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# GLOBAL SYMMETRIES & MACROSCOPIC QUANTUM SYSTEMS

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# SUMMARY

* Macroscopic quantum systems
* Global symmetries and Generalized Coherent States
* Entangling dynamics of micro & macro
* Measurement process

# MACROSCOPIC QUANTUM SYSTEMS

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spin-ring


$\hat{S} \equiv \sum_i \hat{s}_i \qquad |\hat{S}|^2 = S(S+1)$

QUANTUM : finite dimension of the EFFECTIVELY EXPLORED Hilbert space

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$S$ = constant :

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? $S$ = constant ? :

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$S = N/2$ ~ classical

# A QUANTUM THEORY

$$Q_N$$

A QUANTUM THEORY with A GLOBAL SYMMETRY

$$\mathcal{Q}_N \qquad + \qquad \mathbb{X}(N)$$

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$$\hat{A}^N$$

GLOBAL PROPERTY / COLLECTIVE PHYSICAL QUANTITY

$$[\hat{A}^N, \mathcal{U}] = 0 \quad : \quad \forall \mathcal{U} \in \mathbb{X}(N)$$

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$$[\hat{A}^N, \mathcal{U}] = 0 \quad : \quad \forall\, \mathcal{U} \in \mathbb{X}(N)$$

$$\downarrow$$

$$\mathcal{U}\,|\Xi^{\ell}\rangle_N = |\Xi^{j}\rangle_N \qquad \langle \Xi^{\ell}|\hat{A}^N|\Xi^{\ell}\rangle_N = \langle \Xi^{j}|\hat{A}^N|\Xi^{j}\rangle_N$$

$$\{|\Xi^{i}\rangle_N\}_{\sim}$$

! SYM-EQUIVALENT !

A QUANTUM THEORY with A GLOBAL SYMMETRY

$$Q_N \qquad + \qquad \mathbb{X}(N)$$

$$\{ |\Xi^i\rangle_N \}_\sim$$

SYM-EQUIVALENT

A QUANTUM THEORY with A GLOBAL SYMMETRY

$$Q_N \qquad + \qquad \mathbb{X}(N)$$

$$\left\{ |\Xi^i\rangle_N \right\}_{\sim}$$

SYM-EQUIVALENT

?

$$N \to \infty$$

A QUANTUM THEORY with A GLOBAL SYMMETRY

$$Q_N \quad + \quad \mathbb{X}(N)$$

$$\{|\Xi^i\rangle_N\}_{\sim}$$

SOME SYM-EQUIVALENT

?

$N \to \infty$ BECOME

CLASSICALLY EQUIVALENT

!

$$\{|\Omega^i\rangle_N\}_{\sim}$$

$$: \quad \lim_{N\to\infty} \langle \Omega^i | \hat{A}^N | \Omega^i \rangle_N = A(\Omega) < \infty$$

$N \to \infty$

L.G. YAFFE Rev. Mod Phys. 54, 407 (1982)

# $N \to \infty$

Q : Hilbert space, lie algebra, $\hat{H}$ & dynamical group $G$, $\langle \Omega | \hat{A} | \Omega \rangle$

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C : Phase-space, Poisson brackets, $h(\Omega)$, $A(\Omega)$

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?

" CAN ONE FIND A CLASSICAL SYSTEM WHOSE DYNAMICS IS EQUIVALENT TO SOME $N \to \infty$ LIMIT OF A GIVEN QUANTUM THEORY "

L.G. YAFFE Rev. Mod. Phys. <u>54</u>, 407 (1982)

# GENERALIZED COHERENT STATES

ZHANG, FENG, and GILMORE, Rev. Mod. Phys. 62 (1990) 867

# GENERALIZED COHERENT STATES

| $\mathcal{H}$ | $\hat{H}$ , $G$ | $\vert R\rangle$ |
|---|---|---|
| Hilbert space | Dynamical group | Reference state |

ZHANG, FENG, and GILMORE, Rev. Mod. Phys. **62** (1990) 867

# GENERALIZED COHERENT STATES

$\mathcal{H}$ $\qquad\qquad$ $\hat{H}$ , $G$ $\qquad\qquad$ $|R\rangle$

Hilbert space $\qquad$ Dynamical group $\qquad$ Reference state

$$F : \hat{f}\,|R\rangle = e^{i\varphi_f}|R\rangle \;\; \forall \hat{f} \in F \quad , \quad G/F \quad , \quad \hat{\Omega} \in G/F$$

$$|\Omega\rangle = \hat{\Omega}\,|R\rangle$$

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$$|\Omega\rangle = \hat{\Omega}\,|R\rangle$$

$$|\Omega\rangle \longleftrightarrow \hat{\Omega} \in G/F \longleftrightarrow \Omega \text{ in a manifold } \mathcal{M}$$

ONE-TO-ONE CORRESPONDENCE

!

$$\int_{\mathcal{M}} d\mu(\Omega)\, |\Omega\rangle\langle\Omega| = \mathbb{1}_{\mathcal{H}} \qquad d\mu(\Omega) \text{ invariant measure} \qquad \langle\Omega|\Omega'\rangle \neq \delta(\Omega - \Omega')$$

ZHANG, FENG, and GILMORE, Rev. Mod. Phys. 62 (1990) 867

$Q_N$

$G_N$

$|\Omega\rangle_N$ , $\mathcal{H}_N$

$Q_N$ with $X(N)$ symmetry

$G_N$

$|\Omega\rangle_N$ , $\mathcal{H}_N$

sym-equivalent $\{|\Omega^i\rangle_N\}_\sim$

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$|\Omega\rangle_N \,,\ \mathcal{H}_N$

sym-equivalent $\{|\Omega^i\rangle_N\}_N$

$N \to \infty$

$\mathcal{C}$

$Q_N$ with $X(N)$ symmetry

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$|\Omega\rangle_N \,,\ \mathcal{H}_N$

sym-equivalent $\quad \{|\Omega^i\rangle_N\}_\sim$

$N \to \infty$

$C$

$\mathcal{H}_N \longrightarrow$ phase-space

classically equivalent $\quad \{|\Omega^i\rangle_N\}_\sim \longrightarrow \Omega$

${}_N\langle\Omega^i|\,\hat{A}_N\,|\Omega^i\rangle_N \longrightarrow A(\Omega) < \infty$

