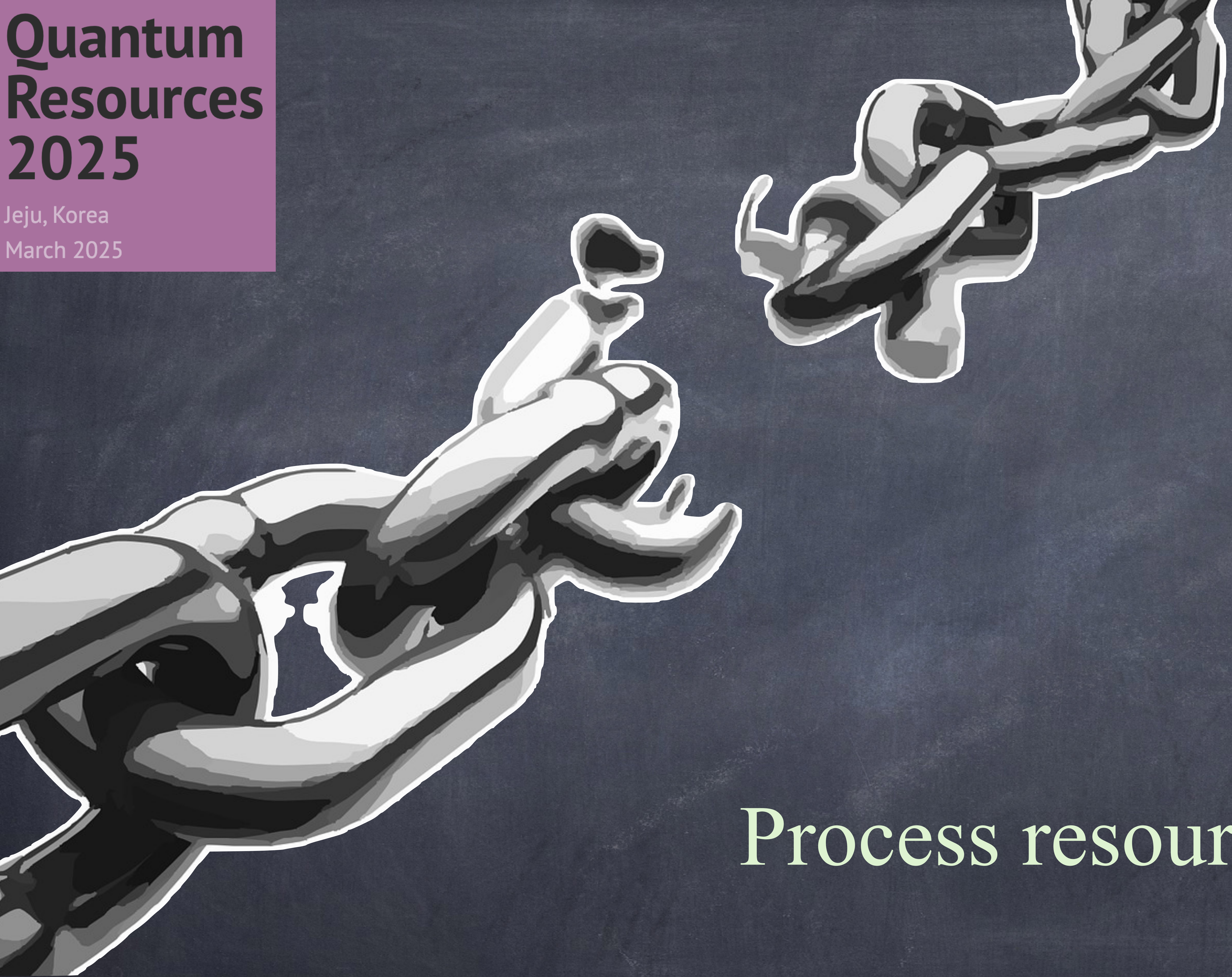
Quantum Resources 2025

Jeju, Korea
March 2025



Process resource-breaking channels

Rivu Gupta 20/03/2025
with Ayan Patra, Alessandro Ferraro, and Aditi Sen (De)

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Process resource-breaking channels the case for magic in universal quantum computation

Rivu Gupta 20/03/2025
with Ayan Patra, Alessandro Ferraro, and Aditi Sen (De)

Resource breaking channels

Shared quantum property :

Entanglement ⟶ **communication, key distribution, MBQC** Rev. Mod. Phys. 81, 865 (2009)

Resource breaking channels

Shared quantum property :

Entanglement ⟶ **communication, key distribution, MBQC** Rev. Mod. Phys. 81, 865 (2009)

Non-locality ⟶ **communication complexity, device independence, randomness generation**
Rev. Mod. Phys. 86, 419 (2014)

Resource breaking channels

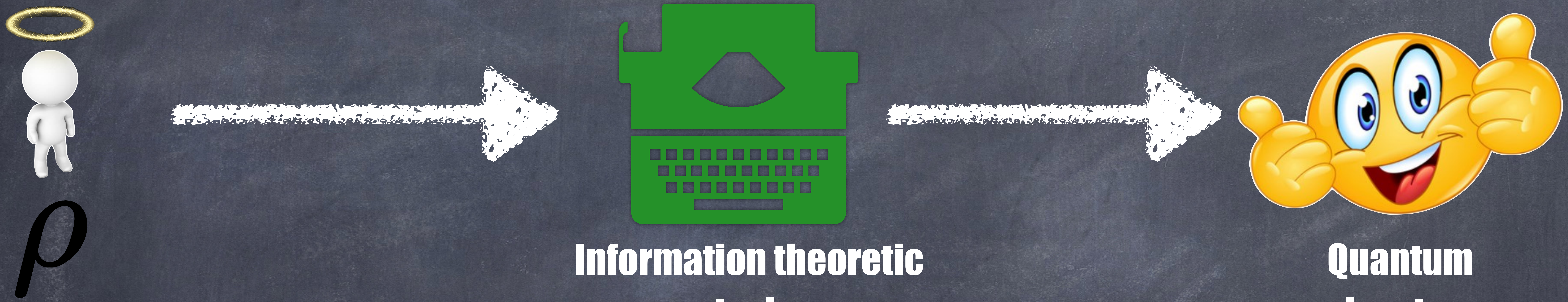
"Broken" quantum property :

Entanglement → ~~**communication, key distribution, MBQC**~~ Rev. Math. Phys. 15, 629 (2003)

Non-locality → ~~**communication complexity, device independence, randomness generation**~~

J. Phys. A: Math. Theor. 48 155302 (2015)

Process resource-breaking channels

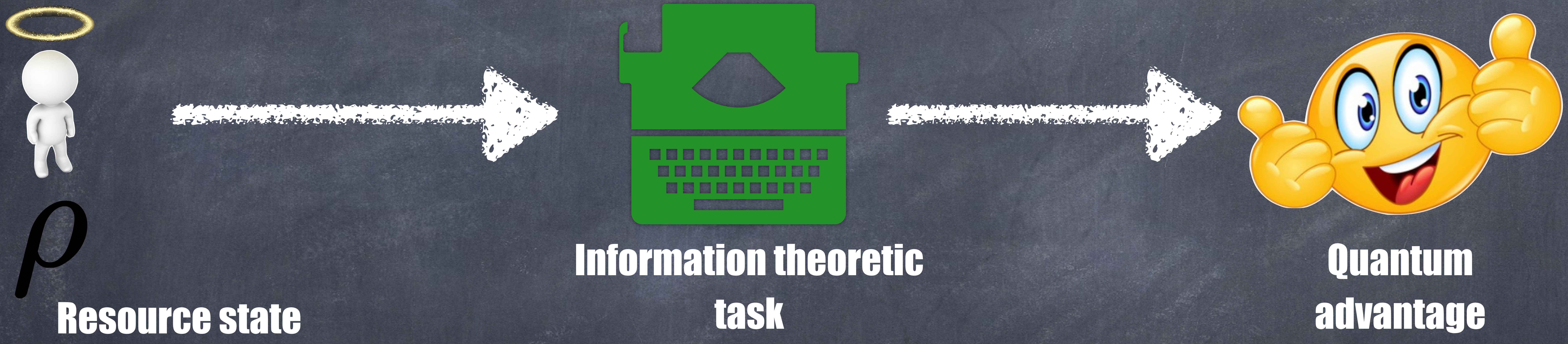


Resource state

Information theoretic task

Quantum advantage

Process resource-breaking channels



$$\mathcal{Q}^{\mathcal{P}}_{\rho} > \mathcal{Q}^{\mathcal{P}}_{\mathrm{cl}} \text{ with } \mathcal{M}(\rho) > 0$$

$$\text{e.g. } DCC > \log_2 d_A, F > \frac{2}{d+1}$$

Phys. Rev. Lett. 69, 2881 (1992)

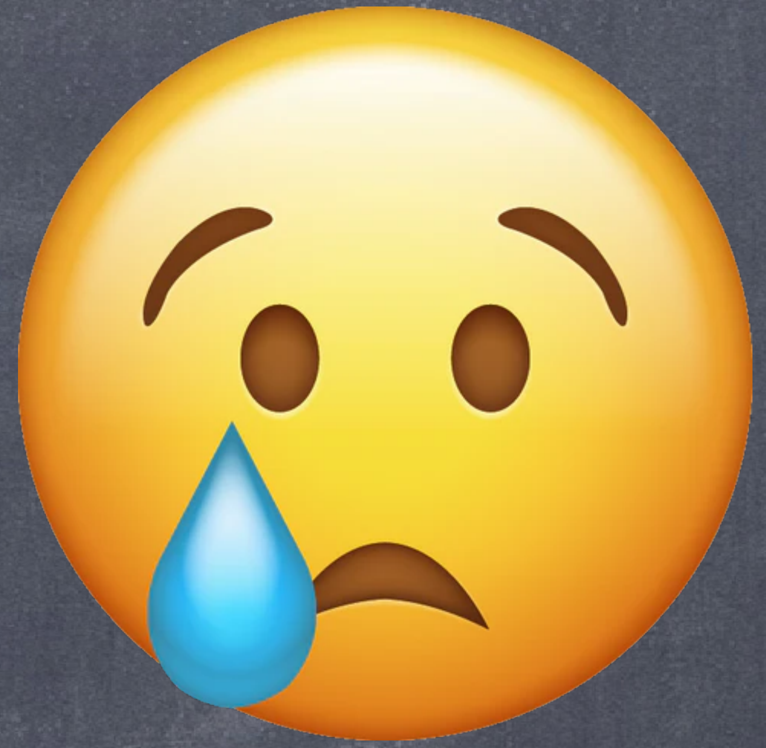
Phys. Rev. Lett. 70, 1895 (1993)

Process resource-breaking channels

$(\Lambda_{\text{PBT}} \otimes \mathbb{I})\rho$

Resource state

Information theoretic task



No quantum advantage

$$Q^{\mathcal{P}}_{\rho} \leq Q^{\mathcal{P}}_{\text{cl}} \text{ with } \mathcal{M}(\rho) > 0$$

$$\text{e.g. } DCC \leq \log_2 d_A, F \leq \frac{2}{d+1}$$

arxiv: 2309.03108

A. Muhuri, A. Patra, **R.G.**, A. Sen (De)

Process - Universal Quantum Computation

Process - Universal Quantum Computation

Non-stabilizerness

Process - Universal Quantum Computation

Non-stabilizerness

Magic

Process - Universal Quantum Computation

Hinder UQC ⟶
Magic-breaking channels

arxiv: 2409.04425

A. Patra, **R.G.**, A. Ferraro, A. Sen (De)

Bucket List

- Define magic-breaking channels (MB)
- Properties of MB independent of dimension
- Geometry of qubit channels (preprequisite)
- Single-qubit MB – necessary and sufficient conditions
- Different classes of MB
- Multi-qubit MB

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Magic-breaking channels : Definition

$$\mathscr{M} = \left\{ \Lambda^{\mathbb{C}^d \to \mathbb{C}^d} : \Lambda^{\mathbb{C}^d \to \mathbb{C}^d}(\rho) \in STAB(\mathbb{C}^d) \forall \rho \in \mathbb{C}^d \right\}$$

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convert any input state to stabilizer state at output

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convert any input state to stabilizer state at output

- necessary for fault tolerance
- efficiently simulable on classical computers

Group22: Procs. of the XXII Int. Coll. on Group Theoretical Methods in Physics

Magic-breaking channels : Definition

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Magic-breaking

$$\tilde{\mathscr{M}} = \left\{ \Lambda^{\mathbb{C}^d \to \mathbb{C}^d} : U_{NC} \circ \Lambda^{\mathbb{C}^d \to \mathbb{C}^d}(\rho) \in STAB(\mathbb{C}^d) \forall \rho \in \mathbb{C}^d \right\}$$

Strictly magic-breaking

convert any input state to stabilizer state at output even with non-Clifford post-processing

(similar to absolute separable states Phys. Rev. A. 63, 032307 (2001))

Bucket List

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Properties

- Unitaries can never be MB

Properties

- Unitaries can never be MB

STAB is a discrete and finite set in any dimension

Unitaries involve infinitesimal rotations as well

=> cannot always transform any state to a stabilizer

Properties

-
- Channels destroying magic of pure states can do so for all states

$$\rho = \sum_i p_i |\psi_i\rangle\langle\psi_i| \text{ and STAB is convex}$$

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-

- Channels destroying magic of pure states can do so for all states

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Does not hold for breaking channels in non-convex resource theories

