eman ta zabal zazu
Universidad del País Vasco — Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center
ikerbasque
Basque Foundation for Science

Qubit alive thanks to the anomaly

Enrique Rico Ortega
Friday, 13/05/2022

Max Planck Institute of Quantum Optics, Munich

Gauge Workshop Munich 2022

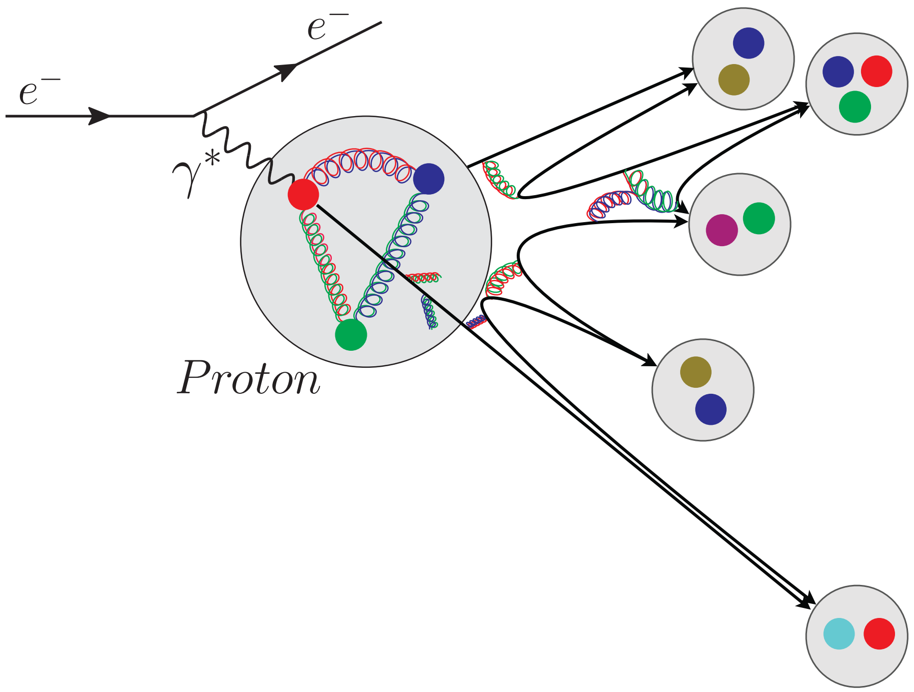
May 9 – 13, 2022
Max Planck Institute of Quantum Optics

Universidad del País Vasco Euskal Herriko Unibertsitatea

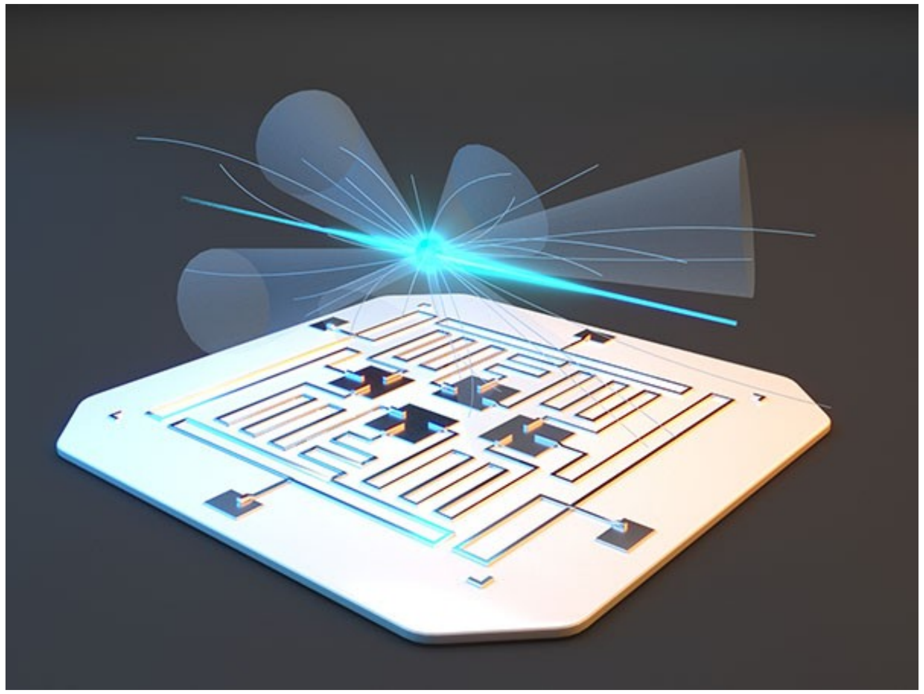
EHU QC
EHU Quantum Center

ikerbasque Basque Foundation for Science

A fruitful dialogue (two-way communication)

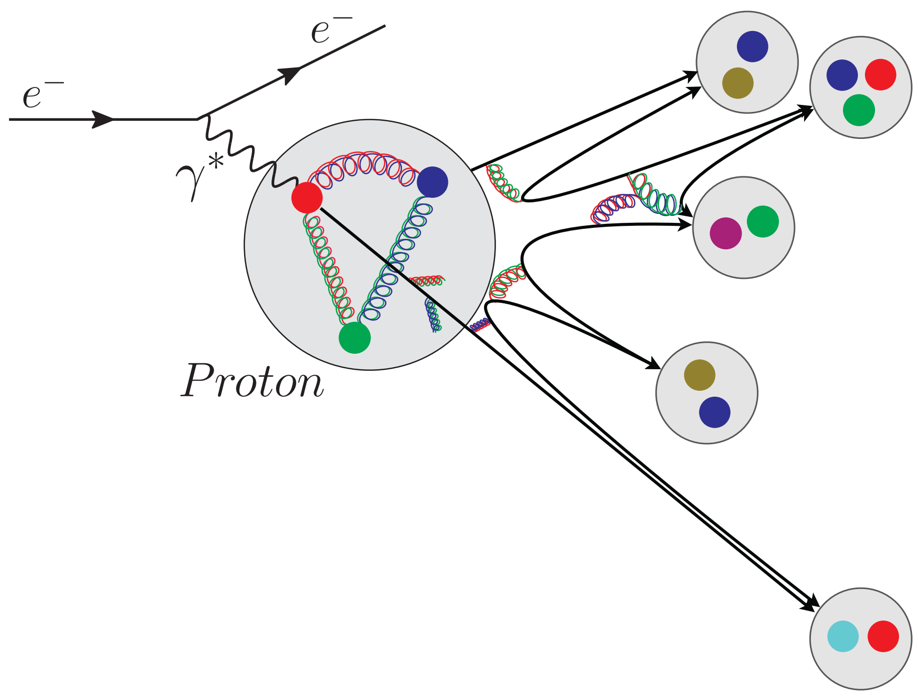


High-Energy and Nuclear Physics

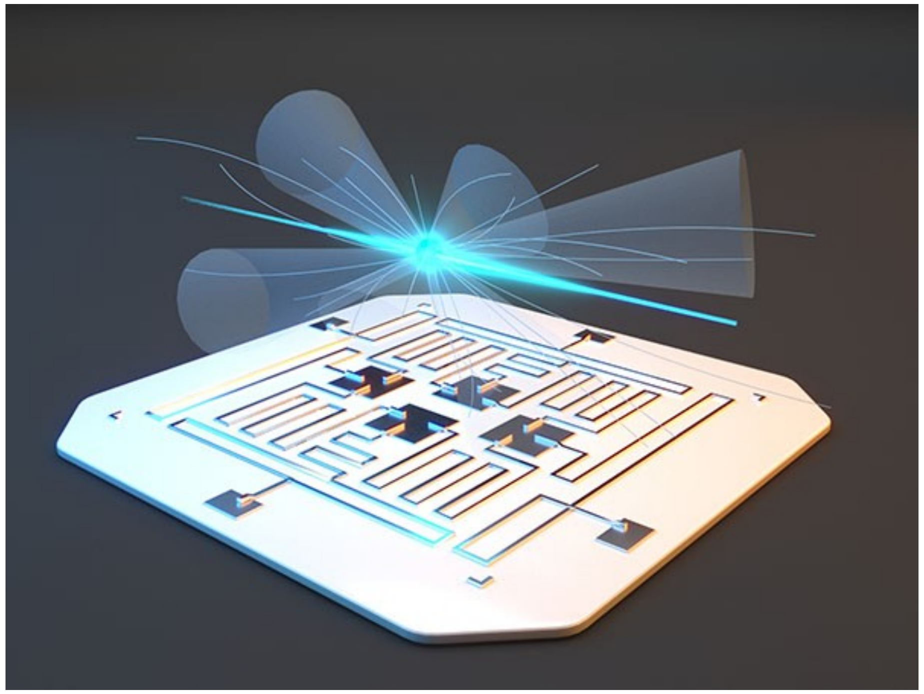


Quantum Information Science and Technology

A fruitful dialogue (two-way communication)



High-Energy and Nuclear Physics



Quantum Information Science and Technology

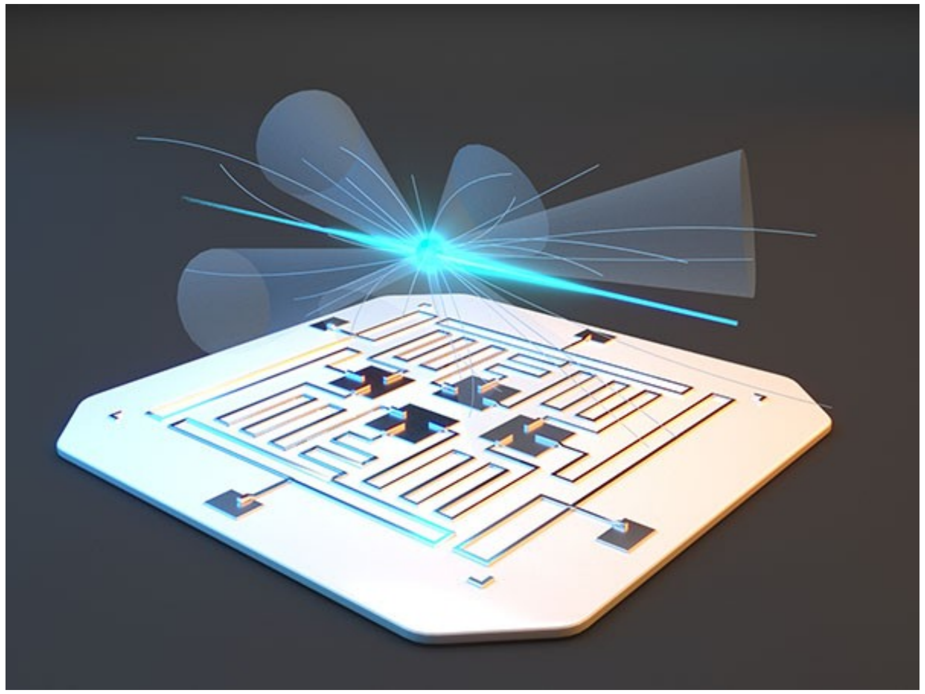
Qubit alive thanks to the anomaly

I.L. Egusquiza,[1,*] A. Iñiguez,[2,†] E. Rico,[3,4,‡] and A. Villarino[3,§]

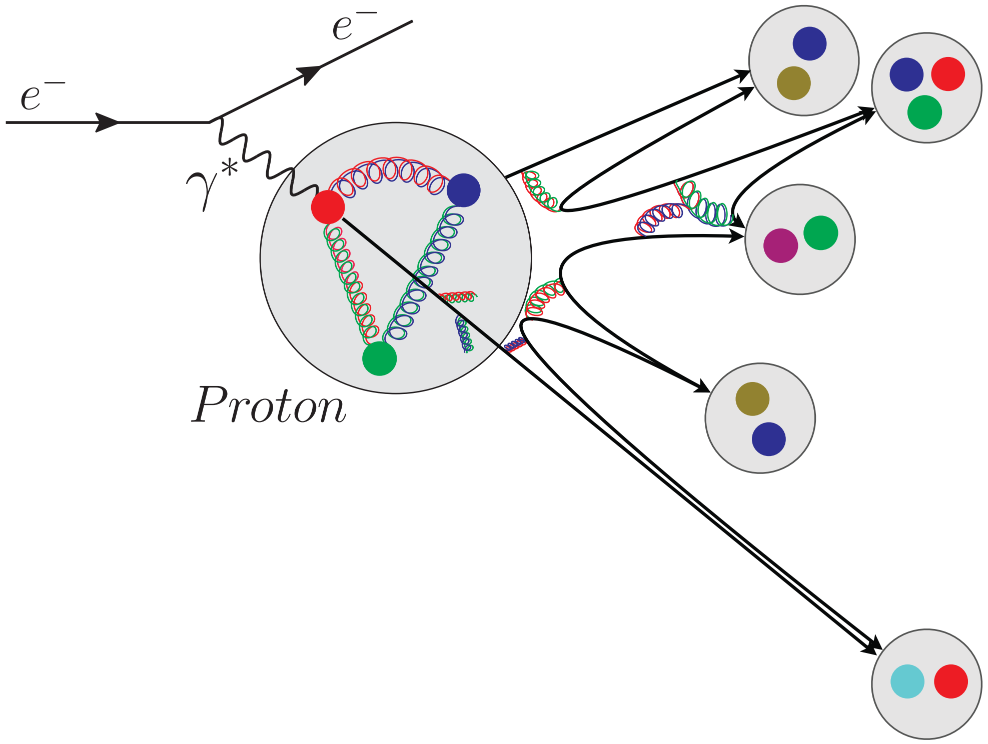
[1] *Department of Physics, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[2] *Department of Mathematics, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[3] *Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[4] *IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain*

arXiv:2109.11824v1

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center
ikerbasque
Basque Foundation for Science



Simulating lattice gauge theories within quantum technologies



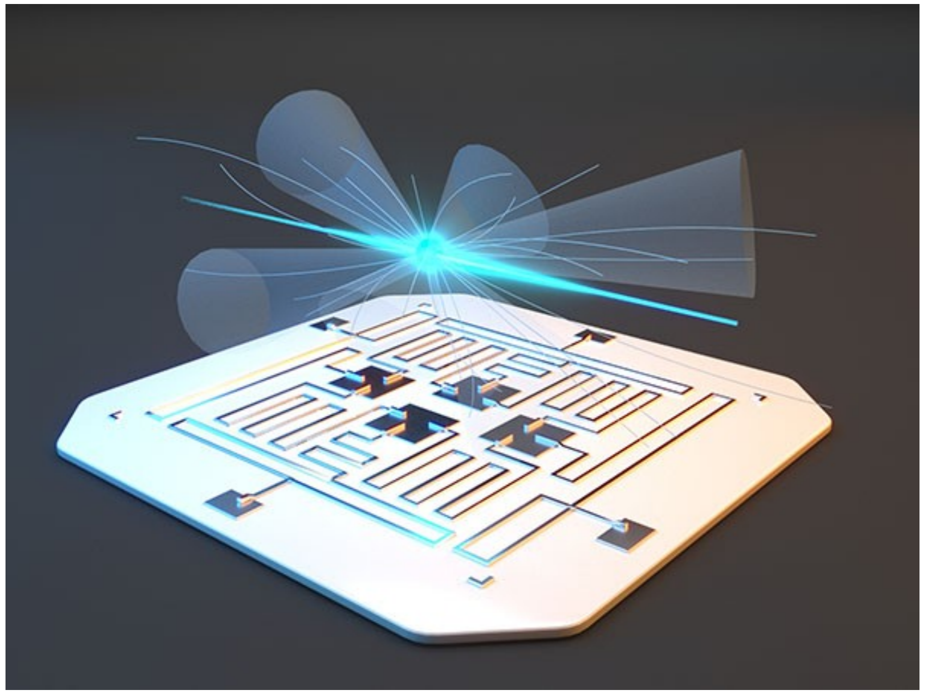
Quantum simulation of light-front parton correlators

Universidad del País Vasco Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

ikerbasque
Basque Foundation for Science

Simulating lattice gauge theories within quantum technologies



Collaborators: M. Dalmonte, S. Montangero, U.-J. Wiese, P. Zoller…

Eur. Phys. J. D (2020) 74: 165
https://doi.org/10.1140/epjd/e2020-100571-8

THE EUROPEAN PHYSICAL JOURNAL D

Colloquium

Simulating lattice gauge theories within quantum technologies

Mari Carmen Bañuls[1,2], Rainer Blatt[3,4], Jacopo Catani[5,6,7], Alessio Celi[3,8], Juan Ignacio Cirac[1,2], Marcello Dalmonte[9,10], Leonardo Fallani[5,6,7], Karl Jansen[11], Maciej Lewenstein[8,12,13], Simone Montangero[14,15,a], Christine A. Muschik[3], Benni Reznik[16], Enrique Rico[17,18], Luca Tagliacozzo[19], Karel Van Acoleyen[20], Frank Verstraete[20,21], Uwe-Jens Wiese[22], Matthew Wingate[23], Jakub Zakrzewski[24,25], and Peter Zoller[3]

Universidad del País Vasco / Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

ikerbasque
Basque Foundation for Science

PHYSICAL REVIEW D **104,** 014512 (2021)

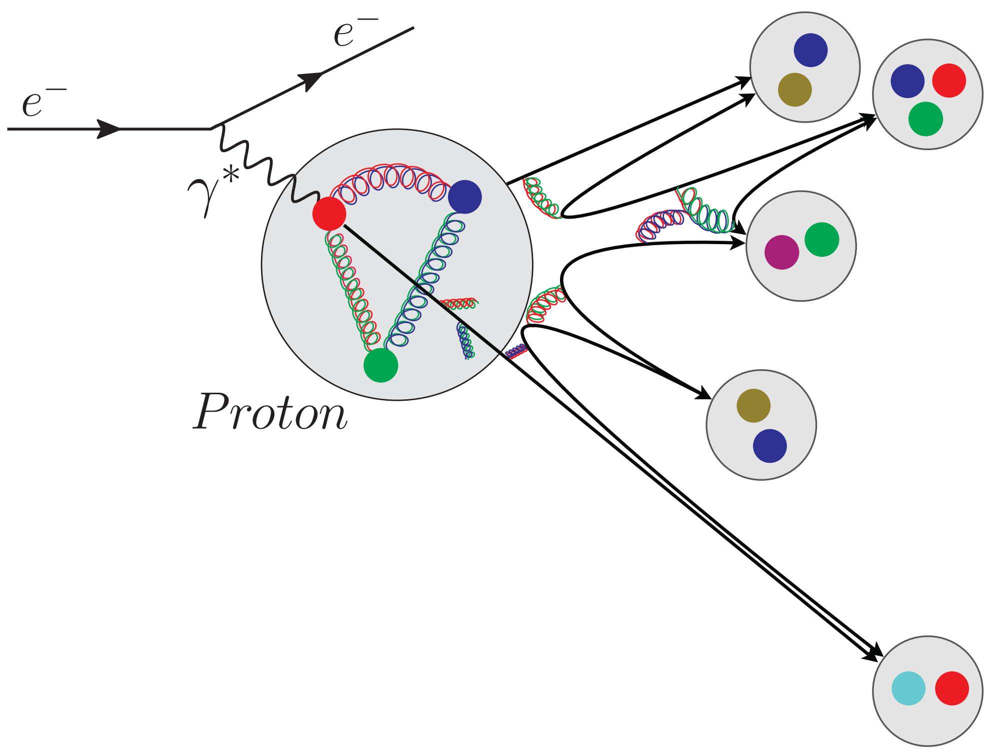
Quantum simulation of light-front parton correlators

M. G. Echevarria,[1,*] I. L. Egusquiza,[2,†] E. Rico,[3,4,‡] and G. Schnell[2,4,§]

arXiv:2011.01275

Phys. Rev. D 104, 014512 (2021)

Project in progress with: M.G. Echevarria, I.L. Egusquiza, G. Schnell

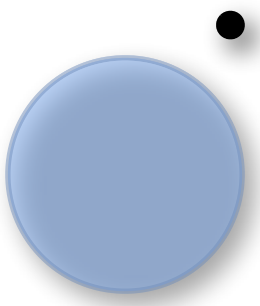


Quantum simulation of light-front parton correlators

Three ingredients to describe Nature

Three ingredients to describe Nature

- Quantum matter as the basic building block

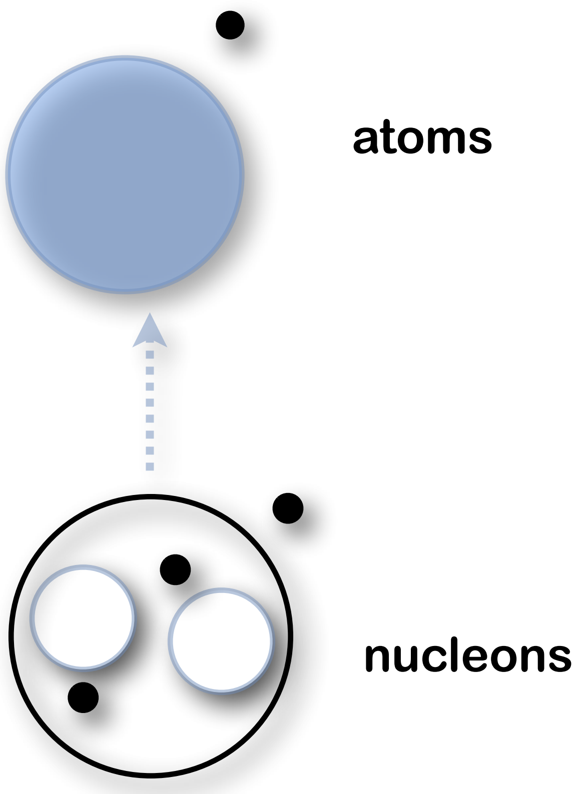


atoms

Three ingredients to describe Nature

- Quantum matter as the basic building block

- Gauge symmetry as a fundamental principle and at the origin of every force

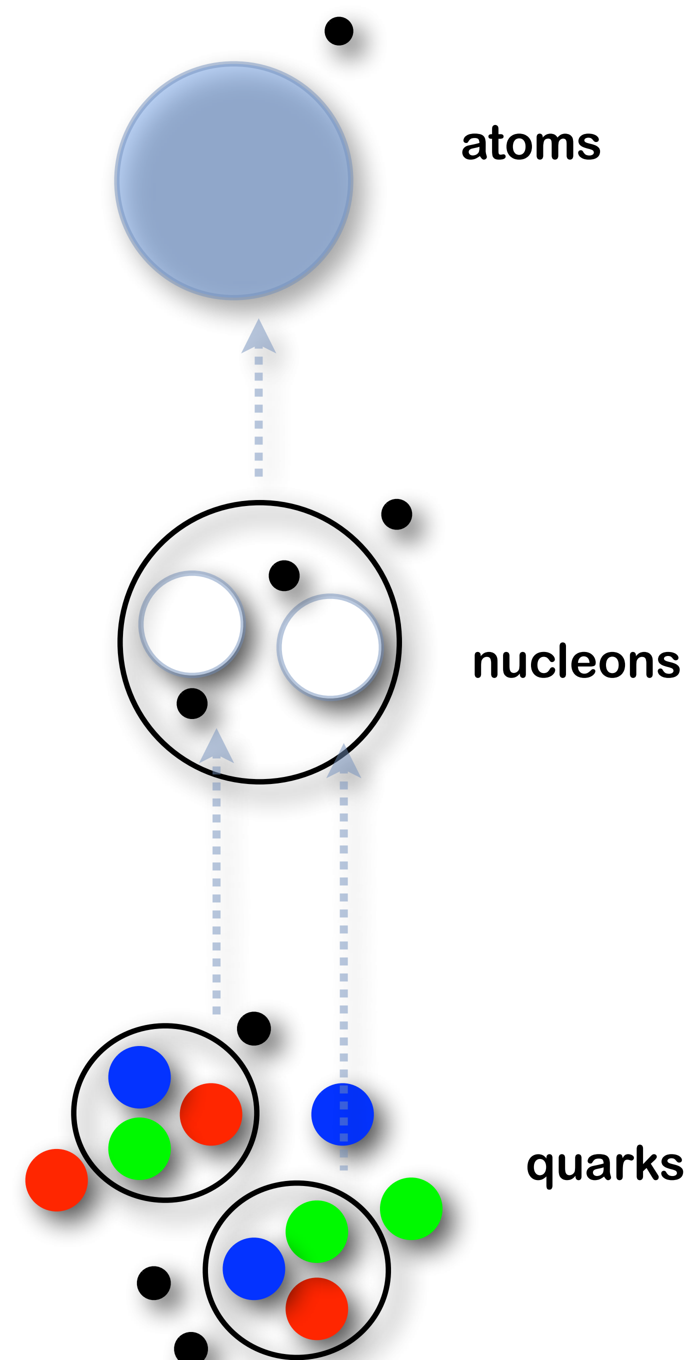


Three ingredients to describe Nature

- Quantum matter as the basic building block

- Gauge symmetry as a fundamental principle and at the origin of every force

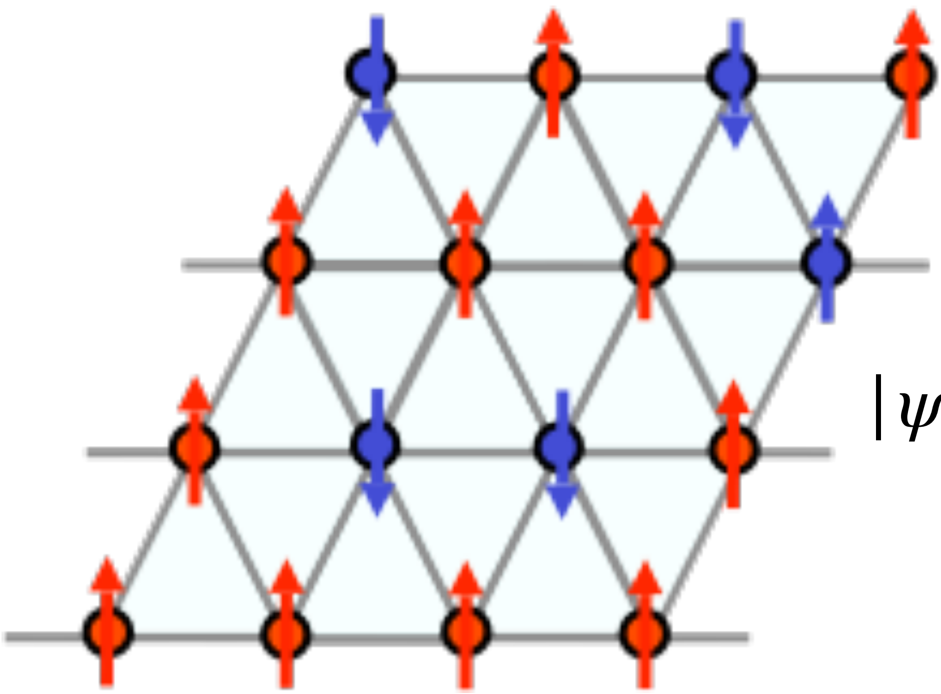
- Renormalisation group as a tool to study Nature at different scales



