

ICFP 2026

Astrophysical Graviton Squeezing Can Be Hidden in the Far Field

Cheng-Jun Fang Zong-Kuan Guo Zhen-Hong Lyu
Jing Shu Yu-Heng Sun **Zi-Zheng Zhou**

Institute of Theoretical Physics, CAS

Based on arXiv:2608.17015

The International Conference on Fundamental Physics from Quanta to Cosmos
24–26 October 2026 | Yanqi Lake, Beijing

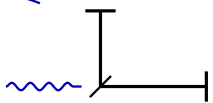
Quantum Gravity with Gravitational Waves

Gravitational-wave measurements are becoming more precise.

Can we probe gravity's quantum nature?

$$\hat{h}(t) \propto \hat{a}\, e^{-i\omega t} + \hat{a}^\dagger e^{i\omega t}$$

Quantum Nature



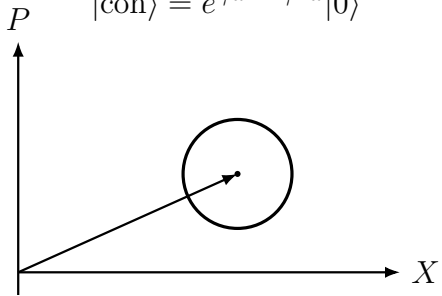
Gravitational-wave measurements

Can quantum properties enhance gravitational-wave detection?

Coherent and Squeezed States

Coherent state

$$|\mathrm{coh}\rangle = e^{\gamma \hat{a}^\dagger - \gamma^* \hat{a}}|0\rangle$$

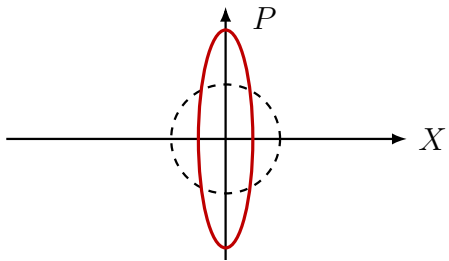


γ: displacement

Squeezed vacuum

$$|\mathrm{sq}\rangle = e^{\frac{s}{2}(\hat{a}^2 - \hat{a}^{\dagger 2})}|0\rangle$$

Wigner contours

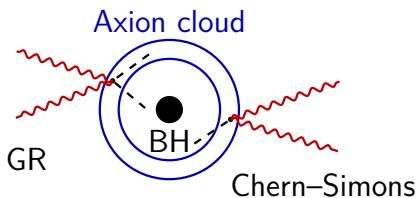


s: squeezing

Quantum optics: Yuen, Phys. Rev. A 13, 2226 (1976).

Astrophysical Sources of Squeezing

Superradiant axion cloud

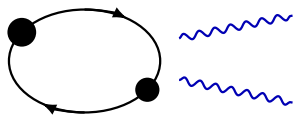


GR: $\varphi + \varphi \longrightarrow h + h$

CS: $\varphi \longrightarrow h + h$

Dorlis et al.
PRL 135, 151501 (2025).

Binary black-hole inspiral



Linear interaction: coherent state

Quadratic interaction: squeezing

Kanno, Soda & Taniguchi
PRL 136, 061404 (2026).

Quantifying Observable Squeezing

$\hat{E}_D^{(\pm)} = \partial_t \hat{h}_D^{(\pm)}$: radiation amplitude

$\hat{E}_D^{(+)} \propto \hat{b}_D, \quad \hat{E}_D^{(-)} \propto \hat{b}_D^\dagger$ $\hat{b}_D$: selected radiation mode

$$g^{(2)} = \frac{\langle \hat{E}_D^{(-)} \hat{E}_D^{(-)} \hat{E}_D^{(+)} \hat{E}_D^{(+)} \rangle}{\langle \hat{E}_D^{(-)} \hat{E}_D^{(+)} \rangle^2} = 2 + \frac{|M_D|^2}{N_D^2}$$

Zero: no pair coherence

Normal

$N_D = \langle \hat{E}_D^{(-)} \hat{E}_D^{(+)} \rangle \propto \langle \hat{b}_D^\dagger \hat{b}_D \rangle$

