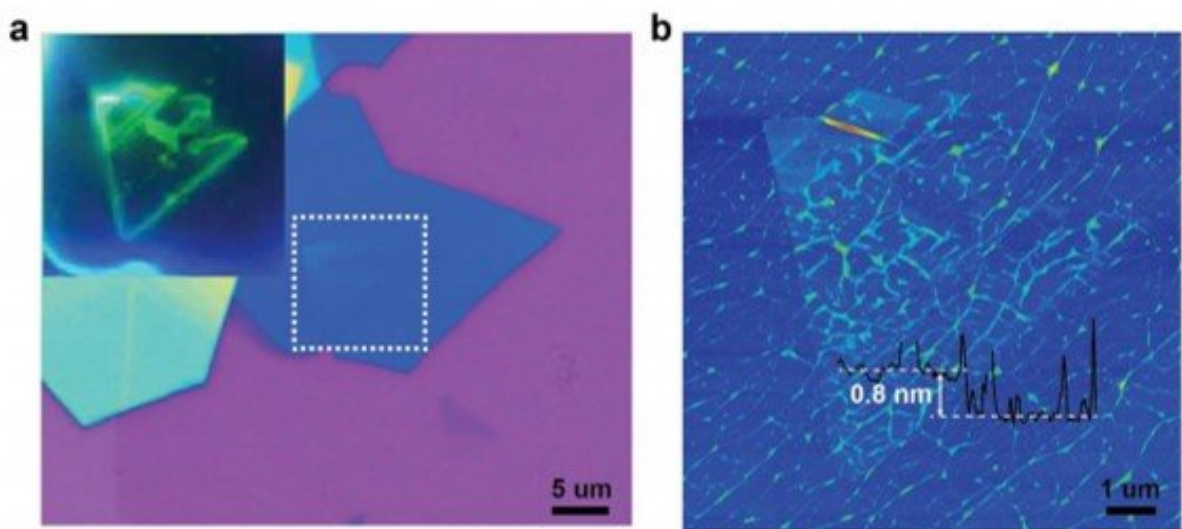


Giant gate-tunable bandgap renormalization and excitonic effects in a 2-D semiconductor

