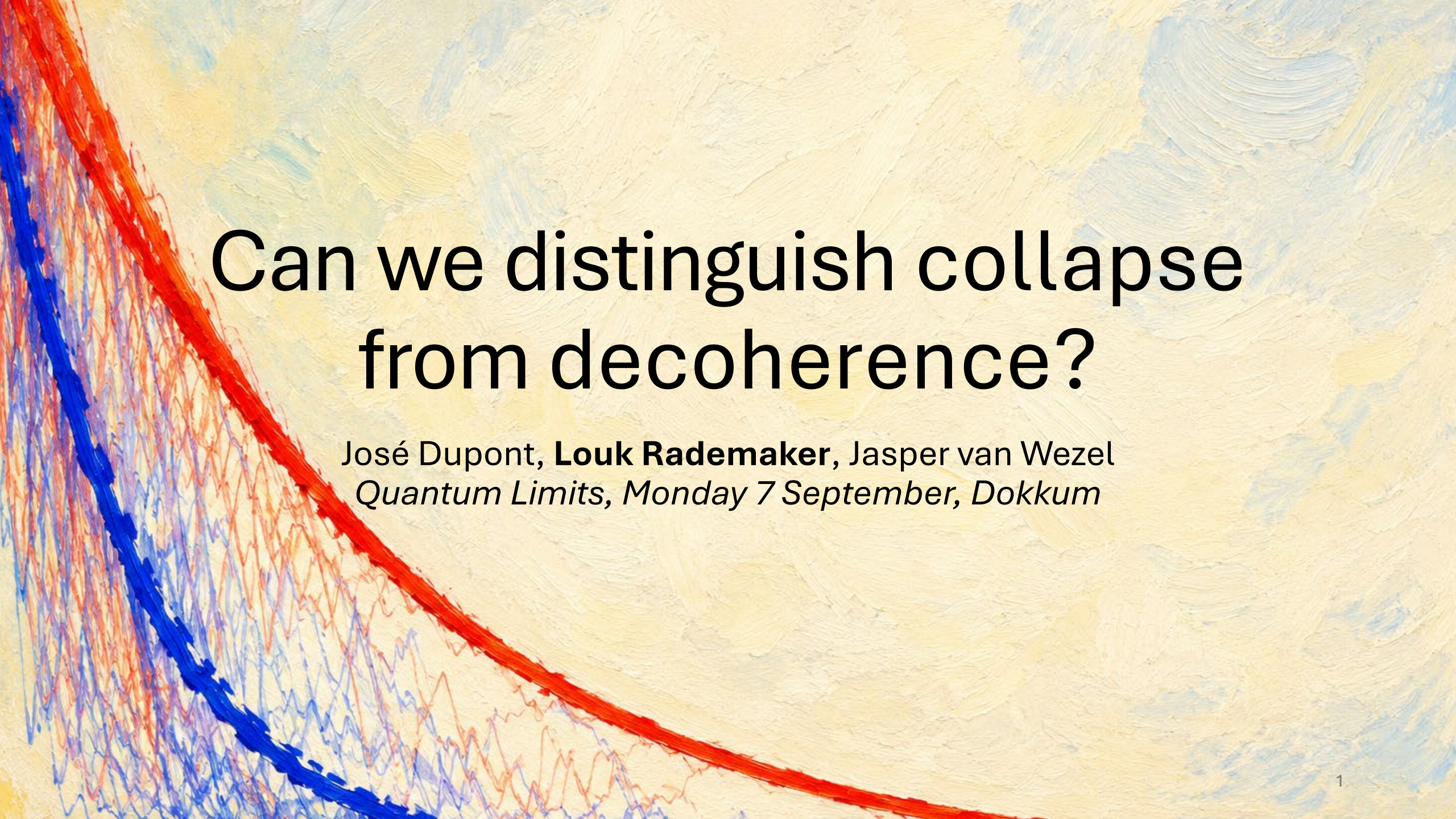
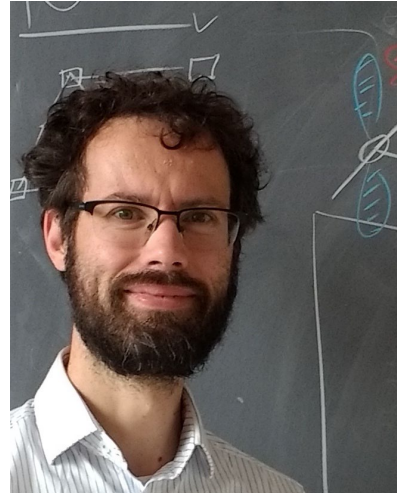




