INSIGHTS INTO THE FLOW OF INFORMATION AND THE BLACK HOLE INFORMATION PROBLEM

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MOTIVATION

- Is information lost?

    Where is information encoded? What must an observer have access to in order to recover it?

    - Ordinary thermal radiation
    - Coarse-graining (classical and quantum)
    - Black holes
    - Extension to flow of time?

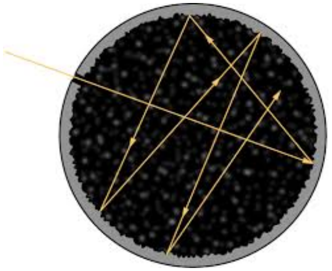
ORDINARY THERMAL RADIATION: BURN A LUMP OF COAL

[AA-S, M. Visser, Phys. Lett. B 757 (2016)]

➢ Clean control experiment in standard thermodynamics: Blackbody radiation

- Transfer of thermodynamic entropy (in bits) to the radiation field (per photon):

$$\hat{S}_2 = \frac{\hbar\omega}{k_B T \ln 2}$$



- Averaging the energy per photon (Bose Einstein distribution)

$$\langle E\rangle = \hbar\,\langle\omega\rangle \Rightarrow \langle\hat{S}_2\rangle = \frac{\pi^4}{30\,\zeta(3)\ln 2}$$

$$\boxed{\langle\hat{S}_2\rangle \approx 3.9 \pm 2.5} \quad \text{bits/photon}$$

Underlying physics is unitary ➡ entropy compensated by hidden information

$$S_{coarse\ grained} = S_{before\ coarse\ graining} + S_{correlations} \rightarrow I_{correlations}$$

COARSE-GRAINING: HOW INFORMATION IS HIDDEN

- Nature of coarse graining is intuitively "obvious" but it is rather difficult to find explicit and calculable models in the literature

We show explicit and calculable processes: Take an arbitrary system and monotonically and controllably drive the entropy to the maximum value (gedanken experiment)

- Use adjustable smearing parameters to continuously interpolate
- Information has become inaccessible to this description → not destroyed

$$I_{correlations} = S_{coarse\ grained} - S_{before\ coarse\ graining}$$

Coarse graining the classical Shannon entropy

- Continuum → continuum: Diffusion process
- Continuum → discretium: Box averaging
- Discretium → discretium: Aggregation/averaging

Coarse graining the quantum Von Neumann entropy

- Maximal mixing
- Full/tunable partial decoherence
- Tunable Partial traces

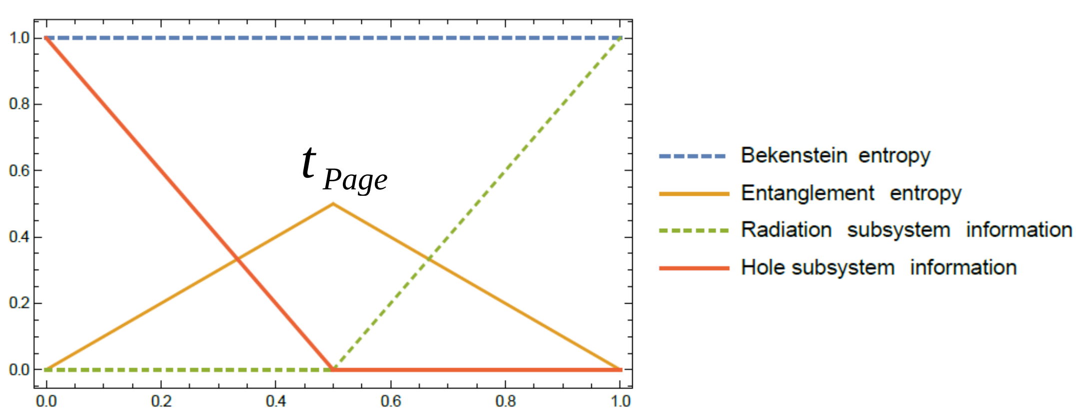
[AA-S, M. Visser, Entropy 19 (2017)]