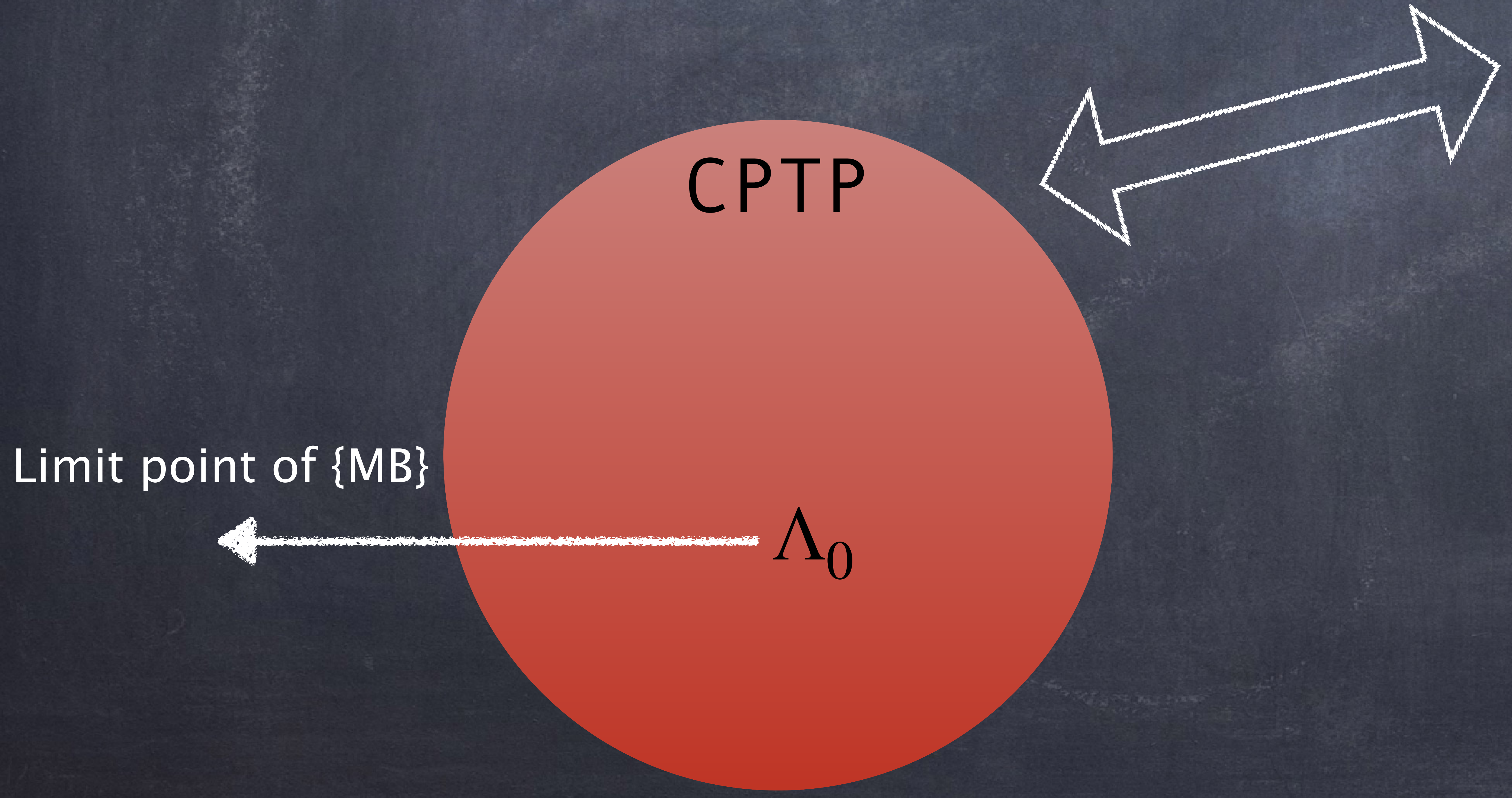
Properties

- MB channels form a convex and compact set

$\Longleftrightarrow$ STAB is convex

Properties

- MB channels form a convex and compact set



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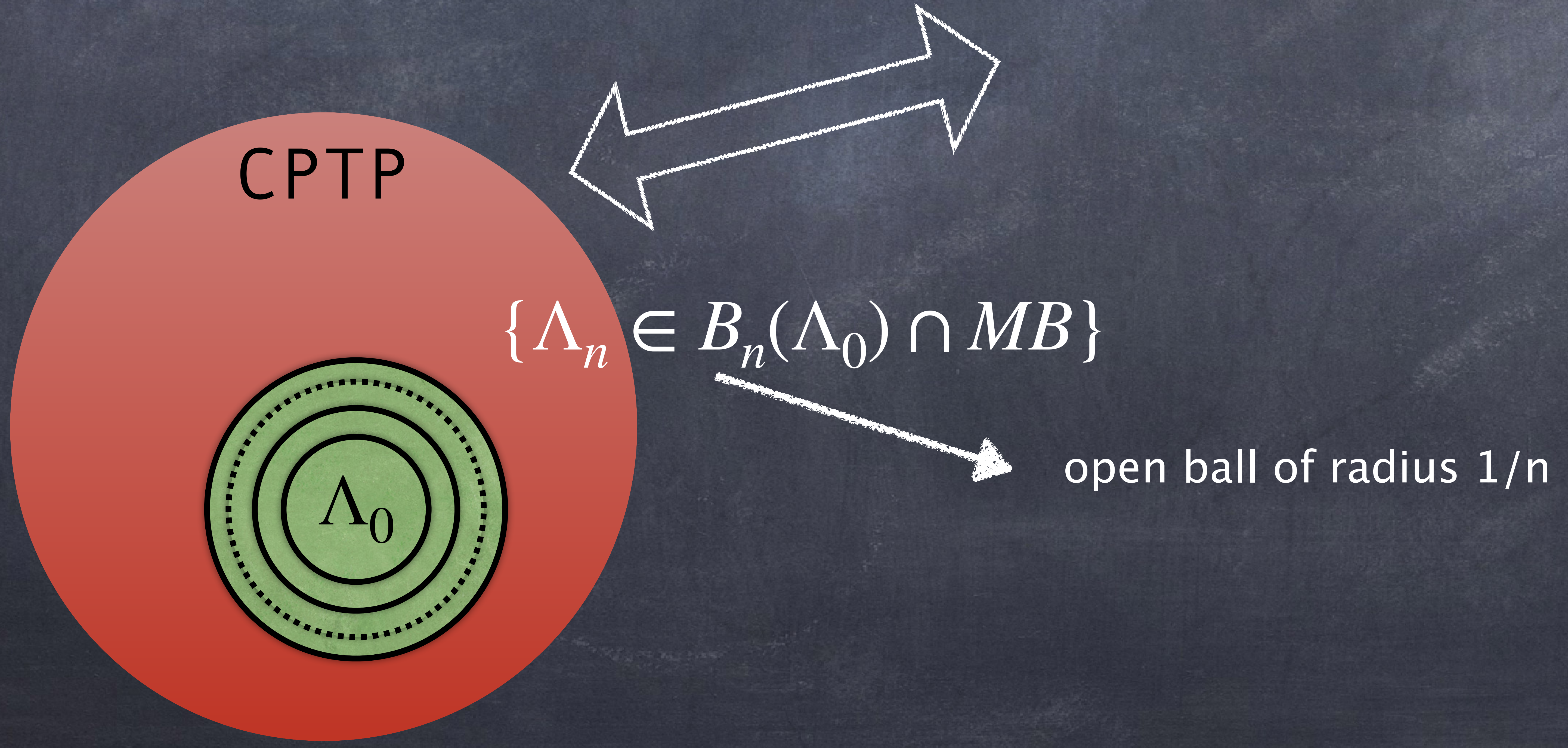

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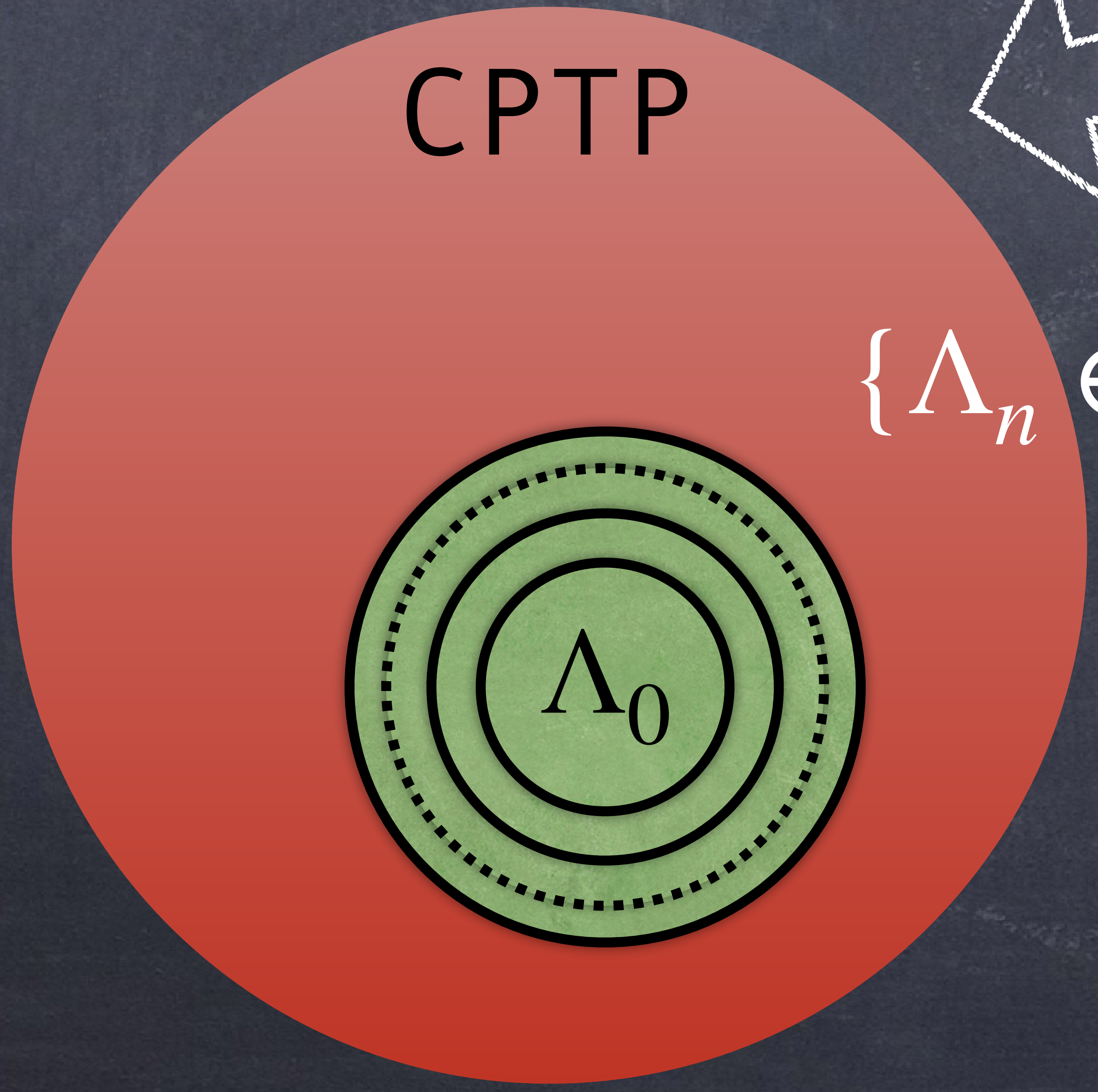


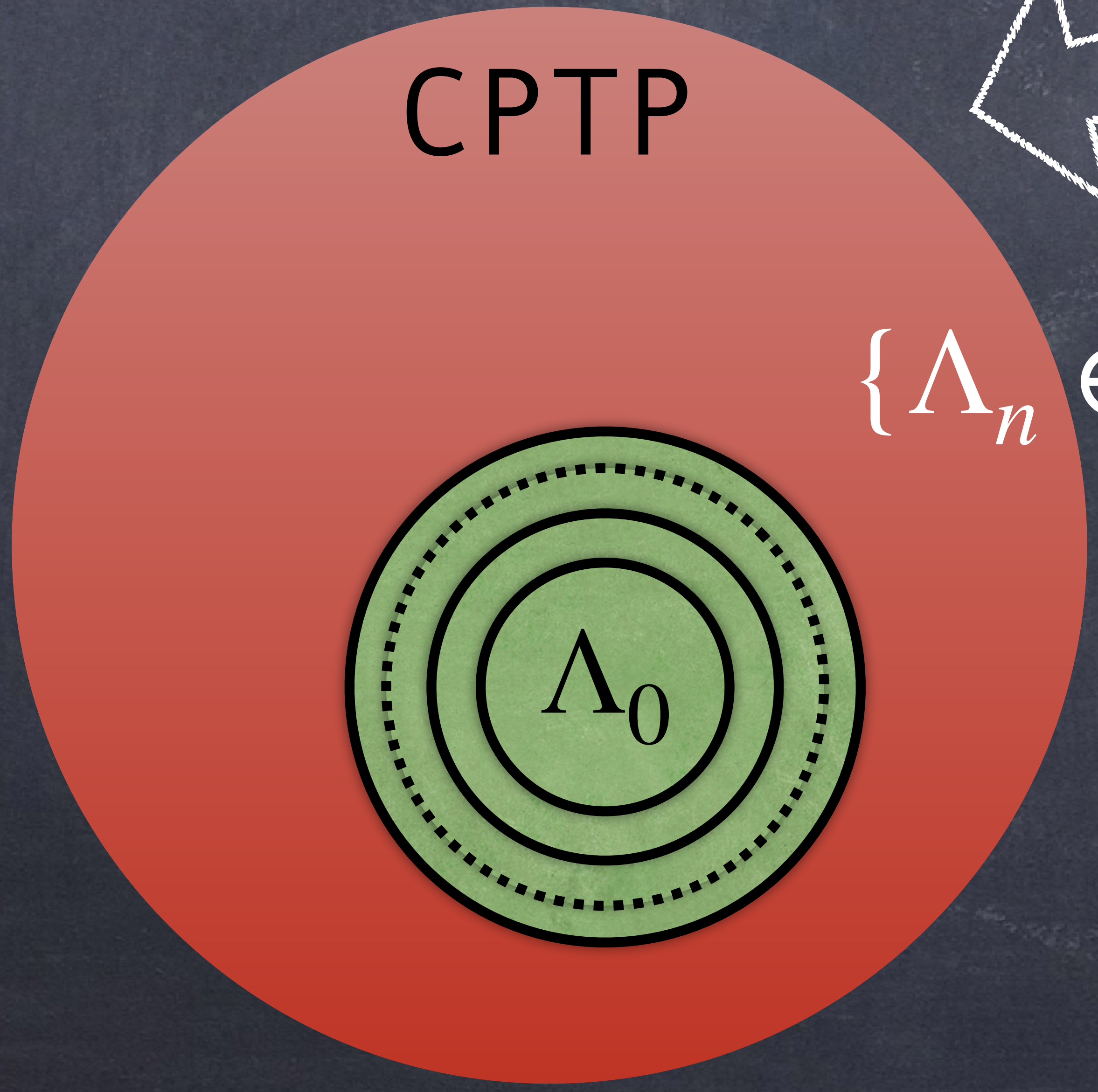
$\{\Lambda_n \in B_n(\Lambda_0) \cap MB\}$

open ball of radius 1/n

$\lim_{n\to\infty} \Lambda_n \to \Lambda_0$

Properties

- MB channels form a convex and compact set



$$\{\Lambda_n \in B_n(\Lambda_0) \cap MB\}$$

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$$\{\tau_n = \Lambda_n(\rho) \in \text{STAB}\}$$

