HARNESSING THE POWER OF REFLECTIONLESS SCATTERING MODES IN ATOMIC AND MOLECULAR SYSTEMS

MICHELINE SOLEY
UNIVERSITY OF WISCONSIN-MADISON
CHICAGO QUANTUM EXCHANGE

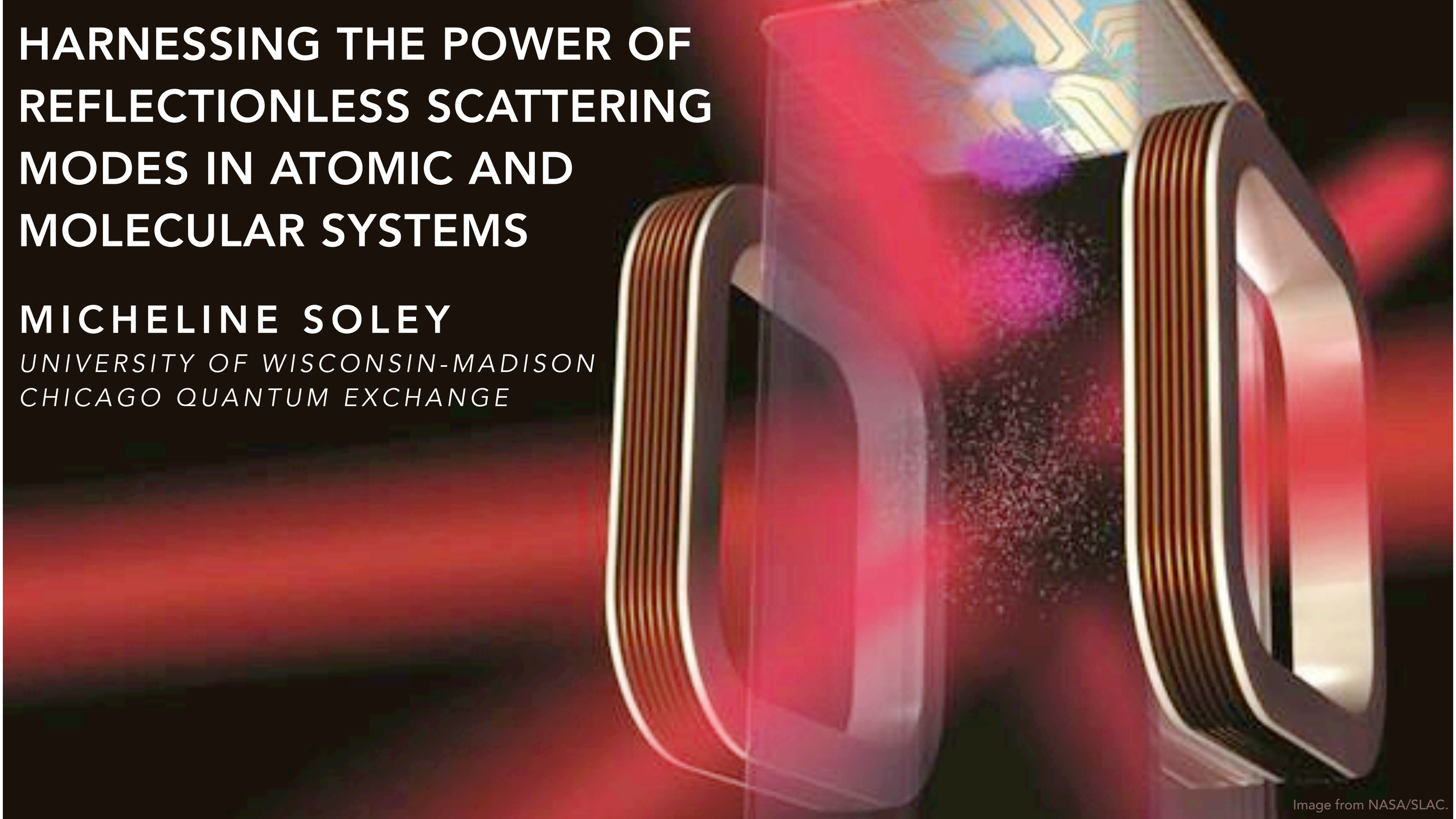
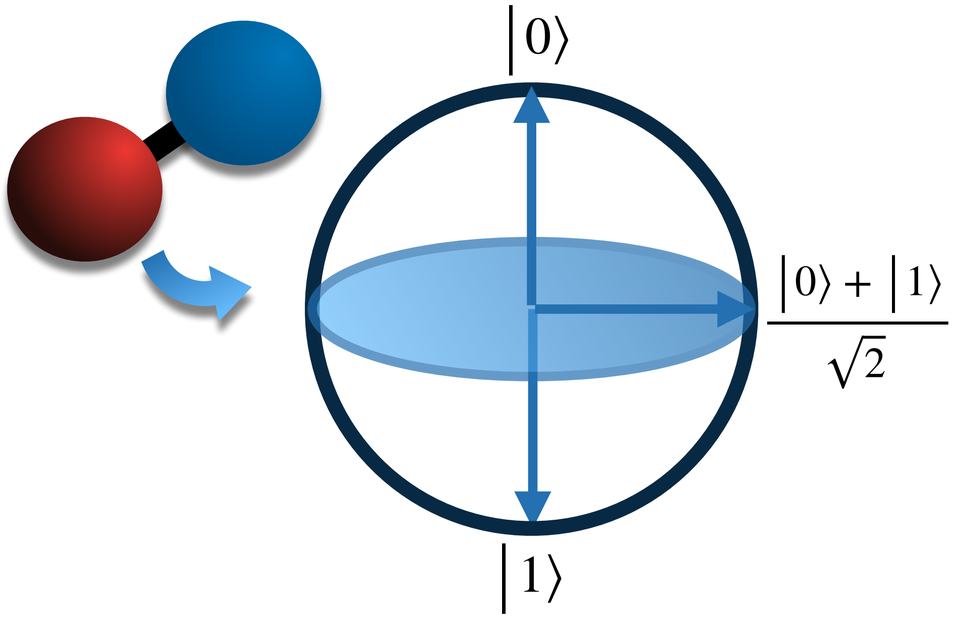


Image from NASA/SLAC.

IMPACT OF ULTRACOLD MOLECULES

Quantum Computing

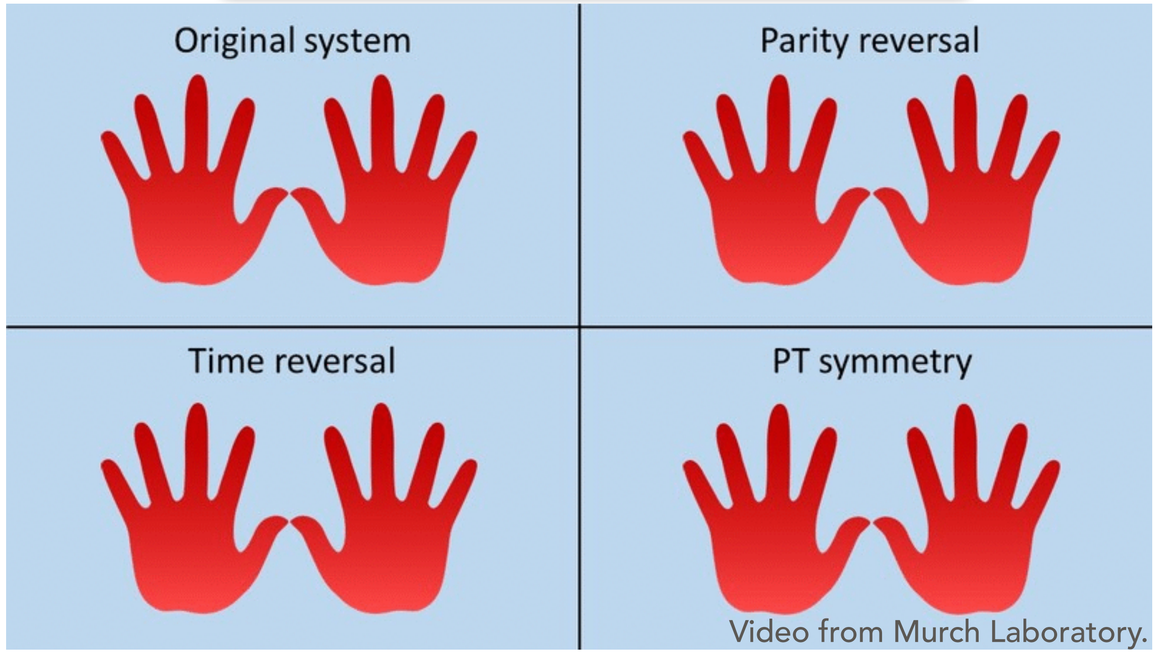


Molecule = Qubit

Fundamental Unit of Data on a Quantum Computer

K.-K. Ni, T. Roseband, D. D. Grimes, Chem. Sci. 9 (2018) 6830.
D. DeMille, Phys. Rev. Lett. 88 (2002) 067901.
S. F. Yelin, K. Kirby, R. Côté, Phys. Rev. A 74 (2006) 050301.

Fundamental Quantum Mechanics



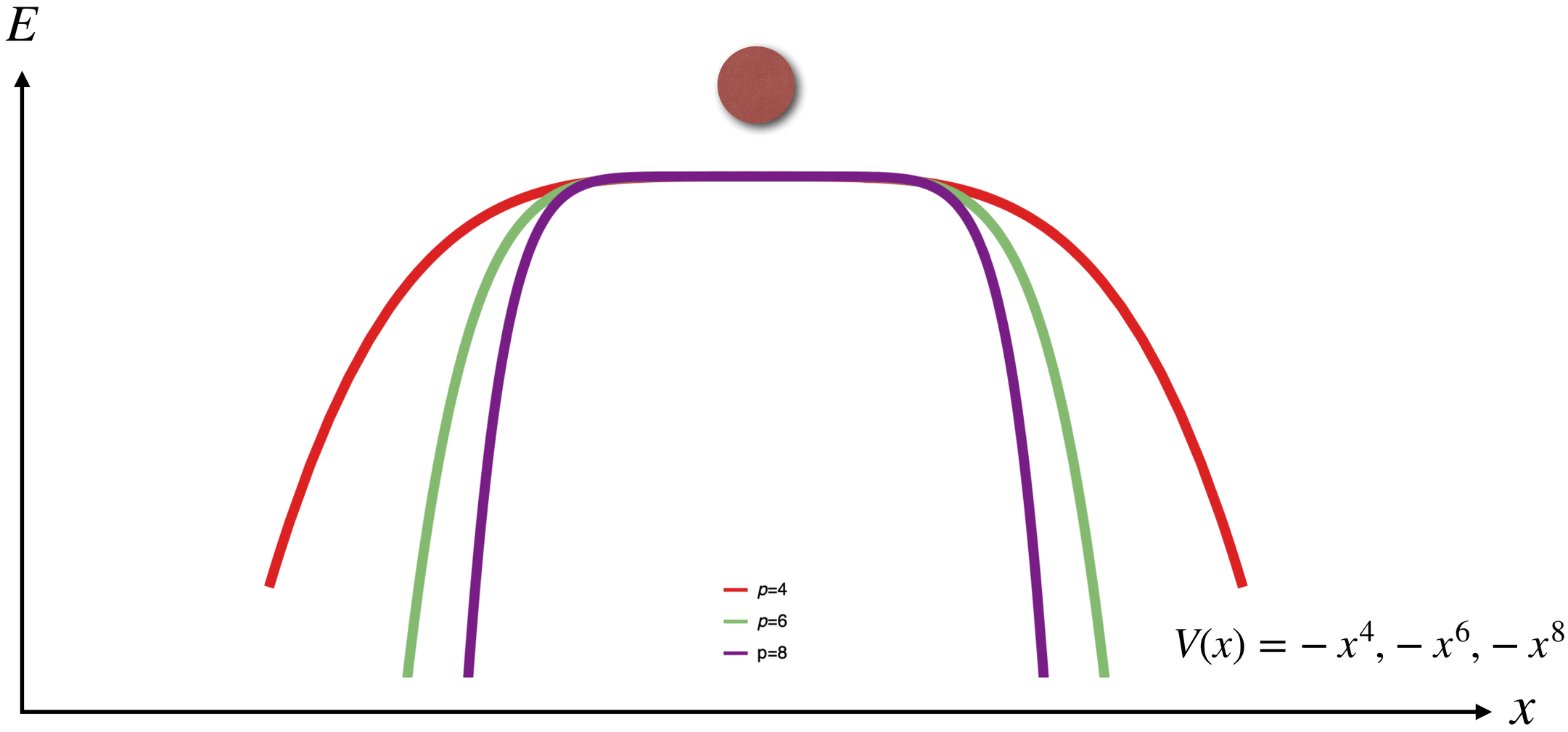
$\mathscr{PT}$ Symmetry

$$\varepsilon(x) = \varepsilon^{\star}(-x) \leftrightarrow V(x) = V^{\star}(-x)$$

