Title: Topics in collapse

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Abstract:

Topics in Collapse

CSL Collapse Description

CQC Completely Quantized Collapse

- Energy conservation
- Time operator
- Two models of quantized random field

QRCSL Quasi Relativistic Model

- Relativistic models: what goes wrong?
- The best I can do

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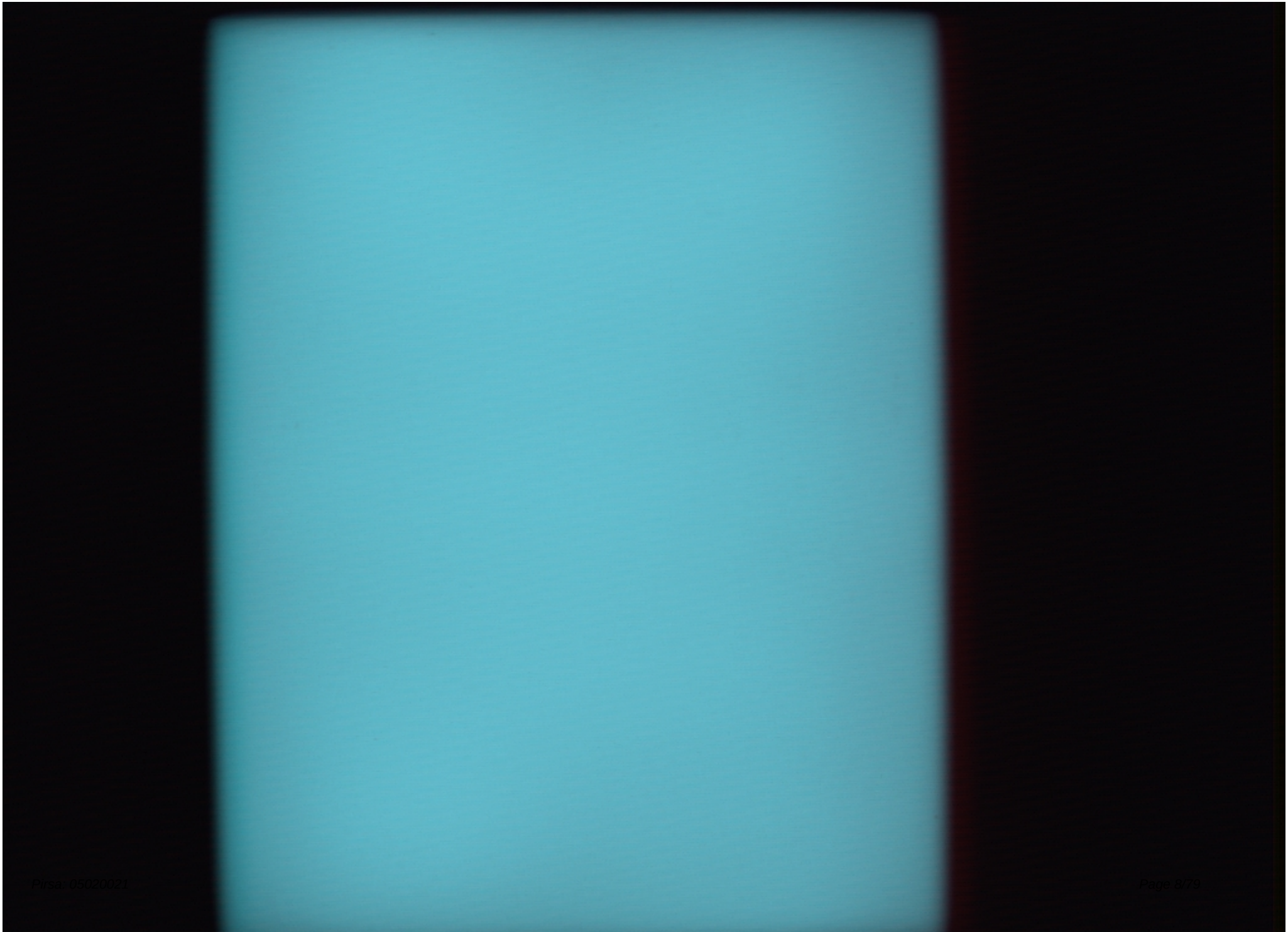
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CSL lite

Evolution: $|\psi,t\rangle_w^S = \mathcal{N} e^{-\int_0^t dt' \{iH + \frac{1}{4\lambda}[W(t') - 2\lambda A]^2\}} |\psi\rangle$

λ: collapse rate

$w(t)$: arbitrary function (white noise class)

A: collapse to A's eigenstates $A|a_n\rangle = a_n|a_n\rangle$

Probability Rule: $P_t(w)\,Dw = \langle \psi,t|\psi,t\rangle_w\, Dw$

$Dw \equiv \prod_{t_i} \left[\frac{dW(t_i)}{\sqrt{2\pi\lambda/dt}}\right]$ discretize time

That's it: calculate!