July 25 2019, by Thamarasee Jeewandara



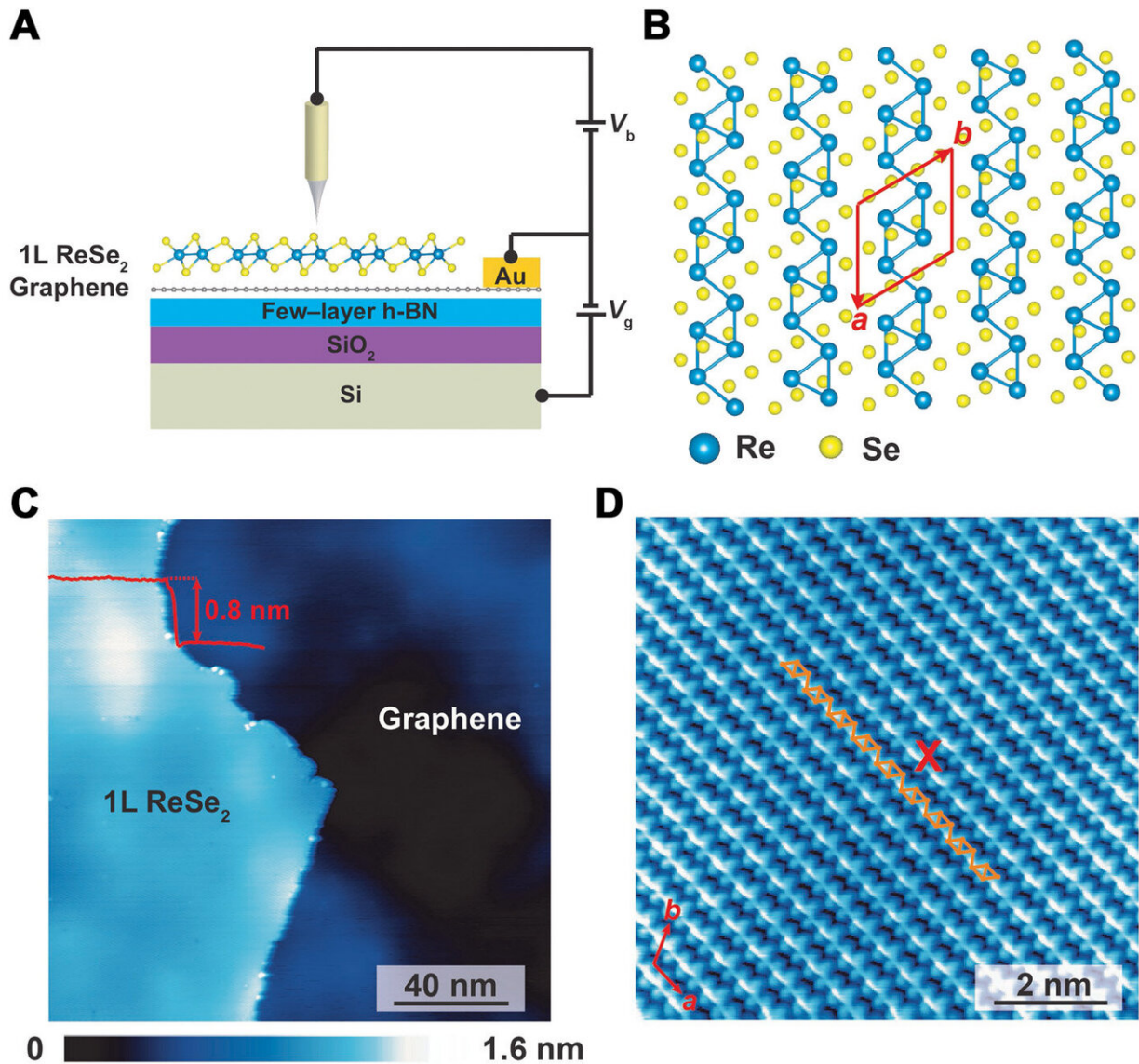
Identify the thickness of monolayer ReSe2. (A) The optical image of monolayer ReSe2 (inside the dashed rectangle) transferred on G/h-BN. The inset image is the dark field optical image for the ReSe2 flake. (B) The AFM image of monolayer ReSe2. Inset: the step height of exfoliated ReSe2 flake is measured to be $\sim 0.8 \pm 0.1$ nm, suggesting a monolayer thickness. Credit: Science Advances, doi: 10.1126/sciadv.aaw2347

Investigating the remarkable [excitonic](#) effects in two-dimensional (2-D) semiconductors and controlling their [exciton binding energies](#) can unlock the full potential of 2-D materials for future applications in [photonic](#) and

[optoelectronic devices](#). In a recent study, Zhizhan Qiu and colleagues at the interdisciplinary departments of chemistry, engineering, advanced 2-D materials, physics and materials science in Singapore, Japan and the U.S. demonstrated large excitonic effects and gate-tunable exciton binding energies in single-layer [rhenium diselenide](#) (ReSe_2) on a back-gated graphene device. They used [scanning tunneling spectroscopy](#) (STS) and [differential reflectance spectroscopy](#) to measure the quasiparticle (QP) electronic and optical bandgap (Eopt) of single-layer ReSe_2 to yield a large exciton binding energy of 520 meV.

The scientists achieved continuous tuning of the electronic bandgap and exciton binding energy of monolayer ReSe_2 by hundreds of milli-electron volts via electrostatic gating. Qiu et al. credited the phenomenon to tunable Coulomb interactions arising from the gate-controlled free carriers in graphene. The new findings are now published on *Science Advances* and will open a new avenue to control bandgap renormalization and exciton binding energies in 2-D semiconductors for a variety of technical applications.

Atomically thin two-dimensional (2-D) semiconductors usually display large [bandgap renormalization](#) (shifts in physical qualities) and extraordinary excitonic effects due to [quantum confinement](#) and reduced [dielectric screening](#). Light-matter interactions in these systems are governed by enhanced excitonic effects, which physicists have studied to develop [exciton-based devices at room temperature](#). A unique feature of 2-D semiconductors is their unprecedented tunability relative to both electric and [optical properties](#) due to [doping and environmental screening](#).



