Improving future gravitational-wave detectors using nondegenerate internal squeezing

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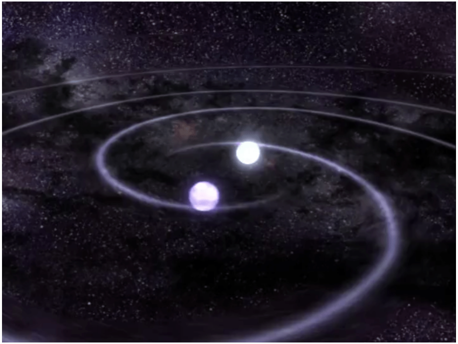
Motivation: kilohertz gravitational waves

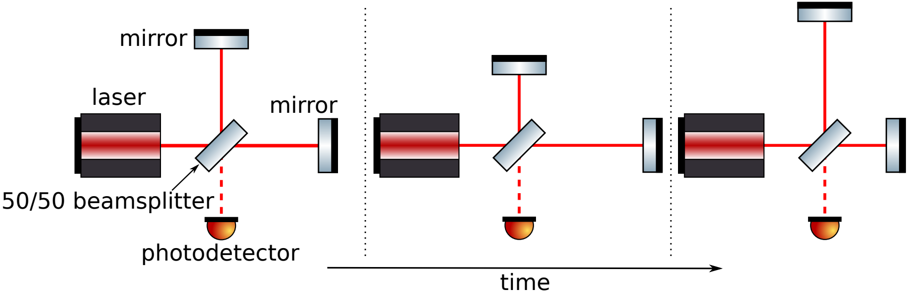


1. Neutron-star equation-of-state
2. Origin of low-mass black holes
3. Post-bounce dynamics of core-collapse supernovae
4. Primordial sources

video credit: [NASA/Goddard Space Flight Center, 2010]

Potential astrophysical science from [K. Ackley, V. B. Adya, and P. Agrawal et al., 2020, *Publ. Astron. Soc. Aust.*, 37]

Current gravitational-wave detectors



(top) image credit: [Christopher Berry, 2015], (bottom) [J. Aasi et al., 2015. *Class. Quantum Grav.*, 32:074001]

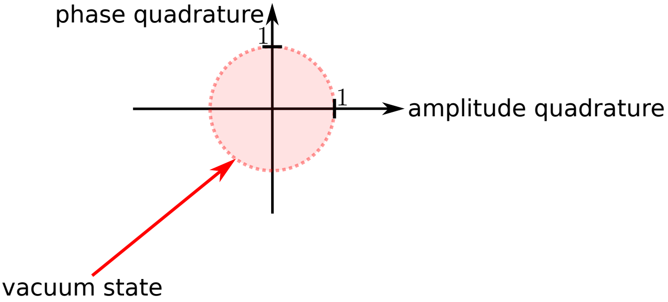
Goal: kilohertz sensitivity

$$\text{kilohertz sensitivity} \approx \frac{\text{signal response}}{\text{quantum phase noise}}$$

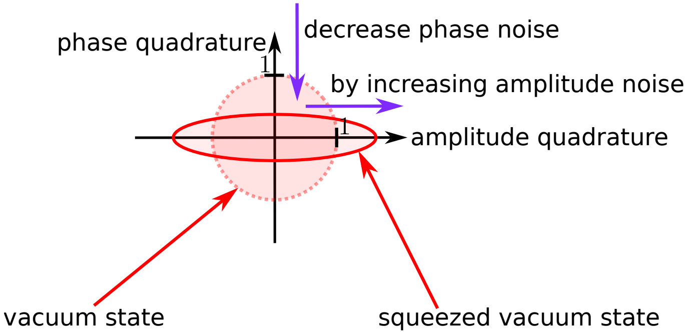
$$\uparrow \text{sensitivity} \Longleftarrow \Uparrow \text{signal} + \uparrow \text{noise}$$

