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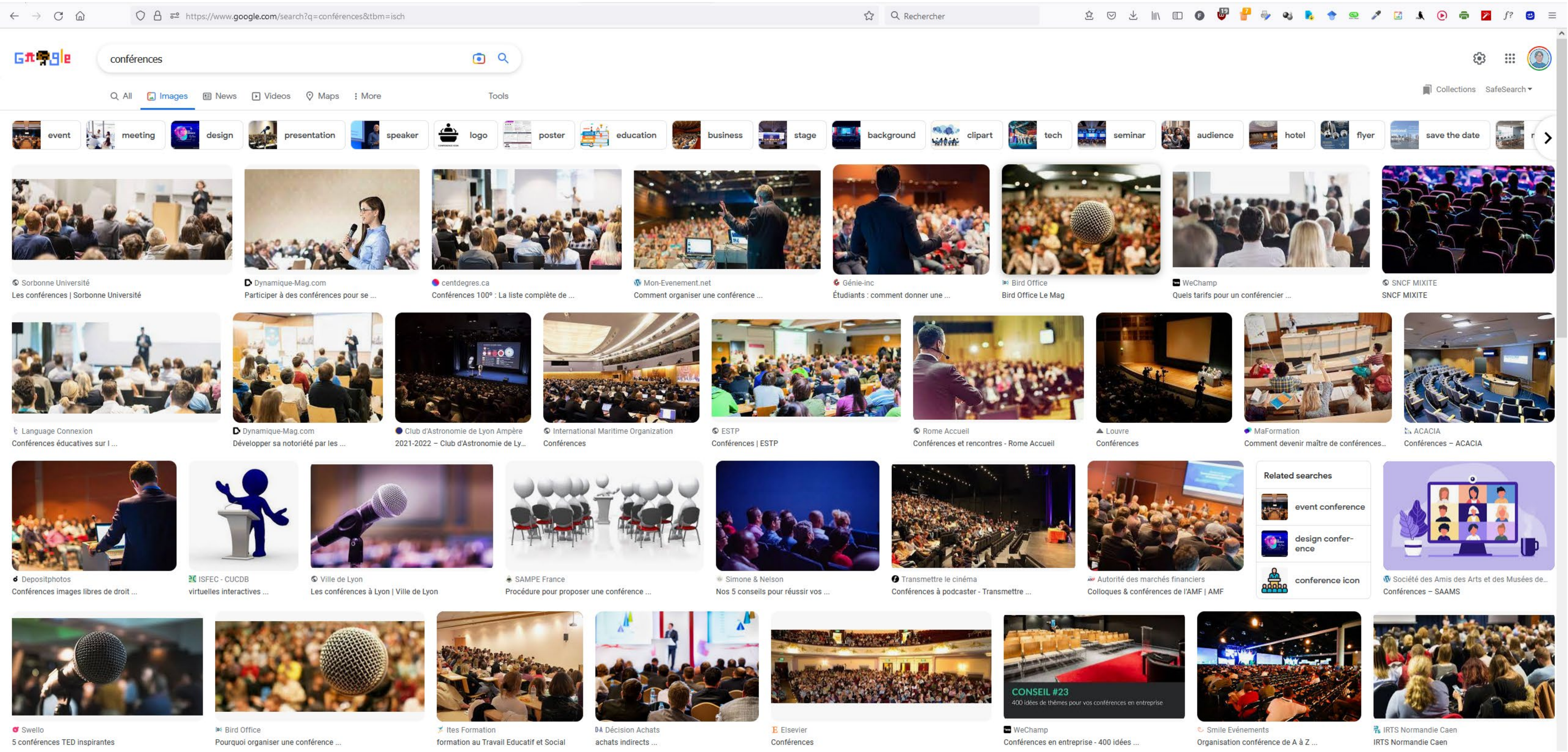

