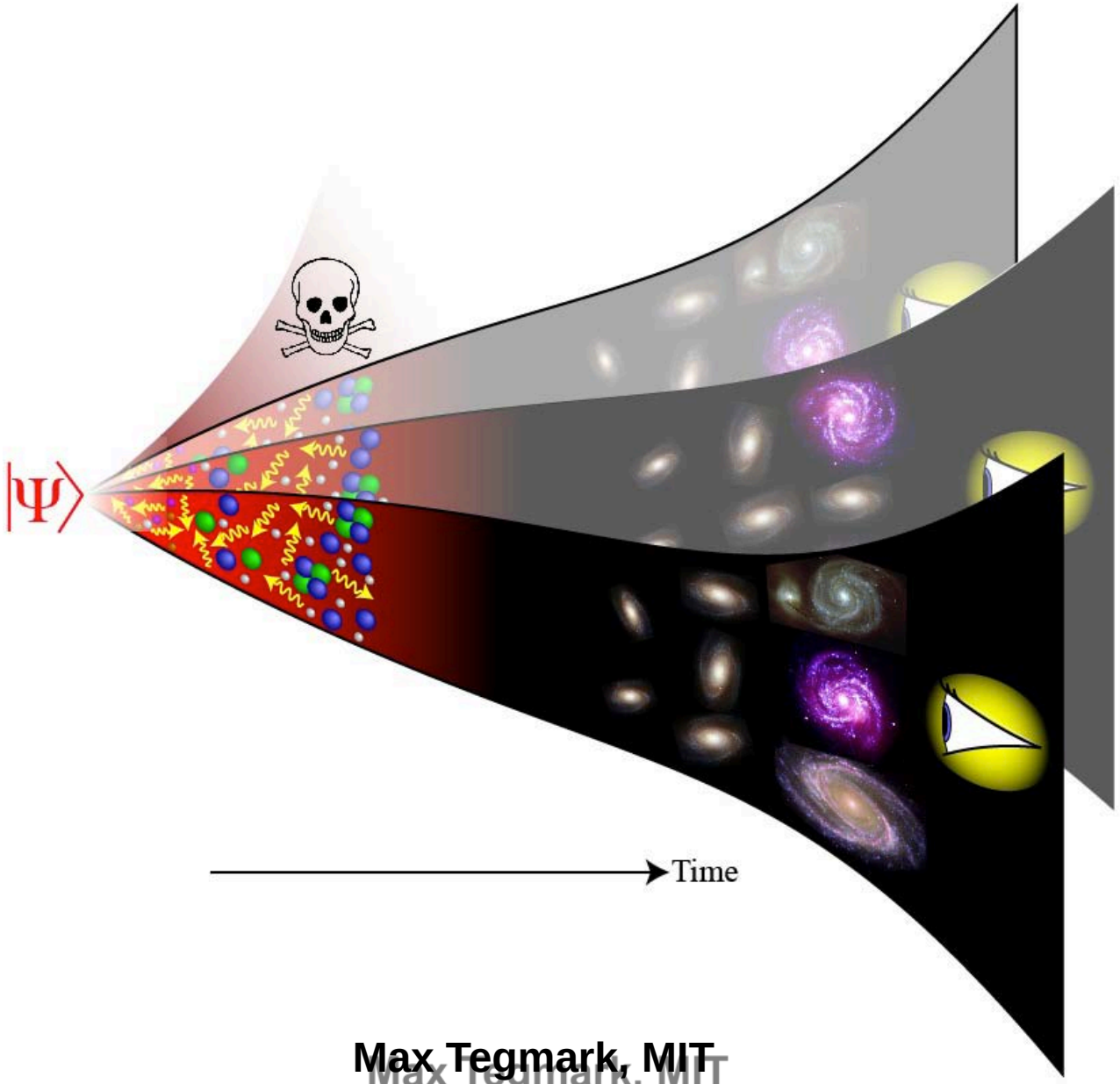
Time and entropy in the multiverse



Max Tegmark, MIT

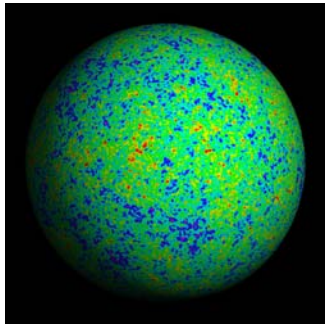

This isn't science!
It's inevitable


Makes sense!
Why not?
I hate it!
AVON

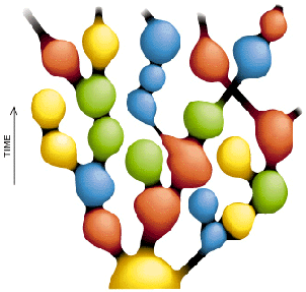

Party on!

Which are the 4 multiverse levels?

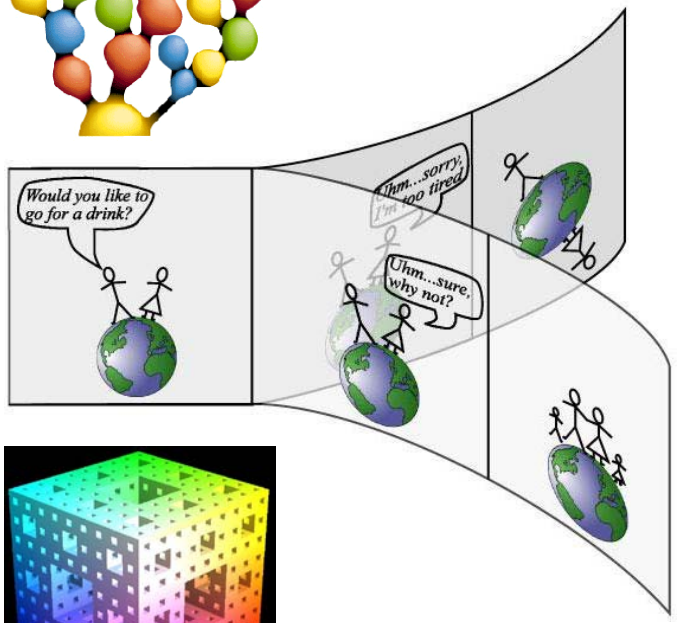
1) Different Hubble volumes



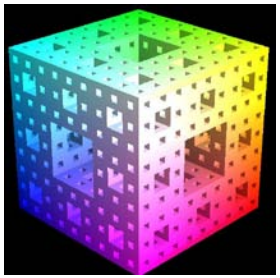
2) Different post-inflationary regions



3) Different decohered branches of the quantum wavefunction



4) Different mathematical structures



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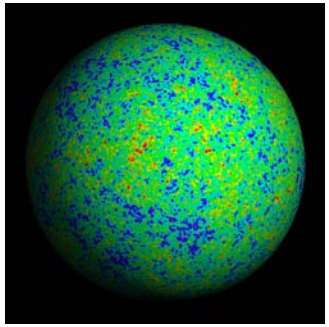
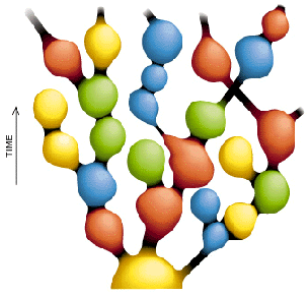
Where are the parallel universes?

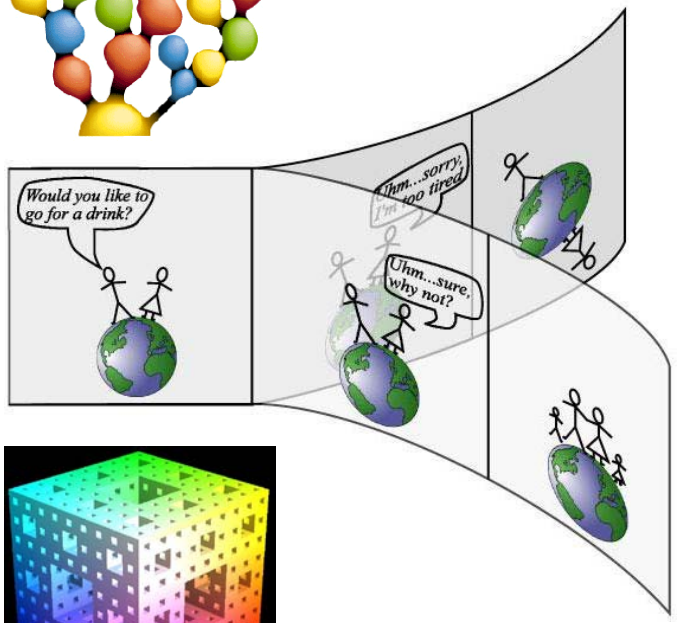
1) Far away in space



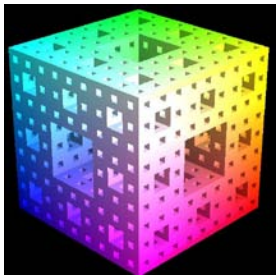
2) Infinitely far away in space



3) Elsewhere in Hilbert space



4) Elsewhere in “math space”



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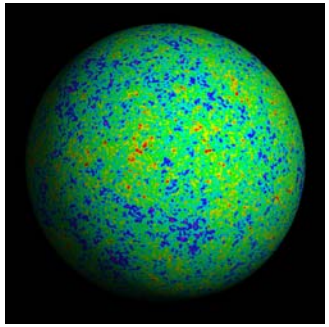
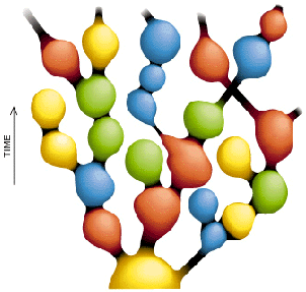
What are the 4 multiverse levels like?