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
Micheline B. Soley, A. D. Stone, in preparation.
C. Killion, A. D. Stone, **Micheline B. Soley**, in preparation.
N. Mantella, C. M. Bender, A. D. Stone, **Micheline B. Soley**, A. M. Steinberg, in preparation.

APPLICATION #1: $\mathscr{PT}$-SYMMETRIC UPSIDE-DOWN POTENTIALS

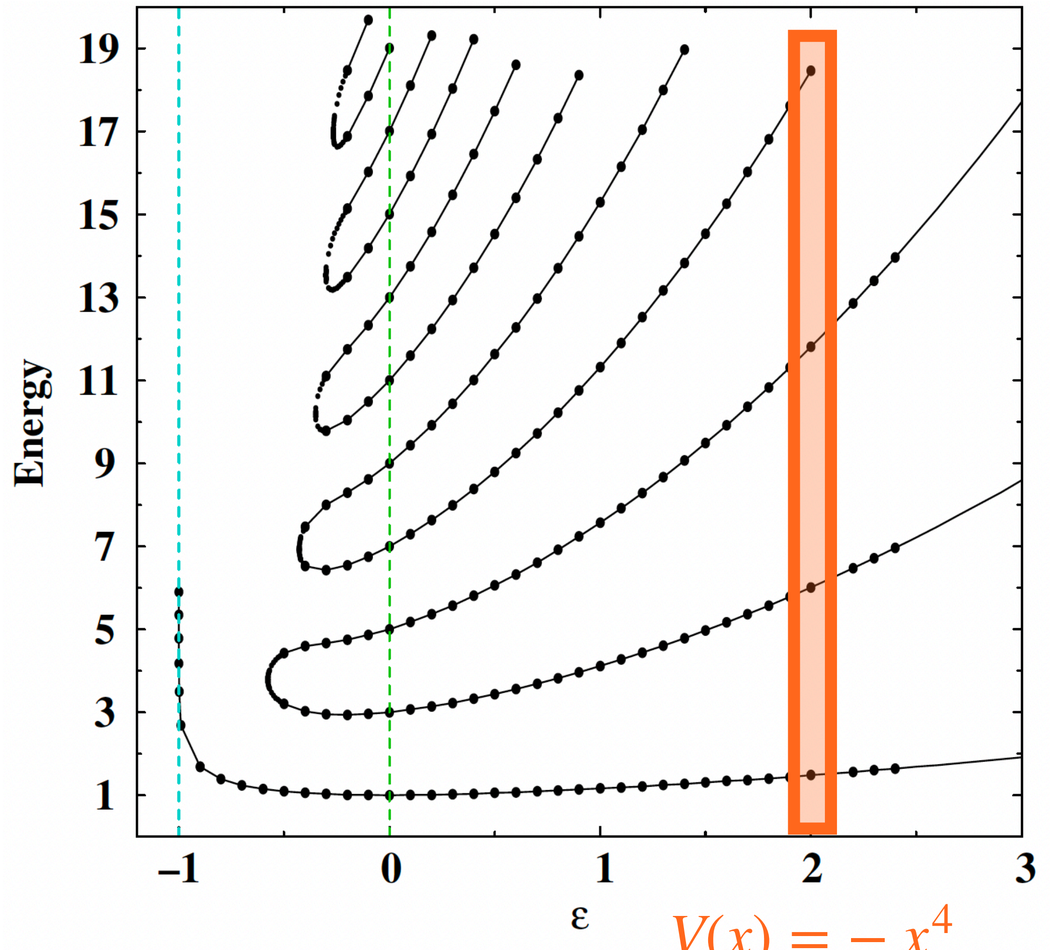
$$V(x) = -x^4, -x^6, -x^8$$



Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
C. M. Bender and M. Gianfreda, Phys. Rev. A 98 (2018) 052118.
C. M. Bender and S. Boettcher, Phys. Rev. Lett. 80 (1998) 5243.

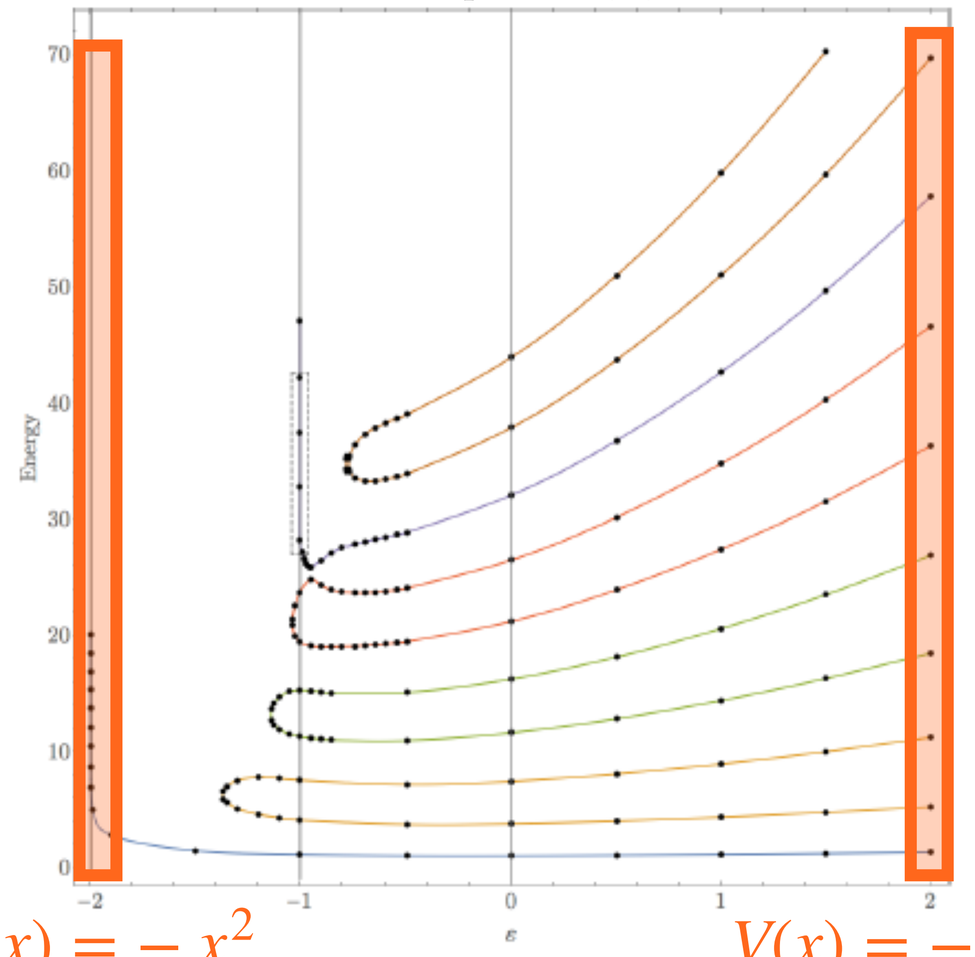
PHENOMENA ALSO PREDICTED FOR PREDICTED ANALYTIC CONTINUATIONS

$H = \hat{p}^2 + \hat{x}^2(\mathrm{i}\hat{x})^\epsilon$



$V(x) = -x^4$

$H = \hat{p}^2 + \hat{x}^4(\mathrm{i}\hat{x})^\epsilon$



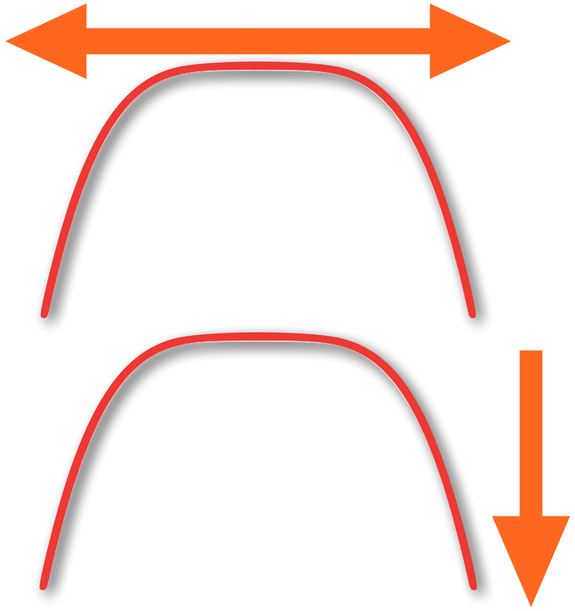
$V(x) = -x^2$ $V(x) = -x^6$

Potentials $V(x) = -x^p$ spectra are purely real for $p = 4$ and $p = 6$ with no real eigenvalues for $p = 2$.

C. M. Bender, Rep. Prog. Phys. 70 (2007) 947.

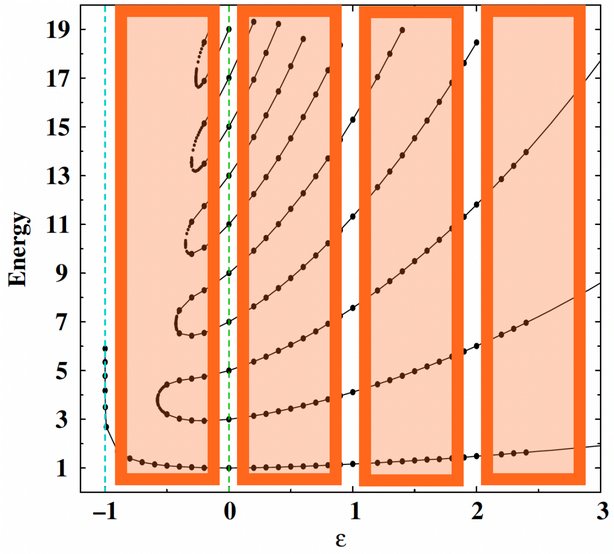
C. M. Bender and S. Boettcher, Phys. Rev. Lett. 80 (1998) 5243.