using *nondegenerate internal squeezing*

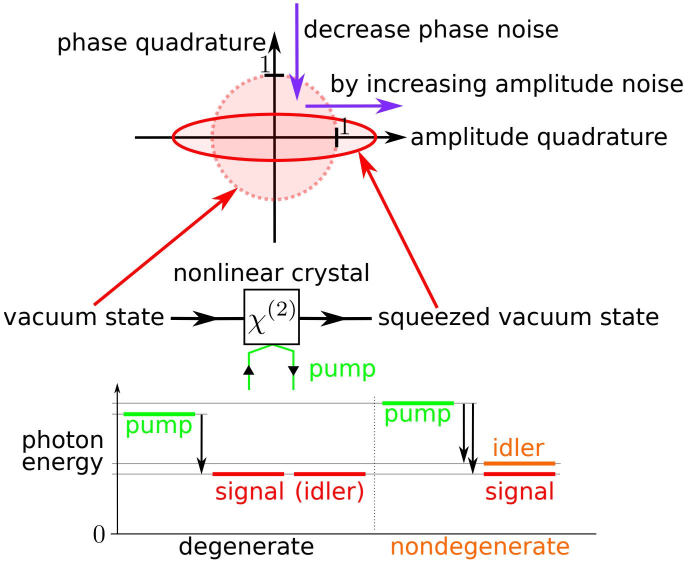
Quantum noise and squeezing



Quantum noise and squeezing

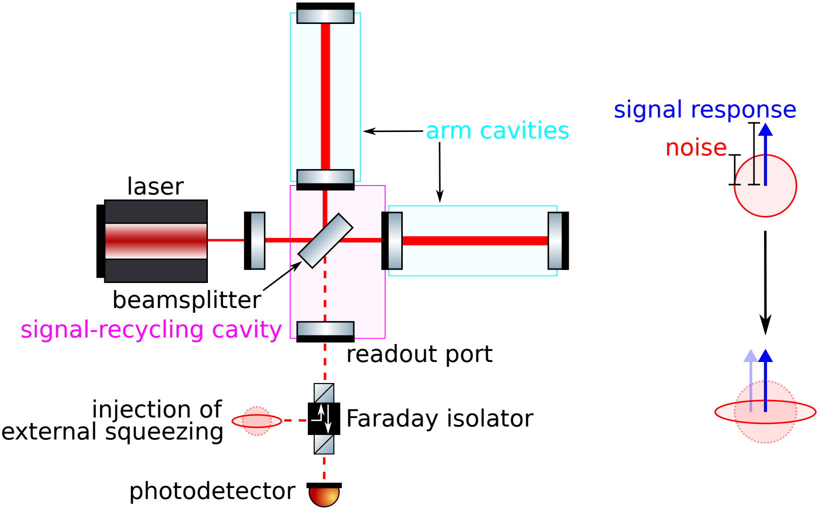


Quantum noise and squeezing



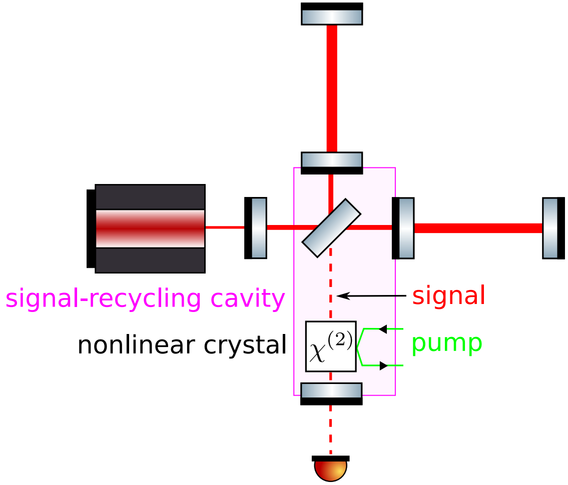
Review of squeezing for gravitational-wave detection in [S. L. Danilishin and F. Y. Khalili. 2012. *Living Rev. Relativ.*, 15(1):5.]

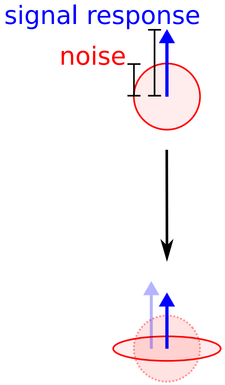
Cavities and external squeezing



External squeezing in LIGO from [M. Tse, H. Yu, N. Kijbunchoo, et al. 2019. *Phys. Rev. Lett.*, 123(23):231107.]

