Quantum Mechanics: 100 Years of Mystery Solved!

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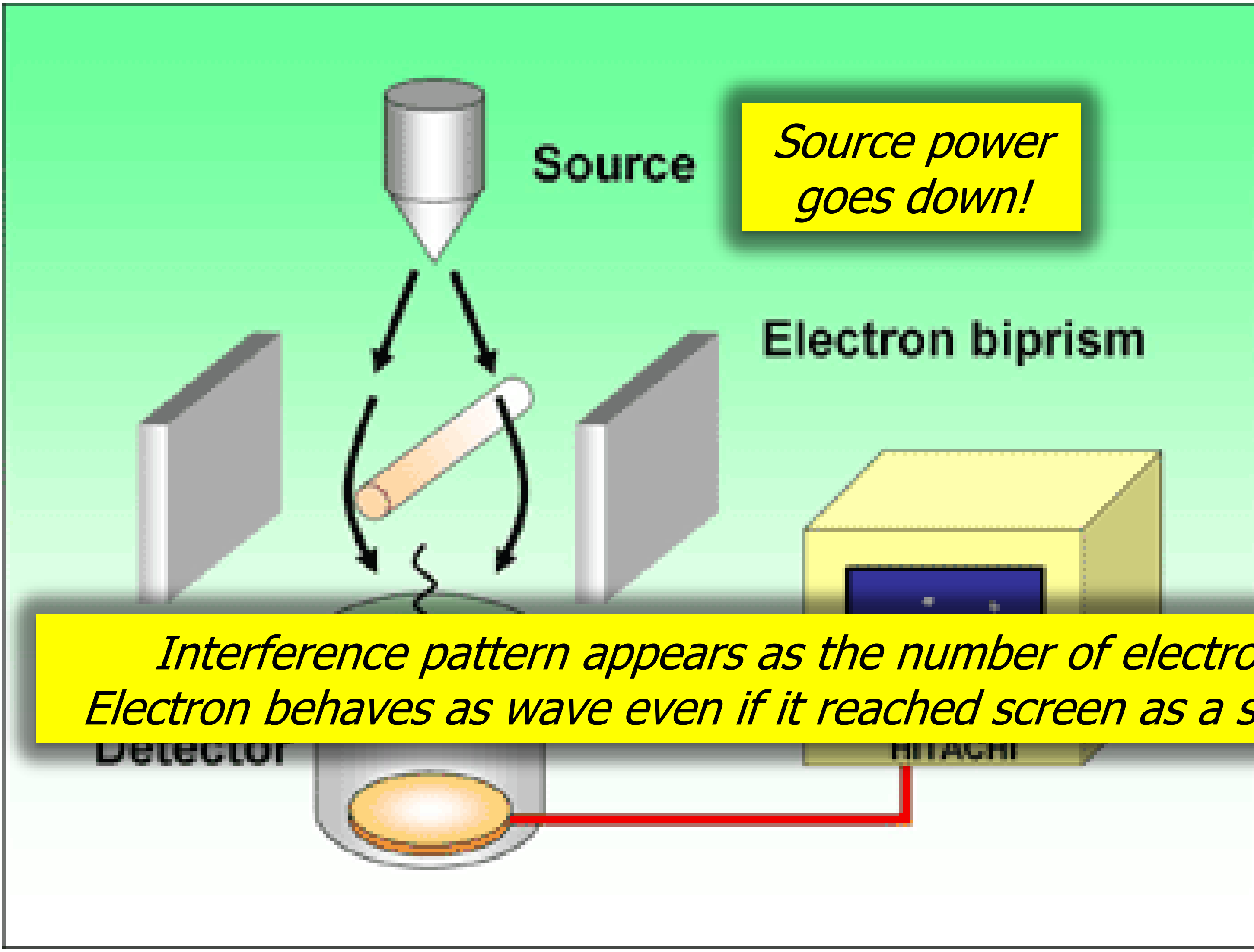
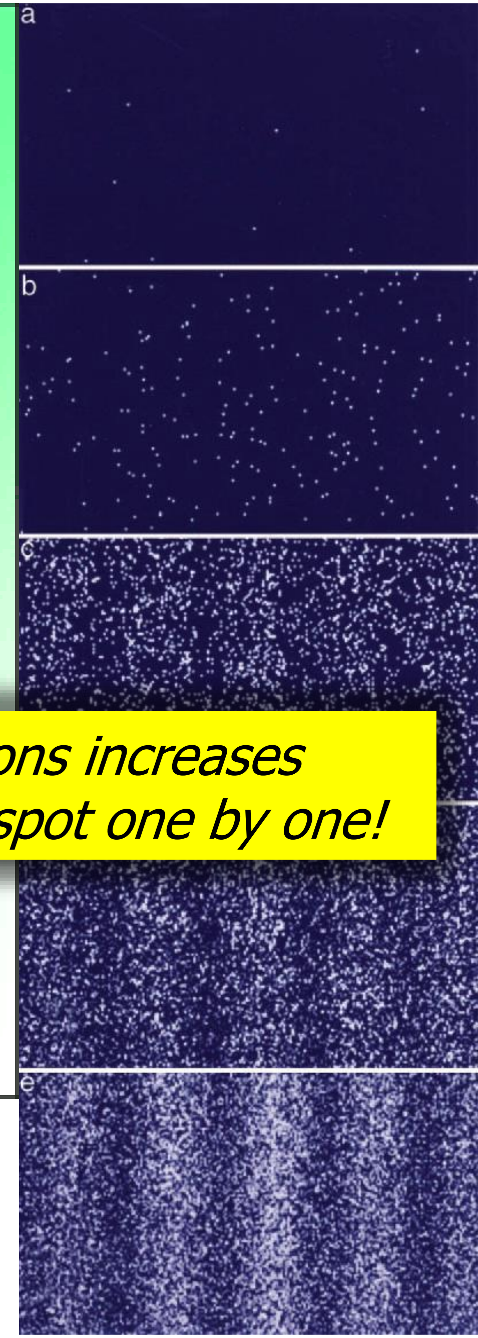
Double-slit phenomenon of electron



Source power goes down!



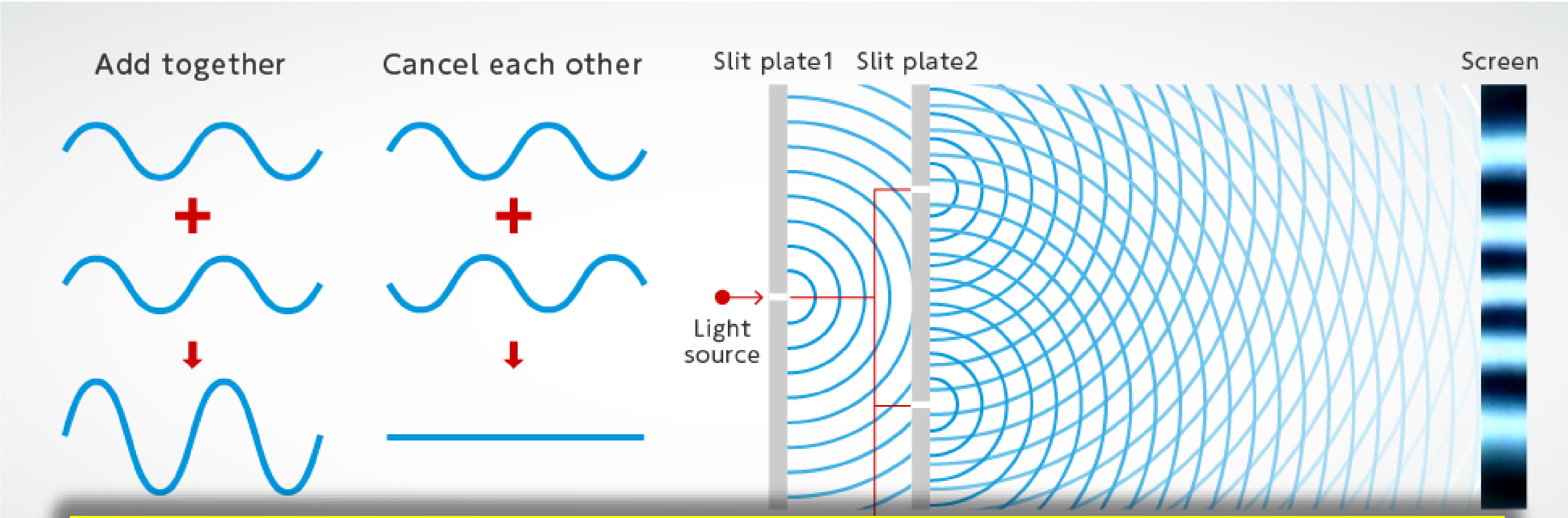
Interference pattern appears as the number of electrons increases
Electron behaves as wave even if it reached screen as a spot one by one!

Fig. 1. Two-beam interference experiment for electrons.

Fig. 2. Build-up of an electron interference pattern. Numbers of electrons are 10 (*a*), 200 (*b*), 6,000 (*c*), 40,000 (*d*), and 140,000 (*e*).

