New Theoretical Perspective on Axions

Surjeet Rajendran,
The Johns Hopkins University

(With David E. Kaplan and Tom Melia)

The Strong CP Problem

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q \qquad \bar{\theta} = \theta_0 + \arg\left(\det m_Q\right) \qquad \bar{\theta} \lessapprox 10^{-9}$$

The Strong CP Problem

Why?

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q} Q \qquad \bar{\theta} = \theta_0 + \arg\left(\det m_Q\right) \qquad \bar{\theta} \lessapprox 10^{-9}$$

The Strong CP Problem

Why?

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q \qquad \bar{\theta} = \theta_0 + \arg\left(\det m_Q\right) \qquad \bar{\theta} \lesssim 10^{-9}$$

Proposed Solutions

The Strong CP Problem

Why?

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q \qquad \bar{\theta} = \theta_0 + \arg(\det m_Q) \qquad \bar{\theta} \lesssim 10^{-9}$$

Proposed Solutions

QCD Axion $$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q + \frac{a}{f_a} G\tilde{G} \implies \frac{a}{f_a} + \bar{\theta} = 0$$

The Strong CP Problem

Why?

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q} Q \qquad \bar{\theta} = \theta_0 + \arg\left(\det m_Q\right) \qquad \bar{\theta} \lesssim 10^{-9}$$

Proposed Solutions

QCD Axion $\quad \mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q} Q + \frac{a}{f_a} G\tilde{G} \implies \frac{a}{f_a} + \bar{\theta} = 0$

Nelson-Barr $\quad$ Propose CP as a symmetry

$$\theta_0 = 0, \arg\left(\det m_Q\right) = 0$$

The Strong CP Problem

Why?

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q \qquad \bar{\theta} = \theta_0 + \arg\left(\det m_Q\right) \qquad \bar{\theta} \lesssim 10^{-9}$$

Proposed Solutions

QCD Axion $\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q + \frac{a}{f_a} G\tilde{G} \implies \frac{a}{f_a} + \bar{\theta} = 0$

Nelson-Barr Propose CP as a symmetry

$$\theta_0 = 0, \arg\left(\det m_Q\right) = 0$$

Fine Tune $\theta_0 + \arg\left(\det m_Q\right) \lesssim 10^{-9}$

The Strong CP Problem

Why?

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q \qquad \bar{\theta} = \theta_0 + \arg\left(\det m_Q\right) \qquad \bar{\theta} \lesssim 10^{-9}$$

Proposed Solutions

QCD Axion $\quad \mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q + \frac{a}{f_a} G\tilde{G} \implies \frac{a}{f_a} + \bar{\theta} = 0$

Nelson-Barr $\quad$ Propose CP as a symmetry

$$\theta_0 = 0, \arg\left(\det m_Q\right) = 0$$

Fine Tune $\quad \theta_0 + \arg\left(\det m_Q\right) \lesssim 10^{-9}$

G. Dvali **Claim: θ_0 comes from choice of quantum state. Not a parameter**

The Strong CP Problem

Why?

$$\mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q \qquad \bar{\theta} = \theta_0 + \arg\left(\det m_Q\right) \qquad \bar{\theta} \lesssim 10^{-9}$$

Proposed Solutions

QCD Axion $\quad \mathcal{L} \supset \theta_0 G\tilde{G} + m_Q \bar{Q}Q + \frac{a}{f_a} G\tilde{G} \implies \frac{a}{f_a} + \bar{\theta} = 0$

Nelson-Barr $\quad$ Propose CP as a symmetry

$$\theta_0 = 0, \arg\left(\det m_Q\right) = 0$$

Fine Tune $\quad \theta_0 + \arg\left(\det m_Q\right) \lesssim 10^{-9}$

G. Dvali **Claim: θ_0 comes from choice of quantum state. Not a parameter**

Consequence: Strong CP can only be solved by dynamical methods i.e. axion!

The Hydrogen Atom

$$H \supset -\frac{e^2}{r}$$

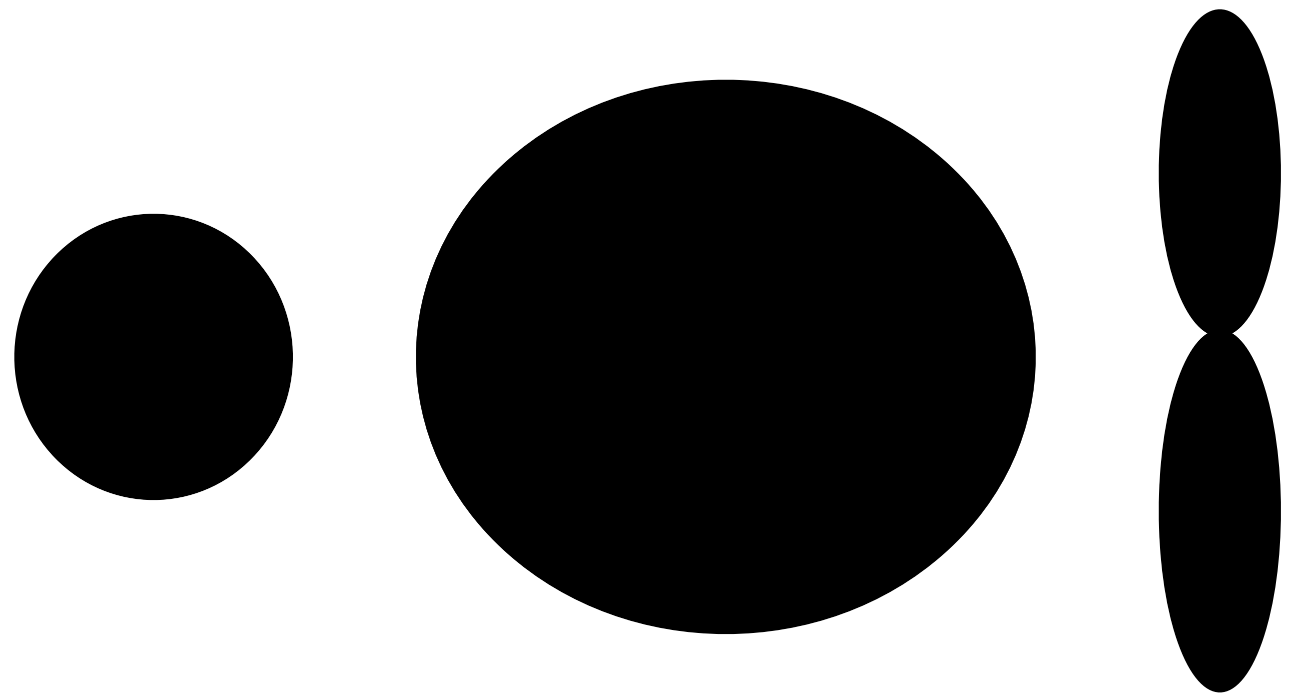
Spherically Symmetric Hamiltonian

The Hydrogen Atom

$$H \supset -\frac{e^2}{r}$$

Spherically Symmetric Hamiltonian

Energy Eigenstates:



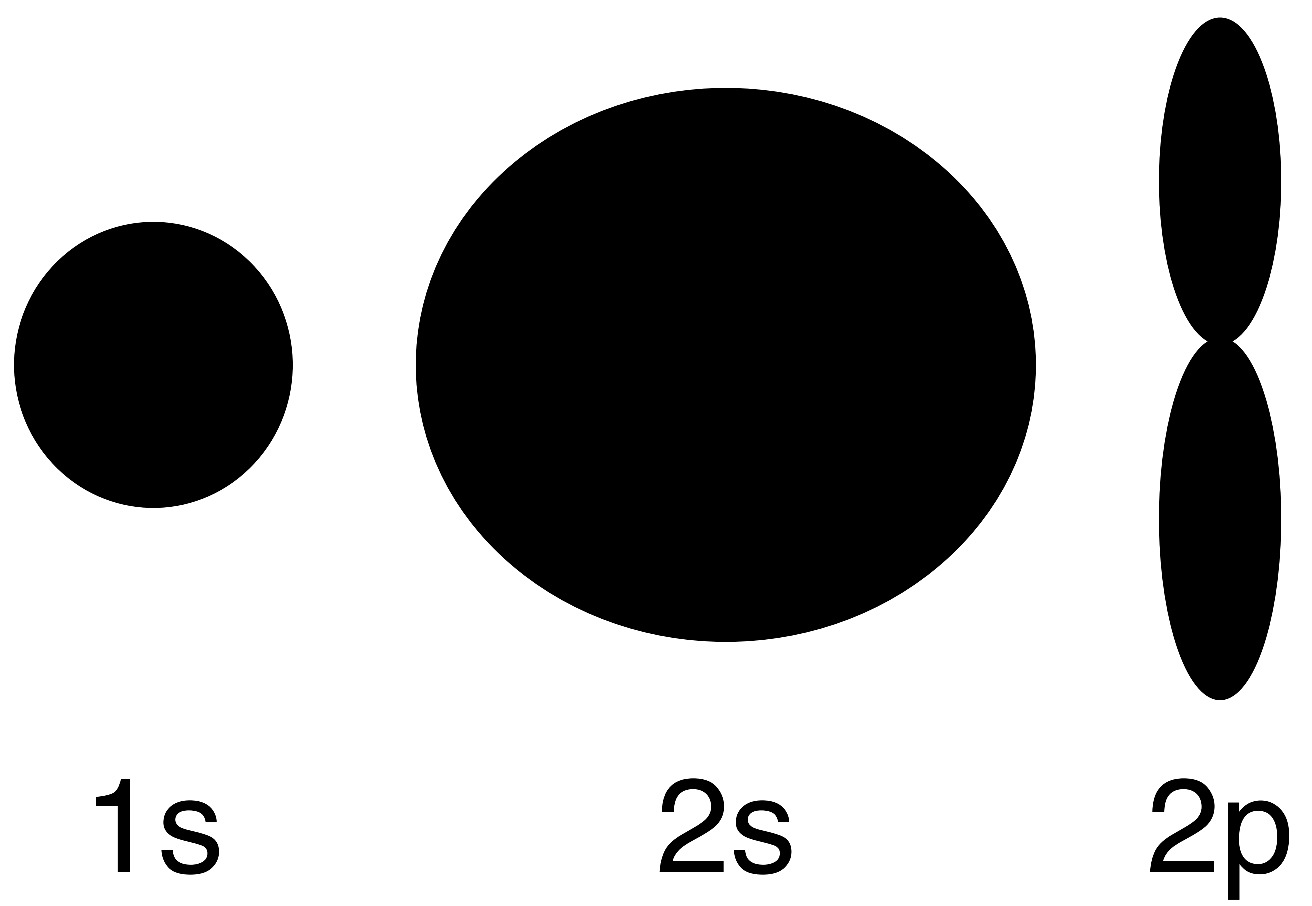
1s 2s 2p

The Hydrogen Atom

$$H \supset -\frac{e^2}{r}$$

Spherically Symmetric Hamiltonian

Energy Eigenstates:



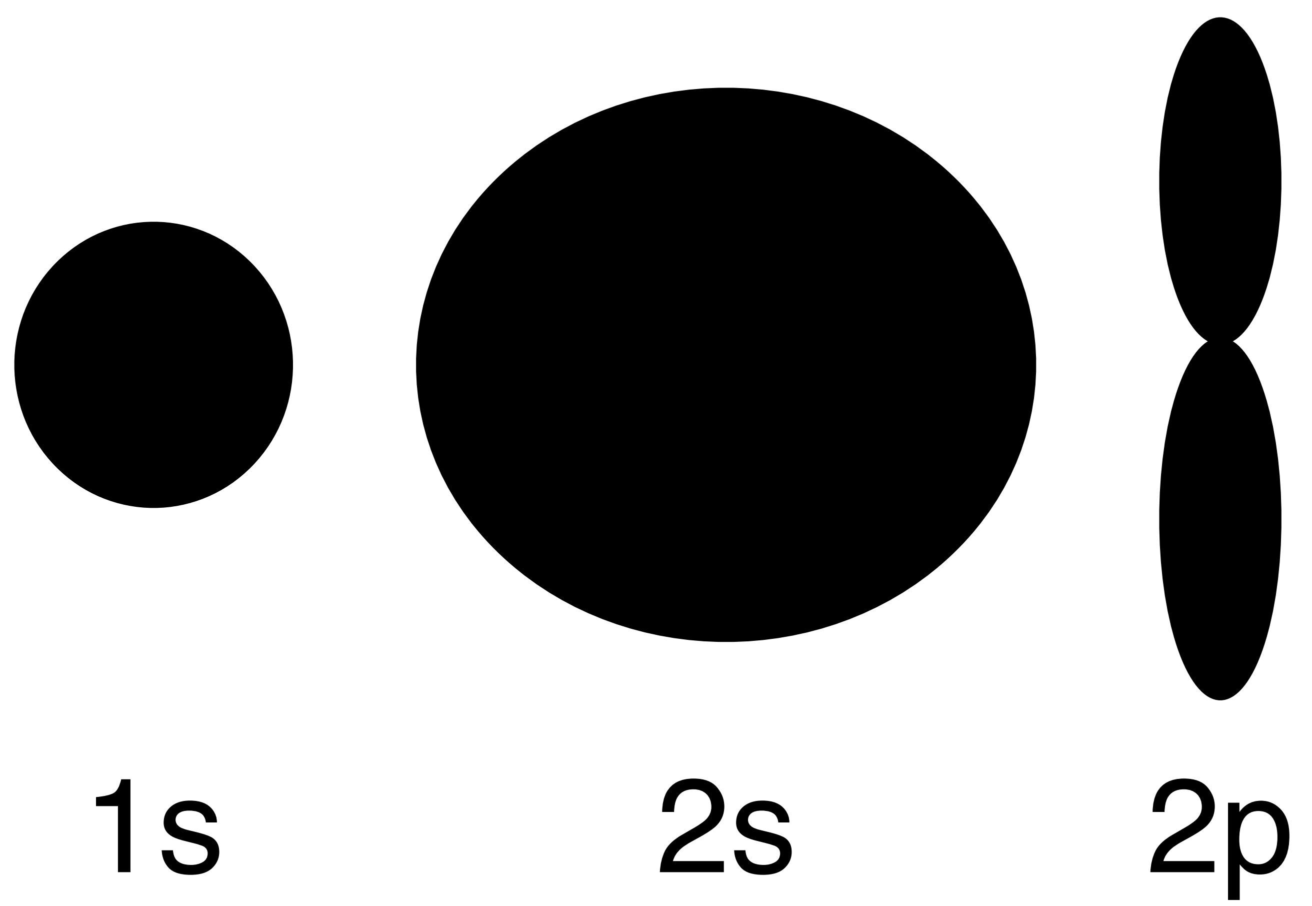
Spherically symmetric Hamiltonian. Non-spherically symmetric states

The Hydrogen Atom

$$H \supset -\frac{e^2}{r}$$

Spherically Symmetric Hamiltonian

Energy Eigenstates:



Spherically symmetric Hamiltonian. Non-spherically symmetric states

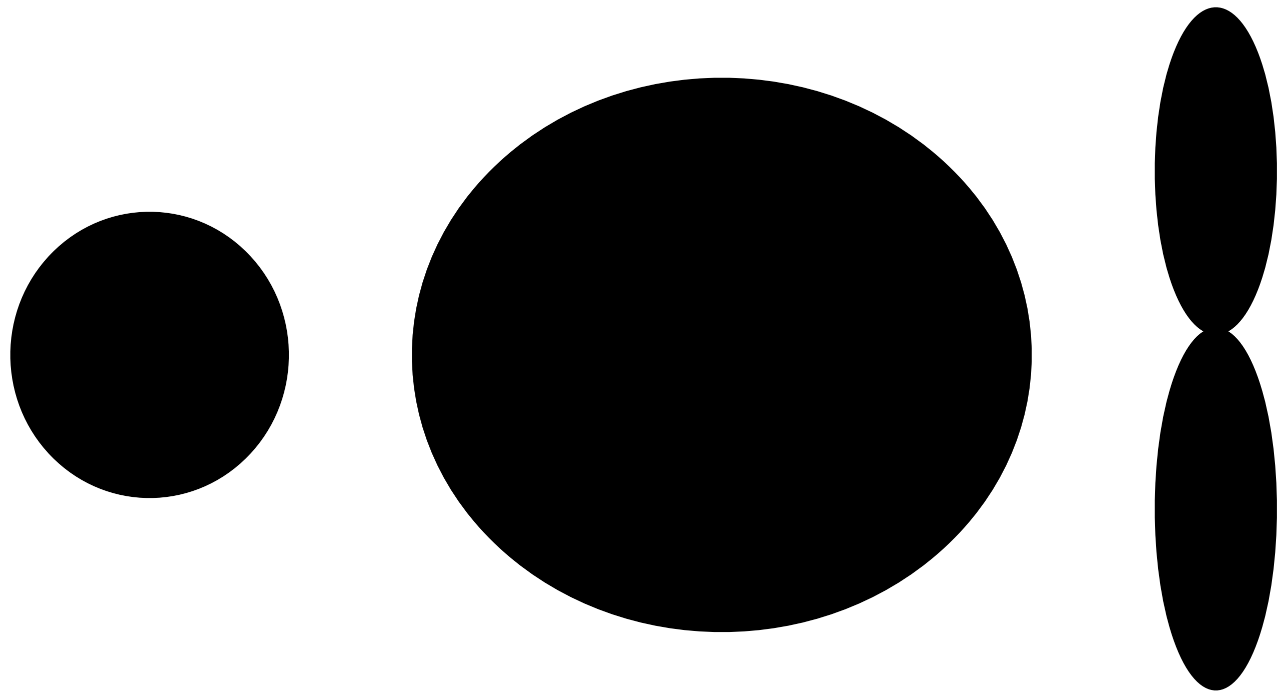
Hydrogen Produced by a number of high energy processes in early universe

The Hydrogen Atom

$$H \supset -\frac{e^2}{r}$$

Spherically Symmetric Hamiltonian

Energy Eigenstates:



1s 2s 2p

Spherically symmetric Hamiltonian. Non-spherically symmetric states

Hydrogen Produced by a number of high energy processes in early universe

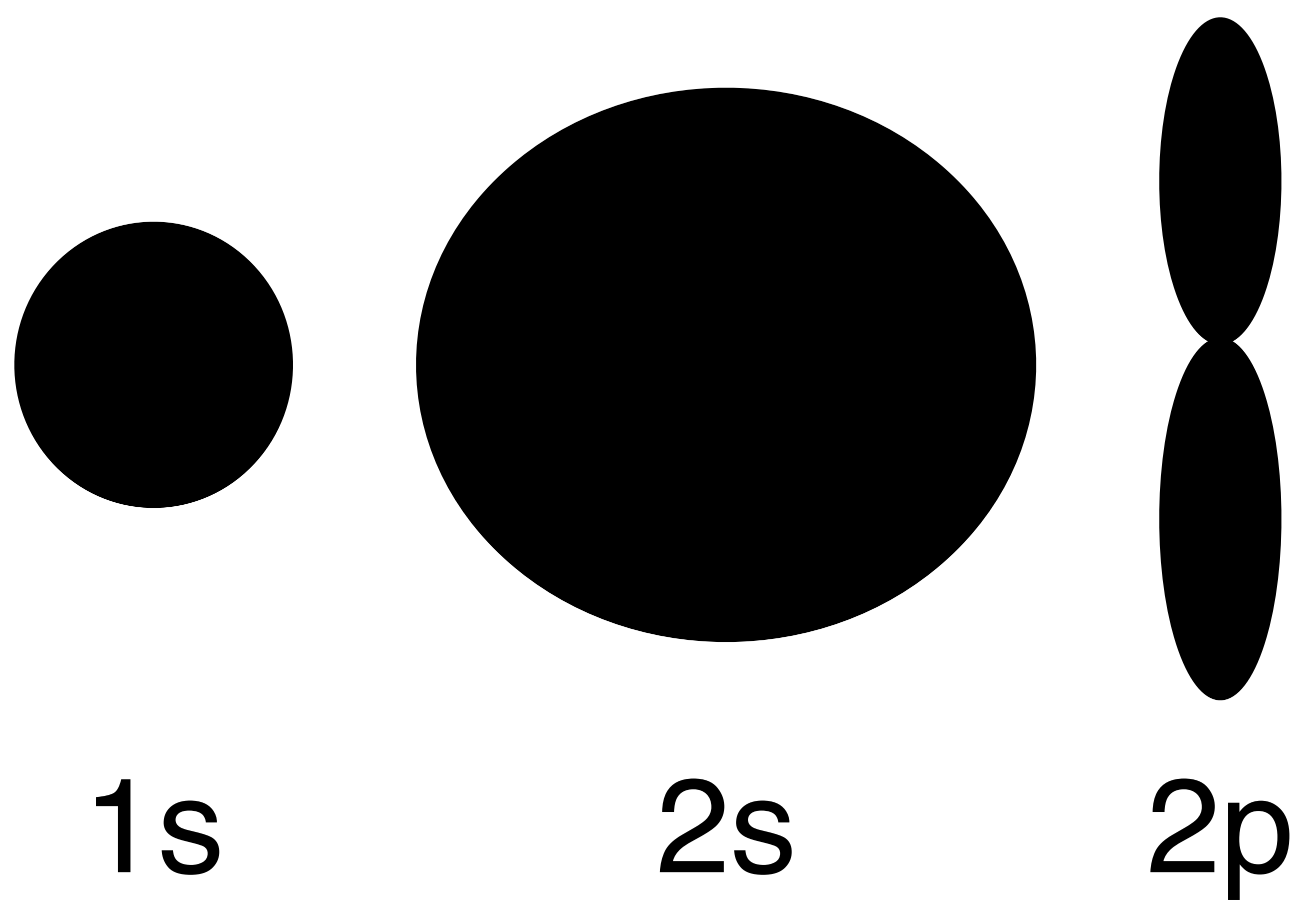
Pretty much all hydrogen we see is in 1s.