DIFFICULTIES FACING DEMONSTRATION OF $\mathscr{PT}$-SYMMETRY BEHAVIORS IN QUANTUM (COLD-ATOM) EXPERIMENTS



$L = \infty$ Infinite Extent

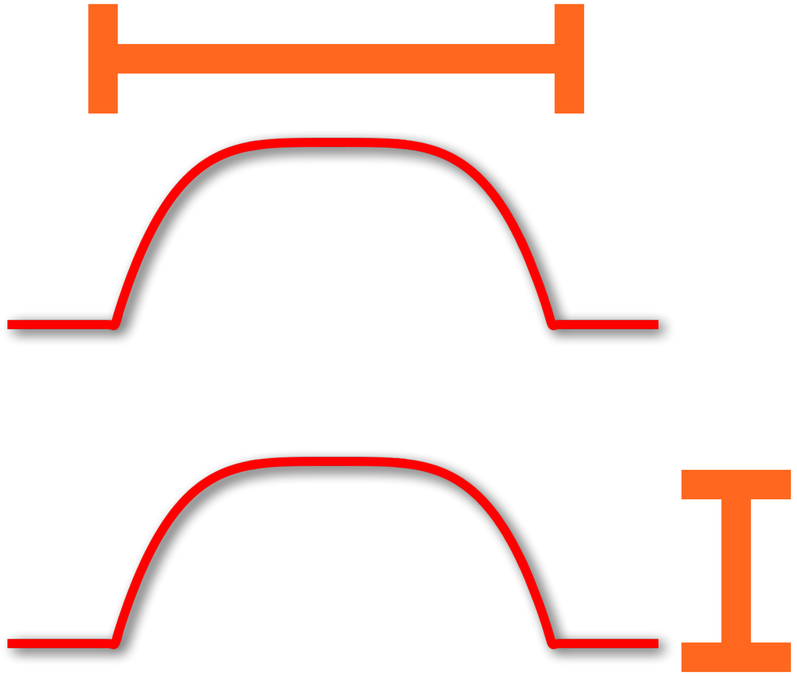
$V \to -\infty$ Unbounded Energies



$V(x) \notin \mathbb{R}$ Complex Potentials

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
C. M. Bender and M. Gianfreda, Phys. Rev. A 98 (2018) 052118.

REQUIREMENTS TO REALIZE NON-HERMITIAN $\mathcal{PT}$-SYMMETRIC SYSTEMS EXPERIMENTALLY



$2L$ Finite Extent

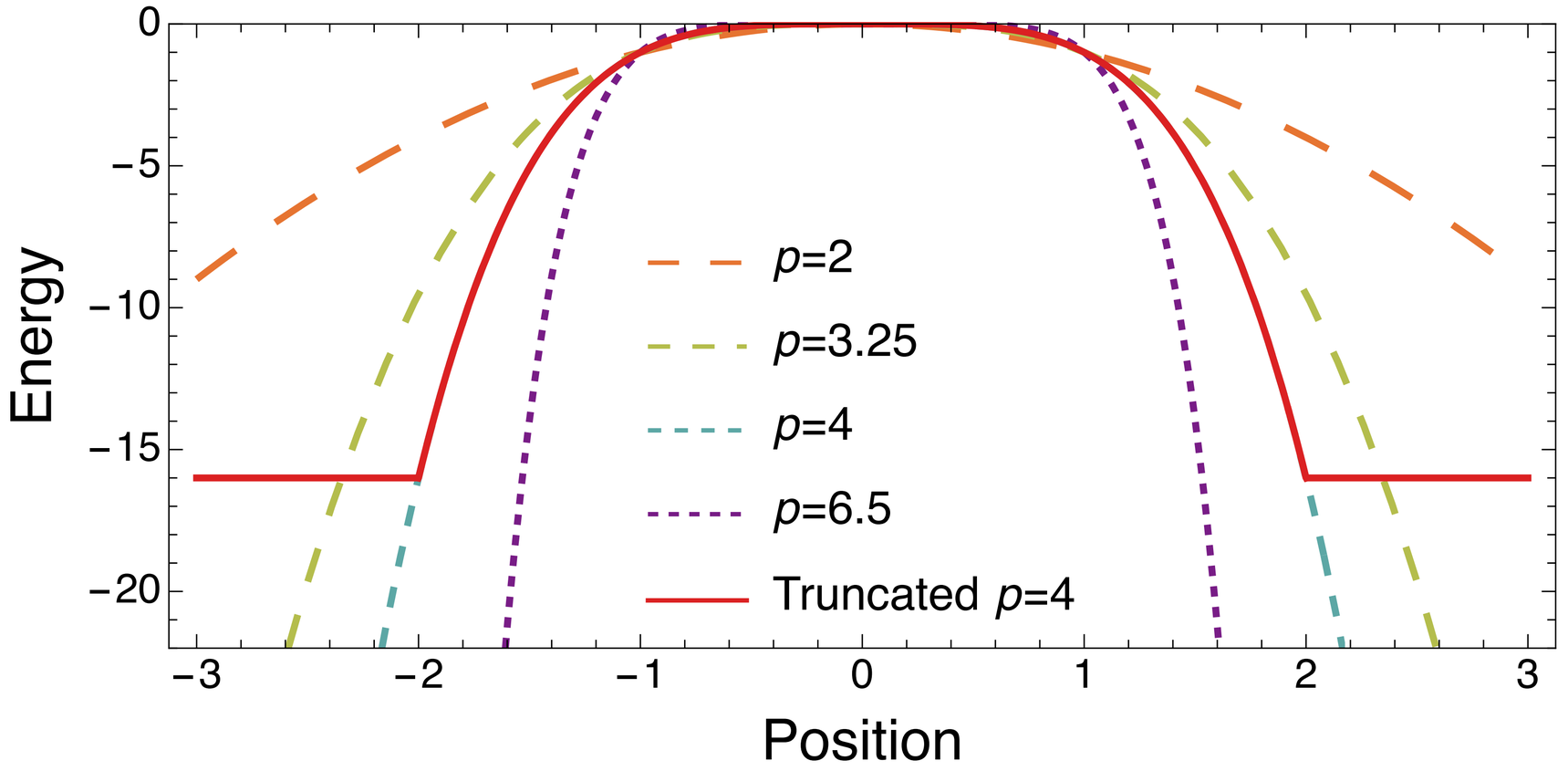
V Bounded Energies

$V(x) \notin \mathbb{R}$ Real Potentials

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
C. M. Bender and M. Gianfreda, Phys. Rev. A 98 (2018) 052118.

NOVEL CLASS OF COMPLETELY REAL POTENTIALS TO DEMONSTRATE $\mathscr{PT}$ -SYMMETRY BEHAVIORS

$V(x) = -|x|^p$ FOR $p \in \mathbb{R}$ TRUNCATED IN LENGTH $-L \leq x \leq L$



$$V(x) = \begin{cases} -L^p, & |x| > L \\ -x^p, & |x| \leq L \end{cases}$$

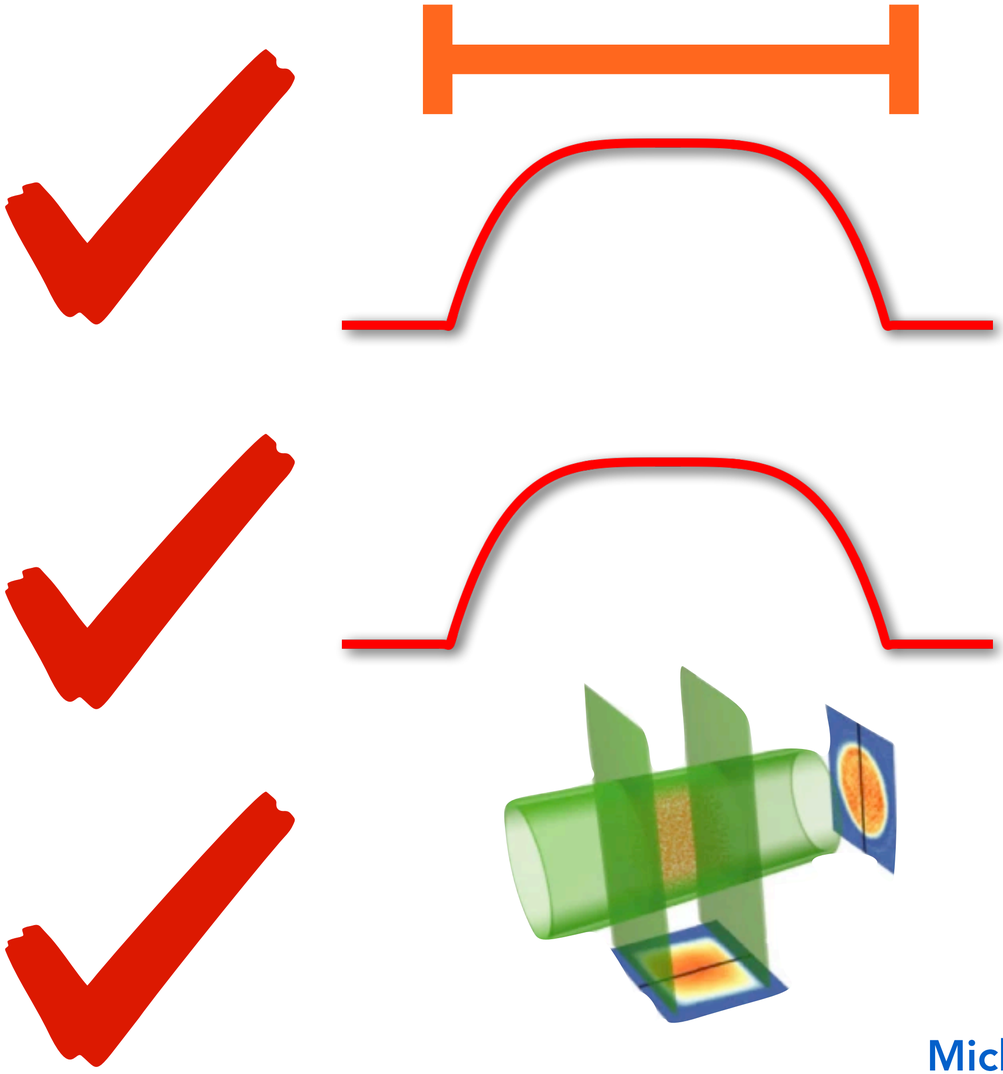
$$V(x) = -x^p f(x, w, L) - L^p f(-x, w, L)$$

$$f(x, w, L) = \frac{1}{1 + \exp\left(-w(x + L)\right)} + \frac{1}{1 + \exp\left(w(x - L)\right)} - 1$$

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.

