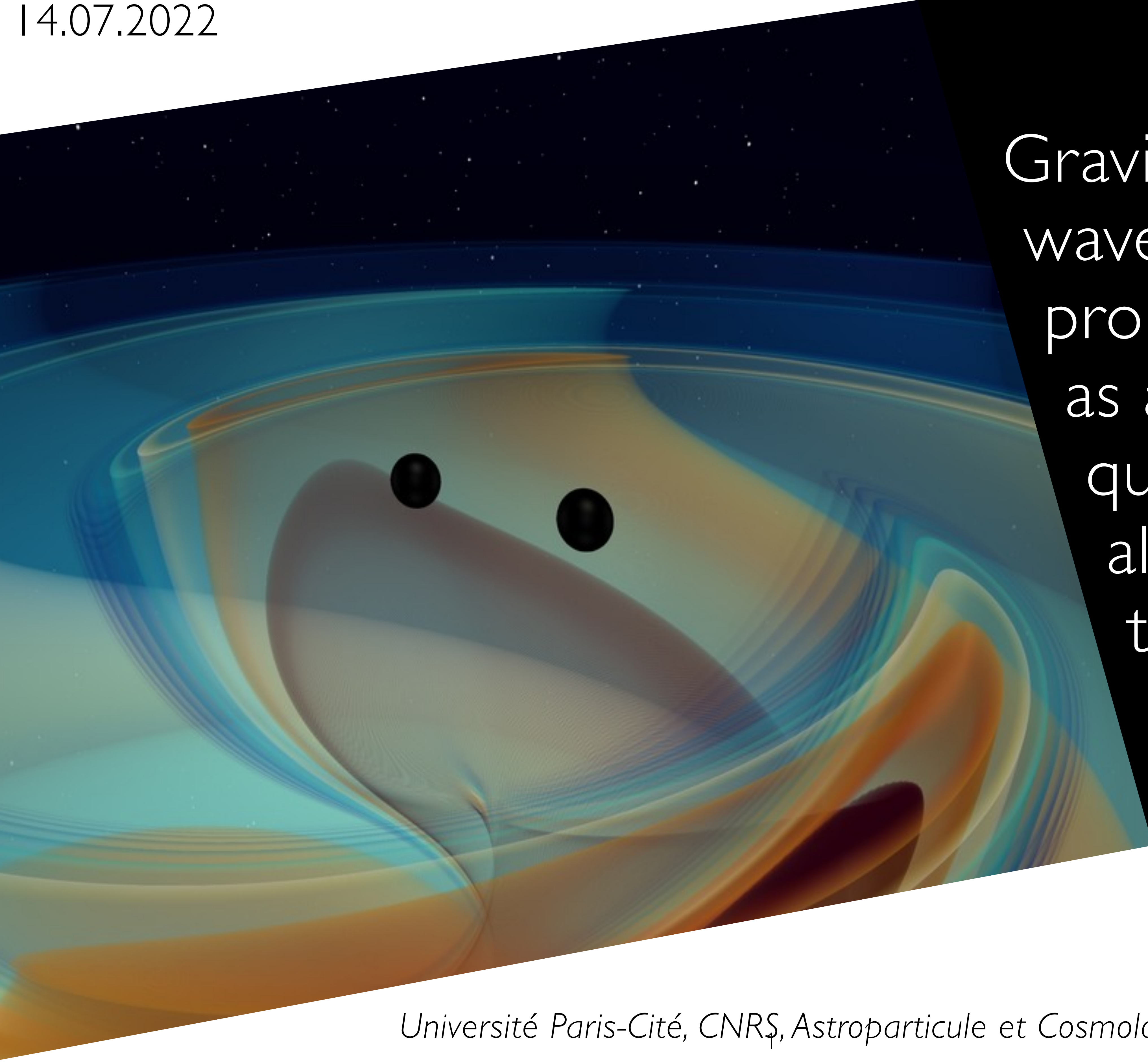
COST18108 QG-MM Conference

14.07.2022



Gravitational waves propagation as a probe of quantum and alternative theories of gravity

Leïla Haegel

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Outline

- **Gravitational waves physics**
  - ↳ nature and sources
  - ↳ detectors and instruments
  - ↳ detection status
  - ↳ analysis methods

- **Propagation tests with multi messenger events**
  - ↳ gravitational waves friction
  - ↳ gravitational waves lensing
  - ↳ speed of gravity
  - ↳ tests of Lorentz invariance violation

- **Propagation tests with gravitational waves signals**
  - ↳ modified dispersion relation
  - ↳ mass of the graviton
  - ↳ tests of Lorentz invariance & CPT breaking
  - ↳ anisotropies and spacetime birefringence

Outline: GW physics

- **Gravitational waves physics**
  ↳ nature and sources
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Gravitational waves primer

- **A propagating space-time perturbation predicted by GR**
  Gravitational waves (GW) modify a spacetime interval as:

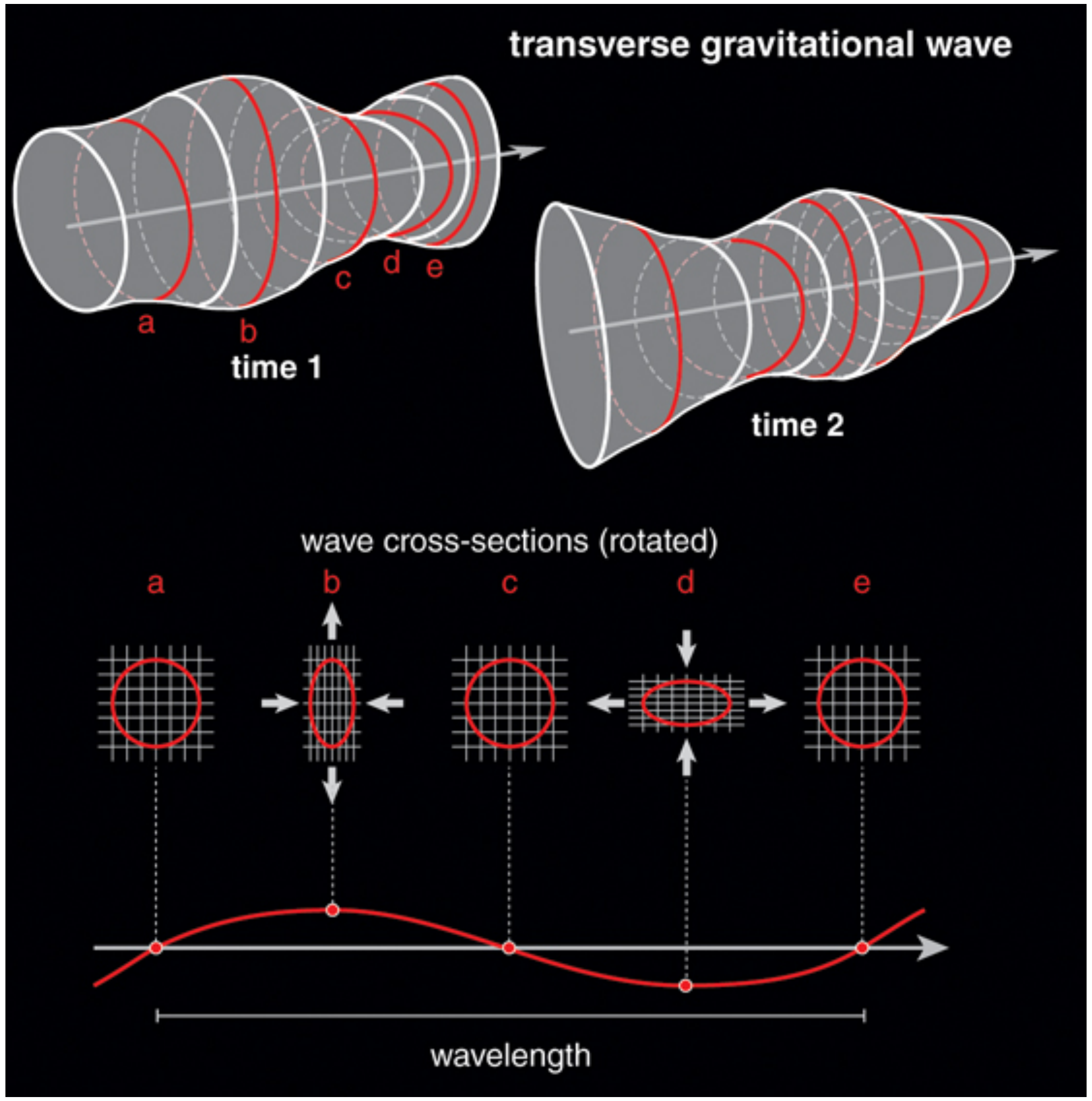
$$ds^2 = -c\ dt^2 + [1 + h(z \pm ct)]\ dx^2 + [1 - h(z \pm ct)]\ dy^2 + dz^2$$

propagate at speed of light — *GW deformation* — *transverse waves*

- **Properties:**
  2 polarisation states, h_+ and $h_\times$
  Tensor perturbation
  Quadrupolar radiation

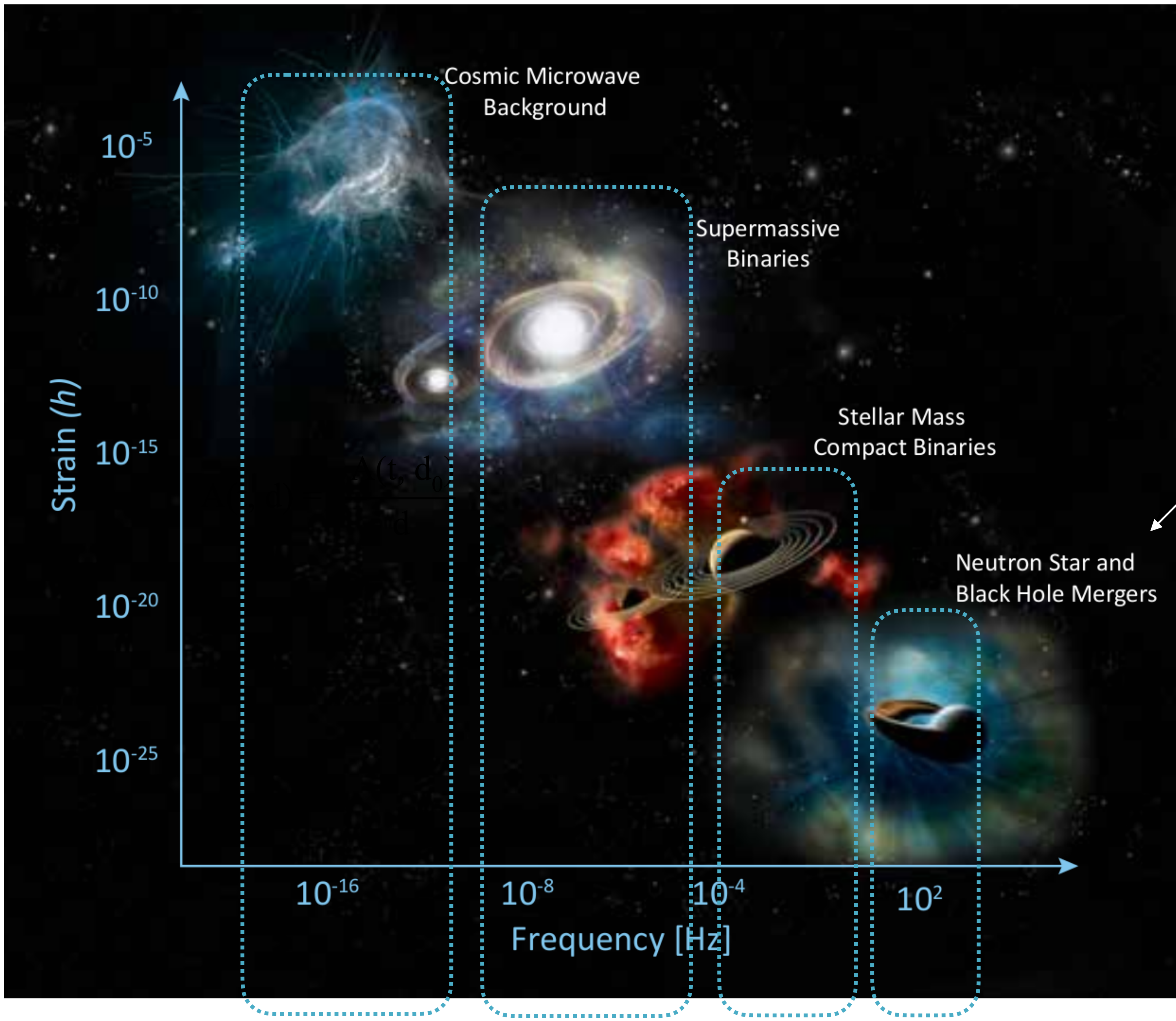
- **Deformation:**
  Strain = fractional change in distance between two points when a GW passes through:

$$\frac{\Delta L}{L} = \frac{1}{2} h_{xx}(0, ct)$$



Gravitational waves sources

Early Universe quantum fluctuations



Credit: SSU EPO/Aurore Simonnet

CMB modes

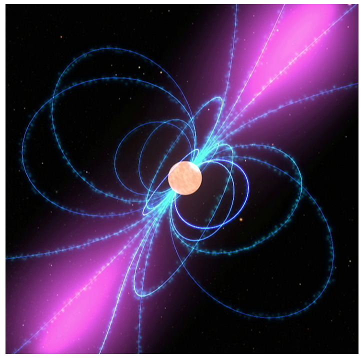
ePTA nanoGRAV

LISA

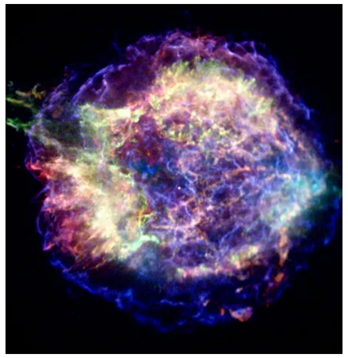
LIGO-Virgo-KAGRA

This talk focuses on those sources

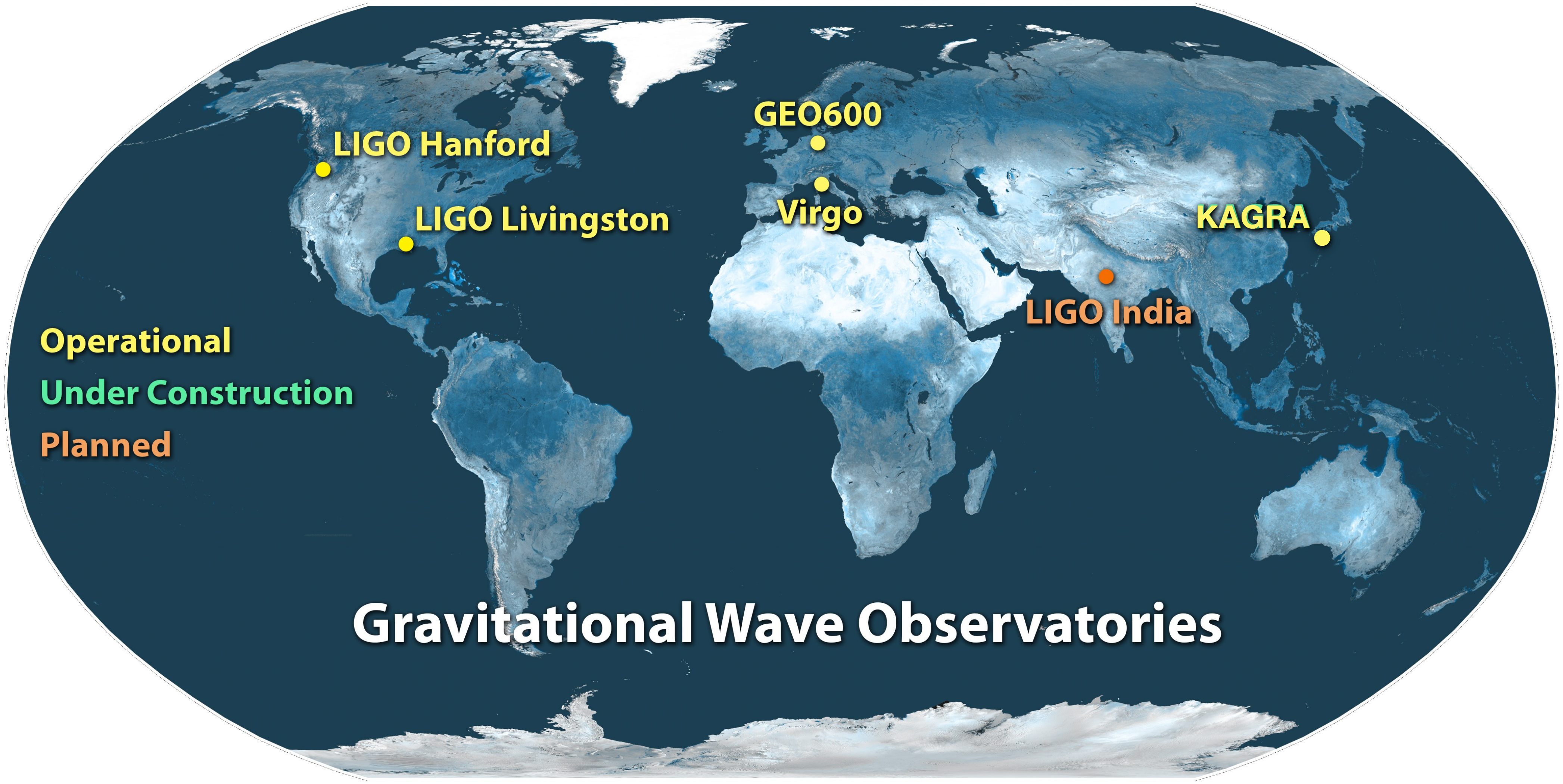
+ pulsars



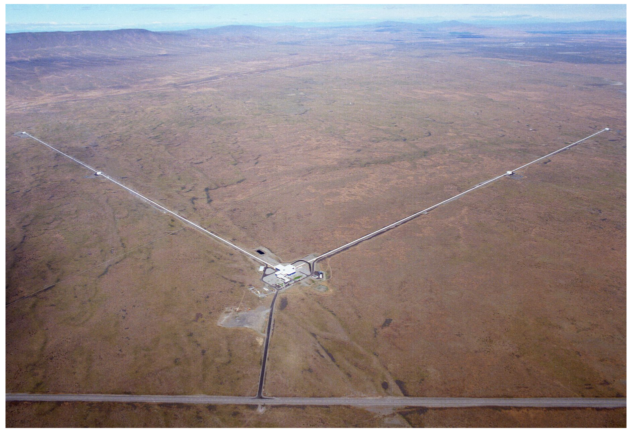
+ supernovae



Gravitational waves observatories



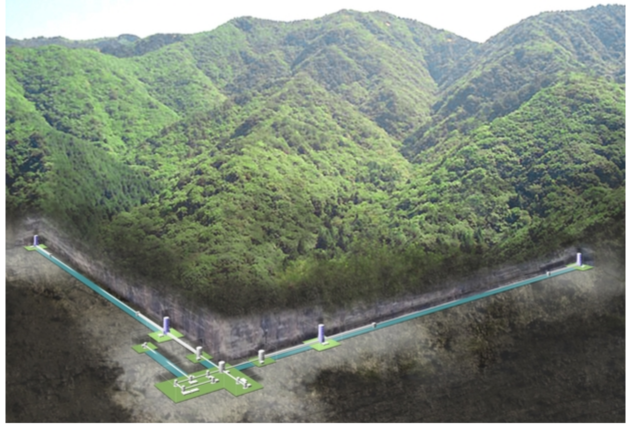
LIGO Hanford



LIGO Livingston

Virgo

KAGRA



Gravitational waves detection: a summary

arXiv
1811.12907
2108.01045
2111.03606

3 GW detection during O1

- First direct detection of GW
- From coalescing binary systems of black holes

8 GW detection during O2

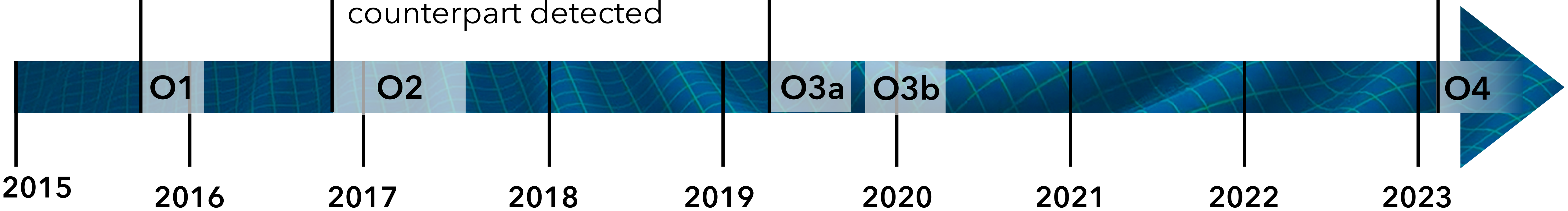
- 1 coalescing binary system of neutron stars: electromagnetic counterpart detected