Universidad del País Vasco / Euskal Herriko Unibertsitatea — EHU QC, EHU Quantum Center — ikerbasque, Basque Foundation for Science

Quantum matter as the basic building block

R.P. Feynman, Int. J. Theor. Phys. (1982)



Preparation of a general quantum state

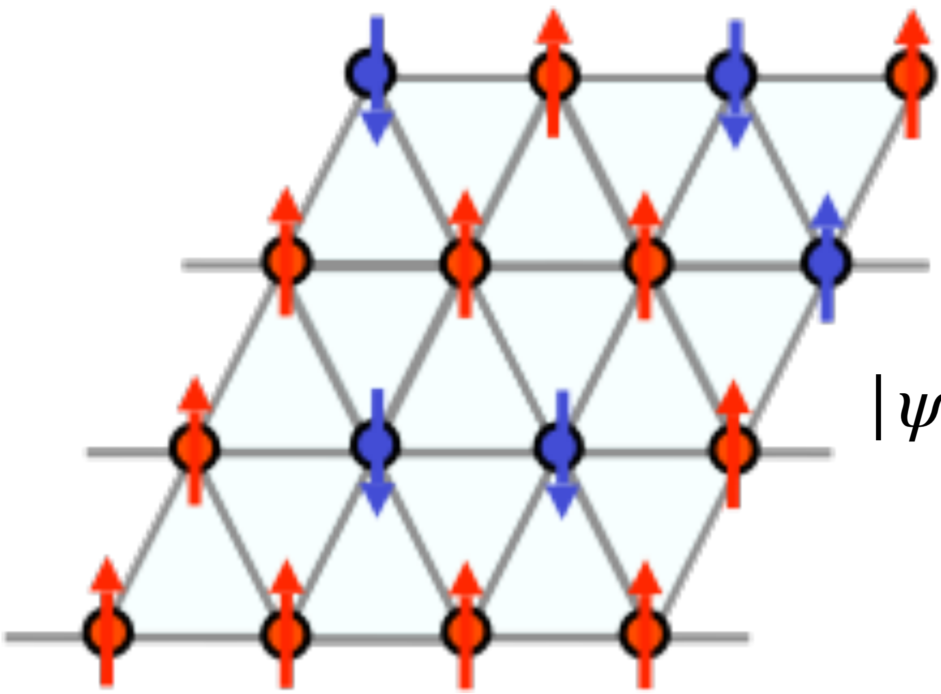
$$|\psi\rangle = c_1 |\uparrow\uparrow\cdots\uparrow\rangle + c_2 |\uparrow\uparrow\cdots\downarrow\rangle + \cdots + c_{2^N} |\downarrow\downarrow\cdots\downarrow\rangle$$

	Classic	vs.	Quantum
Memory	2^N		N

Universidad del País Vasco / Euskal Herriko Unibertsitatea — EHU QC, EHU Quantum Center — ikerbasque, Basque Foundation for Science

Quantum matter as the basic building block

R.P. Feynman, Int. J. Theor. Phys. (1982)



Preparation of a general quantum state

$$|\psi\rangle = c_1 | \uparrow \uparrow \cdots \uparrow \rangle + c_2 | \uparrow \uparrow \cdots \downarrow \rangle + \cdots + c_{2^N} | \downarrow \downarrow \cdots \downarrow \rangle$$

S. Lloyd, Science (1996)

Evolution of a general quantum state

$$|\psi(t)\rangle = U(t) | \psi\rangle$$

	Classic	vs.	Quantum
Memory	2^N		N
Time	2^N		Poly(N)

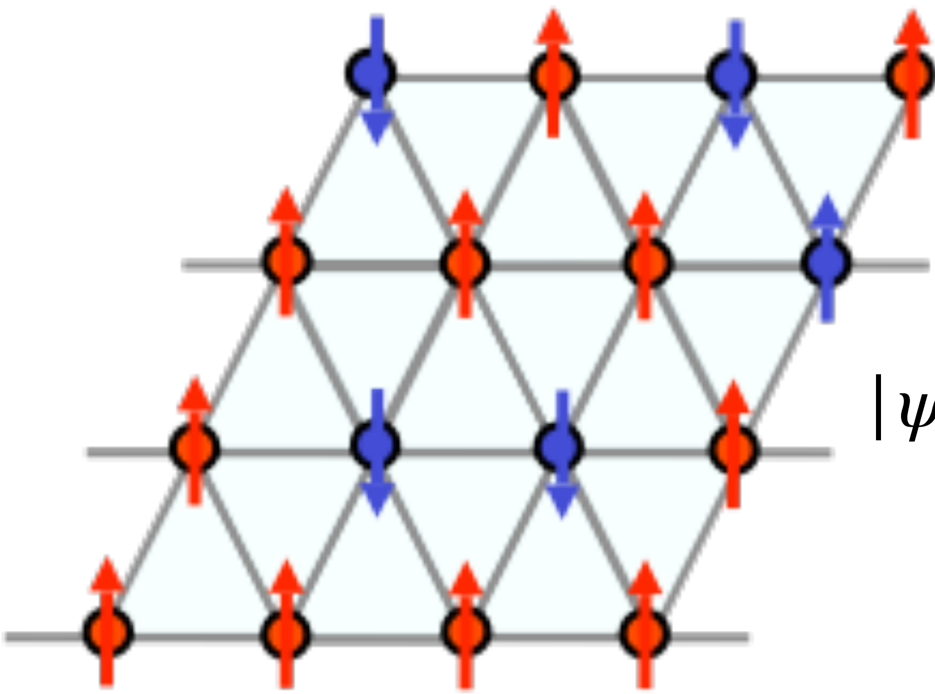
Universidad del País Vasco Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

Quantum matter as the basic building block

ikerbasque
Basque Foundation for Science

R.P. Feynman, Int. J. Theor. Phys. (1982)



Preparation of a general q… state

$$|\psi\rangle = c_1 |\uparrow \uparrow \cdots \uparrow\rangle + \ldots \downarrow\rangle + \cdots + c_{2^N} |\downarrow \downarrow \cdots \downarrow\rangle$$

Quantum advantage in real-time dynamics processes

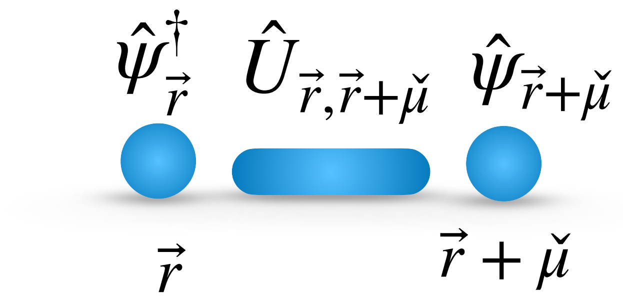
S. Lloyd, Science (1996)

F… a general quantum state

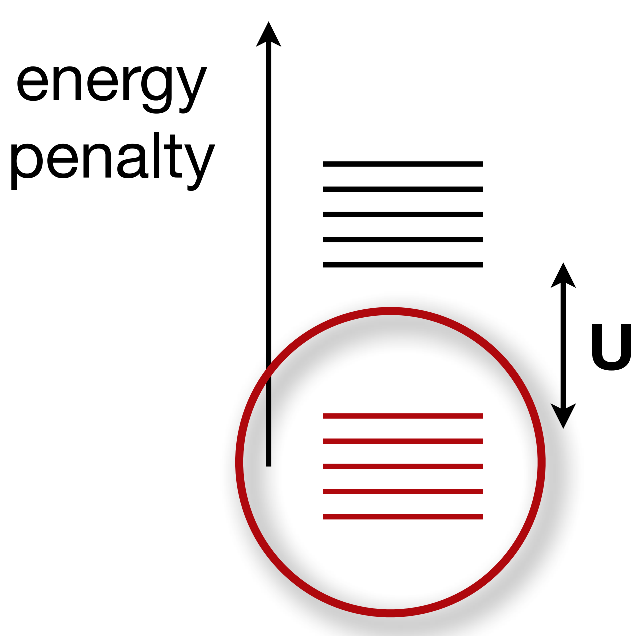
$$|\psi(t)\rangle = U(t)|\psi\rangle$$

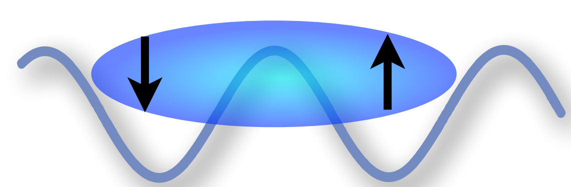
	Classic	vs.	Quantum
Memory	2^N		N
Time	2^N		Poly(N)

Simulating lattice gauge theories within quantum technologies



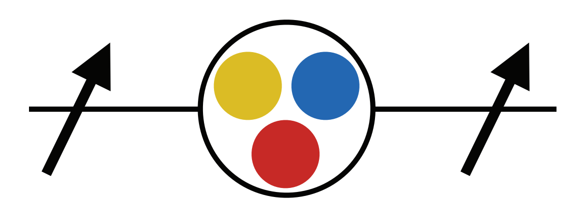
- Implementing the gauge invariant dynamics





color singlet hopping

Internal symmetry



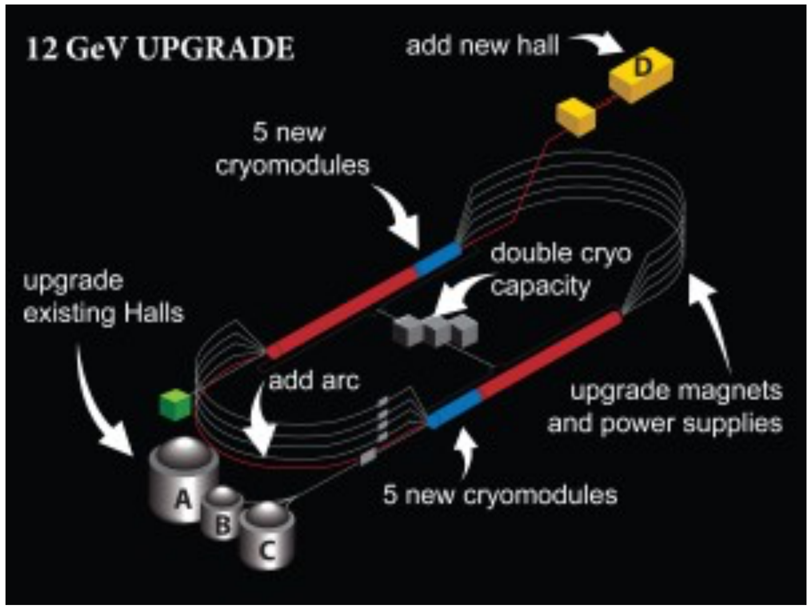
encoding gauge invariant degrees of freedom

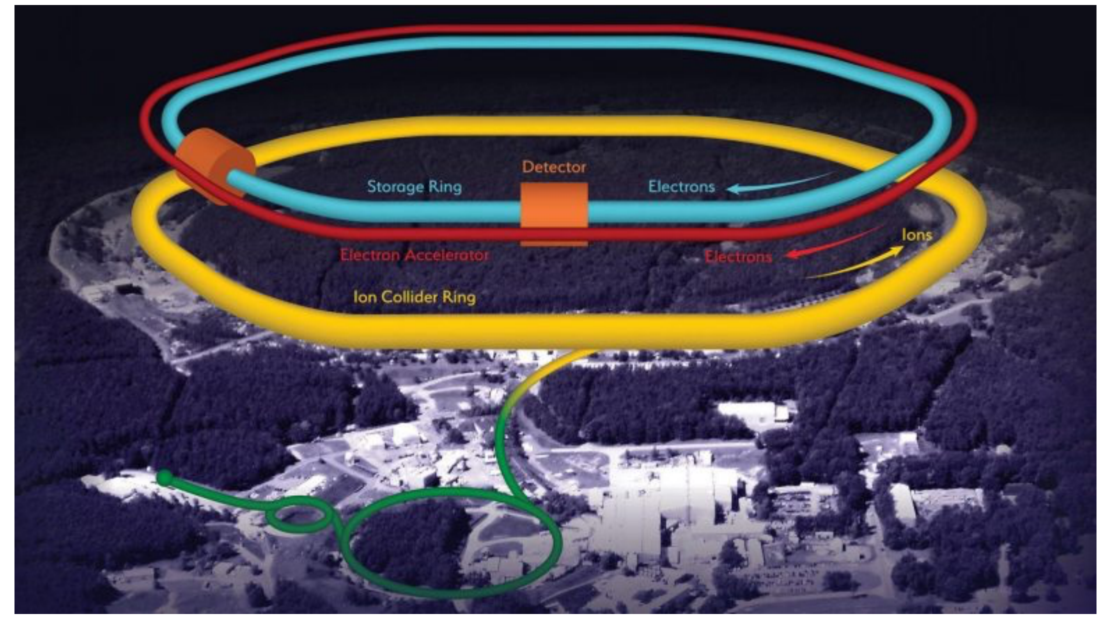
Universidad del País Vasco
Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

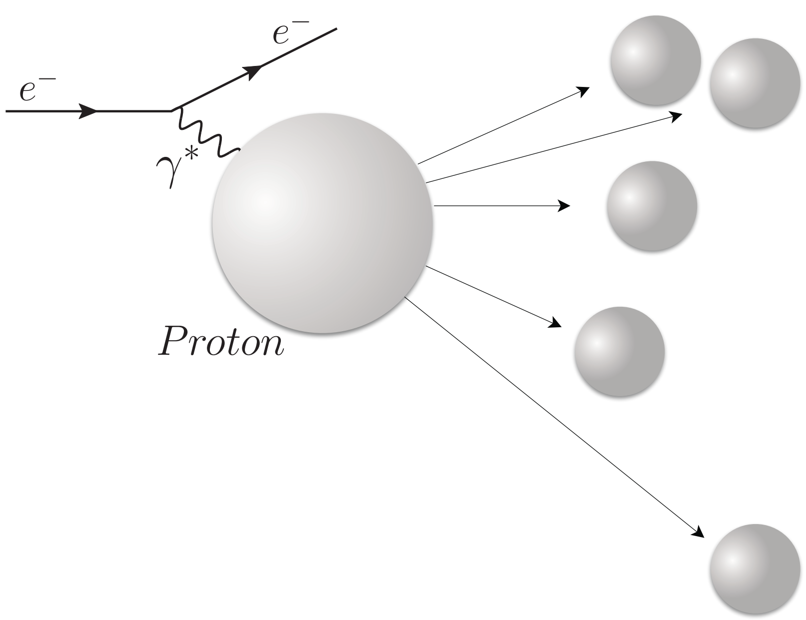
ikerbasque
Basque Foundation for Science

Quantum simulation of light-front parton correlators





modern microscopes



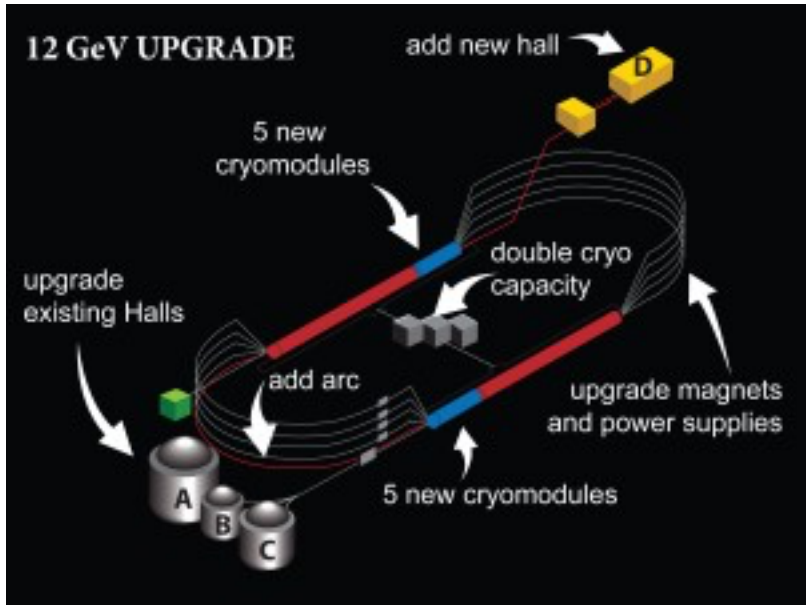
(semi-inclusive) deep-inelastic lepton scattering

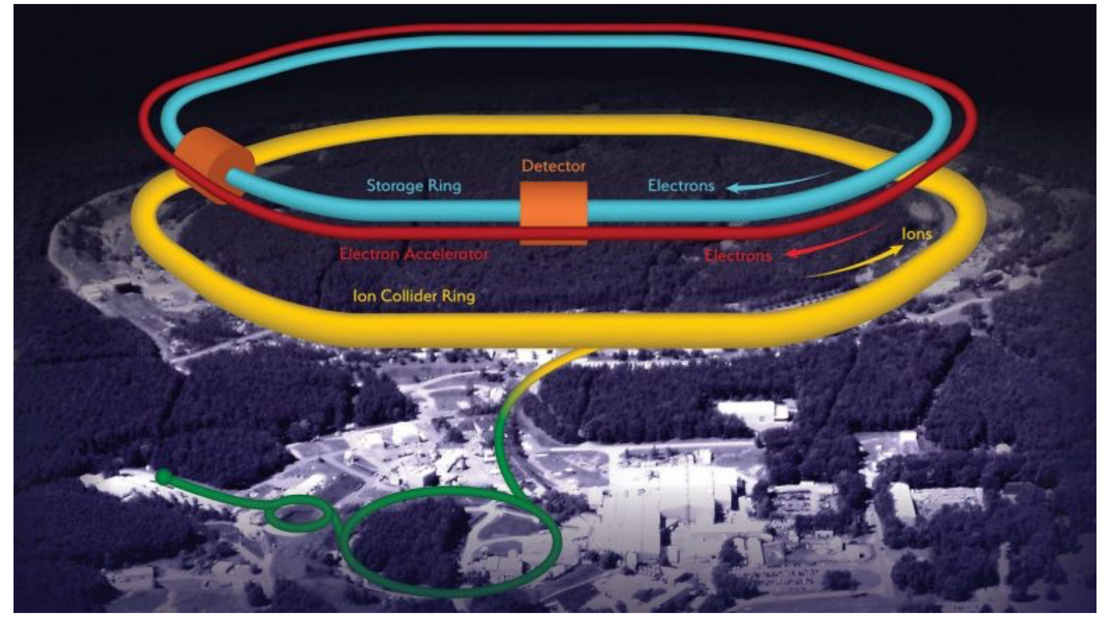
eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

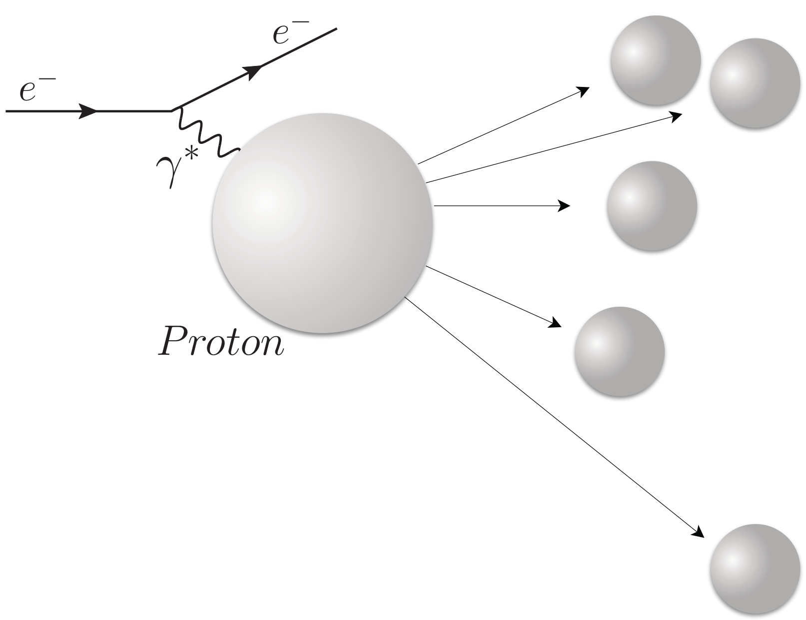
Quantum simulation of light-front parton correlators

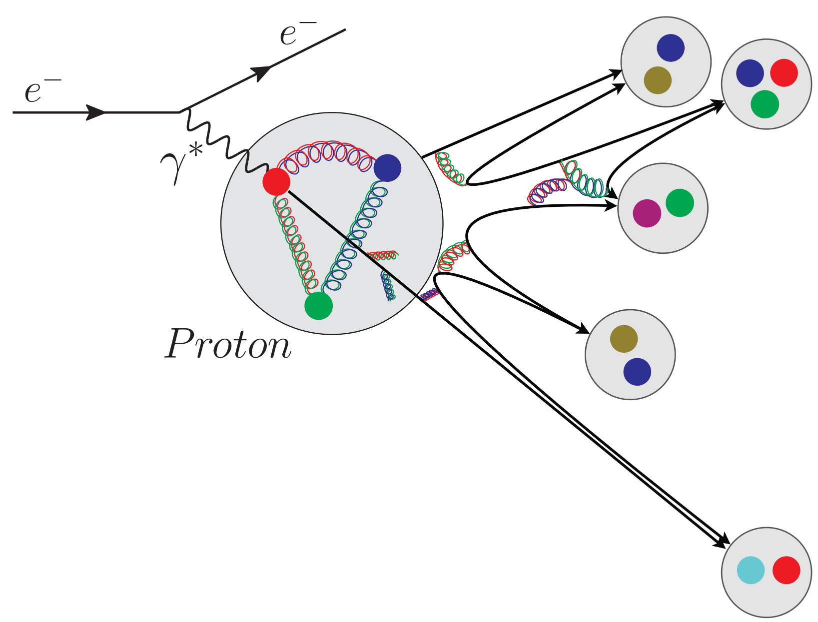
ikerbasque
Basque Foundation for Science





modern microscopes





(semi-inclusive) deep-inelastic lepton scattering

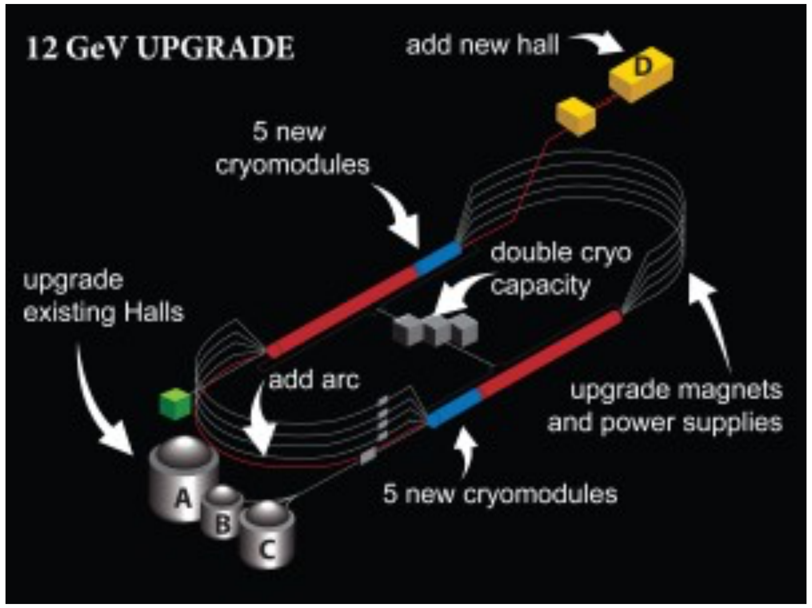
highly virtual photons resolve inner (partonic) structure

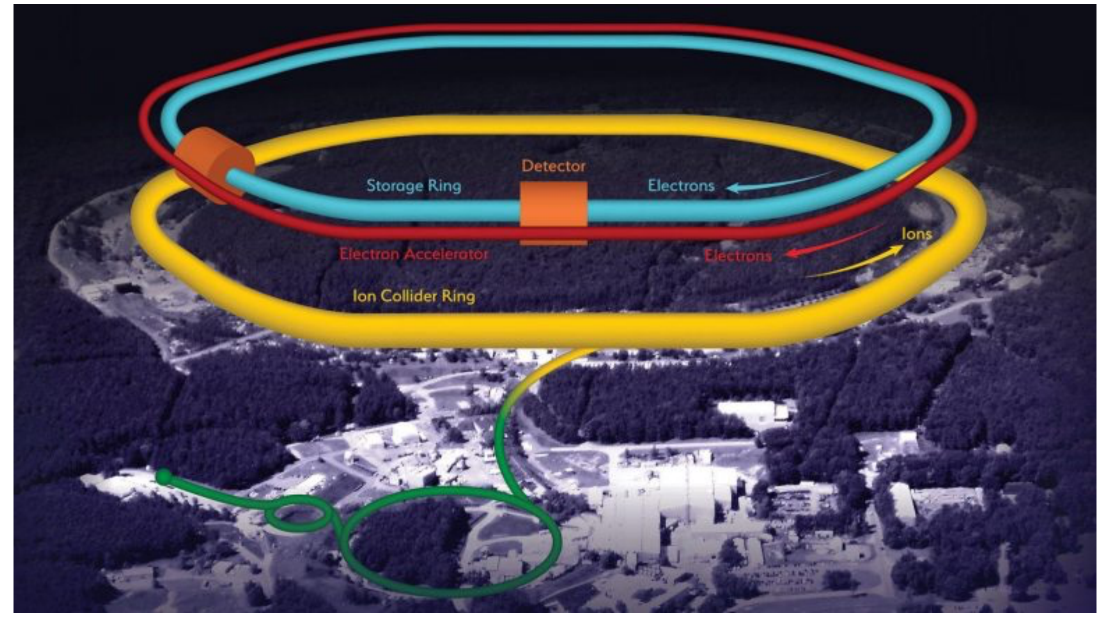
Universidad del País Vasco | Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