The Hydrogen Atom

$$H \supset -\frac{e^2}{r}$$

Spherically Symmetric Hamiltonian

Energy Eigenstates:



Spherically symmetric Hamiltonian. Non-spherically symmetric states

Hydrogen Produced by a number of high energy processes in early universe

Pretty much all hydrogen we see is in 1s.

Not a problem - states decay to 1s

Hydrogen with Massive Photon

$$H \supset -e^2 \, \frac{e^{-m_\gamma r}}{r} \qquad \alpha^2 m_e \lessapprox m_\gamma \lessapprox \alpha m_e$$

Bound states still exist - but a number of stable states

Hydrogen with Massive Photon

$$H \supset -e^2 \, \frac{e^{-m_\gamma r}}{r} \qquad \alpha^2 m_e \lessapprox m_\gamma \lessapprox \alpha m_e$$

Bound states still exist - but a number of stable states

Hydrogen Produced by a number of high energy processes in early universe

Hydrogen with Massive Photon

$$H \supset -e^2 \frac{e^{-m_\gamma r}}{r} \qquad \alpha^2 m_e \lessapprox m_\gamma \lessapprox \alpha m_e$$

Bound states still exist - but a number of stable states

Hydrogen Produced by a number of high energy processes in early universe

Suppose Only See Hydrogen in 1s state

Hydrogen with Massive Photon

$$H \supset -e^2 \, \frac{e^{-m_\gamma r}}{r} \qquad \alpha^2 m_e \lesssim m_\gamma \lesssim \alpha m_e$$

Bound states still exist - but a number of stable states

Hydrogen Produced by a number of high energy processes in early universe

Suppose Only See Hydrogen in 1s state

Solve by imposing spherical symmetry?

Hydrogen with Massive Photon

$$H \supset -e^2 \, \frac{e^{-m_\gamma r}}{r} \qquad \alpha^2 m_e \lessapprox m_\gamma \lessapprox \alpha m_e$$

Bound states still exist - but a number of stable states

Hydrogen Produced by a number of high energy processes in early universe

Suppose Only See Hydrogen in 1s state

Solve by imposing spherical symmetry?

No!

Hydrogen with Massive Photon

$$H \supset -e^2 \frac{e^{-m_\gamma r}}{r} \qquad \alpha^2 m_e \lessapprox m_\gamma \lessapprox \alpha m_e$$

Bound states still exist - but a number of stable states

Hydrogen Produced by a number of high energy processes in early universe

Suppose Only See Hydrogen in 1s state

Solve by imposing spherical symmetry?

No!

Hamiltonian already spherically symmetric - still allows non-spherically symmetric states (2p etc)

Hydrogen with Massive Photon

$$H \supset -e^2 \frac{e^{-m_\gamma r}}{r} \qquad \alpha^2 m_e \lessapprox m_\gamma \lessapprox \alpha m_e$$

Bound states still exist - but a number of stable states

Hydrogen Produced by a number of high energy processes in early universe

Suppose Only See Hydrogen in 1s state

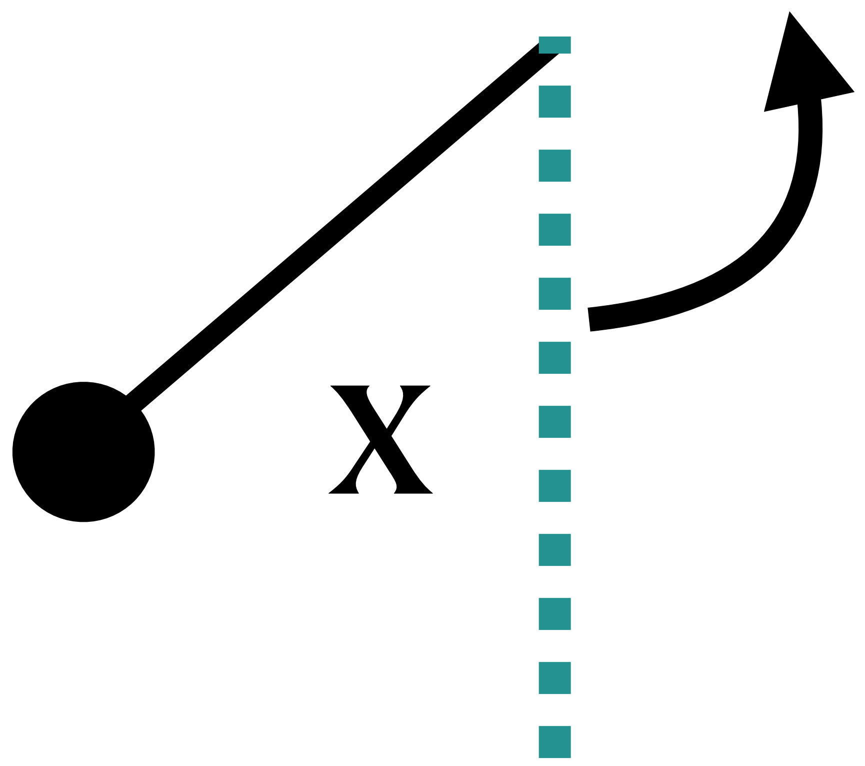
Solve by imposing spherical symmetry?

No!

Hamiltonian already spherically symmetric - still allows non-spherically symmetric states (2p etc)

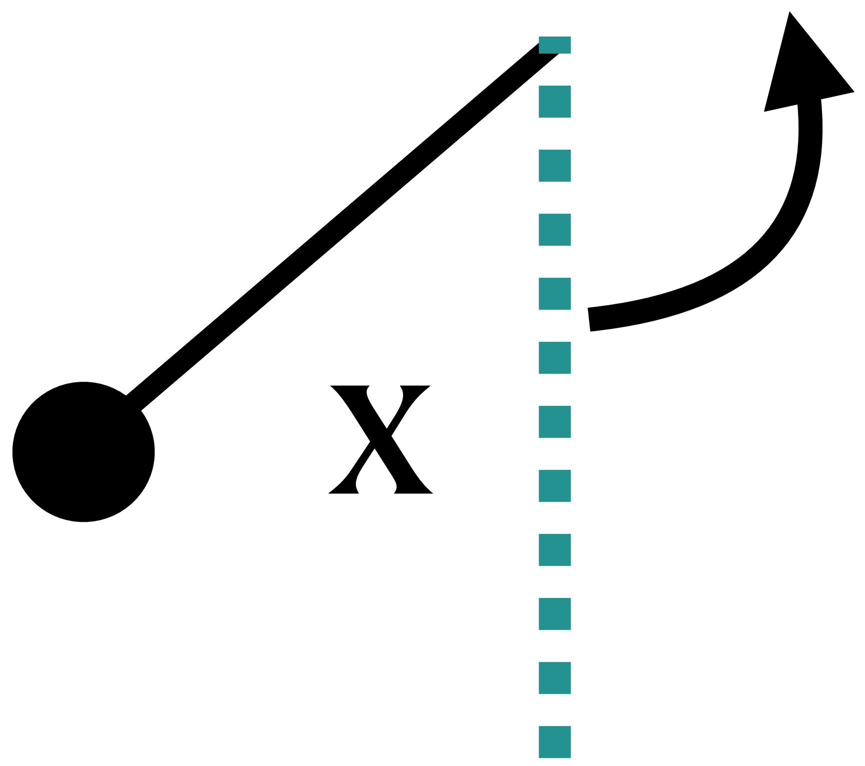
Only solutions are dynamical - e.g. massless hidden photon allowing states to decay, collisions between atoms

Rigid Pendulum in Gravity



$$V(x) = -\kappa \cos(x)$$

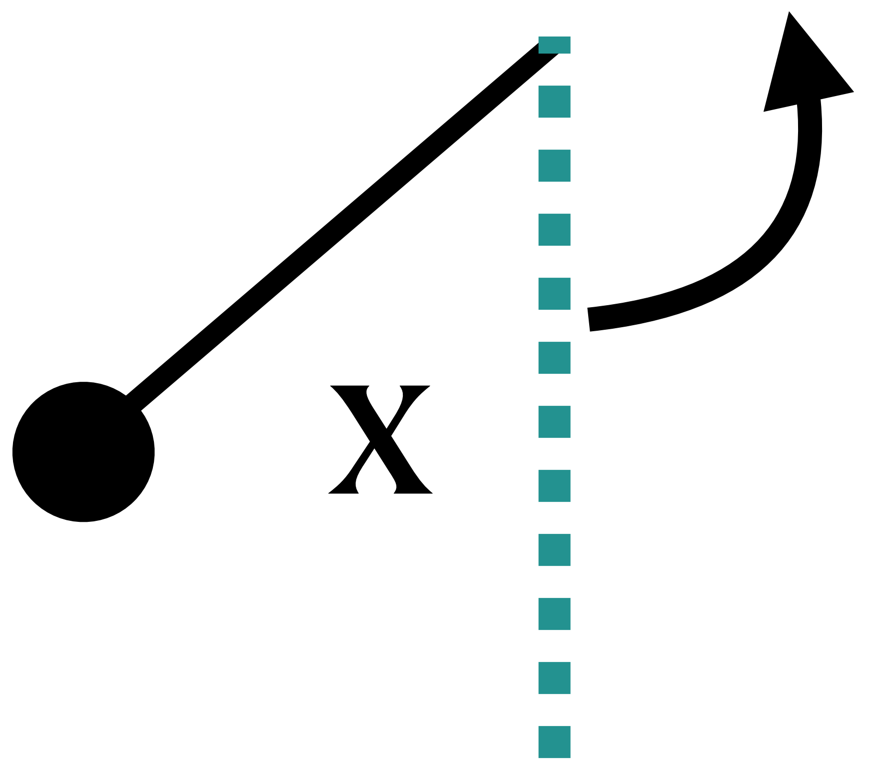
Rigid Pendulum in Gravity



$$V(x) = -\kappa \cos(x)$$

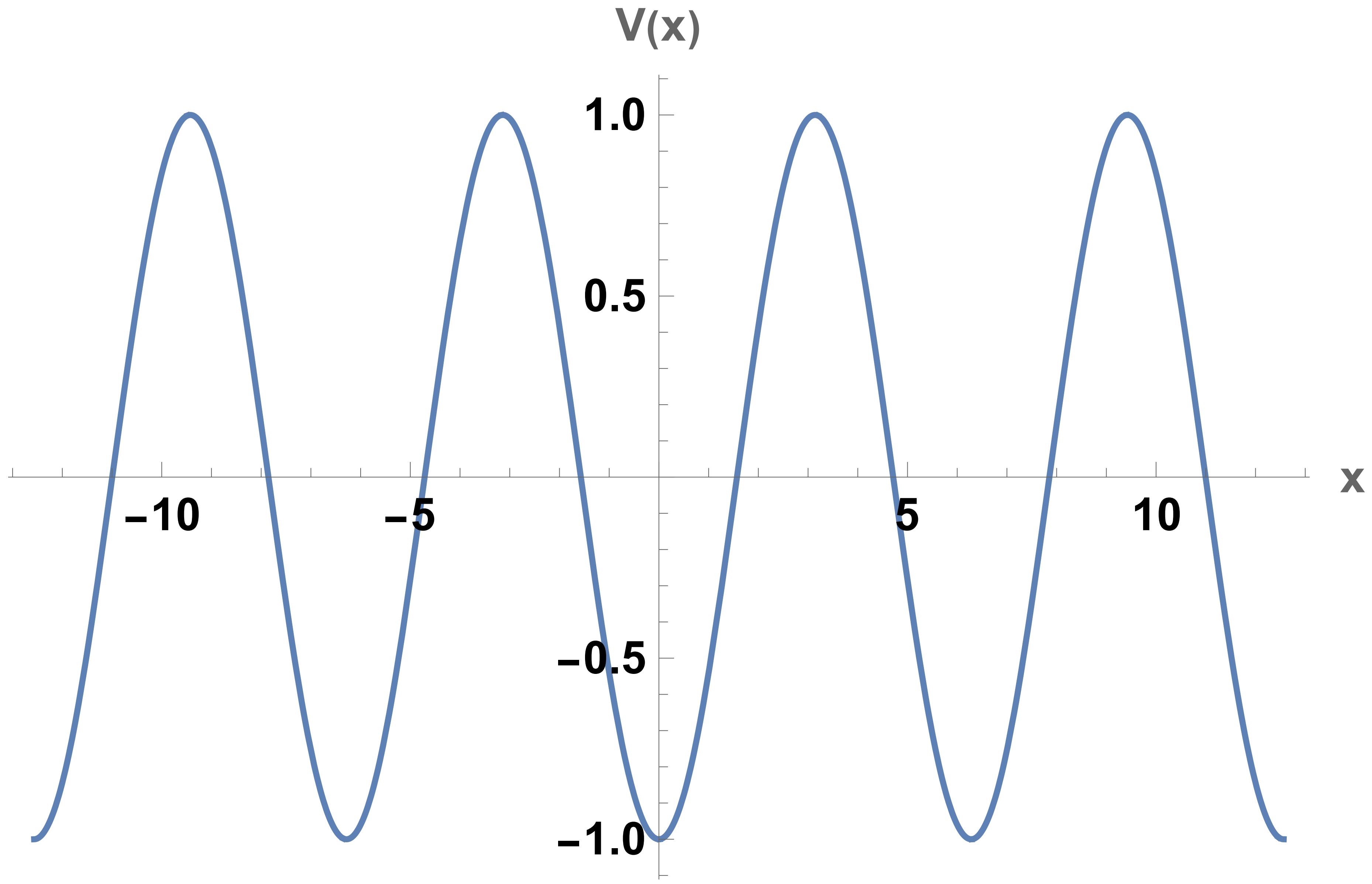
What do the energy eigenstates look like?

Rigid Pendulum in Gravity

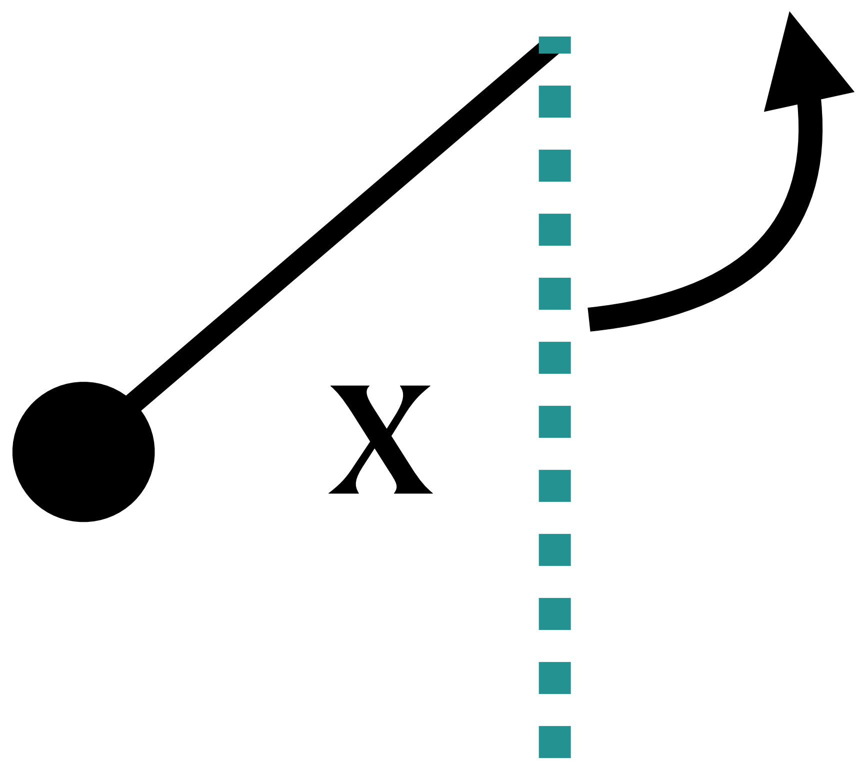


$$V(x) = -\kappa \cos(x)$$

What do the energy eigenstates look like?

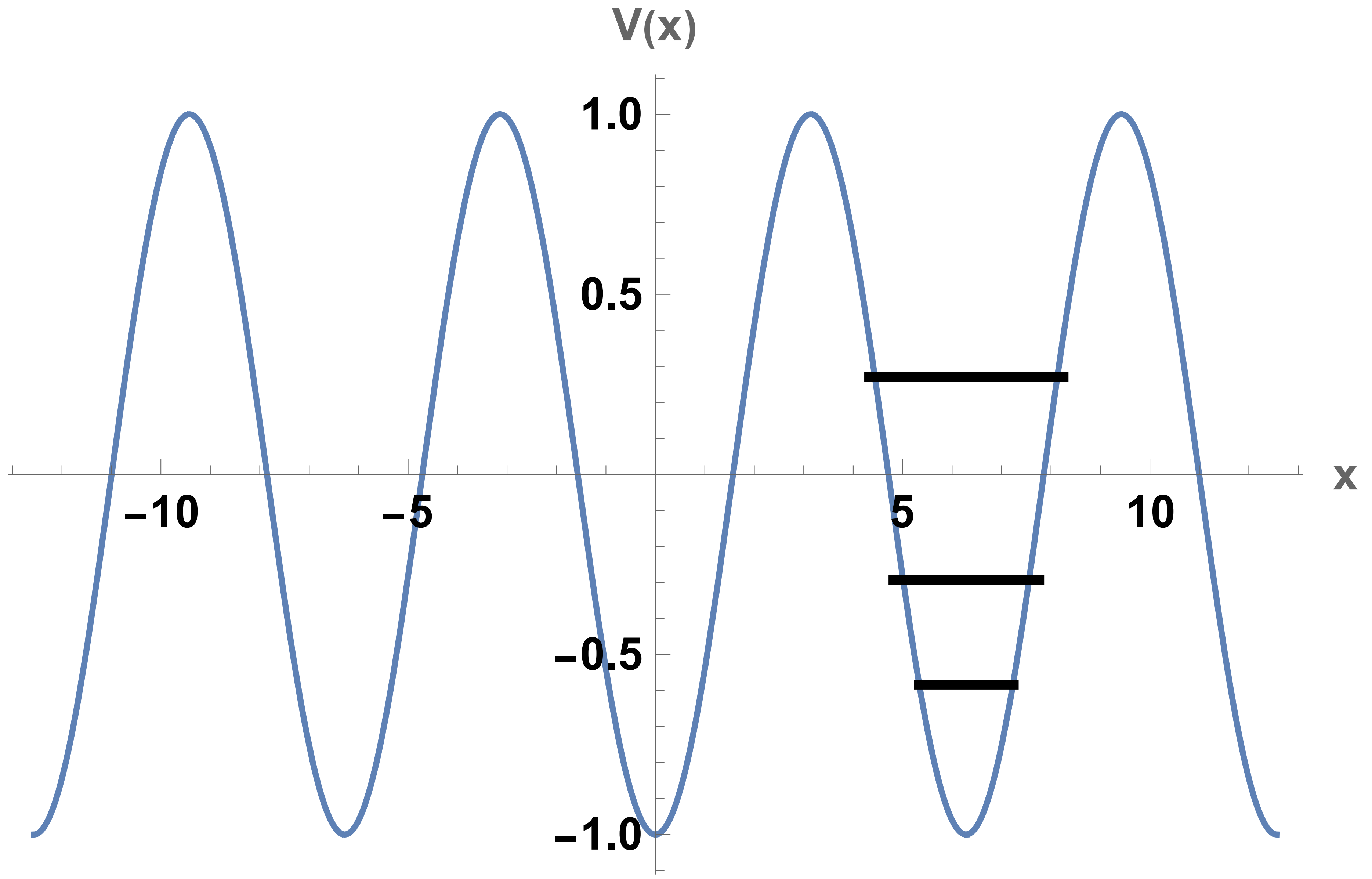


Rigid Pendulum in Gravity

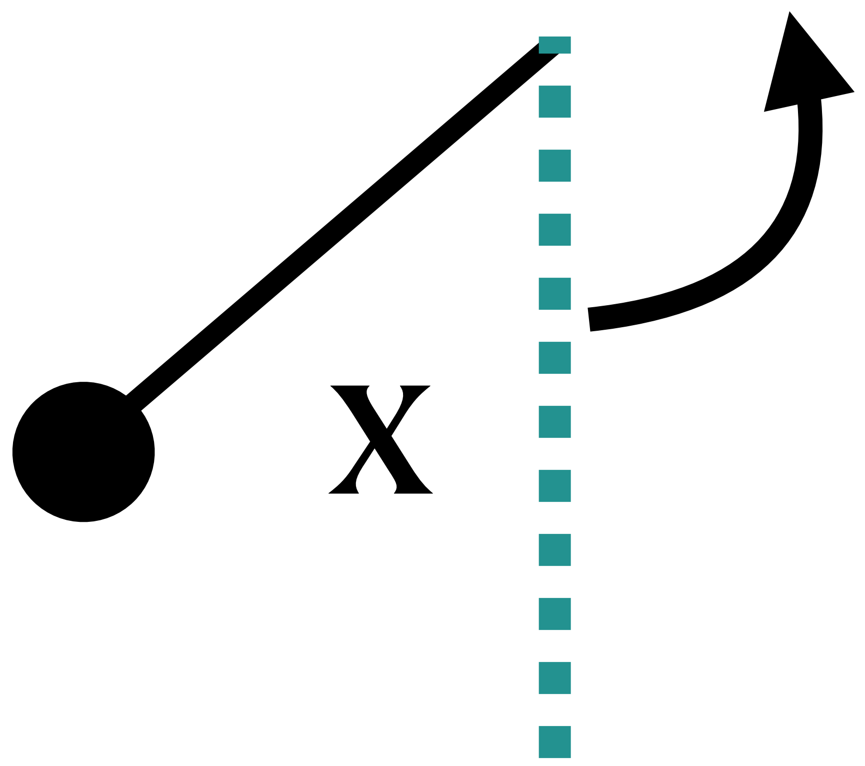


$$V(x) = -\kappa \cos(x)$$

What do the energy eigenstates look like?

