

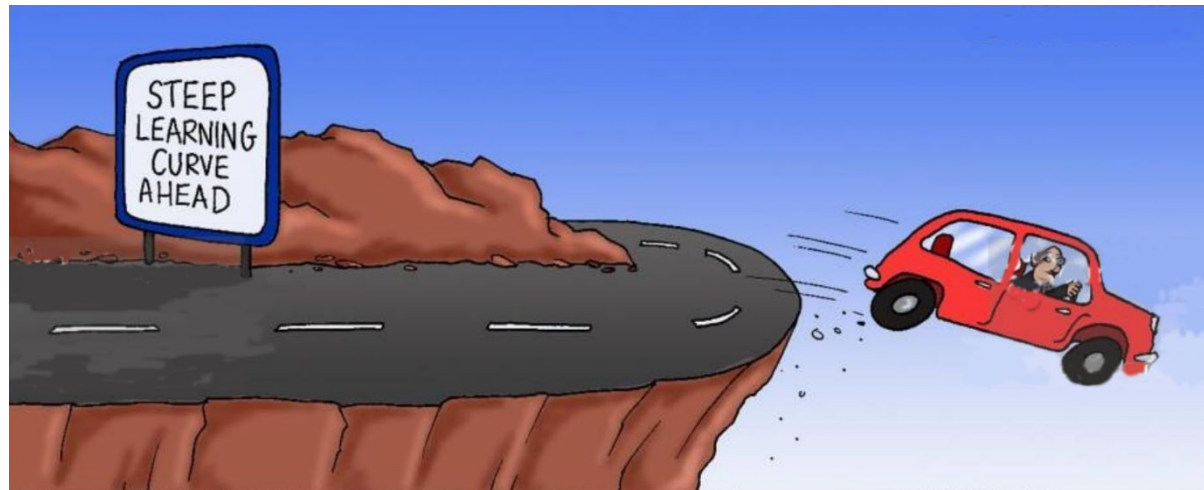
Atoms to applications and the future of electronics

A.F.J. Levi

University of Chicago, Friday February 9, 2024

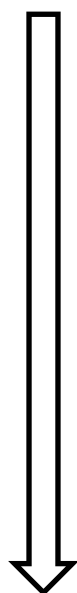
The future of electronics

There is a lot to learn ...

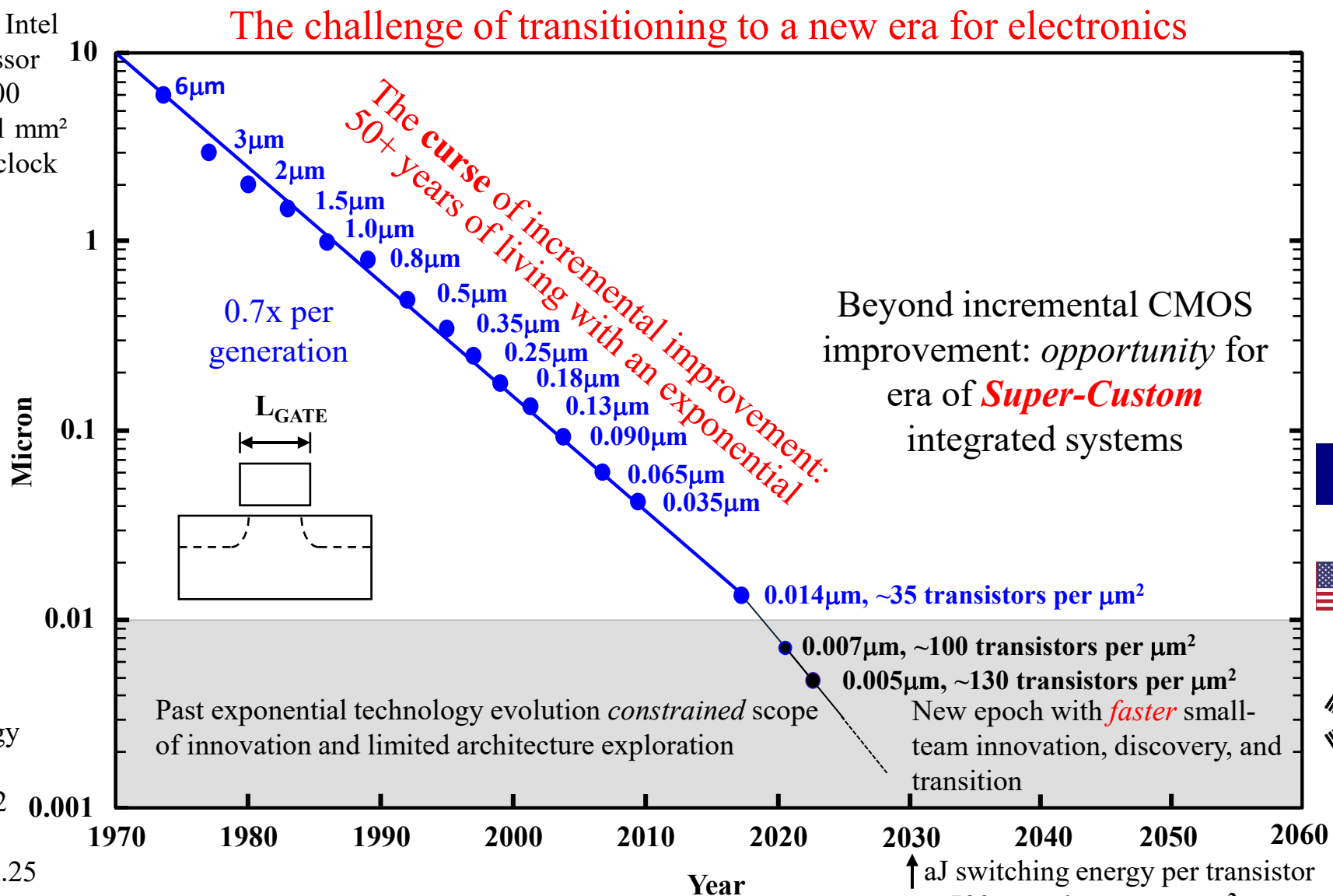


A shift to hardware specialization and heterogeneity for continued system performance and efficiency gains after transistor scaling ends

6 μm technology Intel 8080 8-bit processor in 1974 with 4,500 transistors in 20.1 mm^2 area and 2 MHz clock


 Increase in transistor density 575,000
 Increase in clock frequency 1,500
 Increase in word length 8

0.005 μm (5 nm) CMOS technology Apple M2 64-bit processor in 2022 with 20 billion transistors in 155.25 mm^2 area and 3 GHz clock



A 2020 view



} A transistor-density gap

Geographically ~60x closer to mainland China than US

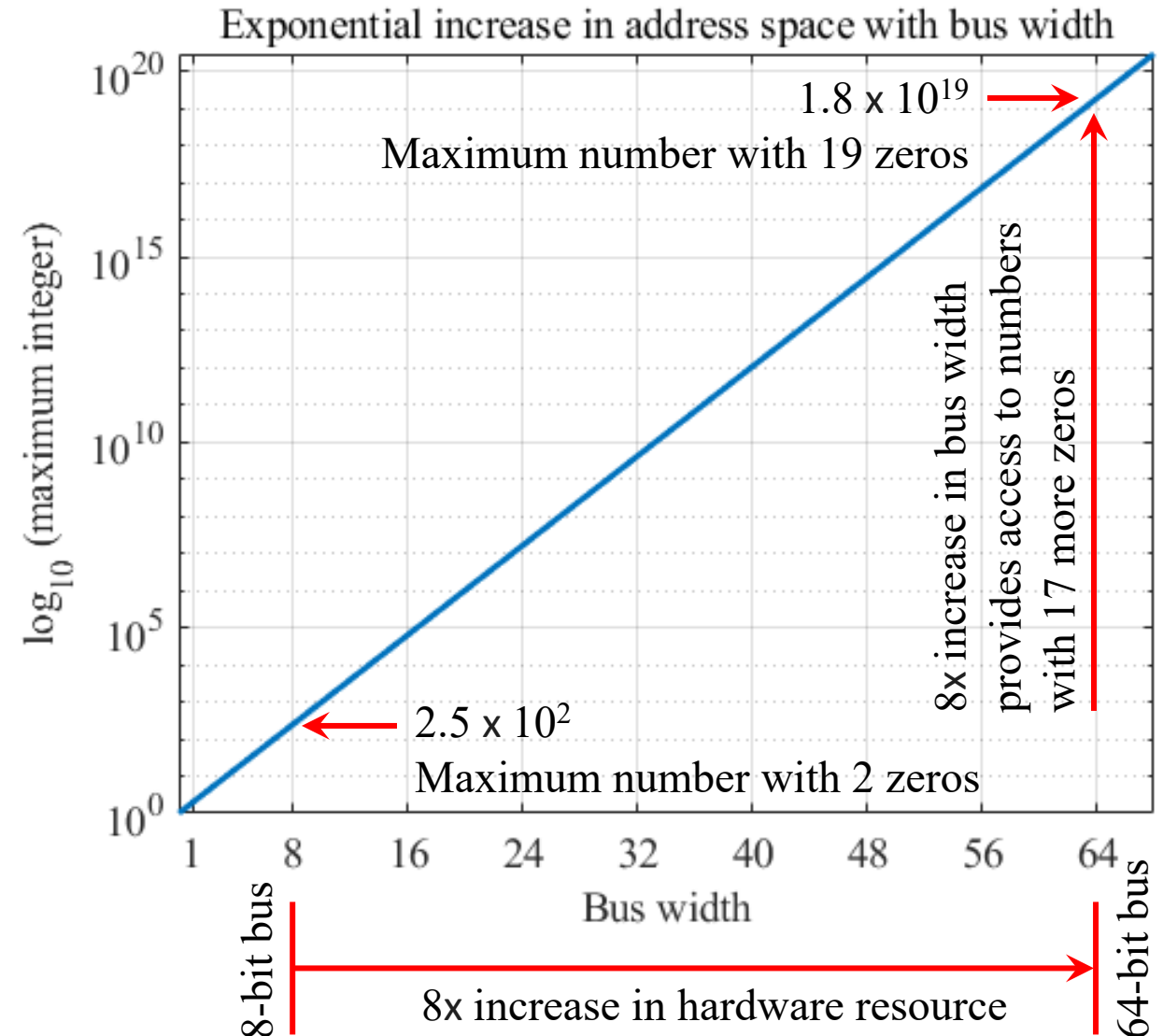
Gravity in economics

“Towards Quantum Engineering”, A F J Levi, *Proceedings of the IEEE* 96, 335 (2008)

A small amount of hardware provides access to an exponentially vast cyber space

Exponential leverage of hardware resources:

- 8-bit bus has address space $2^8 = 256 = 2.5 \times 10^2$
- 64-bit bus address space is $2^{64} = 1.8 \times 10^{19}$
- Efficient double precision FP calculations

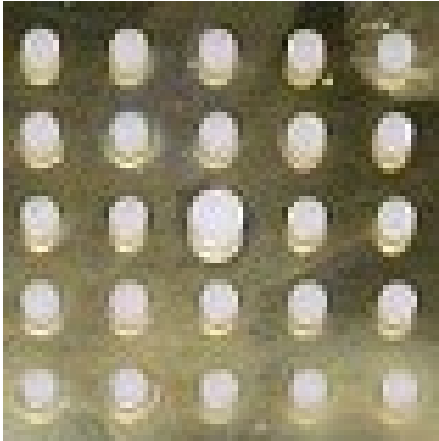


A small amount of hardware provides access to an exponentially vast cyber space

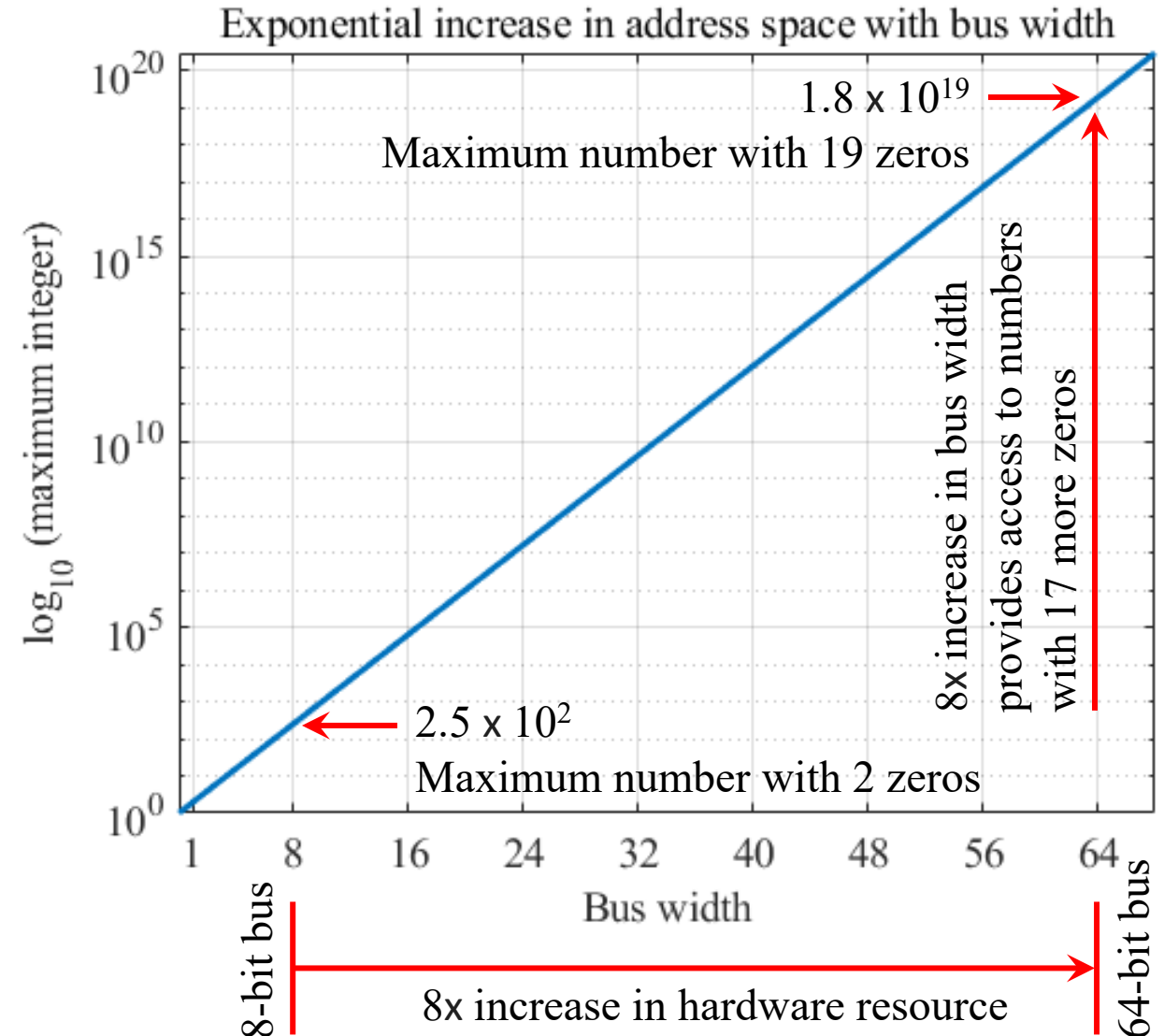
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- Efficient double precision FP calculations

Also, now possible to search for new electronic device and system functionality



Broken symmetry and exponential increase in search space for optimal device function



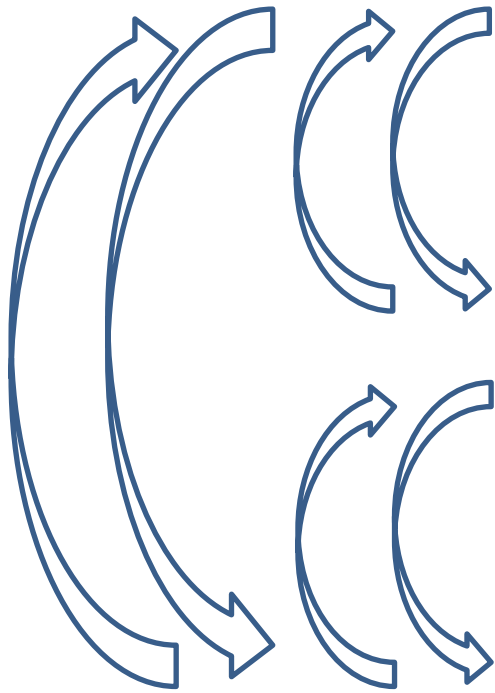
Vast cyber space →  search engine

Vast quantum engineering design space

→ new **Quantum** search engine

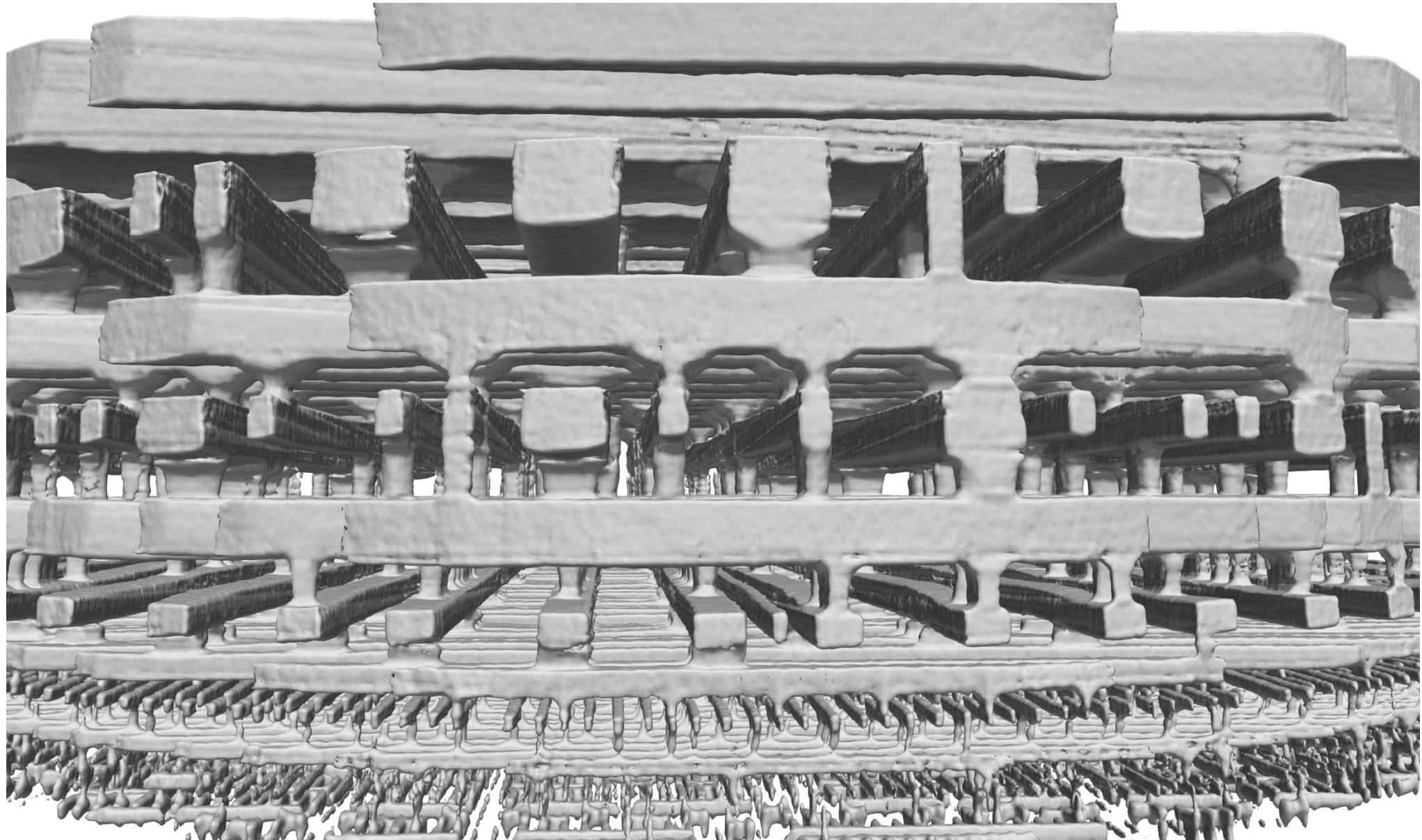
Elements of future **Quantum** search engine

Co-design feedback loops

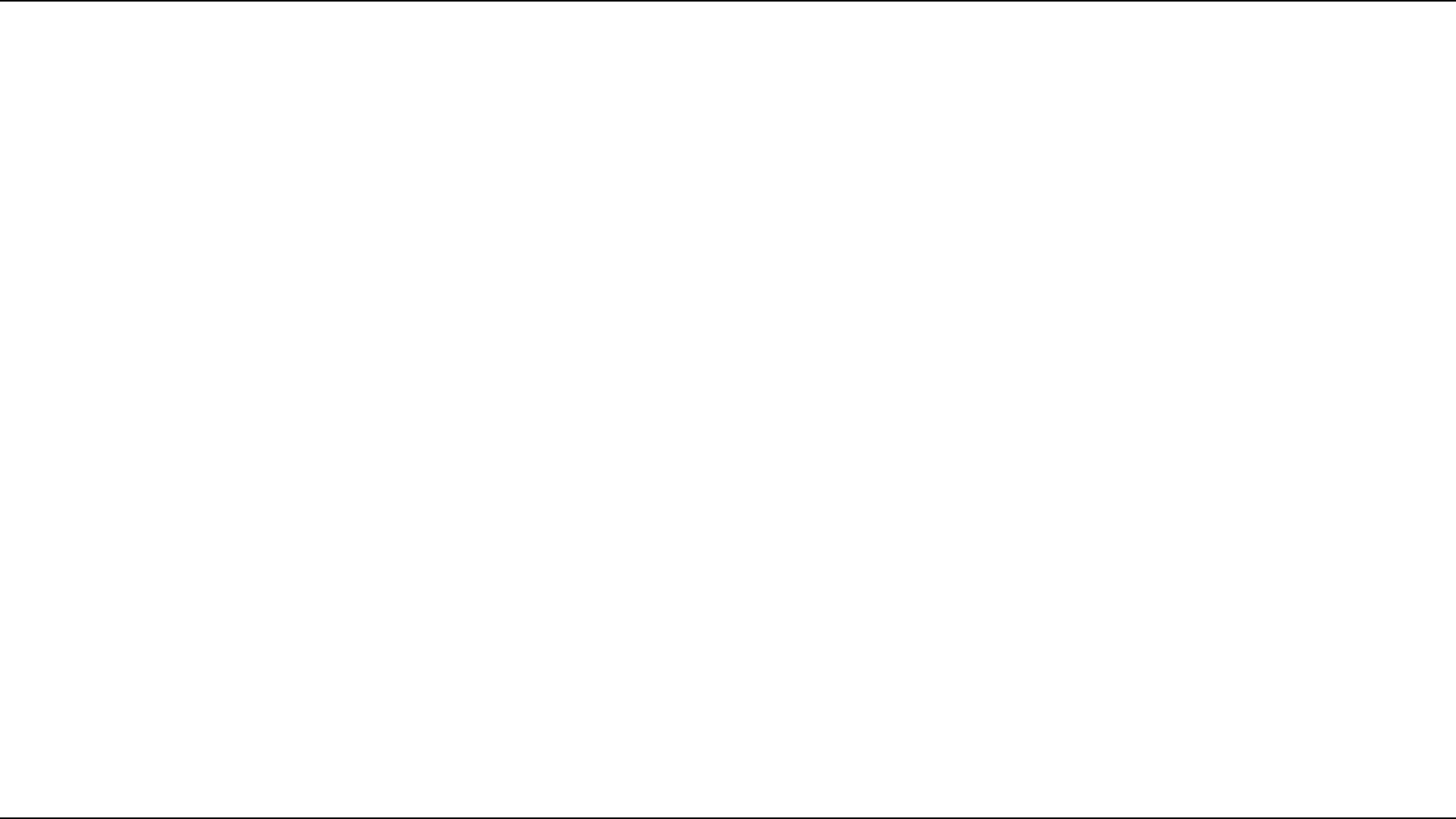


The connectome

Chip Scan: 3D x-ray image of Intel Pentium G3260 processor metal interconnect “connectome” manufactured in 22 nm FinFET technology



500 nm



Atoms to applications

Quantum engineering: Atom position and function

Quantum engineering: Broken symmetry to control density of electron states

Motivation

- Electron transitions determined by golden rule (the first term in the Born series)
 - Use position of atoms to control density of electron states, $N(E)$
- Example: Forward physical model (an *abstraction*) is *long-range* tight binding using s-orbitals with hopping integral interaction strength, $t_{i,j}$, parameterized by power law, α
 - Periodic boundary conditions
 - Full matrix
- In this example, optimization minimizes $\mathcal{L}^\gamma$ ($\gamma=2$) distance measure between simulated and objective density of states

$$\frac{1}{\tau_n} = \frac{2\pi}{\hbar} |W_{mn}|^2 N(E) \delta(E_m - E_n)$$

$$\hat{H}_{\hat{c}^\dagger \hat{c}} = - \sum_{i < j} t_{i,j} (\hat{c}_i^\dagger \hat{c}_j + \hat{c}_i \hat{c}_j^\dagger)$$

$$t_{i,j} = t_{\text{hop}} / |\mathbf{r}_i - \mathbf{r}_j|^\alpha$$

$$C_{\text{cost}} = \sum_j |N_{\text{sim},j} - N_{\text{obj},j}|^2$$

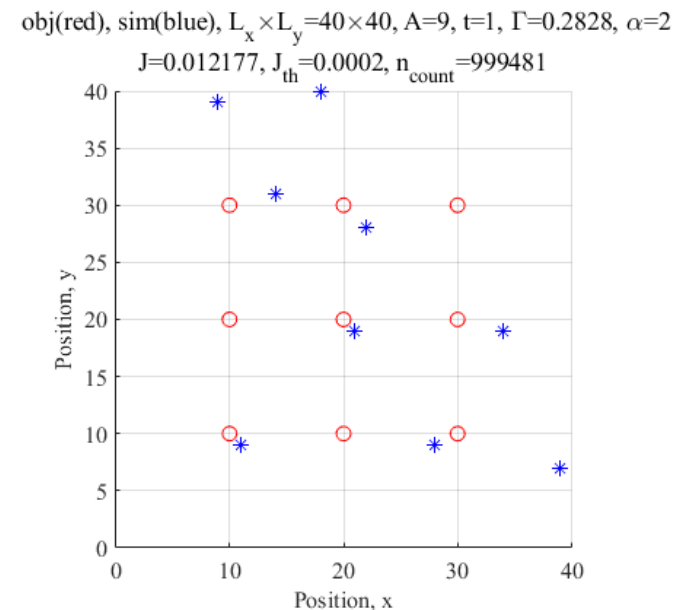
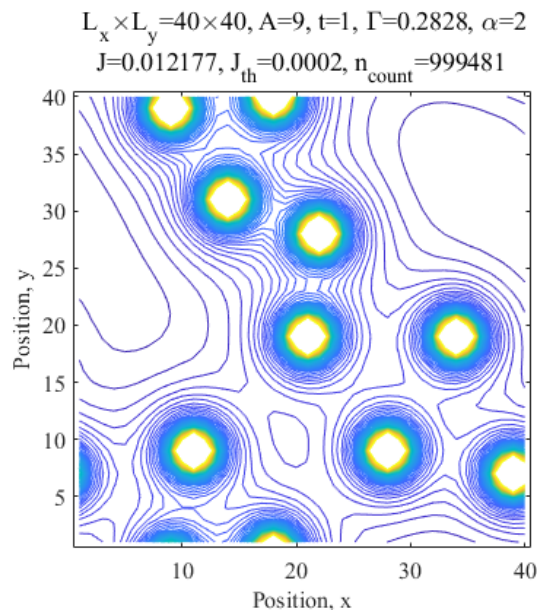
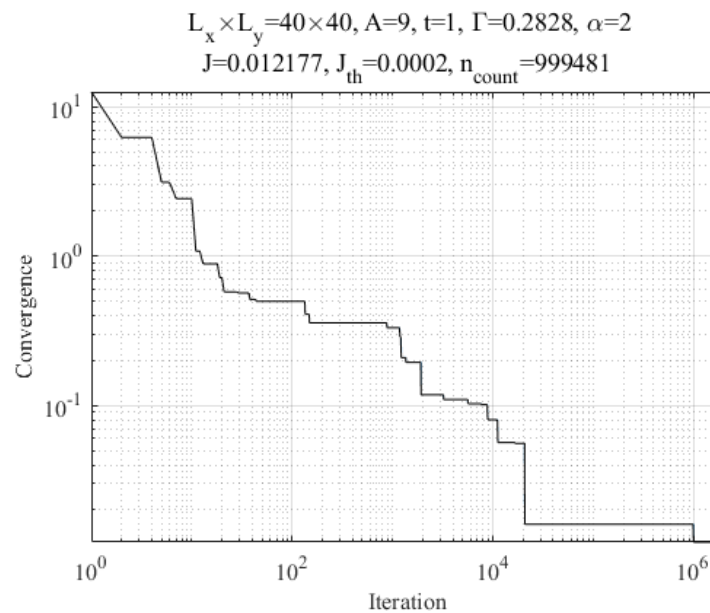
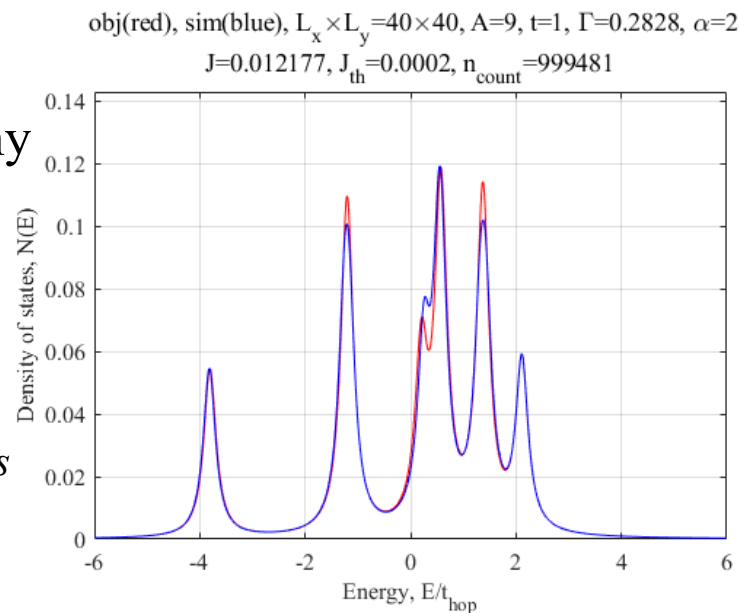
Quantum engineering: Broken symmetry to control density of electron states