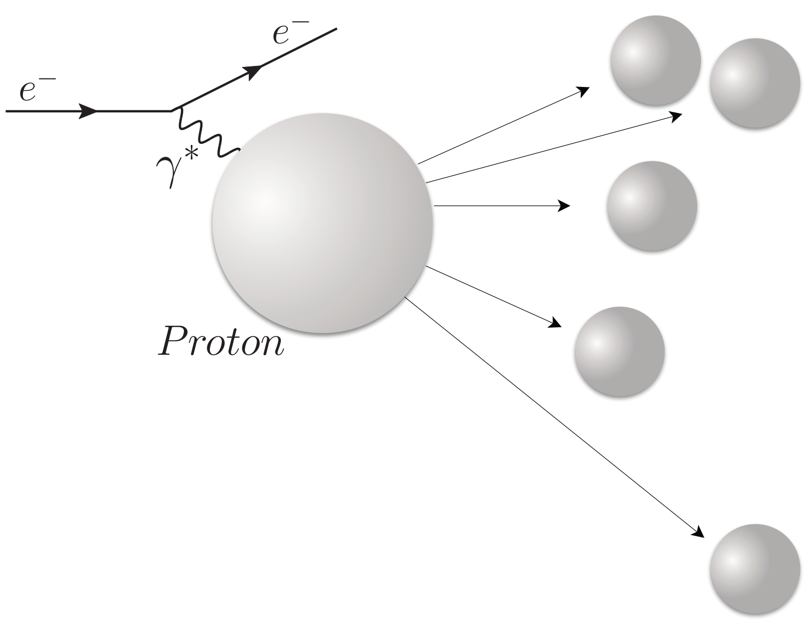
Quantum simulation of light-front parton correlators

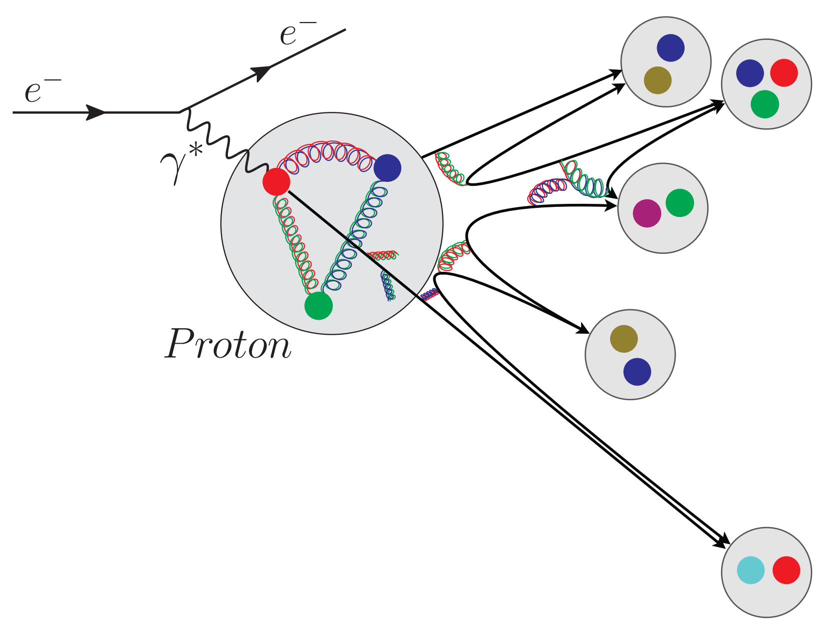
ikerbasque
Basque Foundation for Science

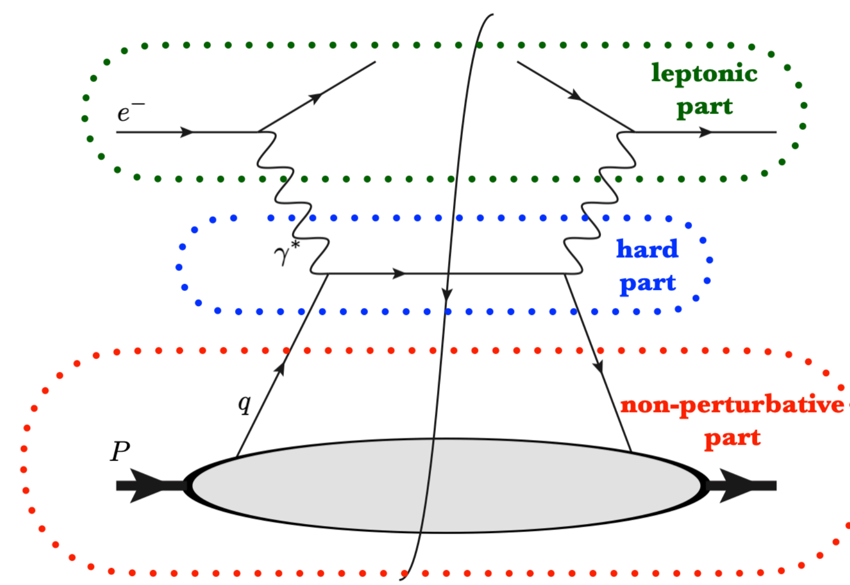




modern microscopes







(semi-inclusive) deep-inelastic lepton scattering

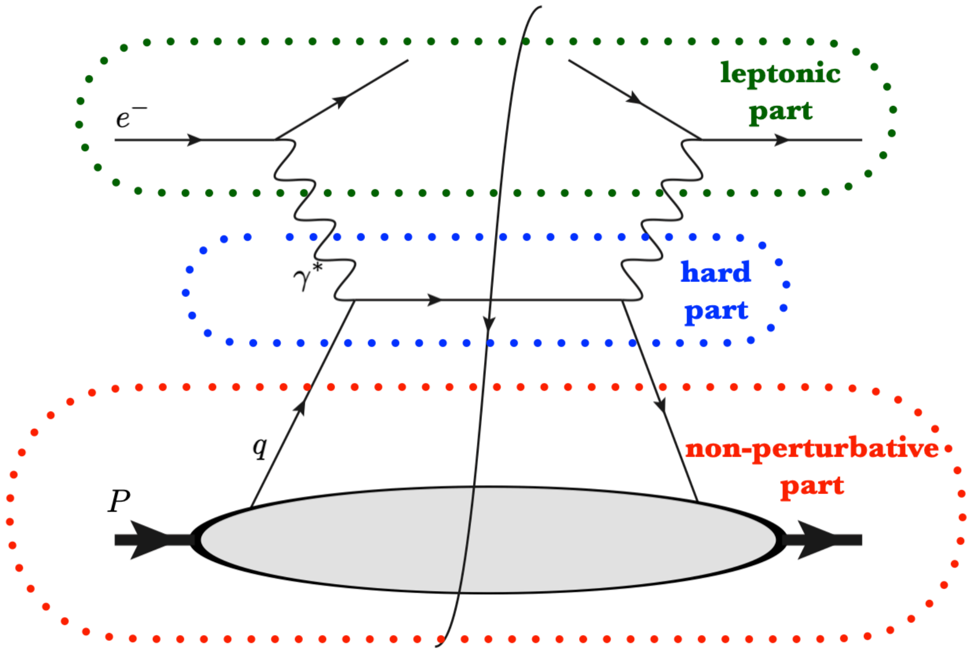
highly virtual photons resolve inner (partonic) structure

factorization theorems separate non-calculable from calculable parts

Quantum simulation of light-front parton correlators

cross section:

$$\sigma(\xi, Q^2) = \sum_f \int_\xi^1 \mathrm{d}\bar{\xi}\, \hat{\sigma}(\bar{\xi}, Q^2)\, f_{f/P}(\xi/\bar{\xi}) \quad + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$

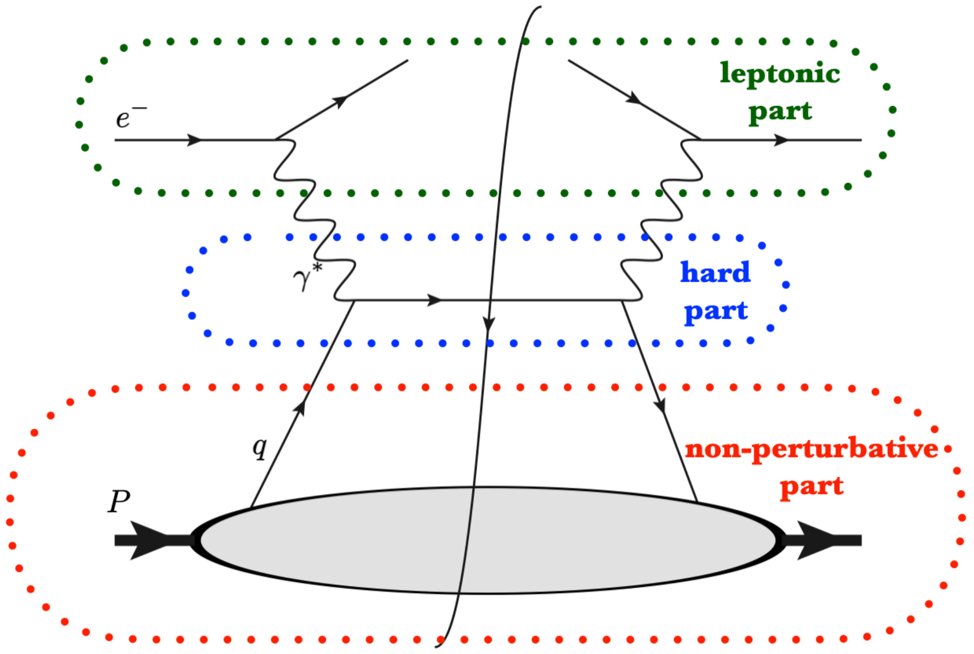


factorization theorems separate non-calculable from calculable parts

Quantum simulation of light-front parton correlators

cross section:

$$\sigma(\xi, Q^2) = \sum_f \int_\xi^1 \mathrm{d}\bar{\xi}\, \hat{\sigma}(\bar{\xi}, Q^2)\, f_{f/P}(\xi/\bar{\xi}) \quad + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$



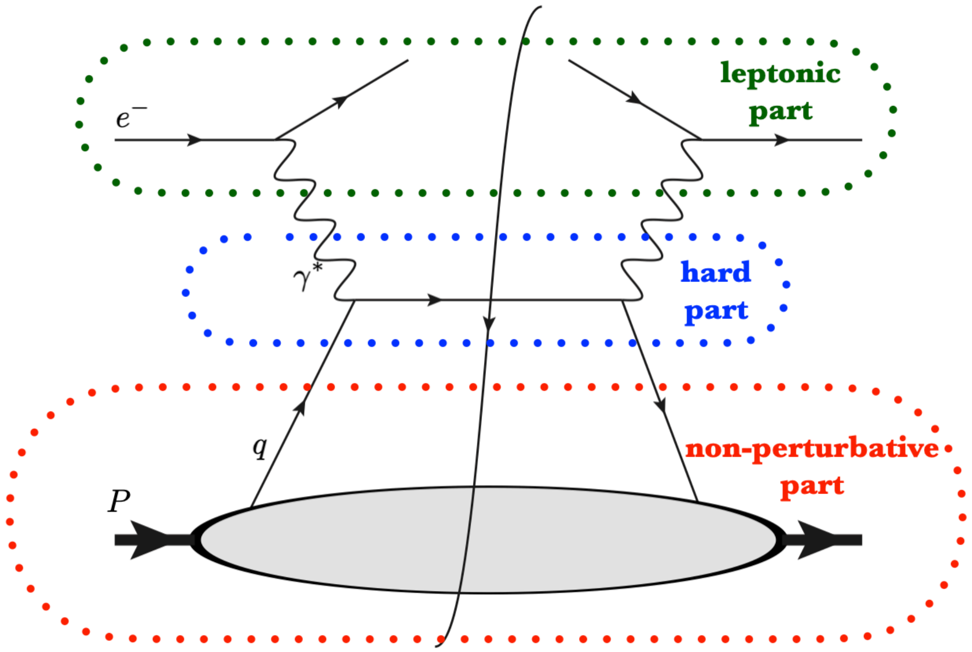
partonic cross section:
calculable

factorization theorems separate non-calculable from calculable parts

Quantum simulation of light-front parton correlators

cross section:

$$\sigma(\xi, Q^2) = \sum_f \int_\xi^1 \mathrm{d}\bar{\xi}\, \hat{\sigma}(\bar{\xi}, Q^2)\, f_{f/P}(\xi/\bar{\xi}) \quad + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$



partonic cross section: calculable

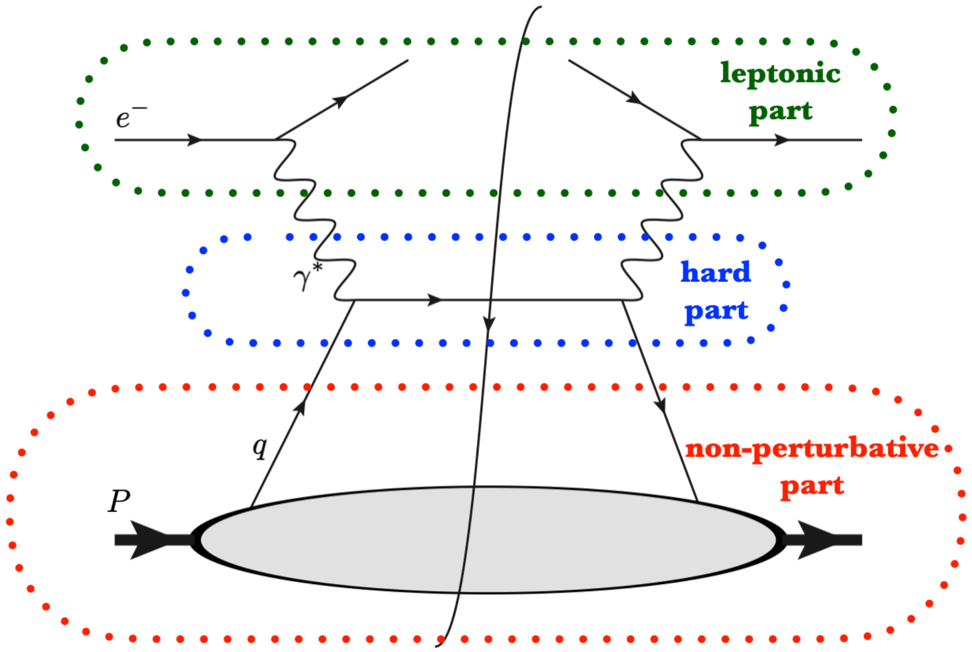
non-perturbative parametrization of nucleon: PDFs, TMDs etc.

factorization theorems separate non-calculable from calculable parts

Quantum simulation of light-front parton correlators

cross section:

$$\sigma(\xi, Q^2) = \sum_f \int_\xi^1 \mathrm{d}\bar{\xi}\, \hat{\sigma}(\bar{\xi}, Q^2)\, f_{f/P}(\xi/\bar{\xi}) \quad + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$



partonic cross section: calculable

non-perturbative parametrization of nucleon: PDFs, TMDs etc.

corrections

factorization theorems separate non-calculable from calculable parts

Universidad del País Vasco | Euskal Herriko Unibertsitatea

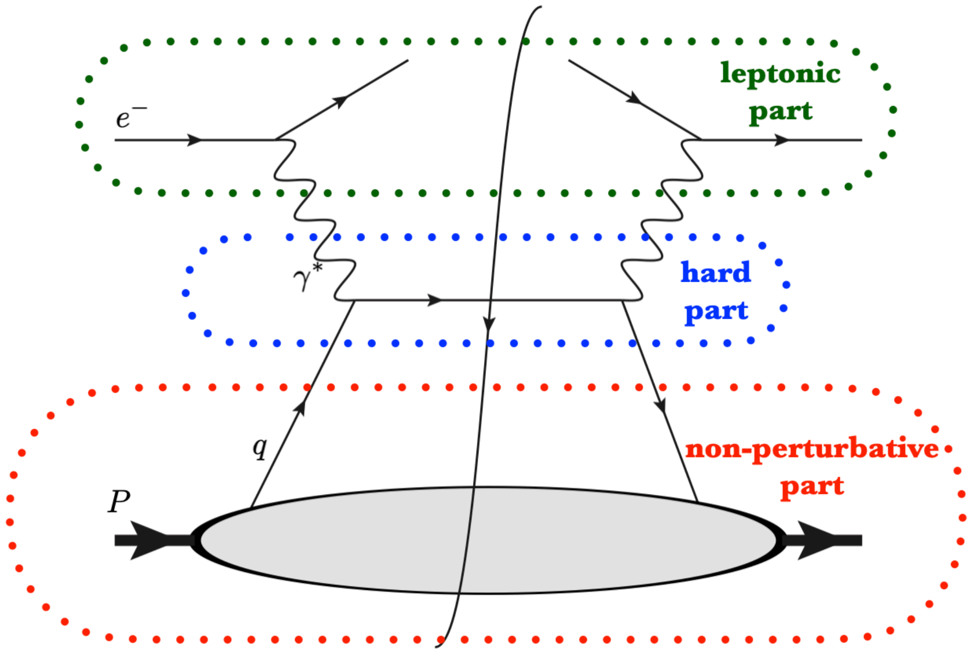
EHU QC
EHU Quantum Center

Quantum simulation of light-front parton correlators

ikerbasque
Basque Foundation for Science

cross section:

$$\sigma(\xi, Q^2) = \sum_f \int_\xi^1 \mathrm{d}\bar{\xi}\, \hat{\sigma}(\bar{\xi}, Q^2)\, f_{f/P}(\xi/\bar{\xi}) \quad + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{Q}\right)$$



partonic cross section: calculable

non-perturbative parametrization of nucleon: PDFs, TMDs etc.

corrections

factorization theorems separate non-calculable from calculable parts

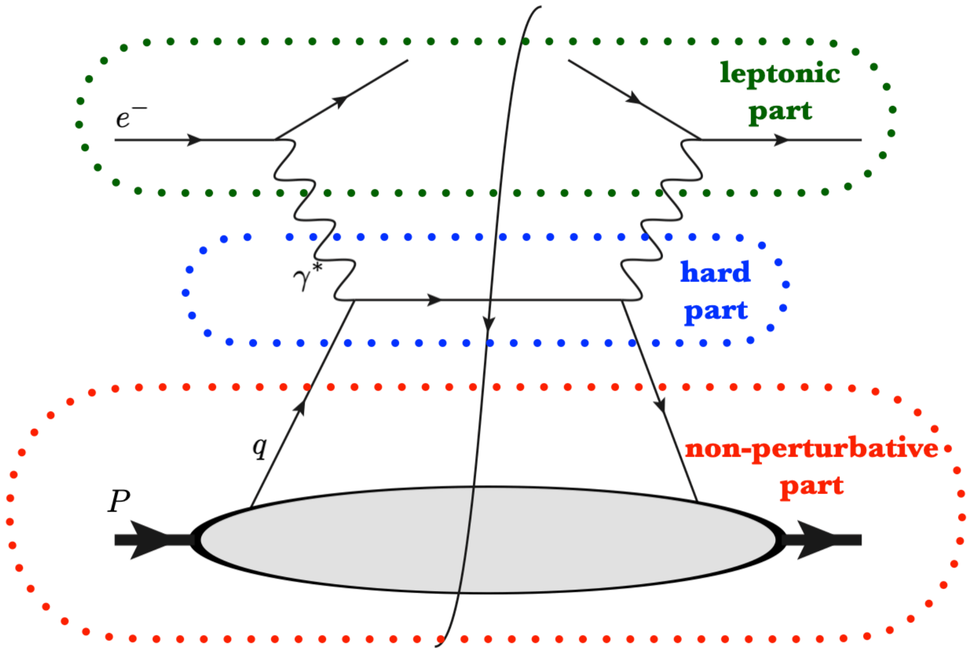
$$f_{f/P}(\xi) = \sum_S \int \frac{dy^-}{2\pi} e^{-i\xi p^+ y^-} \langle PS \,|\, [\bar{\psi}\mathcal{U}]\,(y^-)\,\frac{\gamma^+}{2}\,[\mathcal{U}^\dagger \psi](0)\,|\, PS\rangle$$

Universidad del País Vasco / Euskal Herriko Unibertsitatea — EHU QC EHU Quantum Center — ikerbasque Basque Foundation for Science

Quantum simulation of light-front parton correlators

cross section:

$$\sigma(\xi, Q^2) = \sum_f \int_\xi^1 d\bar{\xi}\, \hat{\sigma}(\bar{\xi}, Q^2)\, f_{f/P}(\xi/\bar{\xi}) \quad + \mathcal{O}\left(\frac{\Lambda_{\rm QCD}}{Q}\right)$$



partonic cross section: calculable

non-perturbative parametrization of nucleon: PDFs, TMDs etc.

corrections

factorization theorems separate non-calculable from calculable parts

$$f_{f/P}(\xi) = \sum_S \int \frac{dy^-}{2\pi} e^{-i\xi p^+ y^-} \langle PS \,|\, [\bar{\psi}\mathcal{U}](y^-) \frac{\gamma^+}{2} [\mathcal{U}^\dagger \psi](0) \,|\, PS \rangle$$

Non-local (space-time) matrix elements require Wilson lines for gauge invariance
We study the quantum simulation of Wilson loops in space and real-time

Quantum simulation of light-front parton correlators

Non-local (space-time) matrix elements require Wilson lines for gauge invariance
We study the quantum simulation of Wilson loops in space and real-time

$$f_{f/P}(\xi) = \sum_S \int \frac{dy^-}{2\pi} e^{-i\xi p^+ y^-} \langle PS | \left[\bar{\psi}\mathcal{U}\right](y^-) \frac{\gamma^+}{2} \left[\mathcal{U}^\dagger \psi\right](0) | PS \rangle$$

Requirements for the quantum simulation of parton correlators:

Universidad del País Vasco · Euskal Herriko Unibertsitatea · eman ta zabal zazu

EHU QC
EHU Quantum Center

ikerbasque
Basque Foundation for Science

Quantum simulation of light-front parton correlators

Non-local (space-time) matrix elements require Wilson lines for gauge invariance
We study the quantum simulation of Wilson loops in space and real-time

$$f_{f/P}(\xi) = \sum_S \int \frac{dy^-}{2\pi} e^{-i\xi p^+ y^-} \langle PS | \left[\bar{\psi}\mathcal{U}\right](y^-) \frac{\gamma^+}{2} \left[\mathcal{U}^\dagger \psi\right](0) | PS \rangle$$

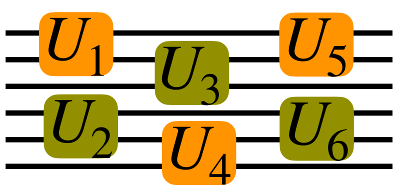
Requirements for the quantum simulation of parton correlators:

- encode in quantum degrees of freedom both matter and gauge fields
- preparation of a reference state, e.g., vacuum, proton, glue-ball
- simulate gauge-invariant quantities, e.g., minimal gauge-matter coupling
- real-time evolution, since the Wilson line is non-local in time
- carry out measurements after the evolution, i.e., quantum interferometer

Quantum simulation of light-front parton correlators

Digital simulation: Universal simulator

$|\psi(0)\rangle$



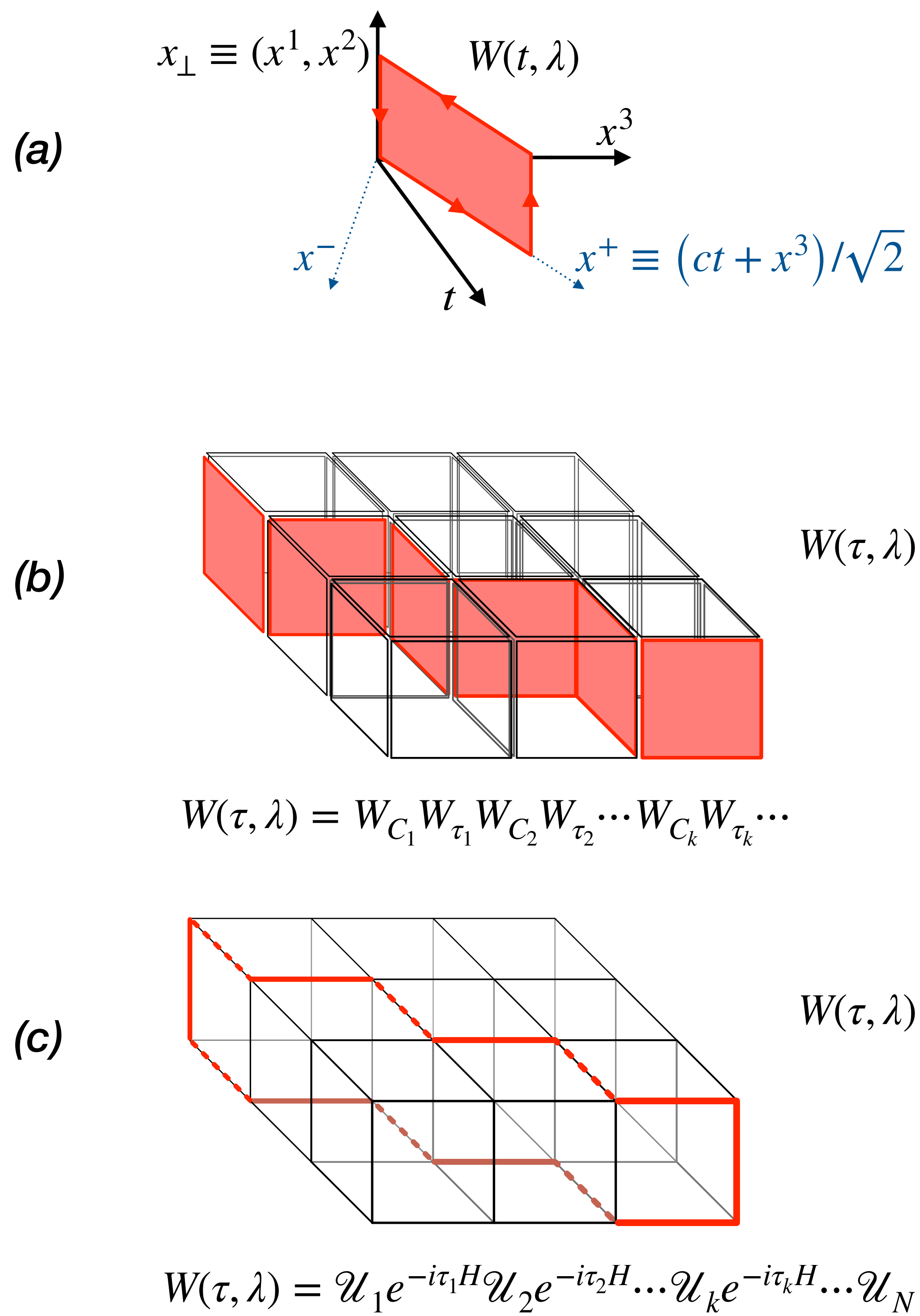
$|\psi(t)\rangle$

Decompose dynamics into sequence of quantum gates

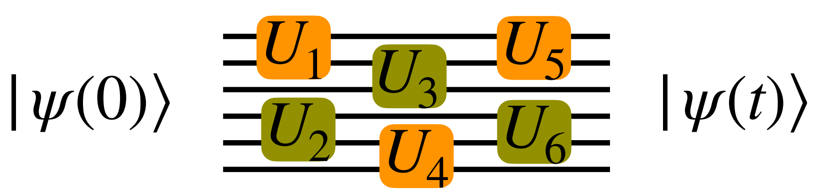
Stroboscopic simulation in an analog simulator