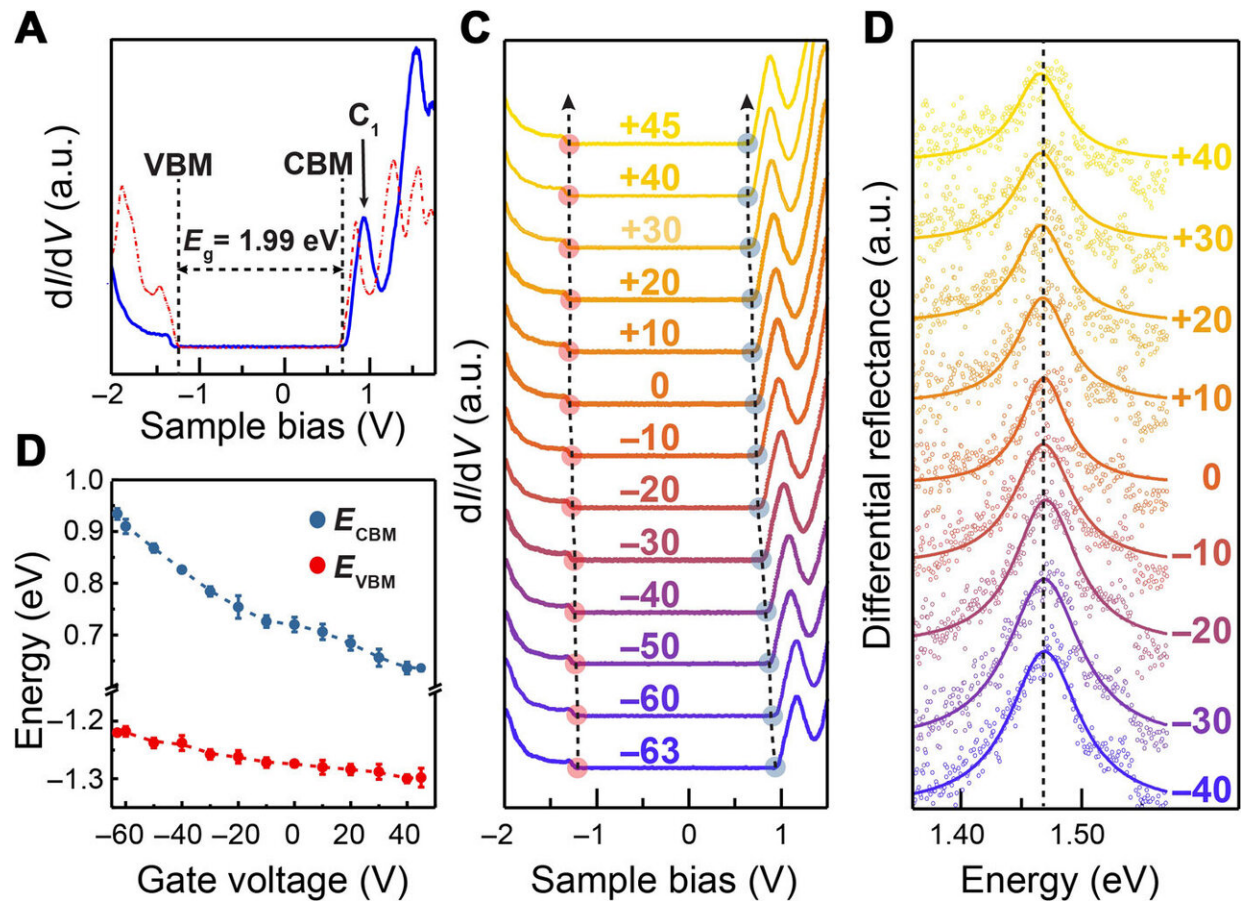
STM images of moiré pattern in monolayer ReSe₂/graphene. (A to C) Representative moiré patterns observed in the experiment. (D to F) Calculated moiré patterns obtained from the geometrical analysis. θ is the stacking angle between ReSe₂ and graphene. Credit: *Science Advances*, doi: 10.1126/sciadv.aaw2347

Researchers can engineer theoretically predicted and experimentally demonstrated Coulomb interactions in 2-D semiconductors to tune the

quasiparticle bandgap (E_g) and exciton binding energies (E_b) of samples, with methods such as [chemical doping](#), [electrostatic gating](#) and [engineering environmental screening](#). Among the reported techniques, electrostatic gating offers additional advantages such as continuous tunability and excellent compatibility for integration in modern devices. However, an overlap of the band-edge absorption step with strong excitonic resonances makes it challenging to accurately determine the E_g of 2-D semiconductors from their optical absorption spectrum alone.