A. Tonomura, “Direct observation of thitherto unobservable quantum phenomena by using electrons,” *Proc. Natl. Acad. Sci. USA* **102**, 14952 (2005)

Double-slit phenomenon of photon



Water-light-wave analogy fails as the source power of light goes down!
Light behaves as particle, photon, as found by spot on the screen
Interference pattern appears as the number of photons increases

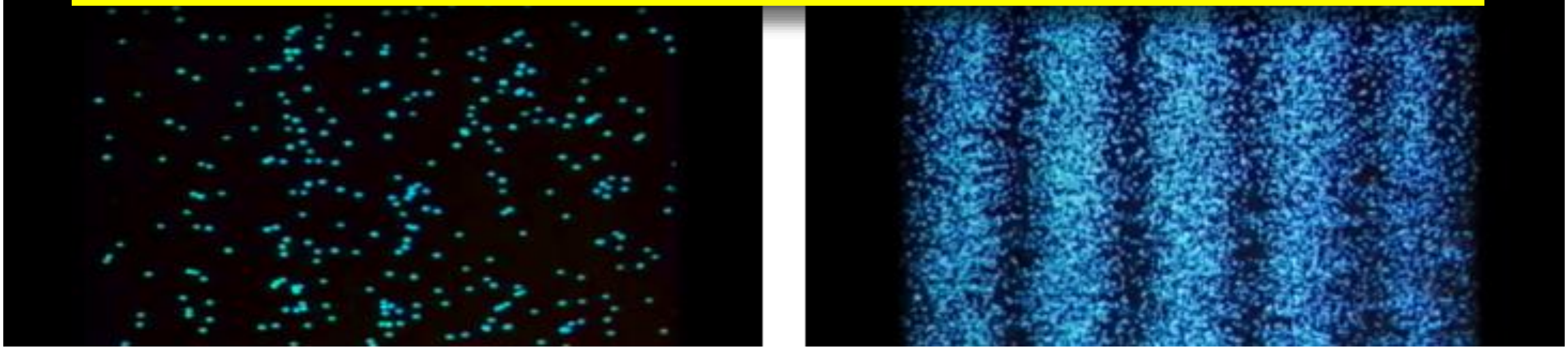
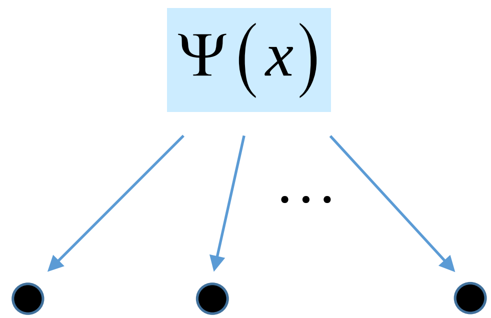


Fig. 3. Double-slit experiment of photon.
(Reproduced from Hamamatsu Photonics, K.K. http://photonterrace.net/en/photon/duality/)

Mystery of quantum mechanics (Feynman said)

Agnosticism

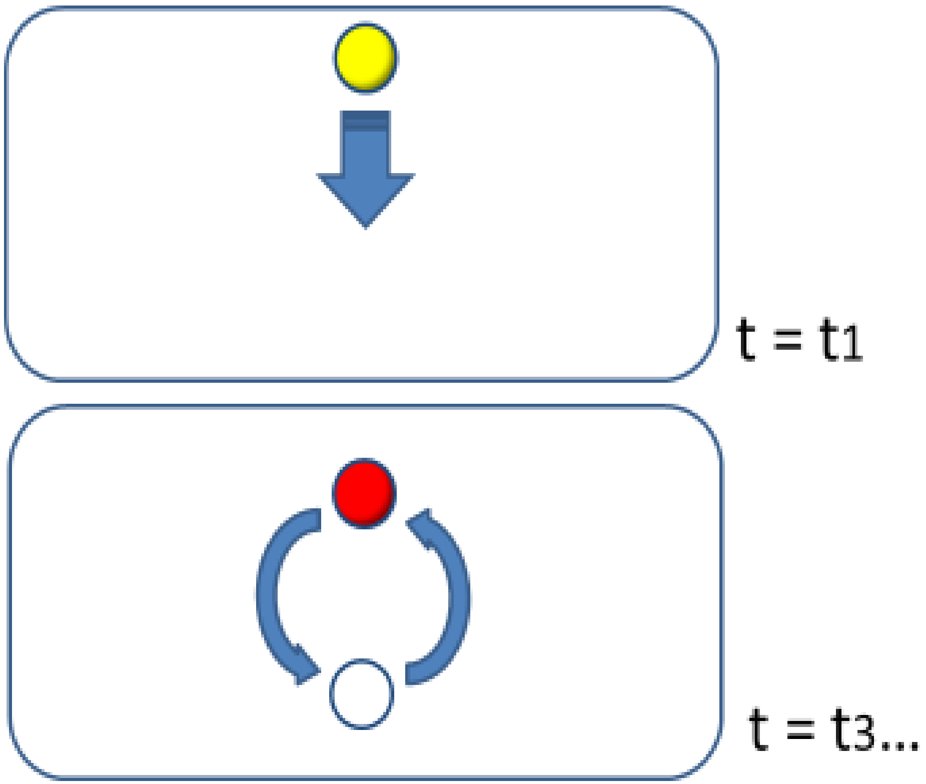


<u>Collapse of wave function</u> occurs **<u>non-deterministically</u>**

Even if with the same initial condition given, the spot on the screen may not be the same nor predicted deterministically

- Interpretation: **<u>collapse</u>** and elementary **"particle"** (mass without volume?) is observed
- Interpretation: **<u>"wave" function</u>** gives its probability distribution until it is observed as particle

Particle number non-conservation

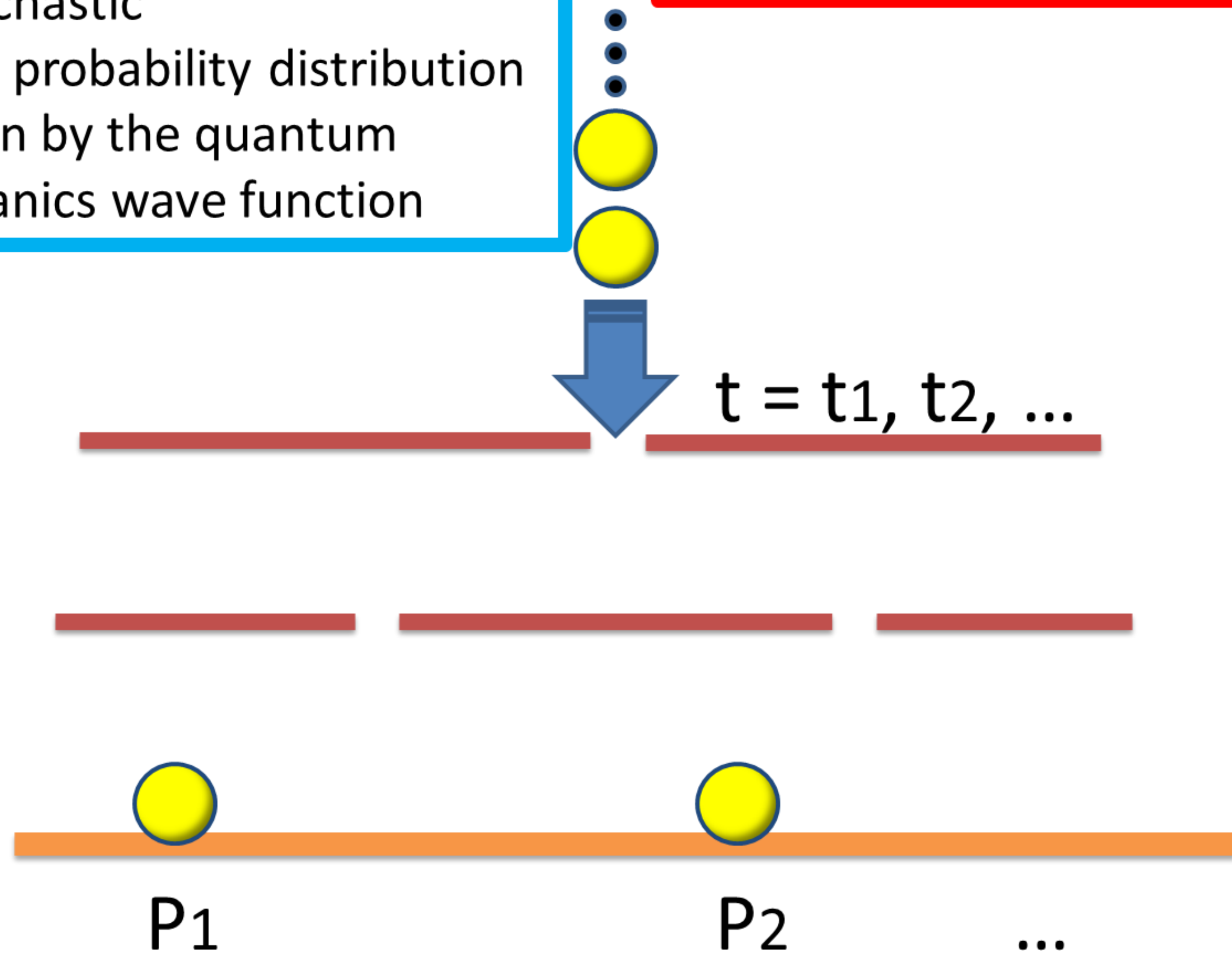


- Photons are incident, charged particles are excited with photon annihilation
- If you follow the time in reverse, electrons and positrons pair annihilate and photons can also be seen as a picture that is being generated
- The alpha-oscillator theory can also describe the existence itself (particles before generation and after disappearance)

Bohr interpretation vs Einstein rebuttal

Bohr (Copenhagen interpretation)
Where to reach the particles?
①Stochastic
②The probability distribution is given by the quantum mechanics wave function

Einstein (rebuttal)
God does not play dice



Quantum theory

Quantum Theory, QT

More accurate!