Quantum simulation of light-front parton correlators

Discretisation of space-time in a Hamiltonian formulation



Digital simulation: Universal simulator



Decompose dynamics into sequence of quantum gates

Stroboscopic simulation in an analog simulator

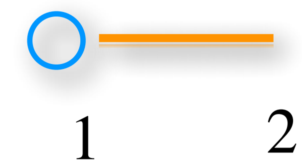
Note: in the Hamiltonian formulation the temporal gauge $A_0=0$ is chosen

Quantum simulation of light-front parton correlators

Moving a single quark:

$$u_{12} = \exp\left\{ \frac{-i\pi}{2} \sum_{\alpha\beta} \left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right] \right\}$$

$$\rightarrow (-i)\left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right],$$

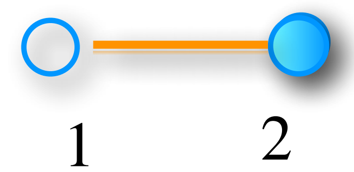


Quantum simulation of light-front parton correlators

Moving a single quark:

$$u_{12} = \exp\left\{ \frac{-i\pi}{2} \sum_{\alpha\beta} \left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right] \right\}$$

$$\to (-i)\left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right],$$

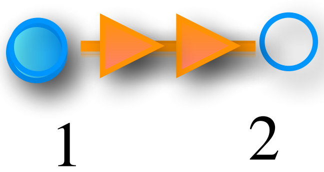


Quantum simulation of light-front parton correlators

Moving a single quark:

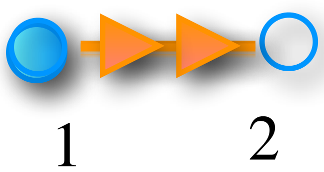
$$u_{12} = \exp\left\{ \frac{-i\pi}{2} \sum_{\alpha\beta} \left[\psi^\dagger_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right] \right\}$$

$$\rightarrow (-i)\left[\psi^\dagger_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right],$$



Quantum simulation of light-front parton correlators

Moving a single quark:



$$u_{12} = \exp\left\{\frac{-i\pi}{2}\sum_{\alpha\beta}\left[\psi^{\dagger}_{\alpha,1}U_{\alpha\beta}(e)\,\psi_{\beta,2} + \mathrm{h.c.}\right]\right\}$$

$$\to (-i)\left[\psi^{\dagger}_{\alpha,1}U_{\alpha\beta}(e)\,\psi_{\beta,2} + \mathrm{h.c.}\right],$$

Starting from a “meson” state:

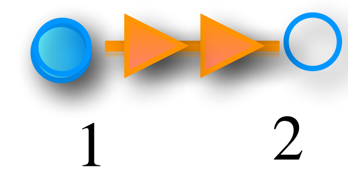
$$|\,\mathrm{m}\rangle \equiv \frac{1}{\mathrm{N}^{1/2}}\sum_{\alpha=1}^{\mathrm{N}}|\,\alpha(1),\bar{\alpha}(2)\rangle$$

Quantum simulation of light-front parton correlators

Moving a single quark:

$$u_{12} = \exp\left\{ \frac{-i\pi}{2} \sum_{\alpha\beta} \left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right] \right\}$$

$$\to (-i) \left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right],$$



Starting from a "meson" state:

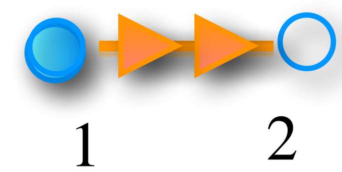
$$|\,\mathrm{m}\rangle \equiv \frac{1}{\mathrm{N}^{1/2}} \sum_{\alpha=1}^{\mathrm{N}} |\,\alpha(1), \bar{\alpha}(2)\rangle$$

Quantum simulation of light-front parton correlators

Moving a single quark:

$$u_{12} = \exp\left\{ \frac{-i\pi}{2} \sum_{\alpha\beta} \left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right] \right\}$$

$$\rightarrow (-i)\left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right],$$



Starting from a “meson” state:

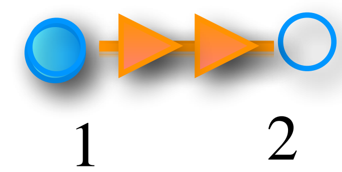
$$|\,\mathrm{m}\rangle \equiv \frac{1}{\mathrm{N}^{1/2}} \sum_{\alpha=1}^{\mathrm{N}} |\,\alpha(1), \bar{\alpha}(2)\rangle$$

Quantum simulation of light-front parton correlators

Moving a single quark:

$$u_{12} = \exp\left\{ \frac{-i\pi}{2} \sum_{\alpha\beta} \left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right] \right\}$$

$$\to (-i)\left[\psi^{\dagger}_{\alpha,1} U_{\alpha\beta}(e)\, \psi_{\beta,2} + \mathrm{h.c.} \right],$$



Starting from a “meson” state:

$$|\,\mathrm{m}\rangle \equiv \frac{1}{\mathrm{N}^{1/2}} \sum_{\alpha=1}^{\mathrm{N}} |\,\alpha(1), \bar{\alpha}(2)\rangle$$

$$\mathcal{U}(A_1, B_L) = \frac{1}{N^{1/2}} \sum_{\alpha\beta\cdots\mu\nu\omega\cdots\theta\phi} |\,\alpha(A_1)\rangle U_{\alpha\beta}(e_1)\cdots U_{\mu\nu}(e_{L/2-1}) U^{*}_{\omega\nu}(e_{L/2})\cdots U^{*}_{\phi\theta}(e_{L-1})\,|\,\bar{\phi}(B_L)\rangle$$

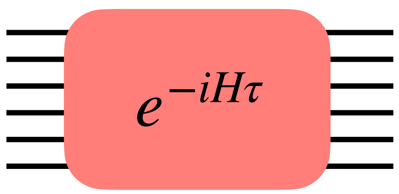
$$= \frac{1}{N^{1/2}} \sum_{\alpha\phi} |\,\alpha(A_1)\rangle \mathcal{U}_{\alpha\phi}(e_1, \cdots, e_{L-1})\,|\,\bar{\phi}(B_L)\rangle$$

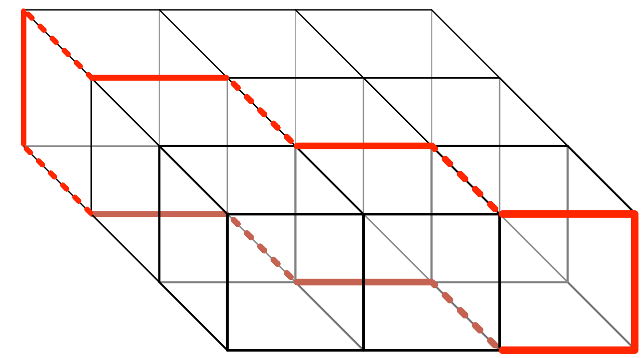
we built a spatial Wilson line

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center
ikerbasque
Basque Foundation for Science

Quantum simulation of light-front parton correlators

Time-evolution by a single time step

$|\psi(0)\rangle$  $|\psi(\tau)\rangle$



$W(\tau, \lambda)$

$$W(\tau, \lambda) = \mathcal{U}_1 e^{-i\tau_1 H} \mathcal{U}_2 e^{-i\tau_2 H} \dots \mathcal{U}_k e^{-i\tau_k H} \dots \mathcal{U}_N$$

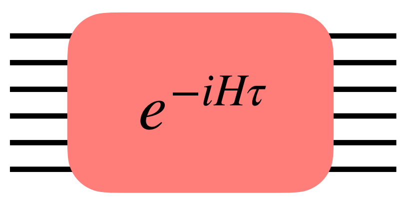
Universidad del País Vasco Euskal Herriko Unibertsitatea

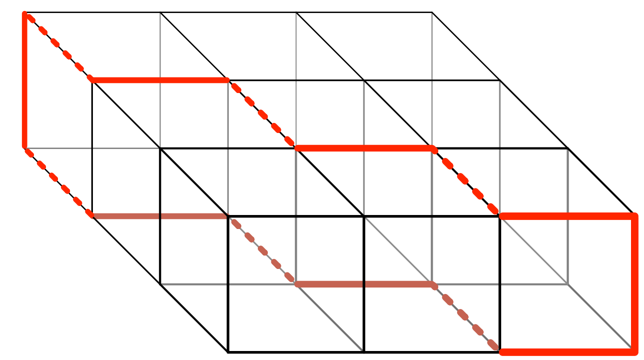
EHU QC
EHU Quantum Center

Quantum simulation of light-front parton correlators

ikerbasque
Basque Foundation for Science

Time-evolution by a single time step

$|\psi(0)\rangle$  $|\psi(\tau)\rangle$



$W(\tau, \lambda)$

$$W(\tau, \lambda) = \mathscr{U}_1 e^{-i\tau_1 H} \mathscr{U}_2 e^{-i\tau_2 H} \dots \mathscr{U}_k e^{-i\tau_k H} \dots \mathscr{U}_N$$

Decompose dynamics induced by systems' Hamiltonian into sequence of quantum gates

Digital simulation can simulate any model but requires many gate operations

Stroboscopic simulation in an analog simulator

$$H = H_{\text{el}} + H_{\text{mag}}$$

Efficient for local interactions

$$e^{-iH} \simeq \left[e^{-iH_{\text{el}}/2n_T} e^{-i\lambda H_{\text{mag}}/n_T} e^{-iH_{\text{el}}/2n_T} \right]^{n_T}$$

Trotter-Suzuki approximation

S. Lloyd, Science (1996)

Quantum simulation of light-front parton correlators

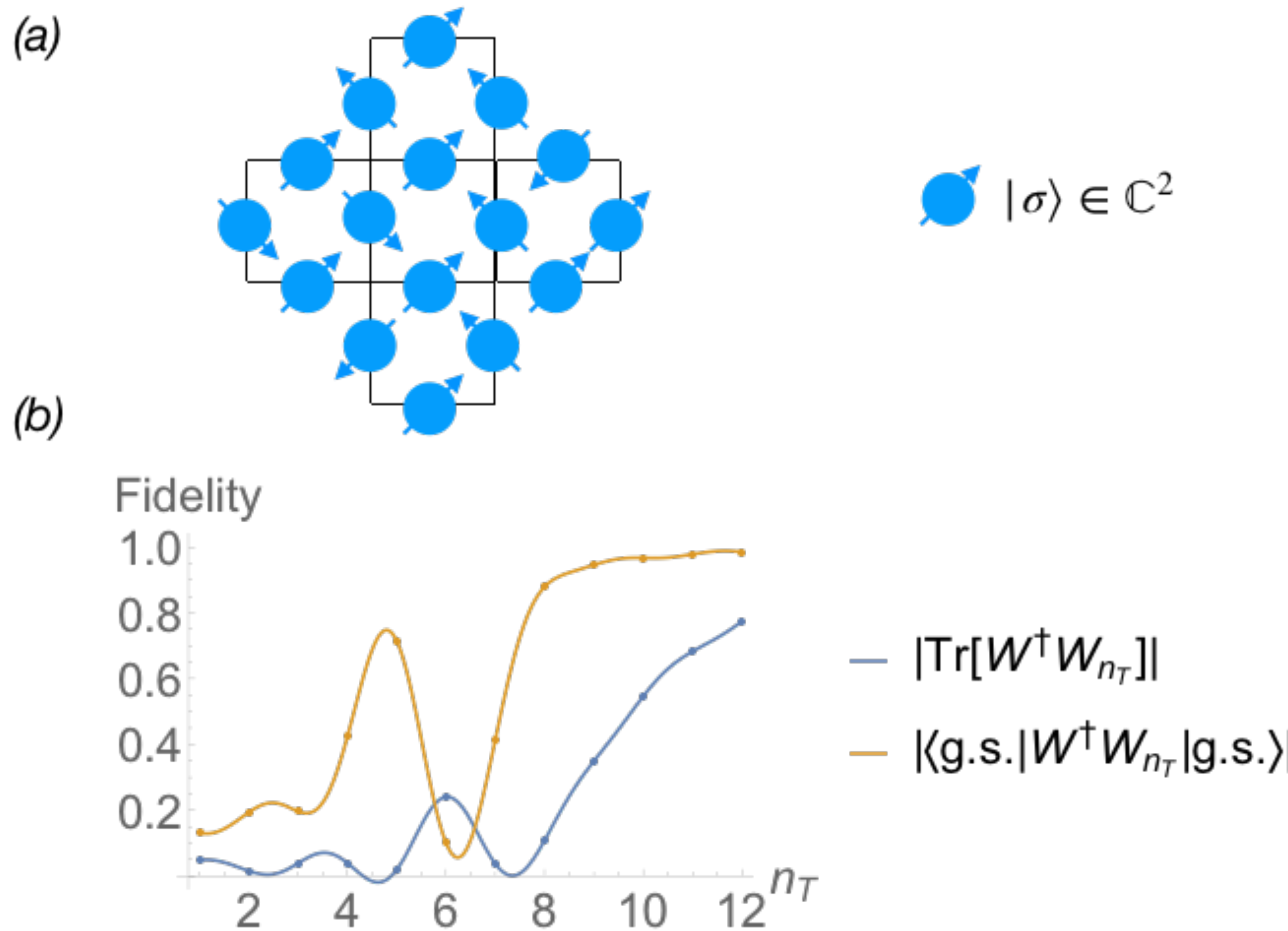
Proof of principle: Z_2 pure gauge model

operator norm:

$$\left|\mathrm{Tr}\left[\mathscr{W}^\dagger \mathscr{W}_{n_T}\right]\right|$$

ground state fidelity:

$$\left|\langle g.s.|\mathscr{W}^\dagger \mathscr{W}_{n_T}|g.s.\rangle\right|$$



within a few Trotter steps a fidelity closed to one is achieved

PHYSICAL REVIEW D **104**, 014512 (2021)

Quantum simulation of light-front parton correlators

M. G. Echevarria,[1,*] I. L. Egusquiza,[2,†] E. Rico,[3,4,‡] and G. Schnell[2,4,§]

arXiv:2011.01275

Project in progress with: M.G. Echevarria, I.L. Egusquiza, G. Schnell

Collaborators: M. Dalmonte, S. Montangero, U.-J. Wiese, P. Zoller…

Eur. Phys. J. D (2020) 74: 165
https://doi.org/10.1140/epjd/e2020-100571-8

THE EUROPEAN PHYSICAL JOURNAL D

Colloquium

Simulating lattice gauge theories within quantum technologies

Mari Carmen Bañuls[1,2], Rainer Blatt[3,4], Jacopo Catani[5,6,7], Alessio Celi[3,8], Juan Ignacio Cirac[1,2], Marcello Dalmonte[9,10], Leonardo Fallani[5,6,7], Karl Jansen[11], Maciej Lewenstein[8,12,13], Simone Montangero[14,15,a], Christine A. Muschik[3], Benni Reznik[16], Enrique Rico[17,18], Luca Tagliacozzo[19], Karel Van Acoleyen[20], Frank Verstraete[20,21], Uwe-Jens Wiese[22], Matthew Wingate[23], Jakub Zakrzewski[24,25], and Peter Zoller[3]

Universidad del País Vasco
Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center
ikerbasque
Basque Foundation for Science

Qubit alive thanks to the anomaly

Enrique Rico Ortega

Friday, 13/05/2022

Max Planck Institute of Quantum Optics, Munich

Gauge Workshop Munich 2022

May 9 – 13, 2022
Max Planck Institute of Quantum Optics

Quantum anomaly

In quantum physics an anomaly or quantum anomaly appears when the symmetry of a classical theory is not equally represented by the quantum theory.

Universidad del País Vasco Euskal Herriko Unibertsitatea

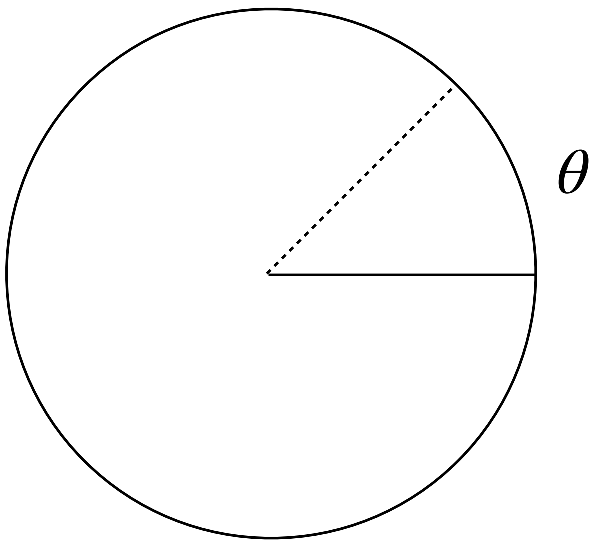
EHU QC
EHU Quantum Center

ikerbasque
Basque Foundation for Science

Quantum anomaly

In quantum physics an anomaly or quantum anomaly appears when the symmetry of a classical theory is not equally represented by the quantum theory.

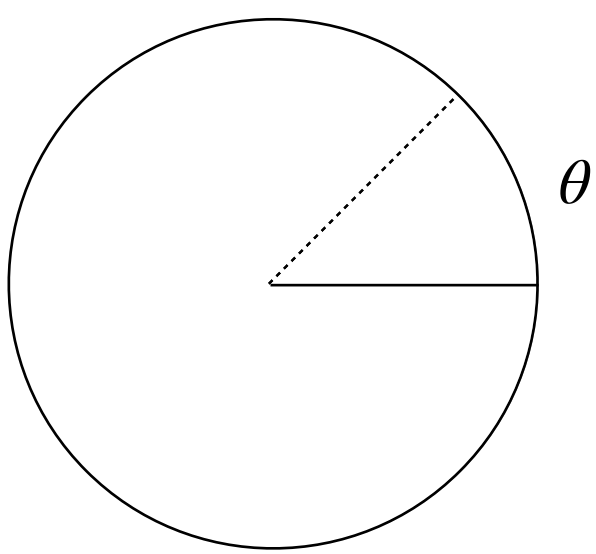
Classical group symmetry of the ring

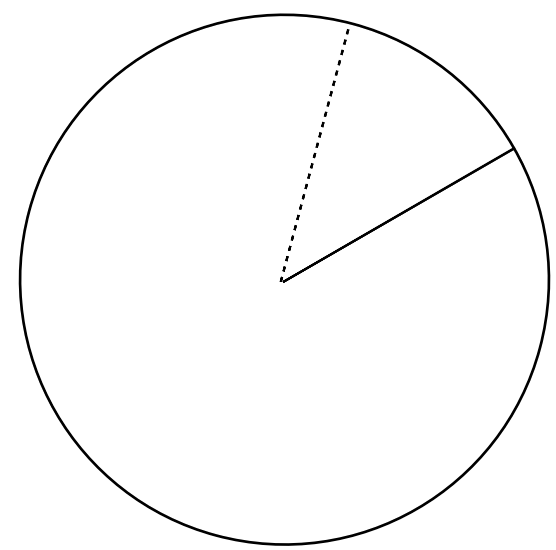


Quantum anomaly

In quantum physics an anomaly or quantum anomaly appears when the symmetry of a classical theory is not equally represented by the quantum theory.

Classical group symmetry of the ring





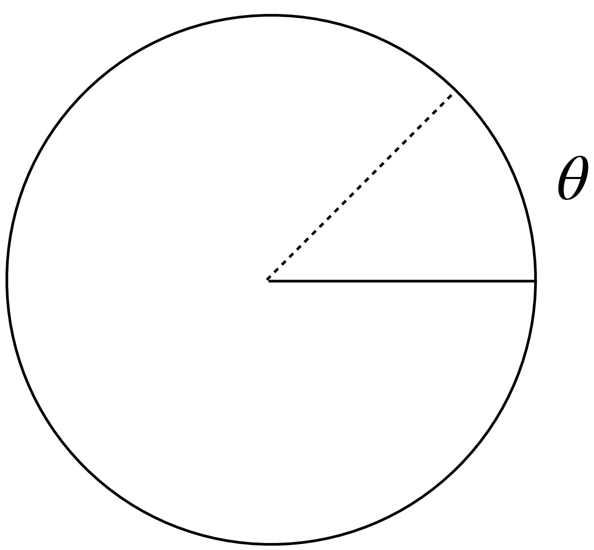
Rotation by any angle

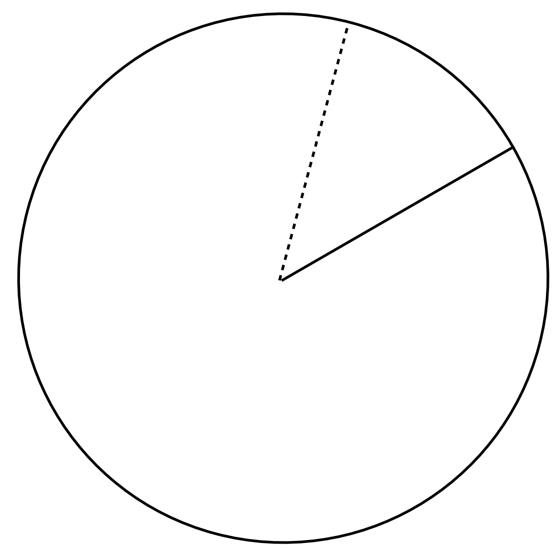
$SO(2)$

Quantum anomaly

In quantum physics an anomaly or quantum anomaly appears when the symmetry of a classical theory is not equally represented by the quantum theory.

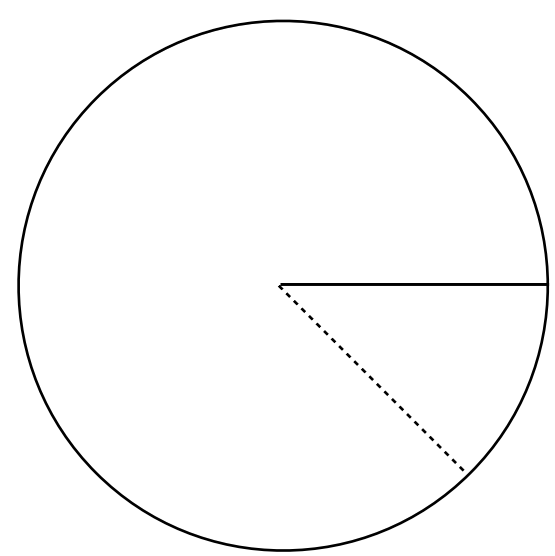
Classical group symmetry of the ring





Rotation by any angle

$SO(2)$



Reflexion by an axis

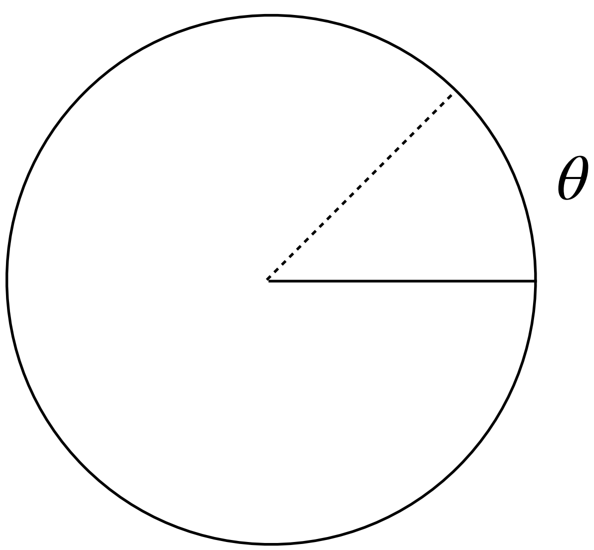
$\mathbb{Z}_2$

Universidad del País Vasco | Euskal Herriko Unibertsitatea | EHU QC EHU Quantum Center | ikerbasque Basque Foundation for Science

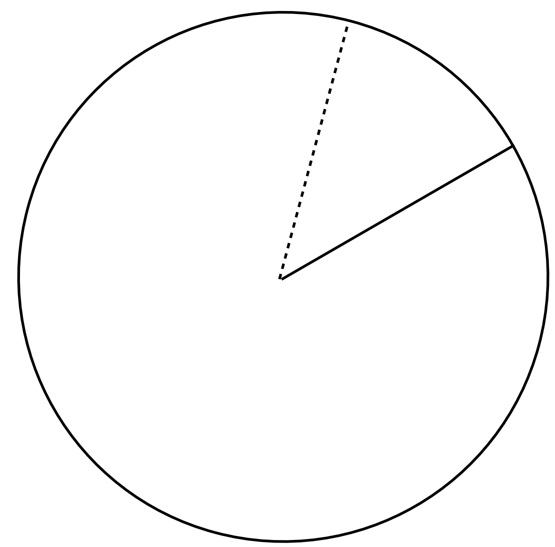
Quantum anomaly

In quantum physics an anomaly or quantum anomaly appears when the symmetry of a classical theory is not equally represented by the quantum theory.

