# Death and Resurrection
# of the
# Zero-th principle of thermodynamics

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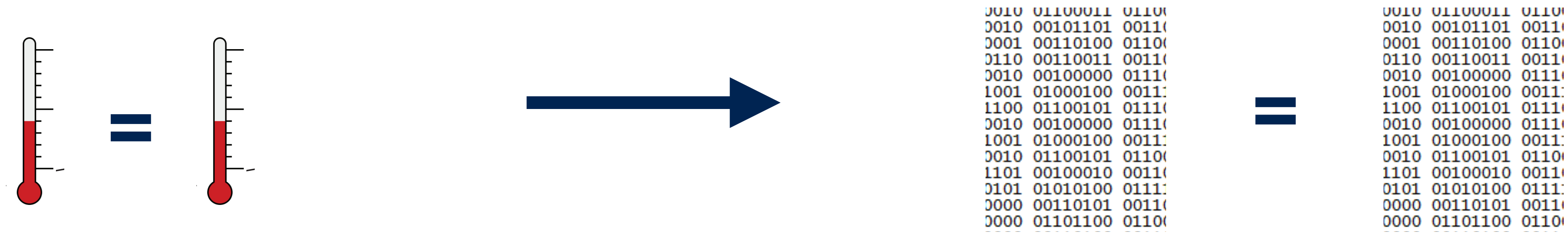
*with Hal Haggard. Also: Eugenio Bianchi, Aldo Riello, Goffredo Chirco, FQXi postdoc*

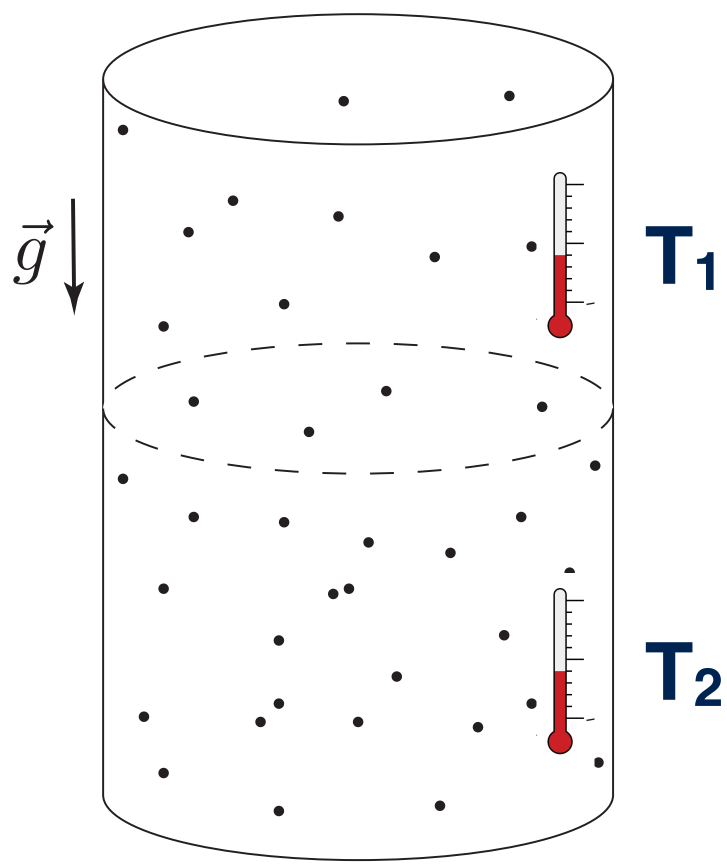


**From equal temperature to equal information**

0th : Temperature is constant at equilibrium

1st : Energy is constant in time

2nd : Entropy grows in time




$$T_1 = T_2$$

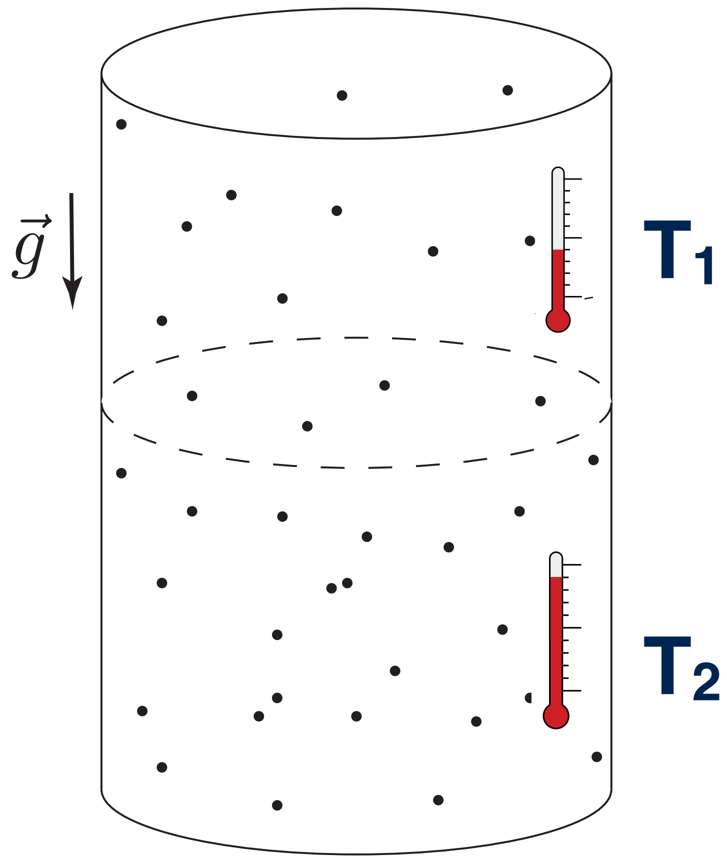
**False !**

# 0th : Temperature is not constant at equilibrium in a gravitational field

$$T_2 = T_1 \left(1 + \frac{gh}{c^2}\right)$$

Tolman-Erhenfest effect (1930)