Can we distinguish collapse from decoherence?

José Dupont, **Louk Rademaker**, Jasper van Wezel
Quantum Limits, Monday 7 September, Dokkum

Acknowledgements



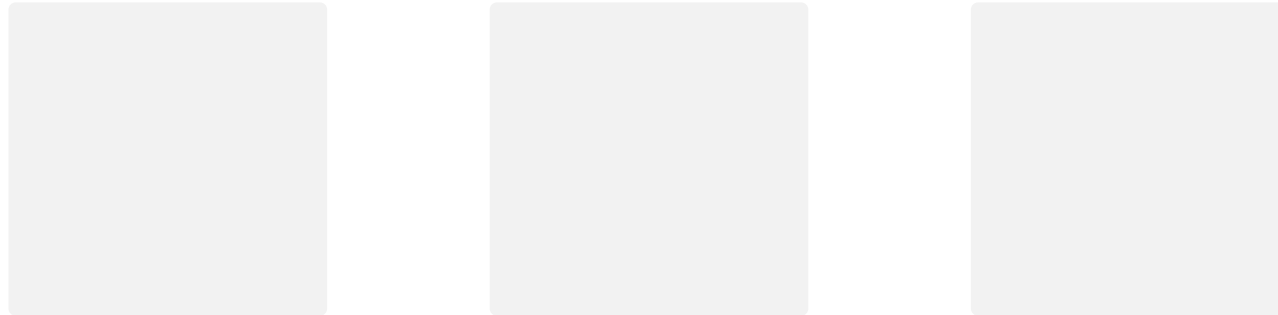
Jasper van Wezel (UvA)



José Dupont (Leiden)

Quantum Mechanics postulates

1. **States** are described by a vector
(which allows **superpositions**)