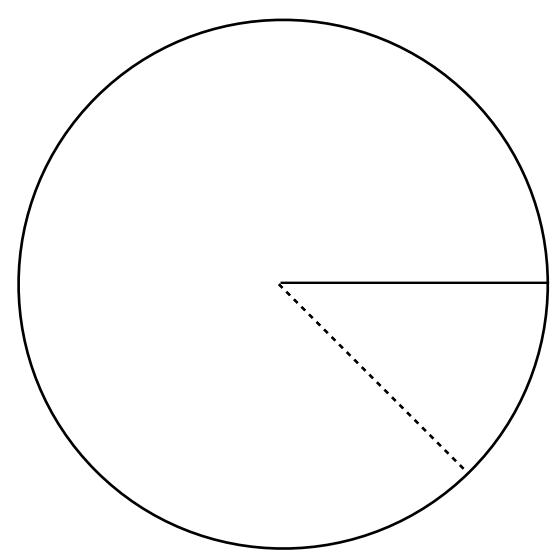
Classical group symmetry of the ring



$$O(2) = SO(2) \times \mathbb{Z}_2$$

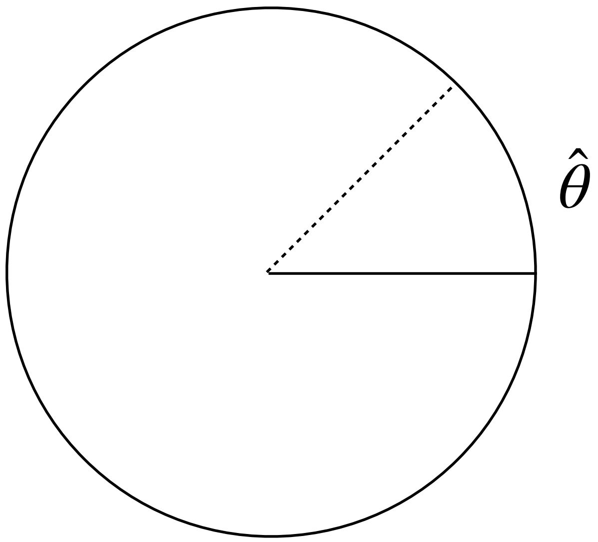


Rotation by any angle — $SO(2)$



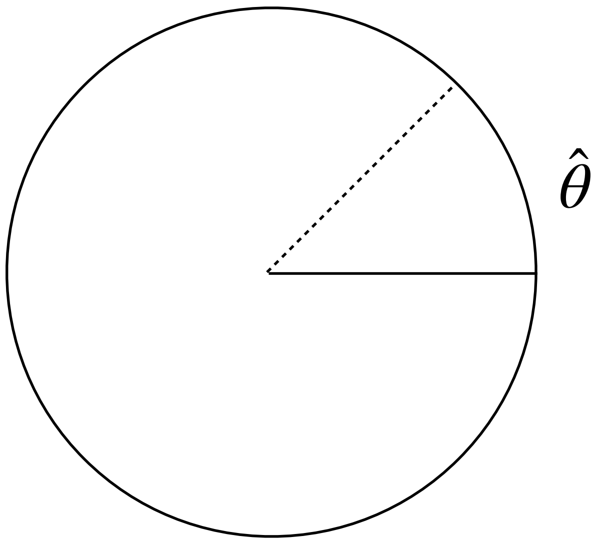
Reflexion by an axis — $\mathbb{Z}_2$

Free quantum particle on a ring



$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2 \qquad \left[\hat{\theta}, \hat{n}\right] = i$$

Free quantum particle on a ring



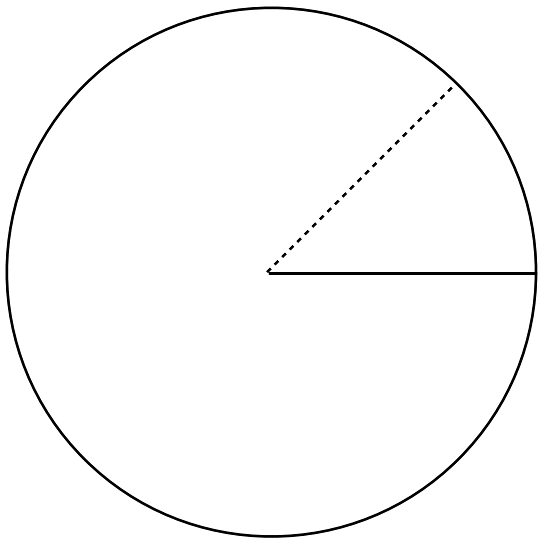
$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2$$

vector potential or magnetic flux

$$\left[\hat{\theta}, \hat{n}\right] = i$$

conjugate variables

Free quantum particle on a ring



$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2$$

vector potential or magnetic flux

$$\left[\hat{\theta}, \hat{n}\right] = i$$

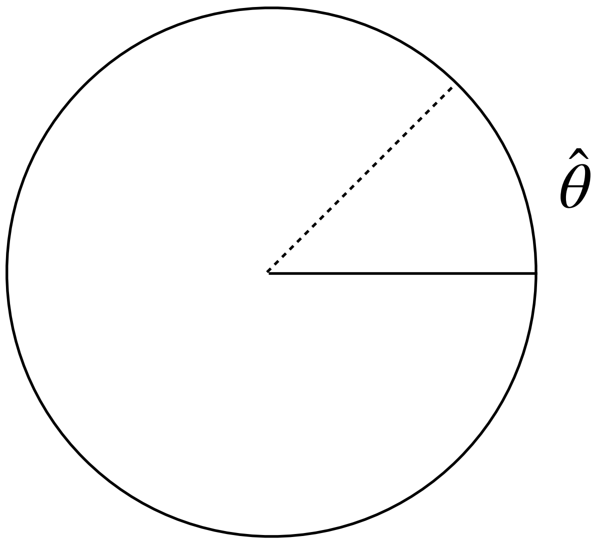
conjugate variables

$$\theta \in (-\pi, +\pi]$$

compact variable

$$\text{spect}\left(\hat{\text{n}}\right) \in \mathbb{Z}$$

Free quantum particle on a ring



$$\hat{H} = E_c \left(\hat{n} - n_g\right)^2$$

vector potential or magnetic flux

$$\left[\hat{\theta}, \hat{n}\right] = i$$

conjugate variables

$$\theta \in (-\pi, +\pi]$$

compact variable

$$\text{spect}\left(\hat{\text{n}}\right) \in \mathbb{Z}$$

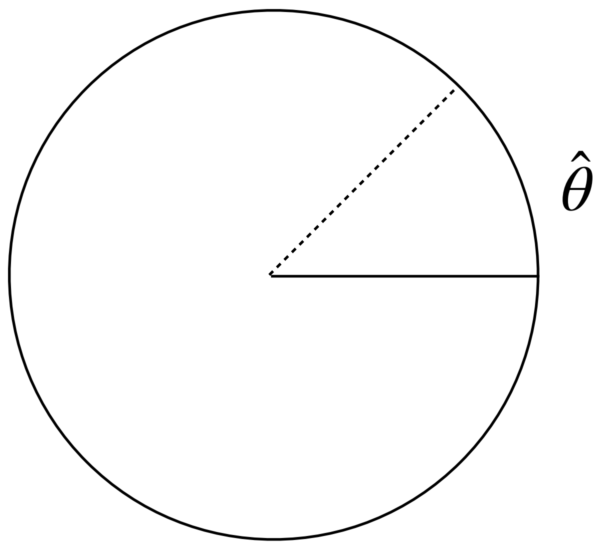
Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $\quad SO(2) \sim U(1)$

Universidad del País Vasco · Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

Free quantum particle on a ring

ikerbasque
Basque Foundation for Science



$$\hat{H} = E_c \left(\hat{n} - n_g\right)^2$$

vector potential or magnetic flux

$$\left[\hat{\theta}, \hat{n}\right] = i$$

conjugate variables

$$\theta \in (-\pi, +\pi]$$

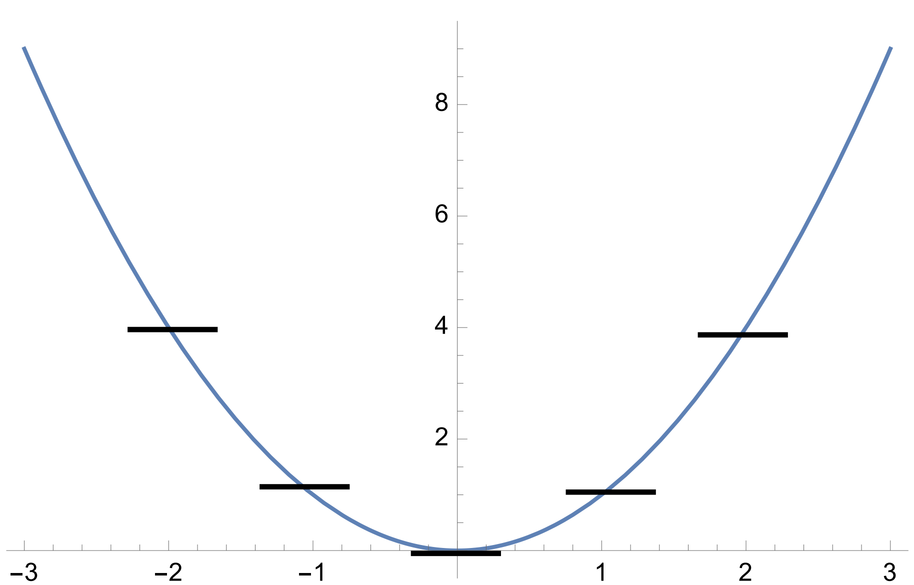
compact variable

$$\text{spect}\left(\hat{\mathrm{n}}\right) \in \mathbb{Z}$$

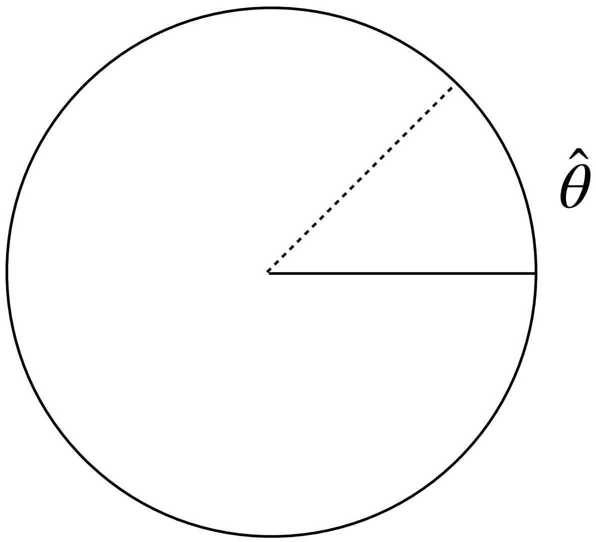
Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $SO(2) \sim U(1)$

About the reflexion symmetry… $\text{spect}\left(\hat{\mathrm{H}}\right)$

$n_g = 0$



Free quantum particle on a ring



$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2$$

vector potential or magnetic flux

$$\left[\hat{\theta}, \hat{n}\right] = i$$

conjugate variables

$$\theta \in (-\pi, +\pi]$$

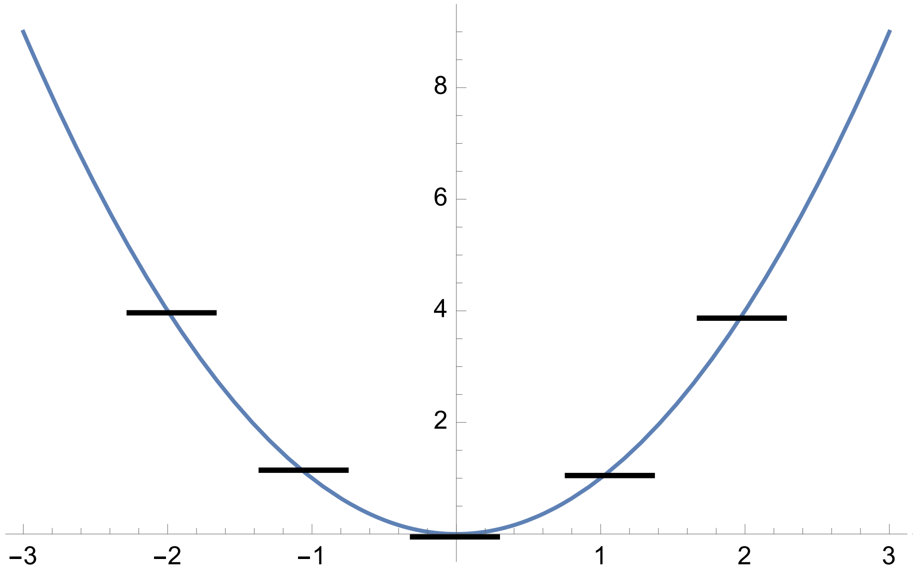
compact variable

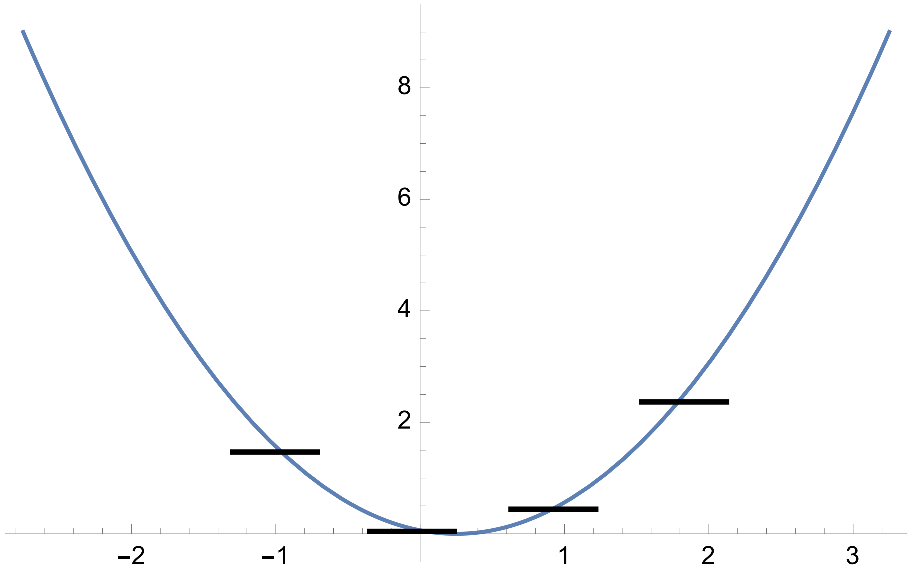
$$\text{spect}\left(\hat{n}\right) \in \mathbb{Z}$$

Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $\quad SO(2) \sim U(1)$

About the reflexion symmetry… $\text{spect}\left(\hat{H}\right)$

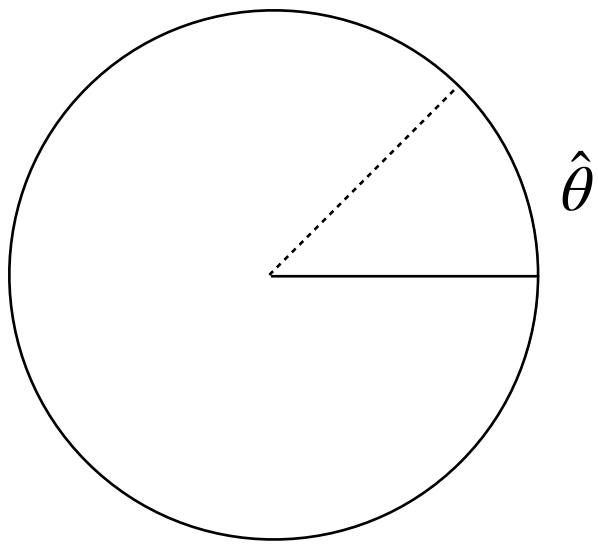
$n_g = 0$ $\quad n_g = 1/4$





Universidad del País Vasco Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center
ikerbasque
Basque Foundation for Science

Free quantum particle on a ring



$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2$$

vector potential or magnetic flux

$$\left[\hat{\theta}, \hat{n}\right] = i$$

conjugate variables

$$\theta \in (-\pi, +\pi]$$

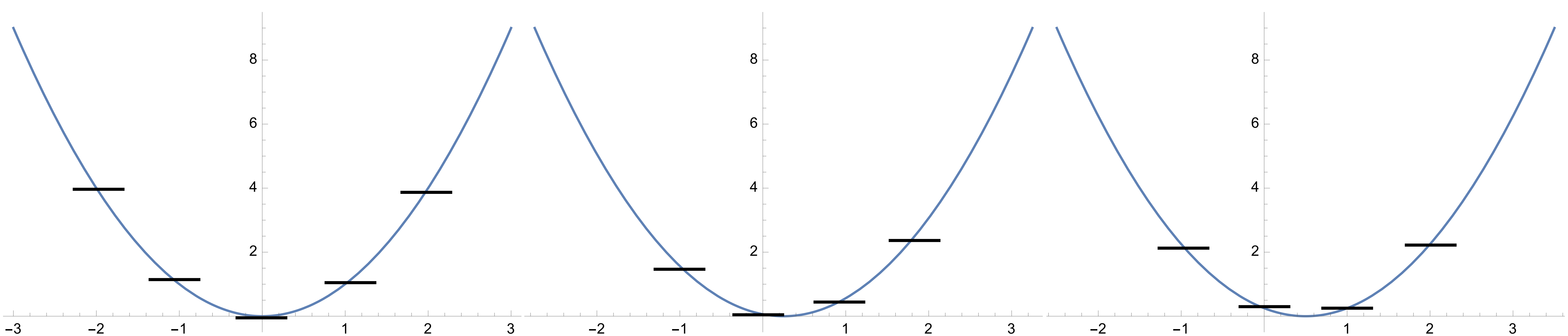
compact variable

$$\mathrm{spect}\left(\hat{\mathrm{n}}\right) \in \mathbb{Z}$$

Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $\quad SO(2) \sim U(1)$

About the reflexion symmetry… $\mathrm{spect}\left(\hat{\mathrm{H}}\right)$

$n_g = 0$ $\quad$ $n_g = 1/4$ $\quad$ $n_g = 1/2$



eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center

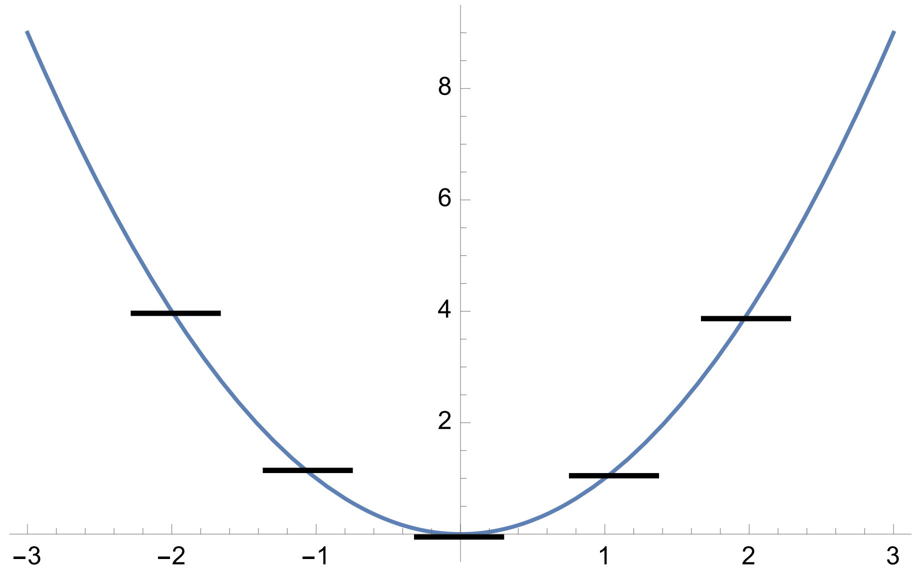
Free quantum particle on a ring

ikerbasque
Basque Foundation for Science

Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $\qquad SO(2) \sim U(1)$

About the reflexion symmetry…

$n_g = 0$



$\hat{U}_P \qquad \begin{aligned} n &\to -n \\ \theta &\to -\theta \end{aligned}$

$$\hat{U}_P \hat{U}_\alpha \hat{U}_P = \hat{U}_{-\alpha}$$

$$O(2) = SO(2) \times \mathbb{Z}_2$$

eman ta zabal zazu
Universidad del País Vasco
Euskal Herriko Unibertsitatea
EHU QC
EHU Quantum Center

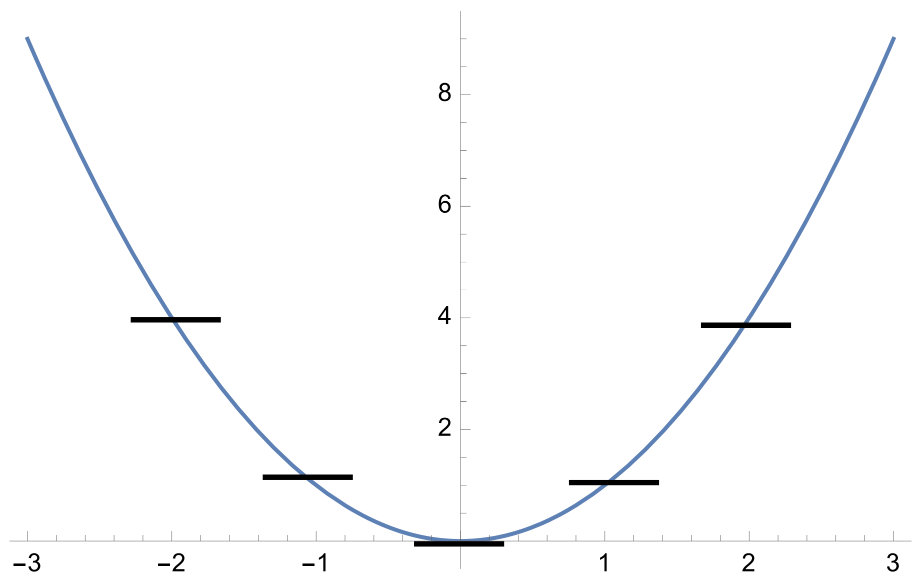
Free quantum particle on a ring

ikerbasque
Basque Foundation for Science

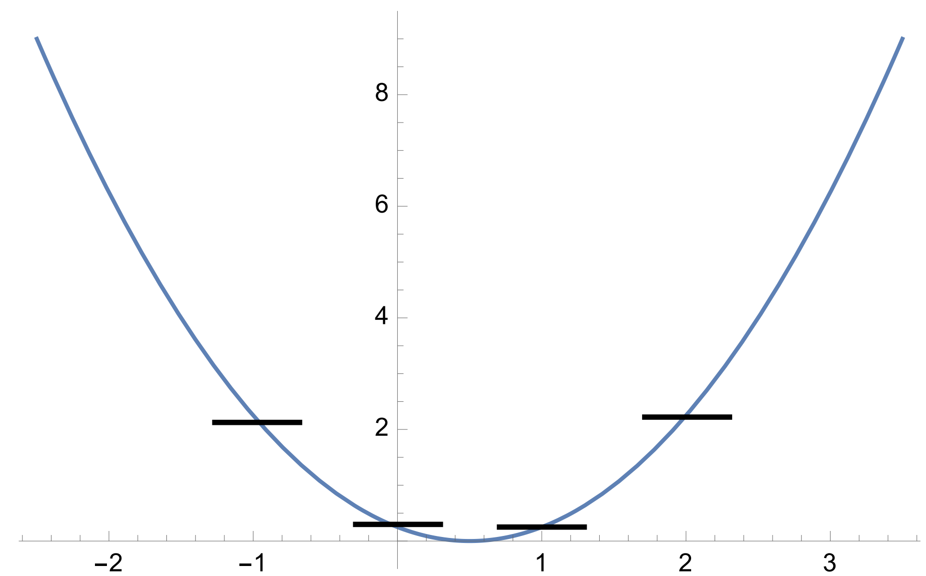
Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $SO(2) \sim U(1)$

About the reflexion symmetry…

$n_g = 0$



$n_g = 1/2$



$\hat{U}_P$ $\quad n \to -n$, $\quad \theta \to -\theta$

$$\hat{U}_P \hat{U}_\alpha \hat{U}_P = \hat{U}_{-\alpha}$$

$$O(2) = SO(2) \times \mathbb{Z}_2$$

$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P$ $\quad n \to 1 - n$, $\quad \theta \to -\theta$

$$\hat{V}_P \hat{U}_\alpha \hat{V}_P = e^{-i\alpha}\hat{U}_{-\alpha}$$

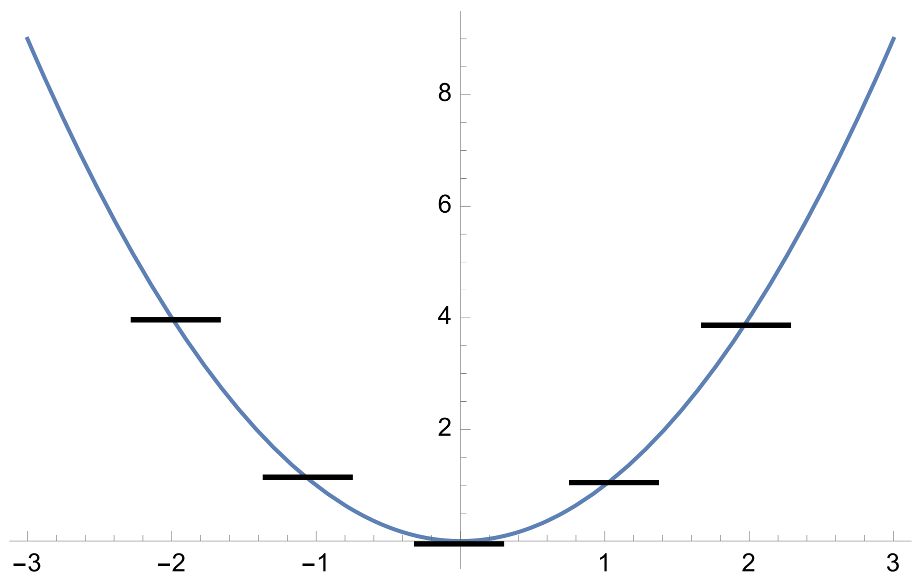
Universidad del País Vasco · Euskal Herriko Unibertsitatea · EHU QC · EHU Quantum Center · ikerbasque Basque Foundation for Science