Scientists had therefore used scanning tunneling spectroscopy and optical spectroscopy to directly probe the E_b of 2-D semiconductors and [measure \$E_g\$](#) and the [optical bandgap \(\$E_{opt}\$ \)](#). In the present work, Qiu et al. similarly used this approach to demonstrate gate-tunable E_g and excitonic effects in monolayer ReSe_2 on a back-gated graphene [field-effect transistor](#) (FET) device. They observed a large E_b of 520 meV for monolayer ReSe_2 at zero gate voltage, followed by continuously tuning from 460 to 680 meV via electrostatic gating due to gate-controlled free carriers in graphene. The ability to precisely tune the bandgap and excitonic effects of 2-D graphene semiconductors will provide a new route to optimize interfacial charge transport or light-harvesting efficiency. Qui et al. expect the present findings to profoundly impact new electronic and optoelectronic devices based on artificially engineered [van der Waals heterostructures](#).

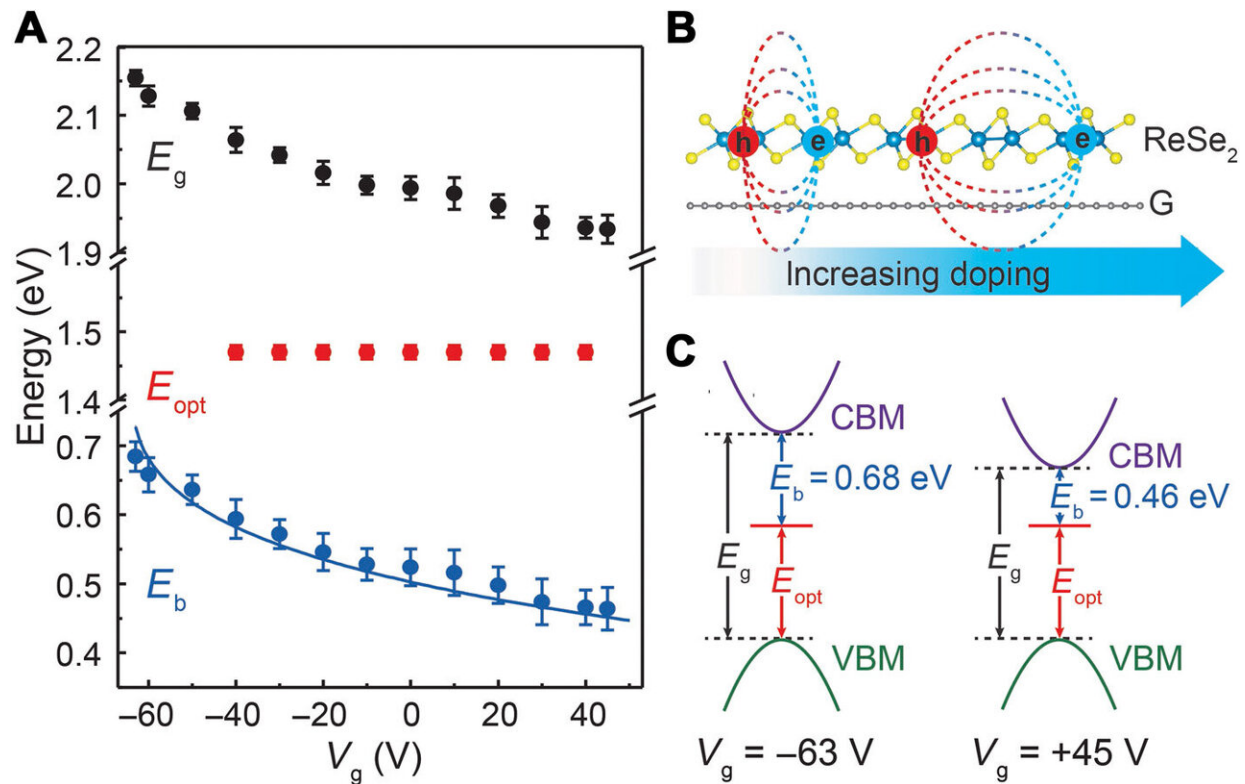
Qui et al. first imaged the monolayer ReSe_2 to show a distorted $1T$ structure with [triclinic](#) symmetry. The four Re atoms slipped from their regular octahedral sites due to charge decoupling to form a 1D chain-like structure with interconnected diamond-shaped units. Due to the topological features, the monolayer ReSe_2 exhibited unique in-plane anisotropic electronic and optical properties useful for near-infrared [polarization-sensitive optoelectronic applications](#).