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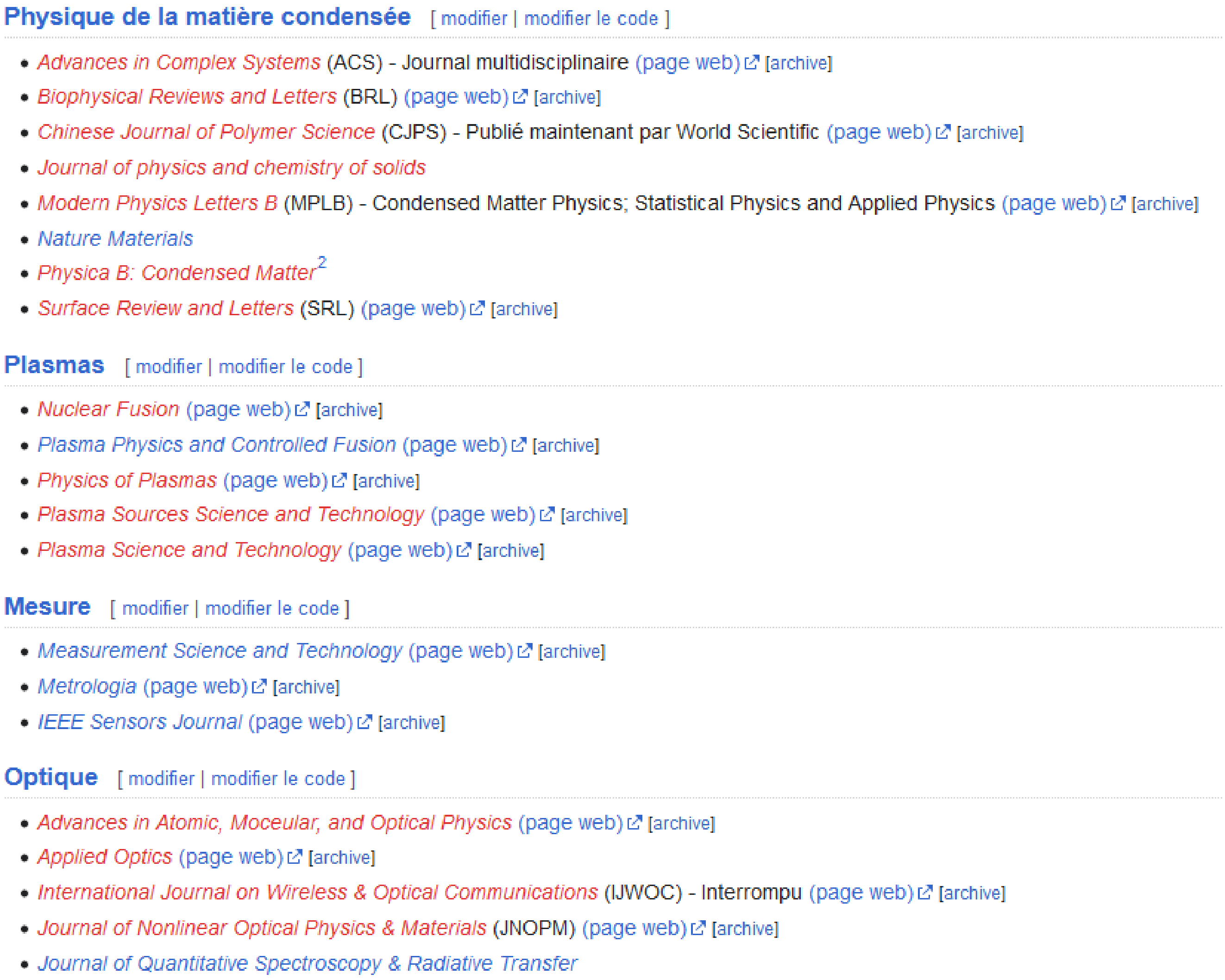

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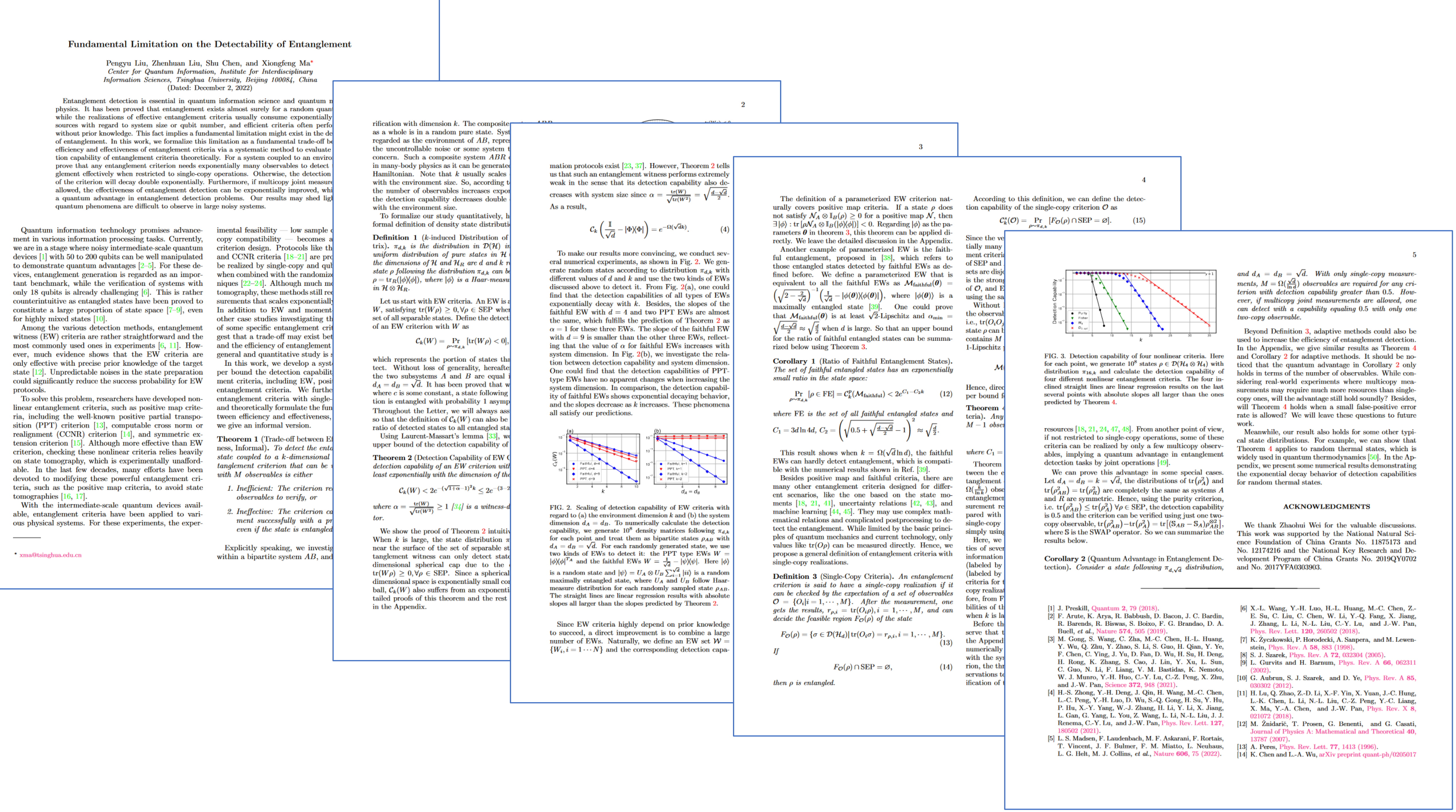

