2018.7/5 Fifteenth Marcel Grossmann Meeting,
University of Rome "La Sapienza"

Polarization test of gravitational waves from compact binary coalescences

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Abstract

- The observation of gravitational waves(GW) from compact binary coalescences(CBC) enabled some experimental studies to probe into the nature of gravity.

- the separability of the polarization modes for the inspiral GW from the CBC systematically.
- The three polarization modes of the GW would be separable even with the global network of three detectors to some extent
- With four detectors, even the four polarization modes would be separable.

1. Polarization of Gravitational Wave

Polarization mode of GW

Generic metric theory allows 6 polarizations.

$$h_{ab}(t,\hat{\Omega}) = h_A(t)e^A_{ab}(\hat{\Omega})$$

$$A = +, \times, x, y, b, l$$

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

$$e^y_{ab} = \hat{e}_y \otimes \hat{e}_z - \hat{e}_z \otimes \hat{e}_y$$

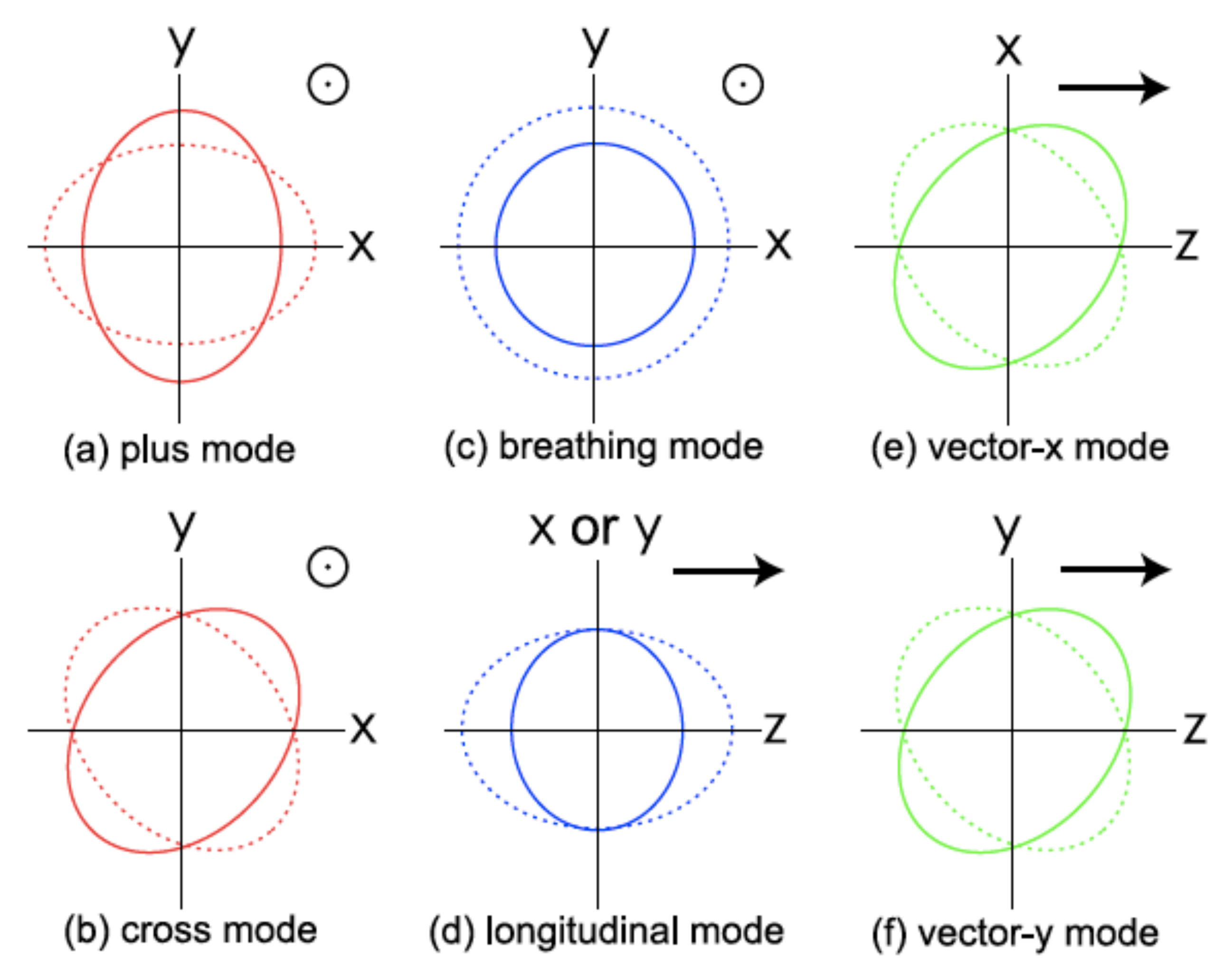
Scalar

breathing

$$e^b_{ab} = \hat{e}_x \otimes \hat{e}_x + \hat{e}_y \otimes \hat{e}_y$$

longitudinal

$$e^l_{ab} = \sqrt{2}\hat{e}_z \otimes \hat{e}_z.$$



A. Nishizawa et al., Physical Review D 79, 082002 (2009).

Test of Gravity Theory with GW polarization

modes allowed in a theoretical model

Theory	plus	cross	vector x	vector y	breathing	longitudinal
General Relativity	O	O				
Kaluza-Klein theory	O	O	O	O	O	
Brans-Dicke theory	O	O			O	O
$f(R)$ theory	O	O			O	O
Bimetric theory	O	O	O	O	O	O

Test of Polarization modes of GW is a powerful tool for pursuing the nature of space-time.

Separate and Reconstruct polarization modes of GW model independently from detector signal

GW Interferometric Signal

Detector Signal

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

Antenna pattern functions

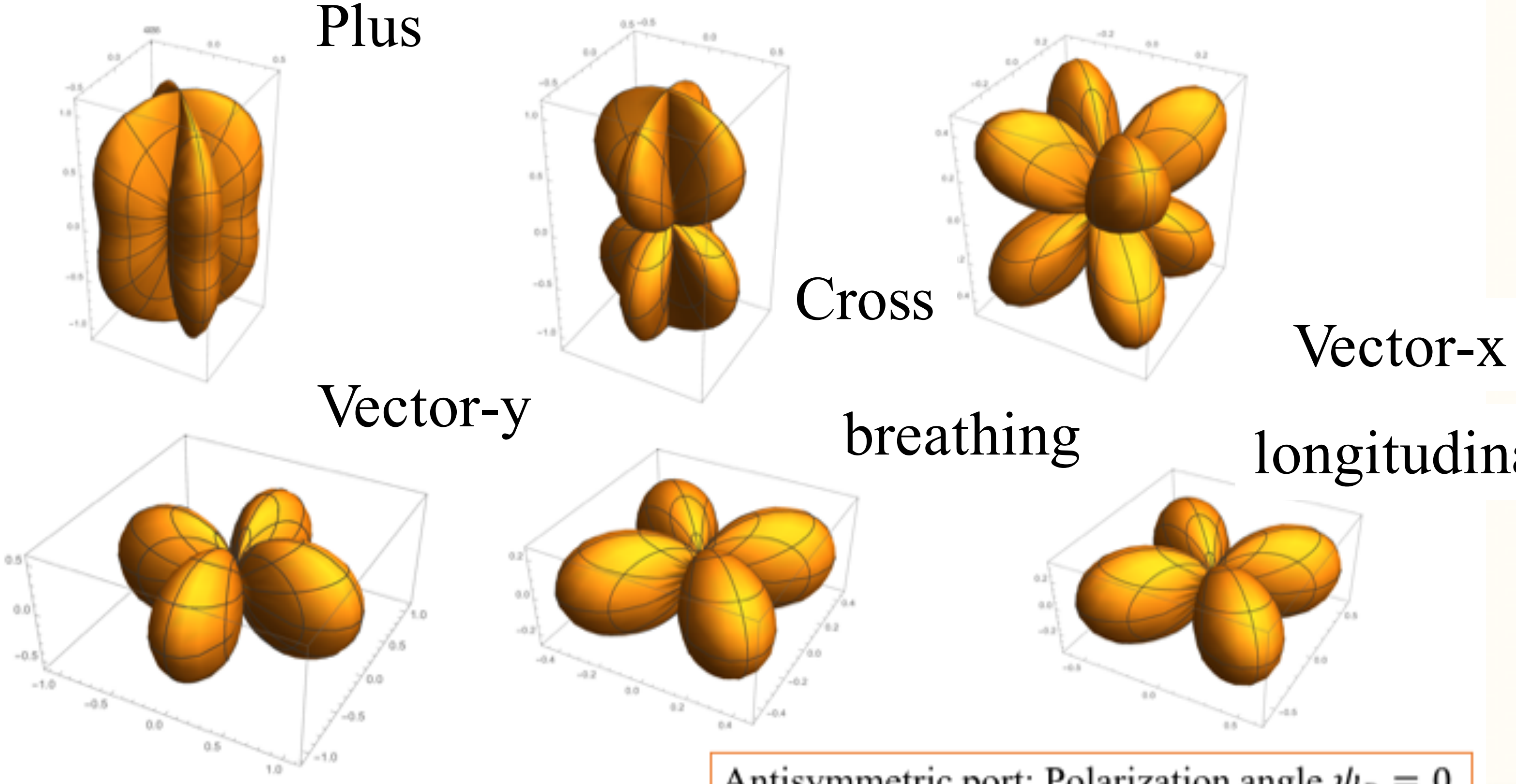
GW amplitude for polarization mode "A"