Gate-dependent dI/dV and differential reflectance spectra of a monolayer ReSe₂ on graphene. (A) dI/dV spectrum of monolayer ReSe₂ (blue line) at $V_g = 0$ V together with the calculated LDOS (dashed red line). (B) Energy position of VB maximum (VBM; red points) and CB minimum (CBM; dark blue points) as a function of the gate voltage. (C) Gate-dependent dI/dV spectra of the monolayer ReSe₂ on graphene/h-BN measured at 4.5 K. As-applied gate voltage is indicated above each STS curve. The VBM and CBM were indicated by light red and light blue points, respectively. (D) Gate-dependent differential reflectance spectra of the monolayer ReSe₂ on graphene/h-BN measured at 5 K. The corresponding gate voltage is indicated on the side of each differential reflectance spectrum. Note: The original differential reflectance spectra after background subtraction (circles); fitted curves using the Lorentzian function (solid lines). a.u., arbitrary units. Credit: *Science Advances*, doi: 10.1126/sciadv.aaw2347.

To probe carrier-dependent excitonic effects, the scientists first transferred a monolayer ReSe_2 flake on to a clean back-gated graphene [FET \(field effect transistor\) device](#). The device constituted of several components according to [a previously established recipe](#) to include a SiO_2 substrate, which contrasted with the constituent [atomic flatness of hexagonal boron nitride \(hBN\)](#) that markedly reduced surface roughness and charge inhomogeneity in graphene. The use of graphene allowed direct scanning tunneling microscopy (STM) measurements of the gated single-layer ReSe_2 while [improving the electrical contact](#) to monolayer ReSe_2 .

After STM imaging the atomically resolved image revealed a diamond chain-like structure [as expected for monolayer \$\text{ReSe}_2\$](#) with a distorted $1T$ atomic structure. The scientists observed the stacking alignment of the material along two crystallographic orientations as [moiré patterns](#), where monolayer ReSe_2 containing a triclinic lattice symmetry lay on graphene with a honeycomb lattice.



Gate-tunable bandgap renormalization and exciton binding energy of monolayer ReSe₂ on graphene. (A) A plot of QP bandgap E_g (black points), optical bandgap E_{opt} (red points), and exciton binding energy E_b (blue points) as a function of gate voltage. Note: The $E_{opt} = 1.47 \pm 0.01$ eV remains constant when the gate voltage increases from -40 to 40 V. Note: The same E_{opt} is used for the calculation of E_b at the gate voltage of -63 , -60 , -50 , and $+45$ V. The solid blue line refers to the theoretically predicted E_b as a function of the gate voltage (refer to section S8 for more details). (B) Illustration of the screening of electron-hole interactions in monolayer ReSe₂ by the gate-controlled free carriers in graphene. (C) Schematic illustration of gate-tunable E_g and E_b of monolayer ReSe₂ at the gate voltage of -63 and $+45$ V, respectively. Credit: Science Advances, doi: 10.1126/sciadv.aaw2347.