$Q_N$

$Q_N$ with $X(N)$ symmetry

$G_N$

$\mathcal{H}_N$ , $|\Omega\rangle_N$

$Q_N$

$Q_N$ with $X(N)$ symmetry

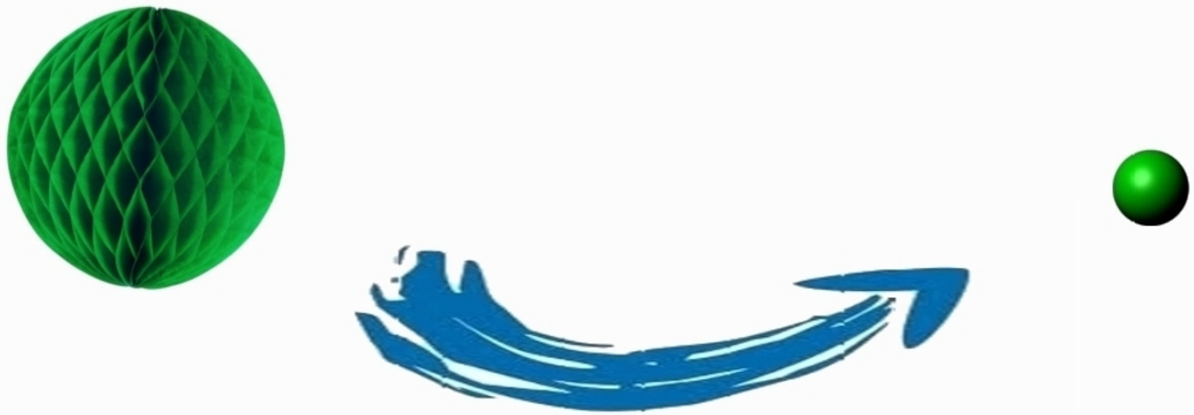
$$G_N \underset{gl}{\longleftrightarrow} G_K$$

$\mathcal{H}_N$ , $|\Omega\rangle_N$ $\qquad$ $\mathcal{H}_K$ , $|\Omega\rangle_K$