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

detector response to GW

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 of GW Polarization

e.g. The number of detector =3, and 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)

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

Polarization test with GW from CBC

In principle, (The number of polarization modes) = (The number of detectors)

More polarization modes can be probed with the larger number of detectors

However

Few studies have focused on the reconstruction of the polarization of GW from CBC

Because…

Waveforms of GW from CBC have the source model parameters,
which determine the frequency evolution in time and are correlated each other.

It is necessary to gain a better understanding of the correlations and degeneracies among the parameters in a realistic waveform of CBC including nontensorial modes

2. Parameter Estimation

Polarization Model

Parameter estimation by Fisher Information matrix

Model TS1: Tensor(+,×)
Scalar(dipole)

$$h_I = \{\mathcal{G}_{T,I} + \underline{A_{S_1}}\mathcal{G}_{S_1,I}\}h_{\mathrm{GR}}$$

Model TS2: Tensor (+,×)
Scalar(quadrupole)

$$h_I = \{\mathcal{G}_{T,I} + \underline{A_{S_2}}\mathcal{G}_{S_2,I}\}h_{\mathrm{GR}}$$

Model TV: Tensor (+,×)
Vector-x, Vector-y

$$h_I = \{\mathcal{G}_{T,I} + \underline{A_{V_x}}\mathcal{G}_{V_x,I} + \underline{A_{V_y}}\mathcal{G}_{V_y,I}\}h_{\mathrm{GR}}$$

Model T: GR model

Model TVxS2: Tensor (+,×), Scalar(quadrupole), Vector-x

Model TVyS1: Tensor (+,×), Scalar(dipole), Vector-y

Geometrical factor for nontensorial modes

quadrupole formula

$$\mathcal{G}_{V_x,I} := \sqrt{\frac{525}{56}} \sin 2\iota F_{V_x,I}(\boldsymbol{\theta_s},\boldsymbol{\theta_e}) e^{i\phi_{D,I}(\theta_s,\phi_s,\theta_e,\phi_e)}$$

Vector x

$$\mathcal{G}_{V_y,I} := \sqrt{\frac{15}{2}} \sin \iota F_{V_y,I}(\boldsymbol{\theta_s},\boldsymbol{\theta_e}) e^{i\phi_{D,I}(\theta_s,\phi_s,\theta_e,\phi_e)}$$