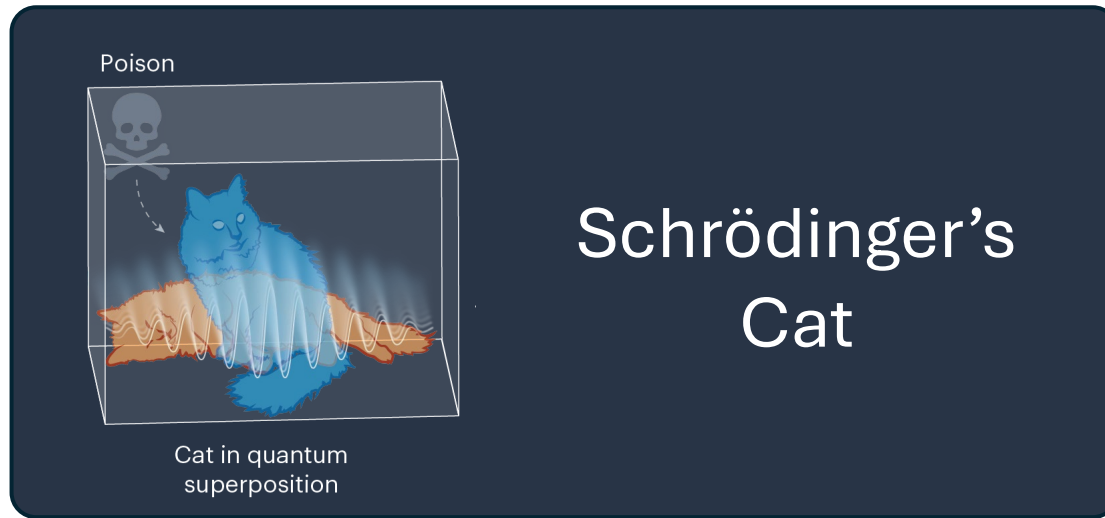


2. **Unitary** time evolution



Hamiltonian

Big superpositions: third postulate



↓ measurement
or

3. Projective measurements follow **Born's rule**

Probability for , probability for

Looks **irreversible**

Reversible versus irreversible

Main question:

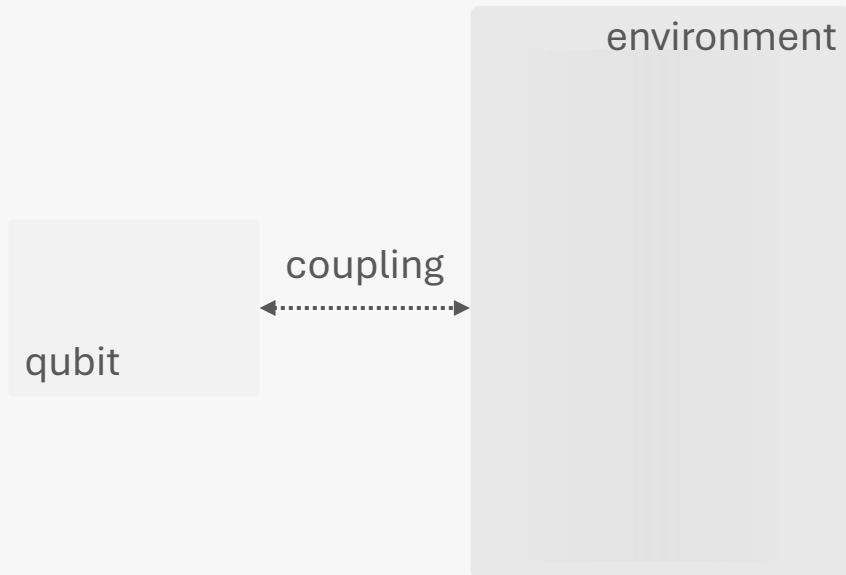
does the evolution?