Quantum engineering: Broken symmetry to control density of electron states

Typical heuristics

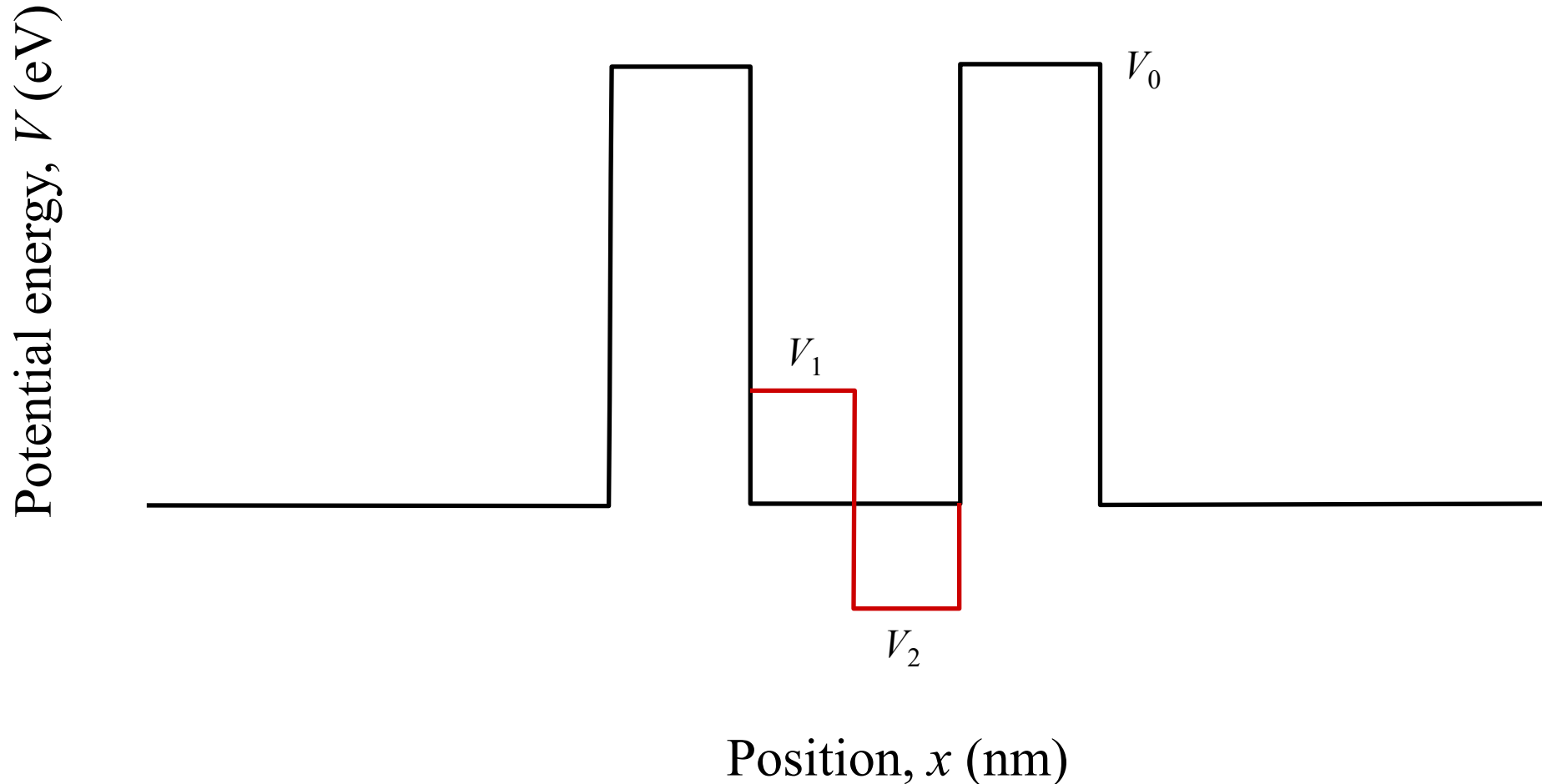
- Non-convex landscape with many local minima
- The optimization algorithm provides a *single-point solution*
 - *No understanding*. The optimization algorithm *does not explain the physics* or why the solution works
- Degeneracy from symmetries
 - Example: rotational symmetry
- Dilute limit has hierarchy of symmetric primitive building blocks that contribute to the objective density of states, $N(E)$
 - Dimers for symmetric $N(E)$
 - Trimers and larger molecular configurations can add asymmetry to $N(E)$



Expanding electronic device design space using quantum engineering of crystalline atomic layers for function

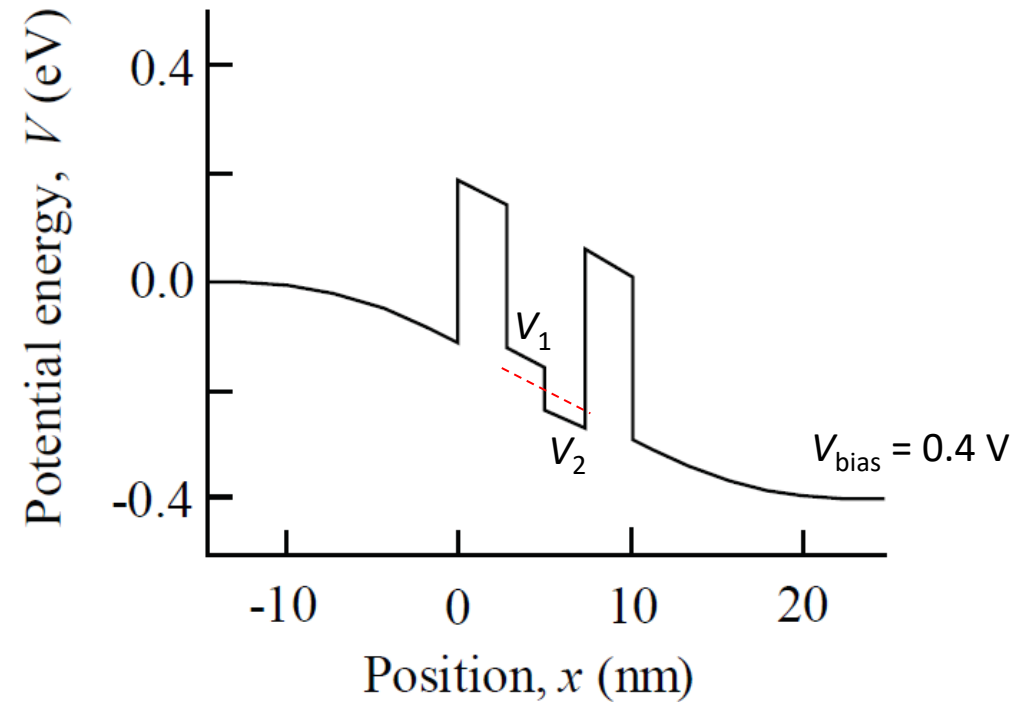
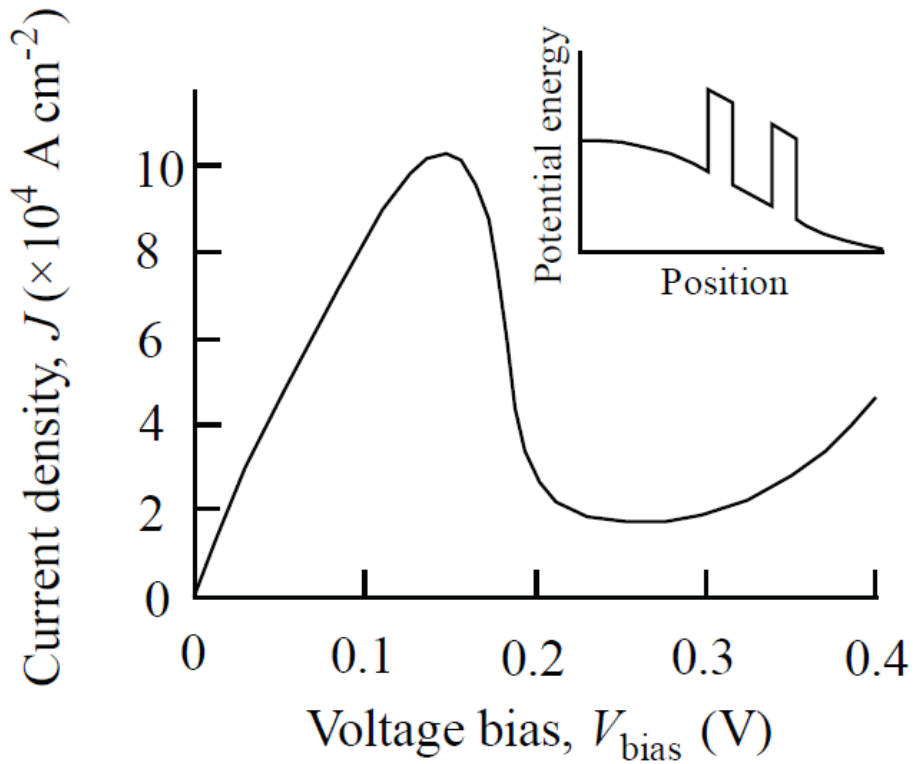
The resonant tunnel diode: Near degenerate solutions

- $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{As}$ with $-0.15 \text{ eV} \leq U_j \leq 0.3 \text{ eV}$
- $n_0 = 1.0 \times 10^{18} \text{ cm}^{-3}$
- $m_{\text{eff}}=0.07$, $V_0=0.3 \text{ eV}$, $L_w=4.52 \text{ nm}$, $L_b=2.83 \text{ nm}$



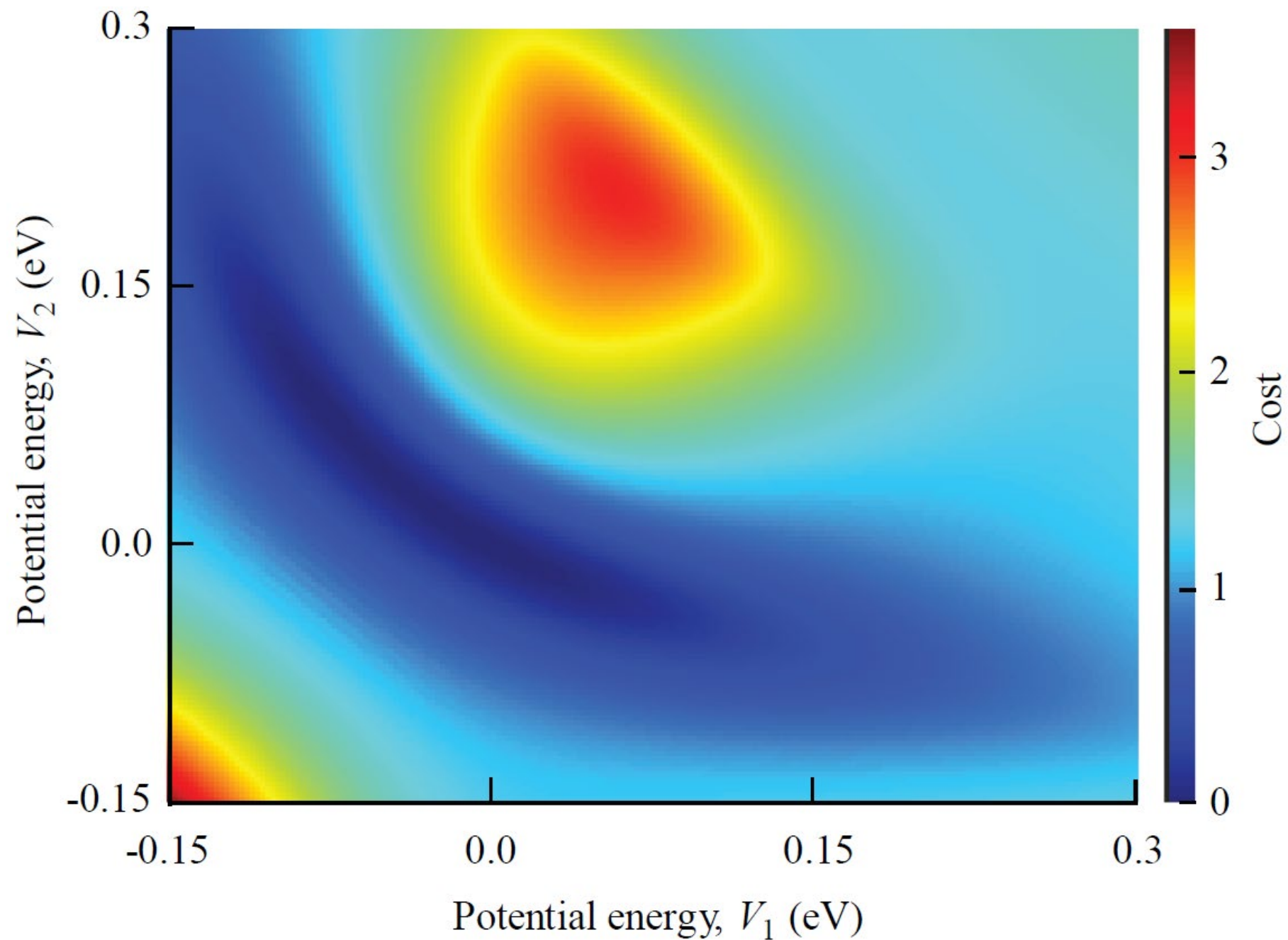
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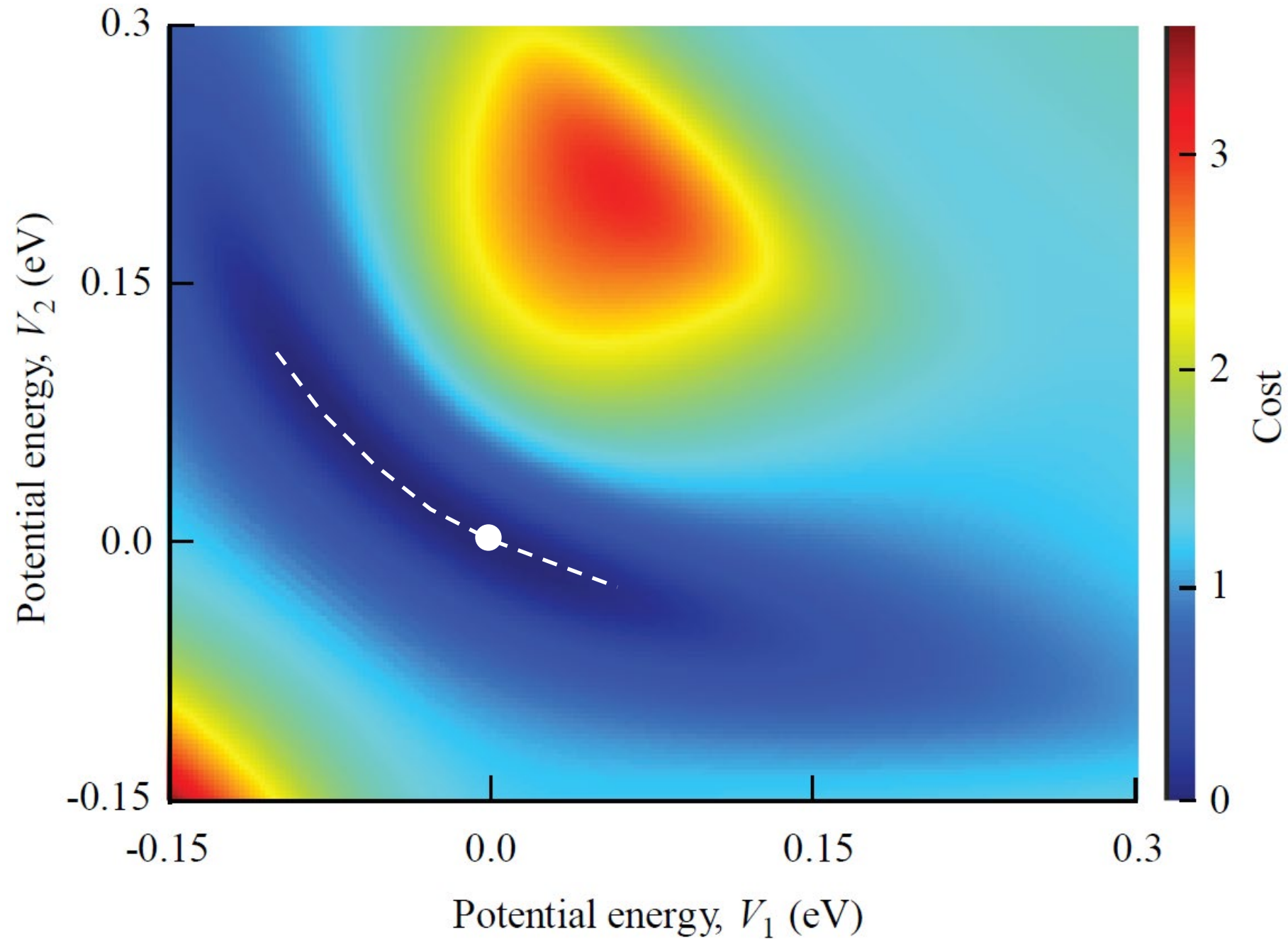


Near degenerate solution

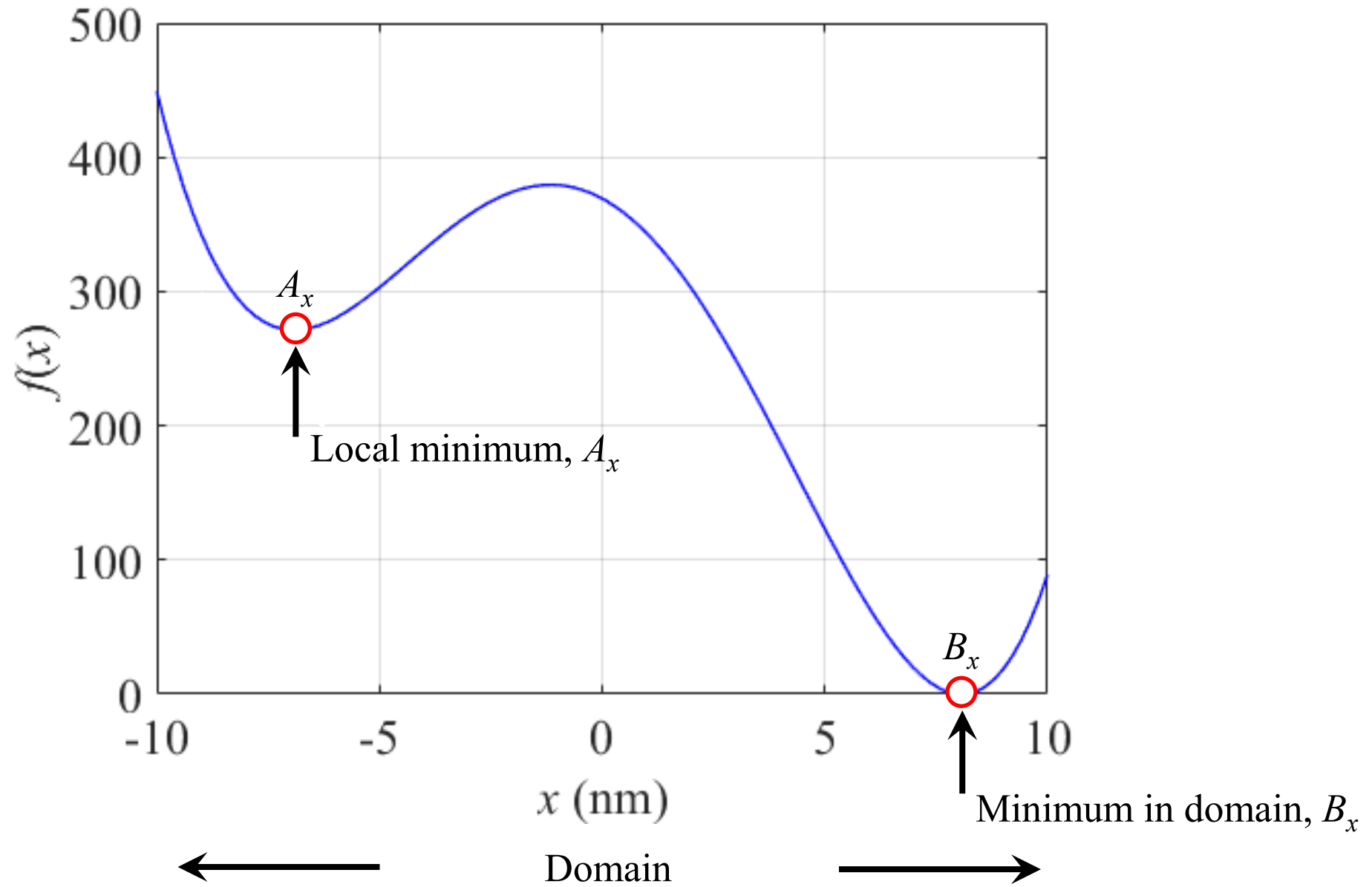
The resonant tunnel diode: Near degenerate solutions



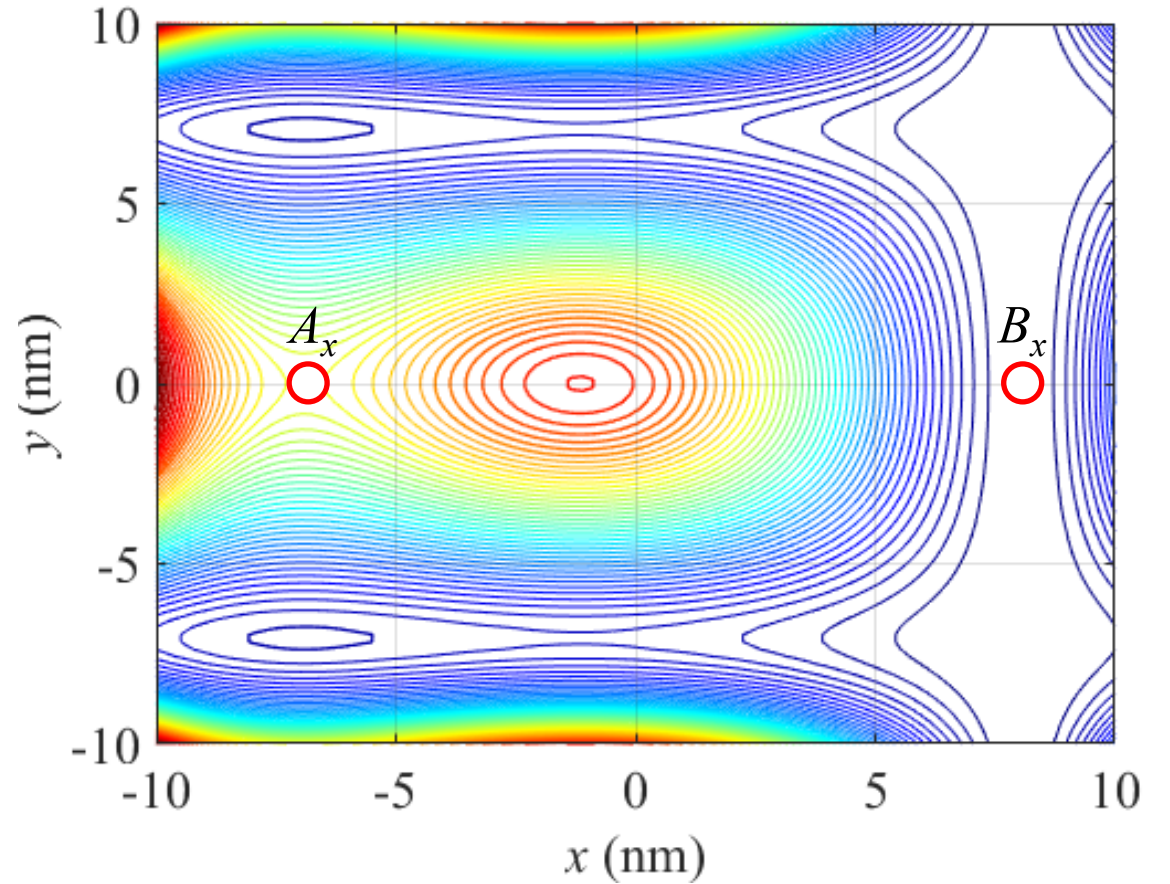
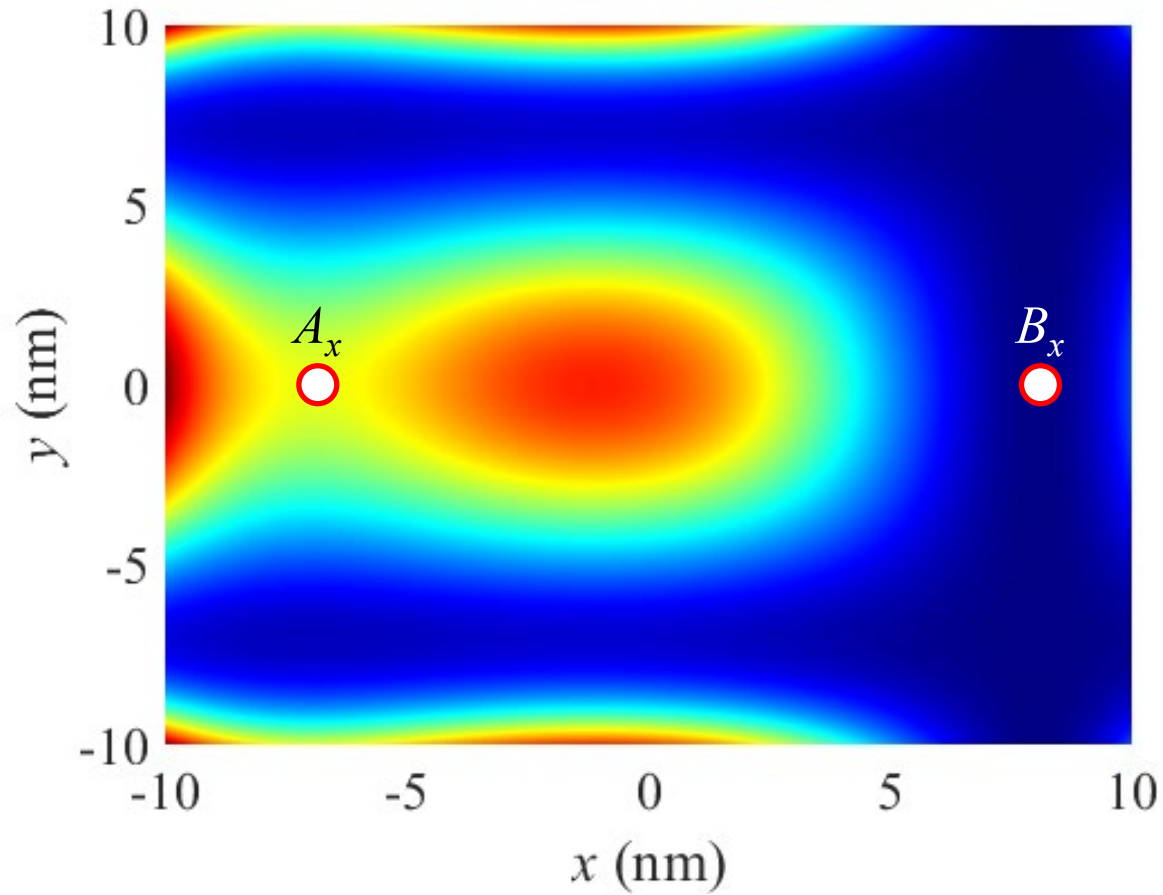
The resonant tunnel diode: Near degenerate solutions