Vector y

$$\mathcal{G}_{S_2,I} := \sqrt{\frac{225}{8}} \sin^2 \iota F_{b,I}(\boldsymbol{\theta_s},\boldsymbol{\theta_e}) e^{i\phi_{D,I}(\theta_s,\phi_s,\theta_e,\phi_e)}.$$

scalar quadrupole

A scalar degree of freedom
e.g. Brans-Dicke theory

$$\mathcal{G}_{S_1,I} := \sqrt{\frac{45}{2}} \sin \iota F_{b,I}(\boldsymbol{\theta_s},\boldsymbol{\theta_e}) e^{i\phi_{D,I}(\theta_s,\phi_s,\theta_e,\phi_e)}.$$

scalar dipole

Parameter estimation including nontensorial GW polarizations

Setup

・Parameter estimation by Fisher Information matrix

・ the inspiral waveform up to 3.0 PN in amplitude & 3.5 PN in phase

・11 model parameters in GR + $(\log \mathcal{M}, \log \eta, t_c, \phi_c, \log d_L, \chi_s, \chi_a, \boxed{\theta_s, \phi_s, \cos \iota, \psi_p})$
additional polarization parameters, $(A_{S1}, A_{Vx}$ ...) fiducial value unity uniformly random

・Source (500)
binary black holes (BBH) with equal mass 10M⊙ at z = 0.05
binary neutron stars (BNS) with equal mass 1.4M⊙ at z = 0.01

・Detector Network
Two aLIGO detectors at Hanford- Livingston-AdV(HLV)
Two aLIGO detectors at Hanford-Livingston-AdV-KAGRA(HLVK)
all design sensitivity