$Q_N$ AND $Q_k$

$Q_N$ with $X(N)$ symmetry

$Q_K$ with $k = \frac{1}{N}$



$$G_N \underset{\mathfrak{gl}}{\longleftrightarrow} G_K$$

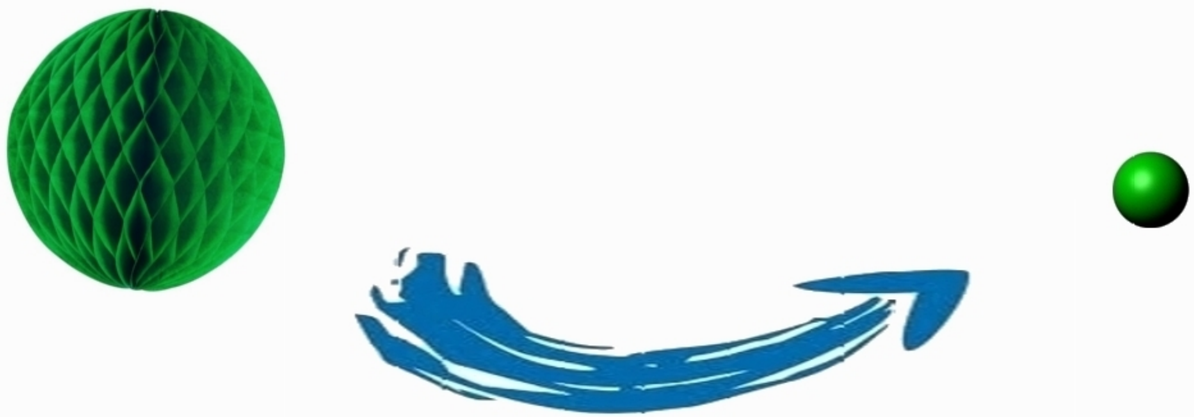
$\mathcal{H}_N$ , $|\Omega\rangle_N$

$\mathcal{H}_k$ , $|\Omega\rangle_k$

EXACT | | EFFECTIVE
--- | --- | ---
$Q_N$ | AND | $Q_k$

$Q_N$ with $X(N)$ symmetry

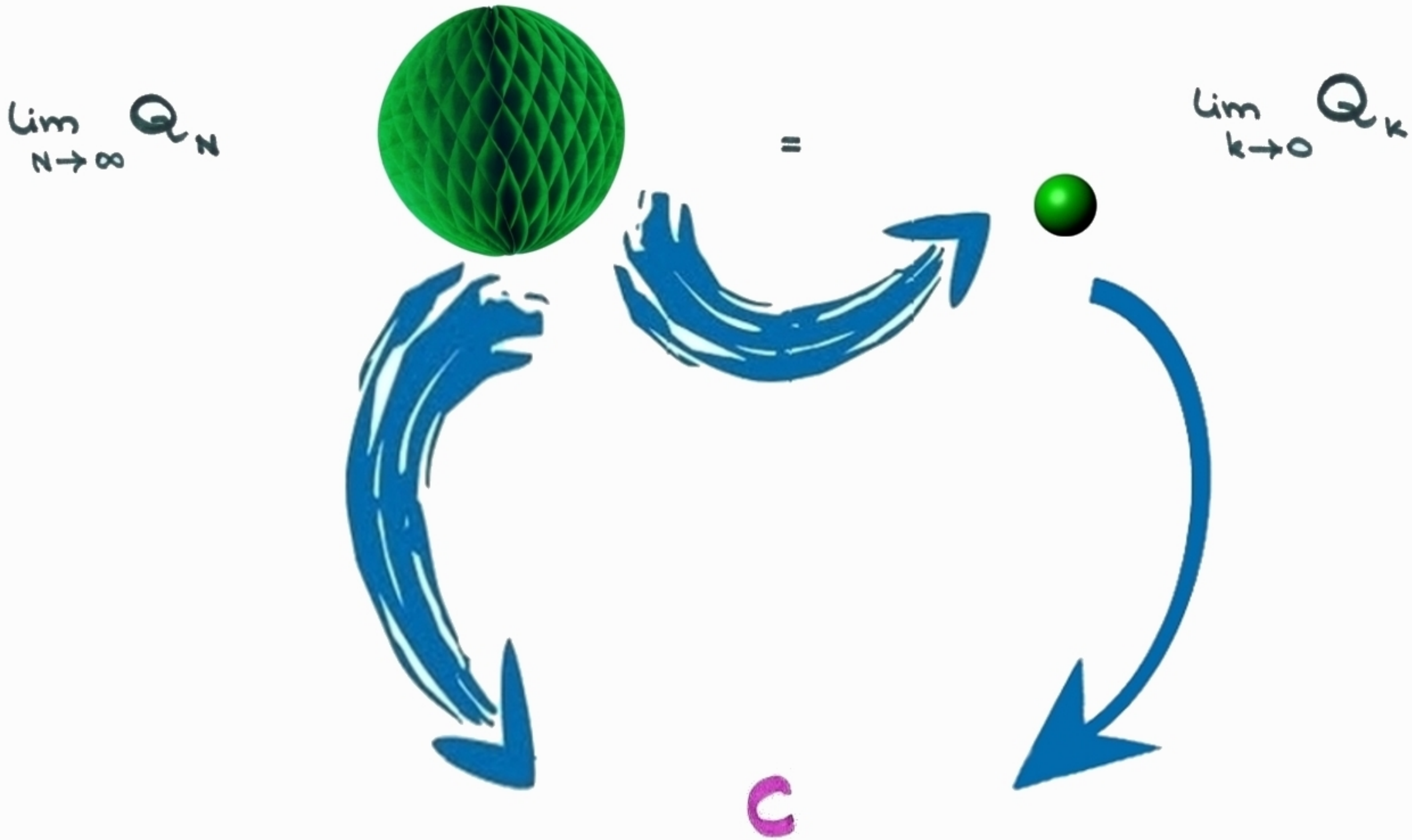
$Q_K$ with $k = \frac{1}{N}$

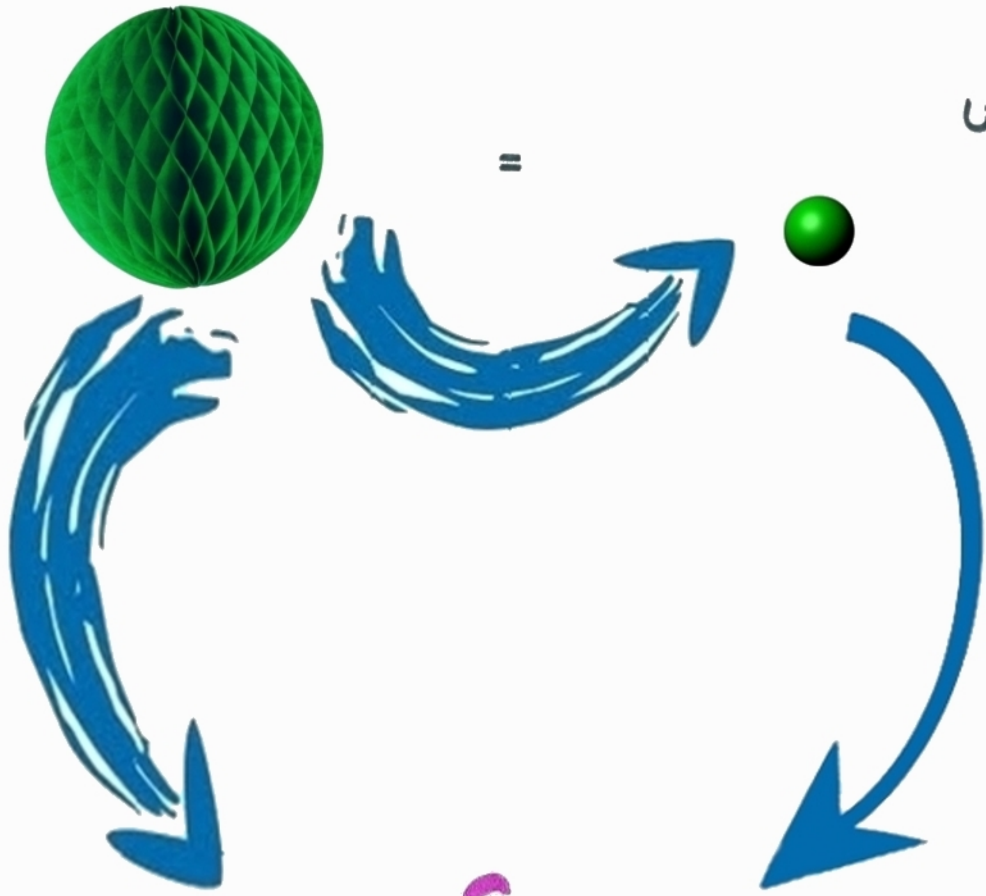


$$G_N \underset{gl}{\longleftrightarrow} G_K$$

$\mathcal{H}_N \,,\ |\Omega\rangle_N$

$\mathcal{H}_K \,,\ |\Omega\rangle_K$


$\lim_{N\to\infty} Q_N$
=
$\lim_{k\to 0} Q_k$
C

$\lim_{N\to\infty} Q_N$  $=$ $\lim_{k\to 0} Q_k$

$C$

$\mathcal{M}_N \longrightarrow$ phase-space $\longleftarrow \mathcal{M}_k$

$\{|\Omega^{\pm}\rangle_N\}_{\sim} \longrightarrow$ $\sim$ classically equivalent $\longleftarrow |\Omega\rangle_k$

${}_N\langle\Omega^{\pm}|\,\hat{A}_N\,|\Omega^{\pm}\rangle_N \longrightarrow A(\Omega)$ finite $\longleftarrow {}_k\langle\Omega|\hat{A}_k|\Omega\rangle_k$

# ENTANGLING DYNAMICS OF MACRO with μICRO

MACRO $\Xi$ with μICRO $\Gamma$

environment / apparatus

principal system

$Q_N$ with large $N$

# ENTANGLING DYNAMICS OF MACRO with MICRO

MACRO $\Xi$ with MICRO $\Gamma$

environment / apparatus principal system

$Q_k$ with small $k$

$|\Xi + \Gamma\rangle$

# ENTANGLING DYNAMICS OF MACRO with MICRO

MACRO $\Xi$ with MICRO $\Gamma$

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$Q_k$ with small $k$

$$|\Xi + \Gamma\rangle$$

introduce GCS for $\Xi$ only

$$\int_{\mathcal{M}} d\mu(\Omega)\,|\Omega\rangle\, \chi(\Omega)\, |\phi(\Omega)\rangle$$