79 GW detection during O3

- 44 during O3a, including 1 confirmed binary system of neutron stars
- 35 during O3b, including 2 confirmed systems of neutron stars - black holes
- No electromagnetic counterpart

O4 to start in 2023

- Duration: 1 year



90 GW detections reported

Coalescence of black holes and neutron stars

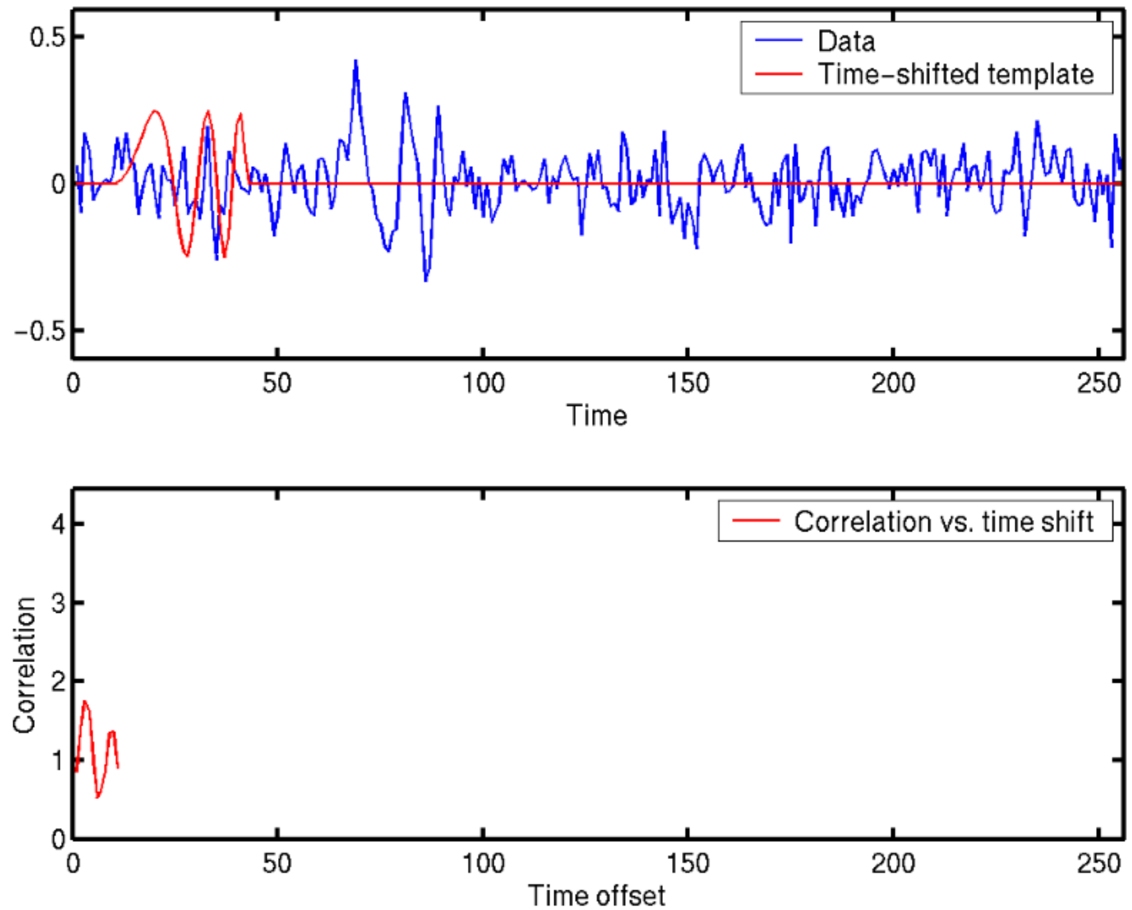
1 multimessenger event (GW + EM observation)

Mass range 1.2 → 107 $M_\odot$ (stellar)

Distance range 40 Mpc → 8 Gpc (z → 1.14)

Matched filtering analysis

- **Matched filtering**: correlation between the signal template h and the data s
  most efficient way to find a very low amplitude signal



Source: L. Candonati

$$z(t) = 4\int h^*(f)\ s(f)\ \exp(2\pi i f t)\ df$$

GW analysis with matched filtering

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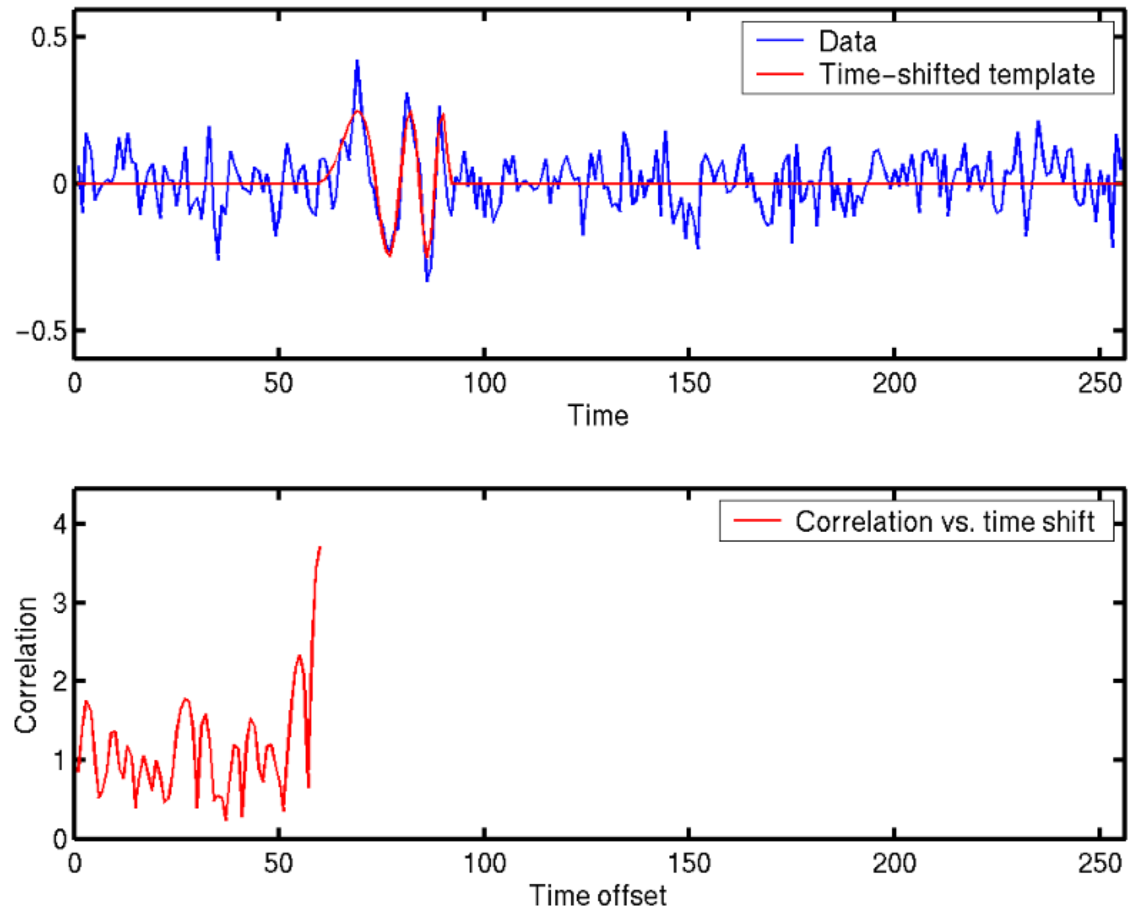

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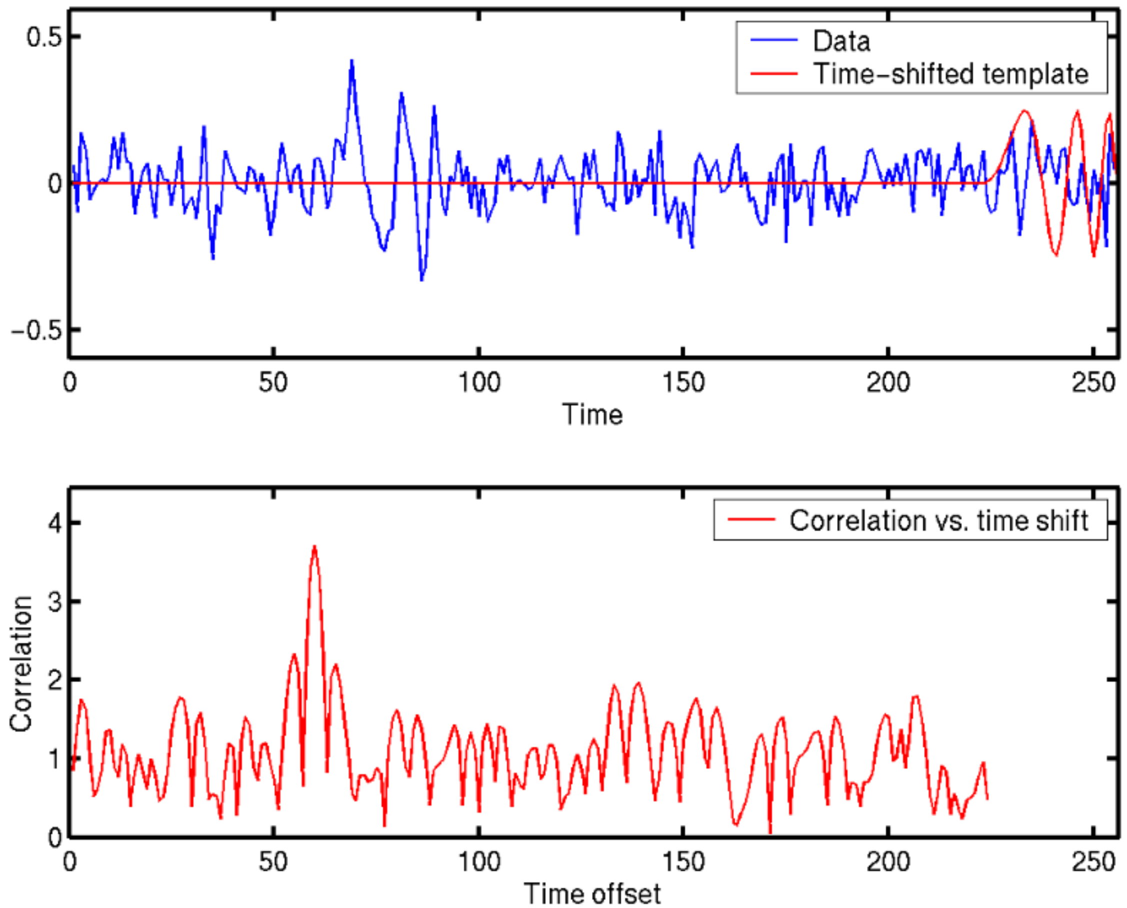

Source: L. Candonati

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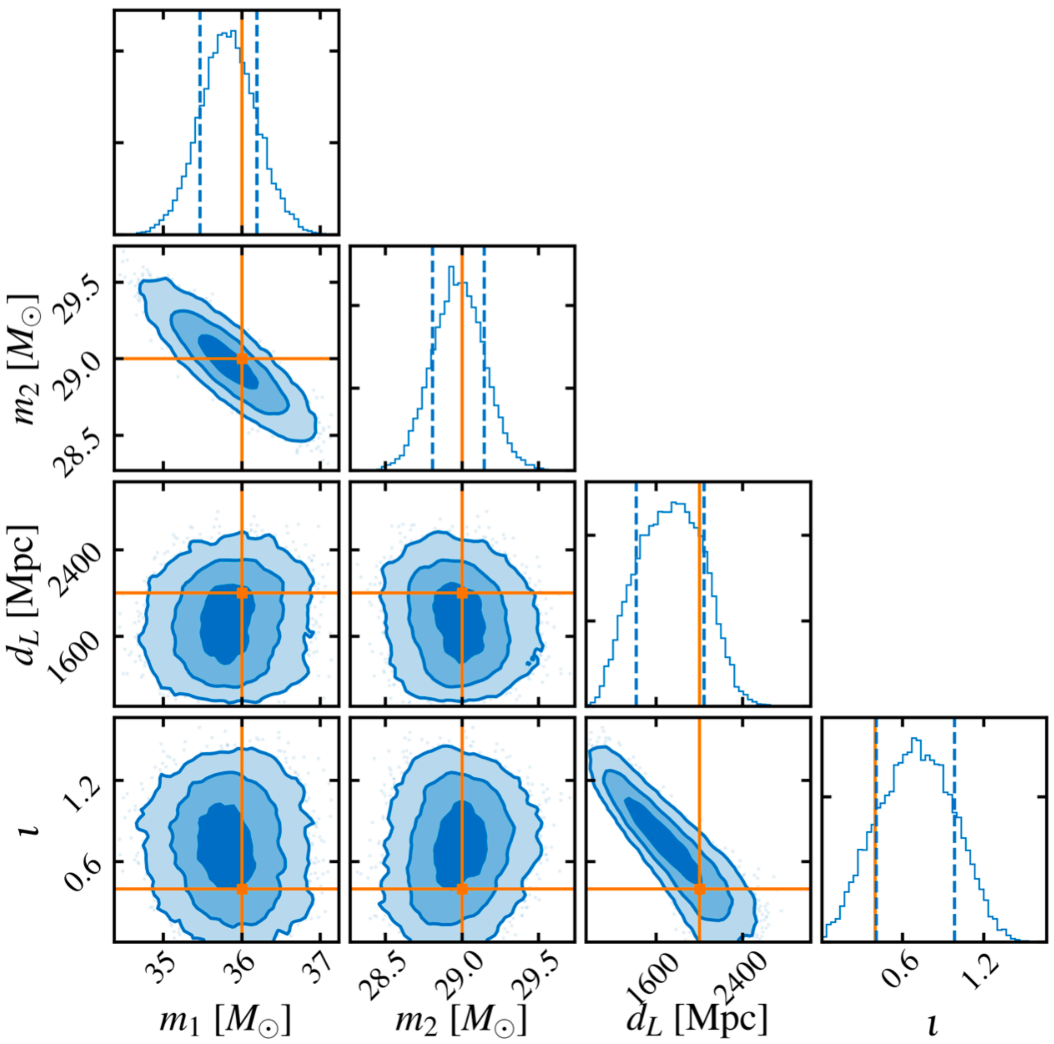
GW parameter estimation

- **Bayesian analyses**: joint posterior probabilities of source parameters
  Markov chains sampling methods (Nested sampling, MCMC)

- **Binary systems of black holes and/or neutron stars**:
  15 parameters minimum
  - 2 masses
  - 2 spin magnitudes
  - 2 angles for each spin
  - Reference time
  - Orbital phase at reference time
  - Luminosity distance
  - Right ascension & declination
  - Inclination angle
  - Polarisation angle

  + tidal parameters in neutron stars



Ashton et al, Astrophys.J.Suppl. 241 (2019) 2, 27

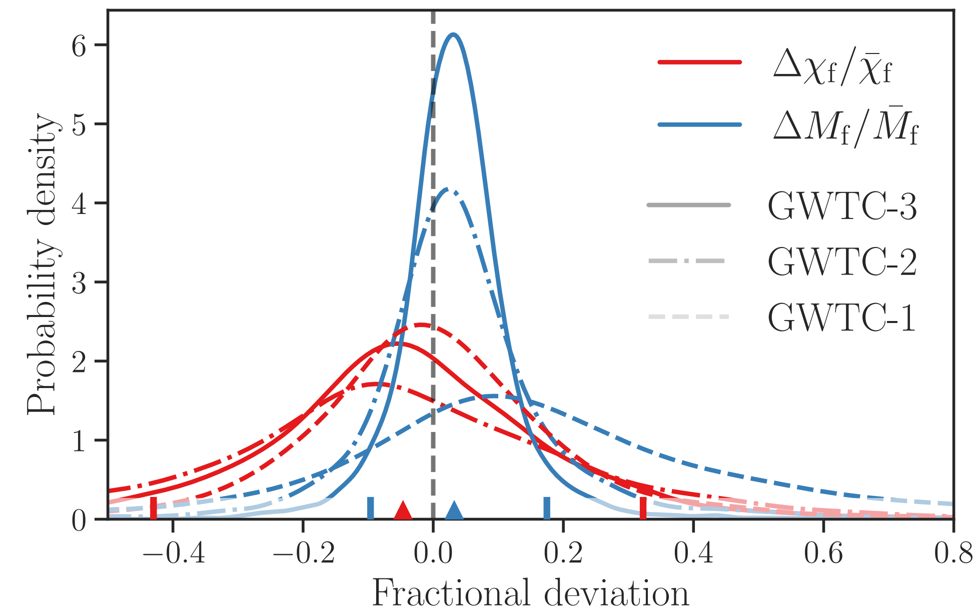
Tests of general relativity

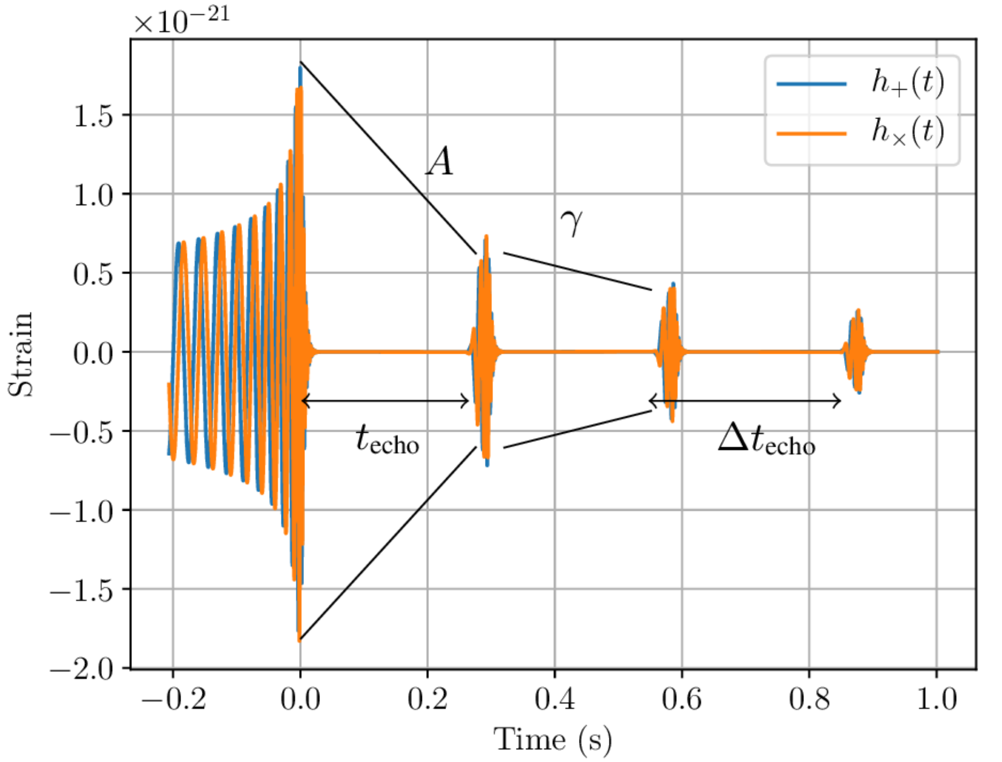
- **Gravitational waves (GW) enable to test fundamental physics in the gravitational sector**
  ↳ complementary to tests with solar system, pulsars, gravitational lensing…