Avoid local minima by *increasing* dimensionality: Example local minimum in 1D



Escape local minimum in 1D by increasing dimensionality to 2D



In general, statistical probability of *escaping* local minimum in dimension N by *increasing dimensionality* to M

Expanding electronic device design space using quantum engineering of multiple crystalline atomic layers for function

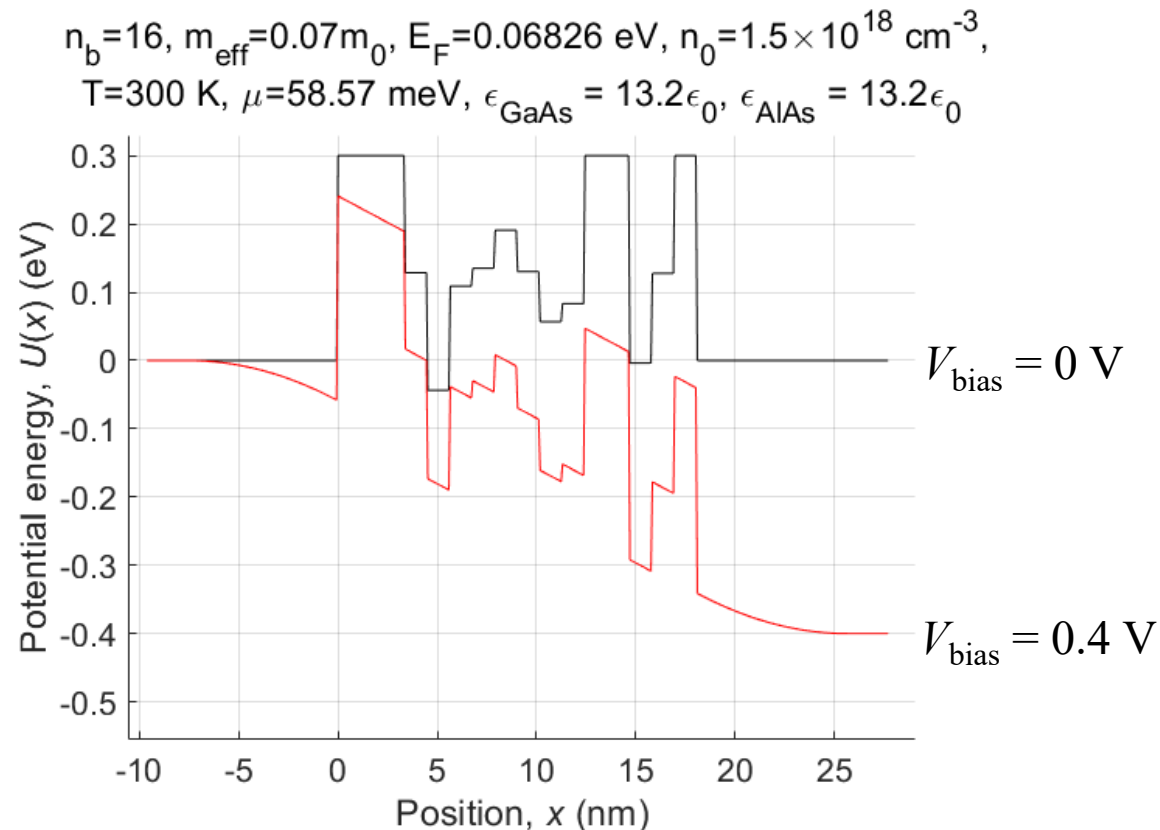
Example materials systems featuring atomic-layer precision:

- MBE compound semiconductors and other single-crystal layered materials
- vdW heterostructures

Quantum engineering and electron transport: Non-intuitive design

Motivation

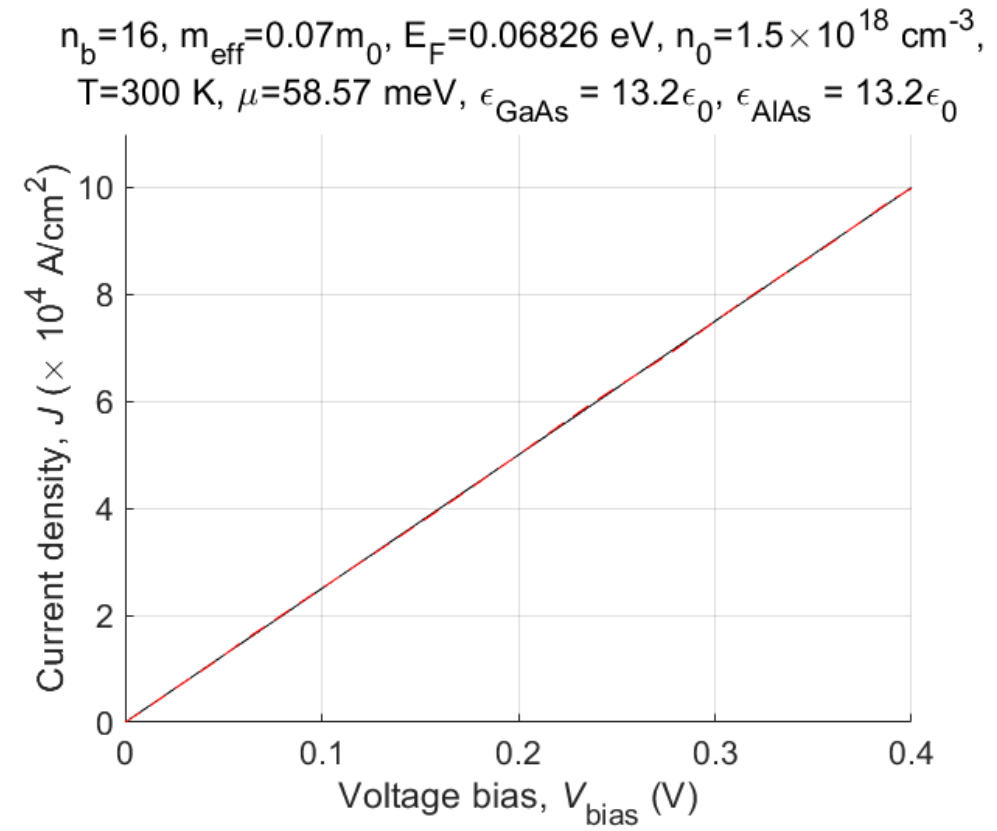
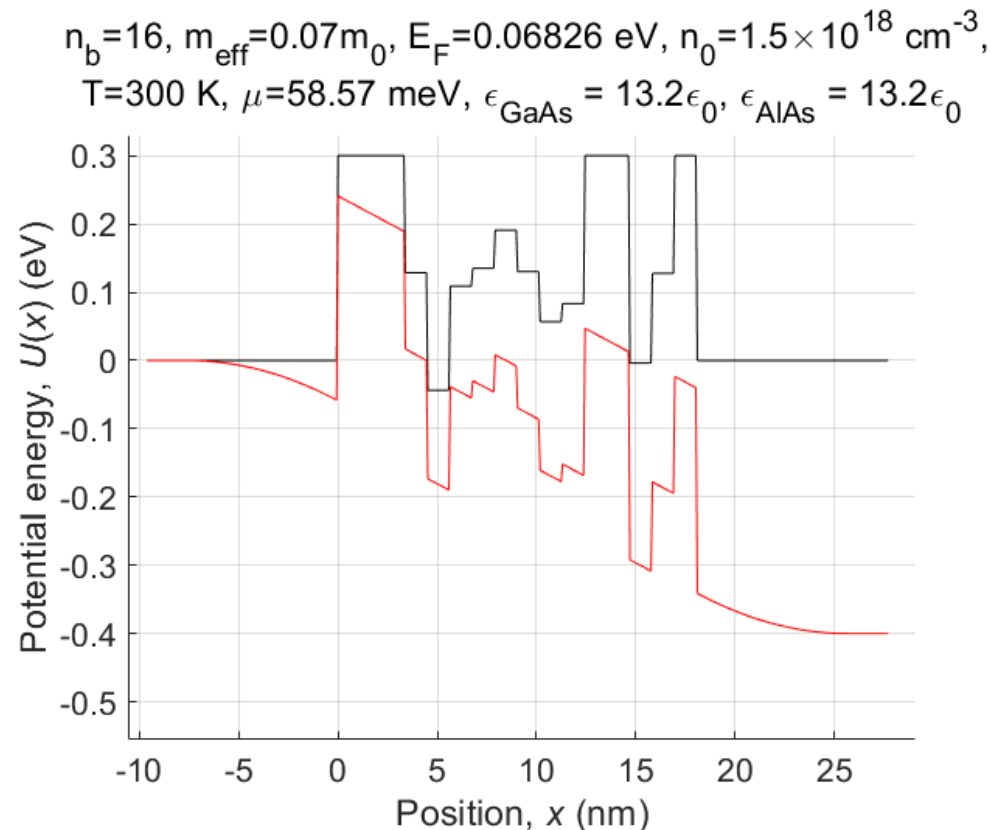
- What is the current-voltage characteristic for this semiconductor diode conduction band potential profile?
- $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{As}$ n-i-n diode with $-0.15 \text{ eV} \leq U_j \leq 0.3 \text{ eV}$ and lattice constant $L = 0.5653 \text{ nm}$
- 16 layers, each 1.131 nm thick
- $n_0 = 1.5 \times 10^{18} \text{ cm}^{-3}$, effective electron mass $m^* = 0.07 \times m_0$



Quantum engineering and electron transport: Non-intuitive design

Motivation

- What is the current-voltage characteristic for this semiconductor diode conduction band potential profile?
- Solution: Linear
 - Could you have guessed that? A *totally different* approach to creating the precise linear transfer function of a “resistor”
 - The optimization algorithm provides a *single-point solution*. There is *no understanding*. The optimization algorithm *does not explain the physics*, why the solution is *robust*, and *why the solution works so well*

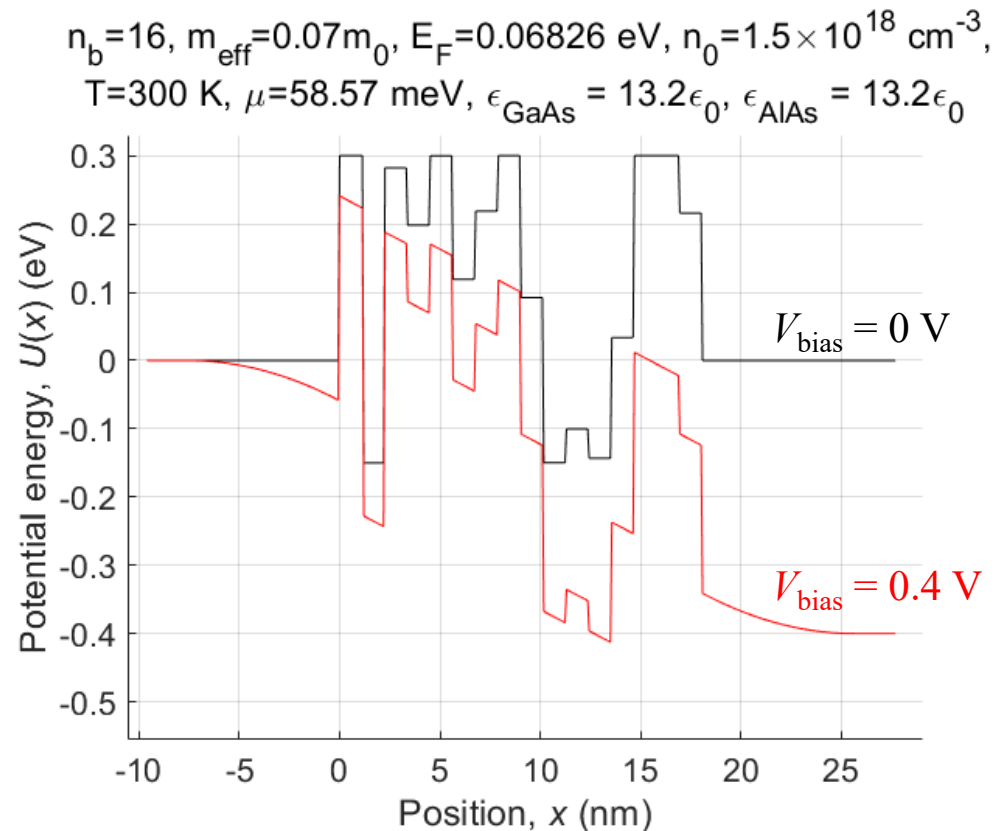




Quantum engineering and electron transport: Non-intuitive design

Motivation

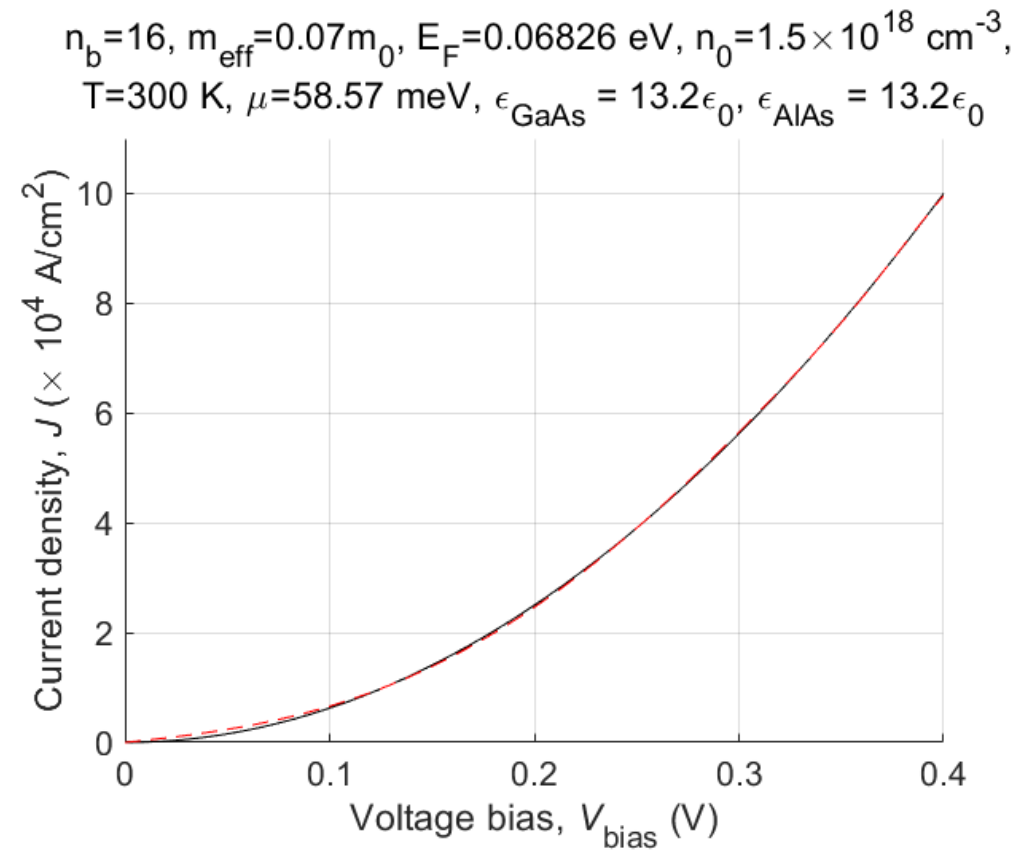
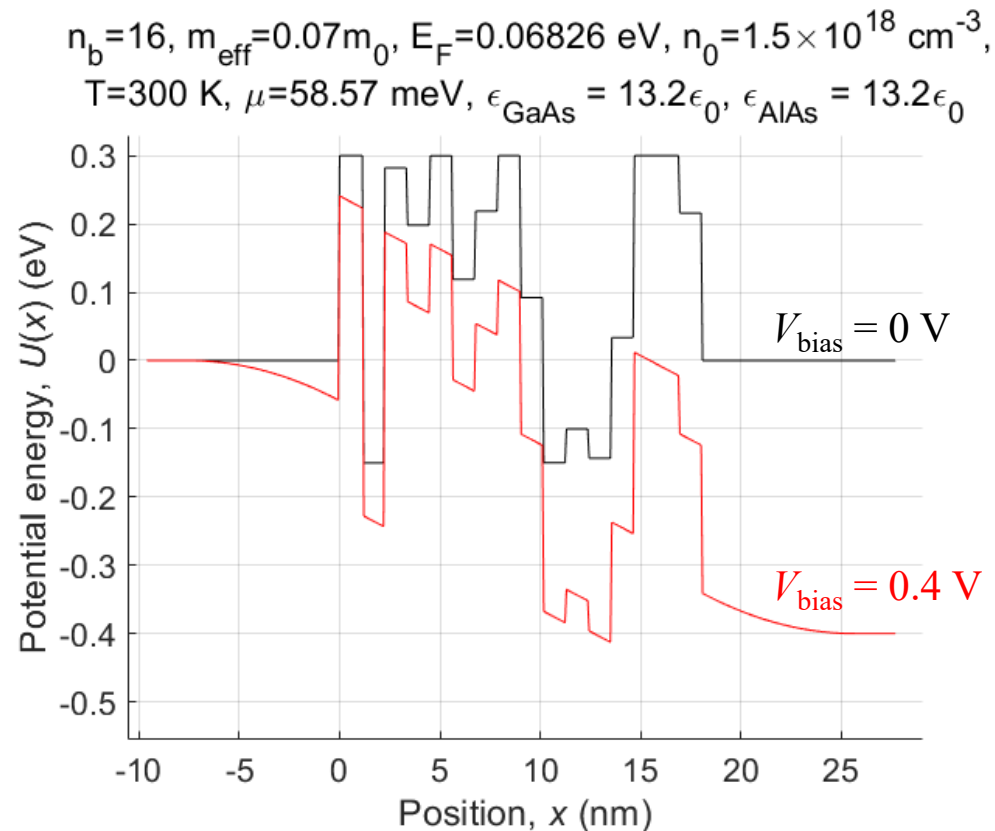
- What is the current-voltage characteristic for this semiconductor diode conduction band potential profile?
- $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{As}$ n-i-n diode with $-0.15 \text{ eV} \leq U_j \leq 0.3 \text{ eV}$
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- $n_0 = 1.5 \times 10^{18} \text{ cm}^{-3}$



Quantum engineering and electron transport: Non-intuitive design

Motivation

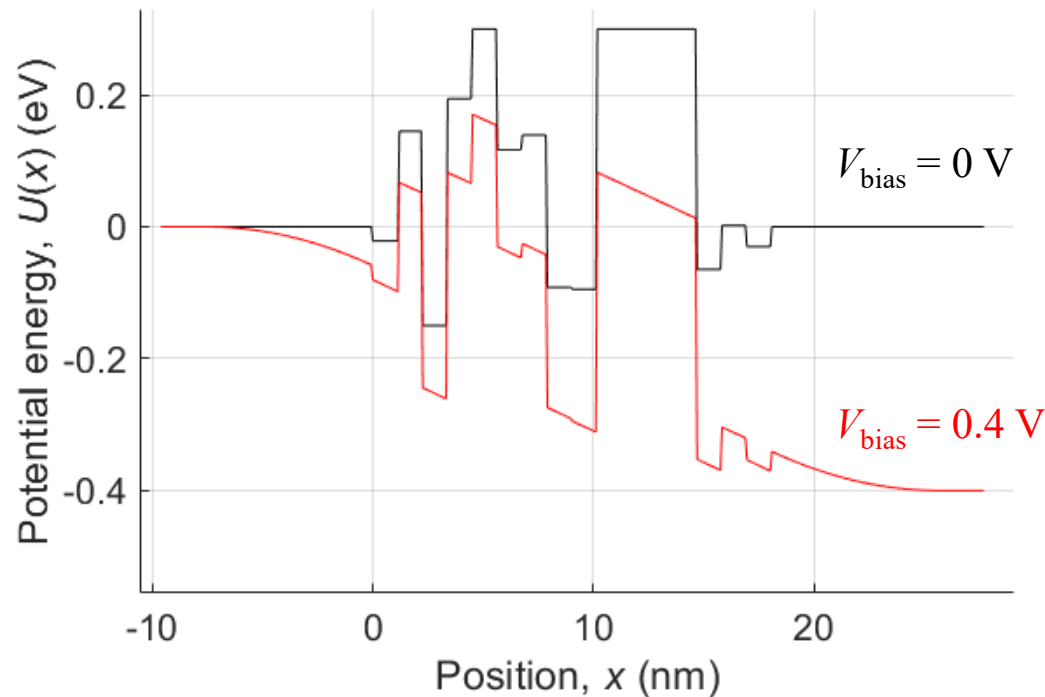
- What is the current-voltage characteristic for this semiconductor diode conduction band potential profile?
- Solution: Quadratic
 - Could you have guessed that?



