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Information Broadcasting During Decoherence

Jarek K. Korbicz (Gdańsk University Of Technology)

In collaboration with:

P. Horodecki
R. Horodecki
J. Tuziemski

John Templeton Foundation

POLITECHNIKA GDAŃSKA

⟨KC|K⟩ Krajowe Centrum Informatyki Kwantowej

- The fundamental question:

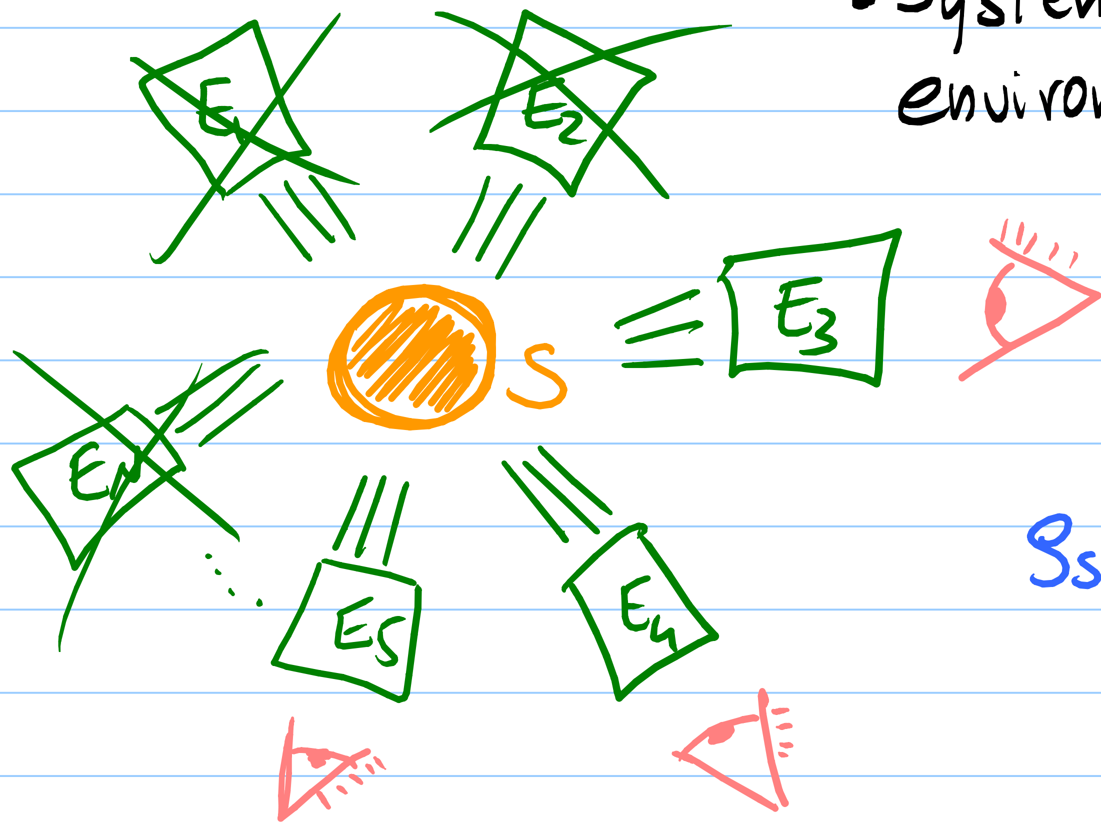
  What process leads from fragile quantum information to objectively existing classical one?

- What is "objectivity"?

  An operational definition by Zurek:

  > "A state of a system S exists objectively if many observers can find it out independently without perturbing it."
  >
  > W. Zurek, Nat. Phys. 5, 181 (2009)

Quantum Darwinism Setup:



- System S interacts with many environments $E_1, \ldots, E_N$ monitored by observers
- Decoherence: $t \gg \tau_D$

$$\rho_S \equiv \mathrm{tr}\, \rho_{S:E} \approx \sum_i p_i |i\rangle\langle i|$$

pointer basis

Partially traced state
$$\rho_{S:fE} = \mathrm{tr}_{E_{unobs}}\, \rho_{S:E}$$

observed fraction

Making the Definition precise:

- **Bohr non-disturbance** (EPR-Bohr 1935 debate)

  (H. Wisemann, 2012)