C. M. Bender and M. Gianfreda, Phys. Rev. A 98 (2018) 052118.

FIRST EXPERIMENTALLY REALIZABLE CLOSED SCHRÖDINGER QUANTUM NON-HERMITIAN, $\mathscr{PT}$-SYMMETRIC SYSTEM



$2L$ Finite Extent

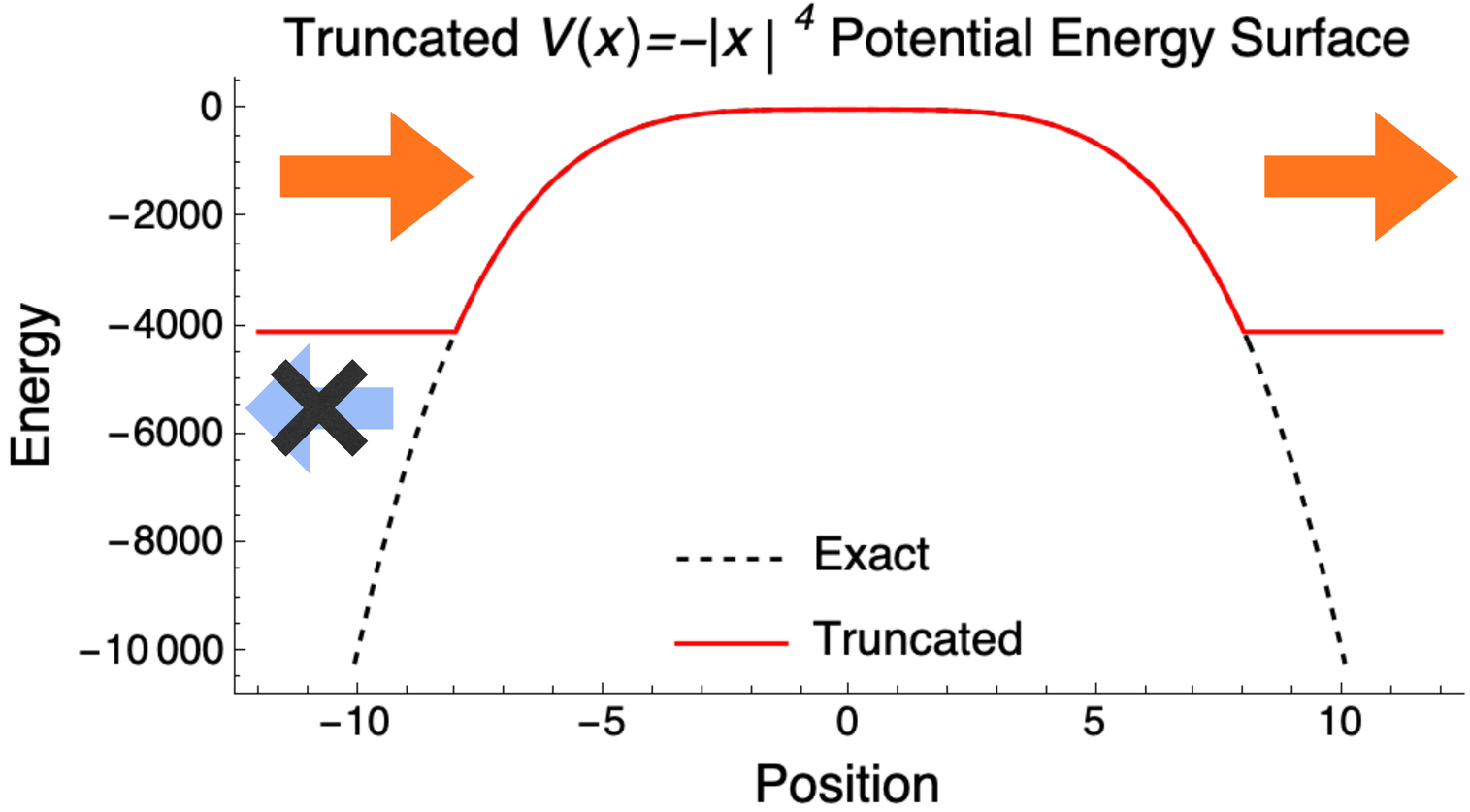
V Bounded Energies

$V(x) \notin \mathbb{R}$ Real Potentials

COLD-ATOM SYSTEMS

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
C. M. Bender and M. Gianfreda, Phys. Rev. A 98 (2018) 052118.
N. Navon, R. P. Smith, Z. Hadzibabic, Nat. Phys. 17 (2021) 1334.

PROPERTIES OF THE TRUNCATED $V(x) = -|x|^4$ $\mathscr{PT}$ -SYMMETRIC SYSTEM



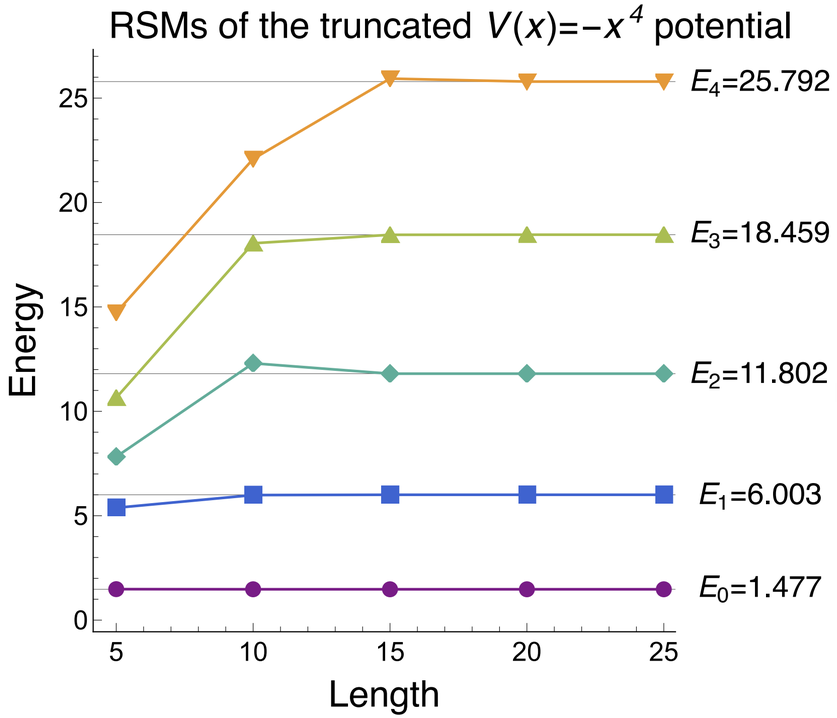
- No bound states
- Continuous spectrum
- **Discrete, above-barrier reflectionless states**

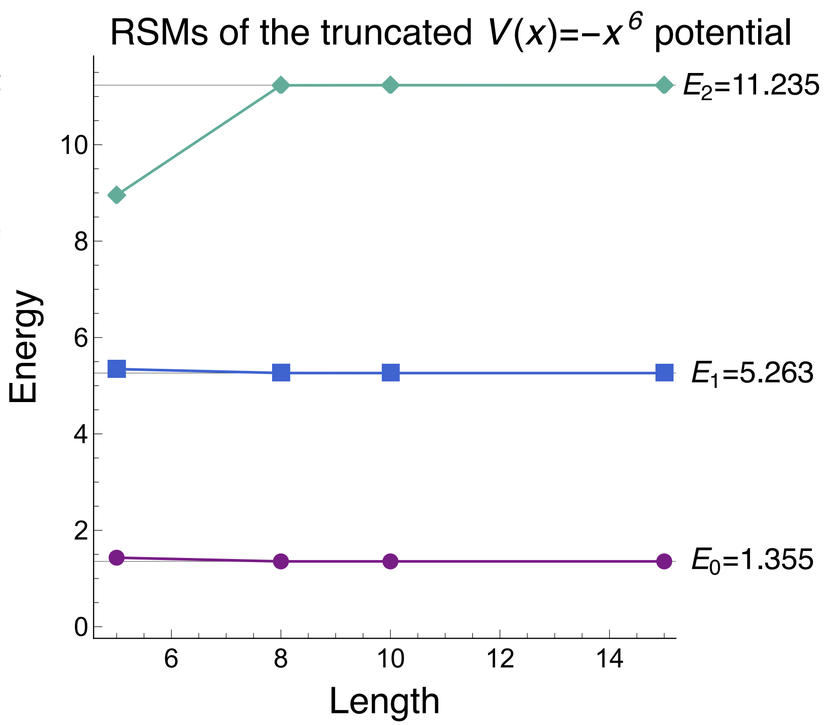
The reflectionless states in the experiment are expected to exhibit properties related to the "reflection-free" eigenstates of the infinite potential.

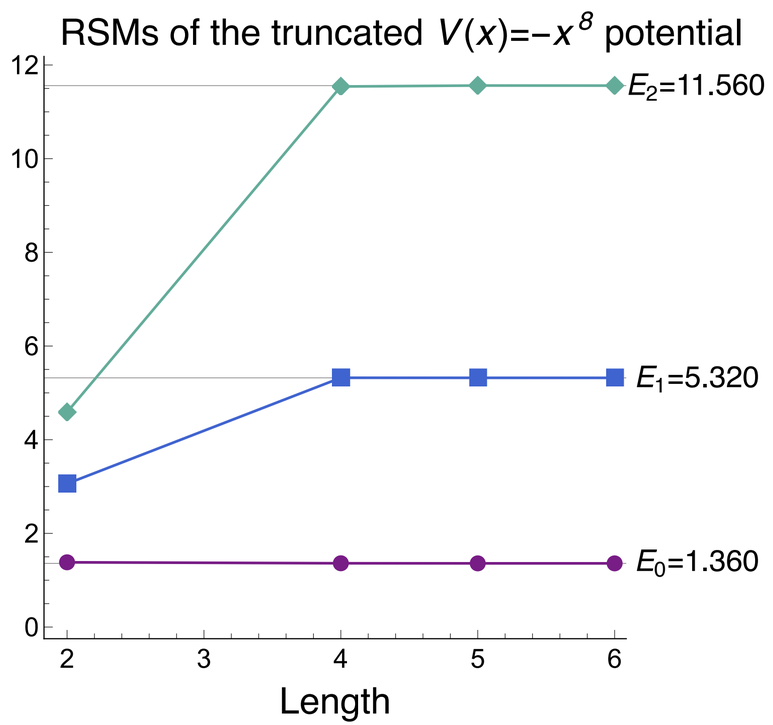
Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.

ENERGIES OF THE TRUNCATED $V(x) = -|x|^p$ $\mathcal{PT}$-SYMMETRIC SYSTEM

Reflection scattering mode theory successfully determines low-energy reflectionless eigenvalues of the truncated potential $V(x) = -|x|^p$ in agreement with analytic even-integer $p = 4,6,8$ results with **7-8 digits of accuracy** for sufficiently large L.