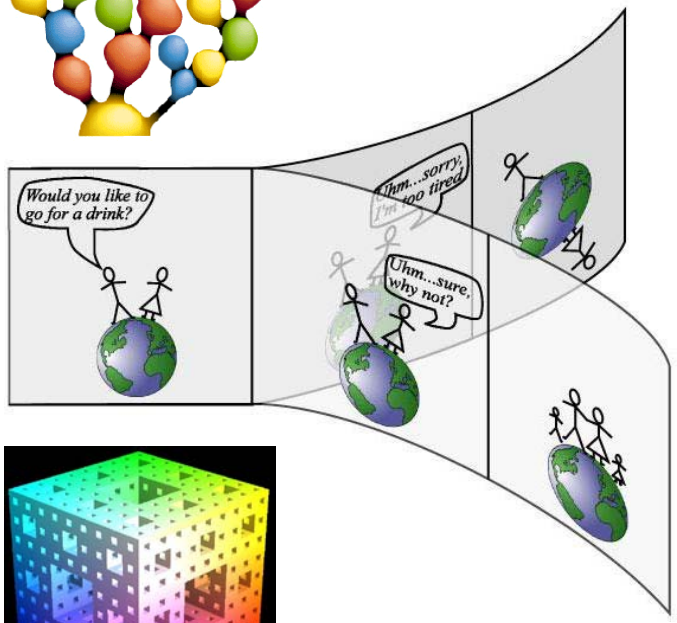
1) Same effective laws of physics, different initial conditions



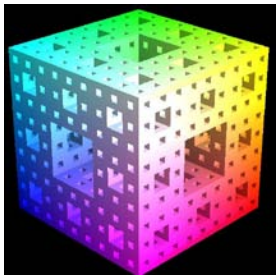
2) Same fundamental laws of physics, different effective laws (“bylaws”)



3) Nothing qualitatively new



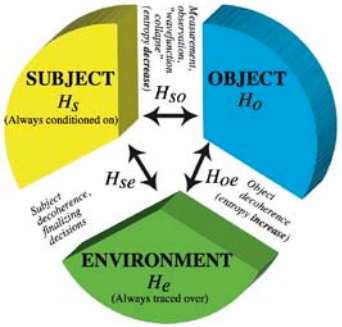
4) Different fundamental laws of physics



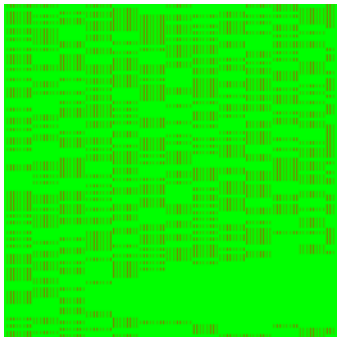
Summary:

- How lower entropy?

Basically, the entropy of something decreases when you look at it and increases when you don't (quant-ph/9907009, arXiv:1108.3080)



- How lower entropy by a lot? (inflate+observe!)



- Our future: the Big Snap?

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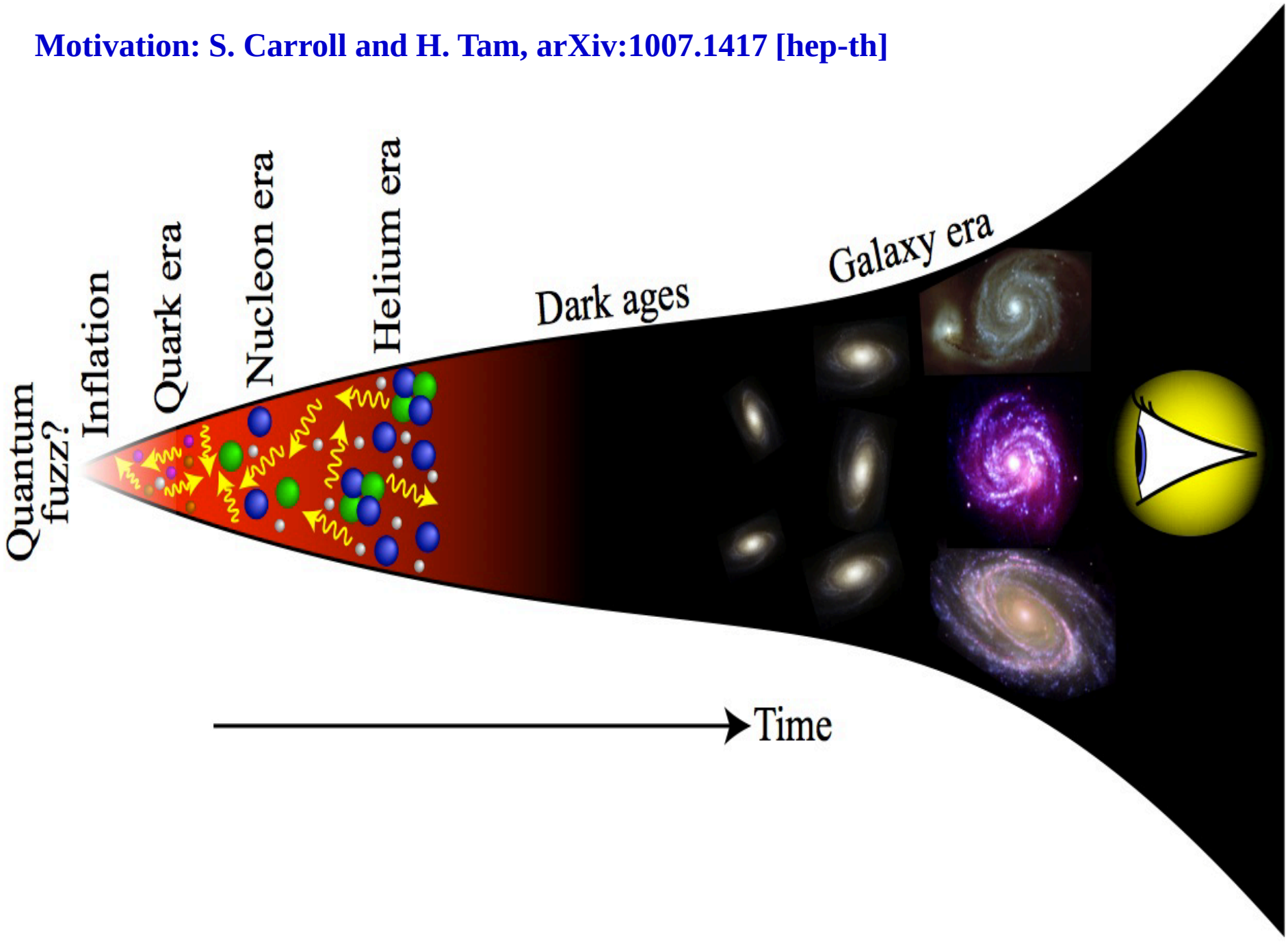
Motivation: S. Carroll and H. Tam, arXiv:1007.1417 [hep-th]



"[Thinking] that entropy has anything to do with what we know about a system is a bad misleading mistake."

Author?

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"[Thinking] that entropy has anything to do with what we know about a system is a bad misleading mistake."

David Albert, Copenhagen, Aug. 28, 2011

(Boltzmann's viewpoint vs Gibbs' viewpoint.)

I'm interested in using physics to make predictions about my future. Knowing the full quantum state of the whole multiverse

1) **Isn't enough:**

I also need to take into account what I know about my location:

- in 3D space
- in Hilbert space

2) **Isn't necessary:**

I only need to know the quantum state "nearby"