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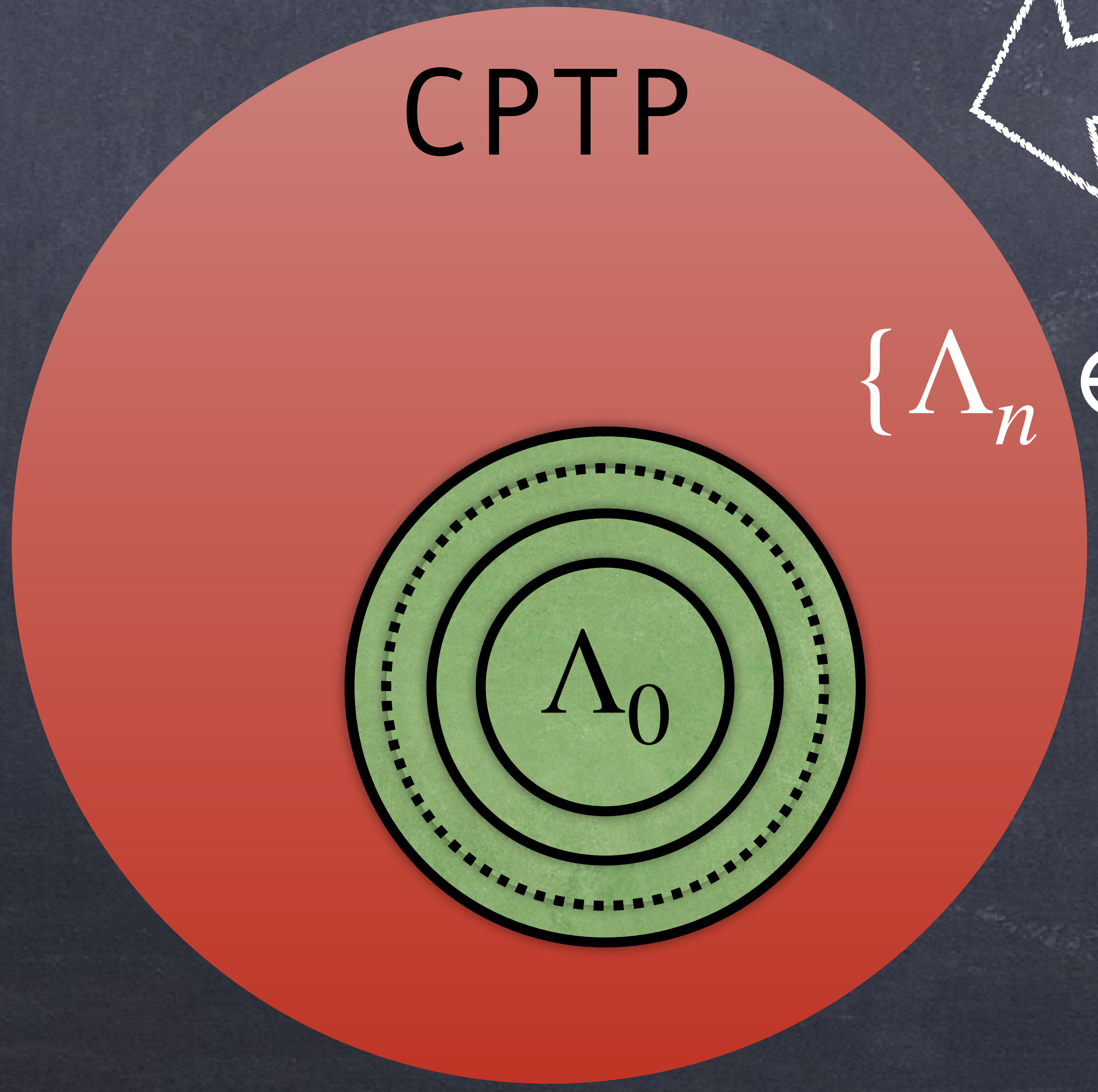

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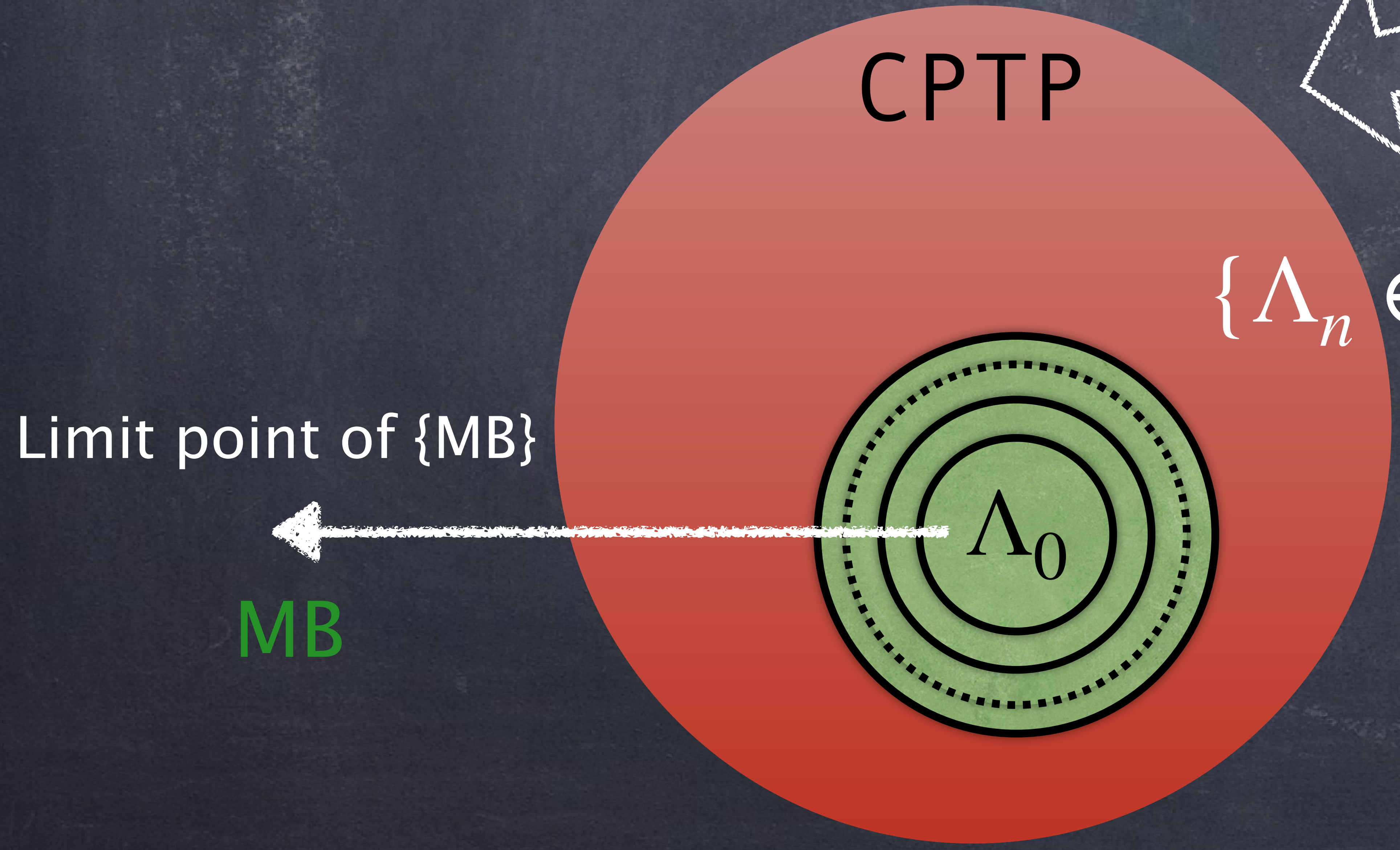

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Properties

- Extreme points of {MB} contain measure-preapre channels preparing non-orthogonal stabilizer states

$$\sum_k |\eta_k\rangle\langle\eta_k|\langle e_k|\rho|e_k\rangle : \langle e_j|e_k\rangle = \delta_{jk} \;\&\; \langle\eta_j|\eta_k\rangle \neq 0$$

Extreme CQ channels preparing non-orthogonal states are extreme CPTP maps

Rev. Math. Phys. 15, 629 (2003)

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Qubit channels - geometric analysis

Lin. Alg. Appl. 347 159 (2002)

$$\Lambda = U_{post} \circ \Lambda_C \circ U_{pre}$$

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Gives valid state - Can ignore this

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Gives valid state - Can ignore this

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ t_1 & \lambda_1 & 0 & 0 \\ t_2 & 0 & \lambda_2 & 0 \\ t_3 & 0 & 0 & \lambda_3 \end{pmatrix}$$

Qubit channels - geometric analysis

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$$\Lambda = U_{post} \circ \Lambda_C \circ U_{pre}$$

Gives valid state - Can ignore this

$$\begin{pmatrix} \cos\frac{\theta}{2} e^{i(2\pi-\phi-\psi)/2} & i\sin\frac{\theta}{2} e^{-i(\phi-\psi)/2} \\ i\sin\frac{\theta}{2} e^{i(\phi-\psi)/2} & \cos\frac{\theta}{2} e^{-i(2\pi-\phi-\psi)/2} \end{pmatrix}$$

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ t_1 & \lambda_1 & 0 & 0 \\ t_2 & 0 & \lambda_2 & 0 \\ t_3 & 0 & 0 & \lambda_3 \end{pmatrix}$$

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$$\rho(\{m_i\}) = \frac{1}{2}(\mathbb{I}_2 + \sum_i m_i \sigma_i)$$

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$$\rho(\{m_i\}) = \frac{1}{2}(\mathbb{I}_2 + \sum_i m_i \sigma_i) \xrightarrow{\Lambda_C} \rho(\{m_i'\}) = \frac{1}{2}(\mathbb{I}_2 + \sum_i m_i' \sigma_i)$$

$$m_i'(m_i, \lambda_i, t_i) = \lambda_i m_i + t_i$$

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$$m_i'(m_i, \lambda_i, t_i) = \lambda_i m_i + t_i$$

$$m_i'' = f(m_j', \theta, \phi, \psi)$$

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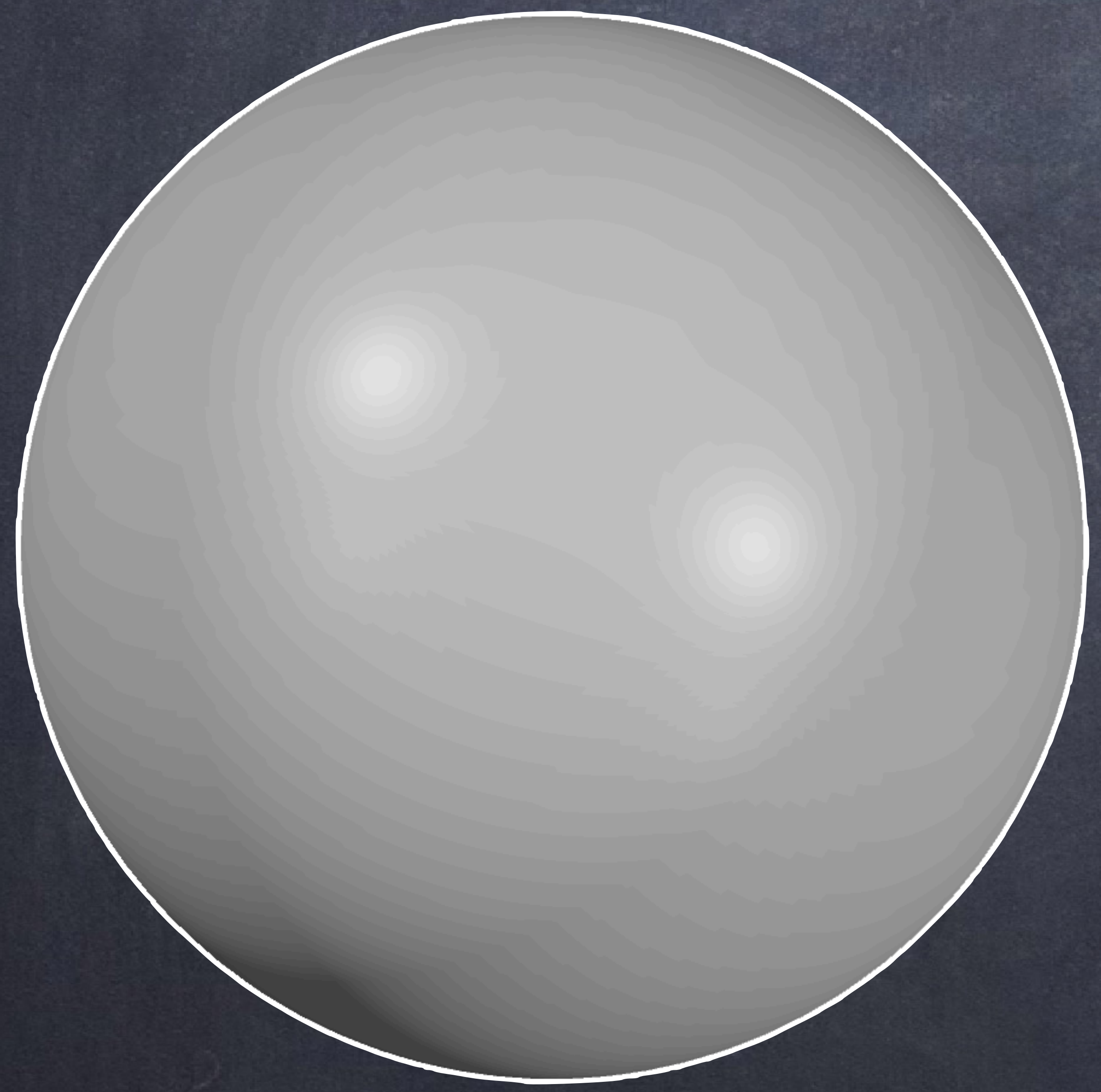