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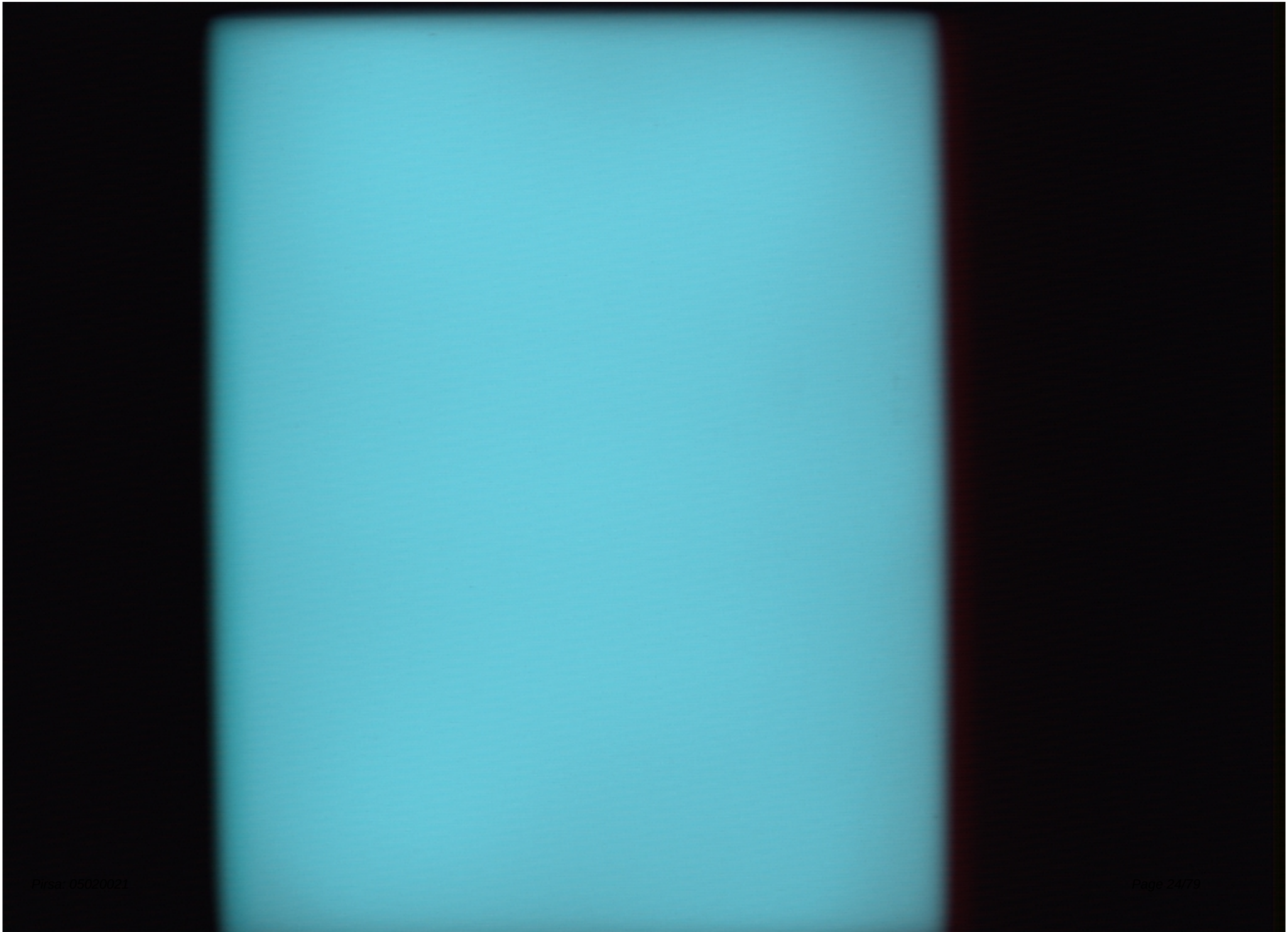
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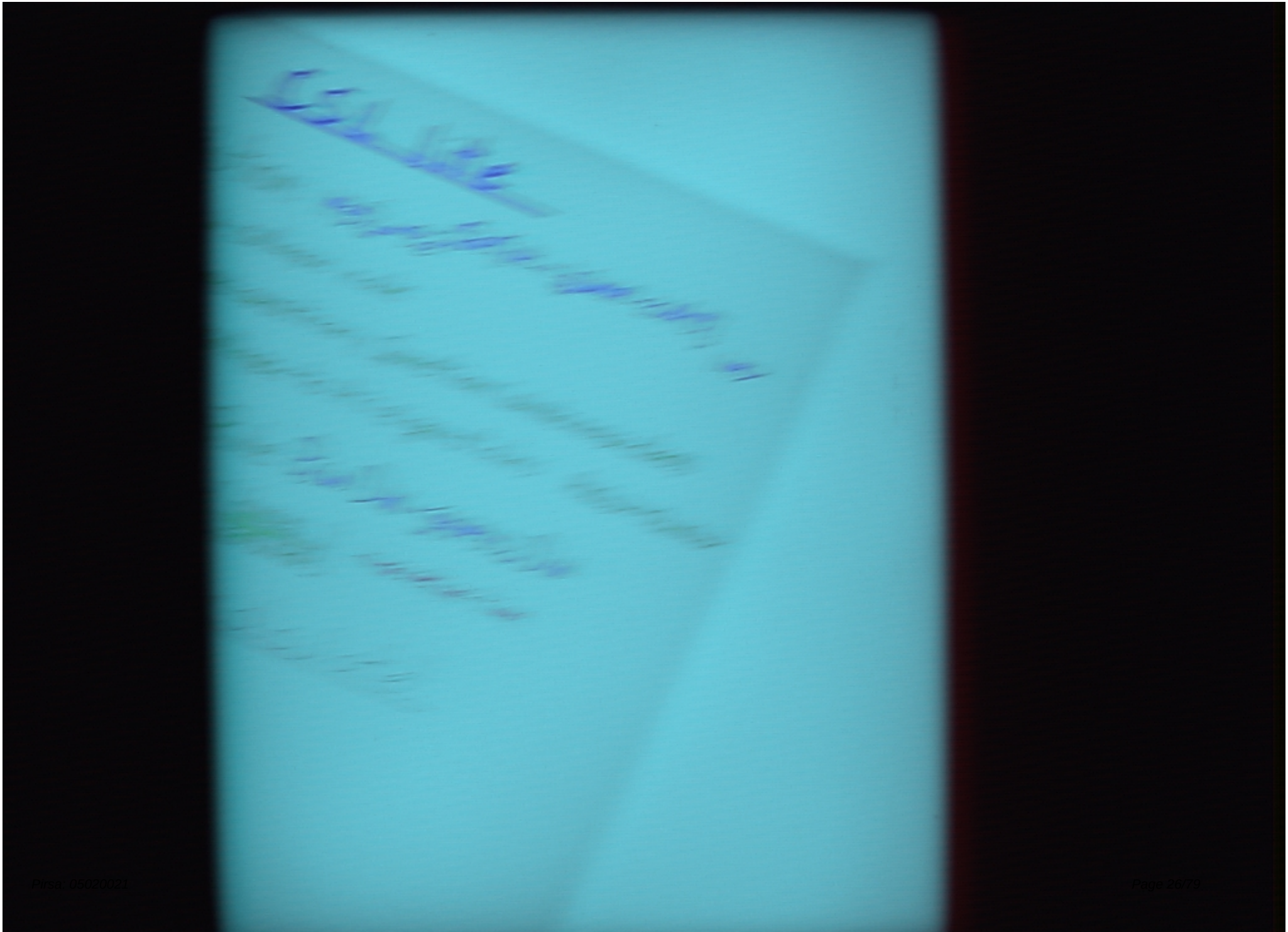
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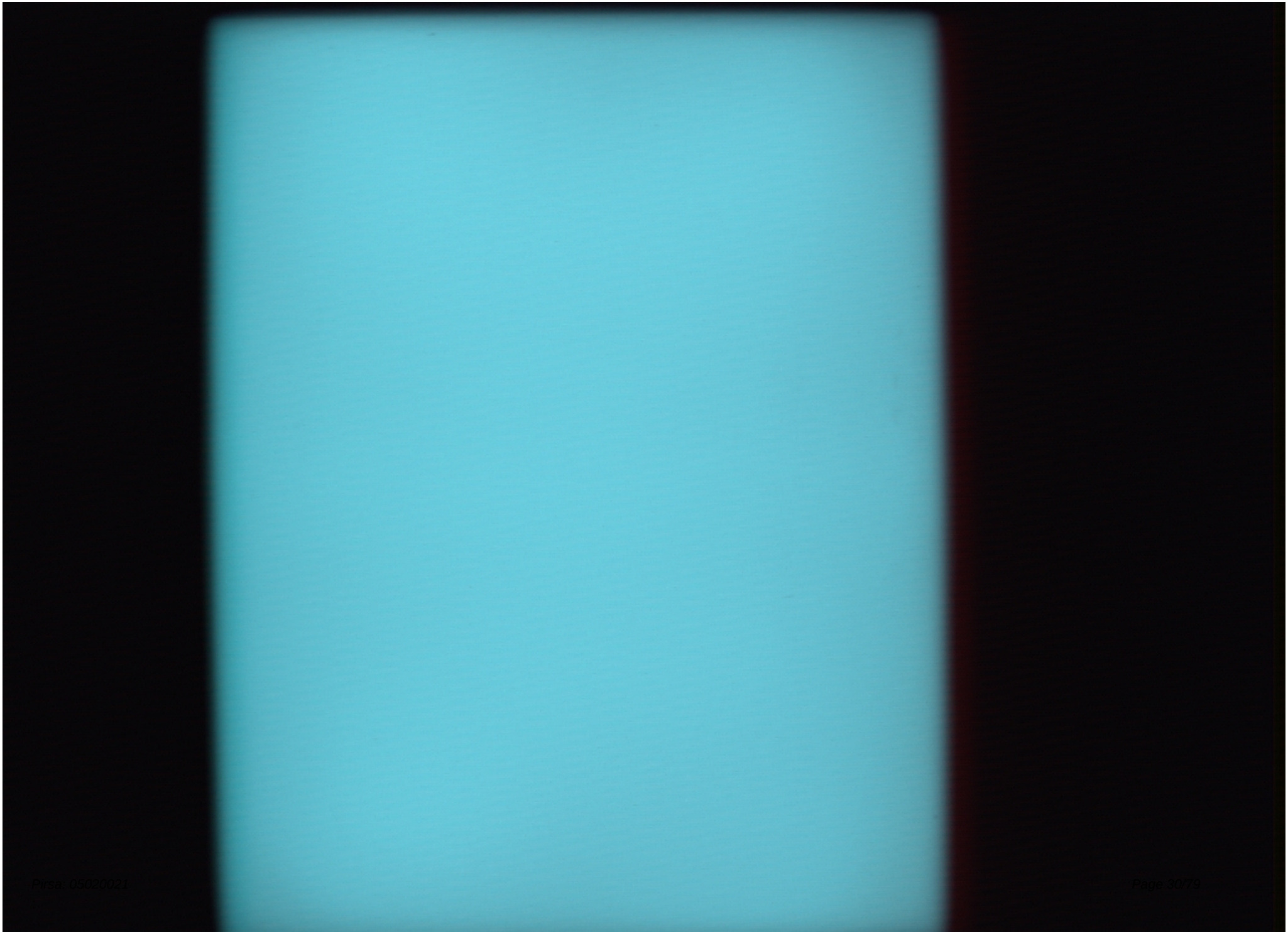
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How It Works

