

Comparison of Gravitational Waveforms in General Relativity and Scalar–Tensor Theories

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Two topics:

PART I

A prediction of GR

- Spin inversions of supermassive black-hole binaries
- Detector: **LISA**
- Comparison: signal **without** spin inversion
- Karácsonyi & **Gergely**, accepted in *Universe* (2026)

PART II

A test of GR

- Scalar dipole radiation in scalar-tensor theories
- Detector: **Einstein Telescope**
- Comparison: GR waveform
- Karácsonyi & **Keresztes**, in preparation (2026)

The toolkit

Noise-weighted inner product

$$(h_1|h_2) = 4 \operatorname{Re} \int_{f_{\min}}^{f_{\max}} \frac{\tilde{h}_1(f) \tilde{h}_2^*(f)}{S_n(f)} df$$

Optimal signal-to-noise ratio, SNR $\rho[h] = \sqrt{(h_1|h_2)}$

Match

$$\mathcal{M}(h_1, h_2) = \max_{\Delta t, \Delta \phi} \frac{(h_1|h_2)}{\sqrt{(h_1|h_1)(h_2|h_2)}}$$

$\varepsilon = 1 - \mathcal{M}$ is the mismatch

 Part I: full search over a template family · Part II: component SNRs and overlaps

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$\varepsilon = 1 - \mathcal{M}$ is the mismatch

Subtract the best-fitting **competitor** waveform:

$$\rho_{\text{res}} = \rho_{\star} \sqrt{1 - \mathcal{M}^2}$$

- small ρ_{res} : the effect **hides in the noise**
- big ρ_{res} : measurable structure **cannot be reproduced**

● Part I: full search over a template family · Part II: component SNRs and overlaps

PART I

Spin-inversion Degeneracies in Restricted Inspiral Waveforms for LISA

K. Karácsonyi & L. Á. Gergely

Detecting spin inversions with LISA?

Part I

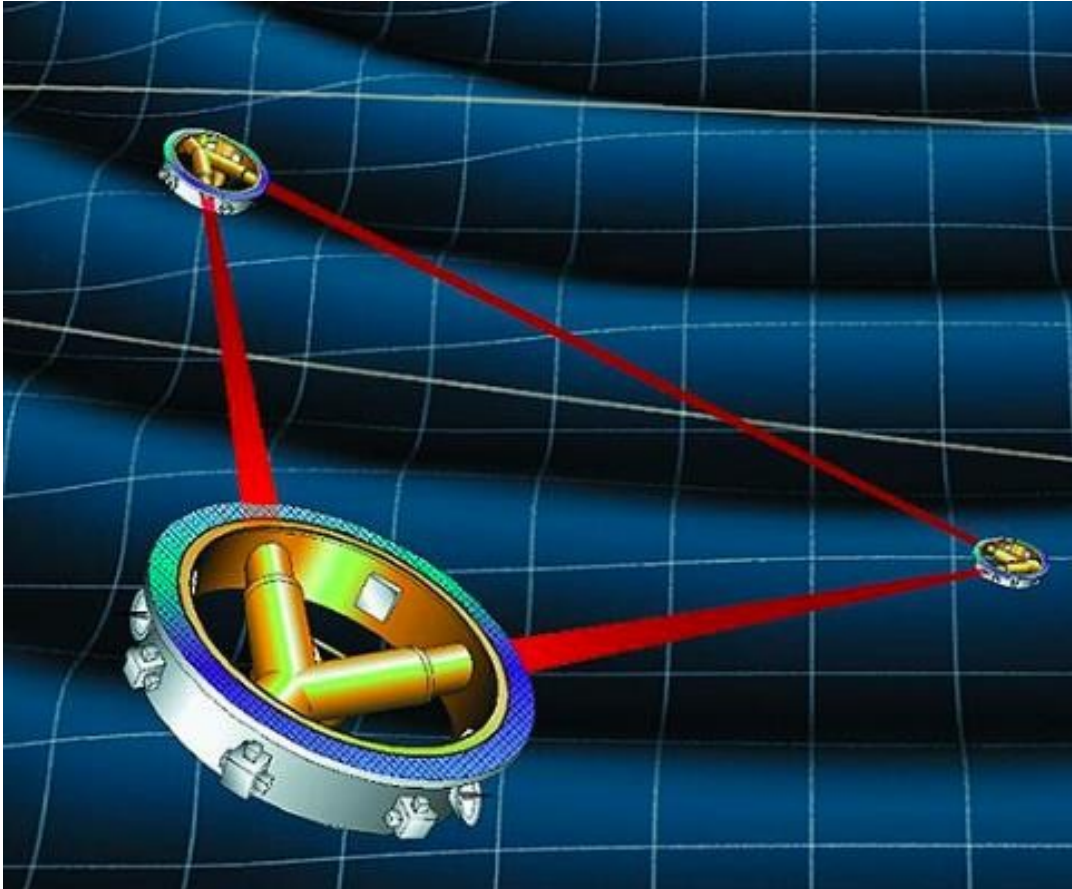


Illustration: LISA (NASA)

- Space-based interferometer: three spacecraft
2.5 million km arms
- Sensitive in the **millihertz** band
- Spin dynamics evolves over the observation time
 ≈ 0.9 yr from 0.2 to 10 mHz
- ESA mission, launch planned for the mid-2030s
- LISA sensitivity curve from Robson, Cornish & Liu (2019)

Three routes to a spin inversion

Part I

1. Single spin flip

- Supermassive BH binaries in the early inspiral
- intermediate mass ratios $1/30 \lesssim q \lesssim 1/3$

Gergely & Biermann 2009; Gergely, Biermann & Caramete 2010

2. Recurrent flip-flops

- Found in numerical relativity at $q = 1$
- 3.5PN continuation predicts repeated flip-flops

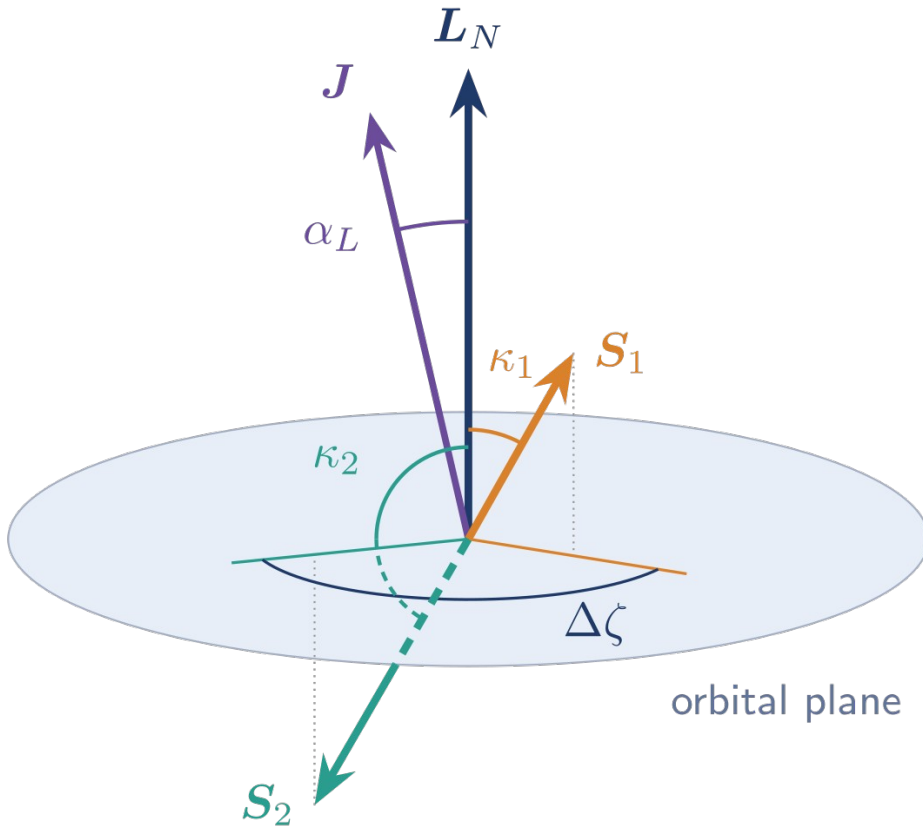
Lousto & Healy 2015; Lousto, Healy & Nakano 2016

3. Quadrupole-induced flip-flops

- Driven by the spin-induced mass quadrupole, e.g.
 - $w \simeq 1$ – Kerr
 - $w \simeq 3$ – neutron star

Keresztes, Tápai & Gergely 2021

Can any of them be **identified in gravitational-wave data**?



Internal configuration $(\kappa_1, \kappa_2, \Delta\zeta)$: independent of the observer

$\mathbf{J} \simeq \mathbf{L}_N + \mathbf{S}_1 + \mathbf{S}_2$ nearly fixed on the precession timescale:

$$\cos \kappa_i = \hat{\mathbf{S}}_i \cdot \hat{\mathbf{L}}_N, \quad \cos \gamma = \hat{\mathbf{S}}_1 \cdot \hat{\mathbf{S}}_2$$

$$\Delta\zeta = \zeta_1 - \zeta_2 \quad \zeta_i \text{ are the azimuthal angles of the spins around } \mathbf{L}_N$$

$$\Delta\kappa_i = \kappa_{i,\max} - \kappa_{i,\min} \quad \text{for a complete flip-flop } \Delta\kappa_i \approx \pi$$

- **Azimuthal precession:** spins and $\mathbf{L}_N$ rotate about $\mathbf{J}$
- **Nutation:** the angles κ_i change, only this can invert a spin

● **Spin inversion:** the spin crosses the orbital plane.

2PN spin-angle dynamics

Part I

Evolution of the internal angles $\kappa_1, \kappa_2, \Delta\zeta$

$$v = (\pi M f)^{1/3}, \quad \tau = t/M, \quad x_i = \chi_i v, \quad Q_i = -w_i \frac{S_i^2}{m_i} \quad (w_i = 1 : \text{Kerr})$$

$$\begin{aligned} \frac{d\kappa_1}{d\tau} &= \frac{3}{2} \eta v^5 (1 + q - x_1 \cos \kappa_1 - q w_2 x_2 \cos \kappa_2) x_2 \sin \kappa_2 \sin \Delta\zeta \\ \frac{d\kappa_2}{d\tau} &= -\frac{3}{2} \eta v^5 (1 + q^{-1} - x_2 \cos \kappa_2 - q^{-1} w_1 x_1 \cos \kappa_1) x_1 \sin \kappa_1 \sin \Delta\zeta \\ \frac{d\Delta\zeta}{d\tau} &= \frac{3}{2} \eta v^5 \mathcal{F}(\kappa_1, \kappa_2, \Delta\zeta; q, x_i, w_i) \end{aligned}$$

Circular limit of the orbit-averaged system of Keresztes, Tápai & Gergely, PRD 103, 084024 (2021)

Cross-driven nutation

Each spin drives the other one's nutation:
 $d\kappa_1/d\tau \propto x_2, d\kappa_2/d\tau \propto x_1$

Weak spin, big motion

A dominant spin can flip a weak one while barely moving itself

2PN couplings

Spin-orbit (1.5PN), spin-spin and quadrupole-monopole (2PN), coupled to $dv/d\tau$

The dominant-spin limit $(\chi_2 \ll \chi_1)$

Part I

We simplify the spin-evolution equations.
During it, we introduce:

$$\mathcal{B} = -\left(1 + q^{-1} - q^{-1}w_1x_1 \cos \kappa_1\right) x_1 \sin \kappa_1$$

$$\mathcal{A} = q - q^{-1} + \left(1 + 2q^{-1} - w_1 - q^{-1}w_1x_1 \cos \kappa_1\right) x_1 \cos \kappa_1$$

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We also introduce $d\lambda = (3/2)\eta v^5 d\tau$.

From the simplified equation for κ_2 :

$$\frac{d \cos \kappa_2}{d\lambda} = -\mathcal{B} \sin \kappa_2 \sin \Delta\zeta = -\mathcal{B} Y$$

Using two simplified evolution equations, we find that Y obeys a harmonic-oscillator equation:

$$\frac{d^2 Y}{d\lambda^2} + \Omega_{\text{ff}}^2 Y = 0$$

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Quadrupole-induced motion

$$1 + 2q^{-1} - w_1 = \mathcal{O}(v) \Rightarrow w_1 \simeq 1 + \frac{2}{q} \longrightarrow q \approx 1 \text{ means } w_1 \approx 3$$

● This is one way spins can move. But how do they affect the gravitational radiation?

Gravitational radiation changes the orbit, v increases during the inspiral:

$$\frac{dv}{d\tau} = \frac{32}{5}\eta v^9 \left[1 - \left(\frac{743}{336} + \frac{11}{4}\eta \right) v^2 + (4\pi - \beta) v^3 + \left(\frac{34103}{18144} + \frac{13661}{2016}\eta + \frac{59}{18}\eta^2 + \sigma \right) v^4 \right]$$

Kidder 1995; Mikóczi, Vasúth & Gergely 2005; Gergely & Mikóczi 2009

1.5PN spin-orbit interaction

$$\beta = \frac{1}{12} \sum_i \chi_i \cos \kappa_i \left[113 \left(\frac{m_i}{M} \right)^2 + 75\eta \right]$$

- Each spin enters through its **signed projection** $\chi_i \cos \kappa_i$
- Because β is subtracted, $\cos \kappa_i$ influences how fast the system evolves
- If $\cos \kappa_i = 1$, β is large – the orbital acceleration slows
- If $\cos \kappa_i = -1$, β is negative – the orbital acceleration grows



A visually dramatic inversion may change the phase only a little

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2PN interactions

$$\begin{aligned} \sigma &= \sigma_{S_1 S_2} + \sigma_{\text{self}} + \sigma_{\text{QM}} \\ \sigma_{S_1 S_2} &\propto 721 \cos \kappa_1 \cos \kappa_2 - 247 \cos \gamma \\ \sigma_{\text{self}} &\propto 6 + \sin^2 \kappa_i \\ \sigma_{\text{QM}} &\propto w_i (3 \cos^2 \kappa_i - 1) \end{aligned}$$

- **Spin-spin:** mutual interaction between the two spins
- **Self-spin:** how one body's spin interacts with its own gravitational field
- **Quadrupole-monopole:** how the rotationally-induced deformation of the bodies affects their orbital evolution



A visually dramatic inversion may change the phase only a little

Restricted waveform model we used

Stationary phase approximation of the evolved inspiral

$$\tilde{h}(f) = A(f) e^{i\Psi(f)}, \quad A(f) = \frac{2\eta M}{D_L} \frac{v^2}{\sqrt{\dot{f}}} \mathcal{Q}[\iota(f)]$$

$$\mathcal{Q}(\iota) = \left[\left(\frac{1 + \cos^2 \iota}{2} \right)^2 + \cos^2 \iota \right]^{1/2}$$

$$\cos \iota(f) = \cos \alpha_L \cos \theta_{JN} + \sin \alpha_L \sin \theta_{JN} \cos \lambda_L$$

θ_{JN} : angle between the initial total angular momentum J and the line of sight

ι : angle between the instantaneous orbital angular momentum L_N and the line of sight

α_L : the orbital tilt relative to J

Spin inversions enter through:

- $\beta(\mathbf{f}), \sigma(\mathbf{f})$ in the phase
- and in $1/\sqrt{\dot{f}}$
- and through $\mathfrak{t}(\mathbf{f})$ in $\mathcal{Q}$

Quasi-circular, adiabatic inspiral ($e = 0$).
Gravitational radiation circularizes the orbit [Peters 1964]

A circular inspiral is the standard first approximation in the LISA band.

Spin-orbit, spin-spin and QM terms: Kidder 1995; Mikóczi, Vasúth & Gergely 2005

Can a waveform without inversion reproduce it?

We generated many comparison binaries using **the same secular spin dynamics**. Their spins were still allowed to precess and nutate. But: $\cos \kappa_1, \cos \kappa_2$ never reach zero

Any candidate that crossed zero was rejected.