- **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

LVK, arxiv:2112.06861





Outline: tests with multi messenger events

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  - ↳ gravitational waves friction
  - ↳ gravitational waves lensing
  - ↳ speed of gravity
  - ↳ tests of Lorentz invariance violation

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 $h_\times$

GW friction and speed of gravity: Can be probed with multimessenger events

Mass of graviton and polarisation mixing: Can be probed from GW signal (pattern & polarisation)

Gravitational waves propagation

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GW friction

Amplitude
does not scale
as 1/distance

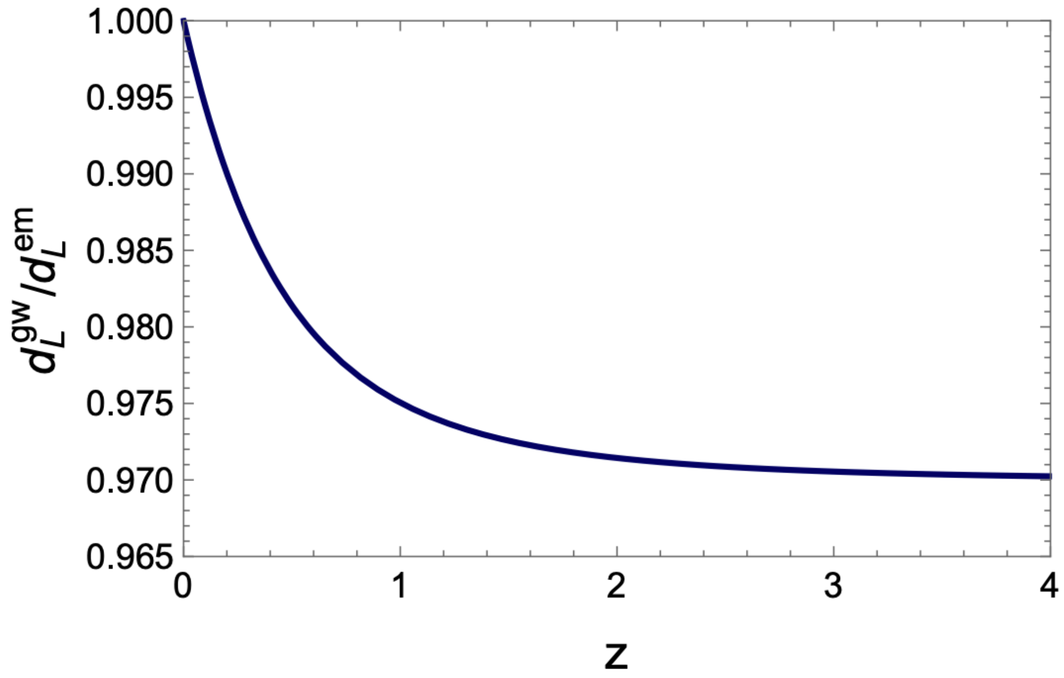
Gravitational waves friction

- **GW friction:** a dispersion impacting the amplitude of the waveform
- **Observable:** the luminosity distance is modified compared to GR

$$d_L^{GW}(z) = d_L^{EM} \exp\left[\frac{1}{2}\int_0^z \frac{\alpha_M(z')}{1+z'}dz'\right]$$

- $\alpha_M(z)$ can be mapped to different alternative theories of gravitation
- In GR, $\alpha_M(z) = 0$

Running Planck mass example



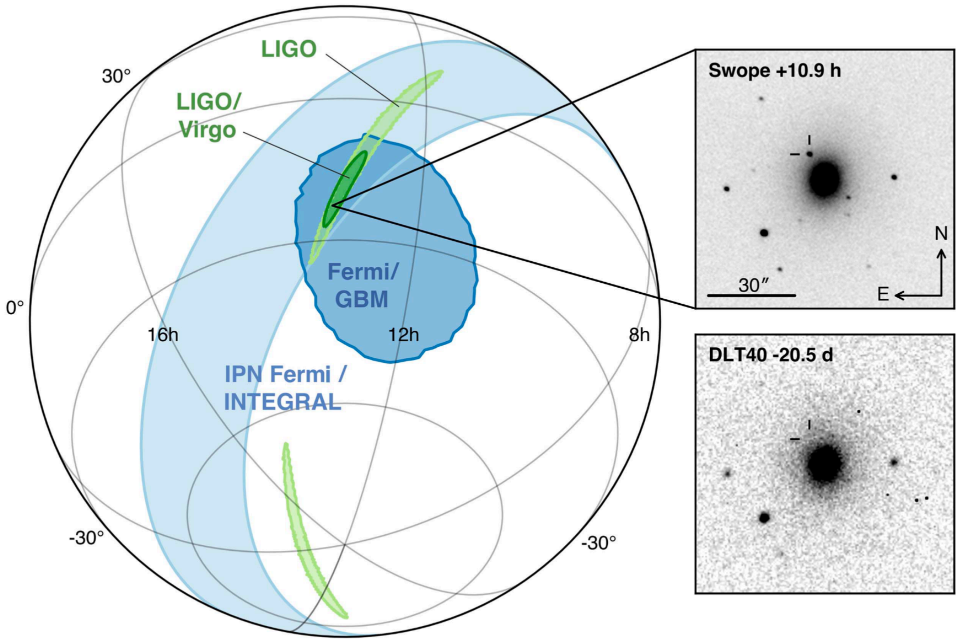
Belgacem, Dirian, Foffa, Maggiore, Phys. Rev. D 97, 104066 (2018)

Standard sirens

- **Standard siren** = simultaneous observation of electromagnetic and gravitational radiation from the same event

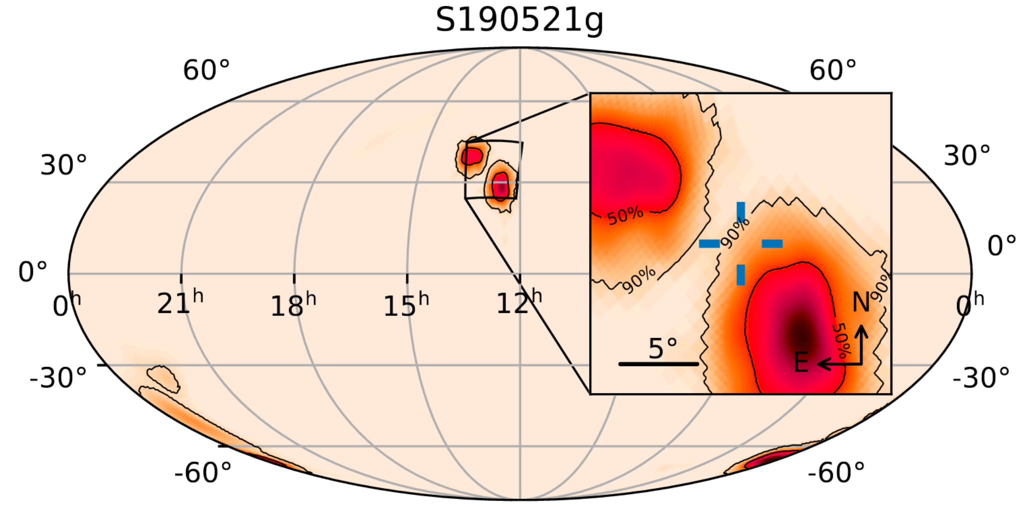
- **The distance (luminosity distance & redshift)** can be separately inferred from the two signals, enabling to measure cosmological and GW friction parameters

- GW170817:
  - binary neutron star merger
  - $z \simeq 0.01$



LVC, Phys. Rev. Lett. 119, 161101 (2017)

- GW190521:
  - binary black holes merger
  - potential location in AGN disk creating electromagnetic signal (not confirmed)
  - $z \simeq 0.44$

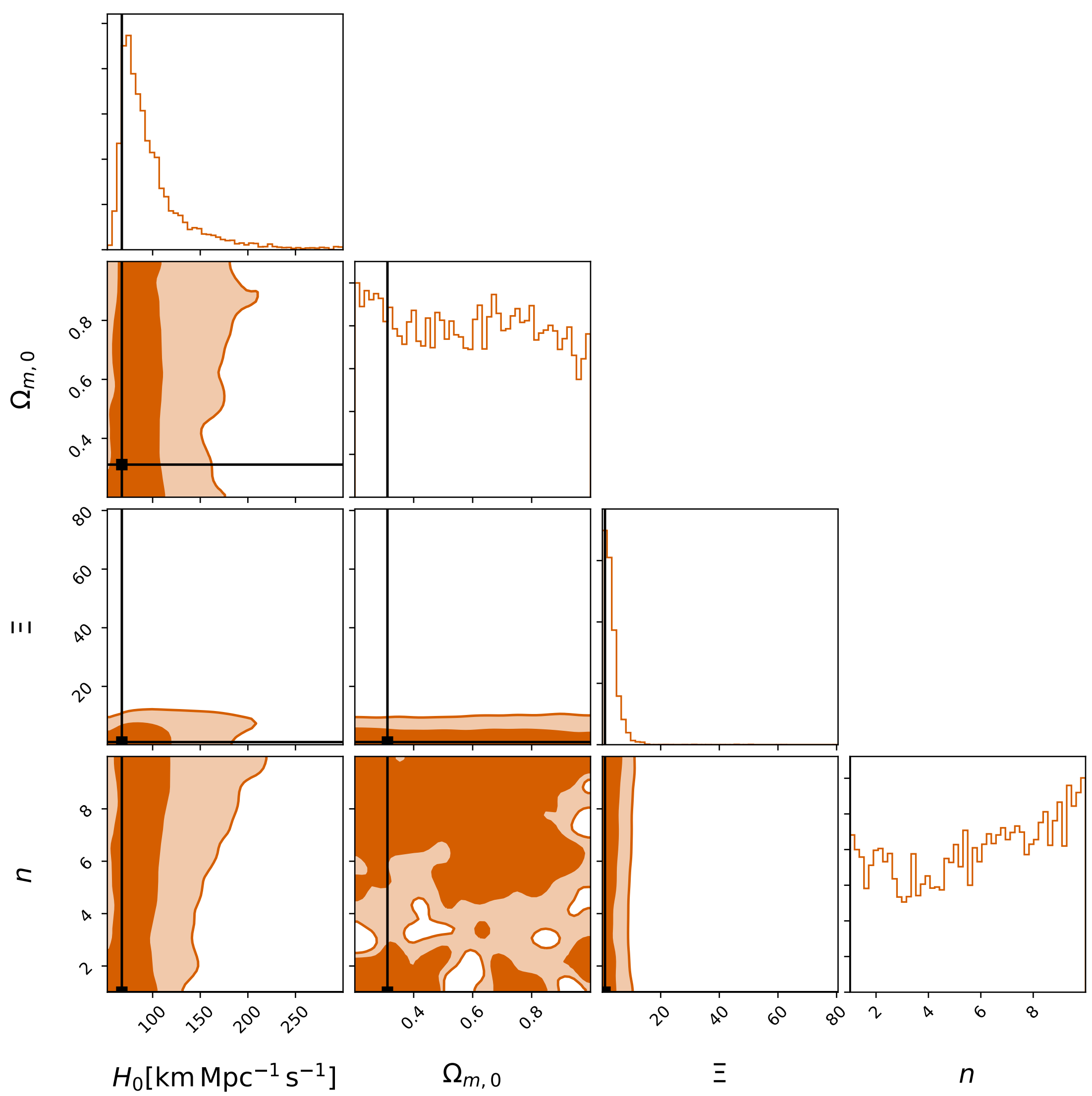


LVC, Phys. Rev. Lett. 125, 101102 (2020)
Graham et al, Phys. Rev. Lett. 124, 251102 (2020)

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	$\frac{\beta\phi_0}{2M_{\rm Pl}}$	$\frac{\dot{\phi}_0}{H_0\phi}$	[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	$\lambda\left(\ln a_{acc} + \frac{C}{2}\chi_{acc}\right)$	$\frac{C/H_0 - 2}{\ln a_{acc}^2 - C\chi_{acc}}$	[66]

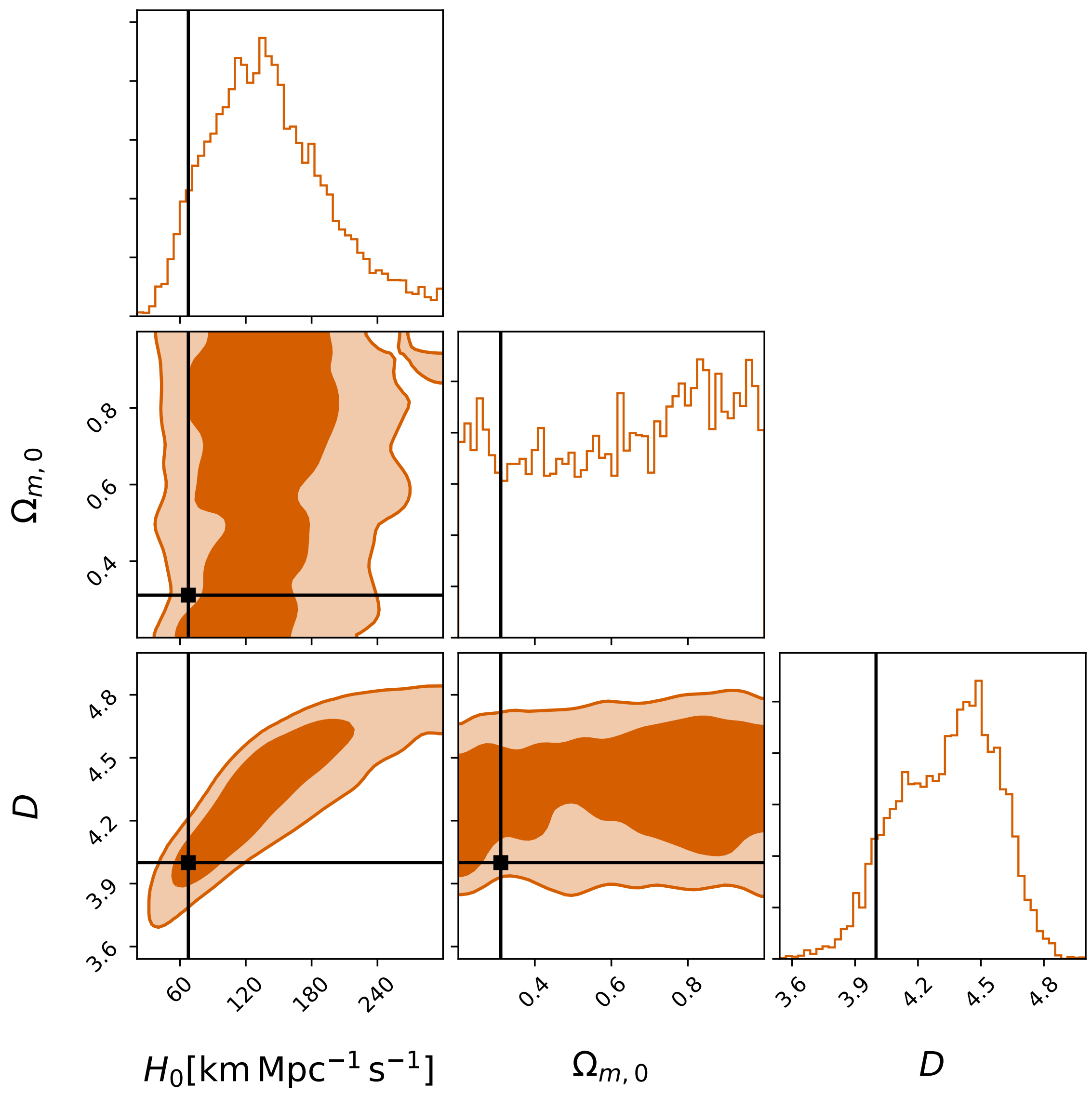
Mastrogiovanni, Haegel, Karathanasis, Magana-Hernandez, Steer, JCAP 02 (2021) 043

Belgacem et al, JCAP07 (2019) 024

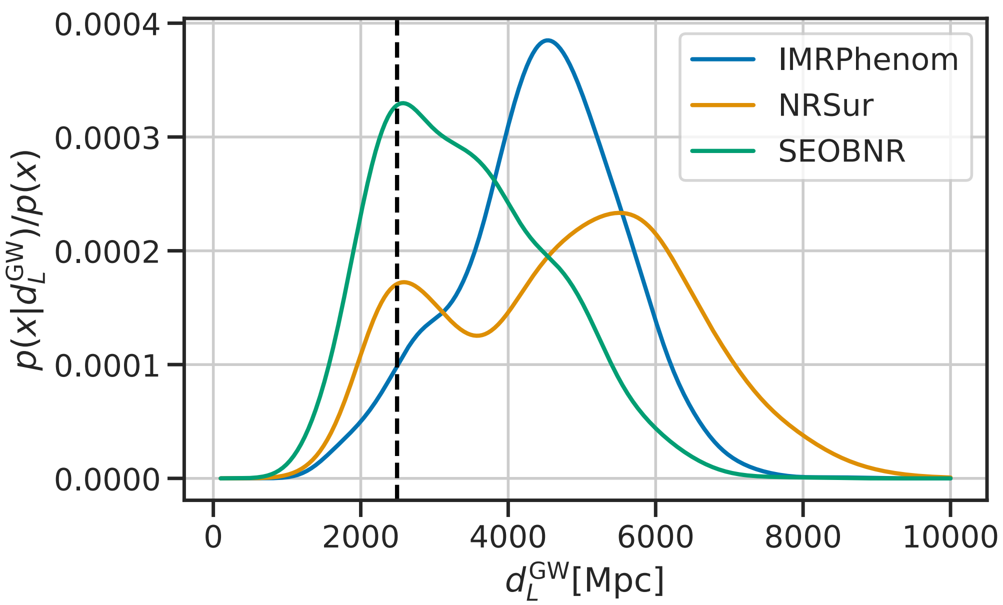
GW friction and extra dimensions

- **Extra dimensions**
  DGP gravity (4+1 dimensions),
  quantum gravity models of large extra dimensions