Initial state: $|\psi\rangle = \sum_n \alpha_n |q_n\rangle$

Evolution ($H=0$): $|\psi,t\rangle = \sum_n \alpha_n e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t')-2\lambda q_n]^2} |q_n\rangle$

Probability: $P_t(w) = \sum_n |\alpha_n|^2 e^{-\frac{1}{2\lambda}\int_0^t dt' [W(t')-2\lambda q_n]^2}$

Example: $W(t') = 2\lambda q_1$

$$|\psi,t\rangle = \alpha_1 |q_1\rangle + \sum_{n\neq 1} \alpha_n e^{-\lambda t (q_n - q_1)^2} |q_n\rangle \longrightarrow \alpha_1 |q_1\rangle$$

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Generally: $\lim_{t\to\infty} \frac{1}{t}\int_0^t dt' W_a(t') \equiv 2\lambda a$

If $a \neq a_n$, $\int Dw\, e^{-\frac{1}{2\lambda}\int_0^t dt' [W_a(t')-2\lambda q_n]^2} \longrightarrow 0$: $P_t(W_a), |\psi,t\rangle \to 0$

If $a = a_m$, $\int Dw\, e^{-\frac{1}{2\lambda}\int_0^t dt' [W_{a_m}(t')-2\lambda q_n]^2} \longrightarrow \delta_{mn}$

So $\int P_t(W_{an})\, DW \longrightarrow |\alpha_n|^2$, $|\psi,t\rangle \longrightarrow \sim |a_n\rangle$

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Collapse!

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Initial state: $|\psi\rangle = \sum_n \alpha_n |q_n\rangle$

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Example: $W(t') = 2\lambda q_1$

$$|\psi,t\rangle = \alpha_1 |q_1\rangle + \sum_{n\neq 1} \alpha_n e^{-\lambda t (q_n - q_1)^2} |q_n\rangle \longrightarrow \alpha_1 |q_1\rangle$$

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Pirsa: 05020021

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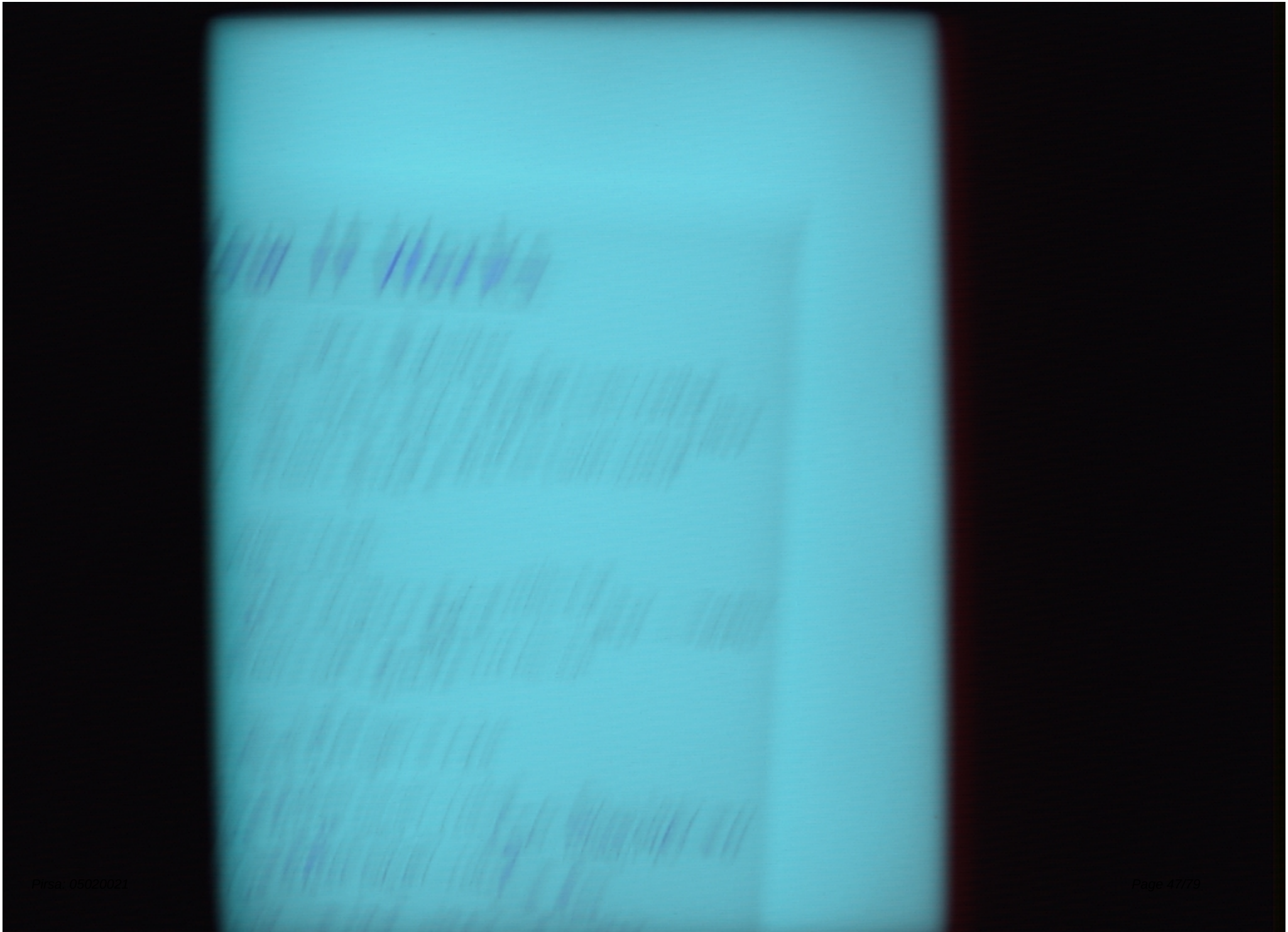
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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

Interaction Picture: $|\psi,t\rangle_w \equiv e^{iHt}|\psi,t\rangle_w^S$, $A(t) \equiv e^{iHt} A e^{-iHt}$

$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A(t')]^2} |\psi\rangle$$

Density Matrix: $\rho(t) = \int Dw\, P_t(w)\, |\psi,t\rangle_w \langle\psi,t|$ / ~~$\langle\psi,t|\psi,t\rangle_w$~~

$$\rho(t) = \int Dw\, \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_L(t')]^2} |\psi\rangle\langle\psi| \mathcal{T}_R e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_R(t')]^2}$$

$$\rho(t) = \mathcal{T} e^{-\frac{\lambda}{2}\int_0^t dt' [A_L(t') - A_R(t')]^2} \rho(0)$$

$$\frac{d\rho(t)}{dt} = -\frac{\lambda}{2}[A(t), [A(t), \rho(t)]]$$

Example: $\rho(0) = \sum_{n,m} \alpha_n \alpha_m^* |a_n\rangle\langle a_m|$

$$\rho(t) = \sum_{n,m} \alpha_n \alpha_m^* |a_n\rangle\langle a_m| e^{-\frac{\lambda}{2} t (a_n - a_m)^2}$$