Sphere

Qubit channels - geometric analysis

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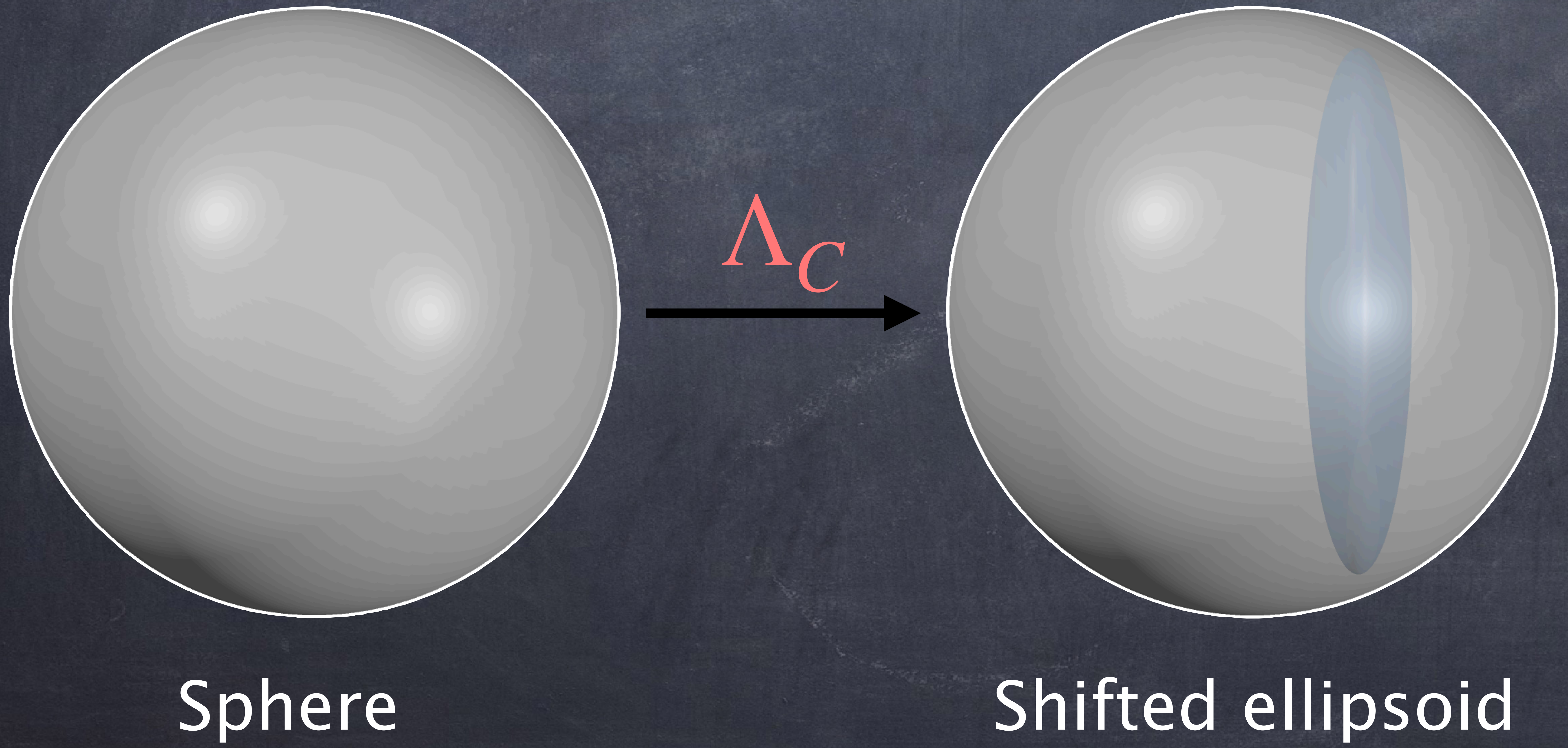

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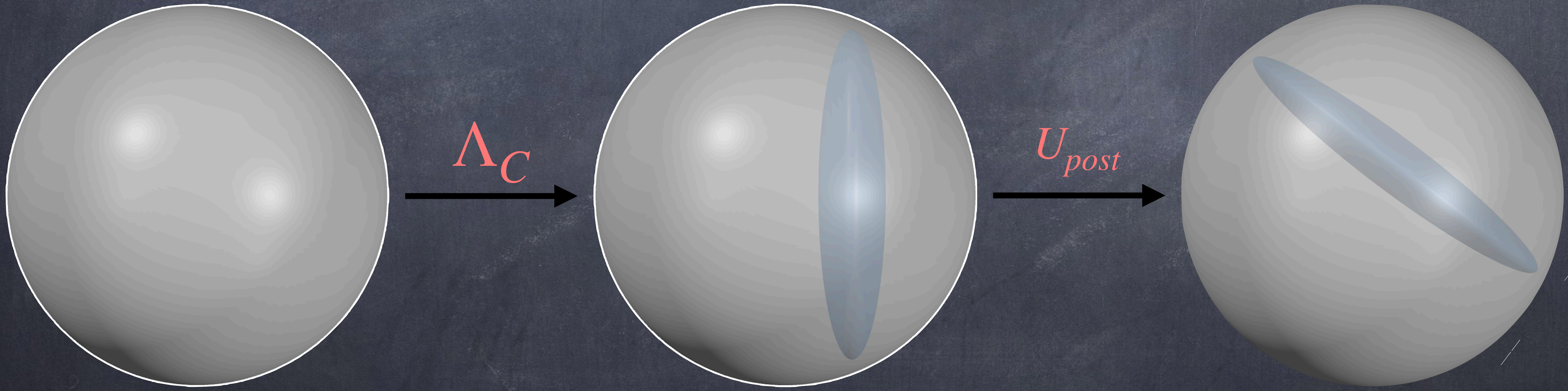


Sphere | Shifted ellipsoid | Rotated shifted ellipsoid

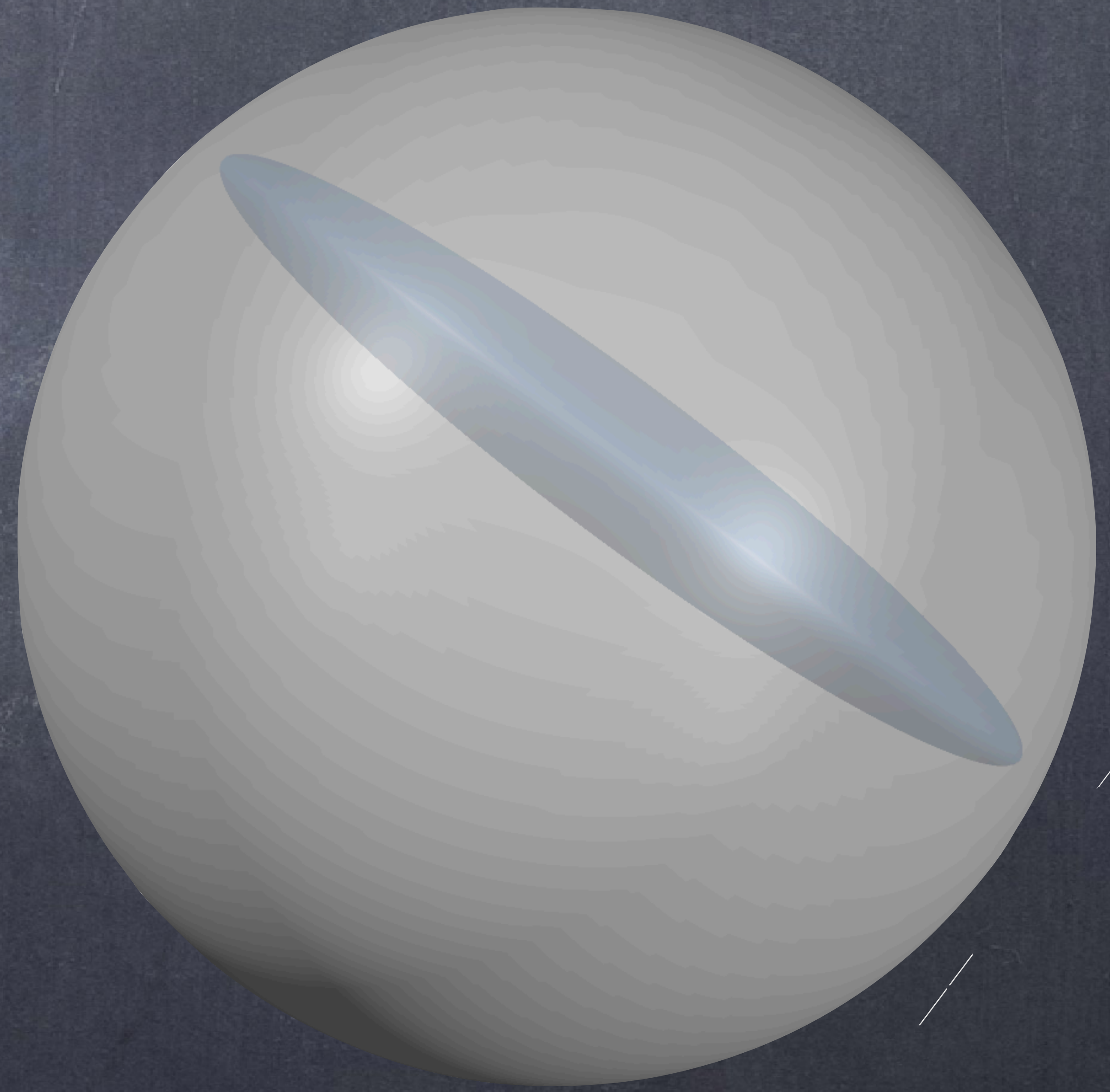
Qubit channels - geometric analysis

$$\Lambda = U_{post} \circ \Lambda_C \circ U_{pre}$$

$$\mu_1 = \frac{\sin\psi\left(m_3''\sin\theta + \cos\theta\left(m_2''\cos\phi - m_1''\sin\phi\right)\right)}{\lambda_1}\frac{\cos\psi\left(m_1''\cos\phi + m_2''\sin\phi\right)}{\lambda_1} - \frac{t_1}{\lambda_1}$$

$$\mu_2 = \frac{m_3''\cos\psi\sin\theta - \sin\psi\left(m_1''\cos\phi + m_2''\sin\phi\right)}{\lambda_2}\frac{\cos\theta\cos\psi\left(m_2''\cos\phi - m_1''\sin\phi\right)}{\lambda_2} - \frac{t_2}{\lambda_2},$$

$$\mu_3 = \frac{\cos\theta\left(m_3'' - m_2''\cos\phi\tan\theta + m_1''\sin\phi\tan\theta\right)}{\lambda_3}\frac{t_3}{\lambda_3}$$