PNAS <u>110</u> (2013) 6748

# ENTANGLING DYNAMICS OF MACRO with MICRO

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$Q_k$ with small $k$

$$|\Xi + \Gamma\rangle$$

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$$\int_{\mathcal{M}} d\mu(\Omega)\,|\Omega\rangle\, \chi(\Omega)\, |\phi(\Omega)\rangle$$

PNAS **110** (2013) 6748

$$|\phi^{\Psi}(\Omega)\rangle = \frac{1}{\chi^{\Psi}(\Omega)} \sum_{\gamma} f^{\gamma}(\Omega)\,|\gamma\rangle \quad ; \quad f_{\gamma}(\Omega) = \sum_{\xi} c_{\gamma\xi} \langle \Omega | \xi \rangle$$

$$\chi^{\Psi}(\Omega) = \sqrt{\sum_{\gamma} |f_{\gamma}(\Omega)|^2}$$

$\Omega$-dependence iff $|\Psi\rangle$ entangled

$$\int_{\mathcal{M}} d\mu(\Omega) \left(\chi^{\Psi}(\Omega)\right)^2 = 1$$

normalized distribution on $\mathcal{M}$

MEASURE-LIKE DYNAMICS (standard model)

$$\hat{H}_\Psi = g\,\hat{O}_\Omega \otimes \hat{D}_\Xi + \hat{H}_{0\Xi}$$

# MEASURE-LIKE DYNAMICS (standard model)

$$\hat{H}_\psi = g\,\hat{O}_\Omega \otimes \hat{D}_\Xi + \hat{H}_{0\Xi}$$

$$\sum_\gamma c_\gamma |\gamma\rangle |\Xi\rangle \longrightarrow \sum_\gamma c_\gamma |\gamma\rangle e^{-\frac{it}{\hbar}\hat{H}^\gamma} |R\rangle$$

$$\hat{H}^\gamma = g\omega_\gamma \hat{D}_\Xi + \hat{H}_\Xi$$

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$$\hat{H}^\gamma = g\omega_\gamma \hat{D}_\Xi + \hat{H}_\Xi$$

$$\int_\Omega d\mu(\Omega) |\Omega\rangle\, \chi(\Omega) |\phi(\Omega)\rangle$$

$$\chi_t^2(\Omega) = \sum_\gamma |c_\gamma|^2 |\langle\Omega | R_t^\gamma\rangle|^2 = \sum_\gamma |c_\gamma|^2 h_t^\gamma(\Omega)$$

# MEASURE - LIKE DYNAMICS (standard model)

$$\hat{H}_\psi = q\,\hat{O}_\Omega \otimes \hat{D}_\Xi + \hat{H}_{0\Xi}$$

$$\sum_\gamma c_\gamma |\gamma\rangle |\Xi\rangle \longrightarrow \sum_\gamma c_\gamma |\gamma\rangle e^{-\frac{it}{\hbar}\hat{H}^\gamma} |R\rangle$$

$$\hat{H}^\gamma = q\,\omega_\gamma \hat{D}_\Xi + \hat{H}_\Xi$$

$$\int_{\mathcal{M}} d\mu(\Omega) |\Omega\rangle\, \chi(\Omega)\, |\phi(\Omega)\rangle$$

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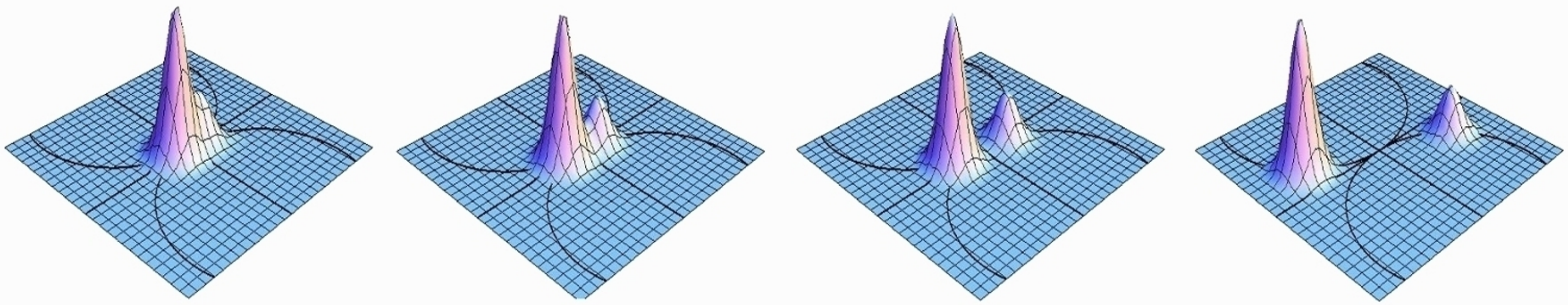

$\hat{H}_{qb} = \nu \hat{b}^+ \hat{b} + q\sqrt{\hbar}\, \hat{\sigma}^z (\hat{b} + \hat{b}^+)$ ; $[b, b^+] = \hbar$ ; $\mathcal{M}$ complex plane

$\hat{\sigma}^z$ qubit (MICRO) $\quad$ $b, b^+$ field (MACRO)

# MEASURE-LIKE DYNAMICS (standard model)

$$\hat{H}_{\psi} = g\,\hat{O}_{\Omega} \otimes \hat{D}_{\Xi} + \hat{H}_{0\Xi}$$

$$\sum_{\gamma} c_{\gamma} |\gamma\rangle |\Xi\rangle \longrightarrow \sum_{\gamma} c_{\gamma} |\gamma\rangle\, e^{-\frac{it}{\hbar}\hat{H}^{\gamma}} |R\rangle$$

$$\hat{H}^{\gamma} = g\omega_{\gamma}\hat{D}_{\Xi} + \hat{H}_{\Xi}$$

$$\int_{\mathcal{M}} d\mu(\Omega) |\Omega\rangle\, \chi(\Omega)\, |\phi(\Omega)\rangle$$