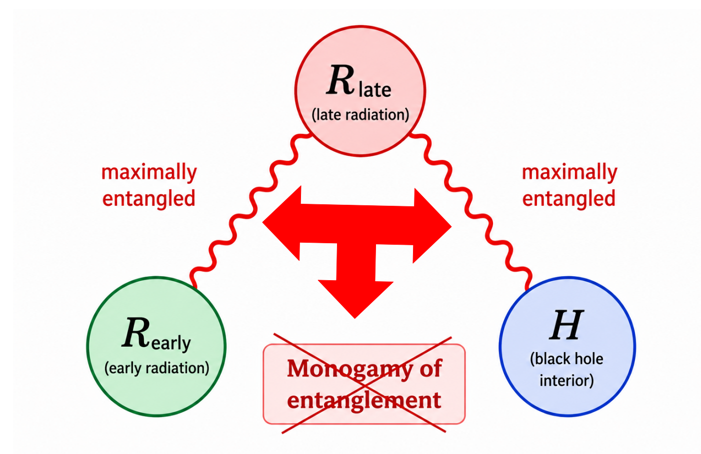
- Entropy is contextual and can be observer dependent

PAGE CURVE: HOW THE ENVIRONMENT CHANGES THE STORY

- Entropy/information "puzzle" related to the black hole evaporation process
  - Unitarity; & radiation carries information away (Page calculations)
  - Existence of horizons: apparent/trapping horizons (information escapes)
  - Complete evaporation process

- Page curve [D. N. Page, PRL 71(1993)]
  - Bipartite factorization $\mathcal{H}_{AB} = \mathcal{H}_A \otimes \mathcal{H}_B$
  - Average subsystem entropy $\hat{S}_A = \hat{S}_B \leq \ln \min\{\dim(\mathcal{H}_A), \dim(\mathcal{H}_B)\} \in \left(\ln m - \frac{1}{2}, \ln m\right)$





- Environment matters!
  - Tripartite factorization $\mathcal{H}_{\mathrm{HRE}} = \mathcal{H}_{\mathrm{H}} \otimes \mathcal{H}_{\mathrm{R}} \otimes \mathcal{H}_{\mathrm{E}}$

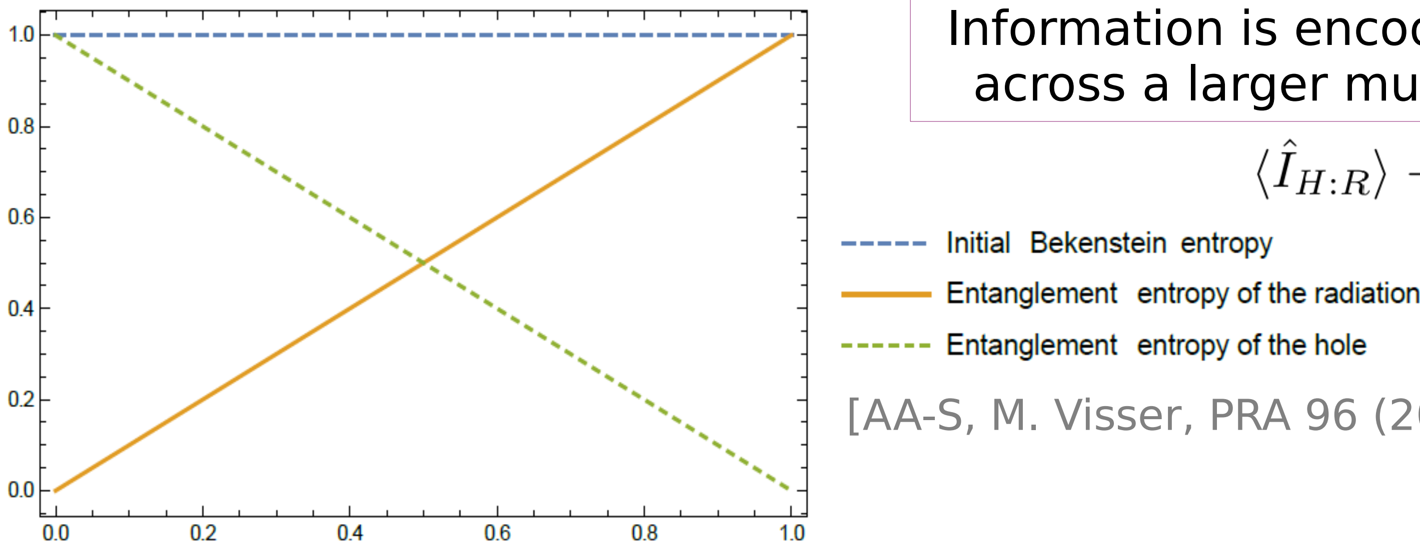
    so, $S_H(t) = S_{ER}(t) \quad S_R(t) = S_{HE}(t) \quad S_E(t) = S_{HR}(t)$