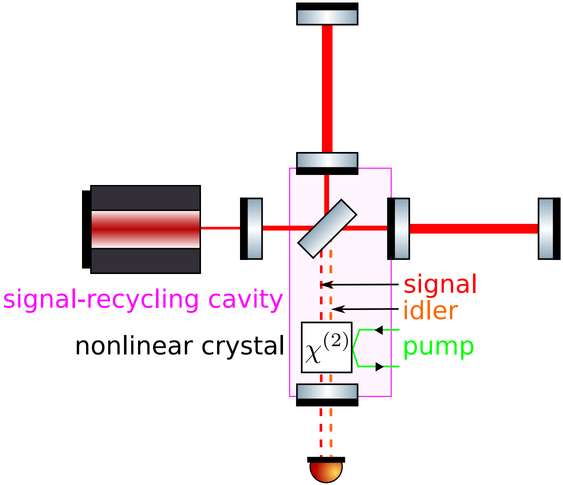
Degenerate internal squeezing

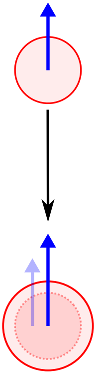




Degenerate internal squeezing from [M. Korobko, Y. Ma, Y. Chen, et al., 2019, *Light Sci. Appl.*, 8(1):118]

Nondegenerate internal squeezing





Methods

Analytic model of nondegenerate internal squeezing:

Hamiltonian

↓

Heisenberg-Langevin equations-of-motion

↓

Approximations, e.g. single-mode, reservoir pump

↓

Fourier transform, linear algebra

↓

measured quadratures

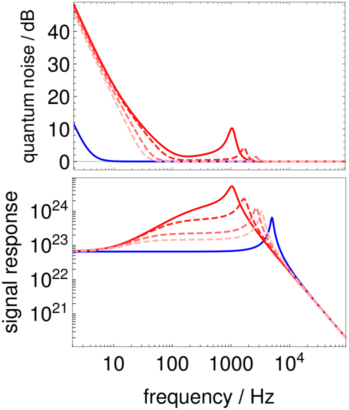
Lossless Hamiltonian from [X. Li, M. Goryachev, Y. Ma, et al., 2020, *arXiv:2012.00836 [quant-ph]*]

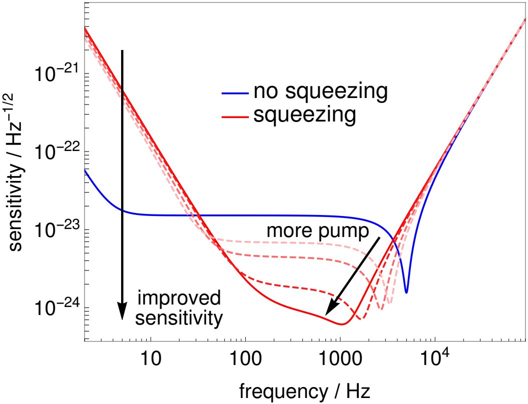
Results

1. Validation
2. Dynamical stability and squeezing threshold – a new method
3. **Characterisation of sensitivity**
4. **Tolerance to detection optical loss** and other losses
5. Comparison to optomechanical analogue
6. **Comparison to astrophysical kilohertz target**
7. **Idler readout scheme**

Optomechanical analogue from [X. Li, M. Goryachev, Y. Ma, et al., 2020, *arXiv:2012.00836 [quant-ph]*]