Intensity

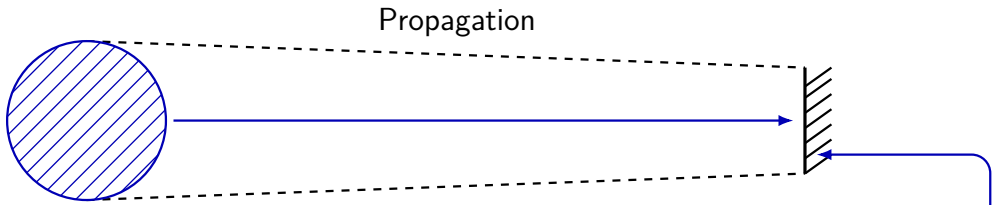
Anomalous

$M_D = \langle \hat{E}_D^{(+)} \hat{E}_D^{(+)} \rangle \propto \langle \hat{b}_D \hat{b}_D \rangle$

Pair coherence

Quantum optics: Glauber, Phys. Rev. 130, 2529 (1963).

Is Source Squeezing Visible in the Far Field?



Source squeezing

Propagation loss

Limited mode access

$\frac{|M_D|}{N_D}$ Received pair coherence relative to intensity

Quadratic Coupling and Bogoliubov Coefficients

Effective interaction

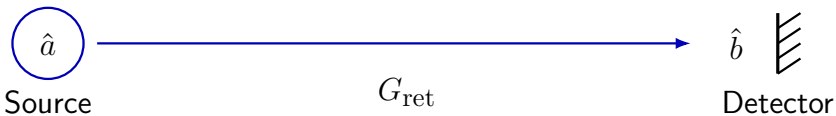
$$\hat{H}_{\rm int} \sim \int \mathrm{d}^3x\, \xi\, \hat{h}\hat{h}$$

ξ: GW source

Pair-production term

$$\hat{H}_{\rm pair} = \frac{1}{2}\int \mathrm{d}I\, \mathrm{d}J\, [\mathcal{F}_{IJ}(t)\hat{a}^\dagger_I \hat{a}^\dagger_J + \mathrm{h.c.}]$$

$\mathcal{F}$: pair source in momentum space



$$\hat{b}_I(t) = \int \mathrm{d}J\, [\alpha_{IJ}(t)\hat{a}_J + \beta_{IJ}(t)\hat{a}^\dagger_J]$$

$$\alpha = \mathbf{1} + \alpha_{\rm sc}, \qquad \alpha_{\rm sc}(-\infty) = \beta(-\infty) = 0$$

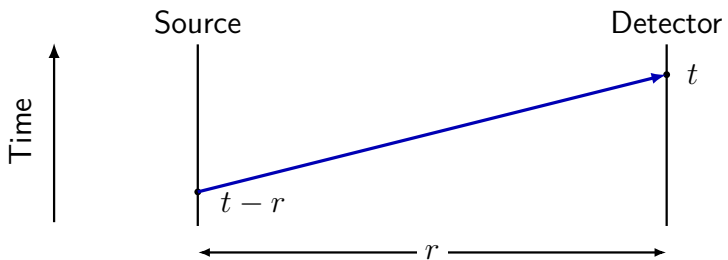
$$\dot{\beta} = -i\mathcal{F} - i\mathcal{F}\alpha^*_{\rm sc}, \qquad \dot{\alpha}_{\rm sc} = -i\mathcal{F}\beta^*$$

Finite-Time Evolution $\Rightarrow$ Retarded Propagator

Positive-frequency mode evolution

$$G_{\rm ret}(\omega,p) = -i\int_{-\infty}^{t} \mathrm{d}t'\, e^{i(\omega-p)(t-t')} = \frac{1}{\omega-p+i0}$$

$$= -i\pi\delta(\omega-p) + \mathrm{PV}\frac{1}{\omega-p}$$



Retarded Propagator: Outgoing Pole Selection

$$\begin{pmatrix} \alpha_{\rm sc} \\ \beta \end{pmatrix} = \int \frac{\mathrm{d}\omega}{2\pi} \frac{e^{-i(\omega-p)t}}{\omega - p + i0} \begin{pmatrix} \cdots \\ \cdots \end{pmatrix}$$

$$\hat{E}_D^{(+)}: \qquad \underbrace{e^{i\mathbf{p}\cdot\mathbf{x}}} \qquad \xrightarrow{\hat{\mathbf{p}}=\pm\hat{\mathbf{n}}} e^{\pm ipr}$$