Many A's: $[A^r, A^s] = 0$ $A^r |a_i\rangle = a_i^r |a_i\rangle$

$$|\psi,t\rangle_w \sim \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' \sum_r [W_r(t') - 2\lambda A^r(t')]^2} |\psi\rangle$$

↳ many W's

Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

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$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A(t')]^2} |\varphi\rangle$$

Density Matrix: $\rho(t) = \int Dw\, P_t(w)\, |\psi,t\rangle_w \langle\psi,t|$ / ~~$\langle\psi,t|\psi,t\rangle_w$~~

$$\rho(t) = \int Dw\, \mathcal{T}_L e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_L(t')]^2} |\varphi\rangle\langle\varphi| \mathcal{T}_R e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_R(t')]^2}$$

$$\rho(t) = \mathcal{T} e^{-\frac{\lambda}{2}\int_0^t dt' [A_L(t') - A_R(t')]^2} \rho(0)$$

$$\frac{d\rho(t)}{dt} = -\frac{\lambda}{2}[A(t), [A(t), \rho(t)]]$$

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↳ many W's

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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

Interaction Picture: $|\psi,t\rangle_w \equiv e^{iHt}|\psi,t\rangle_w^S$, $A(t) \equiv e^{iHt} A e^{-iHt}$

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↳ many W's

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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

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$$\rho(t) = \mathcal{T} e^{-\frac{\lambda}{2}\int_0^t dt' [A_L(t') - A_R(t')]^2} \rho(0)$$

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$$\rho(t) = \sum_{n,m} \alpha_n \alpha_m^* |a_n\rangle\langle a_m| e^{-\frac{\lambda}{2} t (a_n - a_m)^2}$$

Many A's: $[A^r, A^s] = 0$ $A^r |a_i\rangle = a_i^r |a_i\rangle$

$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' \sum_r [W_r(t') - 2\lambda A^r(t')]^2} |\varphi\rangle$$

↳ many W's

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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

Interaction Picture: $|\psi,t\rangle_w \equiv e^{iHt}|\psi,t\rangle_w^S$, $A(t) \equiv e^{iHt} A e^{-iHt}$

$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A(t')]^2} |\psi\rangle$$

Density Matrix: $\rho(t) = \int Dw\, P_t(w)\, |\psi,t\rangle_w \langle\psi,t|$ / ~~$\langle\psi,t|\psi,t\rangle_w$~~

$$\rho(t) = \int Dw\, \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_L(t')]^2} |\psi\rangle\langle\psi| \mathcal{T}_R e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_R(t')]^2}$$

$$\rho(t) = \mathcal{T} e^{-\frac{\lambda}{2}\int_0^t dt' [A_L(t') - A_R(t')]^2} \rho(0)$$

$$\frac{d\rho(t)}{dt} = -\frac{\lambda}{2}[A(t), [A(t), \rho(t)]]$$

Example: $\rho(0) = \sum_{n,m} \alpha_n |a_n\rangle\langle a_m| \alpha_m^*$

$$\rho(t) = \sum_{n,m} \alpha_n \alpha_m^* |a_n\rangle\langle a_m| e^{-\frac{\lambda}{2} t (a_n - a_m)^2}$$

Many A's: $[A^r, A^s] = 0$ $A^r|a_i\rangle = a_i^r |a_i\rangle$

$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' \sum_r [W_r(t') - 2\lambda A^r(t')]^2} |\psi\rangle$$

↑ many W's

Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

Interaction Picture: $|\psi,t\rangle_w \equiv e^{iHt}|\psi,t\rangle_w^S$, $A(t) \equiv e^{iHt} A e^{-iHt}$

$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A(t')]^2} |\psi\rangle$$

Density Matrix: $\rho(t) = \int DW\, P_t(W)\, |\psi,t\rangle_w \langle\psi,t|$

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$$\rho(t) = \mathcal{T} e^{-\frac{\lambda}{2}\int_0^t dt' [A_L(t') - A_R(t')]^2} \rho(0)$$

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$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' \sum_r [W_r(t') - 2\lambda A^r(t')]^2} |\psi\rangle$$

↑ many W's

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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

Interaction Picture: $|\psi,t\rangle_w \equiv e^{iHt}|\psi,t\rangle_w^S$, $A(t) \equiv e^{iHt} A e^{-iHt}$

$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A(t')]^2} |\psi\rangle$$

Density Matrix: $\rho(t) = \int Dw\, P_t(w)\, |\psi,t\rangle_w \langle\psi,t|$ / ~~$\langle\psi,t|\psi,t\rangle_w$~~

$$\rho(t) = \int Dw\, \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_L(t')]^2} |\psi\rangle\langle\psi| \mathcal{T}_R e^{-\frac{1}{4\lambda}\int_0^t dt' [W(t') - 2\lambda A_R(t')]^2}$$

$$\rho(t) = \mathcal{T} e^{-\frac{\lambda}{2}\int_0^t dt' [A_L(t') - A_R(t')]^2} \rho(0)$$

$$\frac{d\rho(t)}{dt} = -\frac{\lambda}{2}[A(t), [A(t), \rho(t)]]$$

Example: $\rho(0) = \sum_{n,m} \alpha_n |a_n\rangle\langle a_m| \alpha_m^*$

$$\rho(t) = \sum_{n,m} \alpha_n \alpha_m^* |a_n\rangle\langle a_m| e^{-\frac{\lambda}{2} t (a_n - a_m)^2}$$

Many A's: $[A^r, A^s] = 0$ $A^r|a_i\rangle = a_i^r |a_i\rangle$

$$|\psi,t\rangle_w = \mathcal{T} e^{-\frac{1}{4\lambda}\int_0^t dt' \sum_r [W_r(t') - 2\lambda A^r(t')]^2} |e\rangle$$

↳ many W's

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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

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↳ many W's

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Some Bits of Formalism

Schrödinger Eq'n: $\frac{d|\psi,t\rangle_w^S}{dt} = [-iH - \frac{1}{4\lambda}(W(t) - 2\lambda A)^2]\,|\psi,t\rangle_w^S$