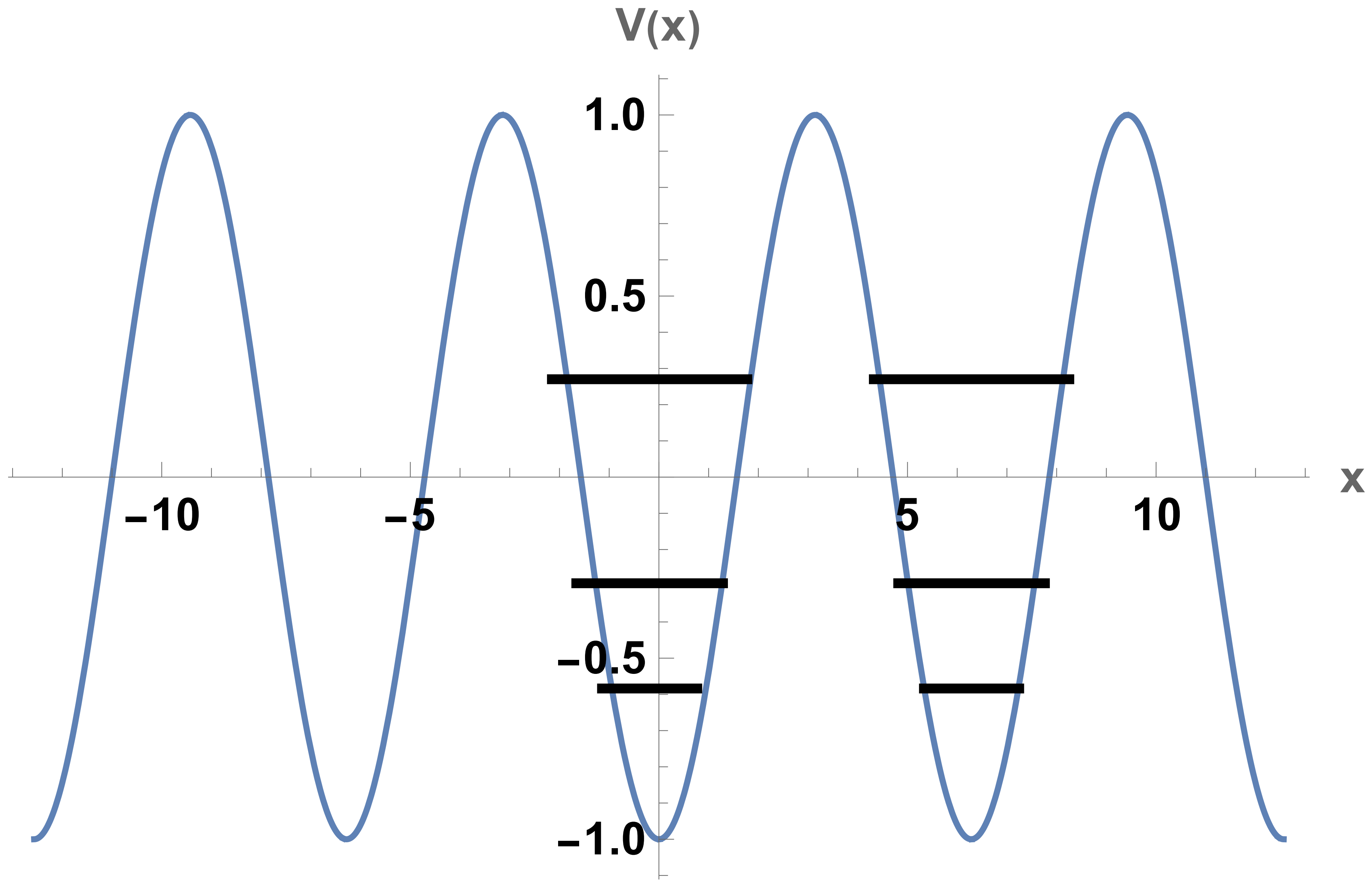


Rigid Pendulum in Gravity

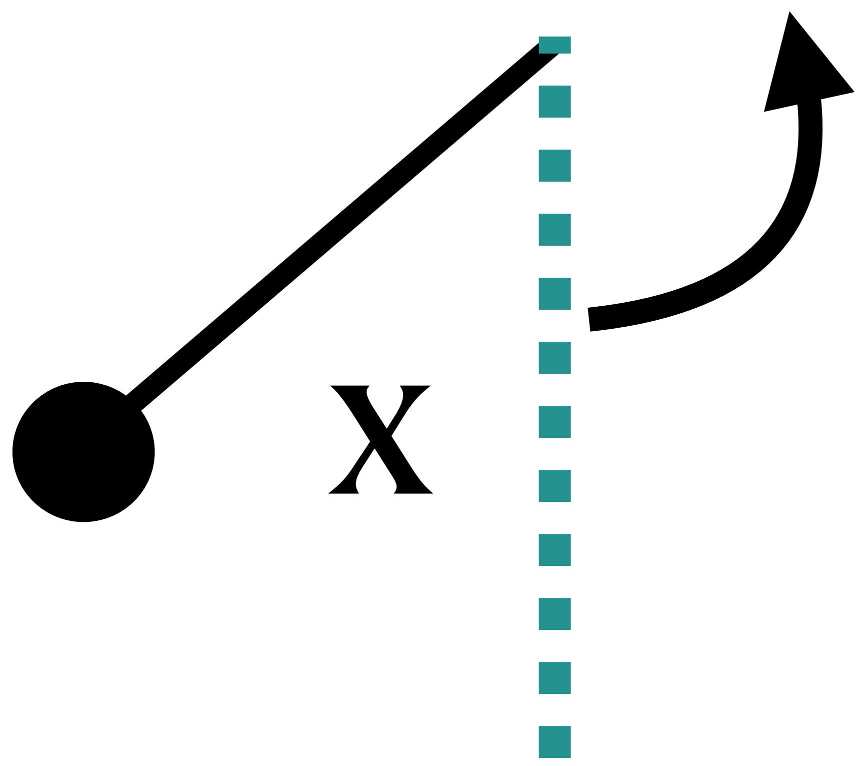


$$V\left(x\right) = -\kappa\cos\left(x\right)$$

What do the energy eigenstates look like?

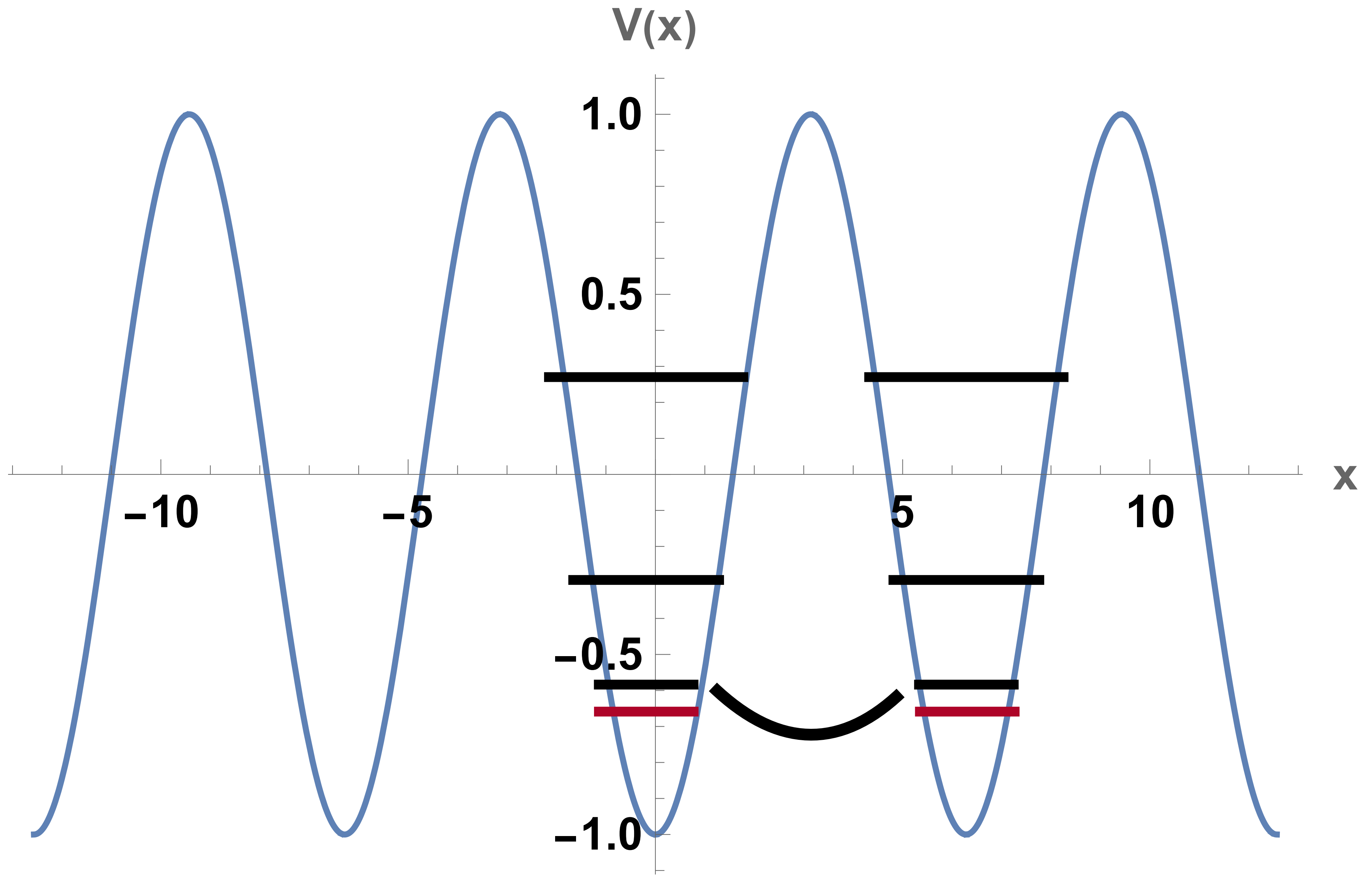


Rigid Pendulum in Gravity



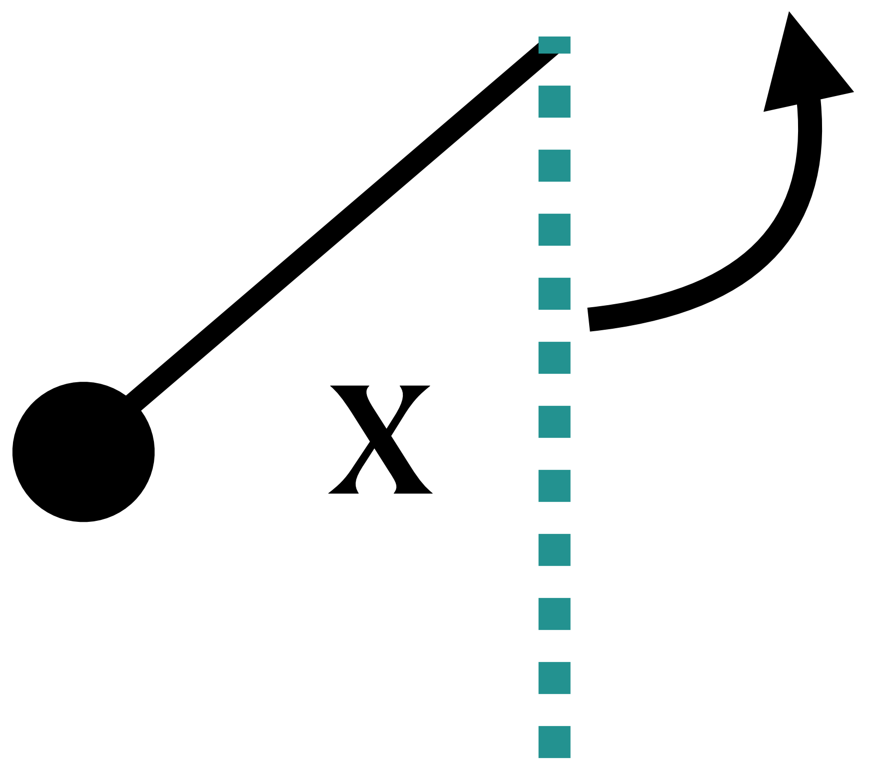
$$V(x) = -\kappa \cos(x)$$

What do the energy eigenstates look like?



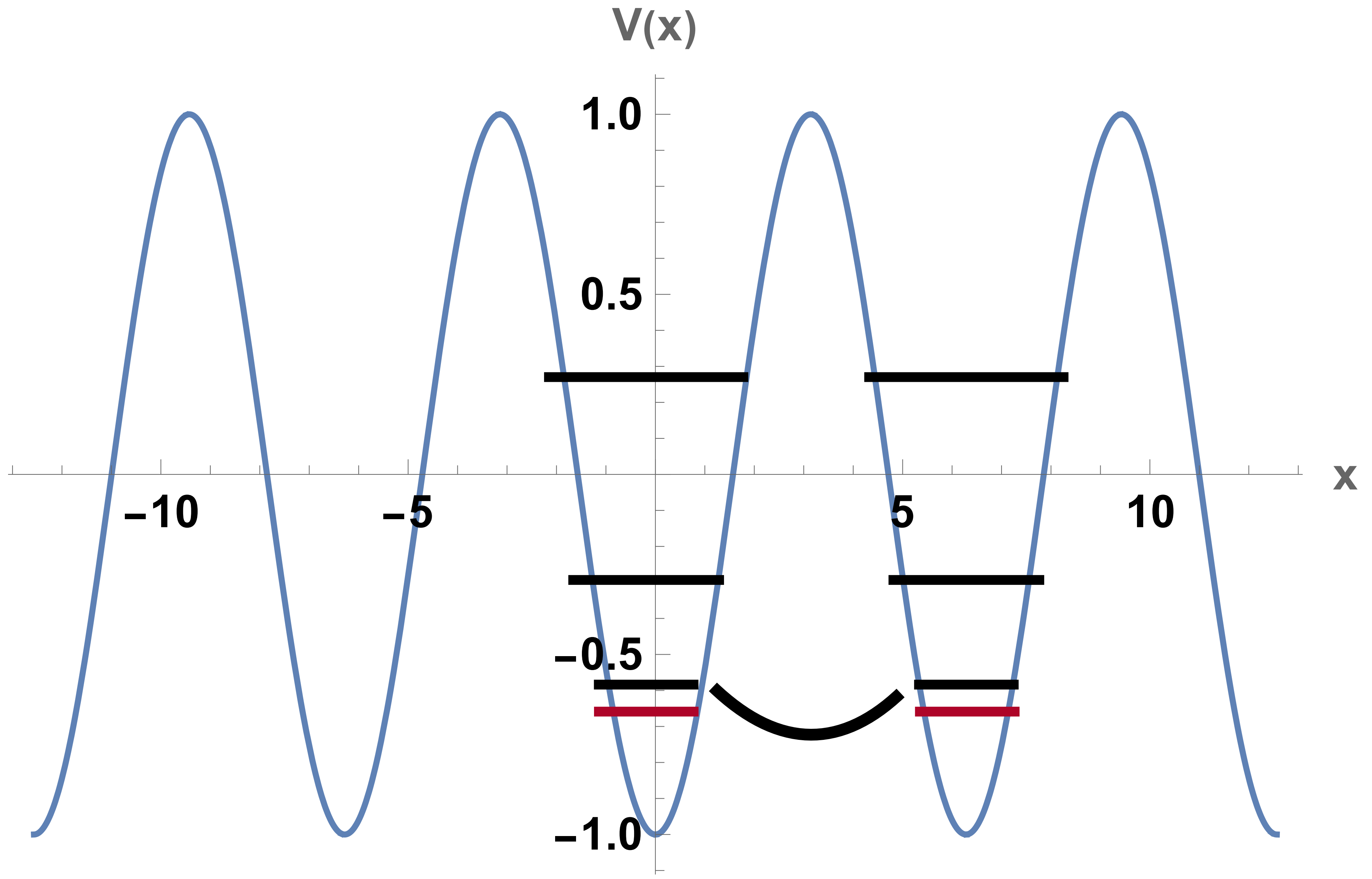
Quantum Tunneling

Rigid Pendulum in Gravity



$$V(x) = -\kappa \cos(x)$$

What do the energy eigenstates look like?



Quantum Tunneling

Nearly degenerate ground states

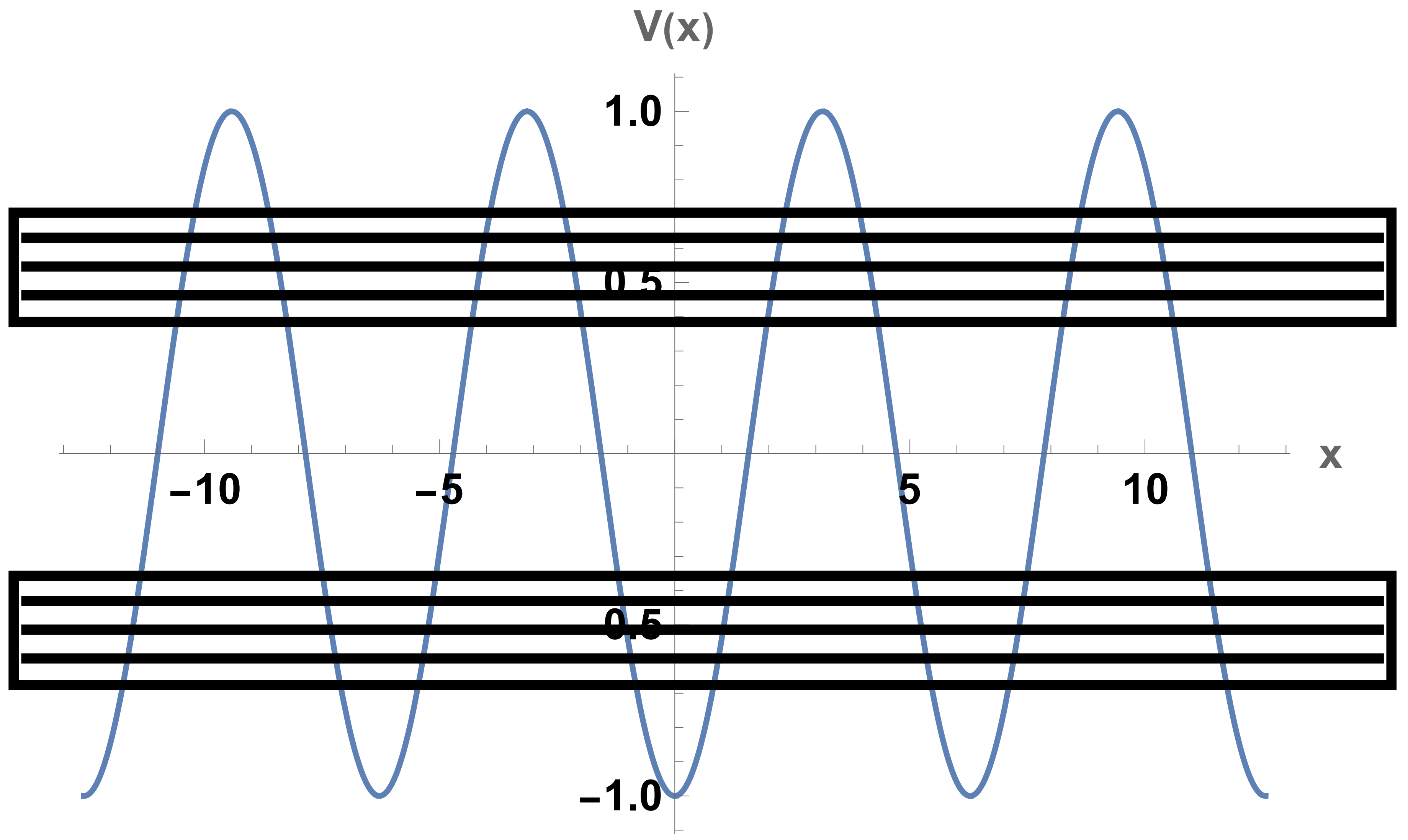
Eigenstates of Parity (x -> -x)

Rigid Pendulum in Gravity

What do the energy eigenstates look like?