Decoherence vs spontaneous collapse

Decoherence

Only **unitary, reversible** evolution



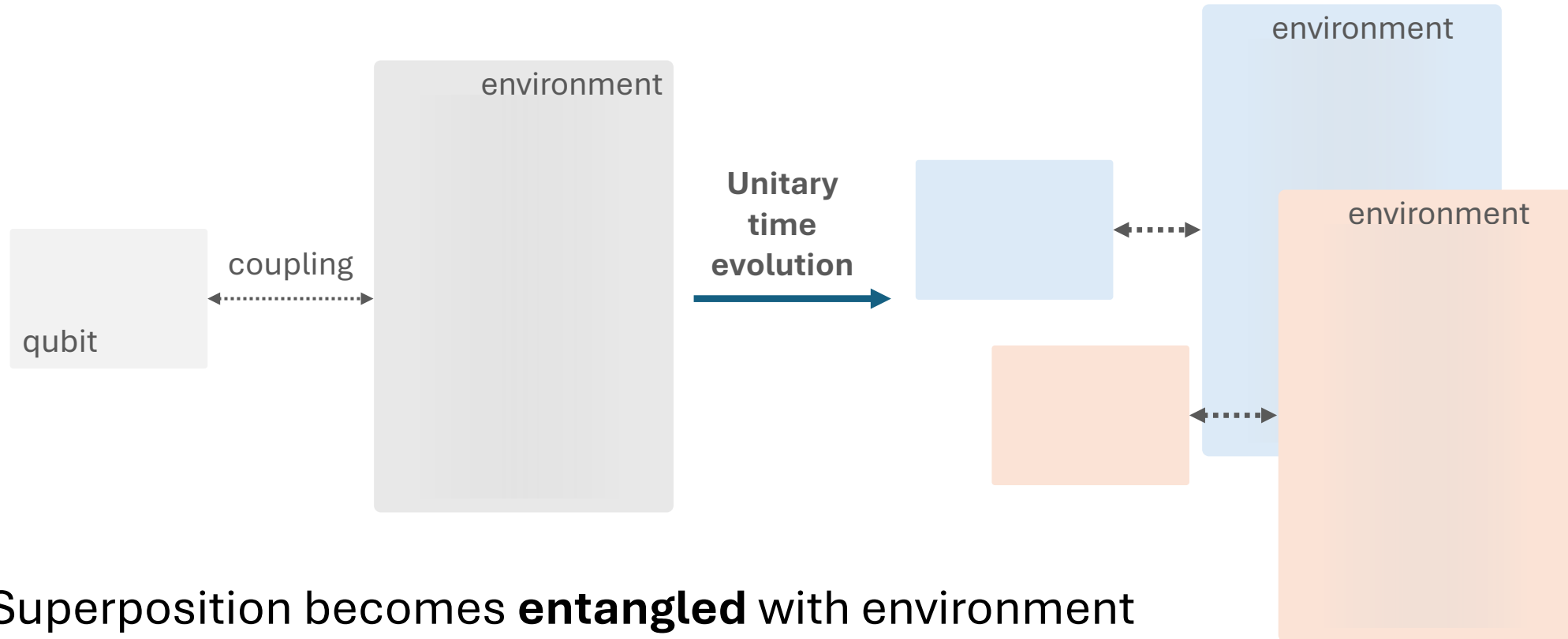
Complexity of **environment** causes
'irreversible' evolution of qubit