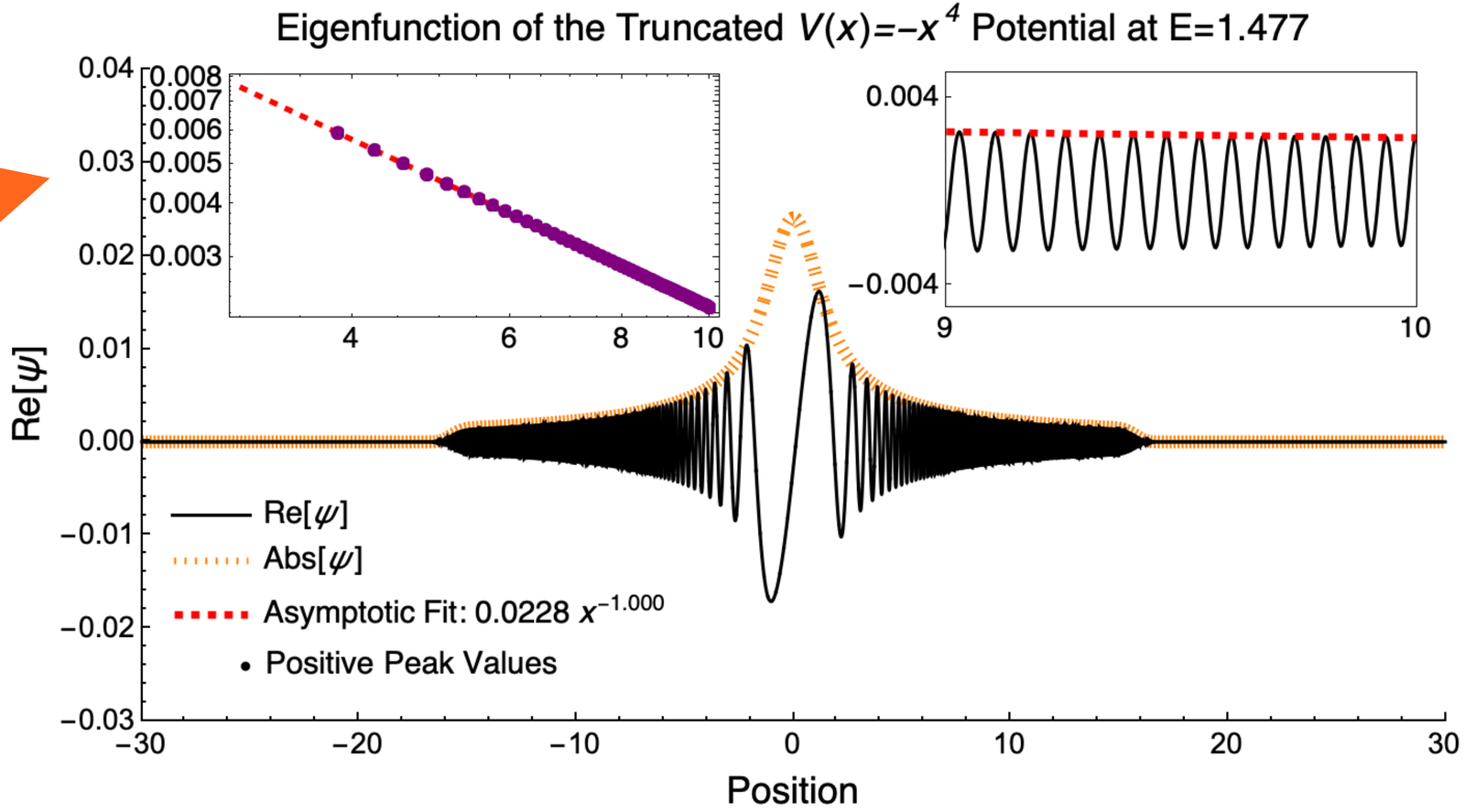


Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.

WAVEFUNCTIONS OF THE TRUNCATED $V(x) = -|x|^p$ $\mathcal{PT}$-SYMMETRIC SYSTEM

Reflectionless scattering mode theory also successfully determines wavefunctions in the truncated $V(x) = -x^4$ potential, which exhibit expected properties of the eigenfunctions of the unbounded system.

Predicted $1/x$ Asymptotic Behavior

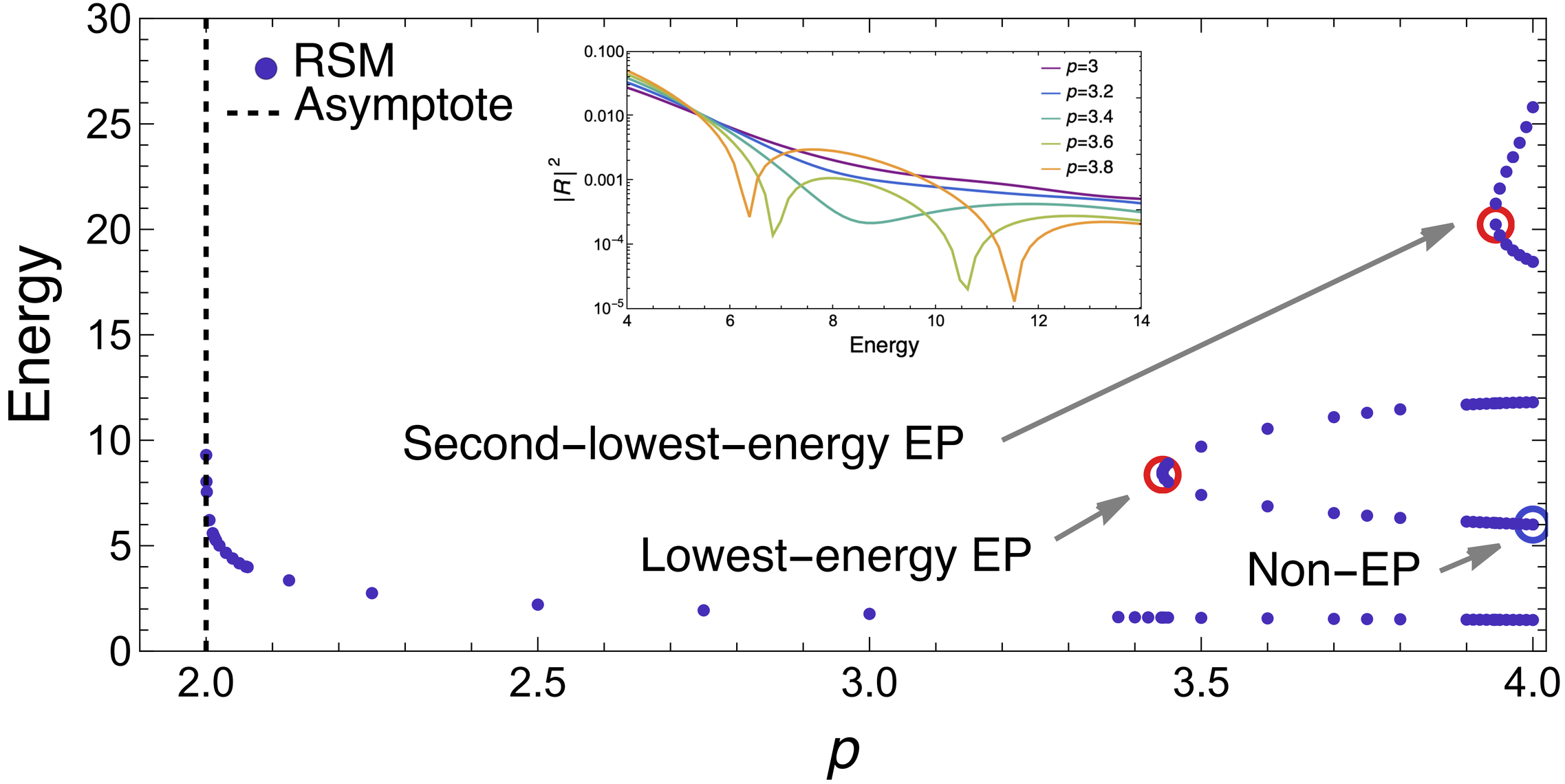


Highly Oscillatory

Symmetric Probability Density

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.

EXCEPTIONAL POINTS IN THE TRUNCATED $V(x) = -|x|^p$ $\mathscr{PT}$-SYMMETRIC SYSTEM

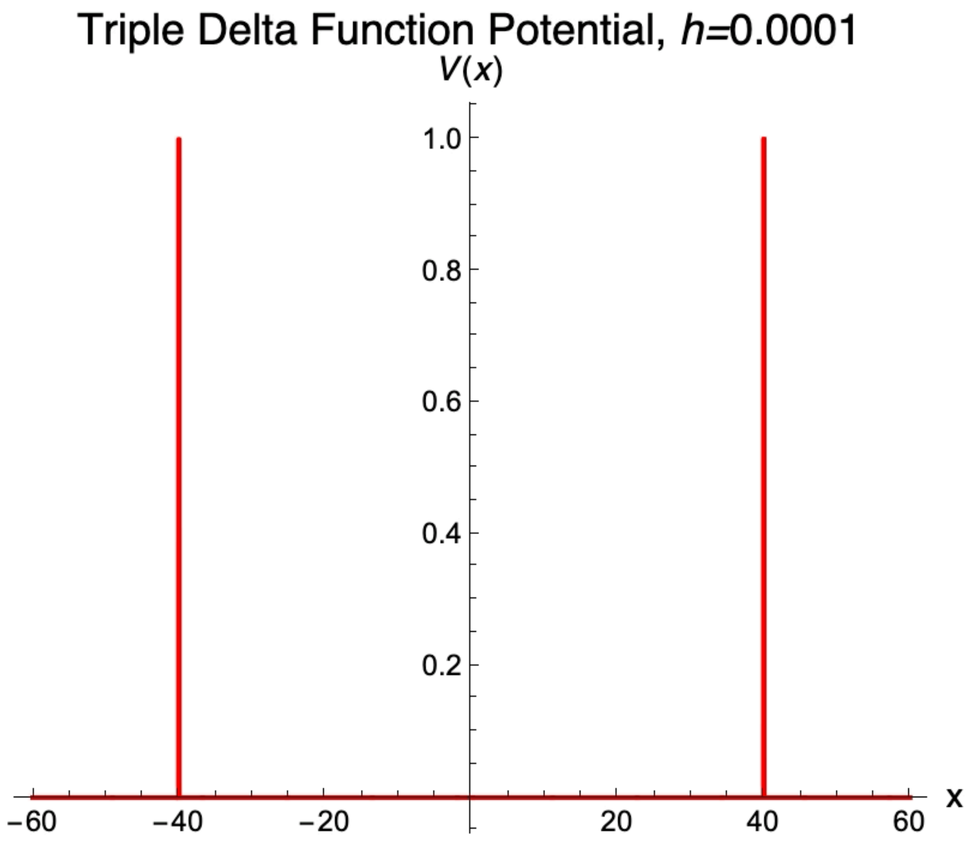


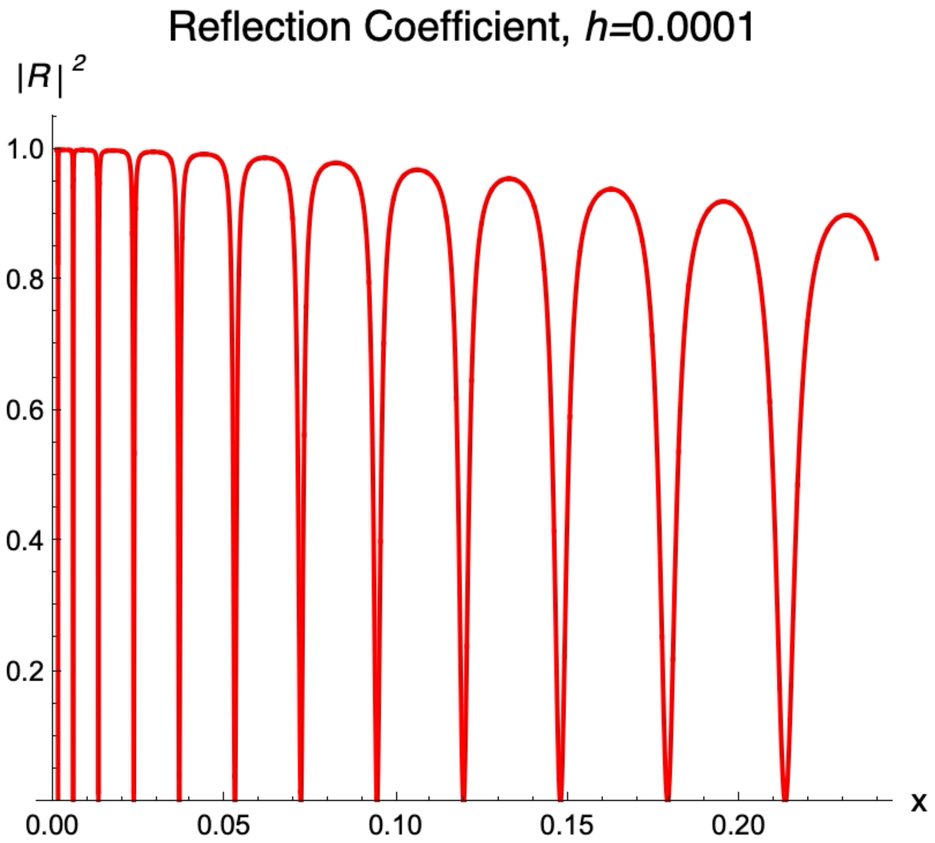
Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.