Rotated shifted ellipsoid

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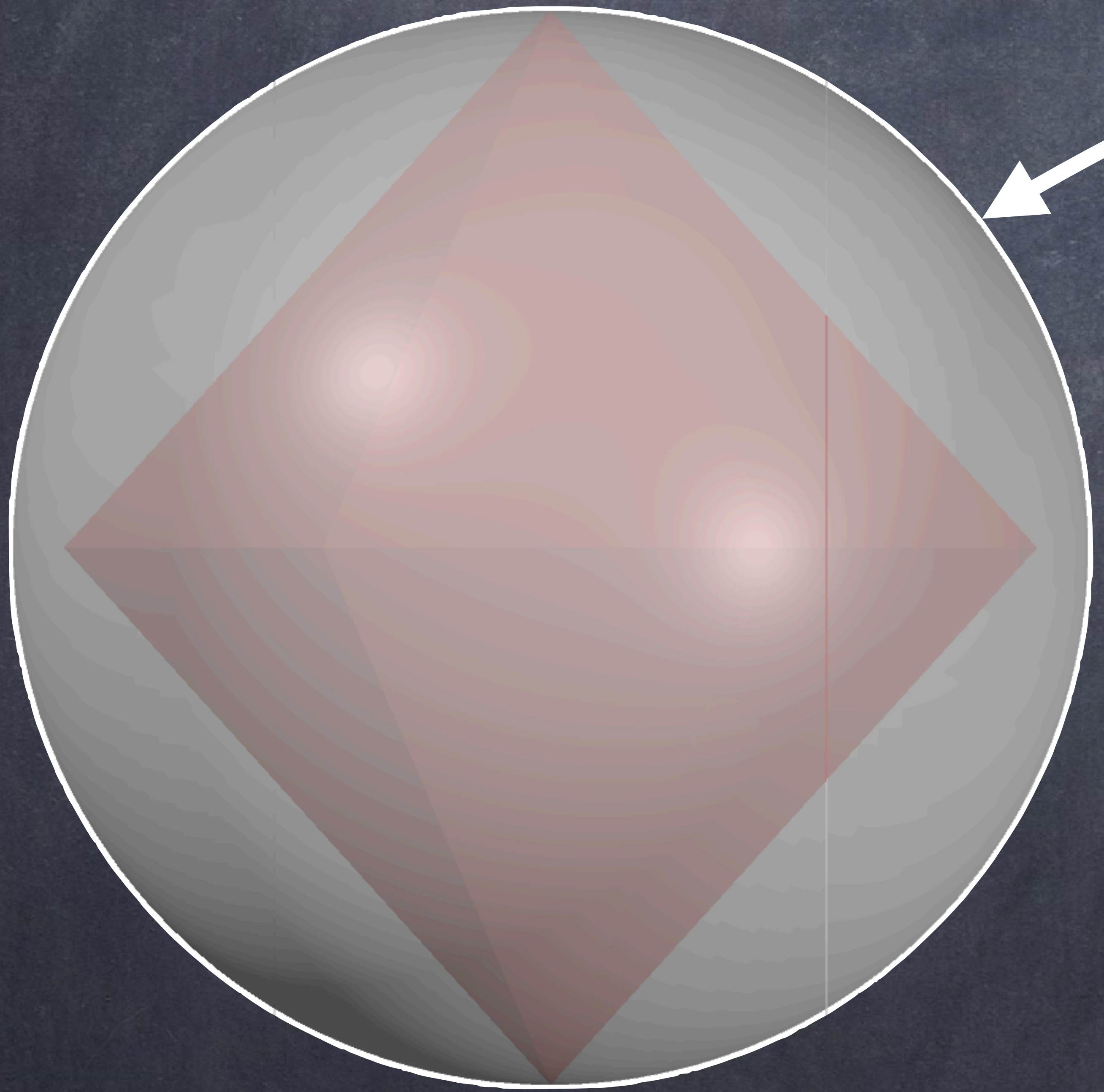
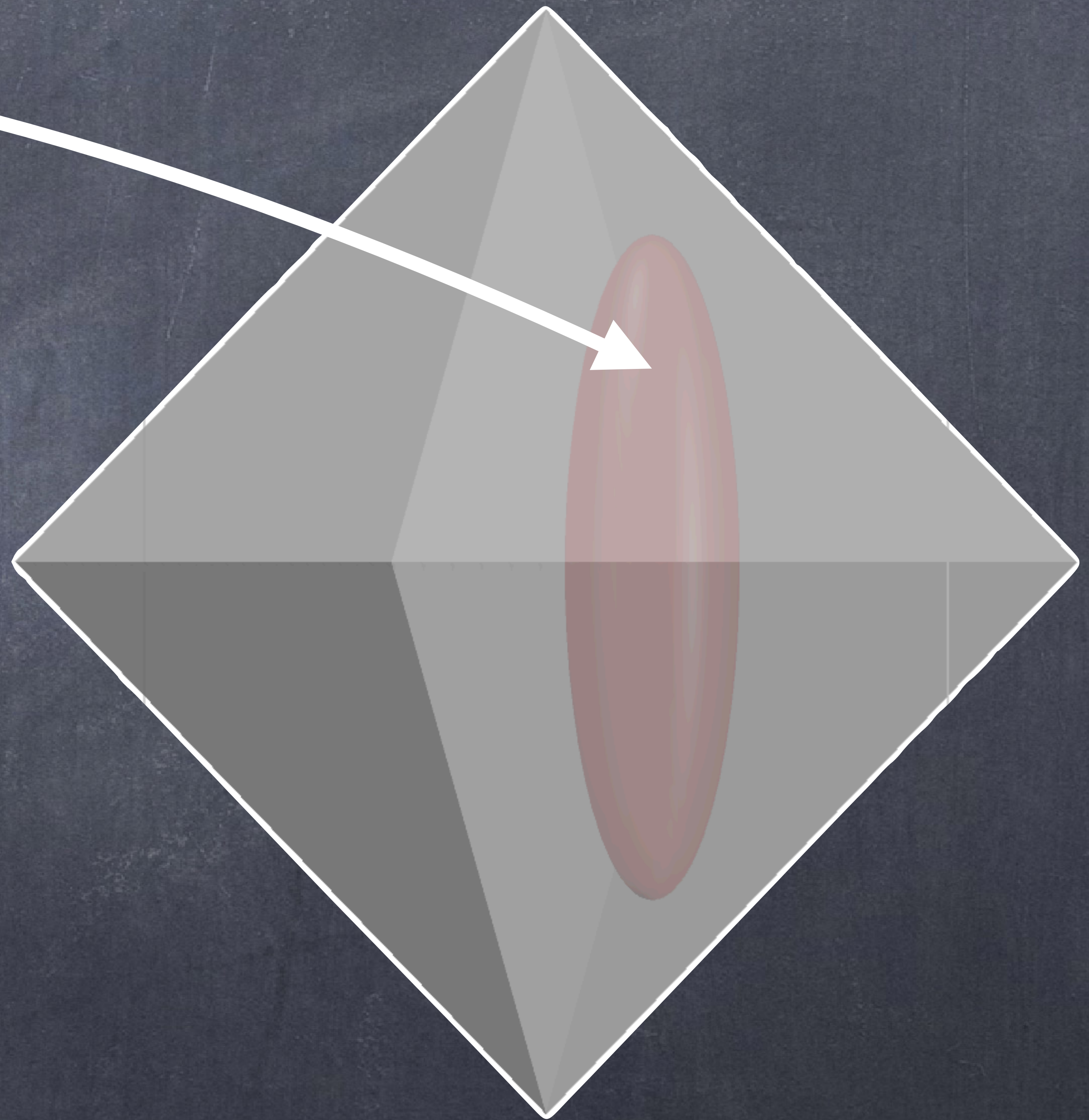
Qubit MB channels – geometric analysis



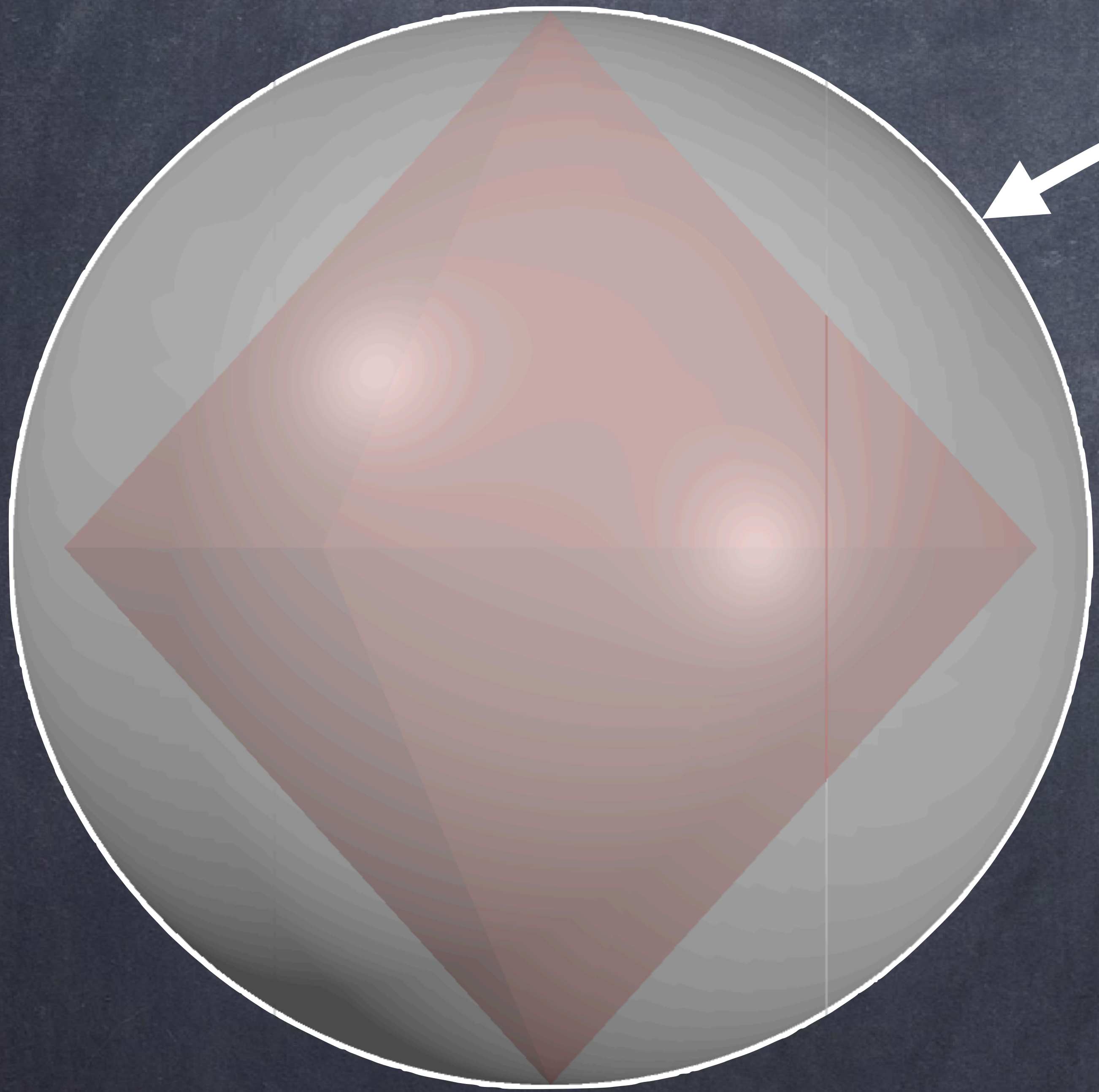
Stabilizer polytope
(useless states for UQC)

$$\Lambda_{MB}(\rho) \in STAB$$



Rotated shifted ellipsoid
within stabilizer polytope

Qubit MB channels - geometric analysis



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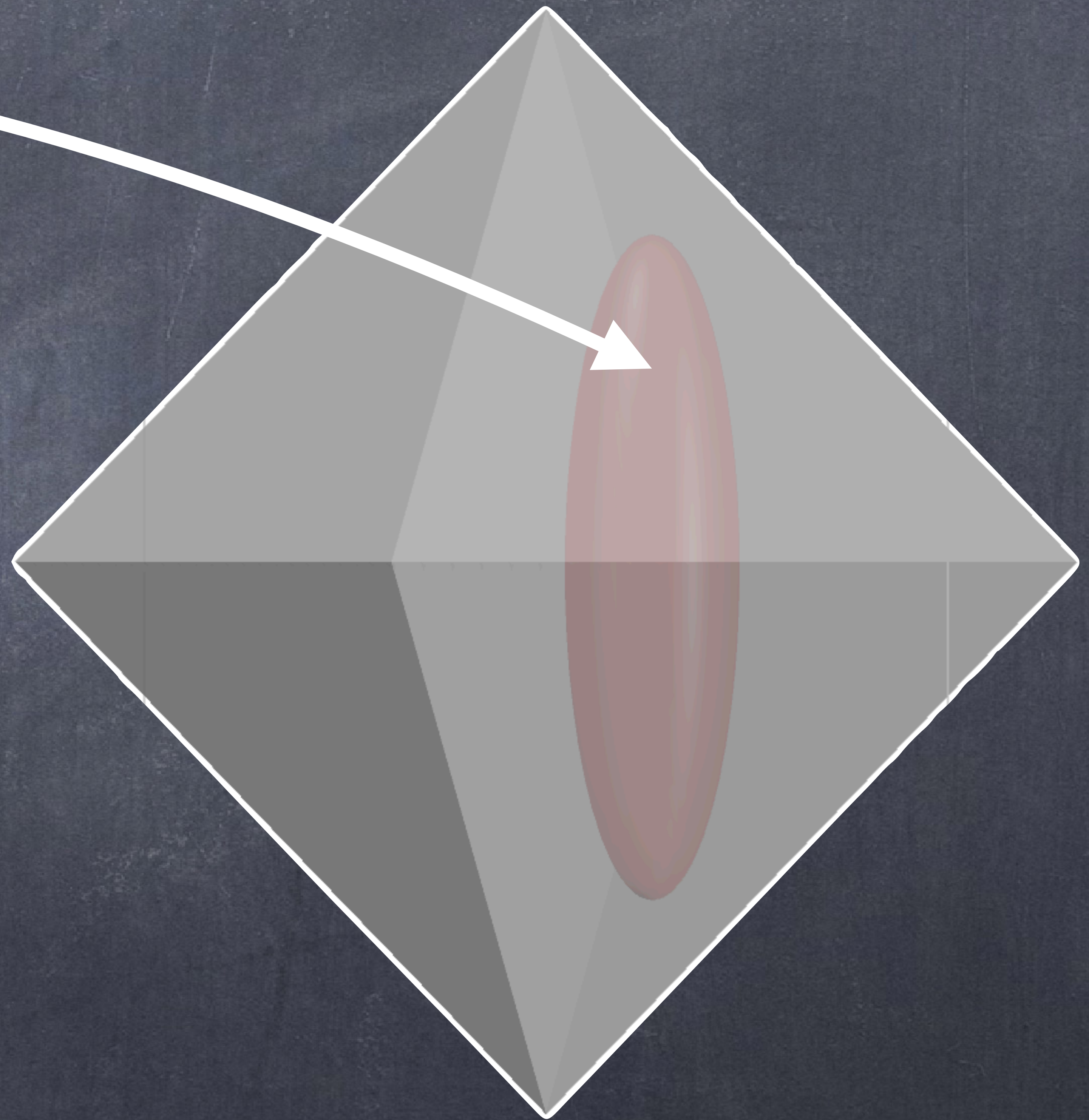

Rotated shifted ellipsoid
within stabilizer polytope

Condition for MB

Simultaneously solve the rotated shifted ellipsoid and the stabilizer polytope equations

Condition for MB

Simultaneously solve the rotated shifted ellipsoid and the stabilizer polytope equations