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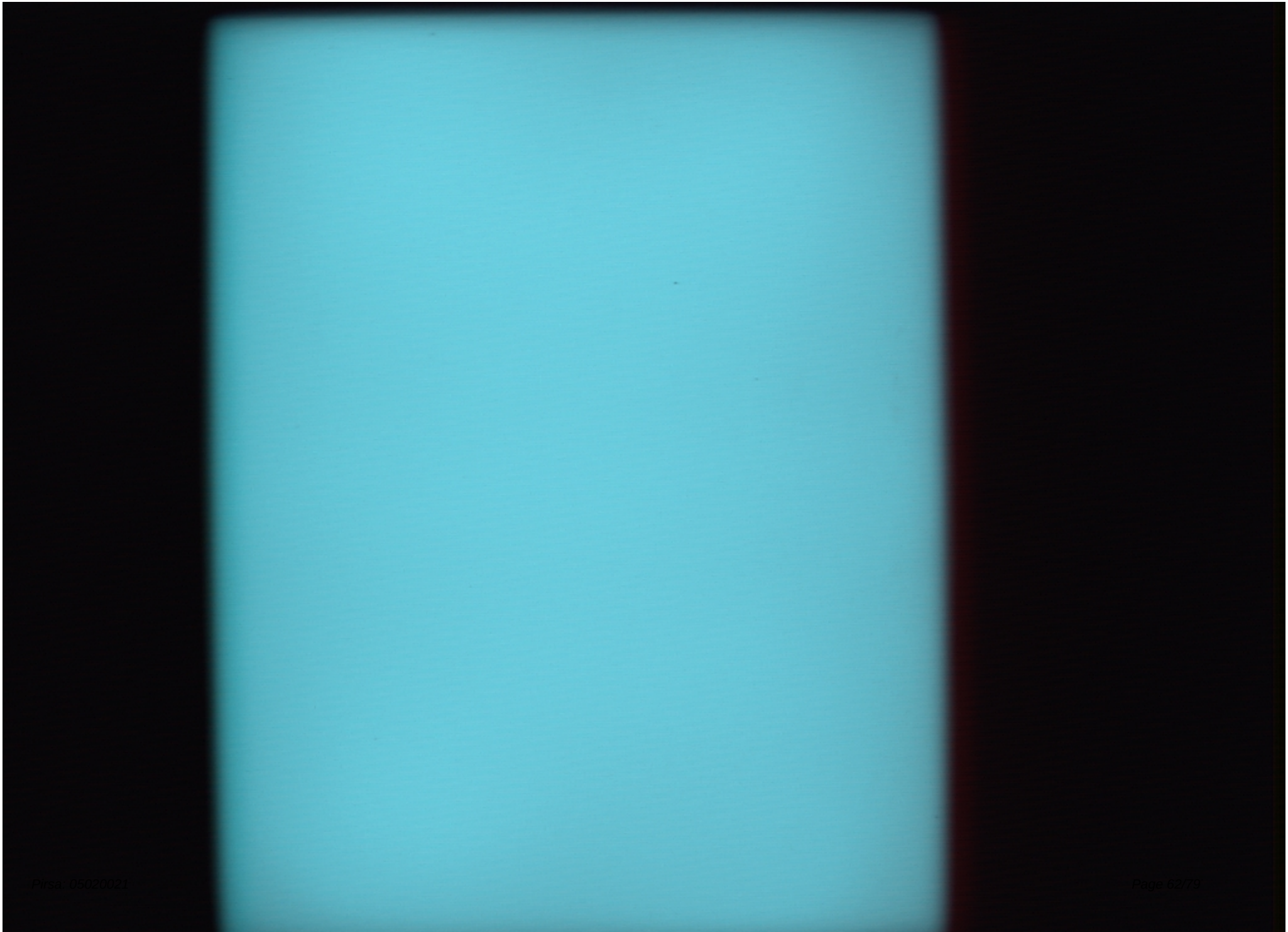
$$\rho(t) = \sum_{n,m} \alpha_n \alpha_m^* |a_n\rangle\langle a_m| e^{-\frac{\lambda}{2} t (a_n - a_m)^2}$$

Many A's: $[A^r, A^s] = 0$ $A^r|a_i\rangle = a_i^r |a_i\rangle$

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↳ many W's

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Full Blown CSL

$$|\psi,t\rangle_w = \mathcal{N} e^{-\frac{1}{4\lambda}\int d\vec{x}\int_0^t dt\,[W(\vec{x},t)-2\lambda A(\vec{x},t)]^2}\,|\psi\rangle$$

$W(\vec{x},t)$ is fluctuating field

$$A(\vec{x}) \equiv \int d\vec{z}\,\frac{1}{(\pi a^2)^{3/4}}\, e^{-\frac{(\vec{x}-\vec{z})^2}{2a^2}} \sum_s \frac{m_s}{m_0} N_s(\vec{z}) \qquad N_s(\vec{z}) \sim \xi_s^\dagger(\vec{z})\,\xi_s(\vec{z})$$

is $\simeq$ particle mass in sphere of radius a about $\vec{x}$

$a \simeq 10^{-5}$ cm (GRW's scale parameter)

$\lambda^{-1} \simeq 10^{16}$ sec $\simeq$ 300 my (GRW's rate parameter)

If $|\psi\rangle = \alpha_1|\bullet\rangle + \alpha_2|$ (neutron) $\rangle \Rightarrow$: Collapse time $\simeq 10^{16}$ sec.

$|\psi\rangle = \alpha_1|\vec{q}\rangle + \alpha_2|$ ("pointer, n nucleons") $\rangle \Rightarrow$: Collapse time $\simeq \frac{10^{16}}{n^2}$ sec

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Full Blown CSL

$$|\psi,t\rangle_w = \mathcal{T}\, e^{-\frac{1}{4\lambda}\int d\vec{x}\int_0^t dt\,[W(\vec{x},t)-2\lambda A(\vec{x},t)]^2}\,|\psi\rangle$$

$W(\vec{x},t)$ is fluctuating field

$$A(\vec{x}) \equiv \int d\vec{z}\,\frac{1}{(\pi q^2)^{3/4}}\, e^{-\frac{(\vec{x}-\vec{z})^2}{2q^2}} \sum_s \frac{m_s}{m_o} N_s(\vec{z}) \qquad \xi_s^\dagger(\vec{z})\,\xi_s(\vec{z})$$

is ≃ particle mass in sphere of radius q about $\vec{x}$

$q \simeq 10^{-5}$ cm (GRW's scale parameter)

$\lambda^{-1} \simeq 10^{16}$ sec ≃ 300 my (GRW's rate parameter)

If $|\psi\rangle = \alpha_1 |\bullet\rangle_{\text{neutron}} + \alpha_2 |\quad\rangle \Rightarrow$: Collapse time ≃ 10^{16} sec.

$|\psi\rangle = \alpha_1 |\bullet\rangle_{\text{"pointer, n nucleons"}} + \alpha_2 |\quad\rangle \Rightarrow$: Collapse time ≃ $\frac{10^{16}}{n^2}$ sec

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Full Blown CSL

$$|\psi,t\rangle_w = \mathcal{N} e^{-\frac{1}{4\lambda}\int d\vec{x}\int_0^t dt\,[W(\vec{x},t)-2\lambda A(\vec{x},t)]^2}\,|\psi\rangle$$

$W(\vec{x},t)$ is fluctuating field

$$A(\vec{x}) \equiv \int d\vec{z}\,\frac{1}{(\pi a^2)^{3/4}}\, e^{-\frac{(\vec{x}-\vec{z})^2}{2a^2}} \sum_s \frac{m_s}{m_o} N_s(\vec{z}) \qquad N_s(\vec{z}) \sim \xi_s^\dagger(\vec{z})\,\xi_s(\vec{z})$$

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$|\psi\rangle = \alpha_1 |$ ("pointer, n nucleons") $\rangle + \alpha_2 |$ ⚬ $\rangle$: Collapse time $\simeq \frac{10^{16}}{n^2}$ sec

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Completely Quantized Collapse

c-number $w(t)$ ⟶ quantized noise $W(t)$

$$W(t) \equiv (\lambda/2\pi)^{1/2} \int_{-\infty}^{\infty} d\omega \left[e^{-i\omega t} b(\omega) + e^{i\omega t} b^\dagger(\omega) \right]$$

$$\Pi(t) \equiv i/(8\pi\lambda)^{1/2} \int_{-\infty}^{\infty} d\omega \left[-e^{-i\omega t} b(\omega) + e^{i\omega t} b^\dagger(\omega) \right]$$

$[b(\omega), b^\dagger(\omega')] = \delta(\omega - \omega')$ etc.

