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Prospects of constraining on the polarizations of gravitational waves from binary black holes using space- and ground-based detectors

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Phys. Rev. D 108, 124047 (2023). arXiv:2307.05568.

Outline

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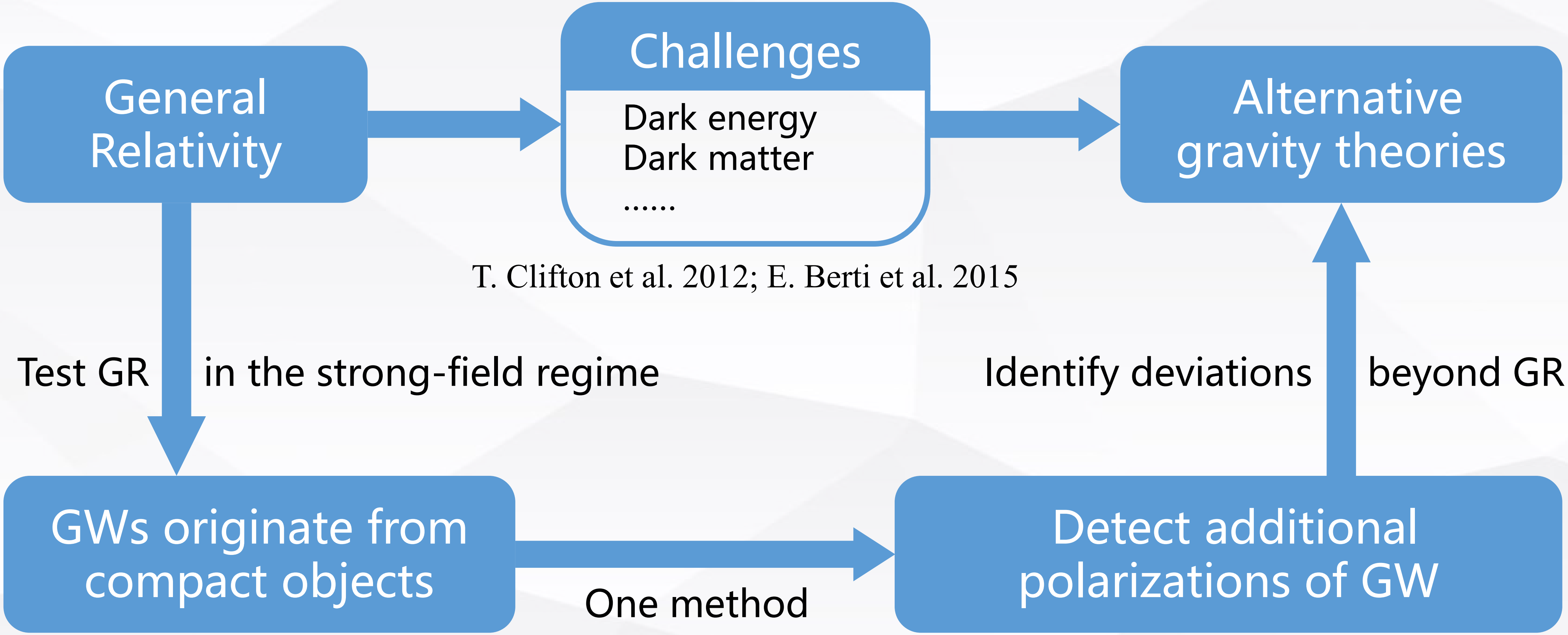
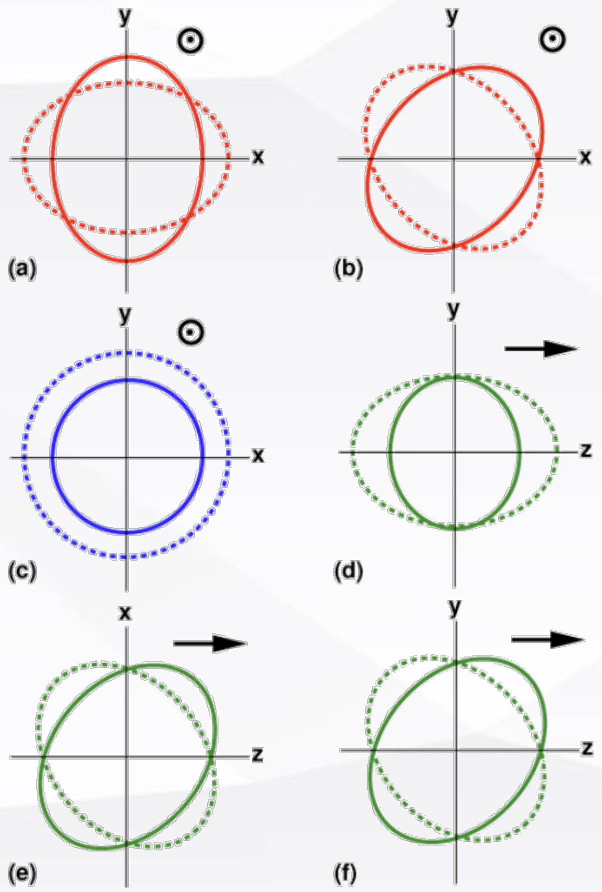
- **Test GR**