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

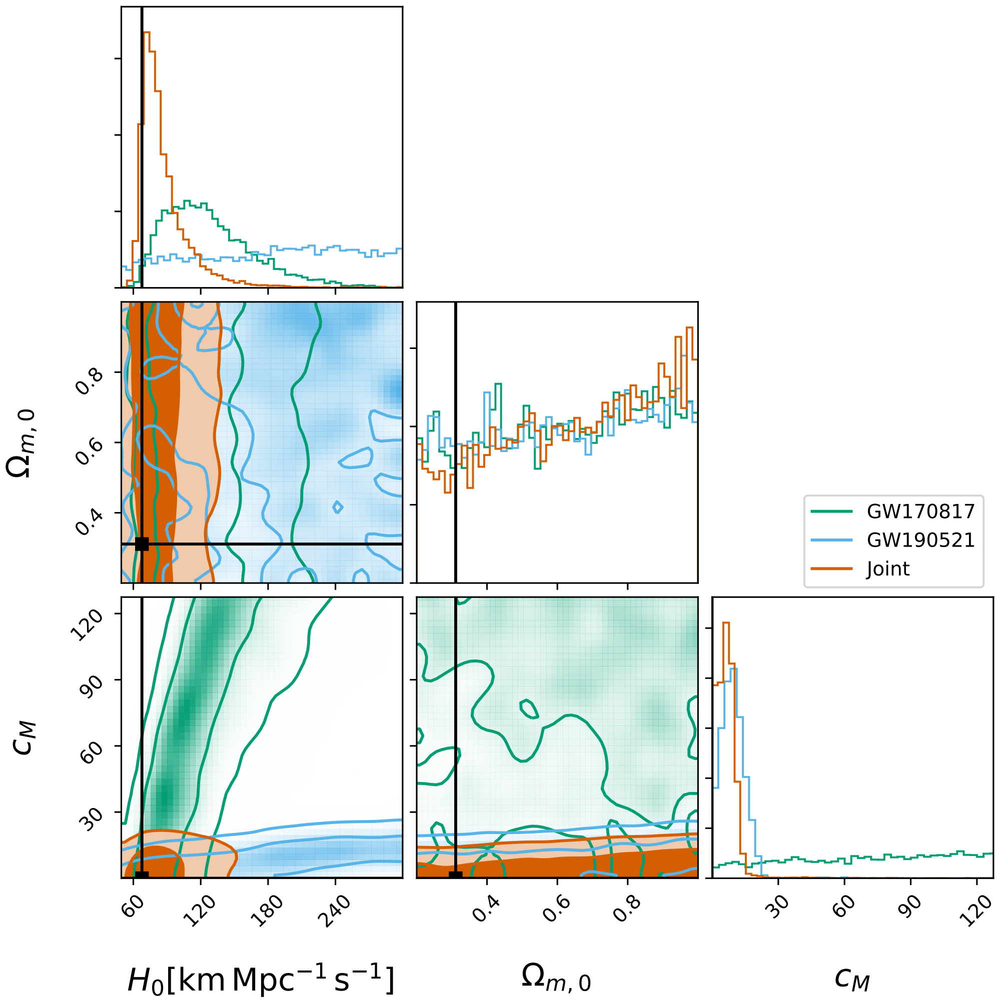


- **D=4 is on the edge on the contour**
  due to the luminosity distance posterior skewed towards large values



Mastrogiovanni, Haegel, Karathanasis, Magana-Hernandez, Steer, JCAP 02 (2021) 043

Dark energy motivated friction



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

- **Dynamical dark energy models:**
  α_M is linked to the energy content of the Universe

$$\alpha_M = c_M \frac{\Omega_{\Lambda(z)}}{\Omega_{\Lambda(0)}}$$

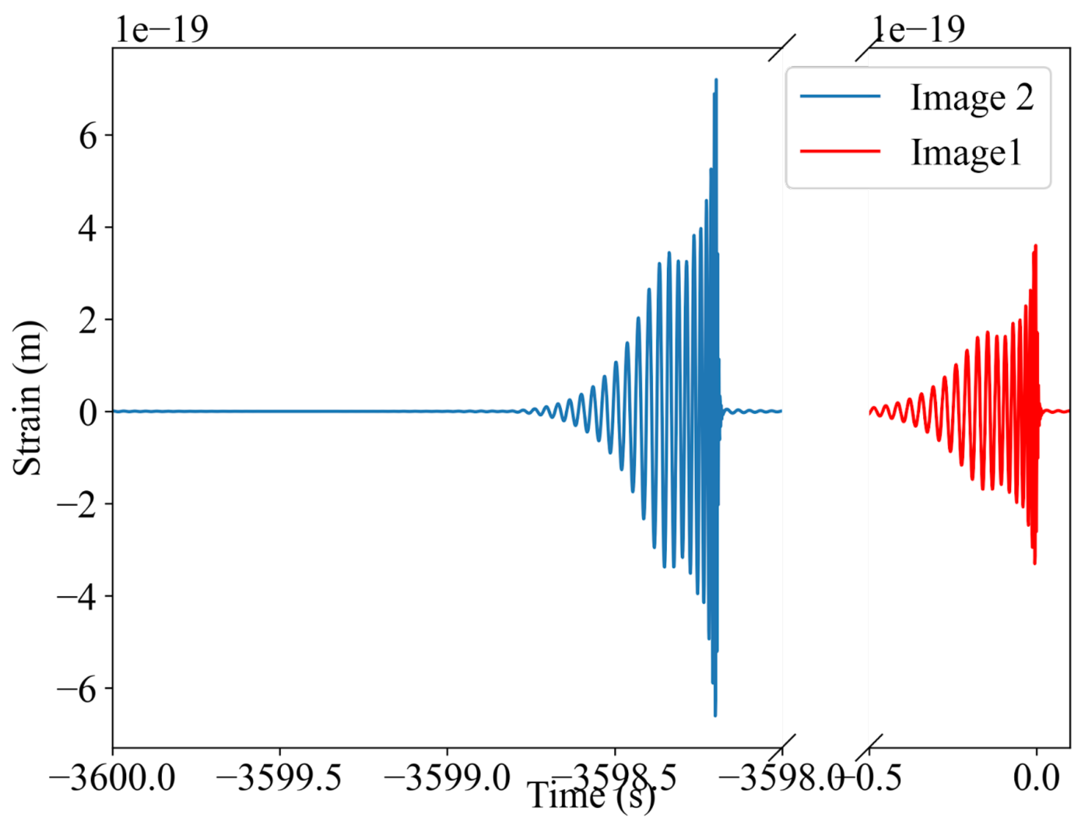
$$d_L^{GW}(z) = d_L^{EM}(z)\, exp\left[\frac{c_M}{2\Omega_{\Lambda,0}}\, ln \frac{1+z}{\Omega_{m,0}\,(1+z)^3 + \Omega_{\Lambda,0}}\right]$$

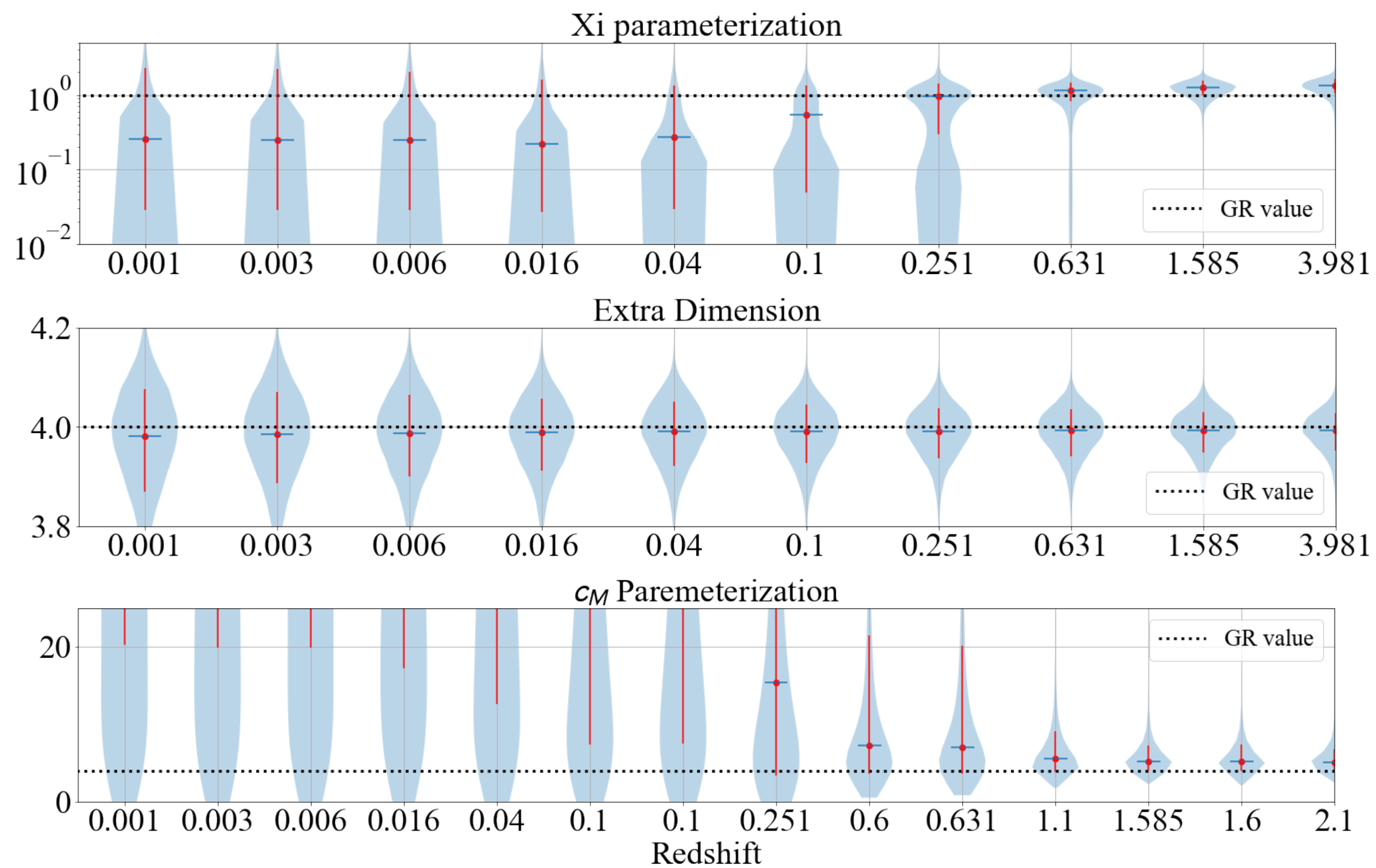
$c_M = 0$ is the GR case

GW friction and lensing

- **Quadruply lensed GW events**
  event amplitude and arrival time modified due to the presence of gravitational lensing

- **Several images of same event**
  better sky localisation reconstruction
  can be matched with host galaxy





- **Access to larger distance**
  more accuracy on some parameters

- **Work with Nikhef group**
  see H. Narola talk at GR23 [C3]

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)

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

Speed of gravity

Speed of GW $\neq c$

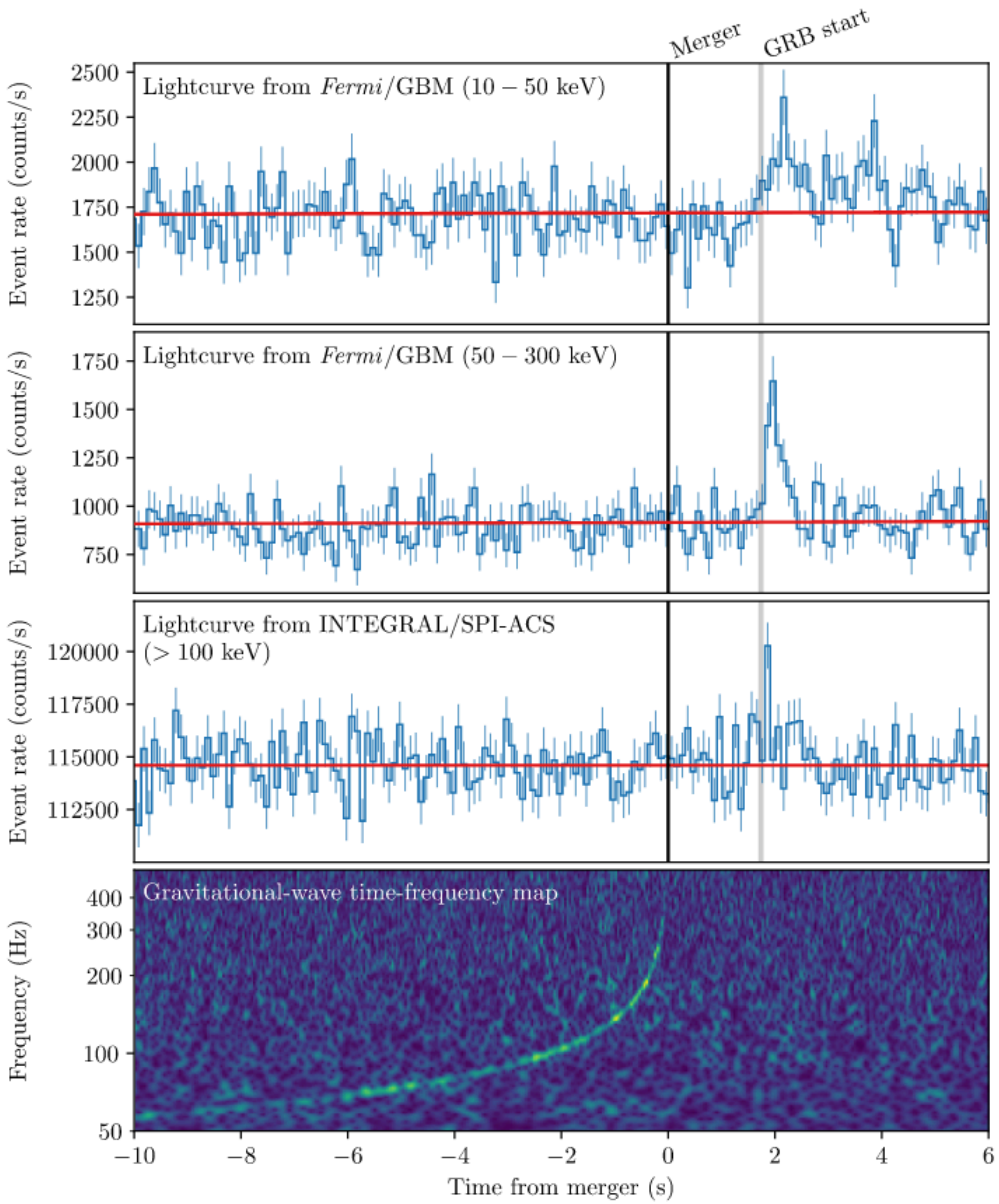
Speed of gravity

- **GW170817:** binary neutron star merger
- **Time delay:** between GW and GRB

$$\Delta t = 1.74 \pm 0.05 \text{ s}$$

- **Speed of gravity:** can be measured from Δt

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



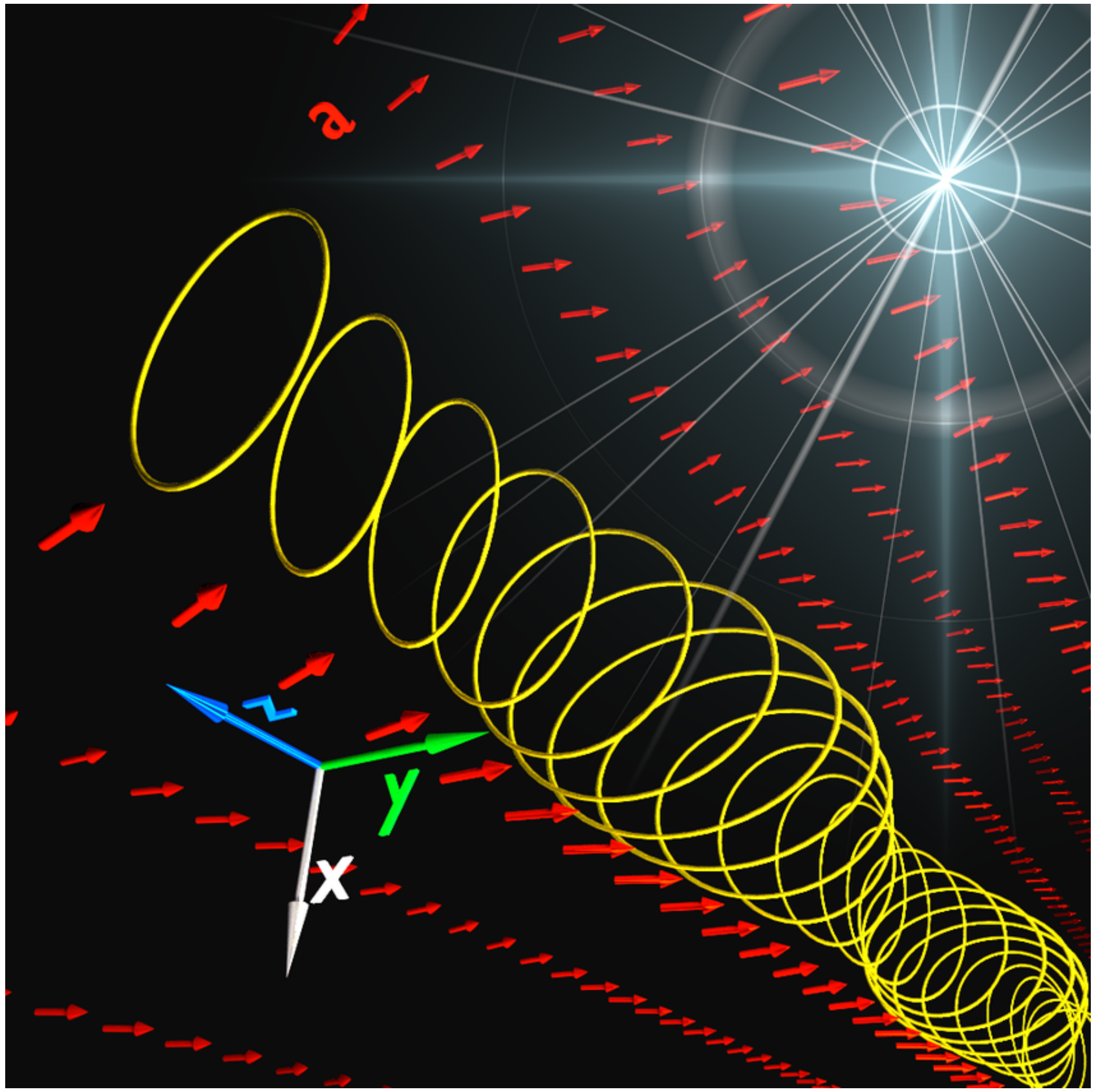
LVC, Fermi, Integral, Astrophys.J.Lett. 848 (2017) 2, L13

The Standard Model Extension (SME) framework

- **A framework to probe new physics:**
  Lagrangian description of new physics
  New fields coupling know physics
  Extensive constraints from the (astro)particle physics sector

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

Kostelecky & Russell, arxiv:0801.0287



Schreck, arXiv:1603.07452

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):

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

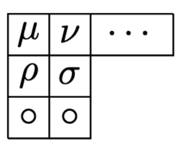
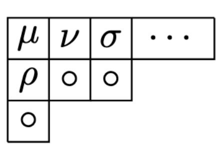
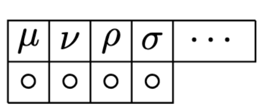
Tableau	Operator $\widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma}$	CPT	d	Number
	$s^{(d)\mu\rho\circ\nu\sigma\circ\circ^{d-4}}$	even	even, ≥ 4	$(d-3)(d-2)(d+1)$
	$q^{(d)\mu\rho\circ\nu\circ\sigma\circ\circ^{d-5}}$	odd	odd, ≥ 5	$\frac{5}{2}(d-4)(d-1)(d+1)$
	$k^{(d)\mu\circ\nu\circ\rho\circ\sigma\circ\circ^{d-6}}$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

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

→ Impact GW velocity (first row)

Kostelecky & Mewes, Phys. Lett. B757:510-514 (2016)

EFT for spacetime symmetry breaking

- **Lorentz-violating coefficients** from SME can be constrained from speed of gravity

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

$\bar{s}^{(4)}_{\ell m}$: gravitational sector

$c^{(4)}_{(I)\ell m}$: electromagnetic sector

ℓ	This Work Lower	Coefficient	This Work Upper
0	-2×10^{-14}	$\bar{s}^{(4)}_{00}$	5×10^{-15}
1	-3×10^{-14}	$\bar{s}^{(4)}_{10}$	7×10^{-15}
	-1×10^{-14}	$-\mathrm{Re}\ \bar{s}^{(4)}_{11}$	2×10^{-15}
	-3×10^{-14}	$\mathrm{Im}\ \bar{s}^{(4)}_{11}$	7×10^{-15}
2	-4×10^{-14}	$-\bar{s}^{(4)}_{20}$	8×10^{-15}
	-1×10^{-14}	$-\mathrm{Re}\ \bar{s}^{(4)}_{21}$	2×10^{-15}
	-4×10^{-14}	$\mathrm{Im}\ \bar{s}^{(4)}_{21}$	8×10^{-15}
	-1×10^{-14}	$\mathrm{Re}\ \bar{s}^{(4)}_{22}$	3×10^{-15}
	-2×10^{-14}	$-\mathrm{Im}\ \bar{s}^{(4)}_{22}$	4×10^{-15}

LVC, Fermi, Integral, Astrophys.J.Lett. 848 (2017) 2, L13

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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