Free quantum particle on a ring

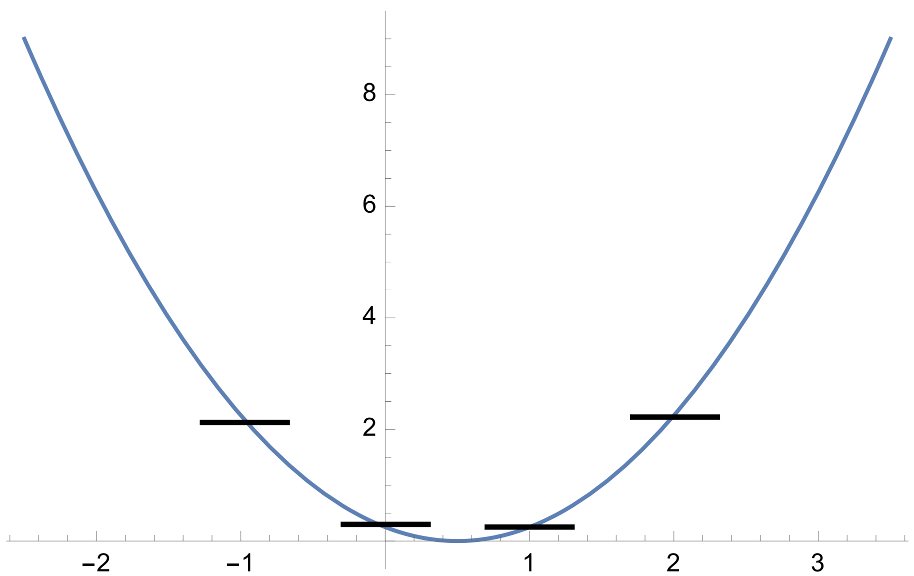
Any rotation is a symmetry of the quantum Hamiltonian: $\hat{U}_\alpha = e^{i\hat{n}\alpha}$ $\quad SO(2) \sim U(1)$

About the reflexion symmetry…

$n_g = 0$



$n_g = 1/2$



$\hat{U}_P \quad n \to -n, \quad \theta \to -\theta$

$$\hat{U}_P \hat{U}_\alpha \hat{U}_P = \hat{U}_{-\alpha}$$

$$O(2) = SO(2) \times \mathbb{Z}_2$$

$\hat{V}_P = e^{-i\hat{\theta}} \hat{U}_P \quad n \to 1 - n, \quad \theta \to -\theta$

$$\hat{V}_P \hat{U}_\alpha \hat{V}_P = e^{-i\alpha} \hat{U}_{-\alpha}$$

redefining: $\hat{W}_\alpha = e^{i\alpha/2} \hat{U}_\alpha \quad \begin{cases} \hat{V}_P \hat{W}_\alpha \hat{V}_P = \hat{W}_{-\alpha} \\ \hat{W}_{2\pi} = -1 \end{cases}$

double cover of $O(2)$

Quantum particle on a ring with a potential

Minimal model with potential term that still keeps similar symmetry features

$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2 - E_J \cos\left(2\hat{\theta}\right)$$

Quantum particle on a ring with a potential

Minimal model with potential term that still keeps similar symmetry features

$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2 - E_J \cos\left(2\hat{\theta}\right)$$

About the reflexion symmetry…

$n_g = 0$

$\hat{U}_P$ $\quad n \rightarrow -n$, $\quad \theta \rightarrow -\theta$

$n_g = 1/2$

$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P$ $\quad n \rightarrow 1 - n$, $\quad \theta \rightarrow -\theta$

Universidad del País Vasco / Euskal Herriko Unibertsitatea — EHU QC, EHU Quantum Center — ikerbasque, Basque Foundation for Science

Quantum particle on a ring with a potential

Minimal model with potential term that still keeps similar symmetry features

$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2 - E_J \cos\left(2\hat{\theta}\right)$$

About the reflexion symmetry…

$n_g = 0$

$\hat{U}_P$ $\quad n \to -n$, $\quad \theta \to -\theta$

$n_g = 1/2$

$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P$ $\quad n \to 1 - n$, $\quad \theta \to -\theta$

About the (discrete) rotation symmetry: $\hat{U}_\pi = e^{i\hat{n}\pi}$ $\quad \mathbb{Z}_2$

Universidad del País Vasco / Euskal Herriko Unibertsitatea — EHU QC EHU Quantum Center — ikerbasque Basque Foundation for Science

Quantum particle on a ring with a potential

Minimal model with potential term that still keeps similar symmetry features

$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2 - E_J \cos\left(2\hat{\theta}\right)$$

About the reflexion symmetry…

$n_g = 0$	$n_g = 1/2$
$\hat{U}_P$: $n \to -n$, $\theta \to -\theta$	$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P$: $n \to 1-n$, $\theta \to -\theta$

About the (discrete) rotation symmetry: $\hat{U}_\pi = e^{i\hat{n}\pi}$ $\mathbb{Z}_2$

$n_g = 0$	*parameter*	$n_g = 1/2$
commute $\hat{U}_P\hat{U}_\pi = \hat{U}_\pi\hat{U}_P$	*multiplication relations*	$\hat{V}_P\hat{U}_\pi = -\hat{U}_\pi\hat{V}_P$ anti-commute
$\mathbb{Z}_2 \times \mathbb{Z}_2$	*group symmetry*	D_4

Quantum particle on a ring with a potential

Minimal model with potential term that still keeps similar symmetry features

$$\hat{H} = E_c\left(\hat{n} - n_g\right)^2 - E_J\cos\left(2\hat{\theta}\right)$$

About the reflexion symmetry…

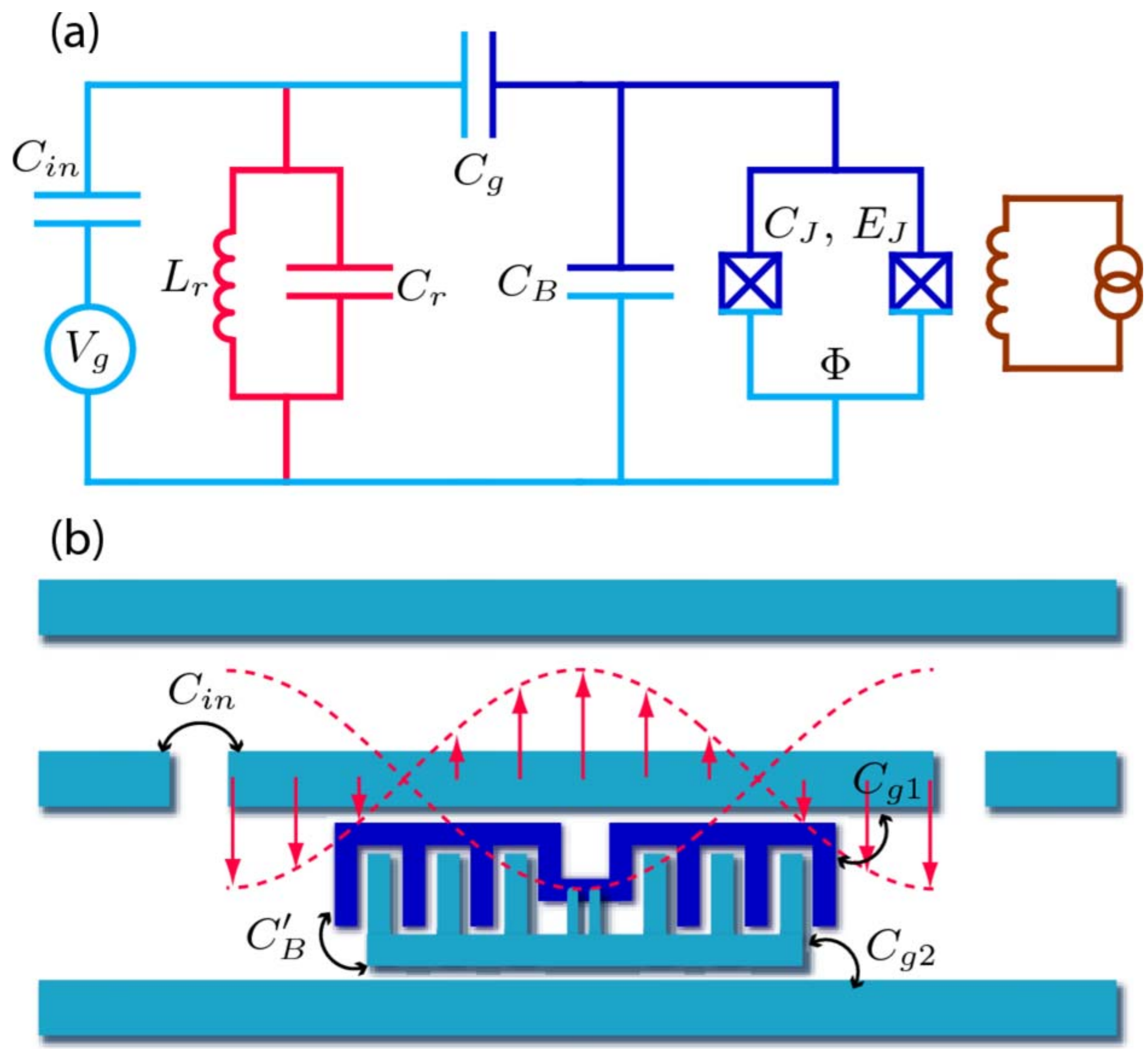
$n_g = 0$		$n_g = 1/2$	
$\hat{U}_P$	$n \to -n$, $\theta \to -\theta$	$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P$	$n \to 1 - n$, $\theta \to -\theta$

About the (discrete) rotation symmetry: $\hat{U}_\pi = e^{i\hat{n}\pi}$ $\quad\mathbb{Z}_2$

	$n_g = 0$	*parameter*	$n_g = 1/2$	
commute	$\hat{U}_P\hat{U}_\pi = \hat{U}_\pi\hat{U}_P$	*multiplication relations*	$\hat{V}_P\hat{U}_\pi = -\hat{U}_\pi\hat{V}_P$	anti-commute
	$\mathbb{Z}_2 \times \mathbb{Z}_2$	*group symmetry*	D_4	↓ two-fold degeneracy

Superconducting qubits

Example: the transmon

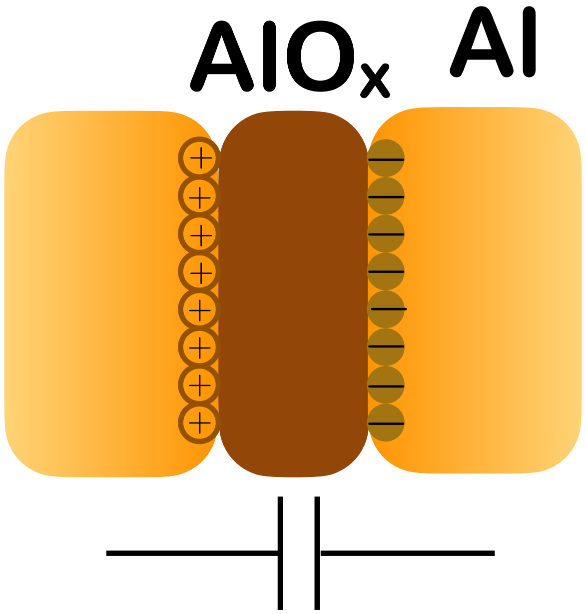


J. Koch et al., Phys. Rev. A (2007)

Superconducting qubits

Charging hamiltonian of the SC:
Junction also acts as a capacitor

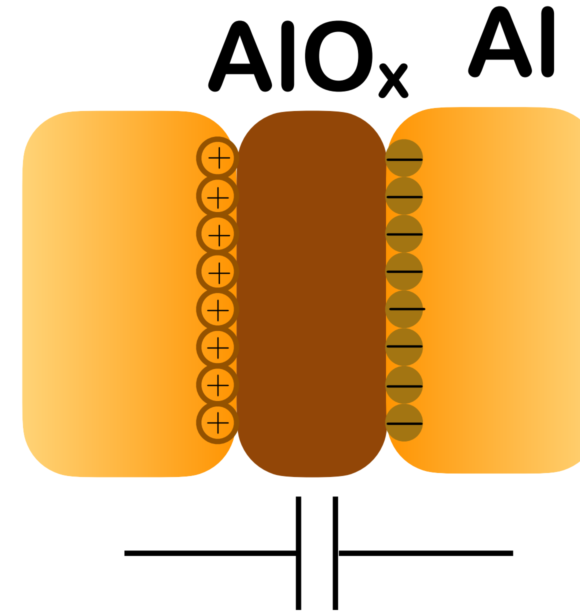
$$\hat{H} = \frac{(2e)^2}{2C}\hat{n}^2 = 4E_C\hat{n}^2$$



Superconducting qubits

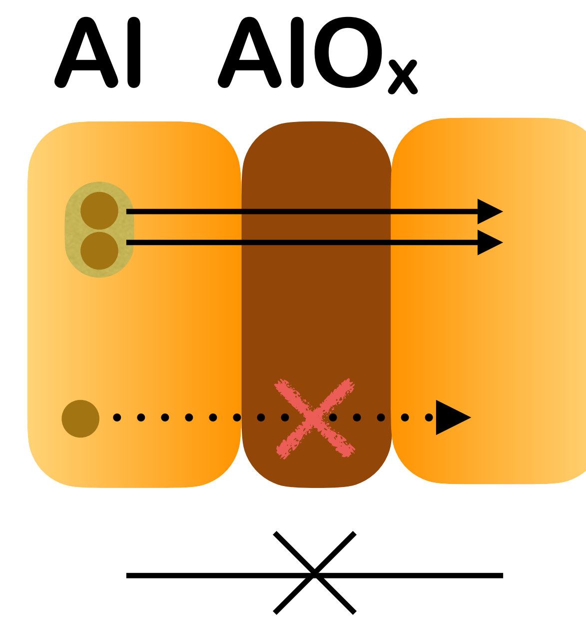
Charging hamiltonian of the SC:
Junction also acts as a capacitor

$$\hat{H} = \frac{(2e)^2}{2C}\hat{n}^2 = 4E_C\hat{n}^2$$

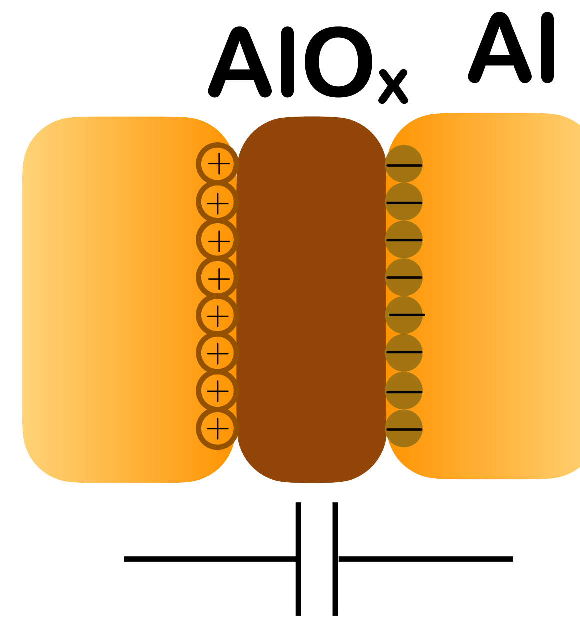


Josephson tunnelling:

- couple two superconductors via oxide layer
- oxide layer acts as tunnelling barrier
- superconducting gap inhibits electron tunnelling

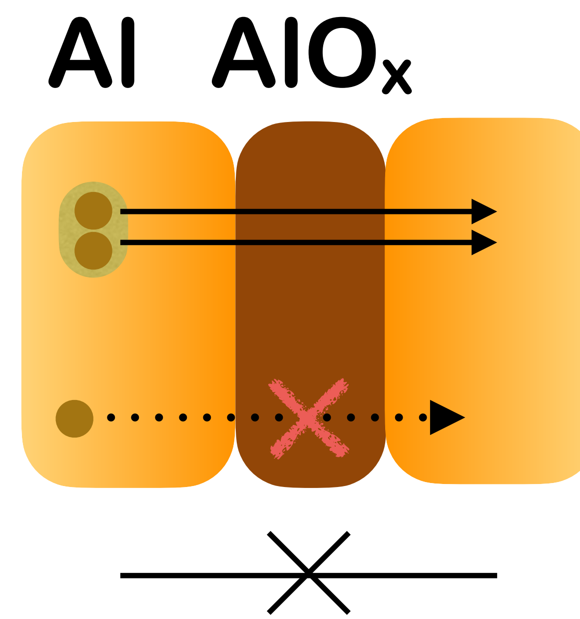


Superconducting qubits



Charging hamiltonian of the SC:
Junction also acts as a capacitor

$$\hat{H} = \frac{(2e)^2}{2C}\hat{n}^2 = 4E_C\hat{n}^2$$



Josephson tunnelling:

- couple two superconductors via oxide layer
- oxide layer acts as tunnelling barrier
- superconducting gap inhibits electron tunnelling

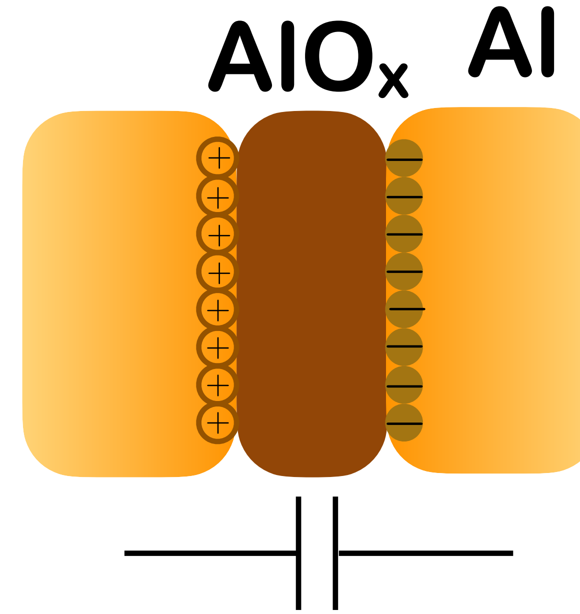
Josephson Hamiltonian:

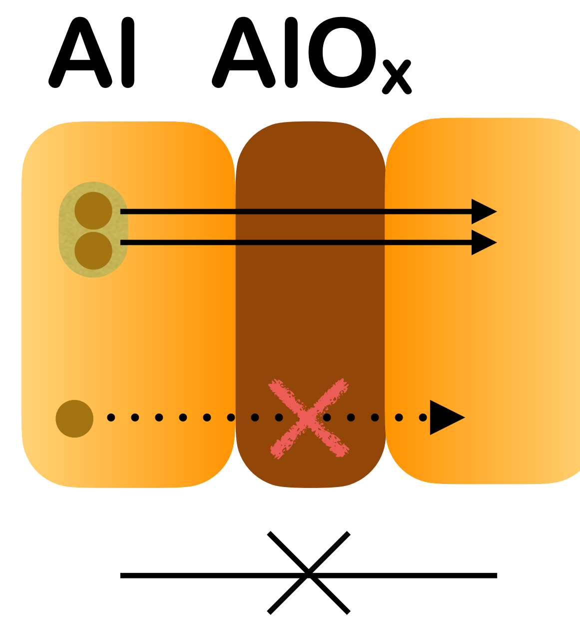
$$\hat{H}_J = -\frac{E_J}{2}\sum_n |n\rangle\langle n+1| + |n+1\rangle\langle n|$$

Superconducting qubits

Charging hamiltonian of the SC:
Junction also acts as a capacitor

$$\hat{H} = \frac{(2e)^2}{2C}\hat{n}^2 = 4E_C\hat{n}^2$$





Josephson tunnelling:

- couple two superconductors via oxide layer
- oxide layer acts as tunnelling barrier
- superconducting gap inhibits electron tunnelling

Josephson Hamiltonian:

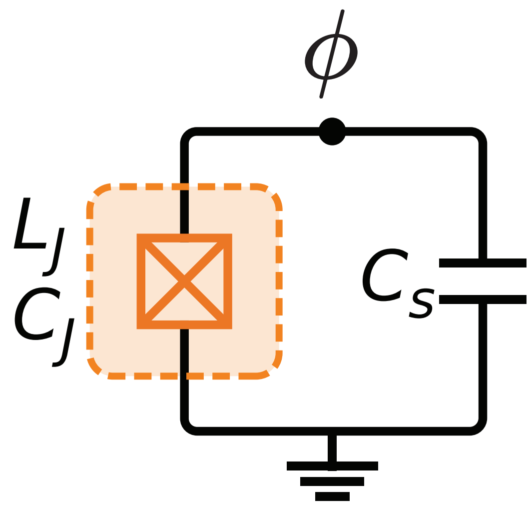
$$\hat{H}_J = -\frac{E_J}{2}\sum_n |n\rangle\langle n+1| + |n+1\rangle\langle n|$$

$$= -E_J \cos\hat{\theta}$$

written in terms of the conjugate variable
(Fourier transform)
Physically: difference of the SC phases

$$\left[\hat{\theta}, \hat{n}\right] = i$$

Energy parameters



$$\hat{H} = 4E_C\hat{n}^2 - E_J\cos\hat{\theta}$$

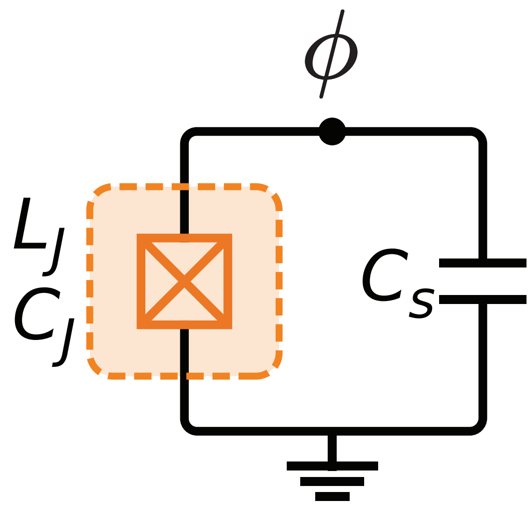
Designed regime:

(Potential dominated)

$$E_J \gg E_C$$

$$\omega = \sqrt{8E_CE_J}$$

Energy parameters



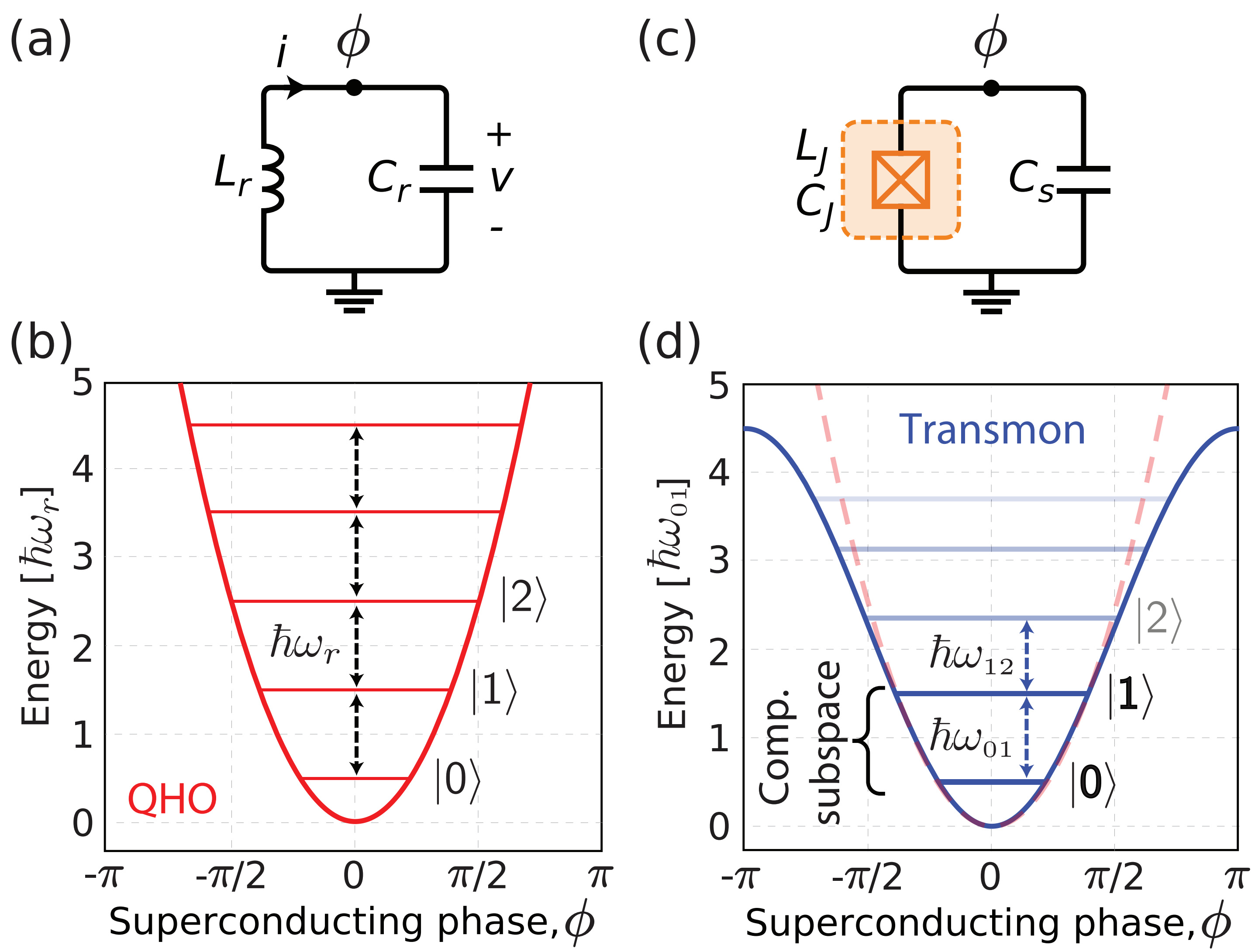
$$\hat{H} = 4E_C\hat{n}^2 - E_J\cos\hat{\theta}$$

Designed regime:

(Potential dominated)

$$E_J \gg E_C$$

$$\omega = \sqrt{8E_CE_J}$$



anharmonicity
non-linear inductance

P Krantz et al. App. Phys. Rev. (2019)