- in 3D space
- in Hilbert space

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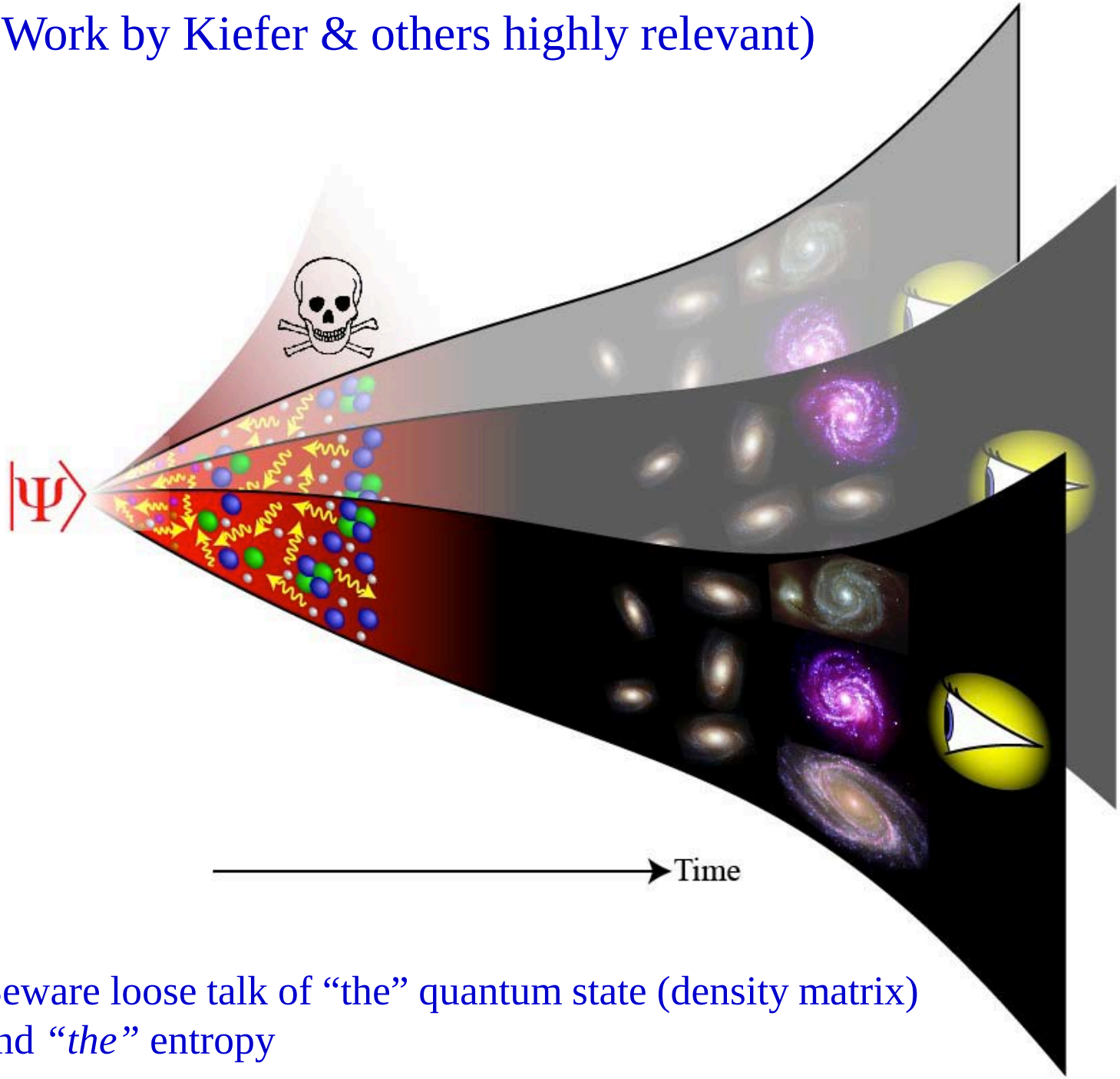
(Work by Kiefer & others highly relevant)



Beware loose talk of "the" quantum state (density matrix) and "*the*" entropy

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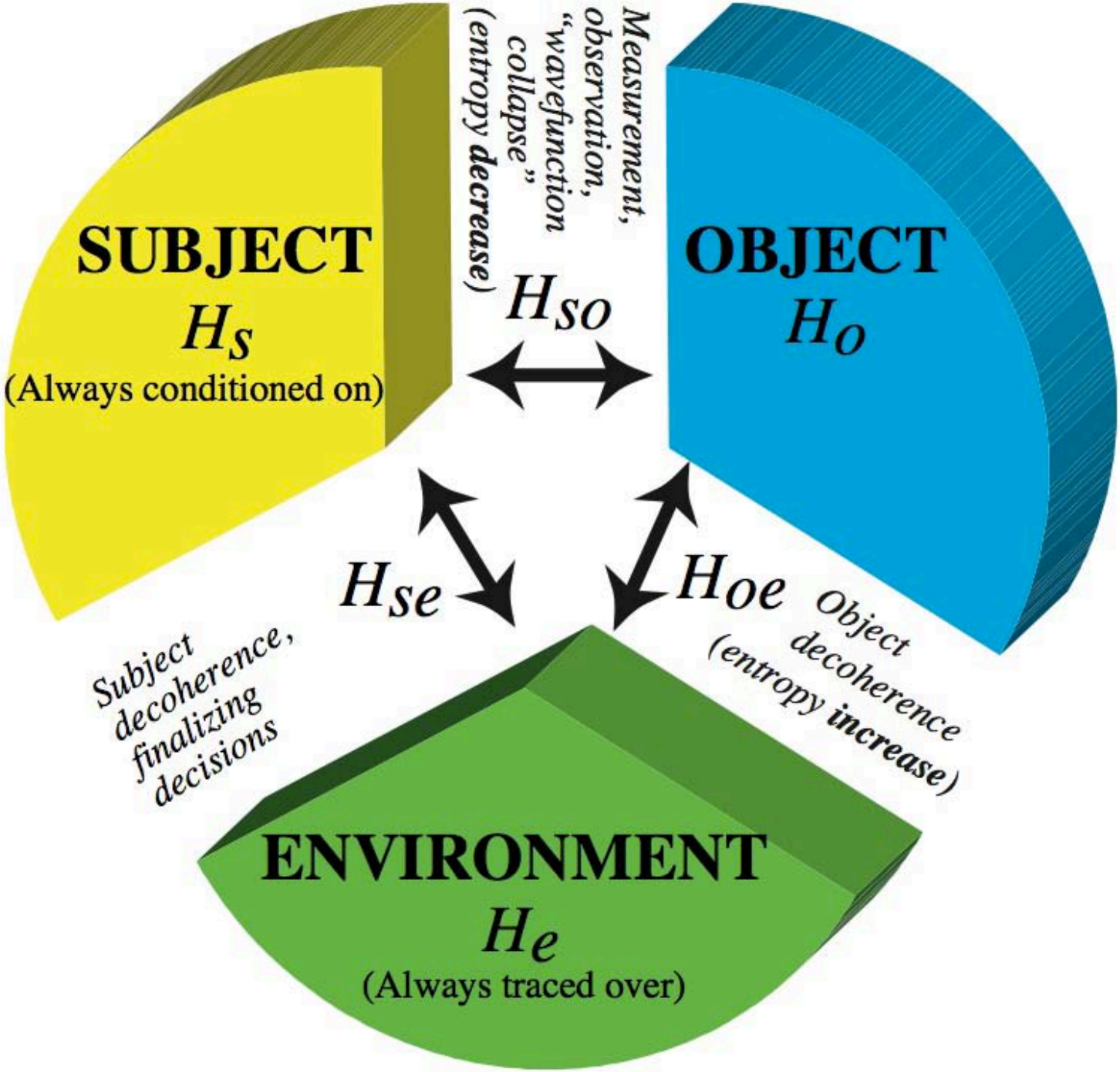