Four sectors defined:



- **Within the sectors we varied:**

$M, q, \chi_1, \chi_2, \kappa_{1,0}, \kappa_{2,0}, \Delta\zeta_0$ (+ orbital azimuth for $\theta_{\text{JN}} \neq 0$)

- **Maximized:** time, phase

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Part I

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- **Maximized:** time, phase

Among all allowed no-inversion binaries, find the one whose waveform matches the spin-inverting waveform best:

$$\mathcal{M}_{\text{best}} = \max_{\theta \in \Theta_{\text{NI}}} \mathcal{M}[h_{\text{inv}}, h_{\text{NI}}(\theta)]$$

$$\rho_{\text{res}} = \rho_{\star} \sqrt{1 - \mathcal{M}_{\text{best}}^2}, \quad \rho_{\star} = 100$$

Interpretation

The residual found is an **upper bound** on the smallest residual achievable within the no-inversion templates.

A small value proves degeneracy, a large value suggests distinguishability.

Analytical LISA sensitivity curve from Robson, Cornish & Liu (2019)

Five spin-inverting injections

Part I

$M = 2 \times 10^5 M_\odot$ (detector frame), $D_L = 1$ Gpc, $0.2 \text{ MHz} \leq f \leq 10 \text{ MHz}$ ($0.085 \leq v \leq 0.314$, ≈ 0.89 yr)

Case	q	χ_1	χ_2	$\kappa_{1,0}$	$\kappa_{2,0}$	$\Delta\zeta_0$	w_1	w_2	$\Delta\kappa_1$	$\Delta\kappa_2$	N_1	N_2
K0	0.97	0.95	0.50	90°	18°	135°	1	1	80°	155°	3	6
KW	0.97	0.95	0.05	90°	18°	135°	1	1	5°	133°	5	9
KH1	0.94	0.95	0.95	70°	110°	80°	1	1	84°	90°	14	14
KH2	0.97	0.95	0.95	35°	138°	180°	1	1	139°	139°	6	6
Q	0.97	0.70	0.05	150°	18°	45°	3.06	3	10°	128°	0	5

$\Delta\kappa_i = \kappa_{i,\max} - \kappa_{i,\min}$ (angular excursion); N_i = number of orbital-plane crossings of spin i

K0

two substantial spins

KW

similar to K0, weak secondary

KH1

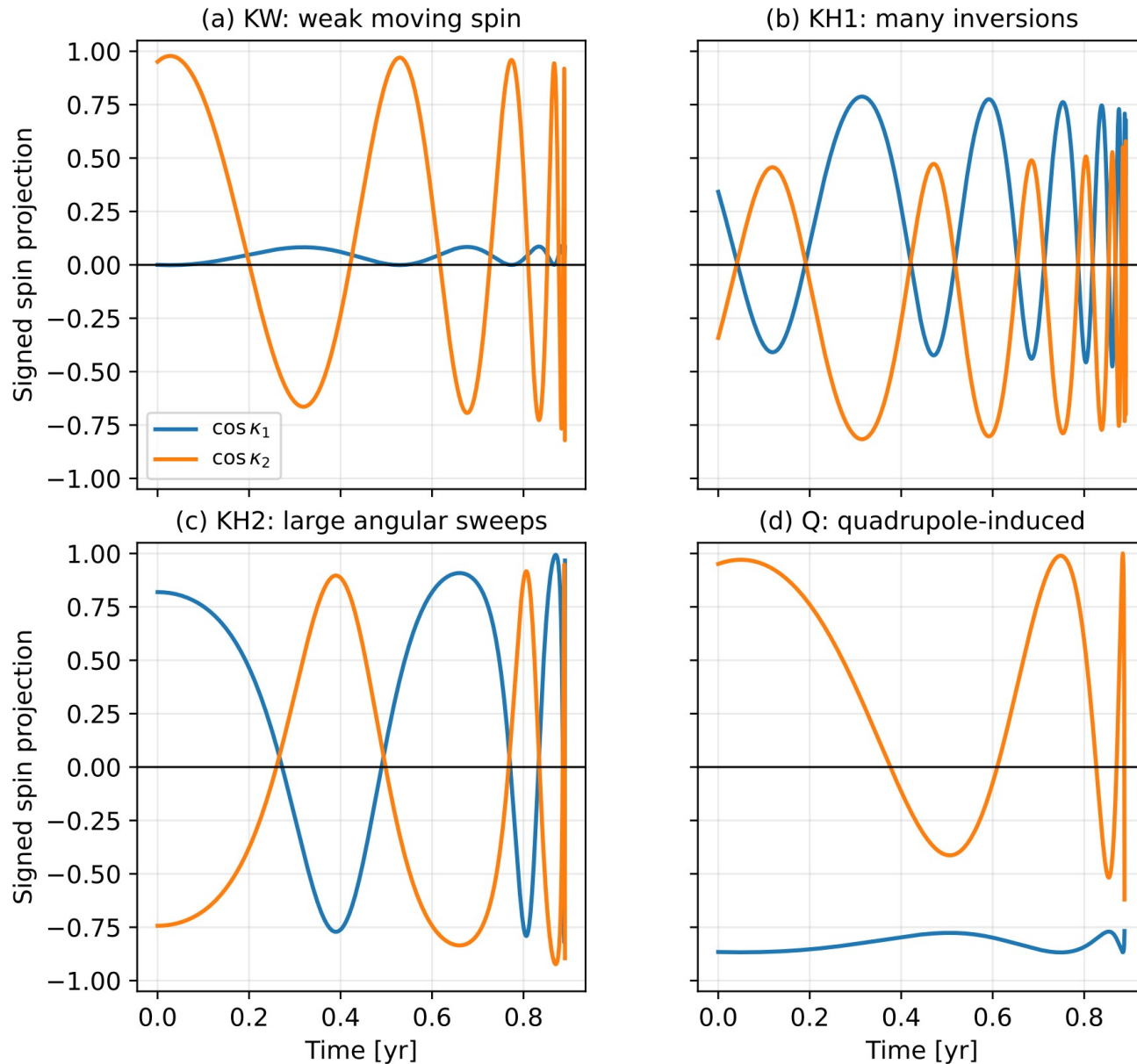
many inversions

KH2

large angular sweeps

Q

non-Kerr, quadrupole-induced

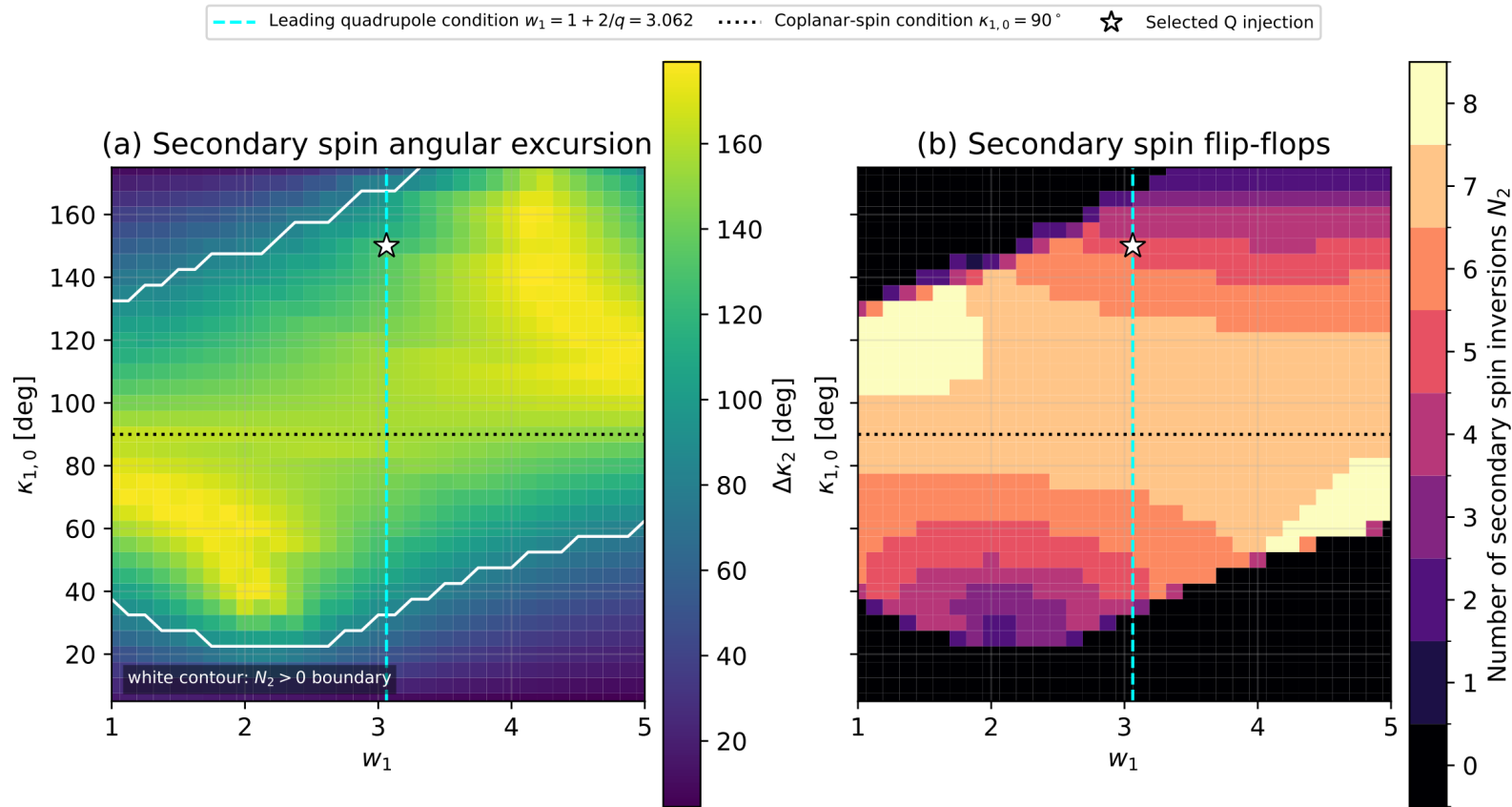


- **K0** (not shown): same initial angles as KW, but $\chi_2 = 0.50$
- **KW**: a spin with $\chi_2 = 0.05$ sweeps 133° and crosses the plane 9 times
- **KH1**: both spins invert 14 times
- **KH2**: both spins sweep $\approx 139^\circ$
- **Q**: dominant spin stays anti-aligned; the weak secondary crosses 5 times

Flip-flops speed up as the binary approaches merger.

Quadrupole-induced inversions

Part I



The scan varies the quadrupole strength w_1 and $\kappa_{1,0}$

(a) how far the weak spin swings, $\Delta\kappa_2$; inside the white contour it crosses the orbital plane

(b) how many times it crosses, N_2

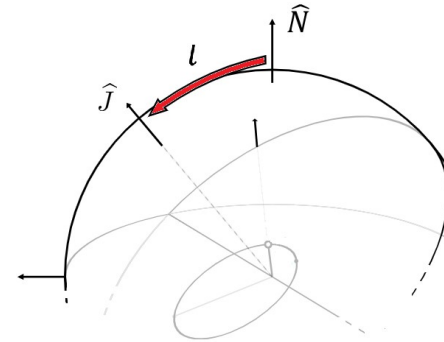
- Band at $\kappa_{1,0} = 90^\circ$ (dotted): the usual Kerr flip-flop, dominant spin in the orbital plane
- near $w_1 \approx 1 + 2/q = 3.06$ (cyan): flip-flops with the dominant spin far from the plane; ★ = Q

● A non-Kerr quadrupole ($w_1 \approx 3$) can flip the weak spin even when the dominant spin stays far from the orbital plane

Viewed along J ($\theta_{JN} = 0^\circ$): degeneracies

Part I

Case	Best sector	M_{best}	$1 - M_{\text{best}}$	$\rho_{\text{res}} (\rho^\star = 100)$
K0	(+,+)	0.999972	2.8×10^{-5}	0.75
KW	(+,+)	0.999967	3.3×10^{-5}	0.81
KH1	(-,+)	0.999865	1.3×10^{-4}	1.64
KH2	(+,+)	0.999973	2.7×10^{-5}	0.73
Q	(-,-)	0.999990	1.0×10^{-5}	0.45



Inclination

$$\iota = \theta_{JN} = \angle(\hat{N}, \hat{J})$$

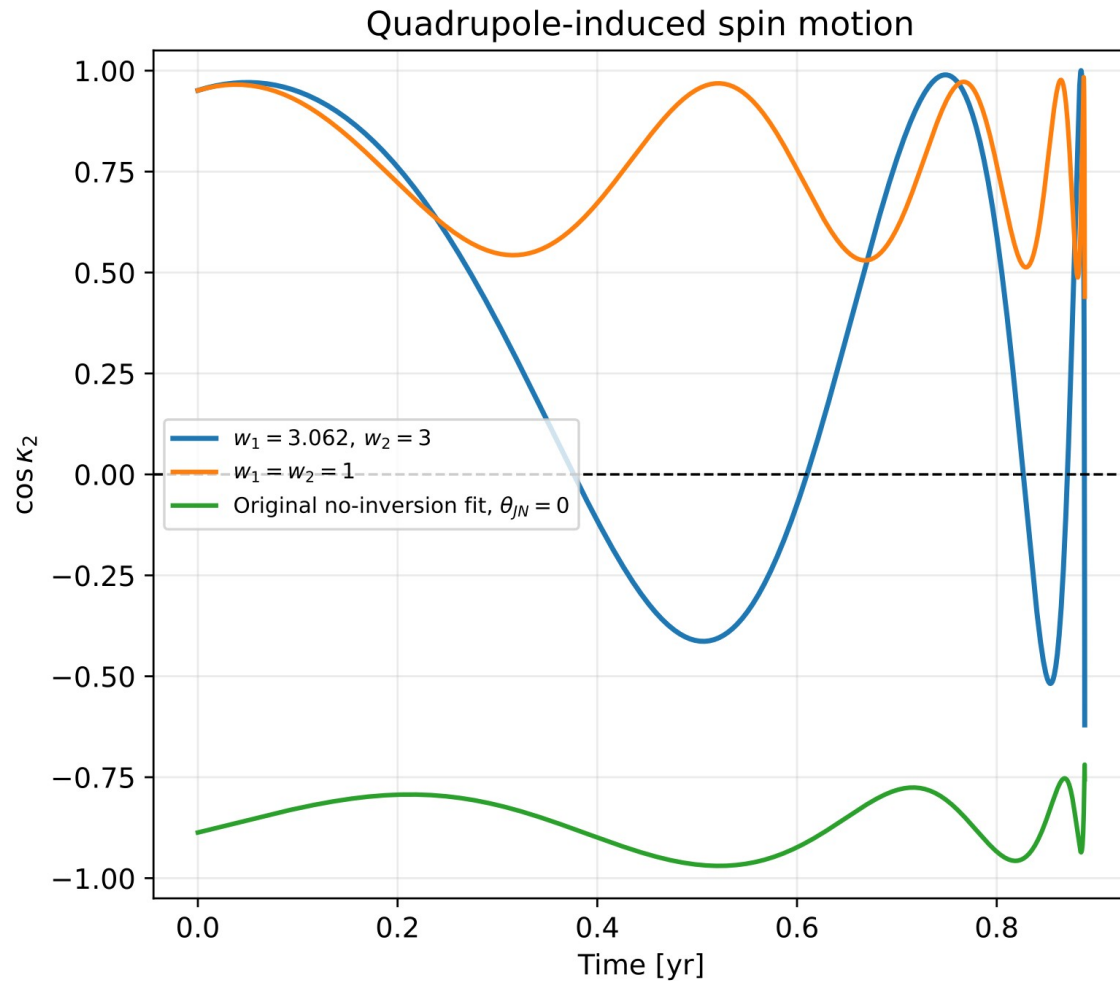
$\hat{N}$: line of sight, $\hat{J}$: total angular momentum

$\iota = 0^\circ$: face-on, viewed along J

$\iota = 90^\circ$: edge-on

- A **135° motion** of spins (KW, K0) is almost completely reproduced
- Larger spins or sweeps (K0, KH2) do **not** increase the residual
- Even **many (14) crossings** of each spin (KH1) are closely matched
- Quadrupole-induced spin flip-flops seem **invisible**

● Size of the angular motion $\neq$ observability of the inversion



● **Q ($w_1 = 3.06, w_2 = 3$)**

Secondary crosses the orbital plane 5 times

● **Same source, Kerr $w_1 = w_2 = 1$**

Stays on the aligned side $\Rightarrow$ inversion caused by the non-Kerr quadrupole; control with $w_2 = 1$ still gives $N_2 = 5$

● **Best no-inversion fit, $(-, -)$ sector**

$(q, \chi_1, \chi_2) = (0.965, 0.255, 0.565)$; $M_{\text{best}} = 0.99999$, $\rho_{\text{res}} = 0.45$

Windowing inversions

Keep the best full-band candidate and refit only time, phase and amplitude inside a window around the crossings.