T. Clifton et al. 2012; E. Berti et al. 2015

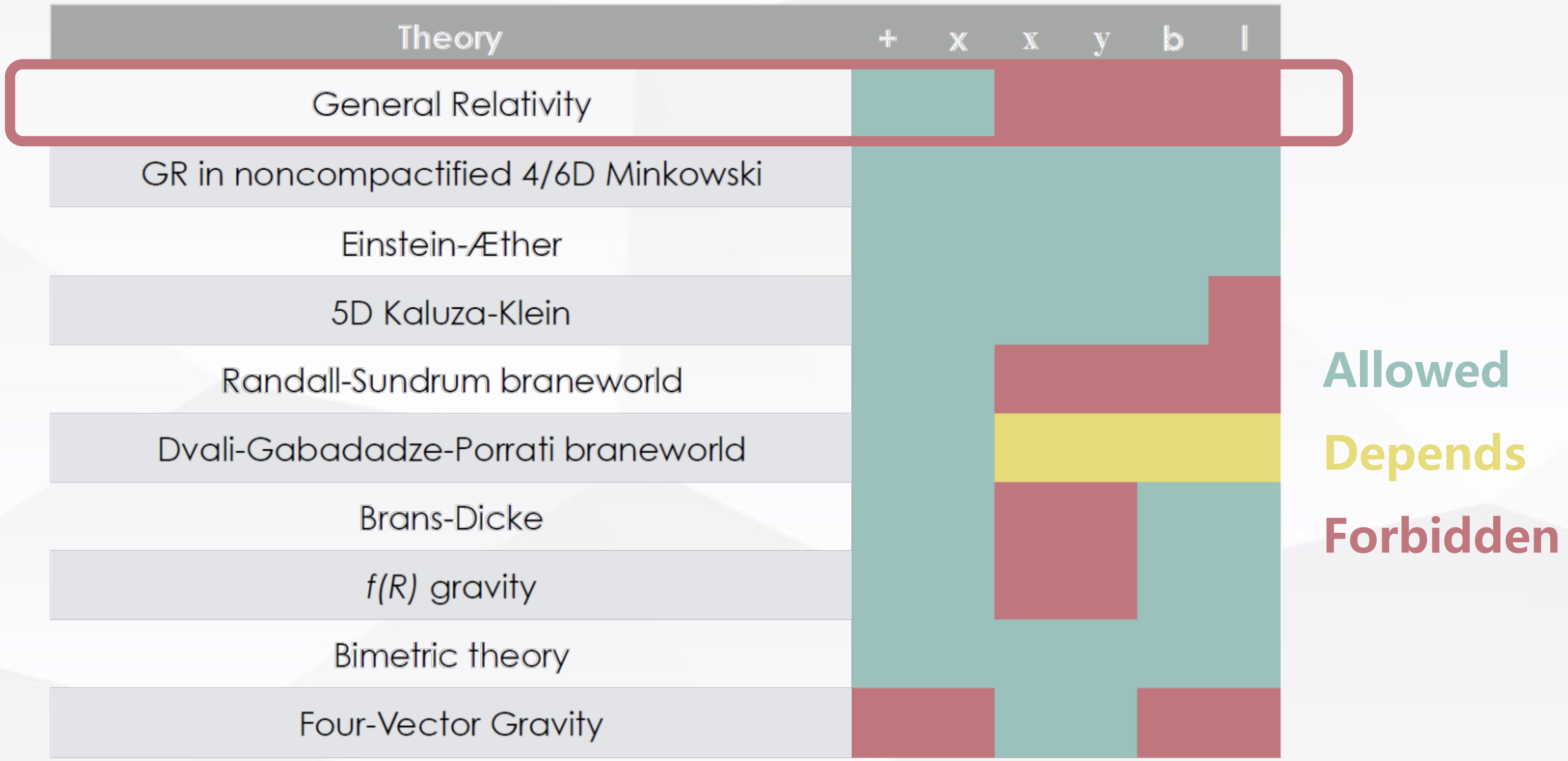
B.S. Sathyaprakash & B.F. Schutz 2009

- **Polarizations of GW**



C. M. Will 2014

General Relativity allows **two** (tensor) polarizations.
General metric theories allow **six** polarizations.