APPLICATION #2: TRIPLE DELTA-FUNCTION POTENTIAL

$\mathscr{PT}$-symmetry behavior with a simple, purely real potential:

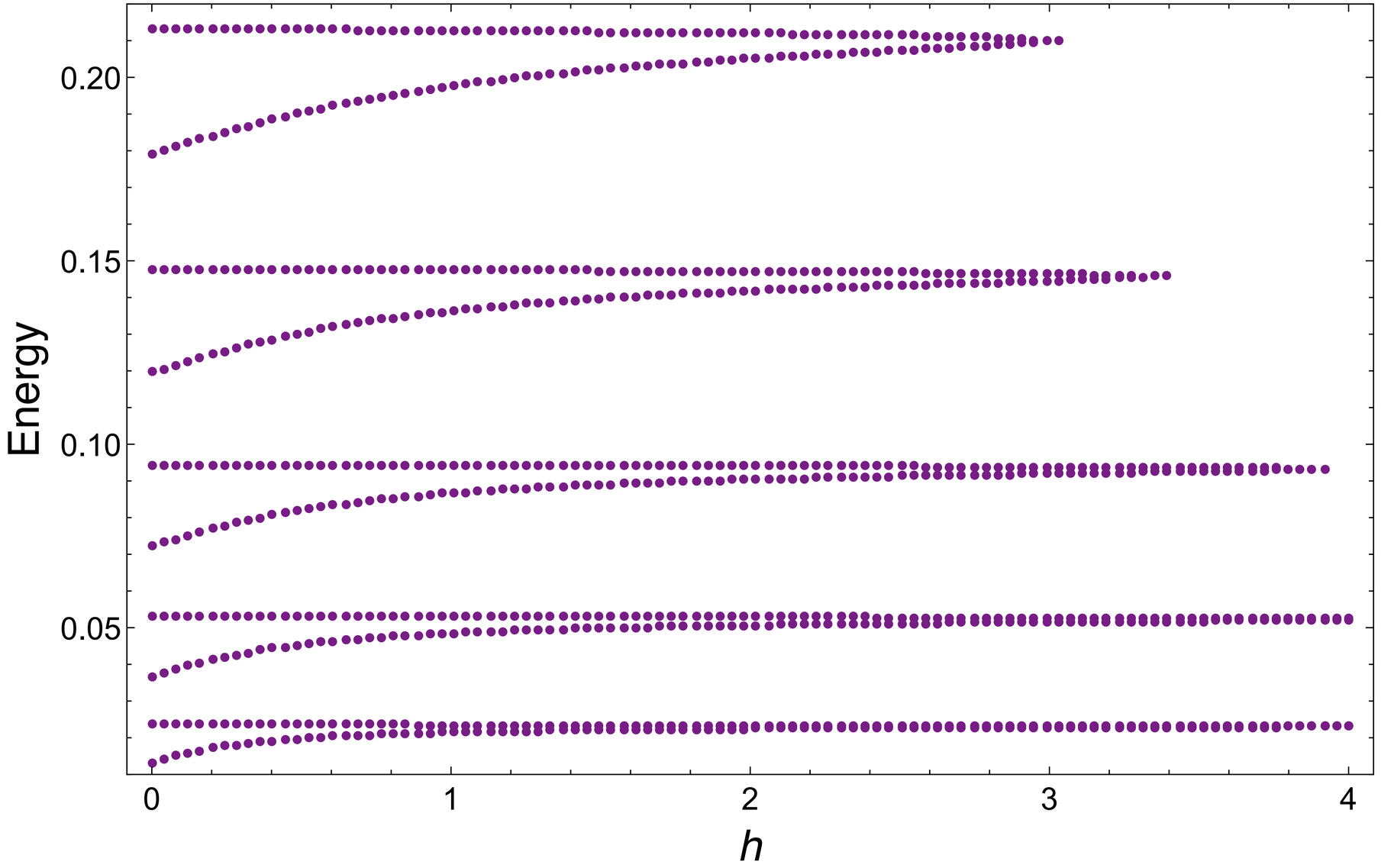
$$V(x) = \delta(x + a) + h\delta(x) + \delta(x - a)$$





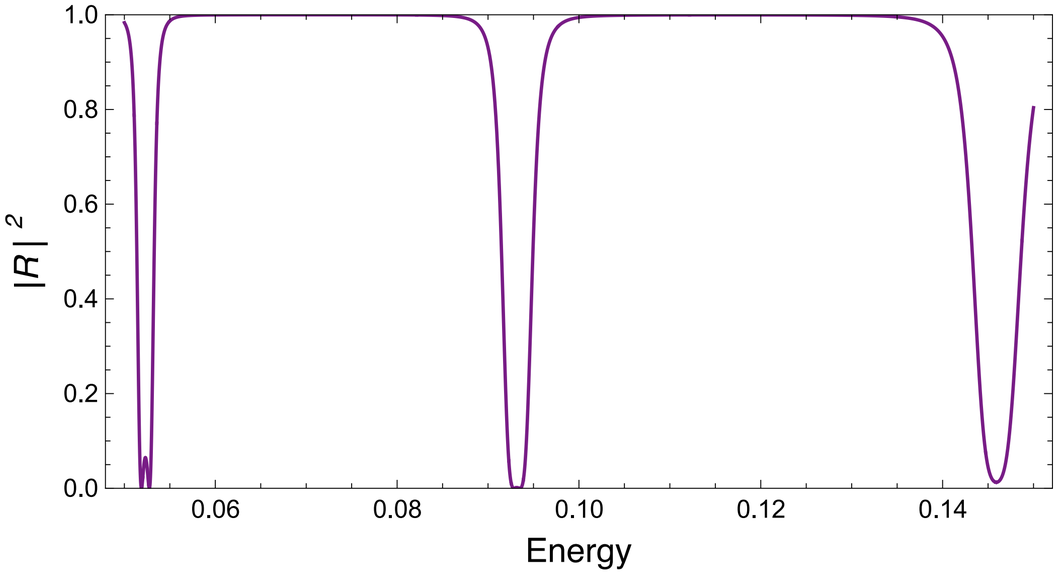
Micheline B. Soley, A. D. Stone, in preparation.

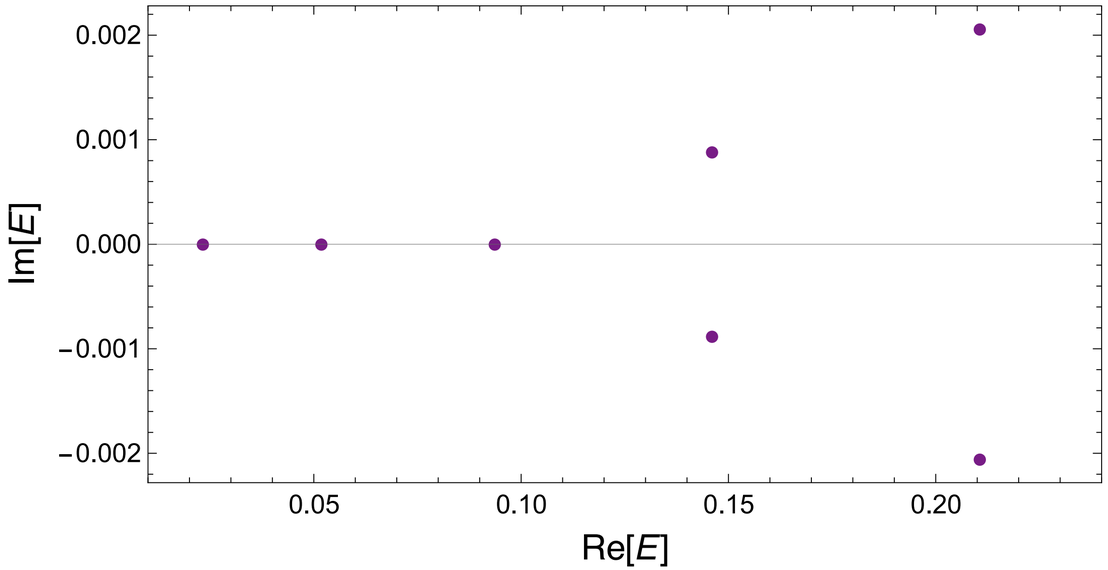
EXCEPTIONAL POINTS IN THE TRIPLE DELTA-FUNCTION POTENTIAL



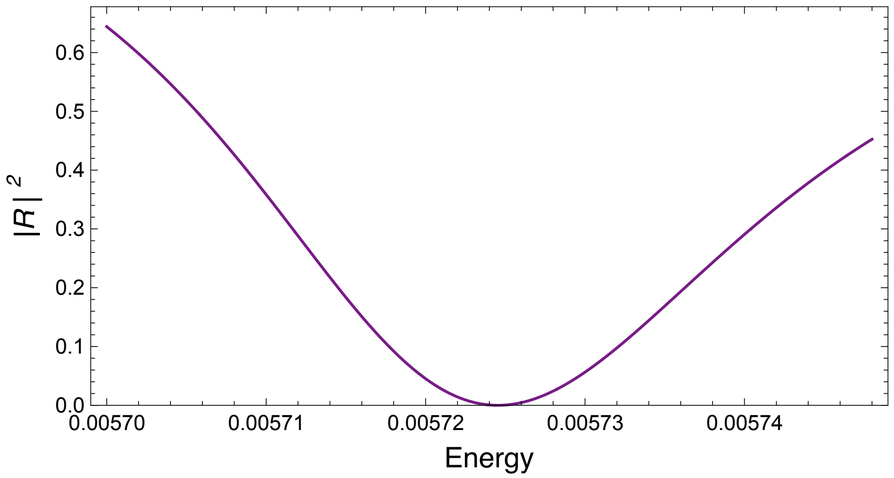
Micheline B. Soley, A. D. Stone, in preparation.