Fundamental Limitation on the Detectability of Entanglement

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Center for Quantum Information, Institute for Interdisciplinary
Information Sciences, Tsinghua University, Beijing 100084, China
(Dated: December 2, 2022)

Entanglement detection is essential in quantum information science and quantum m
physics. It has been proved that entanglement exists almost surely for a random quan
while the realizations of effective entanglement criteria usually consume exponentially
sources with regard to system size or qubit number, and efficient criteria often perfo
without prior knowledge. This fact implies a fundamental limitation might exist in the de
of entanglement. In this work, we formalize this limitation as a fundamental trade-off be
efficiency and effectiveness of entanglement criteria via a systematic method to evaluate
tion capability of entanglement criteria theoretically. For a system coupled to an enviro
prove that any entanglement criterion needs exponentially many observables to detect
glement effectively when restricted to single-copy operations. Otherwise, the detection
of the criterion will decay double exponentially. Furthermore, if multicopy joint measure
allowed, the effectiveness of entanglement detection can be exponentially improved, whi
a quantum advantage in entanglement detection problems. Our results may shed ligh
quantum phenomena are difficult to observe in large noisy systems.

Quantum information technology promises advancement in various information processing tasks. Currently, we are in a stage where noisy intermediate-scale quantum devices [1] with 50 to 200 qubits can be well manipulated to demonstrate quantum advantages [2–5]. For these devices, entanglement generation is regarded as an important benchmark, while the verification of systems with only 18 qubits is already challenging [6]. This is rather counterintuitive as entangled states have been proved to constitute a large proportion of state space [7–9], even for highly mixed states [10].

Among the various detection methods, entanglement witness (EW) criteria are rather straightforward and the most commonly used ones in experiments [6, 11]. However, much evidence shows that the EW criteria are only effective with precise prior knowledge of the target state [12]. Unpredictable noises in the state preparation could significantly reduce the success probability for EW protocols.

To solve this problem, researchers have developed nonlinear entanglement criteria, such as positive map criteria, including the well-known positive partial transposition (PPT) criterion [13], computable cross norm or realignment (CCNR) criterion [14], and symmetric extension criterion [15]. Although more effective than EW criterion, checking these nonlinear criteria relies heavily on state tomography, which is experimentally unaffordable. In the last few decades, many efforts have been devoted to modifying these powerful entanglement criteria, such as the positive map criteria, to avoid state tomographies [16, 17].

With the intermediate-scale quantum devices available, entanglement criteria have been applied to various physical systems. For these experiments, the exper-

imental feasibility — low sample c
copy compatibility — becomes a
criterion design. Protocols like th
and CCNR criteria [18–21] are pro
be realized by single-copy and qub
when combined with the randomize
niques [22–24]. Although much mo
tomography, these methods still req
surements that scales exponentially
In addition to EW and moment
other case studies investigating th
of some specific entanglement crit
gest that a trade-off may exist bet
and the efficiency of entanglement
general and quantitative study is s

In this work, we develop a syste
per bound the detection capabilit
ment criteria, including EW, posi
entanglement criteria. We furthe
entanglement criteria with single-
and theoretically formulate the fun
tween efficiency and effectiveness,
we give an informal version.

Theorem 1 (Trade-off between Ef
ness, Informal). *To detect the enta
state coupled to a k-dimensional
tanglement criterion that can be
with M observables is either*

1. *Inefficient: The criterion re
observables to verify, or*
2. *Ineffective: The criterion ca
ment successfully with a pr
even if the state is entangled*

Explicitly speaking, we investig
within a bipartite system AB, and

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[*] xma@tsinghua.edu.cn

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rification with dimension k. The composite
as a whole is in a random pure state. Syst
regarded as the environment of AB, repre
the uncontrollable noise or some system t
concern. Such a composite system ABR
in many-body physics as it can be generate
Hamiltonian. Note that k usually scales
with the environment size. So, according t
the number of observables increases expon
the detection capability decreases double
with the environment size.