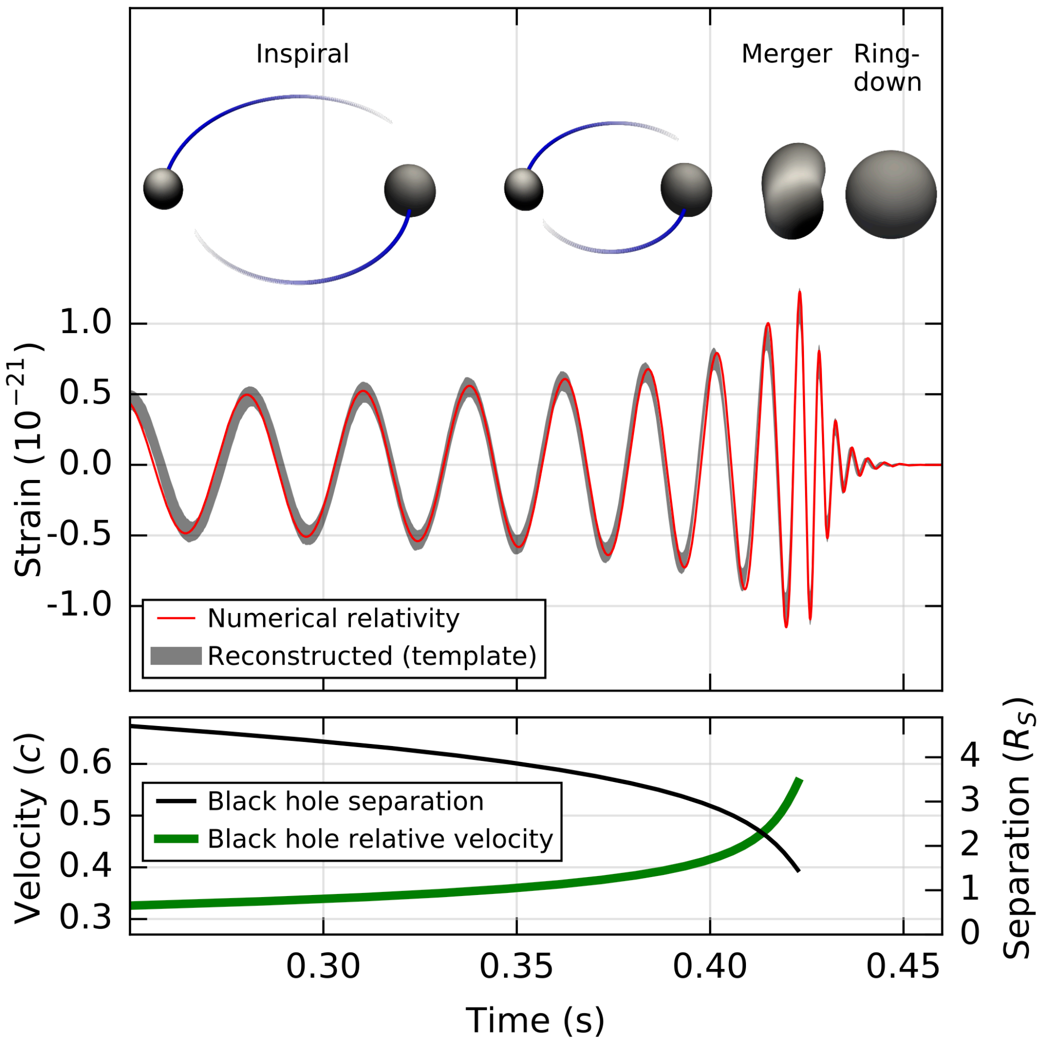
Non-0 graviton mass

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:

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

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

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

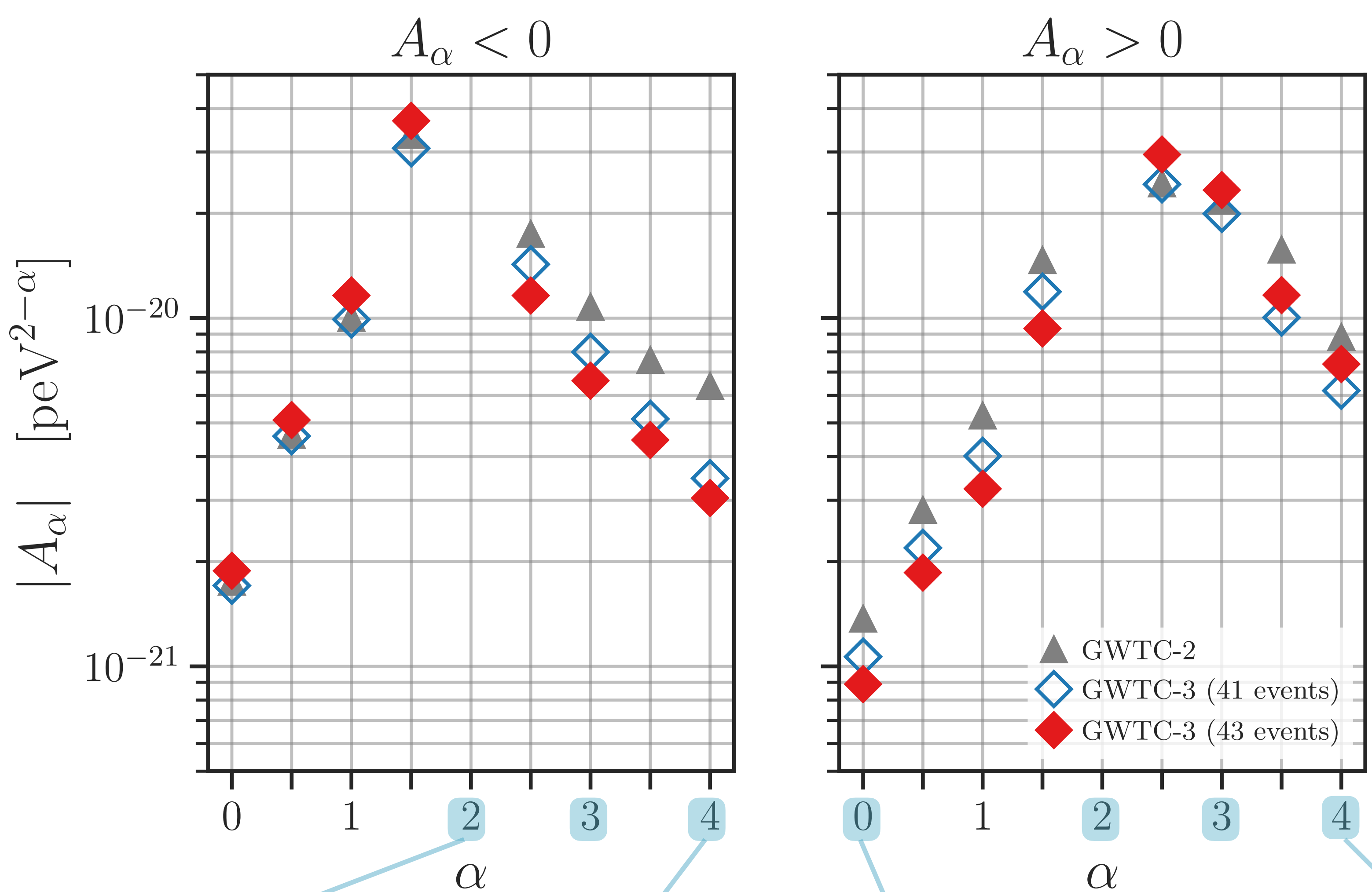
- The dispersion is:
  - isotropic
  - polarisation independent
  - possibly mapped to alternative theories of gravitation

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

Constraints on modified dispersion relation

- Constraints on $\mathbb{A}$ from GWTC-3: $E^2 = p^2c^2 + m_g^2c^4 + \mathbb{A}p^\alpha c^\alpha$

LVK, arxiv:2112.06861



degeneracy with coalescence time

Doubly Special Relativity

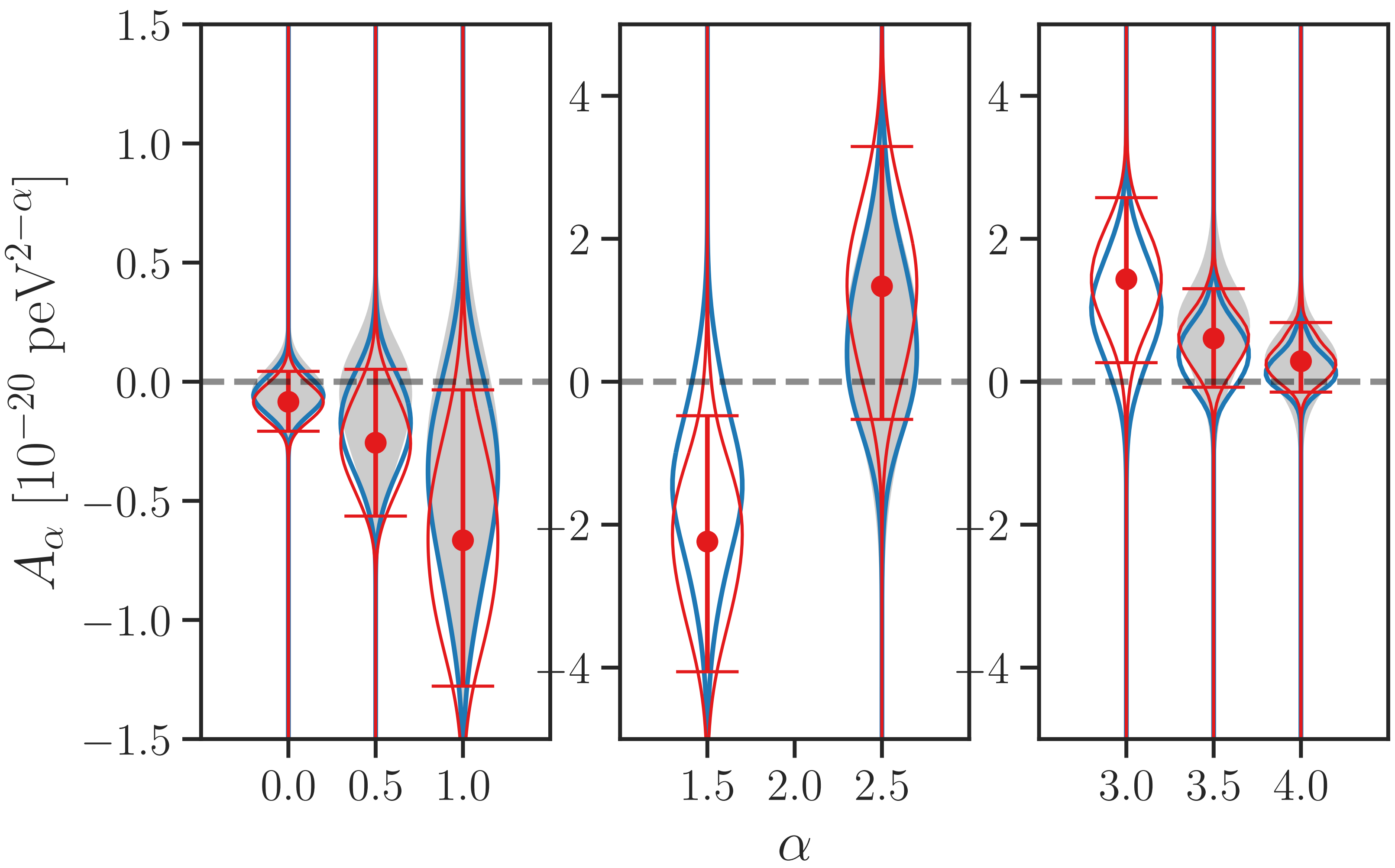
massive graviton
$m_g < 1.76 \cdot 10^{-23} eV/c^2$

extra dimensions / Hořava-Lifshitz / non commutative geometry

Constraints on modified dispersion relation

- Constraints on $\mathbb{A}$ from GWTC-3: $E^2 = p^2c^2 + m_g^2c^4 + \mathbb{A}p^\alpha c^\alpha$

LVK, arxiv:2112.06861



— w/ GW200219_094415 & GW200225_060421

— w/o GW200219_094415 & GW200225_060421

} 2 events presenting a bias with lowest p-value in residual tests

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)

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

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):

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

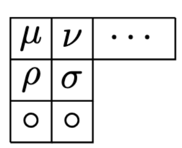
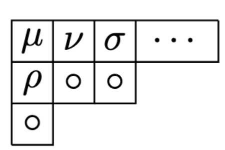
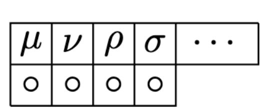
Tableau	Operator $\widehat{\mathcal{K}}^{(d)\mu\nu\rho\sigma}$	CPT	d	Number
	$s^{(d)\mu\rho\circ\nu\sigma\circ\circ^{d-4}}$	even	even, ≥ 4	$(d-3)(d-2)(d+1)$
	$q^{(d)\mu\rho\circ\nu\circ\sigma\circ\circ^{d-5}}$	odd	odd, ≥ 5	$\frac{5}{2}(d-4)(d-1)(d+1)$
	$k^{(d)\mu\circ\nu\circ\rho\circ\sigma\circ\circ^{d-6}}$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

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

→ Impact GW momentum: dispersion effect

Kostelecky & Mewes, Phys. Lett. B757:510-514 (2016)

Polarisation-dependent, anisotropic dispersion

- **New fields coupling with the metric**: dispersion impacting the GW signal

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

$$\delta \;=\; \omega^{(d-4)}\,\tau\,\zeta^0$$

$$\beta \;=\; \omega^{(d-4)}\,\tau\,|\,\vec{\zeta}\,|$$

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

frequency-dependent dispersion

coefficients to constraint

anisotropic effect

polarisation-dependent dispersion: analogous to birefringence

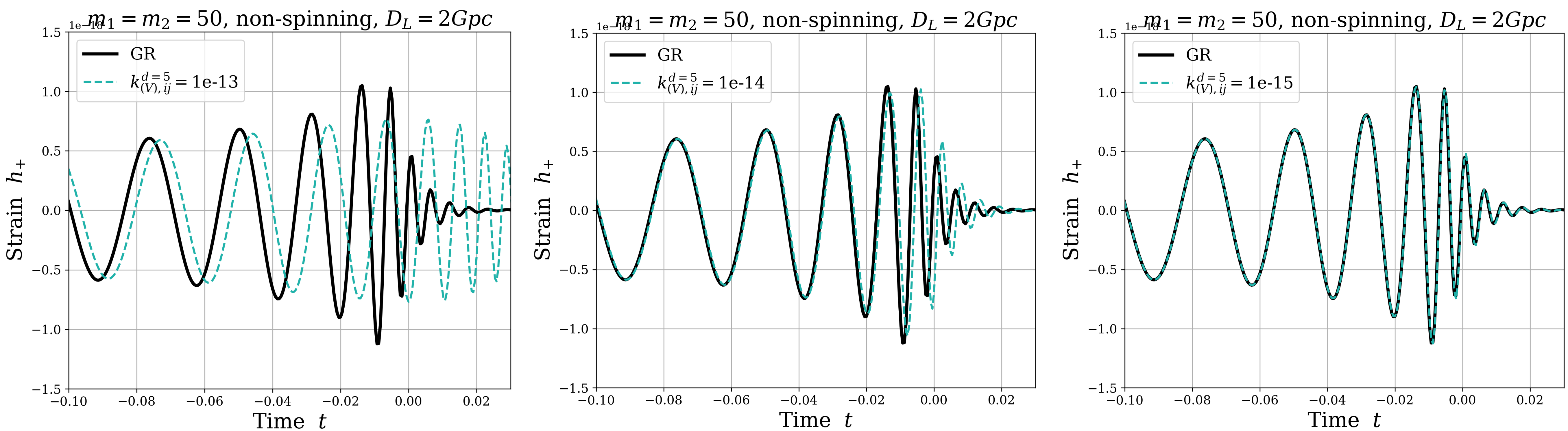
Mewes, Phys. Rev. D 99, 104062 (2019)

Measuring SME coefficients for d=5

- **Dispersion**: starts at mass dimension $d = 5$
  controlled by 16 coefficients $k^{(d=5)}_{(V),ij}$
  includes Lorentz invariance and CPT breaking

- **Modified GW signal**: $h_+ = \cos\beta \, h_+^{GR} - \sin\beta \, h_\times^{GR}$

$$\beta = \omega^2 \, \tau \sum_{i=16} Y_{i,j} \, k^{(d=5)}_{(V)ij}$$

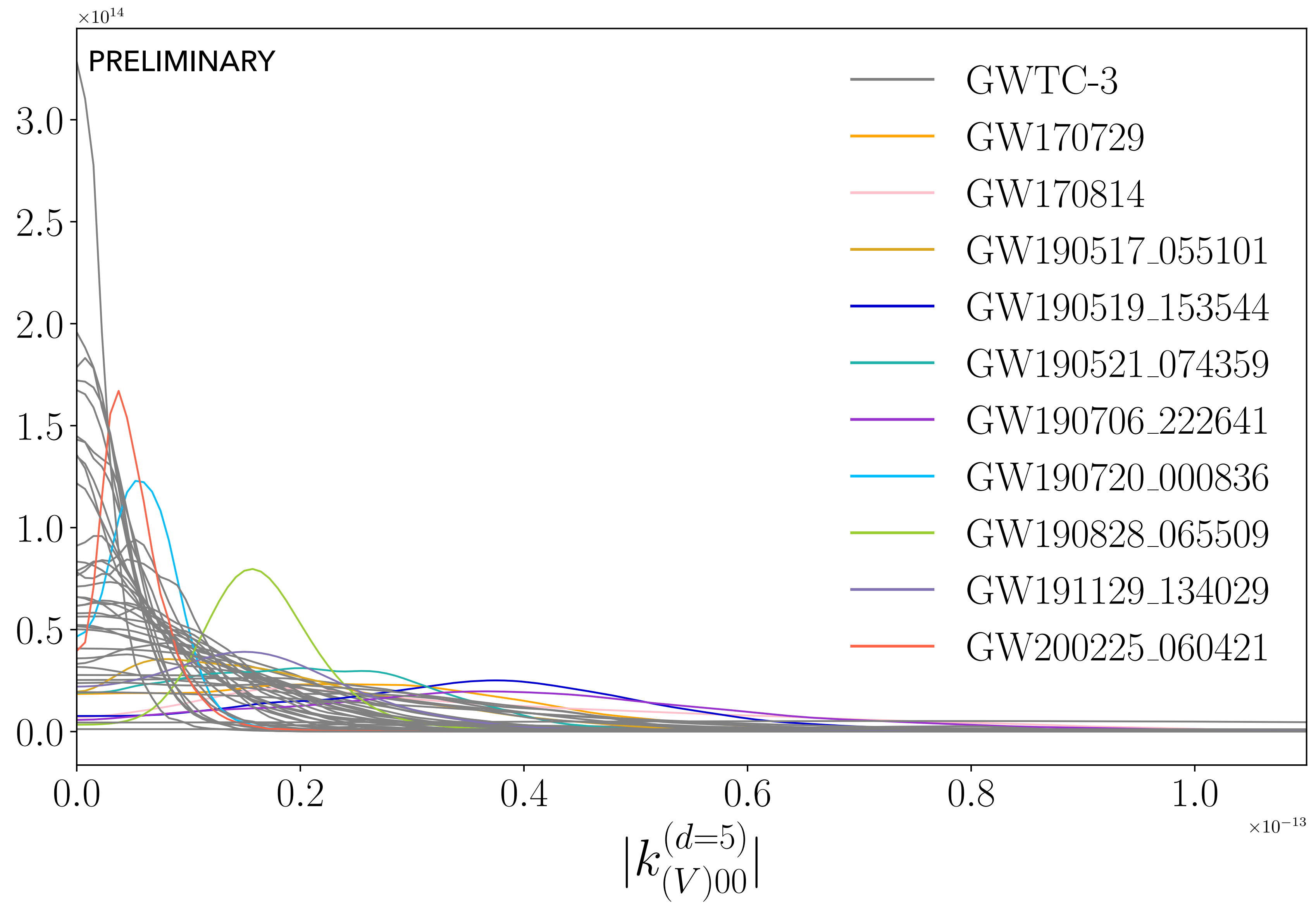


Ault-O'Neal, Bailey, Dumerchat, Haegel, Tasson, Universe 2021, 7(10), 380 (2021)