A. Nishizawa et al. 2009

- Related studies

1 ppE framework

N. Yunes & F. Pretorius, *PRD* **80**, 122003 (2009)
N. Cornish et al., *PRD* **84**, 062003 (2011)
K. Chatziioannou et al., *PRD* **86**, 022004 (2012)
S. Tahura & K. Yagi, *PRD* **98**, 084042 (2018)
……

2 Pulsar timing-arrays

N. Yunes & X. Siemens, *LRR* **16**, 9 (2013)
L. O'Beirne et al., *PRD* **99**, 124039 (2019)
……

3 Ground-based detectors

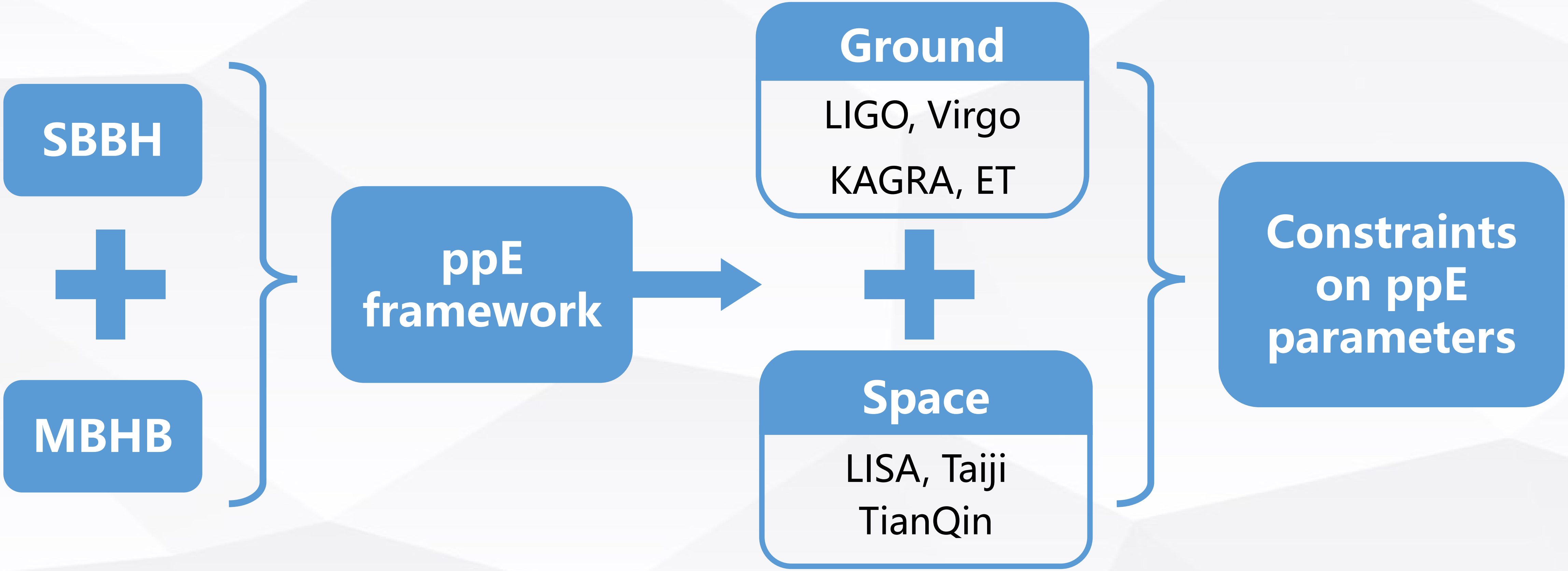
T. Narikawa & H. Tagoshi, *PTEP* **2016**, 093E02 (2016)
R. Nair et al., *PTEP* **2016**, 053E01 (2016)
H. Takeda et al., *PRD* **100**, 042001 (2019)
……

4 Space-based detectors

C. Huwyler et al., *PRD* **91**, 024037 (2015)
C. Liu et al., *PRD* **102**, 124050 (2020)
G. Wang & W.-B. Han, *PRD* **103**, 064021 (2021)
N. Xie et al., *PRD* **106**, 124017 (2022)
……

1 Background & motivation

- Our work



GW source → Waveform → Detectors → Results

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- **GW waveform**

The extended **ppE framework** is utilized to construct a **model-independent** test for GR.