Can predict the Lamb shift, anomalous magnetic moment of electron, etc. over and above QM!

Quantum Mechanics, QM

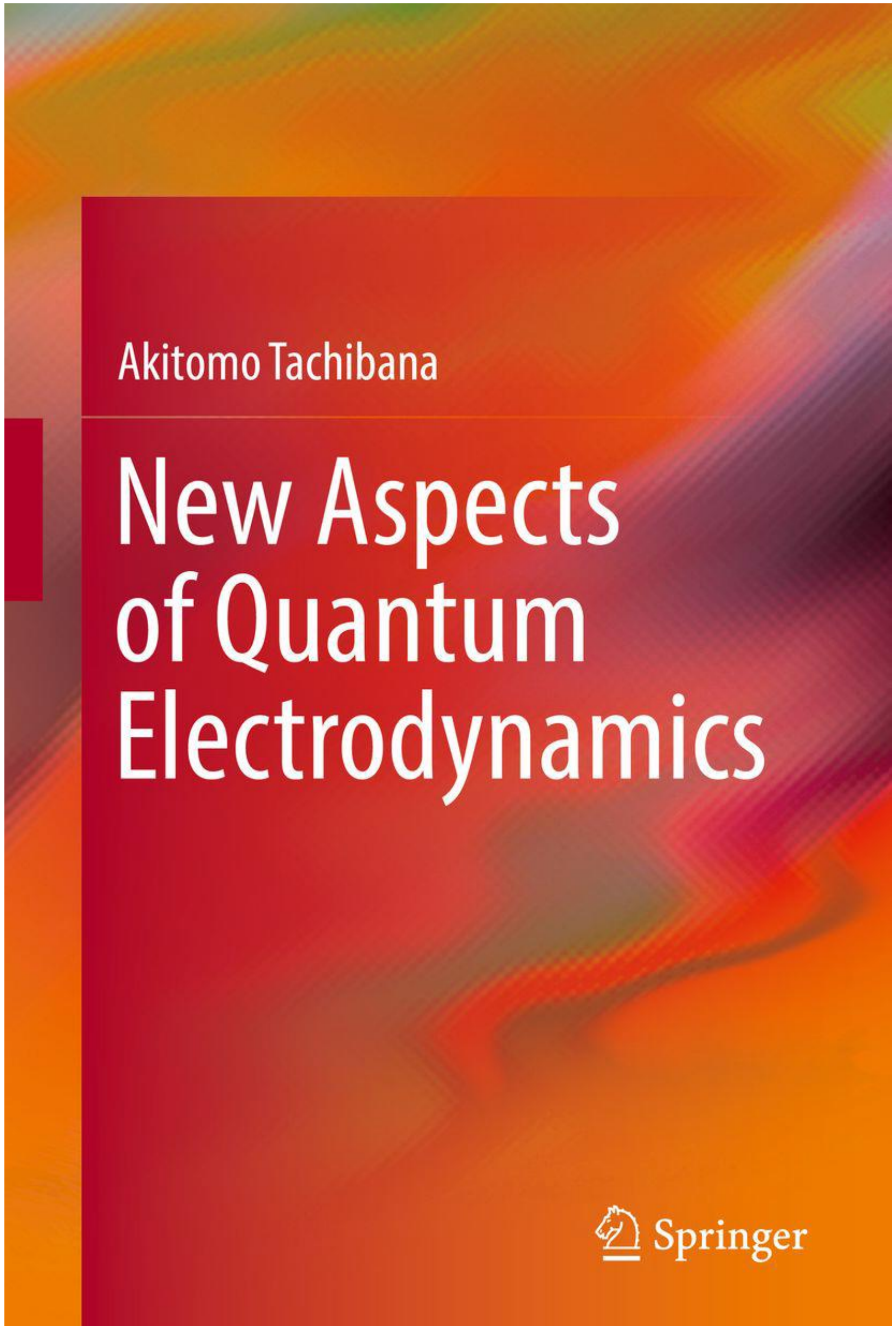
Nonrelativistic QM
Relativistic QM

Relativistic Quantum Field Theory, QFT

Standard Theory
- Quantum Electrodynamics, QED
- Glashow-Weinberg-Salam Electroweak Theory
- Quantum Chromodynamics, QCD

Simple question?

QM suffers from fundamental mystery of the measurement problem on the position of particle
Then, how about the measurement problem of the event in QED?



Akitomo Tachibana
New Aspects of Quantum Electrodynamics

▶ Makes use of abundant figures to help the reader grasp ideas quickly
▶ Includes many equations to help the reader to follow the logic step by step
▶ Provides an ample range of appendices and references to facilitate in-depth learning

- **Hardcover:** 189 pages
- **Publisher:** Springer; 1st ed. 2017 (2017/2/17)
- **Language:** English
- **ISBN-10:** 9811031312
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Time-dependent QED Hamiltonian

QED Hamiltonian operator

$$\hat{H}_{\mathrm{QED}}(t) = \int d^3\vec{x} : \hat{H}_{\mathrm{QED}}(x) :$$

$$\frac{\partial}{\partial t}\hat{H}_{\mathrm{QED}}(t) \neq 0$$

Remark!

Solution for the time-dependent QED Hamiltonian had not been established!

QED Hamiltonian density operator

$$\hat{H}_{\mathrm{QED}}(x) = \frac{1}{8\pi}\left(\left(\hat{\vec{E}}_T(x)\right)^2 + \left(\mathrm{rot}\hat{\vec{A}}(x)\right)^2\right)$$
$$-\frac{1}{c}\hat{\vec{j}}(x)\bullet\hat{\vec{A}}(x) + \frac{1}{2c}\hat{j}_0(x)\hat{A}_0(x) + \hat{\bar{\psi}}(x)\left(-i\hbar\gamma^k\partial_k + mc\right)\hat{\psi}(x)\times c$$

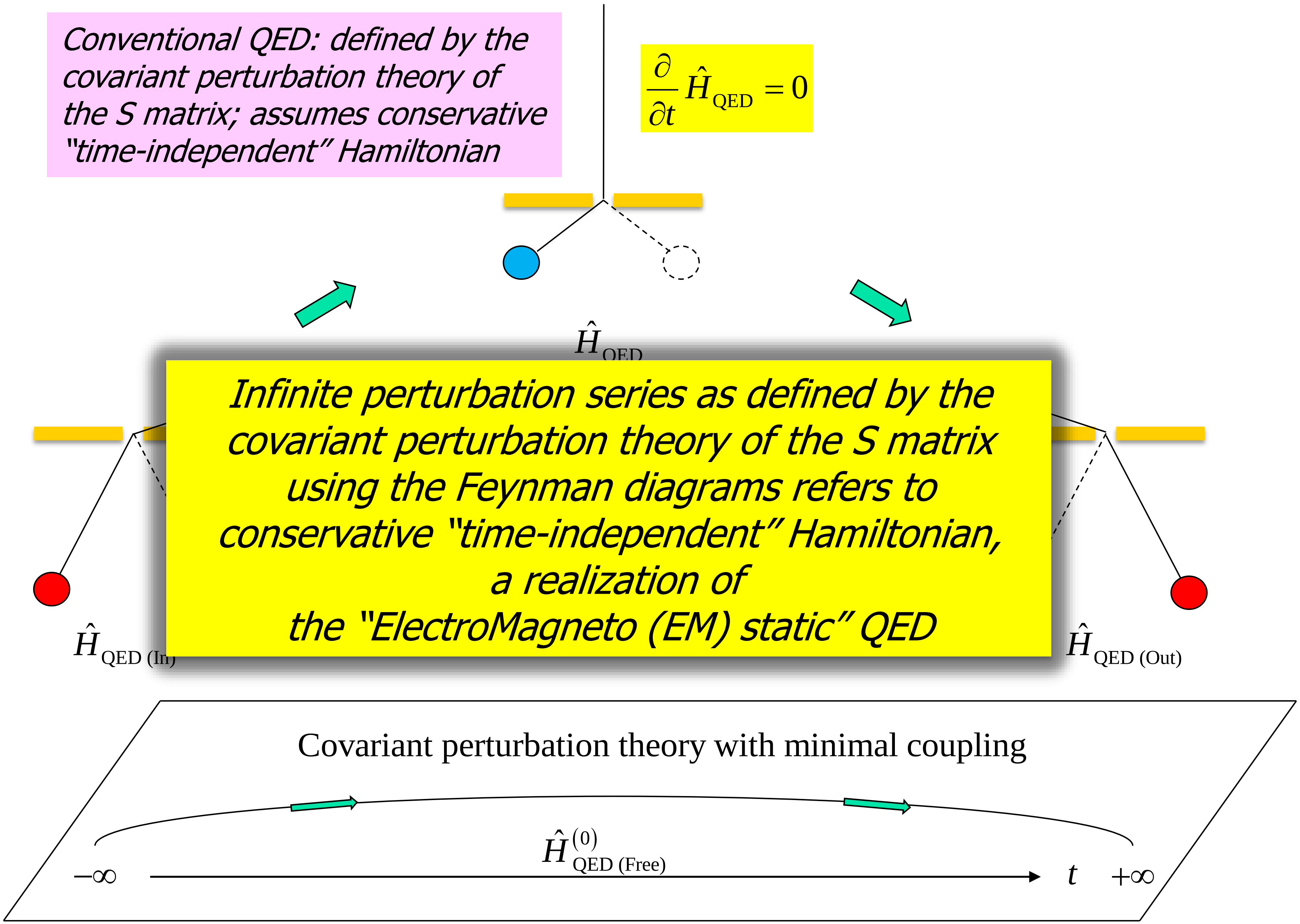
Lorentz scalar

the Coulomb gauge

$$\hat{A}_0(x) = \int_{-\infty}^{\infty} d^3\vec{y}\,\frac{\hat{\rho}(y)\big|_{y^0=x^0}}{|\vec{x}-\vec{y}|}$$