Constraints from individual events

- **Analysis**: GWTC-3 (O1 + O2 + O3)
  45 events with higher SNR chosen (FAR > 2 / year)
  joint measurement of source and SME parameters

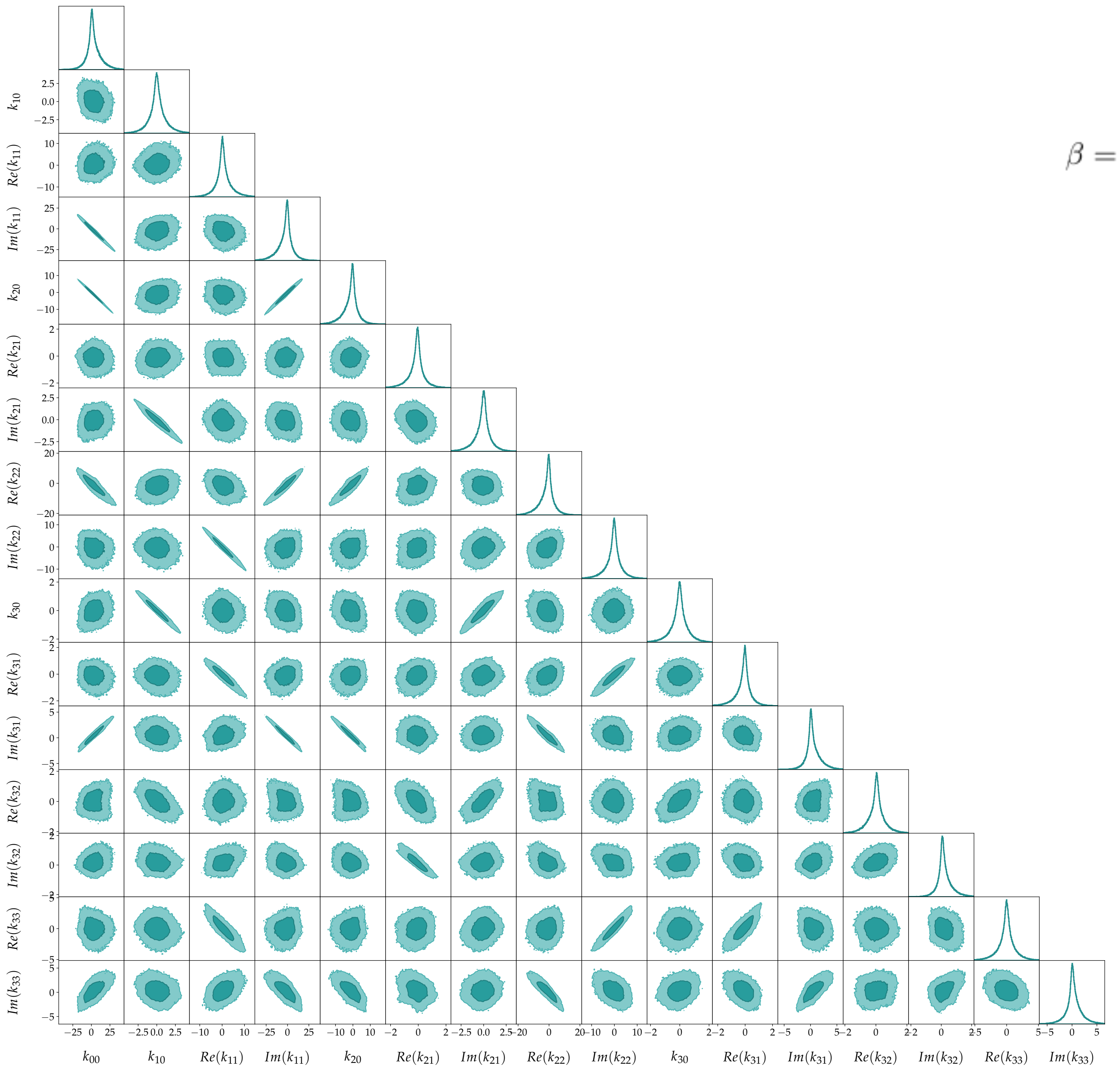
- **Constraints**: individual = $\mathcal{O}(10^{-13})$
  combined = $\mathcal{O}(10^{-15})$



Constraints from combined events

- **Modified GW signal**: $h_+ = \cos\beta \, h_+^{GR} - \sin\beta \, h_\times^{GR}$

$$\beta = \omega^2 \, \tau \sum_{i=16} Y_{i,j} \, \boxed{k^{(d=5)}_{(V)ij}}$$

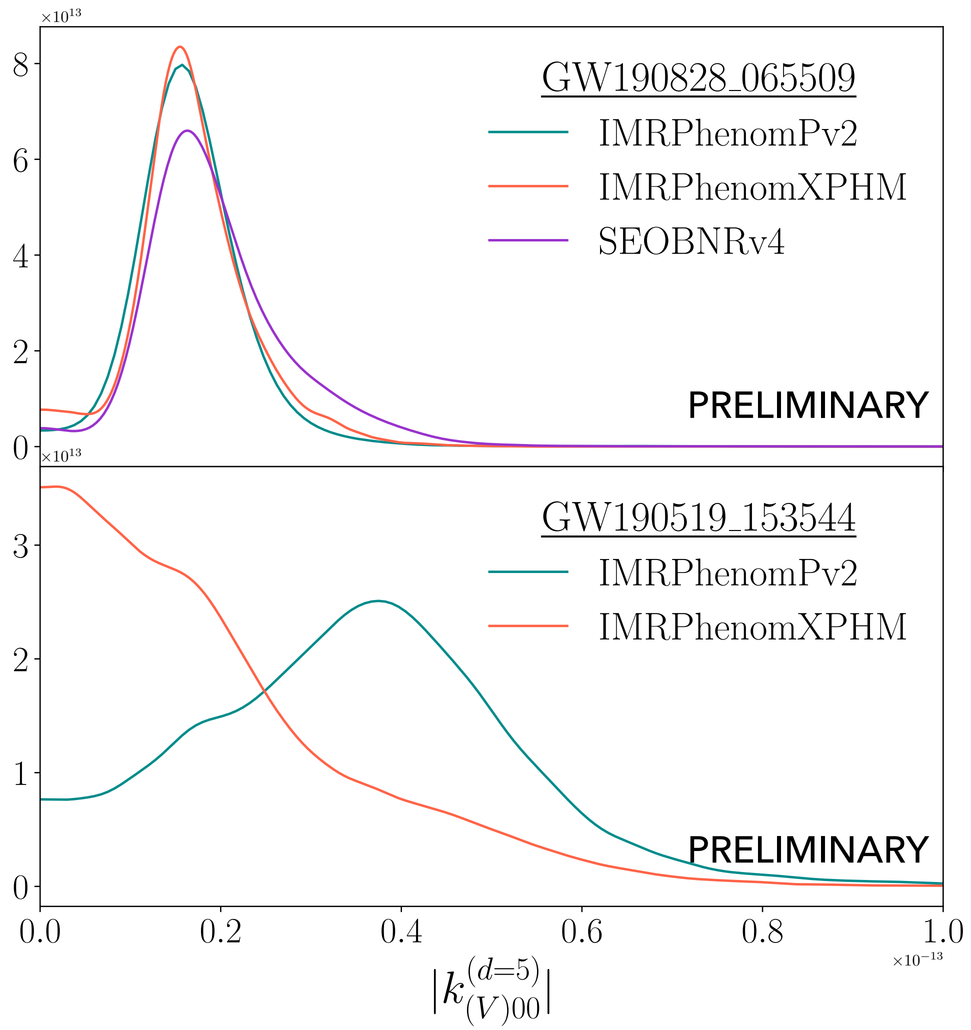


$$\begin{aligned}
\beta = \omega^2 \, \tau \, | \quad & \frac{1}{2}\frac{1}{\sqrt{\pi}} \, k_{00} \\
& + \frac{1}{2}\sqrt{\frac{3}{\pi}} \cos\theta \; k_{10} \\
& - \sqrt{\frac{3}{2\pi}} \sin\theta \; (\cos\phi \; Re(k_{11}) - \sin\phi \; Im(k_{11})) \\
& + \frac{1}{4}\sqrt{\frac{5}{\pi}} (3\cos^2\theta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

Robustness of the analysis

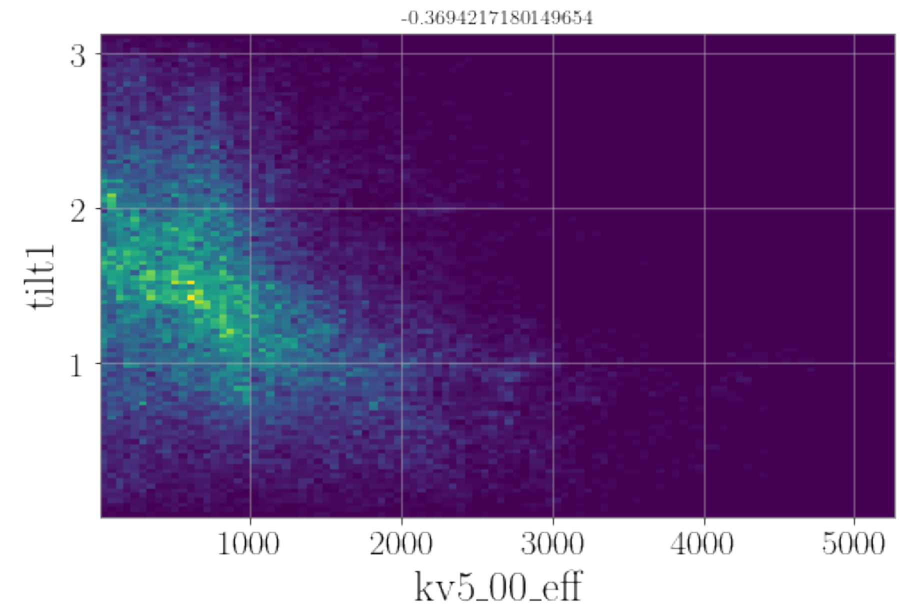
- **Impact of waveform model**

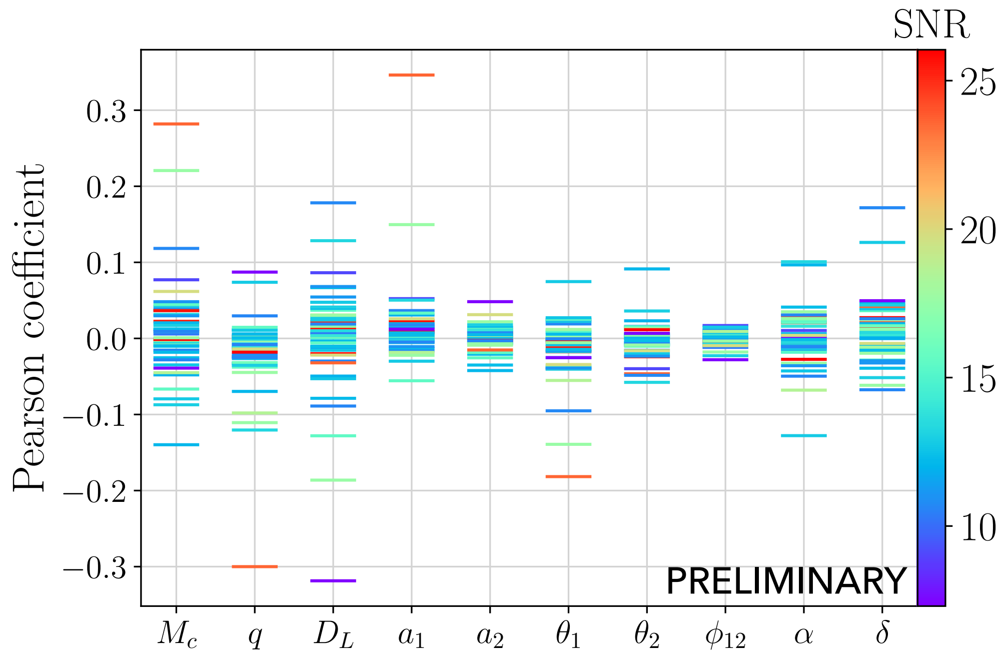
  How the $h^{GR}_{+,\times}$ modelling impact the SME constraints



- **Correlation with source parameters**

  How the SME posteriors depend on the astrophysical parameters



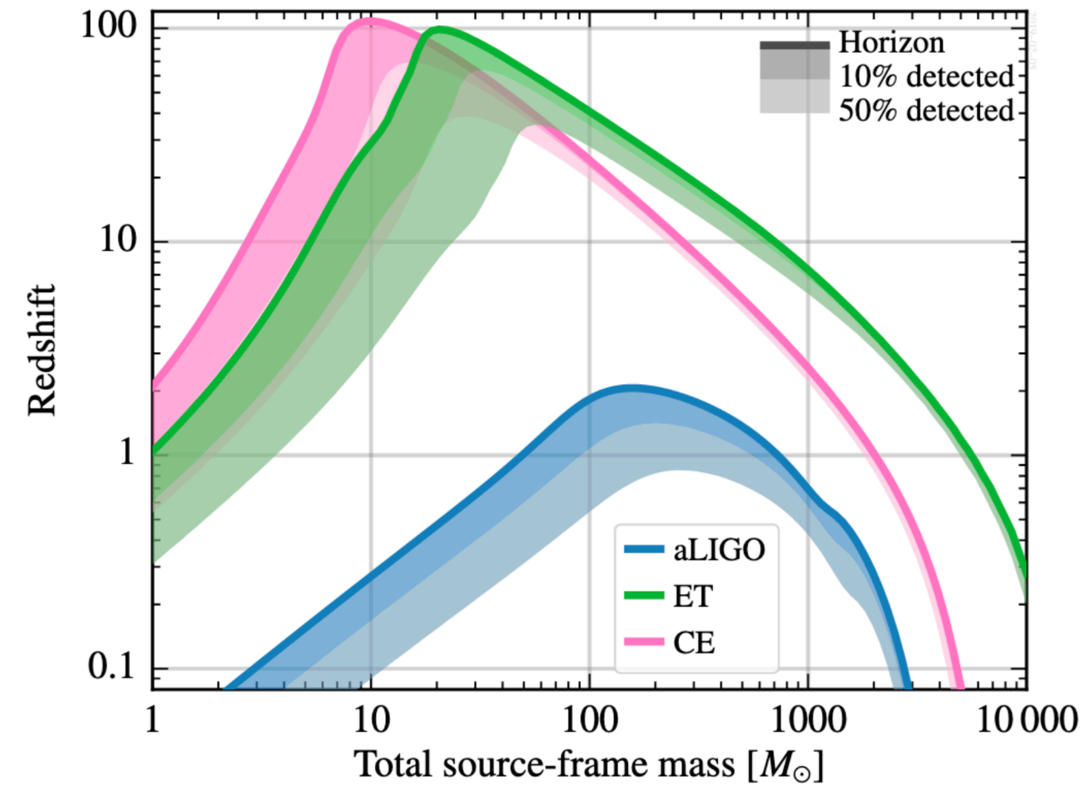


Conclusion

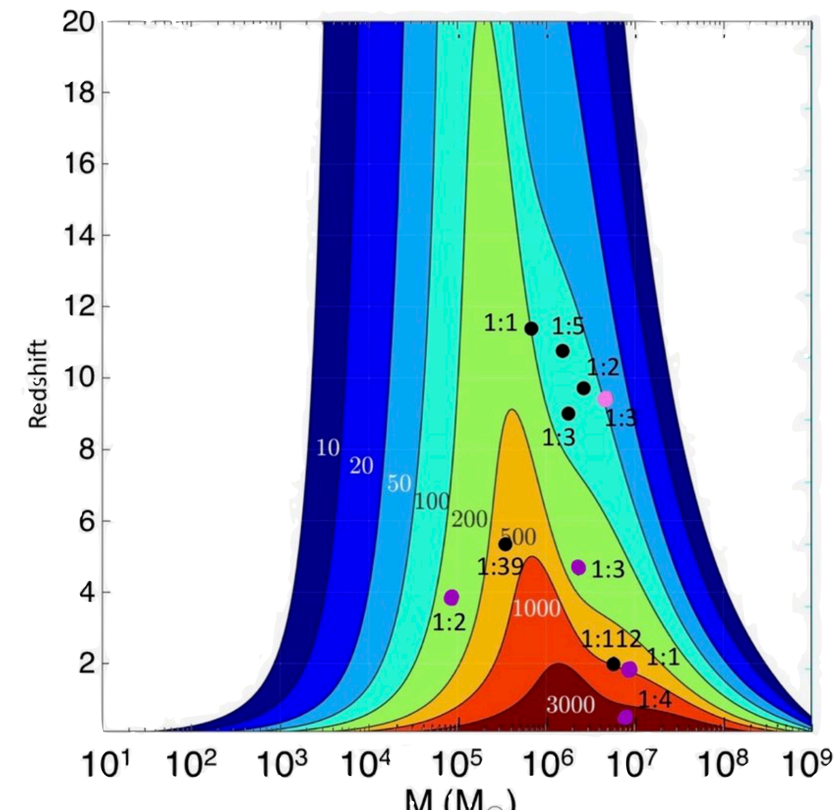
- **GW enable to test several beyond-GR phenomenology:**
  - speed of gravity
  - graviton mass
  - spacetime symmetry breaking
  - scalar-tensor theories of gravitation
  - "agnostic" deviations

- **Current sensitivities are still relatively low**
  - next generation instruments will probe a larger volume of the Universe
  - 3G terrestrial detectors: Einstein Telescope / Cosmic Explorer can detect up to $z = 100$
  - Spatial mission: LISA will have access to lower frequencies & higher redshifts

Maggiore et al, JCAP 03 (2020) 050



Bellovary et al, MRAS 482 (2019) 3



Supplementary material

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`

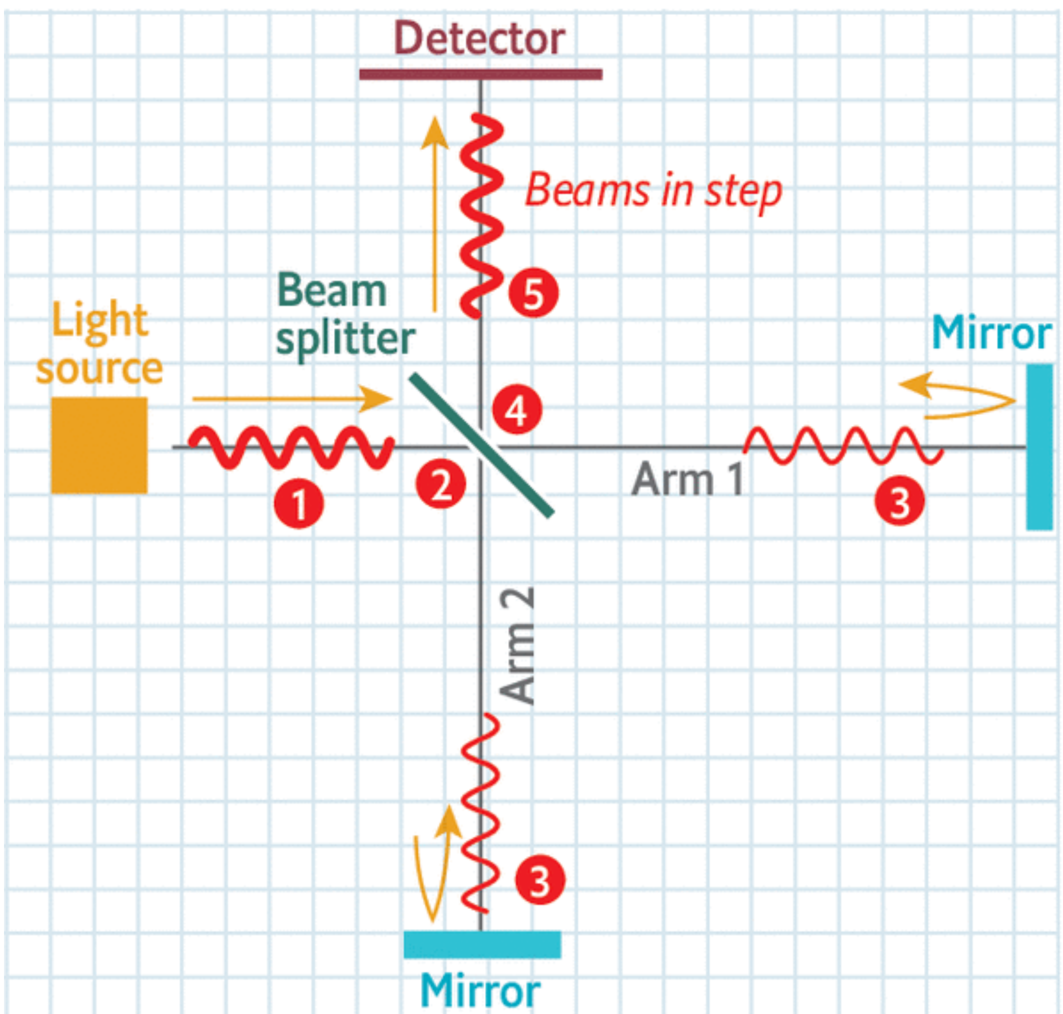
- **DGP gravity:**
  Extension of the Einstein–Hilbert action to a 4+1 Minkowski space. Motivation: acceleration of the Universe expansion without Λ.
  `Dvali, Gabadadze, Porrati. Phys. Lett. B 485:208-214 (2000)`