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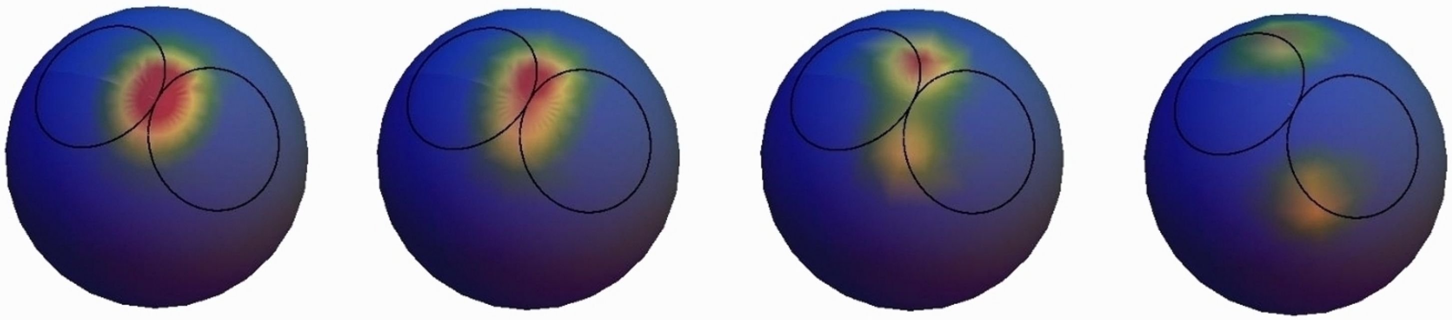
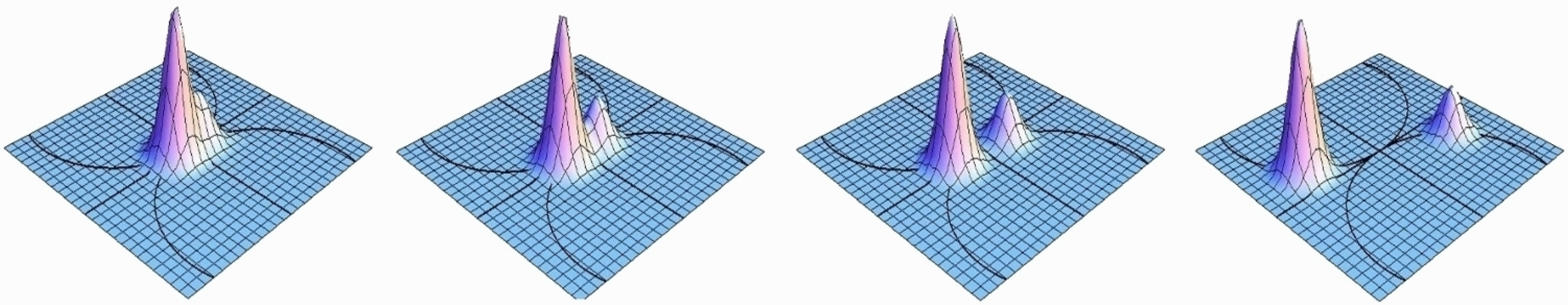


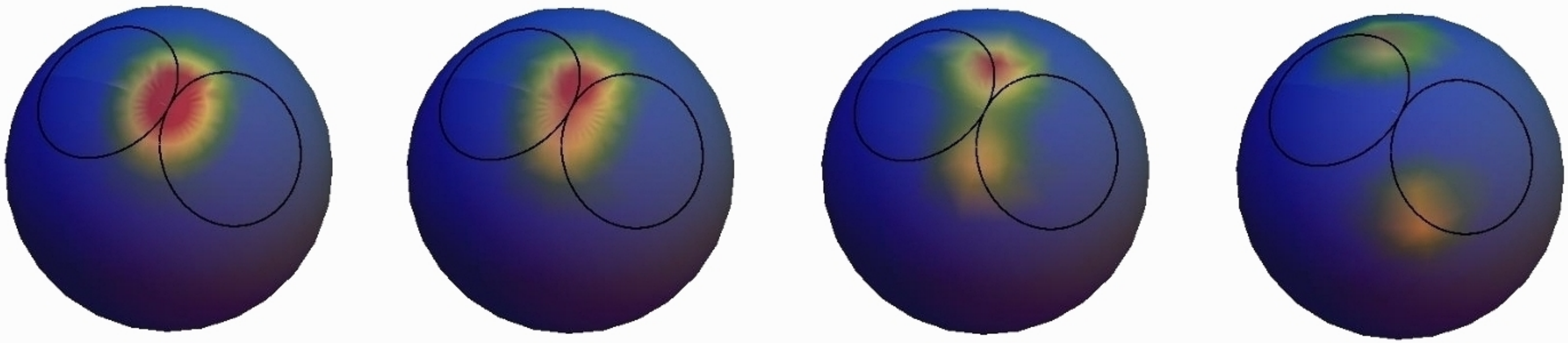
$$\hat{H}_{qJ} = h\hat{J}_z + g\hat{\sigma}^z(\hat{J}_x)$$ ; $[\hat{J}_{\alpha}, \hat{J}_{\beta}] = i\varepsilon^{\alpha\beta\delta}\hat{J}^{\delta}$ ; $\mathcal{M}$ unit 2-sphere

$\hat{\sigma}^z$ qubit (MICRO) $\quad$ $\hat{J}^{\alpha}$ magnet (MACRO)

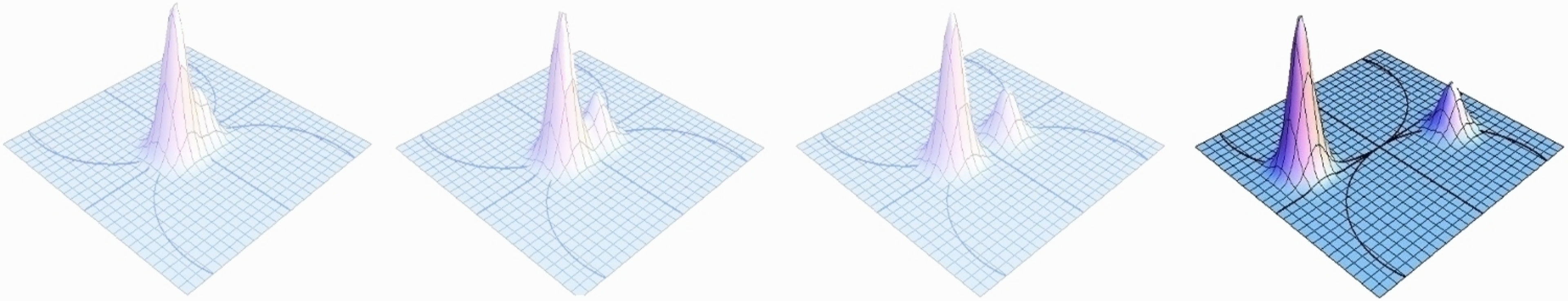


$x_t^2(\Omega) = \sum_\gamma |c_\gamma|^2 \, h_t^\gamma(\Omega)$ normalized distributions on $\mathcal{H}$ with $\varepsilon$-support