Band Structure
(Bloch Waves)

$$\Psi\left(x\right)=e^{i\theta x}u\left(x\right)$$

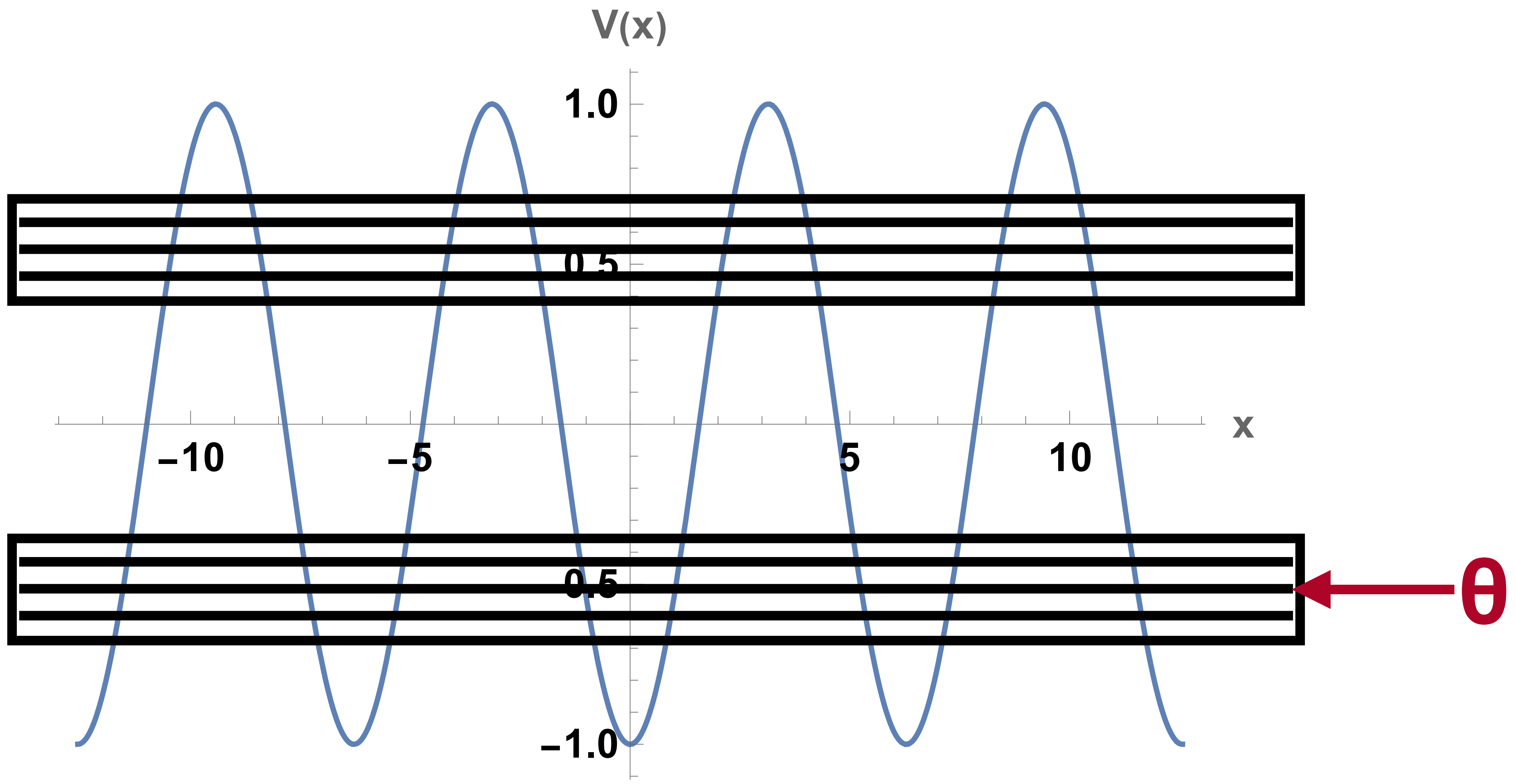


Rigid Pendulum in Gravity

What do the energy eigenstates look like?

Band Structure
(Bloch Waves)

$$\Psi\left(x\right) = e^{i\theta x}u\left(x\right)$$



State Label (like 1s, 2s, 2p for H)

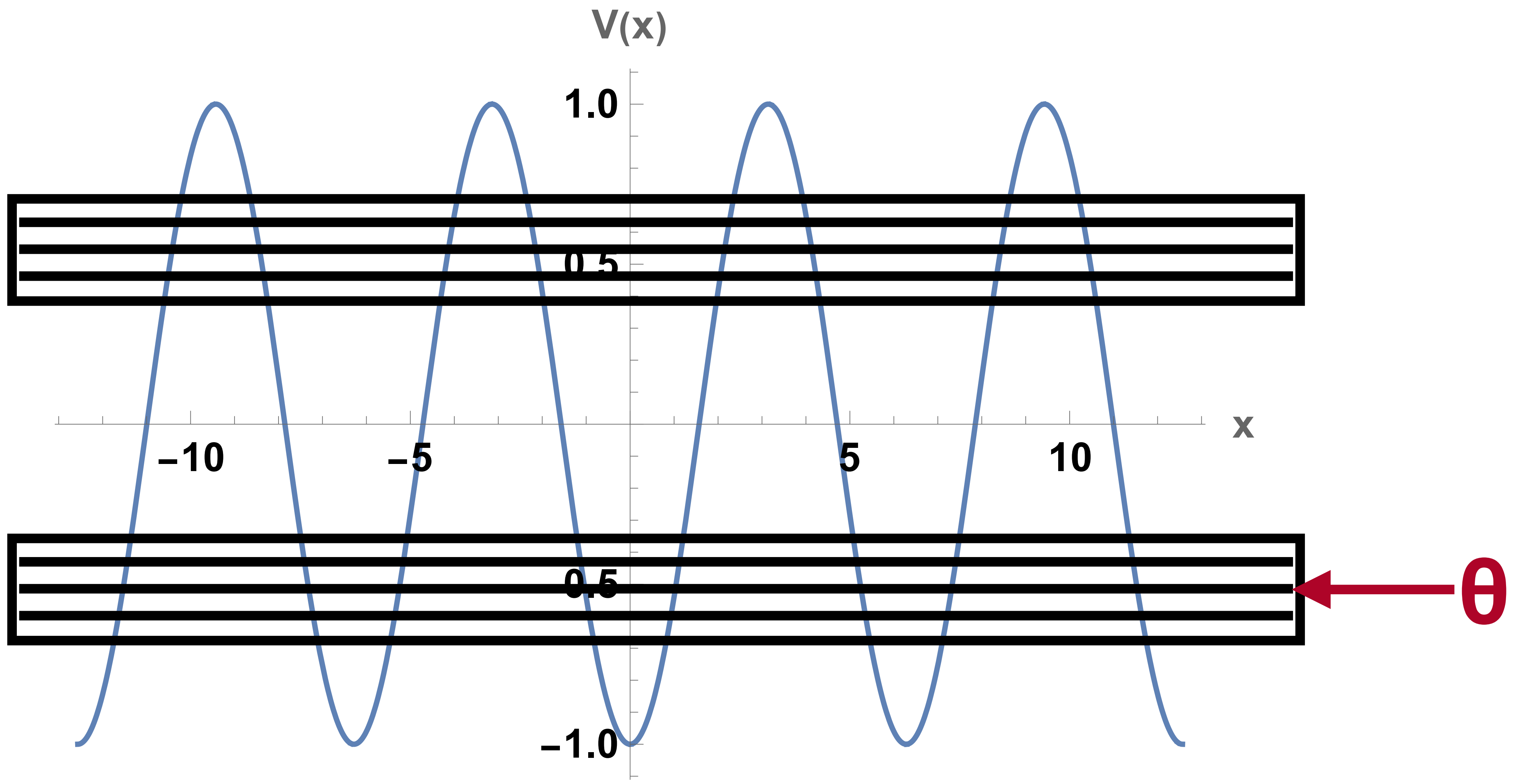
Lowest energy band - continuous set of states, labelled by θ

Rigid Pendulum in Gravity

What do the energy eigenstates look like?

Band Structure
(Bloch Waves)

$$\Psi(x) = e^{i\theta x} u(x)$$



State Label (like 1s, 2s, 2p for H)

Lowest energy band - continuous set of states, labelled by θ

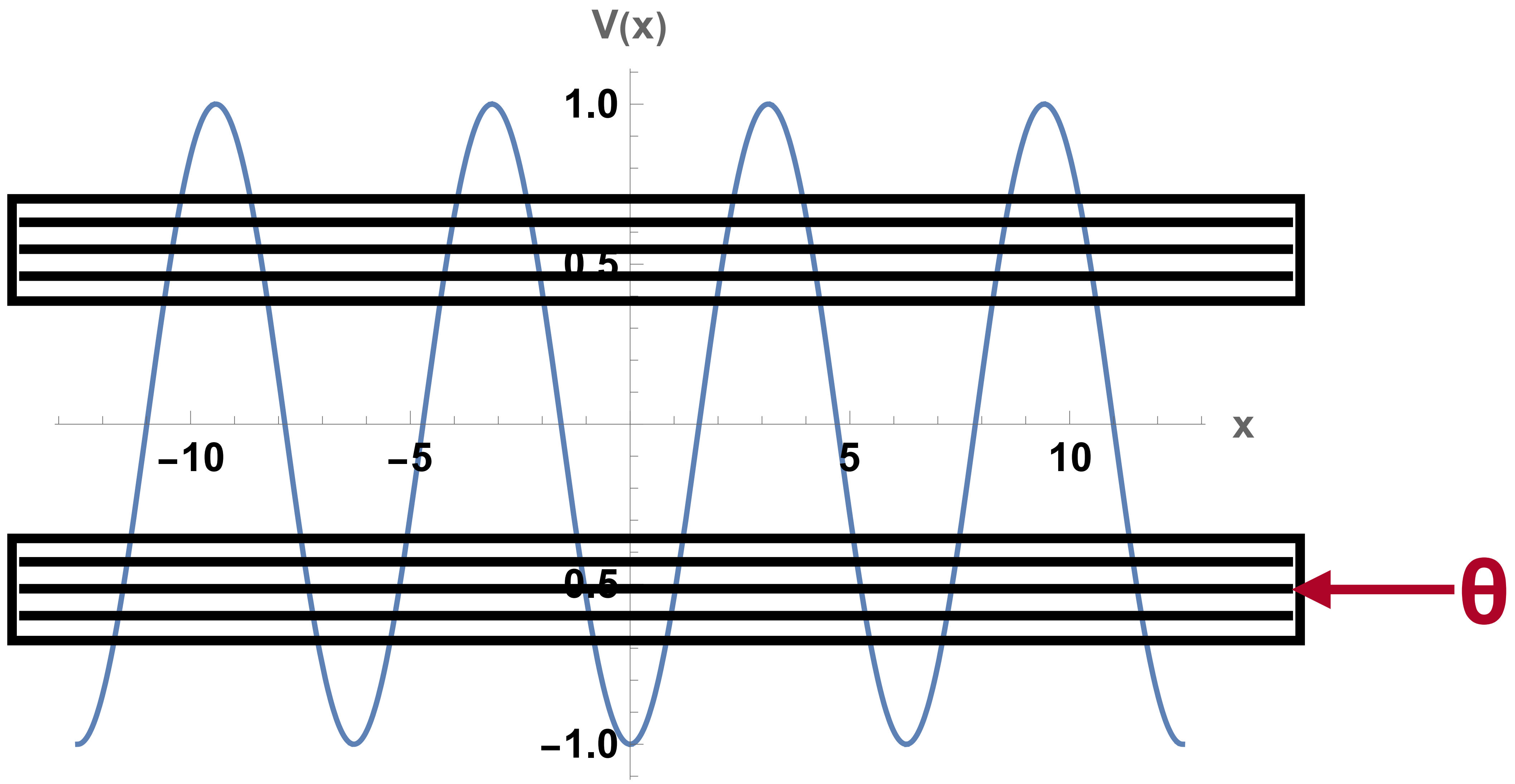
Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

Rigid Pendulum in Gravity

What do the energy eigenstates look like?

Band Structure
(Bloch Waves)

$$\Psi\left(x\right) = e^{i\theta x} u\left(x\right)$$



State Label (like 1s, 2s, 2p for H)

Lowest energy band - continuous set of states, labelled by θ

Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

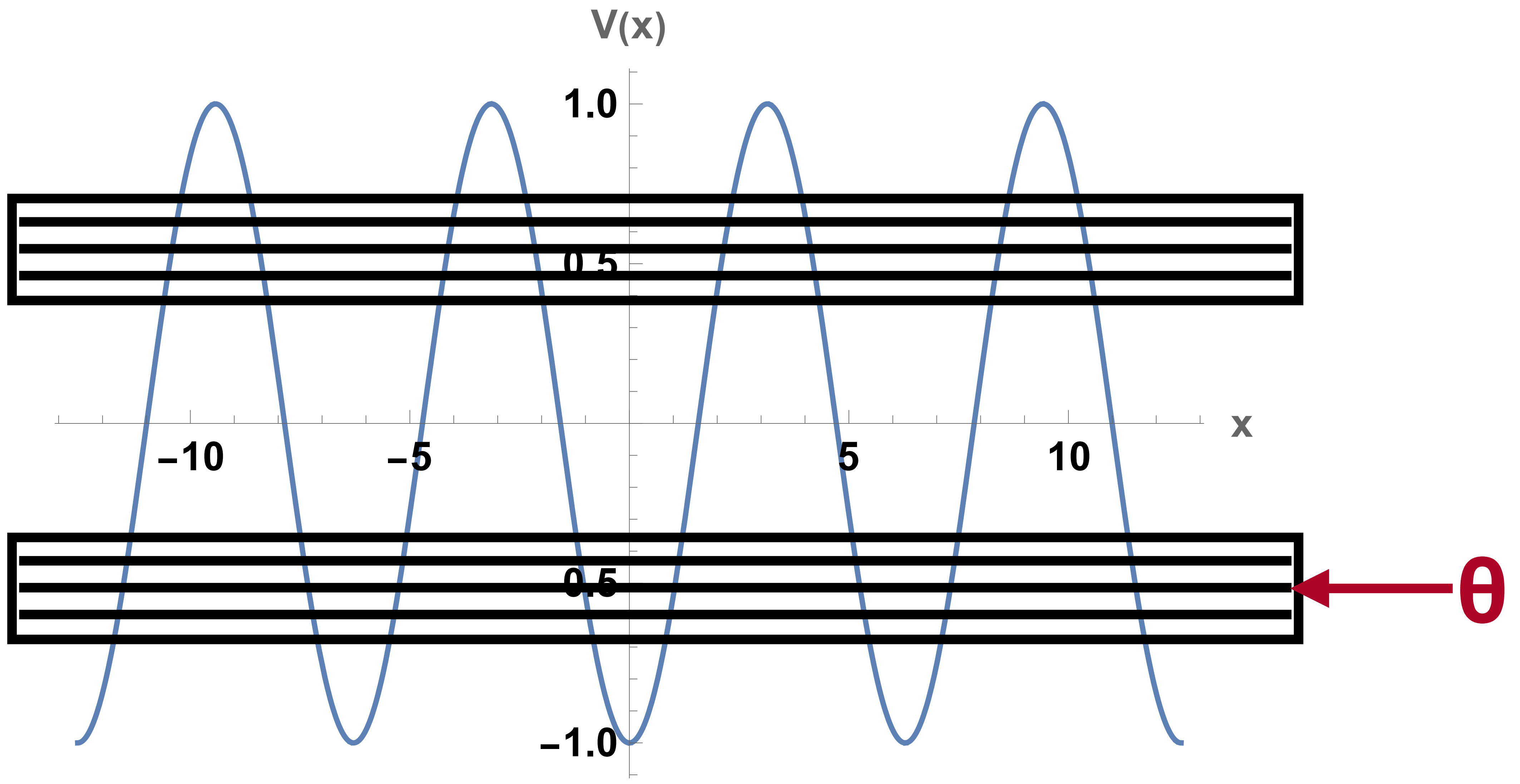
Solve by imposing Parity?
NO: Hamiltonian already Parity symmetric. States need not be

Rigid Pendulum in Gravity

What do the energy eigenstates look like?

Band Structure
(Bloch Waves)

$$\Psi\left(x\right) = e^{i\theta x} u\left(x\right)$$



State Label (like 1s, 2s, 2p for H)

Lowest energy band - continuous set of states, labelled by θ

Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

Solve by imposing Parity?
NO: Hamiltonian already Parity symmetric. States need not be

Only Dynamical Solutions Possible - e.g. couple to photon to allow decay

Hamiltonian To Lagrangian

Given $|\Psi(0)\rangle$, what is $|\Psi(T)\rangle$?

Hamiltonian To Lagrangian

Given |Ψ(0)>, what is |Ψ(T)>?

$$|\Psi(0)\rangle = \int dx\, f(x)\, |x\rangle$$

Hamiltonian To Lagrangian

Given |Ψ(0)>, what is |Ψ(T)>?

$$|\Psi(0)\rangle = \int dx\, f(x)\, |x\rangle$$

$$|x\rangle \to \int dy\, K(y, T; x, 0)\, |y\rangle$$

$$|\Psi(T)\rangle = \int dx\, dy\, f(x)\, K(y, T; x, 0)\, |y\rangle$$

Initial State **Propagator**

Hamiltonian To Lagrangian

Given |Ψ(0)>, what is |Ψ(T)>?

$$|\Psi(0)\rangle = \int dx\, f(x)\, |x\rangle$$

$$|x\rangle \to \int dy\, K(y,T;x,0)\, |y\rangle$$

$$|\Psi(T)\rangle = \int dx\, dy\, f(x)\, K(y,T;x,0)\, |y\rangle$$

Initial State **Propagator**

$$K(y,T;x,0) = \langle y|\mathrm{e}^{-iHT}|x\rangle = \int_{\gamma(0)=x}^{\gamma(T)=y} D\gamma\, e^{i\int_0^T dt\, L(x,\dot{x})}$$

Hamiltonian To Lagrangian

$$V(x) = -\kappa \cos(x)$$

$$L(x, \dot{x}) = \frac{1}{2} M \dot{x}^2 - V(x)$$

Hamiltonian To Lagrangian

$$V(x) = -\kappa\cos(x)$$

$$L(x,\dot{x}) = \frac{1}{2}M\dot{x}^2 - V(x)$$

There is no θ in the Lagrangian

Hamiltonian To Lagrangian

$$V(x) = -\kappa \cos(x)$$

$$L(x, \dot{x}) = \frac{1}{2} M \dot{x}^2 - V(x)$$

There is no θ in the Lagrangian

But - this is the same quantum problem and thus the same band structure

$$|\Psi(T)\rangle = \int dx\, dy\, f(x)\, K(y, T; x, 0)\, |y\rangle$$

↓

Got to pick initial state - states labelled by θ

Hamiltonian To Lagrangian

Band Structure
(Bloch Waves)

$$\Psi(x) = e^{i\theta x} u(x)$$

Want to understand quantum mechanics of state θ (e.g. calculate energy)

Hamiltonian To Lagrangian

Band Structure
(Bloch Waves)

$$\Psi(x) = e^{i\theta x} u(x)$$

Want to understand quantum mechanics of state θ (e.g. calculate energy)

$$|x\rangle = \int d[x]\, g(x, [x])\, |[x]\rangle$$

$$T(x \to x+1)\, |[x]\rangle \to e^{i\theta} |[x]\rangle$$

Hamiltonian To Lagrangian

Band Structure
(Bloch Waves)

$$\Psi\left(x\right)=e^{i\theta x}u\left(x\right)$$

Want to understand quantum mechanics of state θ (e.g. calculate energy)

$$|x\rangle=\int d[x]\,g\left(x,[x]\right)|[x]\rangle$$

$$T\left(x\to x+1\right)|[x]\rangle\to e^{i\theta}|[x]\rangle$$

$$K_\theta\left(y,T;x,0\right)=P_\theta\left(\langle y|\mathrm{e}^{-iHT}|x\rangle\right)=\int_{\gamma(0)=x}^{\gamma(T)=y}D\gamma\,e^{i\int_0^T dt\,L_\theta(x,\dot{x})}$$

$$L_\theta=\frac{1}{2}M\dot{x}^2+\theta\dot{x}-V\left(x\right)$$

Hamiltonian To Lagrangian

Band Structure
(Bloch Waves)

$$\Psi\left(x\right) = e^{i\theta x} u\left(x\right)$$

Want to understand quantum mechanics of state θ (e.g. calculate energy)

