Thermal operations from informational equilibrium

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Joint work with:
Seok Hyung Lie (UNIST, South Korea)
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arXiv:2507.16637

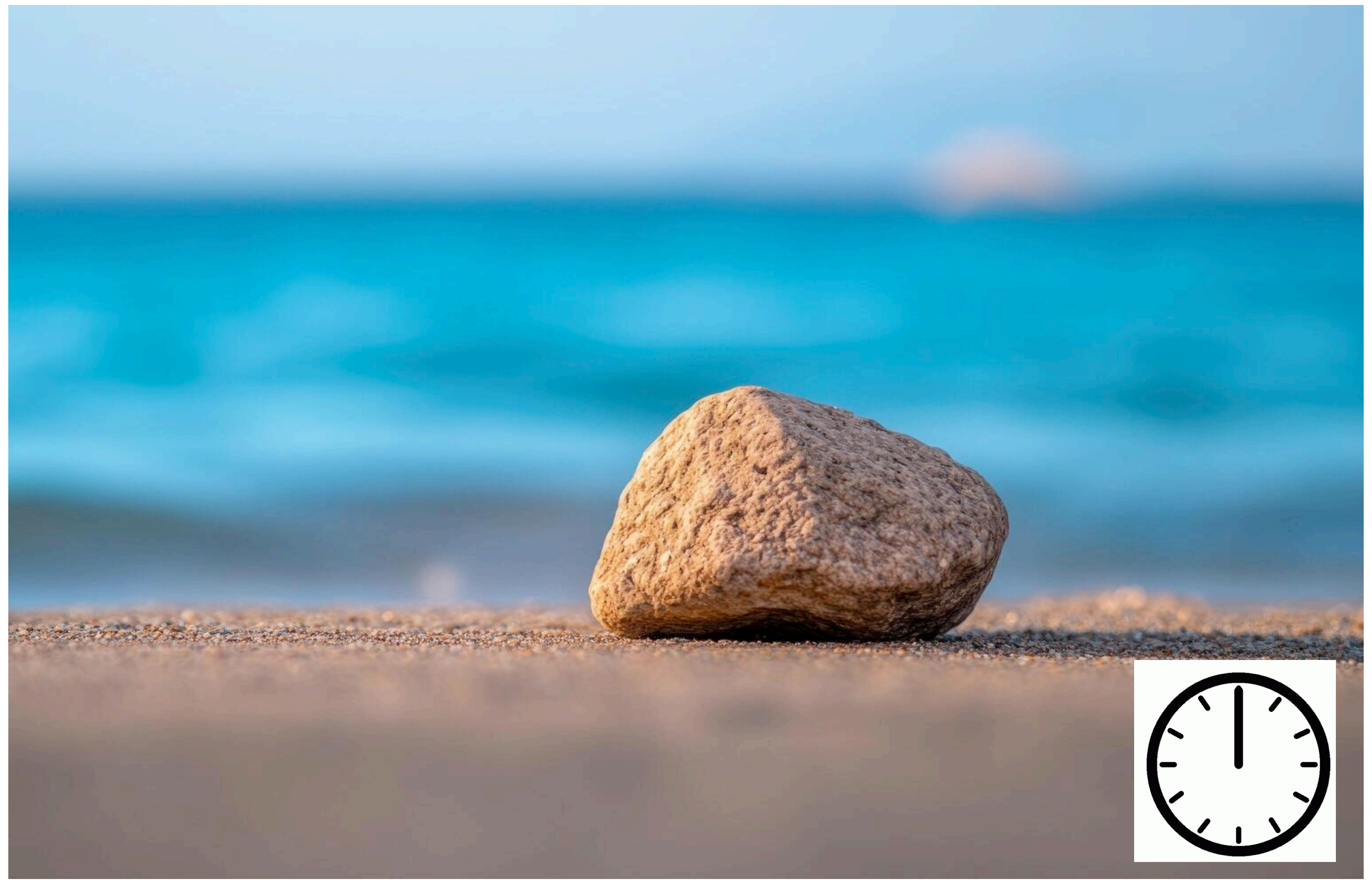
Other works mentioned

A hierarchy of thermal processes collapses under catalysis
arXiv:2303.13020 (Quantum Sci. Technol. 10, 015011 (2024))
Jeongrak Son, NN

Robust Catalysis and Resource Broadcasting: The Possible and the Impossible
arXiv:2412.06900
Jeongrak Son, Ray Ganardi, Shintaro Minagawa, Francesco Buscemi, Seok Hyung Lie, NN

Time-translation symmetry and thermality in Gaussian operations
(Soon to be on arXiv! Stay tuned)
Xueyuan Hu, Lea Lautenbacher, Giovanni Spaventa, Martin Plenio, NN, Jeongrak Son

Two intuitive notions of equilibrium



Stationarity: A single system being invariant under natural time evolution

Given some time evolution $\mathscr{E}_t$, we say that ω is stationary w.r.t. $\mathscr{E}_t$ if $\mathscr{E}_t(\omega) = \omega$.

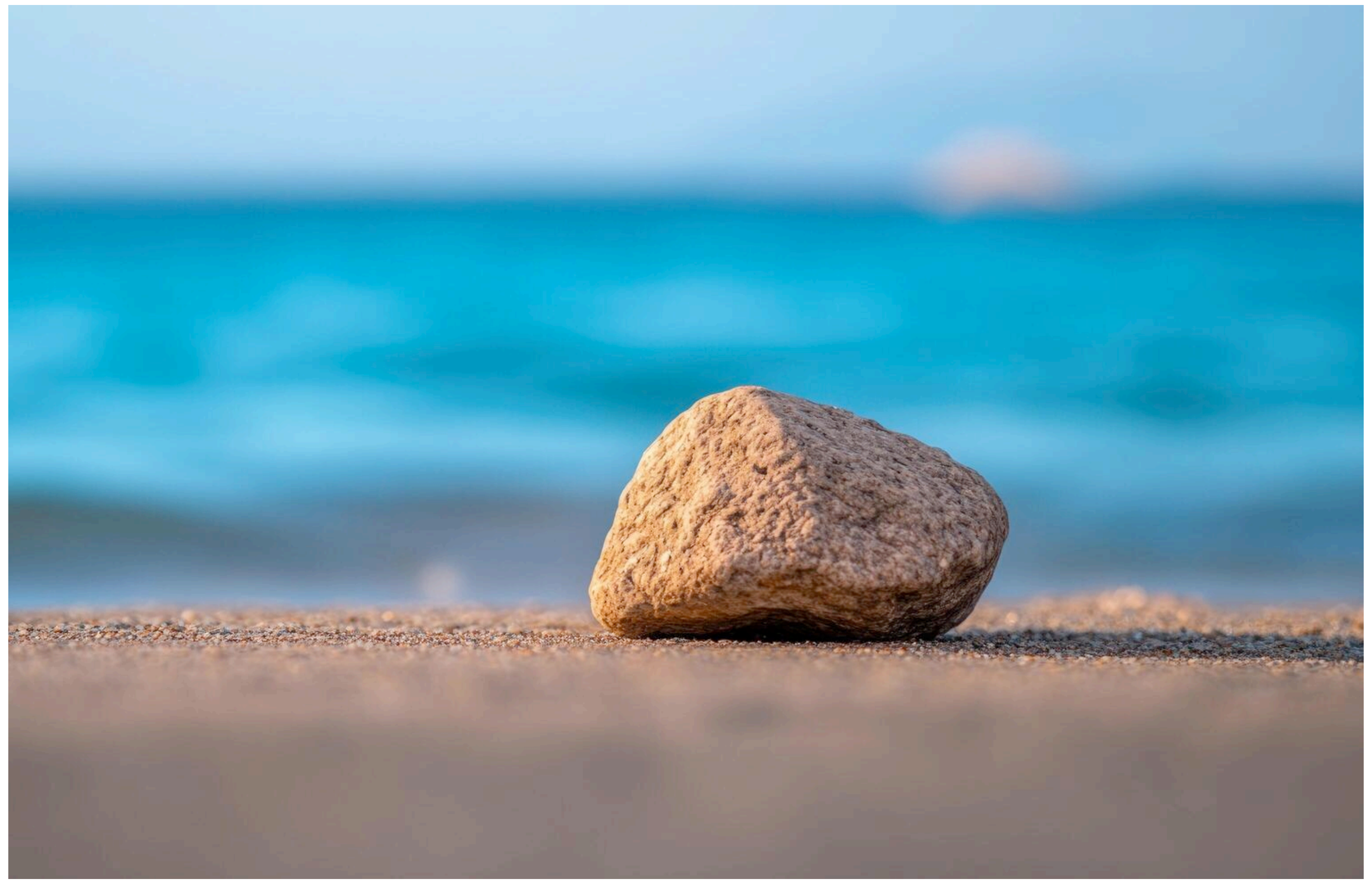
Relational equilibrium: Multiple systems being invariant under natural interactions

Given some time evolution U_{AB}, we say that ω_A, ω_B are in equilibrium w.r.t. U_{AB} if $U_{AB}(\omega_A \otimes \omega_B)U_{AB}^\dagger = \omega_A \sim \omega_B$.

Equilibration: a process that drives systems towards a state of equilibrium

Two intuitive notions of equilibration

This motivates interest in the full set of Gibbs-preserving maps as a description of equilibration



Stationarity: A single system being invariant under natural time evolution

Given some time evolution $\mathscr{E}_t$, we say that ω is stationary w.r.t. $\mathscr{E}_t$ if $\mathscr{E}_t(\omega) = \omega$.

Given any quantum channel $\mathscr{E}_t$ that admits a fixed point ω, then by data processing inequality, we have

$$D(\rho\|\omega) \geq D(\mathscr{E}_t(\rho)\|\omega)$$

where $D(\rho\|\sigma)$ is the quantum relative entropy.

We can so far discuss notions of equilibrium without invoking any energetic considerations.

However, if we now consider ω to be a thermal state of some Hamiltonian $\hat{H}$ at temperature β *(this is always possible when ω is full rank)*, then the map $\mathscr{E}_t$:

1) takes the input state ρ closer to the thermal state,
2) is a **Gibbs-preserving map**, i.e. captures the notion of equilibrium via **stationarity**.

Two intuitive notions of equilibration

This motivates interest in the full set of effective maps on A fulfilling such features, as a description of equilibration

Given ω_A, ω_B, if there exists some U_{AB} such that ω_A, ω_B are in relational equilibrium w.r.t. U_{AB}, then consider the map

$T_A(\,\cdot\,) = \mathrm{tr}_B \left[U_{AB} \left(\,\cdot \otimes \omega_B \right) U_{AB}^{\dagger} \right]$. It captures:

1) an explicit description of an environment induced equilibration process on A,
2) in a way that encodes:
    1) **local stationarity** of both ω_A and ω_B — when the input system is (locally) stationary, then the environment is also (locally) stationary,
    2) in principle allowing still for correlations to build up between A and B.

Relational equilibrium: Multiple systems being invariant under natural interactions

Given some time evolution U_{AB},
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Two intuitive notions of equilibration

This motivates interest in the full set of maps that have equilibrating dilations, as a description of equilibration

Given ω_A, ω_B, if there exists some U_{AB} such that ω_A, ω_B are in relational equilibrium w.r.t. U_{AB}, then consider the map

$$T_A(\,\cdot\,) = \mathrm{tr}_B\left[U_{AB}\left(\,\cdot \otimes \omega_B\right)U_{AB}^\dagger\right].$$

Definition: suppose that a quantum channel T_A has a fixed point ω_A. We say that T_A has an **equilibrating dilation** if there exists a dilation U_{AB}, ω_B, such that:

1. $T_A(\,\cdot\,) = \mathrm{tr}_B\left[U_{AB}\left(\,\cdot \otimes \omega_B\right)U_{AB}^\dagger\right]$,
2. $\mathrm{tr}_A\left[U_{AB}(\omega_A \otimes \omega_B)U_{AB}^\dagger\right] = \omega_B$.

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$$T_A(\,\cdot\,) = \mathrm{tr}_B\left[U_{AB}\left(\,\cdot \otimes \omega_B\right) U_{AB}^{\dagger}\right].$$

If we associate ω_A, ω_B again with Gibbs states of some Hamiltonian H_A, H_B at the same temperature, then the archetypal **thermal operations** are the special case where U_{AB} commutes with $\omega_A \otimes \omega_B$.

*** However, note that it isn't yet clear that all maps of the above form must necessarily be thermal operations (U_{AB} doesn't yet need to commute with $\omega_A \otimes \omega_B$ in order to satisfy relational equilibrium).