  There exists a non-demolition measurement leaving the whole state $\rho_{S:fE}$ unchanged

- **Strong independence**

  The only correlation between the environments should be the common information about S

Spectrum Broadcast Structure

(R. Horodecki, JKK, P. Horodecki, PRA 91, 032122, 2015)

$$\varrho_{S:fE} = \sum_i p_i |x_i\rangle\langle x_i| \otimes \varrho_i^{E_1} \otimes \dots \otimes \varrho_i^{E_{fN}}$$

$$\varrho_i^{E_k} \varrho_{i' \neq i}^{E_k} = 0$$

- Spectrum broadcasting (JKK, P.&R. Horodecki, PRA 86, 042319, 2012)

Much weaker form of quantum state broadcasting

For ϱ, $Sp\,\varrho \equiv \{p_i\}$, find $\varrho^{s\text{-}br}_{E_1 \cdots E_N}$ s.t.

$$\mathrm{tr}_{E_1 \cdots \widehat{E_k} \cdots E_N} \varrho^{s\text{-}br}_{E_1 \cdots E_N} = \sum p_i \varrho_i^{E_k}, \quad \varrho_i^{E_k} \varrho_{i' \neq i}^{E_k} = 0$$

- The spectrum (or classical state $\{p_i\}$) can be locally recovered by projecting on the orthogonal supports of $\varrho_i^{E_k}$'s
- The details of the encoding states $\varrho_i^{E_k}$ are irrelevant as long as perfectly distinguishable (purifications)

Objectivity becomes a property of a quantum state.

"Objectivity witness" by Zurek & co:

$$I(\varrho_{S:fE}) = H_S \ \forall f \quad \Leftarrow \text{sufficiency unknown!}$$

How to look for SBS in the models?

① DECOHERENCE

$$\Gamma_{i,i'}(t) \approx 0$$

② PERFECT DISTINGUISHABILITY

$$B\left(\varrho_i^{E_k}(t), \varrho_{i'}^{E_k}(t)\right) \approx 0$$

Generalized overlap: $B(\varrho, \sigma) = \mathrm{tr}\sqrt{\sqrt{\varrho}\,\sigma\,\sqrt{\varrho}}$