K. Chatziioannou et al. 2012
D. Hansen et al. 2015

$$h(t) = \sum_A F^A h_A(t), \qquad \frac{d\omega}{dt} = \alpha_D \eta^{2/5} \frac{G\mathcal{M}}{c^3}\omega^3 + \alpha_Q \left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} \omega^{11/3},$$

$$h_+ = \mathcal{A}_T (1+\cos^2\iota)/2 \cos(2\Phi + 2\Phi_0),$$
$$h_\times = \mathcal{A}_T \cos\iota \sin(2\Phi + 2\Phi_0),$$
$$h_X = \mathcal{A}_V \cos\iota \cos(\Phi + \Phi_0),$$
$$h_Y = \mathcal{A}_V \sin(\Phi + \Phi_0),$$
$$h_B = \mathcal{A}_B \sin\iota \cos(\Phi + \Phi_0),$$
$$h_L = \mathcal{A}_L \sin\iota \cos(\Phi + \Phi_0),$$

$$\mathcal{A}_T = \frac{4}{D_L}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\omega}{c}\right)^{2/3},$$
$$\mathcal{A}_V = \frac{\alpha_V}{D_L}\left(\frac{G\mathcal{M}}{c^2}\right)^{4/3}\left(\frac{\omega}{c}\right)^{1/3},$$
$$\mathcal{A}_B = \frac{\alpha_B}{D_L}\left(\frac{G\mathcal{M}}{c^2}\right)^{4/3}\left(\frac{\omega}{c}\right)^{1/3},$$
$$\mathcal{A}_L = \frac{\alpha_L}{D_L}\left(\frac{G\mathcal{M}}{c^2}\right)^{4/3}\left(\frac{\omega}{c}\right)^{1/3},$$