Relational equilibrium: Multiple systems being invariant under natural interactions

Given some time evolution U_{AB},
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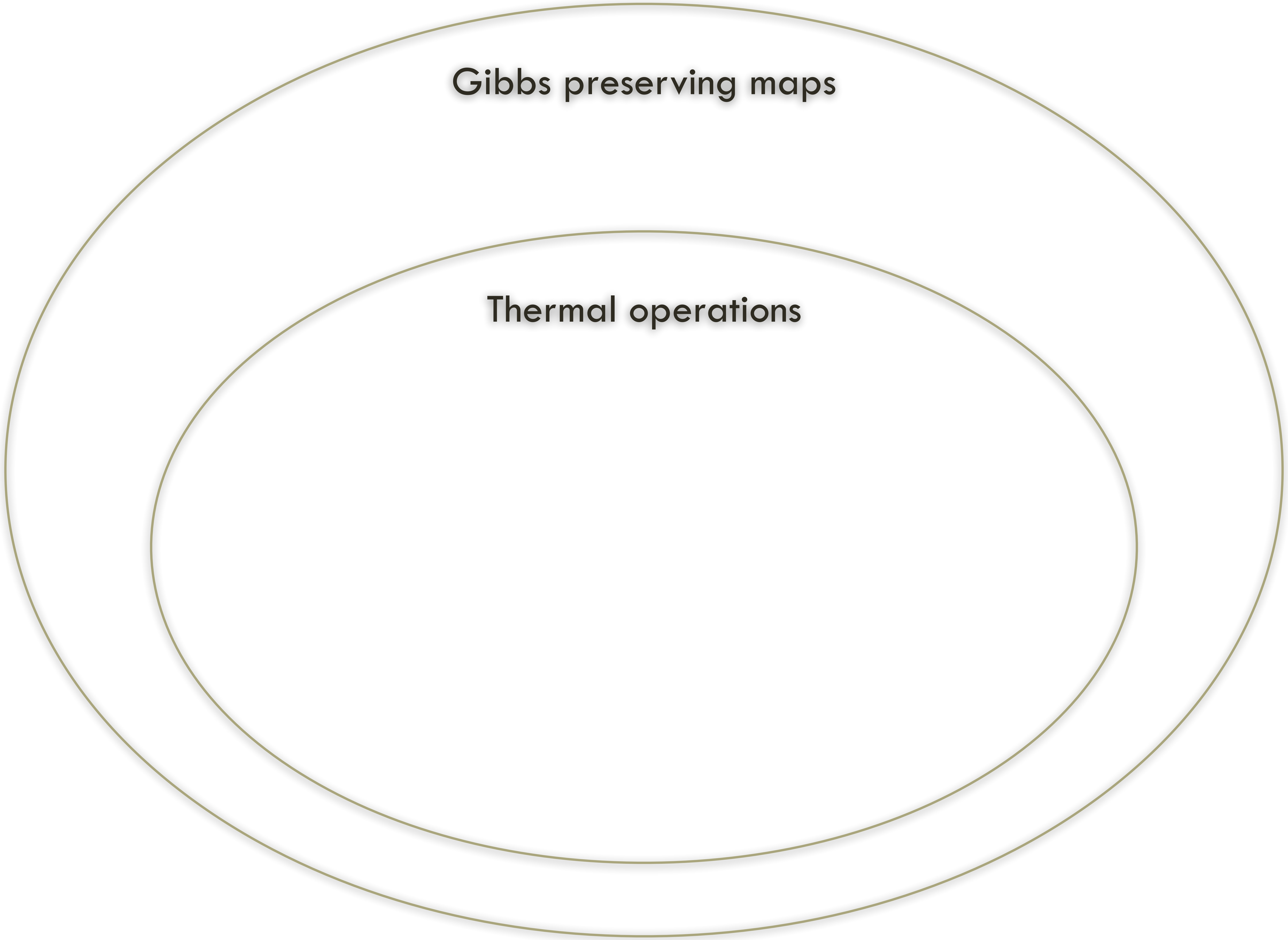
Distinct notions of equilibration: GP maps vs thermal operations



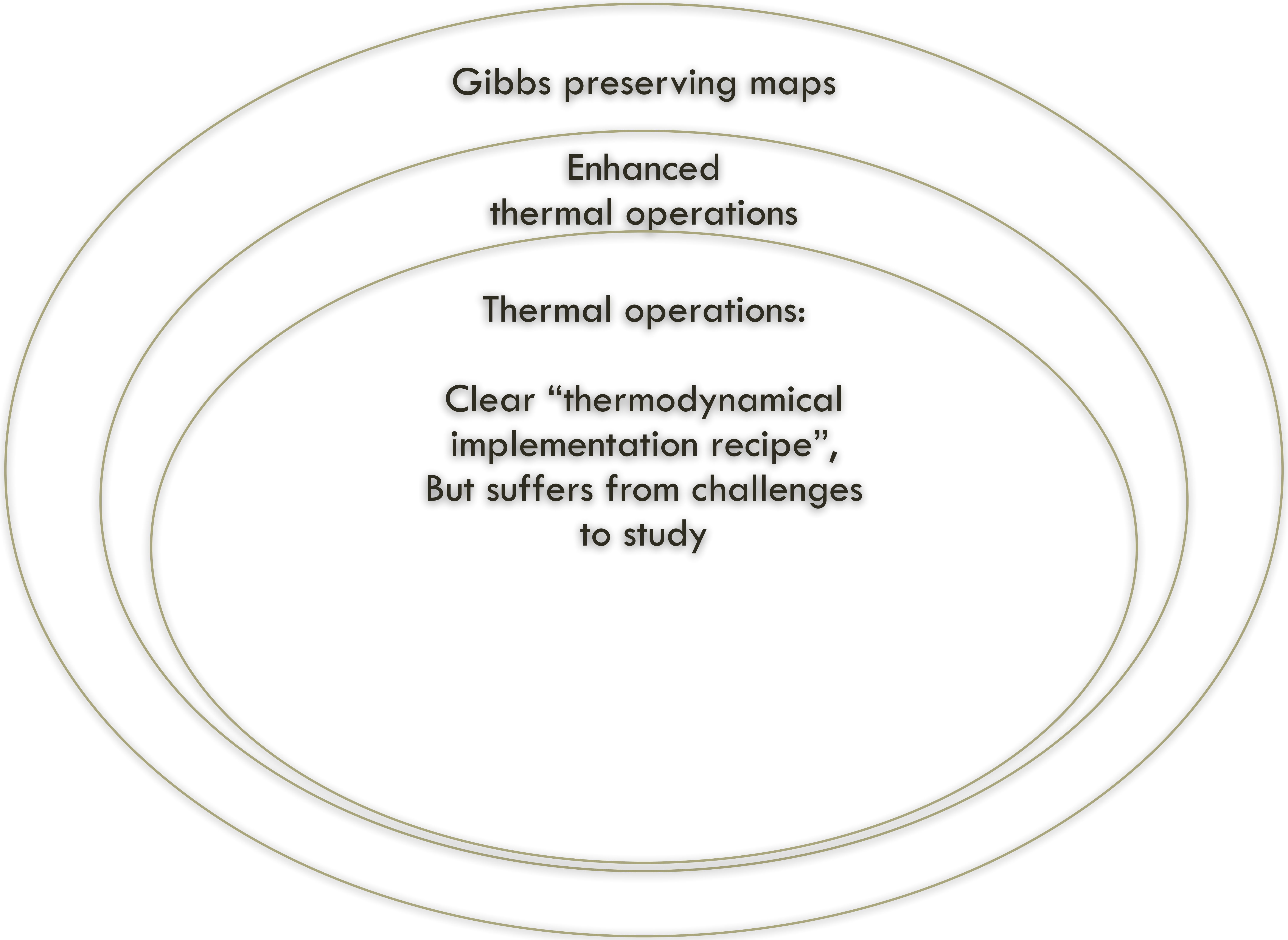
A strict gap is known to exist between these two sets:

- on the level of power in inducing incoherent state transitions $\rho \to \rho'$: they are equal [Horodecki, Oppenheim, Nat. Commun. 4 205 (2013)]

- on the level of power in inducing arbitrary state transitions $\rho \to \rho'$: GP maps can create energetic coherences, while TOs cannot [Faist et.al., NJP 17, 4, 043003 (2015)]

- GP maps can require an infinite amount of coherence to implement [Tajima, Takagi, PRL 134, 170201 (2025)]

A hierarchy of thermal processes



Gibbs preserving maps

Enhanced
thermal operations

Thermal operations:

Clear “thermodynamical
implementation recipe”,
But suffers from challenges
to study

We want single-shot reversibility!

Motivated by
generalisation,
easy mathematical
characterization
and reversibility

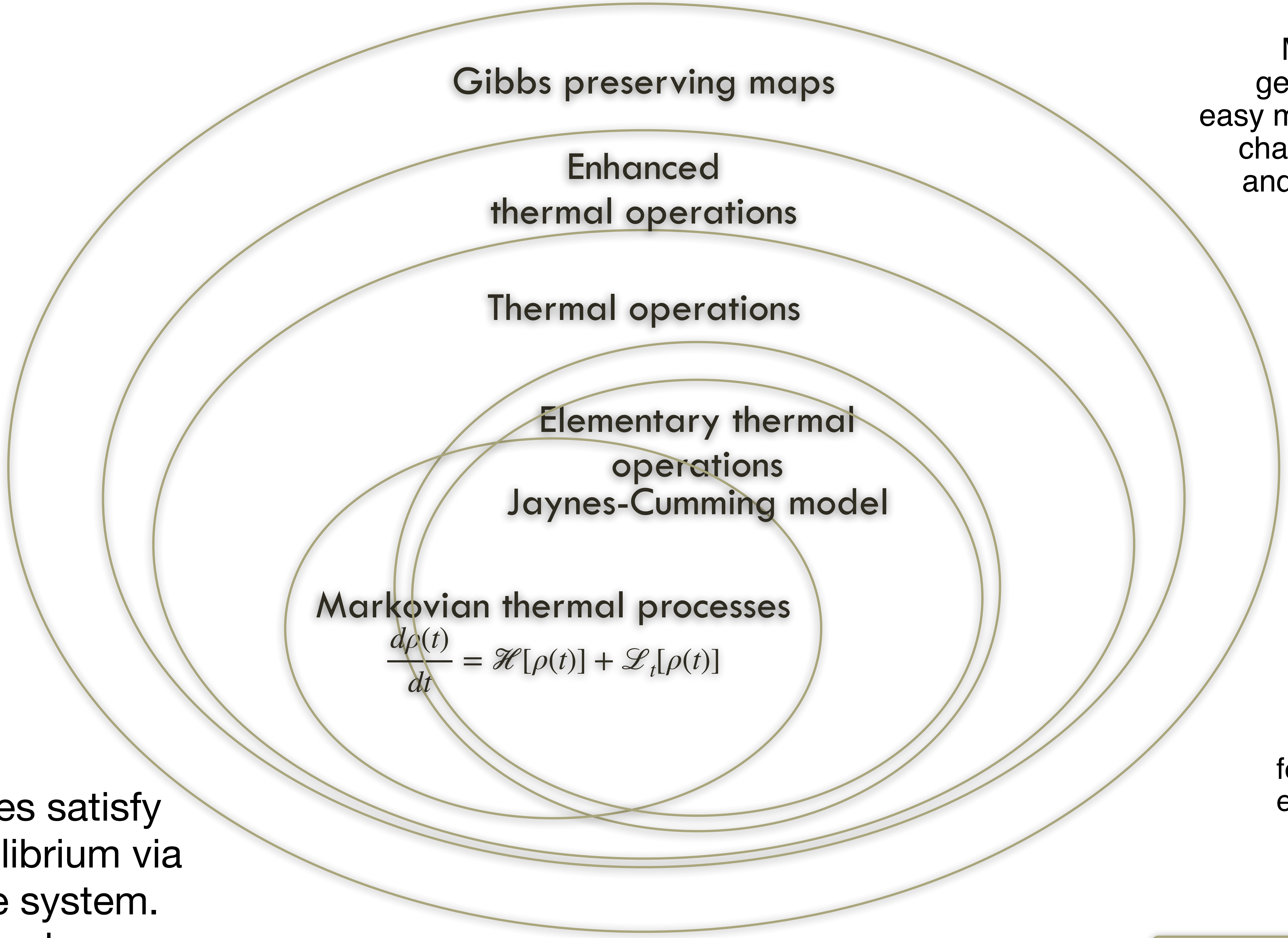
Physical meaning?

