7th KAGRA International Workshop 2020. 12/19

Polarization tests of GW170814 and GW170817 using waveforms consistent with alternative theories of gravity

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Polarization

Generic metric theory allows 6 polarizations.

$$h_{ab}(t,\hat{\Omega}) = h_A(t)e^A_{ab}(\hat{\Omega}), \quad A = +\,,\times\,,\, x,\, y,\, b,\, l$$

Tensor

Plus $$e^{+}_{ab} = \hat{e}_x \otimes \hat{e}_x - \hat{e}_y \otimes \hat{e}_y,$$

Cross $$e^{\times}_{ab} = \hat{e}_x \otimes \hat{e}_y + \hat{e}_y \otimes \hat{e}_x,$$

Vector

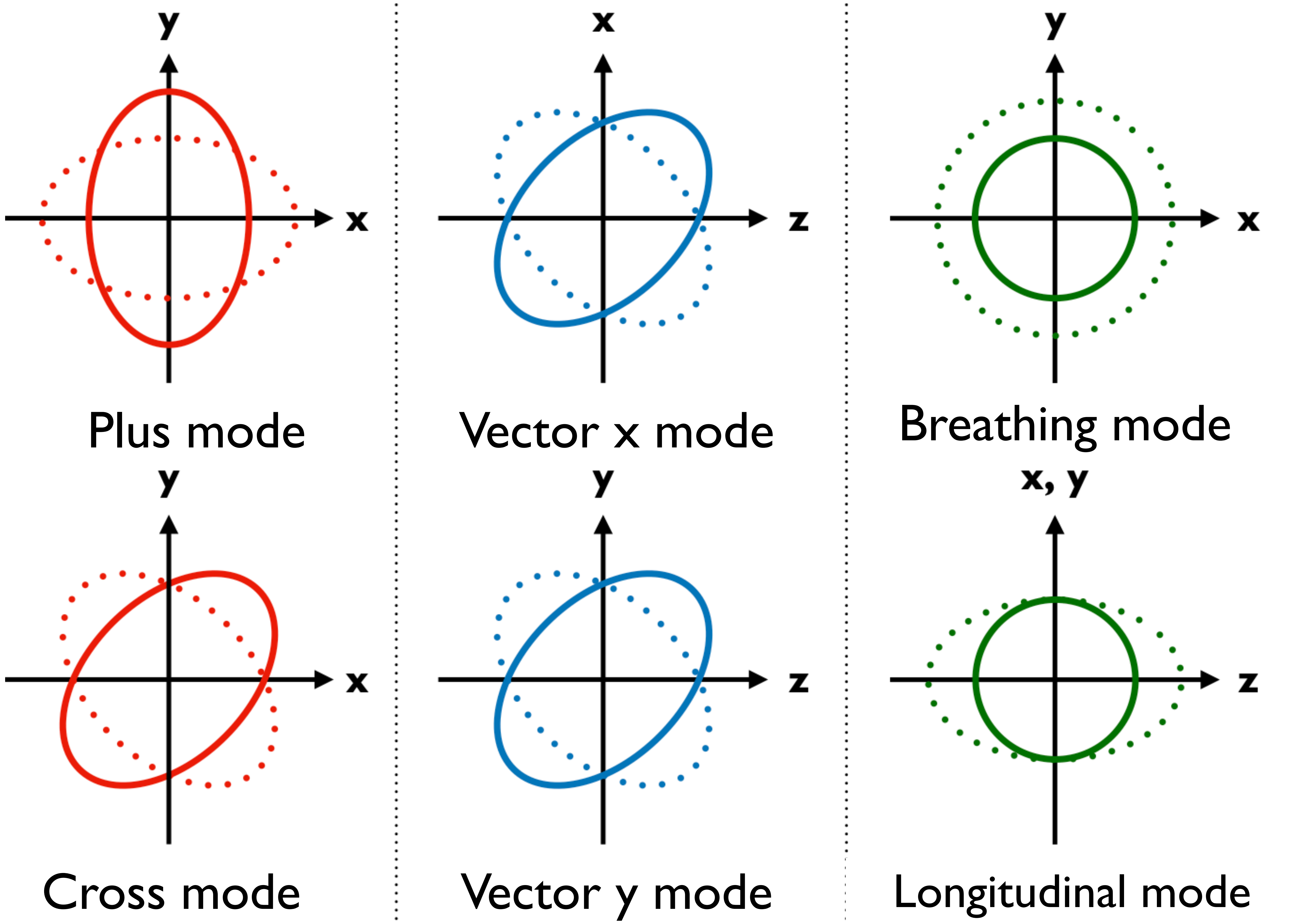
Vector x $$e^{x}_{ab} = \hat{e}_x \otimes \hat{e}_z + \hat{e}_z \otimes \hat{e}_x,$$

Vector y $$e^{y}_{ab} = \hat{e}_y \otimes \hat{e}_z + \hat{e}_z \otimes \hat{e}_y,$$

Scalar

Breathing $$e^{b}_{ab} = \hat{e}_x \otimes \hat{e}_x + \hat{e}_y \otimes \hat{e}_y,$$

Longitudinal $$e^{l}_{ab} = \sqrt{2}\hat{e}_z \otimes \hat{e}_z,$$



Tests of GR by polarization

Possible polarization modes in a specific theory.

Theory	Plus	Cross	Vector x	vector y	Breathing	Longitudinal
General Relativity	✓	✓				
Kaluza-Klein theory	✓	✓	✓	✓	✓	
Brans-Dicke theory	✓	✓			✓	✓
f(R) theory	✓	✓			✓	✓
Bimetric theory	✓	✓	✓	✓	✓	✓

Separating the polarization modes from detector signals.