- **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)`

Gravitational waves detection with interferometry

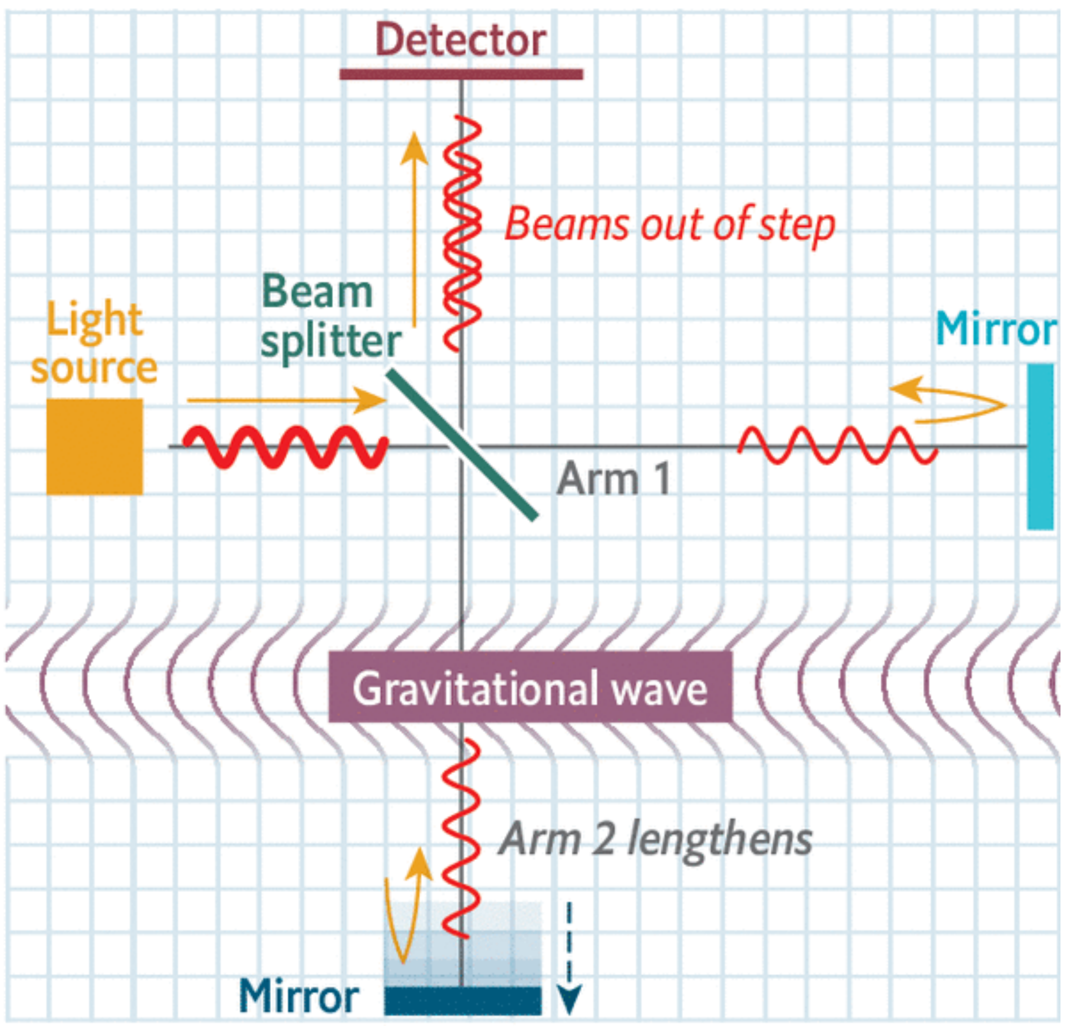
- The variation of space-time interval is measured with **light interferometry**.
- A light beam is divided in **two beams** travelling along orthogonal arms.
- Mirrors in the end of the arms reflect the beams back to a **photodetector**.
- If no gravitational wave passes through, the arm length remains the same and **the interference pattern is the sum of the splitted electromagnetic waves**.



Source: The Economist

Gravitational waves detection with interferometry

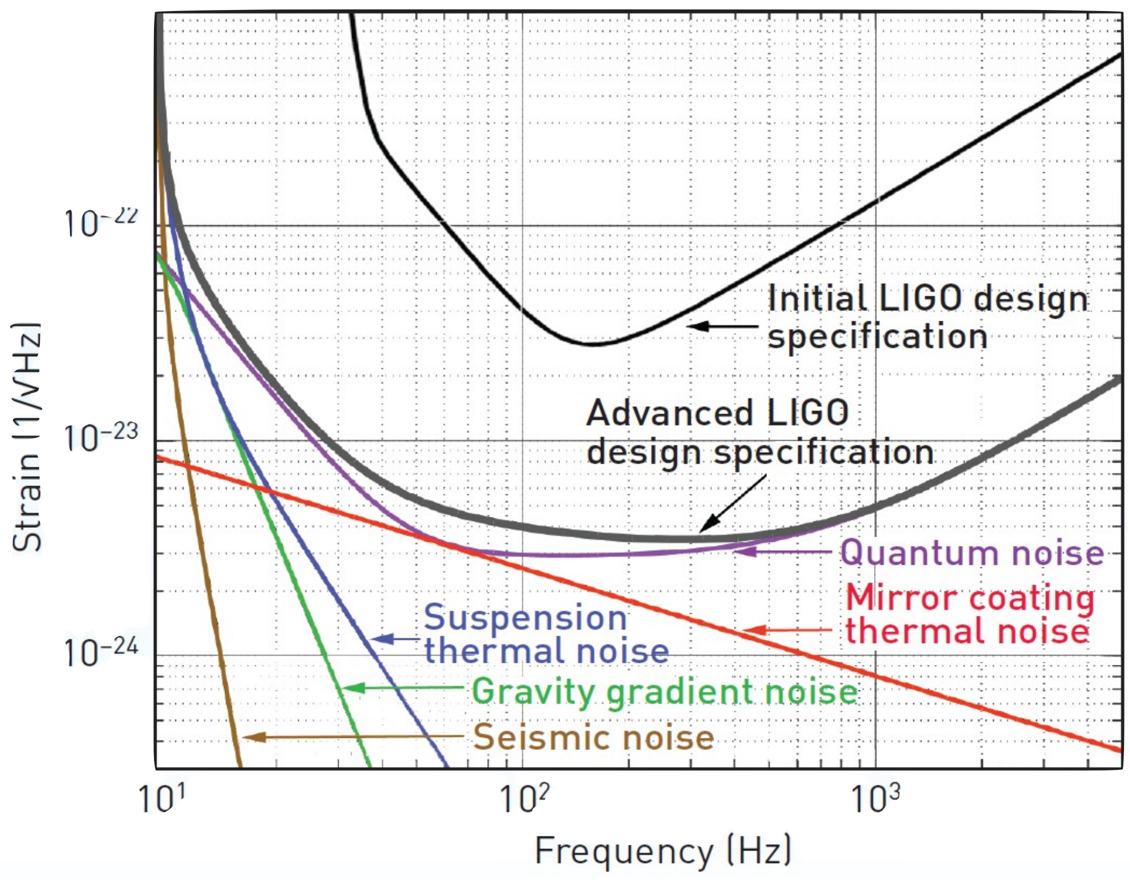
- The variation of space-time interval is measured with **light interferometry**.
- A light beam is divided in **two beams** travelling along orthogonal arms.
- Mirrors in the end of the arms reflect the beams back to a **photodetector**.
- If a gravitational wave passes through, the arm length is different and **the interference pattern is distorted**.



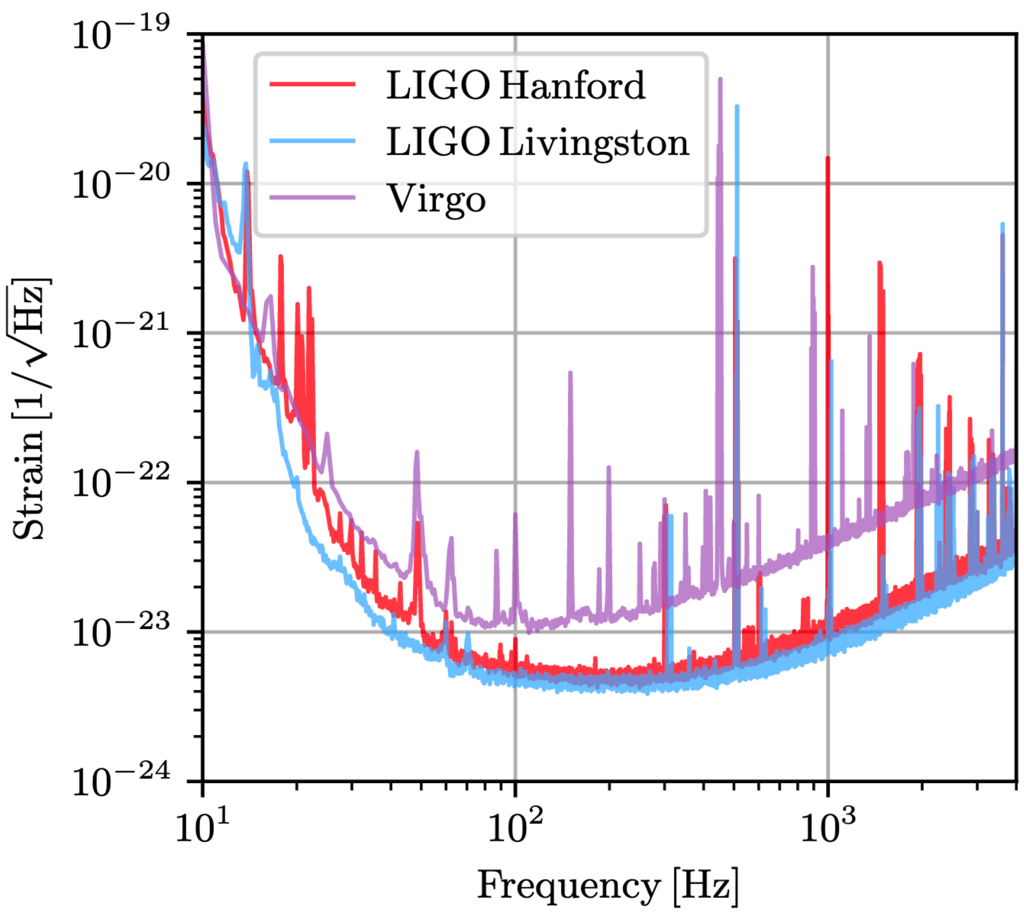
Source: The Economist

LIGO-Virgo sensitivities

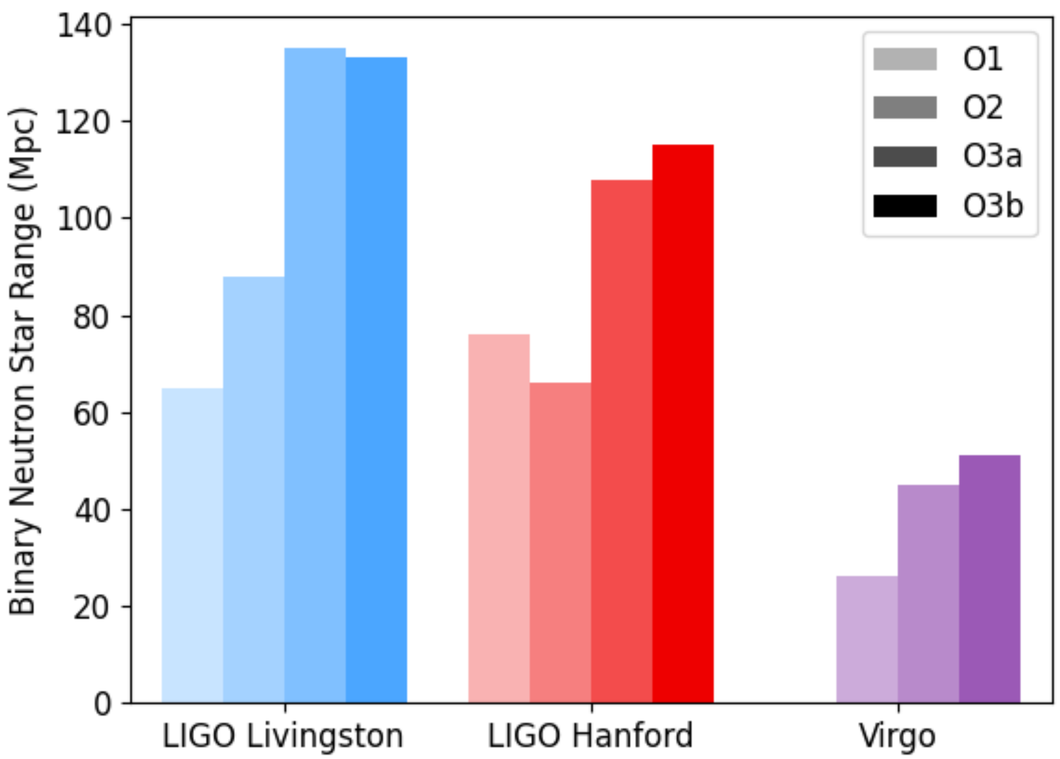
- Ground-based light interferometers are sensitive to the **frequency range 10 - 10^3 Hz**
- Signals entering the detection range are **coalescence of compact binaries** (stellar-mass black holes or neutron stars) and possibly pulsars



O3 sensitivity



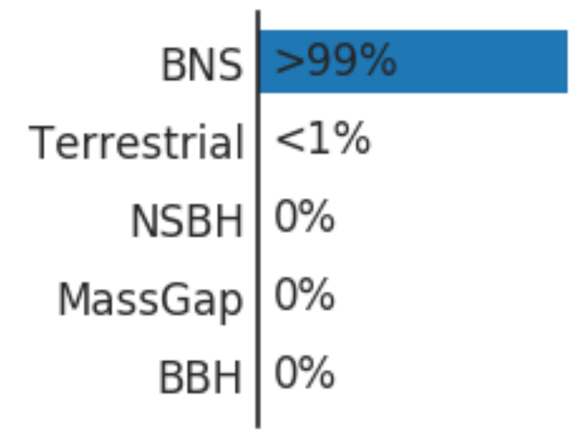
GW detection



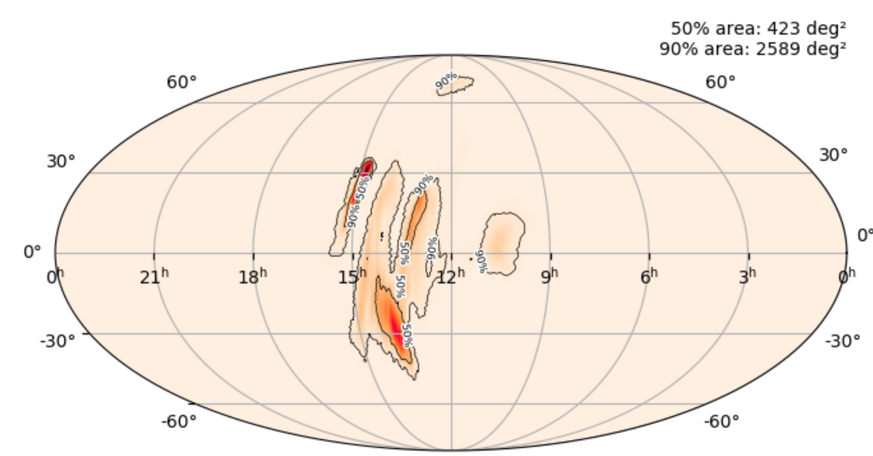
Detection range: during O3a run

Different type of searches:

- 4 modelled searches pipelines
- 2 unmodelled searches pipelines

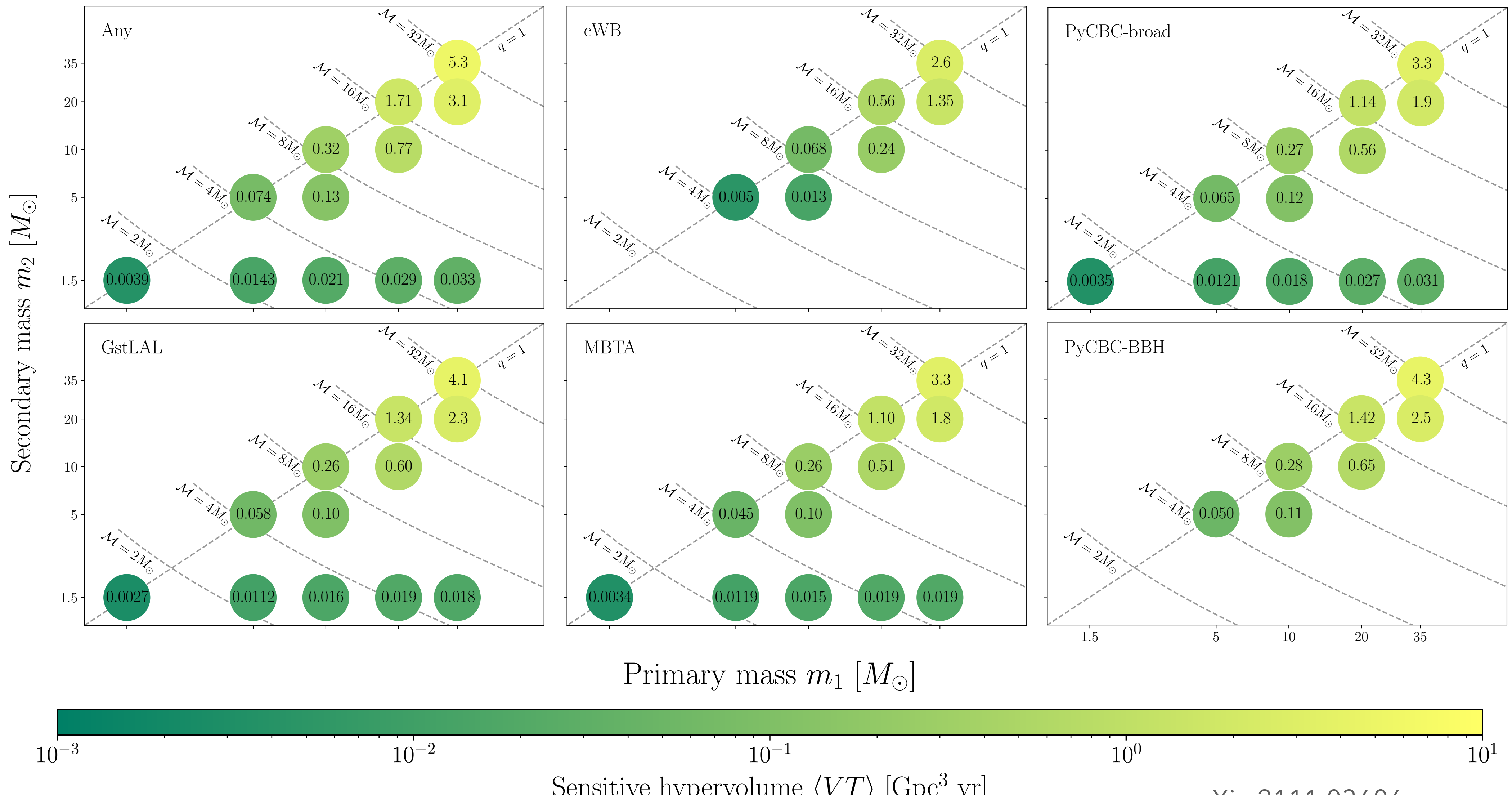


- **Database automatically updated:**
  - GraceDB contains low-latency information about the event
  - In case of possible neutron star, alert sent to satellites and telescopes to search for electromagnetic counterpart