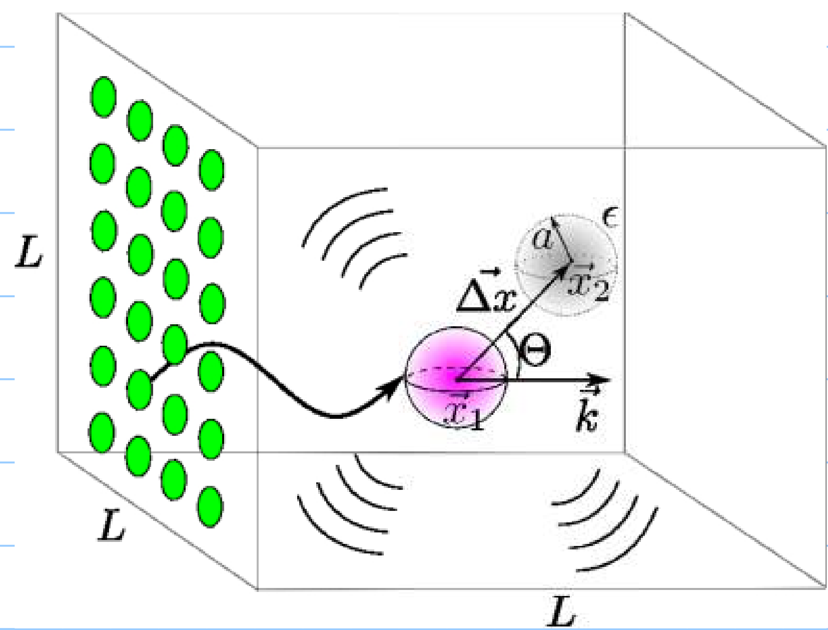
Weak interaction ⇒ macrofractions

$$\varrho_a^{mac}(t) \equiv \bigotimes_{\kappa} \varrho_a^{\kappa}(t)$$

① Small sphere illuminated by photons

E. Joos, H. D. Zeh, Z. Phys. B 59, 223 (1985)

- Box normalization

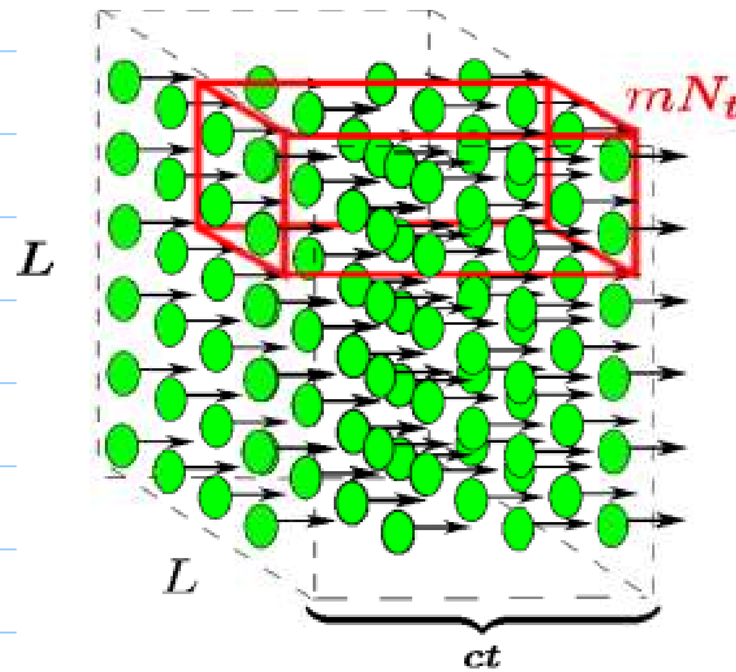


$k \Delta x \ll 1$

Thermodyn. limit $L \to \infty$, $N \to \infty$

$N/V = \text{const}$

- Division into macro-fractions



$N_t = L^2 \frac{N}{V} c t \equiv M \cdot \left(L^2 m \frac{N}{V} c t \right)$

macrofraction

Evolution - Controlled Unitary:

$$U_{S:E}(t) = \sum_{i=1,2} |x_i\rangle\langle x_i| \otimes S_{x_i} \otimes \dots \otimes S_{x_i}$$

Initial state: $\varrho_{0S} \otimes (\varrho_0^{ph})^{\otimes N}$, $\varrho_0^{ph} = \sum' p(\vec{k}) |\vec{k}\rangle\langle\vec{k}|$

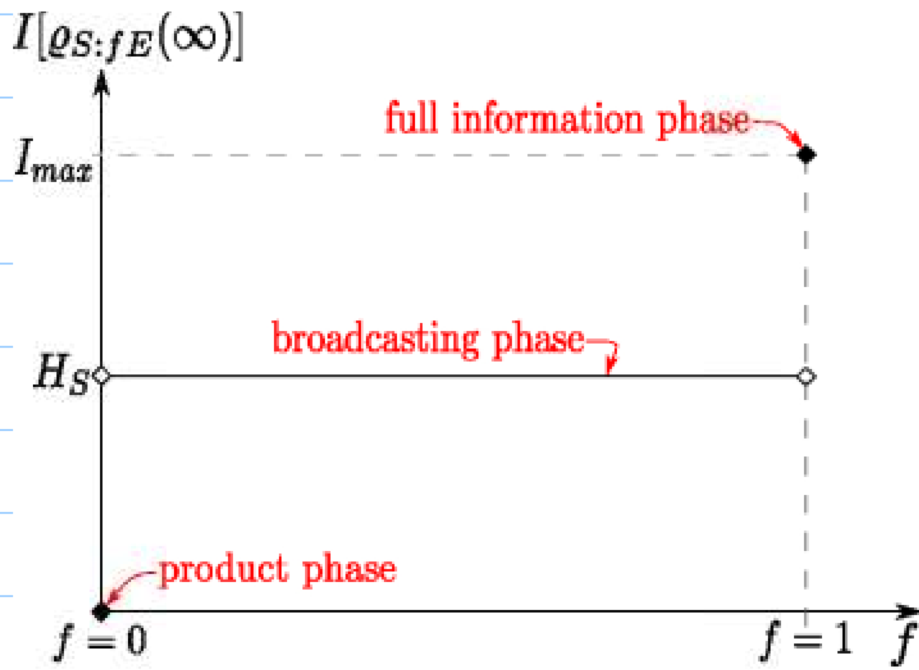
- $\Gamma_{x_1 x_2}(t) \underset{\text{therm.}}{\sim} e^{-\frac{(1-f)}{\tau_D} t} \xrightarrow[t \gg \tau_D/(1-f)]{} 0$