->We can test GR by the polarization modes of the gravitational waves.

Detector Signal

GW amplitude for polarization mode A

Detector signal

$$h_I(t,\hat{\Omega}) = \sum_A F_I^A(\hat{\Omega}) h_A$$

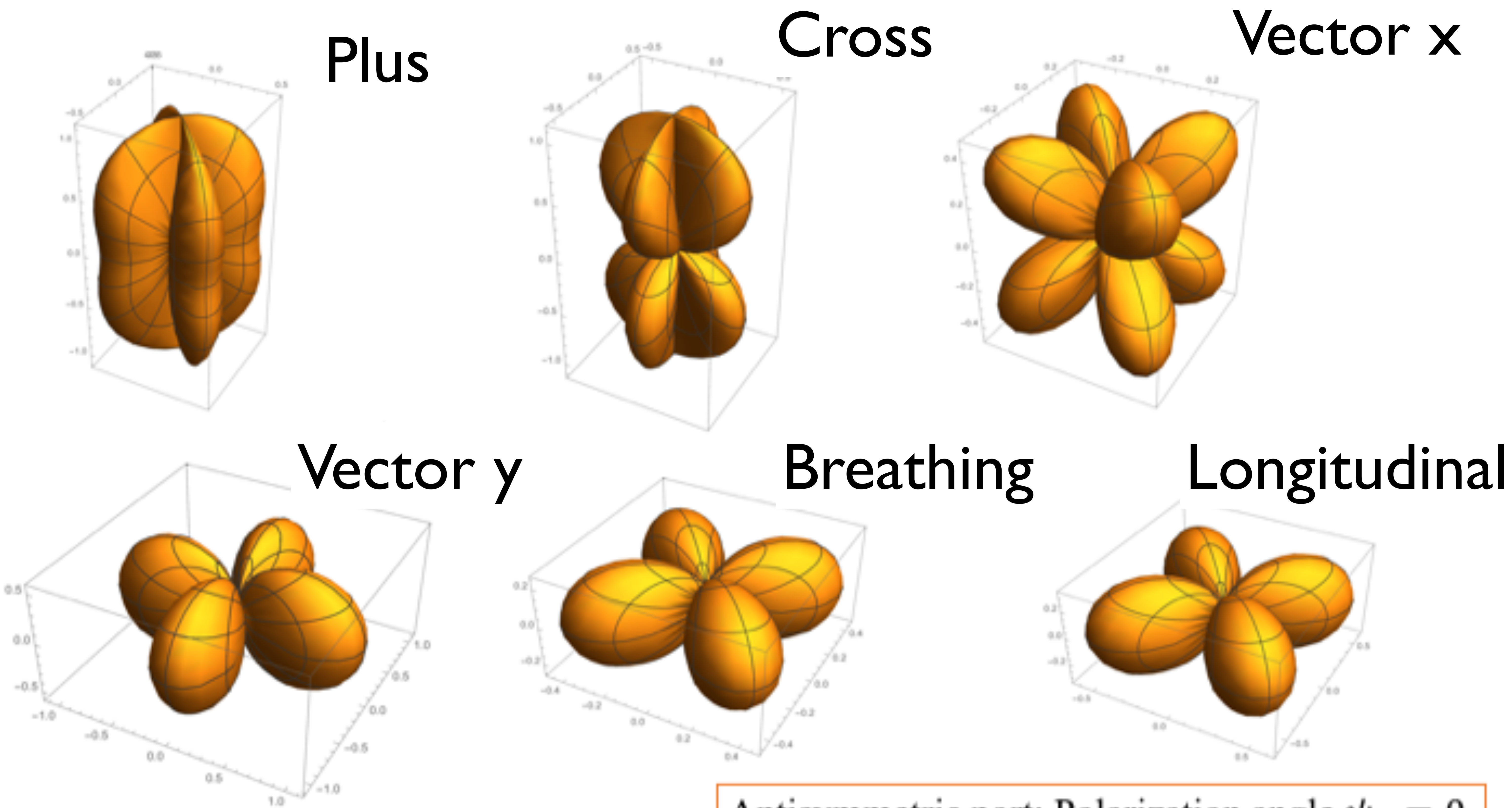
Antenna pattern functions

$$F_I^A(\hat{\Omega}) := d_I^{ab} e_{ab}^A(\hat{\Omega}).$$

represent detector response.

Detector tensor

$$d_I := \frac{1}{2}(\hat{u}_I \otimes \hat{u}_I - \hat{v}_I \otimes \hat{v}_I),$$



Antisymmetric port: Polarization angle $\psi_p = 0$

Reconstruction

In principle, (The number of polarizations) = (The number of detectors)

e.g. Detector =3, modes = $(+, \times, b)$

$$h_1 = F_1^+ h_+ + F_1^\times h_\times + F_1^b h_b$$
$$h_2 = F_2^+ h_+ + F_2^\times h_\times + F_2^b h_b$$
$$h_3 = F_3^+ h_+ + F_3^\times h_\times + F_3^b h_b$$

$$\begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix} = F \begin{pmatrix} h_+ \\ h_\times \\ h_b \end{pmatrix} \qquad F := \begin{pmatrix} F_1^+ & F_1^\times & F_1^b \\ F_2^+ & F_2^\times & F_2^b \\ F_3^+ & F_3^\times & F_3^b \end{pmatrix}$$

Reconstruction(Inverse problem)

$$\begin{pmatrix} h_+ \\ h_\times \\ h_b \end{pmatrix} = F^{-1} \begin{pmatrix} h_1 \\ h_2 \\ h_3 \end{pmatrix}$$

Detector network expansion → More polarizations can be probed.