frequency

α_Q, α_D

$\alpha_V, \alpha_B, \alpha_L$

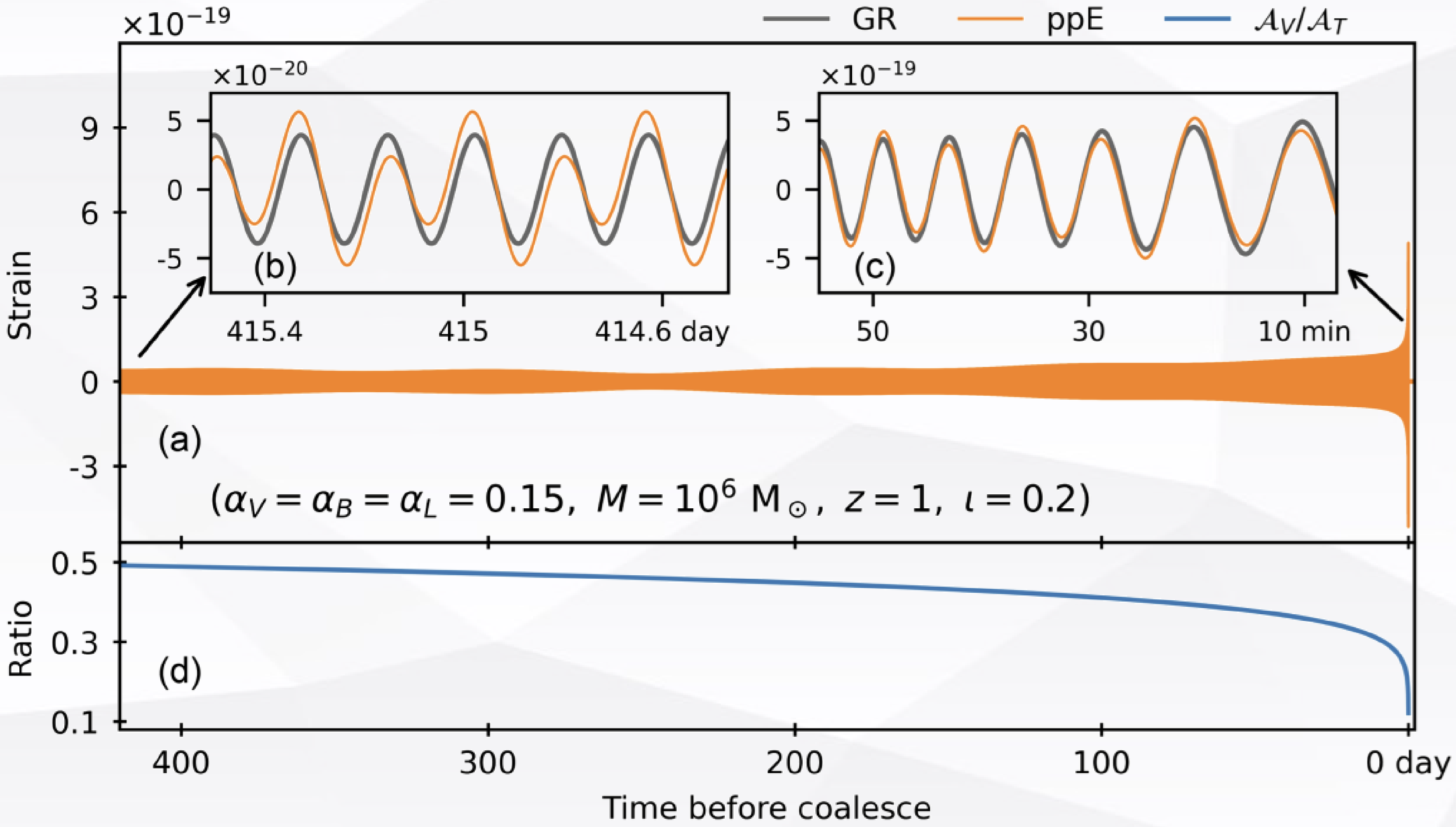
amplitude

ppE parameters

L. O'Beirne et al. 2019; C. Liu et al. 2020

- **GW waveform**

Comparison of **GR** and **ppE** frameworks



The **current** observations of GW events are **transient**

LIGO & Virgo 2023

Quadrupole

Tensor

Dipole

Vector, Scalar

Assumption

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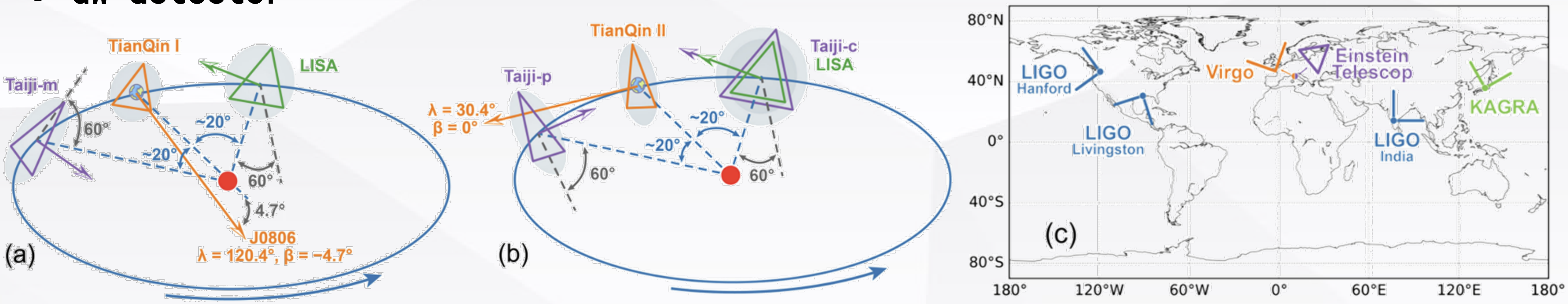
- GW detector



Space

- **LISA** P. Amaro-Seoane et al. 2017
- **Taiji p/c/m** G. Wang et al. 2021
- **TianQin I/II** S.-J. Huang et al. 2020