$$T|\xi| = constant$$




On Earth surface: $$\frac{\Delta T}{T} = 10^{-18} cm^{-1}$$

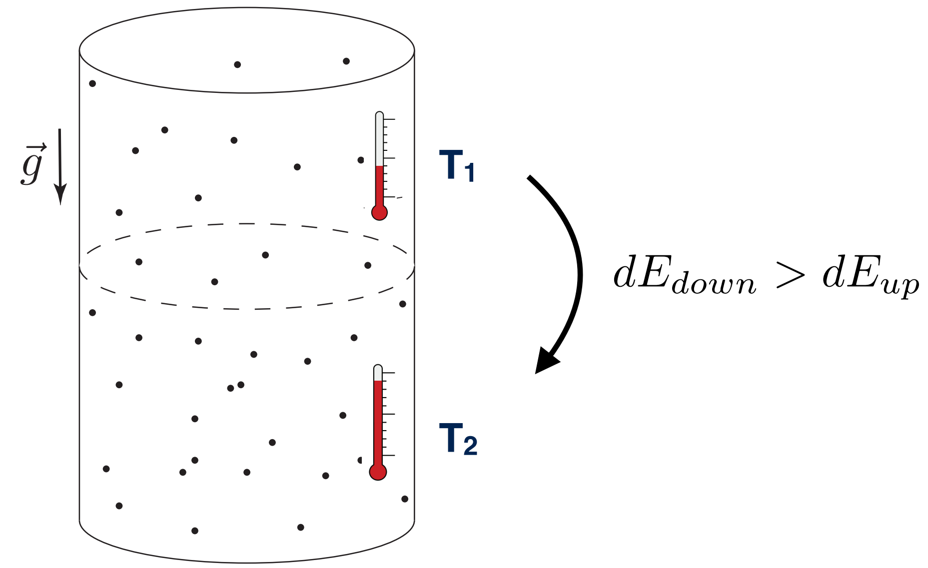
*How can this happen?*

In micro-canonical: $S(E) = k \ln N(E)$

$$\frac{1}{kT} = \frac{dS(E)}{dE}$$

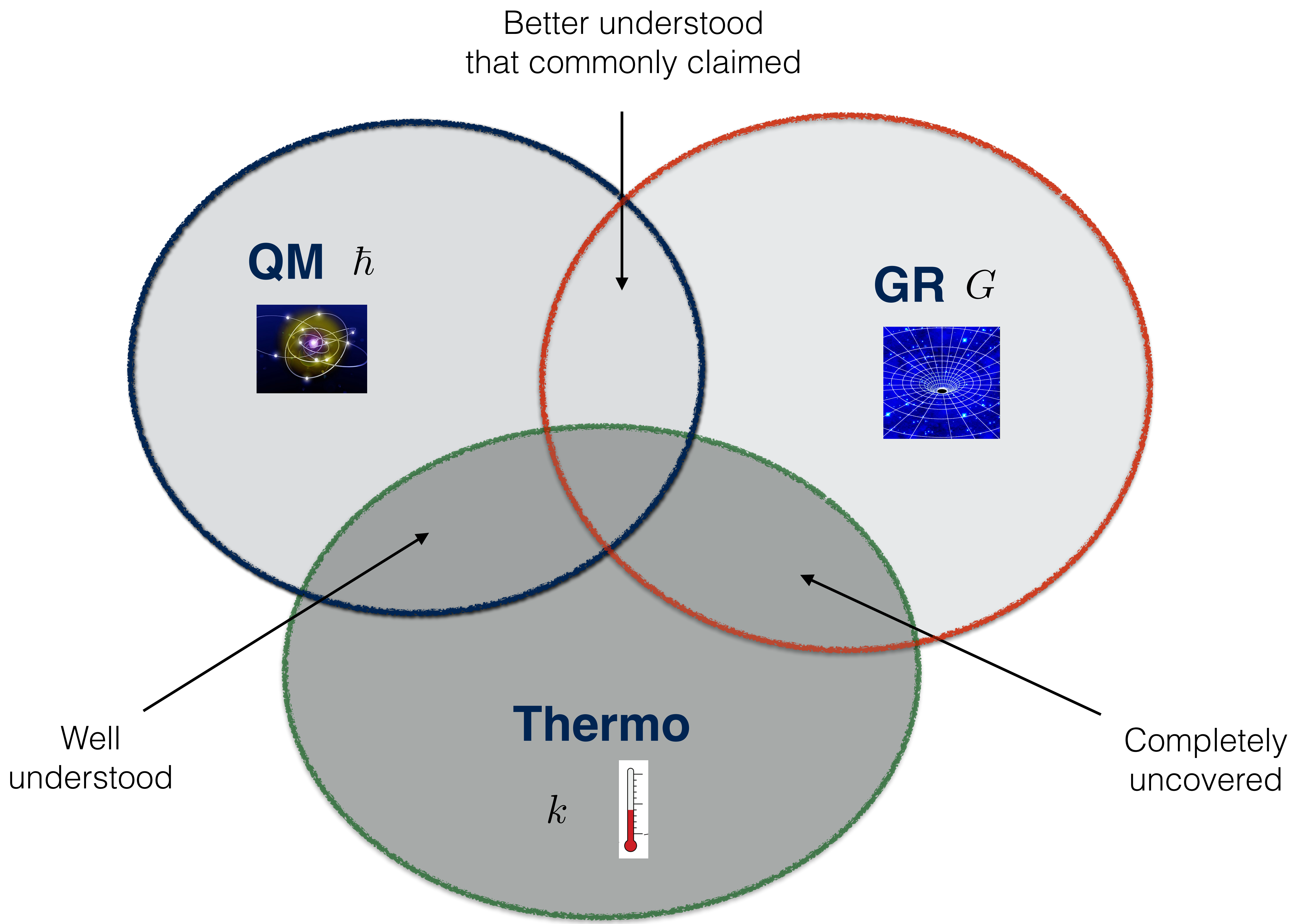
Maximazing $N = N_1 N_2$ under an energy transfer $dE$ gives $T_1 = T_2$.

But conservation of Energy is tricky in GR: $dE$ falls!