Commutators: $[W(t), W(t')] = 0$, $[\Pi(t), \Pi(t')] = 0$, $[W(t), \Pi(t')] = i\delta(t - t')$

Vectors: $W(t)|w\rangle = w(t)|w\rangle$, $|w\rangle = \prod_{t_j} |w(t_j)\rangle$

Vacuum: $b(\omega)|0\rangle = 0 \Rightarrow \left[W(t) + 2i\lambda \frac{1}{i} \frac{\delta}{\delta w(t)} \right] \langle w|0\rangle = 0$

$$\langle w|0\rangle = e^{-\frac{1}{4\lambda} \int_{-\infty}^{\infty} dt' w^2(t')}, \quad \langle \pi|0\rangle = e^{-\lambda \int_{-\infty}^{\infty} dt' \pi^2(t')}$$

Evolution: $|\psi, t\rangle \equiv \mathcal{T} e^{-i2\lambda \int_0^t dt' A(t') \Pi(t')} |0\rangle |\psi\rangle$

$$\langle w|\psi, t\rangle = \mathcal{T} e^{-\frac{1}{4\lambda} \int_0^t dt' [w(t') - 2\lambda A(t')]^2} |\psi\rangle \, e^{-\frac{1}{4\lambda} \left[\int_{-\infty}^{0} + \int_t^{\infty} \right] dt' w^2(t')}$$

↳ CSL evolution!

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CQC Equivalence to CSL

Superselection Rule:

$$|\Psi,t\rangle = \int Dw\, |w\rangle\langle w|\Psi,t\rangle = \sum_{\text{all } w(t)\,\updownarrow} |w(t)\rangle\, |\Psi_{CSL},t\rangle_{w(t)}$$

Schrödinger's "probability catalog"

Usual probability: $Dw\, \langle\Psi,t|w\rangle\langle w|\Psi,t\rangle = Dw_\omega \langle\Psi_{CSL},t|\Psi_{CSL},t\rangle_\omega e^{-\frac{1}{2\lambda}\left[\int_{-\infty}^{t}+\int_{t}^{\infty}\right]dt' w^2(t')}$

Interpretations all work: many worlds, histories, env'tl decoh....

CQC as continuous measurement

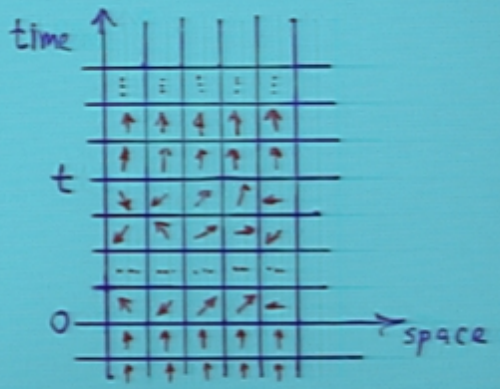
During dt, $|\Psi,t\rangle$'s change is $e^{-i2\lambda A(t)\frac{\partial}{\partial w(t)}} e^{-\frac{dt}{4\lambda}w^2(t)} = e^{-\frac{dt}{4\lambda}[w(t)-2\lambda A(t)]^2}$

von Neumann measurement; pointer

CQC lite



Full-Blown CQC



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1) Ensemble Energy Conservation

W-field energy: $H_W \equiv \int_{-\infty}^{\infty} d\omega \omega b^\dagger(\omega) b(\omega) = \int_{-\infty}^{\infty} dt' \dot{W}(t') \pi(t')$

generates time-translation of $W(t), \pi(t)$.

Schrödinger Picture: $|\psi,t\rangle_S \equiv e^{-iH_A t}|\psi,t\rangle = \overleftarrow{T} e^{-i\int_0^t dt' [H_A + 2\lambda A \pi(t')]} |0\rangle|\psi\rangle$ (time independent)

Sch-Schrödinger Picture: $|\psi,t\rangle_{SS} \equiv e^{-iH_W t}|\psi,t\rangle_S = e^{-i[H_A + H_W + 2\lambda A \pi(0)]t}|0\rangle|\psi\rangle$

$H \equiv H_A + H_W + 2\lambda A \pi(0)$ is conserved energy

Example: CSL lite and $H_A = 0$ and $|\psi\rangle = \sum_n \alpha_n |q_n\rangle$

H-generating function: $\langle\psi,t|e^{-iH\beta}|\psi,t\rangle = \sum_n |\alpha_n|^2 e^{-\frac{\lambda}{2} q_n^2 |B|}$

H_W-generating function: $\sum_n |\alpha_n|^2 e^{-\lambda q_n^2 t}$ and $\sum_n |\alpha_n|^2 e^{-\lambda q_n^2 |B|}$ ↳ $-t < \beta < t$

H-probability density: $P(E) = \frac{1}{\pi} \sum |\alpha_n|^2 \frac{\lambda q_n^2/2}{E^2 + (\lambda q_n^2/2)^2}$

H_W-probability density:

$$P_W(E) = \frac{1}{\pi} \sum_n |\alpha_n|^2 \Big\{ e^{-\lambda q_n^2 t} \Big[\pi \delta(E) - \frac{\sin Et}{E} + \frac{(E \sin Et - \lambda q_n^2 (\cos Et)]}{E^2 + (\lambda q_n^2)^2} + \frac{\lambda q_n^2}{E^2 + (\lambda q_n^2)^2} \Big\}$$

1) Ensemble Energy Conservation

W-field energy: $H_W \equiv \int_{-\infty}^{\infty} d\omega\, \omega\, b^\dagger(\omega) b(\omega) = \int_{-\infty}^{\infty} dt'\, \dot{W}(t')\, \pi(t')$

generates time-translation of $W(t), \pi(t)$.

Schrödinger Picture: $|\psi,t\rangle_S \equiv e^{-iH_A t}|\psi,t\rangle = \mathcal{T} e^{-i\int_0^t dt' [H_A + 2\lambda A \pi(t')]} |0\rangle|\psi\rangle$

(time independent)

Sub Schrödinger Picture: $|\psi,t\rangle_{SS} \equiv e^{-iH_W t}|\psi,t\rangle_S = e^{-i[H_A + H_W + 2\lambda A \pi(0)]t} |0\rangle|\psi\rangle$

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Example: CSL lite and $H_A \neq 0$

First moment conservation:

$$\langle \psi,t|H_A|\psi,t\rangle = \langle\phi|\mathcal{T}\{e^{-\frac{\lambda}{2}\int_0^t dt'[A_L(t')-A_R(t')]^2} H_A\}|\phi\rangle$$

$$\langle \psi,t|H_W|\psi,t\rangle = \frac{\lambda}{2}\langle\phi|\mathcal{T}\{\int_0^t dt' e^{-\frac{\lambda}{2}\int_0^{t'} dt''[A_L(t'')-A_R(t'')]^2}[A(t'),[A(t'),H_A]]\}|\phi\rangle$$

$$\langle \psi,t|H_{int}|\psi,t\rangle = 0$$

$$\frac{d}{dt}\overline{H}_W = -\frac{d}{dt}\overline{H}_A = \frac{\lambda}{2}\langle\phi|\mathcal{T}\{e^{-\frac{\lambda}{2}\int_0^t dt'[A_L(t')-A_R(t')]^2}[A(t),[A(t),H_A]]\}|\phi\rangle$$

Example, collapse of free particle into position states:

$$H = P^2/2m,\quad A = X,\quad A(t) = X + Pt/m$$

$$\langle \psi,t|H_A|\psi,t\rangle = \langle\phi|P^2/2m|\phi\rangle + \lambda t/2m,\quad \langle\psi,t|H_W|\psi,t\rangle = -\lambda t/2m$$

$$P_W(E) \xrightarrow[t\to\infty]{} \langle\phi|\mathcal{T}e^{-\frac{\lambda}{2}\int_0^t dt'[A_L(t')-A_R(t')]^2}$$

$$\cdot \frac{1}{\pi}\frac{\lambda[A^2(t)+A^2(0)]/2}{[E+\lambda t/2m]^2+[\lambda(A^2(t)+A^2(0))/2]^2}|\phi\rangle$$