ρ_{res} at $\rho^* = 100$	K0	KW	KH1	KH2	Q
Full band	0.75	0.81	1.64	0.73	0.45
Interval containing all inversions	0.75	0.63	1.35	0.73	0.45
Largest single-inversion window	0.59	0.18	0.32	0.29	0.27

×5–7

local increase of the normalized mismatch
(KH2, Q)

- Normalized mismatch **can** grow locally
- But short windows carry little power ($\rho_w \approx 1.6, 1.2$), so $\rho_{\text{res},W} \approx 0.01\text{--}0.02$

 A zoomed-in analysis strengthens the result, lowers the residual SNR

What about $\theta_{\text{JN}} \neq 0$?

Part I

For each of the 5 injections and each of the 11 viewing angles θ_{JN} , we searched for the closest binary whose spins **never cross the orbital plane**.

- Same spin dynamics and frequency band
- We changed the observer angle θ_{JN}

For three inclinations, the searches ran on the **Wigner Scientific Computing Laboratory (WSCLAB)** and, for eight of the eleven inclinations, on an **iMac Pro** (3.2 GHz 8-core Intel Xeon W, 32 GB).

Open code and data (Zenodo)



v0.1.0 • aligned view

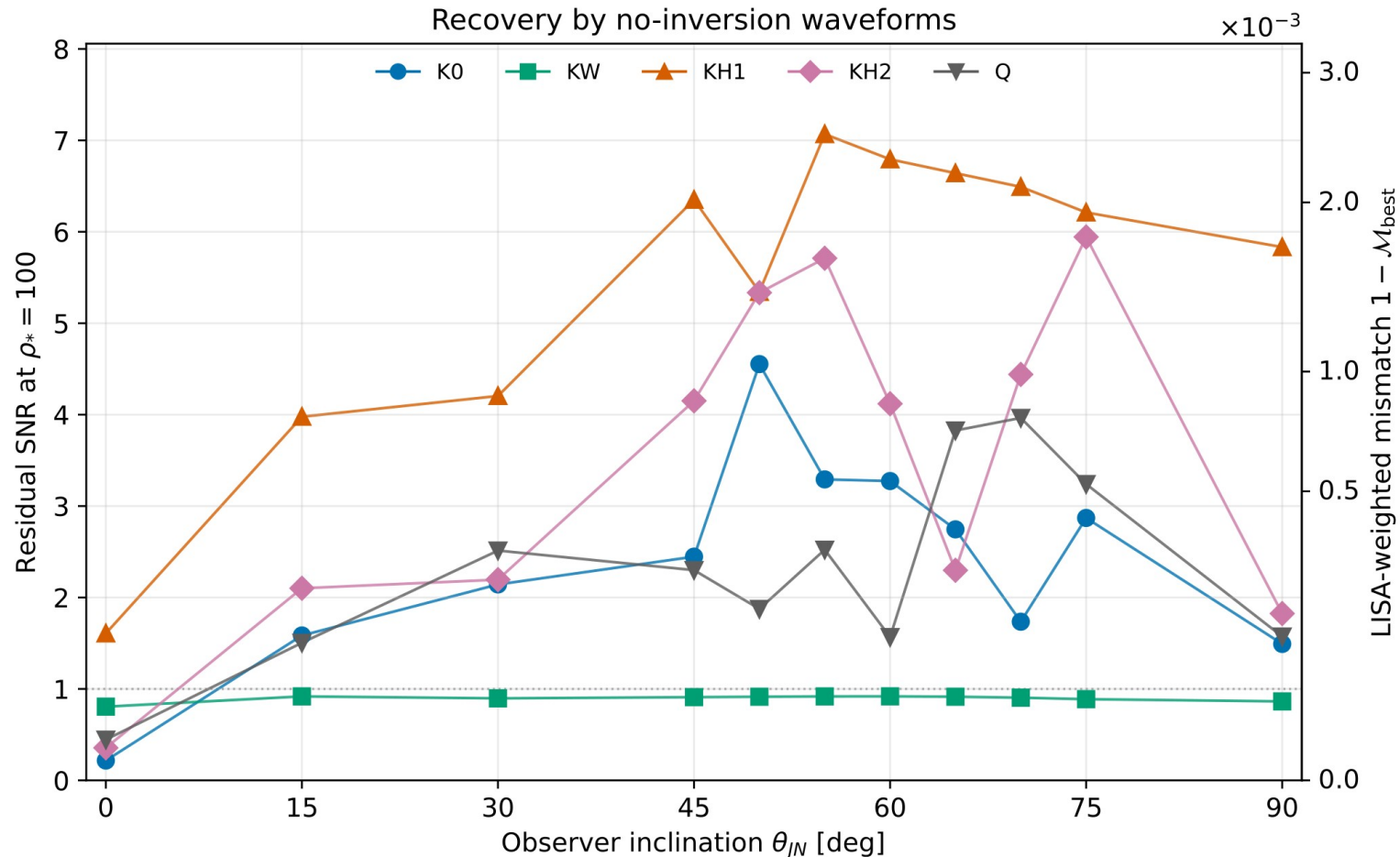
doi.org/10.5281/zenodo.22025538



v0.2.0 • inclination extension

doi.org/10.5281/zenodo.23309463

Searched at $\theta_{\text{JN}} = 0^\circ, 15^\circ, 30^\circ, 45^\circ, 50^\circ, 55^\circ, 60^\circ, 65^\circ, 70^\circ, 75^\circ, 90^\circ$ (5° steps between 45° and 75°, where the residuals peak)



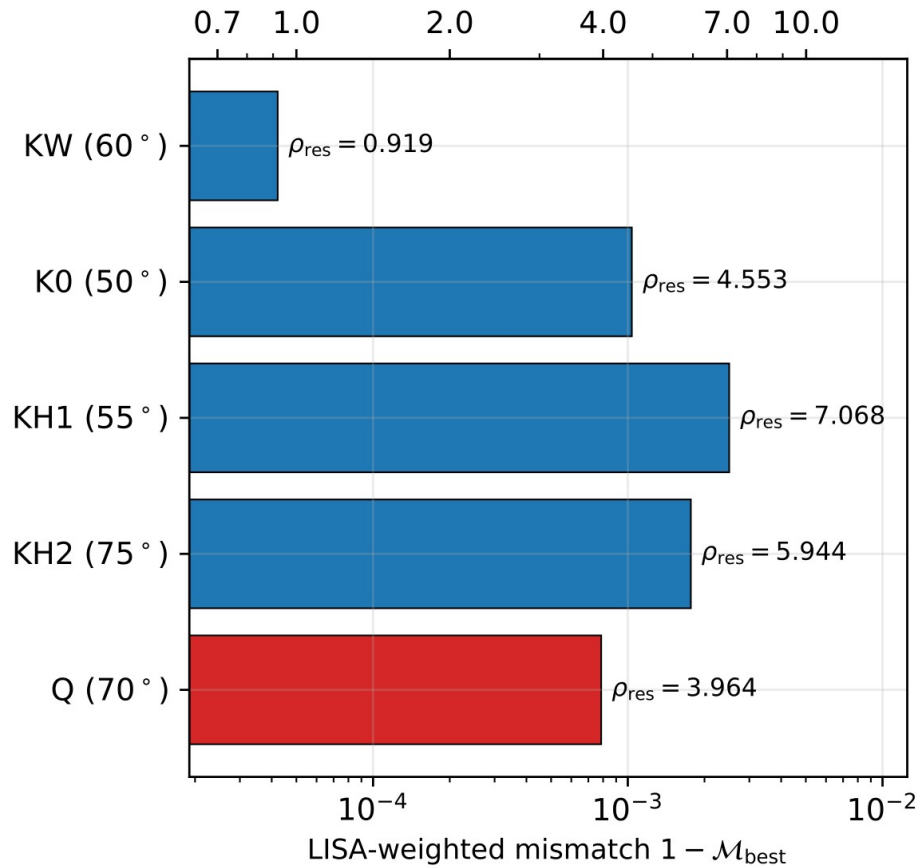
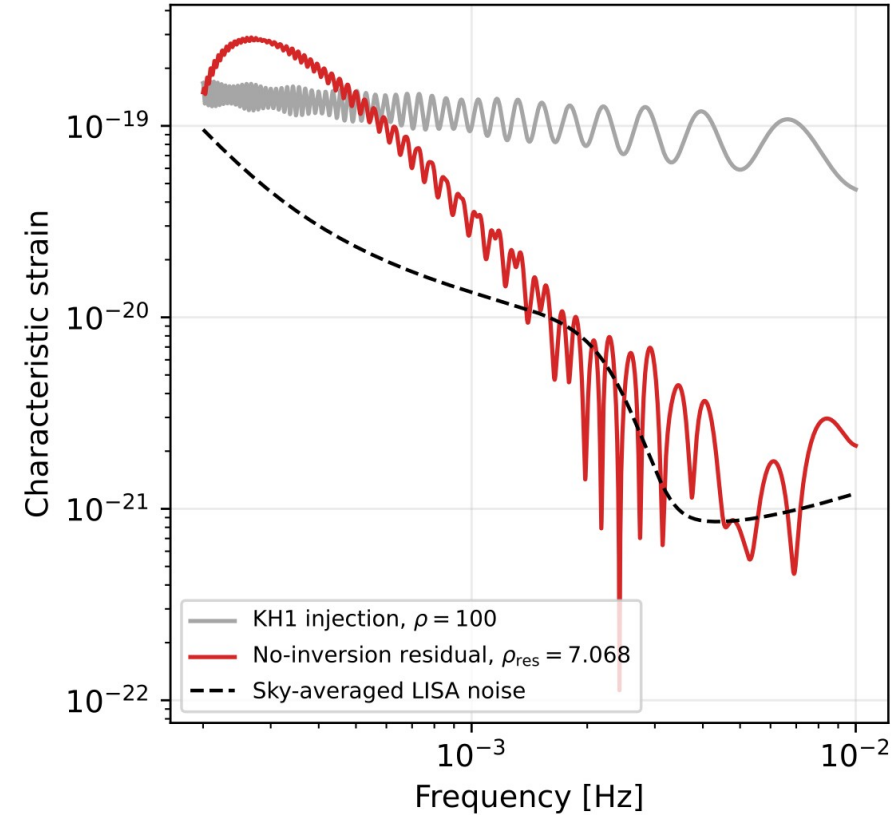
7.07

largest residual SNR: KH1 at $\theta_{\text{JN}} = 55^\circ$

- Each injection renormalized to $\rho_\star = 100$ at every inclination: 55 fits
- **KW** stays below $\rho_{\text{res}} = 1$ at every inclination
- K0 4.55 (50°), KH2 5.94 (75°), Q 3.96 (70°)
- Stable under higher frequency resolution; values are upper bounds

Computed on the Wigner Scientific Computing Laboratory (WSCLAB), HUN-REN Wigner RCP

(a) Largest sampled residuals

(b) KH1 residual spectrum at $\theta_{JN} = 55^\circ$ 

(a) Largest sampled residual per case. (b) KH1 at $\theta_{JN} = 55^\circ$: the residual exceeds the sky-averaged LISA noise mainly at low frequencies; ρ_{res} is the integral over the whole band, not a single-frequency comparison.

Part I: conclusions

Part I

≤ 1.64

residual SNR along J for all five injections ($\rho_\star = 100$)

> 0.99986

matches with no-inversion binaries at $\theta_{\text{JN}} = 0^\circ$

4 – 7

residual SNR at generic inclinations (K0, KH1, KH2, Q)

- Secular 2PN spin dynamics + restricted SPA waveform + sky-averaged LISA noise
- Large spins, large sweeps and many crossings are **not sufficient** for distinguishability
- The **quadrupole branch** near $w_1 \simeq 1 + 2/q$ exists dynamically, yet is absorbed by the fit along J
- At generic viewing angles, spin-inverting signals **may contain measurable structure!**

Outlook: a definitive answer requires a complete precessing waveform with the full time-dependent LISA response.

Code and data: Zenodo, doi:10.5281/zenodo.22025538 (v0.1.0) and doi:10.5281/zenodo.23309463 (v0.2.0)

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Accepted in Universe, 14 October 2026

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K. Karácsonyi · Wigner RMI Theoretical Department Seminar · 16 October 2026

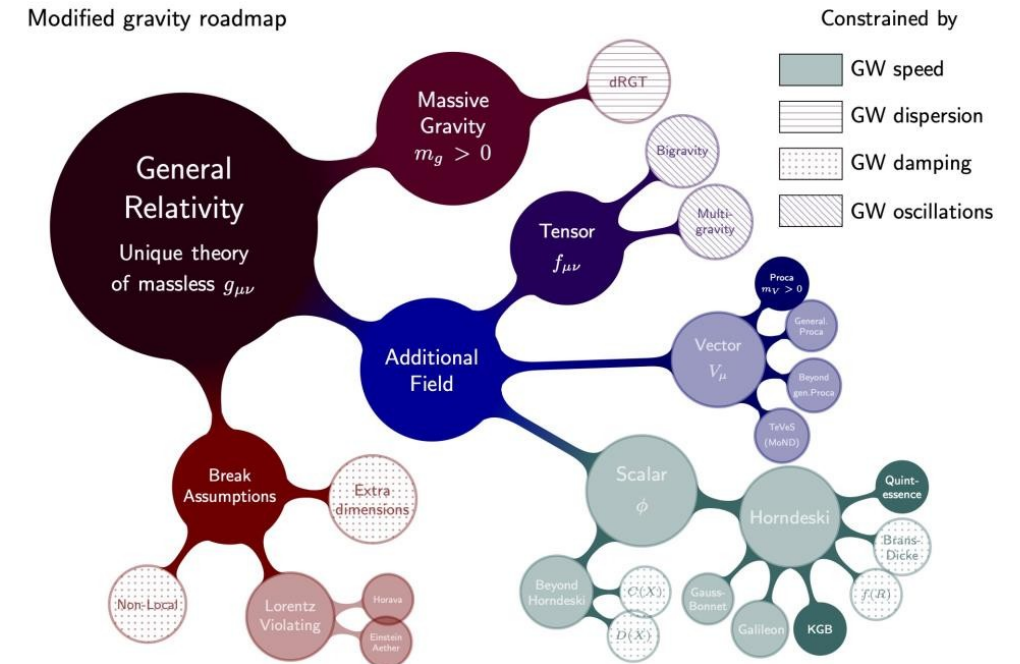
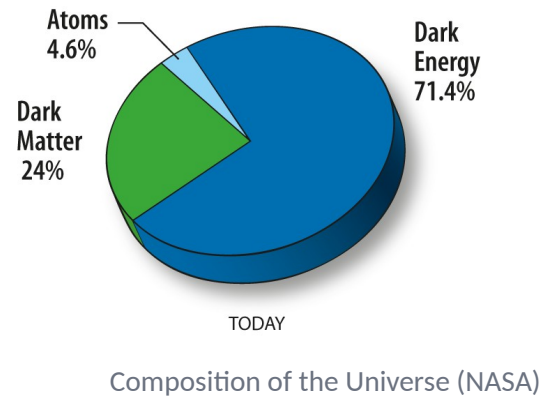
PART II

Dipolar Scalar Gravitational Radiation in Third-generation Detectors

K. Karácsonyi & Z. Keresztes — in preparation (2026)

Why go beyond general relativity?