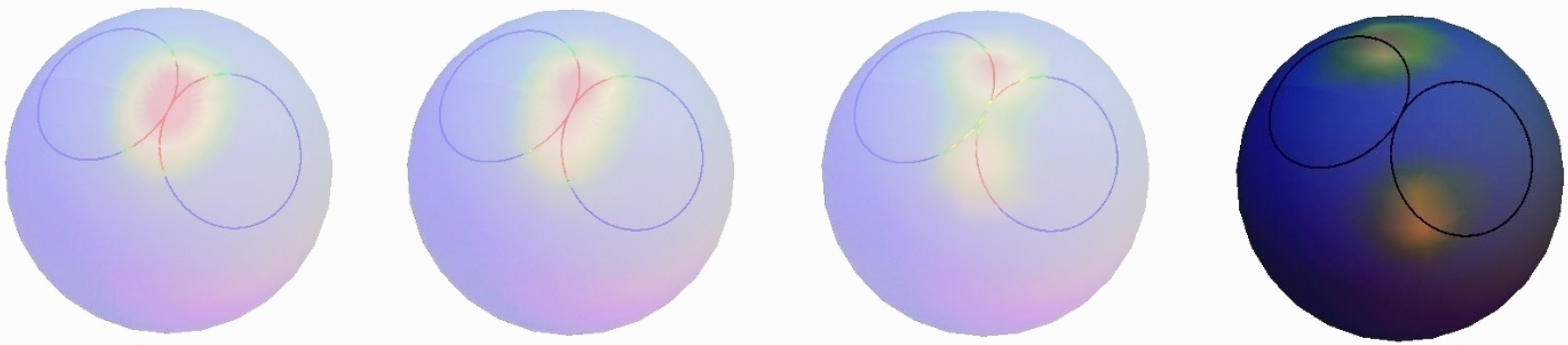
$\mathcal{S}_t^\gamma$ : $h_t^\gamma(\Omega) > \varepsilon$ for $\Omega \in \mathcal{S}_t^\gamma$



# DECOHERENCE



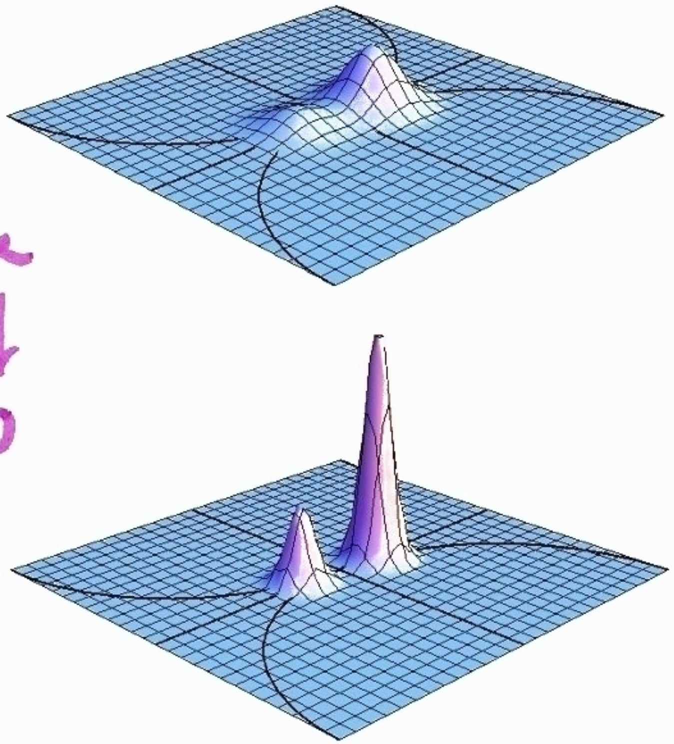
for each $\gamma$ a different trajectory on $\mathcal{M}_k$



after decoherence has occurred $\Omega \in S_t^\gamma$ well defined for different $\gamma$

# BACK TO $Q_N$ VIA CLASSICAL EQUIVALENCE

$k \downarrow 0$

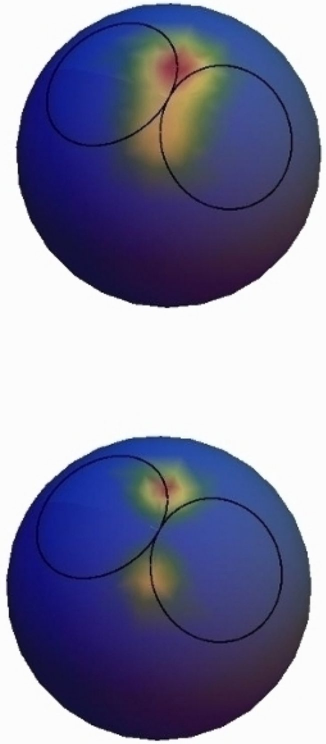


$\Xi$

$k \to 0$

$\sim$

$N \to \infty$



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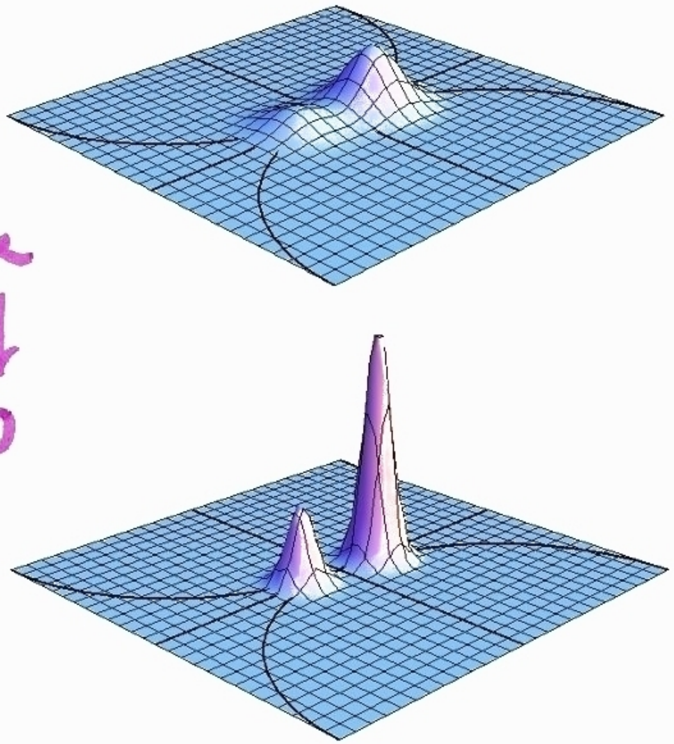