- Solve ellipsoid with $m_1'' + m_2'' + m_3'' = 1$

$$m_j'' = f_j(m_1'', \{\lambda_k, t_k\}, \theta, \phi, \psi) \pm \sqrt{\alpha m_1''^2 + \beta m_1'' + \gamma}$$

Condition for MB

Simultaneously solve the rotated shifted ellipsoid and the stabilizer polytope equations

-

- Magic broken iff ellipsoid entirely within the polytope – finite or no simultaneous solutions

$$\alpha m_1''^2 + \beta m_1'' + \gamma \leq 0$$

Condition for MB

Simultaneously solve the rotated shifted ellipsoid and the stabilizer polytope equations

- Magic broken iff ellipsoid entirely within the polytope – finite or no simultaneous solutions

$$\alpha m_1''^2 + \beta m_1'' + \gamma \leq 0$$

$$\begin{cases} \beta^2 - 4\alpha\gamma \leq 0 & \text{if } \alpha < 0 \text{ and } |\frac{\beta}{4\alpha}| \leq 1 \\ \alpha \pm \beta + \gamma \leq 0 & \text{otherwise.} \end{cases}$$

Necessary and sufficient

Condition for MB

Simultaneously solve the rotated shifted ellipsoid and the stabilizer polytope equations

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- Repeat for all polytope faces

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Classes of MB channels

- Strictly magic-breaking

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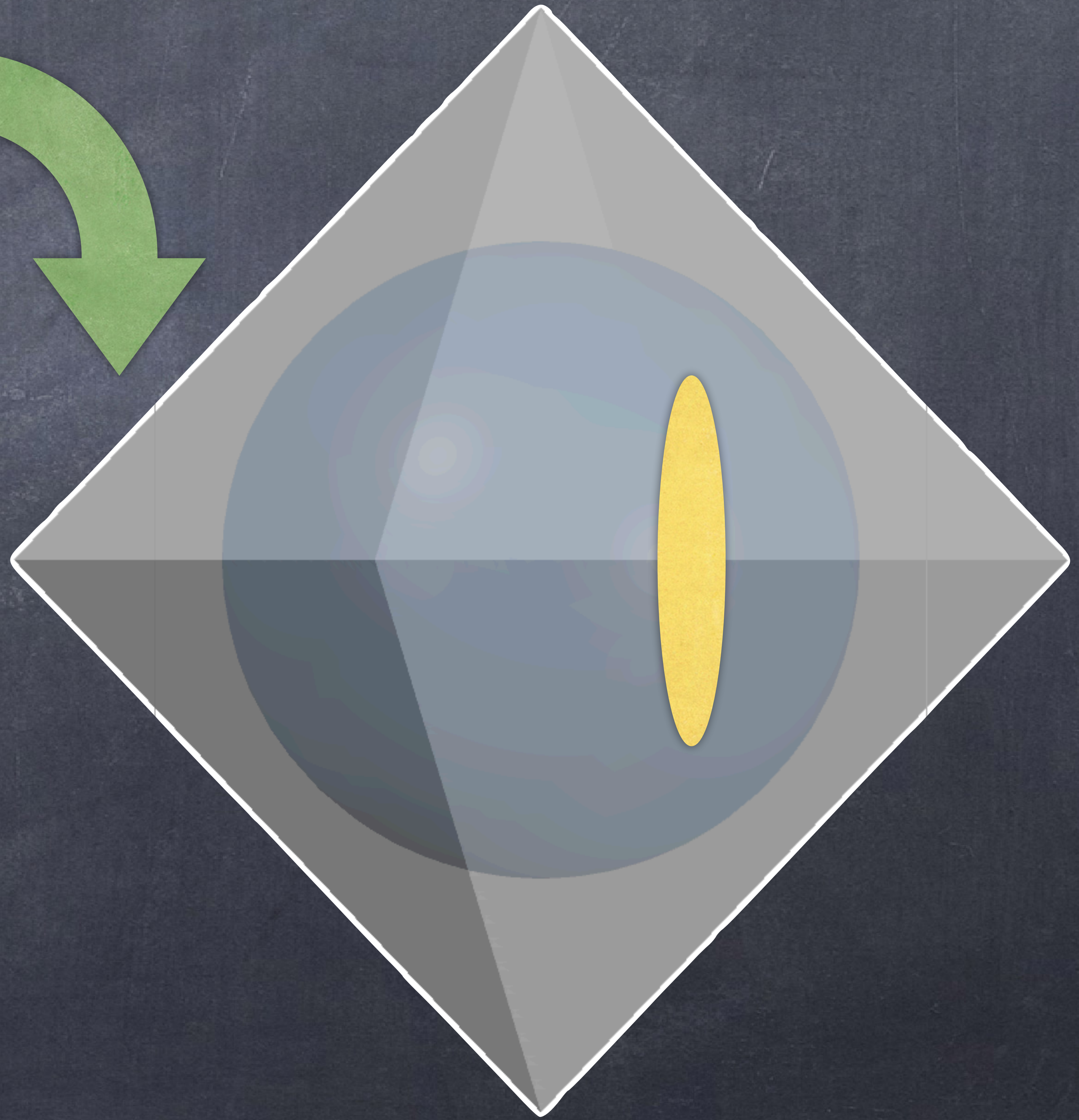
Final ellipsoid inside largest sphere within stabilizer polytope

Classes of MB channels

Strictly magic-breaking

Final ellipsoid inside largest sphere within stabilizer polytope



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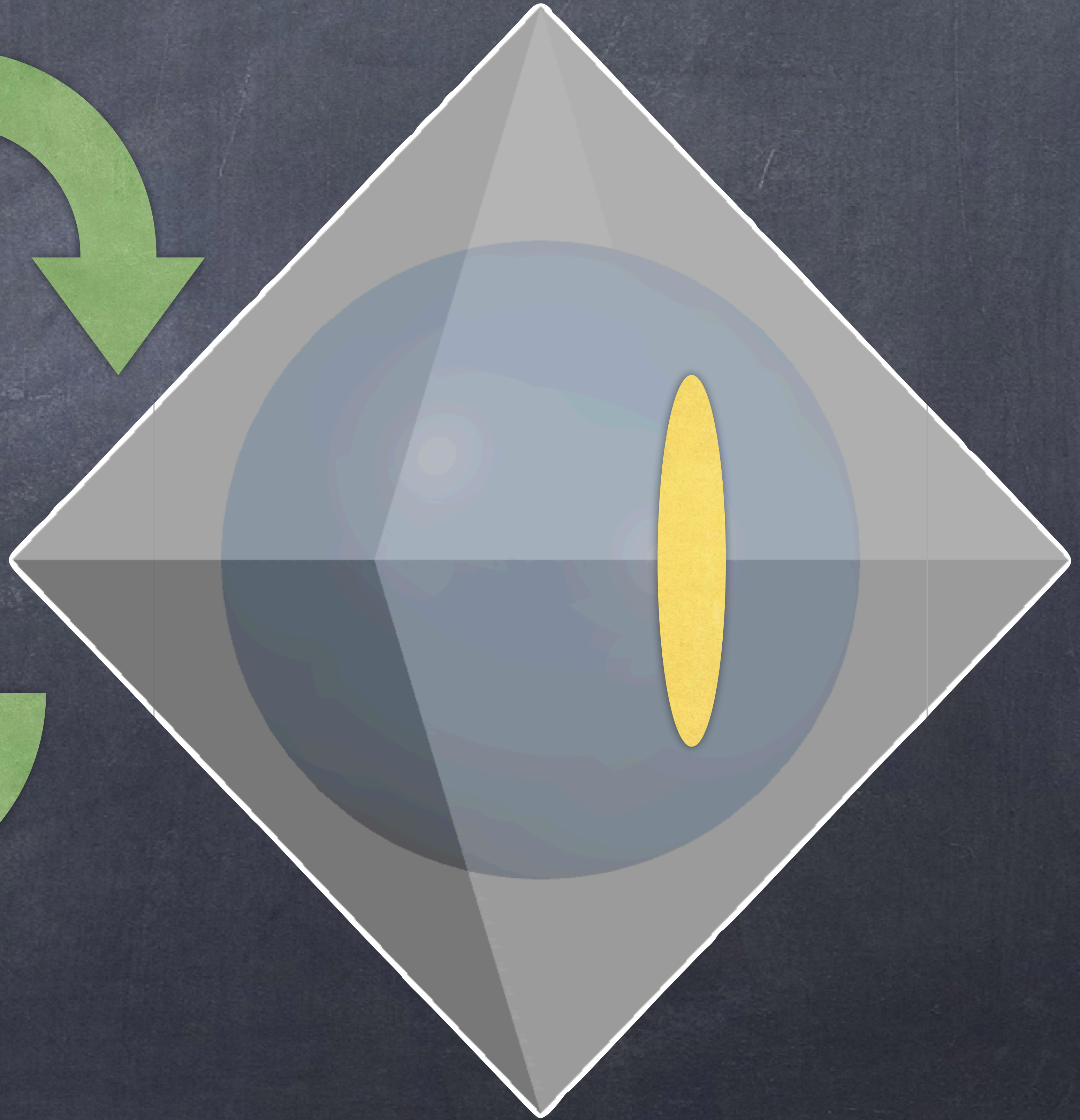
Strictly magic-breaking

Final ellipsoid inside largest sphere within stabilizer polytope



Sufficient

$$|t| + |\lambda_i| \leq \frac{1}{\sqrt{3}} \ \forall\ i : |t| = \sqrt{\sum_k t_k^2}$$

Classes of MB channels

- Channels with Clifford post-processing

Classes of MB channels

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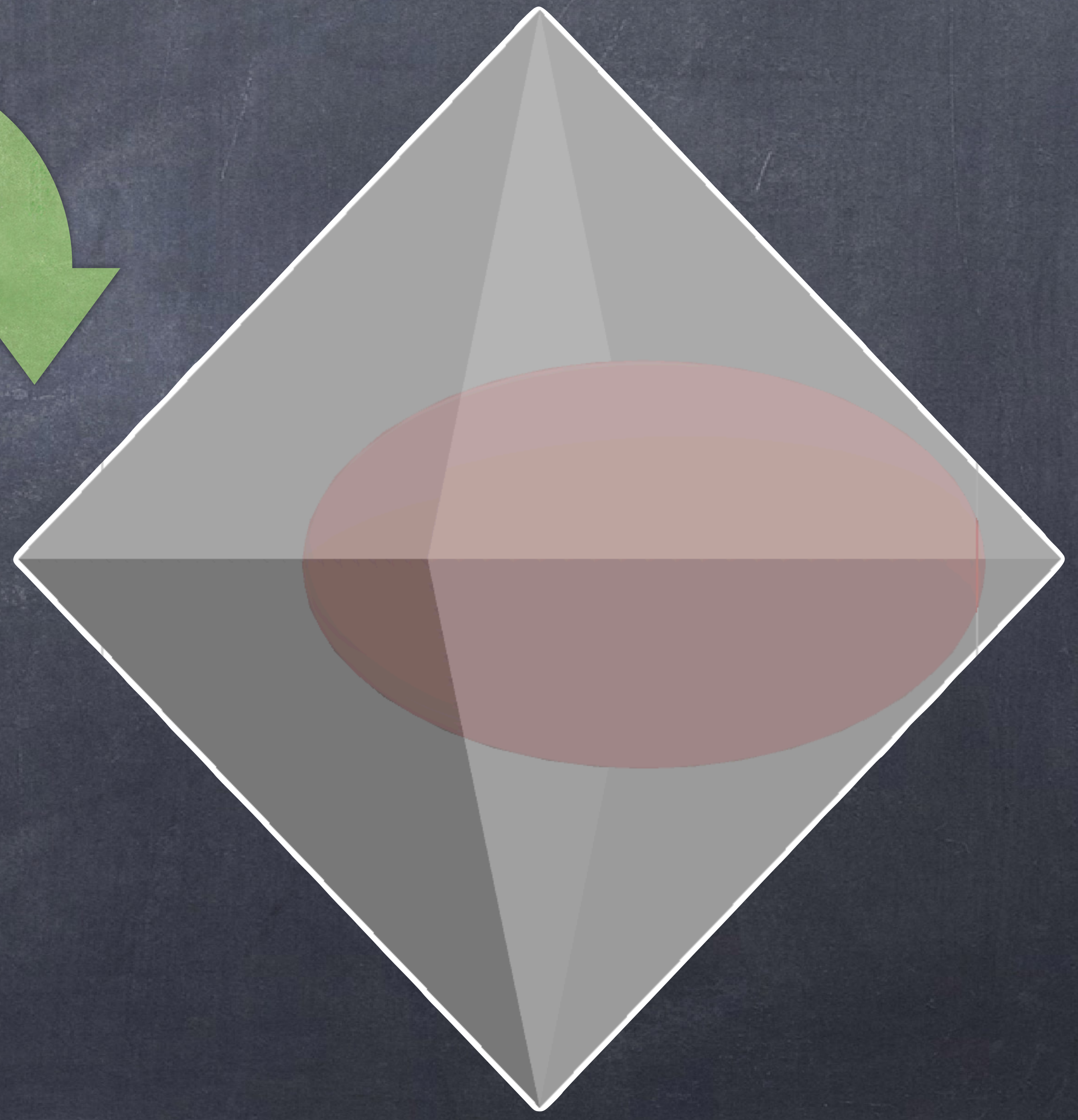
Final ellipsoid within stabilizer polytope