An intermediate ground: enhanced TOs are channels that fulfil

1. Gibbs-preservation, and
2. Covariance, i.e. for all $t \in \mathbb{R}$,
   $$\mathcal{E}\left(e^{-iHt}\rho e^{iHt}\right) = e^{-iHt}\mathcal{E}(\rho)e^{iHt}$$

Covariant maps are known to always have a **free dilation**, i.e. implementable with a **covariant** unitary & auxiliary system.

A hierarchy of thermal processes



$$\frac{d\rho(t)}{dt} = \mathscr{H}[\rho(t)] + \mathscr{L}_t[\rho(t)]$$

But where exactly do the set of equilibrating dilations sit in this hierarchy?

All these processes satisfy the notion of equilibrium via stationarity on the system. Thermal operations have equilibrating dilations.

We want single-shot reversibility!

Motivated by generalisation, easy mathematical characterization and reversibility

Physical meaning?

Motivated by feasibility and experimental-friendliness

More complex characterization for state transitions

We want realistic implementations!

Characterizing equilibrating dilations

This motivates interest in the full set of maps that have equilibrating dilations, as a description of equilibration

Result 1: Relational equilibrium implies no correlations built

Suppose ω_A , ω_B are in equilibrium relative to some U_{AB}. Then

$$U_{AB}(\omega_A \otimes \omega_B)U_{AB}^\dagger = \omega_A \otimes \omega_B\,.$$

Multipartite generalization of Result 1

Given $(\omega_1, \cdots, \omega_N)$, suppose that for some unitary U, it is true that

$$\mathrm{Tr}_{\setminus X}\left(U(\omega_1 \otimes \cdots \otimes \omega_N)U^\dagger\right) = \omega_X,$$

where $\mathrm{Tr}_{\setminus X}$ stands for the partial trace over all subsystems except X. We say that $(\omega_1, \cdots, \omega_N)$ are in equilibrium under U.

Then $U(\omega_1 \otimes \cdots \otimes \omega_N)U^\dagger = \omega_1 \otimes \cdots \otimes \omega_N$.

Relational equilibrium: Multiple systems being invariant under natural interactions

Given some time evolution U_{AB},
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Characterizing equilibrating dilations

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Then $U(\omega_1 \otimes \cdots \otimes \omega_N)U^\dagger = \omega_1 \otimes \cdots \otimes \omega_N$.

Proof for simple tripartite case.

1. Let $\omega_{ABC} = U\omega_A \otimes \omega_B \otimes \omega_C U^\dagger$,

2. Note that

$$I(AB:C)_{\omega_{ABC}} = H(\omega_{AB}) + H(\omega_C) - H(\omega_{ABC}),$$

but due to unitarity,
$H(\omega_{ABC}) = H(\omega_A) + H(\omega_B) + H(\omega_C)$.

3. This means that

$$\begin{aligned} I(AB:C)_{\omega_{ABC}} &= H(\omega_{AB}) - H(\omega_A) - H(\omega_B) \\ &= -I(A:B)_{\omega_{AB}} \end{aligned}$$

Due to non-negativity of mutual information, this means $I(AB:C)_{\omega_{ABC}} = I(A:B)_{\omega_{AB}} = 0$, which concludes that $\omega_{ABC} = \omega_A \otimes \omega_B \otimes \omega_C$.

Consequences of characterizing relational equilibrium via Result 1

Result 1: Relational equilibrium implies no correlations built

Suppose ω_A , ω_B are in equilibrium relative to some U_{AB}. Then

$$U_{AB}(\omega_A \otimes \omega_B)U_{AB}^\dagger = \omega_A \otimes \omega_B \,.$$

Consequence 1: unifying two notions of equilibrium

Relational equilibrium doesn't only imply local notions of equilibrium, i.e.

- the final state is not some generally correlated $\omega_A \sim \omega_B$,
- instead, the composite $\omega_A \otimes \omega_B$ itself is stationary!

Consequences of characterizing relational equilibrium via Result 1

Result 1: Relational equilibrium implies no correlations built

Suppose ω_A , ω_B are in equilibrium relative to some U_{AB}.
Then

$$U_{AB}(\omega_A \otimes \omega_B)U_{AB}^\dagger = \omega_A \otimes \omega_B\,.$$

Consequence 2: a clear physical principle of equilibration singling out thermal operations

Suppose that the quantum channel T admits an equilibrating dilation, i.e. there exists a dilation U_{AB}, ω_B, such that:

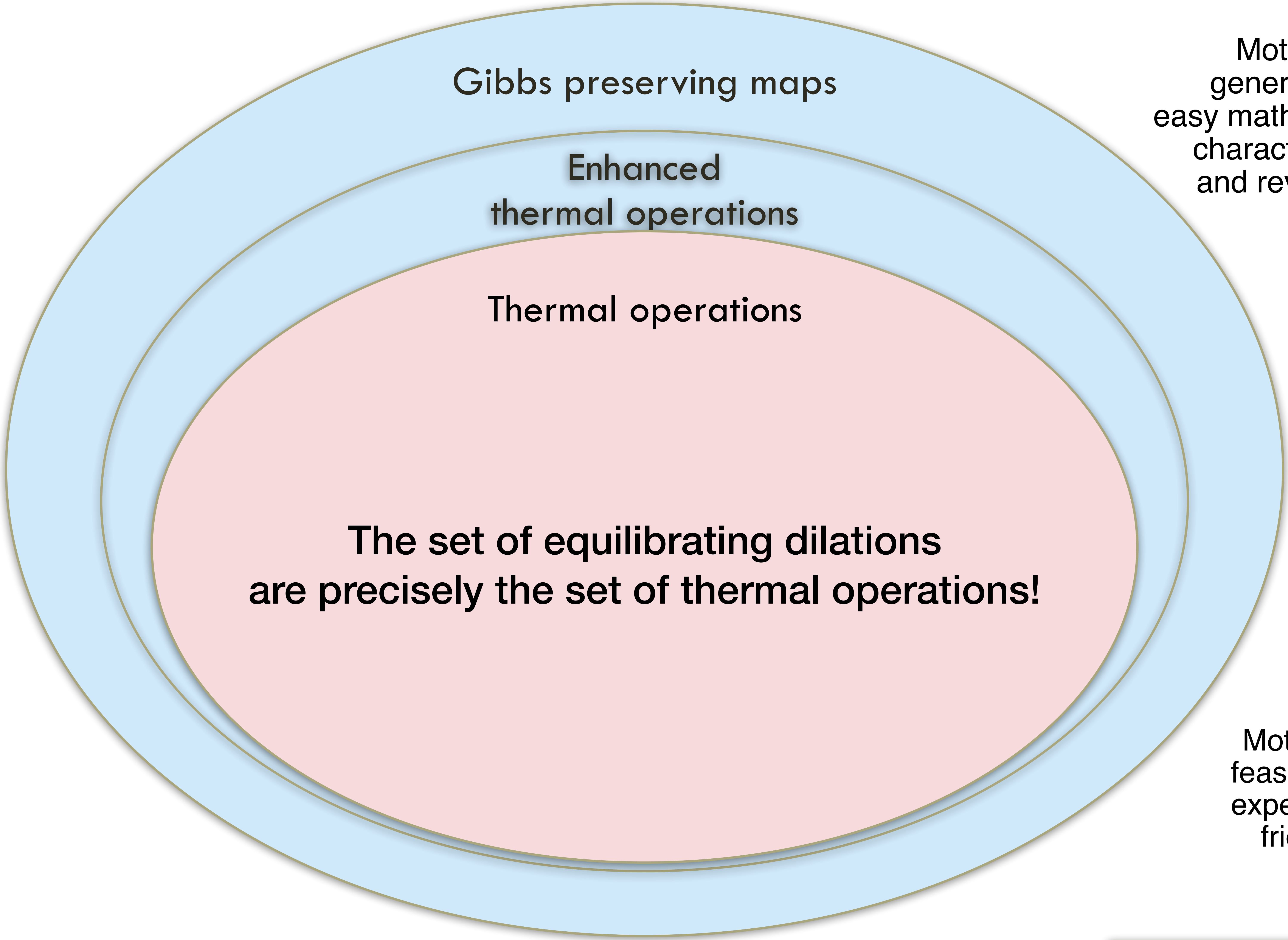
1. $T_A(\,\cdot\,) = \mathrm{tr}_B\left[U_{AB}\left(\,\cdot \otimes \omega_B\right)U_{AB}^\dagger\right]$,
2. $\mathrm{tr}_A\left[U_{AB}(\omega_A \otimes \omega_B)U_{AB}^\dagger\right] = \omega_B$ where ω_A is a fixed point of T_A.

Then the following holds:

1. $\left[U, \omega_A \otimes \omega_B\right] = 0$,
2. for every $t \in \mathbb{R}$, and every state ρ_A on A, we have $T\left(\omega_A^{it}\rho_A\omega_A^{-it}\right) = \omega_A^{it}T\left(\rho_A\right)\omega_A^{-it}$,
3. if ω_A has full rank, then ω_B can be chosen to have full rank.

A hierarchy of thermal processes

non-TO themal processes must contain some form of non-equilibriumness in its environment (i.e. the environment state must change even when we input the fixed point on system!)



Gibbs preserving maps

Enhanced thermal operations

Thermal operations

The set of equilibrating dilations are precisely the set of thermal operations!

We want single-shot reversibility!

Motivated by generalisation, easy mathematical characterization and reversibility

Physical meaning?

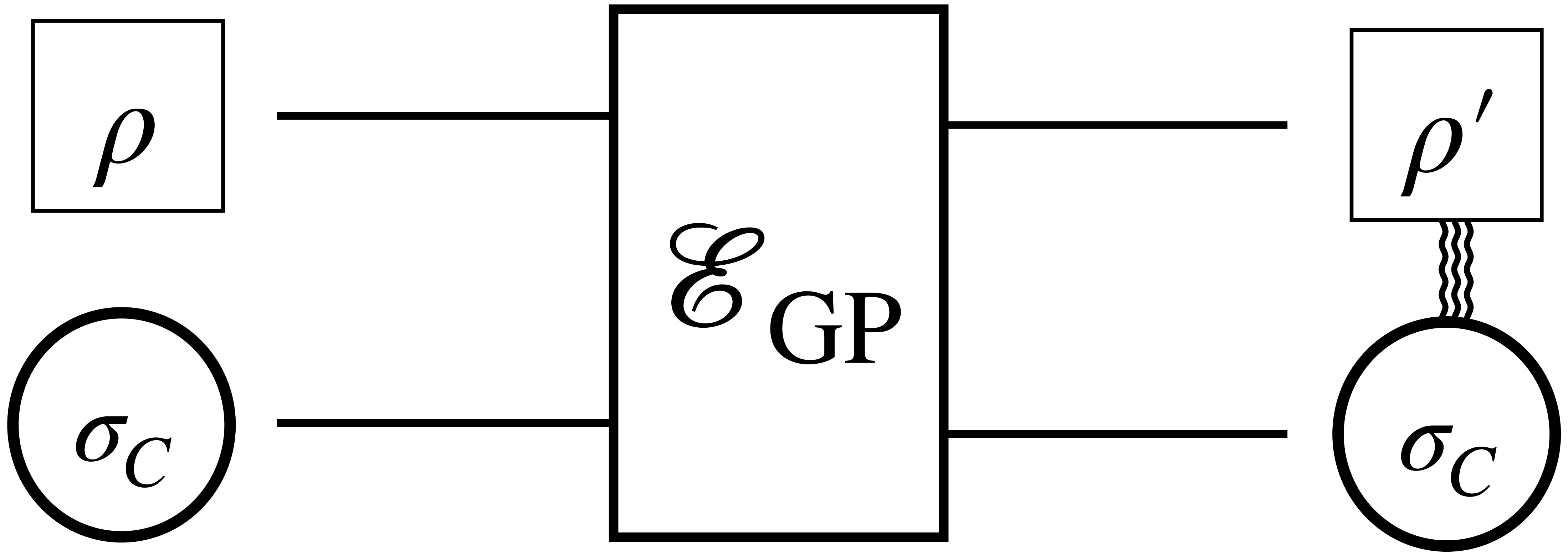
More complex characterization for state transitions

Motivated by feasibility and experimental-friendliness

We want realistic implementations!

Alternative viewpoint that highlights TO from the hierarchy

Catalysis in thermal processes



An auxilliary system σ is used to facilitate a process, in a way that:

- the state transformation from $\rho \rightarrow \rho'$ would not have been possible otherwise (e.g. due to being constrained by equilibrating thermal processes)
- σ_C is returned exactly* after the process, and therefore recyclable!