Motivation

Bayesian model selection between GR and the theory allowing only scalar or vector by simple substitution of the antenna pattern functions. [LVC(2017)PRL, LVC(2019)PRL.]

Tensor vs Vector

$$h_I = \underline{F_I^{\mathrm{T}}}\, h_{\mathrm{T}} \quad \text{vs} \quad h_I = \underline{F_I^{\mathrm{V}}}\, h_{\mathrm{T}} \quad \longrightarrow \quad \begin{cases} \log B_{\mathrm{TV}} > 3 \ (\mathrm{GW170814}) \\ \log B_{\mathrm{TV}} = 20.81 \ (\mathrm{GW170817}) \end{cases}$$

Tensor vs Scalar

$$h_I = \underline{F_I^{\mathrm{T}}}\, h_{\mathrm{T}} \quad \text{vs} \quad h_I = \underline{F_I^{\mathrm{S}}}\, h_{\mathrm{T}} \quad \longrightarrow \quad \begin{cases} \log B_{\mathrm{TS}} > 2.3 \ (\mathrm{GW170814}) \\ \log B_{\mathrm{TS}} = 23.09 \ (\mathrm{GW170817}) \end{cases}$$

⇨

1. Lack of consideration of the angular patterns of non-tensorial radiation.
-> <u>Re-analysis of pure polarization search in the improved framework.</u>

2. Almost all metric theories of gravity predict the mixed polarization modes.
-> <u>Mixed scalar-tensor polarization search.</u>