  - Average subsystem entropy $\langle \hat{S}_H(t) \rangle \approx \ln min[n_H(t), n_R(t) n_E] \approx \ln n_H(t)$

$$\langle \hat{S}_R(t) \rangle \approx \ln min[n_R(t), n_H(t) n_E] \approx \ln n_R(t)$$

$$\langle \hat{S}_E(t) \rangle \approx \ln min[n_E(t), n_H(t) n_R] \approx \ln n_{H_0} \approx \hat{S}_{Bekenstein,0}$$

  - New entropy/information curve:



Apparent tension is resolved: Information is encoded in correlations across a larger multipartite system

$$\langle \hat{I}_{H:R} \rangle \to 0$$

[AA-S, M. Visser, PRA 96 (2017), PLB 776 (2018)]

CONCEPTUAL COMPARISON OF PROPOSALS

➢ What changes?

- Subsystem decompositiom: Include the environment (multipartite analysis)

➢ What is kept?

- Standard quantum mechanics
- Standard semiclassical near-horizon physics
- Unitary
- Spacetime structure

➢ Key points

- No new microscopic physics is required
- The information remains in correlations and no tension with monogamy
- Balance of entropies $S_{\text{Bekenstein}}(t) + S_{\text{Clausius}}(t) = S_{\text{Bekenstein},0}$ and $\frac{\mathrm{d}\hat{S}_2}{\mathrm{d}N} \approx 3.90 \text{ bits}$

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➡ Coarse graining and environment counterattack!

[Šafránek et al., PRA (2019), K. Su et al. JHEP (2021), M. Blake et al. JHEP (2023), J. Chandra et al. JHEP (2023), H. S. Sahota et al. PRD (2025), H. Geng et al. (2026), G. Rubino et al. (2026), …..]

MOVING FROM WHERE TO WHEN

- Boring time-machine [AA-S, S. Schuster, M. Visser, Universe 3 (2024)]
  - Page-Wooters formalism $\mathcal{H} = \mathcal{H}_{\mathrm{C}} \otimes \mathcal{H}_{\mathrm{R}}$
  - Novikov's self consistency

- Work-in-progress
  - Introduce environment and interactions $\mathcal{H} = \mathcal{H}_C \otimes \mathcal{H}_S \otimes \mathcal{H}_E$
  - Global consistency vs. observer-dependent cyclic time

[AA-S, S. Butler, S. Schuster, M. Zych, work in progress]