- General relativity: gravitation = geometry
 - Solar-System tests
 - binary pulsars
 - gravitational waves
- Unresolved problems:
 - cosmological inflation, tensions (H_0 , σ_8)
 - dark matter, dark energy
 - quantum gravity?
- Simplest extension: add a **scalar field** to resolve these problems



Ezquiaga & Zumalacárregui, Front. Astron. Space Sci. 5, 44 (2018)

Gravitational waves provide several ways for testing GR

Scalar–tensor theories extend general relativity

Part II

General relativity

$$S_{\text{EH}} \propto \int d^4x \sqrt{-g} R$$

- Metric tensor field g_{ab}
- **2 tensor** polarizations: +, ×

Scalar–tensor (Horndeski)

$$S_{\text{H}} \propto \int d^4x \sqrt{-g} \sum_{i=2}^5 \mathcal{L}_i[g_{ab}, \phi]$$

- Metric g_{ab} + **scalar field ϕ**
- **2 tensor + 2 scalar** polarizations: +, ×, b, l
- Scalar dipole radiation at –1PN

Horndeski, Int. J. Theor. Phys. 10, 363 (1974)

● A scalar field introduces several changes, like extra polarizations in gravitational waves.

Gravitational waves in weak field

Weak-field approximation

$$g_{ab} = \eta_{ab} + h_{ab}, \quad |h_{ab}| \ll 1$$

General relativity: wave equation (harmonic gauge)

$$\square h_{ab} = -\frac{16\pi G}{c^4} \left(T_{ab} - \frac{1}{2} \eta_{ab} T \right)$$

In vacuum: plane gravitational waves

$$\square h_{ab} = 0 \Rightarrow h_{ab} = \epsilon_{ab} e^{ik_c x^c} + \epsilon_{ab}^* e^{-ik_c x^c}$$

ϵ_{ab} : polarization tensor, k_c : wave 4-vector — the analogue of electromagnetic waves

Scalar-tensor: the scalar field has its own wave equation

$$\square \phi = \frac{8\pi}{c^4} \frac{T}{3 + 2\omega_{\text{BD}}}$$

e.g. Brans–Dicke. In vacuum the scalar perturbation also propagates as a wave $\Rightarrow$ **scalar (breathing) polarization**

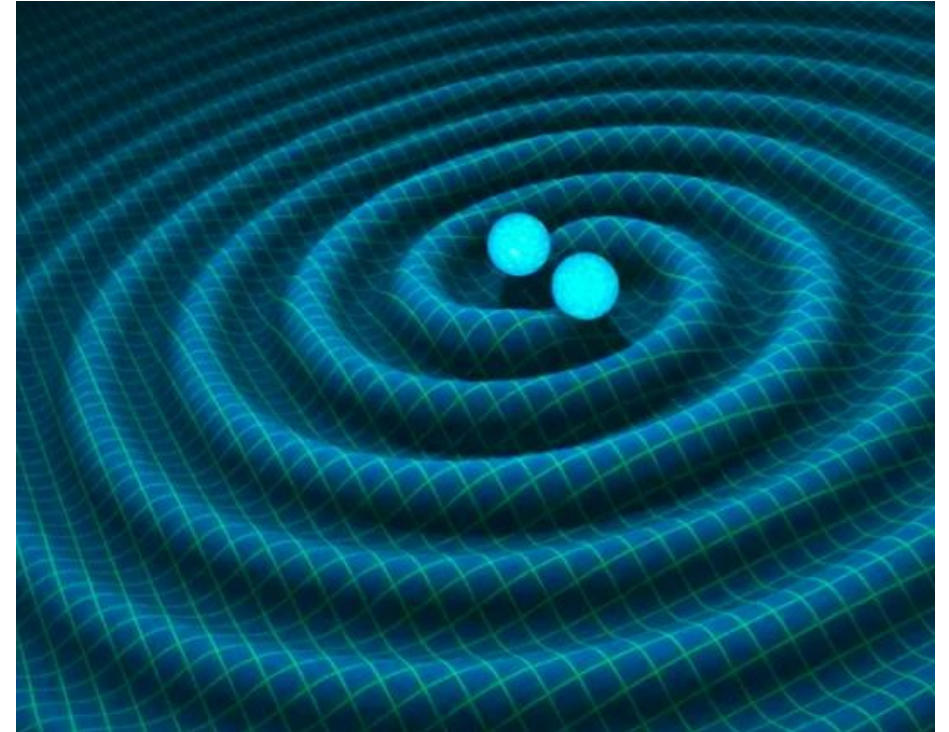
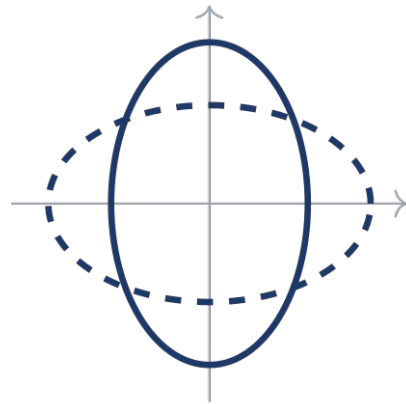


Illustration: R. Hurt / Caltech-JPL

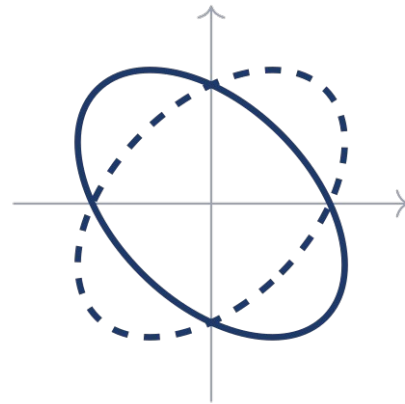
$$h_{ab} = \sum_p h_p \epsilon_{ab}^{(p)}, \quad p = +, \times, b, l$$

tensor (GR)

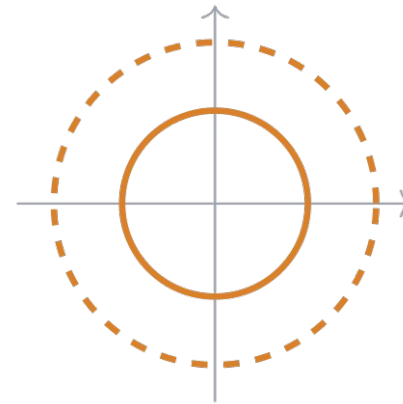
scalar



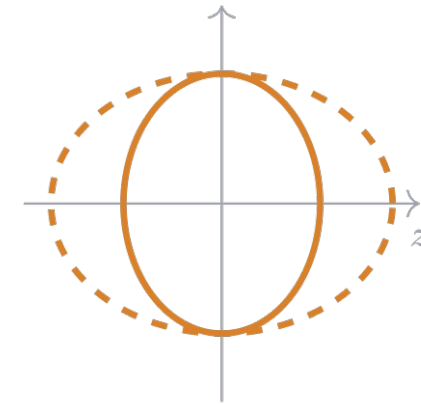
plus



cross



breathing



longitudinal

Ring of free test masses; wave propagating along z (out of the plane for $+$, $\times$, b). Solid and dashed: half a period apart. Based on Nishizawa et al. 2009



GR: only $+$ and $\times$. Scalar-tensor theories add the **breathing (b)** and **longitudinal (l)** modes

What an interferometer measures: antenna patterns

Part II

Measured data $d_I(t) = F_I^p h_p(t) + n_I(t)$

$$F^+ = -\frac{1}{2} (1 + \cos^2 \delta) \cos 2\alpha \cos 2\psi - \cos \delta \sin 2\alpha \sin 2\psi$$

$$F^\times = \frac{1}{2} (1 + \cos^2 \delta) \cos 2\alpha \sin 2\psi - \cos \delta \sin 2\alpha \cos 2\psi$$

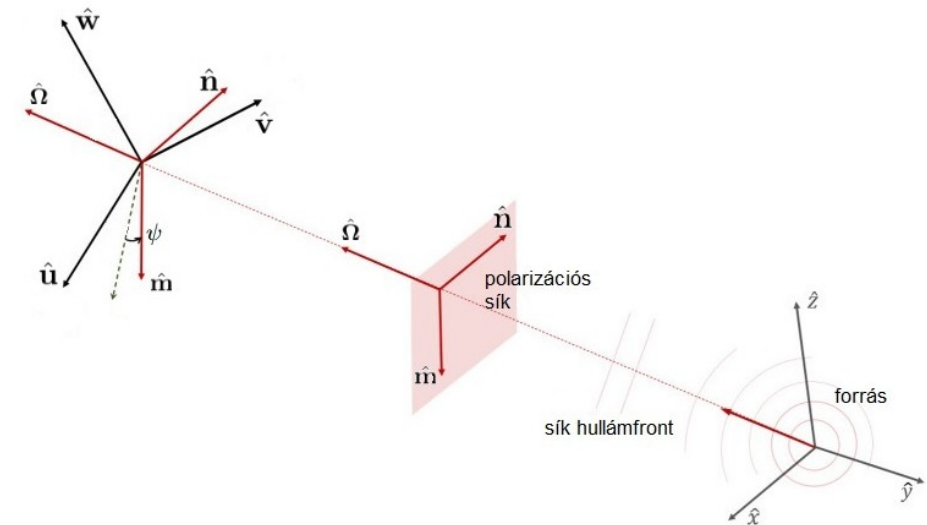
$$F^b = -\frac{1}{2} \sin^2 \delta \cos 2\alpha$$

$$F^l = \frac{1}{\sqrt{2}} \sin^2 \delta \cos 2\alpha$$

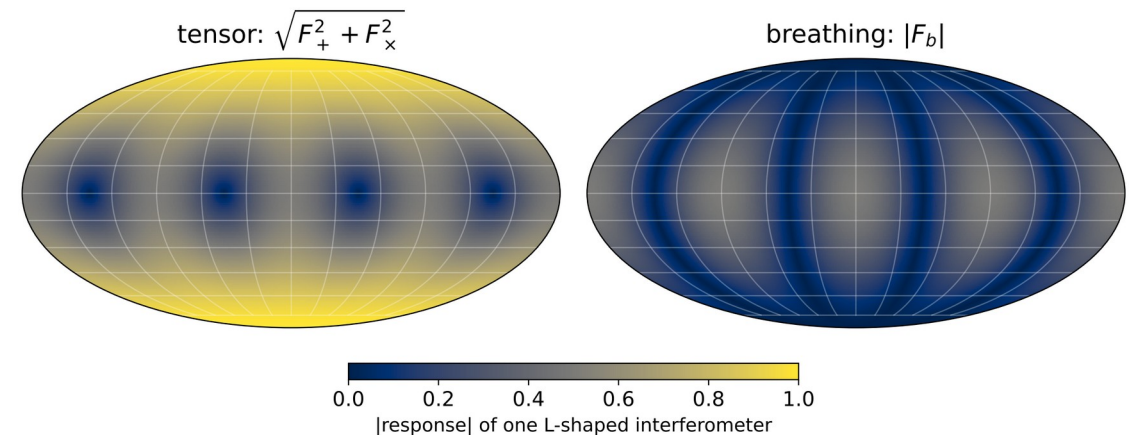
(α, δ) : sky position in the detector frame, ψ : polarization angle.
 $F^b \propto F^l \Rightarrow$ **breathing and longitudinal are indistinguishable** for one interferometer

Tensor and breathing responses peak in **different sky directions**
 $\Rightarrow$ a **network** of differently oriented detectors can separate the polarizations

Nishizawa et al., PRD 79, 082002 (2009)



Plane wave from the source frame to the detector frame ($\hat{u}, \hat{v}, \hat{w}$); polarization plane $\perp \hat{\Omega}$ (thesis figure)



Parametrized scalar-tensor inspiral waveform

Part II

Three key facts

1. The scalar terms **vanish face-on** ($\sin \iota$)

$$h_{+}^{(2)} = -A_2 (1 + \cos^2 \iota) \cos 2\Phi$$

$$h_{\times}^{(2)} = 2A_2 \cos \iota \sin 2\Phi$$

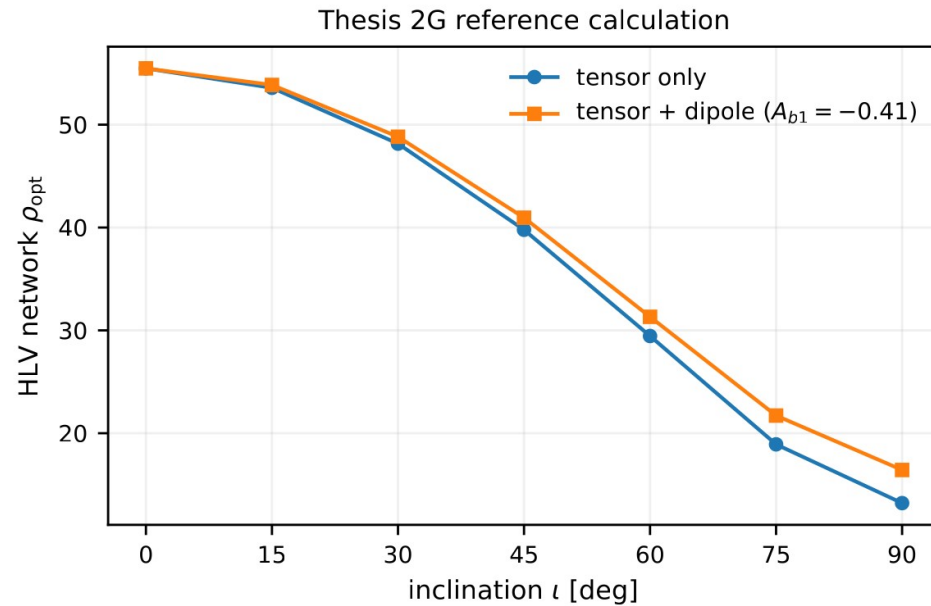
$$h_b^{(1)} = 2A_{b1} \eta^{1/5} A_1 \sin \iota \cos \Phi$$

$$h_b^{(2)} = 2A_{b2} A_2 \sin^2 \iota \cos 2\Phi$$

$$A_2 \propto (\pi f_{22})^{2/3} / d_L, \quad A_1 \propto (\pi f_{22})^{1/3} / d_L$$

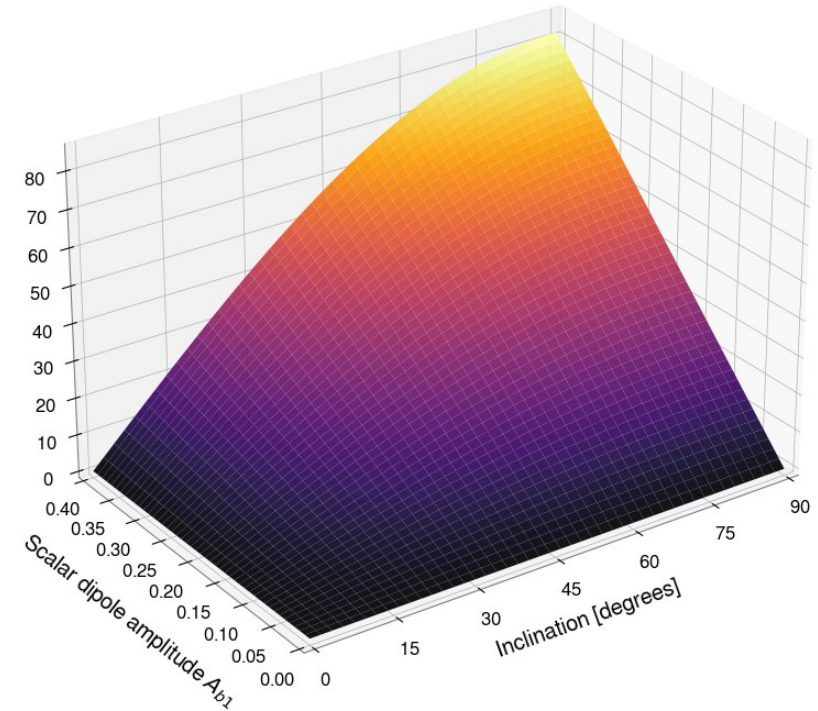
Chatziioannou, Yunes & Cornish 2012; Imafuku et al., PRD 112, 024028 (2025). Φ : orbital phase; A_{b1} , A_{b2} : phenomenological amplitudes

 **waveform.py**: implemented Imafuku et al. Eqs. (8)–(17) with 3.5PN TaylorF2 (Bilby source model)



HL V network SNR, 50+50 $M_{\odot}$, 600 Mpc; tensor only vs. tensor + dipole ($A_{b1} = -0.41$).