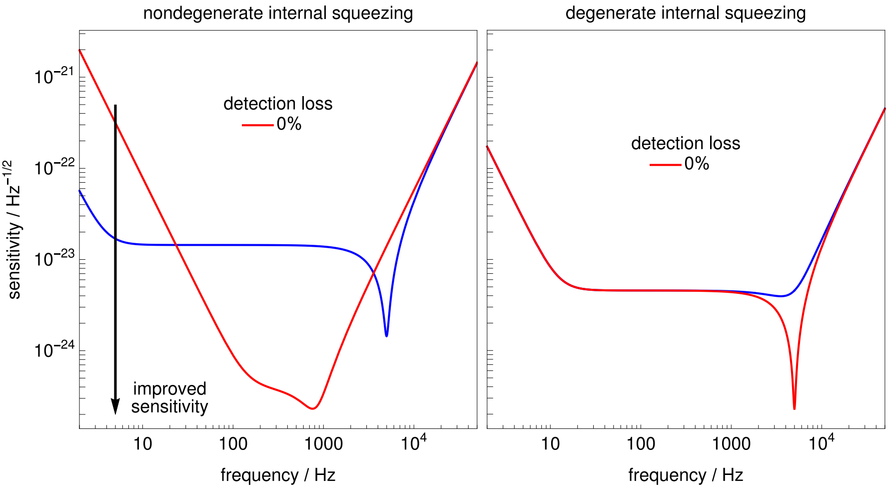
Characterisation of sensitivity





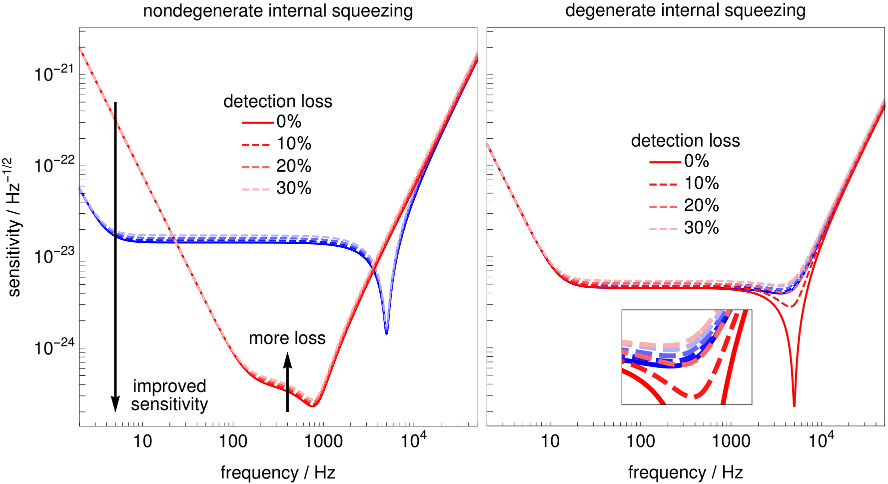
LIGO Voyager parameter set from [R. X. Adhikari, K. Arai, A. F. Brooks, et al. 2020. *Class. Quantum Grav.*, 37(16):165003.]

Tolerance to detection optical loss



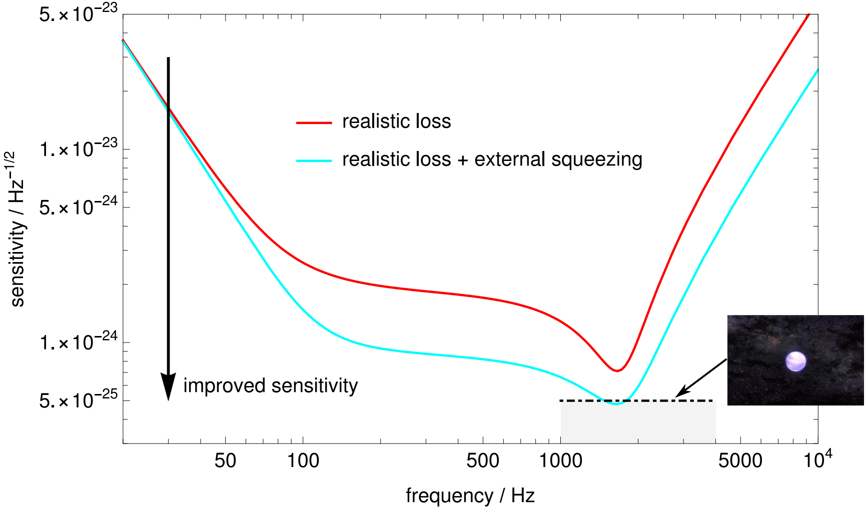
Degenerate internal squeezing model from [M. Korobko, Y. Ma, Y. Chen, et al., 2019, *Light Sci. Appl.*, 8(1):118]

Tolerance to detection optical loss



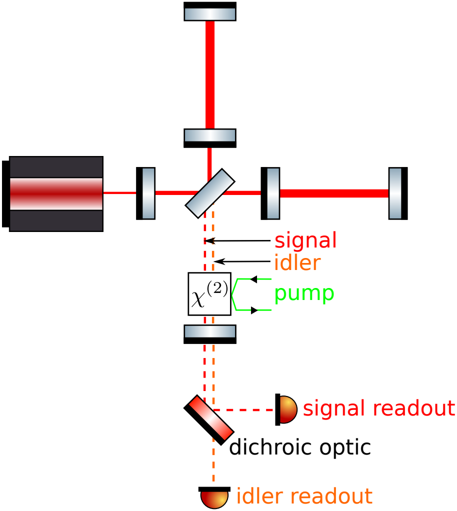
Degenerate internal squeezing model from [M. Korobko, Y. Ma, Y. Chen, et al., 2019, *Light Sci. Appl.*, 8(1):118]