Conventional QED defined by the covariant perturbation theory

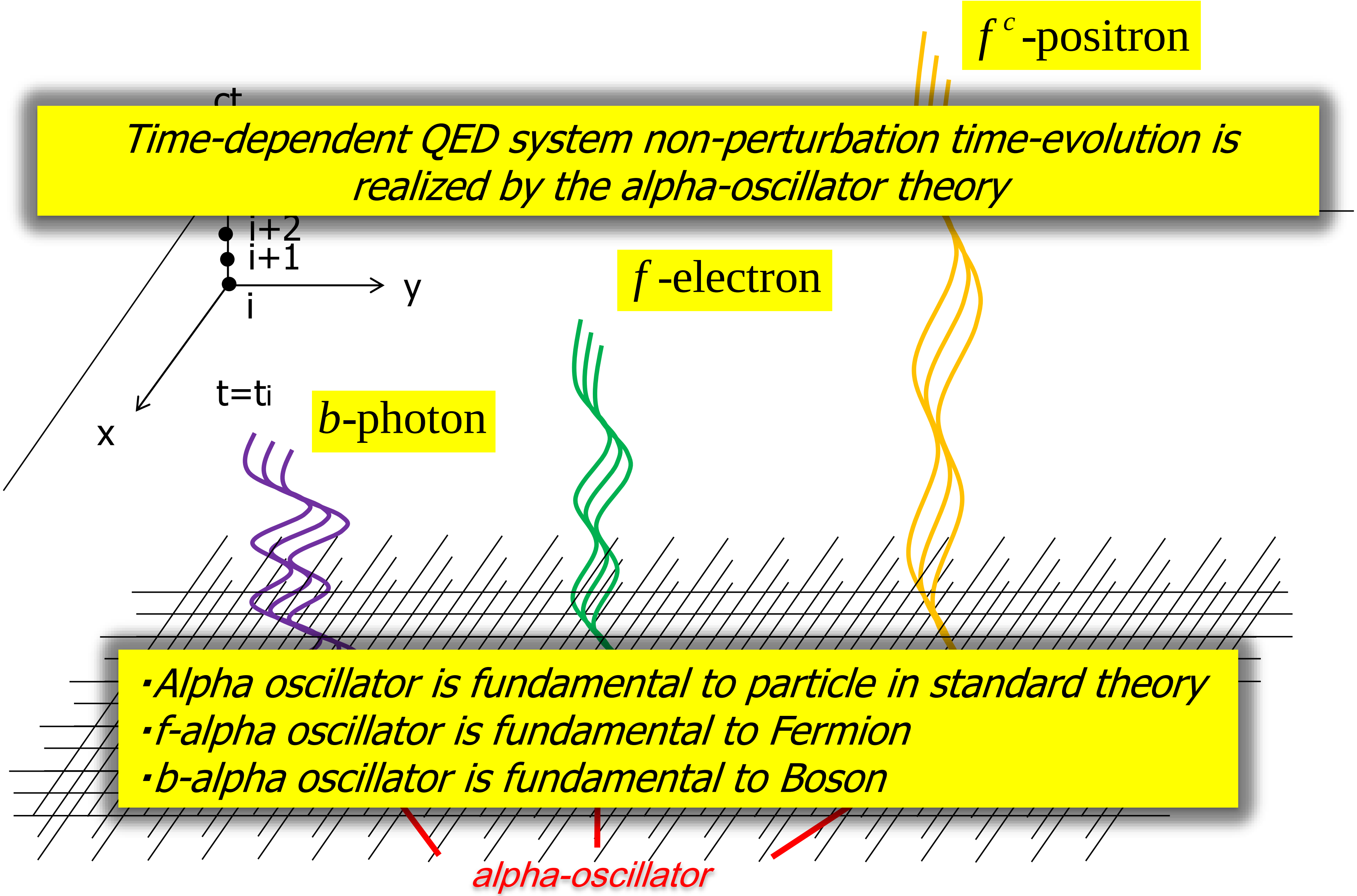
Conventional QED: defined by the covariant perturbation theory of the S matrix; assumes conservative "time-independent" Hamiltonian



Infinite perturbation series as defined by the covariant perturbation theory of the S matrix using the Feynman diagrams refers to conservative "time-independent" Hamiltonian, a realization of the "ElectroMagneto (EM) static" QED

Alpha-oscillator theory

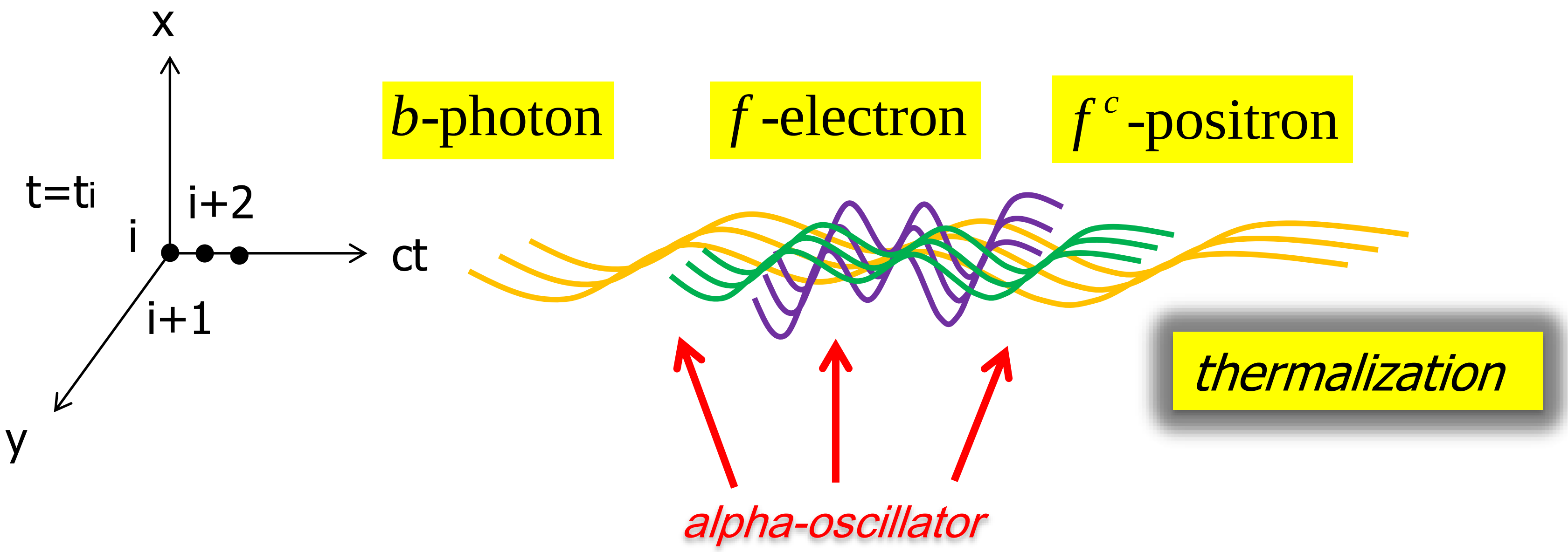
Time-dependent QED system non-perturbation time-evolution is realized by the alpha-oscillator theory



- *Alpha oscillator is fundamental to particle in standard theory*
- *f-alpha oscillator is fundamental to Fermion*
- *b-alpha oscillator is fundamental to Boson*

A. Tachibana, J. Math. Chem., **53**, 1943-1965 (2015)

Thermalization



·Interacting particles are emergent through thermalization of the alpha-oscillators

·Alpha-oscillator algebra is fundamental to particle algebra
·Alpha-oscillator energy is present in a form that can take another form rather than that of particle, a candidate of the dark energy

Time-dependent renormalization with particle

Coarse graining

$$\left[\hat{\alpha}_{\text{particle}}, \hat{\beta}_{\text{particle}}\right]_{\pm} = \int_0^{\infty} d\nu \int_0^{\infty} d\nu' \left[\hat{\alpha}(\nu), \hat{\beta}(\nu')\right]_{\pm}$$