Scalar-dipole sensitivity of the HL V network
At fixed luminosity distance: 50 Mpc



Scalar-only HL V SNR, 10+1.4 $M_{\odot}$, 50 Mpc: $\rho_b \propto |A_{b1}| \sin \iota / d_L$

Tensorial polarizations favour face-on systems, where the scalar polarizations vanish: a selection effect

Parametrized scalar–tensor inspiral waveform

Part II

$$h_{+}^{(2)} = -A_2 (1 + \cos^2 \iota) \cos 2\Phi$$

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Three key facts

1. The scalar terms **vanish face-on** ($\sin \iota$)

2. Back-reaction on the tensor phase

Scalar radiation carries away extra energy (dipole flux at -1PN), so the inspiral speeds up and the tensor phase is shifted:

$$\delta\psi^{(\ell)} = -\frac{5\ell}{3584} \tilde{A}_{b1}^2 \eta^{2/5} u_\ell^{-7} - \frac{\ell}{128} \tilde{A}_{b2}^2 u_\ell^{-5}$$

$\tilde{A}_{b1}, \tilde{A}_{b2}$: back-reaction amplitudes, kept separate from the direct-emission A_{b1}, A_{b2}

 **waveform.py**: implemented Imafuku et al. Eqs. (8)–(17) with 3.5PN TaylorF2 (Bilby source model)

Parametrized scalar–tensor inspiral waveform

Part II

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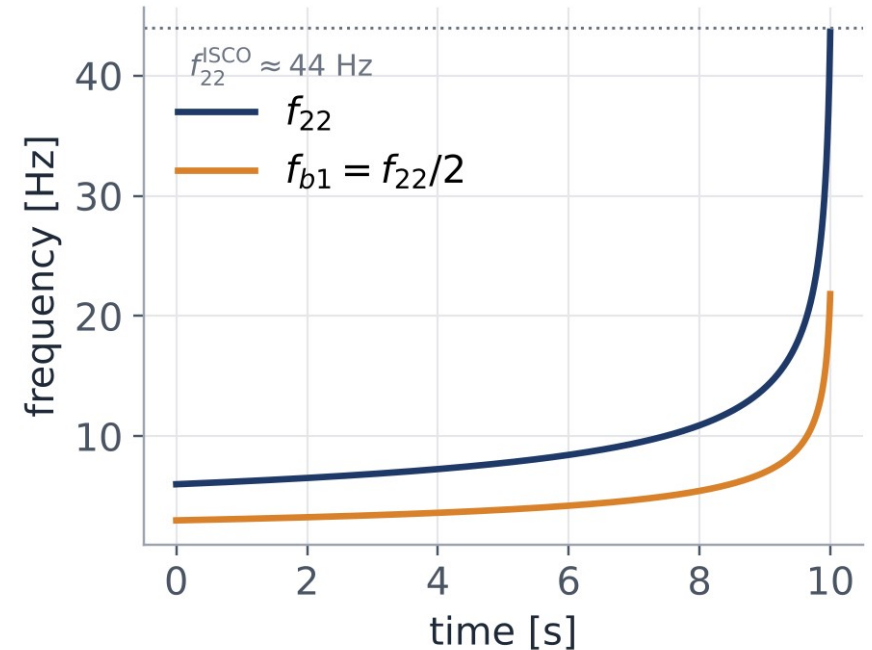
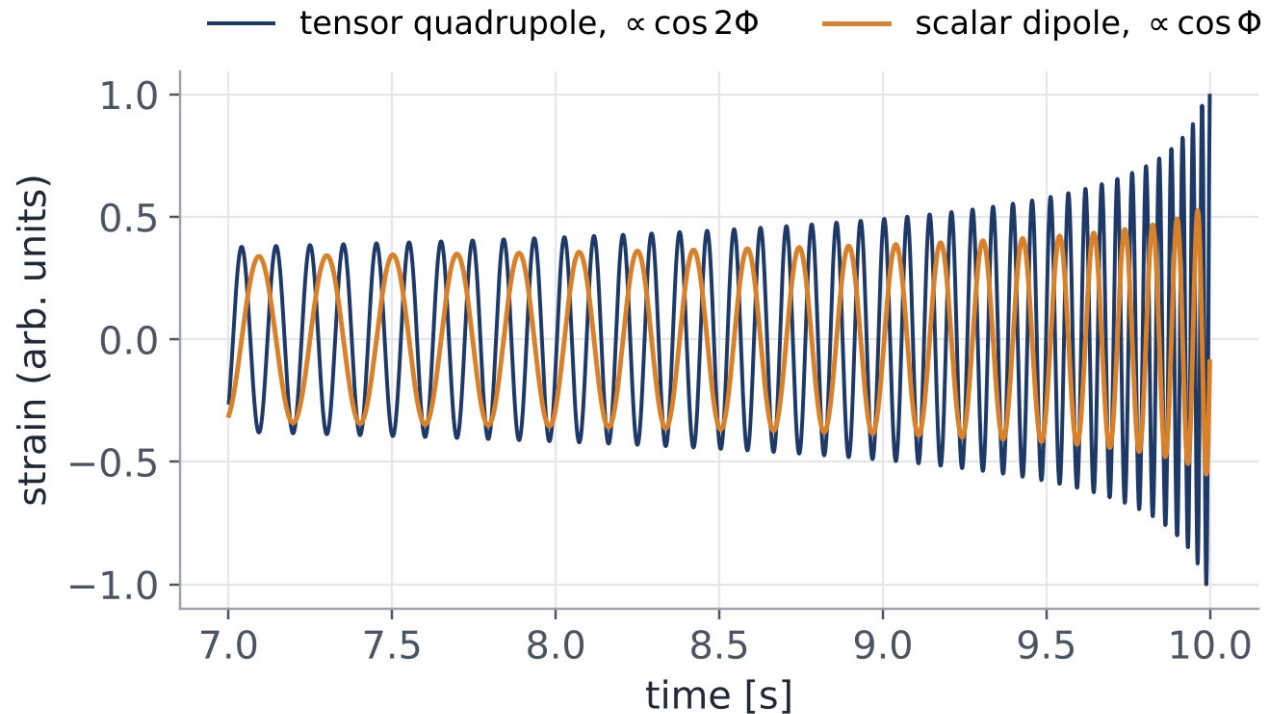
3. The scalar dipole $\propto \cos \Phi$ is radiated at the **orbital frequency**, the quadrupoles $\propto \cos 2\Phi$, $\sin 2\Phi$ at twice it:

$$f_{b1}(t) = \frac{1}{2} f_{22}(t)$$

● Dipolar scalar radiation propagates at half the frequency.

The dipole oscillates half as fast

Part II



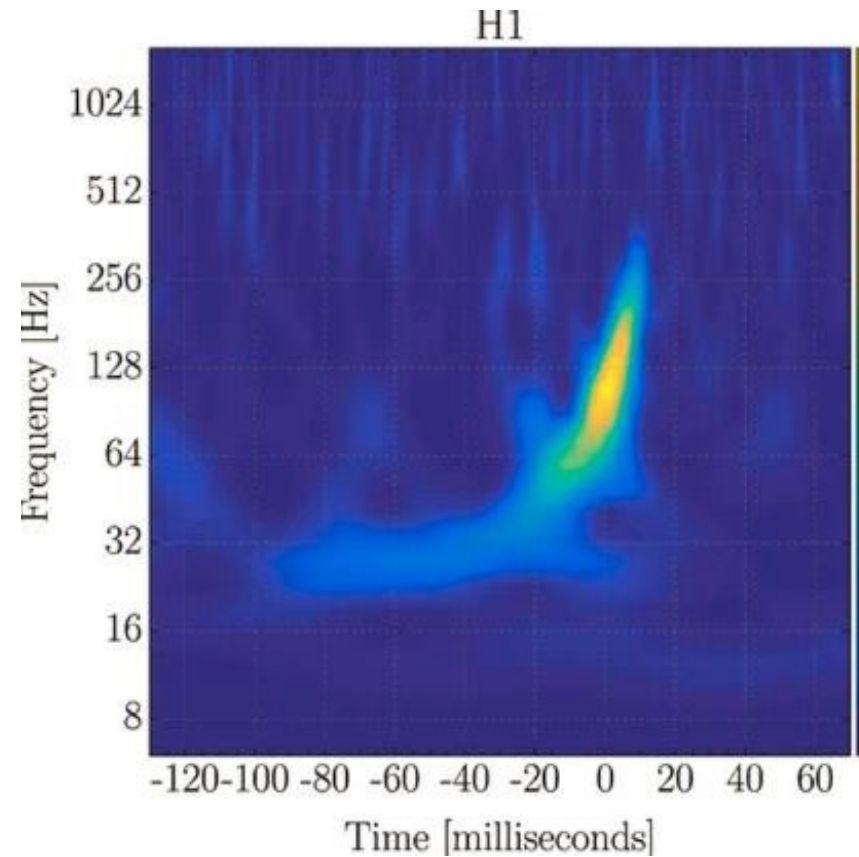
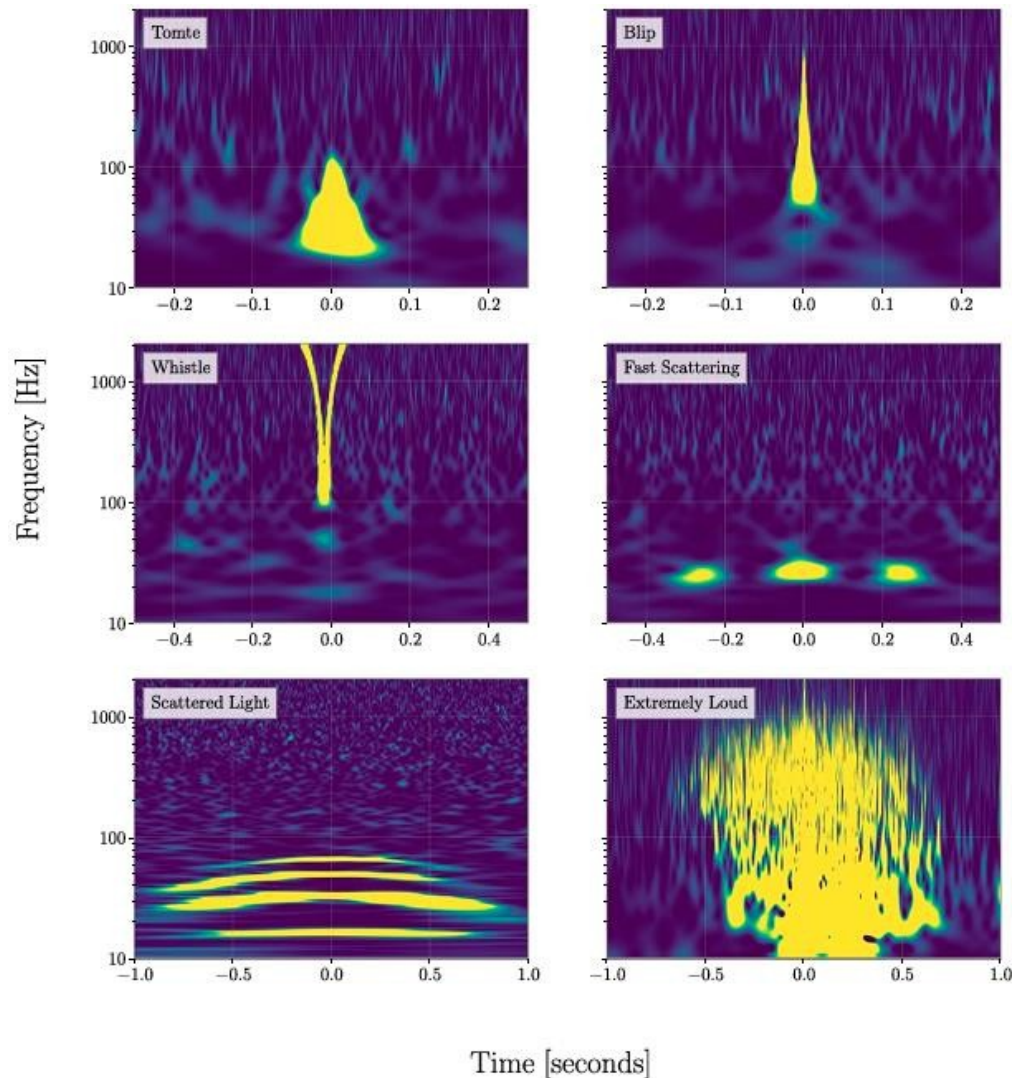
$$f_{22}(t) = \frac{1}{8\pi} \left(\frac{5}{t_c - t} \right)^{3/8} \left(\frac{G\mathcal{M}_c}{c^3} \right)^{-5/8}$$

50+50 $M_\odot$, edge-on, cut at $f_{22}^{\text{ISCO}} \approx 44 \text{ Hz}$

the dipole ends near 22 Hz — the tracks **overlap near the merger**

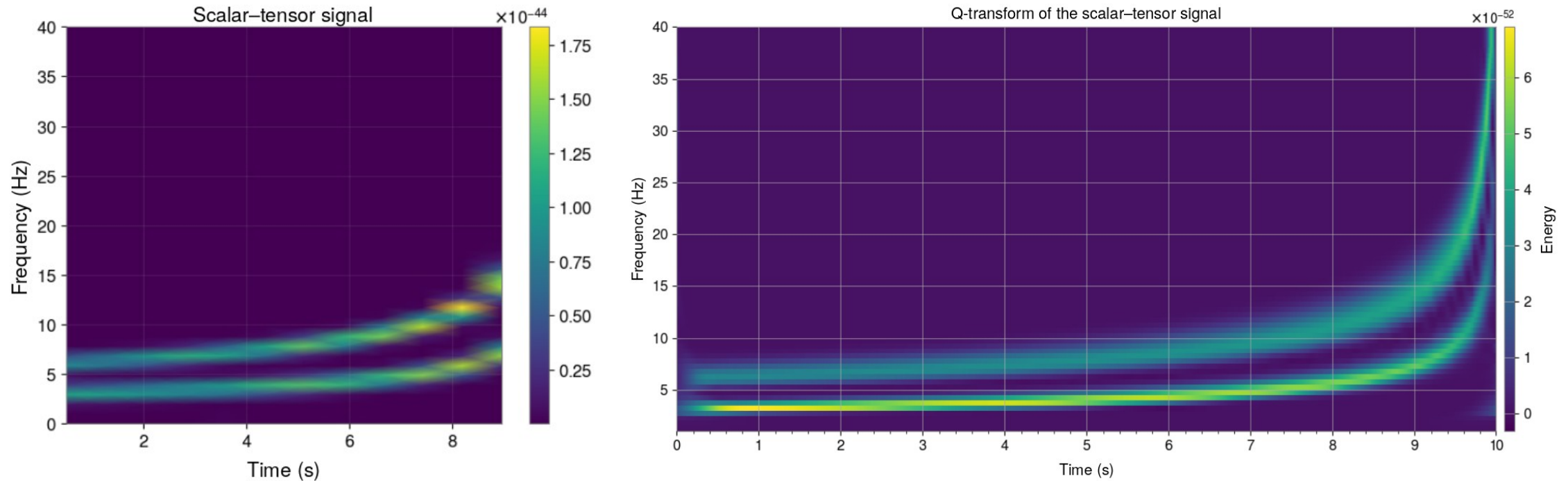
Leading-order inspiral, $A_{b1} = -0.41$; amplitudes in arbitrary units (illustration).