- $B^{mac}_{x_1 x_2}(t) \underset{\text{therm.}}{\sim} e^{-\frac{\alpha m}{\tau_D} t} \xrightarrow[t \gg \frac{\tau_D}{\alpha m}]{} 0$

$\alpha m \leftarrow$ macrofraction size

(JKK, P. Horodecki, R. Horodecki PRL 112, 120402 2014)

Information-theoretical phases:

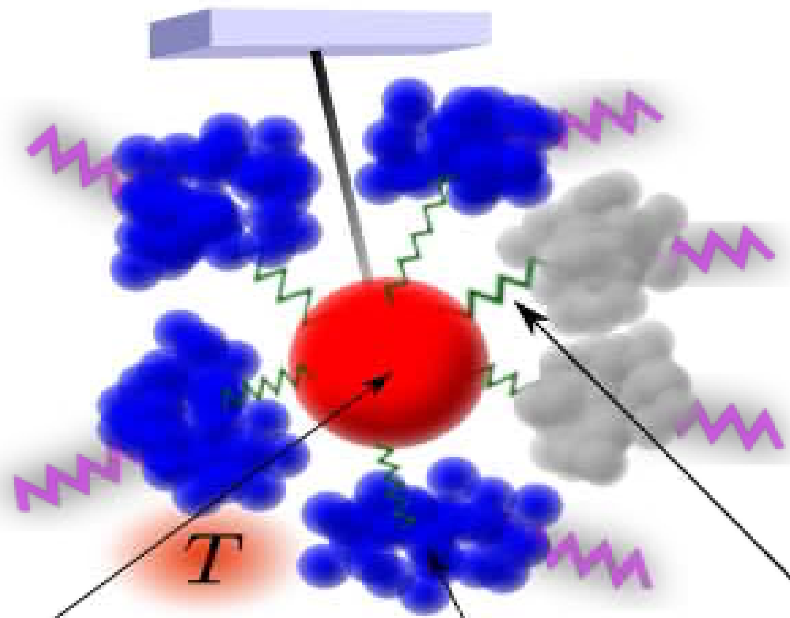


Spectrum Broadcasting Channel:

$$\Lambda(\varrho_{0S}) = \sum_{i=1,2} \langle x_i | \varrho_{0S} x_i \rangle \left[\varrho_i^{mac}(\infty) \right]^{\otimes fM}$$

② Quantum Brownian Motion

The model



$$\hat{H} = \frac{\hat{P}^2}{2M} + \frac{M\Omega^2\hat{X}^2}{2} + \sum_{k=1}^{N}\left(\frac{\hat{p}_k^2}{2m_k} + \frac{m_k\omega_k^2\hat{x}_k^2}{2}\right) + \hat{X}\sum_{k=1}^{N} C_k\hat{x}_k$$

Looking for partially traced state $\varrho_{S:fE}$

J. Tuziemski, JKK EPL 112, 40008 (2015)
—— " —" — Photonics 2, 228 (2015)
—— " — —" — arXiv 1603.04217 (2016)

- Recoiless Limit : Large mass M (opposite to B-M)
- Non-adiabatic Born-Oppenheimer with classical trajectories
- Initially momentum squeezed state of M

$$\begin{cases} U_{S:E}(t) = \int dX_0 \, e^{-itH_S} |X_0\rangle\langle X_0| \otimes \underbrace{\tilde{U}_E(X_0 \cos\Omega t)}_{\text{driven evolution of the environment}} \\ \tilde{U}_E = \bigotimes_{k=1}^{N} e^{i\xi_k(t) X_0^2} e^{-itH_k} D(\alpha_k(t) X_0) \end{cases}$$

- Simple, "mechanical" environment

  discrete i.i.d. $\omega_k \gg \Omega$ (off resonant)

  (no continuous spectral density)