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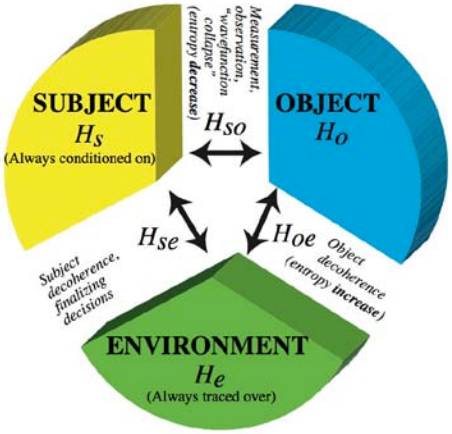
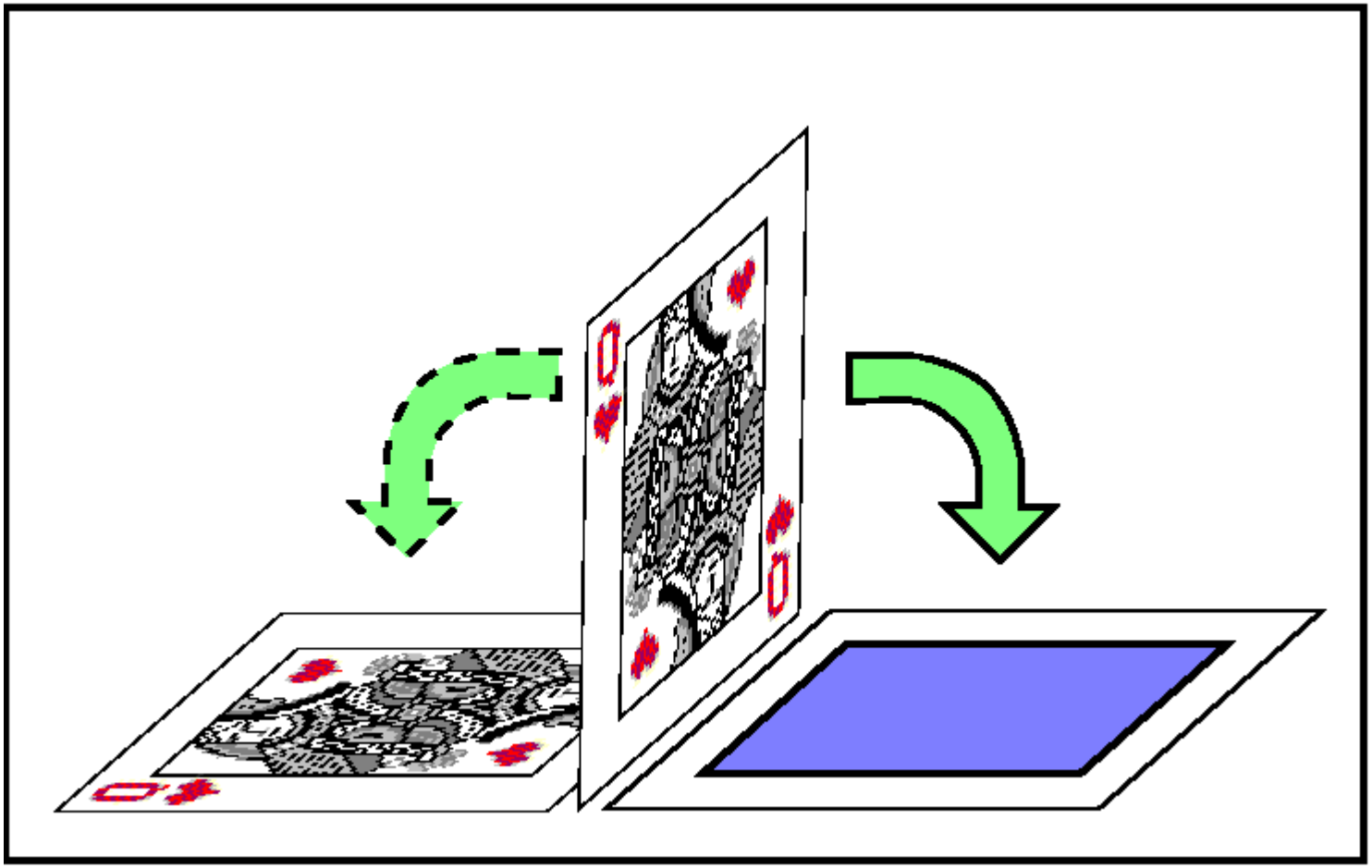
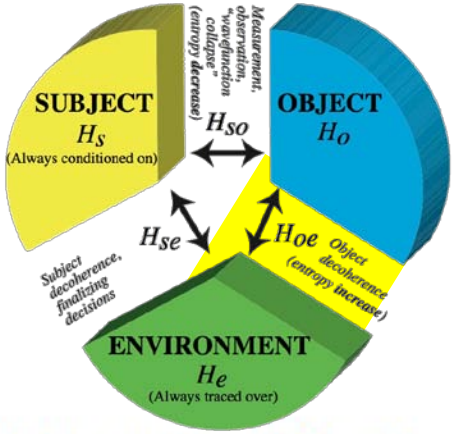
Unitary evolution



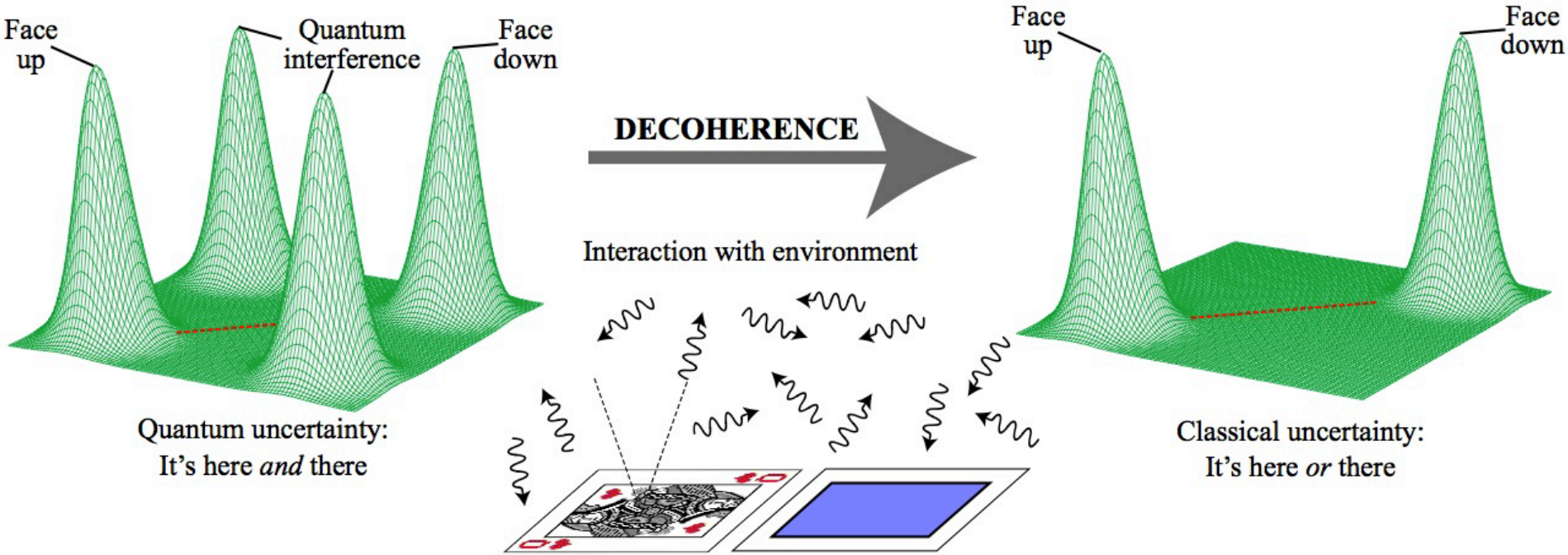


Decoherence

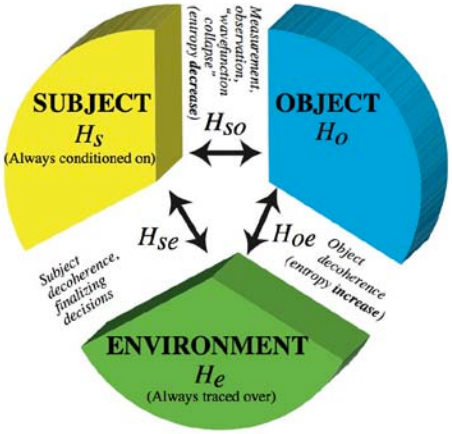


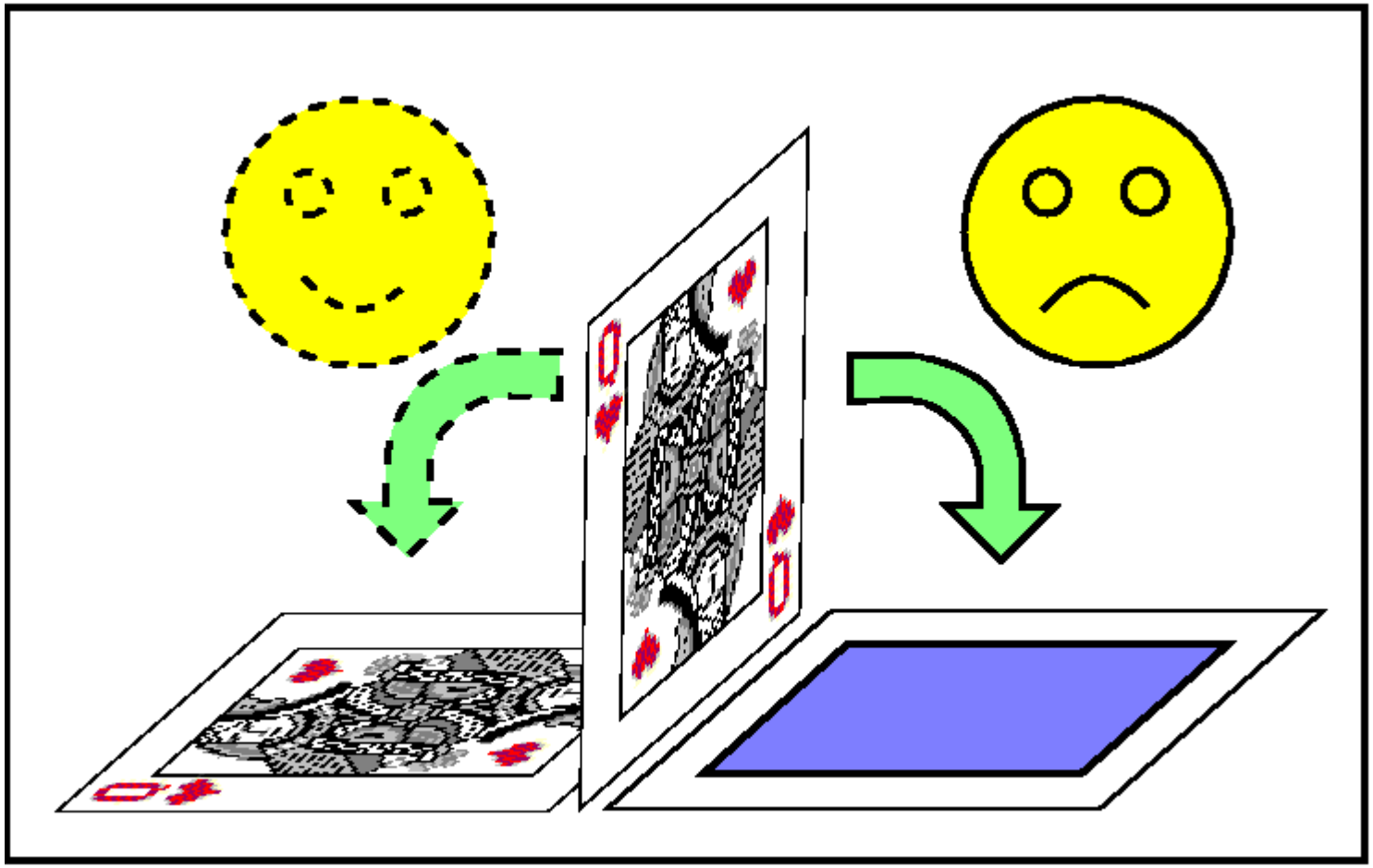
$$\begin{pmatrix} 0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix} = \text{"It's equally here } \textit{and} \text{ there at the same time"}$$

$$\begin{pmatrix} 0.5 & 0 \\ 0 & 0.5 \end{pmatrix} = \text{"It's here } \textit{or} \text{ there — I just don't know which"}$$