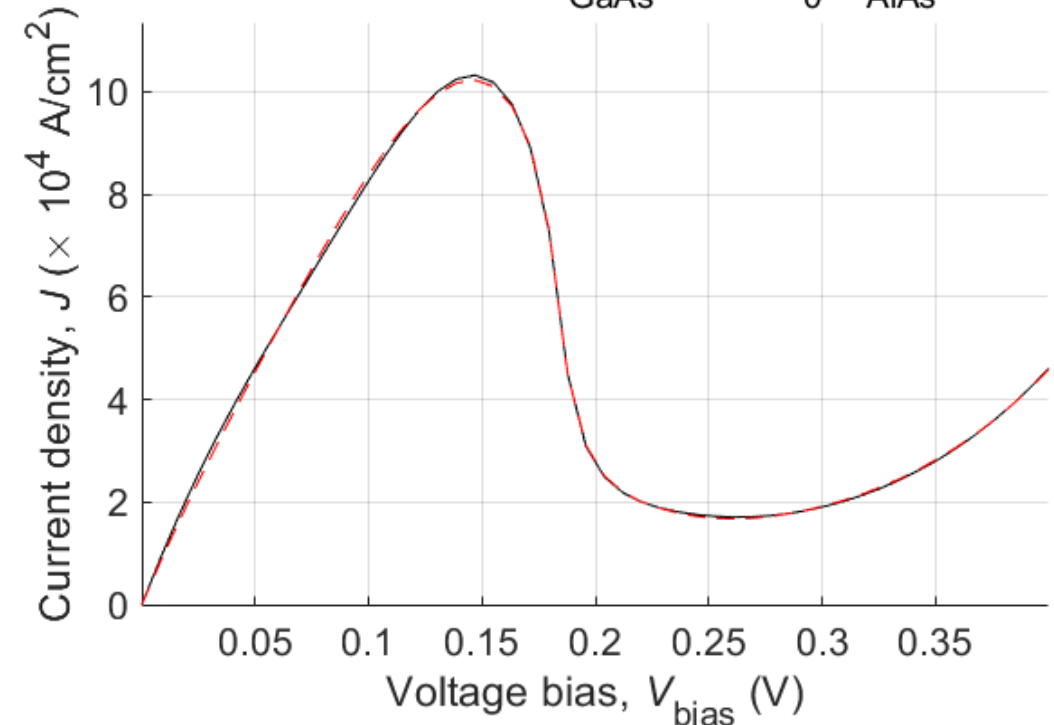
Quantum engineering and electron transport: Non-intuitive design

- $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{As}$ with $-0.15 \text{ eV} \leq U_j \leq 0.3 \text{ eV}$
- 16 layers, each 1.131 nm thick
- $n_0 = 1.5 \times 10^{18} \text{ cm}^{-3}$
- Polynomial objective

$n_b=16$, $m_{\text{eff}}=0.07m_0$, $E_F=0.06826 \text{ eV}$, $n_0=1.5 \times 10^{18} \text{ cm}^{-3}$,
 $T=300 \text{ K}$, $\mu=58.57 \text{ meV}$, $\epsilon_{\text{GaAs}} = 13.2\epsilon_0$, $\epsilon_{\text{AlAs}} = 13.2\epsilon_0$



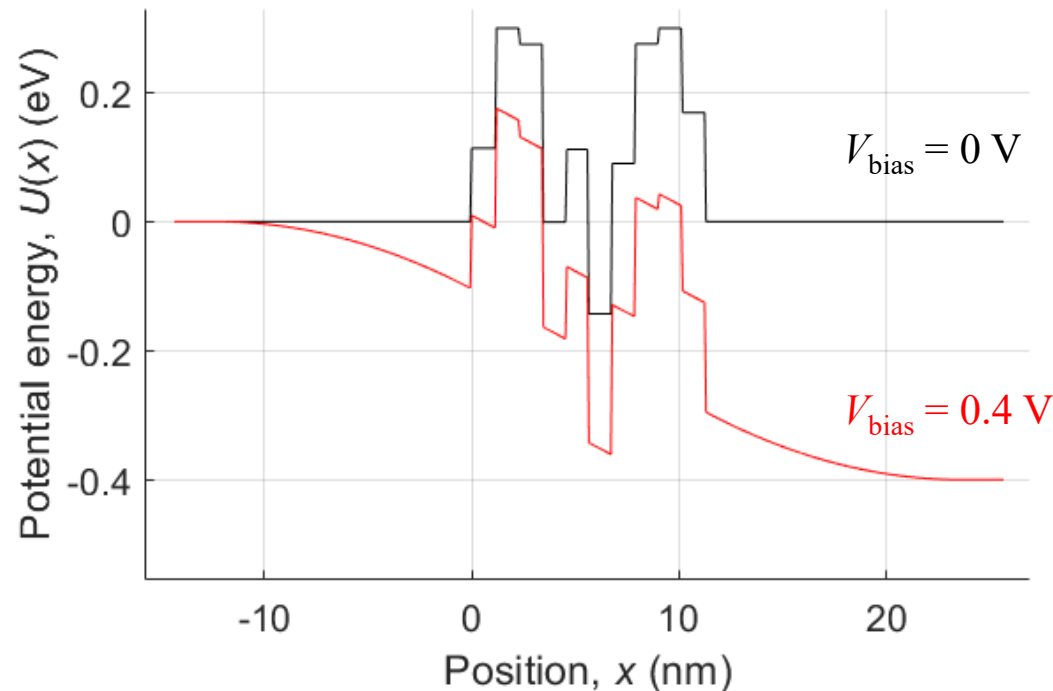
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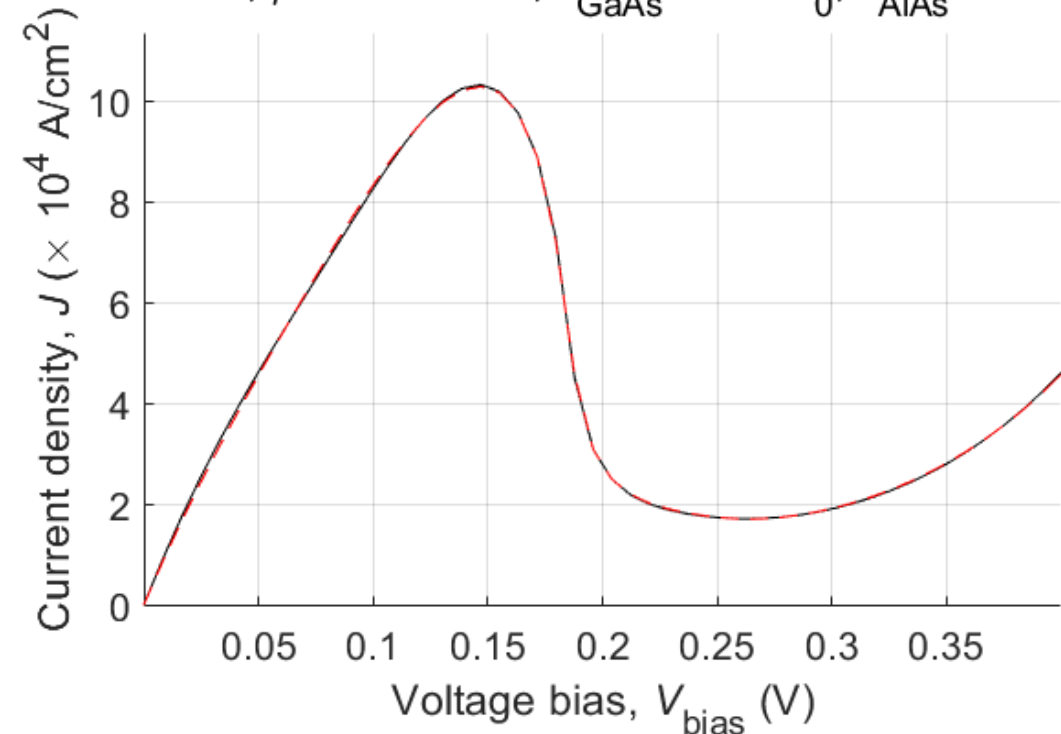
Quantum engineering and electron transport: Non-intuitive design

- $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{As}$ with $-0.15 \text{ eV} \leq U_j \leq 0.3 \text{ eV}$
- 10 layers, each 1.131 nm thick
 - Reducing number of layers from 16 (over provisioned) to 10 achieves same objective
- $n_0 = 1.0 \times 10^{18} \text{ cm}^{-3}$
- Polynomial objective

$n_b=10$, $m_{\text{eff}}=0.07m_0$, $E_F=52.09 \text{ meV}$, $n_0=1.0 \times 10^{18} \text{ cm}^{-3}$,
 $T=300 \text{ K}$, $\mu=38.92 \text{ meV}$, $\epsilon_{\text{GaAs}} = 13.2\epsilon_0$, $\epsilon_{\text{AlAs}} = 13.2\epsilon_0$



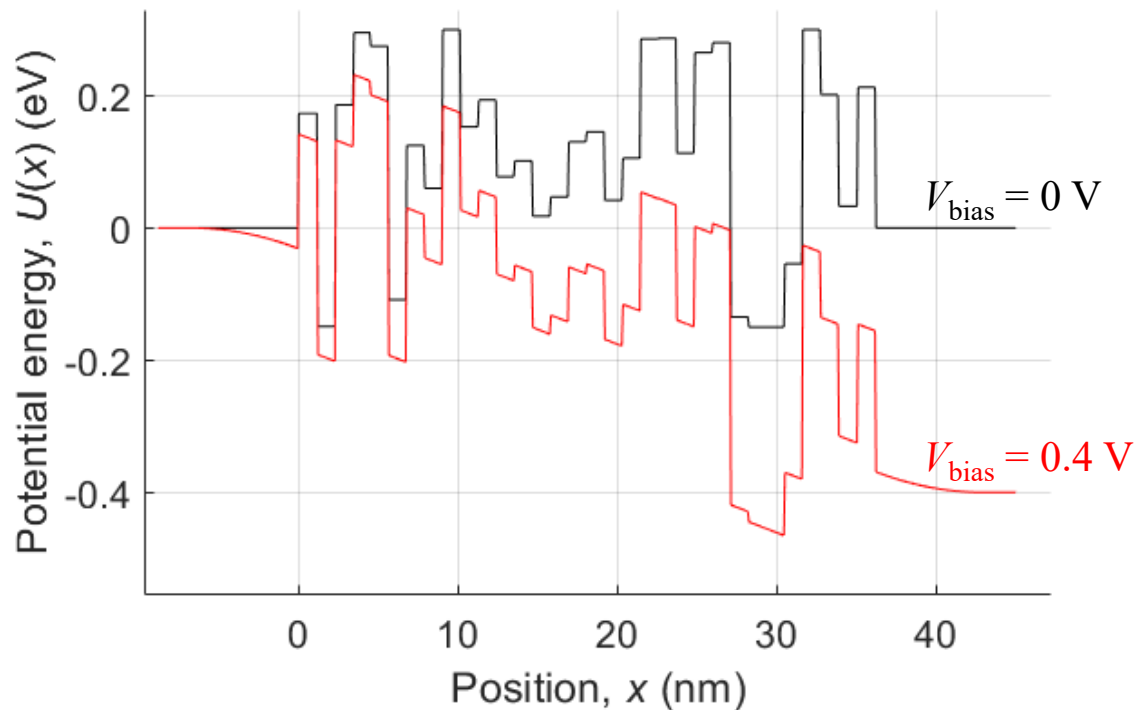
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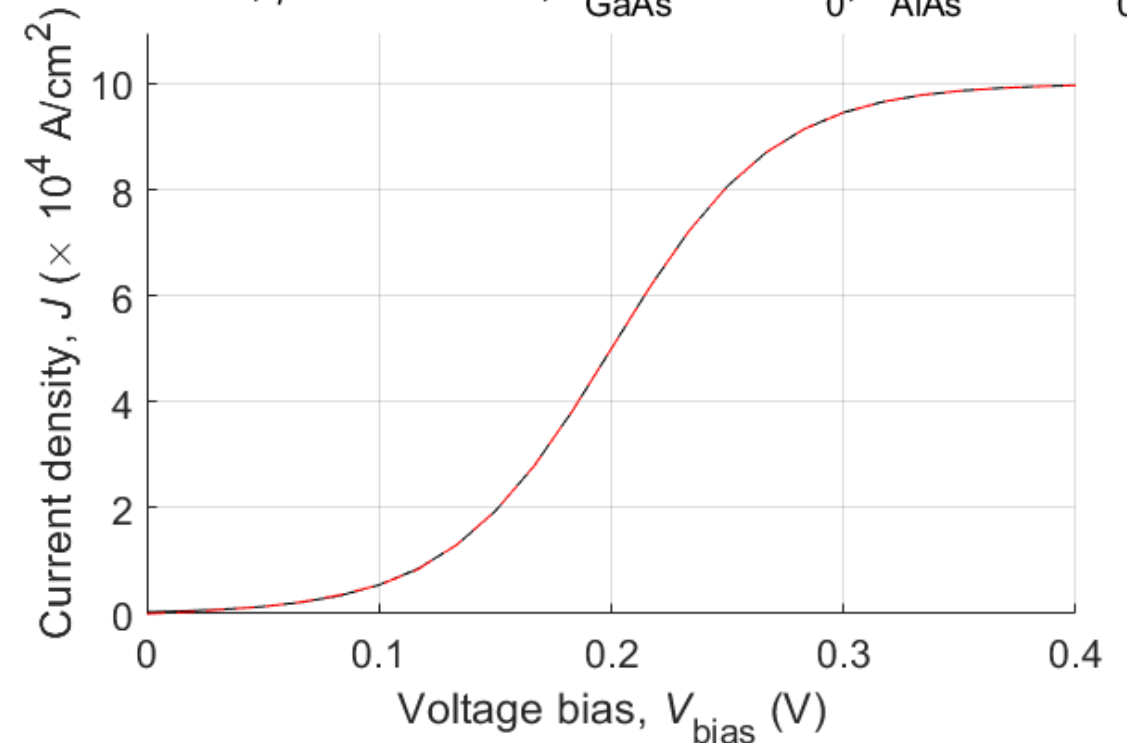
Quantum engineering and electron transport: Non-intuitive design

- $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{As}$ with $-0.15 \text{ eV} \leq U_j \leq 0.3 \text{ eV}$
- 32 layers, each 1.131 nm thick
- $n_0 = 1.0 \times 10^{18} \text{ cm}^{-3}$
- Softmax objective

$n_b=32$, $m_{\text{eff}}=0.07m_0$, $E_F=52.09 \text{ meV}$, $n_0=1.0 \times 10^{18} \text{ cm}^{-3}$,
 $T=300 \text{ K}$, $\mu=38.92 \text{ meV}$, $\epsilon_{\text{GaAs}} = 13.2\epsilon_0$, $\epsilon_{\text{AlAs}} = 13.2\epsilon_0$



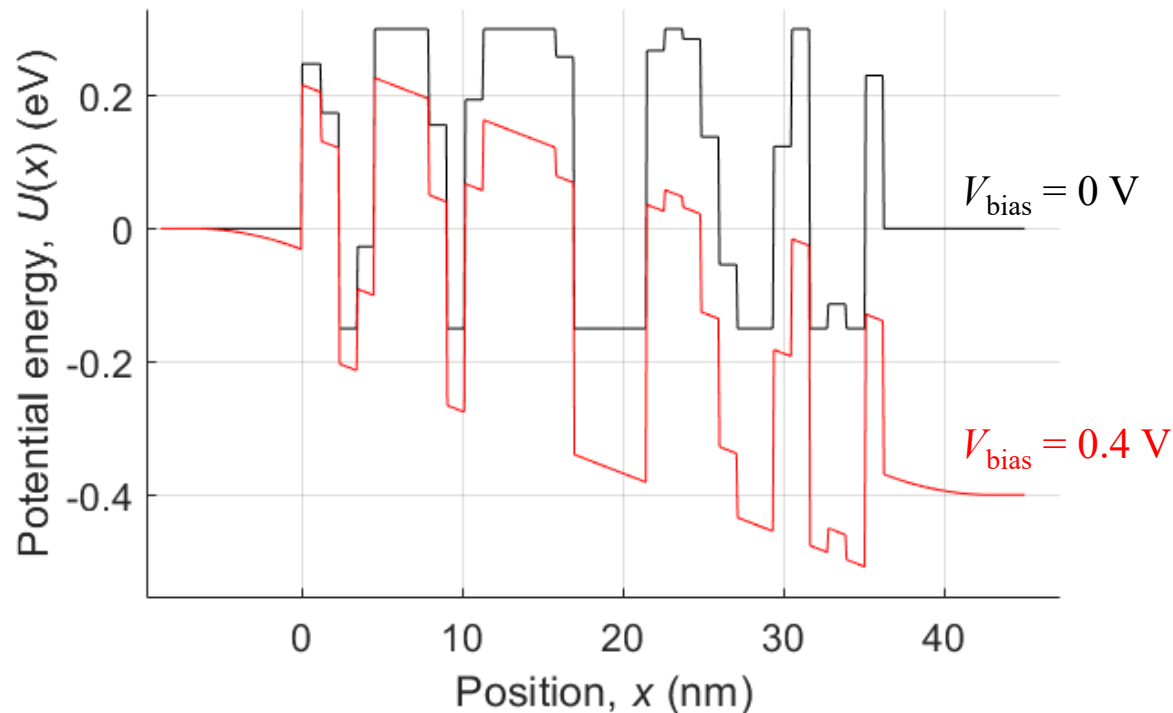
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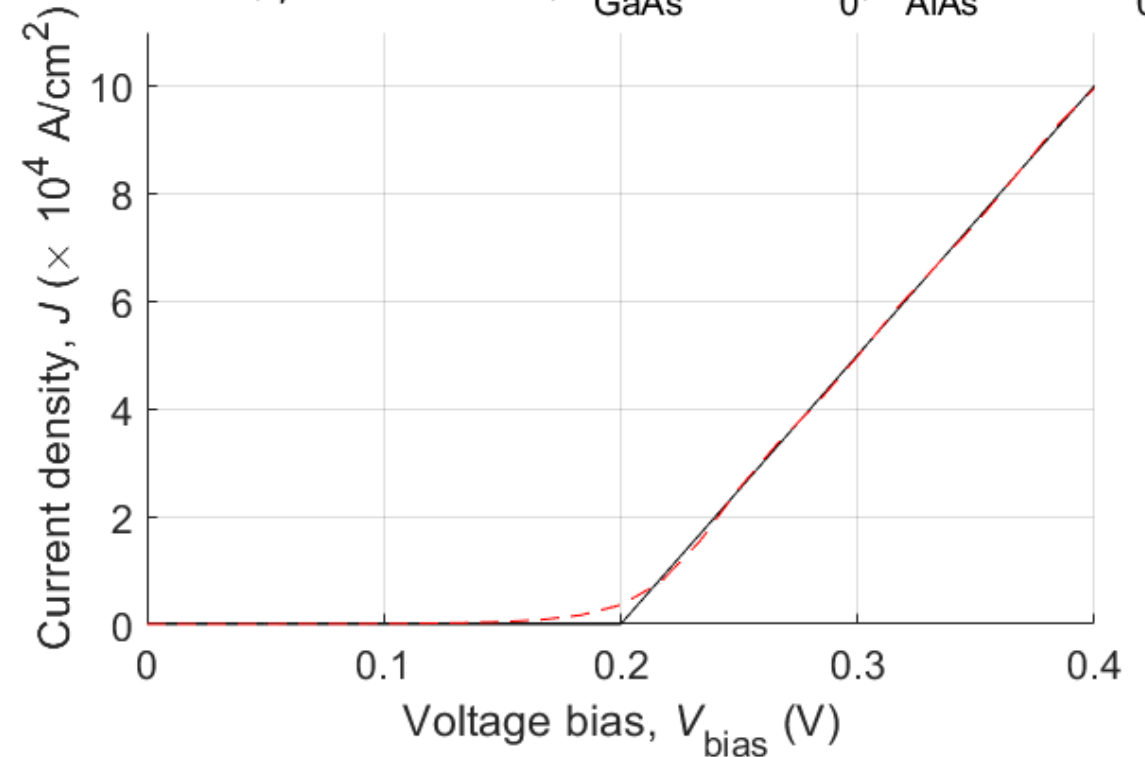
Quantum engineering and electron transport: Non-intuitive design

- $\text{Al}_x\text{In}_y\text{Ga}_{1-x-y}\text{As}$ with $-0.15 \text{ eV} \leq U_j \leq 0.3 \text{ eV}$
- 32 layers, each 1.131 nm thick
- $n_0 = 1.0 \times 10^{18} \text{ cm}^{-3}$
- ReLU objective

$n_b=32$, $m_{\text{eff}}=0.07m_0$, $E_F=52.09 \text{ meV}$, $n_0=1.0 \times 10^{18} \text{ cm}^{-3}$,
 $T=300 \text{ K}$, $\mu=38.92 \text{ meV}$, $\epsilon_{\text{GaAs}} = 13.2\epsilon_0$, $\epsilon_{\text{AlAs}} = 13.2\epsilon_0$



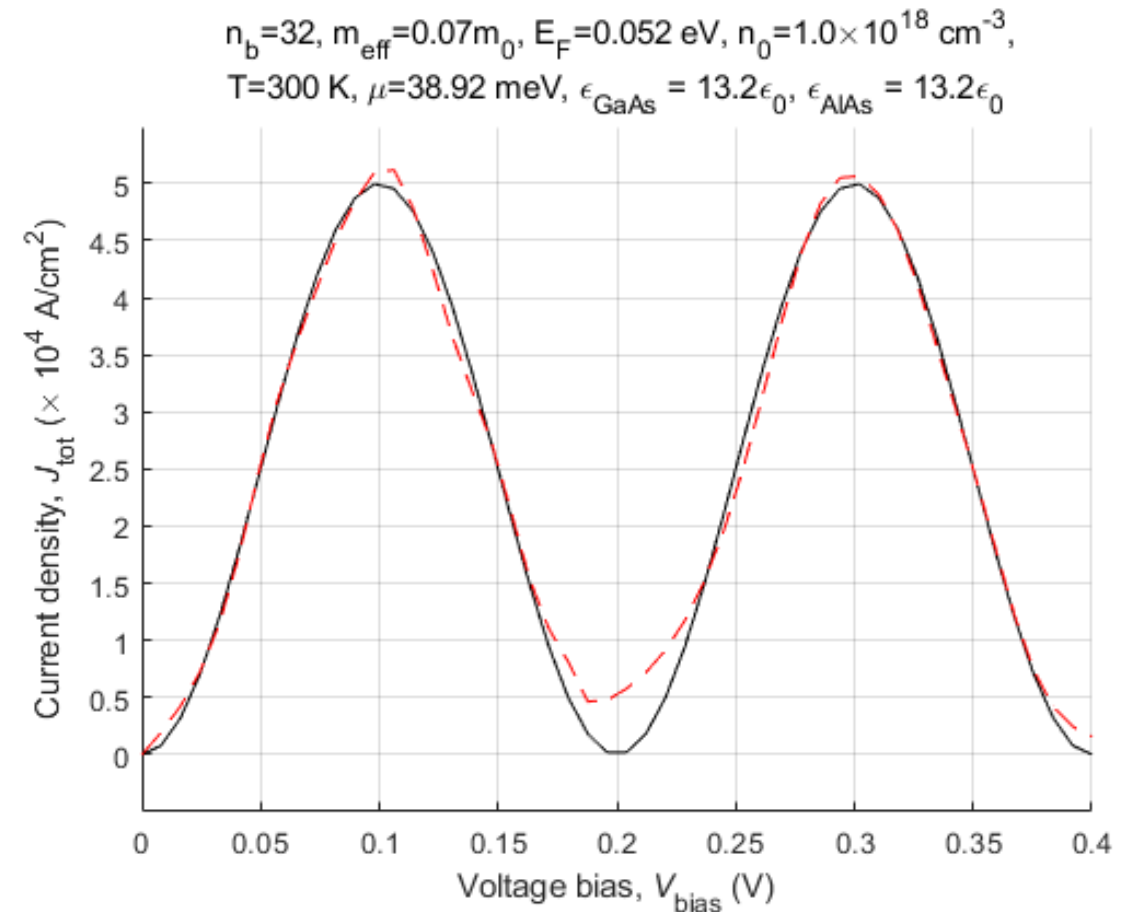
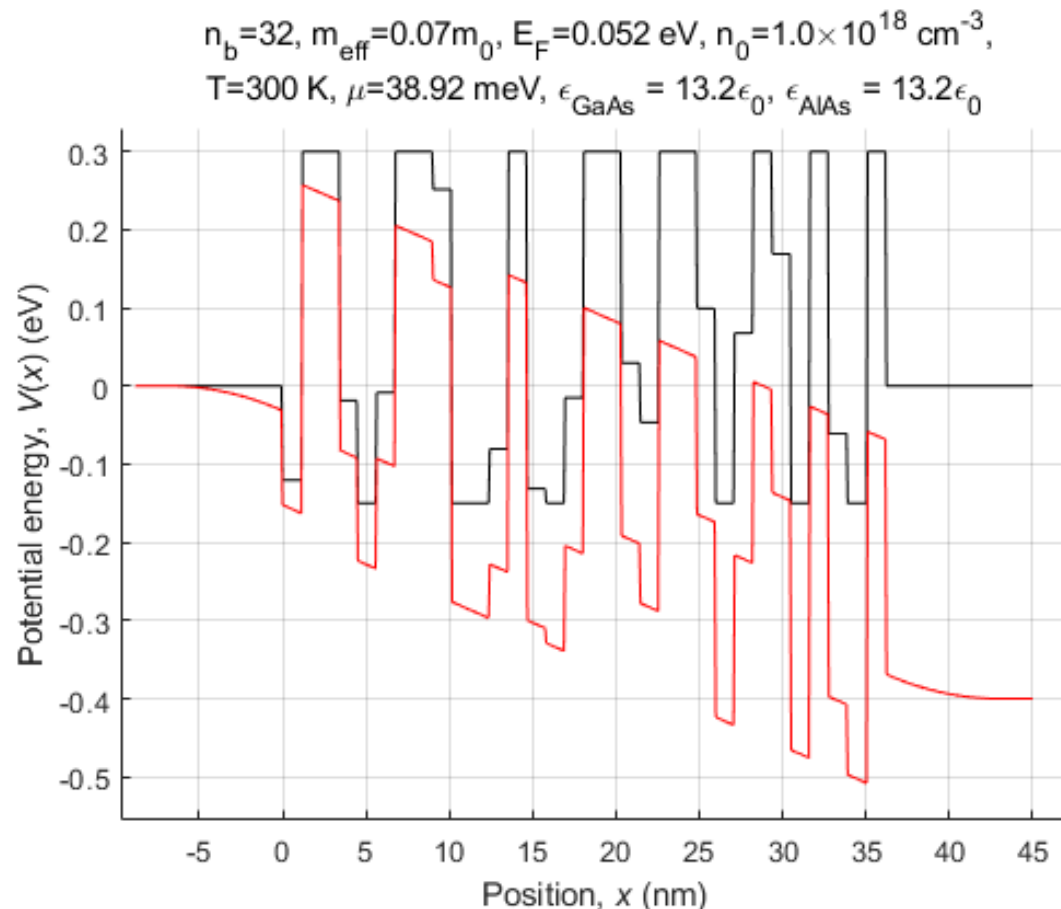
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Quantum engineering and electron transport: Non-intuitive design

Motivation

- What is the current-voltage characteristic for this semiconductor diode conduction band potential profile?
- $n_0 = 1.0 \times 10^{18} \text{ cm}^{-3}$
- Sinusoidal objective



Electron tunneling through a potential barrier

- A useful electron device consists of material, geometry, *and* a model
 - A tunnel diode has a potential barrier of energy V_B that separates two electrodes and a model describing electron transport through the device
 - A single-electron description of the device that involves solving the Schrödinger equation may also provide insight into single photon and classical optics devices that are modelled using the Helmholtz equation
 - Transient response in *classical* electrical circuit design suggests existence of a tunneling-electron transit time, t_{barrier}
- *Concept* of collision time
 - Time collision takes is difference with and without potential (F. T. Smith, “Lifetime Matrix in Collision Theory”, *Phys. Rev.* **118**, 349-356 (1960), T. E. Hartman, “Tunneling of a Wave Packet” , *J. Appl. Phys.* **33**, 3427-3433 (1962))
- *Concept* of pure imaginary tunneling-time
 - D. W. McLaughlin, “Complex Time, Contour Independent Path Integrals, and Barrier Penetration”, *J. Math. Phys.* **13**, 1099 (1972) and K. F. Freed, “Path Integrals and Semiclassical Tunneling, Wavefunctions, and Energies”, *J. Chem. Phys.* **56**, 692 (1972)
 - For an electron mass m^* and energy $E < V_B$ in the region of a rectangular barrier of energy V_0 then $dt = \sqrt{m^*/2(E-V_B)} dx$ and so transit time t_{barrier} is pure imaginary. In the Feynman path description, the particle travels in real-time until it enters the tunneling region at which point real-time stops and the trajectory evolves in imaginary time. When the particle leaves the tunneling region real-time continues to advance
- *Concept* of a real tunneling-time
 - Time an electron spends traversing the potential barrier (M. Buttiker and R. Landauer, “Traversal Time for Tunneling”, *Phys. Rev. Lett.* **49**, 1739-1742 (1982))

Beyond effective electron mass:
Complex band structure as a degree of freedom for design

Single-electron wave functions in a periodic potential

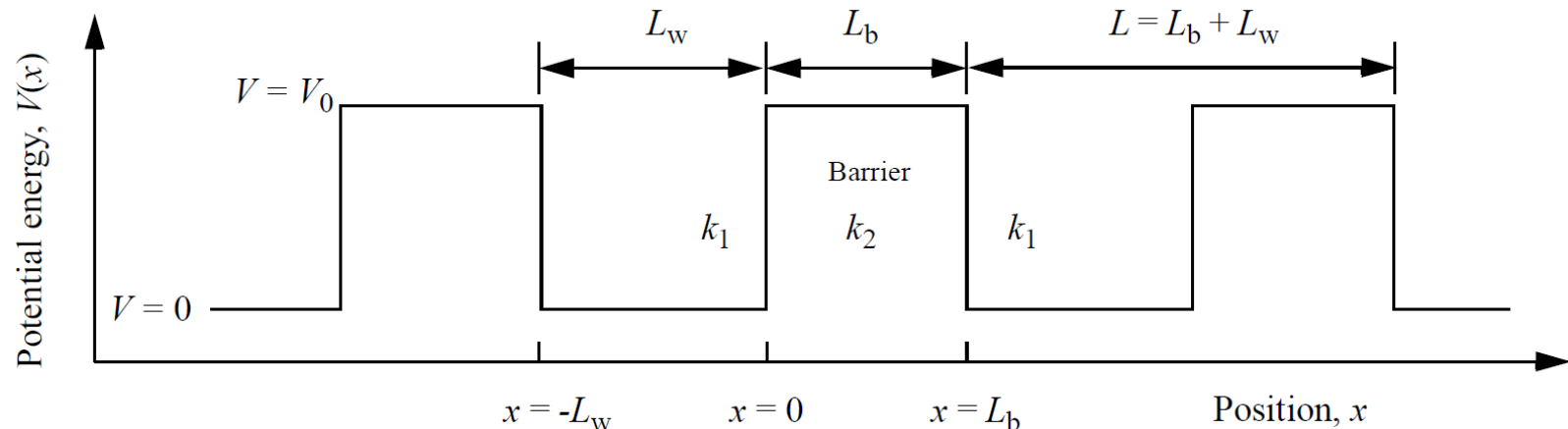
- Kronig-Penney
- Electron tunneling through potential barriers with lattice period L
- Bloch wave vector k with dispersion $\omega(k)$
- Propagating states have real k
- Non-propagating states have complex wave vector
- Example: $V_0=2\text{eV}$, $L=1\text{nm}$, $L_b=0.5\text{nm}$, $L_w=0.5\text{nm}$

$$\begin{vmatrix} 1 & 1 & -1 & -1 \\ k_1 & -k_1 & -k_2 & k_2 \\ -e^{ikL-ik_1L_w} & -e^{ikL+ik_1L_w} & e^{ik_2L_b} & e^{-ik_2L_b} \\ -k_1e^{ikL-ik_1L_w} & k_1e^{ikL+ik_1L_w} & k_2e^{ik_2L_b} & -k_2e^{-ik_2L_b} \end{vmatrix} = 0$$

$$\cos(kL) = \cos(k_2L_b) \cos(k_1L_w) - \frac{(k_2^2 + k_1^2)}{2k_1k_2} \sin(k_2L_b) \sin(k_1L_w) = \theta_B$$