Spectrogram vs. Q-transform



- Standard in LIGO-Virgo for **transients and glitches**: glitch classes [Glanzer et al. 2023] and GW150914 [Abbott et al. 2016]

Spectrogram vs. Q-transform



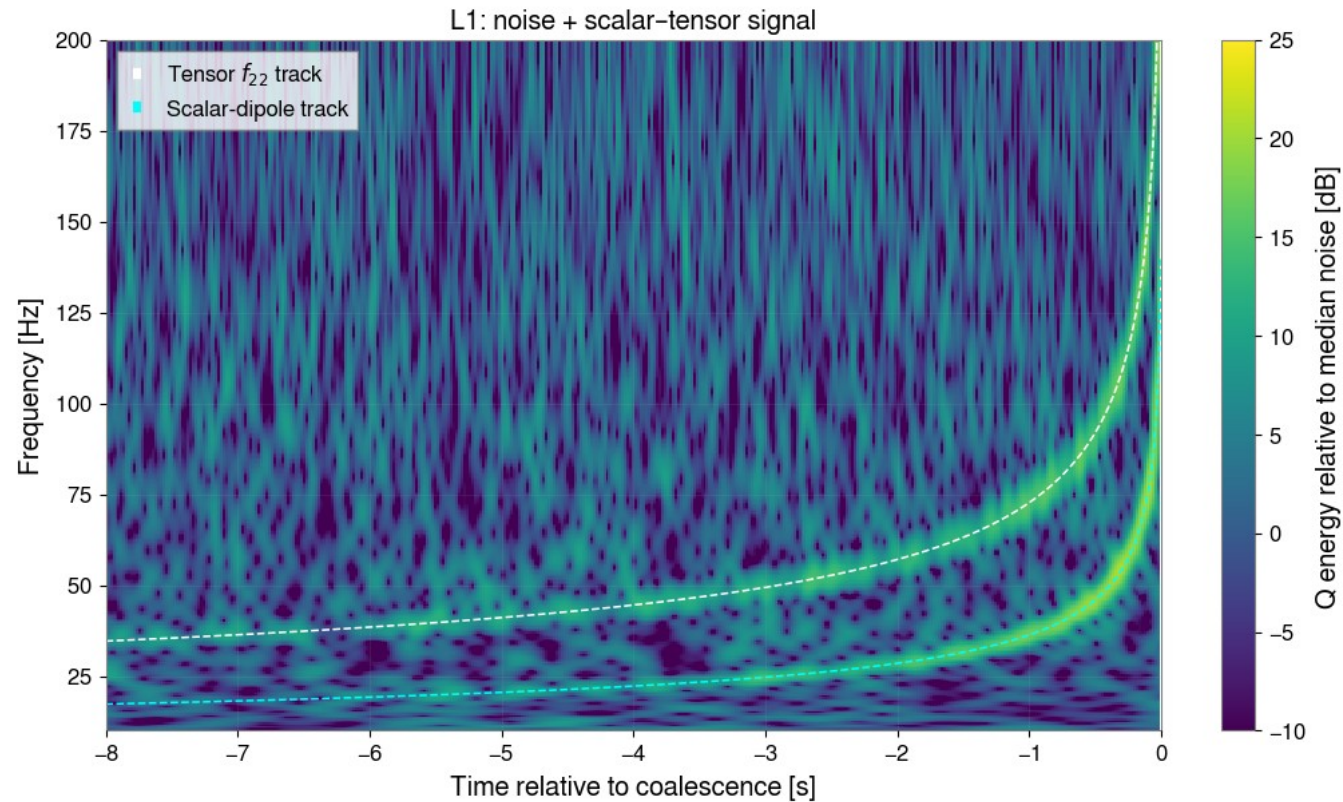
Left: short-time Fourier spectrogram (SciPy). Right: Q-transform (GWpy). 50+50 $M_{\odot}$, edge-on, $A_{b1} = -0.41$, noise-free; from the thesis

Constant Q

$$Q = \frac{f}{\Delta f}$$

window $\propto 1/f$: sharp in time at high f , sharp in frequency at low f

Validation in Gaussian detector noise (HLV)



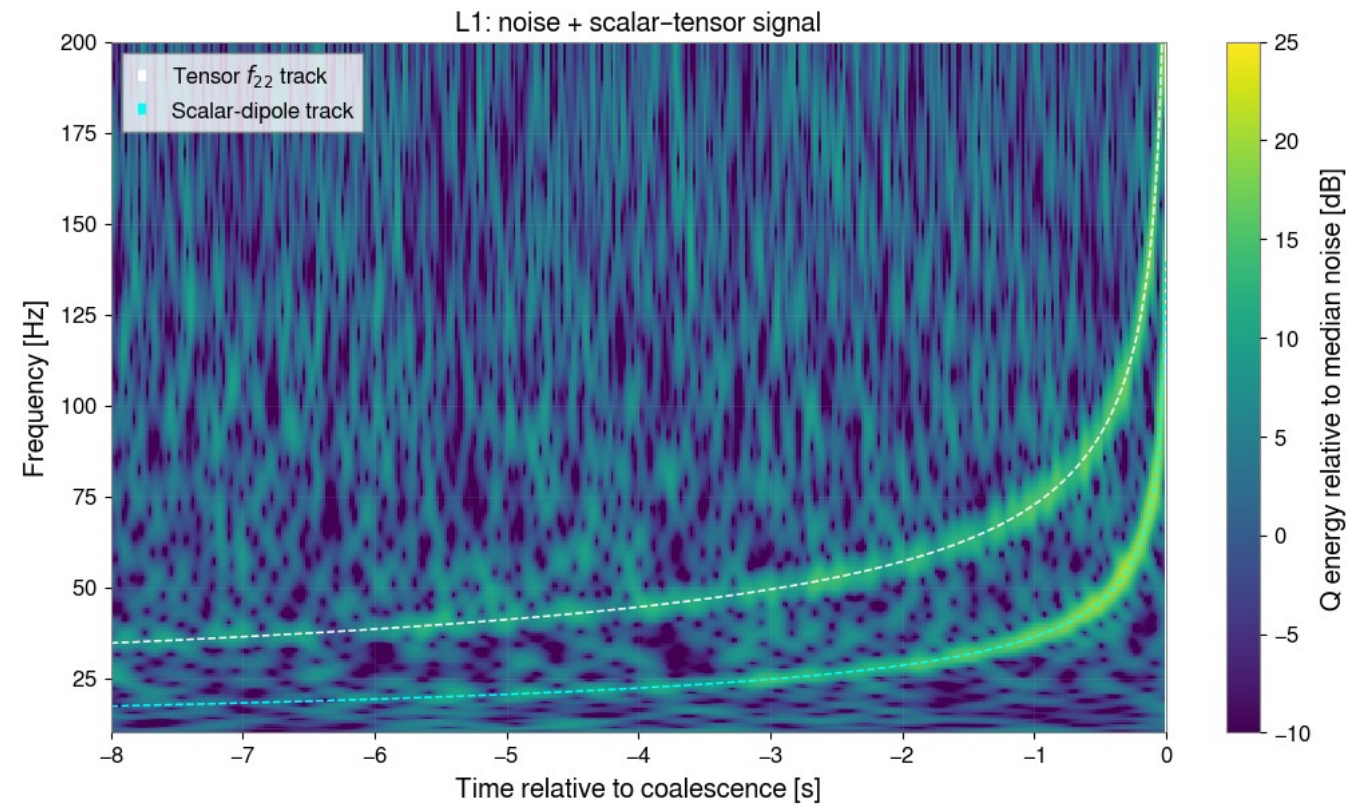
Whitened L1 constant-Q map; energy relative to median noise; dashed: analytic tracks

Validation in Gaussian detector noise (HLV)

10+1.4 M $\odot$ (NSBH-like), 50 Mpc, $\iota = 60^\circ$, $A_{b1} = 0.3$;
O4 / AdV noise curves, 512 s

	ρ_{GR}	ρ_b
HLV	68.1	52.7

- Loud, known injection was a **validation**



Whitened L1 constant-Q map; energy relative to median noise; dashed: analytic tracks

● LIGO–Virgo see the dipole only above ~10–20 Hz, in the last seconds.
To follow it at low frequency we need a detector that reaches a few Hz → the **Einstein Telescope**

Einstein Telescope

Part II

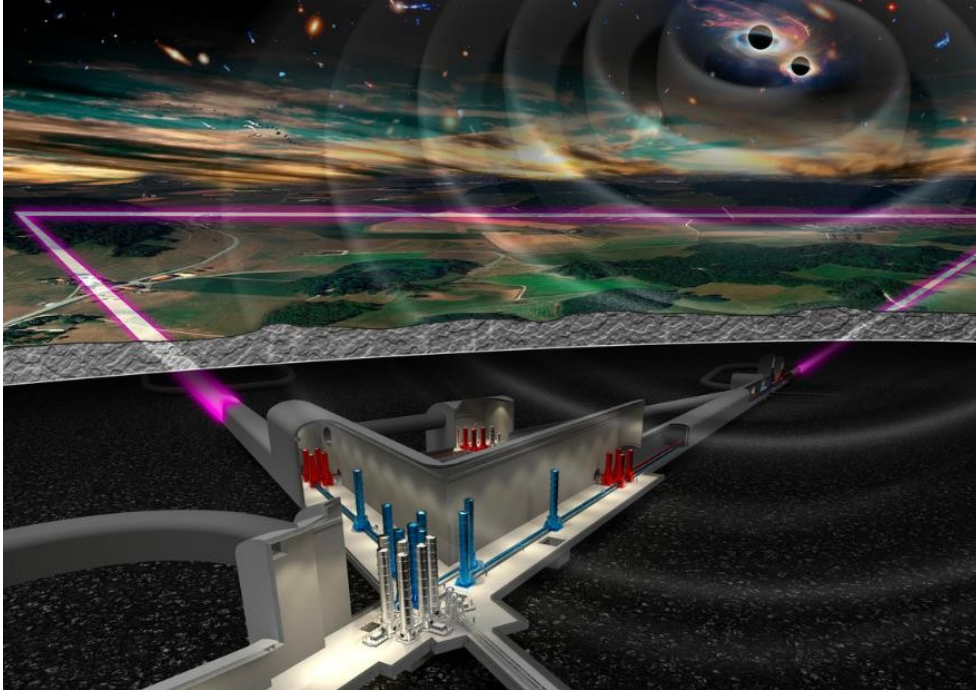


Illustration: Einstein Telescope (NIKHEF)

2L

Two 15 km L-shaped detectors at two sites, 45° relative orientation (our runs: Sardinia + Meuse–Rhine)

Triangle

Three 10 km, 60° Michelsons at one site

ESFRI Roadmap (2021)

ET is on the European research-infrastructure roadmap since 2021

Candidate sites

- Sardinia (Sos Enattos, Italy)
- Euregio Meuse–Rhine (BE–NL–DE)
- Lusatia (Saxony, Germany)

Site decision expected in the second half of 2027; Sardinia and Lusatia signed a joint 2L bid (July 2026)

NEWS

Geometry Comparison Report

A site-independent comparison of the geometric configuration options for the Einstein Telescope

9 October 2026
Einstein
Telescope
Organisation

Geometry Comparison Report
(7 October 2026) evaluates precisely the 10 km triangle and the 15 km two-site L configuration

Source: ET Organisation news, 9 October 2026

Long signals feel the Earth rotate

Part II

10+1.4 M $\odot$, 100 Mpc, $\iota = 80^\circ$, $A_{b1} = 0.03$, from 3 Hz

1.6 h

quadrupole in band (≈ 5617 s)

15 min

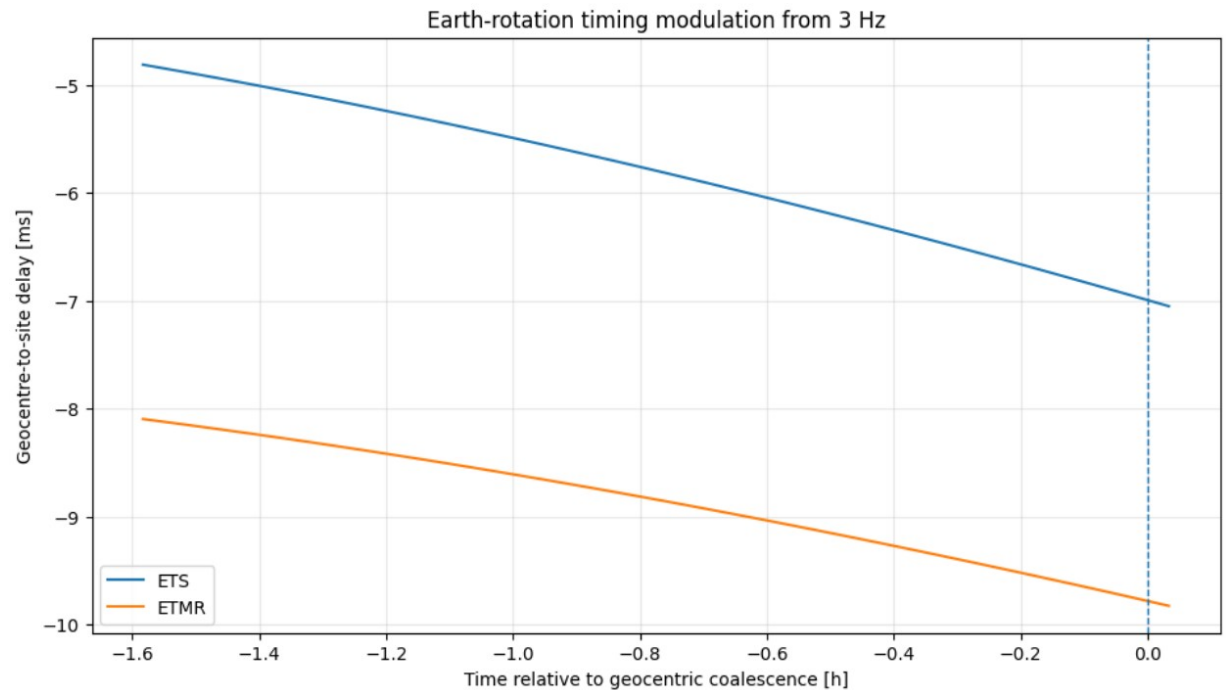
dipole in band (≈ 886 s)

Each harmonic k sees the antenna pattern at its own stationary time

$$t_k(f) = \frac{1}{2\pi} \frac{d\Psi_k}{df}$$

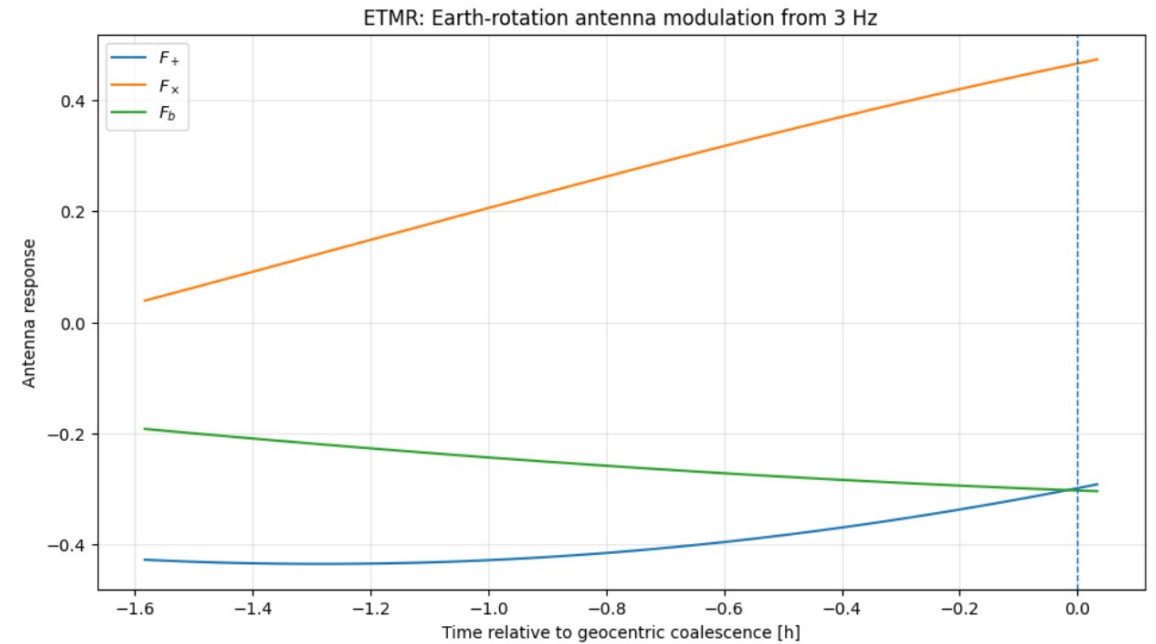
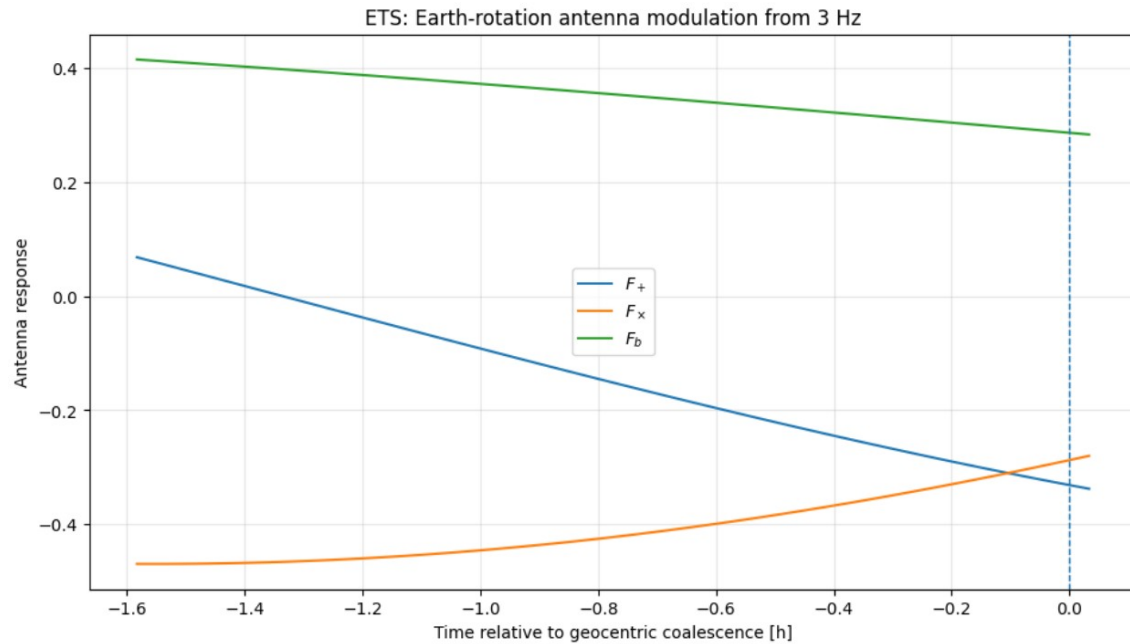
$$\tilde{h}_I(f) = \sum_{A,\ell} F_I^A[t_k(f)] \tilde{h}_A^{(\ell)}(f) e^{-2\pi i f \tau_I(t_k)}$$