Observation

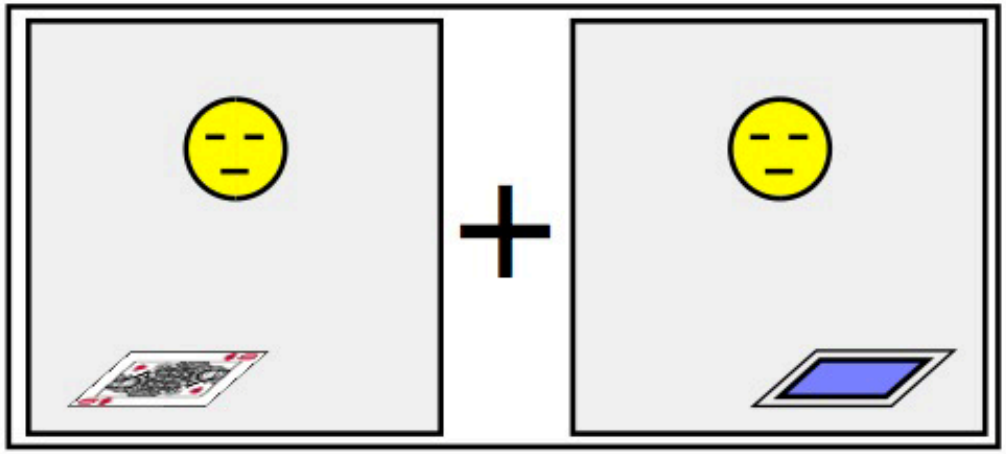




Wavefunction
at 10:00:00 AM:

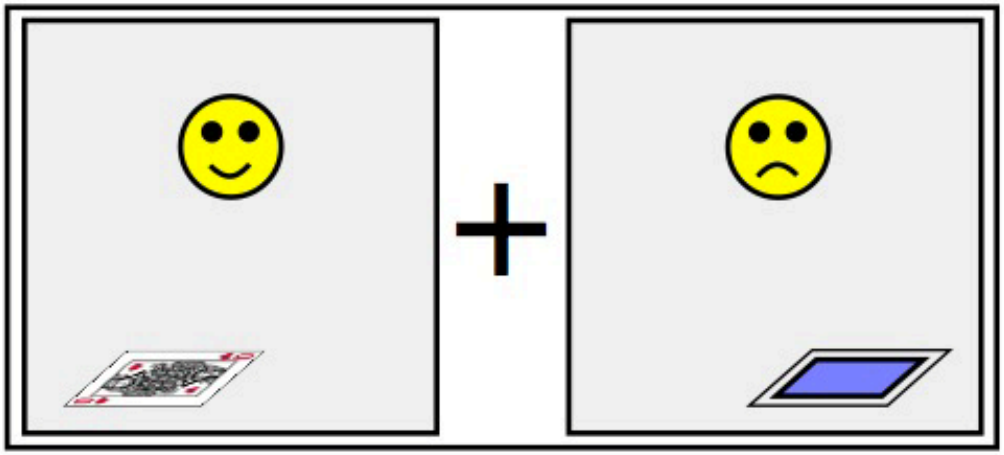
Card Falls

Wavefunction
at 10:00:10 AM:



Eyes opened

Wavefunction
at 10:00:20 AM:



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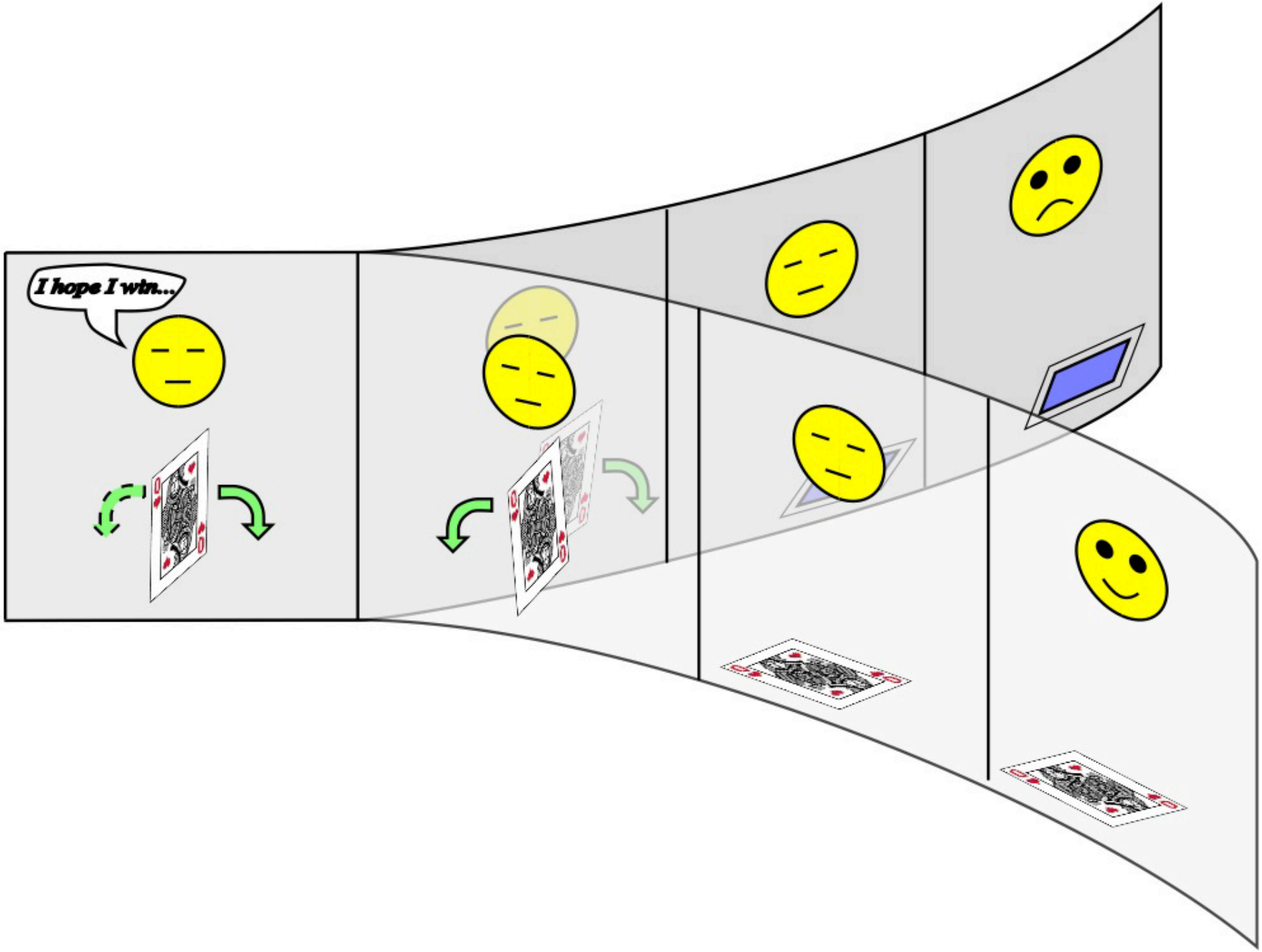
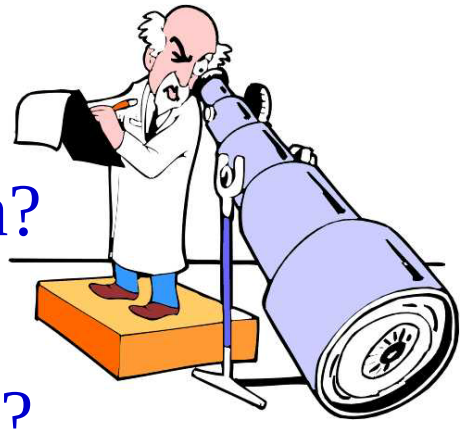
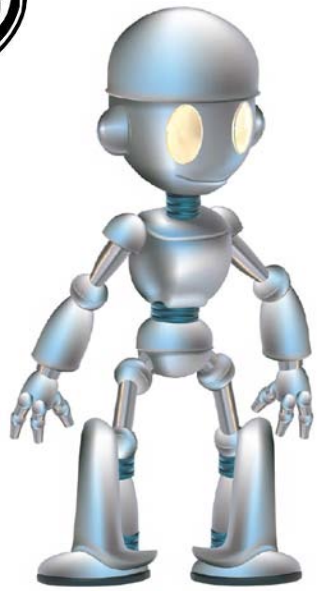

I hope I win...