PROPERTIES OF EXCEPTIONAL POINTS IN THE TRIPLE DELTA-FUNCTION POTENTIAL

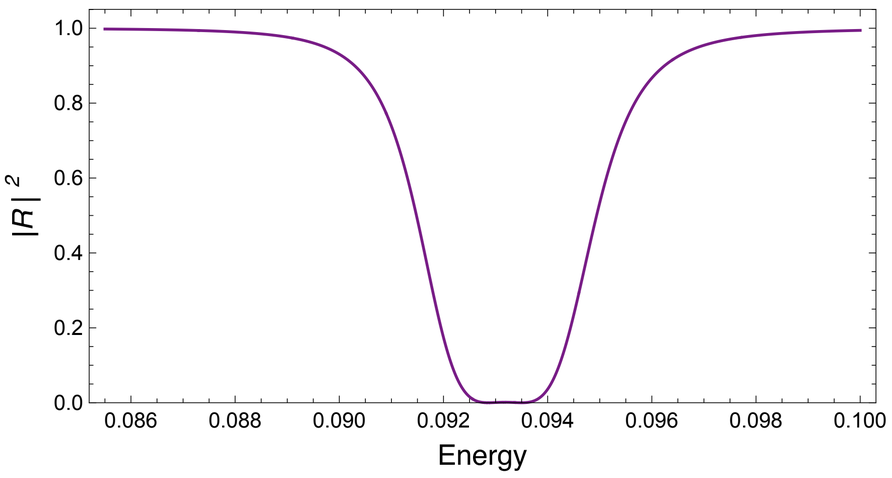




Non-EP

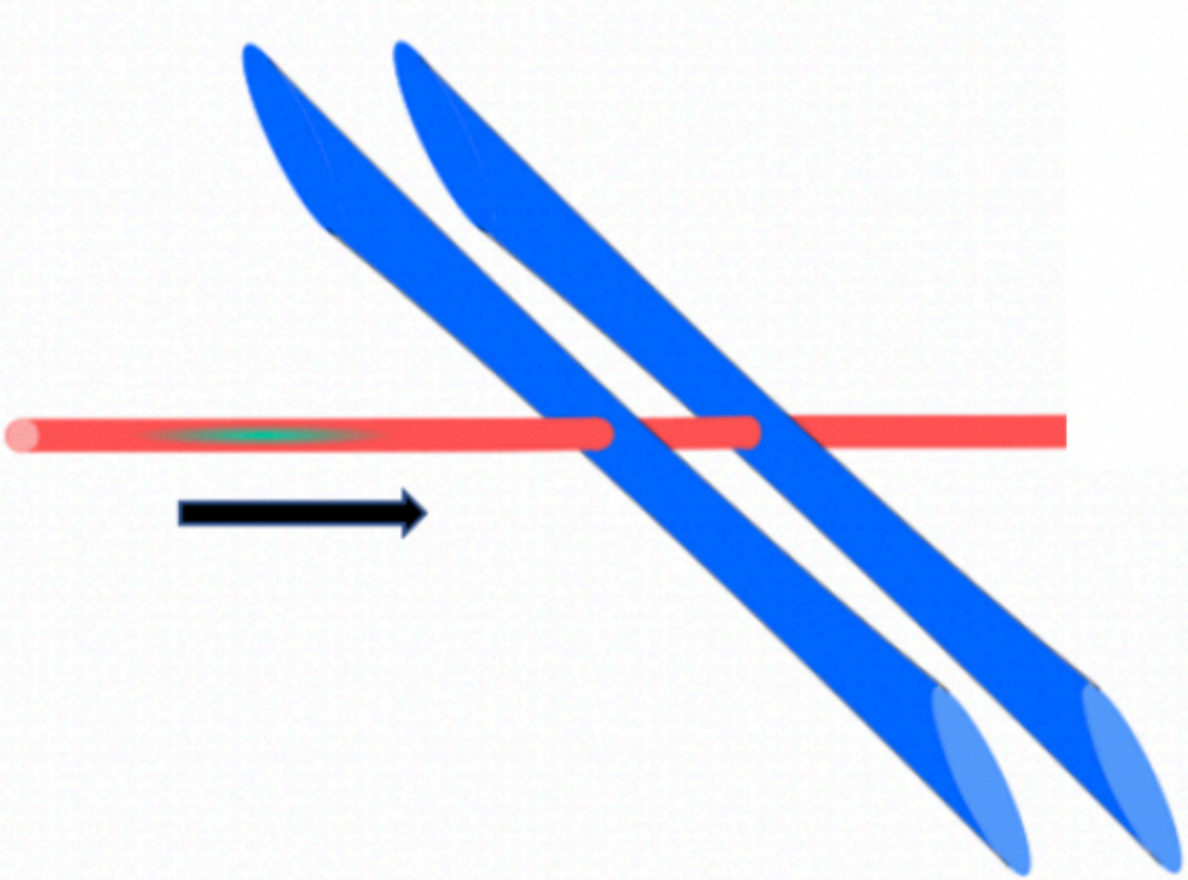


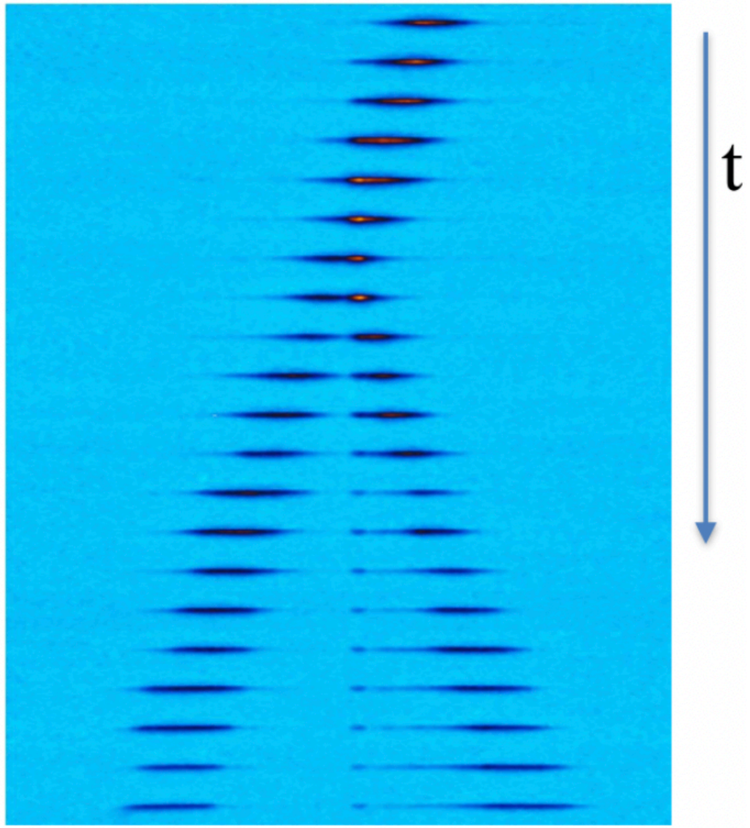
EP



Micheline B. Soley, A. D. Stone, in preparation.

APPLICATION #3: EXPERIMENTAL PLATFORM FOR OBSERVATION OF SIGNATURES OF $\mathcal{PT}$-SYMMETRY BEHAVIORS WITH AN SLM

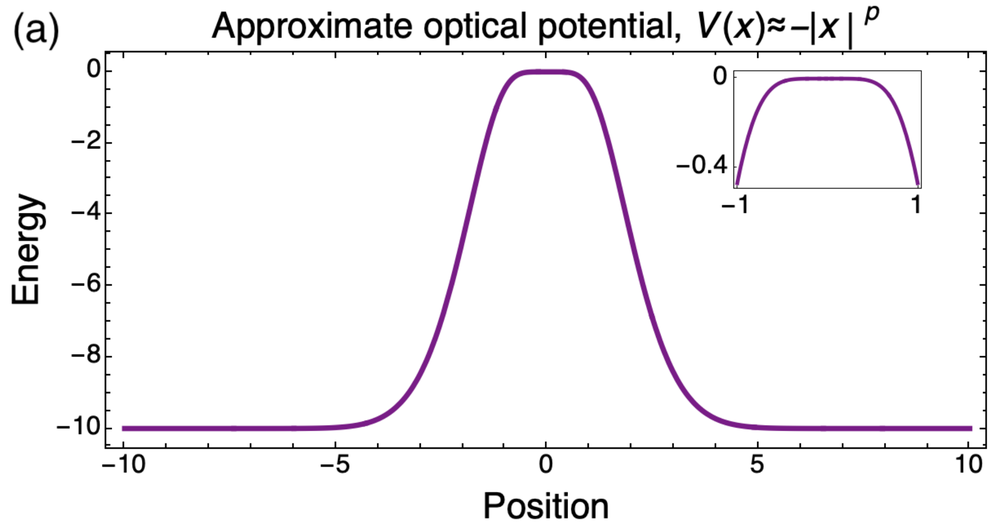


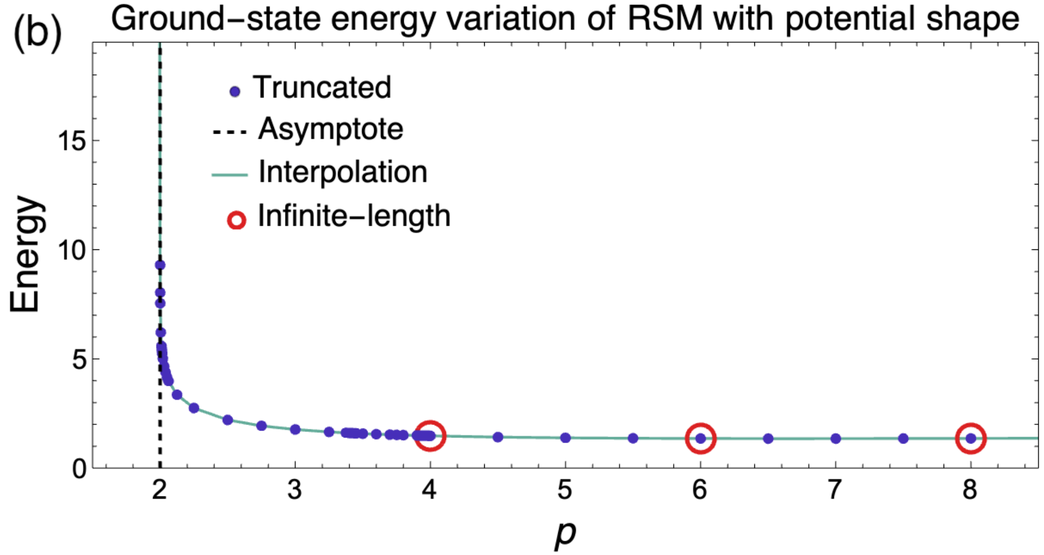


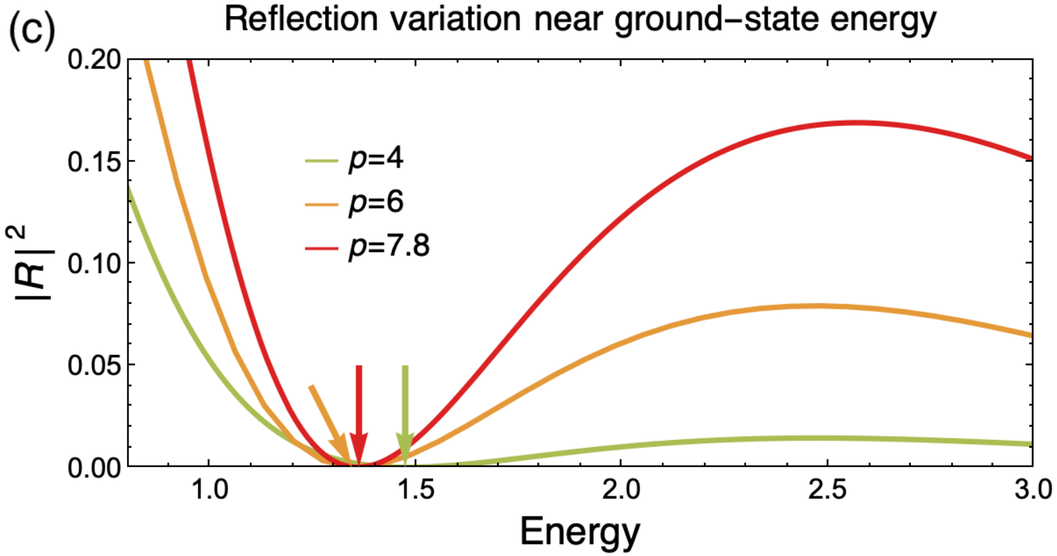
Ultracold Bose-Einstein condensates, confined to quasi-one-dimension, are scattered by an intersecting laser with a spatial light modulator (SLM) against artificially designed potentials