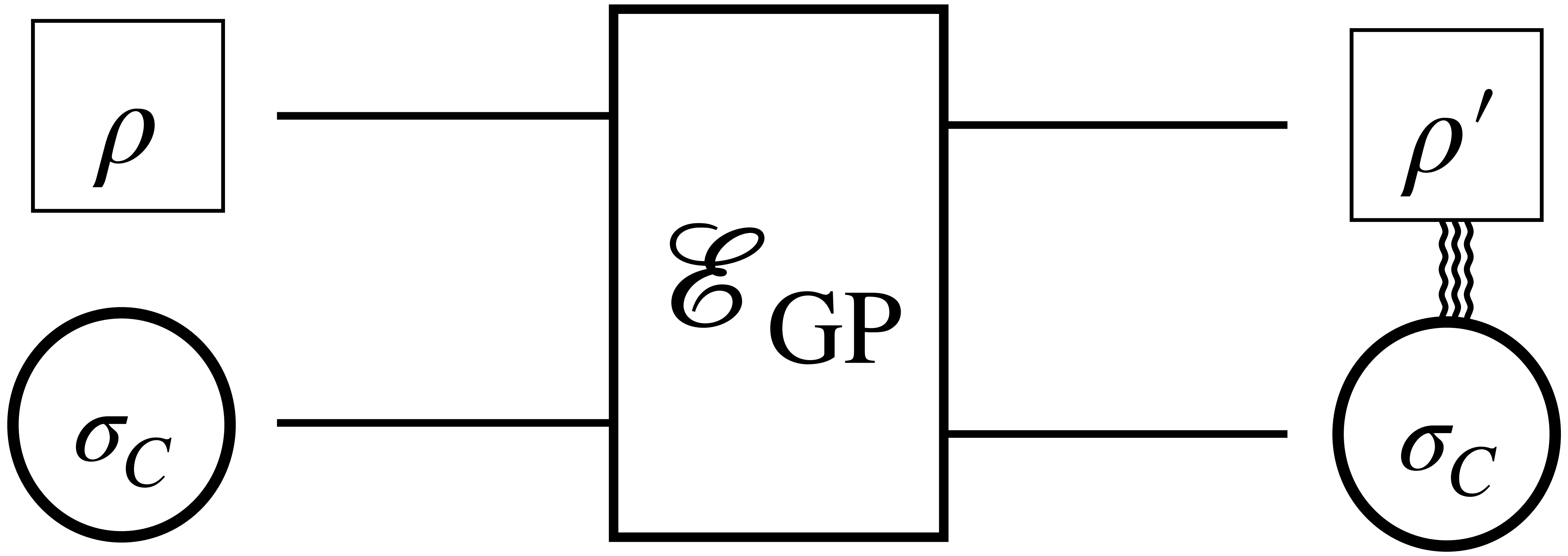
Catalytic processes have a long history in thermodynamics, even beyond resource theories — for example:

- an engine that undergoes a cyclic loop after sequential interactions with multiple heat baths,
- a ticking clock that undergoes some periodic movement, used to keep track of temporal information,
- an infinite heat bath whose temperature does not change etc (hinting at significance in relational equilibrium!),
- an ingredient that captures non-Markovianity/memory effects.

Catalytic effects are long known to be present in thermal operations, see also RMP 96, 025005 (2024) for a review!

** various ways exist as to restricting the amount of error or correlation allowed in the final catalyst. Ideally, exact recovery is important to ensure that one does not embezzle energy/athermality from the catalyst*

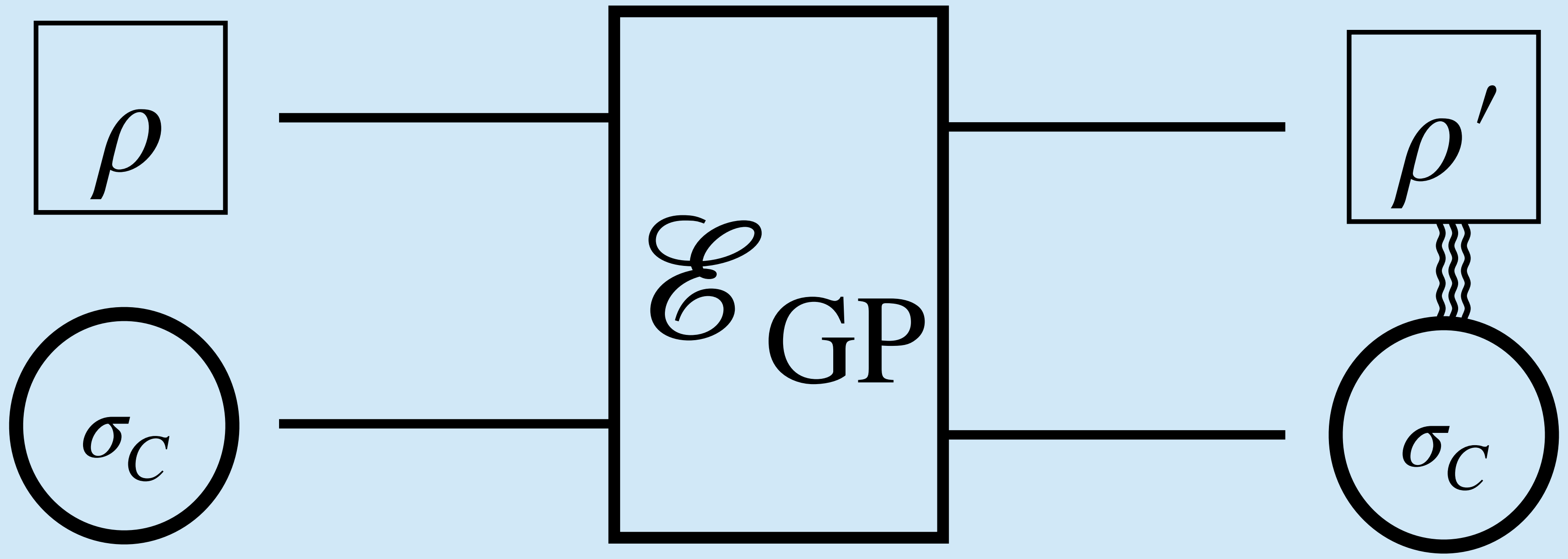
Catalytic processes are not quantum channels in general



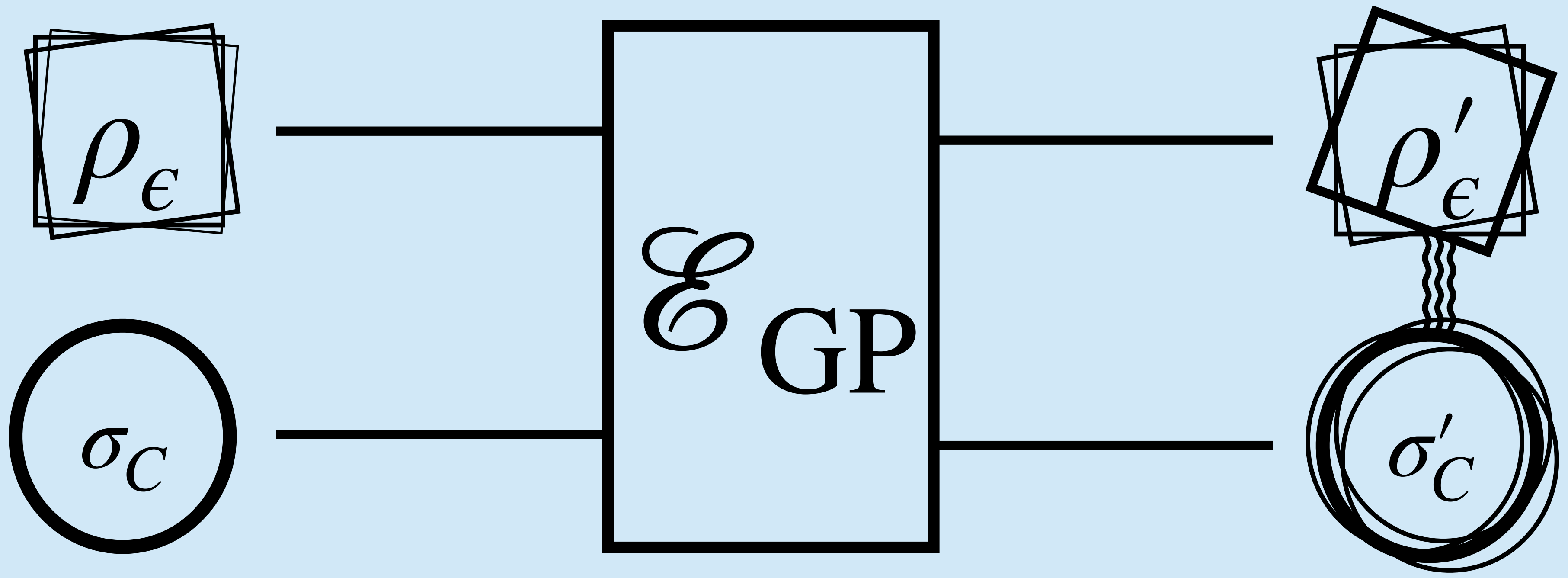
- The catalytic condition that σ must be returned intact is usually demanded only when the system initial state is precisely ρ, and the channel describing their interaction is precisely characterized by $\mathscr{E}_{\mathrm{GP}}$.
- In other words, the catalytic condition is highly system-state (& interaction) dependent; the catalyst state is also heavily fine-tuned w.r.t. ρ.
  - On the one hand, this degree of freedom to choose the catalyst given ρ makes catalysis very powerful in relaxing state transition conditions.
  - On the other hand,
    - knowledge of system state can be costly
    - the catalyst state can be fragile w.r.t. errors
    - embezzling?!

Fragile catalysis

The catalytic condition is satisfied when input is ρ:

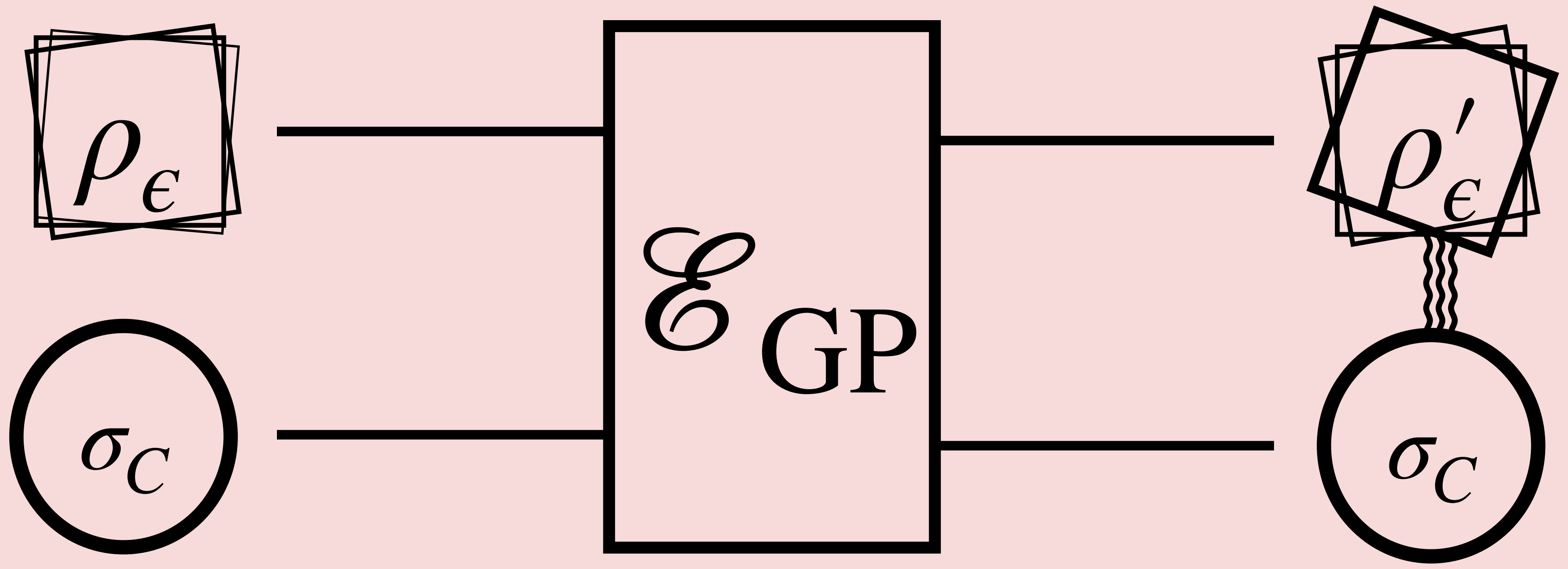


Under errors in system state preparation, the catalyst gets degraded. Further interactions now can gradually degrade the catalyst to a point beyond usage!