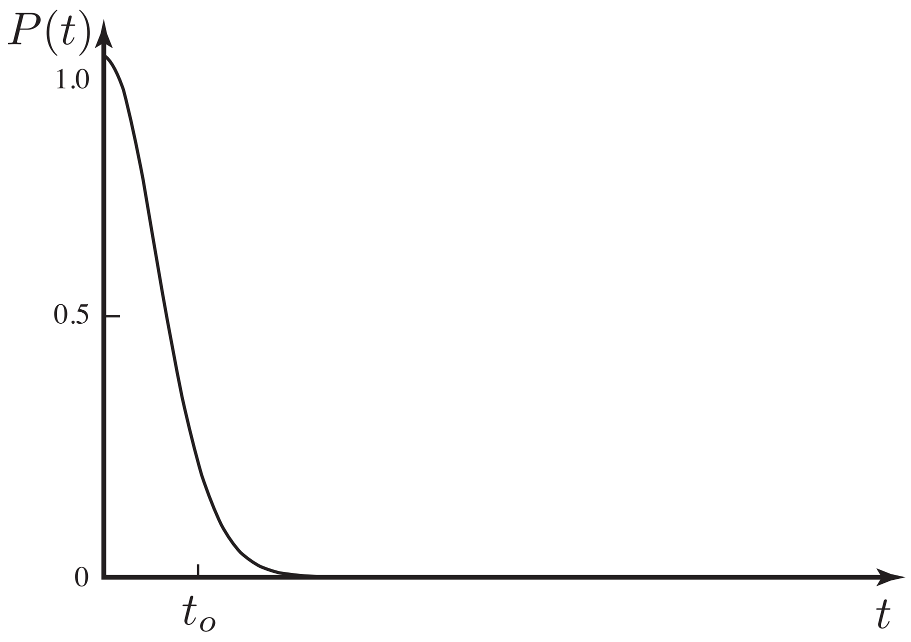
$T_1 = T_2$ ***is dead !***

***What replaces it ?***




Carlo Rovelli @ Vieques

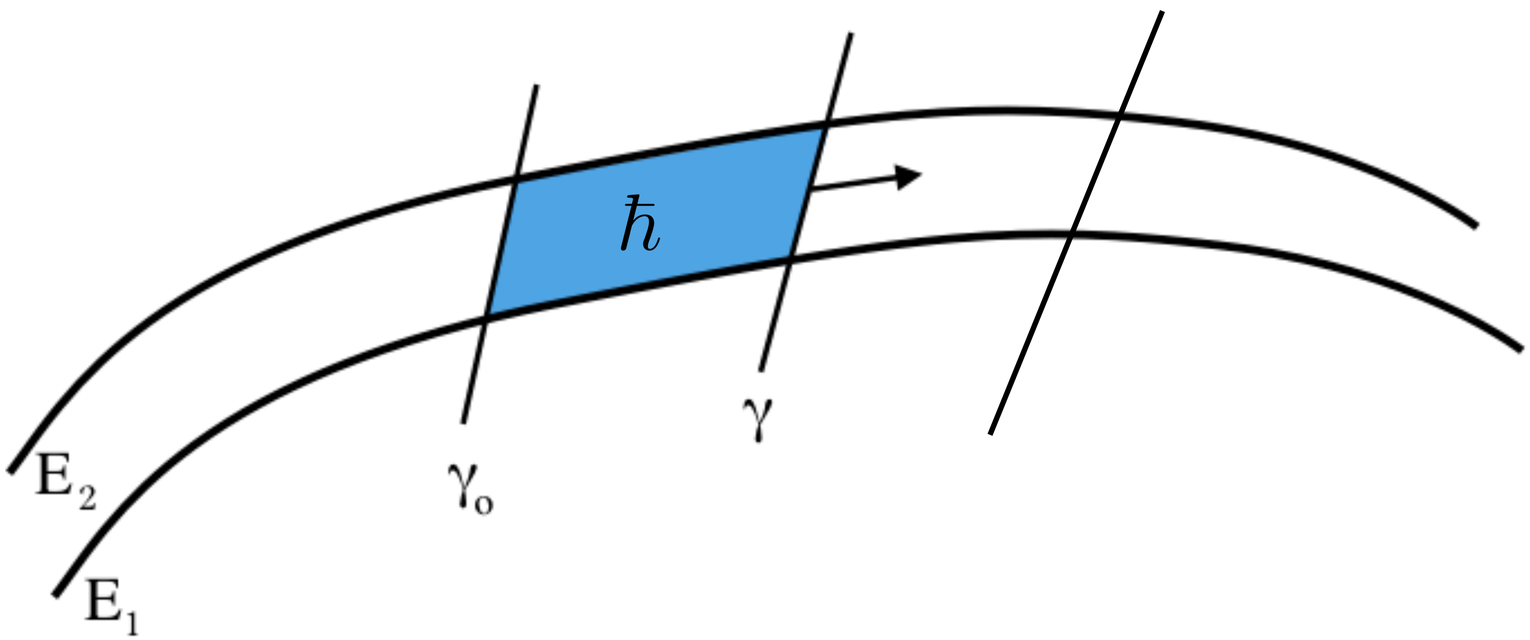
# Time needed by a state to move away from itself




$$P(t) = |\langle\psi(0)|\psi(t)\rangle|^2$$
$$= |\langle\psi(0)|e^{-\frac{i}{\hbar}Ht}|\psi(0)\rangle|^2$$

$$\frac{d^2P}{dt^2} = \frac{1}{\hbar^2}(\langle H\rangle^2 - \langle H^2\rangle) = -\frac{(\Delta E)^2}{\hbar^2}$$

$$t_o = \frac{\hbar}{\Delta E}$$




$$\omega(X) = -dH$$

$$\frac{dV(t)}{dt} = \frac{d}{dt}\int_{R(t)} \omega = \int_\gamma \omega(X)$$

$$= -\int_\gamma dH = E_2 - E_1 \equiv \Delta E$$

$$t_o = \frac{\hbar}{\Delta E}$$

Specialize to thermal states. Then $\Delta E \sim kT$ and therefore

$$t_o = \frac{\hbar}{kT}$$

This is a **universal time step**.
At temperature T, any system moves from a state to an orthogonal state in a time $t_o$!

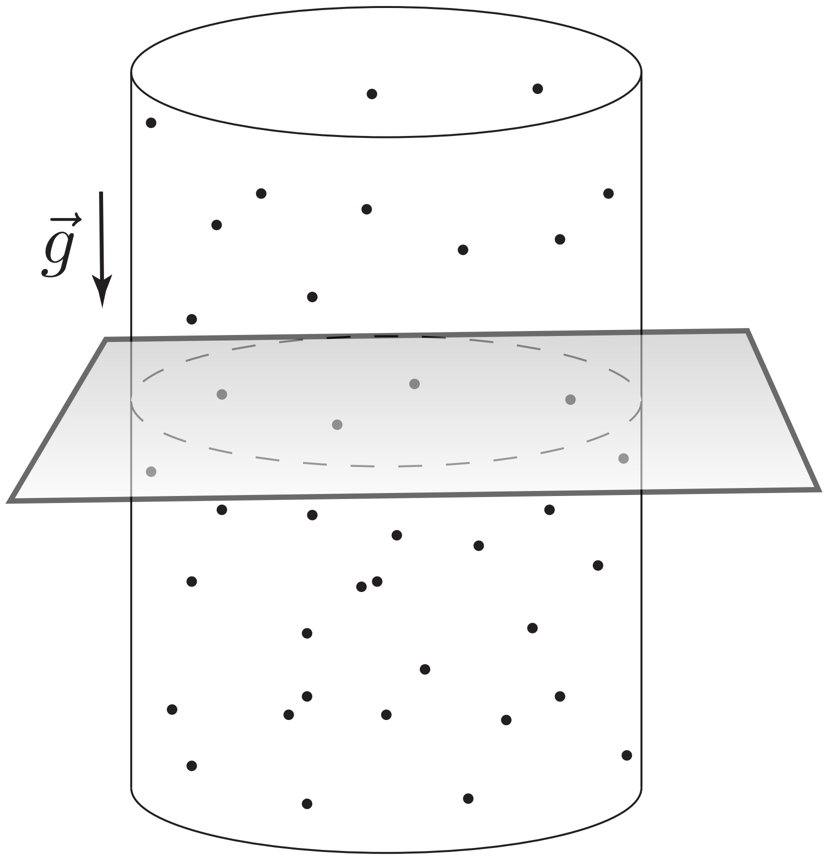
Introduce a "thermal time" $$\tau = \frac{t}{t_o} = \frac{kT}{\hbar}\, t$$

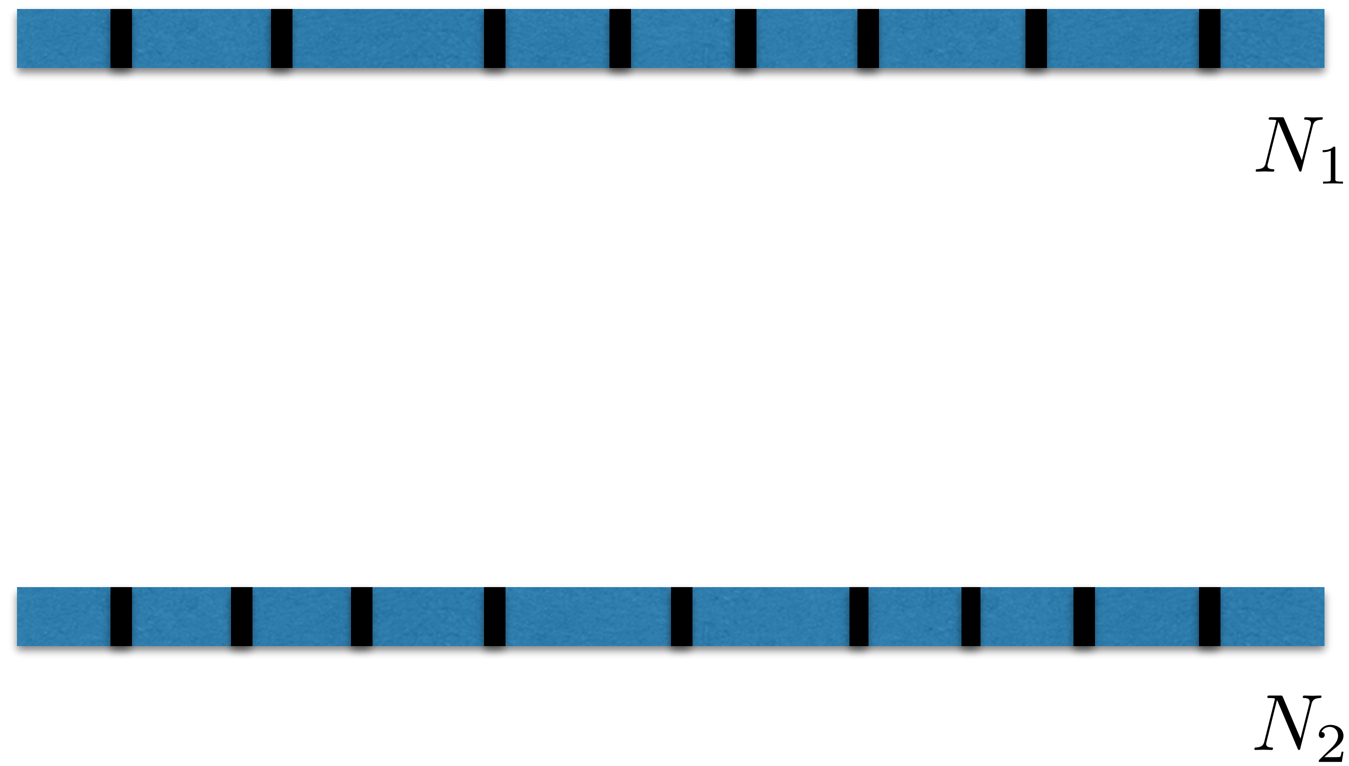
This is precisely the thermal time (Connes-CR): the parameter of the Tomita flow in the algebra of the observables in a generally covariant QFT.