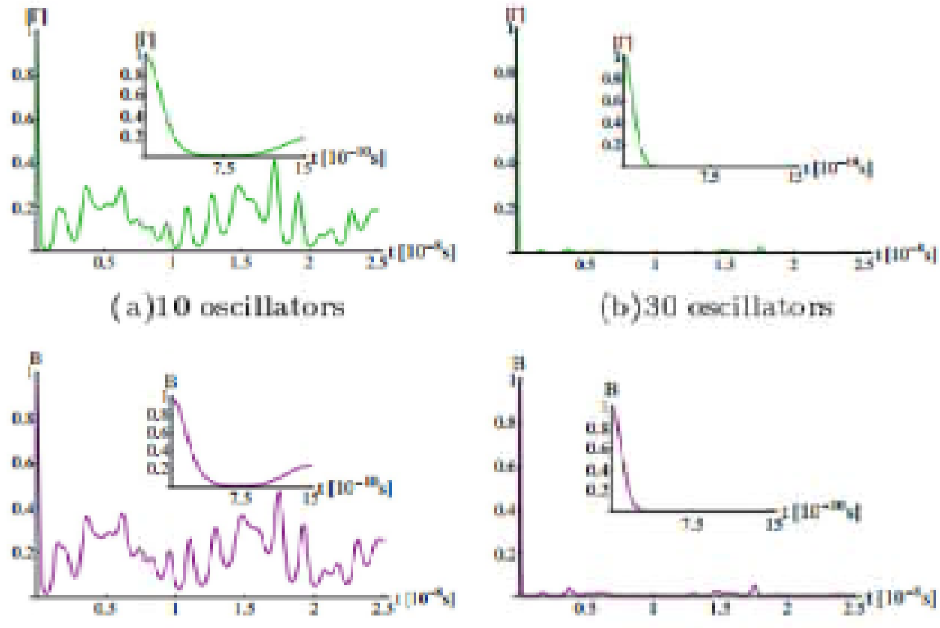
$$\left|\Gamma_{x_0,x_0'}(t)\right| = \exp\left[-\frac{(x_0-x_0')^2}{2}\sum_{k\in \text{unobs}}' |\alpha_k(t)|^2 \coth\left(\frac{\beta\omega_k}{2}\right)\right]$$

$$B^{\text{mac}}_{x_0,x_0'}(t) = \exp\left[-\frac{(x_0-x_0')^2}{2}\sum_{k\in \text{mac}}' |\alpha_k(t)|^2 \tanh\left(\frac{\beta\omega_k}{2}\right)\right]$$

quasi-periodic functions

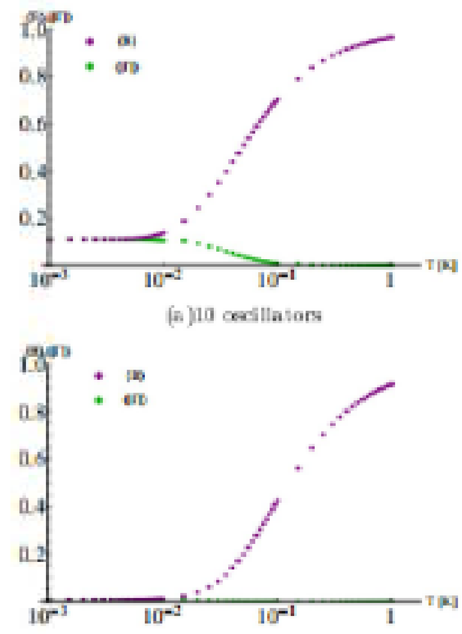
Decoherence and distinguishability

Time dependiencies



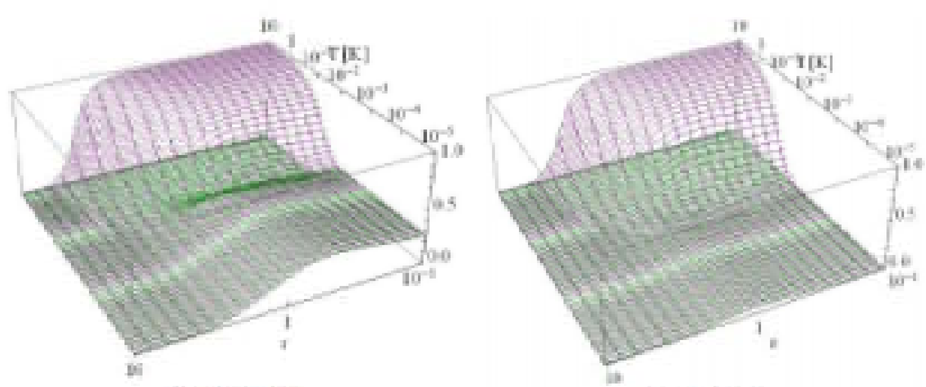
(a)10 oscillators (b)30 oscillators (c)10 oscillators (d)30 oscillators.