$\hookrightarrow -\overline{H}_W$

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2) Time Operator: $[H_{WL}, T] = i$

$$T = \frac{\int_{-\infty}^{\infty} d\omega\, b^\dagger(\omega) \frac{1}{i}\frac{\partial}{\partial\omega} b(\omega)}{\int_{-\infty}^{\infty} d\omega\, b^\dagger(\omega) b(\omega)} = \frac{\int_{-\infty}^{\infty} dt'\, t' \left[(\psi\lambda)^{-1} W^2(t') + \lambda \Pi^2(t')\right]}{\int_{-\infty}^{\infty} dt' \left[(\psi\lambda)^{-1} W^2(t') + \lambda \Pi^2(t')\right]}$$

Eigenfunctions: $\langle w | \prod_{t_i} \left[\int_{-\infty}^{\infty} d\omega\, e^{i\omega t_i} b^\dagger(\omega)\right]^{n(t_i)} |0\rangle \sim \prod_{t_i} H_{n(t_i)}\left[W(t_i)(dt/2\lambda)^{1/2}\right] e^{-\frac{1}{4\lambda}\int_{-\infty}^{\infty} dt' W^2(t')}$

Eigenvalues: $\sum_{t_i} t_i\, n(t_i) \Big/ \sum_{t_i} n(t_i)$ "center of time"

Mean: $\langle \psi, t | T | \psi, t\rangle = \langle \phi | \zeta^\dagger \frac{\int_0^t dt' \mu A_L(t') A_R(t')}{\int_0^t dt' A_L(t') A_R(t')} \left[e^{-\frac{\gamma}{2}\int_0^t dt' [A_L(t') - A_R(t')]^2} - e^{-\frac{\gamma}{2}\int_0^t dt' [A_L(t') + A_R(t')]^2}\right] |\phi\rangle$

Example, $H_A = 0$, $|\phi\rangle = \sum \alpha_n |q_n\rangle$:

$$\langle \psi, t | T | \psi, t\rangle = \frac{\int_0^t dt' t'}{\int_0^t dt'} \left[1 - \sum_n |q_n|^2 e^{-\lambda t q_n^2}\right] \xrightarrow[t\to\infty]{} t/2, \quad \frac{\overline{\Delta T^2}}{\overline{T}^2} \underset{t\to\infty}{\sim} t^{-1}$$

Example, $H_A \neq 0$, $A(t) = At^s$:

$$\langle \psi, t | T | \psi, t\rangle \xrightarrow[t\to\infty]{} \frac{t(2s+1)}{(2s+2)}, \quad \frac{\overline{\Delta T^2}}{\overline{T}^2} \underset{t\to\infty}{\sim} t^{-(2s+1)}$$

Full-blown CSL; A is mass density, $\overline{T} \simeq t$ for large damping rate

$\overline{T} \simeq t/2$ because of wavefunction collapse
$\overline{T} \to \simeq t$ because of gravitational collapse

It is an attractive idea that time is related to collapse: no collapse $\Rightarrow$ no events $\Rightarrow$ no time.

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3) Modeling W(t)

① Collection of quantum fields of Planck mass M, each interacts over Planck time $\tau = M^{-1}$ only.

$$\Phi_t(x) = \frac{C}{(2\pi)^{3/2}} \frac{1}{\sqrt{2M}} \int d\vec{k}\, [e^{i(\vec{k}\cdot\vec{x} - Mt)} b_t(\vec{k}) + e^{-i(\vec{k}\cdot\vec{x} - Mt)} b_t^+(\vec{k})]$$

$$\pi_t(\vec{x}) = \frac{C^{-1}}{(2\pi)^{3/2}} \frac{i}{\sqrt{2M}} \int d\vec{k}\, [-e^{i(\vec{k}\cdot\vec{x} - Mt)} b_t(\vec{k}) + e^{-i(\vec{k}\cdot\vec{x} - Mt)} b_t^+(\vec{k})]$$

$$[\Phi_t(\vec{x}), \pi_{t'}(\vec{x}')] = \delta_{tt'} \delta(\vec{x} - \vec{x}')$$

Vacuum: $\langle \Phi_t | 0 \rangle = e^{-\frac{M}{2C^2} \int d\vec{x}\, \Phi_t^2(\vec{x})}$ so $C = M\sqrt{2\lambda} = \tau^{-1}\sqrt{2\lambda}$

$$\langle \Phi | 0 \rangle = \prod_t \langle \Phi_t | 0 \rangle = e^{-\frac{1}{4\lambda} \tau \sum_t \int d\vec{x}\, \Phi_t^2(\vec{x})} \to e^{-\frac{1}{4\lambda} \int dt\, d\vec{x}\, \Phi_t^2(\vec{x})}$$

Interaction over $(t'+\tau, t')$: $|\psi, t'+\tau\rangle = e^{-\tau i \lambda \int d\vec{x}\, \pi_t(\vec{x}) A(\vec{x}, t)} |\psi, t'\rangle$

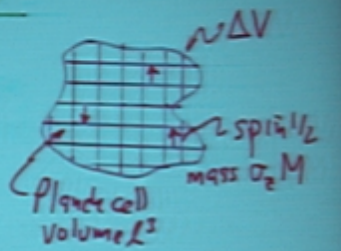
$$\langle \Phi | \psi, t \rangle = \tau e^{-\frac{1}{4\lambda} \sum_{t'=0}^{t} \tau \int d\vec{x}' [\Phi_{t'}(\vec{x}') - \tau\lambda A(\vec{x}', t')]^2} |\varphi\rangle e^{-\frac{1}{4\lambda} [\sum_{t'=-\infty}^{0} + \sum_{t'=t}^{t}] \tau \int d\vec{x}' \varphi_{t'}^2(\vec{x}')}$$

Same as CQC: $W(\vec{x}, t) \to \Phi_t(\vec{x})$, $\Pi(\vec{x}, t) \to M\pi_t(\vec{x})$

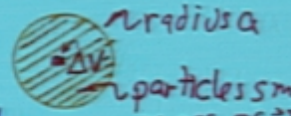
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② Collection of Spins

"Frozen" spins occasionally break loose over τ-interval interact with a thermal bath (temp β^{-1}) and "gravitationally."



$$H = -\sum_{n=1}^{N} G\sigma_n \frac{M\rho(\vec{x}_n)a^3}{a}$$



N = # active spins in ΔV, during Δt $\Rightarrow N = P\frac{\Delta V}{\ell^3}\frac{\Delta t}{\tau}$

Spins in one ΔV, interacting over Δt, $W(\vec{x},t) \sim \sum_{n=1}^{N}\sigma_n/N$:

Statevector: $|\chi\rangle = \sum_{\{s_n\}} |s_1,..s_N\rangle |\text{bath}_{s_1..s_N}\rangle C_{s_1..s_N} \equiv \sum_{S=-N}^{N}\sqrt{\sum_{\{s_n\}\,\text{with}\,\sum s_n = S} |C_{s_1..s_N}|^2}\,|s\rangle$

Density Matrix: $\text{Tr}_{\text{bath}} |\chi\rangle\langle\chi| = \sum_{\{s_n\}} |s_1,..s_N\rangle\langle s_1',..s_N'| \frac{e^{+\alpha\sum_{n=1}^{N} s_n}}{\sum_{\{s_n\}} e^{\alpha\sum_{n=1}^{N} s_n}}$ $\quad \alpha \equiv \beta G M \rho(\vec{x}) a^2$

$$\Rightarrow |\langle s|\chi\rangle|^2 \simeq \frac{e^{-[S-N\tanh\alpha]^2/2N\cosh^2\alpha}}{(2\pi N\cosh^2\alpha)^{1/2}} \underset{\text{small }\alpha}{\simeq} \frac{e^{-\frac{[S-N\alpha]^2}{2N}}}{\sqrt{2\pi N}}$$