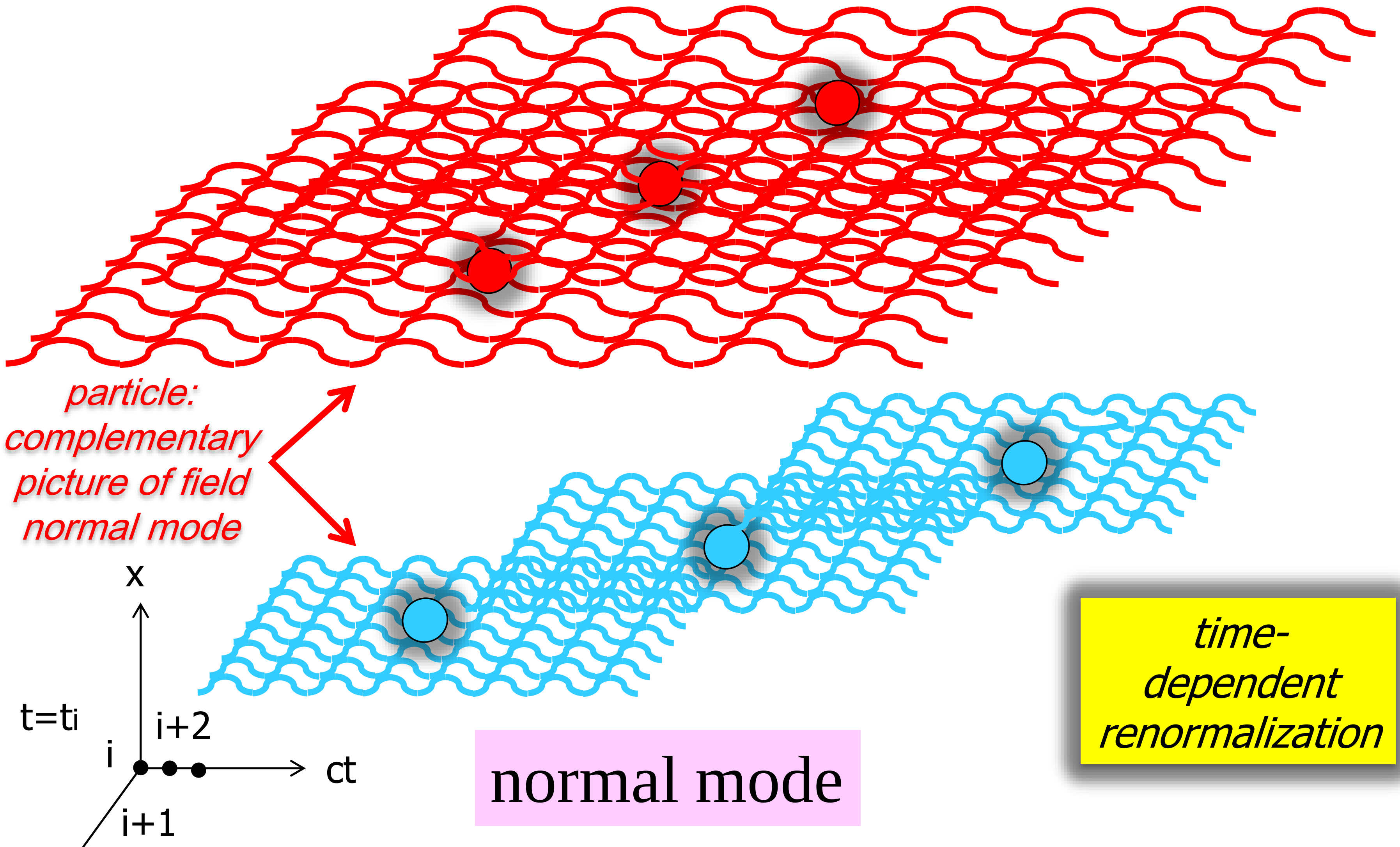
Particle algebra is emergent after coarse graining of alpha-oscillator algebra

Time-dependent renormalization with 3 steps

(I) Particle spectrum condition
(II) Algebra normal mode condition
(III) Field operator renormalization condition

A. Tachibana, J. Math. Chem., **54**, 661-681 (2016)

Normal mode with particle



$$\cdots \rightarrow \hat{H}_{\mathrm{QED}}\left(t_i\right) \rightarrow \hat{H}_{\mathrm{QED}}\left(t_{i+1}\right) \rightarrow \hat{H}_{\mathrm{QED}}\left(t_{i+2}\right) \rightarrow \cdots$$

Dual Cauchy problem

1st Cauchy problem of field

(I) Alpha-oscillator theory

Leading to

Time-dependent Hamiltonian of QED

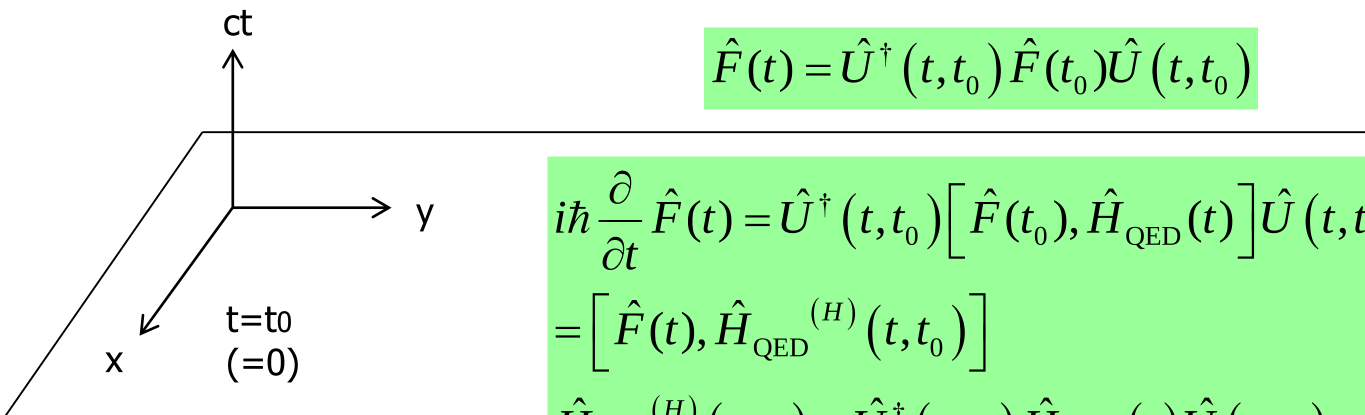
and

(II) Thermalization compatible with initial condition at t=t0
(III) Time-dependent renormalization

2nd Cauchy problem of ket vector with wave function

Initial conditions given for events starting at t=t1, t2, … afterwards

Time-dependent QED Hamiltonian system time-evolution

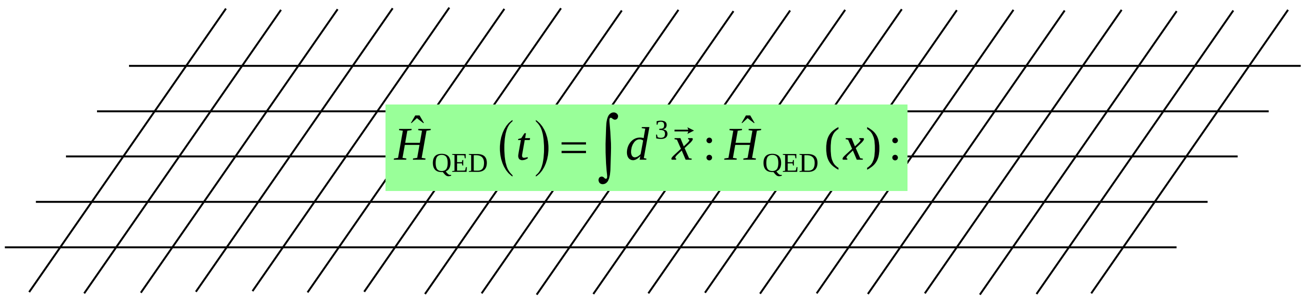


$$\hat{F}(t) = \hat{U}^{\dagger}(t,t_0)\hat{F}(t_0)\hat{U}(t,t_0)$$

$$i\hbar\frac{\partial}{\partial t}\hat{F}(t) = \hat{U}^{\dagger}(t,t_0)\left[\hat{F}(t_0),\hat{H}_{\text{QED}}(t)\right]\hat{U}(t,t_0)$$

$$= \left[\hat{F}(t),\hat{H}_{\text{QED}}{}^{(H)}(t,t_0)\right]$$

$$\hat{H}_{\text{QED}}{}^{(H)}(t,t_0) = \hat{U}^{\dagger}(t,t_0)\hat{H}_{\text{QED}}(t)\hat{U}(t,t_0)$$