Spontaneous collapse

There exists **irreversible** evolution

Irreversible evolution is source of **collapse**

Introduction to Decoherence

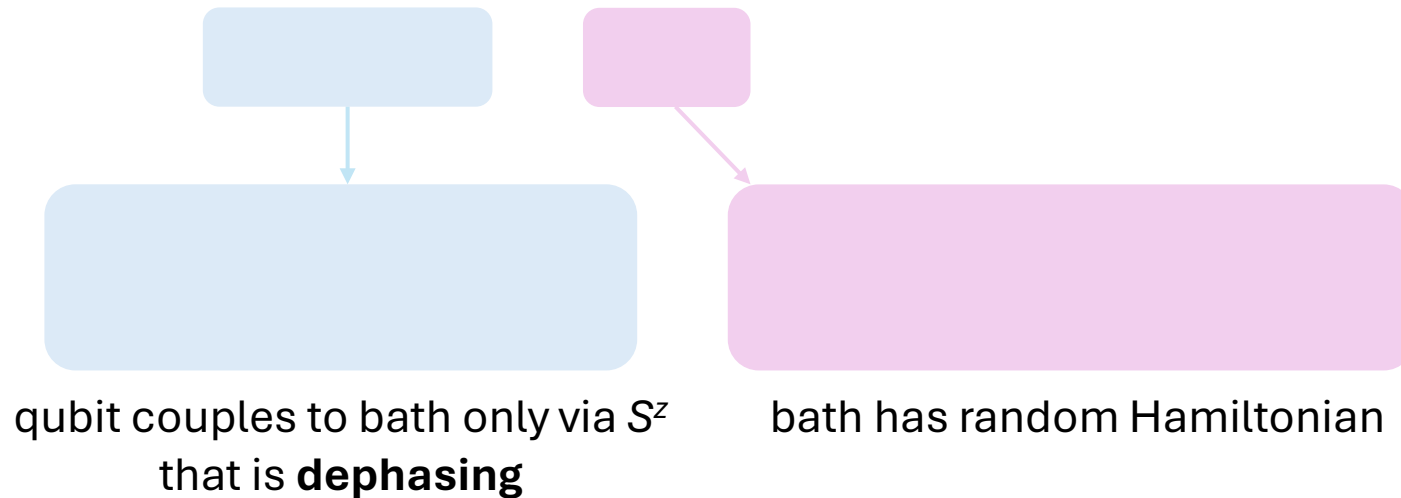


Superposition becomes **entangled** with environment

Environment states become **orthogonal**

Dephasing – an example calculation

Example calculation: one qubit coupled to N ‘**bath**’ qubits



Initial state: qubit in superposition, bath a product state

After time t , we can write

and calculate the overlap

Dephasing – an example calculation (results)

Environment overlap
decays exponentially

Qubit **expectation value** decays:
sign of **decoherence**

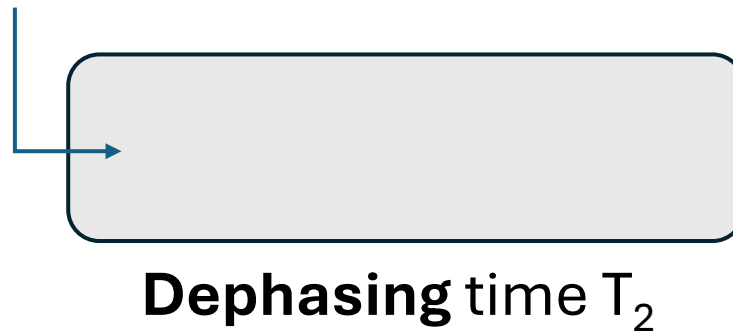
Note: purely **unitary** dynamics that is **reversible** (if we include bath d.o.f.)

Reduced density matrix & dephasing

Trace out the environment

Pure state

becomes



Lindblad formalism

Directly formulate time evolution on the reduced density matrix

Effect of bath in *jump operators* L

For dephasing, use

Gives **exponential decay**

And reproduces the T_2 time of dephasing

Measuring T_2 : Ramsey interferometry

1. Make superposition

For example, apply

on initial state

2. Time evolution

Unitary for a time t

3. Undo superposition

Apply Hadamard again

4. Measure S^z

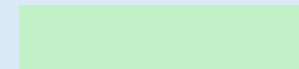
With only unitary evolution, we refind initial state