To formalize our study quantitatively, h
formal definition of density state distributi

Definition 1 (k-induced Distribution of
trix). *$\pi_{d,k}$ is the distribution in $\mathcal{D}(\mathcal{H})$ in
uniform distribution of pure states in $\mathcal{H}$
the dimensions of $\mathcal{H}$ and $\mathcal{H}_R$ are d and k r
state ρ following the distribution $\pi_{d,k}$ can be
$\rho = \mathrm{tr}_R(|\phi\rangle\langle\phi|)$, where $|\phi\rangle$ is a Haar-measu
in $\mathcal{H}\otimes\mathcal{H}_R$.*

Let us start with EW criteria. An EW is a
W, satisfying $\mathrm{tr}(W\rho) \geq 0, \forall\rho \in \mathrm{SEP}$ wher
set of all separable states. Define the detecti
of an EW criterion with W as

$$\mathcal{C}_k(W) = \Pr_{\rho\sim\pi_{d,k}} [\mathrm{tr}(W\rho) < 0],$$

which represents the portion of states tha
tect. Without loss of generality, hereafte
the two subsystems A and B are equal i
$d_A = d_B = \sqrt{d}$. It has been proved that w
where c is some constant, a state following
tion is entangled with probability 1 asymp
Throughout the Letter, we will always ass
so that the definition of $\mathcal{C}_k(W)$ can also be
ratio of detected states to all entangled sta

Using Laurent-Massart's lemma [33], w
upper bound of the detection capability of

Theorem 2 (Detection Capability of EW C
*detection capability of an EW criterion wit
least exponentially with the dimension of th*

$$\mathcal{C}_k(W) < 2e^{-(\sqrt{1+\alpha}-1)^2 k} \leq 2e^{-(3-2$$

*where $\alpha = \frac{\mathrm{tr}(W)}{\sqrt{\mathrm{tr}(W^2)}} \geq 1$ [34] is a witness-d
tor.*

We show the proof of Theorem 2 intuitiv
When k is large, the state distribution π
near the surface of the set of separable st
tanglement witness can only detect state
dimensional spherical cap due to the
$\mathrm{tr}(W\rho) \geq 0, \forall\rho \in \mathrm{SEP}$. Since a spherical
dimensional space is exponentially small co
ball, $\mathcal{C}_k(W)$ also suffers from an exponenti
tailed proofs of this theorem and the rest
in the Appendix.

---

mation protocols exist [23, 37]. However, Theorem 2 tells us that such an entanglement witness performs extremely weak in the sense that its detection capability also decreases with system size since $\alpha = \frac{\mathrm{tr}(W)}{\sqrt{\mathrm{tr}(W^2)}} = \sqrt{\frac{d-\sqrt{d}}{2}}$. As a result,

$$\mathcal{C}_k\left(\frac{\mathbb{I}}{\sqrt{d}} - |\Phi\rangle\langle\Phi|\right) = e^{-\Omega(\sqrt{d}k)}. \quad (4)$$

To make our results more convincing, we conduct several numerical experiments, as shown in Fig. 2. We generate random states according to distribution $\pi_{d,k}$ with different values of d and k and use the two kinds of EWs discussed above to detect it. From Fig. 2(a), one could find that the detection capabilities of all types of EWs exponentially decay with k. Besides, the slopes of the faithful EW with $d = 4$ and two PPT EWs are almost the same, which fulfills the prediction of Theorem 2 as $\alpha = 1$ for these three EWs. The slope of the faithful EW with $d = 9$ is smaller than the other three EWs, reflecting that the value of α for faithful EWs increases with system dimension. In Fig. 2(b), we investigate the relation between detection capability and system dimension. One could find that the detection capabilities of PPT-type EWs have no apparent changes when increasing the system dimension. In comparison, the detection capability of faithful EWs shows exponential decaying behavior, and the slopes decrease as k increases. These phenomena all satisfy our predictions.

FIG. 2. Scaling of detection capability of EW criteria with regard to (a) the environment dimension k and (b) the system dimension $d_A = d_B$. To numerically calculate the detection capability, we generate 10^8 density matrices following $\pi_{d,k}$ for each point and treat them as bipartite states ρ_{AB} with $d_A = d_B = \sqrt{d}$. For each randomly generated state, we use two kinds of EWs to detect it: the PPT type EWs $W = |\phi\rangle\langle\phi|^{T_A}$ and the faithful EWs $W = \frac{\mathbb{I}}{\sqrt{d}} - |\psi\rangle\langle\psi|$. Here $|\phi\rangle$ is a random state and $|\psi\rangle = U_A \otimes U_B \sum_{i=1}^{\sqrt{d}} |ii\rangle$ is a random maximally entangled state, where U_A and U_B follow Haar-measure distribution for each randomly sampled state ρ_{AB}. The straight lines are linear regression results with absolute slopes all larger than the slopes predicted by Theorem 2.

Since EW criteria highly depend on prior knowledge to succeed, a direct improvement is to combine a large number of EWs. Naturally, we define an EW set $\mathcal{W} = \{W_i, i = 1\cdots N\}$ and the corresponding detection capa-

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The definition of a parameterized EW criterion naturally covers positive map criteria. If a state ρ does not satisfy $\mathcal{N}_A \otimes \mathbb{I}_B(\rho) \geq 0$ for a positive map $\mathcal{N}$, then $\exists\,|\phi\rangle : \mathrm{tr}\,[\rho\mathcal{N}_A \otimes \mathbb{I}_B(|\phi\rangle\langle\phi|)] < 0$. Regarding $|\phi\rangle$ as the parameters $\boldsymbol{\theta}$ in theorem 3, this theorem can be applied directly. We leave the detailed discussion in the Appendix.