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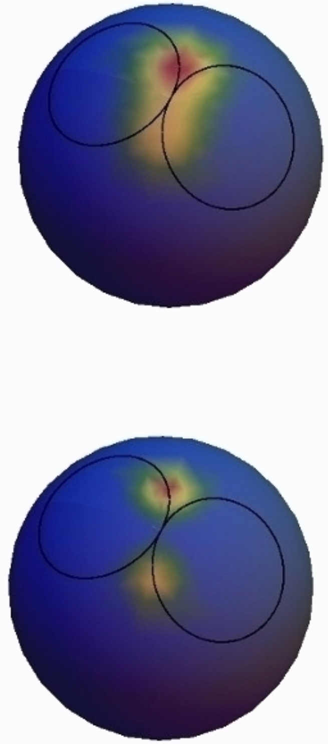


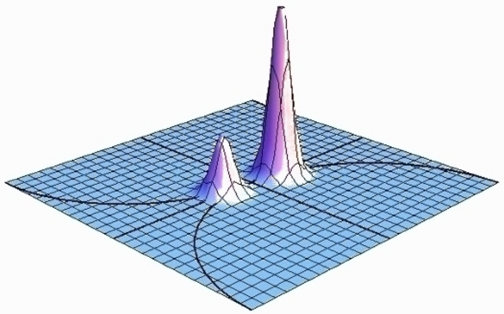
$k \downarrow 0$

LET $k \to 0$ IN $Q_K$ AND SEE $Q_N$ FOR $N \to \infty$

OTHERWISE NOT-ACCESSIBLE

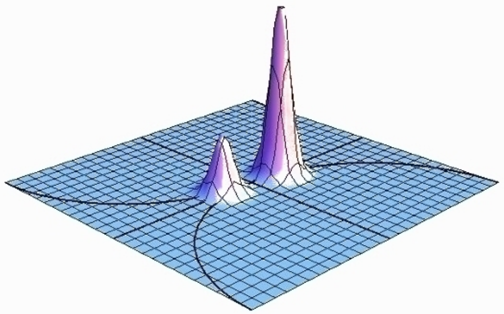
# BACK TO $Q_N$

DIFFERENT $\gamma$ ARE NOT CLASSICALLY EQUIVALENT



# BACK TO $Q_N$

DIFFERENT $\gamma$ ARE NOT CLASSICALLY EQUIVALENT



BUT

THEY ALL HAVE THE SAME ENERGY

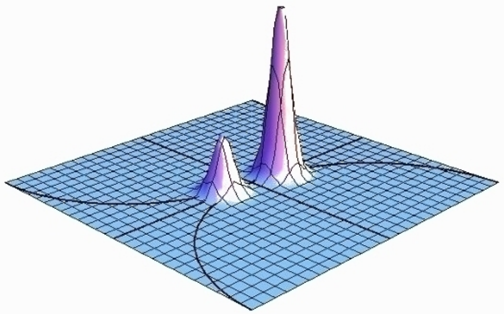
$$\langle \Omega | \hat{H}^N | \Omega \rangle_N = \langle \tilde{\Omega} | \hat{H}^N | \tilde{\Omega} \rangle_N$$

AS FAR AS $\mathcal{X}(N)$ HOLDS

# BACK TO $Q_N$

DIFFERENT $\gamma$ ARE NOT CLASSICALLY EQUIVALENT

BUT



THEY ALL HAVE THE SAME ENERGY

$$\langle \Omega | \hat{H}^N | \Omega \rangle_N = \langle \tilde{\Omega} | \hat{H}^N | \tilde{\Omega} \rangle_N$$

AS FAR AS $\mathbb{X}(N)$ HOLDS

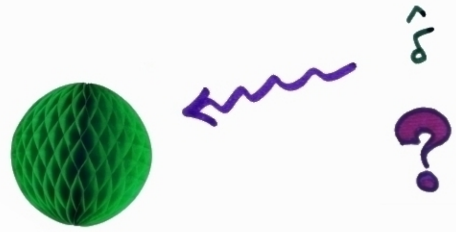
$$|\Omega_t\rangle_N = e^{-it(\hat{H}^{\gamma}_N - \hat{H}^{\gamma'}_N)} |\Omega'_t\rangle_N$$

$\in \{|\Omega^i\rangle_N\}^{\gamma}_{\sim}$ $\qquad\qquad$ $\in \{|\Omega^i\rangle_N\}^{\gamma'}_{\sim}$

$\forall \gamma, \gamma'$

(because they have the same initial state)

# BREAKING $\mathbb{X}(N)$ BY A LOCAL PERTURBATION $\delta$




$$[\hat{\delta}, \mathcal{U}] \neq 0 \qquad \mathcal{U} \in \mathbb{X}(N)$$

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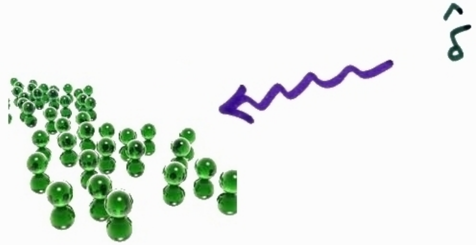
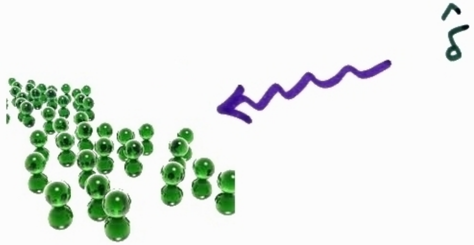



degeneracy of different trajectories
IS REMOVED

$$\langle \Omega | \hat{\delta}^N | \Omega \rangle_N \neq \langle \tilde{\Omega} | \hat{\delta}^N | \tilde{\Omega} \rangle_N$$

for $|\Omega\rangle_N \in \{|\Omega^i\rangle_N\}^{\gamma}_{\sim}$ and $|\Omega^i\rangle_N \in \{|\Omega^i\rangle_N\}^{\gamma'}_{\sim}$ $\gamma \neq \gamma'$