with dephasing

1.
→

2.
→

3.
→

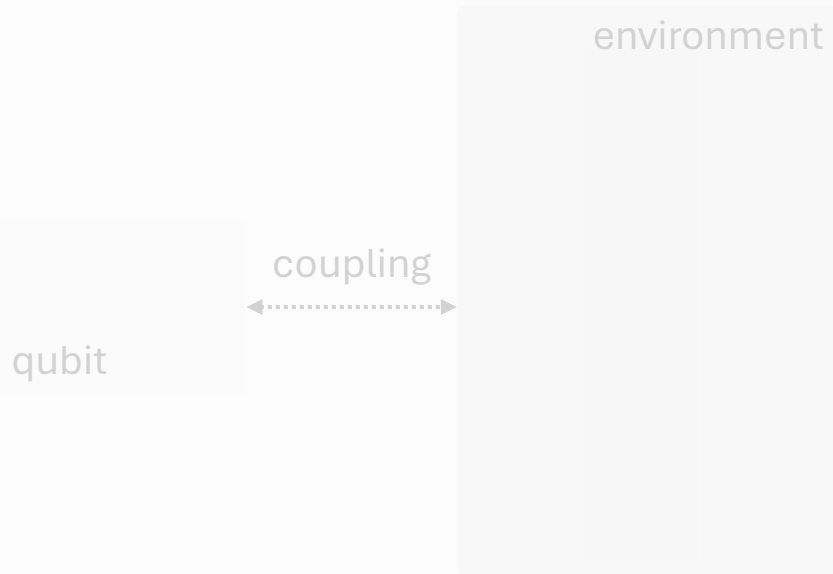


4. Probability to measure 0 after time t decays from 1 to 1/2. **Repeat protocol** to get T_2

Decoherence vs spontaneous collapse

Decoherence

Only **unitary, reversible** evolution



Complexity of **environment** causes
'irreversible' evolution of qubit

Spontaneous collapse

There exists **irreversible** evolution

Irreversible evolution is source of **collapse**

‘Spontaneous collapse’ theories

Opposed to decoherence, we can **extend** quantum mechanics

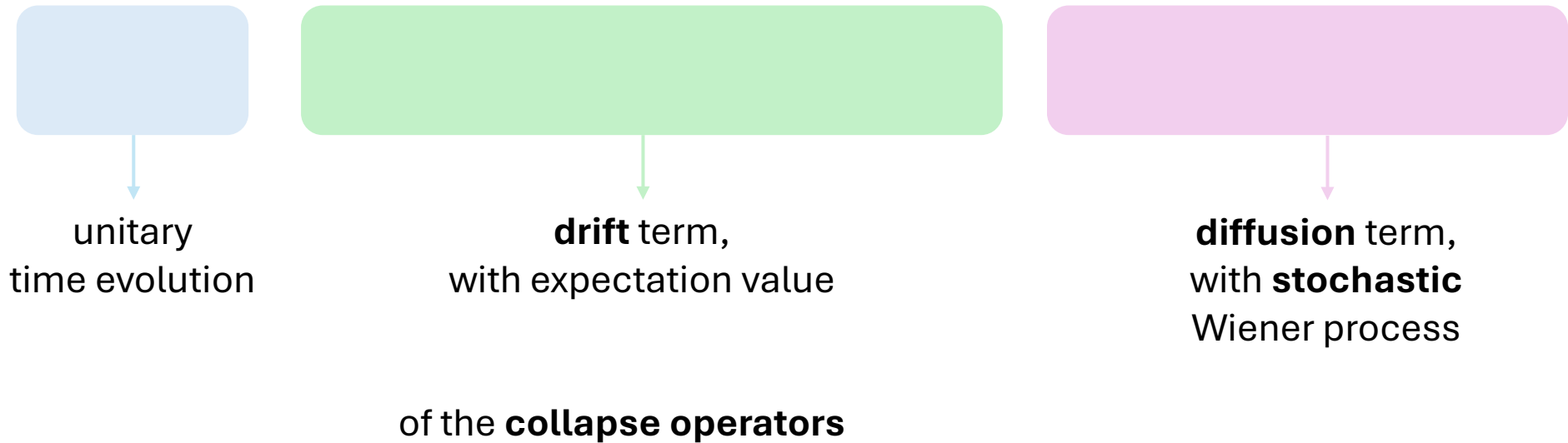
Constraints:

1. Should reproduce **Born’s rule**
2. Explains why it only works for “**big**” superpositions
3. Preserve **causality**

The extension must be:

- I. Nonlinear (and thus non-unitary)
- II. Stochastic (contains randomness)

Stochastic Schrödinger equation



SSE **satisfies** the constraints

Collapse operators determine in which basis the '**measurement**' occurs

Example – Spontaneous collapse

Solve the SSE with
collapse operators

Thin lines = **random trajectories**

Thick line = **average**

Decoherence vs spontaneous collapse

It is **not possible** to tell the difference

Average of repeated measurements
cannot tell whether there was
reversible or irreversible dynamics

(for a *simple* superposition)

Entanglement

Bell pair used to probe **Bell's inequality**

Need **two qubits q and Q** with **separate environments**



Decoherence on a Bell pair

Initial state: Bell pair of q and Q :

Separate environments for q and Q :