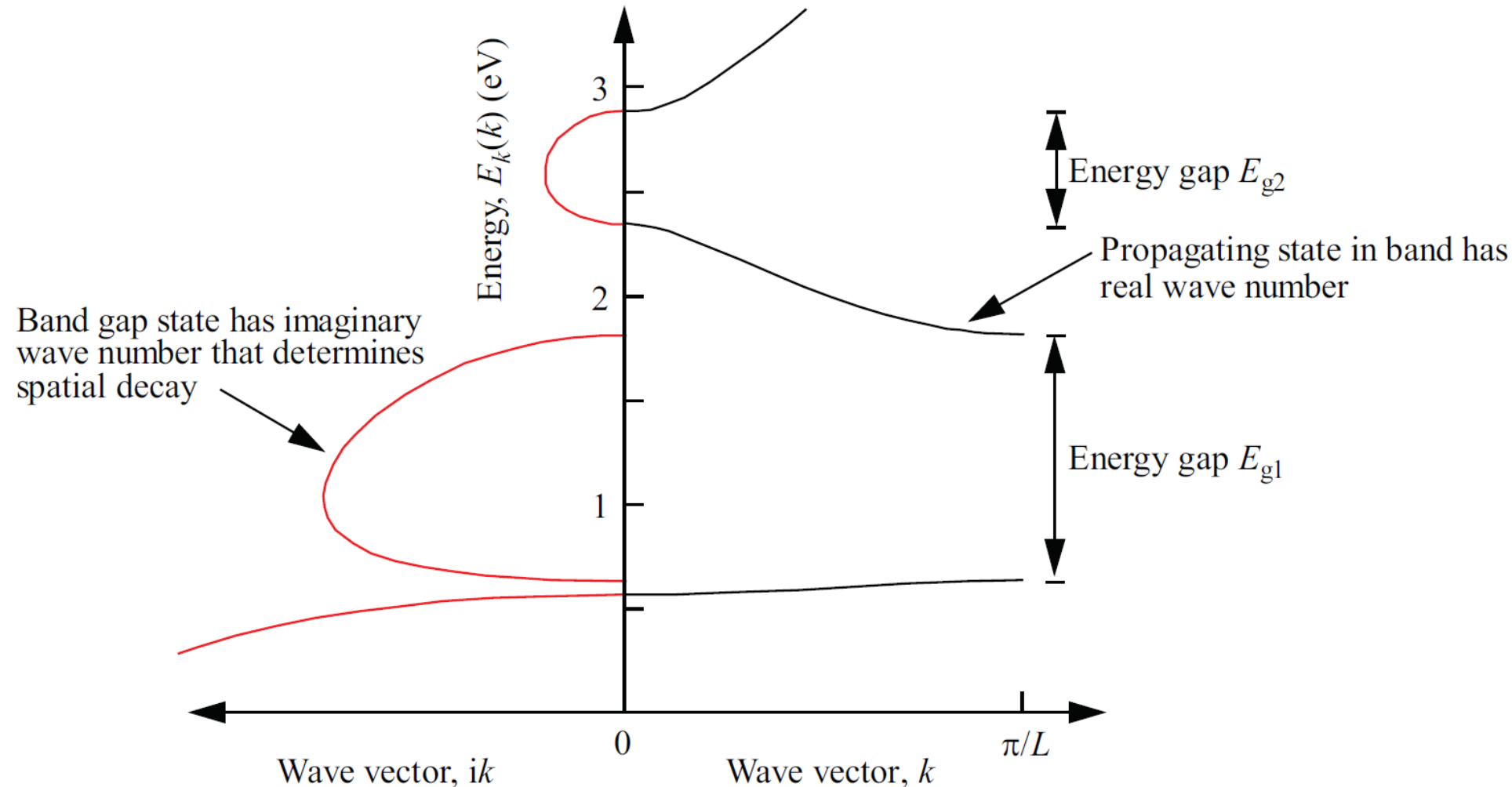
Real k such that $kL = \frac{\arccos(\theta_B)}{\pi}$ when $|\theta_B| < 1$

Complex k such that $kL = \frac{\text{acosh}(\theta_B)}{\pi}$ when $|\theta_B| \geq 1$

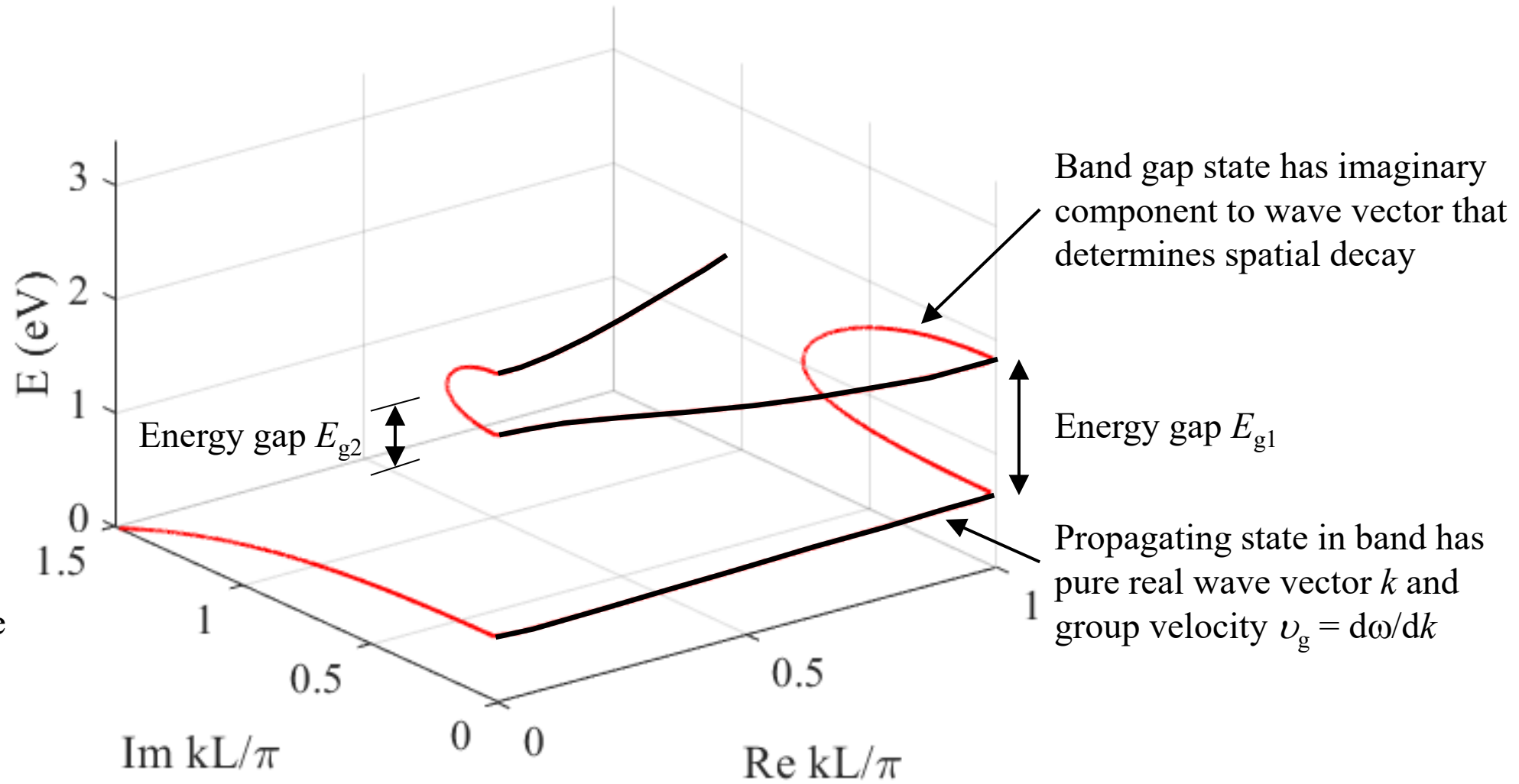


Complex band structure

- Kronig-Penney
- Bloch wave vector k with dispersion $\omega(k)$
- Propagating states have pure real k and group velocity $v_g = d\omega/dk$
- Non-propagating states have imaginary component to wave vector
- Band extrema can often be characterized by effective electron mass
- In general, magnitude of band curvature not the same where real and imaginary bands meet
- Example: $V_0=2\text{eV}$, $L=1\text{nm}$, $L_b=0.5\text{nm}$, $L_w=0.5\text{nm}$



Complex band structure



- Kronig-Penney
- Propagating states have pure real k and group velocity $v_g = d\omega/dk$
- Example: $V_0=2\text{eV}$, $L=1\text{nm}$, $L_b=0.5\text{nm}$, $L_w=0.5\text{nm}$

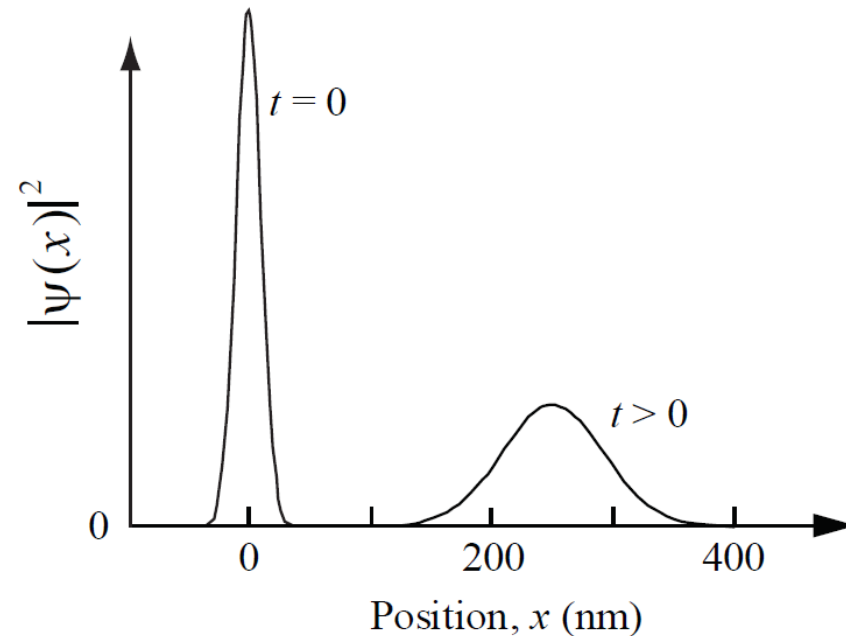
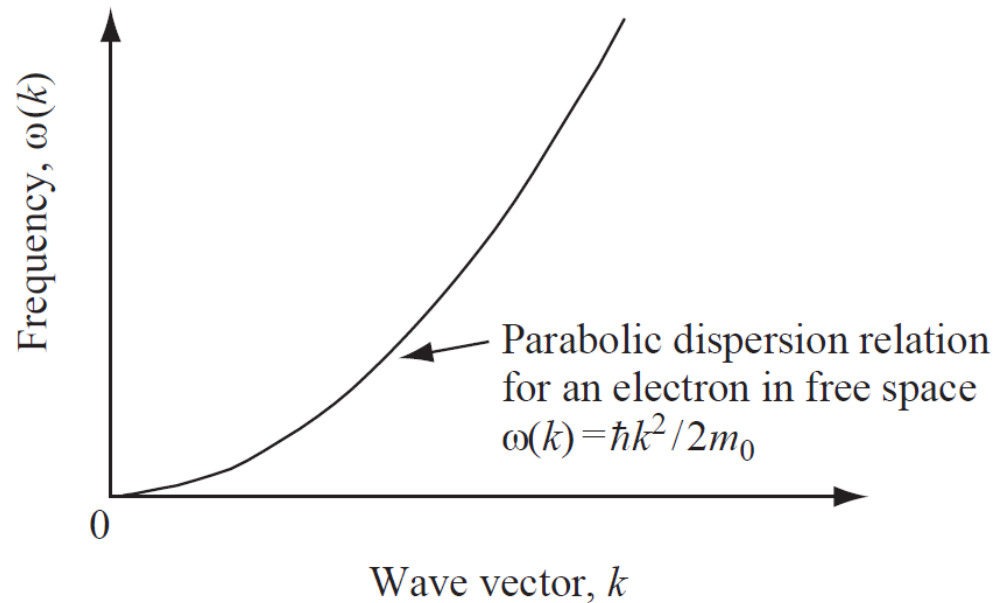
Electron wave packet dispersion

Electron dispersion in free-space

- Quadratic dispersion, $\omega = \hbar k^2/2m_0$, group velocity $v_g = d\omega/dk = \hbar k/m_0$, phase velocity $v_p = \omega/k = \hbar k/2m_0$
- Gaussian electron wave packet spreads with time but has time-independent wave vector spectrum

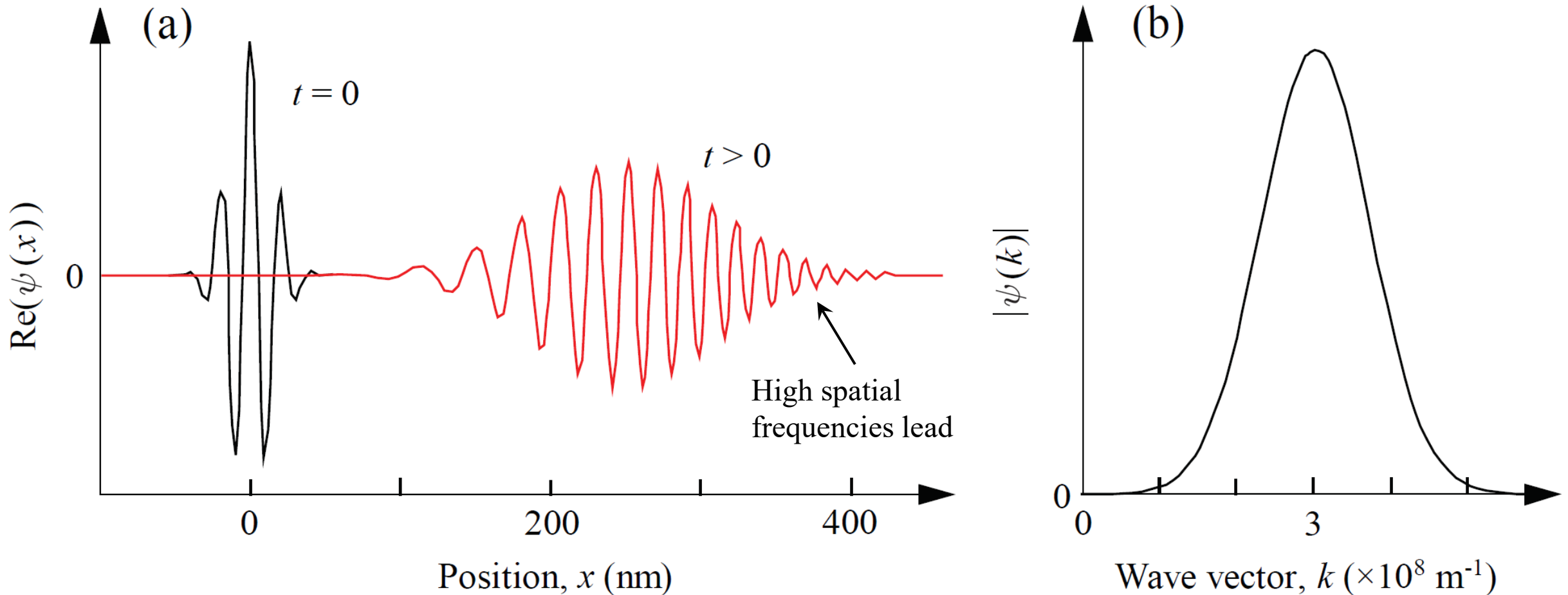
$$|\psi(x, t)|^2 = \frac{1}{\sqrt{2\pi\Delta x^2(t)}} e^{-\left(x-x_0-\frac{\hbar k_0 t}{m_0}\right)^2 / (2\Delta x^2(t))}$$

$$\Delta x(t) = \sqrt{\sigma_x^2 + \frac{\hbar^2 t^2}{4m_0^2 \sigma_x^2}}$$



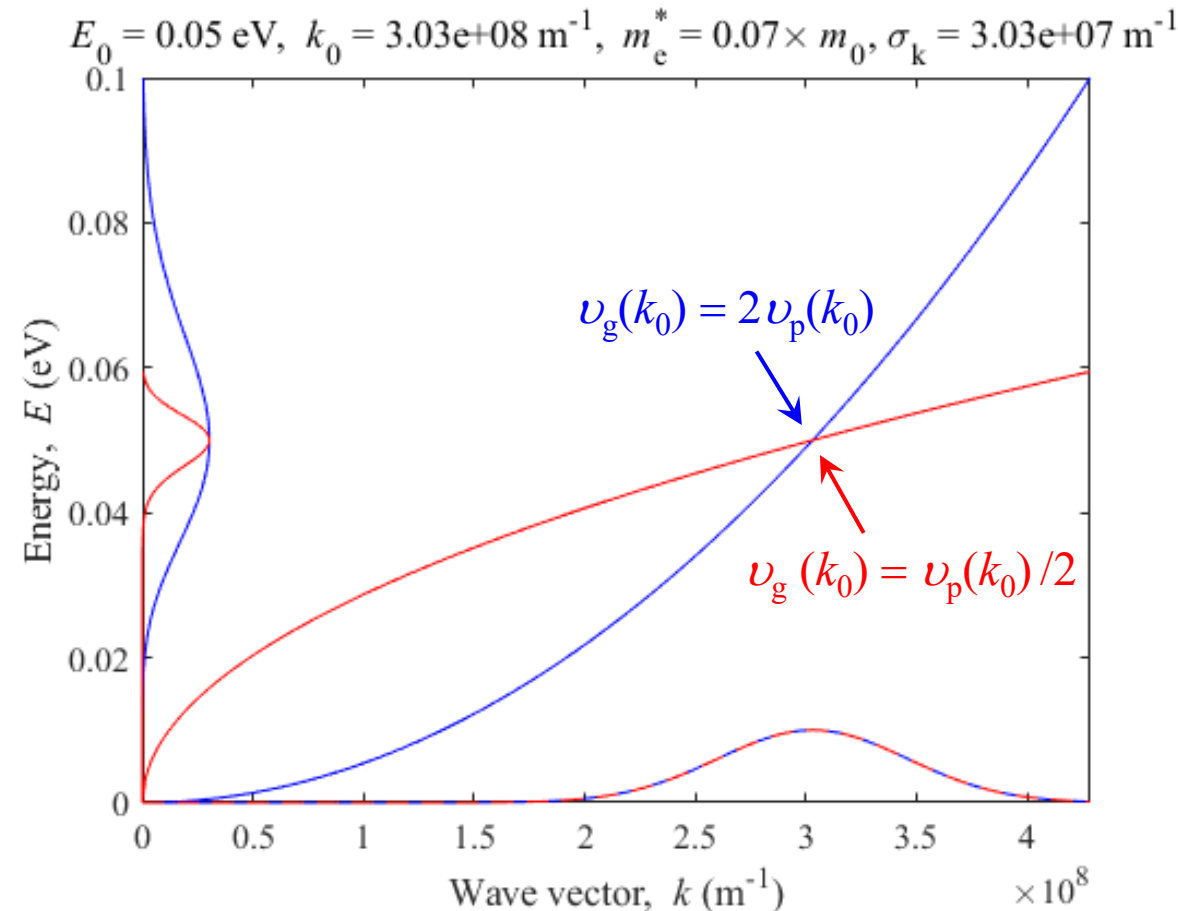
Homogeneous isotropic continuum medium with electron dispersion quadratic in k

- Dispersion $\omega = \hbar k^2/2m^*$, effective electron mass m^* , group velocity $v_g = d\omega/dk = \hbar k/m^*$, phase velocity $v_p = \omega/k = \hbar k/2m^*$
- (a) Gaussian electron wave packet with (b) *time-independent* wave vector spectrum
- $m^* = 0.07 \times m_0$, $E_0 = 0.05$ eV, $\sigma_x = 10$ nm, $k_0 = 3 \times 10^8$ m⁻¹, $v_g(k_0) = 5 \times 10^5$ m s⁻¹, $t = 0$, $t = 0.5$ ps



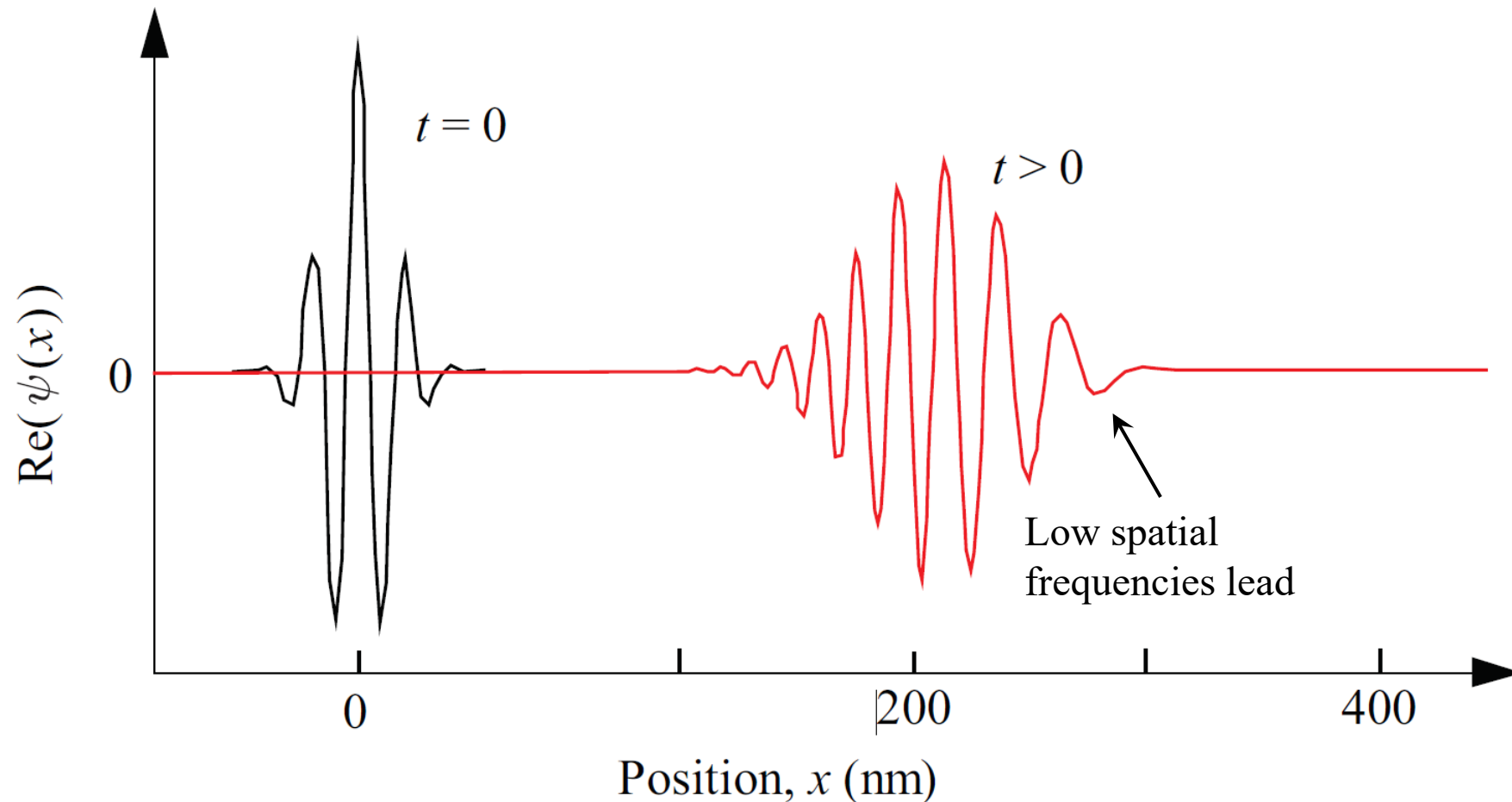
Difference between electron dispersion that is quadratic and square-root in k

- Quadratic dispersion, $\omega = \hbar k^2/2m^*$, group velocity $v_g = d\omega/dk = \hbar k/m^*$, phase velocity $v_p = \omega/k = \hbar k/2m^*$
- Dispersion square-root in wave vector, $\omega = a \times \text{sqrt}(k)$, velocity $v_g = d\omega/dk = a/(2 \times \text{sqrt}(k))$, $v_p = \omega/k = a/\text{sqrt}(k)$, and, for comparison purposes, set $a = \hbar^2 \times (k_0)^{3/2}/2m^*$
- Gaussian electron wave packet centered at $k_0 = 3 \times 10^8 \text{ m}^{-1}$ and $E_0 = 0.05 \text{ eV}$



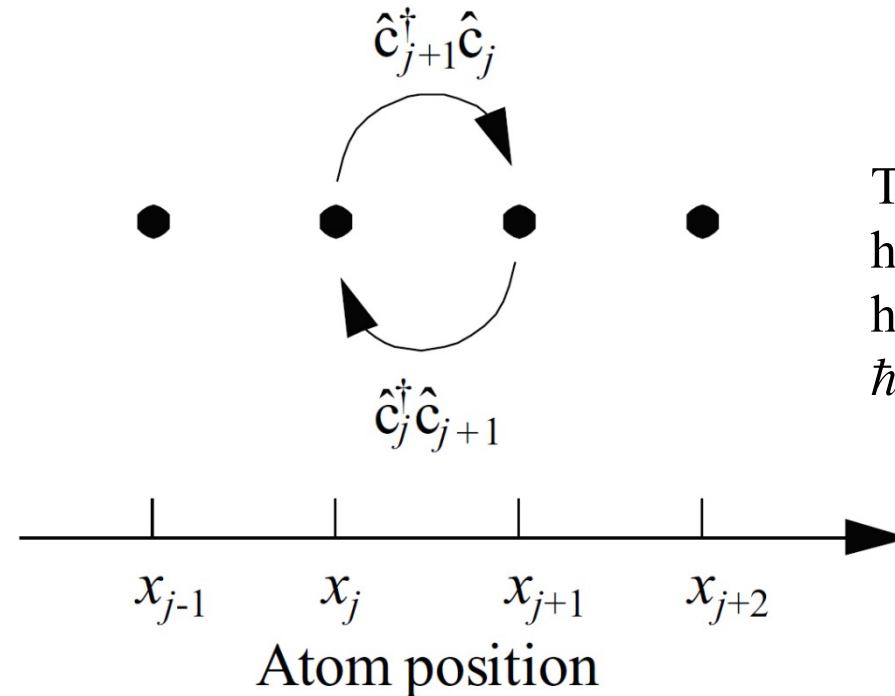
Homogeneous isotropic continuum medium with square-root electron dispersion