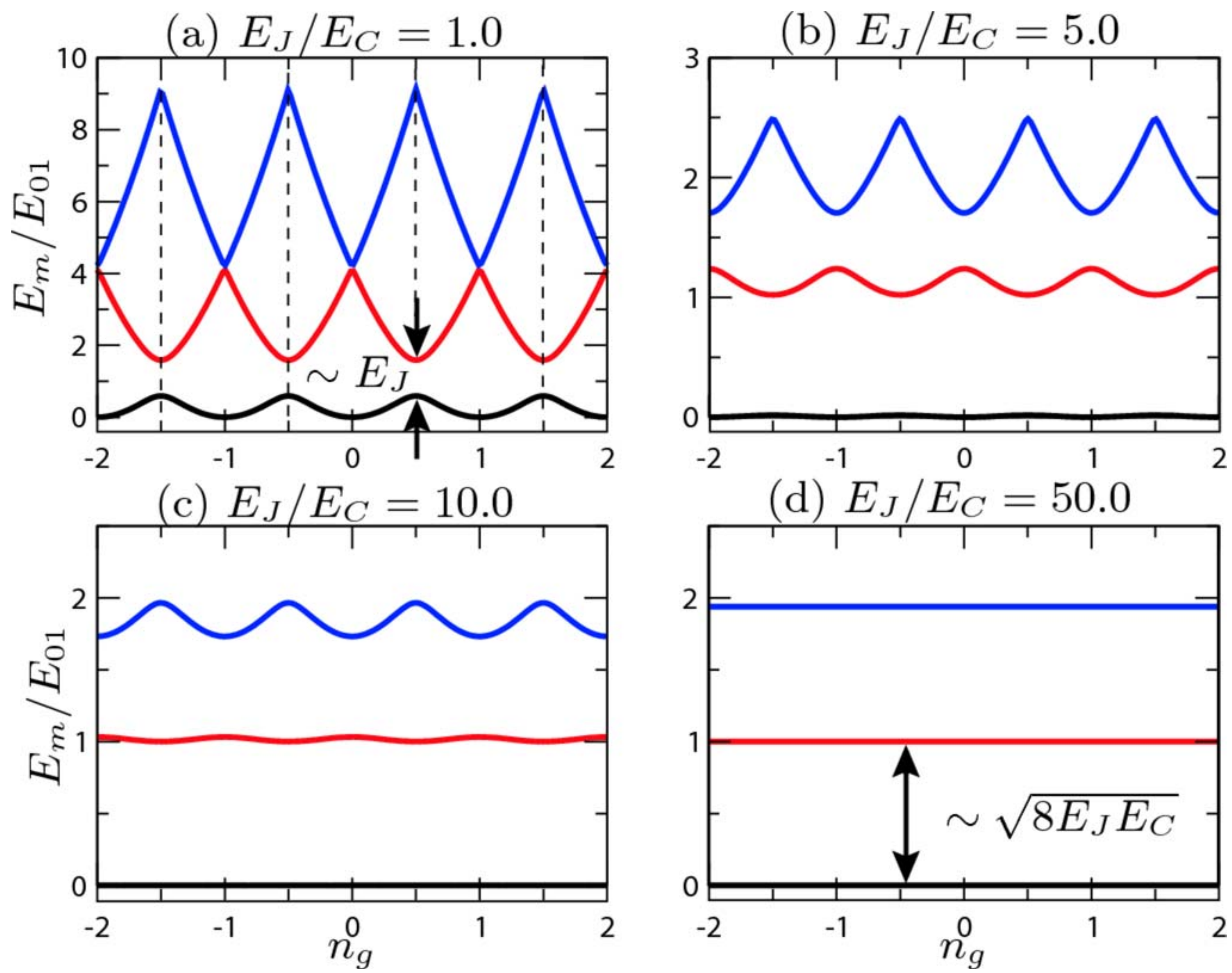
Other (control) parameters

$$\hat{H} = 4E_C\left(\hat{n} - n_g\right)^2 - E_J \cos\hat{\theta}$$

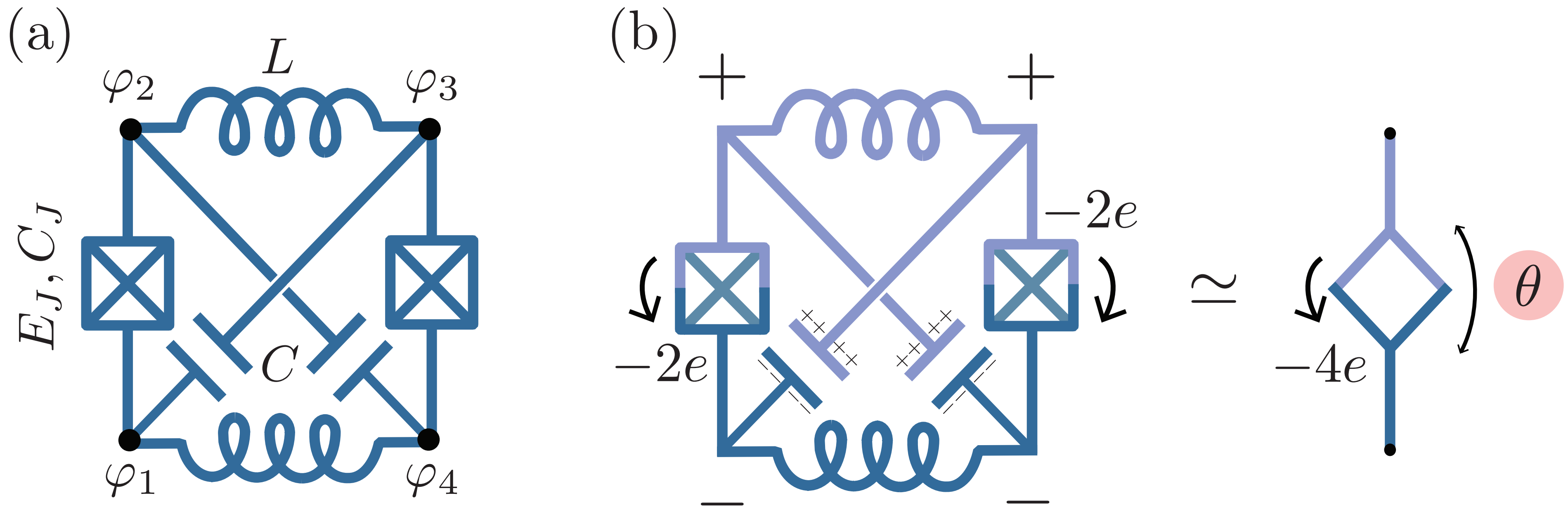
$n_g \rightarrow$ Gate charge

Transmon: insensitive to charge noise

J. Koch et al., Phys. Rev. A (2007)

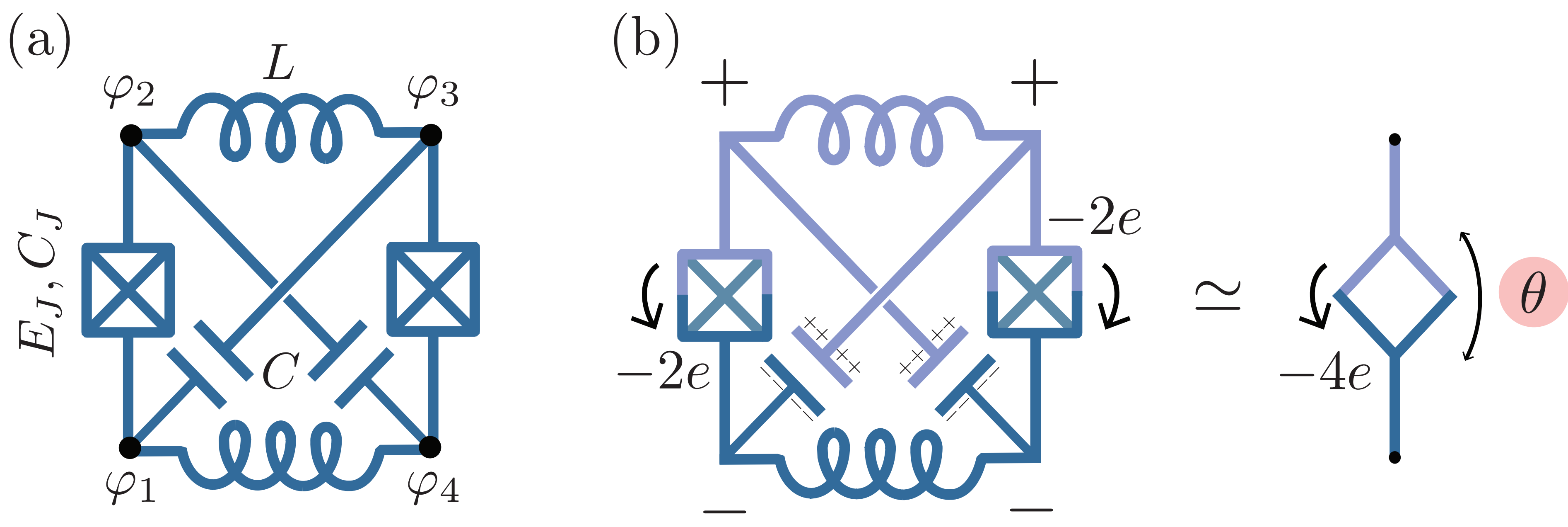


$0 - \pi$ qubit



A. Di Paolo, et al. New J. Phys. (2019)

0-π qubit

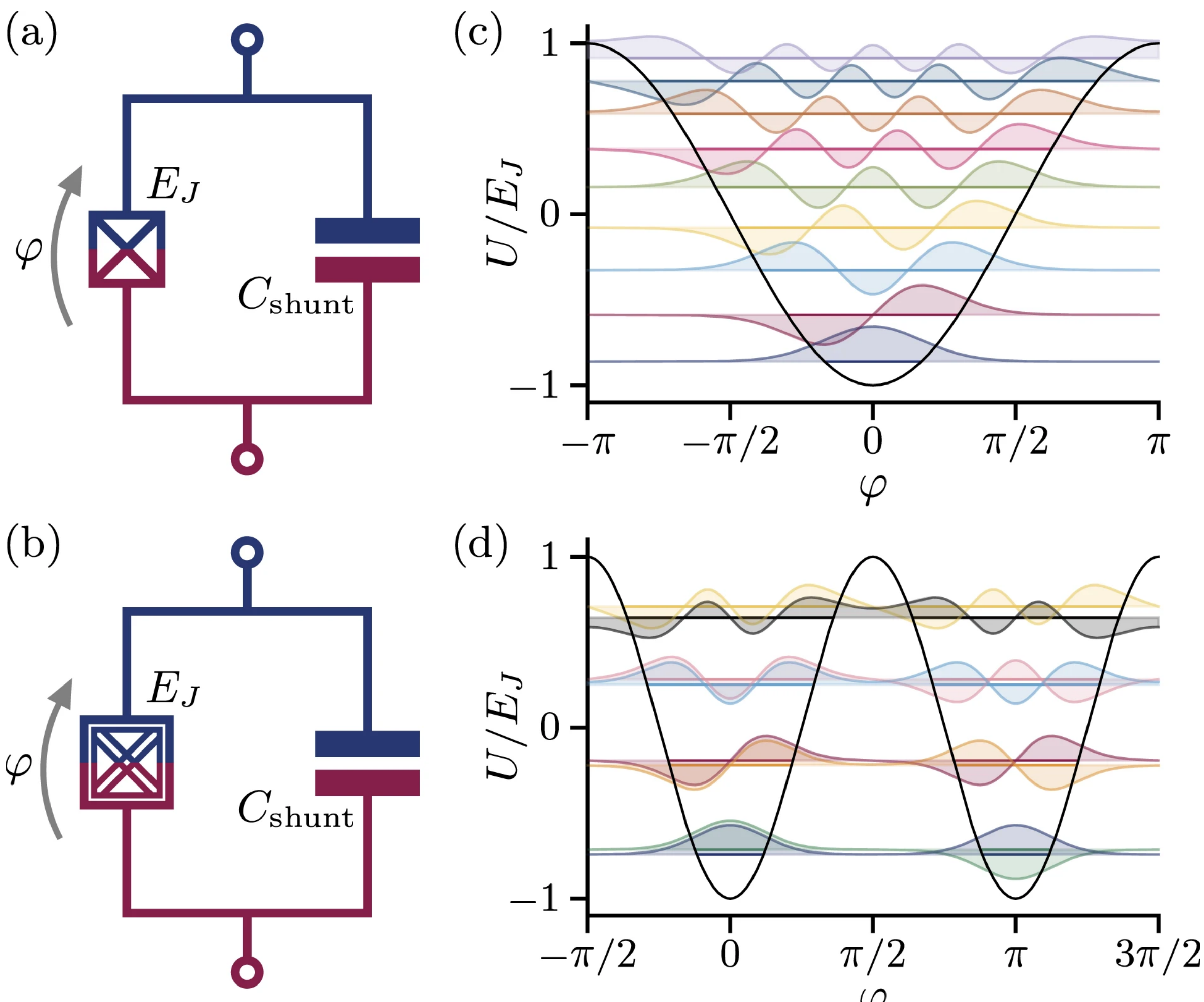


$$H_{0\text{-}\pi} = 4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2 + 4E_{C_s}\left(\hat{n}_\theta - n_g\right)^2 - 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)$$

Protected from both charge noise and flux noise

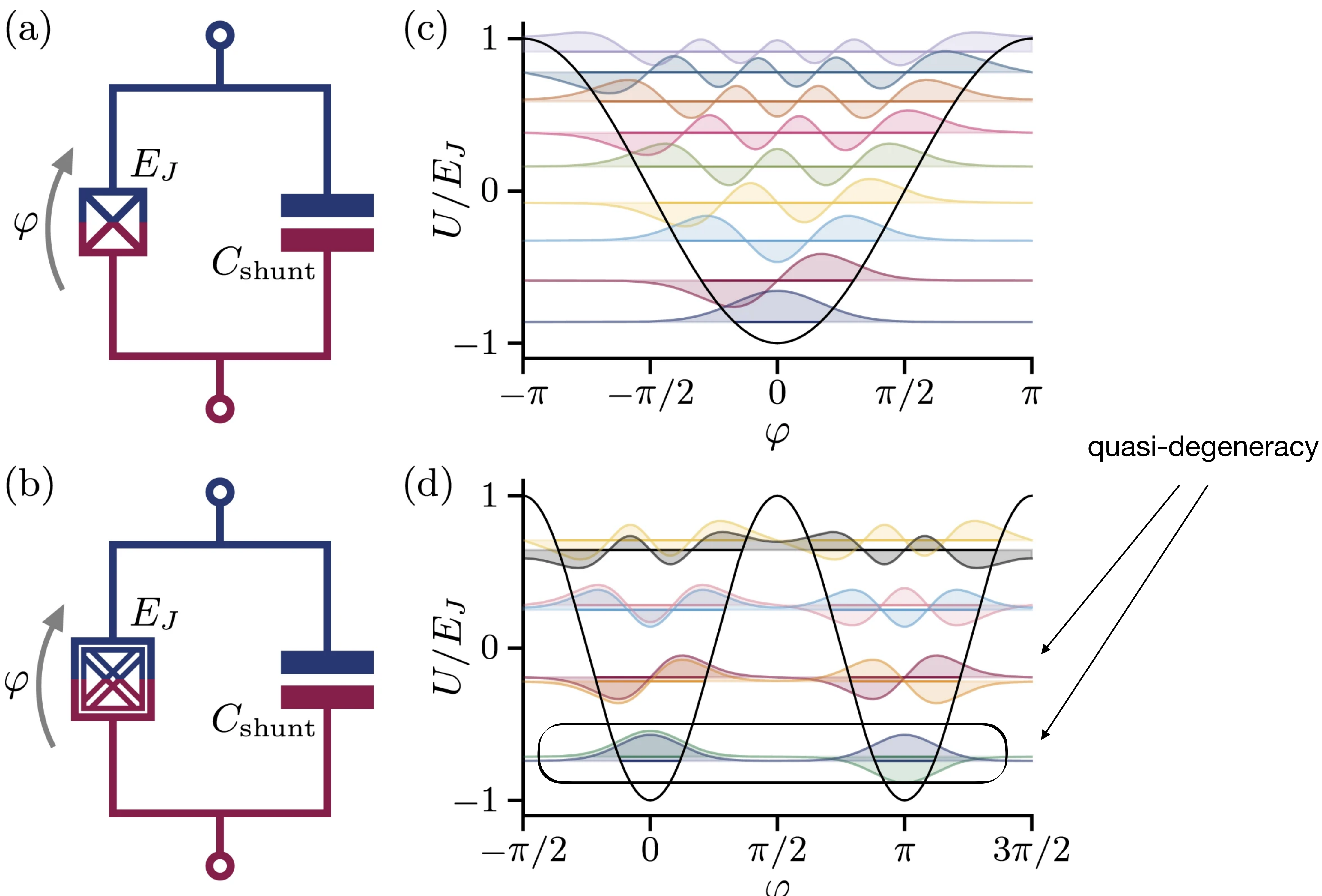
A. Di Paolo, et al. New J. Phys. (2019)

0 - π qubit



W.C. Smith, et al. Quant. Info. (2020)

$0 - \pi$ qubit



W.C. Smith, et al. Quant. Info. (2020)

$0-\pi$ qubit

A. Kitaev, Protected qubit based on a superconducting current mirror, arXiv:cond-mat/0609441.

P. Brooks, A. Kitaev, and J. Preskill, Protected gates for superconducting qubits, Phys. Rev. A **87**, 052306 (2013).

B. Douçot and J. Vidal, Pairing of Cooper Pairs in a Fully Frustrated Josephson Junction Chain, Phys. Rev. Lett. **88**, 227005 (2002).

L. B. Ioffe and M. V. Feigel'man, Possible realization of an ideal quantum computer in Josephson junction array, Phys. Rev. B **66**, 224503 (2002).

J. M. Dempster, B. Fu, D. G. Ferguson, D. I. Schuster, and J. Koch, Understanding degenerate ground-states of a protected quantum circuit in the presence of disorder, Phys. Rev. B **90**, 094518 (2014).

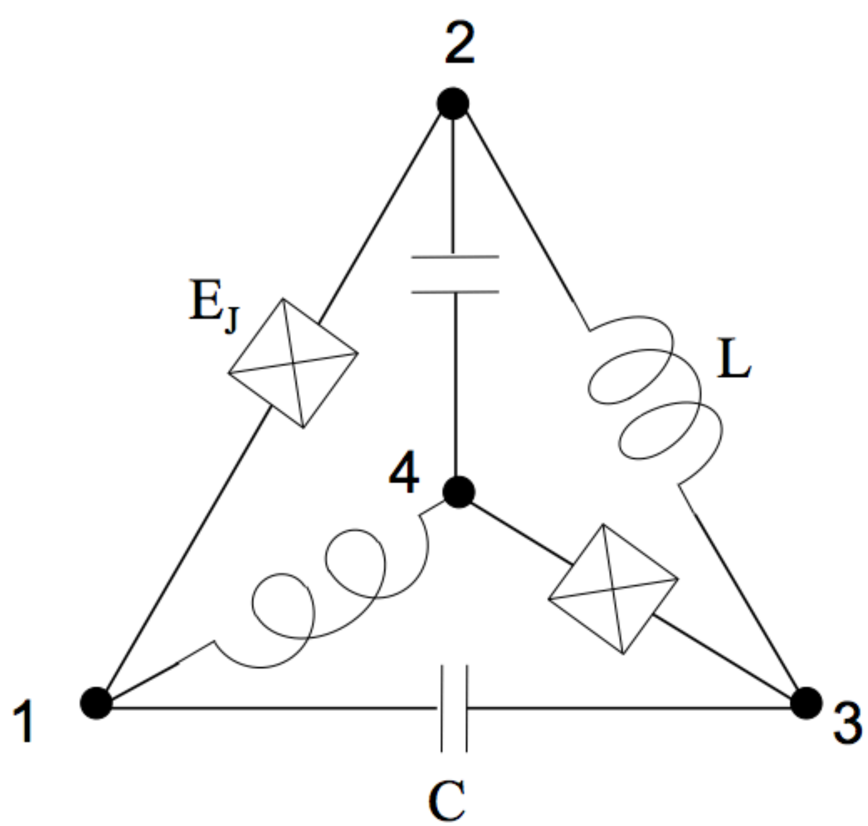
W. C. Smith, A. Kou, X. Xiao, U. Vool, and M. H. Devoret, Superconducting circuit protected by two-Cooper-pair tunneling, npj Quantum Inf. **6**, 8 (2020).

P. Groszkowski, A. Di Paolo, A. L. Grimsmo, A. Blais, D. I. Schuster, A. A. Houck, and J. Koch, Coherence properties of the 0-π qubit, New J. Phys. **20**, 043053 (2018).

A. Di Paolo, A. L. Grimsmo, P. Groszkowski, J. Koch, and A. Blais, Control and coherence time enhancement of the 0-π qubit, New J. Phys. **21**, 043002 (2019).

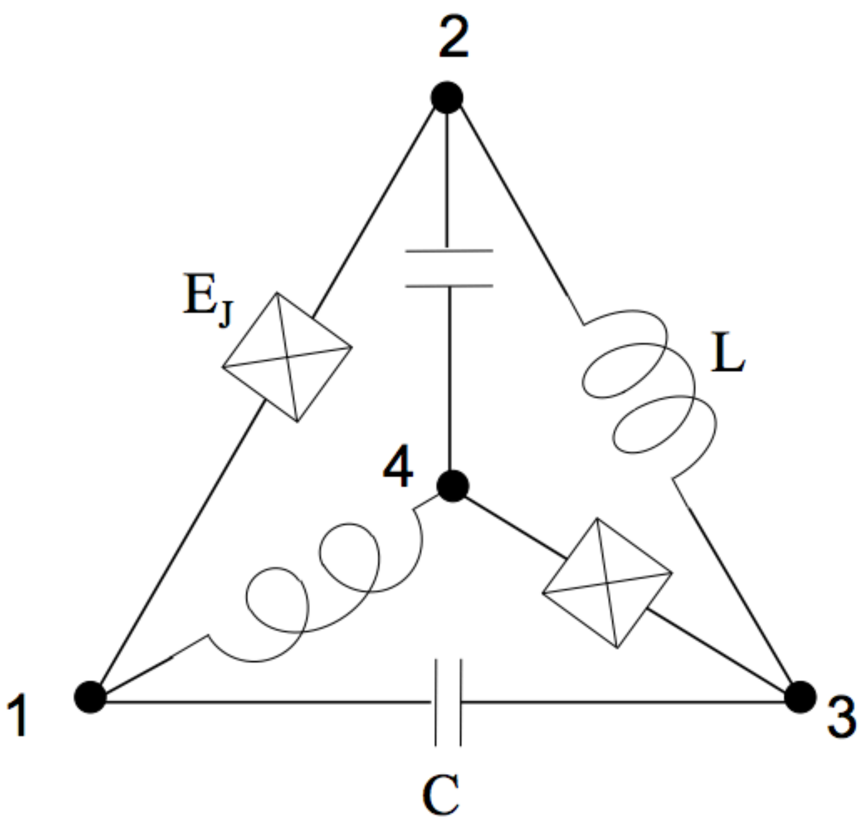
A. Gyenis, P. S. Mundada, A. Di Paolo, T. M. Hazard, X. You, D. I. Schuster, J. Koch, A. Blais, and A. A. Houck, Experimental realization of a protected superconducting circuit derived from the 0-π qubit, PRX Quantum **2**, 010339 (2021).

0-π Hamiltonian



$$H_{0\text{-}\pi} = 4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2 + 4E_{C_s}\left(\hat{n}_\theta - n_g\right)^2 - 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)$$

$0\text{-}\pi$ Hamiltonian

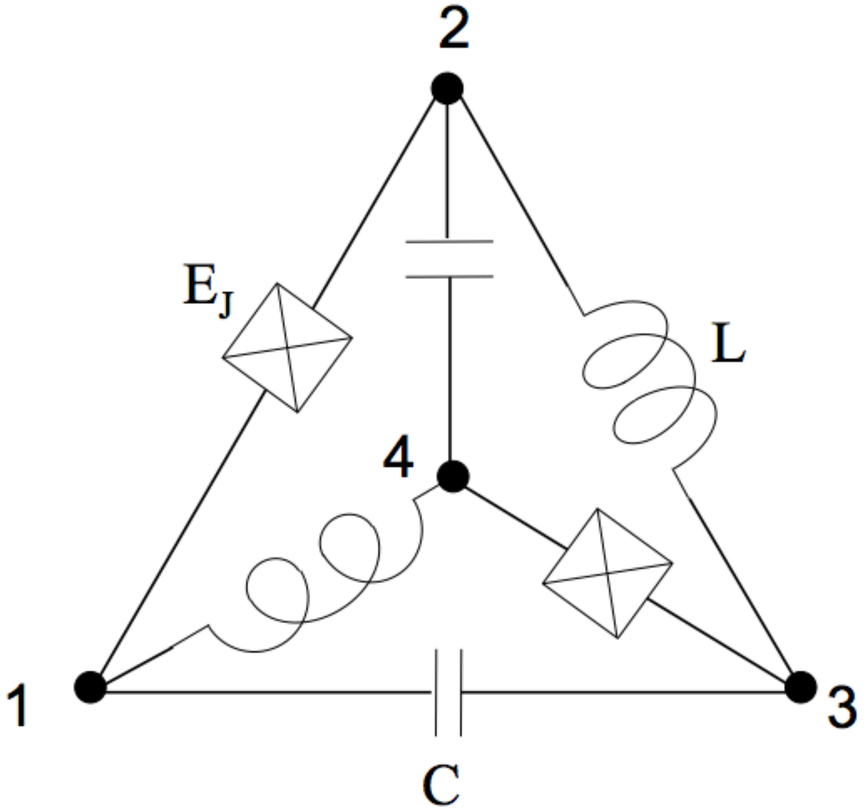


$$H_{0\text{-}\pi} = \underbrace{4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2}_{\text{harmonic oscillator}} + 4E_{C_s}\underbrace{\left(\hat{n}_\theta - n_g\right)^2}_{\text{diagonal}} - \underbrace{2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)}_{\text{interaction}}$$

$$\left[\hat{\theta}, \hat{n}_\theta\right] = i \qquad \theta \in (-\pi, +\pi] \qquad \text{spect}\left(\hat{\text{n}}\right) \in \mathbb{Z}$$

$$\left[\hat{\phi}, \hat{Q}_\phi\right] = i \qquad \phi \in \mathbb{R} \qquad \hat{Q}_\phi \in \mathbb{R}$$