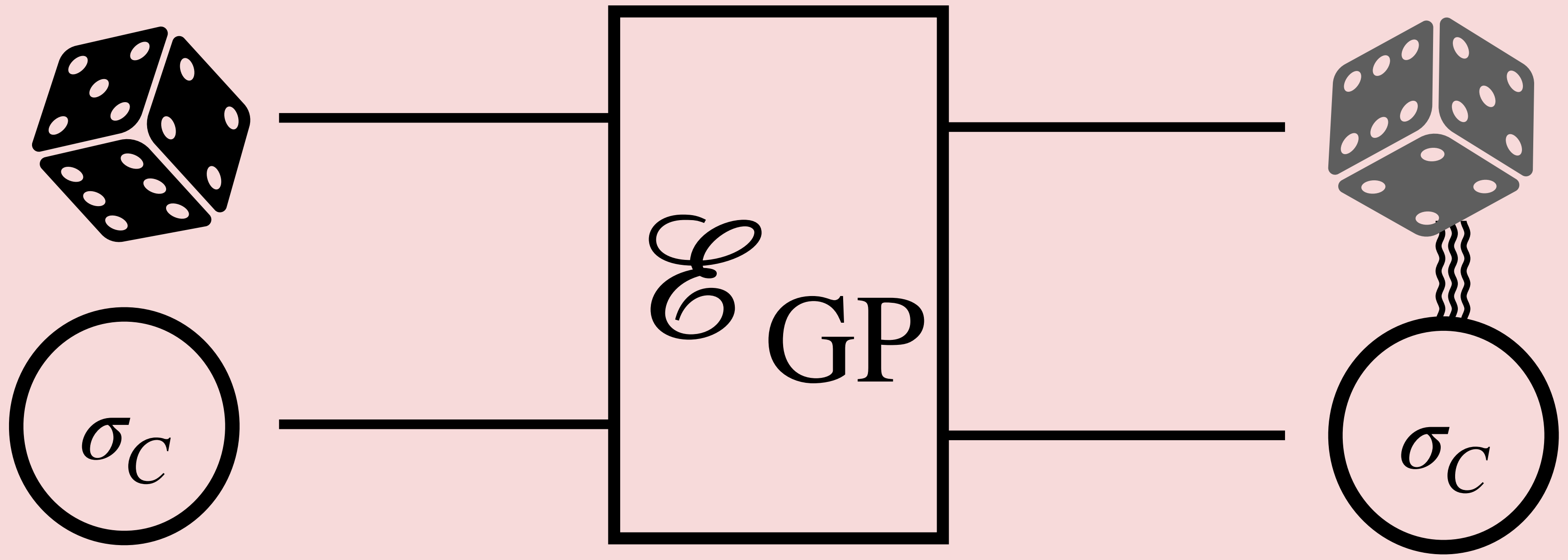
This is the predominant type of catalysis in literature. In other words, the catalytic process is studied only on the level of activating state transitions, not channels.

Robust catalysis



We say that a channel $\mathcal{E}_{GP}$ implements a (ρ, ϵ)-robust catalytic thermal process, if there exists a catalyst ω_C, such that $\mathrm{Tr}_S[\Lambda(\rho_\epsilon \otimes \tau_C)] = \tau_C$ for all $\rho_\epsilon \approx \rho$ (e.g. in trace distance).

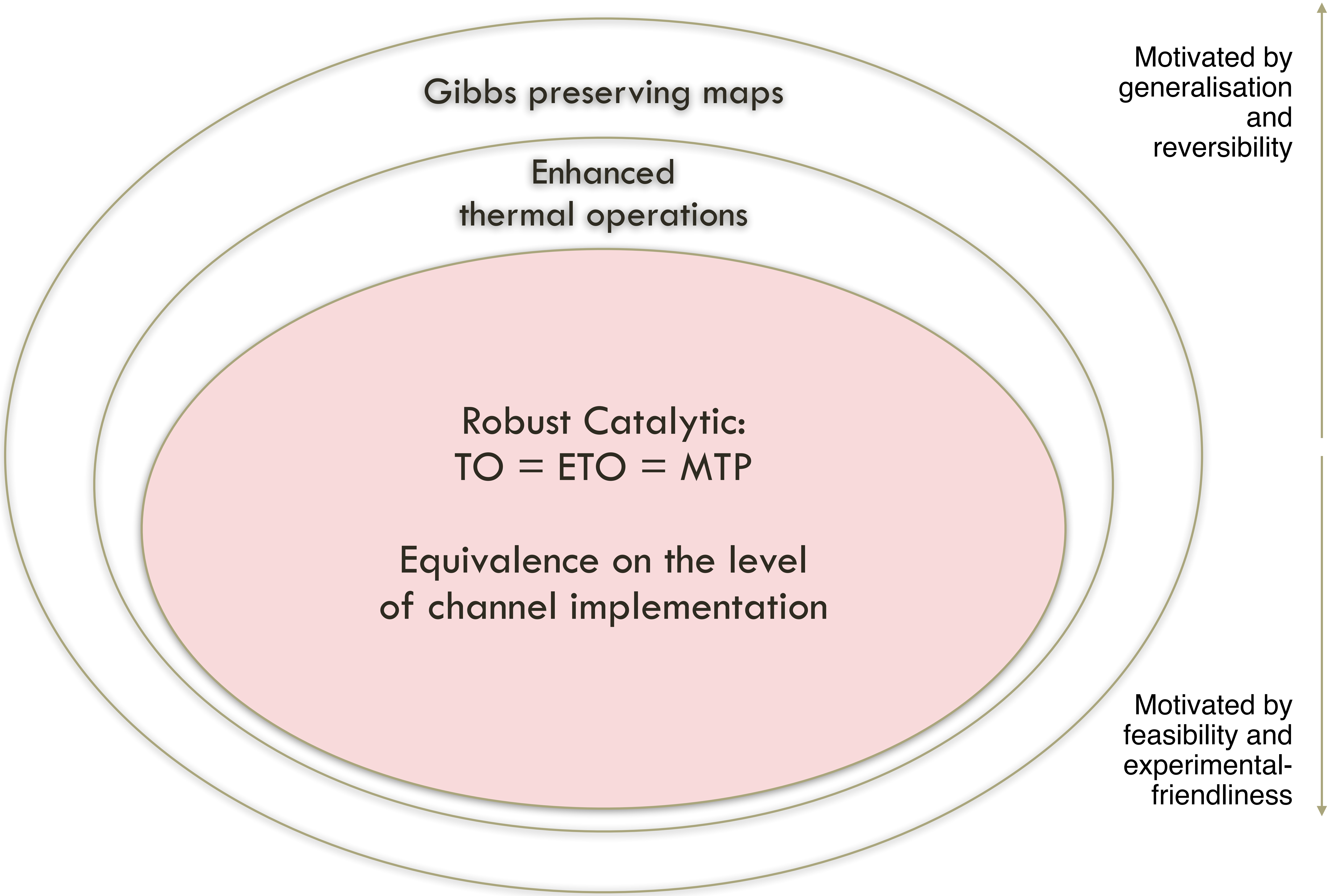
In arXiv:2412.06900, we show that demanding for any $\epsilon > 0$ is equivalent for demanding maximal $\varepsilon = 1$! This lifts the catalytic condition to the level of channel implementation.



Robust catalysis simplifies the hierarchy (partially)

Key intuition:

- Two-level unitaries are universal, so when we can concatenate ETOs, originally it was hoped to be equivalent to TOs
- It didn't work directly, since ETOs assumed that the bath is refreshed after each step (in-built source of Markovianity)
- Once we allow to keep parts of the bath as a catalyst (and restore it for free later which is possible via ETOs), we have a recipe to expand ETO via robust catalysis to TO!
- Do we have robust catalytic advantage for other parts of the hierarchy?



Gibbs preserving maps

Enhanced
thermal operations

Robust Catalytic:
TO = ETO = MTP

Equivalence on the level
of channel implementation

Motivated by
generalisation
and
reversibility

Motivated by
feasibility and
experimental-
friendliness

Jeongrak Son, Nelly Ng, Quantum Sci. Technol. 10, 015011 (2024)

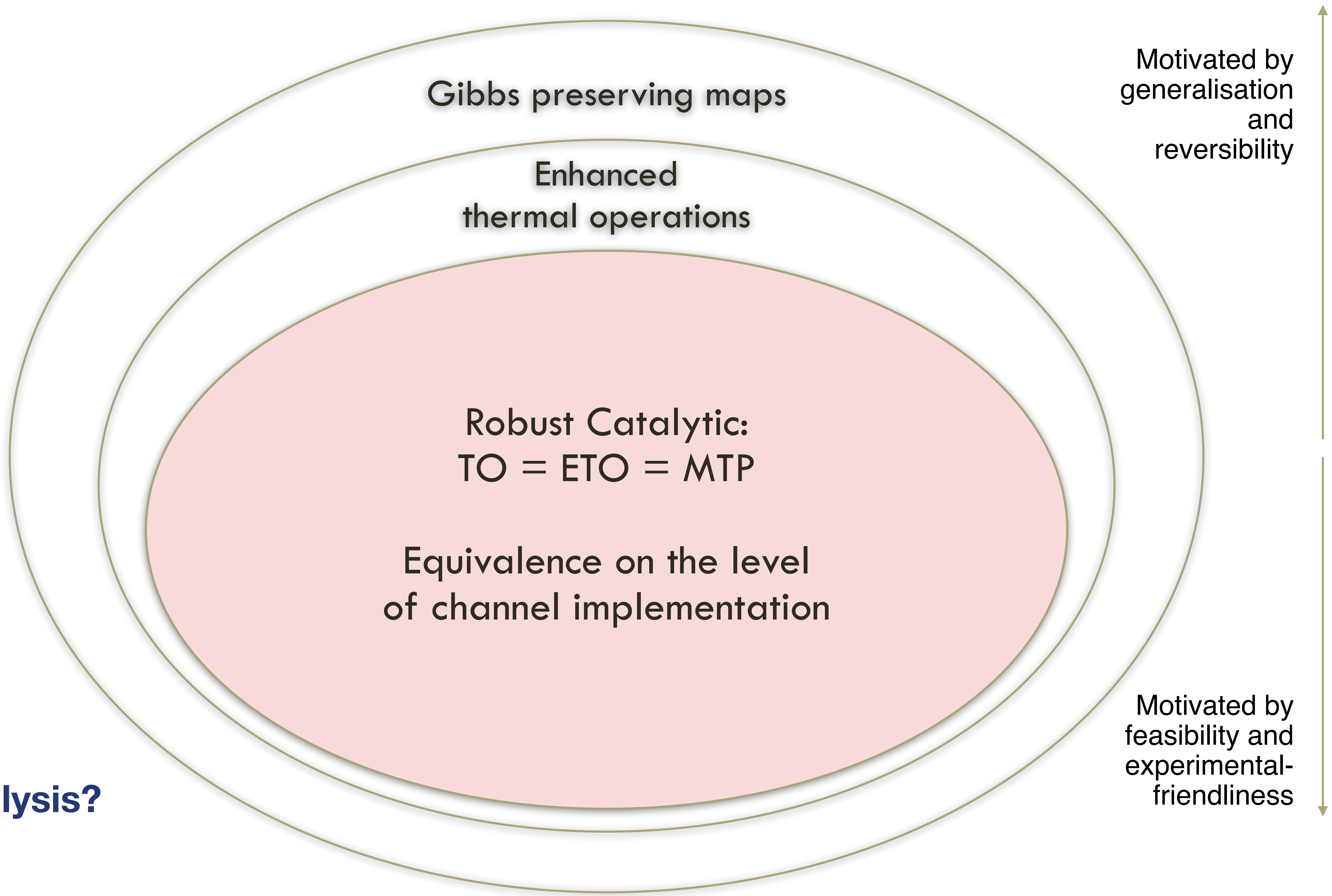
Robust catalysis cannot fully simplify the hierarchy

There is no robust catalytic advantage for GP maps

- comes from the fact that GP maps correspond to the maximal set of non-athermality generating operations, which we prove that for generic resource theories cannot exhibit robust catalysis

There is no robust catalytic enhanced thermal operations

What about TOs? Can they be further expanded via robust catalysis?