Ground

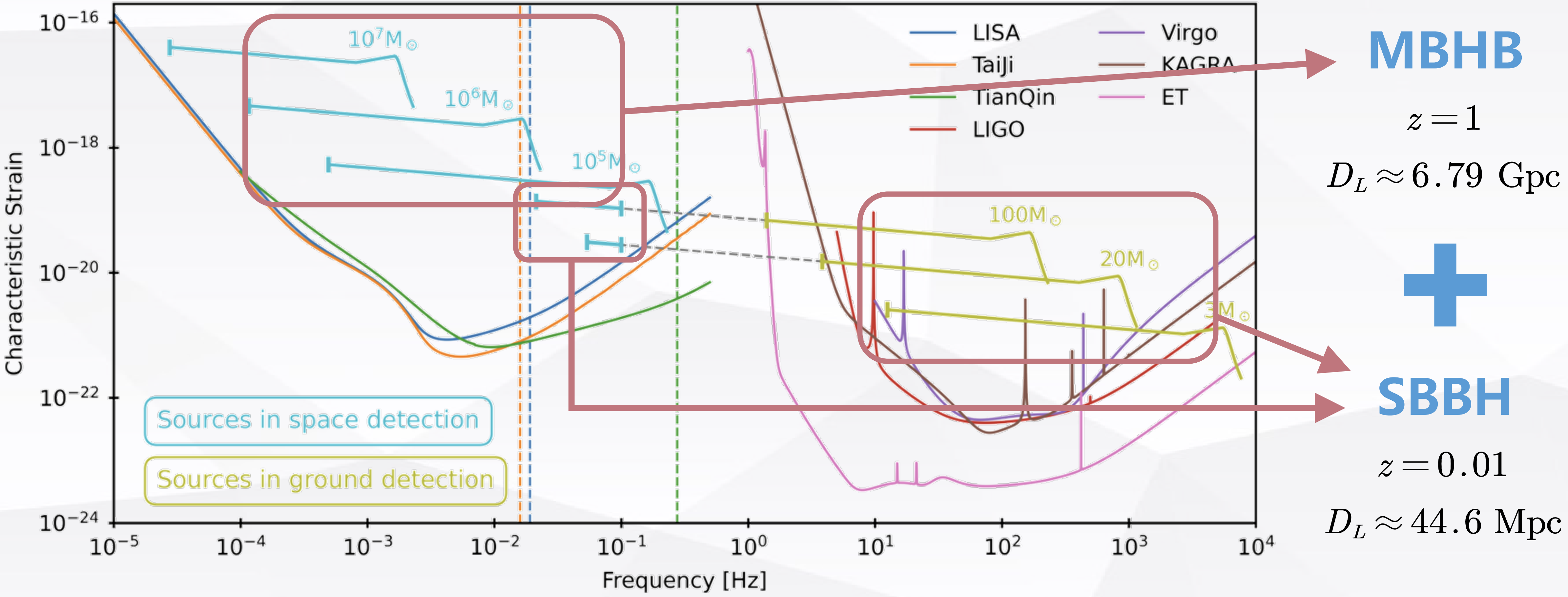
- **LIGO** J. Aasi et al. 2015
- **Virgo** F. Acernese et al. 2015
- **KAGRA** K. Somiya et al. 2012
- **ET** M. Punturo et al. 2010

On networks

R.-G. Cai et al. 2023; J. Wu & J. Li 2023

- **GW source**

Multiband observation of BBHs



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- Data analysis

14 parameters

$$\xi = \{t_c, m_1, m_2, D_L, \iota, \Phi_0, \phi_e, \theta_e, \psi, \alpha_Q, \alpha_D, \alpha_V, \alpha_B, \alpha_L\},$$

$$(a|b) = 4\mathrm{Re}\left[\int_0^\infty \frac{\tilde{a}^*(f)\tilde{b}(f)}{S_n(f)}\mathrm{d}f\right],$$

$$\rho^2 = (h|h), \qquad \Gamma_{ij} = \left(\frac{\partial h}{\partial \xi_i}\middle|\frac{\partial h}{\partial \xi_j}\right),$$

$$\Delta\xi_i = \sqrt{\Sigma_{ii}}.$$

SNR and **uncertainty**

$$f_{\mathrm{ISCO}} = \frac{c^3}{6\sqrt{6}\pi GM}.$$

0.1 Hz

90 days (space) → **MBHB**

10 min (ground) → **SBBH**

1 year (space) → **SBBH**

cut-off frequency and **duration**

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M. Vallisneri 2008; C. Liu et al. 2020