1. Pure polarization search

arXiv:2010.14538

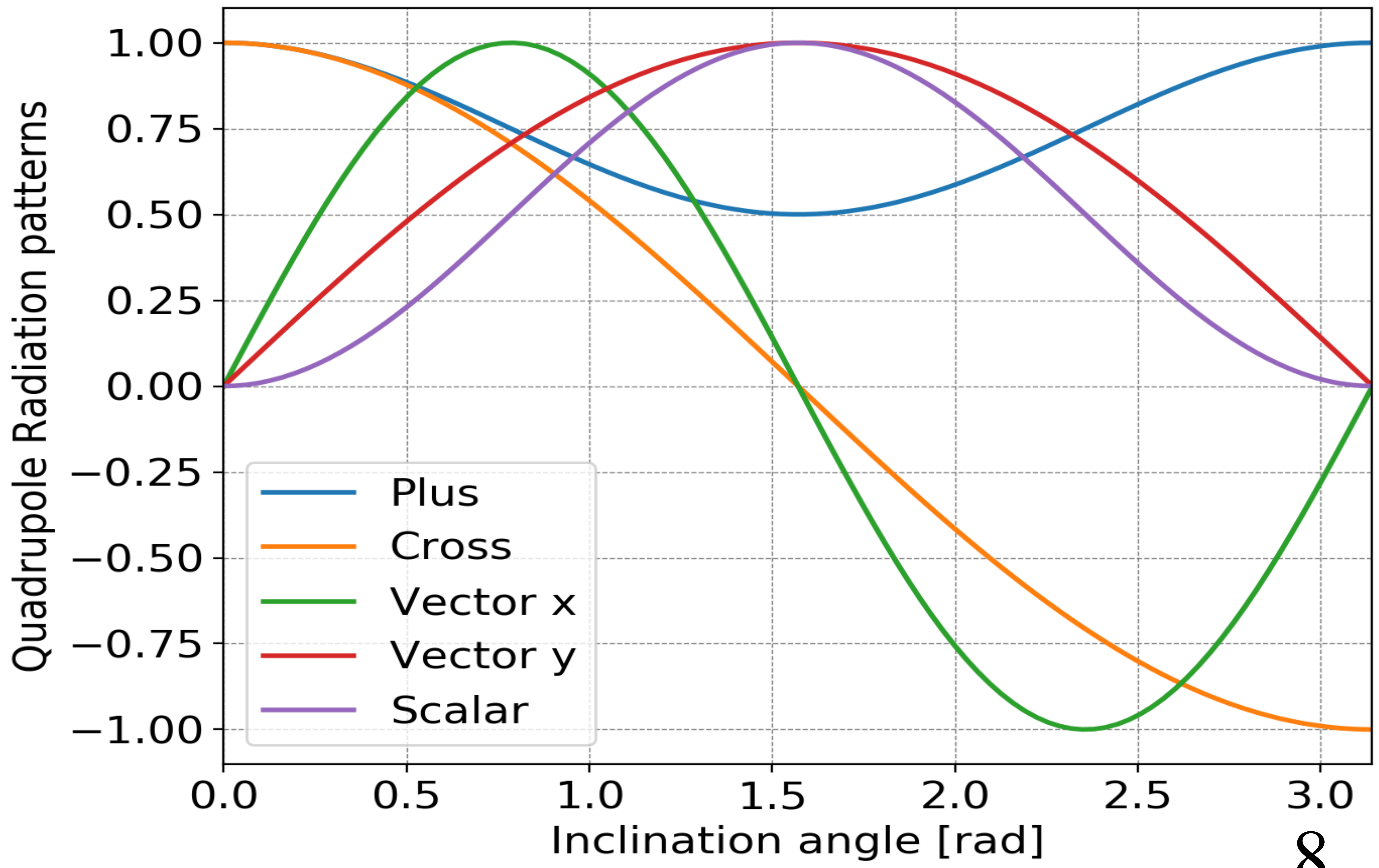
Radiation patterns

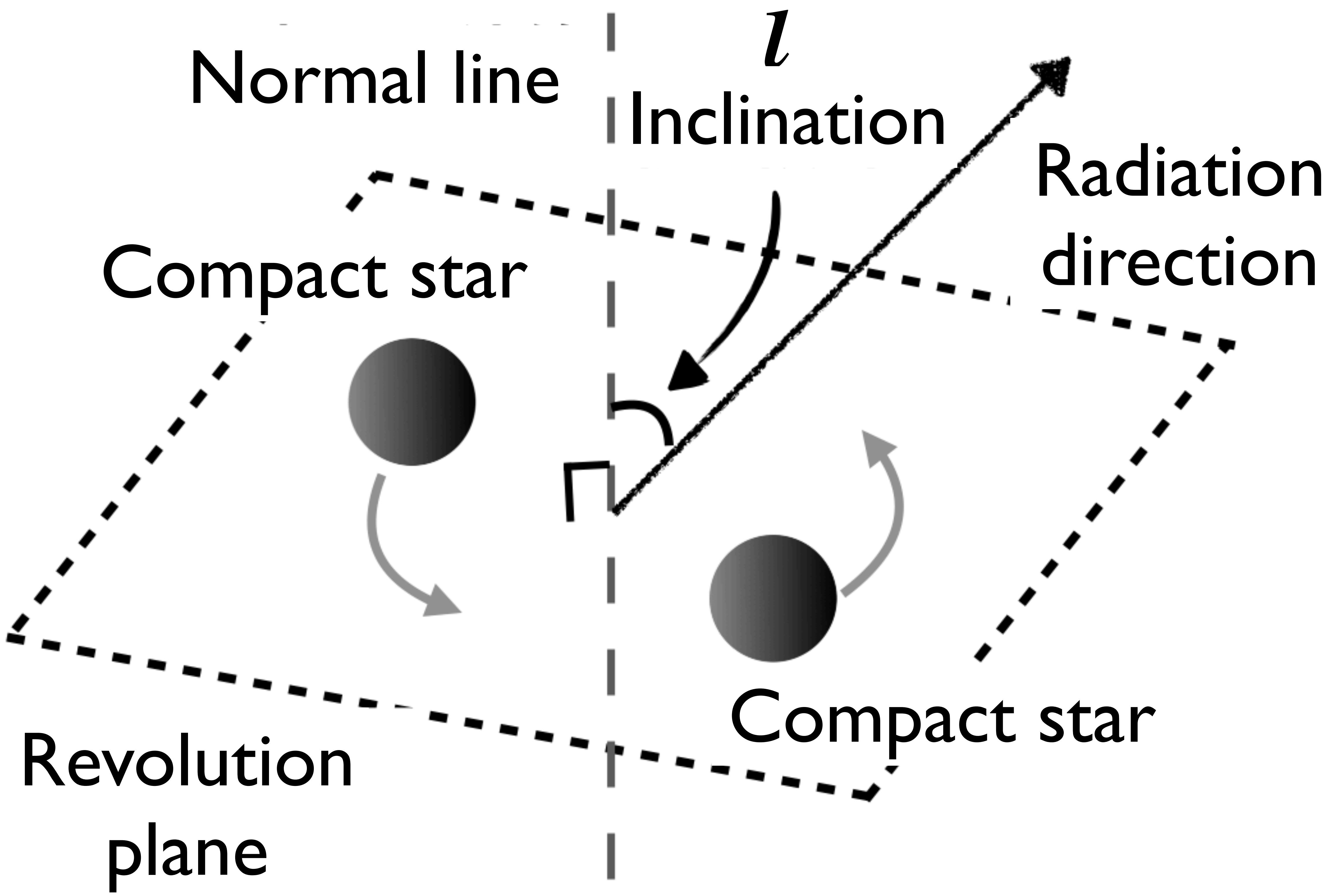
- Re-analyze pure polarization modes considering the angular patterns of radiation.

<u>- Inclination angle dependence is determined by the geometry of the system in general.</u>

(Orbital angular freq. : ω_s, reduced mass: μ, orbital radius: r, retarded time: $t_{\rm ret}$)

e.g. $$h_b = -\frac{4\mu\omega_s^2 R^2}{r}\frac{\sin^2\iota}{2}\cos(2\omega_s t_{\rm ret} + 2\phi)$$





Analysis

<u>Hypotheses:</u>

$$\mathscr{H}_\mathrm{S}: h_I(t,\hat{\Omega}) = F_I^b(\hat{\Omega})\underline{\sin^2\iota}\, h_{+,\mathrm{GR}}$$

$$\mathscr{H}_\mathrm{V}: h_I(t,\hat{\Omega}) = F_I^x(\hat{\Omega})\underline{\sin 2\iota}\, h_{+,\mathrm{GR}}(t) + F_I^y(\hat{\Omega})\underline{\sin\iota}\, h_{\times,\mathrm{GR}}(t)$$

$$\mathscr{H}_\mathrm{T}: h_I(t,\hat{\Omega}) = F_I^+(\hat{\Omega})\underline{\frac{1+\cos^2\iota}{2}}\, h_{+,\mathrm{GR}}(t) + F_I^\times(\hat{\Omega})\underline{\cos\iota}\, h_{\times,\mathrm{GR}}(t)$$

$h_{+,\mathrm{GR}}, h_{\times,\mathrm{GR}}$: Waveforms in GR -> IMRPhenomD, IMRPhenomD_NRTidal

parameters: $\boldsymbol{\theta} = (\alpha, \delta, \iota, \psi, d_L, t_c, \phi_c, m_1, m_2, \chi_1, \chi_2, \Lambda_1, \Lambda_2)$