Candidate identification with modelled searches

- **Modelled search:**
  - algorithms comparing template banks signals with datastream
  - calibrated to binary black holes templates with masses in [2 - 750 $M_\odot$]
  - matched filtered correlation triggers detection
  - 3 different pipelines: MBTA, pyCBC, GstLAL

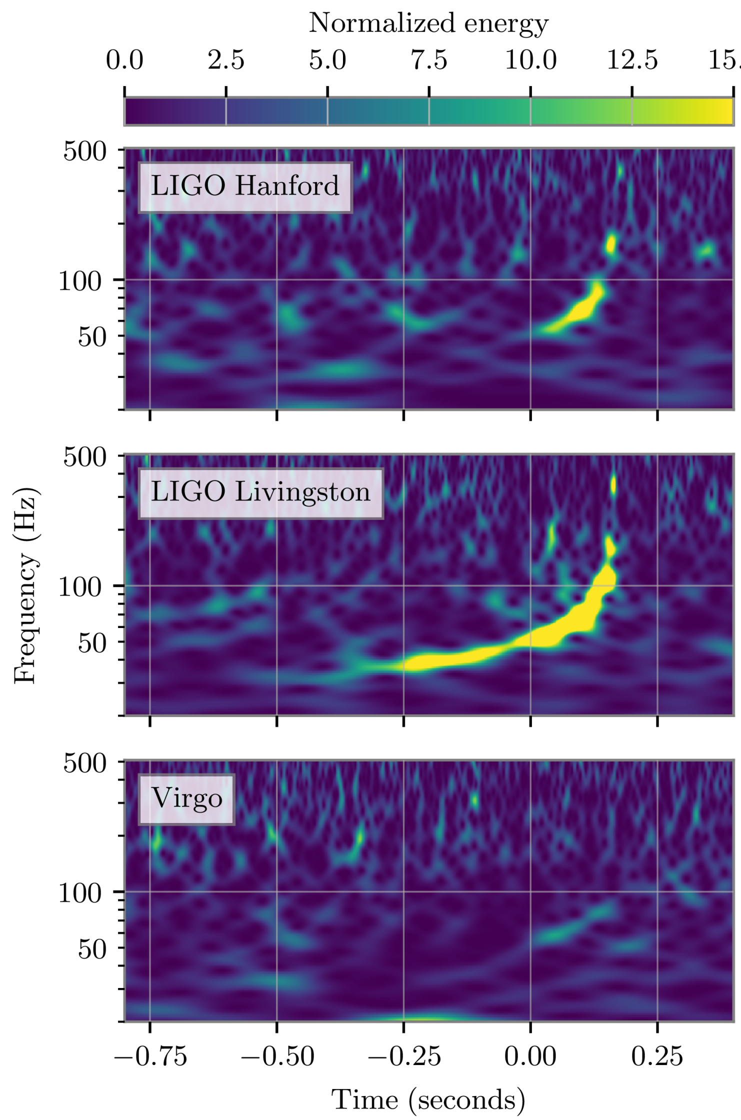


arXiv:2111.03606

Candidate identification with unmodelled searches

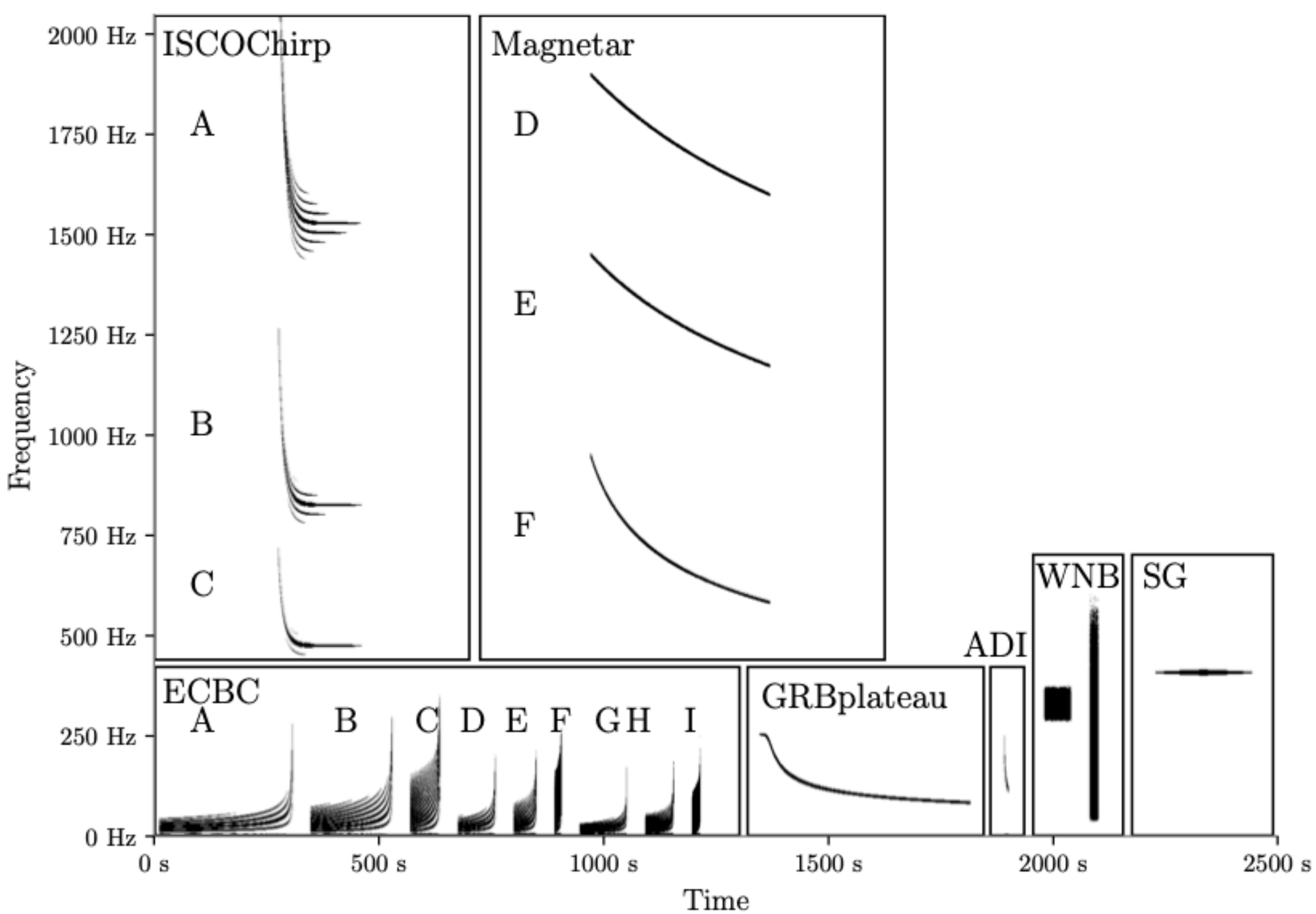
- **Unmodelled search:**
  - Search for coherent excess power
  - Target events not in template banks (supernovae, spacetime defects, etc)
  - 1 pipeline: cWB

Binary black holes system (GW190412)



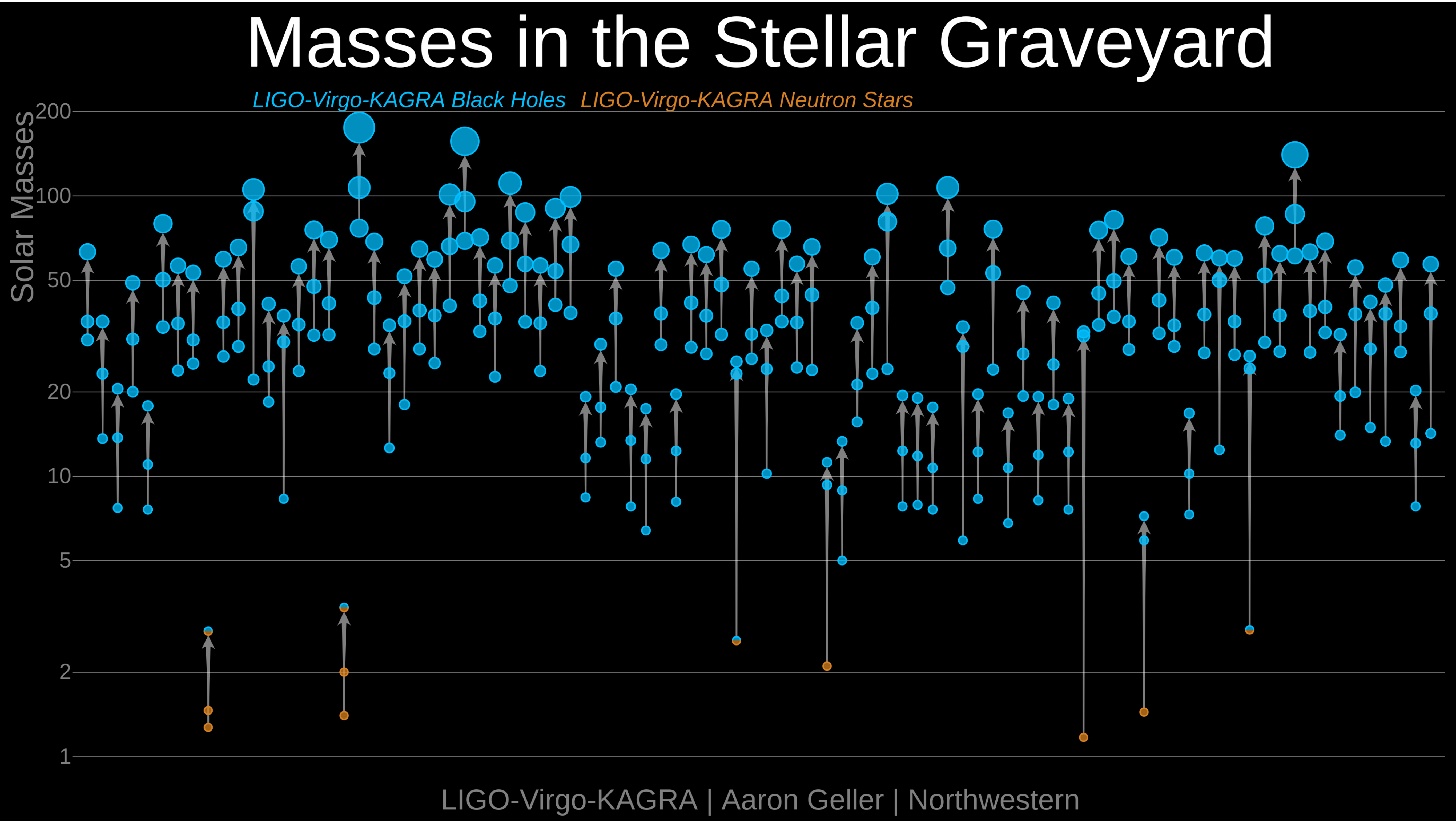
arXiv:2004.08342

Other type of systems

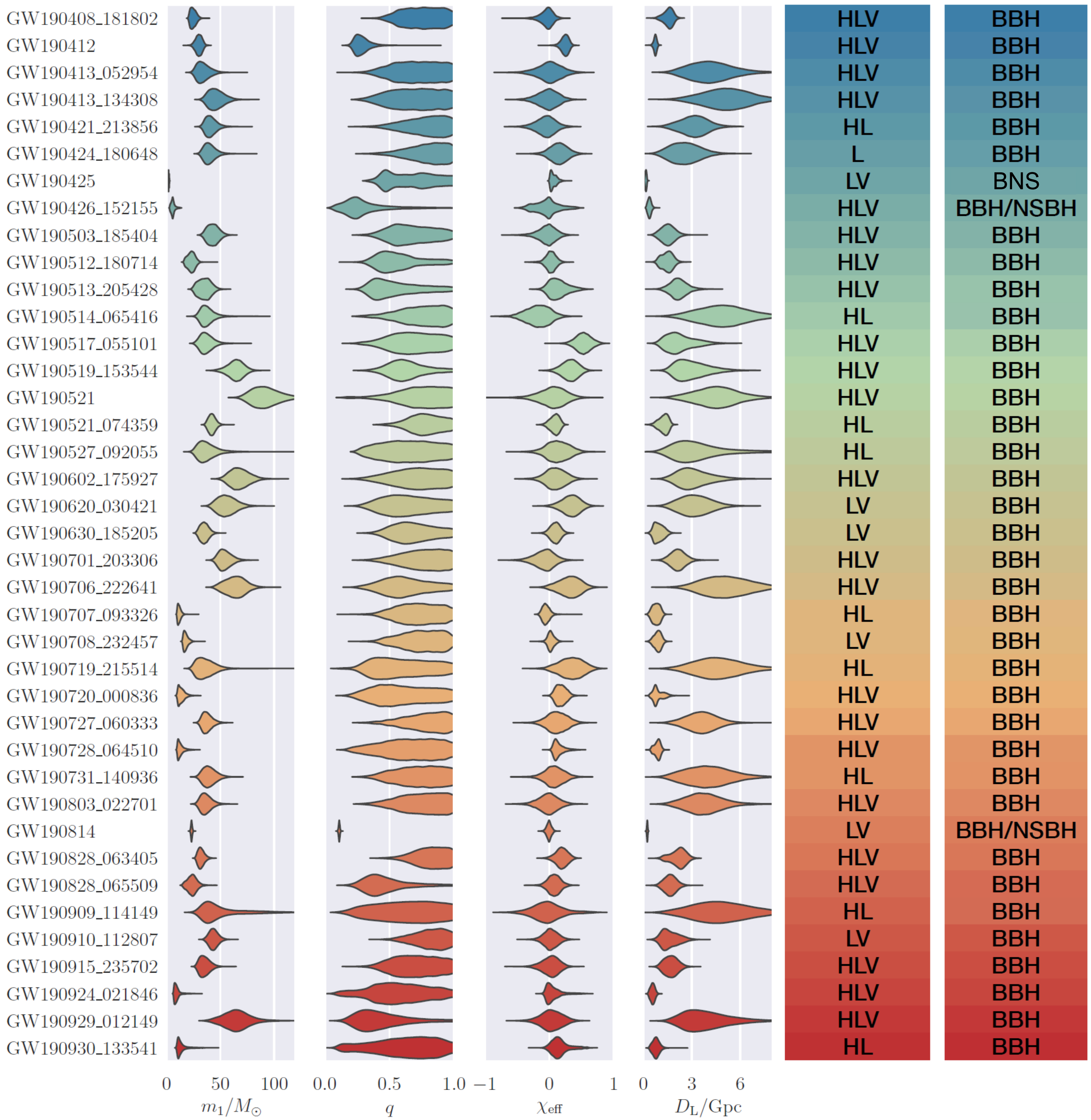


arXiv:2107.13796

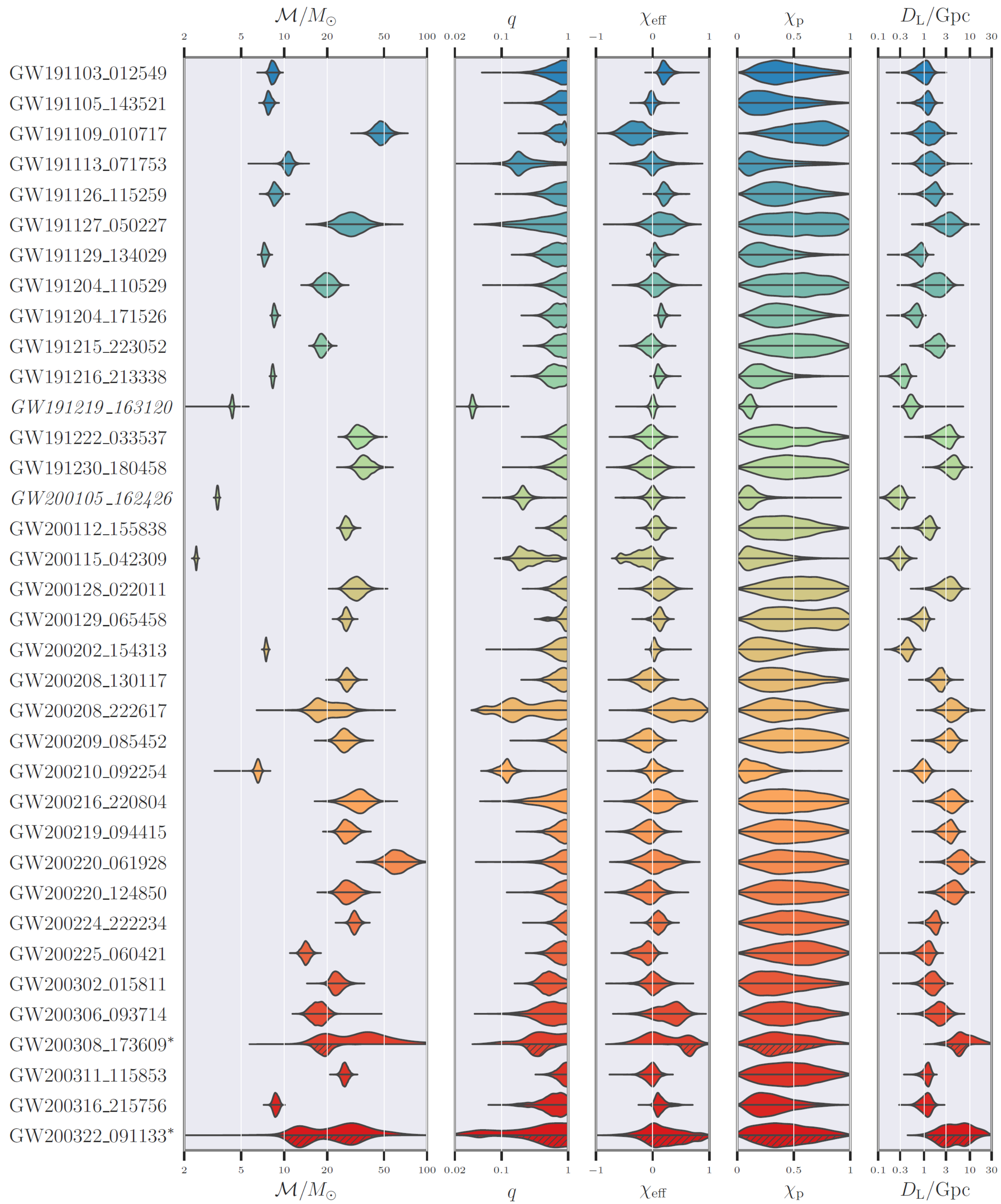
All GW sources ever detected



O3a event properties



O3b event properties



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Network observation plan

- 2 more observation runs planned (up to 2027)
- Post O5 plans under discussion