Physical meaning of Temperature ( $\hbar = k = 1$ ):

**Temperature is number of states transited per unit of time**

(room temperature ~ $3 \times 10^{12}\, s^{-1}$ ).




Amount of information about 1 that 2 has access to: $N_1$ $$I_1 = \ln N_1$$

Amount of information about 2 that 1 has access to: $N_2$ $$I_2 = \ln N_2$$

**Postulate: equilibrium is** $$\delta I = I_2 - I_1 = 0$$

$$\delta I = 0$$

$$\tau = \frac{t}{t_o} = \frac{kT}{\hbar} t$$

Non relativistic physics $t_1 = t_2$

$$T_1 = T_2$$

On curved spacetime

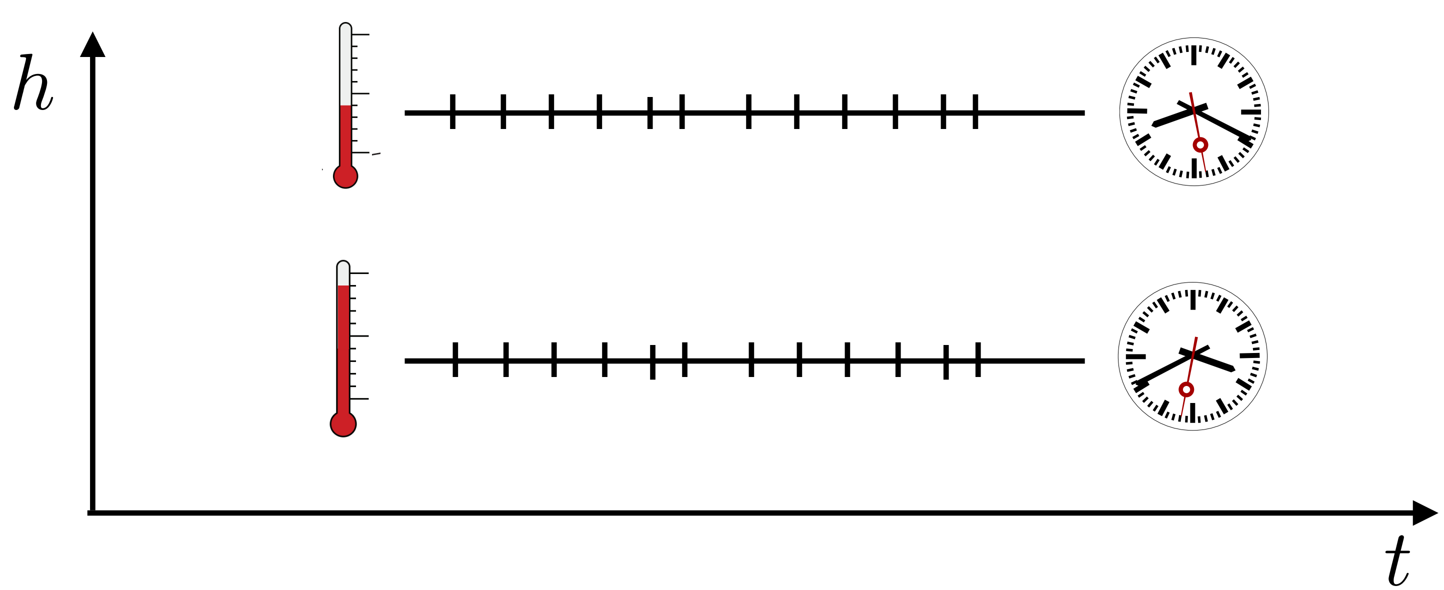
$$d\tau = \frac{kT}{\hbar} ds$$

Proper time along an orbit:

$$ds = |\xi| dt$$

$$|\xi_1| T_1 = |\xi_2| T_2$$

$$T|\xi| = constant$$




$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = \left(1 - \frac{gh}{c^2}\right) dt^2 - d\vec{x}^2$$

- *Resurrected 0th principle of thermodynamics:*

$$I_1 = I_2$$

Two histories are in equilibrium if the net **information** flow between them is zero: if they transit the same number of states during the interaction period.

- *Temperature is the rate at which a system moves from state to state.*

- *Thermal time:* $\tau = \frac{kT}{\hbar} t$ *dimensionless time, in unit of universal step.*

## The components of the world in fundamental physics

*Newton*: Particles — Space — Time

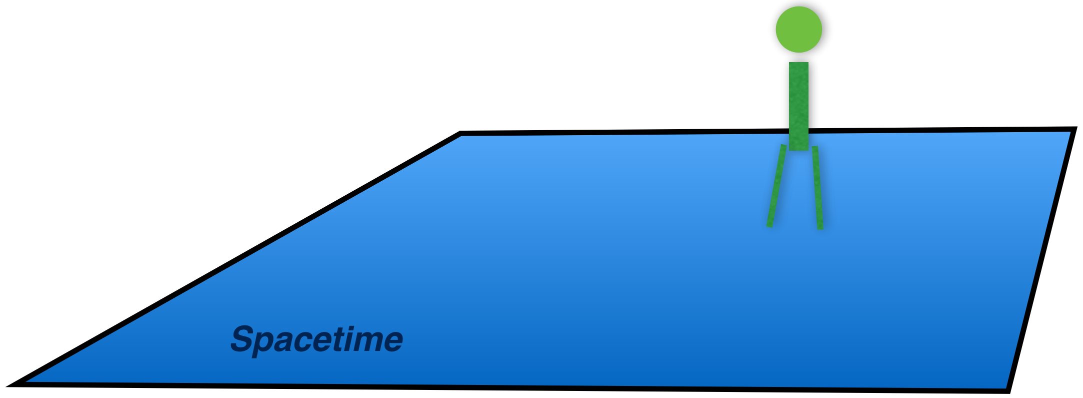
*Faraday-Maxwell*: Particles — Fields — Space — Time