Results

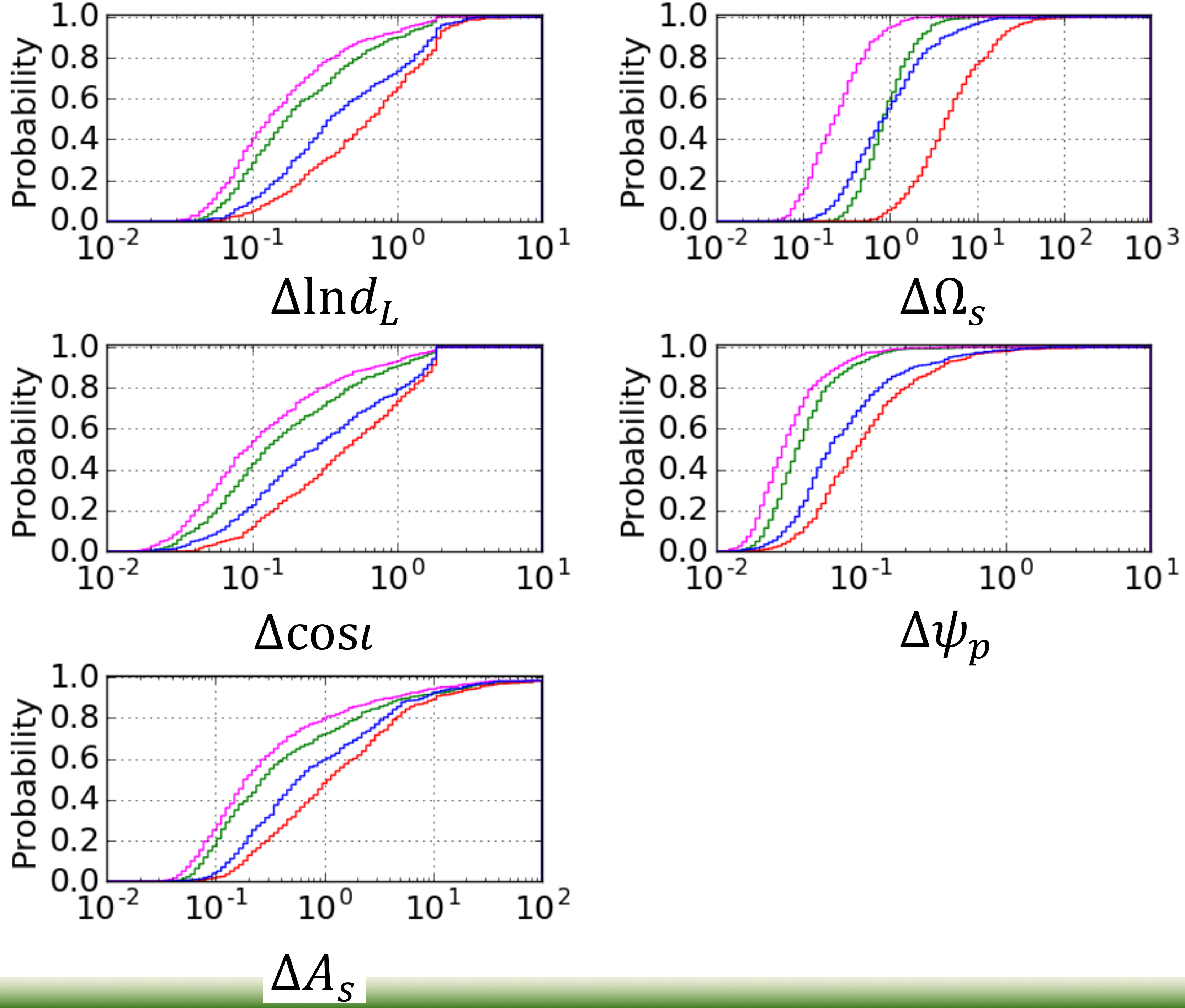
Model TS1

red: BBH-HLV

green: BBH-HLVK

blue: BNS-HLV

magenta: BNS-HLVK



can break a degeneracy among amplitude parameters.

Tensor-Scalar Models (3 modes)

		BBH(HLV)	BBH(HLVK)	Improvement Factor	BNS(HLV)	BNS(HLVK)	Improvement Factor
ModelTS1	$\Delta \ln d_L$	0.678	0.179	3.79	0.359	0.134	2.68
	$\Delta\Omega_s[\mathrm{deg}^2]$	4.74	0.912	5.20	0.919	0.250	3.68
	ΔA_{S1}	1.16	0.284	4.08	0.606	0.197	3.08
	$C(A_{S1}, \log d_L)$	0.998	0.989		0.996	0.984	
	$C(A_{S1}, \cos\iota)$	-0.553	-0.500		-0.231	-0.159	
ModelTS2	$\Delta \ln d_L$	0.676	0.182	3.71	0.358	0.134	2.67
	$\Delta\Omega_s[\mathrm{deg}^2]$	4.74	0.913	5.09	0.862	0.246	3.50
	ΔA_{S2}	1.51	0.385	3.92	0.765	0.256	2.99
	$C(A_{S2}, \log d_L)$	0.997	0.989		0.996	0.984	
	$C(A_{S2}, \cos\iota)$	-0.609	-0.564		-0.246	-0.189	

ModelTS1, TS2

- improved by factor 4 in ΔA_s(BBH), about 3 in ΔA_s(BNS)
- A_s is correlated with $\ln d_L$ and $\cos\iota$ (for all models)
- BBH estimation is worse than BNS with HLV due to the short signal of BBH.

Tensor-Vector Model (4 modes)