$$\hat{H}_{\text{QED}}(t) = \int d^3\vec{x} : \hat{H}_{\text{QED}}(x) :$$

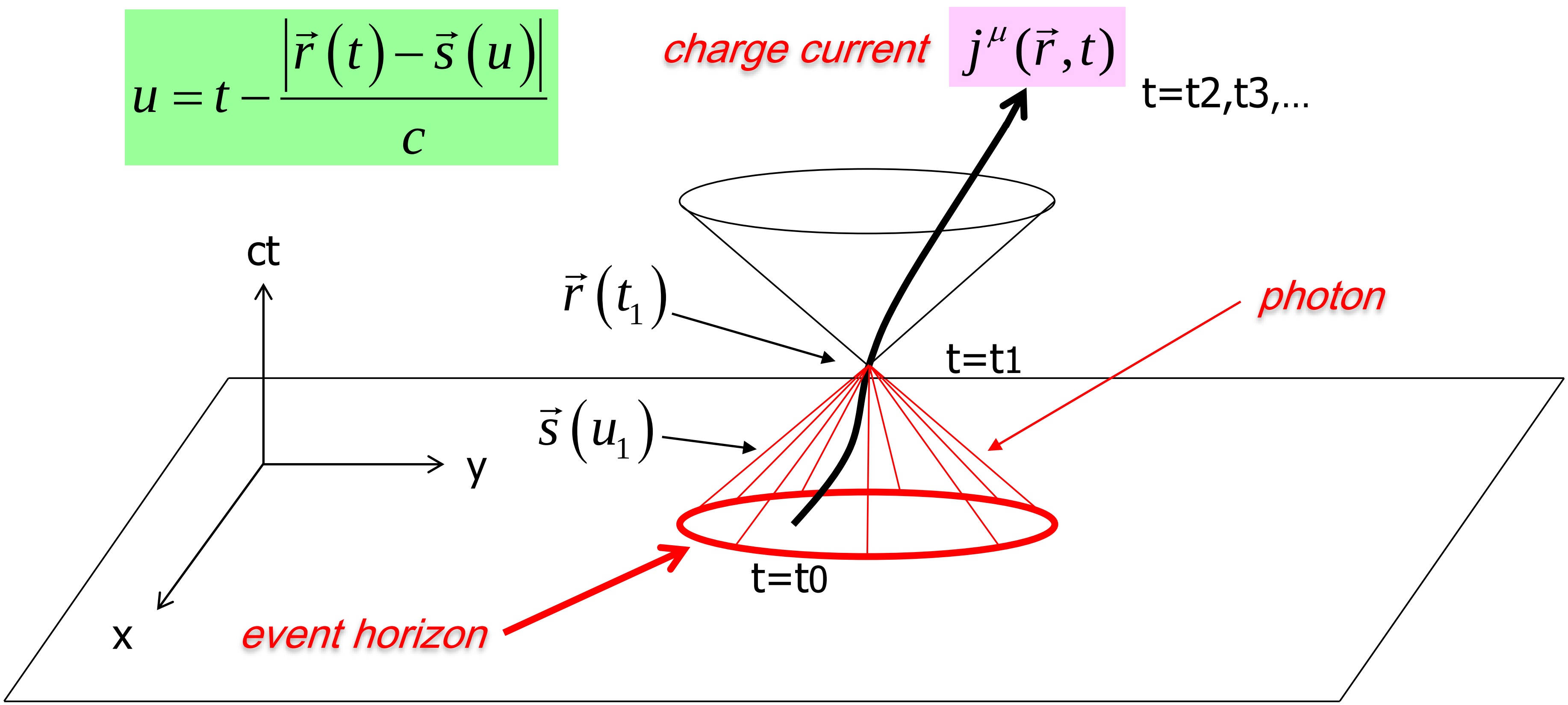
Time-dependent measurement problem of event using time-dependent Hamiltonian of QED should be formulated in terms of the dual Cauchy problem for (i) fields and (ii) wave functions

Event horizon

World line of charge current in the Minkowski spacetime

From t=t0 onward, any events inside the event horizon can emit photon and affect the charge current through the Liénard–Wiechert potentials. Outside the event horizon, any light emitted from the event cannot reach the charge current, and hence cannot affect it.

$$u = t - \frac{\left|\vec{r}(t) - \vec{s}(u)\right|}{c}$$

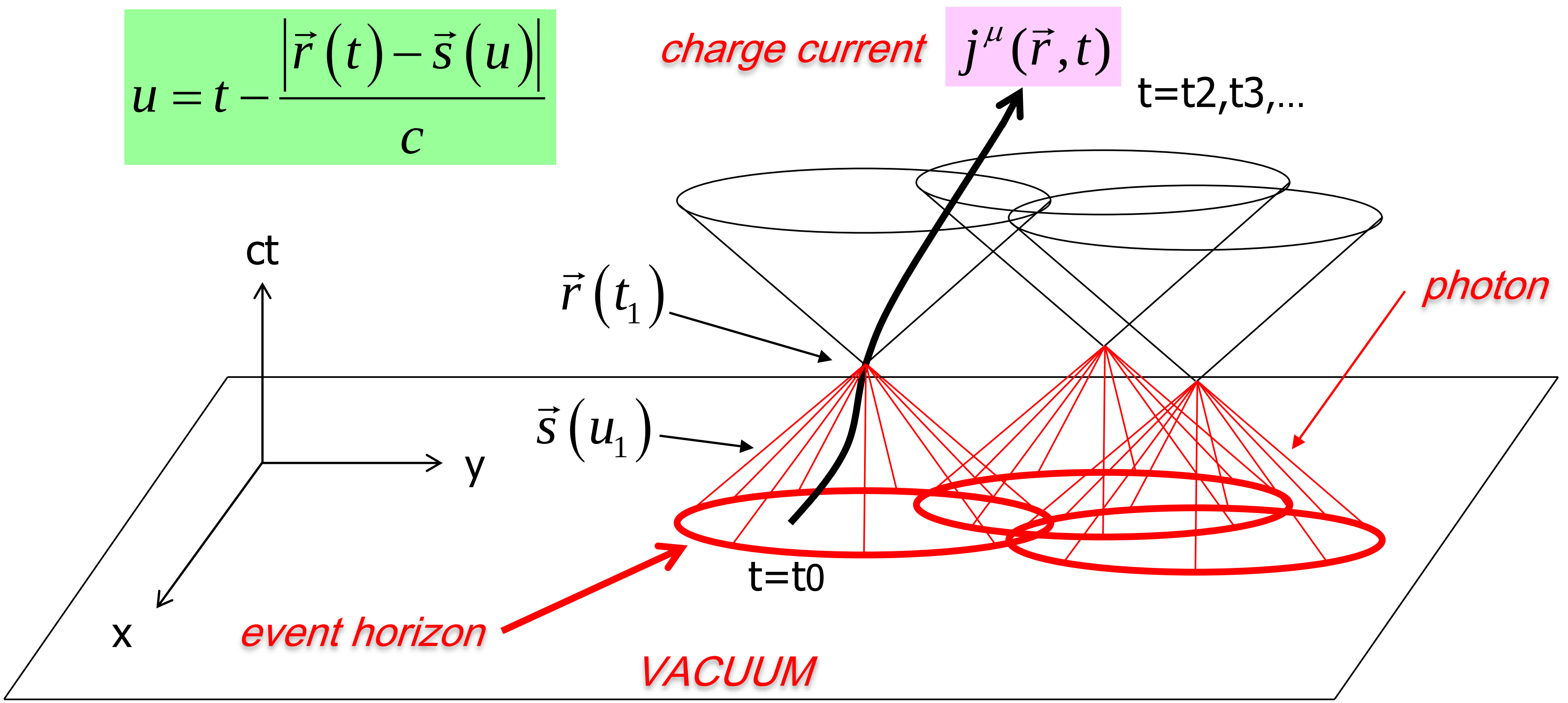


Synchronization of clocks at t=t0

Synchronization of clocks located at different space points at t=t0
Canonical quantization at t=t0
Definition of vacuum at t=t0

The charge current develops forward t>t0 with the retarded interactions mediated by photon. The vacuum and field operators are not defined backward t<t0.