Q: What counts as an observer?



- A human?
- A mouse?
- A robot?
- A photon?

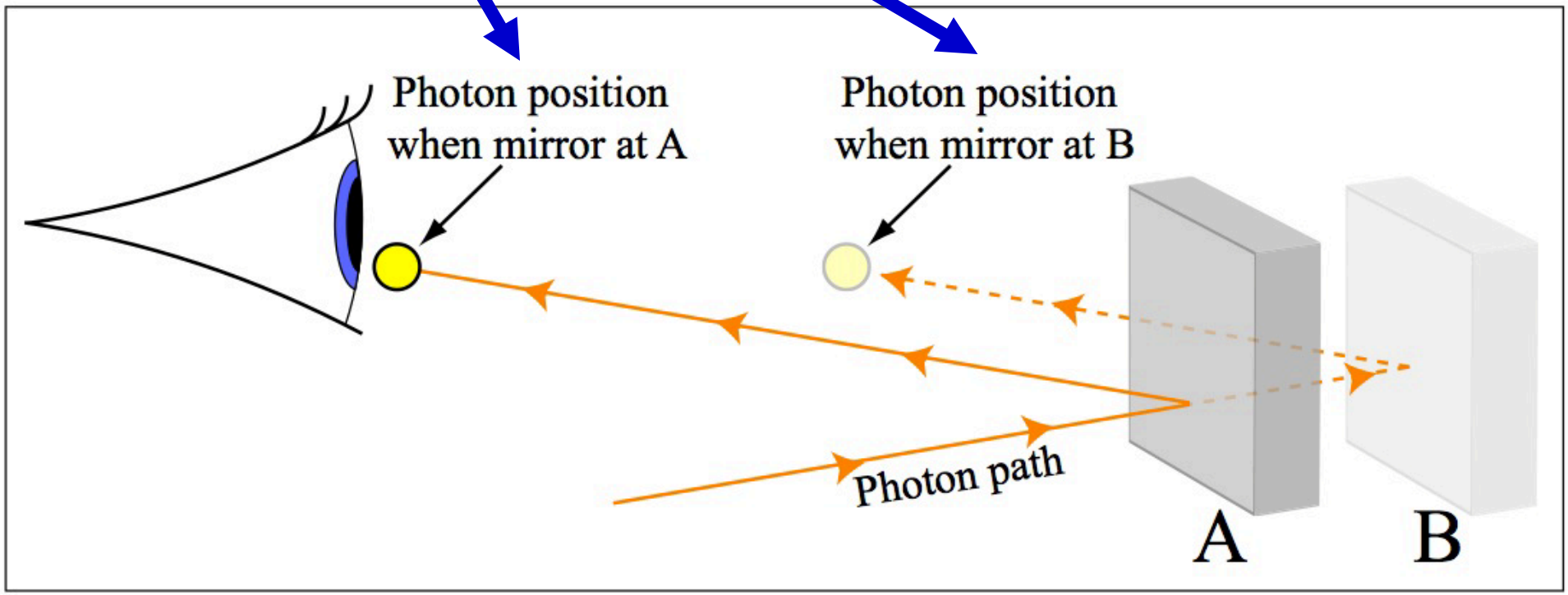


A: All of the above!

(It’s simply information transfer that matters)

Photon as observer:

It's position encodes whether block is at A or B



Second law of thermodynamics:
The object's entropy can't decrease unless it interacts with the subject.

Another law of thermodynamics:
The object's entropy can't increase unless it interacts with the environment.

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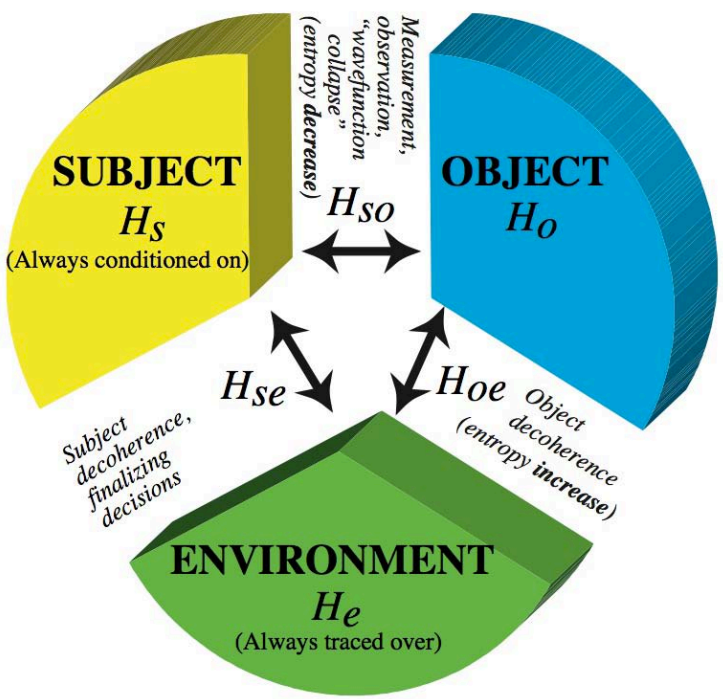
Interaction	Dynamics	Example	Effect	Entropy
Object-object	$\rho \mapsto U\rho U^\dagger$	$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mapsto \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix}$	Unitary evolution	Unchanged
Object-environment	$\rho \mapsto \sum_{ij} P_i \rho P_j \langle \epsilon_j \vert \epsilon_i \rangle$	$\begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix} \mapsto \begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix}$	Decoherence	Increases
Object-subject	$\rho \mapsto \frac{\Pi_i^\dagger \rho \Pi_i}{\mathrm{tr}\, \Pi_i \rho \Pi_i}, \quad \Pi_i = \sum_j \langle s_i \vert \sigma_j \rangle P_j$	$\begin{pmatrix} \frac{1}{2} & 0 \\ 0 & \frac{1}{2} \end{pmatrix} \mapsto \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$	Observation	Decreases

Decoherence

$$U|e_0\rangle|o_i\rangle = |\epsilon_i\rangle|o_i\rangle$$



Interaction	Dynamics	Example	Effect	Entropy
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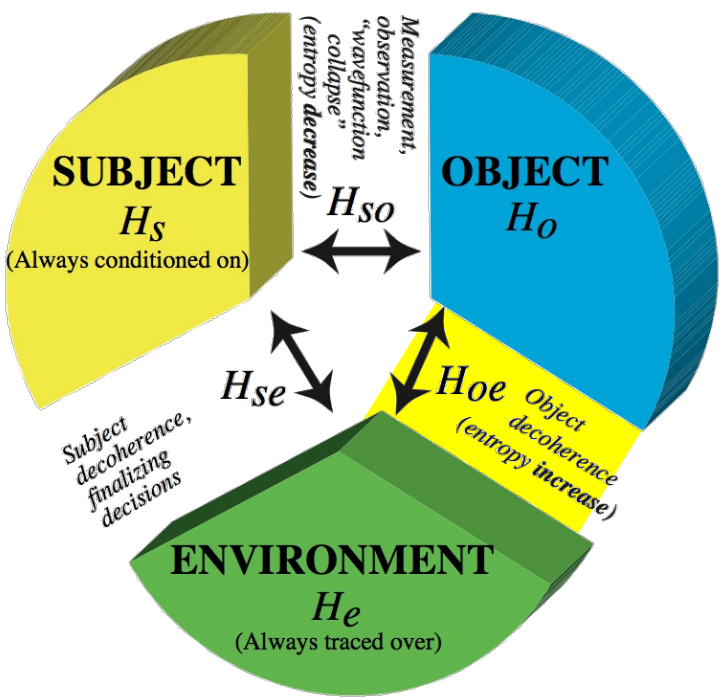
Decoherence