<u>Bayesian inference:</u>

prior -> [LVC(2019)PRX.]

likelihood

bilby, cpnest ⇒

<u>posterior</u> $p(\boldsymbol{\theta}|h_I, \mathscr{H}_\mathrm{X}) = \dfrac{p(\boldsymbol{\theta})p(h_I|\boldsymbol{\theta}, \mathscr{H}_\mathrm{X})}{p(h_I|\mathscr{H}_\mathrm{X})}$

evidence

<u>Bayes factor</u> $B_\mathrm{XY} := \dfrac{p(h_I|\mathscr{H}_\mathrm{X})}{p(h_I|\mathscr{H}_\mathrm{Y})}$

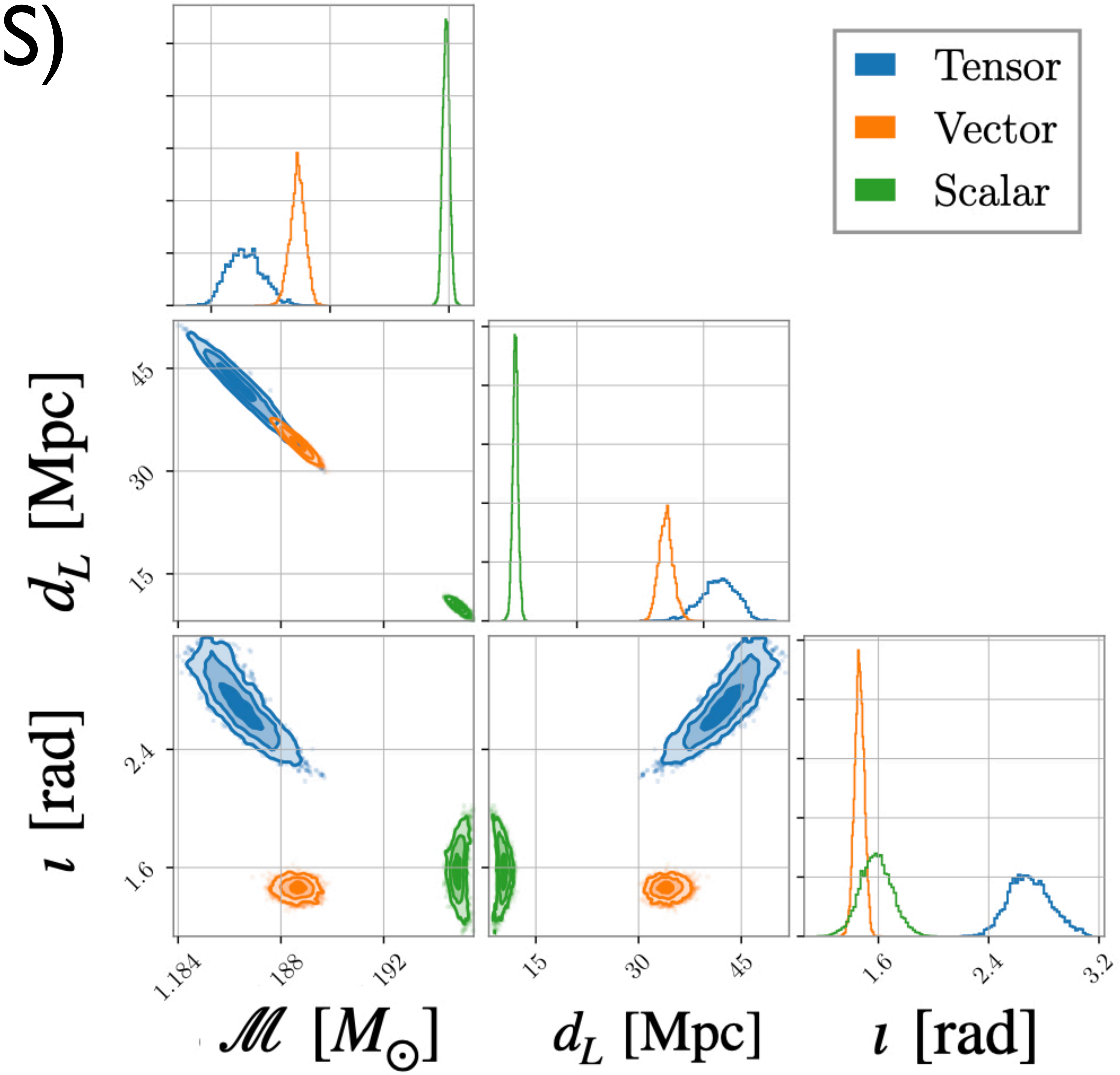
How much GR is preferred compared to pure scalar or vector model.

Result: GW170817(BNS)

- We impose the priors on (α, δ, d_L) from the host galaxy NGC4993.

$$\log B_{\mathrm{TV}} = 21.078$$
$$\log B_{\mathrm{TS}} = 44.544$$

<u>We obtain the improved Bayes factors supporting GR.</u>



Result: GW170817(BNS)

- In addition, we impose the jet prior on the inclination angle (from the constraint of the observational angle by the gamma ray burst GRB170817A.)