$A \in \{+, \times, b\}$; tensor and scalar quadrupole use $t_2(f)$, scalar dipole uses $t_1(f)$



ET 2L: geocentre-to-site time delays. Dashed line: coalescence.

Long signals feel the Earth rotate



ET 2L: antenna factors at Sardinia (left) and Meuse-Rhine (right). Dashed line: coalescence.

ET network SNRs with the rotating response

Part II

Configuration	ρ_{tensor}	ρ_{b}	ρ_{total}	ρ_{fixed}	$\Delta\rho/\rho$	ϵ_{rot}
2L, 15 km	356.9	56.3	361.3	361.8	-0.14 %	0.083
Triangle, 10 km	220.5	46.0	225.3	227.6	-1.03 %	0.092

ρ_{fixed} : antenna response frozen at coalescence. 60 s vs 30 s response grid: $< 10^{-5}$.

$$\epsilon_{\text{rot}} = \frac{\|h_{\text{rot}} - h_{\text{fix}}\|}{\|h_{\text{rot}}\|}$$

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0.1–1 %

change of the total SNR

8–9 %

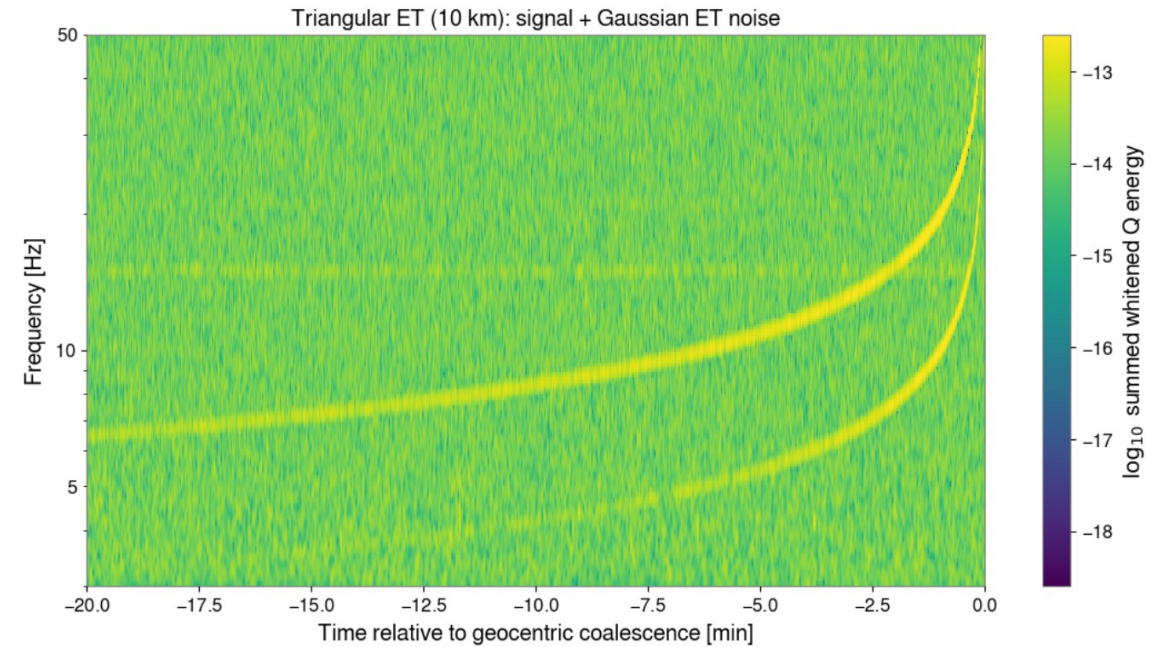
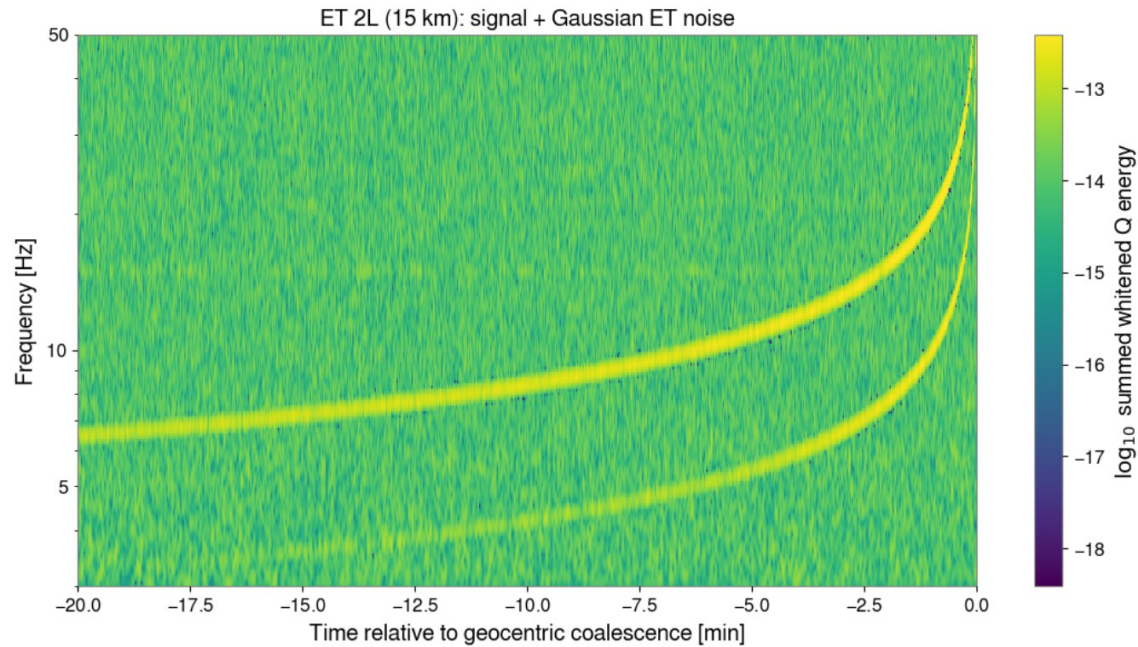
change of the waveform

$$\epsilon_{\text{rot}} = \frac{\|h_{\text{rot}} - h_{\text{fix}}\|}{\|h_{\text{rot}}\|}$$

- A fixed antenna pattern is **not adequate** for few-Hz signals, the **lowest frequencies matter** most for the scalar

Simulating signals in ET, with noise

Part II



ET noise curves from [ET CoBA sensitivity data, ET-0304B-22](https://apps.et-gw.eu/tds/?r=18213) (S. Danilishin and T. Zhang, 2023): apps.et-gw.eu/tds/?r=18213

Sites and orientations from [GWFAST](https://gwfast.readthedocs.io) detector definitions (Branchesi et al., 2023): gwfast.readthedocs.io

One obstacle though: GR higher modes.

The real competitor: GR higher modes

Where does the (2,1) mode come from?

- GR radiation = **mass multipoles** I_L + **current multipoles** J_L
- Mass monopole and dipole are conserved (total mass, momentum) $\Rightarrow$ **no dipole radiation in GR**
- Leading: **mass quadrupole** $\rightarrow$ (2,2) mode at 2Φ
- Next: **current quadrupole** (mass currents, like a magnetic dipole in EM) $\rightarrow$ **(2,1) mode at Φ** , the same track as the scalar dipole

(2,1) is suppressed by v and by $\delta = (m_1 - m_2)/M$: it **vanishes for equal masses** and grows with asymmetry

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Scalar dipole vs. GR (2,1)

Lighter primary (larger v at fixed f , smaller δ) favours the scalar. Our source: $10+1.4 M_\odot$, $m_1/m_2 \approx 7.1$

Multipoles: Thorne, RMP 52, 299 (1980); Blanchet, LRR 17, 2 (2014)
(ℓ, m) modes: Kidder, PRD 77, 044016 (2008)
(2,1) at 3PN: Henry, Faye & Blanchet, CQG 38, 185004 (2021)

Multimode injection

IMRPhenomXHM: (2,2), (2,1), (3,3), (3,2), (4,4) + additive scalar dipole ($A_{b1} = 0.003$); each mode at its own stationary time

● We have to implement higher modes into our scalar-tensor signals.

Higher harmonics have already been observed

Part II

GW190412

$30 + 8 M_{\odot}$

Strong evidence for higher harmonics.

$$\log_{10} B \gtrsim 3$$

Strongest: (3,3); inspiral-track evidence

R. Abbott et al., PRD 102, 043015 (2020)

GW190814

$23 + 2.6 M_{\odot}$

Very strong evidence for higher harmonics.

$$\log_{10} B \simeq 9.6$$

Strongest: (3,3); $\rho_{33,\perp} \simeq 6.6$

R. Abbott et al., ApJL 896, L44 (2020)

These detections establish **higher harmonics in unequal-mass binaries**, motivating their inclusion in our GR waveform. The **(2,1)** mode itself was not independently established.

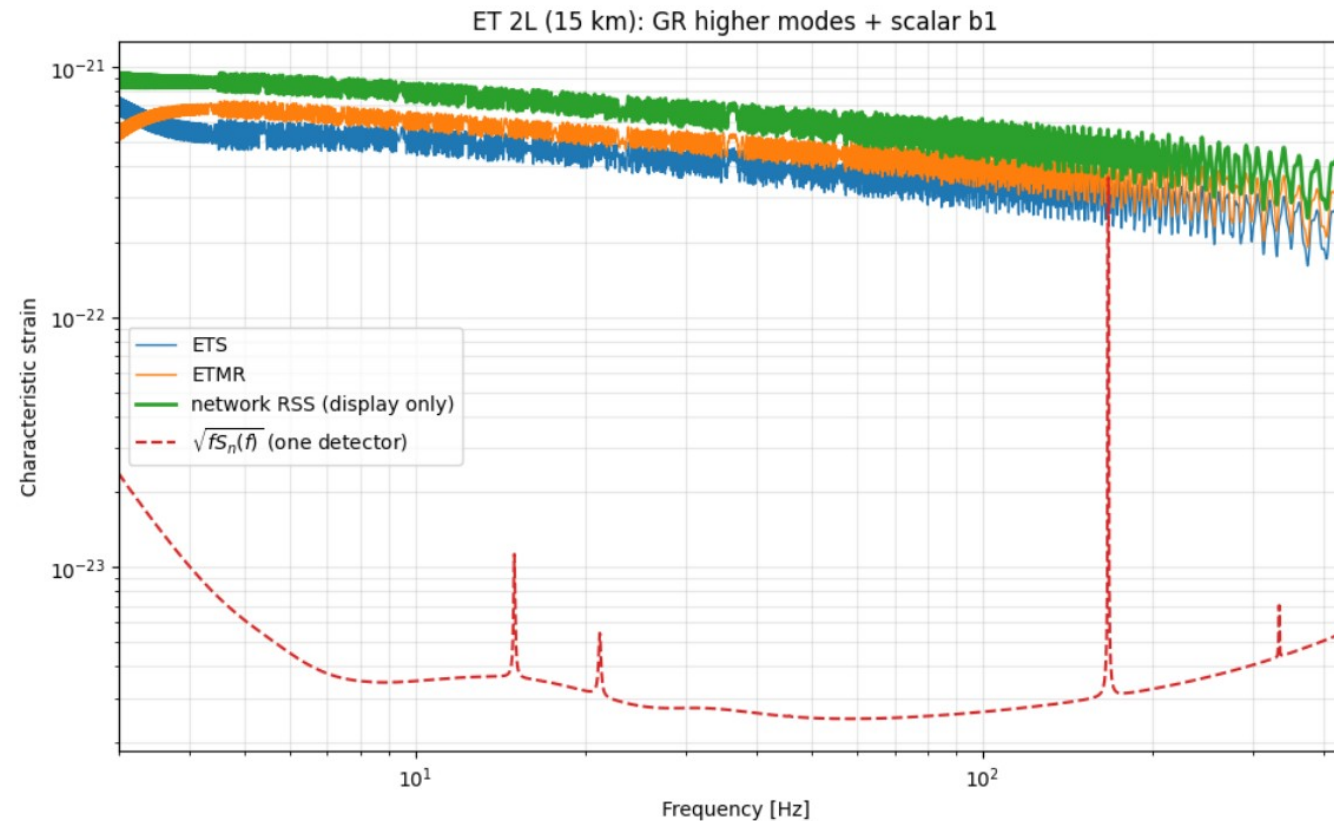
● Our $10+1.4 M_{\odot}$ NSBH ($q \approx 0.14$) lies between these two events $\Rightarrow$ GR higher modes **must** be in the baseline

Simulating GR higher modes + scalar dipole

Part II

Simulating GR higher modes + scalar dipole

Part II



Higher modes from:
[LALSuite: IMRPhenomXHM](#)
(C. García-Quirós et al., 2020)

ET 2L (15 km): the same total signal (GR higher modes + scalar b1) in each interferometer (blue, orange) and the network RSS (green; display only). Dashed: one-detector noise $\sqrt{f S_n}$. GR and scalar parts are not separated here.

● But how loud is each mode in this signal?

How loud is each harmonic? Optimal SNRs in ET

ET design	Band [Hz]	ρ_{21}	ρ_{33}	ρ_{b1}	$\rho_{GR, HM}$	ρ_{inj}
2L	3–50	31.1	107.1	9.3	873.7	873.7
2L	3–512	47.6	171.8	9.9	1062.6	1062.7
Triangle	3–50	20.1	73.0	7.6	601.7	601.8
Triangle	3–512	30.5	116.2	8.1	723.7	723.8

- ρ_{21}, ρ_{33} : GR higher harmonics (tensor), each projected on its own
- ρ_{b1} : scalar dipole, breathing polarization ($A_{b1} = 0.003$)
- $\rho_{GR, HM}$: full GR signal, all five harmonics
- ρ_{inj} : GR + scalar

● GR (2,1) also propagates at the scalar's f/2 track, but they may differ in certain configurations

How loud is each harmonic? Optimal SNRs in ET

Part II

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- ρ_{inj} : GR + scalar

Remember: $\rho_b \propto |A_{b1}|$

Further study shows:

1. At $A_{b1} = 0.01$:
 ρ_b is **comparable** to ρ_{21} in 2L, above it in the triangle
2. At $A_{b1} = 0.1$:
 ρ_b **exceeds** ρ_{21} over the full band in both designs

● GR (2,1) also propagates at the scalar's f/2 track, but they may differ in certain configurations

What A_{b1} value is realistic?