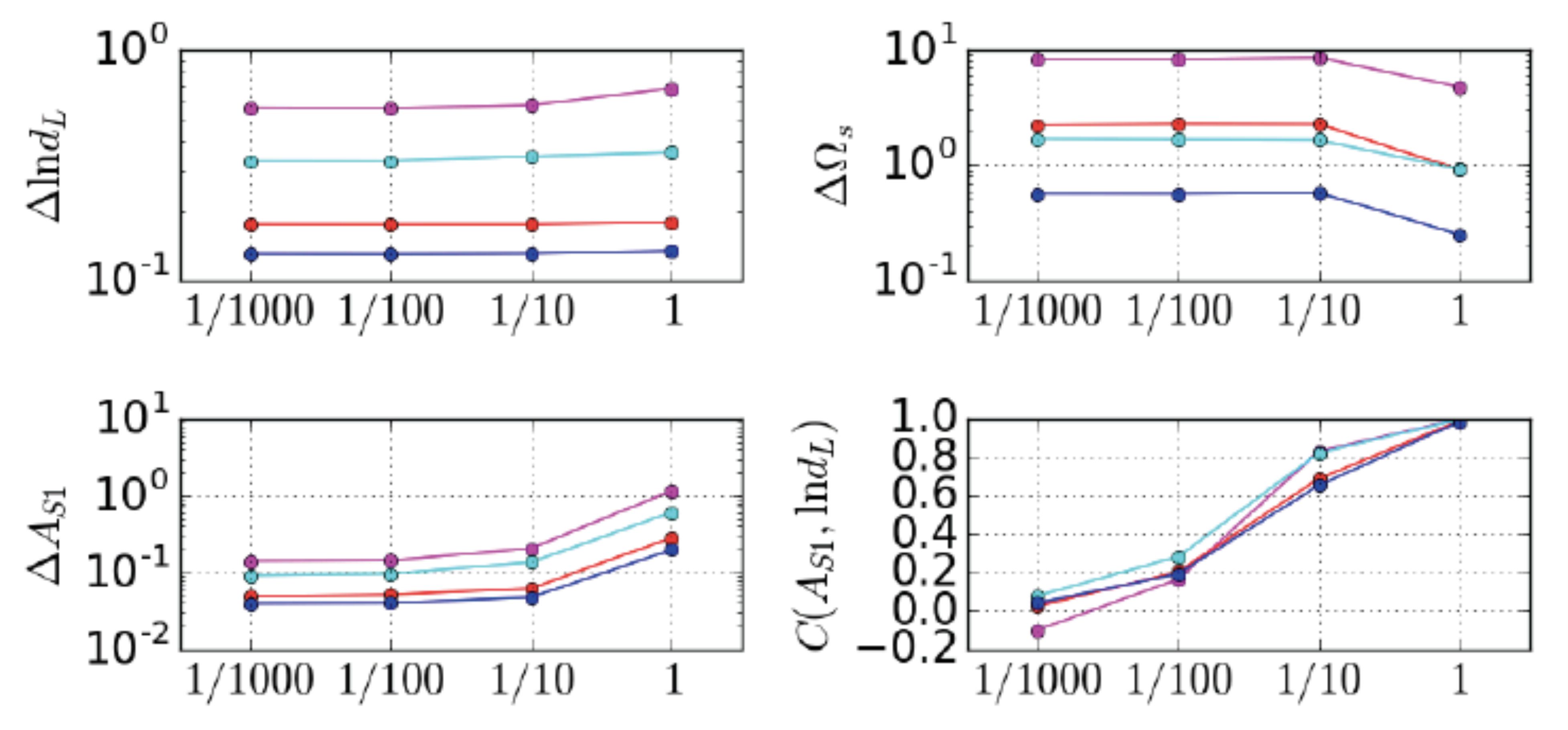
		BBH(HLV)	BBH(HLVK)	Improvement Factor	BNS(HLV)	BNS(HLVK)	Improvement Factor
ModelTV	$\Delta \ln d_L$	1.98	0.310	6.39	1.22	0.193	6.32
	$\Delta\Omega_s[\mathrm{deg}^2]$	5.68	0.795	7.14	0.813	0.187	4.35
	ΔA_{V_x}	2.55	0.420	6.07	1.37	0.241	5.68
	ΔA_{V_y}	3.91	0.513	7.62	2.12	0.298	7.11
	$C(A_{V_y}, \log d_L)$	0.999	0.993		0.998	0.991	
	$C(A_{V_y}, \cos\iota)$	-0.846	-0.335		-0.307	-0.207	
	$C(A_{V_x}, A_{V_y})$	0.987	0.814		0.948	0.624	

Model TV

- Model TV(4 modes) more improved than in Model TS1,TS2(3 modes).
- the error is more than 5 times improved for both BBH and BNS

<u>even the four polarization modes would be separable with four detectors.</u>

Detection Limit



Change the fiducial value A_{S1} from 1 to 1/10, 1/100, 1/1000.
The error of A_{S1} approaches 1/SNR

Conclusion

・Even if the number of detectors is equal to the number of the polarization modes, it is difficult to separate the modes depending on the correlation among the amplitude parameters.

・The three polarization modes would be more separable by breaking a degeneracy of the polarization modes and even the four polarization modes would be separable **with the global four detectors network**.

・ The participation of KAGRA in the network of the GW detectors will make it possible to extract the polarization information.

Thank you for listening!!