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Jeongrak Son, Ray Ganardi, Shintaro Minagawa, Francesco Buscemi, Seok Hyung Lie, NN
“Robust Catalysis and Resource Broadcasting: The Possible and the Impossible”, arXiv:2412.06900

No additional robust catalytic advantage

Result 2: Any robust catalytic advantage is already fully captured by thermal operations

All robust catalytic thermal operations can be implemented simply with thermal operations (without an additional catalyst).

Proof sketch:

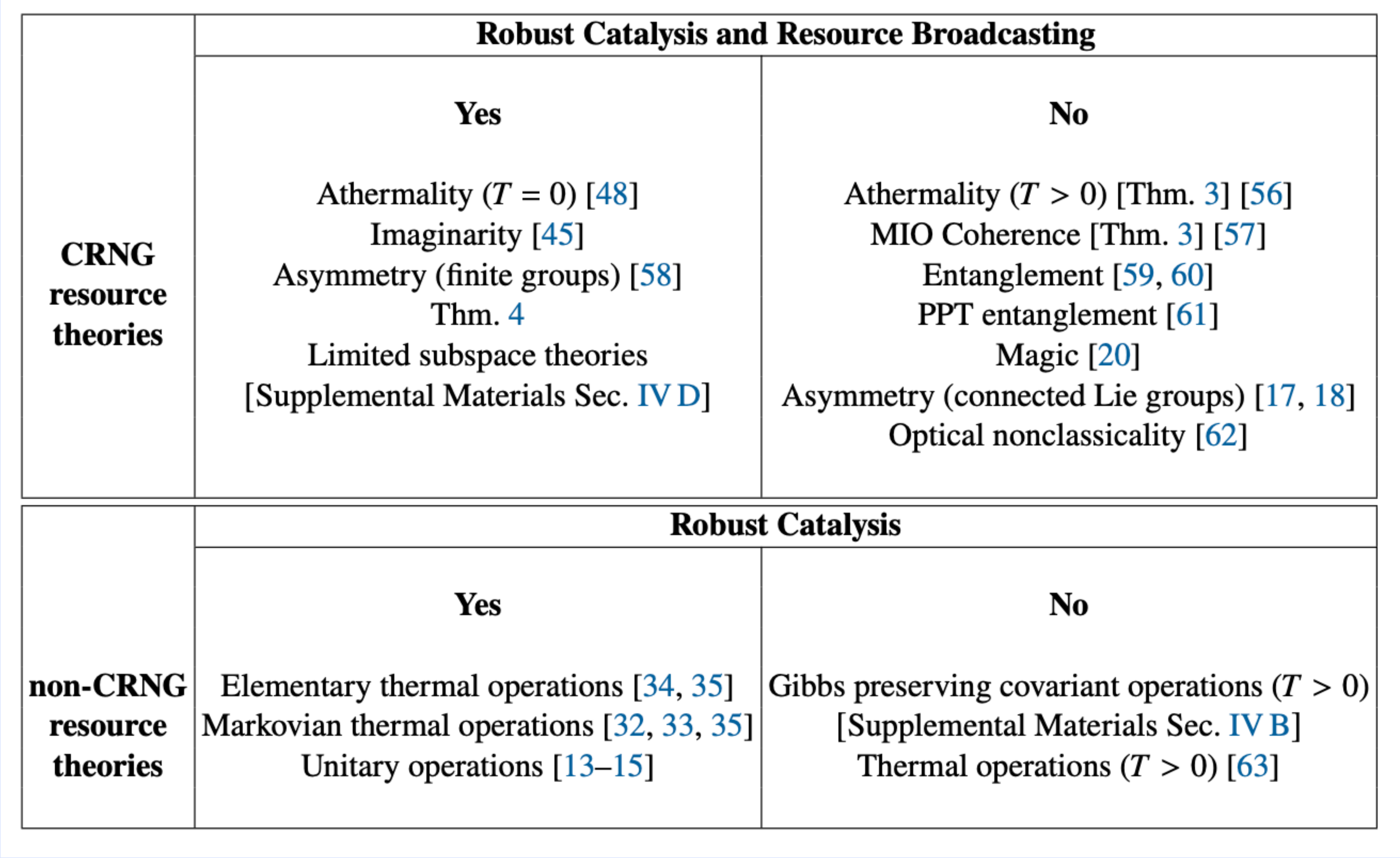
1. Assume that there exists a robust catalytic thermal operation on system A, i.e. $T(\rho_A) = \mathrm{Tr}_C(\mathscr{B}(\rho_A \otimes \tau_C))$, such that
   a) $\mathscr{B}$ is a thermal operation: there exists some dilation $\mathscr{B}\left(\varrho_{AC}\right) = \mathrm{Tr}_B\left(U\varrho_{AC} \otimes \omega_B U^\dagger\right)$, and $[U, \omega_A \otimes \omega_C \otimes \omega_B] = 0$.
   b) Catalysis is robust: (recall that we show robustness necessarily means that) $\mathrm{Tr}_{AB}\left(U\rho_A \otimes \tau_C \otimes \omega_B U^\dagger\right) = \tau_C$,

2. The channel T_A is Gibbs-preserving (from monotonicity of relative entropy),

3. System B stays invariant, i.e. $\mathrm{Tr}_{AC}\left(U\omega_A \otimes \tau_C \otimes \omega_B U^\dagger\right) = \omega_B$,

4. The above implies that $\omega_A, \tau_C, \omega_B$ are in equilibrium w.r.t. U. Result 1 then implies that U commutes with it. Hence we can simply interpret τ_C as just another thermal state (consistent with U). This concludes the proof.

Tangent: robust catalysis in other quantum resources



	Robust Catalysis and Resource Broadcasting	
	Yes	**No**
CRNG resource theories	Athermality ($T = 0$) [48] Imaginarity [45] Asymmetry (finite groups) [58] Thm. 4 Limited subspace theories [Supplemental Materials Sec. IV D]	Athermality ($T > 0$) [Thm. 3] [56] MIO Coherence [Thm. 3] [57] Entanglement [59, 60] PPT entanglement [61] Magic [20] Asymmetry (connected Lie groups) [17, 18] Optical nonclassicality [62]

	Robust Catalysis	
	Yes	**No**
non-CRNG resource theories	Elementary thermal operations [34, 35] Markovian thermal operations [32, 33, 35] Unitary operations [13–15]	Gibbs preserving covariant operations ($T > 0$) [Supplemental Materials Sec. IV B] Thermal operations ($T > 0$) [63]

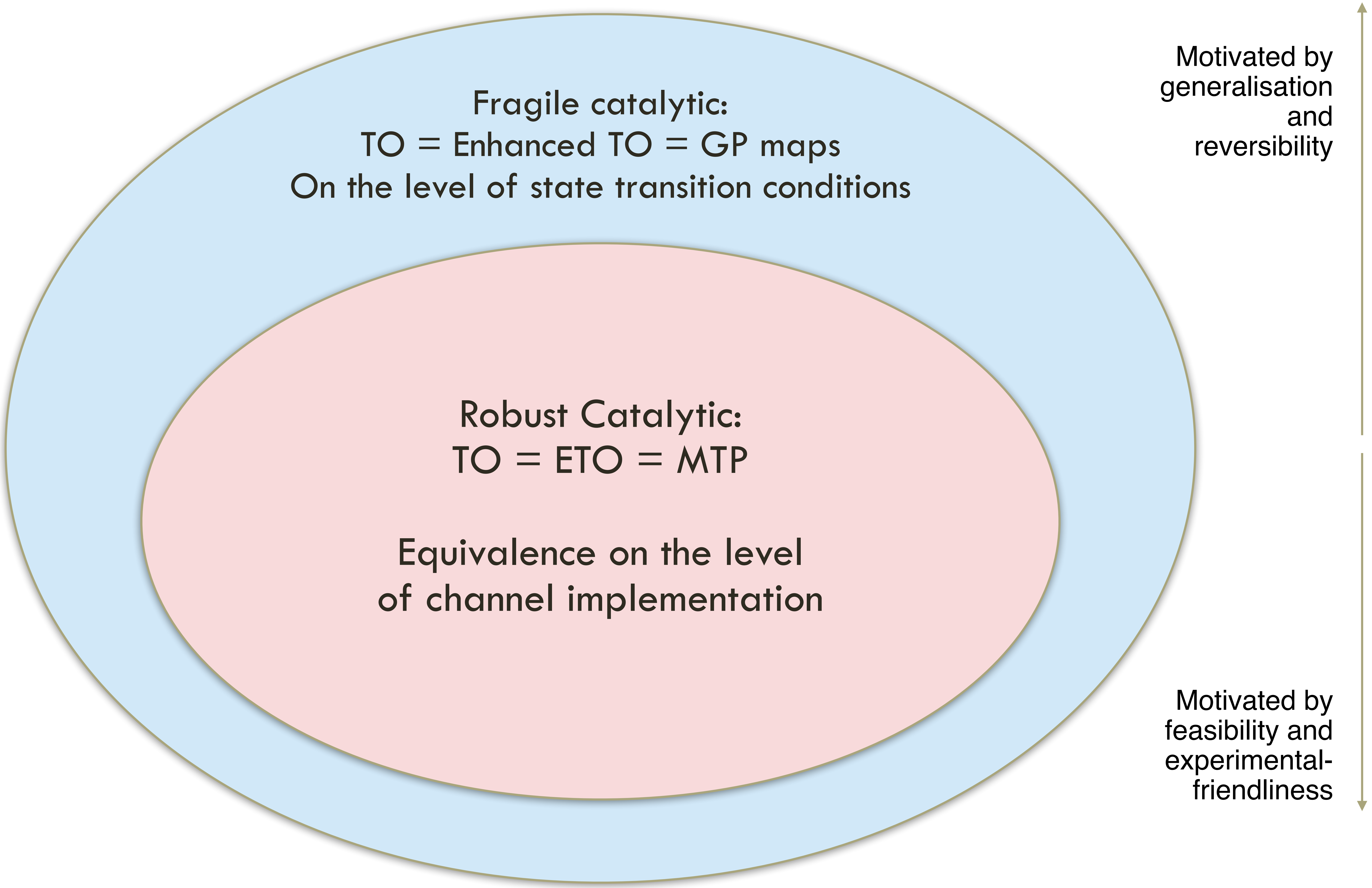
Robust Catalysis and Resource Broadcasting: The Possible and the Impossible
arXiv:2412.06900

Catalysis simplifies the hierarchy* and restores reversibility

Shiraishi, N., & Sagawa, T. (2021). Quantum thermodynamics of correlated-catalytic state conversion at small scale. *PRL 126*(15), 150502.

N. Shiraishi
"Quantum thermodynamics with coherence: Covariant Gibbs-preserving operation is characterized by the free energy." *PRL 134*(16), 160402 (2025).