Another example of parameterized EW is the faithful entanglement, proposed in [38], which refers to those entangled states detected by faithful EWs as defined before. We define a parameterized EW that is equivalent to all the faithful EWs as $\mathcal{M}_{\mathrm{faithful}}(\boldsymbol{\theta}) = \left(\sqrt{2 - \frac{2}{\sqrt{d}}}\right)^{-1}\left(\frac{\mathbb{I}}{\sqrt{d}} - |\phi(\boldsymbol{\theta})\rangle\langle\phi(\boldsymbol{\theta})|\right)$, where $|\phi(\boldsymbol{\theta})\rangle$ is a maximally entangled state [39]. One could prove that $\mathcal{M}_{\mathrm{faithful}}(\boldsymbol{\theta})$ is at least $\sqrt{2}$-Lipschitz and $\alpha_{\min} = \sqrt{\frac{d-\sqrt{d}}{2}} \approx \sqrt{\frac{d}{2}}$ when d is large. So that an upper bound for the ratio of faithful entangled states can be summarized below using Theorem 3.

Corollary 1 (Ratio of Faithful Entanglement States). *The set of faithful entangled states has an exponentially small ratio in the state space:*

$$\Pr_{\rho\sim\pi_{d,k}} [\rho \in \mathrm{FE}] = \mathcal{C}_k^p(\mathcal{M}_{\mathrm{faithful}}) < 2e^{C_1 - C_2 k} \quad (12)$$

where FE *is the set of all faithful entangled states and* $C_1 = 3d\ln 4d$, $C_2 = \left(\sqrt{0.5 + \sqrt{\frac{d-\sqrt{d}}{2}}} - 1\right)^2 \approx \sqrt{\frac{d}{2}}$.

This result shows when $k = \Omega(\sqrt{d}\ln d)$, the faithful EWs can hardly detect entanglement, which is compatible with the numerical results shown in Ref. [39].

Besides positive map and faithful criteria, there are many other entanglement criteria designed for different scenarios, like the one based on the state moments [18, 21, 41], uncertainty relations [42, 43], and machine learning [44, 45]. They may use complex mathematical relations and complicated postprocessing to detect the entanglement. While limited by the basic principles of quantum mechanics and current technology, only values like $\mathrm{tr}(O\rho)$ can be measured directly. Hence, we propose a general definition of entanglement criteria with single-copy realizations.

Definition 3 (Single-Copy Criteria). *An entanglement criterion is said to have a single-copy realization if it can be checked by the expectation of a set of observables $\mathcal{O} = \{O_i | i = 1, \cdots, M\}$. After the measurement, one gets the results, $r_{\rho,i} = \mathrm{tr}(O_i\rho), i = 1, \cdots, M$, and can decide the feasible region $F_{\mathcal{O}}(\rho)$ of the state*

$$F_{\mathcal{O}}(\rho) = \{\sigma \in \mathcal{D}(\mathcal{H}_d) |\, \mathrm{tr}(O_i\sigma) = r_{\rho,i}, i = 1, \cdots, M\}. \quad (13)$$

If

$$F_{\mathcal{O}}(\rho) \cap \mathrm{SEP} = \varnothing, \quad (14)$$

then ρ is entangled.

According to this definition, we can define the detection capability of the single-copy criterion $\mathcal{O}$ as

$$\mathcal{C}_k^s(\mathcal{O}) = \Pr_{\rho\sim\pi_{d,k}} [F_{\mathcal{O}}(\rho) \cap \mathrm{SEP} = \varnothing]. \quad (15)$$

Since the ve
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Theorem 4
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FIG. 3. Detection capability of four nonlinear criteria. Here for each point, we generate 10^8 states $\rho \in \mathcal{D}(\mathcal{H}_4 \otimes \mathcal{H}_4)$ with distribution $\pi_{16,k}$ and calculate the detection capability of four different nonlinear entanglement criteria. The four inclined straight lines are linear regression results on the last several points with absolute slopes all larger than the ones predicted by Theorem 4.

resources [18, 21, 24, 47, 48]. From another point of view, if not restricted to single-copy operations, some of these criteria can be realized by only a few multicopy observables, implying a quantum advantage in entanglement detection tasks by joint operations [49].

We can prove this advantage in some special cases. Let $d_A = d_B = k = \sqrt{d}$, the distributions of $\mathrm{tr}(\rho_A^2)$ and $\mathrm{tr}(\rho_{AB}^2) = \mathrm{tr}(\rho_R^2)$ are completely the same as systems A and R are symmetric. Hence, using the purity criterion, i.e. $\mathrm{tr}(\rho_{AB}^2) \leq \mathrm{tr}(\rho_A^2)\ \forall\rho \in \mathrm{SEP}$, the detection capability is 0.5 and the criterion can be verified using just one two-copy observable, $\mathrm{tr}(\rho_{AB}^2) - \mathrm{tr}(\rho_A^2) = \mathrm{tr}[(\mathbb{S}_{AB} - \mathbb{S}_A)\rho_{AB}^{\otimes 2}]$, where $\mathbb{S}$ is the SWAP operator. So we can summarize the results below.