$$u = t - \frac{\left|\vec{r}(t) - \vec{s}(u)\right|}{c}$$



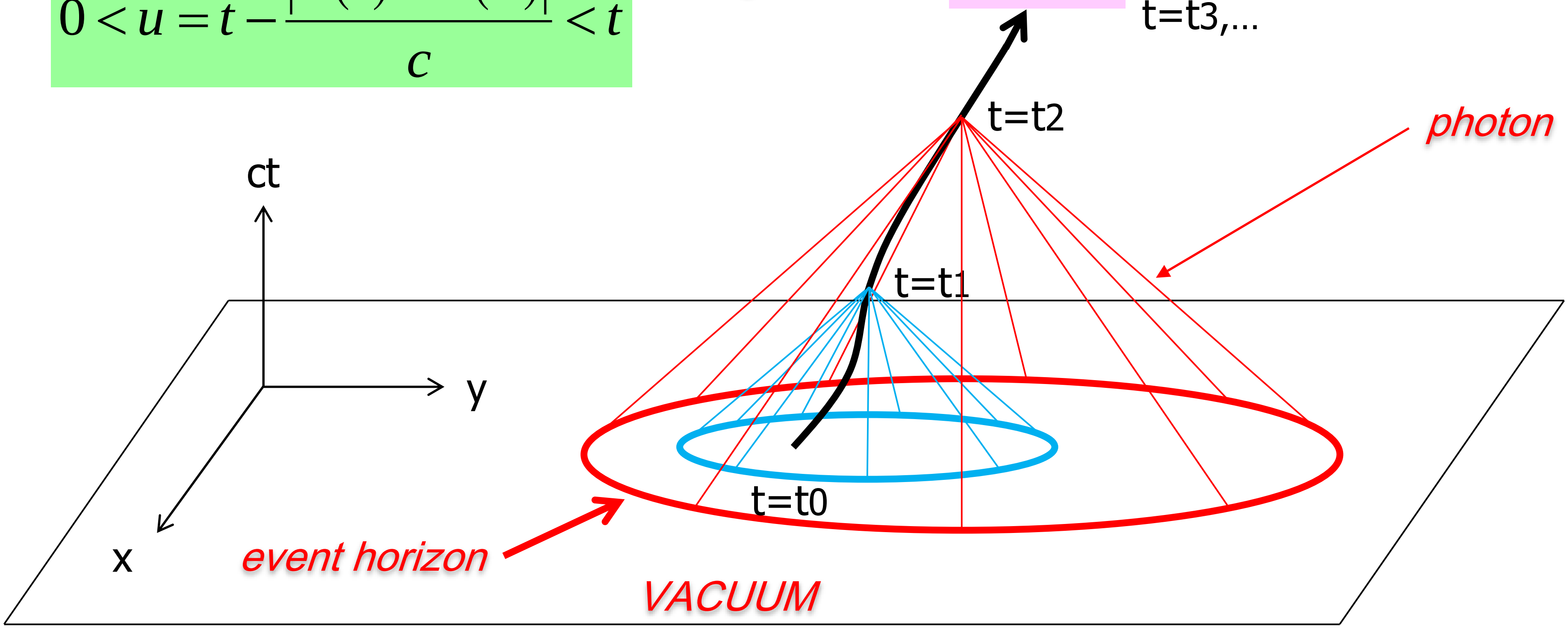
Cauchy problem of charged particle

causality $j^{\mu}(\vec{s},u)=0, \quad u>t$

initial condition $j^{\mu}(\vec{s},u)=0, \quad u<0$

$$0<u=t-\frac{\left|\vec{r}(t)-\vec{s}(u)\right|}{c}<t$$

charge current $j^{\mu}(\vec{r},t)$



Cauchy problem of photon

$$\vec{A}(\vec{r},t)=\vec{A}_{\text{radiation}}(\vec{r},t)+\frac{1}{c}\int_{-\infty}^{\infty}du'\int d^3\vec{s}\,\frac{\vec{j}_{\mathrm{T}}(\vec{s},u')}{|\vec{r}-\vec{s}|}\delta\left(u'-\left(t-\frac{|\vec{r}-\vec{s}|}{c}\right)\right)$$

$$=\vec{A}_{\text{radiation}}(\vec{r},t)+\frac{1}{c^2\pi}\int_0^t du'\int_{-\infty}^{\infty}d\alpha\int d^3\vec{s}\,\vec{j}_{\mathrm{T}}(\vec{s},u')e^{i\alpha\left((u'-t)^2-\frac{(\vec{r}-\vec{s})^2}{c^2}\right)}$$

$$0<u=t-\frac{|\vec{r}(t)-\vec{s}(u)|}{c}<t$$

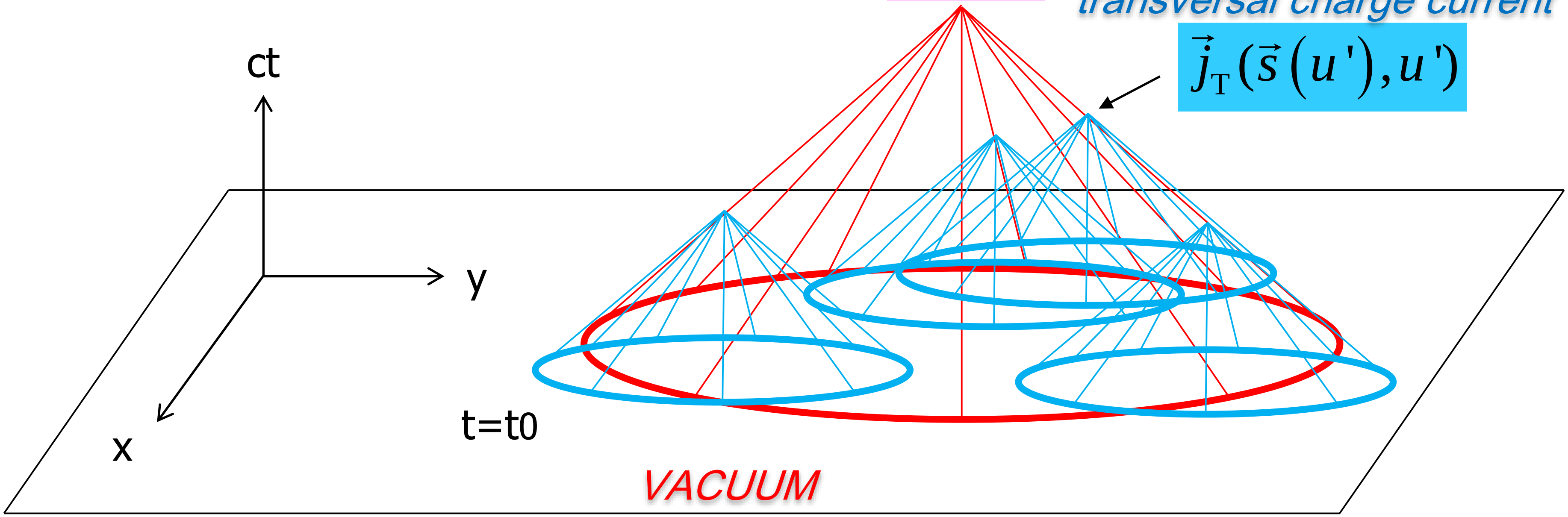
separation of variables!

vector potential of photon

$\vec{A}(\vec{r},t)$

transversal charge current

$\vec{j}_{\mathrm{T}}(\vec{s}(u'),u')$



Renormalized ket vector and wave function

2nd Cauchy problem of wave function

$$\left|\tilde{\Psi}\left(\alpha_i,t_i;t\right)\right\rangle_{H\ \mathrm{or}\ S}$$
$$=\sum_{N=0}^{\infty}\int d\tilde{\omega}_1\left(t_i\right)\cdots d\tilde{\omega}_N\left(t_i\right)\left|t_i;\tilde{\omega}_1\left(t_i\right),\cdots,\tilde{\omega}_N\left(t_i\right),t\right\rangle_{H\ \mathrm{or}\ S}$$
$$\times\tilde{\Phi}_N\left(\alpha_i,t_i;\tilde{\omega}_1\left(t_i\right),\cdots,\tilde{\omega}_N\left(t_i\right),t\right)$$

$$i\hbar\frac{\partial}{\partial t}\left|\tilde{\Psi}\left(\alpha_i,t_i;t\right)\right\rangle_H=0$$

$$i\hbar\frac{\partial}{\partial t}\left|\tilde{\Psi}\left(\alpha_i,t_i;t\right)\right\rangle_S=\hat{H}_{\mathrm{QED}}\left(t\right)\left|\tilde{\Psi}\left(\alpha_i,t_i;t\right)\right\rangle_S$$
$$\left|\tilde{\Psi}\left(\alpha_i,t_i;t\right)\right\rangle_S=\hat{U}\left(t,t_i\right)\left|\tilde{\Psi}\left(\alpha_i,t_i;t\right)\right\rangle_H$$

Renormalized wave function

Wave function

$$i\hbar\frac{\partial}{\partial t}\tilde{\Phi}_N(\alpha_i,t_i;\tilde{\omega}_1(t_i),\cdots,\tilde{\omega}_N(t_i),t)$$
$$=\sum_{M=0}^{\infty}\int d\tilde{\omega}'_1(t_i)\cdots d\tilde{\omega}'_M(t_i)H_{NM}(t_i;\tilde{\omega}_1(t_i),\cdots,\tilde{\omega}_N(t_i),\tilde{\omega}'_1(t_i),\cdots,\tilde{\omega}'_M(t_i),t)$$
$$\times\tilde{\Phi}_M(\alpha_i,t_i;\tilde{\omega}'_1(t_i),\cdots,\tilde{\omega}'_M(t_i),t)$$

$$H_{NM}(t_i;\tilde{\omega}_1(t_i),\cdots,\tilde{\omega}_N(t_i),\tilde{\omega}'_1(t_i),\cdots,\tilde{\omega}'_M(t_i),t)$$
$$={}_H\left\langle t_i;\tilde{\omega}_1(t_i),\cdots,\tilde{\omega}_N(t_i),t\right|\hat{H}_{\mathrm{QED}}{}^{(H)}(t,t_i)\left|t_i;\tilde{\omega}'_1(t_i),\cdots,\tilde{\omega}'_M(t_i),t\right\rangle_H$$
$$={}_S\left\langle t_i;\tilde{\omega}_1(t_i),\cdots,\tilde{\omega}_N(t_i),t_i\right|\hat{H}_{\mathrm{QED}}(t)\left|t_i;\tilde{\omega}'_1(t_i),\cdots,\tilde{\omega}'_M(t_i),t_i\right\rangle_S$$

$$\frac{\partial}{\partial t}H_{NM}(t_i;\tilde{\omega}_1(t_i),\cdots,\tilde{\omega}_N(t_i),\tilde{\omega}'_1(t_i),\cdots,\tilde{\omega}'_M(t_i),t)\neq 0$$

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Measurement problem

QED vs quantum mechanics

Remark!