Spatial Fourier phase

$$I_\pm = \int \mathrm{d}p \, \frac{\cdots e^{\pm ipr}}{\omega - p + i0}$$

Outgoing

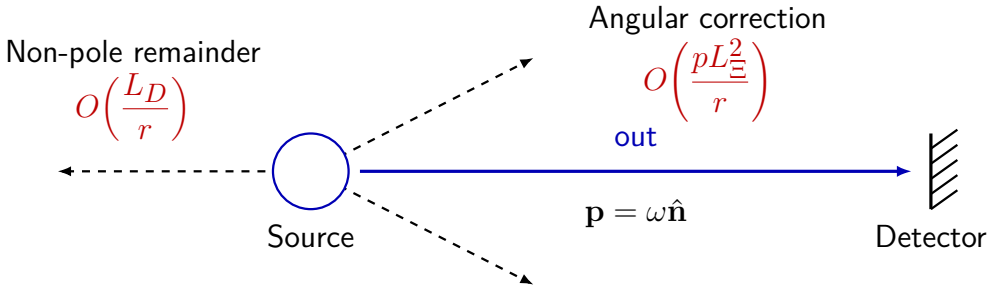
$$I_+^{\rm pole} \propto \underbrace{-i\pi}_{\delta} + \underbrace{(-i\pi)}_{\rm PV}$$

Incoming

$$I_-^{\rm pole} \propto \underbrace{-i\pi}_{\delta} + \underbrace{(+i\pi)}_{\rm PV} = 0$$

Leading far field: $p = \omega \implies \alpha_{\rm sc}^{\rm out},\ \beta^{\rm out}$

The Far Field Selects the Outgoing Packet



$$\hat{E}^{(+)}_{D;\omega,\lambda}(t, r\hat{\mathbf{n}}) \propto \frac{e^{-i\omega(t-r)}}{r}\,\hat{b}^{\text{out}}_{\mathbf{p},\lambda}$$

Source dynamics remains in $\hat{b}^{\text{out}}$: α^{out}, β^{out}.

Source Contributions to Bogoliubov Coefficients

$$\hat{b}_{\mathbf{p}} = \int \mathrm{d}^3 q \, [\alpha_{\mathbf{pq}} \hat{a}_{\mathbf{q}} + \beta_{\mathbf{pq}} \hat{a}^\dagger_{\mathbf{q}}]$$

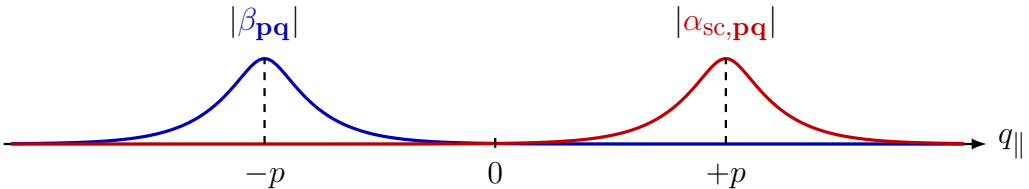
$$\mathcal{F}_{\mathbf{pq}} \propto \widetilde{\xi}(\mathbf{p}+\mathbf{q}), \qquad |\mathbf{p}+\mathbf{q}| \lesssim k_* \ll |\mathbf{p}|$$

β: pair production

$$\mathbf{p} \xrightarrow{\mathcal{F}} \mathbf{q} \simeq -\mathbf{p}$$

α_{sc}: mode scattering

$$\mathbf{p} \xrightarrow{\mathcal{F}} \boldsymbol{\ell} \simeq -\mathbf{p} \xrightarrow{\mathcal{F}^*} \mathbf{q} \simeq +\mathbf{p}$$



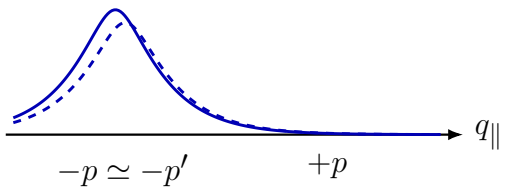
$\mathbf{p}$: detected mode; $\mathbf{q}$: input mode; $\mathbf{p}+\mathbf{q}$: source momentum

Suppression from Overlap Mismatch

Vacuum input: only $\langle \hat{a}_{\mathbf{q}} \hat{a}^{\dagger}_{\mathbf{q}'} \rangle = \delta^3(\mathbf{q} - \mathbf{q}')$ survives.