Corollary 2 (Quantum Advantage in Entanglement Detection). *Consider a state following $\pi_{d,\sqrt{d}}$ distribution, and $d_A = d_B = \sqrt{d}$. With only single-copy measurements, $M = \Omega(\frac{\sqrt{d}}{\ln d})$ observables are required for any criterion with detection capability greater than 0.5. However, if multicopy joint measurements are allowed, one can detect with a capability equaling 0.5 with only one two-copy observable.*

Beyond Definition 3, adaptive methods could also be used to increase the efficiency of entanglement detection. In the Appendix, we give similar results as Theorem 4 and Corollary 2 for adaptive methods. It should be noticed that the quantum advantage in Corollary 2 only holds in terms of the number of observables. While considering real-world experiments where multicopy measurements may require much more resources than single-copy ones, will the advantage still hold soundly? Besides, will Theorem 4 holds when a small false-positive error rate is allowed? We will leave these questions to future work.

Meanwhile, our result also holds for some other typical state distributions. For example, we can show that Theorem 4 applies to random thermal states, which is widely used in quantum thermodynamics [50]. In the Appendix, we present some numerical results demonstrating the exponential decay behavior of detection capabilities for random thermal states.

ACKNOWLEDGMENTS

We thank Zhaohui Wei for the valuable discussions. This work was supported by the National Natural Science Foundation of China Grants No. 11875173 and No. 12174216 and the National Key Research and Development Program of China Grants No. 2019QY0702 and No. 2017YFA0303903.