- Dispersion $\omega = a \times \text{sqrt}(k)$
- Gaussian electron wave packet with time-independent wave vector spectrum
- $m^* = 0.07 \times m_0$, $E_0 = 0.05$ eV, $\sigma_x = 10$ nm, $k_0 = 3 \times 10^8 \text{ m}^{-1}$, $v_g(k_0) = 1.25 \times 10^5 \text{ m s}^{-1}$, $t = 0$, $t = 2.0$ ps



Single-electron propagation on a 1D lattice *and* tunneling

Real-space nearest-neighbor single-electron hopping on a 1D lattice



Tight-binding nearest-neighbor hopping energy t_h for s-orbitals has propagating k-state dispersion $\hbar\omega = -2 t_h \cos(kL)$

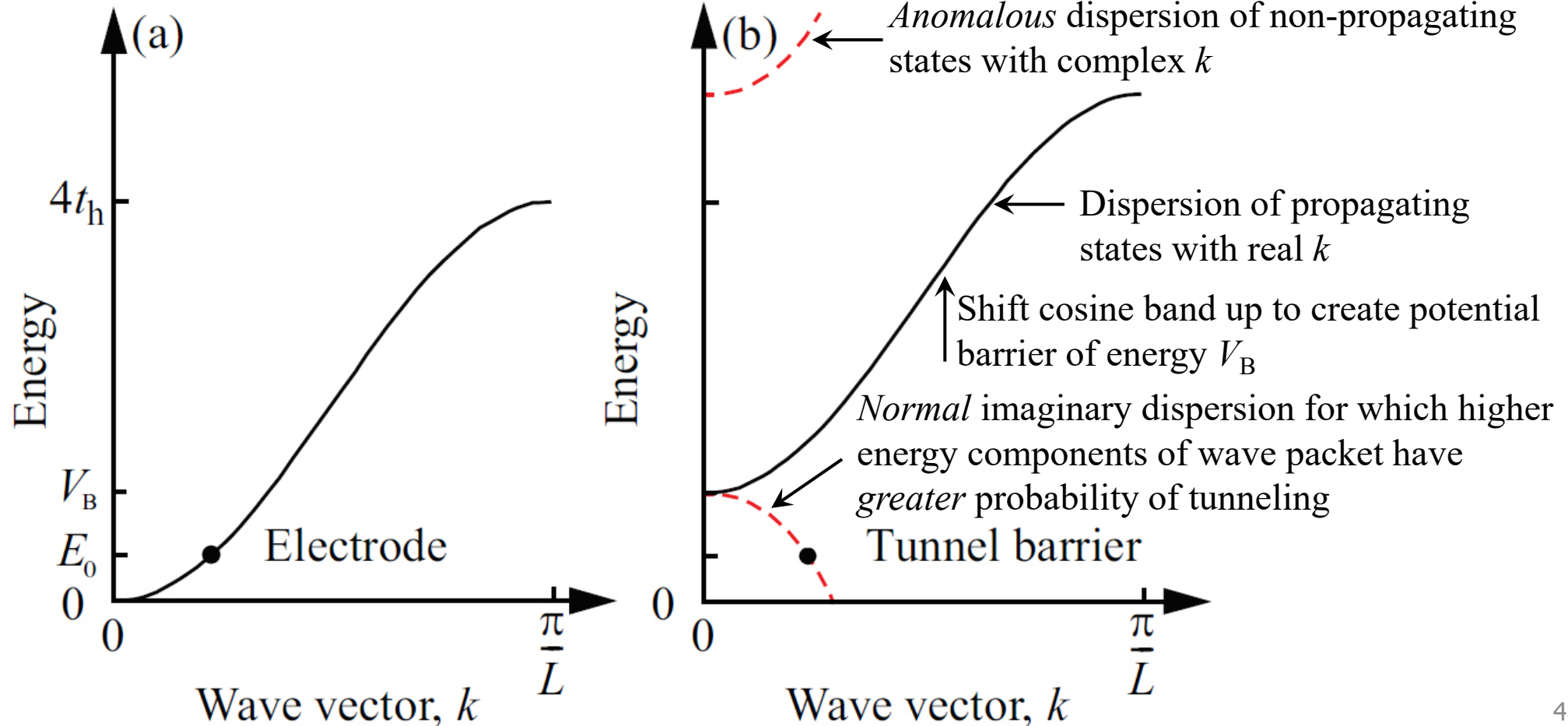
$$H = T + V$$

$$= -t_h \sum_{j=1}^N \left(c_j^\dagger c_{j+1} + c_{j+1}^\dagger c_j \right) + \sum_{j \in \mathcal{J}} U_j c_j^\dagger c_j$$

Nearest-neighbor tight-binding dispersion in electrode and tunnel barrier

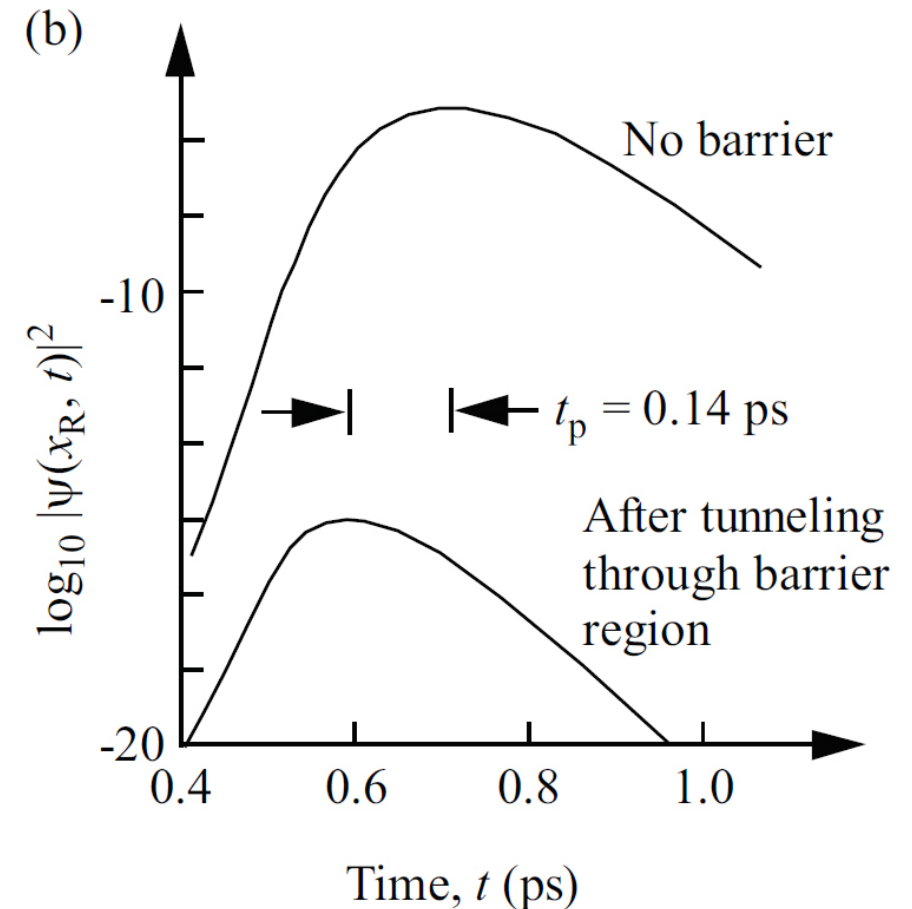
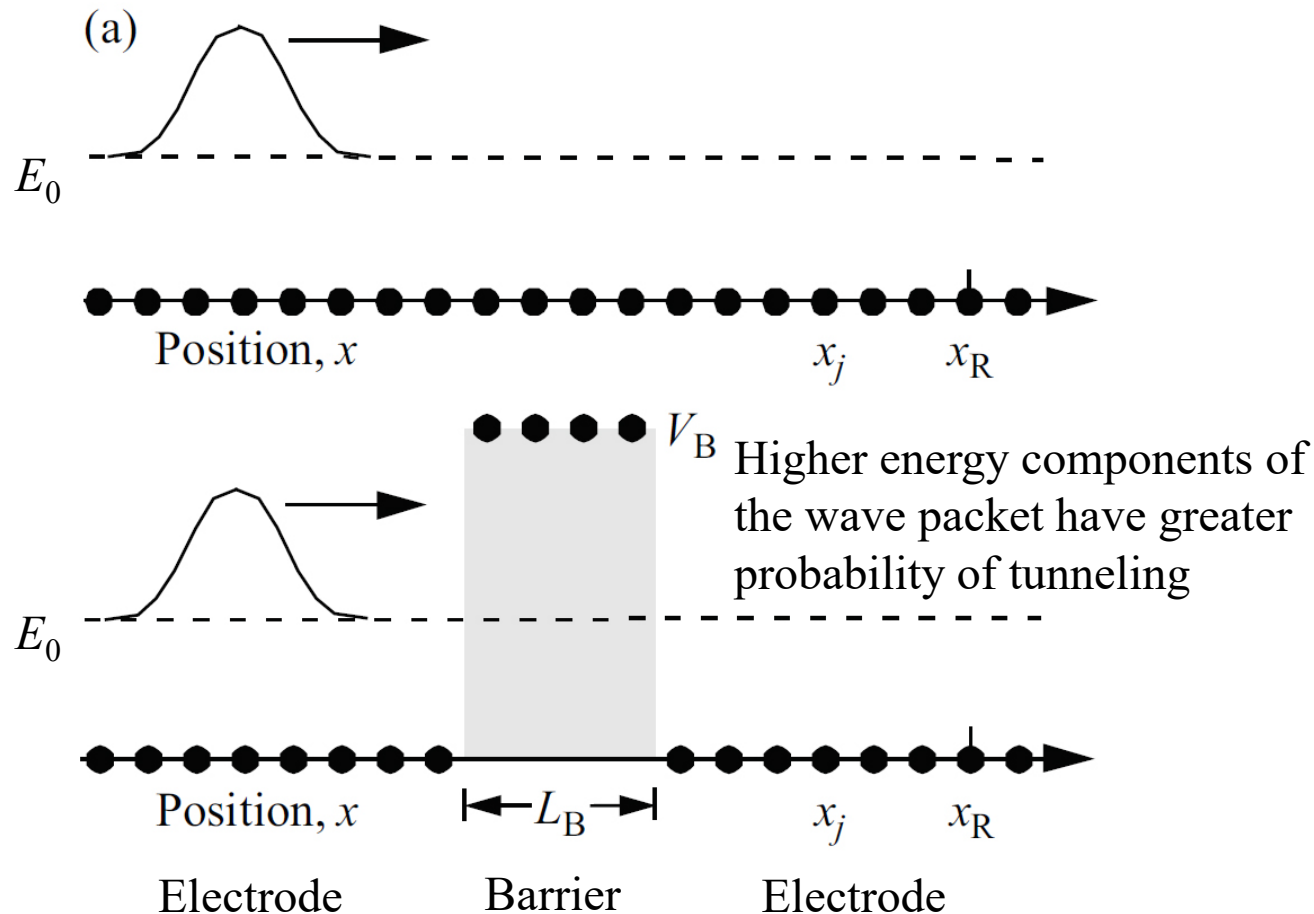
- (a) Propagating electron state (dot) of energy E_0 in the real nearest-neighbor tight-binding s-orbital cosine band of the electrode (black curve).
- (b) Cosine band shifted up in energy relative to (a) to form a potential barrier of energy V_B . An electron of energy E_0 incident on the potential barrier may be viewed as tunneling via the imaginary k -state (dot) in the *normal* imaginary dispersion in the band structure (red dashed curve with *negative slope and curvature*)

Tight-binding nearest-neighbor hopping energy t_h for s-orbitals propagating k -state dispersion
 $\hbar\omega = 2 t_h (1 - \cos(kL))$



Single-electron pulse dynamics at a tunnel barrier

- (a) Electron wave packet propagating in a constant potential (upper sketch) and incident on a rectangular potential barrier of energy V_B (lower sketch). Measurement at fixed position, x_R , far to right of potential barrier
- (b) Probability of measuring the electron at x_R as a function of time with and without a potential barrier. With *normal* imaginary dispersion the peak in detection probability after tunneling occurs *before* the peak for an electron propagating in the absence of the potential barrier

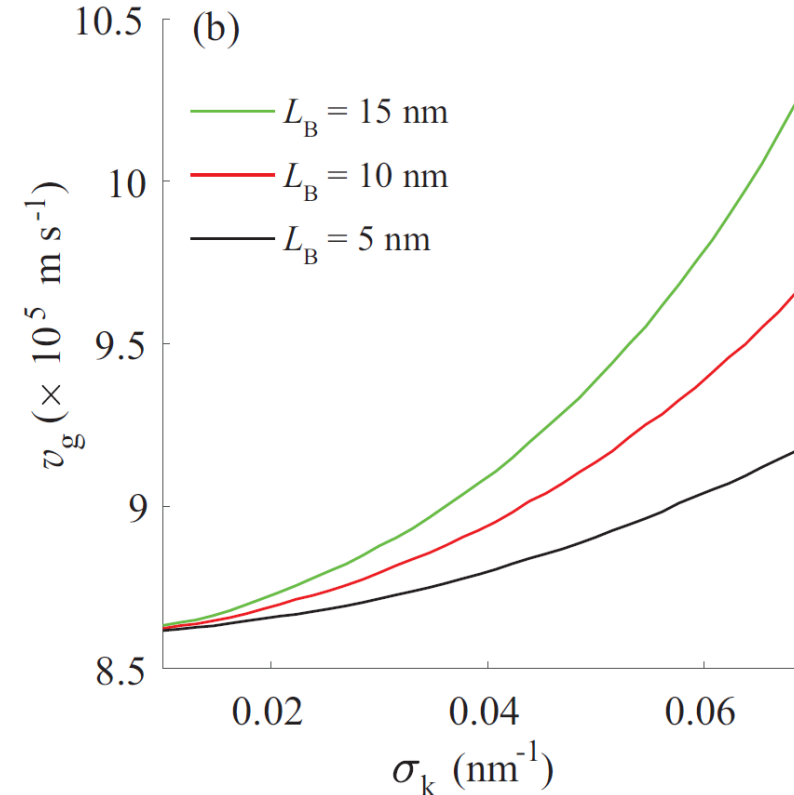
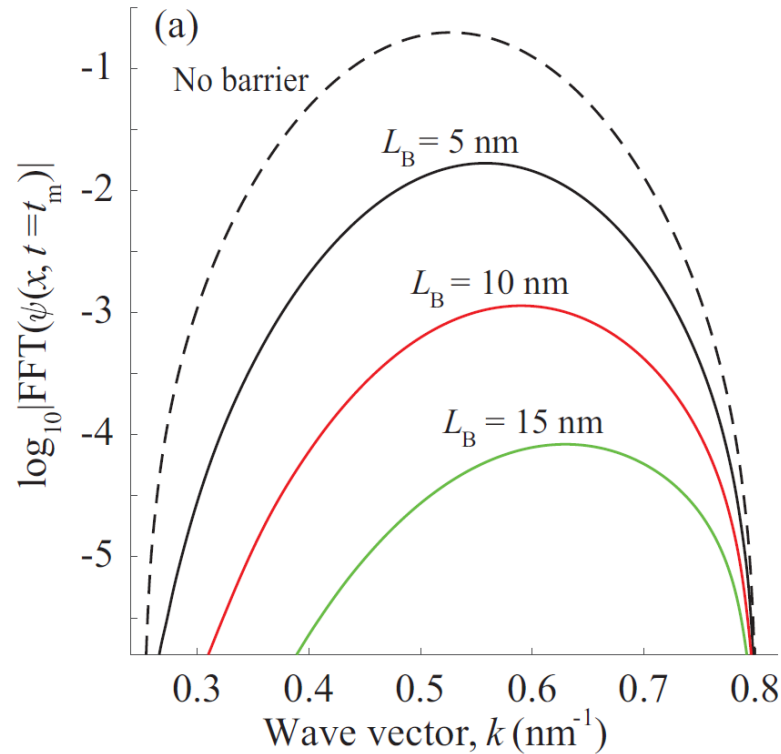


Single-electron pulse dynamics at a tunnel barrier

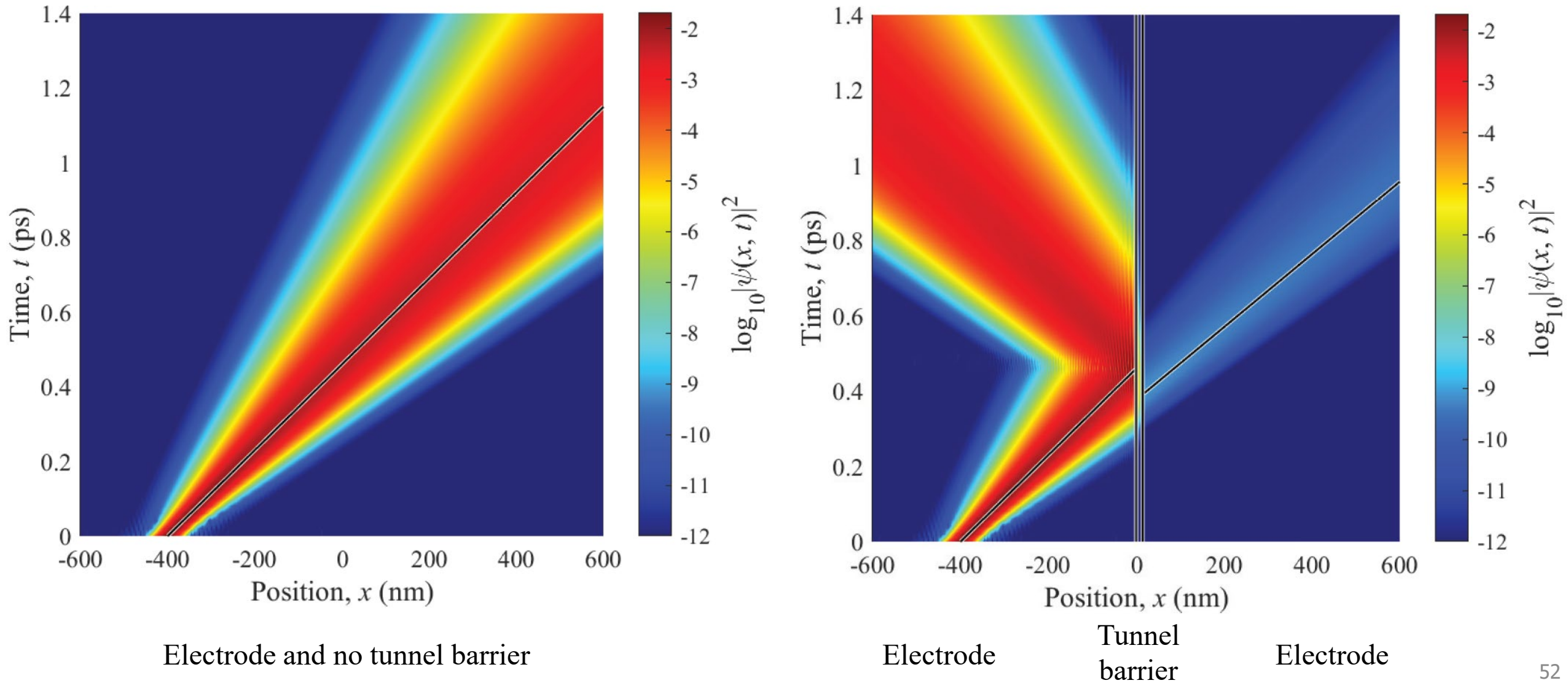


High-pass k -space filter in a tunnel barrier

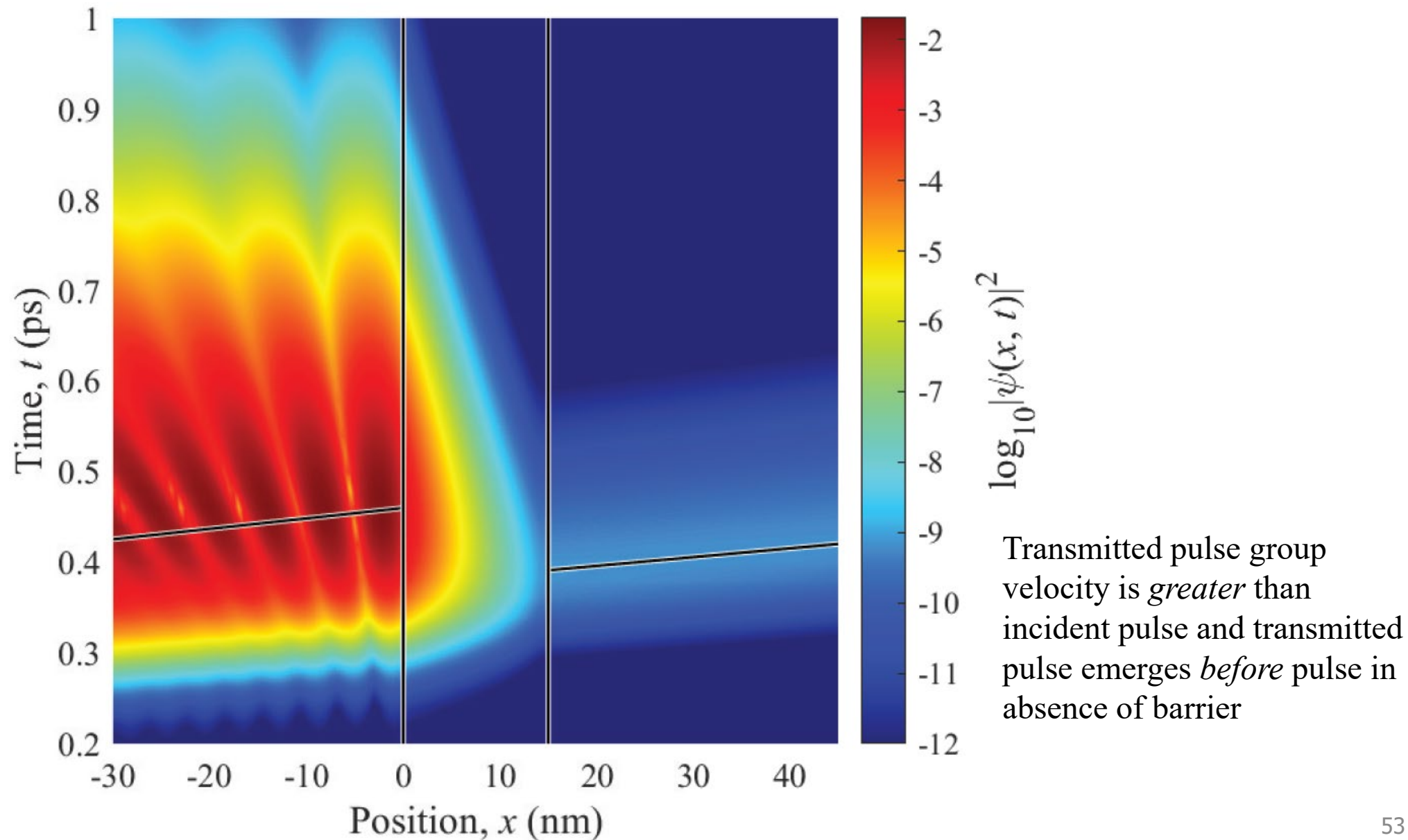
- (a) Incident electron wave packet of energy E_0 in the electrode has distribution of k -space amplitudes with standard deviation σ_k about wave vector k_c . Because, with *normal* imaginary dispersion, higher energy components of the wave packet have greater probability of tunneling, the tunnel barrier of thickness L_B acts as a high-pass filter for wave vector amplitudes. The transmitted pulse is distorted relative to the incident pulse, contains k -states with amplitudes that peak at $k' > k_c$, and has a group velocity, v_g , that is greater than that of the incident pulse. The transmitted pulse has a time-independent wave vector spectrum
- (b) Transmitted pulse group velocity, v_g , depends on σ_k and L_B . Example: $E_0 = 0.15$ eV, $V_B = 0.35$ eV, and $m^* = 0.07 \times m_0$