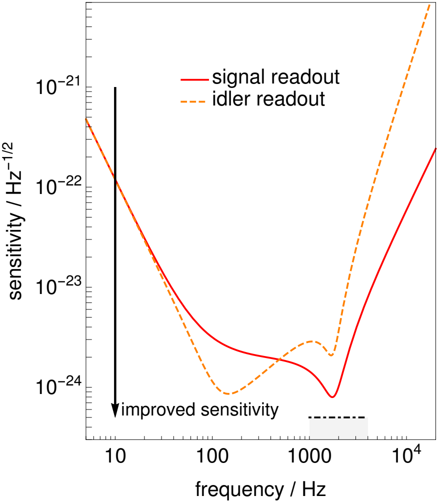
Comparison to astrophysical kilohertz target



Astrophysical target from [H. Miao, H. Yang, and D. Martynov., 2018, *Phys. Rev. D*, 98(4):044044]

Idler readout scheme





Future work

1. **Coherently combined readout scheme**
2. Extended model
   2.1 Analytic additions, e.g. pump depletion
   2.2 Numerical validation
   2.3 Parity-time symmetry – future collaboration
3. Experimental table-top demonstration

Conclusions

Nondegenerate internal squeezing

1. Detection loss–resistant, all-optical configuration
2. Well-characterised by analytic model
3. Can improve kilohertz (1–4 kHz) or broadband (0.1–4 kHz) sensitivity to gravitational waves

gravitational-wave detection $\Longrightarrow$ new physics!

Thank you, CGA!

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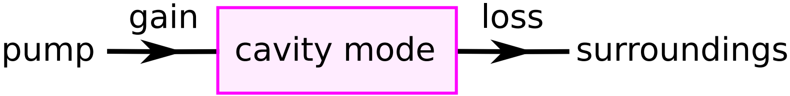
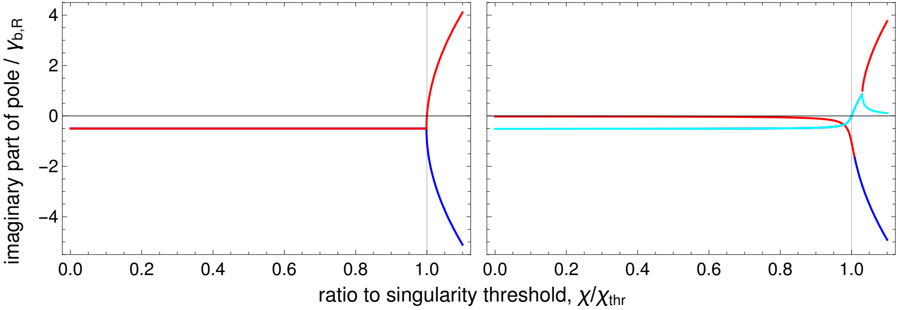
Threshold



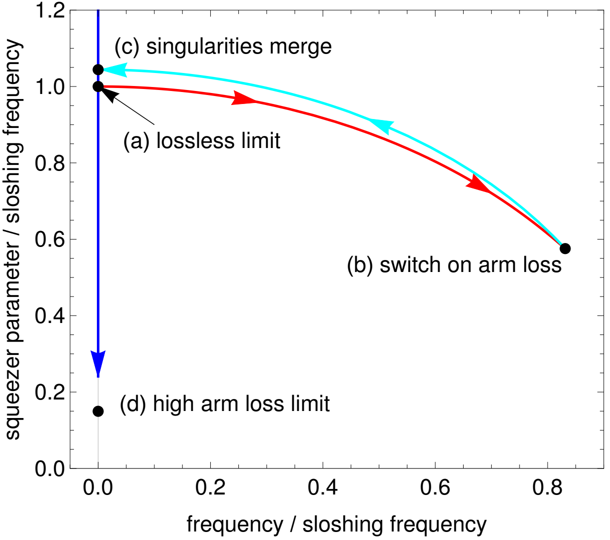
threshold: gain=loss

threshold + no pump depletion $\implies$ borderline unstable

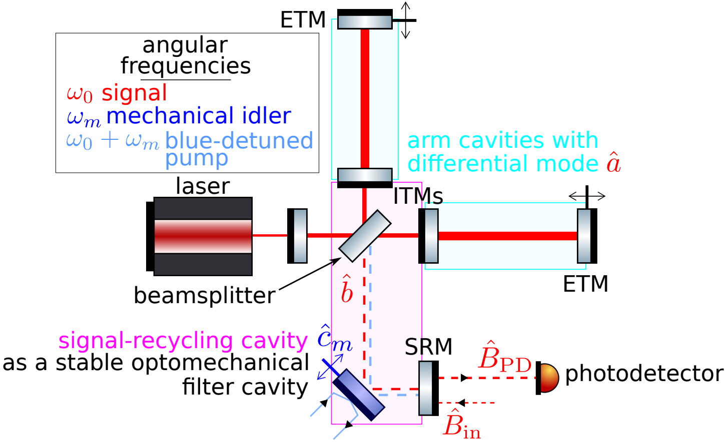
Stability of nondegenerate internal squeezing