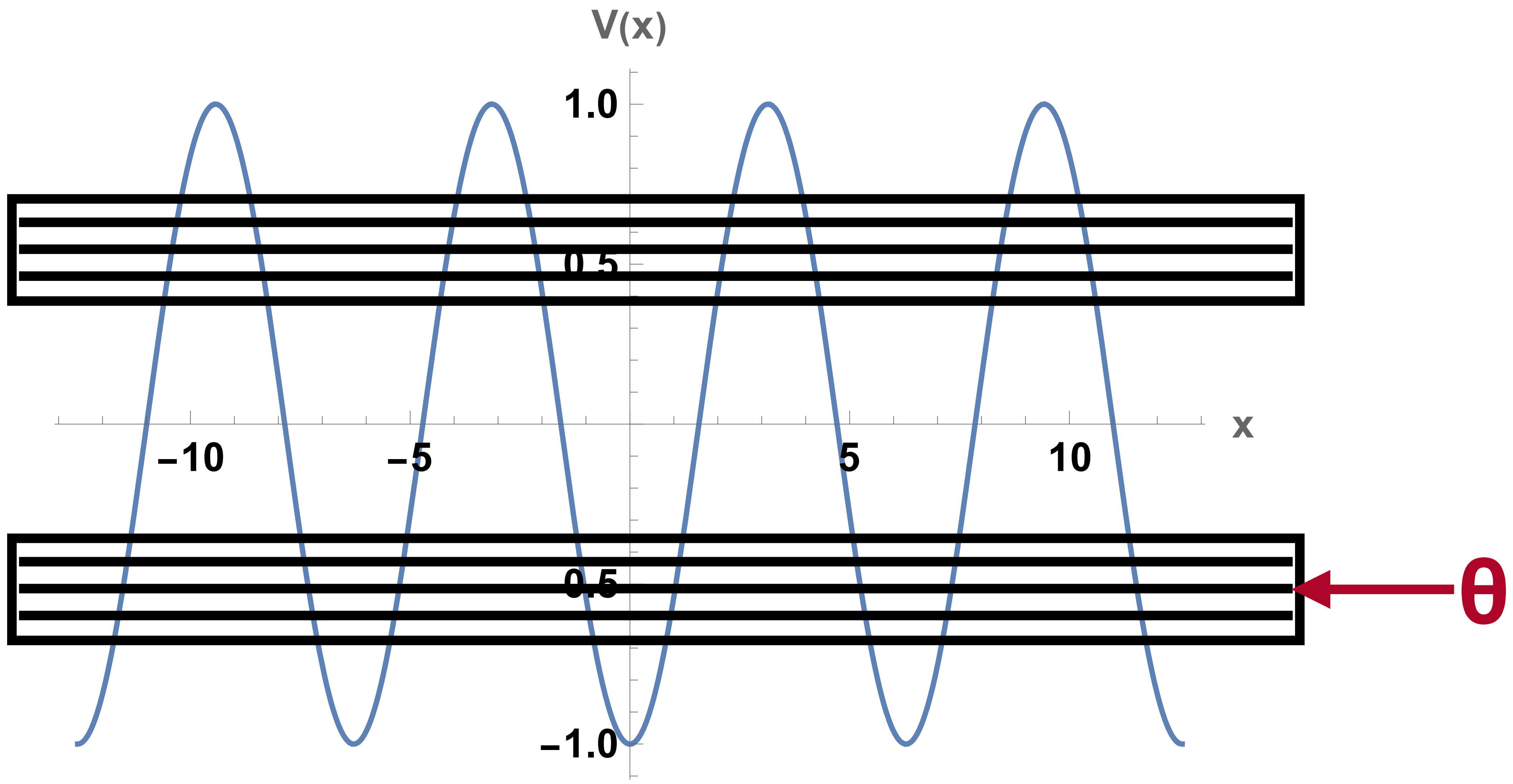
$$|x\rangle = \int d[x]\, g\left(x, [x]\right) |[x]\rangle \qquad T\left(x \to x+1\right) |[x]\rangle \to e^{i\theta} |[x]\rangle$$

$$K_\theta\left(y, T; x, 0\right) = P_\theta\left(\langle y| \mathrm{e}^{-iHT} |x\rangle\right) = \int_{\gamma(0)=x}^{\gamma(T)=y} D\gamma\, e^{i\int_0^T dt\, L_\theta(x,\dot{x})}$$

$$L_\theta = \frac{1}{2} M \dot{x}^2 + \theta \dot{x} - V\left(x\right)$$

θ enters Lagrangian - looks like a parameter, but actually reflects restriction to specific quantum state θ

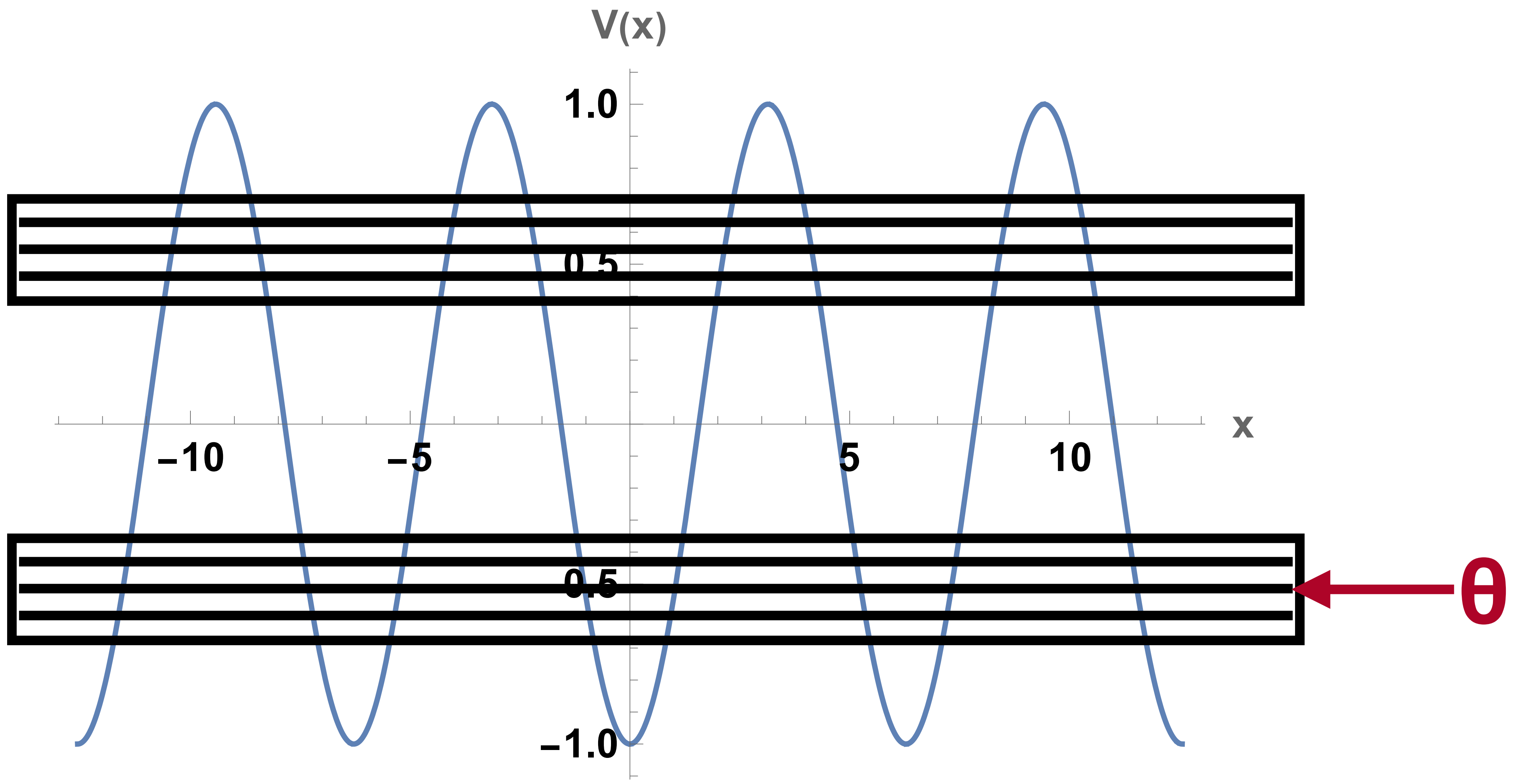
Rigid Pendulum in Gravity



State Label (like 1s, 2s, 2p for H)

Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

Rigid Pendulum in Gravity

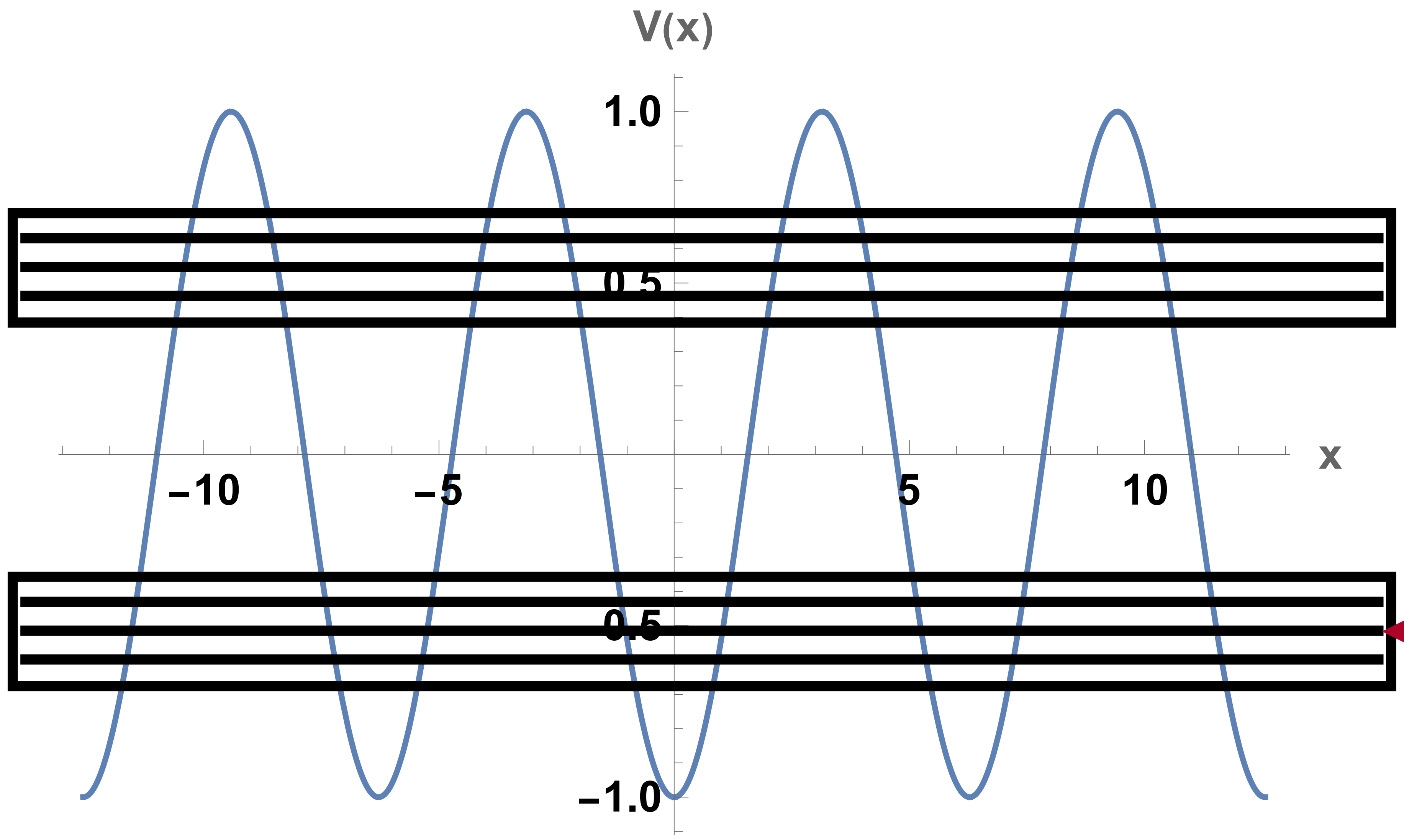


State Label (like 1s, 2s, 2p for H)

Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

$$L_\theta = \frac{1}{2} M \dot{x}^2 + \theta \dot{x} - V(x)$$

Rigid Pendulum in Gravity



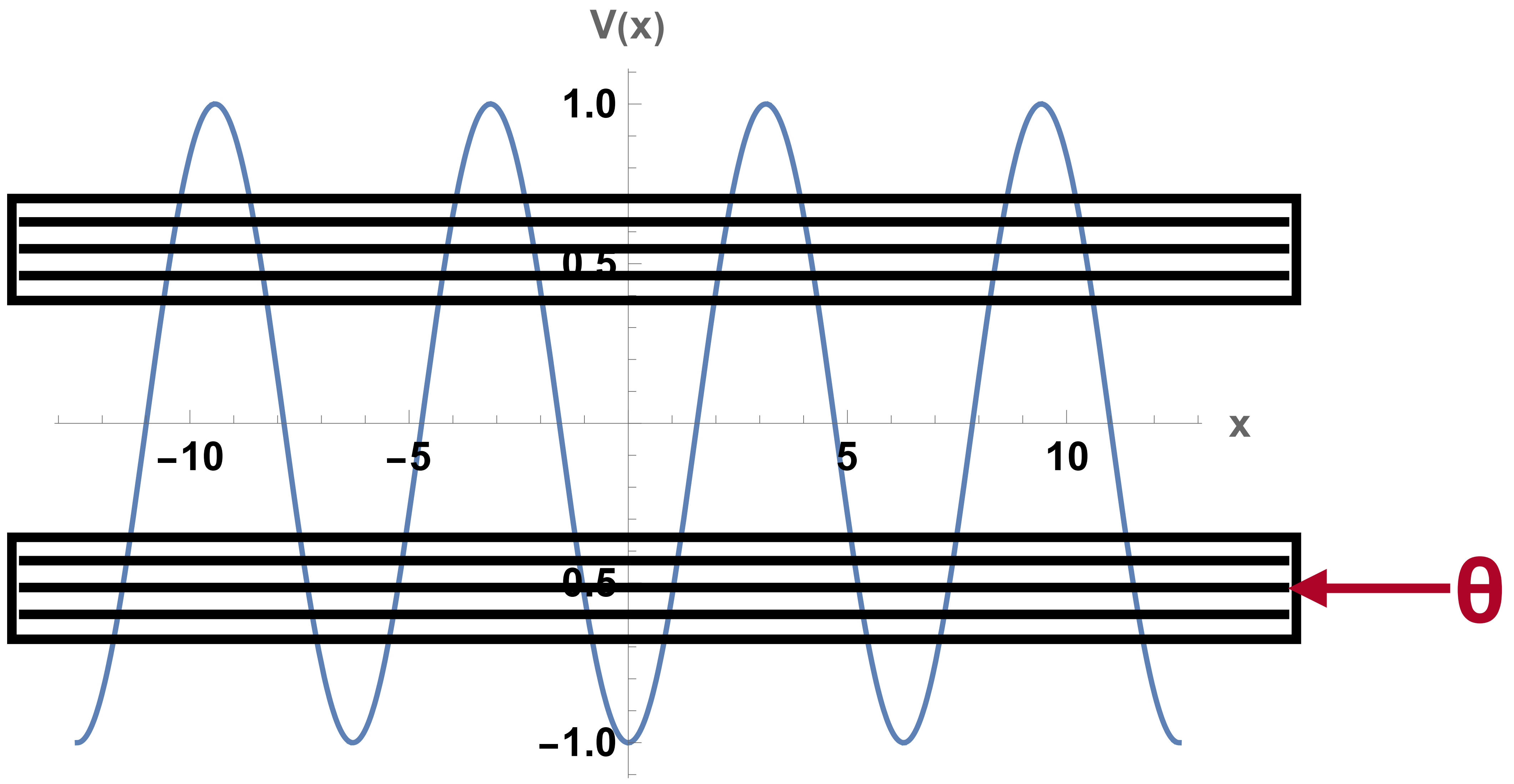
θ **State Label (like 1s, 2s, 2p for H)**

Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

$$L_\theta = \frac{1}{2} M\dot{x}^2 + \cancel{\theta x} - V(x)$$

Solve problem by imposing parity x-> -x

Rigid Pendulum in Gravity



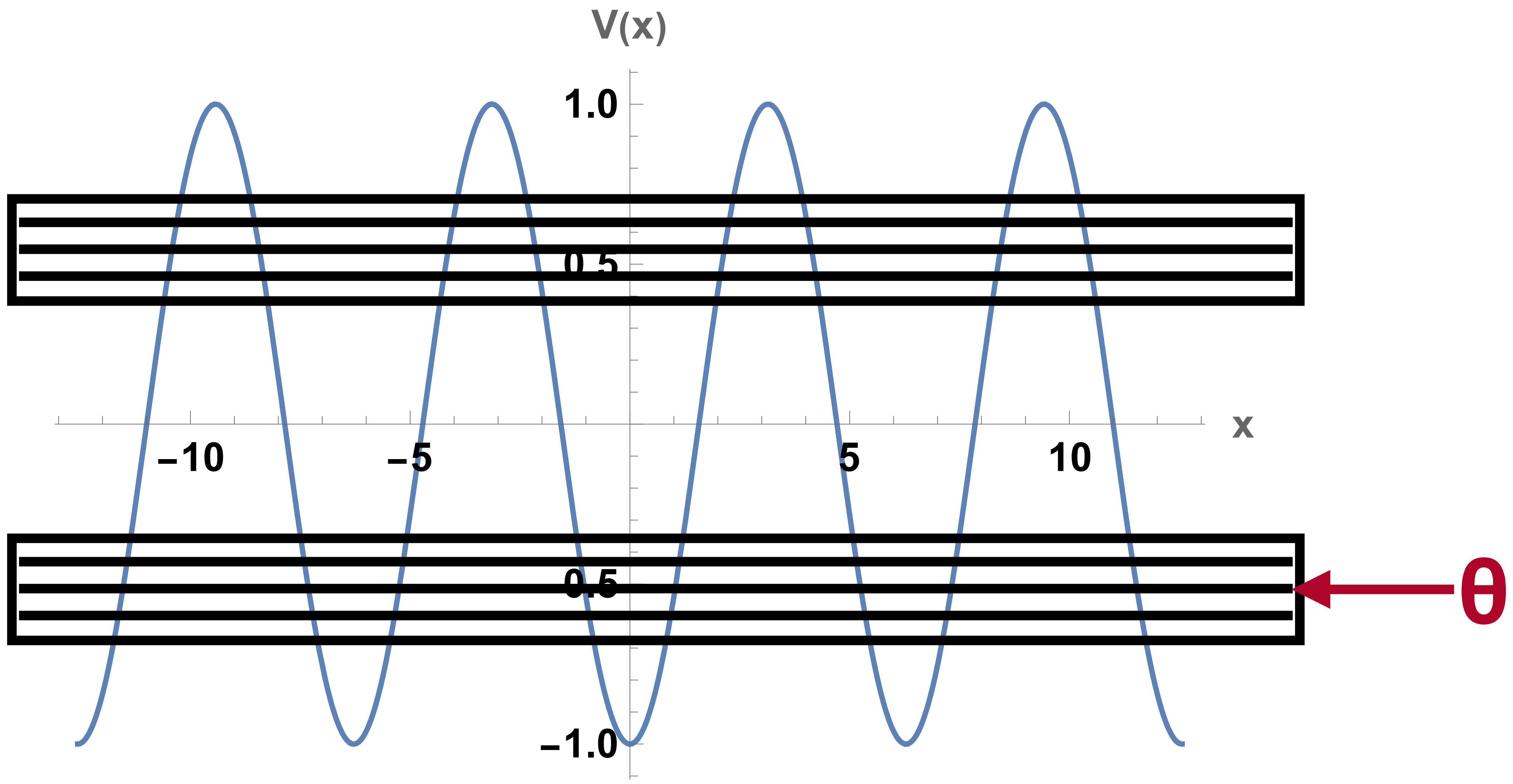
State Label (like 1s, 2s, 2p for H)

Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

$$L_\theta = \frac{1}{2}M\dot{x}^2 + \theta x - V(x)$$

Solve problem by imposing parity x-> -x

Rigid Pendulum in Gravity



State Label (like 1s, 2s, 2p for H)

Find a bunch of such pendulums, all formed at high energy - but if we only see state θ = 0?

$$L_\theta = \frac{1}{2} M \dot{x}^2 + \theta x - V(x)$$

Solve problem by imposing parity x-> -x

V(x) still periodic - band structure persists. Choice of quantum state
Need dynamical solution

QCD

$$H\left(A^{a}, E^{a}\right)$$ **CP invariant, no θ**

QCD

$$H\left(A^a, E^a\right)$$ **CP invariant, no θ**

What are the θ vacua?

QCD

$$H\left(A^a, E^a\right)$$ **CP invariant, no θ**

What are the θ vacua?

Need to define vacuum - i.e. state of lowest energy

One choice |A> = 0 - has zero color electromagnetic field

QCD

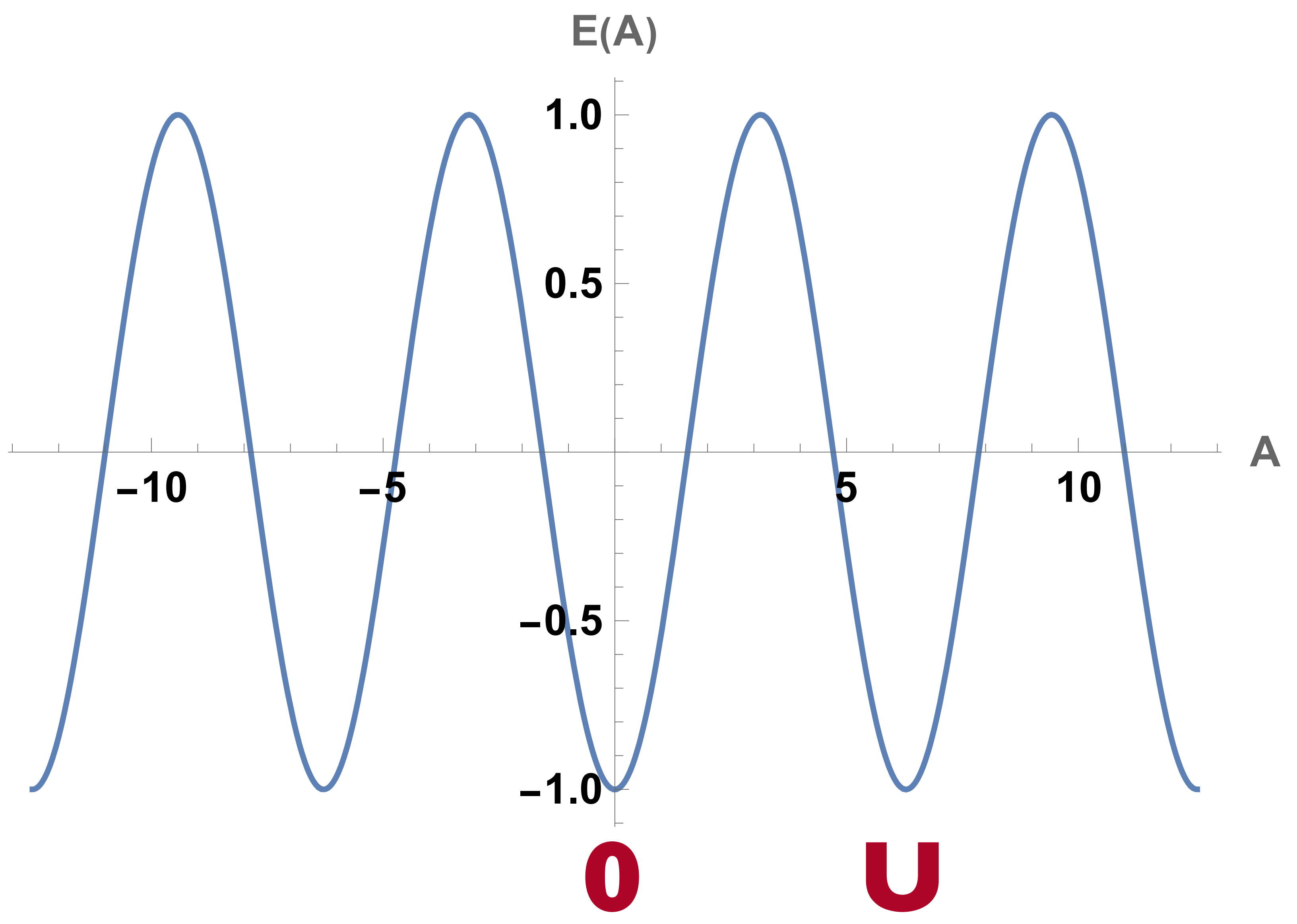
$$H\left(A^a, E^a\right)$$ **CP invariant, no θ**

What are the θ vacua?