(large N)

All Spins: $|\langle s|\chi\rangle|^2 \simeq e^{-\sum_{t'=0,\vec{x}}^{t}[S_{\vec{x},t'} - N\beta G M a^2 \rho(\vec{x})]^2/4N}$

$$= e^{-\frac{1}{4\lambda}\left[\frac{\rho(\beta m_0)^2}{4\lambda\tau(\ell/a)}\right]\sum_{t'=0,\vec{x}}^{t}\Delta t\Delta V\left[\frac{S_{\vec{x},t'}/N}{\beta(a^{9/2}/2\lambda)} - 2\lambda\left(\frac{a^{3/2}}{m_0}\rho(\vec{x})\right)\right]^2}$$

$\frac{1}{4\lambda}\left[\frac{\rho(\beta m_0)^2}{4\lambda\tau(\ell/a)}\right] = 1$; $\frac{S_{\vec{x},t'}/N}{\beta(a^{9/2}/2\lambda)} = W(\vec{x},t')$; $\left(\frac{a^{3/2}}{m_0}\rho(\vec{x})\right) = A(\vec{x})$

Same as CQC!

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What's wrong with relativistic models?

White noise models: $|\Psi,\sigma\rangle = \mathcal{T} e^{-\frac{1}{4\lambda}\int_{\sigma_0}^{\sigma} d^4x\,[W(x) - 2\lambda A(x)]^2} |\Psi,\sigma_0\rangle$

($A(x)$: quantum fields $\bar{\Phi}(x)$, $\bar{\pi}(x)\pi(x)$, etc)

white noise has all $\vec{k}$'s, ω's, so each mode in vacuum excited a little — (lowest order)

but number of modes $= \infty$, so ∞ energy/sec-vol vacuum excitation

Colored noise model: $|\Psi,\sigma\rangle = \mathcal{T} e^{-\frac{1}{4\lambda}\int_{\sigma_0}^{\sigma} d^4x\, d^4x' [W(x) - 2\lambda A(x)] G(x-x') [W(x') - 2\lambda A(x')]} |\Psi,\sigma_0\rangle$

$G(x-x') = \frac{1}{(2\pi)^4}\int d^4k\, \delta[k^2 - \vec{k}^2 + \mu^2]$ (lowest order)

tachyonic noise spectrum doesn't excite vacuum (no tachyons!)

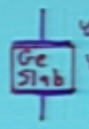
second order: ∞ vacuum excitation: $\frac{1}{-k^2 + \vec{k}^2 + m^2 - i\epsilon}$ ← propagator has all $\vec{k}$'s, ω's

cure? remove $\mathcal{T} \Rightarrow$ propagator $\delta(-k^2 + \vec{k}^2 + m^2)$ ← RCSL: finite to all orders

but highly nonlocal and, (lowest order) too much nuclear excitation.

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Collapse excitation of ^{74}Ge

Avignone et al exp't:  ≈1 kg ≈1 yr

2^+ .596 MeV 0^+ < .03 ct/kg-day

CSL excitation rate: ~dipole excitation = 0 : mass proportionality

$$\Gamma_{CSL} = \left(\frac{\pi}{15}\right)\frac{\lambda}{a^4}R \qquad R \equiv \sum_{m_f,m_i=-2}^{2} \left|\langle 2^+,m_f|\sum_{n=1}^{A}\vec{X}_n^2 Y_{2,m}(\Theta_n,\Phi_n)|0^+\rangle\right|^2$$

RCSL excitation rate:

$$\Gamma_{RCSL} = \left(\frac{4}{15^2\pi}\right)\lambda a k^5 R \qquad k \approx 3.2\times10^{10}\,cm^{-1}\ (.596\ MeV\ photon\ wave\#)$$

Reason: nonrelativistic CSL narrows wavefunction to a relativistic CSL $a \to \frac{1}{\sqrt{a^{-2}+(E_f-E_i)^2}} \approx \frac{1}{E_f-E_i}$ ($\sim 10^{-10}$) $\ll a$ ($\sim 10^{-5}$)

Lifetime of 2^+ state: ~Blatt & Weisskopf

$$\tau^{-1} = \left(\frac{4\pi}{3\cdot5^2}\right)ck^5\left(\frac{e^2}{\hbar c}\right)R \quad \text{so } \Gamma_{CSL} \approx 10^{-15}\ ct/kg\text{-}day,\ \Gamma_{RCSL} \approx 10^{11}\ ct/kg\text{-}d$$

Desirable Properties	CSL	RCSL$_1$	RCSL	Q RCSL
1) relativistic invariance	×	✓	✓	≈
2) locality	✓	✓	×	≈
3) Markovian (white noise)	✓	✓	×	✓
4) no vacuum excitation	✓	×	✓	✓
5) consistent with experiment	✓	×	×	✓

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Quasirelativistic Collapse Model QRCSL

Evolution: $|\psi,\sigma\rangle = \mathcal{T} e^{-\frac{1}{4\lambda}\int_{\sigma_0}^{\sigma} d^4x\,[W(x)-2\lambda A(x)]^2}|\psi,\sigma_0\rangle$

Quantum field: $\phi^-(x) \equiv \frac{1}{(2\pi)^{3/2}}\int d\vec{p}\left(\frac{M}{E}\right)^{1/2} e^{-ip\cdot x} a^\dagger(\vec{p})$

$A(x) =:$

CSL	QRCSL
$(4\pi q^2)^{3/4} e^{\frac{1}{2}q^2\nabla^2}(\rho^\dagger\rho)(\vec{x},t)$	$(4\pi q^2)^{3/4} e^{\frac{1}{2}q^2\Box}(\phi^-\phi^+)(x)$
$(\pi q^2)^{-3/4}\int d\vec{b}\, e^{-\frac{\vec{b}^2}{2q^2}}(\rho^\dagger\rho)(\vec{x}+\vec{b},t)$	$2^{\frac{1}{2}}(\pi q^2)^{-5/4}\int d\vec{b}\,db_0\, e^{-\frac{1}{2q^2}[\vec{b}^2+b_0^2]} \cdot(\phi^-\phi^+)(\vec{x}+\vec{b},t+ib_0)$

Manifestly covariant but <u>not relativistically invariant</u>

because $[A(x), A(x')] \neq 0$ for $(x-x')^2 > 0$ (spacelike separation)

so $\mathcal{T}$ in one frame is not $\mathcal{T}$ in another frame.

Commutator: $[A(\vec{x},t), A(\vec{x}',t')] = \frac{1}{2\pi^{3/2}q^5}\int d\vec{b}\,db_0\,d\vec{b}'db_0' e^{-\frac{1}{2q^2}[\vec{b}^2+b_0^2+\vec{b}'^2+b_0'^2]}$
$\cdot[\phi^-(\vec{x}+\vec{b},t+ib_0)\phi^+(\vec{x}'+\vec{b}',t'+ib_0') - \phi^-(\vec{x}'+\vec{b}',t'+ib_0')\phi^+(\vec{x}+\vec{b},t+ib_0)]$
$\cdot[\phi^+(\vec{x}+\vec{b},t+ib_0),\phi^-(\vec{x}'+\vec{b}',t'+ib_0')]$

$M^2\frac{K_1[Mz]}{\sqrt{z}}$ $\quad z \equiv [(\vec{x}-\vec{x}'+\vec{b}-\vec{b}')^2+(b_0-b_0')^2]^{1/2}$ (b_0-b_0' of order a)

$\sim e^{-Ma} \simeq e^{-10^9}$

"Almost" commutes $\Rightarrow$ "Quasi"-relativistic!

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