When they probed the local electronic properties of ReSe₂ using STS (scanning tunneling spectroscopy) the scientists observed differential

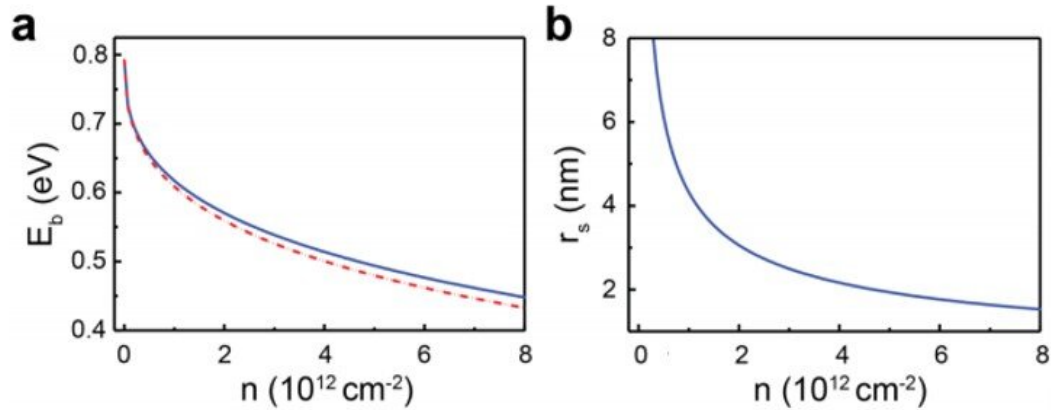
conductance (dI/dV) spectra in several moiré regions to exhibit similar features. As a unique feature of the study, Qiu et al. probed the quasiparticle (QP) band structures as a function of gate voltage.

The optical bandgap (E_{opt}) remained nearly constant at all gate voltages in contrast to the monotonic reduction of E_g , in agreement with [previous experimental studies](#). To verify this, they performed photoluminescence measurements of the monolayer ReSe_2 /graphene/h-BN sample at different gate voltages at room temperature (RT). The gate-dependent photoluminescence spectra revealed a nearly constant E_{opt} of monolayer ReSe_2 .

The scientists then determined the exciton binding energy and derived a large, gate-tunable bandgap renormalization for ReSe_2 in the hybrid device. They sought the physical origins of the gate-tunable QP bandgap renormalization and exciton binding energy in the monolayer ReSe_2 by excluding contributions from the out-of-plane field-induced polarization wave functions and substantiated their origin from gate-induced free carriers in graphene. Theoretical results of the study also showed that moderate doping in graphene could substantially reduce exciton binding energy (E_b) by hundreds of milli-electron volts as the free-carrier concentration in graphene increased. In addition, Qiu et al. directly compared the theory with their experimental results.

In this way, Zhizhan Qiu and co-workers successfully tailored the QP bandgap and exciton binding energy in a 2-D semiconductor by controlling doping of the underlying graphene with electrostatic gating. The results showed that screening from a graphene substrate had profound impact on Coulomb interactions that lead to broad tunability of the electronic band gap and exciton binding energy. The findings revealed [many-electron physics](#) in hybrid 2-D semiconductors or [graphene](#) systems. The work will pave the way to control excitonic effects and precisely tune the exciton binding energies in 2-D

semiconductors for a variety of technical applications.



Calculation of E_b in monolayer ReSe2 as a function of the carrier density in graphene substrate. Exciton binding energy (E_b) and Thomas-Fermi screening radius (r_s) as a function of electron concentration (n) in graphene. (A) The carrier-dependent E_b for

More information: Zhizhan Qiu et al. Giant gate-tunable bandgap renormalization and excitonic effects in a 2-D semiconductor, *Science Advances* (2019). [DOI: 10.1126/sciadv.aaw2347](https://doi.org/10.1126/sciadv.aaw2347)

Miguel M. Ugeda et al. Giant bandgap renormalization and excitonic effects in a monolayer transition metal dichalcogenide semiconductor, *Nature Materials* (2014). [DOI: 10.1038/nmat4061](https://doi.org/10.1038/nmat4061)

Dmitrii Unuchek et al. Room-temperature electrical control of exciton flux in a van der Waals heterostructure, *Nature* (2018). [DOI: 10.1038/s41586-018-0357-y](https://doi.org/10.1038/s41586-018-0357-y)

Jyoti Katoch et al. Giant spin-splitting and gap renormalization driven by trions in single-layer WS₂/h-BN heterostructures, *Nature Physics* (2018).
[DOI: 10.1038/s41567-017-0033-4](https://doi.org/10.1038/s41567-017-0033-4)

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