Space-time plot of *high-pass* k -space filter in a tunnel barrier

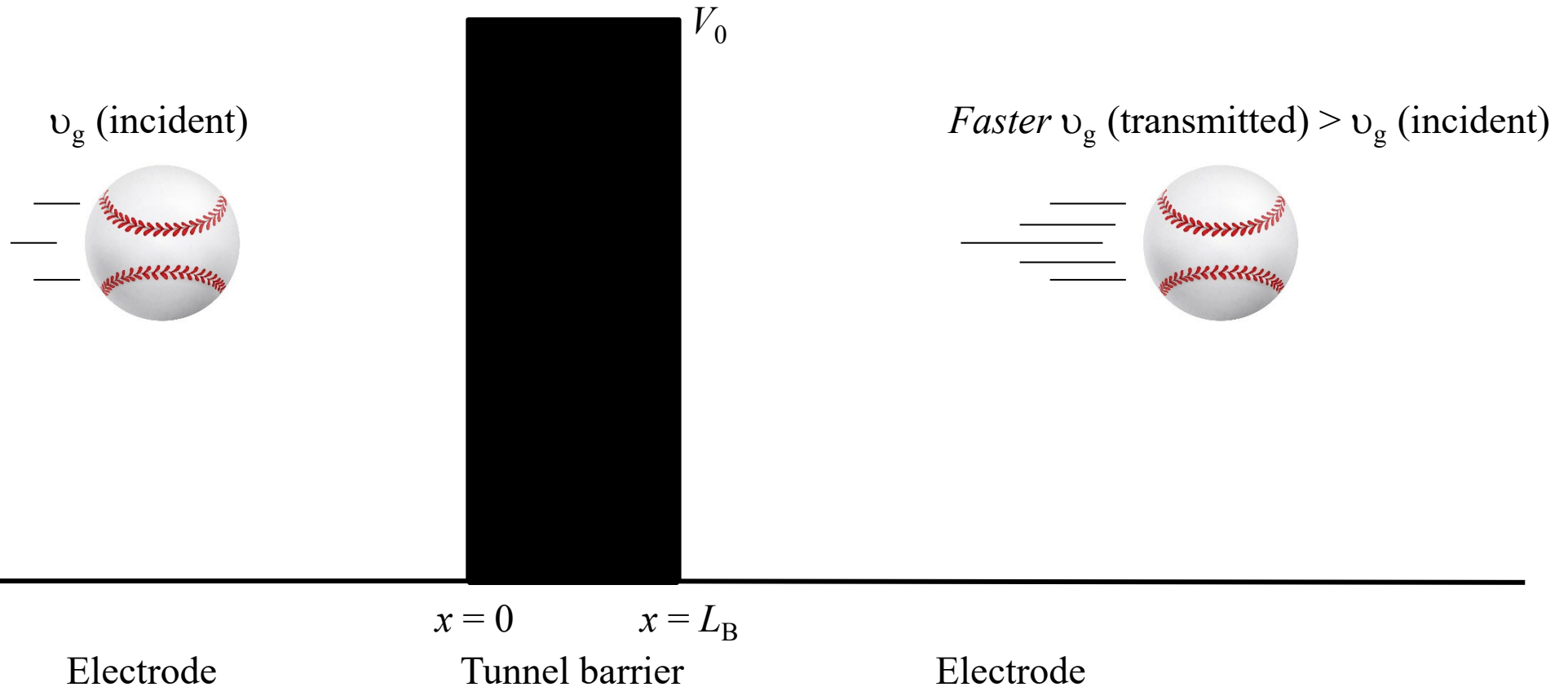


Space-time plot of *high-pass* k -space filter in a tunnel barrier



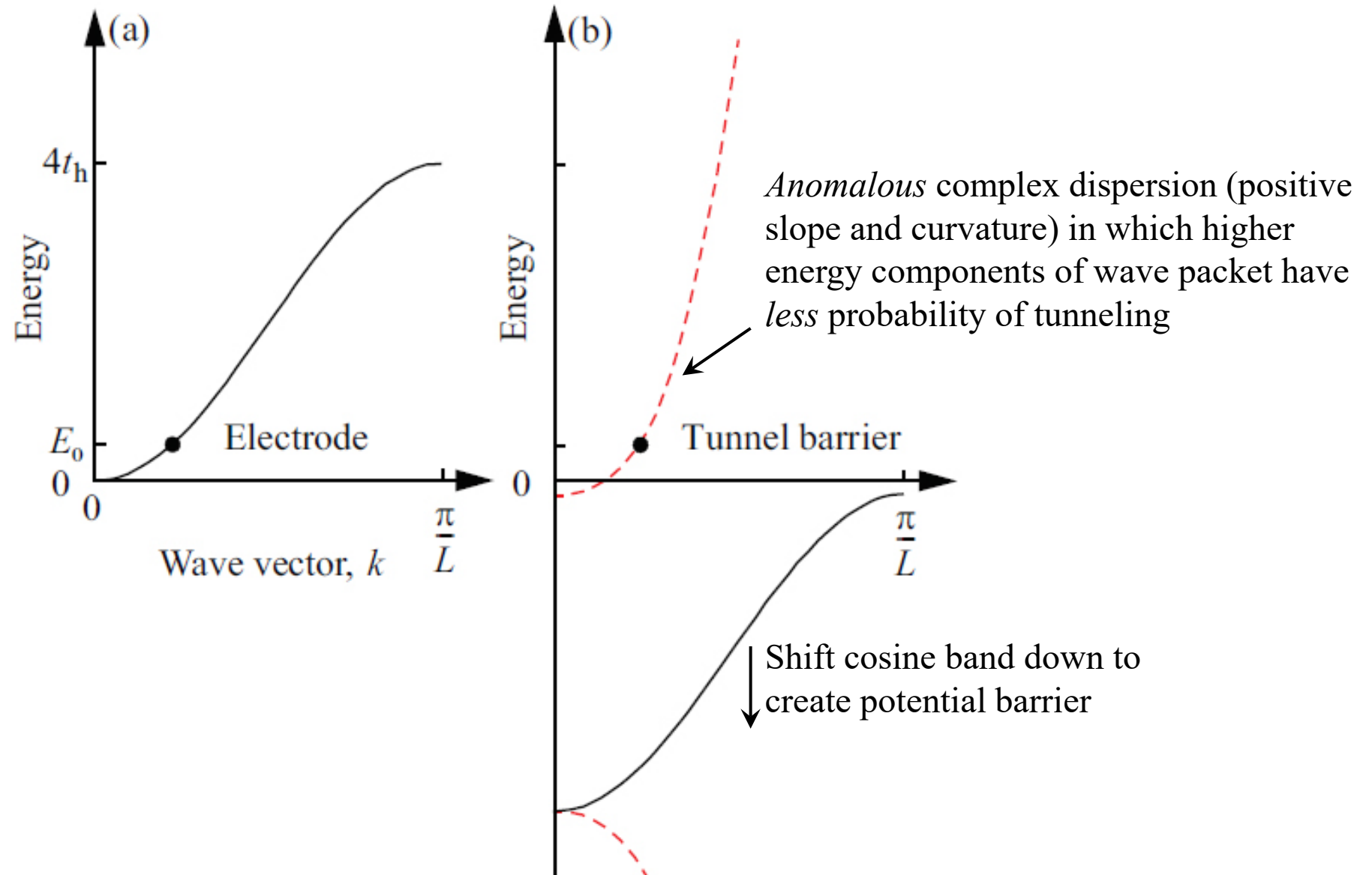
Summary

- A coherent single-particle wave-packet incident on a classically impenetrable barrier can be reflected and interfere with itself
- The particle can also be transmitted by tunneling
- The tunnel-transmitted particle can move *faster* (has a greater group velocity) than the incident particle
- The transmitted particle can arrive on the far side of the barrier *before* the case when there is no barrier present



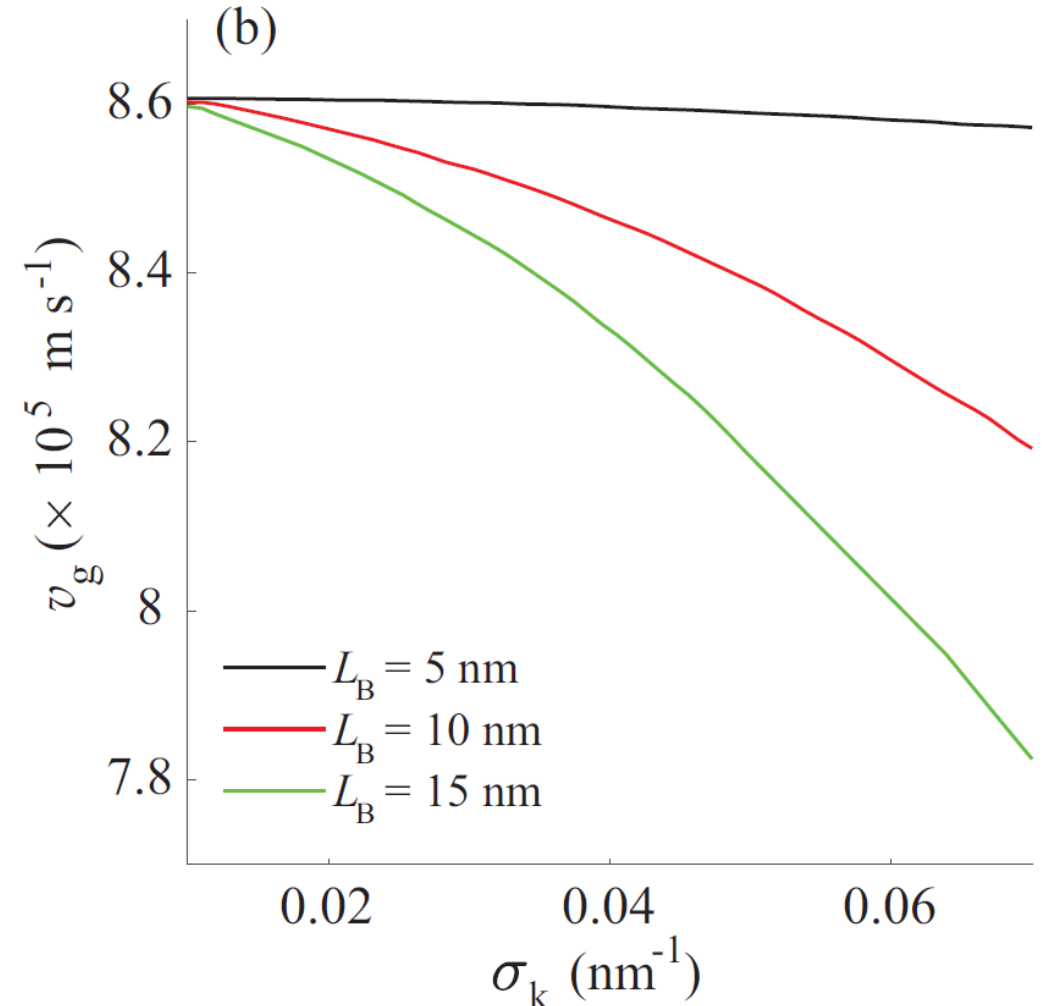
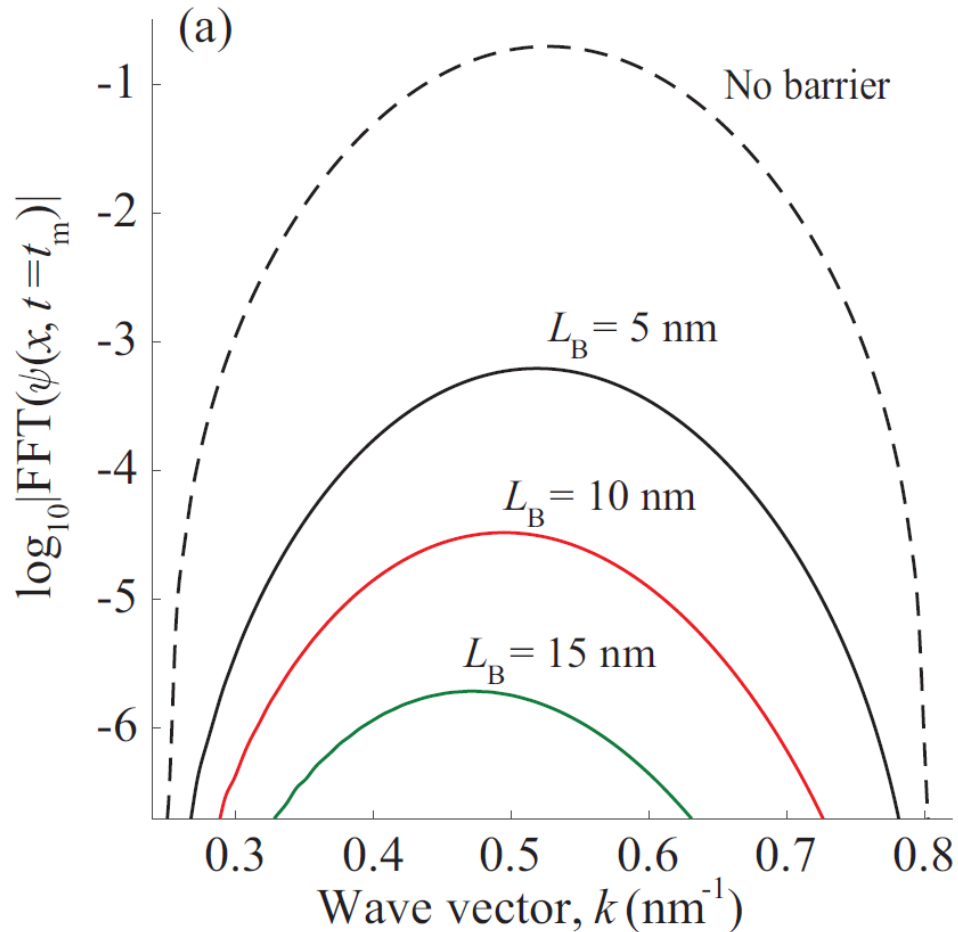
Controlling dispersion in the tunnel barrier

Tunnel barrier dispersion for a *low-pass* k -space filter

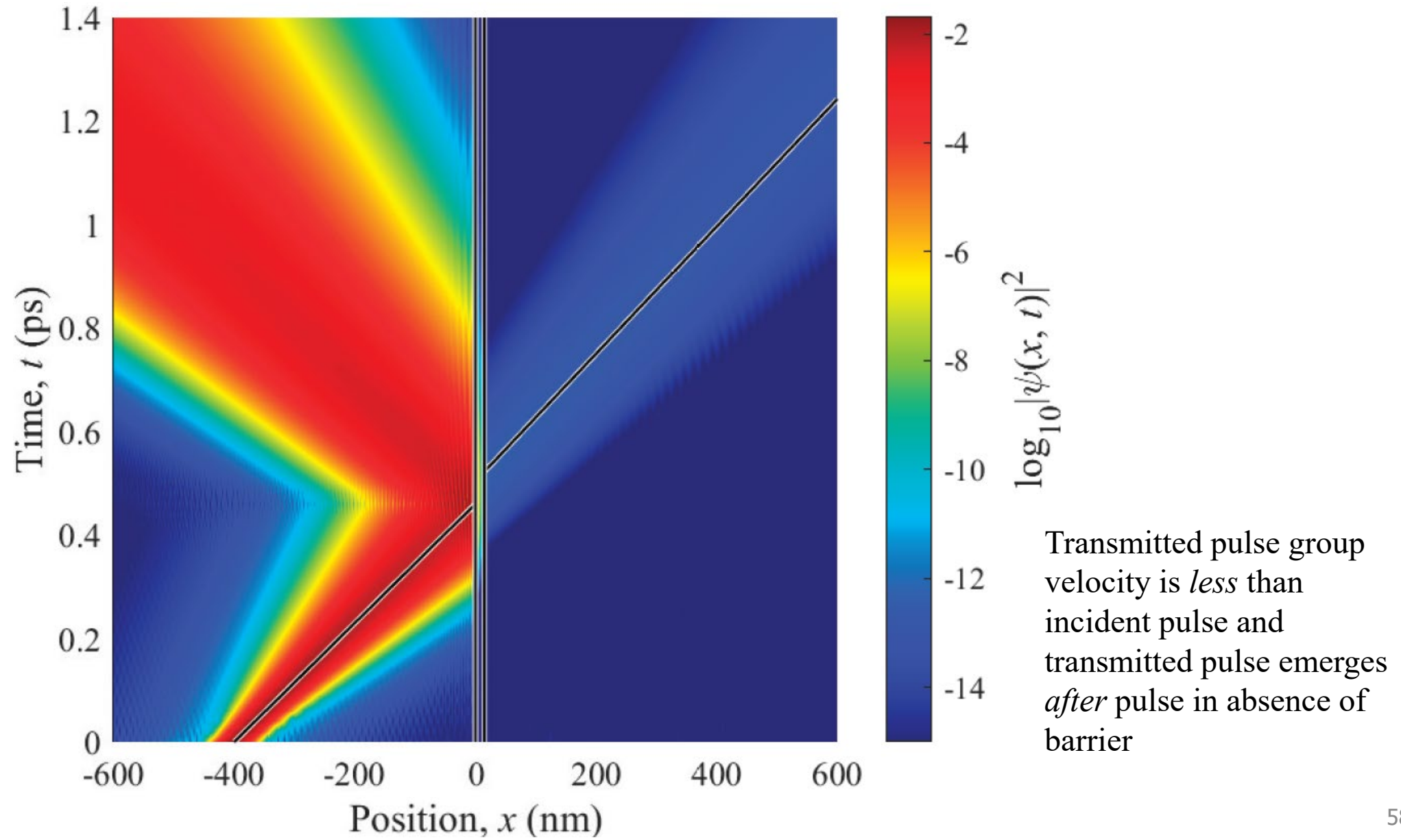


Tunnel barrier dispersion for a *low-pass* k -space filter

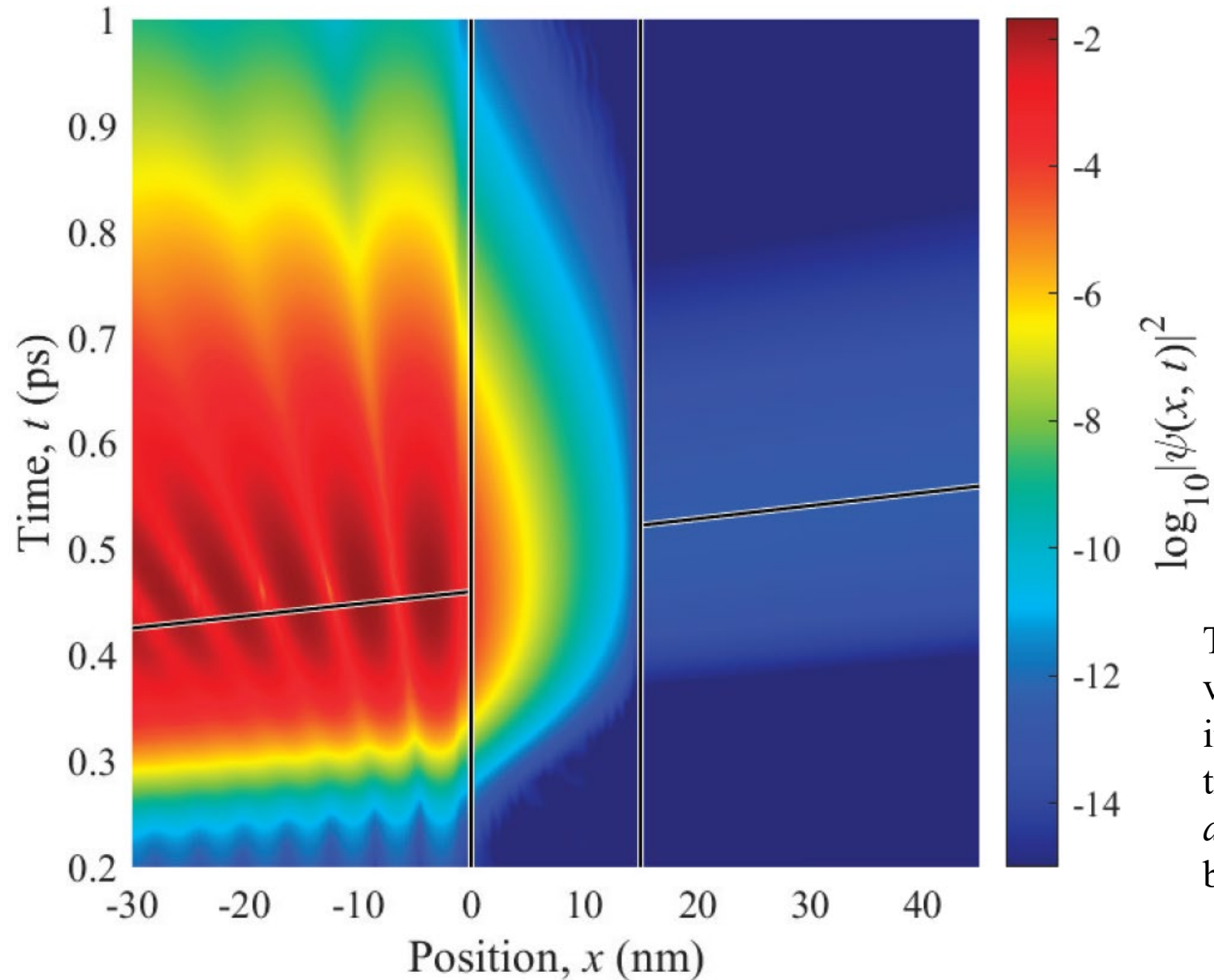
- (a) A tunnel barrier of thickness L_B with *anomalous* imaginary dispersion acts as a *low-pass* k -space filter. The transmitted pulse contains k -states with amplitudes that peak at a value $k' < k_c$ and has group velocity *less* than that of the incident pulse. The transmitted pulse has a time-independent wave vector spectrum
- (b) Transmitted pulse group velocity, v_g , depends on σ_k and L_B



Space-time plot of *low-pass* k -space filter in a tunnel barrier



Space-time plot of *low-pass* k -space filter in a tunnel barrier

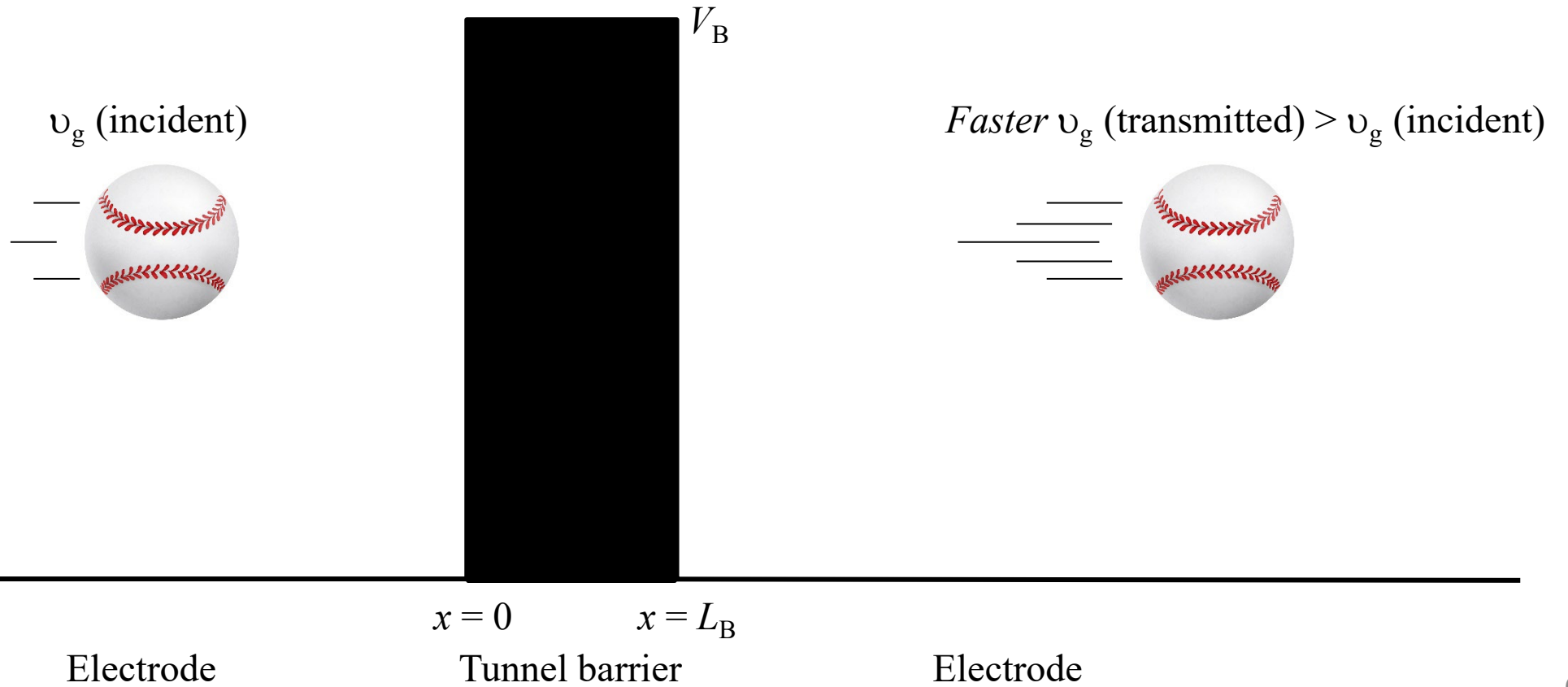


Transmitted pulse group velocity is *less* than incident pulse and transmitted pulse emerges *after* pulse in absence of barrier

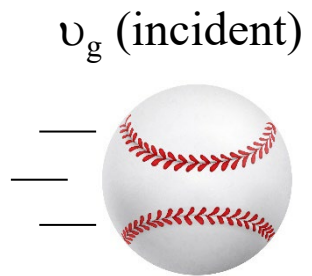
Summary

- The dispersion described by complex band structure due to the periodic potential of a crystal can be used to help explain and control the behavior of single-electron wave-packet propagation, tunneling, *and as a guide* for device design (with the understanding that the Schrödinger equation is to be solved for the actual finite-sized device geometry under consideration)
- A nearest-neighbor tight-binding model of atom s-orbitals on a 1D lattice may be used to illustrate the essential physics
 - The band structure of real k -states controls dispersion of a propagating electron pulse
 - The dispersion of imaginary k -states in a tunnel barrier determines electron wave packet tunneling
- The imaginary k -space dispersion in a tunnel barrier may be viewed as a filter that controls the arrival time, shape, and group velocity of a transmitted single-electron single-peaked wave packet
 - Suggests a methodology that expands electron device design space
 - A resource to reduce complexity, increase peak-to-valley ratio of a RTD, reduce subthreshold slope in a transistor, etc.
- Super-luminal transmission of information is precluded because single-bit information detection requires use of a common bit-detection threshold. This results in the single-bit tunnel transmitted information in the pulse arriving after that of the pulse with no barrier present. *Collision lifetime* and the related *tunneling time* can also be defined by considering such information transport
- “Wave packet tunneling and imaginary wave vector dispersion”, W. Unglaub and A. F. J. Levi, *Physics Open* **17**, 100164 (2023).