What sets A_{b1} ? Scalar charges

- Each compact body may carry an effective **scalar charge** α_A (sensitivity), set by the theory **and** the body's internal structure

$$A_{b1} \propto \alpha_1 - \alpha_2, \quad \frac{\mathcal{F}_{\text{dip}}}{\mathcal{F}_{\text{quad}}} \propto \frac{(\alpha_1 - \alpha_2)^2}{v^2}$$

P. C. Peters and J. Mathews, Phys. Rev. 131, 435 (1963)

So far A_{b1} is **phenomenological**, it stands in for $\alpha_1 - \alpha_2$ (times the coupling).

A concrete theory will give an estimation to the magnitude of A_{b1} . (e.g. Brans–Dicke)

Black holes

No scalar hair in broad classes of theories (Brans–Dicke, shift-symmetric Horndeski) $\Rightarrow \alpha_{\text{BH}} \approx 0$.

Neutron stars

α_{NS} depends on the EoS, compactness and the **matter coupling**
conformal coupling gives $\alpha_{\text{NS}} \neq 0$ (e.g. scalarization);
screening can suppress it

Hawking 1972; Hui & Nicolis 2013

● It matters what type of compact objects we choose.

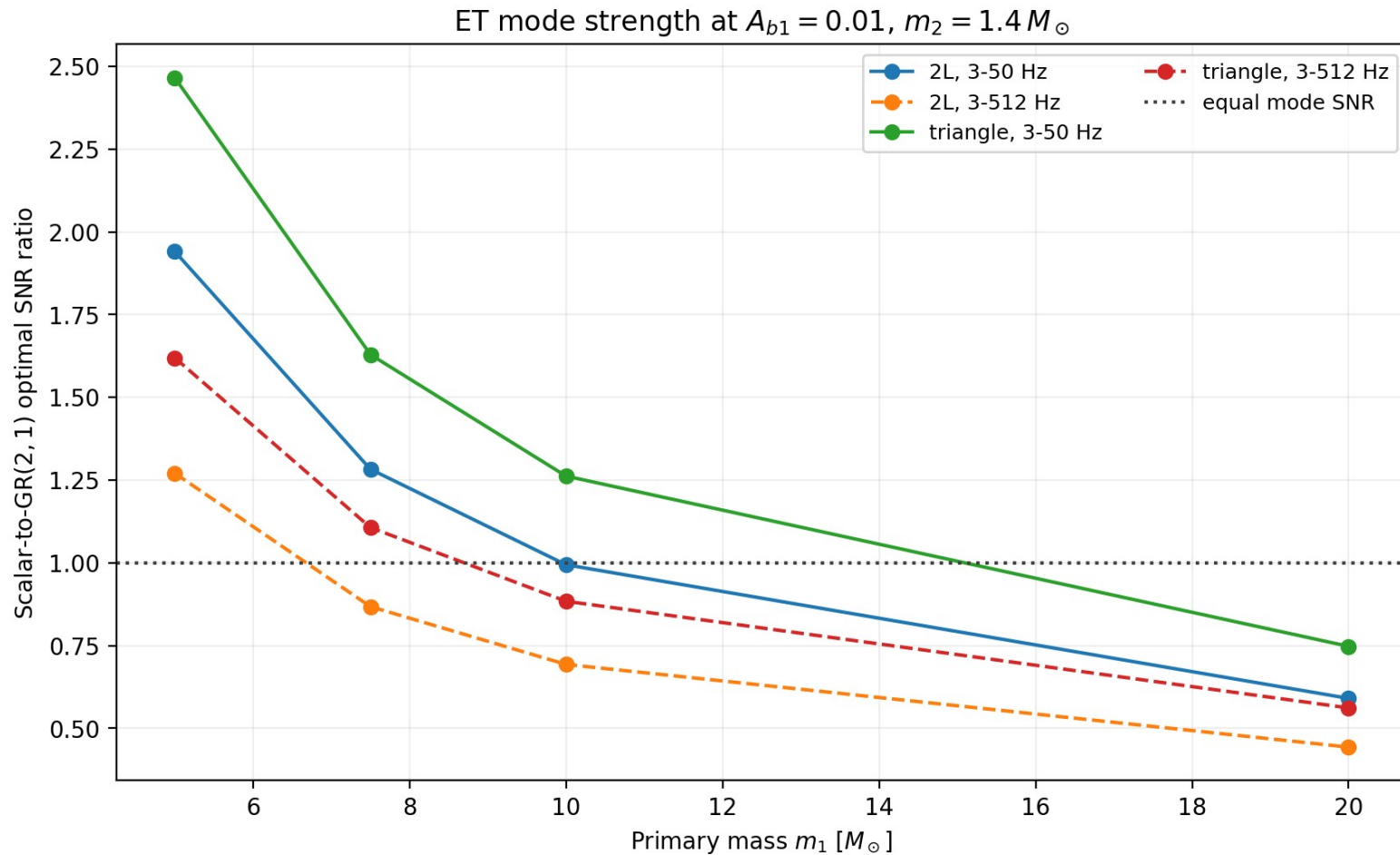
Which binary? NS+BH versus NS+NS

Part II

Binary	Charge difference $\alpha_1 - \alpha_2$	GR (2,1)	Consequence
BH + BH	≈ 0 (no hair)	depends on q	no dipole in most theories
NS + NS	small for similar masses	weak	both suppressed; unequal or scalarized NS can still differ
NS + BH	maximal: $\alpha_{\text{NS}} - 0$	strong for $q \ll 1$	largest dipole, but (2,1) must be modelled
NS + WD (for LISA!)	large	present (likely weak)	sub-Hz target, outside our ET band

NS + WD frequency range: <https://doi.org/10.1093/mnras/stab626>

● The configuration is a trade-off between charge difference and mass asymmetry → mass scan



y: ρ_{b1} / ρ_{21} at fixed $A_{b1} = 0.01$, $m_2 = 1.4 M_\odot$. Dotted: equal SNR. Solid: 3-50 Hz, dashed: 3-512 Hz

What the plot shows

Ratio of the scalar-dipole and GR (2,1) optimal SNRs:
above 1 the scalar is the louder of the two

×3.3

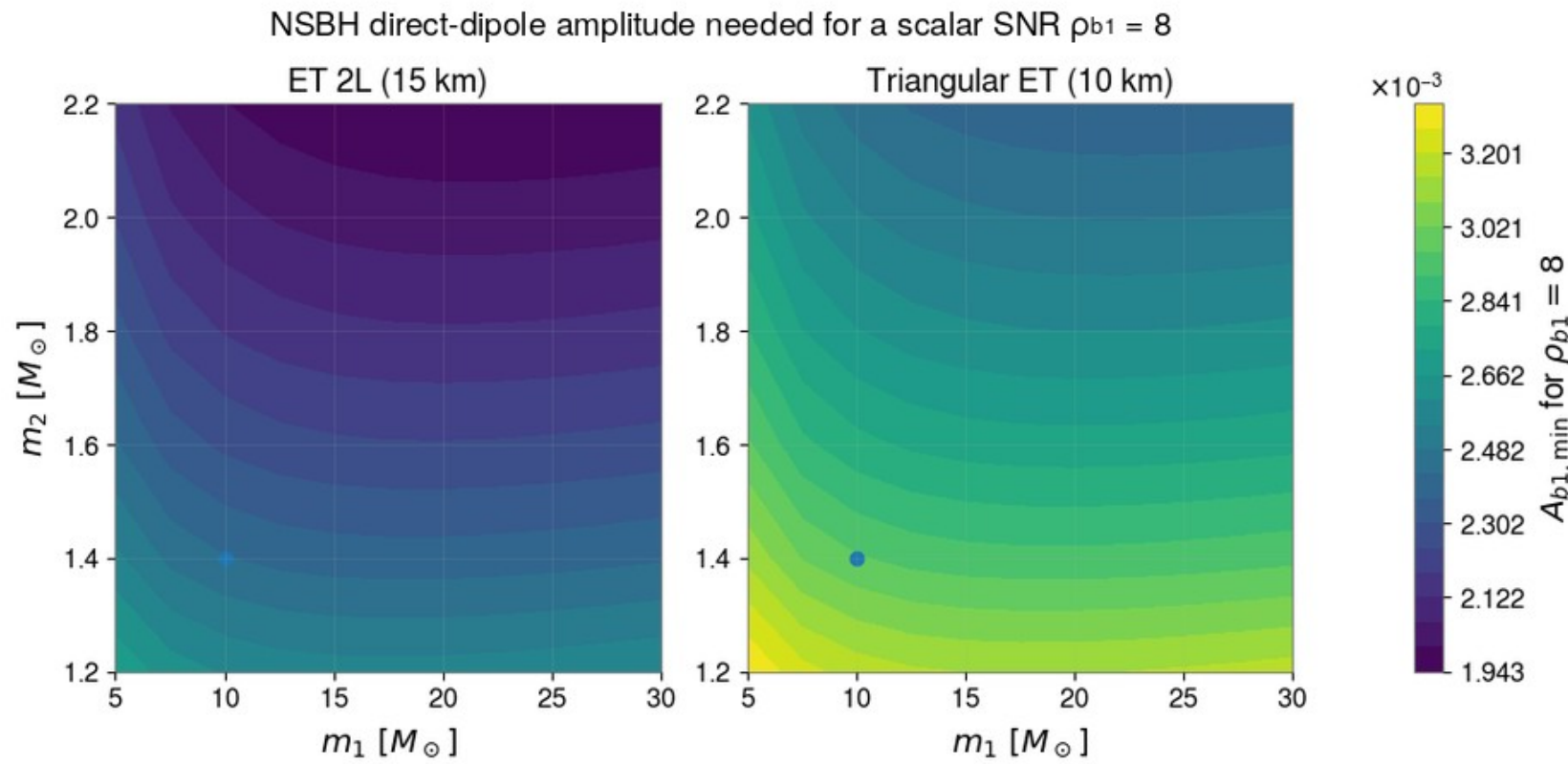
drop of the ratio from $m_1 = 5$ to $20 M_\odot$ (2L, 3-50 Hz: $1.94 \rightarrow 0.59$)

0.008–0.023

A_{b1} for equal SNR, 2L full band, $m_1 = 5 \rightarrow 20 M_\odot$
(triangle: 0.006–0.018)

Lighter primaries favour the scalar, and with theory-based charges, A_{b1} would also vary with the NS mass

Across NSBH masses: how weak a dipole can ET register?



$\approx 2\text{--}3 \times 10^{-3}$

A_{b1} needed for $\rho_{b1} = 8$ everywhere in $m_1 = 5\text{--}30$, $m_2 = 1.2\text{--}2.2 M_\odot$

+22 %

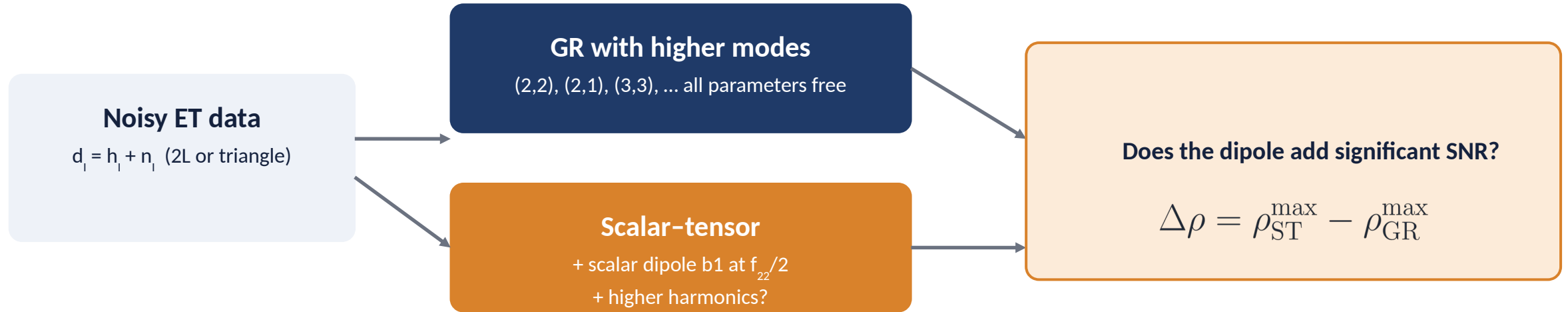
larger A_{b1} needed by the triangle than by 2L, nearly mass-independent

Dot: our 10 + 1.4 $M_\odot$ source. Scalar component only, rotating ET response, from 3 Hz

● We have a sensitivity level for models to reach. What's the next step?

Next step: matched filtering with two waveform families

Part II



Help: a frequency-targeted filter

Filtering along $f_{22}/2 \pm \Delta f$ helps **identify and measure** the scalar and higher GR harmonics:

less leakage from the loud (2,2) chirp, glitches and low-frequency non-stationary noise

Note: time-frequency (WDM wavelet) templates built along carrier tracks, as developed for LISA [Cornish 2026], could make such track-targeted filters efficient

Part II: summary

Part II

$f_{22}/2$

A locked second track. The scalar dipole radiates at the orbital frequency; the track survives projection, whitening and Gaussian noise, and is clearly separated in ET from 3 Hz

8–9 %

ET needs a rotating response. Few-Hz signals last hours: freezing the antenna pattern changes the SNR by ≤ 1 % but the waveform by 8–9 %

(2,1)

The real competitor is GR (2,1) on the same track.

$2-3 \times 10^{-3}$

The A_{b1} level ET can register ($\rho_{b1} = 8$) across NSBH masses; NS+BH maximizes the charge difference



The decisive test is matched filtering against a full GR higher-mode bank

CONCLUSIONS

Spin inversions · LISA

- Secular 2PN spin dynamics + restricted waveform + LISA noise: five Kerr and quadrupole-induced inversions
- Viewed along J , ordinary precessing binaries reproduce them: $\rho_{\text{res}} \leq 1.64$ at $\rho_{\star} = 100$
- At generic inclinations residuals reach 4–7: inversions may leave measurable structure
- Next: a more complete waveform model for LISA, with full precession and the time-dependent detector response

Scalar dipole · ET

- The dipole radiates on a locked track at $f_{22}/2$, mostly below 50 Hz, where ET reaches
- ET requires an Earth-rotating response; $A_{b1} \approx 2-3 \times 10^{-3}$ gives a scalar SNR of 8
- The real competitor is GR (2,1) on the same track; NS+BH trades charge difference against mass asymmetry
- Next, we aim for matched filtering and incorporating scalar charges

Where this work has been presented in 2026

9–13 Mar	LVK Collaboration Meeting, Pisa, Italy Poster + 30 s sparkler (online): “Scalar-Tensor Gravitational-Wave Polarizations and an Investigation of Selection Bias” preliminary inclination-dependence study
7 May	Student Research Conference (TDK), Szeged Talk: “A gravitációs hullámok polarizációi skalár-tenzor elméletekben” (Polarizations of gravitational waves in scalar–tensor theories) supervisor: Z. Keresztes · 1st prize , qualified for the national OTDK 2027
1–3 Jul	9th Int. Conf. Astronomy, Astrophysics, Space & Planetary Sci., Cluj-Napoca Talk: “The Observability of Gravitational Waves in Scalar–Tensor Theories” with Z. Keresztes · same talk also at the 8th Conference of PhD Students in Mathematics, Szeged (3 Jul)
21–25 Sep	LVK Collaboration Meeting, Pune, India Poster + 30 s sparkler (online): “Spin-Inversion Degeneracies in Compact Binary Inspirals” with L. Á. Gergely and Z. Keresztes
Next	Part I: accepted in Universe (14 October 2026) · Part II: national OTDK 2027 and a journal paper in preparation

Thank you for your attention!

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