Intensity N_D

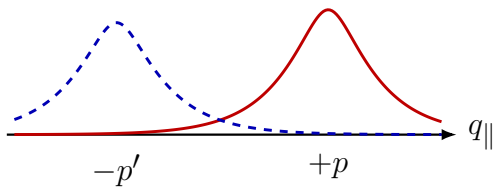
$$N_D \sim \int \mathrm{d}^3 q \, \beta^*_{\mathbf{pq}} \, \beta_{\mathbf{p}'\mathbf{q}}$$



Peaks overlap

Pair coherence M_D

$$M_D \sim \int \mathrm{d}^3 q \, \alpha_{\mathbf{pq}} \, \beta_{\mathbf{p}'\mathbf{q}}$$

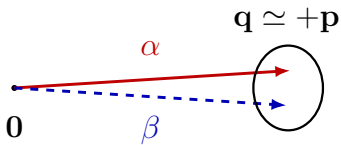


Only tails overlap

M_D is suppressed by the source form factor at $|\mathbf{p} + \mathbf{p}'| \simeq 2\omega \gg k_*$.

Behind the Overlap Mismatch

Aligned peaks

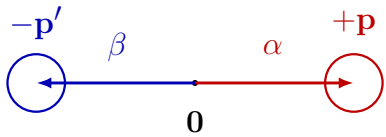


Large overlap

$|\mathbf{p}' + \mathbf{q}| \simeq 2\omega \gg k_*$

Large source momentum required

Opposite peaks



Small overlap

$|\mathbf{p}' + \mathbf{q}| \lesssim k_*$

Natural for an NR source

Shared input $\mathbf{q}$; fixed detected momenta $\mathbf{p} \simeq \mathbf{p}'$

Beyond Leading Order

Do the broadened tails restore the overlap?

$\mathcal{G} = -i \int \mathcal{F}(t)\, \mathrm{d}t$: integrated pair source

$$\beta^{\mathrm{out}} \simeq \mathcal{G} + \frac{\mathcal{G}\mathcal{G}^\dagger \mathcal{G}}{3!} + \cdots$$

$$\alpha_{\mathrm{sc}}^{\mathrm{out}} \simeq \frac{\mathcal{G}\mathcal{G}^\dagger}{2!} + \cdots$$

Odd chains: $\mathbf{q} \simeq -\mathbf{p}$

Pair production

Even chains: $\mathbf{q} \simeq +\mathbf{p}$

Mode scattering

Summation of Higher-Order Contributions

Higher orders retain the exponential momentum suppression.

$$\frac{|M_D|}{N_D} \lesssim \underbrace{e^{-c\mathcal{E}/k_*}}_{\text{Source tail}} \underbrace{\sqrt{1+\frac{1}{n_D}}}_{\text{Occupation}}$$

$$n_D \equiv \frac{N_D}{\mathcal{N}_D}$$

Selected-mode occupation

$\mathcal{N}_D$: wave-packet normalization

$$n_D \gtrsim 1 \quad \Longrightarrow \quad |M_D|/N_D = O(e^{-c\mathcal{E}/k_*})$$

c: source form-factor decay exponent after convolution.

$\mathcal{E}$: pair-momentum mismatch scale; k_*: source momentum width.

Quantitative, Conditional No-Go Criterion

Local production

$$\hat{H}_{\rm int} \sim \int \xi\, \hat{h}^2\, \mathrm{d}^3x$$

Far-field detector

$$r \gg L_D,\ \omega L_\Xi^2$$

Nonrelativistic source

$$k_* \ll \mathcal{E}$$

$$g^{(2)} - 2 = \frac{|M_D|^2}{N_D^2} \lesssim e^{-2c\mathcal{E}/k_*}\left(1 + \frac{1}{n_D}\right) + O\left(\frac{L_D + \omega L_\Xi^2}{r}\right)$$

$\mathcal{E} \simeq 2\omega$: pair-momentum mismatch; k_*: source momentum width; c: decay exponent.
L_Ξ: source scale; L_D: source + detector-window scale.
r: distance; n_D: selected-mode occupation.

Related Work: Tanaka and Collaborators

Miyauchi, Omiya, Ota, Takeda & Tanaka (2026)
arXiv:2608.08803

Global GW state $\xrightarrow[\text{Mode selection}]{}$ Accessible mode A $\xrightarrow[\text{Weak coupling}]{}$ Detector

A squeezed detector removes the need for squeezed incident GWs.

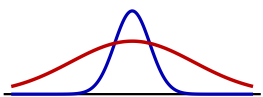
$$W_{\mathrm{det}}^{(Q)} < \tfrac{1}{2}\sin^2\epsilon$$

$W_{\mathrm{det}} = \frac{1}{2} - V_{\mathrm{min}}$ after removing initial detector squeezing.
V_{min}: minimum quadrature variance; ϵ: GW–detector coupling.