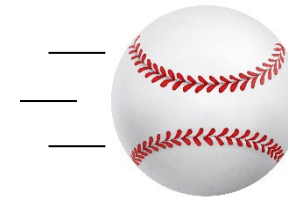
High-pass k -space filter in a tunnel barrier



No tunnel barrier



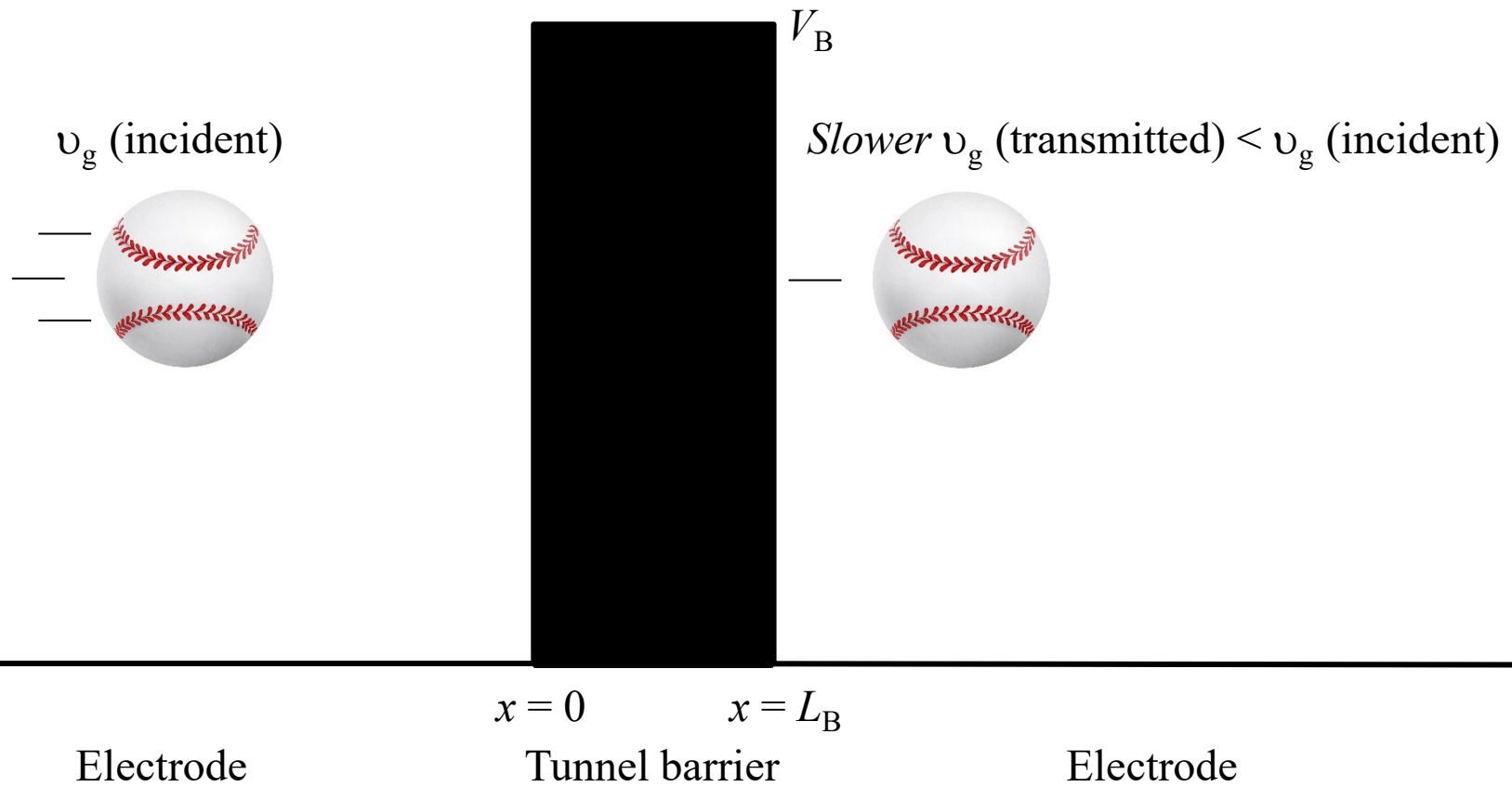
$$v_g \text{ (transmitted)} = v_g \text{ (incident)}$$



Electrode

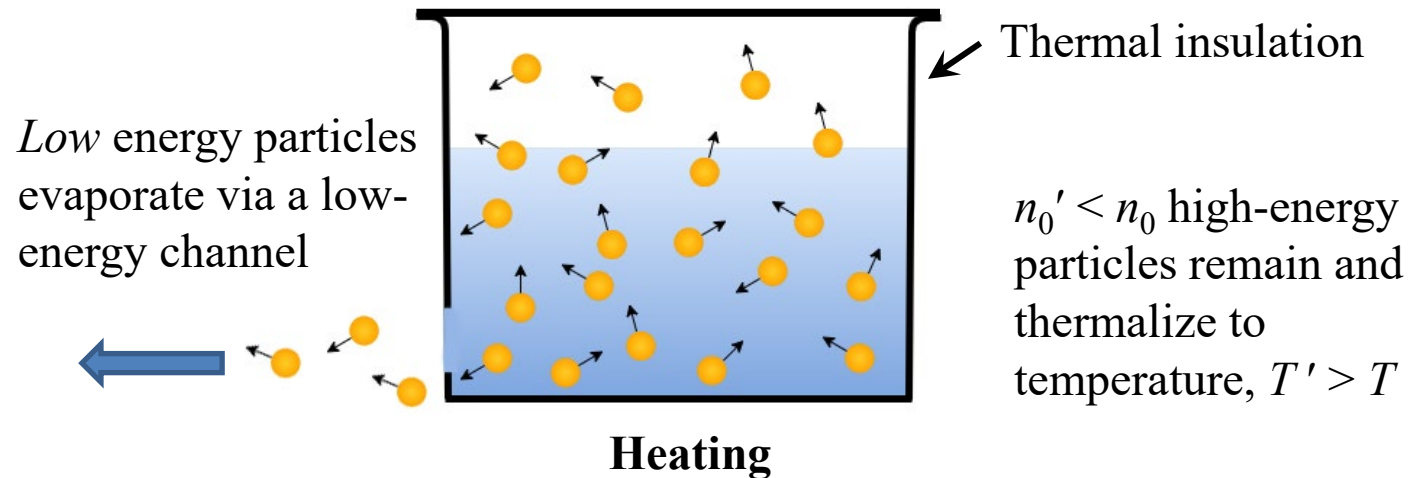
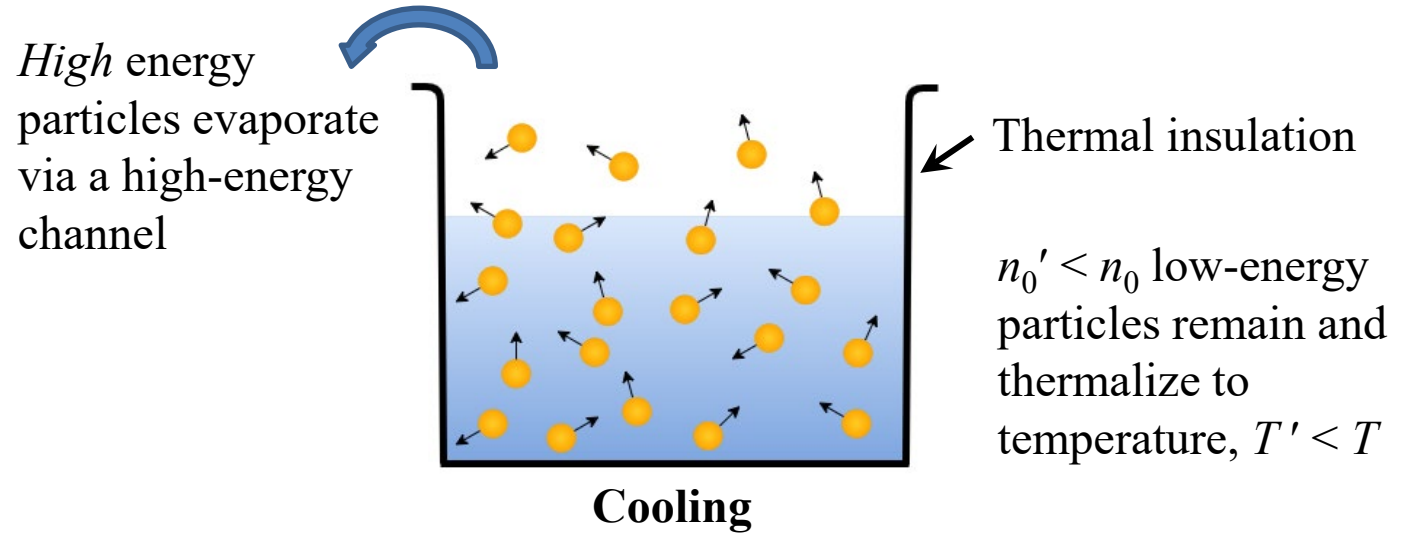
Electrode

Low-pass k -space filter in a tunnel barrier



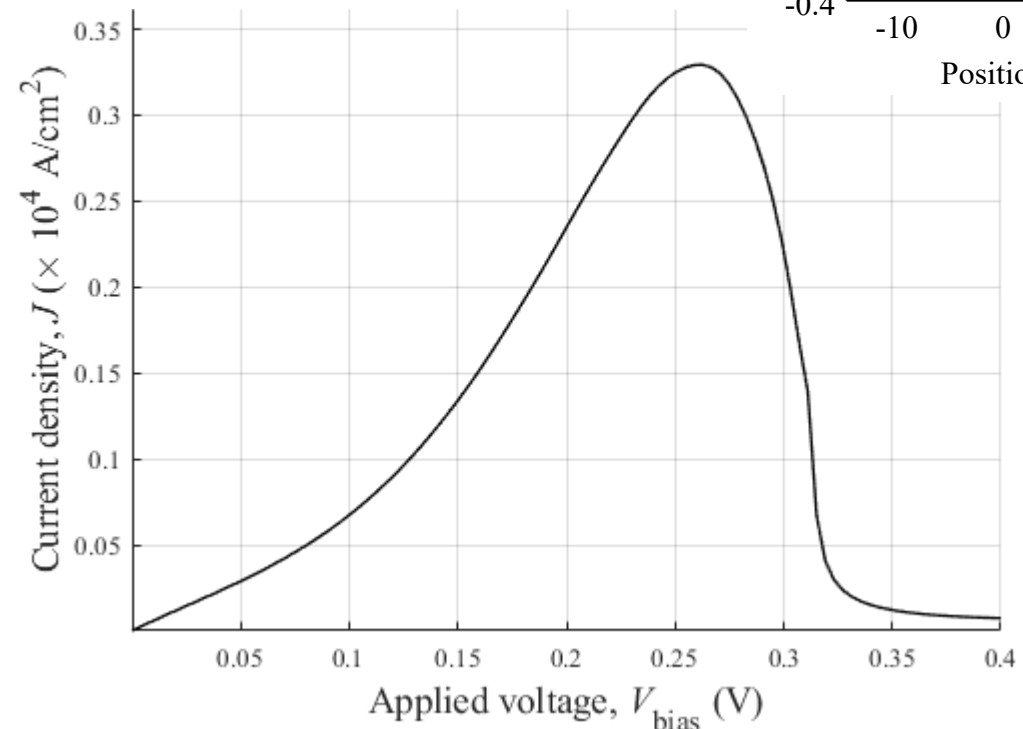
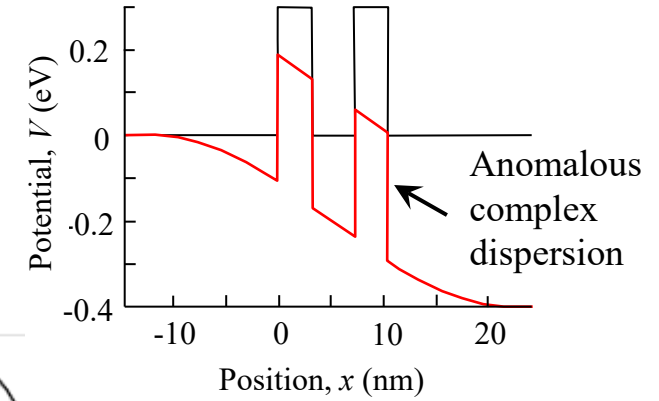
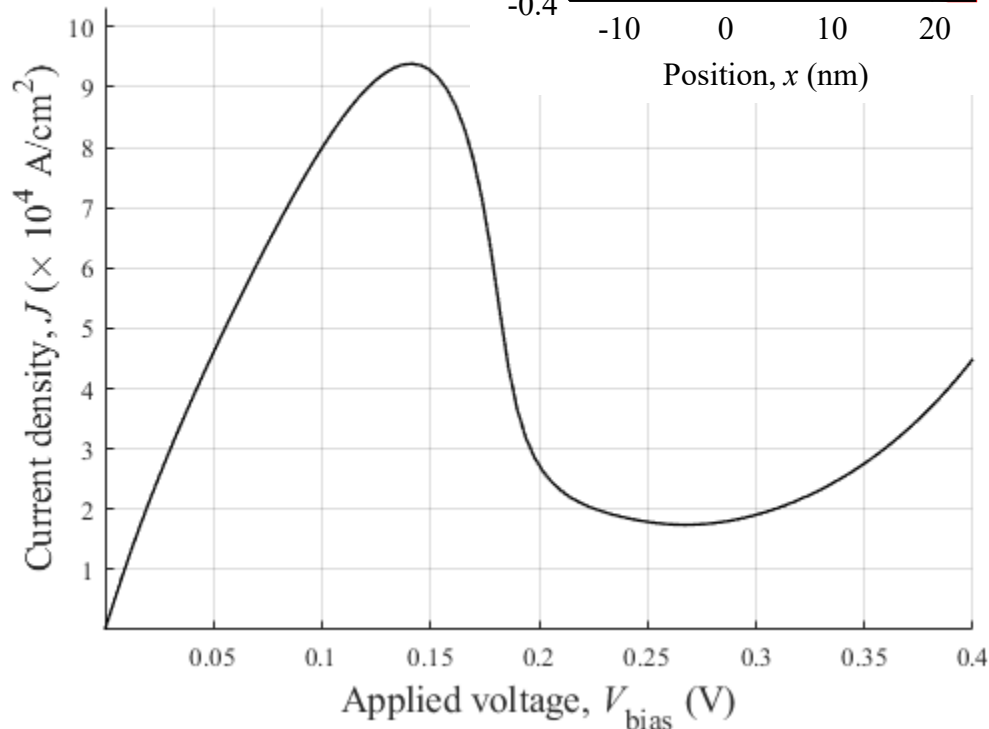
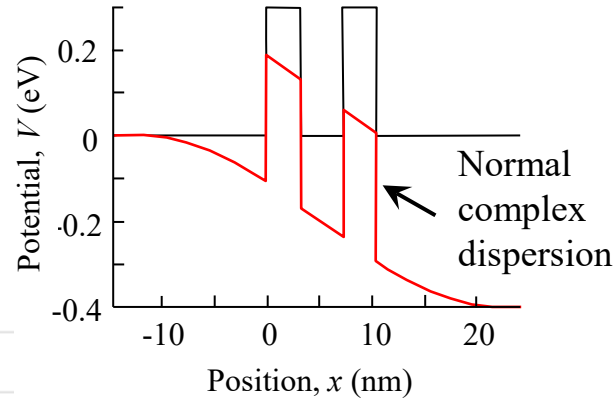
Thermodynamics

- Particles of density n_0 initially at equilibrium and temperature T
- *Evaporation of hot particles* cools down remaining particles of density $n_0' < n_0$ to temperature, $T' < T$
 - High-pass filter removes high-energy particles resulting in cooling of remaining particles
- *Evaporation of cold particles* heats up the remaining particles of density $n_0' < n_0$ to temperature, $T' > T$
 - Low-pass filter removes low-energy particles resulting in heating of remaining particles



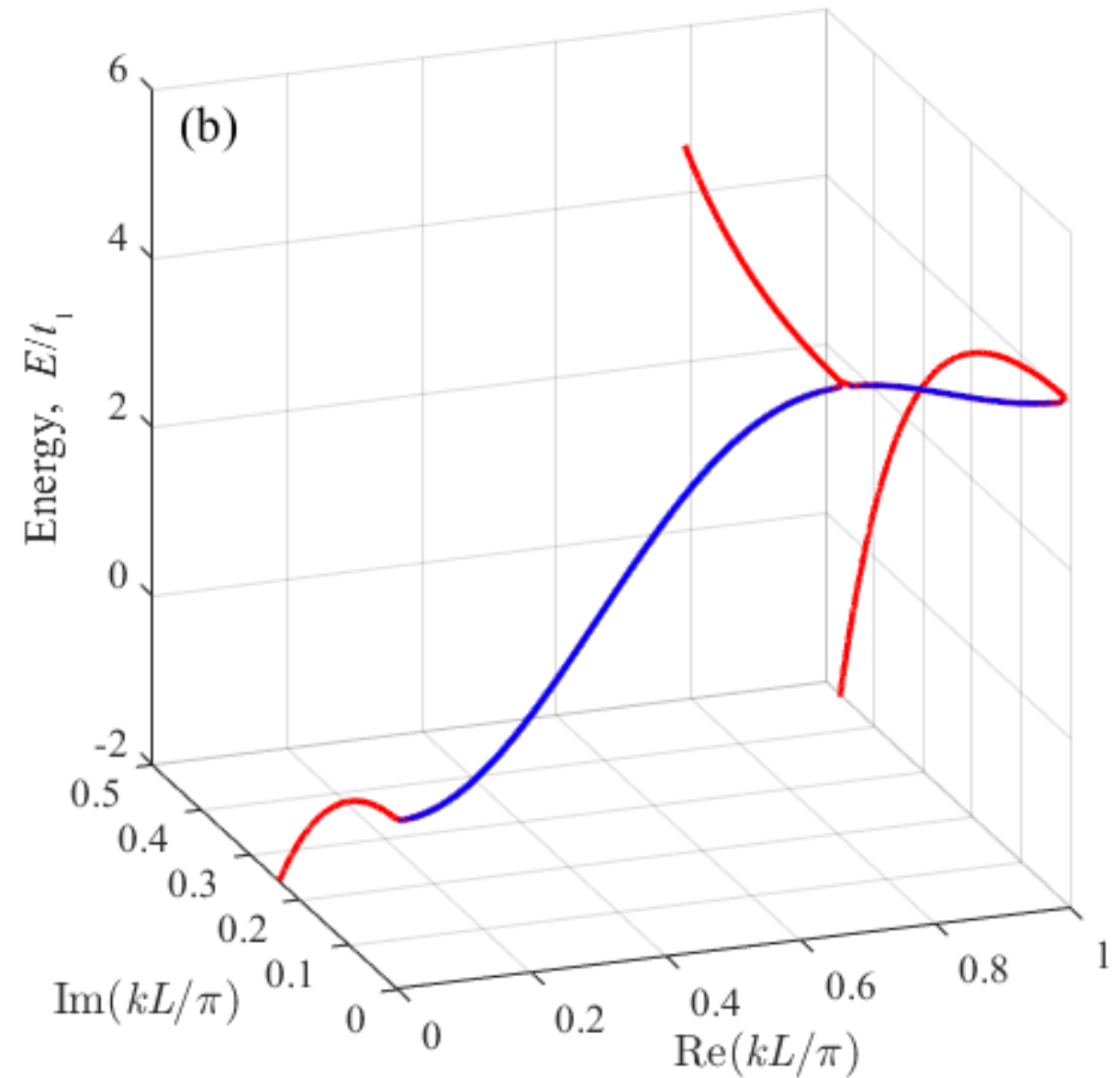
Complex dispersion and a double barrier resonant tunnel diode

- Increase peak-to-valley current ratio from PVR=5 for device with normal complex dispersion (negative slope $\text{Im}(k)$) to PVR=45 with anomalous complex dispersion (positive slope $\text{Im}(k)$) in the second barrier



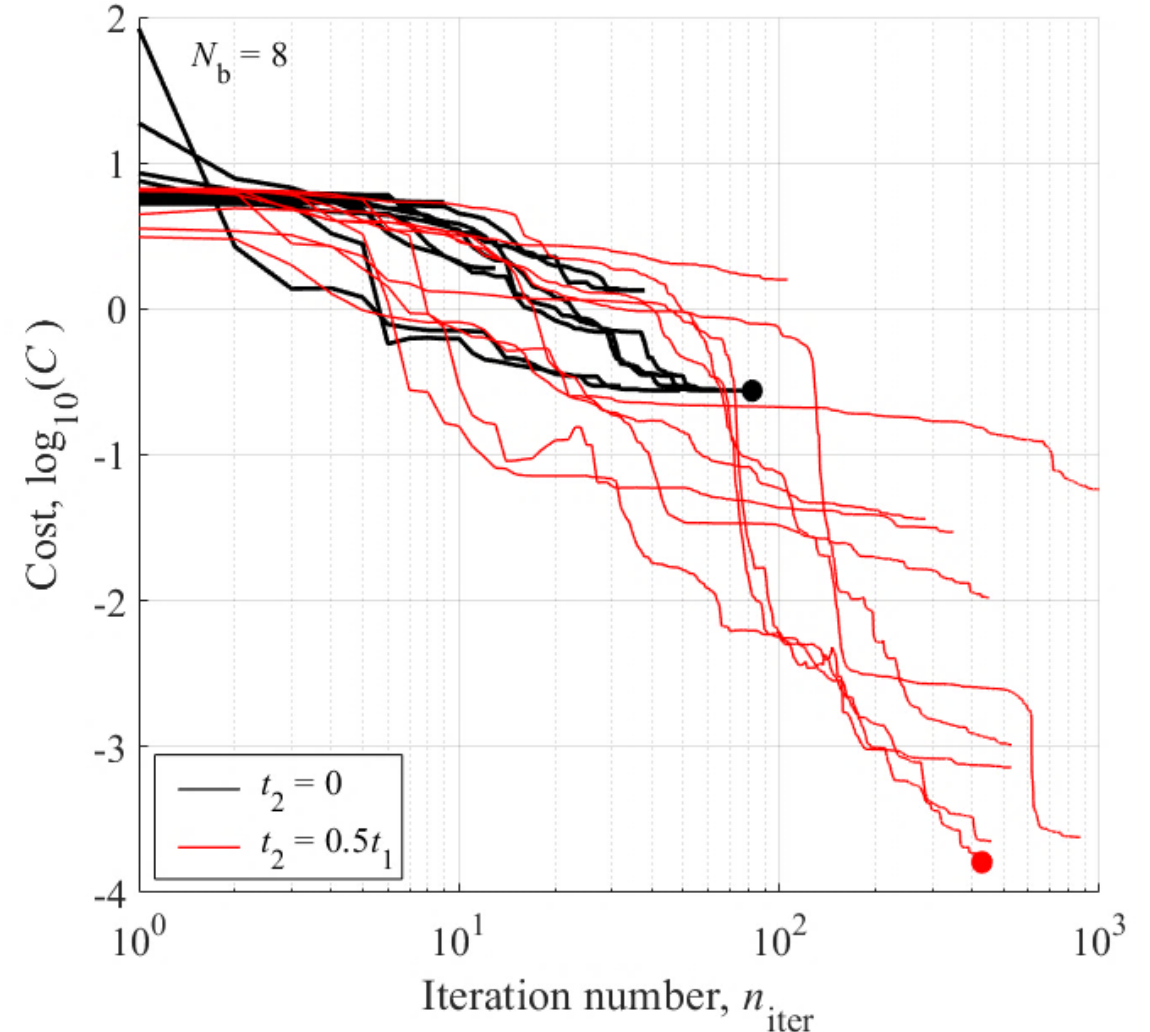
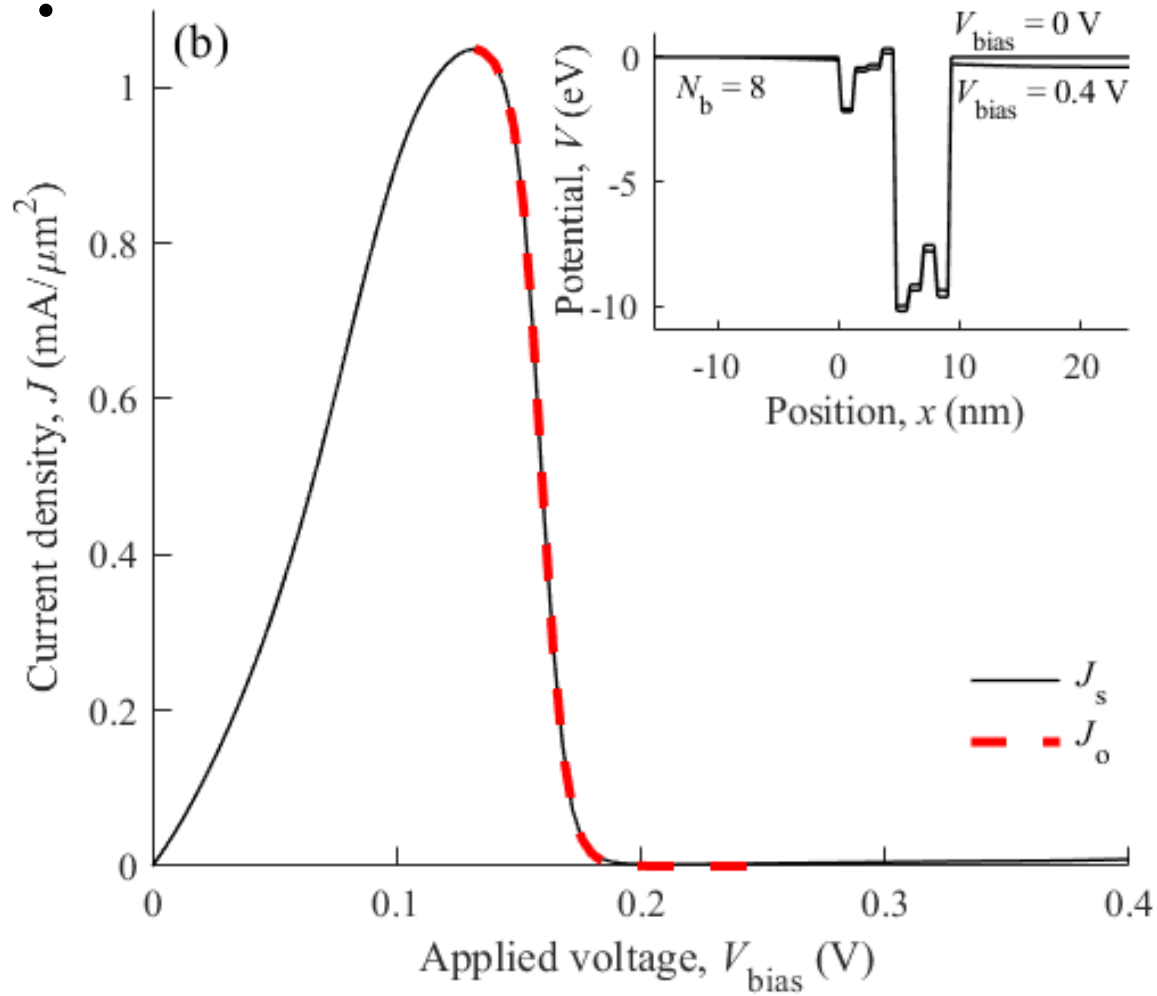
Complex dispersion with next-nearest neighbor

- N_b is resource
- $t_2 = 0.5 t_1$ is resource that enables optimal solution



Complex dispersion and the $N_b=8$ -layer diode

- The number of layers (N_b) and the next nearest neighbor interaction ($t_2 = 0.5 t_1$) are resources
- Example sigmoid current-voltage objective (red dash)
- Do *not* require tunneling to create RTD current-voltage characteristics!



Quantum engineering:
The need for a new search engine

Vast quantum engineering design space

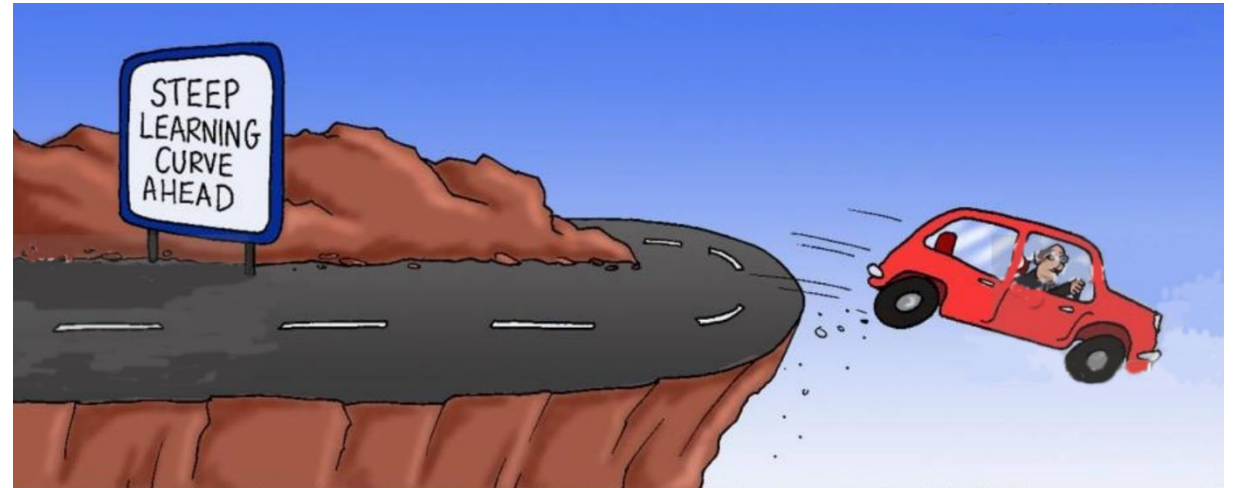
→ new **Quantum** search engine

A. F. J. LEVI

Applied Quantum Mechanics

Third Edition

There is a lot to learn ...





Scale 1 mm²



Divergence of technology: as many as 0.5B transistors per mm² (500 transistors per μm²) in 1 nm CMOS which is 2,000x density of neurons in the brain of an ant (ant brain has 250,000 neurons).

c.f. The Intel 8080 8-bit processor of 1974 with a total of 4,500 transistors in 6 μm technology and 2 MHz clock will fit in a 3 μm x 3 μm area using 1 nm CMOS and consume 4,500 x 1 aJ x 2 MHz > 10 nW power. A total of 110,000 such processors per mm² in 1 nm CMOS consumes > 1 mW.

An exciting *Super-Custom* silicon future: atoms-to-applications faster than software

Leverage 21st Century compute, design, and control technology

Co-design and optimization *before* fabrication

- Designer access and *control* of foundry processes enables modification, optimization and customization to the reticle level
- A massive new design parameter space



Foundry fabrication



Continuous optimization *after* fabrication

- Customized components and *post-manufacture hardware evolution*
- Real-time non-Markovian adaptation and modification of hardware in the wild
- Post-manufacture continuous optimization in both hardware and software in response to tasks
 - Getting better performance from hardware by learning and physically adapting to tasks
- Feedback to factory and designers



Co-design optimization *during* fabrication

User Intent
Design specifications
Designer knowledge
Design priorities
Design constraints



Challenge is manufacturing faster than software redesign (currently 6 weeks for Meta-Facebook)

A hardware ecosystem enabling concept, co-design, to physical product in less than 4 weeks

END