Need to define vacuum - i.e. state of lowest energy

One choice |A> = 0 - has zero color electromagnetic field

But, other choices also possible: |A> = U, where U is pure gauge



QCD

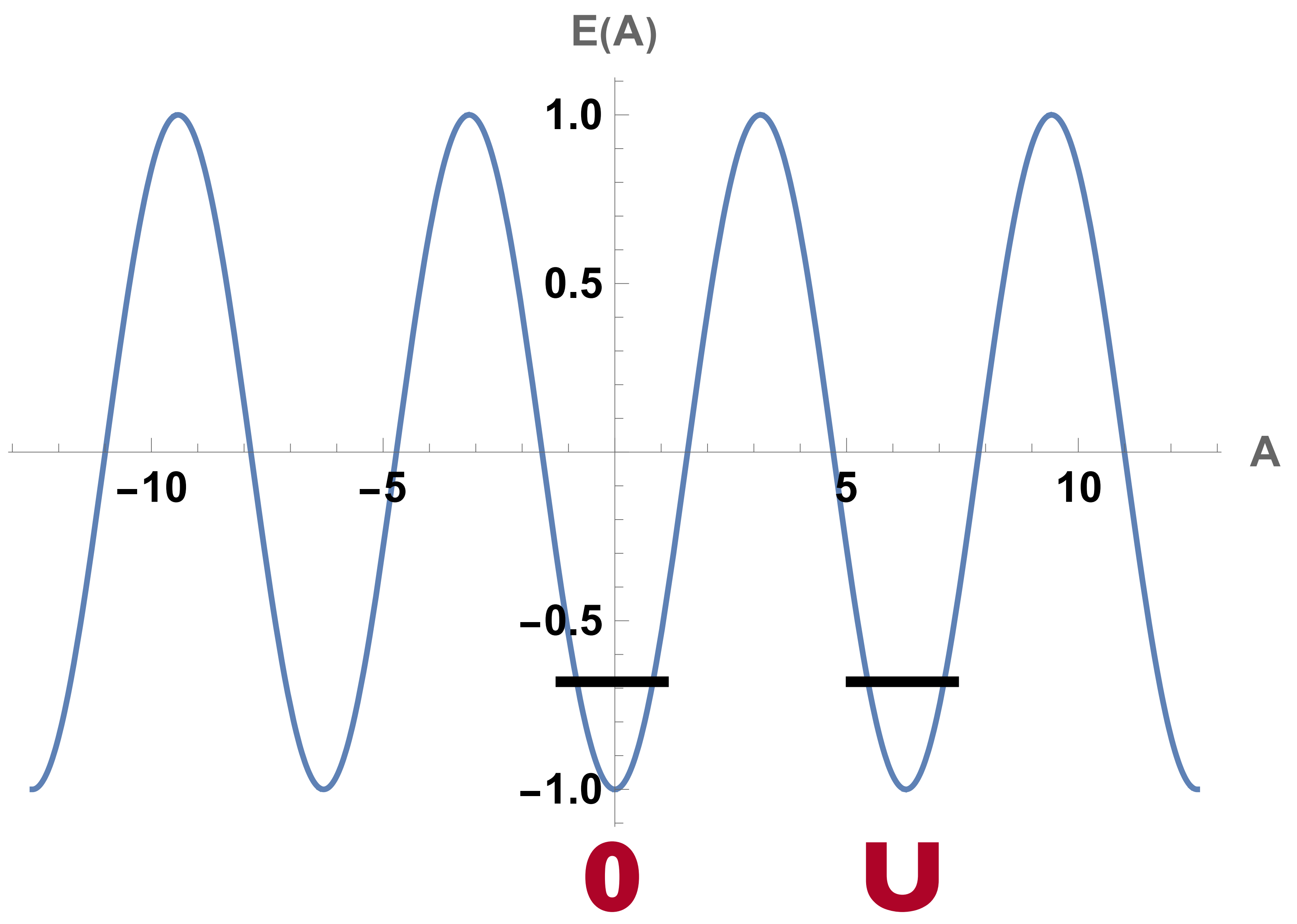
$H\left(A^a, E^a\right)$ **CP invariant, no θ**

What are the θ vacua?

Need to define vacuum - i.e. state of lowest energy

One choice |A> = 0 - has zero color electromagnetic field

But, other choices also possible: |A> = U, where U is pure gauge



QCD

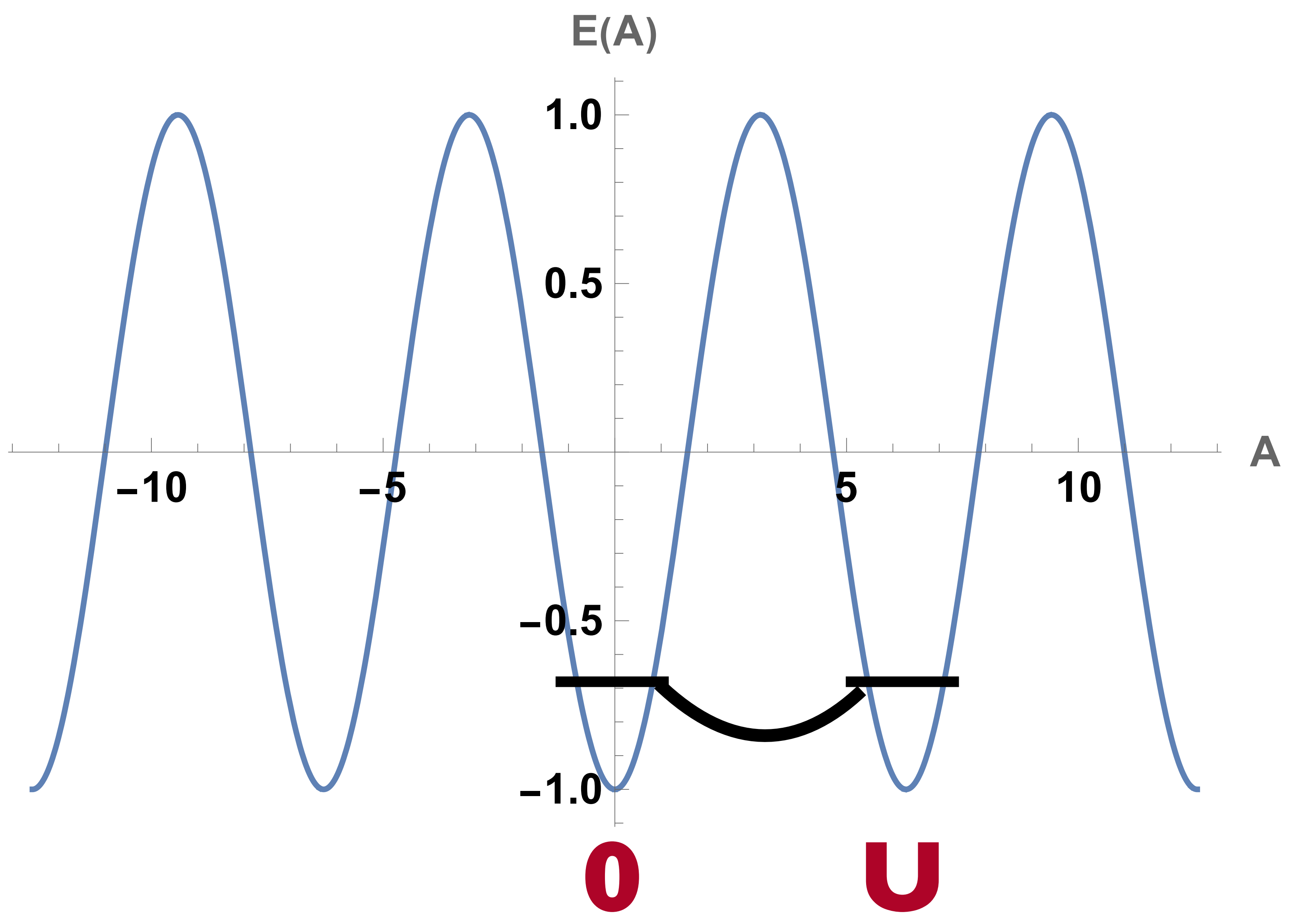
$H\left(A^a, E^a\right)$ **CP invariant, no θ**

What are the θ vacua?

Need to define vacuum - i.e. state of lowest energy

One choice |A> = 0 - has zero color electromagnetic field

But, other choices also possible: |A> = U, where U is pure gauge



Quantum Tunneling

QCD

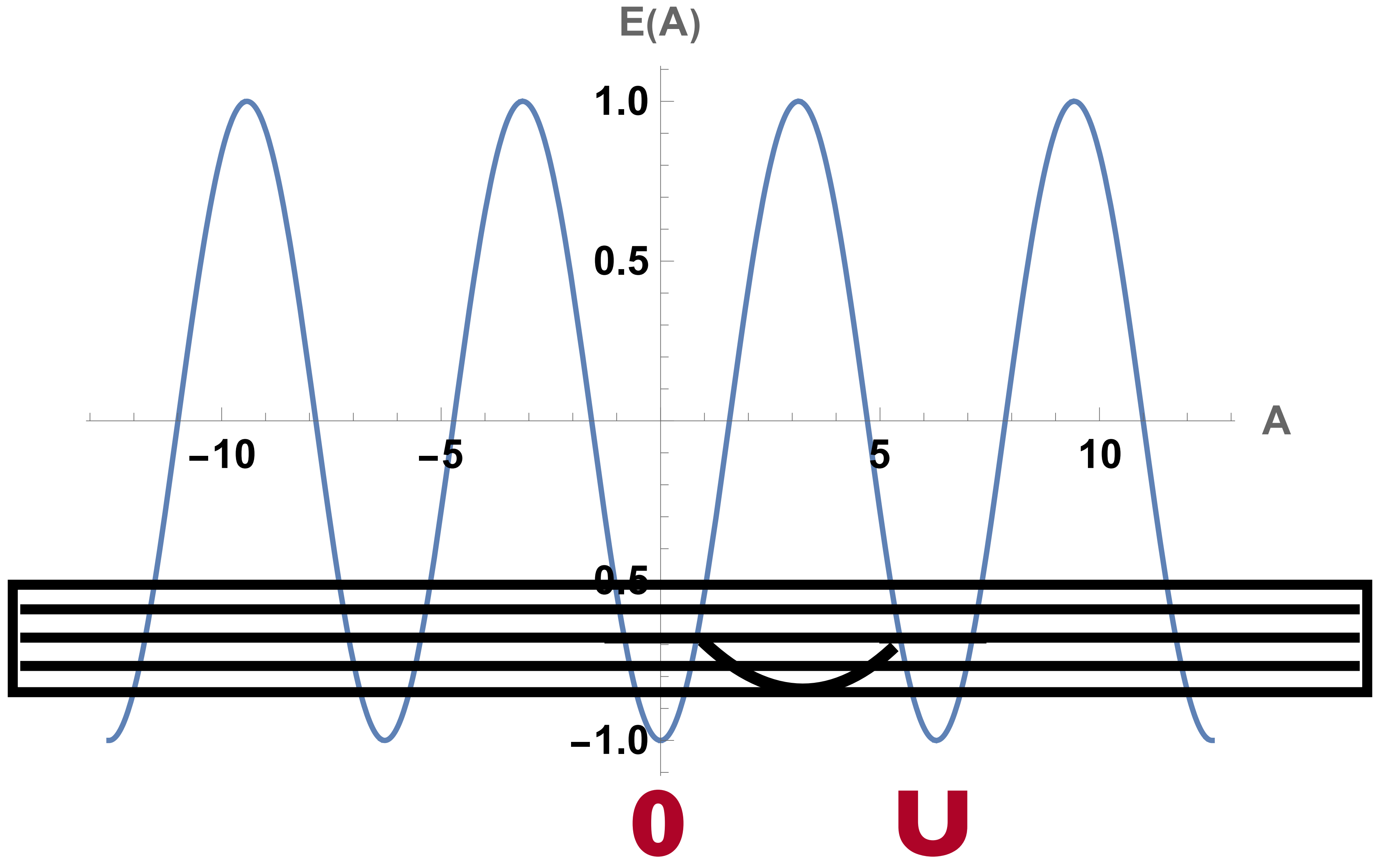
$$H\left(A^a, E^a\right)$$ **CP invariant, no θ**

What are the θ vacua?

Need to define vacuum - i.e. state of lowest energy

One choice |A> = 0 - has zero color electromagnetic field

But, other choices also possible: |A> = U, where U is pure gauge



Quantum Tunneling

QCD

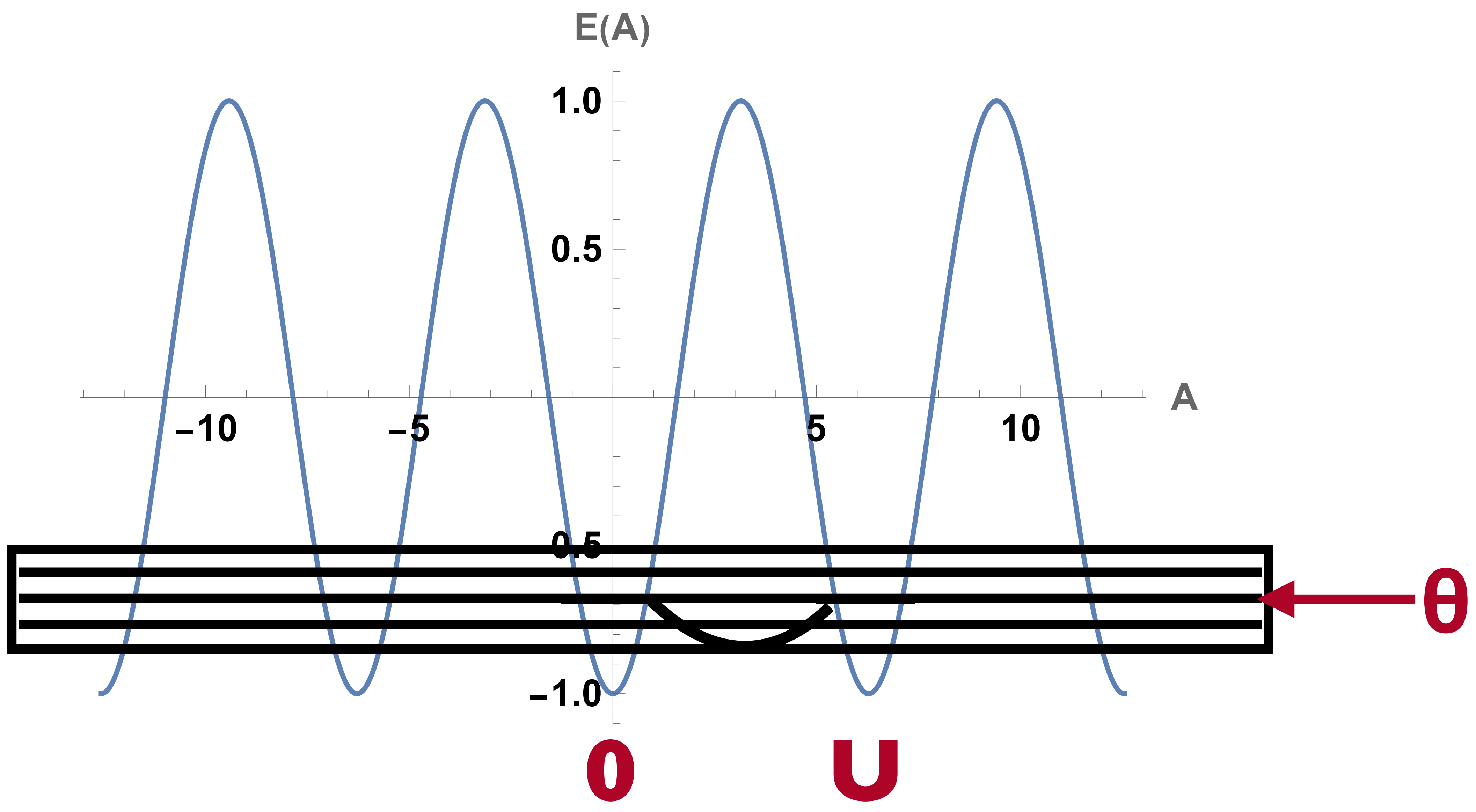
$$H\left(A^a, E^a\right)$$ **CP invariant, no θ**

What are the θ vacua?

Need to define vacuum - i.e. state of lowest energy

One choice |A> = 0 - has zero color electromagnetic field

But, other choices also possible: |A> = U, where U is pure gauge



Quantum Tunneling

State Label

QCD

$$H\left(A^a, E^a\right)$$ **CP invariant, no θ**

Want to understand quantum mechanics of state θ (e.g. calculate energy)

$$\mathcal{L} \supset \theta \tilde{G} G$$

θ enters Lagrangian - looks like a parameter, but actually reflects restriction to specific quantum state θ

QCD

$H\left(A^a, E^a\right)$ **CP invariant, no θ**

Want to understand quantum mechanics of state θ (e.g. calculate energy)

$$\mathcal{L} \supset \theta \tilde{G} G$$

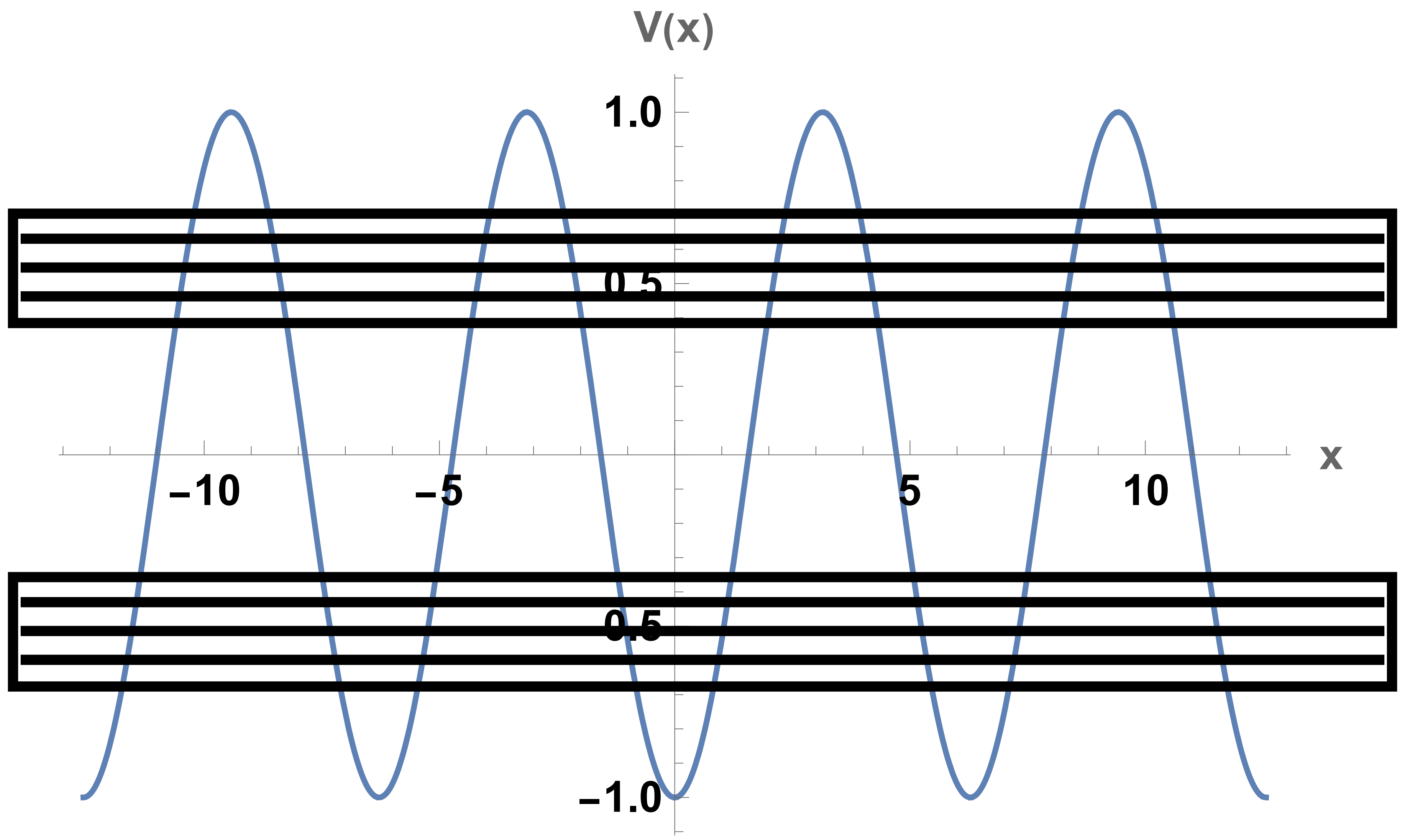
θ enters Lagrangian - looks like a parameter, but actually reflects restriction to specific quantum state θ

From state perspective, pure gauge states separated by large gauge transformations still exist - band structure persists.