$0-\pi$ Hamiltonian



high symmetry point

$$n_g = 1/2,\ \varphi_{\text{ext}} = \pi$$

$$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P \qquad \begin{array}{l} n_\theta \to 1 - n_\theta \\ \theta \to -\theta \end{array}$$

$$\hat{U}_\pi = e^{i\hat{n}_\theta \pi}\hat{P}_\phi \qquad \begin{array}{l} \theta \to \theta + \pi \\ \phi \to -\phi \end{array}$$

$$\hat{V}_P\hat{U}_\pi = -\hat{U}_\pi\hat{V}_P$$

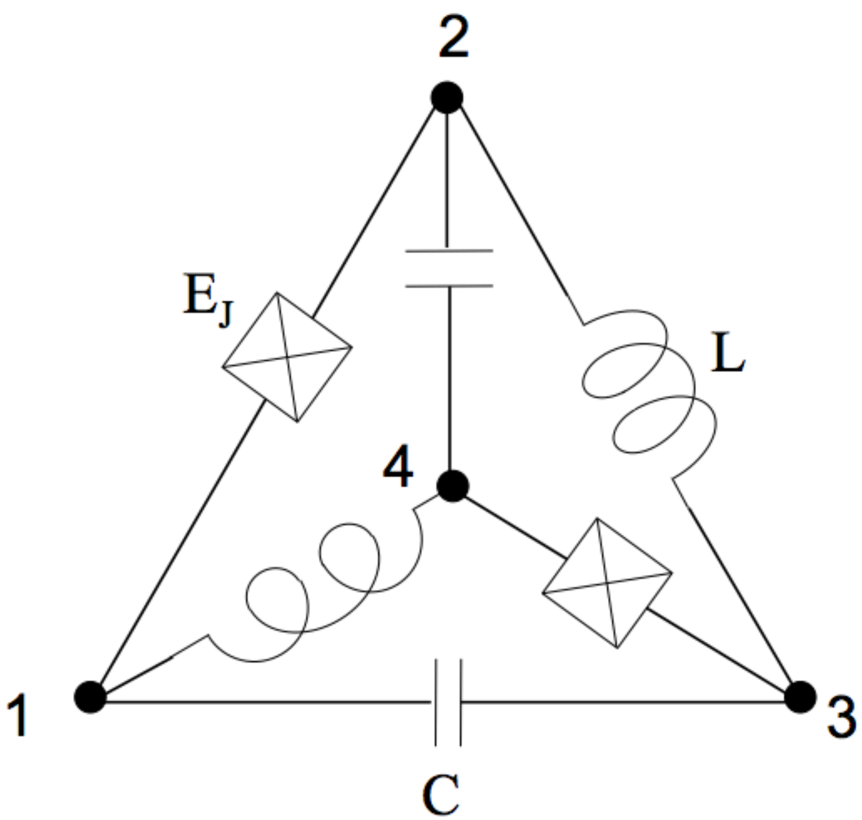
$$H_{0-\pi} = \underbrace{4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2}_{\text{harmonic oscillator}} + \underbrace{4E_{C_s}\left(\hat{n}_\theta - n_g\right)^2}_{\text{diagonal}} \underbrace{- 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)}_{\text{interaction}}$$

$$\left[\hat{\theta}, \hat{n}_\theta\right] = i \qquad \theta \in (-\pi, +\pi] \qquad \text{spect}\left(\hat{n}\right) \in \mathbb{Z}$$

$$\left[\hat{\phi}, \hat{Q}_\phi\right] = i \qquad \phi \in \mathbb{R} \qquad \hat{Q}_\phi \in \mathbb{R}$$

Universidad del País Vasco · Euskal Herriko Unibertsitatea | EHU QC · EHU Quantum Center · ikerbasque Basque Foundation for Science

0-π Hamiltonian



high symmetry point

$$n_g = 1/2,\ \varphi_{\text{ext}} = \pi$$

$$\hat{V}_P = e^{-i\hat{\theta}}\hat{U}_P \qquad n_\theta \to 1 - n_\theta \quad \theta \to -\theta$$

$$\hat{U}_\pi = e^{i\hat{n}_\theta \pi}\hat{P}_\phi \qquad \theta \to \theta + \pi \quad \phi \to -\phi$$

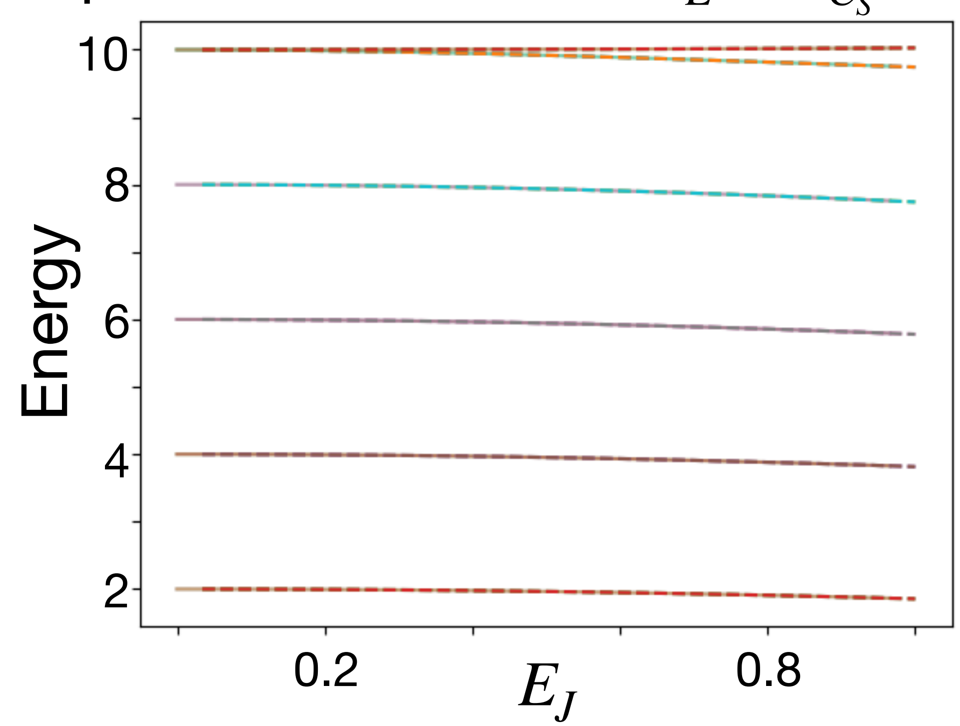
$$\hat{V}_P\hat{U}_\pi = -\hat{U}_\pi\hat{V}_P$$

$$H_{0\text{-}\pi} = \underbrace{4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2}_{\text{harmonic oscillator}} + \underbrace{4E_{C_s}\left(\hat{n}_\theta - n_g\right)^2}_{\text{diagonal}} \underbrace{- 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)}_{\text{interaction}}$$

$$\left[\hat{\theta}, \hat{n}_\theta\right] = i \qquad \theta \in (-\pi, +\pi] \qquad \text{spect}\left(\hat{\text{n}}\right) \in \mathbb{Z}$$

$$\left[\hat{\phi}, \hat{Q}_\phi\right] = i \qquad \phi \in \mathbb{R} \qquad \hat{Q}_\phi \in \mathbb{R}$$

Spectrum in units of $E_L = E_{C_S} = E_{C_J}$



the whole spectrum is two-fold degenerate independent of any energy scales

$0-\pi$ Hamiltonian

$$H_{0-\pi} = 4E_{C_J}\hat{Q}_{\phi}^2 + E_L\hat{\phi}^2 + 4E_{C_s}\left(\hat{n}_{\theta} - n_g\right)^2 - 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)$$

Sensitivity to charge and flux noise exponentially decreased in the regimen:

$$E_{C_J}^2 \gg E_{C_J}E_L \gg E_J^2 \gg E_{C_J}E_{C_s}$$

0 - π Hamiltonian

$$H_{0\text{-}\pi} = 4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2 + 4E_{C_s}\left(\hat{n}_\theta - n_g\right)^2 - 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)$$

Sensitivity to charge and flux noise exponentially decreased in the regimen:

$$E_{C_J}^2 \gg E_{C_J}E_L \gg E_J^2 \gg E_{C_J}E_{C_s}$$

Potential dominance for θ

$$E_J \gg E_{C_s}$$

Transmon regime

Protection against charge noise

0-π Hamiltonian

$$H_{0\text{-}\pi} = 4E_{C_J}\hat{Q}_\phi^2 + E_L\hat{\phi}^2 + 4E_{C_s}\left(\hat{n}_\theta - n_g\right)^2 - 2E_J\cos\hat{\theta}\cos\left(\hat{\phi} - \frac{\varphi_{\text{ext}}}{2}\right)$$

Sensitivity to charge and flux noise exponentially decreased in the regimen:

$$E_{C_J}^2 \gg E_{C_J}E_L \gg E_J^2 \gg E_{C_J}E_{C_s}$$

Kinetic dominance

$$E_{C_J} \gg E_L$$

High delocalisation of ϕ, no effect of φ_{ext}

Protection against flux noise

Potential dominance for θ

$$E_J \gg E_{C_s}$$

Transmon regime

Protection against charge noise

Universidad del País Vasco / Euskal Herriko Unibertsitatea

EHU QC
EHU Quantum Center

0 - π Hamiltonian

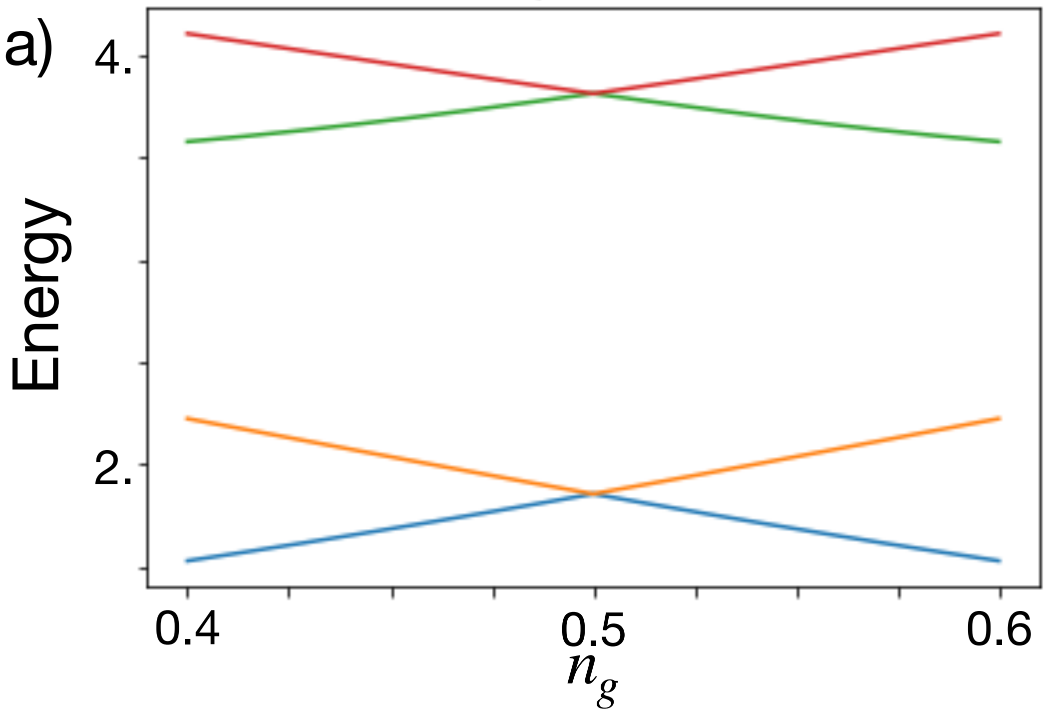
ikerbasque
Basque Foundation for Science

Sensitivity to charge and flux noise exponentially decreased in the regimen:

$$E_{C_J}^2 \gg E_{C_J} E_L \gg E_J^2 \gg E_{C_J} E_{C_s}$$

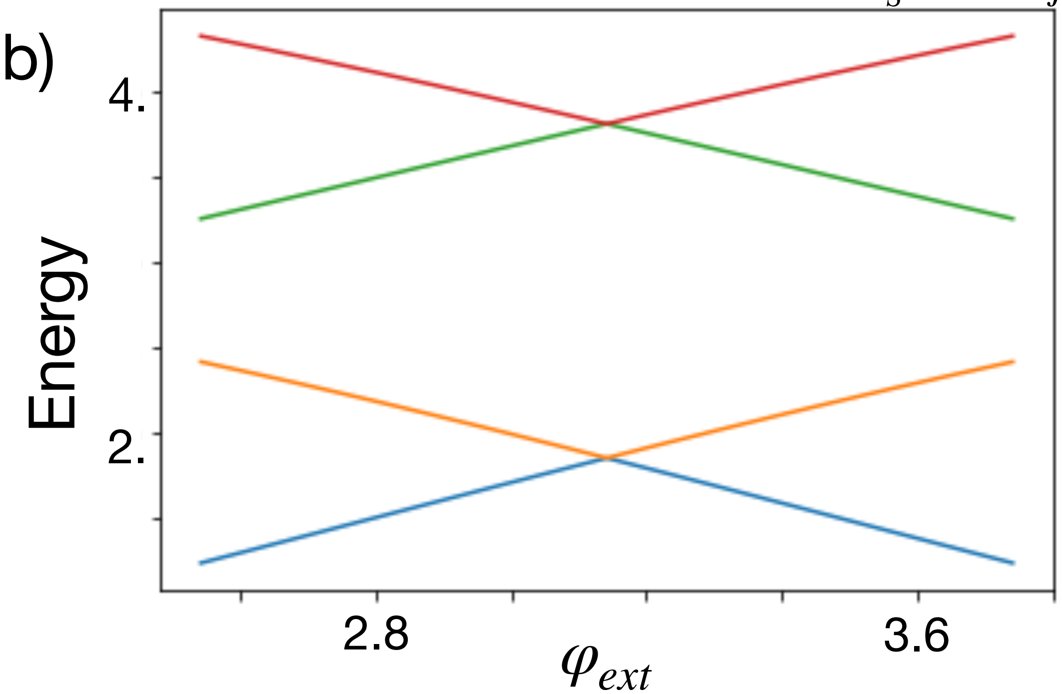
Spectrum in units of $E_L = E_{C_S} = E_{C_J} = E_J$

a)



Spectrum in units of $E_L = E_{C_S} = E_{C_J} = E_J$

b)



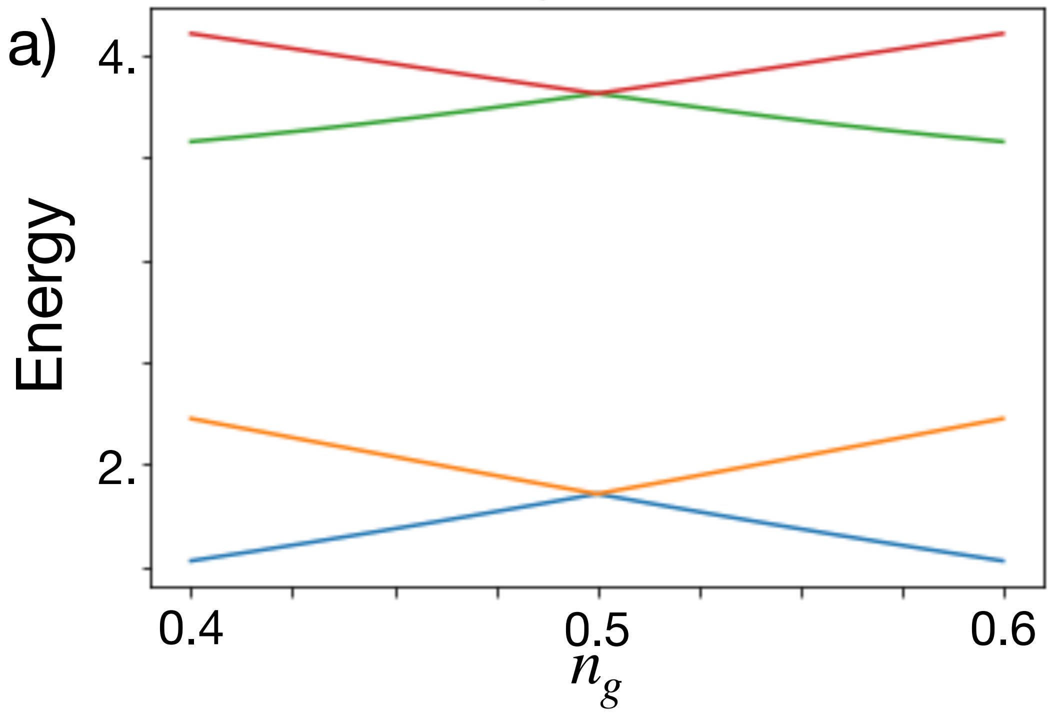
Universidad del País Vasco · Euskal Herriko Unibertsitatea · EHU QC EHU Quantum Center · ikerbasque Basque Foundation for Science

$0-\pi$ Hamiltonian

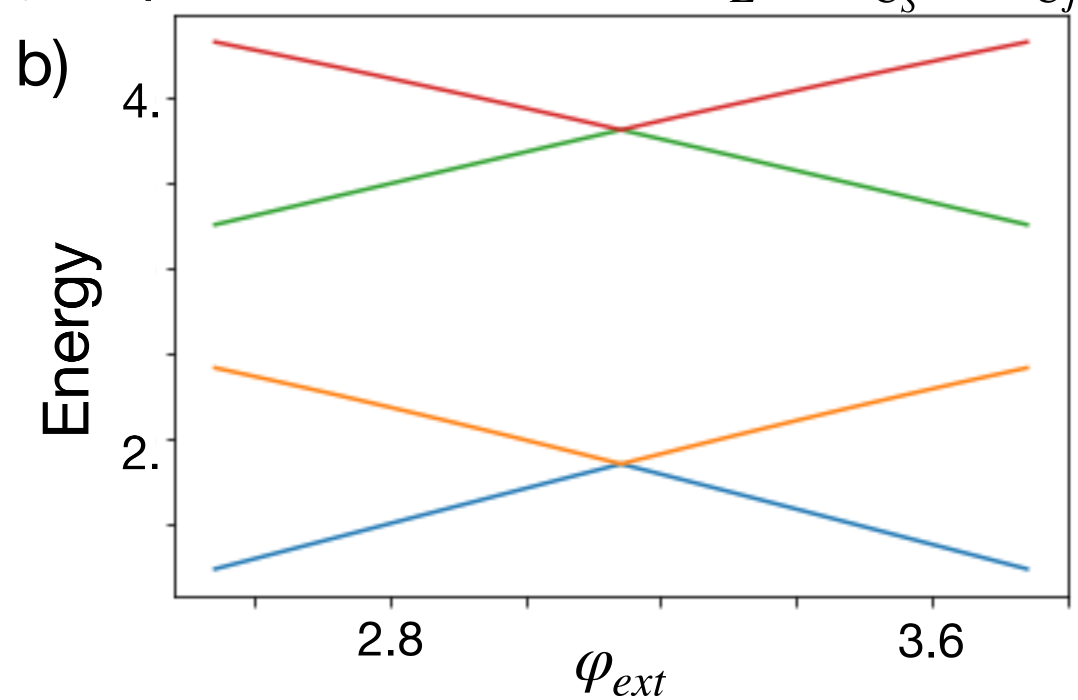
Sensitivity to charge and flux noise exponentially decreased in the regimen:

$$E_{C_J}^2 \gg E_{C_J}E_L \gg E_J^2 \gg E_{C_J}E_{C_s}$$

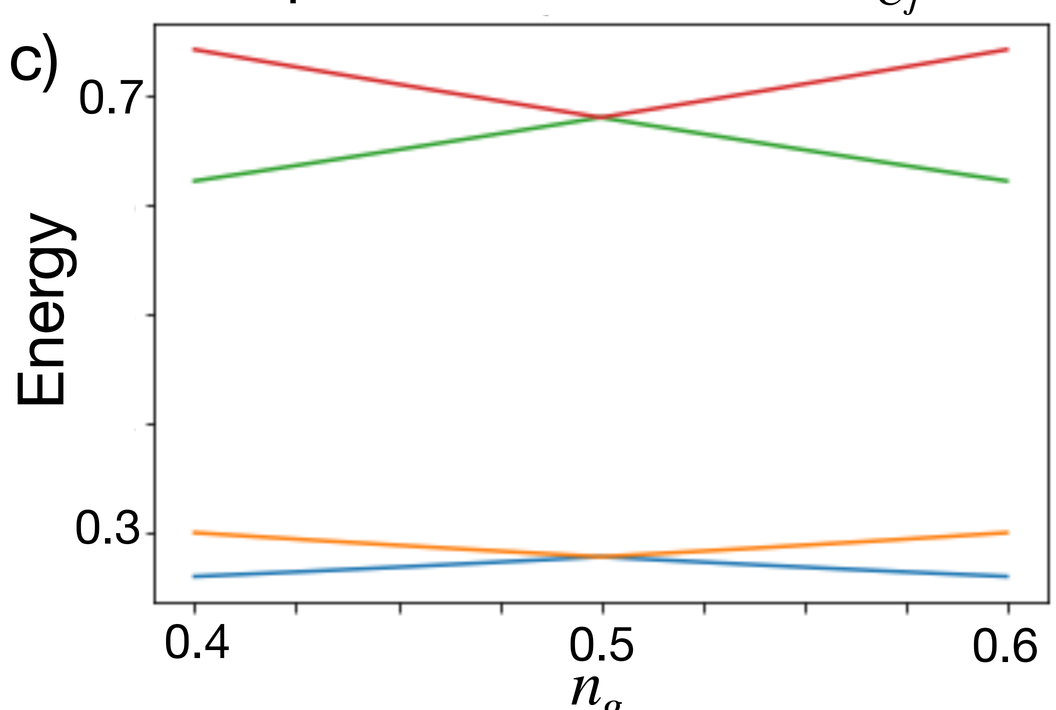
Spectrum in units of $E_L = E_{C_S} = E_{C_J} = E_J$



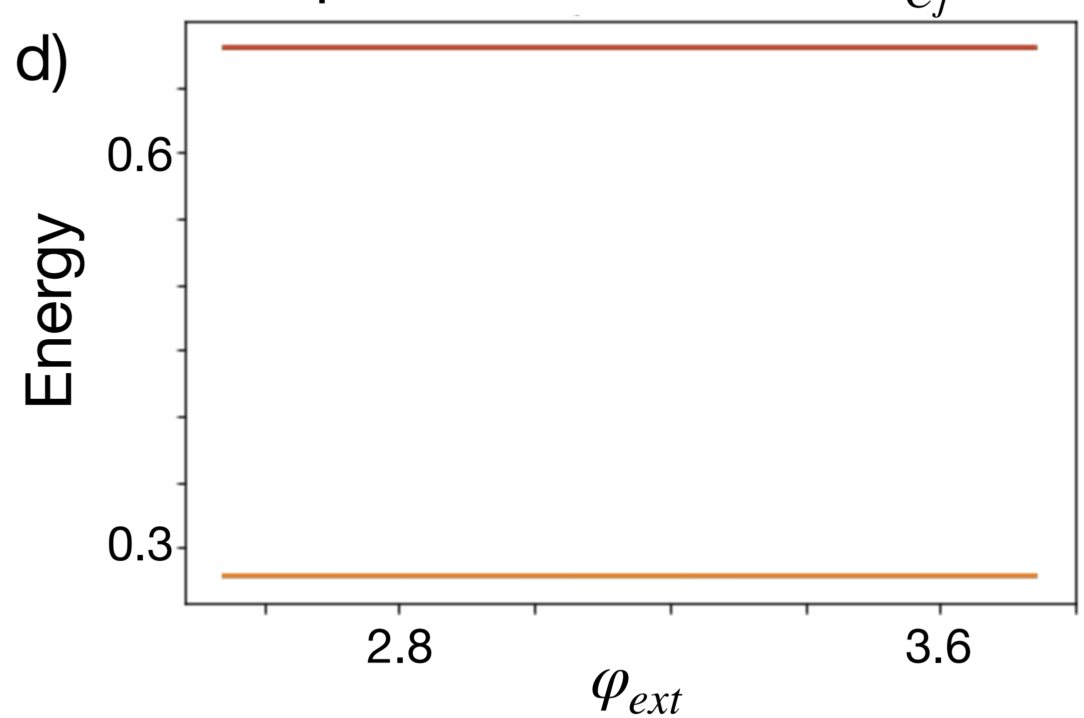
Spectrum in units of $E_L = E_{C_S} = E_{C_J} = E_J$



Spectrum in units of E_{C_J}



Spectrum in units of E_{C_J}



Universidad del País Vasco · Euskal Herriko Unibertsitatea · eman ta zabal zazu

EHU QC
EHU Quantum Center

ikerbasque
Basque Foundation for Science

Qubit alive thanks to the anomaly

There exist anomalous symmetries: degeneracies independent of energy parameters

The degeneracies in the protected regime of the $0-\pi$ quit are a remnant of the anomalous symmetry

PHYSICAL REVIEW B **105**, L201104 (2022)

Letter

Role of anomalous symmetry in 0-π qubits

I. L. Egusquiza,[1,2,*] A. Iñiguez,[3,†] E. Rico,[2,4,5,‡] and A. Villarino[4,§]

[1]*Department of Physics, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[2]*EHU Quantum Center, University of the Basque Country, UPV/EHU, Barrio Sarriena s/n, 48940 Leioa, Biscay, Spain*
[3]*Department of Mathematics, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[4]*Department of Physical Chemistry, University of the Basque Country UPV/EHU, Apartado 644, 48080 Bilbao, Spain*
[5]*IKERBASQUE, Basque Foundation for Science, Plaza Euskadi 5, 48009 Bilbao, Spain*

New trends in complex quantum systems dynamics 2022

In our Quantum Science era where fault-tolerant quantum devices are still not available but Noisy Intermediate-Scale Quantum (NISQ) devices are accessible, quantum information tools to guide their development play a fundamental role. With the foreseen increasing complexity of available NISQ

https://www.uik.eus

Carlos Santamaría Zentroa

Plaza Elhuyar, 2. 20018- Donostia / San Sebastián

Gipuzkoa

20.jun - 24.jun

Confirmed invited speakers

- Mari Carmen Bañuls, MPQ & MCQST (Munich, Germany)
- Alejandro Bermudez, UCM (Madrid, Spain)
- Rainer Blatt, UIBK & IQOQI & Alpine QTech. GmbH (Innsbruck, Austria)
- Marcello Dalmonte, SISSA & ICTP (Trieste, Italia)
- Zohreh Davoudi, Maryland Center, U. Maryland (Maryland, USA)
- Gary Goldstein, Tufts University (Massachusetts, USA)
- Karl Jansen, DESY (Zeuthen, Germany)
- Fedor Jelezko, Inst. Q. Opt., Ulm University (Ulm, Germany)
- Zala Lenarčič, Jozef Stefan Institute (Ljubljana, Slovenia)
- Fernando Luis, INMA, CSIC-U. Zaragoza (Zaragoza, Spain)
- Maria Jose Martínez Pérez, INMA, CSIC-U. Zaragoza (Zaragoza, Spain)
- Hannes Pichler, UIBK & IQOQI (Innsbruck, Austria)
- Alex Retzker, Racah Inst., Hebrew Univ. (Jerusalem, Israel)
- Martin Ringbauer, Inst. Experimentalphys., UIBK (Innsbruck, Austria)
- Sofia Vallecorsa, CERN (Geneva, Switzerland)

https://www.uik.eus/en/new-trends-complex-quantum-systems-dynamics-2022