Time averages



(a)10 oscillators (b)30 oscillators

Influence of squeezing on time averages



(a) 10 oscillators (b) 30 oscillators

Initially x-squeezed state of M, No SBS!

Dynamical objectivity:

$$\varrho_{S:fE}(t) \approx \int dX_0 \, |\langle X_0|\phi_{0S}\rangle|^2 \, |X(t)\rangle\langle X(t)| \otimes \varrho^{mac}(X_0,t) \otimes \cdots$$

$$|X(t)\rangle = e^{-itH_S}|X_0\rangle$$

- Time evolving SBS
- $\rho^{mac}(X_0,t)$ encode not only X_0, but

more details of the classical movemet $X(t) = X_0 \cos\Omega t$

③ Spin-spin systems

P. Mironowicz, JKK & P. Horodecki
arXiv 1607.02478

$$H = \sigma_z \otimes \sum_{k=1}^{N} g_k \sigma_z^{(k)}$$

↑ random, i.i.d. uniformly [0,1]

$$|\Gamma(t)|^2 \approx \exp\left[-N_{unobs}\bar{\chi}(t)\right]$$

$$B^{mac}(t) \approx \exp\left[-N_{mac}\bar{\kappa}(t)\right]$$

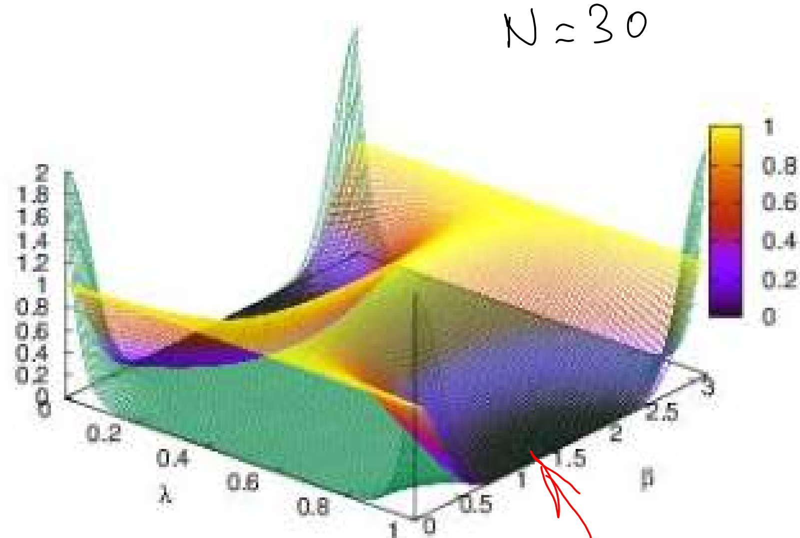
Short time: $\bar{\chi}(t) \approx \frac{4}{5}\langle g_i^2\rangle t^2$

$\bar{\kappa}(t) \approx \frac{1}{5}\langle g_i^2\rangle t^2$

No revival → SBS

Time averaged $|\Gamma(t)|^2$, $B(t)$ as functions of initial (λ, β)