Separate time evolution:

Consider dephasing on q :

Reduced density matrix for q :

is **independent** of evolution of Q :

Dephasing of q is **unaffected** by entanglement with Q :

Controlled-Hadamard Pair (CHaP) state

Can only measure dephasing of q if

Resulting state is

Such that the overlap is

Example evolution

Initial '**CHaP**' state

Random **decoherence** on Q with
jump operators

Reduced density matrix on q is
unaffected

Note: these are 20 different
time evolutions with different
decoherence on Q



Main result 1: T_2 of q is unaffected

T_2 of qubit q is **unaffected** by entanglement with Q

Provided:

Q and q have a **separate environment**

Q and its environment E evolve **unitarily**

Adding projective measurement

As long as Q and E evolve unitary: no change in T_2 of q

What about if we have a **collapse** of Q ?

Start with _____ and do a **projective measurement** on Q

Probabilities of the outcome:

State after measurement:



Adding projective measurement (2)

Reduced density matrix for q 

Average reduced density matrix

So on **average** projective measurement **doesn't affect** dephasing of q

Postselection on Q

Idea: add a **postselection** after measuring Q

For the CHaP state

is **different!**

For a **spontaneous collapse** with collapse rate γ , without dephasing on q :

Postselection on Q simulated

Stochastic Schrodinger equation

Evolution of **CHaP** state

Reduced density matrix of q

(no dephasing on q)

Measurement of Q affects dephasing of q

SSE+Lindblad evolution of CHaP

Lindblad **dephasing** on q ,
spontaneous **collapse** on Q

Only if postselected for $Q=1$
will dephasing of q be faster

Main result 2: T_2 of q is affected (!)

T_2 of qubit q is **affected** by entanglement with Q

Provided:

Q and q have a **separate environment**

Q evolves **fundamentally non-unitary**

Summary of the protocol

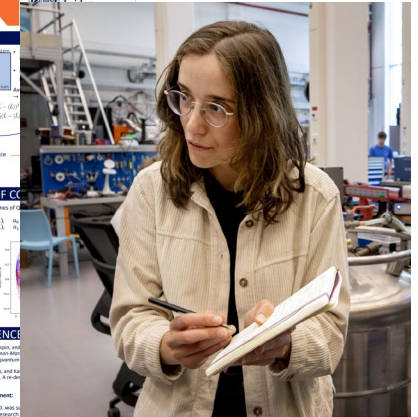
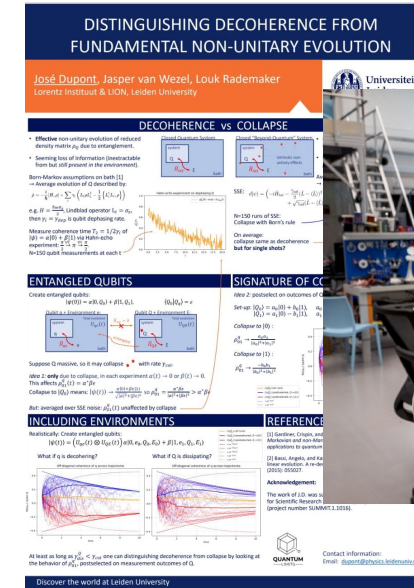
1. **Create** CHaP state with two qubits q and Q
2. **Measure** q using Ramsey interferometry after time t
3. **Measure** Q in S^z basis
4. **[Repeat]**

Postselect on outcome of Q :
does T_2 of q become different for $Q=0$ vs. $Q=1$?

If **yes**: this can only happen due to **non-unitary dynamics of Q**

Outlook

- q and Q need to be *separated well*
- Q needs to be “*large*” to see a collapse model
- What about dissipation on q ?
- Want to know **more**? See poster of **José Dupont**



Summary: we have a clear proposal that can distinguish
(unitary) decoherence
from
(non-unitary) spontaneous collapse