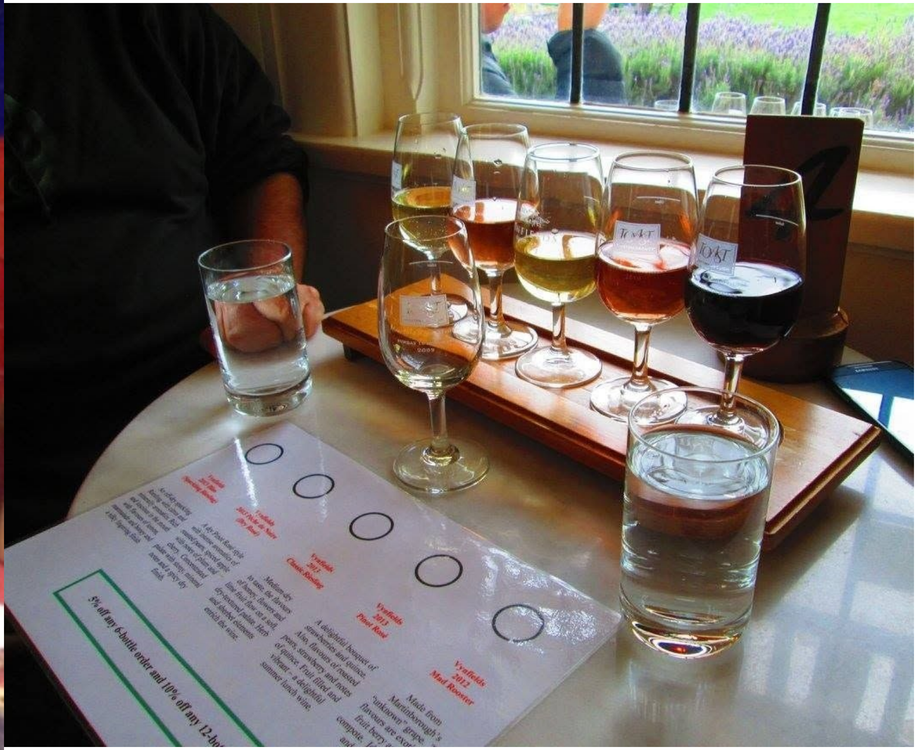
➡ For which clock does the information exist?

[AA-S, M. Liska, M. Piotrak, work in progress]

OUTLOOK

- Thermal does not mean information loss
- Information lives in correlations and can be hidden in coarse-graining
- The environment changes the picture
- Moving to new scenarios….
- Black hole information puzzle: Do we need to introduce new physics or to change the description of the system?

- It is always fun (and enlightening) to work with Matt….

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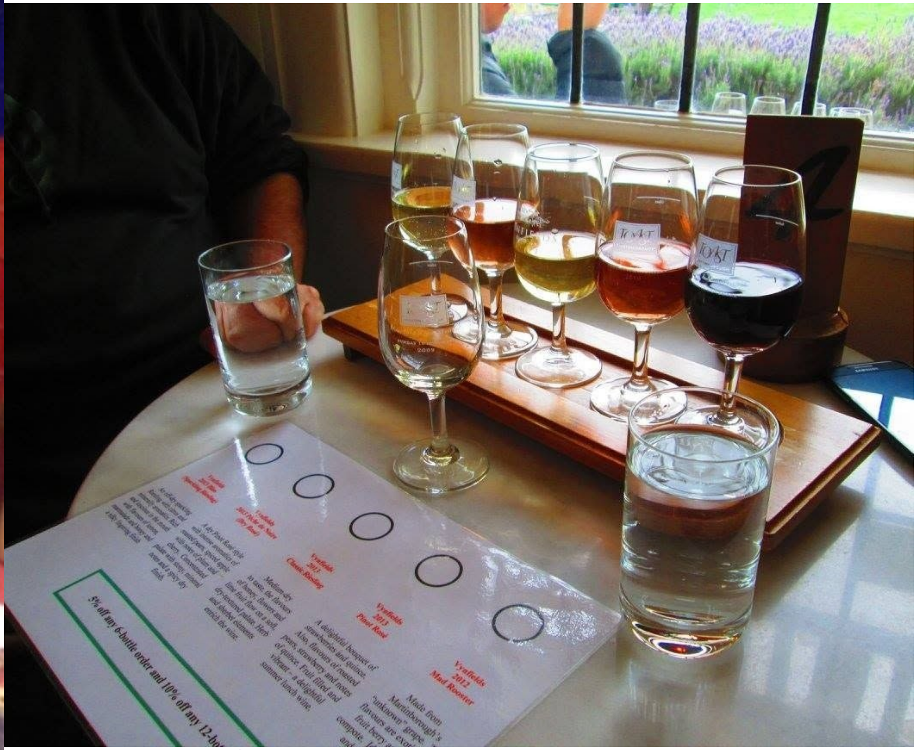

Thank you very much for your attention!

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