*Special relativity*: Particles — Fields — Spacetime

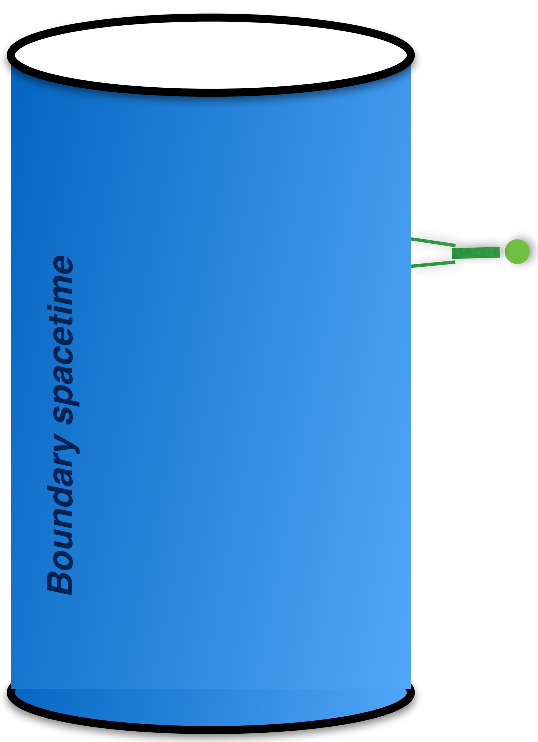
*Quantum mechanics*: Quantum-Fields — Spacetime

*General relativity*: General-covariant fields

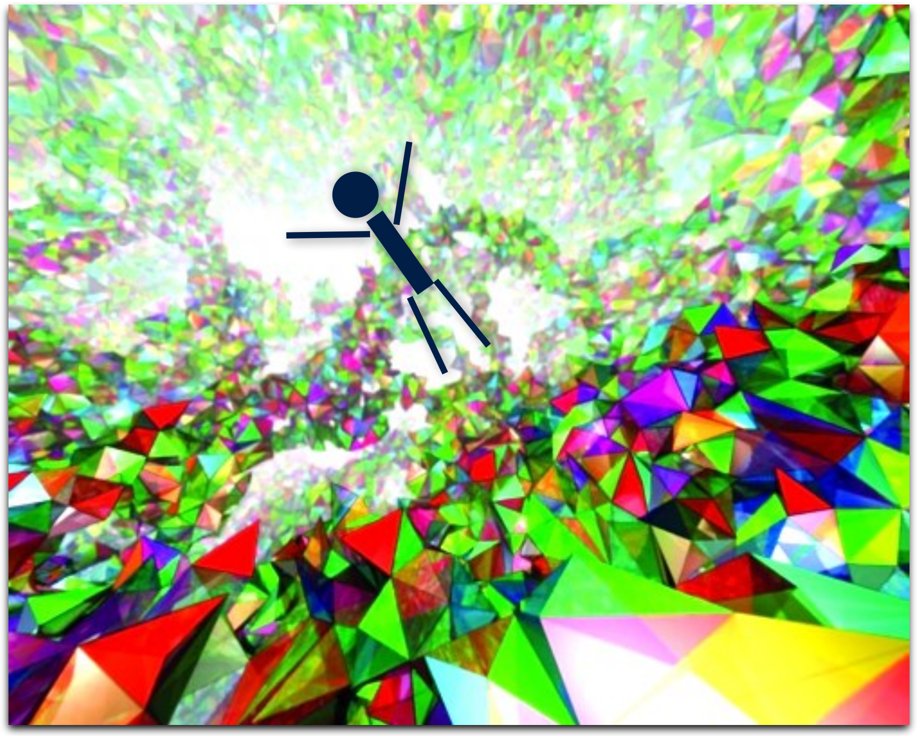
*Quantum gravity*: General-covariant quantum fields




Conventional quantum field theorist




Post-Maldacena string theorist



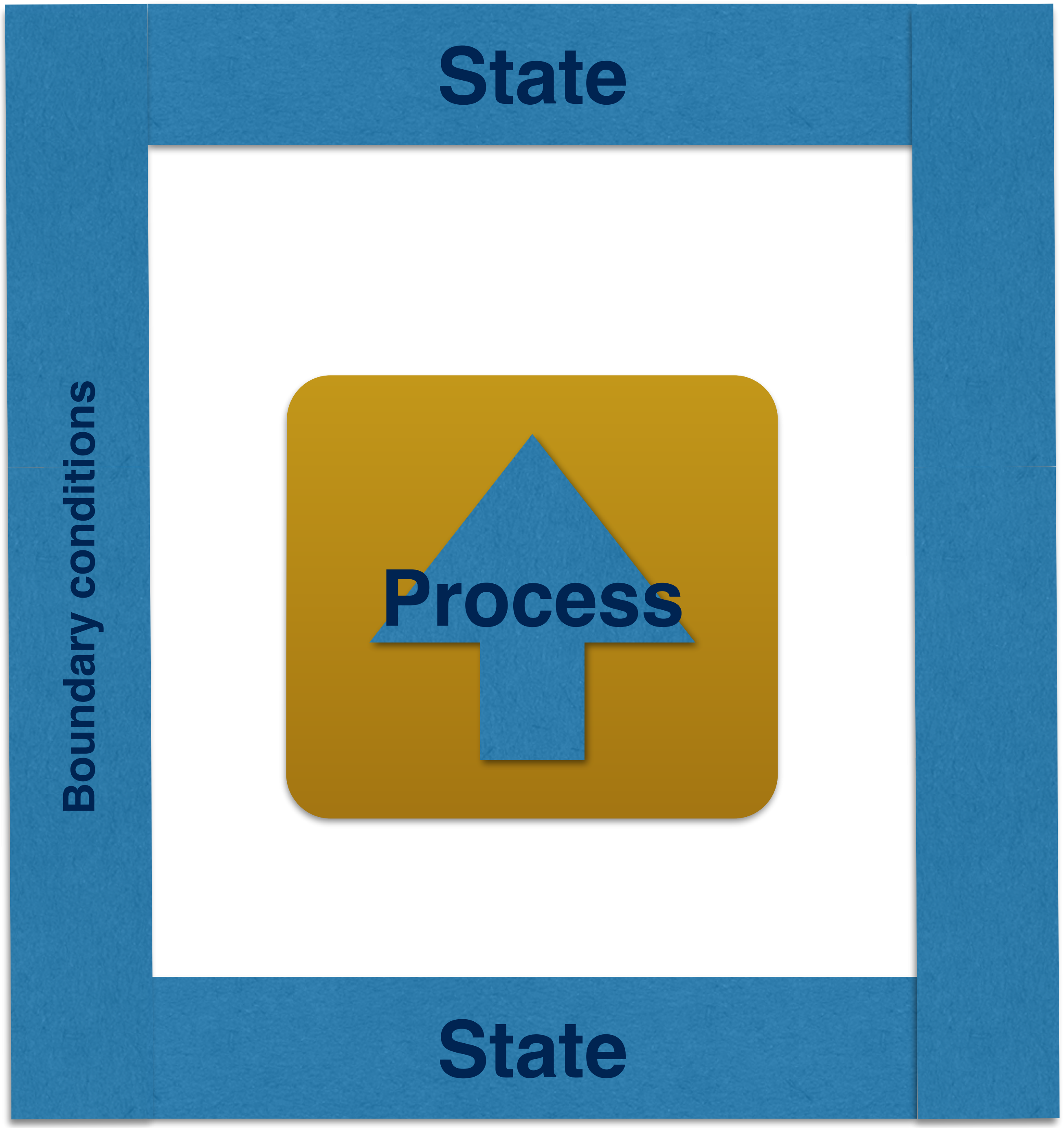
Genuine quantum-gravity physicist

Quantum theory:

**information** exchanged
in interaction between
two systems

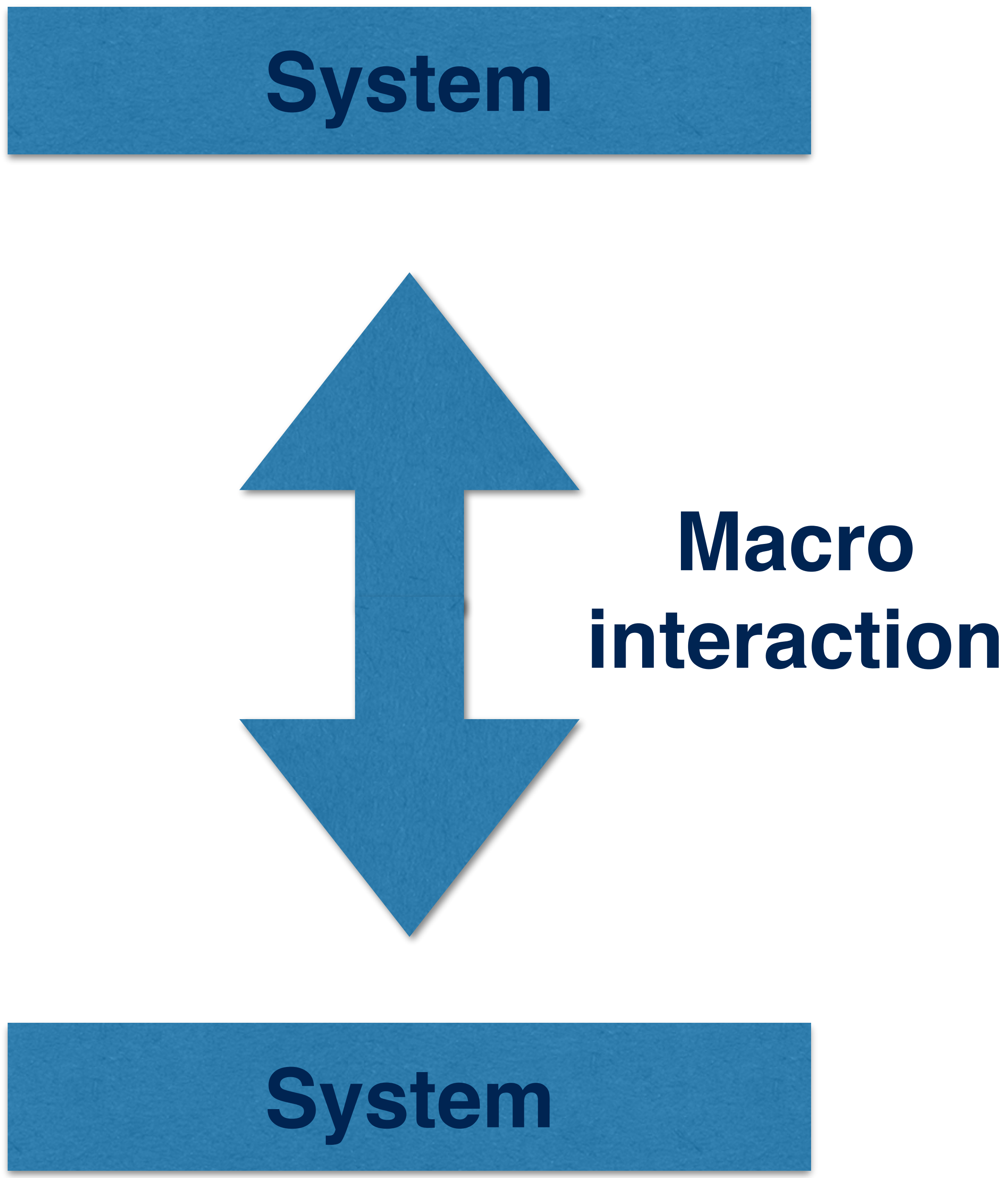
1. There is a finite amount of **<u>information</u>** in a physical system.
2. It is always possible to acquire new **<u>relevant information</u>** on a physical system.

Quantum
field theory



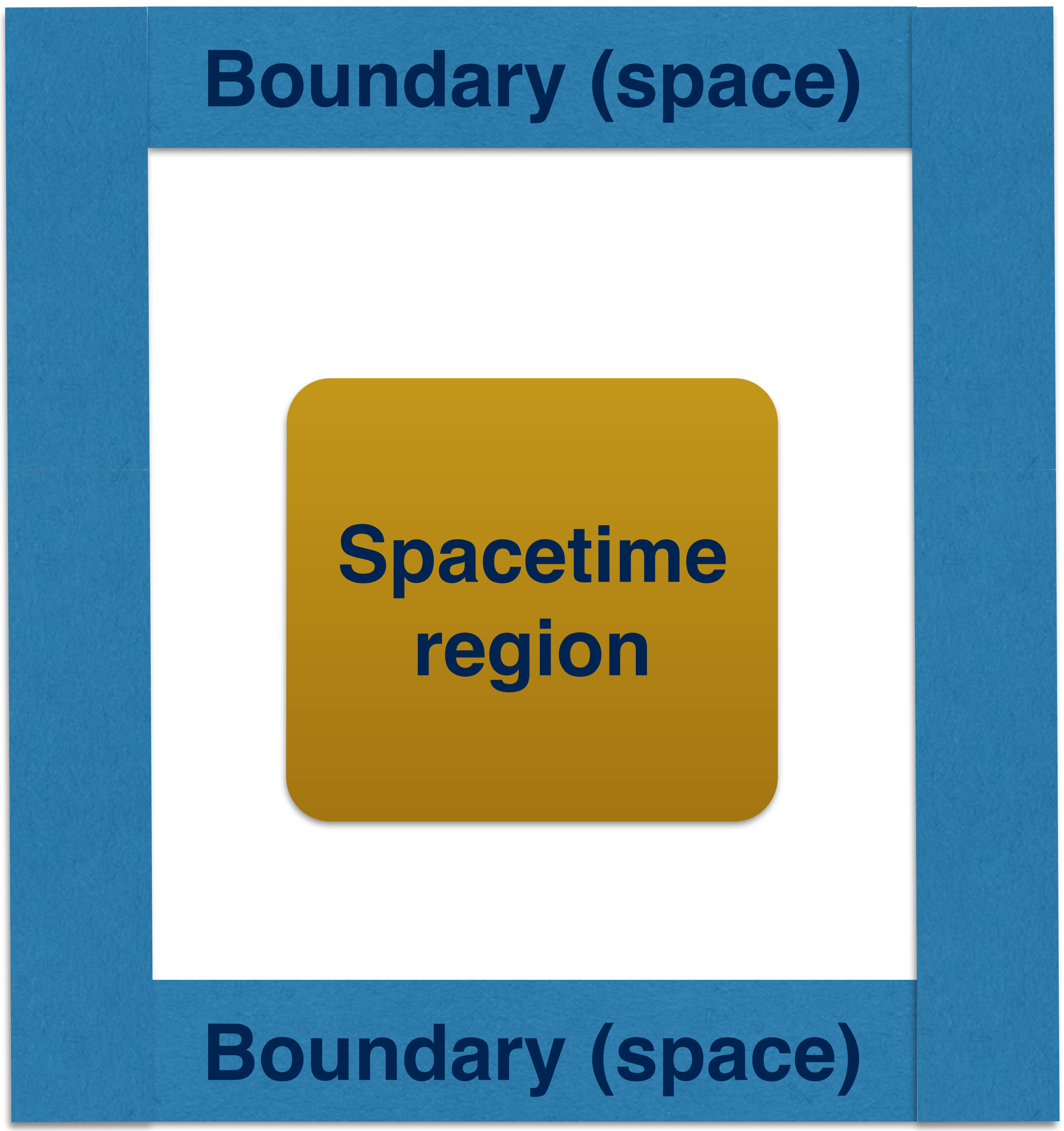
Thermodynamics:

**information** exchanged in interaction between two systems



General relativity:

**localization** defined relationally between physical entities



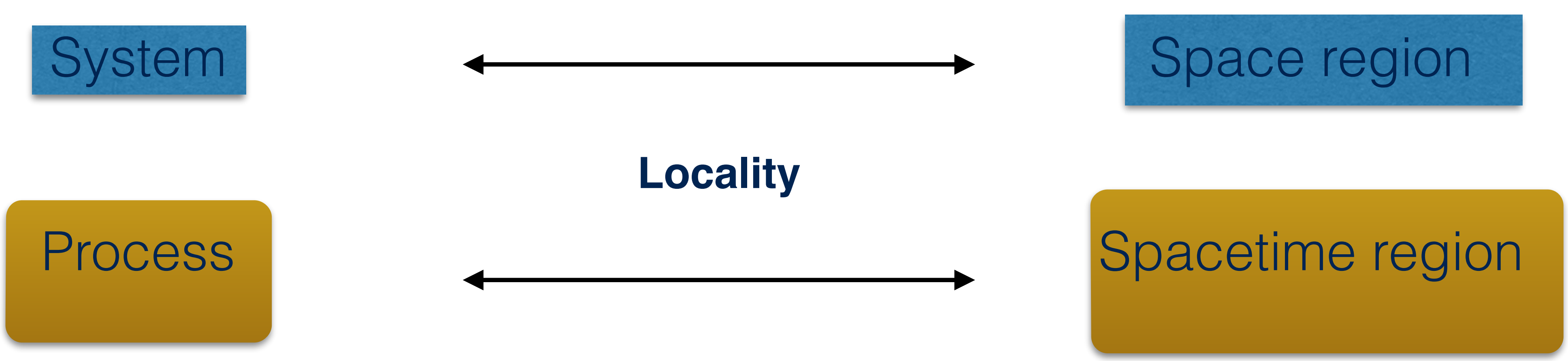
Quantum theory:

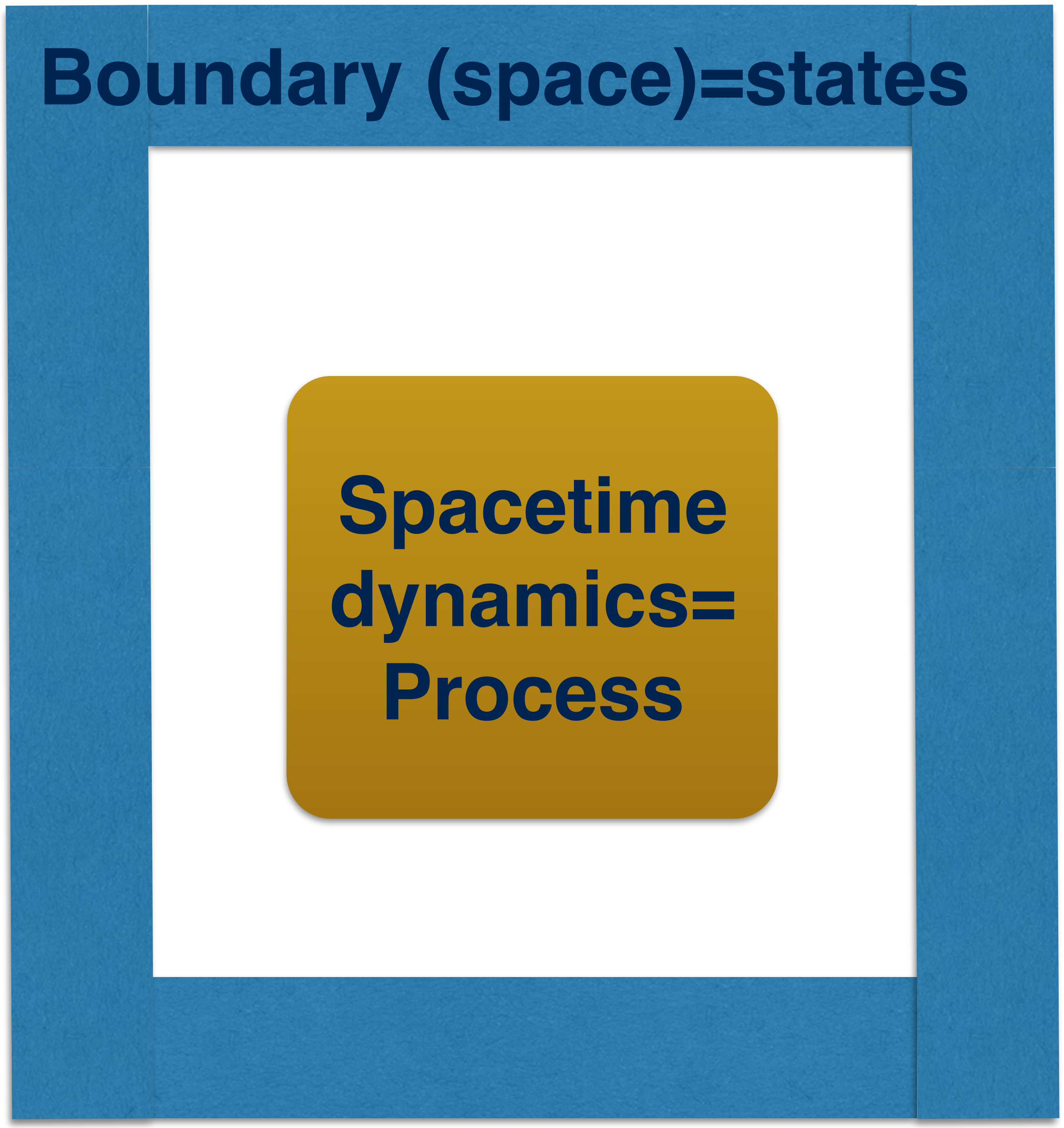
**Relations**
between systems
via **interactions**

General Relativity:

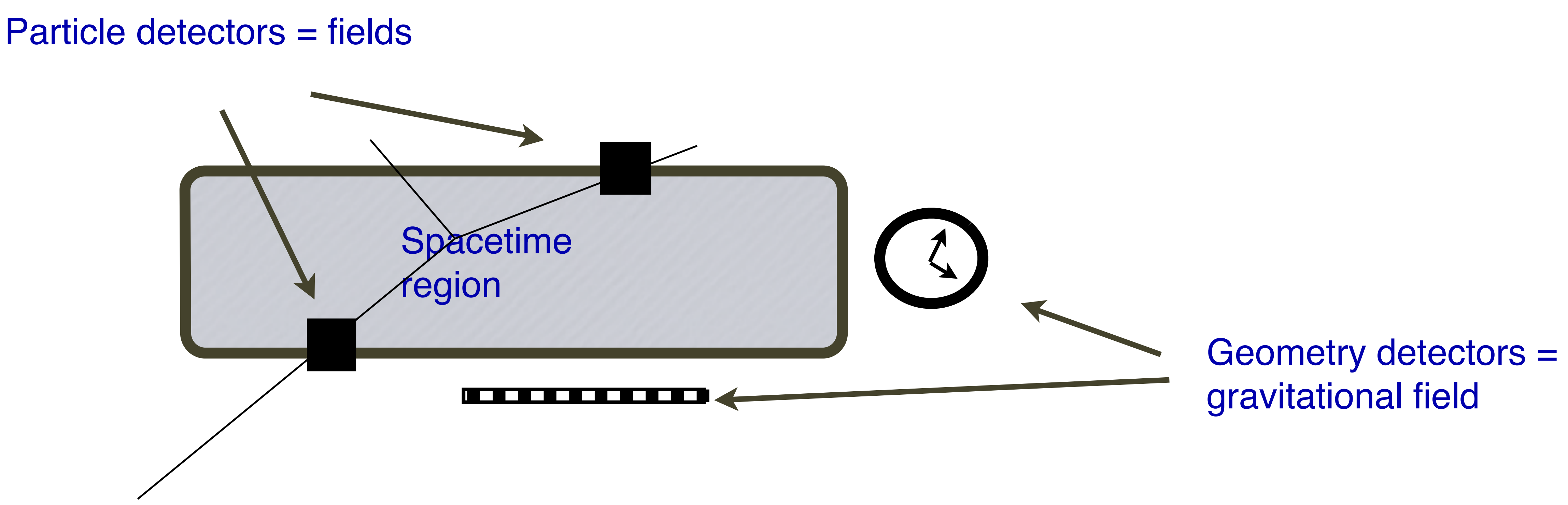
**Relations**
between regions
by **adjacency**