N. Shiraishi, R. Takagi. “Recovery of the second law in fully quantum thermodynamics”. arXiv: 2510.05642 (7 Oct 2025)



Fragile catalytic:
TO = Enhanced TO = GP maps
On the level of state transition conditions

Robust Catalytic:
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Equivalence on the level
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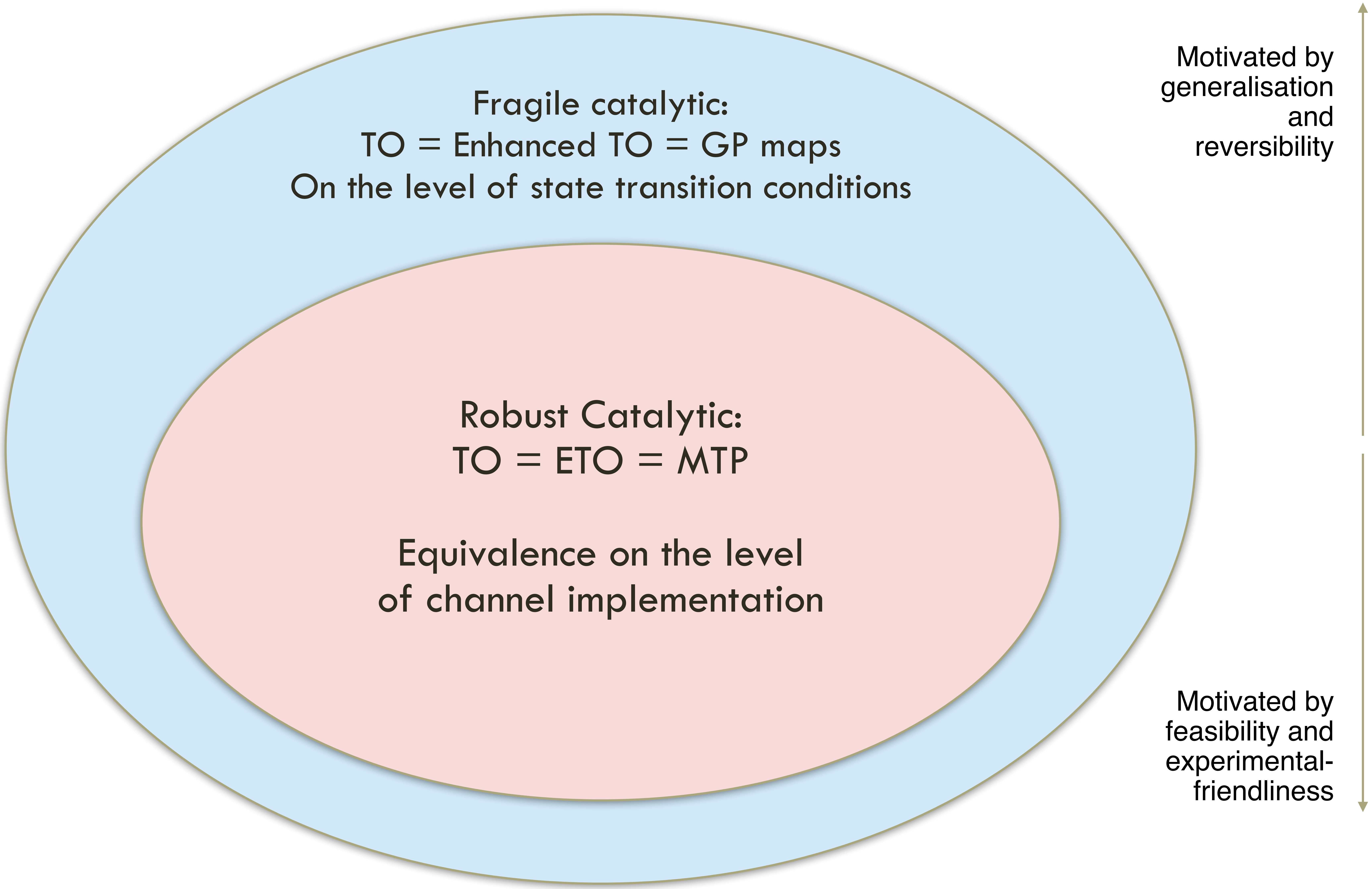
Playing further with the gap

Two questions:

1. Can we understand a simple case where robust catalysis fits into the hierarchy?

Fully degenerate H

2. Can we identify other physical ingredients where gaps in the hierarchy can be bridged?



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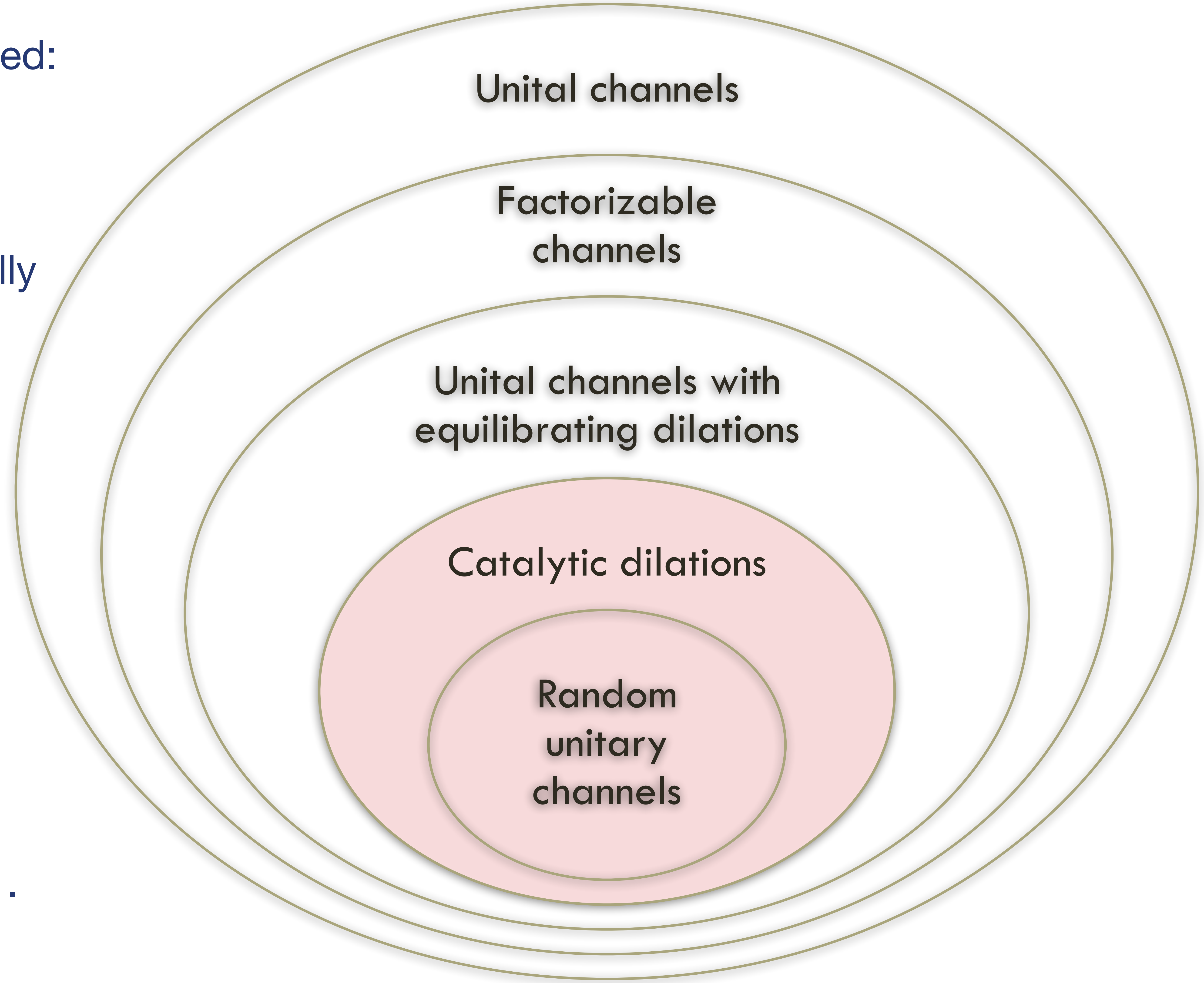
The hierarchy of thermal processes at infinite temperature

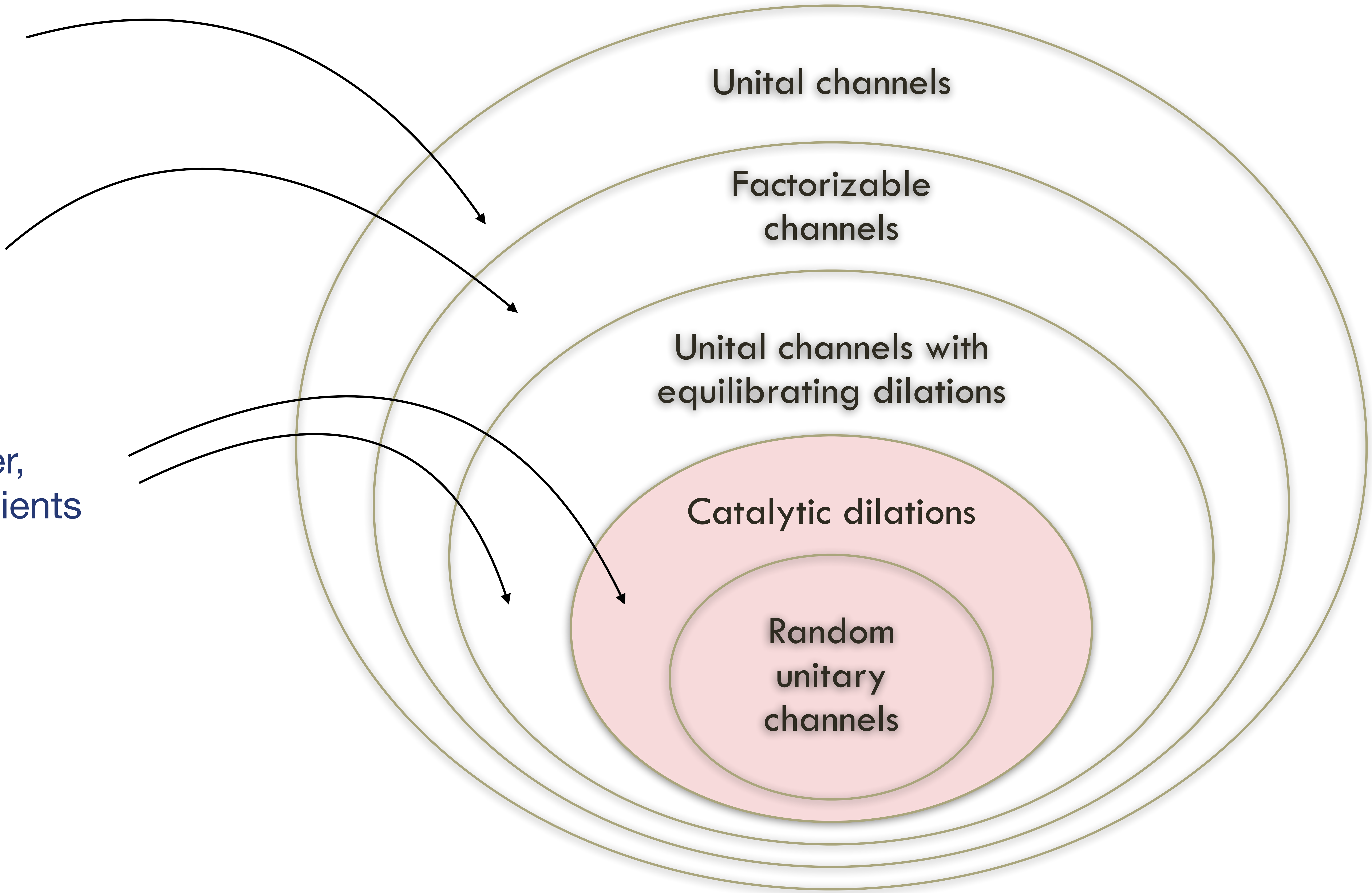
Let ω_A be the maximally mixed state, i.e. Gibbs state of infinite temperature. Then a hierarchy is known and studied:

- the largest set being **unital channels**, i.e. any channel that preserves the fixed point ω_A,
- **Factorizable channels** (implementable with a maximally mixed — but possibly infinite-dimensional ancilla)
- **Strongly factorizable channels** (noisy operations), which exactly correspond to unital channels that have an equilibrating dilation,
- **Random unitary channels**: having the form $T(\rho) = \sum_i p_i U_i \rho U_i^\dagger$,
- **Catalytic dilations**: quantum channels T_A such that

$$\begin{aligned} \mathrm{Tr}_B\left(U\rho \otimes \omega_B U^\dagger\right) &= T_A(\rho), \\ \mathrm{Tr}_A\left(U\rho \otimes \omega_B U^\dagger\right) &= \omega_B, \end{aligned} \quad \text{for some } \left(U, \omega_B\right).$$



This is a strict hierarchy — all inclusions are proper!



U. Haagerup and M. Musat, Communications in Mathematical Physics 303, 555 (2011).

Relies on MIP = RE
Z. Ji, A. Natarajan, T. Vidick, J. Wright, and H. Yuen, Commun. ACM 64, 131–138 (2021).