Classes of MB channels

- Channels with Clifford post-processing

Final ellipsoid within stabilizer polytope



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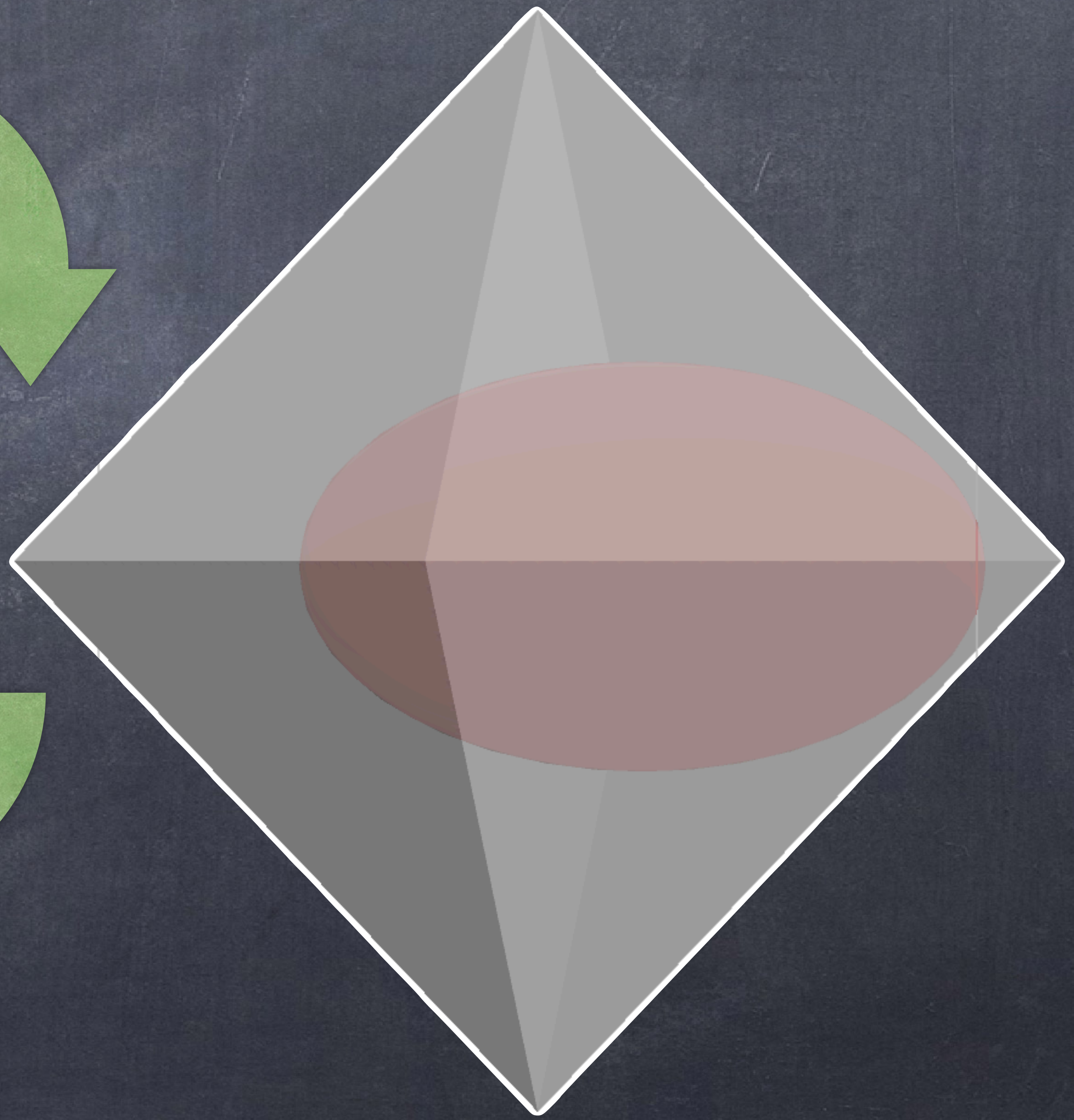
Final ellipsoid within stabilizer polytope