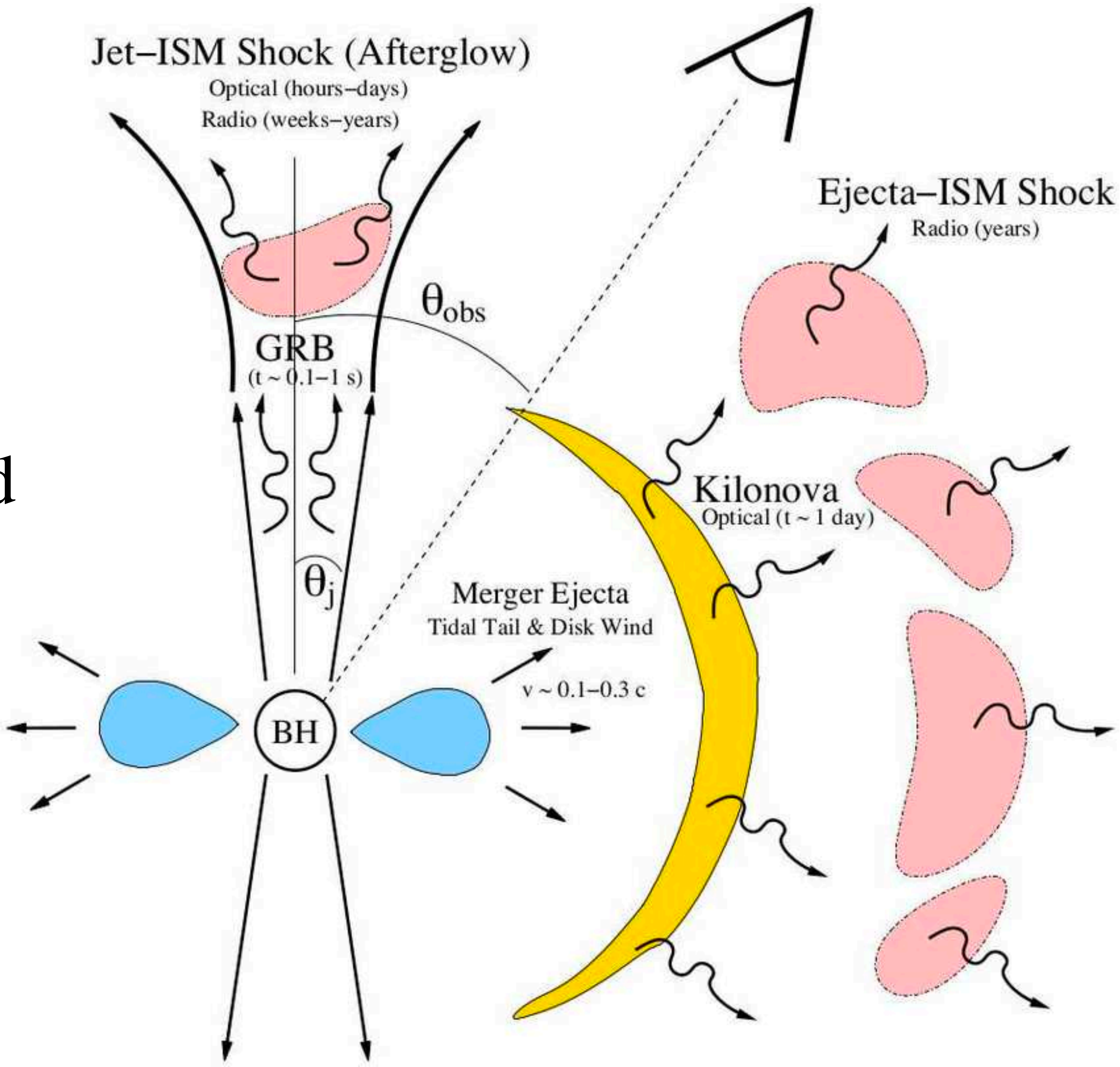
$$0.25\ \mathrm{rad} < \theta_{\mathrm{obs}}(d_L/41\ \mathrm{Mpc}) < 0.45\ \mathrm{rad}$$

[Mooley et. al.(2018)Nature, Hotokezaka et. al.(2019)Nature Astro.]

→ $2.68\,\mathrm{rad} < \iota < 2.92\,\mathrm{rad}$

$$\log B_{\mathrm{TV}} = 51.043$$
$$\log B_{\mathrm{TS}} = 60.271$$

The Bayes factors strongly support GR.



Metzger and Berger(2012)APJ.

2. Scalar-tensor mixed polarization search

Analysis

- We also search for a mixture of polarization modes: a scalar-tensor polarization model.

$$\mathscr{H}_{\mathrm{ST}}: \; h_I(t,\hat{\Omega}) = F_I^{+}(\hat{\Omega})\frac{1+\cos^2\iota}{2}(1+\delta A)h_{+,\mathrm{GR}}(t)e^{i\delta\Psi} + F_I^{\times}(\hat{\Omega})\cos\iota(1+\delta A)h_{\times,\mathrm{GR}}(t)e^{i\delta\Psi}$$
$$+F_I^{s=b}(\hat{\Omega})A_S\sin^2\iota h_{+,\mathrm{GR}}(t)e^{i\delta\Psi},$$

- Amplitude and phase corrections from the additional scalar radiation .