Result 3 of the current paper, building on technical ingredients from Haagerup & Musat

Playing further with the gap

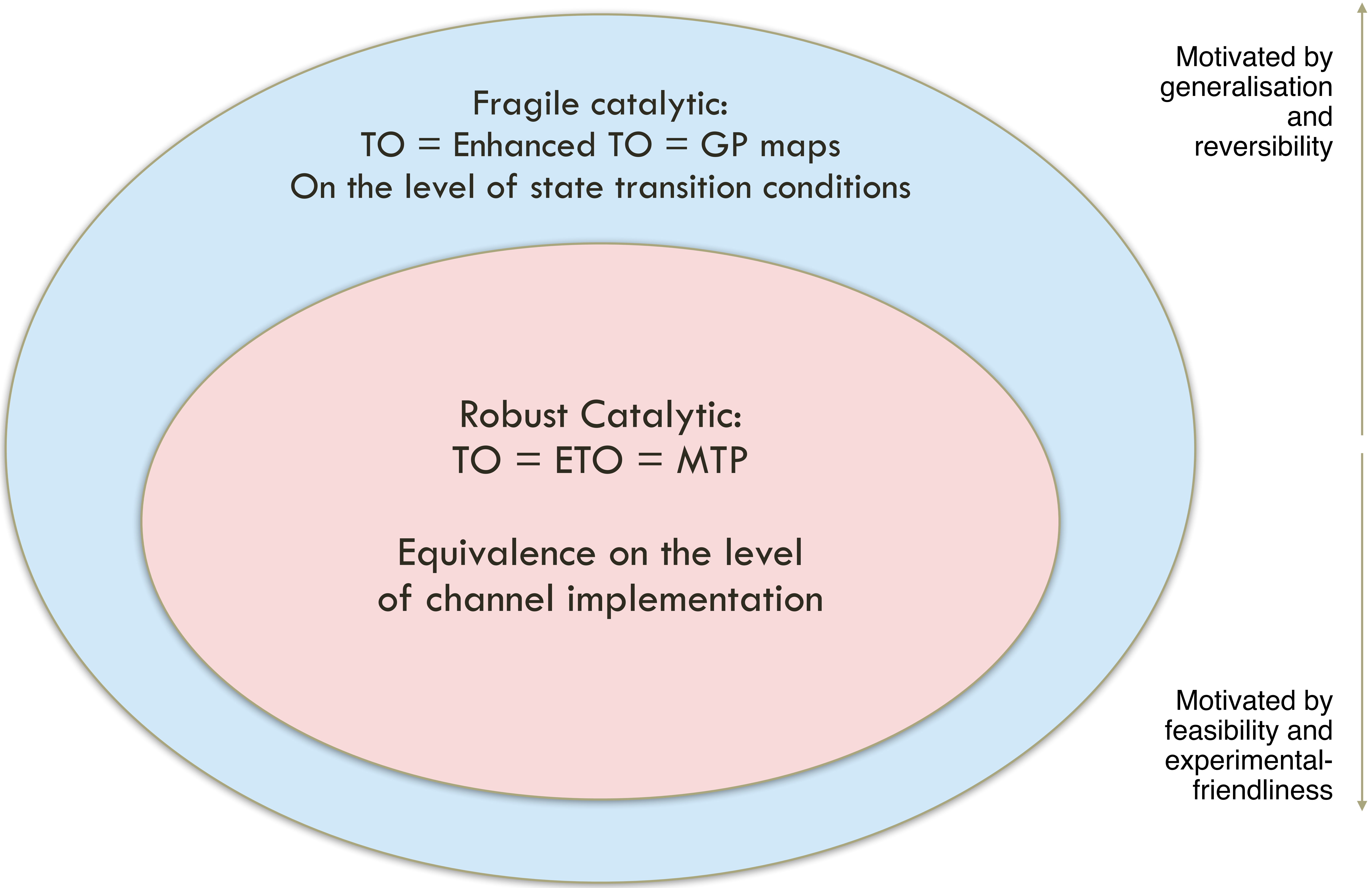
Two questions:

1. Can we understand a simple case where robust catalysis fits into the hierarchy?

Fully degenerate H

2. Can we identify other physical ingredients where gaps in the hierarchy can be bridged?

Gaussian operations



Fragile catalytic:
TO = Enhanced TO = GP maps
On the level of state transition conditions

Robust Catalytic:
TO = ETO = MTP

Equivalence on the level
of channel implementation

Motivated by
generalisation
and
reversibility

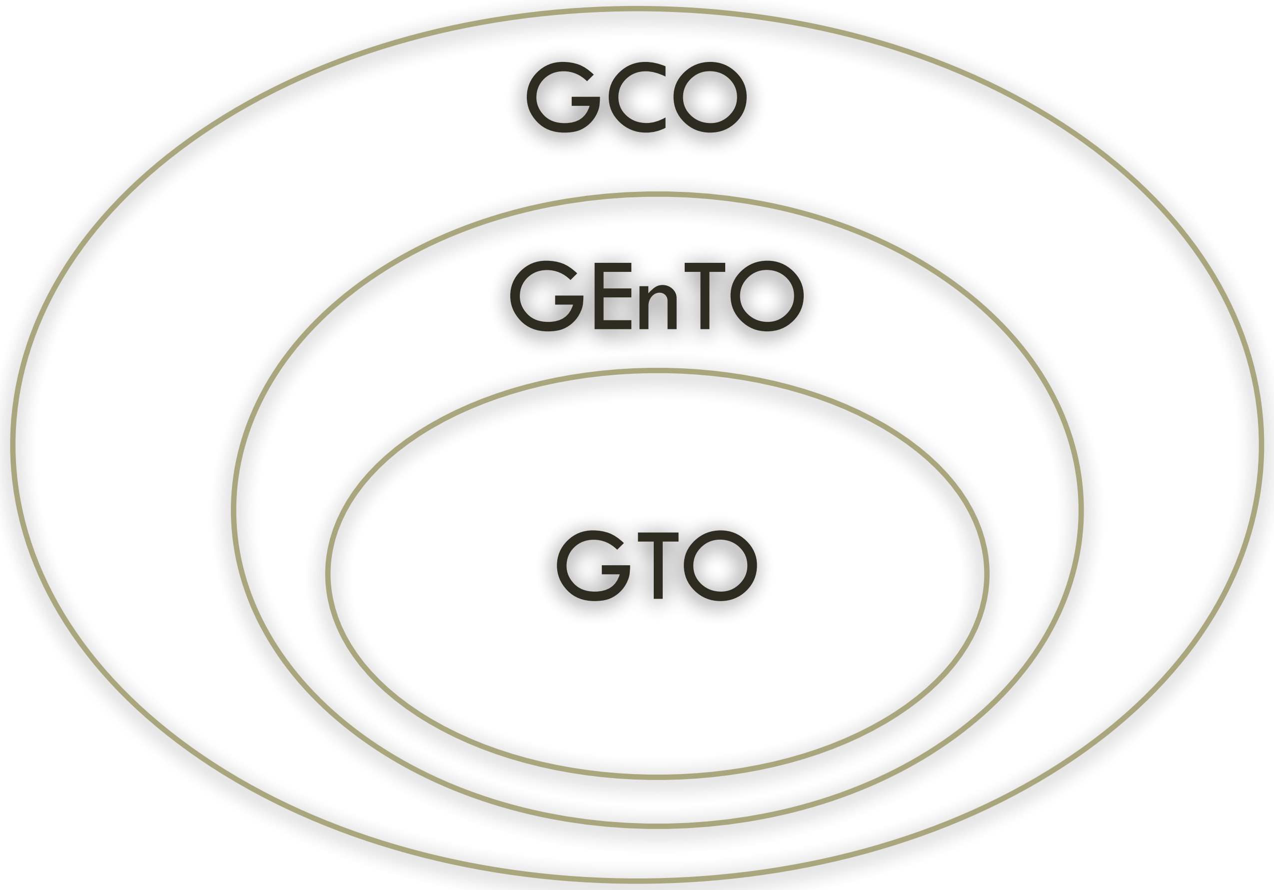
Motivated by
feasibility and
experimental-
friendliness

Considering Gaussian covariant operations

Gaussian covariant operations (GCOs): $\mathscr{E}_{\mathrm{GCO}}$ that are 1) Gaussian-preserving, and 2) commutes with time-translation.

Gaussian enhanced thermal operations (GEnTO): GCOs that are Gibbs-preserving

Gaussian thermal operations: channels that admit a dilation $\mathscr{E}_{\mathrm{GTO}}(\,\cdot\,) = \mathrm{tr}_R(U(\,\cdot \otimes \tau_R)U^\dagger),$ where τ_R is a thermal state of some temperature and U commutes with the global Hamiltonian.

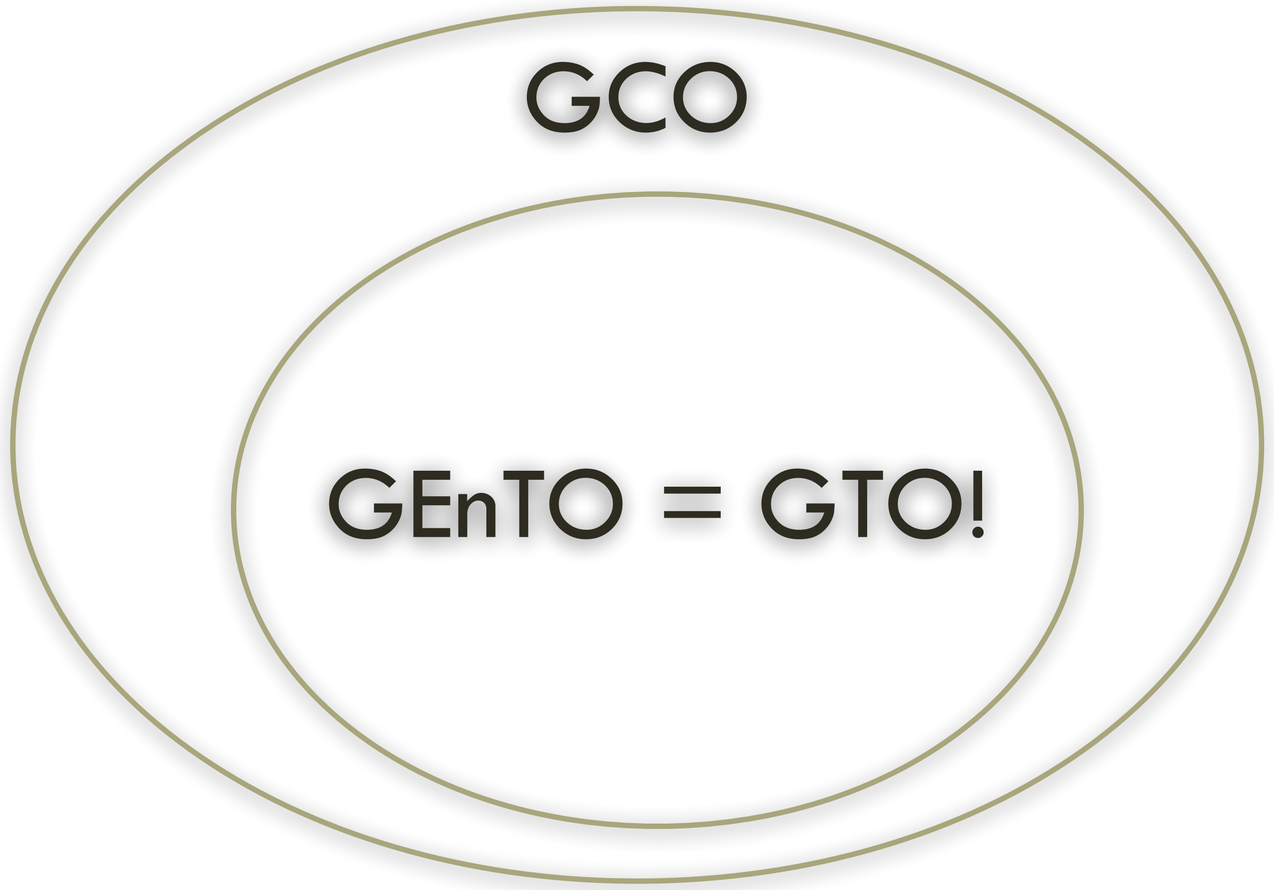


“Time-translation symmetry and thermality in Gaussian operations”, soon to be on arXiv!
Xueyuan Hu, Lea Lautenbacher, Giovanni Spaventa, Martin Plenio, NN, Jeongrak Son

Considering Gaussian covariant operations

Result overview:

1. The gap between enhanced thermal operations and thermal operations vanish when we consider Gaussian channels, i.e. GEnTO = GTO!
2. Recall that covariant operations are known to always have a **free dilation**, i.e. implementable with a covariant unitary & auxilliary system. However, Gaussian covariant channels do not always have a free dilation, i.e. they can't always be implemented by covariant+Gaussian unitary & auxilliary system!*
3. New, non-extensive monotones identified for Gaussian covariant operations
4. No catalytic advantage for single-mode state transformations (even when allowing for a multimode, fragile catalyst)



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Conclusions

There is a hierarchy of equilibration processes motivated by different considerations

Thermal operations occupy a somewhat special position in the hierarchy :)
- physically conservative enough to guarantee notions of equilibrium
- powerful enough to encompass catalytic effects that are robust

Might be fun to think about how thermodynamic resource theories change under additional resource constraints, e.g. Gaussianity

Thank you for listening!