Discussion: Beyond the No-Go Conditions

Which changes could restore accessible pair coherence?

Different source



Relativistic source

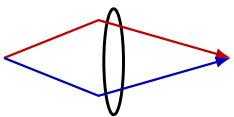
$k_* \sim \mathcal{E}$

Different modes



Access both partner directions

Different propagation



Coherent mixing of relevant modes

Thanks for Your Attention!

B1: Vacuum Contractions

$$\hat{b} = \alpha\hat{a} + \beta\hat{a}^\dagger, \qquad \hat{a}|0\rangle = 0$$

Vacuum input: $\langle \hat{a}\hat{a}^\dagger \rangle = 1$ is the only nonzero contraction.

$$n \equiv \langle \hat{b}^\dagger \hat{b} \rangle = |\alpha|^2 \underbrace{\langle \hat{a}^\dagger \hat{a} \rangle}_{0} + \alpha^* \beta \underbrace{\langle \hat{a}^\dagger \hat{a}^\dagger \rangle}_{0} + \beta^* \alpha \underbrace{\langle \hat{a}\hat{a} \rangle}_{0} + |\beta|^2 \underbrace{\langle \hat{a}\hat{a}^\dagger \rangle}_{1}$$

$$m \equiv \langle \hat{b}\hat{b} \rangle = \alpha^2 \underbrace{\langle \hat{a}\hat{a} \rangle}_{0} + \alpha\beta \underbrace{\langle \hat{a}\hat{a}^\dagger \rangle}_{1} + \beta\alpha \underbrace{\langle \hat{a}^\dagger \hat{a} \rangle}_{0} + \beta^2 \underbrace{\langle \hat{a}^\dagger \hat{a}^\dagger \rangle}_{0}$$

$$n_{\mathbf{pp'}} = \int \mathrm{d}^3 q \, \beta^*_{\mathbf{pq}} \beta_{\mathbf{p'q}}, \qquad m_{\mathbf{pp'}} = \int \mathrm{d}^3 q \, \alpha_{\mathbf{pq}} \beta_{\mathbf{p'q}}$$

B2: Wave-Packet Normalization

$$\hat{E}_D^{(+)} = \int \mathrm{d}I \, f_D(I) \hat{b}_I^{\mathrm{out}} = \sqrt{\mathcal{N}_D}\, \hat{b}_D$$

$$\mathcal{N}_D = \int \mathrm{d}I \, |f_D(I)|^2 = [\hat{E}_D^{(+)}, \hat{E}_D^{(-)}], \qquad [\hat{b}_D, \hat{b}_D^\dagger] = 1$$

f_D: frequency weight, polarization response, observation window and geometric amplitude in the selected radiation channel

$$n_D = \frac{N_D}{\mathcal{N}_D} = \langle \hat{b}_D^\dagger \hat{b}_D \rangle, \qquad m_D = \frac{M_D}{\mathcal{N}_D} = \langle \hat{b}_D \hat{b}_D \rangle$$

B3: Gain Resummation and Time Ordering

All gain powers are retained within the leading-Magnus model.

$$\alpha^{\mathrm{out}} \simeq \cosh\sqrt{\mathcal{G}\mathcal{G}^\dagger}, \qquad \beta^{\mathrm{out}} \simeq \mathcal{G}\,\frac{\sinh\sqrt{\mathcal{G}^\dagger\mathcal{G}}}{\sqrt{\mathcal{G}^\dagger\mathcal{G}}}$$

$\mathcal{G} = -i\int \mathcal{F}(t)\,\mathrm{d}t$: integrated pair source

$$\Omega_2 = \frac{1}{2}\int \mathrm{d}t_1 \int^{t_1} \mathrm{d}t_2\,[K(t_1), K(t_2)]$$

$K(t)$: Bogoliubov evolution generator; Ω_2: next Magnus term

B4: Finite-Band Tail Bound

$$|\mathcal{G}_{\mathbf{pq}}| \le G_0 e^{-d|\mathbf{p}+\mathbf{q}|/k_*}$$

An exponential source envelope is an input, not a consequence of locality alone.

$$|M_D| \le C_D C_{\mathrm{sq}} e^{-d'\mathcal{E}_D/k_*}$$

$$g^{(2)} - 2 \le \frac{C_D^2 C_{\mathrm{sq}}^2}{N_D^2} e^{-2d'\mathcal{E}_D/k_*}$$

$\mathcal{E}_D$: minimum pair-momentum mismatch in the selected band and cone

C_D: window projection; C_{sq}: gain and convolution bound