$$U|e_0\rangle|o_i\rangle = |\epsilon_i\rangle|o_i\rangle$$



Interaction	Dynamics	Example	Effect	Entropy
Object-object	$\rho \mapsto U\rho U^\dagger$	$\begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} \mapsto \begin{pmatrix} \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} \end{pmatrix}$	Unitary evolution	Unchanged
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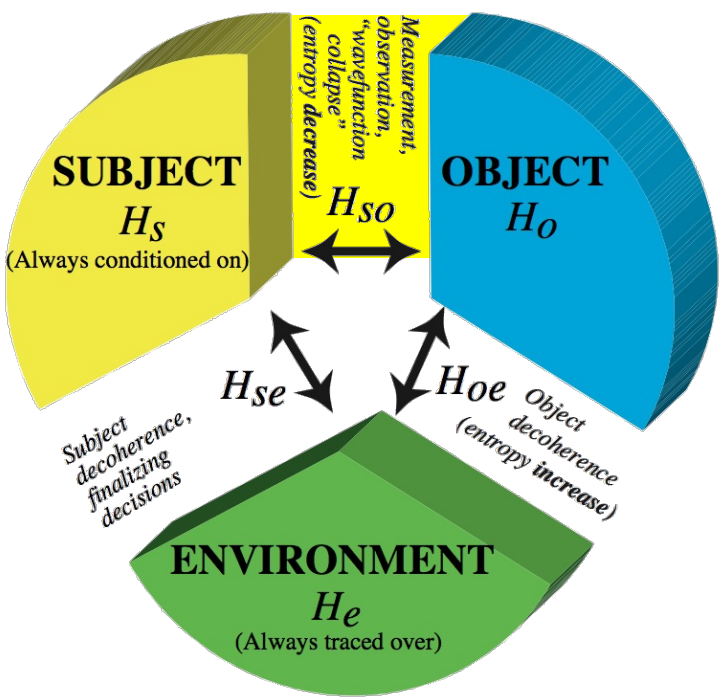
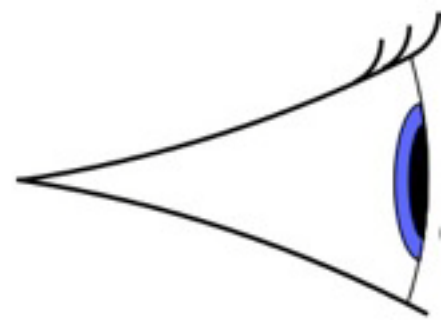
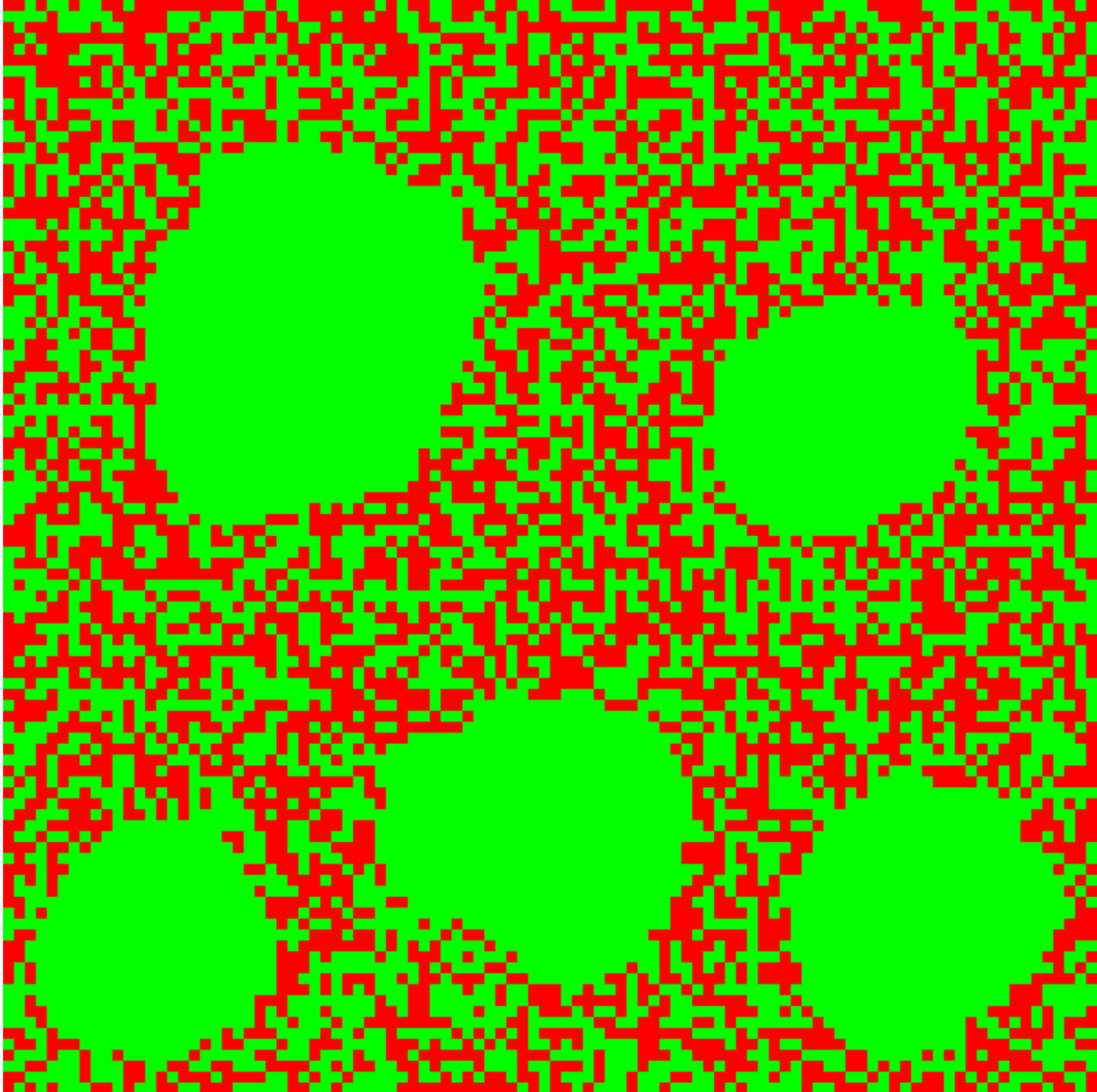
Observation

$$U|s_0\rangle|o_i\rangle = |\sigma_i\rangle|o_i\rangle$$





How decrease entropy by *a lot*?



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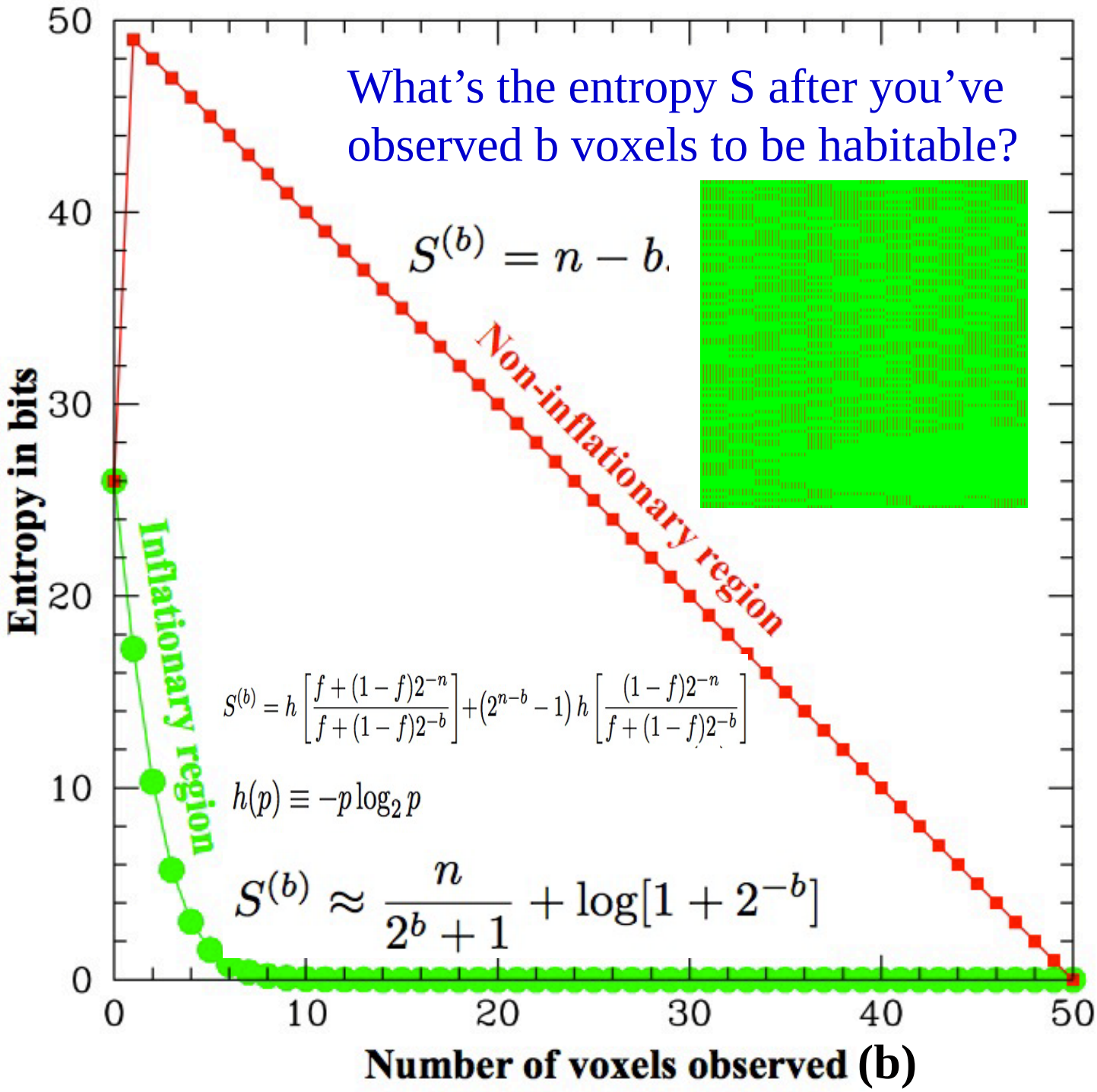

(b)