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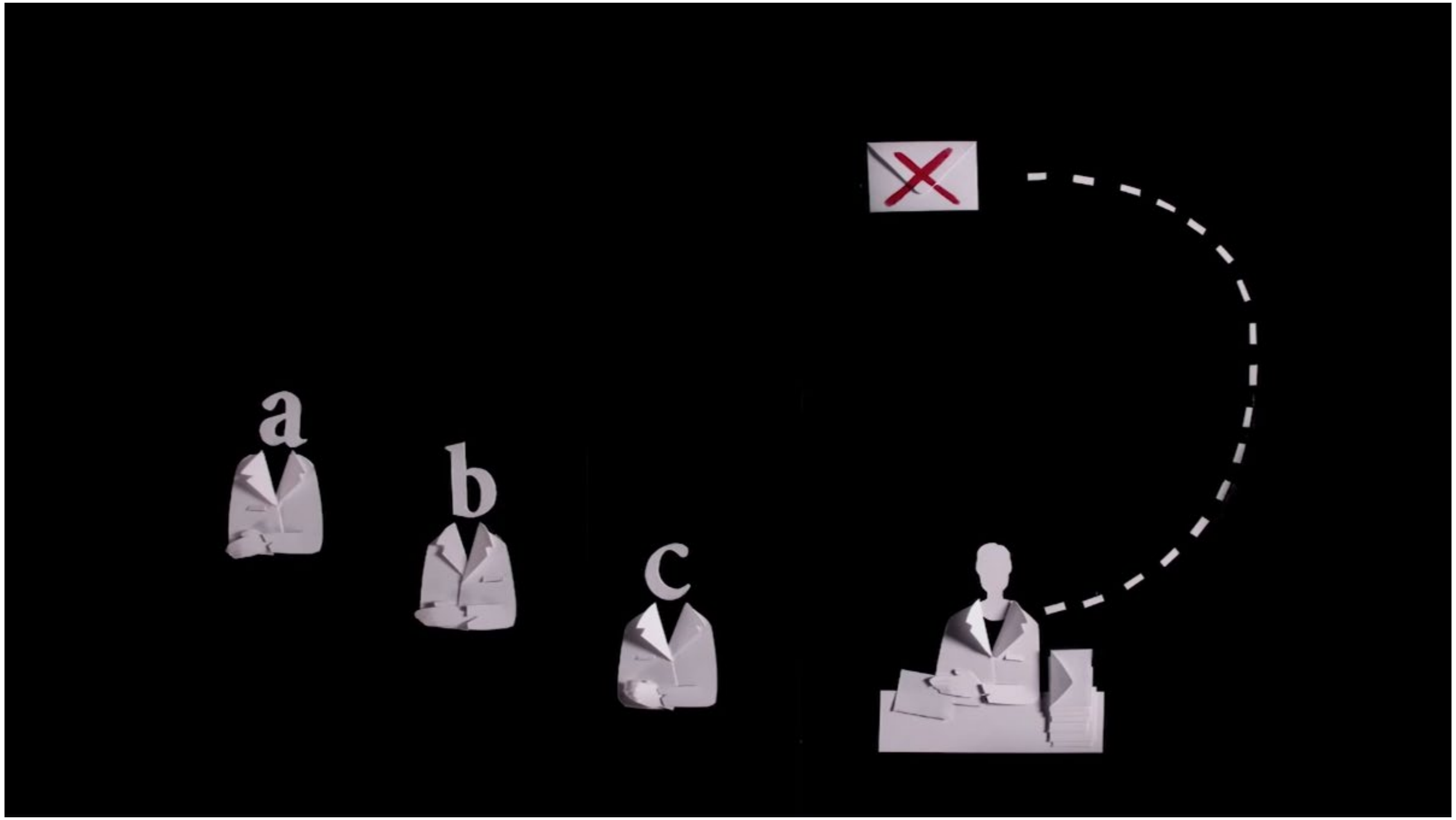
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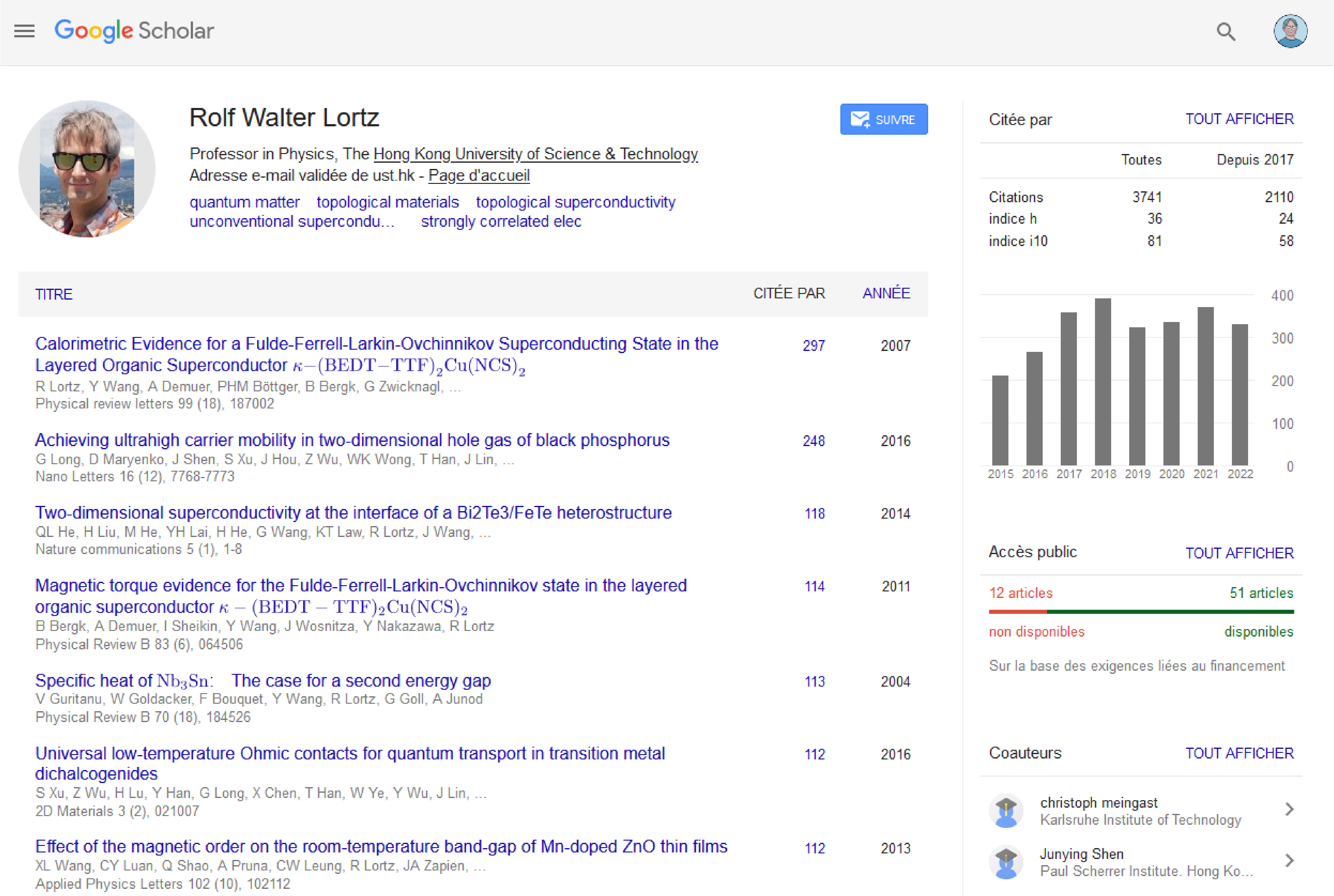