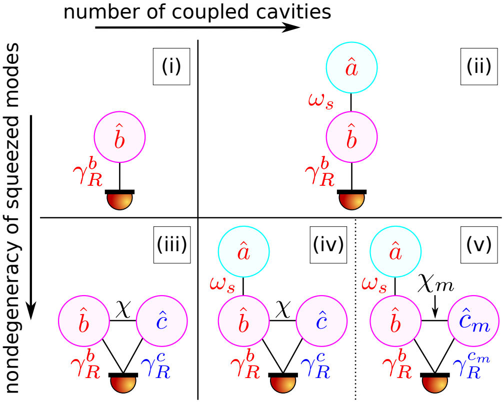
My method: threshold via stability



Stable optomechanical filtering

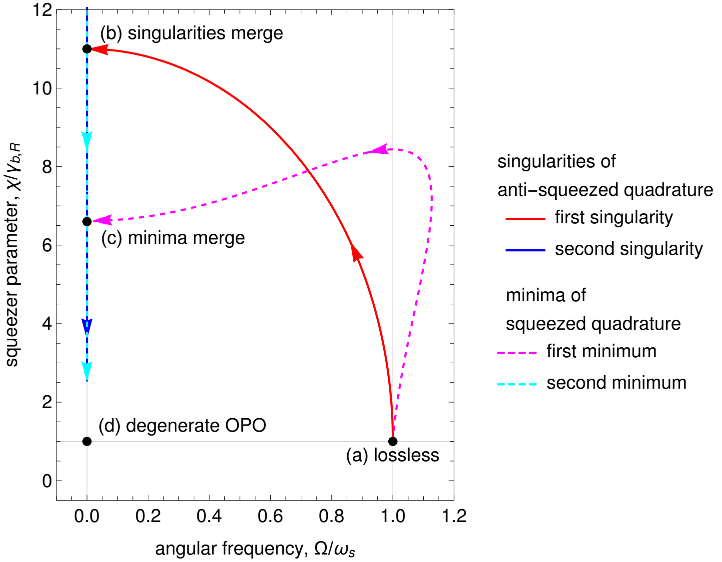


Abstract mode structure



(i) degenerate OPO
(ii) degenerate internal squeezing
(iii) nondegenerate OPO
(iv) nondegenerate internal squeezing
(v) stable optomechanical filtering

Threshold of degenerate internal squeezing



Parity-time (PT) symmetry

$$\hat{H}_I = i\hbar\omega_s(\hat{a}\hat{b}^\dagger - \hat{a}^\dagger\hat{b}) + i\hbar\chi(\hat{b}^\dagger\hat{c}^\dagger - \hat{b}\hat{c}) \qquad (1)$$

1. parity: $\hat{a} \leftrightarrow \hat{c}$
2. time: $\hat{a} \leftrightarrow \hat{a}^\dagger, \hat{c} \leftrightarrow \hat{c}^\dagger$
3. parity-time: $\hat{a} \mapsto \hat{c}^\dagger$ (and $\hat{b} \mapsto \hat{b}$)
4. $\hat{H}_I$ parity-time symmetric at $\omega_s = \chi$

LIGO Voyager parameters

carrier wavelength, λ_0	2 μm	signal mode transmissivity, $T_{\text{SRM},b}$	0.046
arm cavity length, L_{arm}	4 km	signal readout rate, γ_R^b	500 Hz
signal-recycling cavity length, L_{SRC}	1.124 km	idler mode transmissivity, $T_{\text{SRM},c}$	0
circulating arm power, P_{circ}	3 MW	idler readout rate, γ_R^c	0
test mass mass, M	200 kg	arm intra-cavity loss, $T_{l,a}$	100 ppm
input test mass transmissivity, T_{ITM}	0.197	signal mode intra-cavity loss, $T_{l,b}$	1000 ppm
sloshing frequency, ω_s	5 kHz	idler mode intra-cavity loss, $T_{l,c}$	1000 ppm
		detection loss, R_{PD}	10%

LIGO Voyager parameter set from [R. X. Adhikari, K. Arai, A. F. Brooks, et al. 2020. *Class. Quantum Grav.*, 37(16):165003.]