3 Constraints on parameters

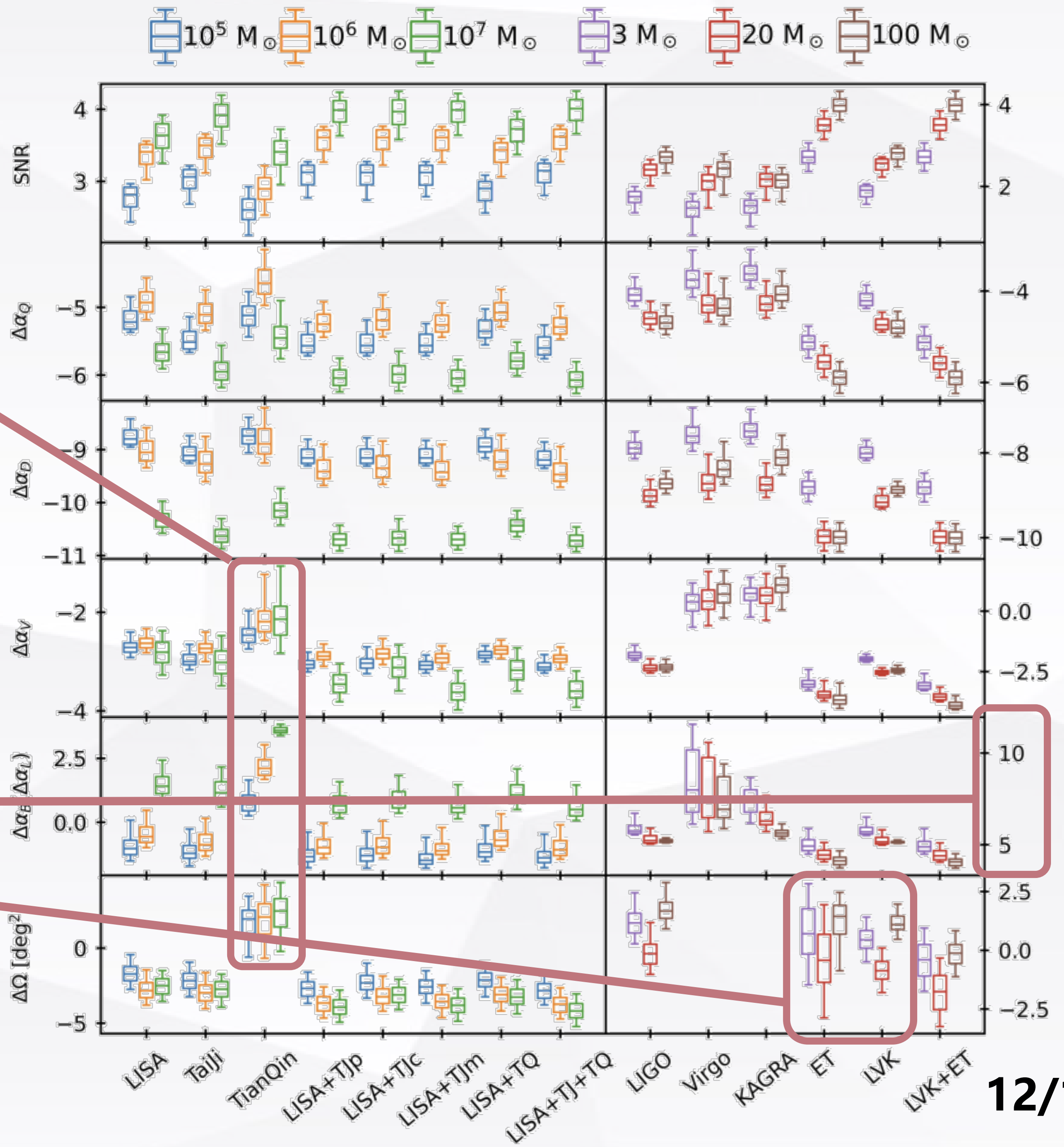
- Results with ppE parameters

Space

- Taiji>LISA>TianQin
- TianQin $\Delta\alpha_{V,B,L}, \Delta\Omega$ (configuration)
- $\Delta\alpha_{V,B,L}, \Delta\Omega$ better than ground
- LISA+TJm is the best

Ground

- ET>LIGO>KAGRA>Virgo
- Scalar mode degeneracy
- ET>LVK (except localization)
- LVK+ET improve localization



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3 Constraints on parameters

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- **Distance & multiband observation**

TABLE II. Proportional coefficient $\mathcal{K}$ corresponding to different ppE parameters. We use logarithmic $\log(\mathcal{K})$ to represent the results in the table.

Detector	$M[M_\odot]$	$\Delta\alpha_Q$	$\Delta\alpha_D$	$\Delta\alpha_V$	$\Delta\alpha_B(\alpha_L)$
LISA	10^5	−9.05	−12.63	−6.55	−4.86
	10^6	−8.76	−12.89	−6.46	−4.39
	10^7	−9.50	−14.17	−6.64	−2.42
TaiJi	10^5	−9.35	−12.94	−6.83	−5.05
	10^6	−8.94	−13.11	−6.57	−4.71
	10^7	−9.78	−14.46	−6.85	−2.68
TianQin	10^5	−8.95	−12.58	−6.30	−3.12
	10^6	−8.47	−12.73	−6.03	−1.72
	10^7	−9.28	−13.99	−5.97	−0.25
LIGO	3	−5.74	−9.54	−3.49	4.10
	20	−6.25	−10.67	−4.02	3.57
	100	−6.35	−10.38	−3.98	3.54
Virgo	3	−5.41	−9.26	−1.27	6.25
	20	−5.96	−10.38	−1.24	5.75
	100	−6.03	−10.04	−0.96	5.35
KAGRA	3	−5.28	−9.14	−0.92	5.76
	20	−5.94	−10.40	−1.01	4.61
	100	−5.73	−9.77	−0.58	3.97
ET	3	−6.77	−10.45	−4.68	3.24
	20	−7.20	−11.62	−5.13	2.79
	100	−7.54	−11.64	−5.32	2.46