Balance law: $\frac{dE}{dt} = -P_{\mathrm{GW}}$ → $\delta A = -\frac{1}{3}A_S^2, \delta\Psi = \frac{1}{64}A_S^2(\pi\mathscr{M}f)^{-5/3}.$

Stationary phase approximation

- $h_{+,\mathrm{GR}}, h_{\times,\mathrm{GR}}$: Waveforms in GR ->TaylorF2, TaylorF2_NRTidal

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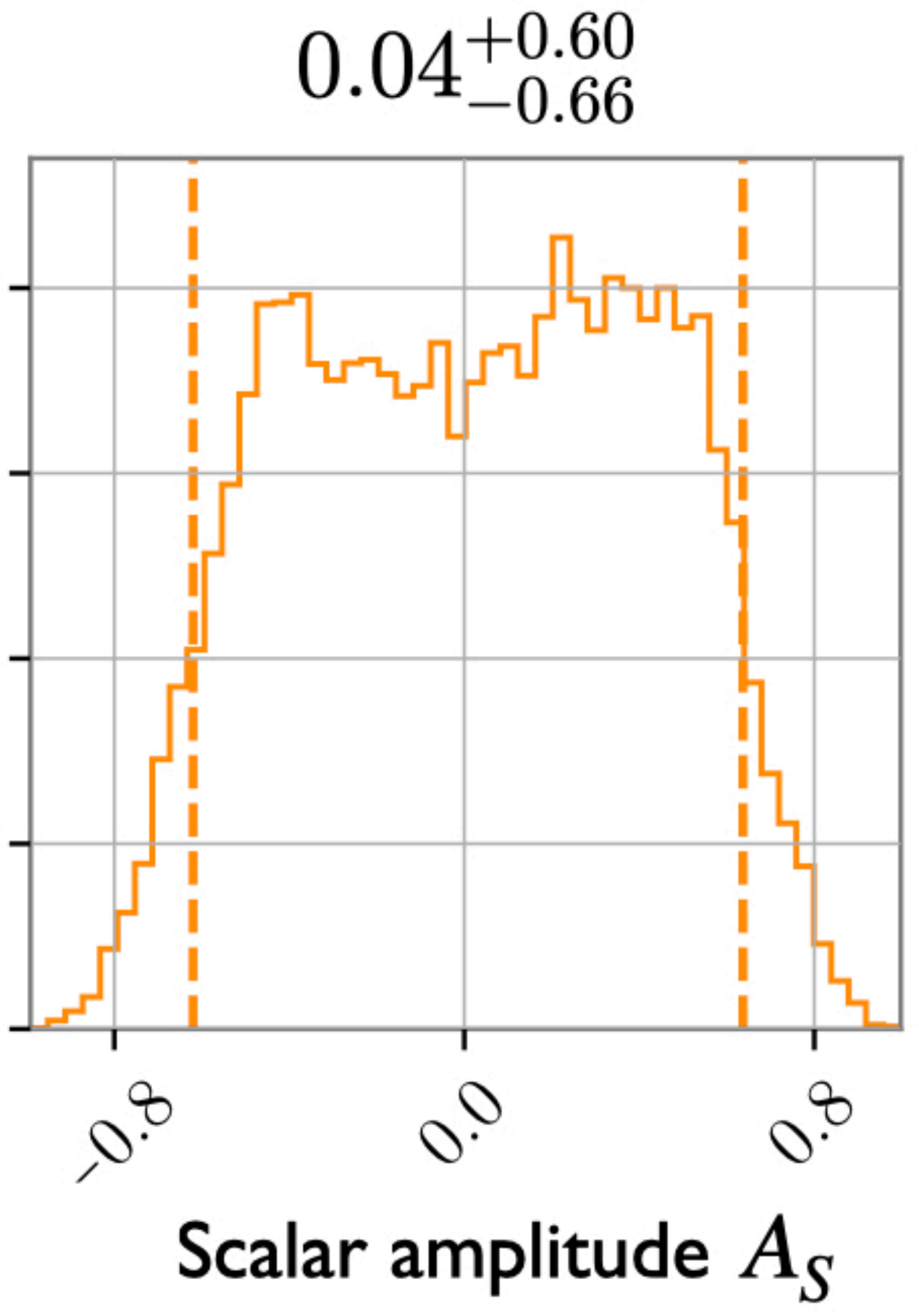
- We perform Bayesian inference for GW170814 (BBH) and for GW170817 (BNS).