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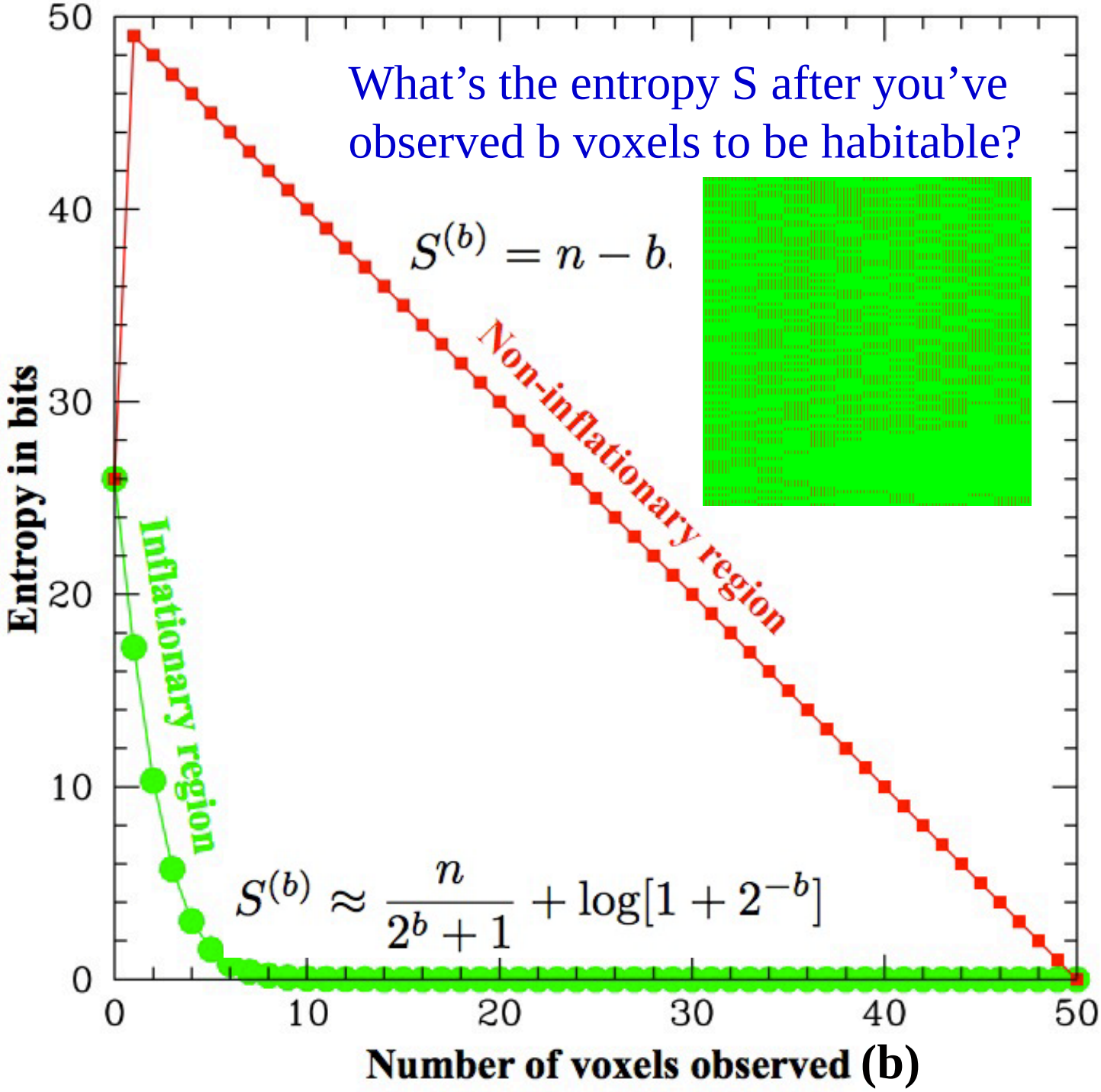
What's the entropy S after you've observed b voxels to be habitable?



(b)

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$$G_{\mu\nu} \overset{?}{\approx} 8\pi G \langle T_{\mu\nu} \rangle$$

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How will it all end?

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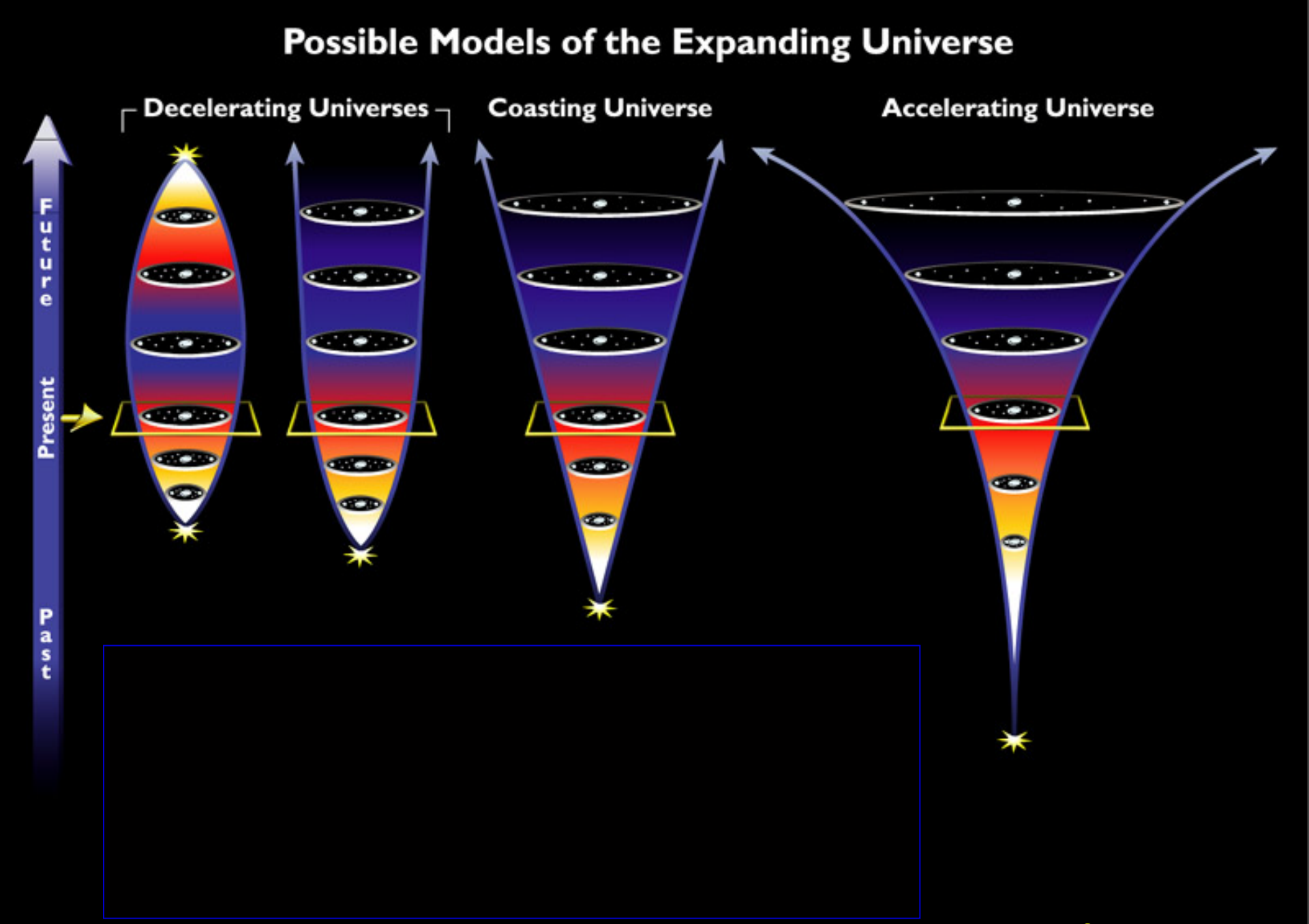


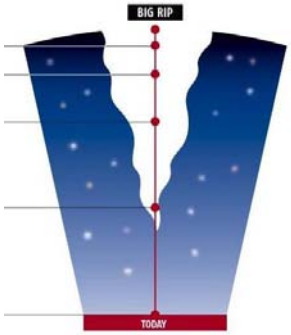
Figure from STScI

How will it all end?

- Big Chill

- Big Crunch

- Big Rip



- Big Snap

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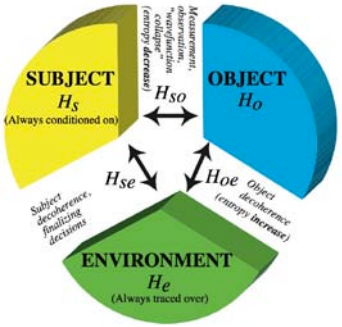
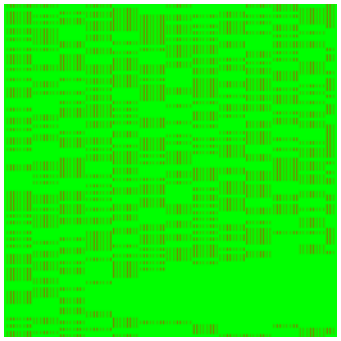
Summary:

- 2nd law generalized: *"The system's entropy can't decrease unless it interacts with the observer, and it can't increase until it interacts with the environment."*



- How lower entropy by a lot? (inflate+observe!)



- Our future: the Big Snap?

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