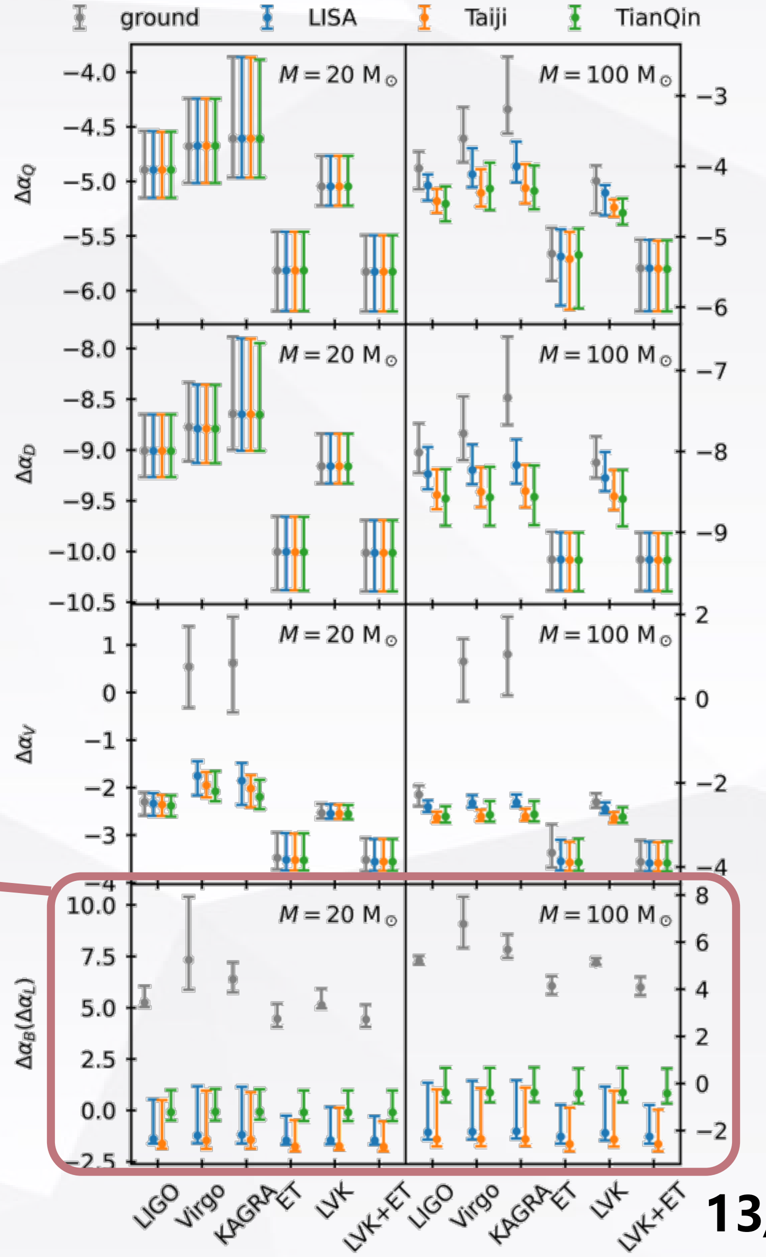
$$\Delta\xi(D_L) = \mathcal{K}D_L + \Delta\xi(0),$$

Distance

- **K: Space<ground**
- **Ground degeneracy**

Multiband

- **Resolve degeneracy**
- **improves outcomes (except ET)**



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4 Summary & outlook

- Summary

Space

- Taiji has the most stringent constraints
- LISA+TJm performs best

Ground

- Scalar mode degeneracy
- ET surpasses 2-gen detector combinations

Multiband

- Effectively mitigate degeneracy

- Outlook

Future

- Longer-duration GW signals
- Non light speed propagation
- Time-delay interferometry
- More general BBHs
- Existing GW events
- Multimessenger observations

Our findings underscore the potential of future GW missions through precise measurements of polarizations.

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THANKS

谢 谢 倾 听

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