N = 30



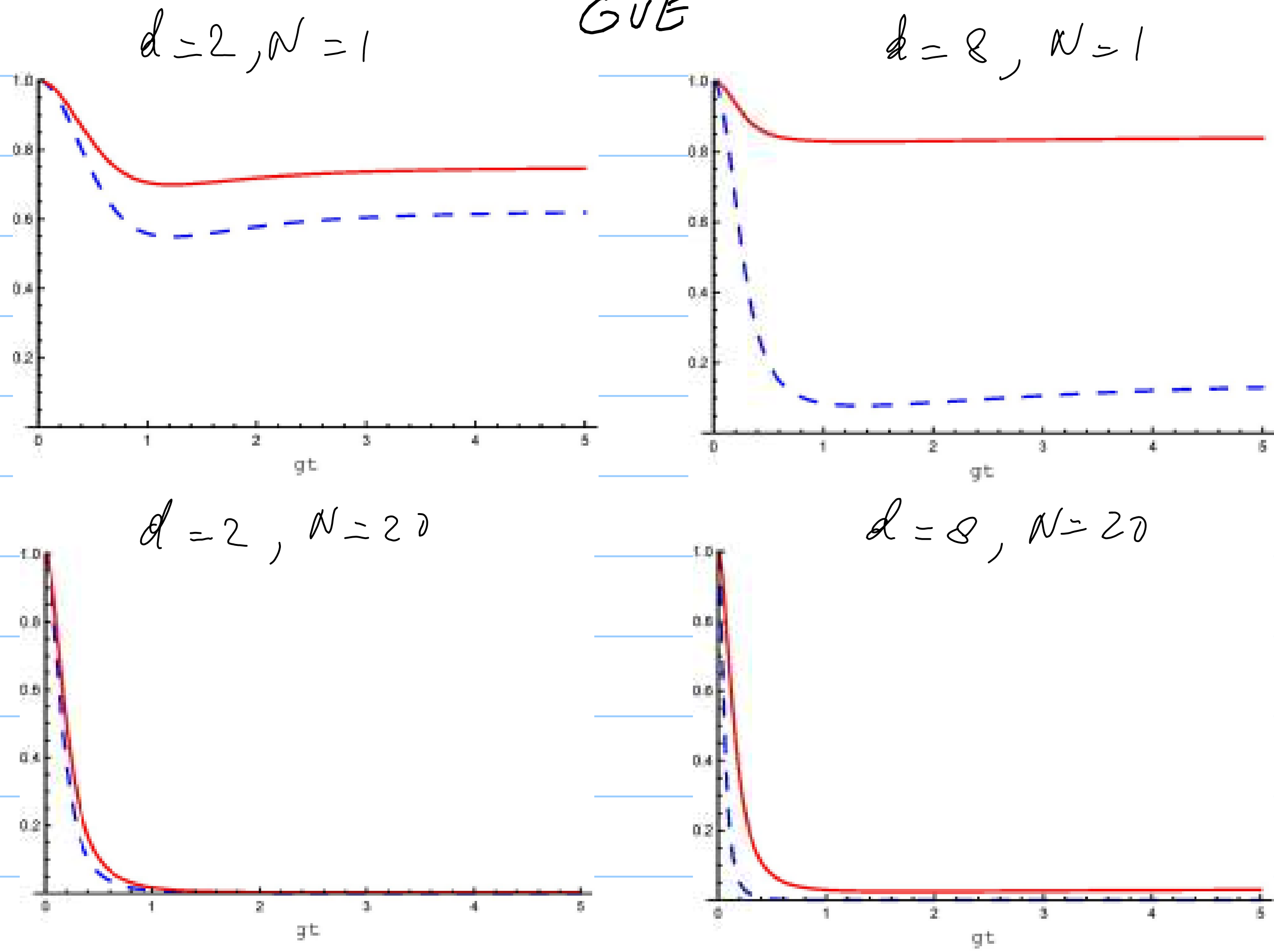
SBS plateau

④ Typicality

Random $H = A \otimes \sum_{k}{}' B_k$; (A: GUE; B_k: iid GUE)

$$\langle\langle \Gamma^{mac}_{a,a'}(t) \rangle\rangle \xrightarrow[t\to\infty]{} \left[\frac{1+\langle tr\,\rho_0^2\rangle}{d+1}\right]^{N_f}$$

(Random with Bures dist.)



$$\langle\langle G^{mac}_{a,a'}(t) \rangle\rangle \xrightarrow[t\to\infty]{} \left\{\frac{1+\langle tr\,\rho_0^2\rangle}{d+1} + 1 - \langle tr\,\rho_0^2\rangle\right\}^{N_f}$$

(superfidelity upper bound)

JKK, E.A. Aguilar, P. Ćwikliński & P. Horodecki

arXiv 1604.02011

1) "Quantum Erlangen Programme"

OBJECTIVE ≡ OBSERVER INVARIANT

Point individualisation through SBS?

$$|x\rangle\langle x| \otimes \rho_x^{E_1} \otimes \dots \otimes \rho_x^{E_N}$$ (see point indiv. in GR-hole argument)

→ Recovery of space, topology, geometry from sth. quantum states?

~~Non commutative geometry~~

THANK YOU!