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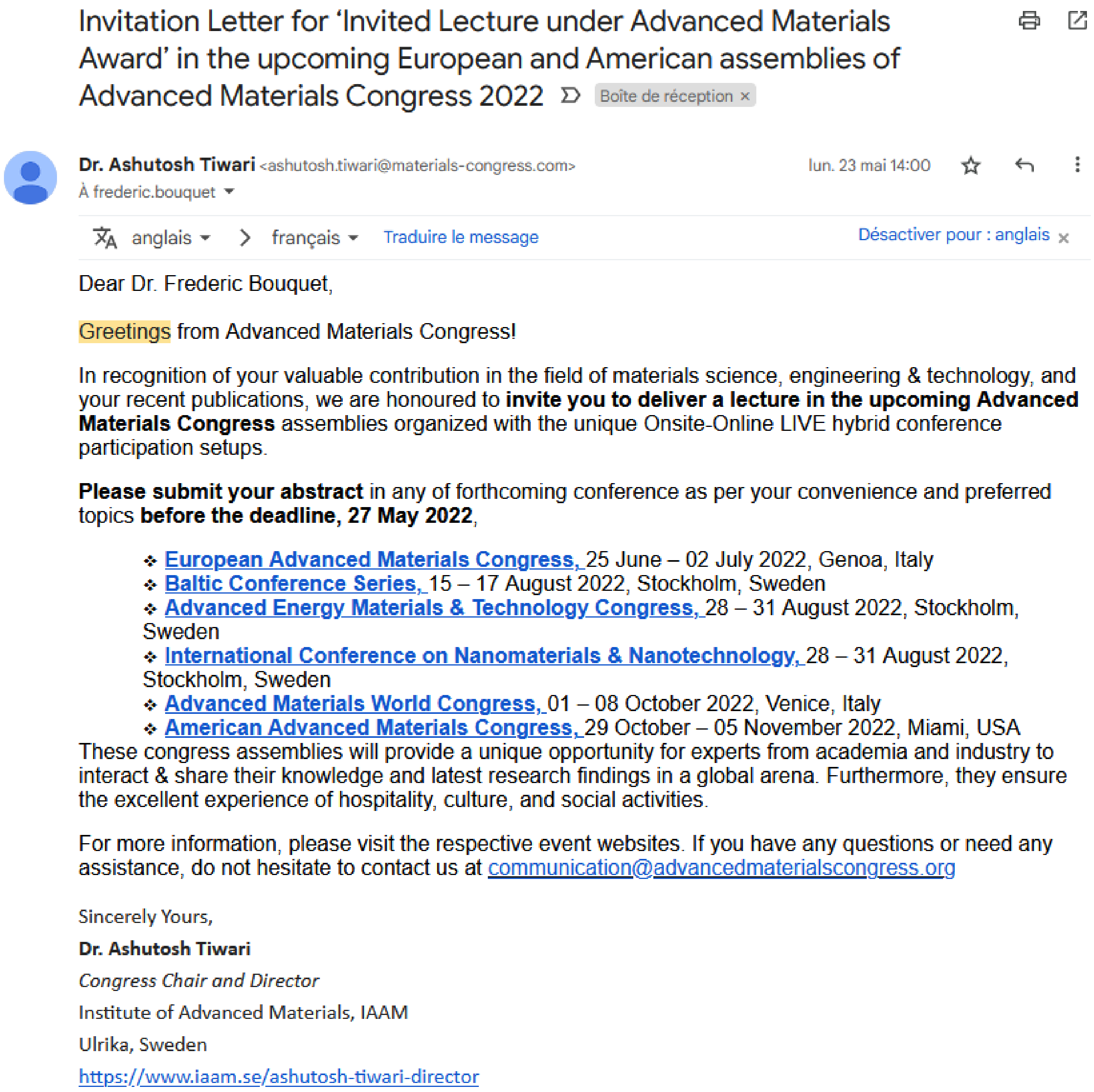

Invitation Letter for 'Invited Lecture under Advanced Materials Award' in the upcoming European and American assemblies of Advanced Materials Congress 2022

Dr. Ashutosh Tiwari <ashutosh.tiwari@materials-congress.com>
À frederic.bouquet
lun. 23 mai 14:00

Dear Dr. Frederic Bouquet,

Greetings from Advanced Materials Congress!

In recognition of your valuable contribution in the field of materials science, engineering & technology, and your recent publications, we are honoured to **invite you to deliver a lecture in the upcoming Advanced Materials Congress** assemblies organized with the unique Onsite-Online LIVE hybrid conference participation setups.

Please submit your abstract in any of forthcoming conference as per your convenience and preferred topics **before the deadline, 27 May 2022**,

- **European Advanced Materials Congress,** 25 June – 02 July 2022, Genoa, Italy
- **Baltic Conference Series,** 15 – 17 August 2022, Stockholm, Sweden
- **Advanced Energy Materials & Technology Congress,** 28 – 31 August 2022, Stockholm, Sweden
- **International Conference on Nanomaterials & Nanotechnology,** 28 – 31 August 2022, Stockholm, Sweden
- **Advanced Materials World Congress,** 01 – 08 October 2022, Venice, Italy
- **American Advanced Materials Congress,** 29 October – 05 November 2022, Miami, USA

These congress assemblies will provide a unique opportunity for experts from academia and industry to interact & share their knowledge and latest research findings in a global arena. Furthermore, they ensure the excellent experience of hospitality, culture, and social activities.

For more information, please visit the respective event websites. If you have any questions or need any assistance, do not hesitate to contact us at communication@advancedmaterialscongress.org

Sincerely Yours,

Dr. Ashutosh Tiwari

Congress Chair and Director

Institute of Advanced Materials, IAAM

Ulrika, Sweden

https://www.iaam.se/ashutosh-tiwari-director

Atelier manipe de cours

Travail par équipe : 2

Préparer une démo de cours :

- Une démo (la manipe)
- Le discours qui va avec (avec support)
- Un plan B…