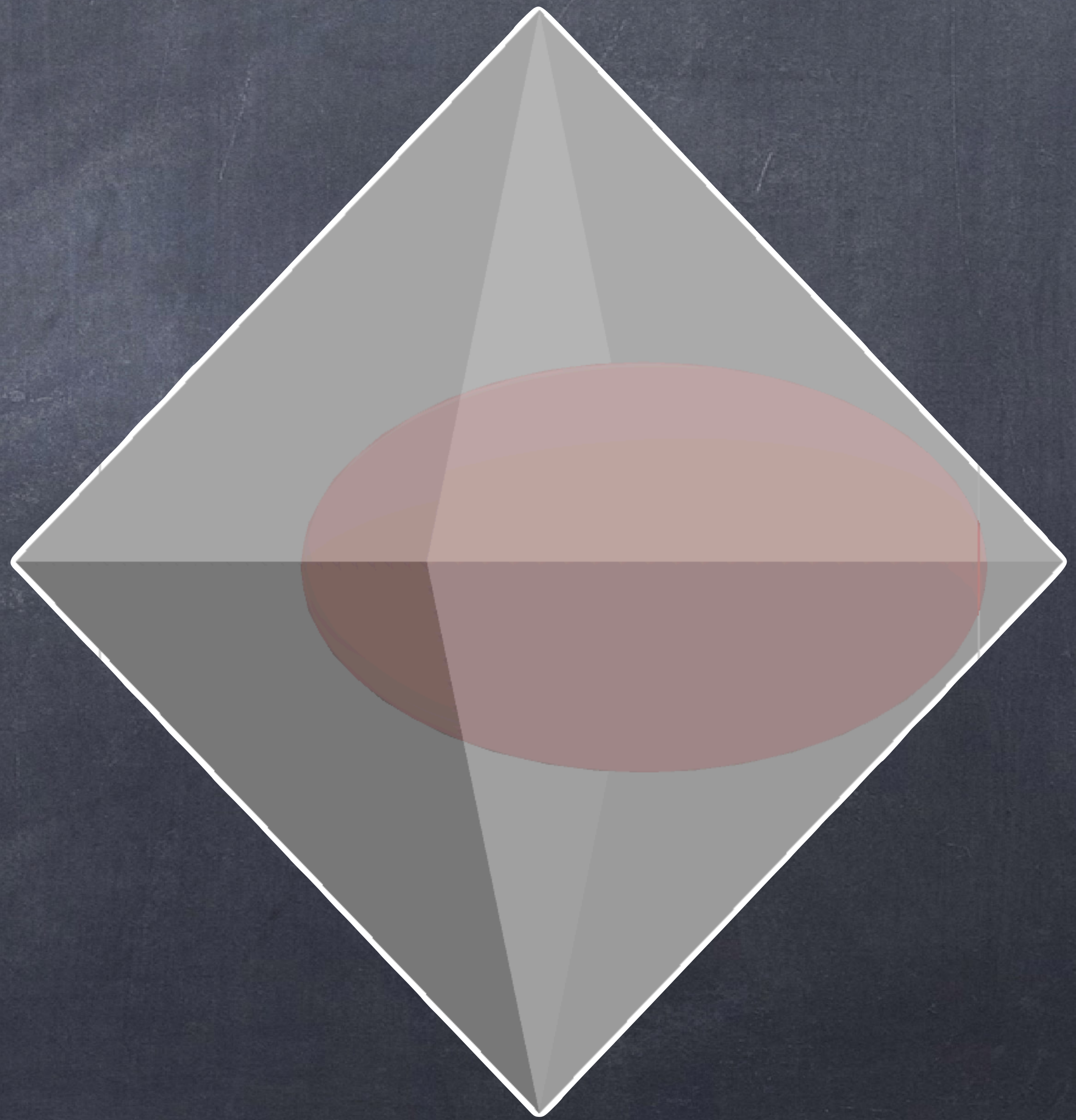


Necessary and sufficient

$$\sum_i \lambda_i^2 \leq (1 - \sum_i |t_k|)^2$$

Classes of MB channels

- Channels with Clifford post-processing - Pauli channels and unital EBT

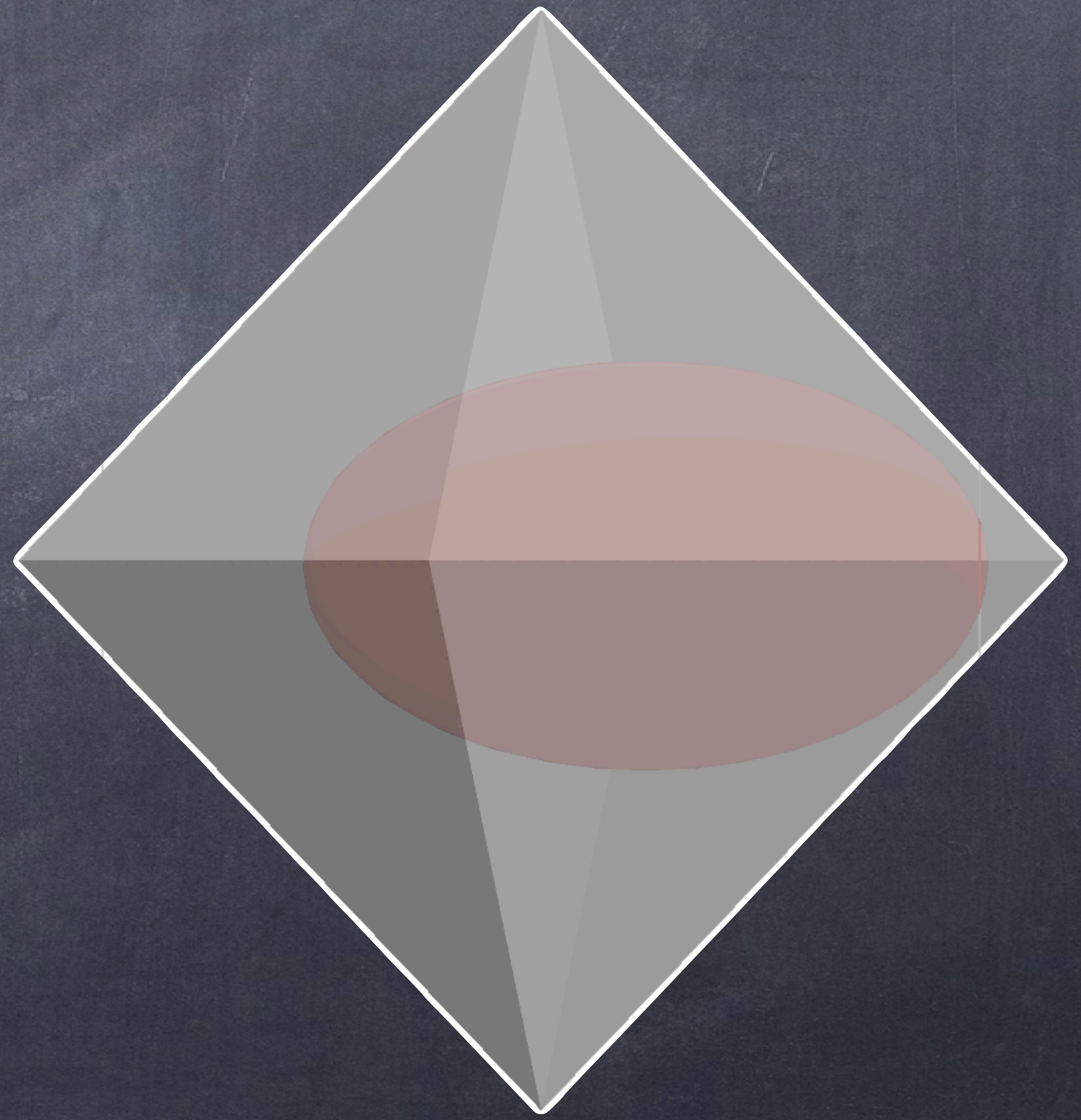


Classes of MB channels

- Channels with Clifford post-processing – Pauli channels and unital EBT

Dephasing

$$\rho \to (1 - p/2)\rho + \frac{p}{2}\sigma_z \rho \sigma_z \; : p = 1$$



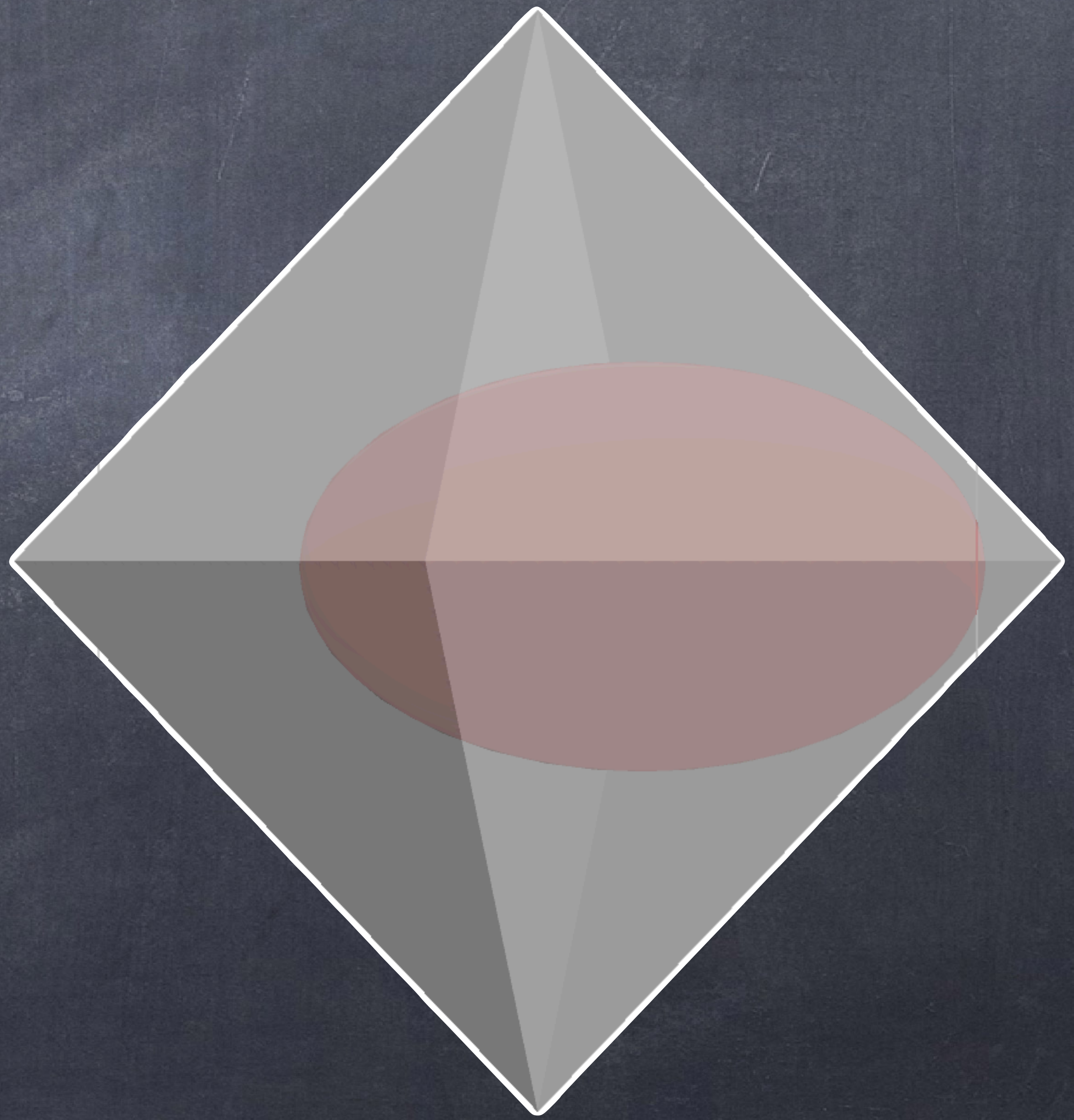
Classes of MB channels

- Channels with Clifford post-processing - Pauli channels and unital EBT

$$\rho \to (1 - p/2)\rho + \frac{p}{2}\sigma_z\rho\sigma_z : p = 1$$

Depolarising

$$\rho \to p\mathbb{1}/2 + (1 - p)\rho : p \geq 1 - 1/\sqrt{3}$$



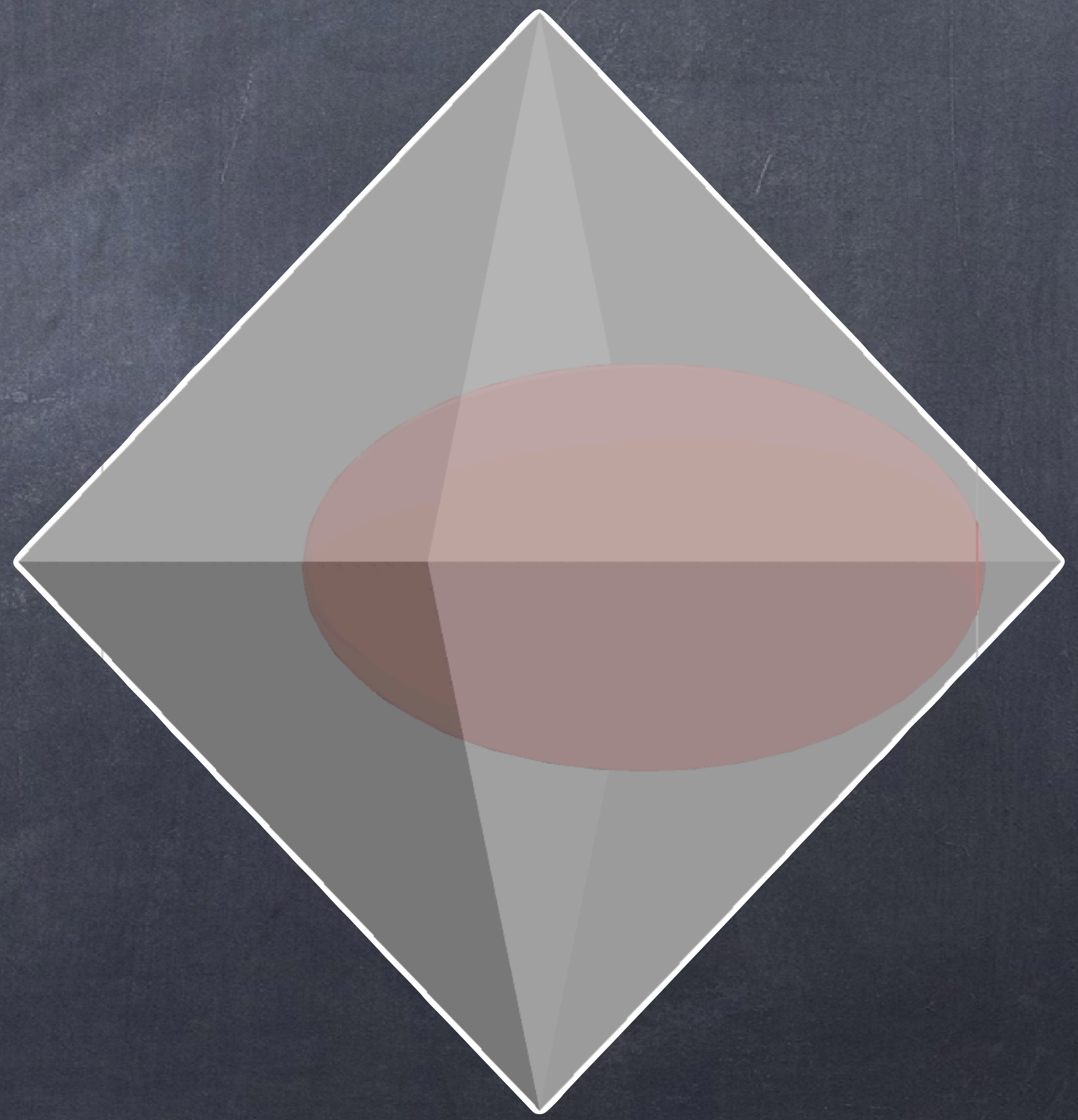
Classes of MB channels

- Channels with Clifford post-processing – Pauli channels and unital EBT

$$\rho \to (1 - p/2)\rho + \frac{p}{2}\sigma_z \rho \sigma_z : p = 1$$

Unital EBT

$$\sum_i |\lambda_i| \leq 1 \implies \sum_i \lambda_i^2 \leq 1 \quad (|\lambda_i| \leq 1)$$



Classes of MB channels

- T-distillability breaking channels ($\mathscr{R}_\rho > 3/\sqrt{7}$: T-distillable)

Classes of MB channels

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Solve for no simultaneous solution of final ellipsoid and $\sum_i |m_i| = 3/\sqrt{7}$

Clifford post-processing

$$\sum_i \lambda_i^2 \leq (\frac{3}{\sqrt{7}} - \sum_i |t_k|)^2$$

Classes of MB channels

T-distillability breaking channels ($\mathscr{R}_\rho > 3/\sqrt{7}$: T-distillable)

Solve for no simultaneous solution of final ellipsoid and $\sum_i |m_i| = 3/\sqrt{7}$

Clifford post-processing

$$\sum_i \lambda_i^2 \leq (\frac{3}{\sqrt{7}} - \sum_i |t_k|)^2$$

Depolarising

$$p \geq 1 - \sqrt{3/7}$$

Dephasing

$$p \geq 0.622$$

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Multiqubit MB channels

Necessary

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Multiqubit MB channels

Necessary

$\otimes_{i=1}^{N} \Lambda_i \in MB$ only if $\Lambda_i \in MB \; \forall \; i$

$$Tr_{\bar{j}}\left[\otimes_{i=1}^{2} \Lambda_i(\rho_{1,2,\ldots j-1,j,j+1,\ldots,N}) \right] = \Lambda_j(\rho_j) \notin STAB$$

Multiqubit MB channels

Necessary

$$\otimes_{i=1}^{N} \Lambda_i \in MB \text{ only if } \Lambda_i \in MB \; \forall \; i$$

$$Tr_{\bar{j}}\left[\otimes_{i=1}^{2} \Lambda_i(\rho_{1,2,\ldots j-1,j,j+1,\ldots,N}) \right] = \Lambda_j(\rho_j) \notin STAB$$

$STAB$

Resource generation through free operation!!

Multiqubit MB channels

Insufficient

$\otimes_{i=1}^{N} \Lambda_i \in MB$ only if $\Lambda_i \in MB \ \forall \ i$

$$\mathscr{R}(\Lambda^{\otimes 2}|\eta\rangle) = 1.0212 : \mathscr{R}(|\eta\rangle) = 1.834$$

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$$\Lambda_C = (\lambda_1 = -0.9, \lambda_2 = -0.3, \lambda_3 = 0.2, \; t_i = 0); U_{post} = \mathbb{I}$$

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$(-0.482 - \imath 0.648)|00\rangle + (0.015 - 0.022\imath)|01\rangle + (-0.131 - 0.098\imath)|10\rangle + (-0.145 - 0.548\imath)|11\rangle$

Multiqubit MB channels: Consequences of insufficiency

- $\otimes_{j=1}^{N} \Lambda_j^{MB}(\sum_i p_i \rho_i^1 \otimes \ldots \otimes \rho_i^N) \in STAB$

Tensor product of MB channels cannot destroy magic present in correlations

Multiqubit MB channels: Consequences of insufficiency

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Tensor product of MB channels cannot destroy magic present in correlations

- $\otimes_{i=1}^{N} \Lambda_i^{MB} \circ \otimes_{j=1}^{N-1} \Lambda_j^{EBT} \in MB$

Multiqubit MB channels: Consequences of insufficiency

-
- Dynamical resource theory of magic preservability : activation of resource preservability

[Quantum 4, 244 (2020)]

Multiqubit MB channels: Consequences of insufficiency

Dynamical resource theory of magic preservability : activation of resource preservability

Quantum 4, 244 (2020)

$\otimes_i \rho_i^{STAB} \in STAB$: {STAB} contitutes *absolutely free states*

no resource activation like non-locality

Multiqubit MB channels: Consequences of insufficiency

Dynamical resource theory of magic preservability : activation of resource preservability

Quantum 4, 244 (2020)

- no resource activation like non-locality
- $\Theta(\mathscr{E}) := \mathscr{P} \circ (\mathscr{E} \otimes \tilde{\Lambda}) \circ \mathscr{Q}$ – superchannel with stabilizer pre– and post–processing

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absolutely magic-breaking channels : $\tilde{\Lambda} \otimes \Lambda^{MB} \in MB$

Multiqubit MB channels: Consequences of insufficiency

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Quantum 4, 244 (2020)

- no resource activation like non-locality
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can destroy magic in correlations - detrimental for UQC

Future directions

- Devise distance-based dynamical resource monotnes

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- Devise distance-based dynamical resource monotnes
- Limitations in practical QC applications

distributed QC : links between quantum processors

blind QC : noisy channel between client and server

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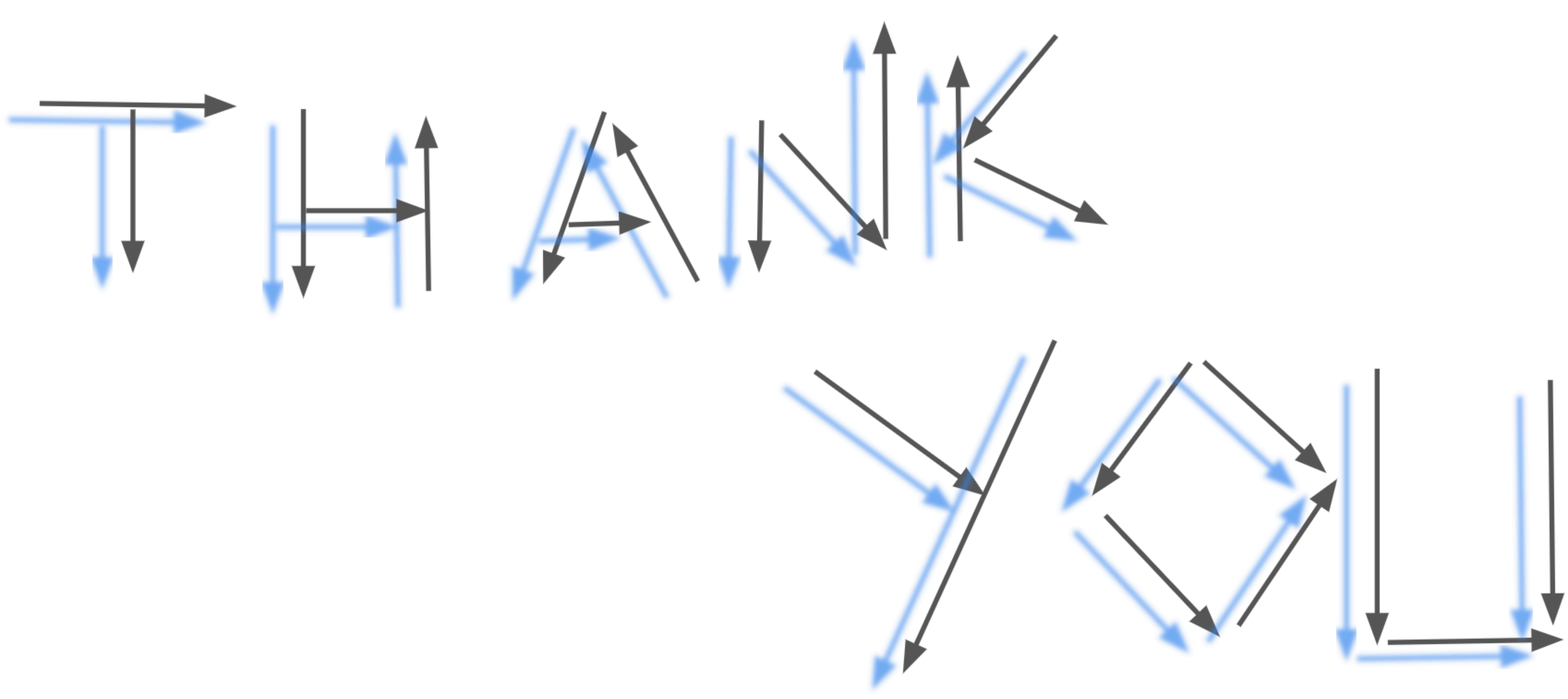
THANK
YOU