θ : choice of quantum state, not a parameter controlled by symmetry

Strong CP Problem

Pendulum in Gravity



Start Pendulum at High Energy

Why end up in $\theta = 0$?

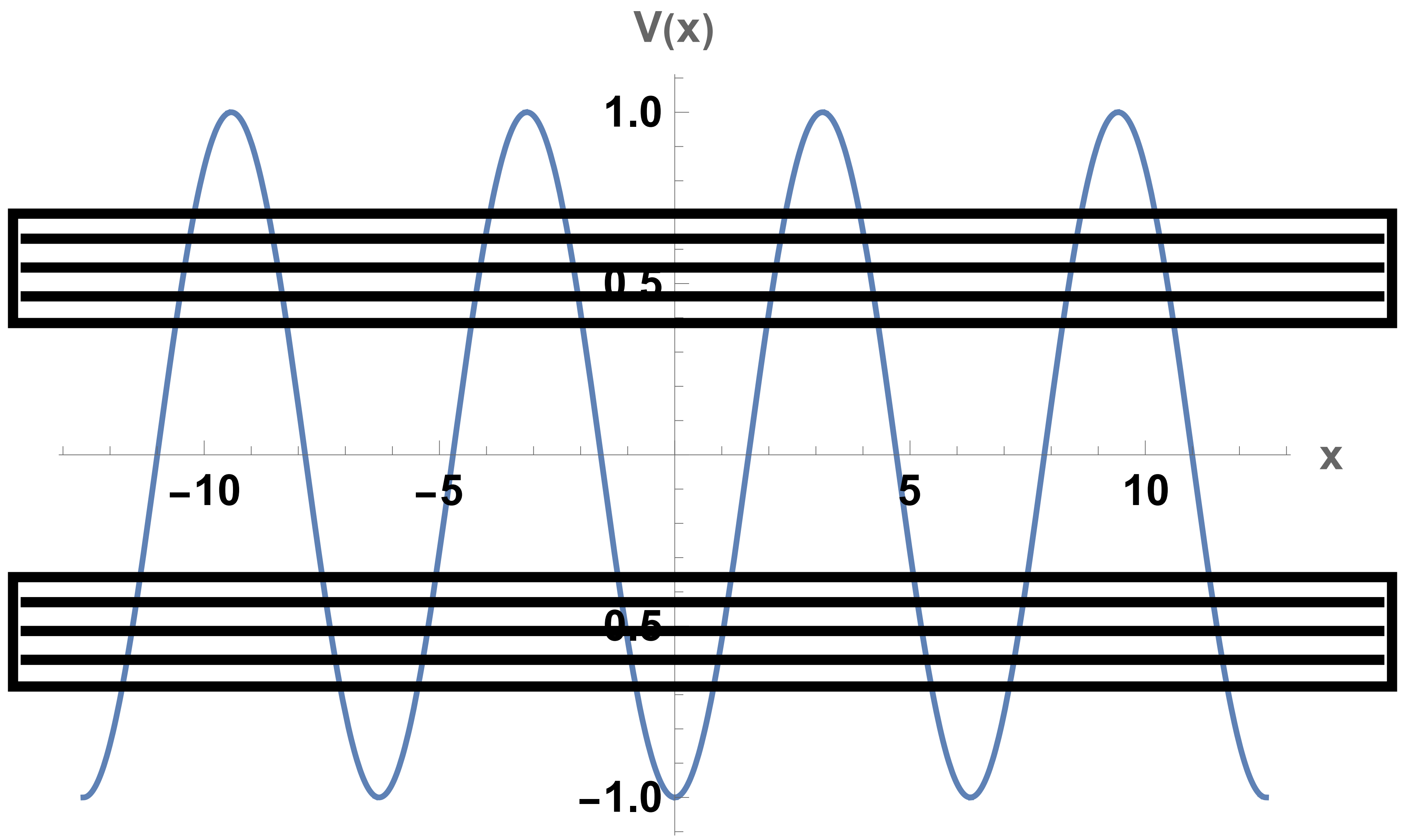
QCD

Gauge Field A initially has some random value

Why end up in $\theta = 0$?

Strong CP Problem

Pendulum in Gravity



Start Pendulum at High Energy

Why end up in θ = 0?

QCD

Gauge Field A initially has some random value

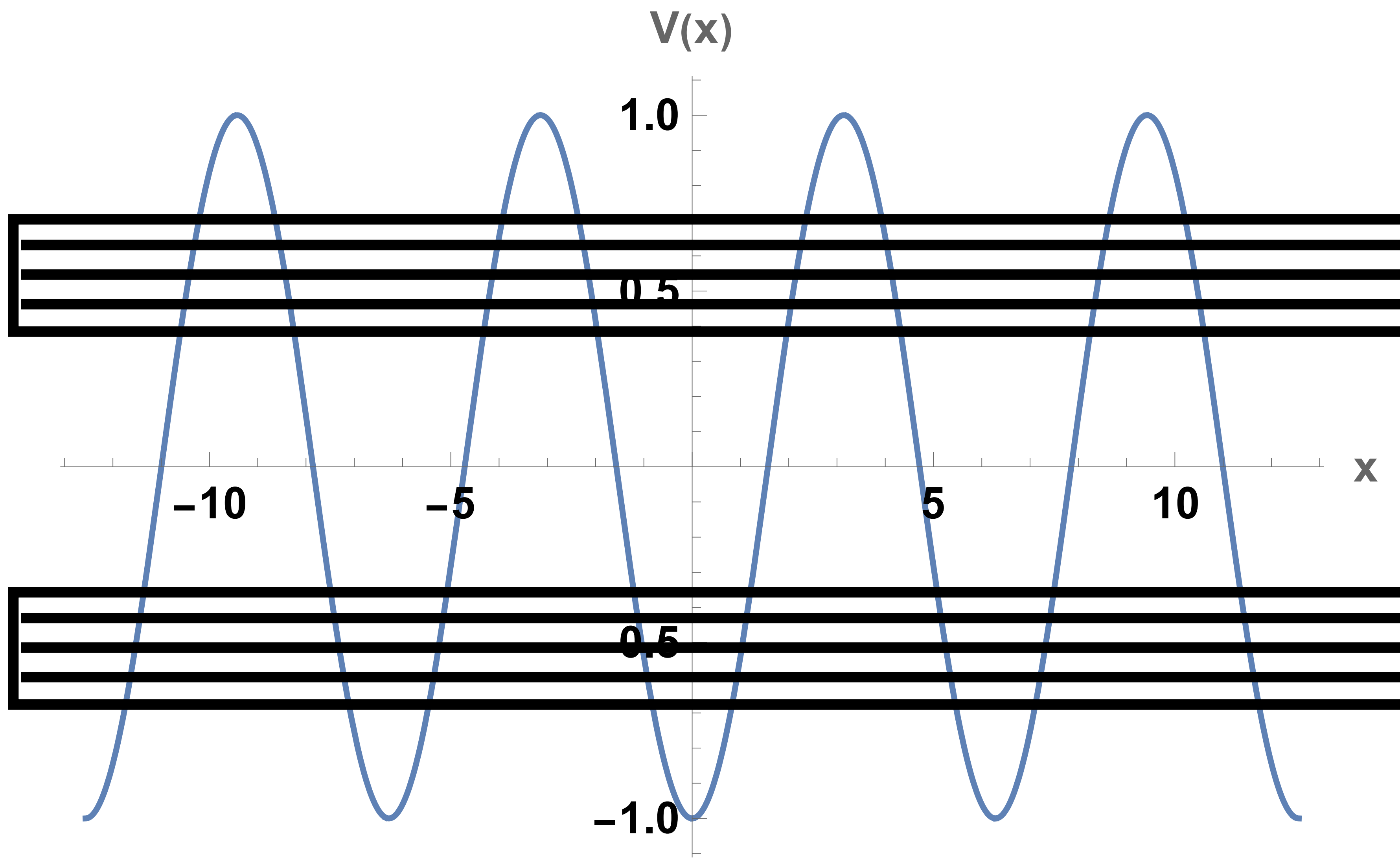
Why end up in θ = 0?

Need Dynamical Solution

QCD Axion

Strong CP Problem

Pendulum in Gravity



Start Pendulum at High Energy

Why end up in $\theta = 0$?

QCD

Gauge Field A initially has some random value

Why end up in $\theta = 0$?

Need Dynamical Solution

QCD Axion

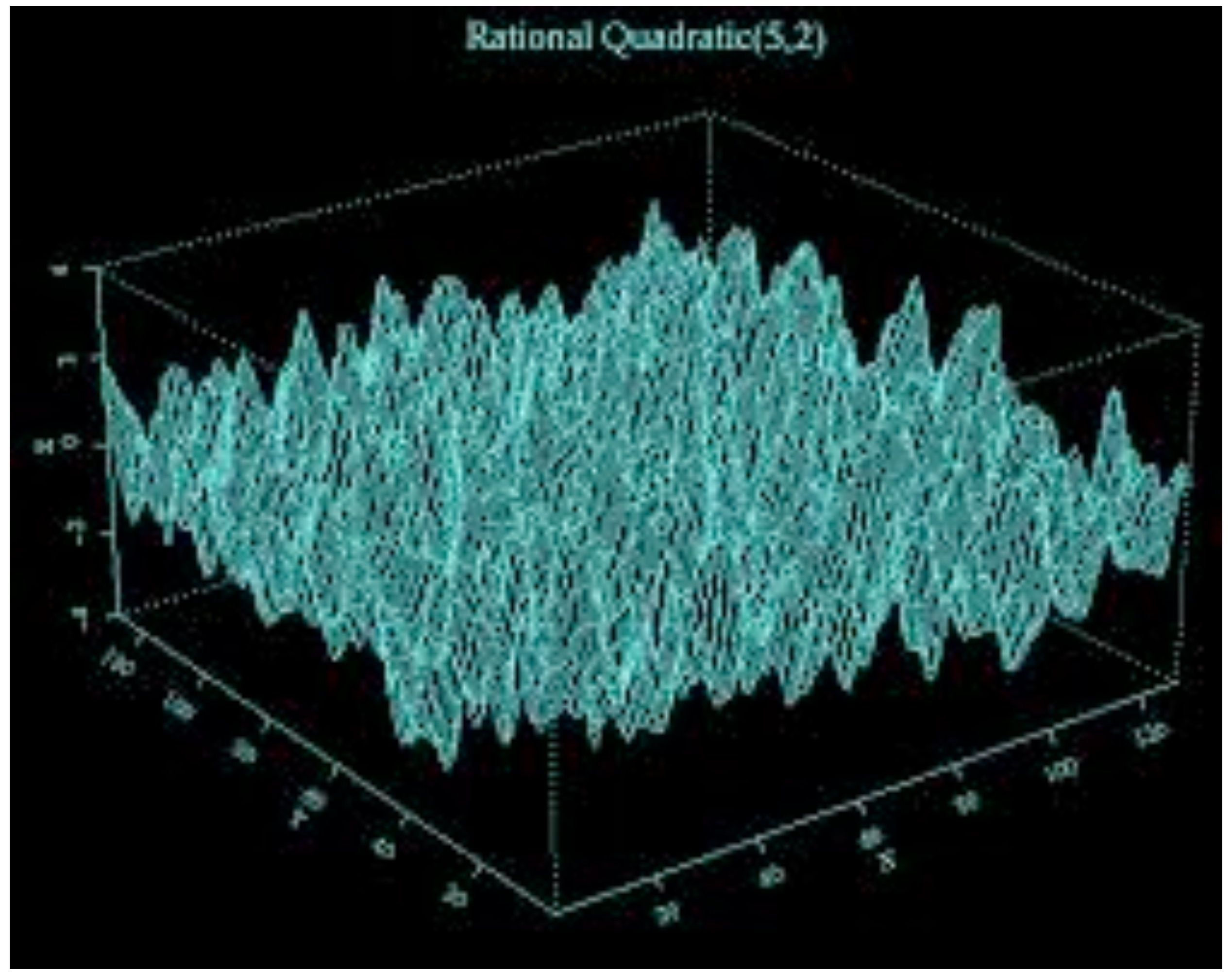
Non-zero cosmological abundance!

Experiment

(With Reza Ebadi, David E. Kaplan and Ron Walsworth)

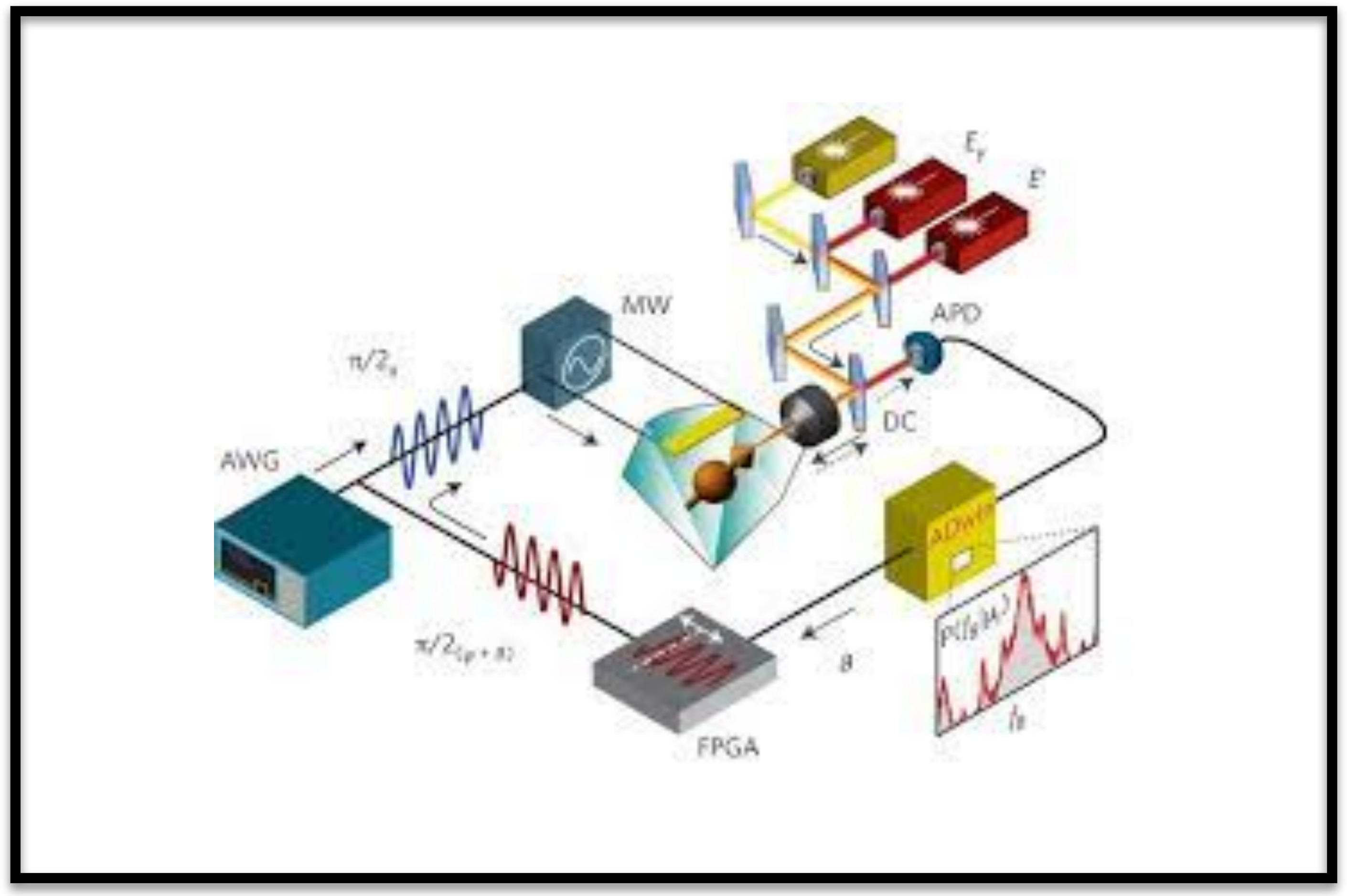
The Axion Landscape

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
(Q ~ 10^6)