N. Mantella, C. M. Bender, A. D. Stone, **Micheline B. Soley**, A. M. Steinberg, in preparation.
N. Mantella, J. McGowan, IV, H. Neeraj, D. Spierings, A. Steinberg, APS DAMOP, 2022

SLM-BASED APPROACH TO BOUND STATE IN THE CONTINUUM
SIGNATURES OF THE $V(x) = -x^6$ POTENTIAL

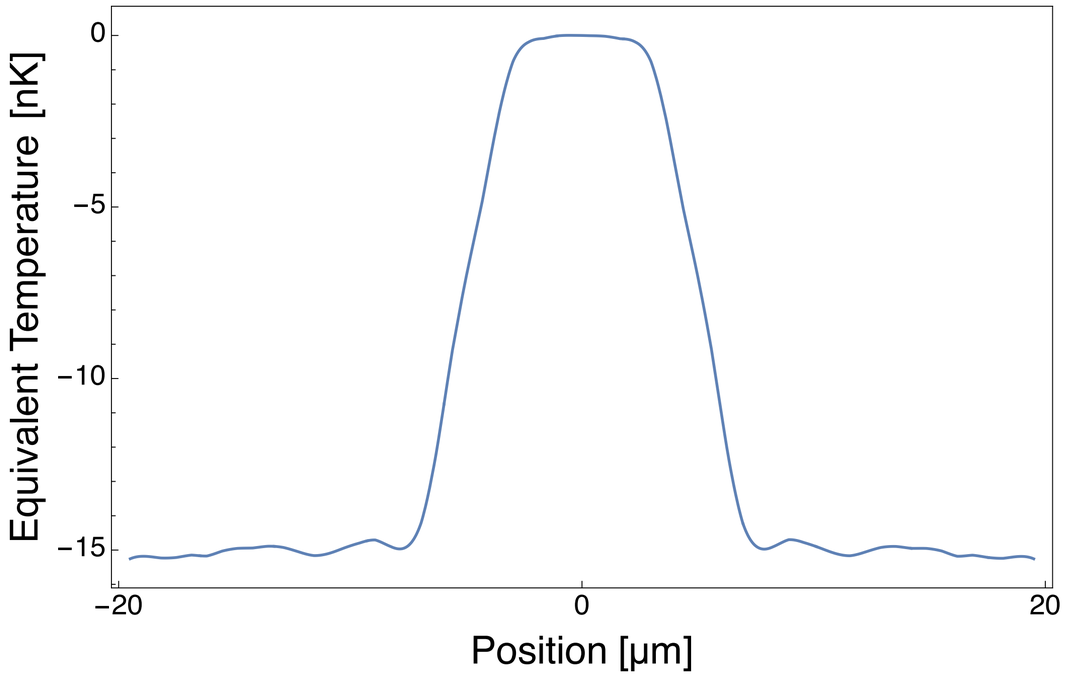


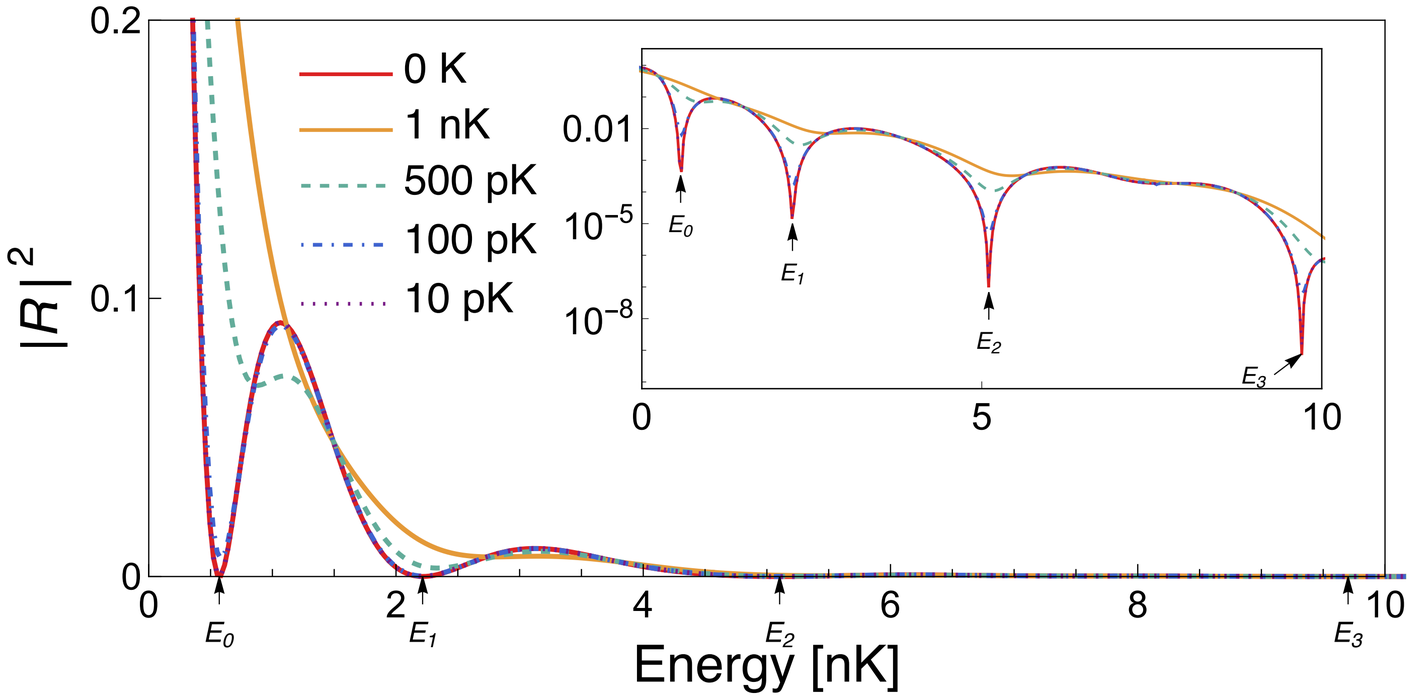




Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
N. Mantella, C. M. Bender, A. D. Stone, **Micheline B. Soley**, A. M. Steinberg, in preparation.

PREDICTED SUCCESS OF THE SLM-BASED APPROACH IN THE PRESENCE OF ERROR AND THERMAL SMEARING



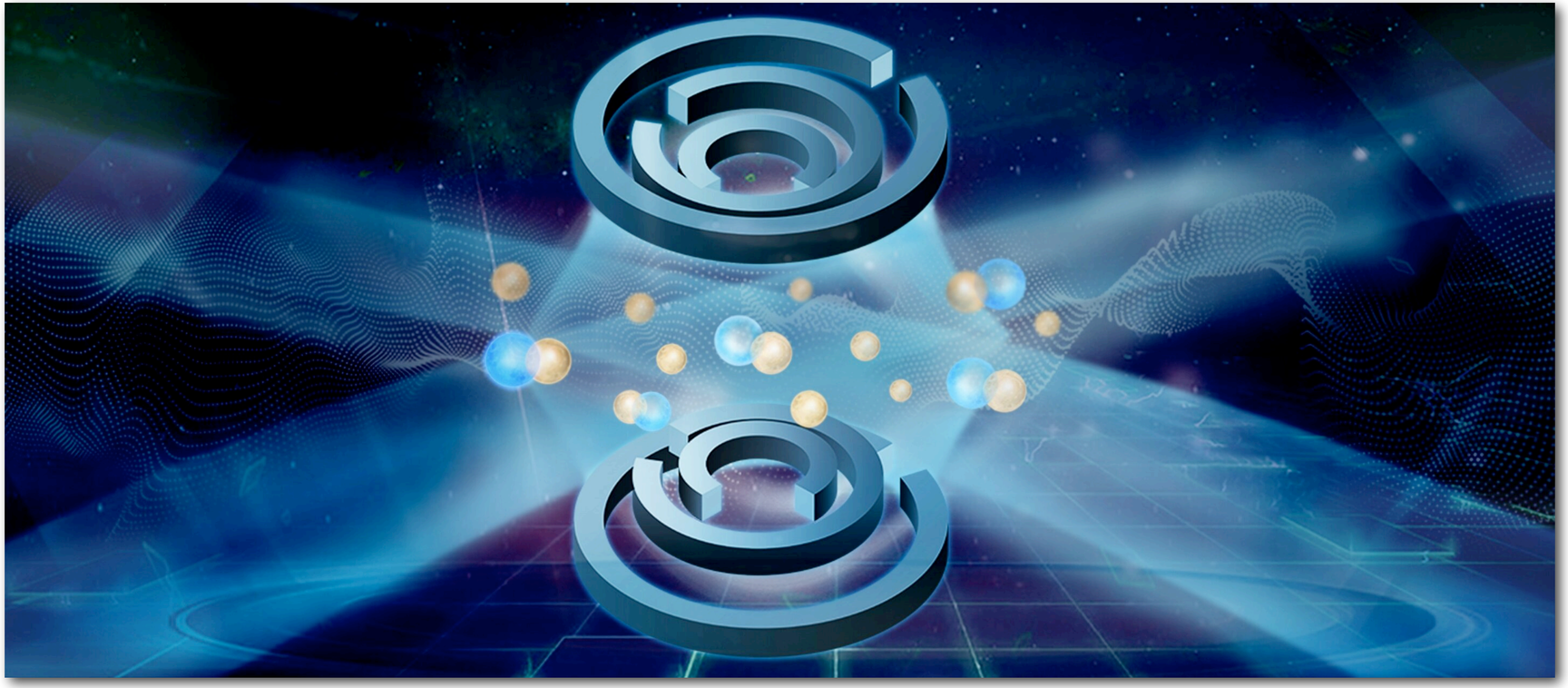


Reflection coefficient at predicted eigenstate energies and are visible below one nanoKelvin — which has already been achieved in experiments — with 100 picoKelvin reachable in the near future.

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
N. Mantella, C. M. Bender, A. D. Stone, **Micheline B. Soley**, A. M. Steinberg, in preparation.

REFLECTIONLESS SCATTERING MODE THEORY FOR OBSERVATION OF LONG-ELUSIVE FUNDAMENTAL QUANTUM PHENOMENA

$\mathscr{PT}$ symmetry in the world of Schrödinger atomic and molecular quantum scattering



Ultracold atomic demonstration underway

Applications: Quantum Sensing and Quantum Computing

Micheline B. Soley, C. M. Bender, A. D. Stone, Phys. Rev. Lett. (2023) 250404.
Micheline B. Soley, A. D. Stone, in preparation.
C. Killion, A. D. Stone, **Micheline B. Soley**, in preparation.
N. Mantella, C. M. Bender, A. D. Stone, **Micheline B. Soley**, A. M. Steinberg, in preparation.

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SIMONS FOUNDATION

EPSRC

YQ

Soley Research Group Members: Ahmed Elkamshishy, Jingcheng Dai, **Camerin Killion**, Atharva Vidwans, Henry Lin, Eric H. Wan, Alexander Miller, **Shrikar Dulam**

Collaborators: **Carl M. Bender** (WUSTL), **A. Douglas Stone** (Yale), **Aephraim M. Steinberg** (UToronto), Eugene Shakhnovich (Harvard), Steven Girvin (Yale), Eleanor Crane (MIT), Christopher Kang (UChicago), Jeremy Richardson (ETH Zürich), Paul Bergold (USurrey), Nathan Wiebe (UToronto), Xuhui Huang (UW-Madison), Yazhen Wang (UW-Madison), Aviva Englander (UW-Madison), Thi Ha Kyaw (LG)

Thank You!