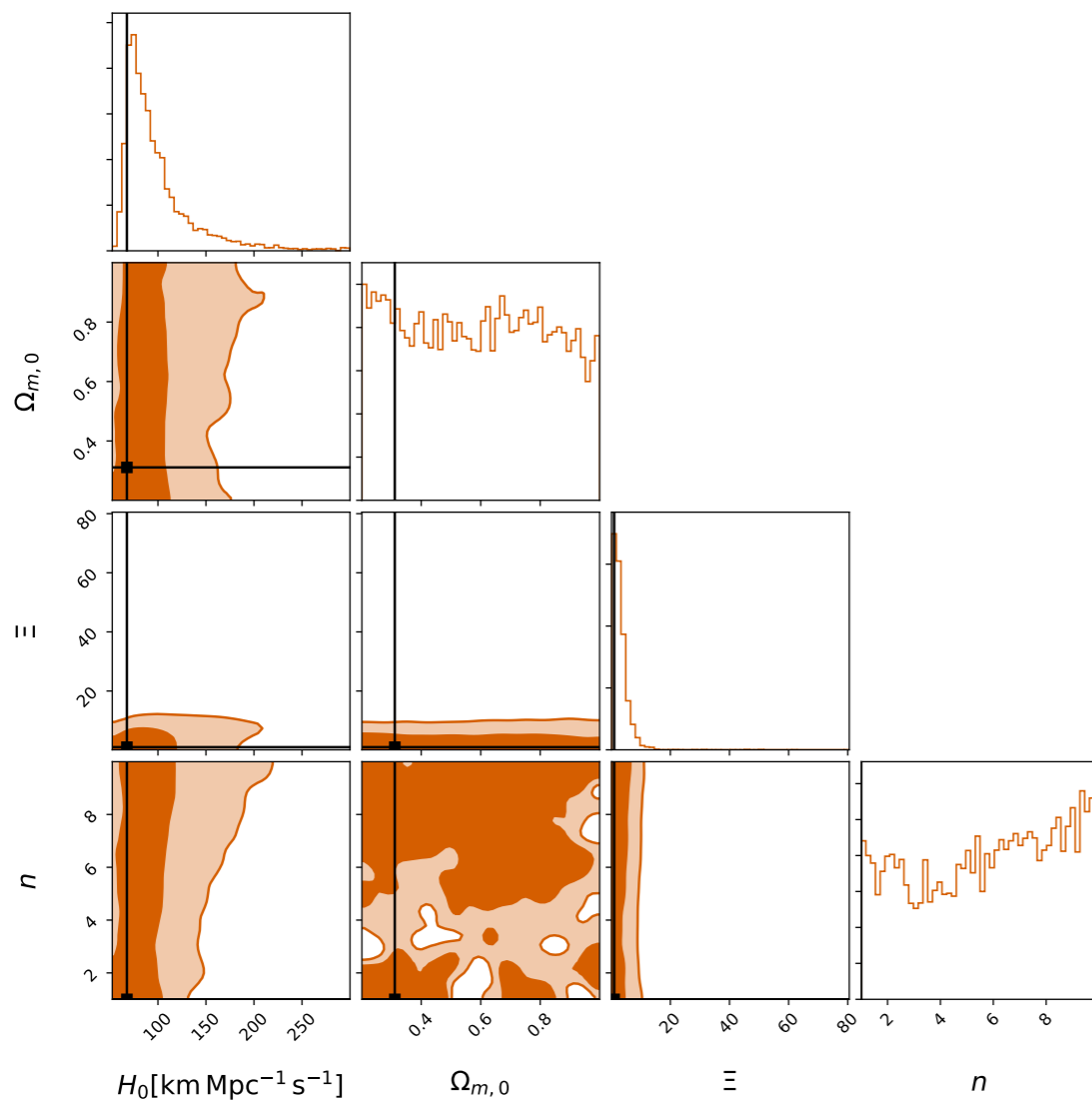
$$d_L^{GW}(z) = \left[ 1 + \left( \frac{d_L^{EM}(z)}{R_c} \right)^n \right]^{\frac{D-2}{2n}}$$



# 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]

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

[Belgacem et al, JCAP07 \(2019\) 024](#)

# 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  $\Lambda$ .

[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-Bonnet). 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 \(2010\)](#)