# BREAKING $\mathbb{X}(N)$ BY A LOCAL PERTURBATION $\delta$




degeneracy of different trajectories
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$$\langle \Omega | \hat{\delta}^N | \Omega \rangle_N \neq \langle \tilde{\Omega} | \hat{\delta}^N | \tilde{\Omega} \rangle_N$$

for $\quad |\Omega\rangle_N \in \{ |\Omega^i\rangle_N \}^{\gamma}_{\sim} \quad$ and $\quad |\Omega^i\rangle_N \in \{ |\Omega^i\rangle_N \}^{\gamma'}_{\sim} \quad \gamma \neq \gamma'$

$N \to \infty$

$\hat{\delta}$ removes the degeneracy of different trajectories
but does not change classical equivalence

$\bigcup_{\gamma} \{ |\dot{a}| >_{N} \}^{\gamma}_{\sim}$

# OUTPUT PRODUCTION

$$\bigcup_{\gamma} \left\{ |\Omega^i\rangle_N \right\}_{\sim}^{\gamma} \xrightarrow[\text{breaking}]{\mathcal{X}(N)\text{ symmetry}} \left\{ |\Omega^i\rangle_N \right\}_{\sim}^{\gamma_{out}}$$

$\gamma_{out}$ is selected

# OUTPUT PRODUCTION & EMERGENCE OF CLASSICALITY

$$\bigcup_{\gamma} \left\{ |\Omega^i\rangle_N \right\}^{\gamma}_{\sim} \xrightarrow[\mathcal{X}(N)\text{ symmetry breaking}]{} \left\{ |\Omega^i\rangle_N \right\}^{\gamma_{out}}_{\sim} \xrightarrow[N \to \infty]{} R_t^{\gamma_{out}} \in \mathcal{M}$$

$\gamma_{out}$ is selected

# OUTPUT PRODUCTION & EMERGENCE OF CLASSICALITY

$$\bigcup_{\gamma} \left\{ |\Omega^i\rangle_N \right\}^{\gamma}_{\sim} \xrightarrow[\mathcal{H}(N)\ \text{symmetry breaking}]{} \left\{ |\Omega^i\rangle_N \right\}^{\gamma_{out}}_{\sim} \xrightarrow[N \to \infty]{} R_t^{\gamma_{out}} \in \mathcal{M}$$

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EPL 111 (2015) 40008

BORN's RULE with probability $|c_\gamma|^2$

# OUTPUT PRODUCTION & EMERGENCE OF CLASSICALITY

$$\bigcup_{\gamma} \{|\Omega^i\rangle_N\}^{\gamma}_{\sim} \xrightarrow[\text{breaking}]{\mathcal{X}(N)\ \text{symmetry}} \{|\Omega^i\rangle_N\}^{\gamma_{out}}_{\sim} \xrightarrow{N \to \infty} R_t^{\gamma_{out}} \in \mathcal{M}$$

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BORN's RULE with probability $|c_\gamma|^2$

final state of $\Omega$

$$\int_{\mathcal{M}} d\mu(\Omega)\, \chi_t(\Omega)\, |\Omega\rangle |\phi_t(\Omega)\rangle$$

$$|\phi_t(\Omega)\rangle = \frac{1}{\chi_t(\Omega)} \sum_\gamma c_\gamma \langle \Omega | \xi \rangle |\gamma\rangle = \sum_\gamma \frac{e^{i\phi_t^\gamma}}{\left(1 + \sum_{\gamma' \neq \gamma} \frac{|c_{\gamma'}|^2 h_t^{\gamma'}(\Omega)}{|c_\gamma|^2 h_t^\gamma(\Omega)}\right)^{1/2}} |\gamma\rangle$$

# OUTPUT PRODUCTION & EMERGENCE OF CLASSICALITY

$$\bigcup_{\gamma} \{ |\Omega^i\rangle_N \}^{\gamma}_{\sim} \xrightarrow[\text{breaking}]{\mathcal{X}(N)\ \text{symmetry}} \{ |\Omega^i\rangle_N \}^{\gamma_{out}}_{\sim} \xrightarrow{N \to \infty} R_t^{\gamma_{out}} \in \mathcal{M}$$

$\gamma_{out}$ is selected

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BORN's RULE with probability $|c_\gamma|^2$

final state of $\Omega$

$$\int_{\mathcal{M}} d\mu(\Omega)\, \chi_t(\Omega)\, |\Omega\rangle |\phi_t(\Omega)\rangle$$

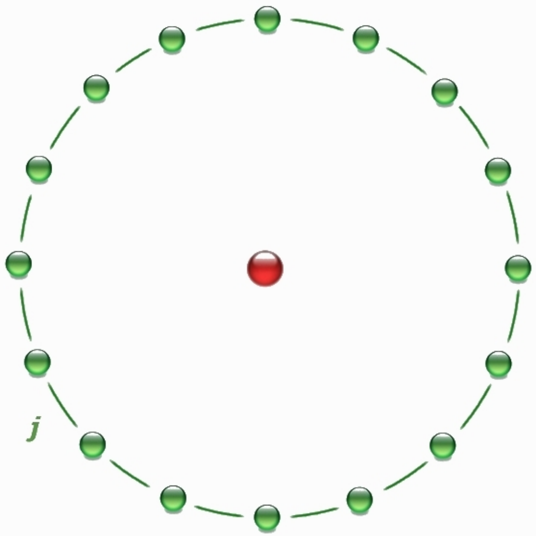
$$|\phi_t(\Omega)\rangle = \frac{1}{\chi_t(\Omega)} \sum_\gamma c_\gamma \langle \Omega | \xi \rangle |\gamma\rangle = \sum_\gamma \frac{e^{i\phi_t^\gamma}}{\left(1 + \sum_{\gamma' \neq \gamma} \frac{|c_{\gamma'}|^2 h_t^{\gamma'}(\Omega)}{|c_\gamma|^2 h_t^{\gamma}(\Omega)}\right)^{1/2}} |\gamma\rangle$$

STATE REDUCTION $|\phi(\Omega)\rangle \longrightarrow |\gamma^{out}\rangle$

# COMMENTS

- no hidden variables
- all components are in genuinely quantum superpositions as far as $\mathcal{K}(N)$ holds
- very unlikely that a local perturbation $\hat{\delta}$ does not enter the game
  that's why macro-quantum states are not "usual"
- the $N \to \infty$ description holds for whatever dynamics (not only measure-like) as far as some $\mathcal{K}(N)$ exists
- experimental test possible by designing "ad hoc" local $\hat{\delta}$

WORK IN PROGRESS




# EXP ?

# THANKS !!

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