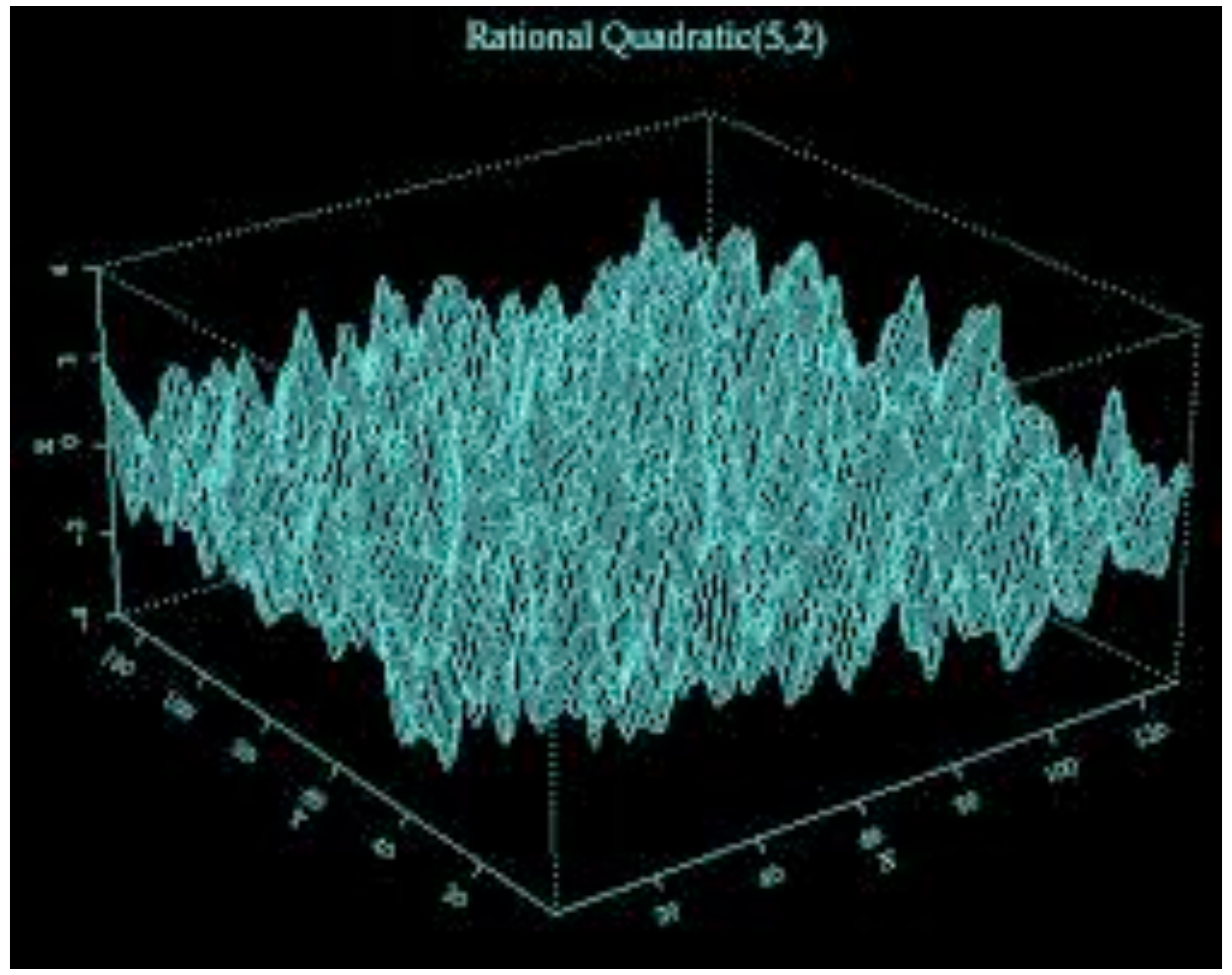
Detect Using suitable Resonator

nHz kHz MHz GHz 10 GHz

CASPEr DMRadio ADMX HAYSTAC

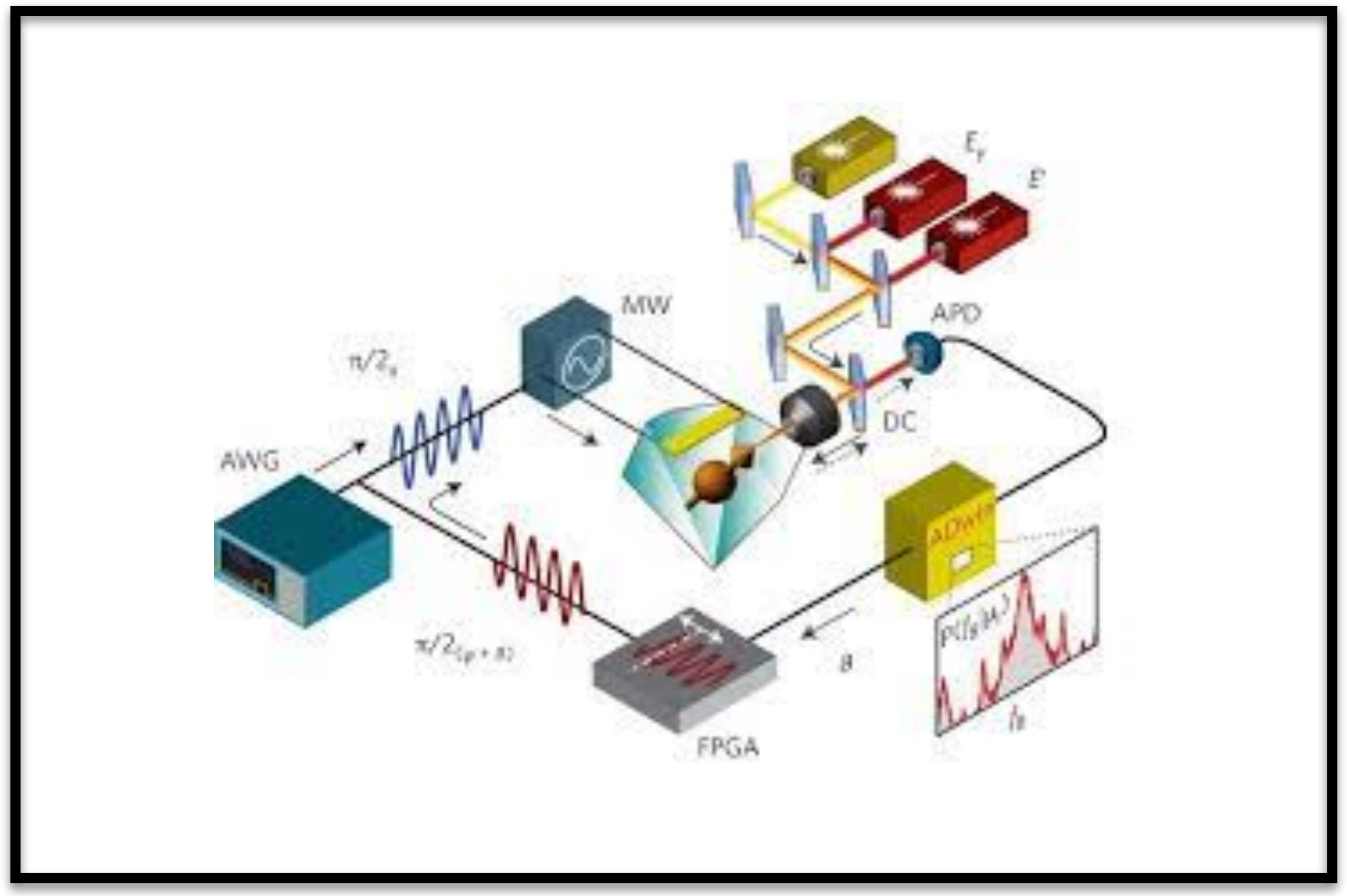
The Axion Landscape

Cosmological Source



Axion Dark Matter

Oscillating signal, narrow band
(Q ~ 10^6)



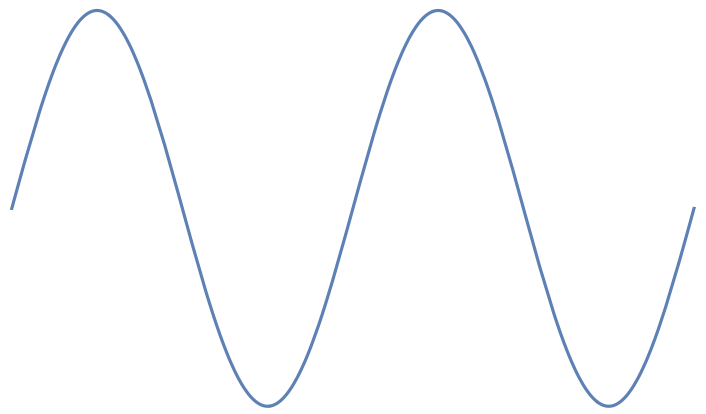
Detect Using suitable Resonator

nHz kHz MHz GHz 10 GHz

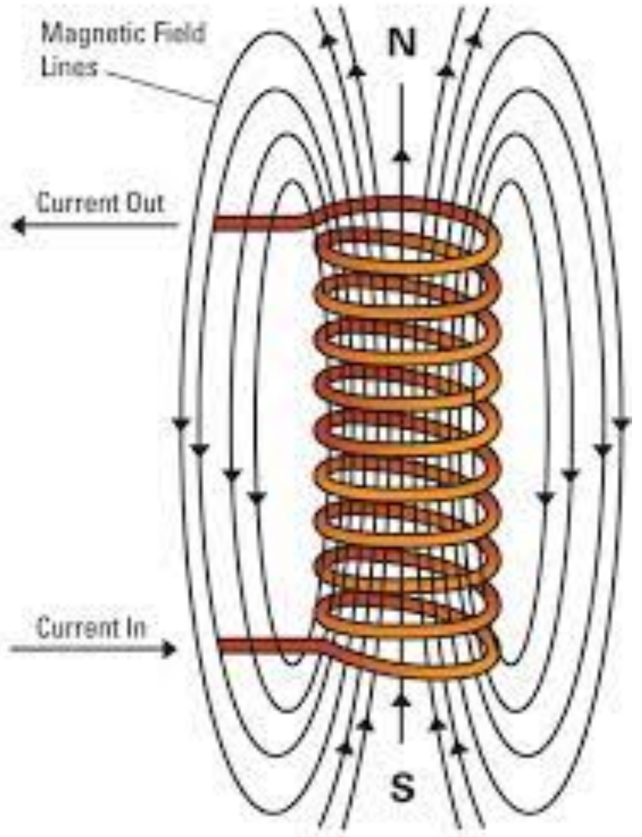
CASPEr DMRadio ADMX HAYSTAC Resonators?

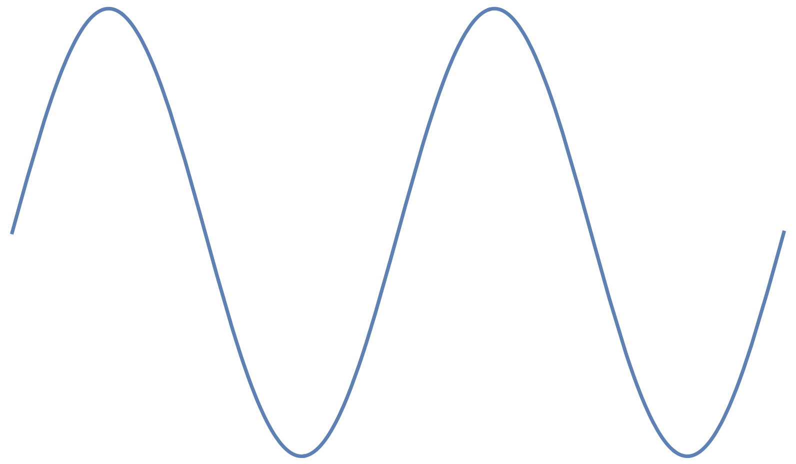
High Frequency Resonators

High Frequency Resonators



oscillating axion field



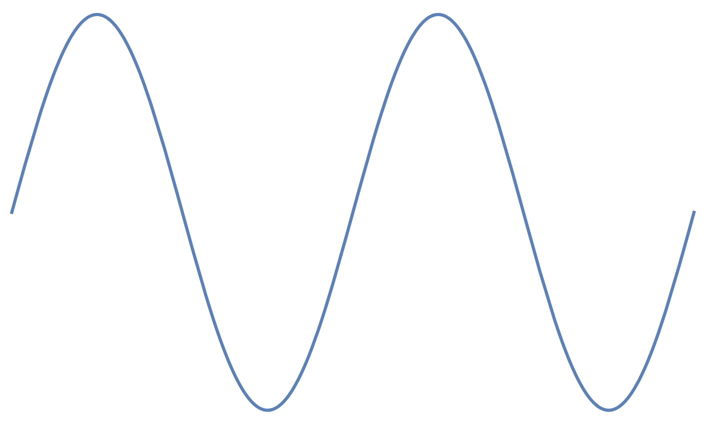


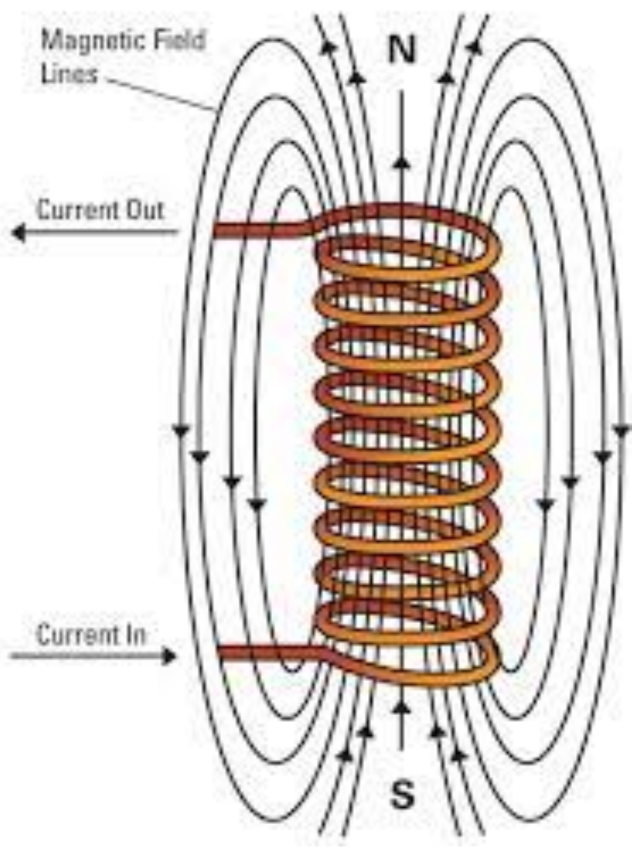
oscillating electric field

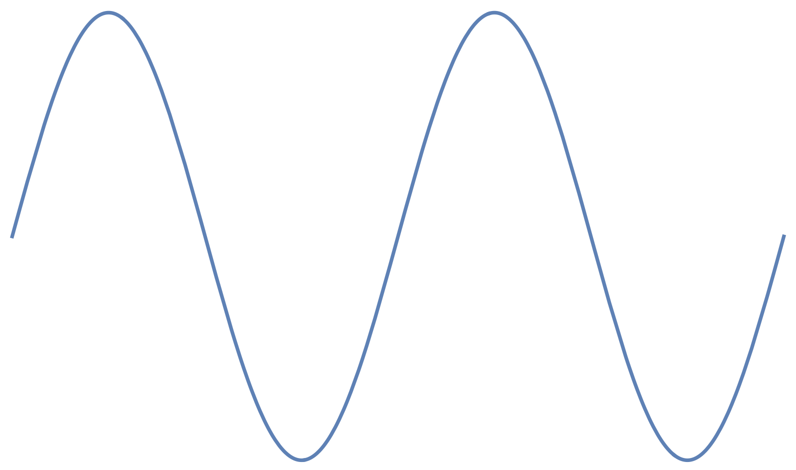
High Frequency Resonators

nHz kHz MHz GHz 10 GHz

CASPEr DMRadio ADMX HAYSTAC Resonators?







oscillating axion field

oscillating electric field

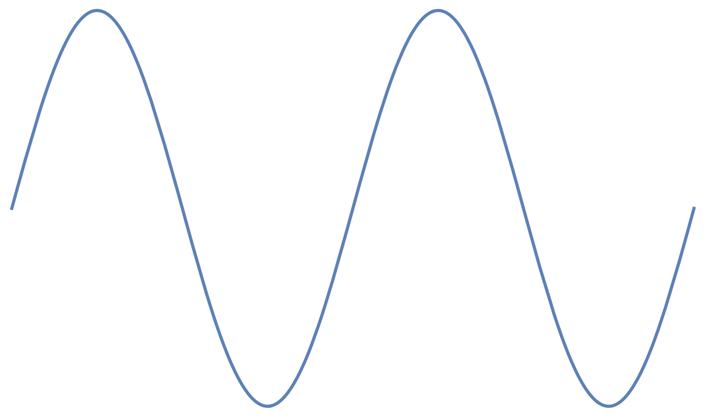
oscillating E' field (dark matter)

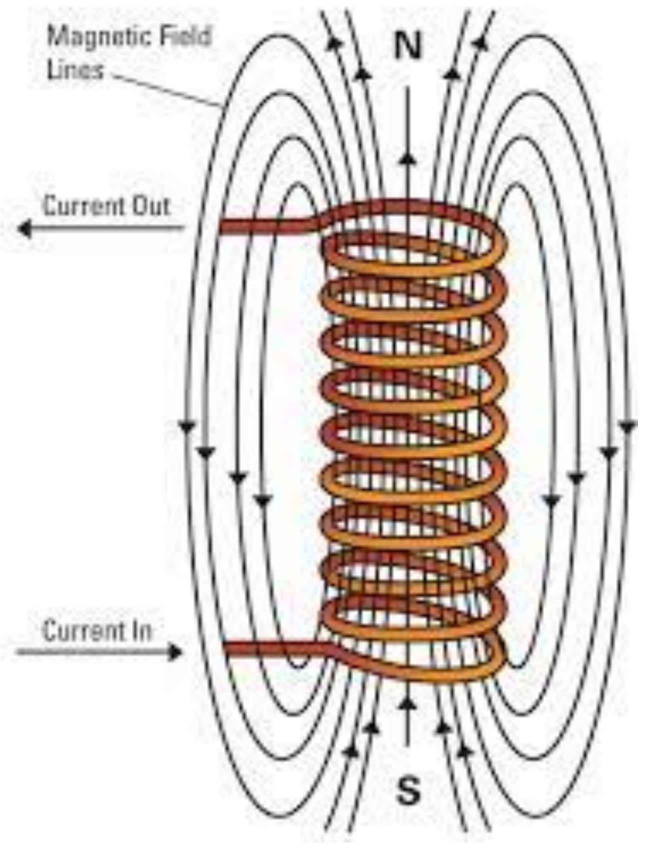
Charge sees small oscillating electric field

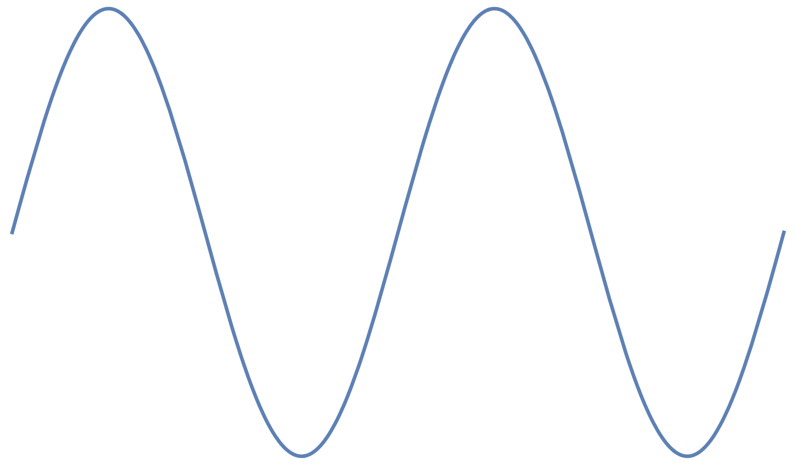
High Frequency Resonators

nHz kHz MHz GHz 10 GHz

CASPEr DMRadio ADMX HAYSTAC Resonators?







oscillating axion field

oscillating electric field

oscillating E' field (dark matter)

Charge sees small oscillating electric field

Detect high frequency oscillating electric field

Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift

Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift

$\vec{E}$

Phase shift depends on index of refraction -
measures time varying electric field

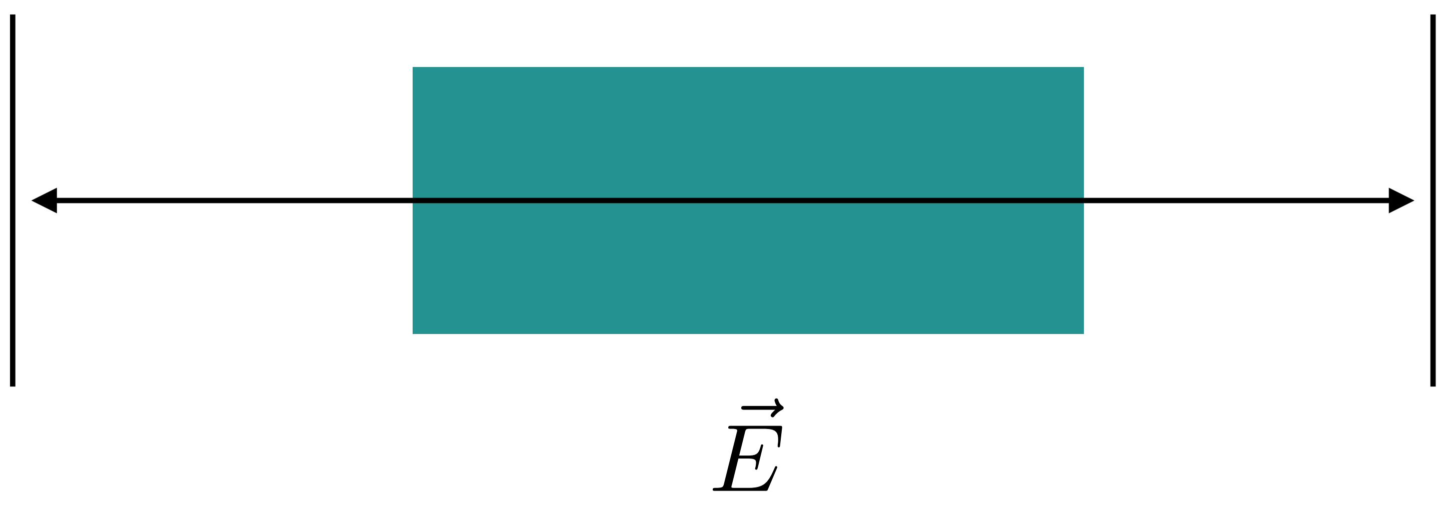
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift



Phase shift depends on index of refraction -
measures time varying electric field

Lowest frequency set by absorption length of light (~km)

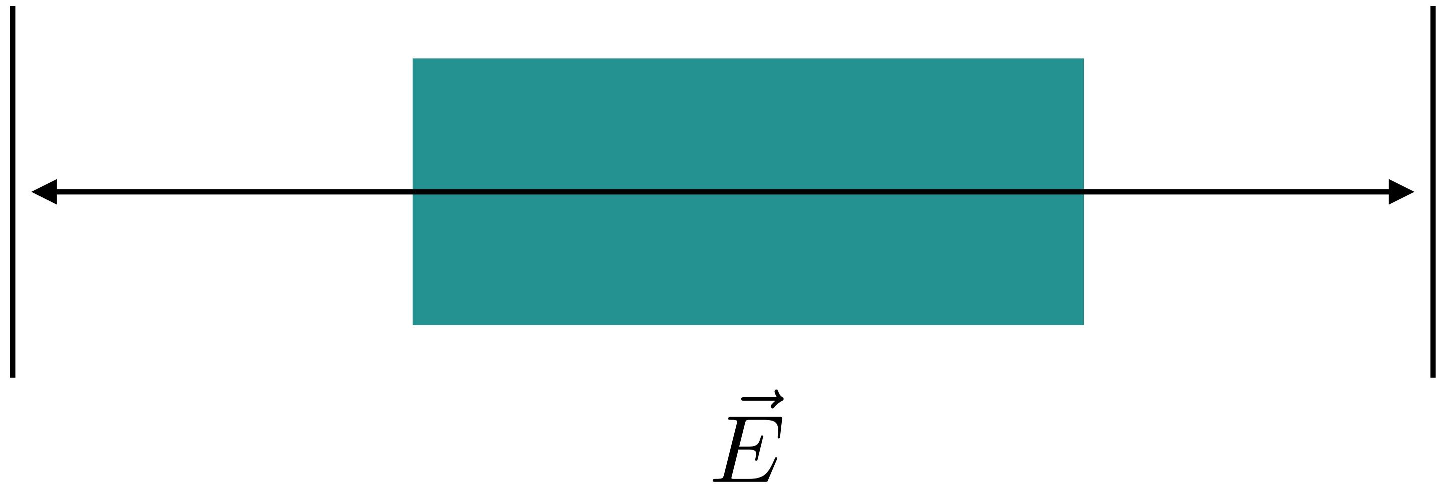
Nonlinear Optics

Detect high frequency oscillating electric field

Crystal with index of refraction with a linear dependence on electric field
(e.g. Lithium Niobate)

Create Optical Cavity with Lithium Niobate - choose length to set resonance frequency

Send light through optical resonator - measure phase shift



Phase shift depends on index of refraction -
measures time varying electric field

Lowest frequency set by absorption length of light (~km)

High frequency cut-off: Nyquist limit, response time of
crystal (> THz)

Projected Sensitivity

Conservative Solid Lines: 1 s averaging

Super aggressive dot dashed: ~ 1 yr averaging, 10 db Squeezing, 10 W

Conclusions

Conclusions

1. Strong CP Problem requires dynamical solution, strongly boosts searches for QCD Axion

2. Exciting opportunities with nonlinear optical elements