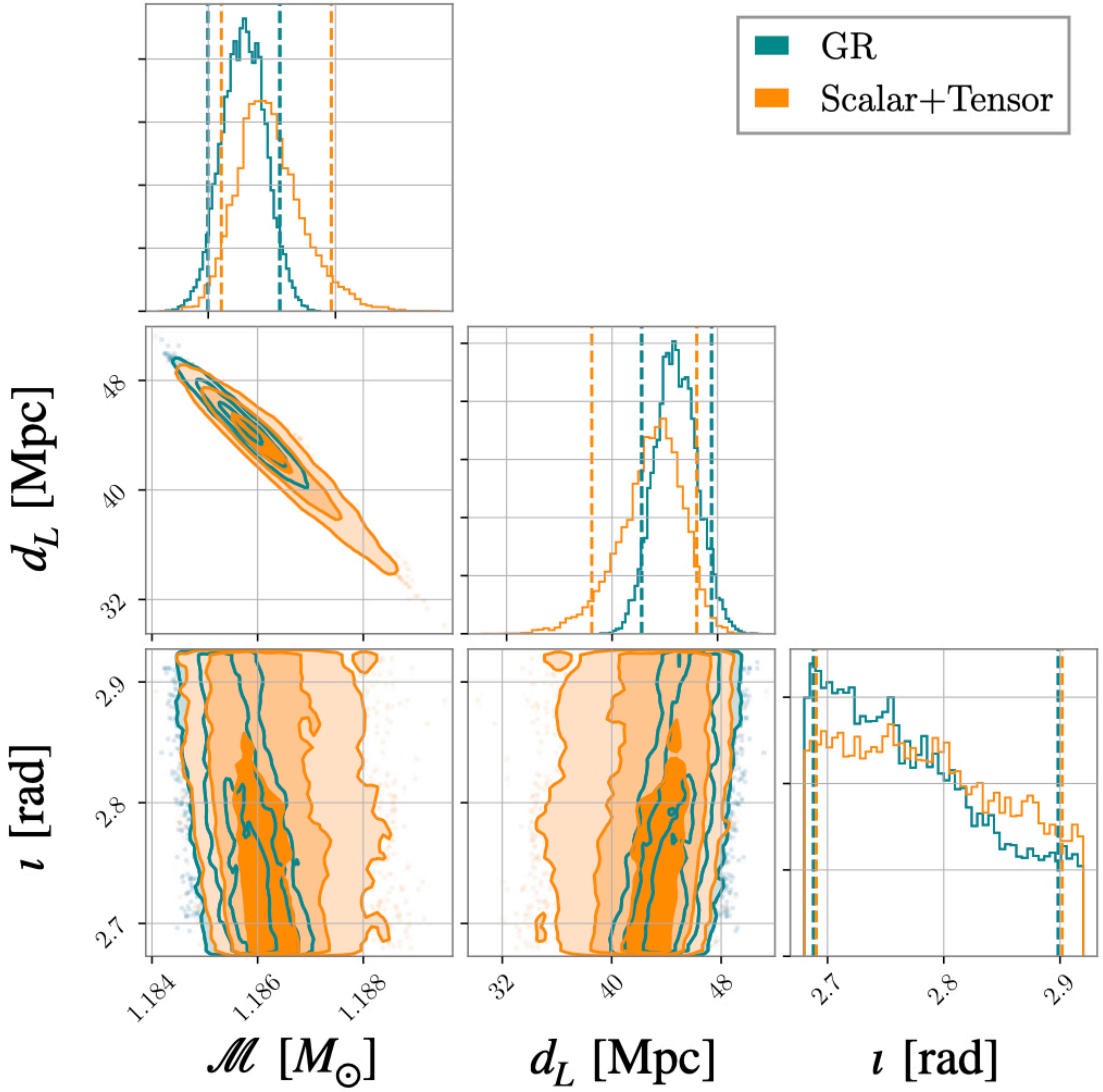
(Location and jet prior)

Result: GW170817(BNS)

The estimated amplitude parameters such as the luminosity distance hardly changed.

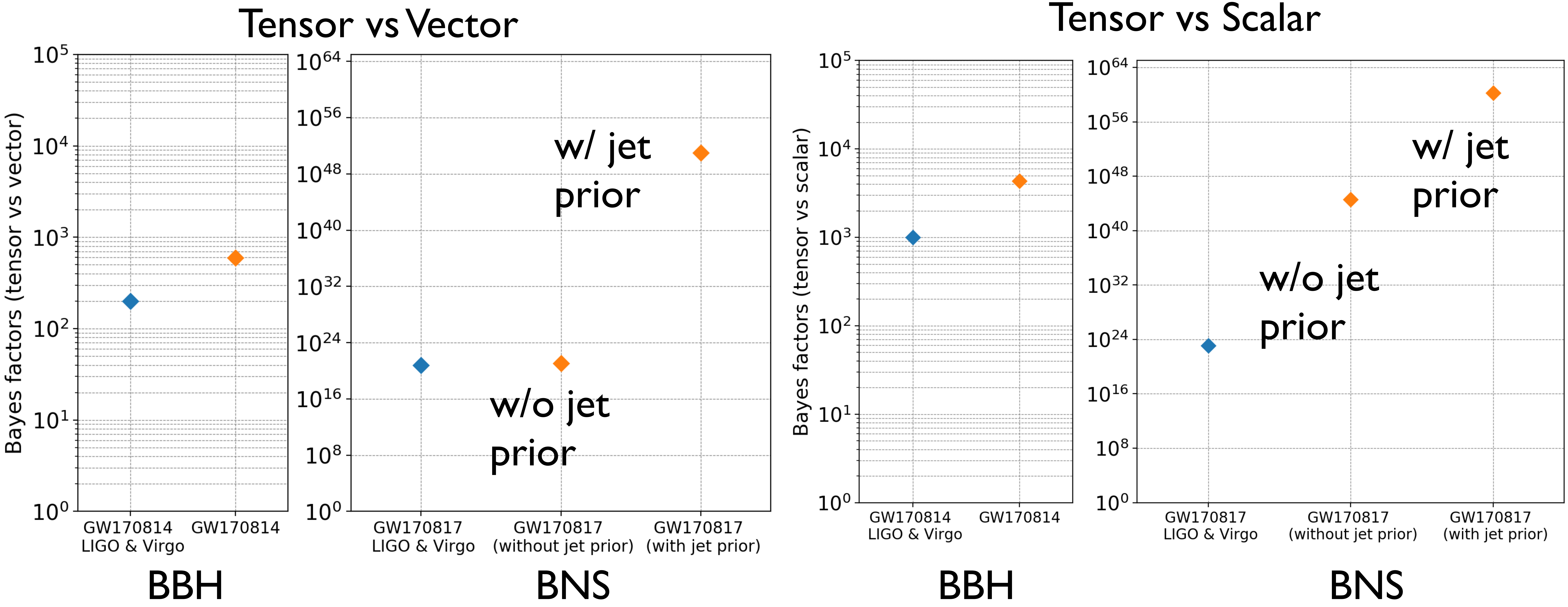
<u>Observational constraint on the amplitude of the additional scalar polarization</u>





Summary

1. We obtained Bayes factors that support GR strongly in the pure polarization search.



2. We found the constraints on the amplitude ratio between tensor modes and scalar mode.

BBH $R_{ST} = -0.0217^{+0.160}_{-0.154}$.

BNS $R_{ST} = 0.00378^{+0.0567}_{-0.0624}$.

Thank you for your attentions!