**Locality**:
*Interactions* are only
among *adjacent* things




Boundary (space)=states
Spacetime
dynamics=
Process

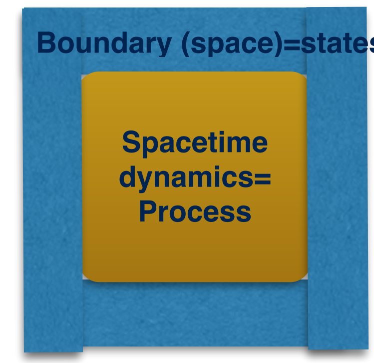
Boundary values of the gravitational field
= geometry of box surface
= distance and time separation of measurements




In GR, distance and time measurements are field measurements like others: they are part of the boundary data of the problem.

Boundary (space)=states

Spacetime dynamics= Process




## Loop Quantum Gravity

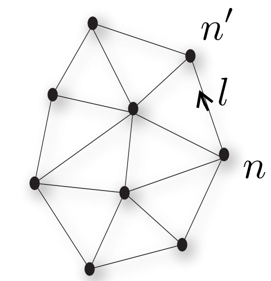
*Kinematics*

State space

$$\mathcal{H}_\Gamma = L^2[SU(2)^L/SU(2)^N]$$

Operators:

$$\vec{L}_l = \{L^i_l\}, i = 1,2,3 \quad \text{where} \quad L^i\psi(h) \equiv \frac{d}{dt}\psi(he^{t\tau_i})\Big|_{t=0}$$




$\Gamma$

*Dynamics*

Transition amplitudes

$$W_{\mathcal{C}}(h_l) = \int_{SU(2)} dh_{vf} \prod_f \delta(h_f) \prod_v A(h_{vf})$$

$$h_f = \prod_v h_{vf}$$

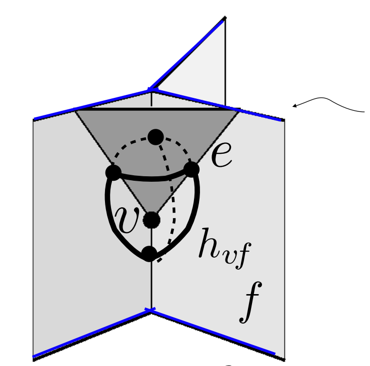
Vertex amplitude

$$A(h_f) = \sum_{j_f} \int_{SL(2,\mathbb{C})} dg_e \prod_f (2j_f+1)\ Tr_j[h_f Y_\gamma^\dagger g_e g_{e'}^{-1} Y_\gamma]$$

Simplicity map

$$Y_\gamma \ : \ \mathcal{H}_j \quad \to \quad \mathcal{H}_{j,\gamma j}$$

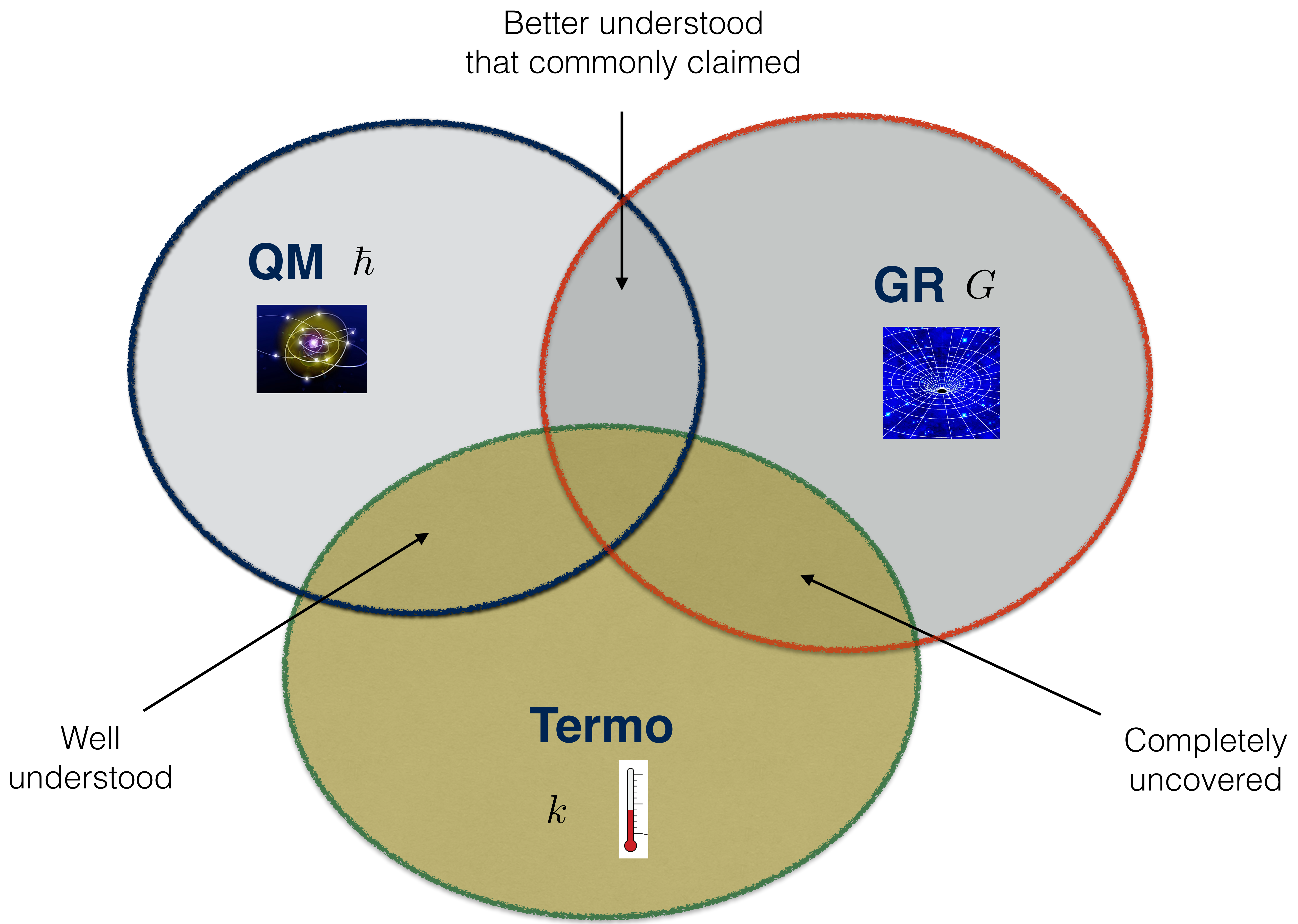
$$|j;m\rangle \ \mapsto \ |j,\gamma(j+1);j,m\rangle$$




$\Gamma$

2-complex $\mathcal{C}$
(vertices, edges, faces)

With a cosmological constant Λ > 0:
Amplitude: SL(2,C) ➞ SL(2,C)_q network evaluation.


Better understood
that commonly claimed
QM $\hbar$
GR $G$
Termo
$k$
Well
understood
Completely
uncovered