Quantum Electrodynamics

Description of $\hat{F}(ct, x, y, z)$ at (ct, x, y, z)

but

Quantum Mechanics

Description of $\hat{F}(ct, \hat{x}, \hat{y}, \hat{z})$

in terms of $\hat{x}, \hat{y},$ and $\hat{z}$ of $\hat{F}(ct, \hat{x}, \hat{y}, \hat{z})$ at t

Time-dependent measurement problem of event in QED is performed
with the Minkowski space-time coordinates as "countable" c-number parameters!

A. Tachibana, "New Aspects of Quantum Electrodynamics," Springer, (2017)

No collapse of wave function in QED

Nor classical observer-apparatus in QED

$$\left\langle \tilde{\hat{F}}^{\text{Alpha}}(t) \right\rangle_{\alpha_i, t_i}$$

Space coordinates are not integrated out to get the expectation value in QED

Remark!

QED

c-number ~~$[\hat{x}, \hat{p}_x] = i\hbar$~~

but

q-number

Quantum Mechanics

$$[\hat{x}, \hat{p}_x] = i\hbar$$

The Minkowski space-time "coordinates" are c-number parameters for the event and

- *not "canonical variables" in QED!*
- *not "observables" in QED!*
- *not "operators" in QED!*

The space coordinates are q-numbers and

- *canonical variables in QM*
- *observables in QM*
- *operators in QM*

A. Tachibana, "New Aspects of Quantum Electrodynamics," Springer, (2017)

Alpha-weighted expectation value

$$\left\langle \hat{\tilde{F}}^{\mathrm{Alpha}}(t) \right\rangle_{\alpha_i, t_i}$$

Remark!

$$\left\langle \hat{\tilde{F}}^{\mathrm{Alpha}}(t) \right\rangle_{\alpha_j, t_j} \quad \text{for } t > t_j$$

is not necessarily identical to $\left\langle \hat{\tilde{F}}^{\mathrm{Alpha}}(t) \right\rangle_{\alpha_i, t_i} \quad \text{for } t > t_i$

even if the initial condition is the same with each other,

$$\alpha_j = \alpha_i \quad \text{for } t_j > t_i$$

Now that the QED Hamiltonian is dependent on time, an event for t>tj is not identical to the event for t>ti, even if the initial condition is the same with each other!

Classical electrodynamics

The Maxwell equations

$$\partial^{\alpha} F^{\beta\gamma} + \partial^{\beta} F^{\gamma\alpha} + \partial^{\gamma} F^{\alpha\beta} = 0 \quad \Leftrightarrow \quad \mathrm{div}\vec{B} = 0, \quad \mathrm{rot}\vec{E} + \frac{1}{c}\frac{\partial}{\partial t}\vec{B} = 0$$

$$\partial_{\nu} F^{\nu\mu} = \frac{4\pi}{c} j^{\mu} \quad \Leftrightarrow \quad \mathrm{div}\vec{E} = 4\pi\rho, \quad \mathrm{rot}\vec{B} - \frac{1}{c}\frac{\partial}{\partial t}\vec{E} = \frac{4\pi}{c}\vec{j}$$

Covariant current of point charged particles

$$j^{\mu}(x) = \left(c\rho(x), \vec{j}(x)\right)$$

$$j^{0}(x) = c\rho(x) = \sum_{n} c q_n \delta^{3}\left(\vec{r} - \vec{a}_n(t)\right)$$

$$\vec{j}(x) = \sum_{n} q_n \delta^{3}\left(\vec{r} - \vec{a}_n(t)\right) \frac{d\vec{a}_n(t)}{dt}$$

Delta function for the trajectory of n'th point charged particle

Quantum Electrodynamics (QED)

Renormalized expectation value for current of one electron

$$\left\langle \hat{\tilde{j}}^{\mu}(x) \right\rangle_{\alpha_i, t_i} = c q_e \frac{N}{D} \delta^3\left(\vec{r} - \vec{a}(t)\right)$$

Delta function as in classical electrodynamics!

$$N = W_N(p;t)\Big|_{\vec{p}=-i\hbar\frac{\partial}{\partial\vec{r}}} \left|\tilde{\Phi}(\alpha_i, t_i; \tilde{\omega}_1(t_i), t_i)\right|^2 \Big|_{\vec{p}=-i\hbar\frac{\partial}{\partial\vec{r}}} \left(\frac{p^{\mu}}{p^0}\right)\Big|_{\vec{p}=-i\hbar\frac{\partial}{\partial\vec{r}}}$$

$$D = W_D(p;t)\Big|_{\vec{p}=-i\hbar\frac{\partial}{\partial\vec{r}}} \left|\tilde{\Phi}(\alpha_i, t_i; \tilde{\omega}_1(t_i), t_i)\right|^2 \Big|_{\vec{p}=-i\hbar\frac{\partial}{\partial\vec{r}}}$$

A. Tachibana, J. Mol. Model., **24**, 257 (2018); J. Compt. Chem., in press

Quantum Electrodynamics (QED)

Trajectory of one electron

$$\vec{a}(t) = \vec{a}(t_i) + \int_{t_i}^{t} dt' \left. \frac{\partial \left(h\nu_{\text{electron}}\left(\vec{p};t'\right)\right)}{\partial \vec{p}} \right|_{\vec{p}=\vec{p}(t_i)}$$

$$\equiv \vec{a}(t_i;t)$$

Partial derivative of the renormalized energy of Alpha-oscillator for the normal mode of electron

Remark!

$$\vec{a}(t_j;t) \neq \vec{a}(t_i;t) \quad \text{even if}$$

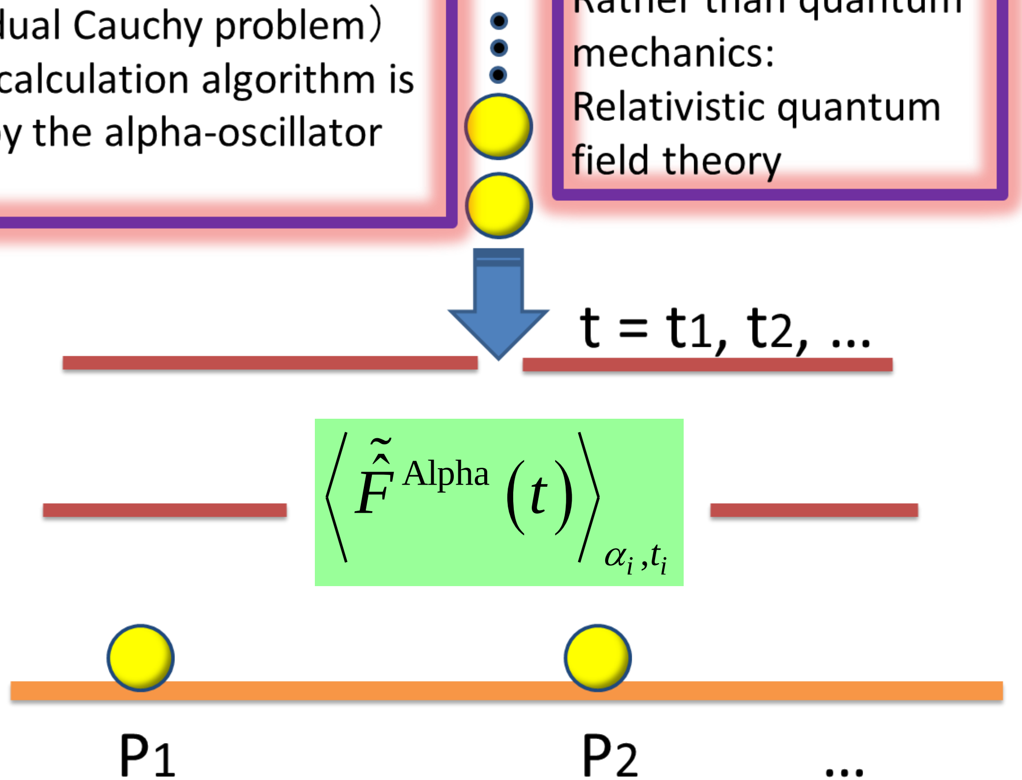
$$\vec{a}(t_j) = \vec{a}(t_i) \quad \text{and} \quad \vec{p}(t_j) = \vec{p}(t_i) \quad \text{for} \quad t_j > t_i$$

Now that the QED Hamiltonian is dependent on time, the trajectory a(tj;t) for t>tj is not identical to a(ti;t) for t>ti even if the initial condition is the same with each other!

Mystery is solved!

Tachibana (new theory)
Where to reach the particles !
①Determined
（QED dual Cauchy problem）
②The calculation algorithm is given by the alpha-oscillator theory

Rather than quantum mechanics:
Relativistic quantum field theory

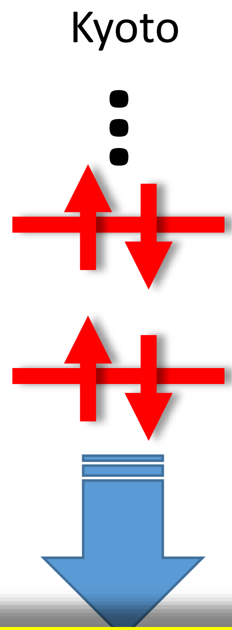


●*Even if with the same initial condition given, different spots on the screen can be predicted deterministically with no introduction of hidden variables*
●*The interference pattern is similar to, but cannot be reproduced quantitatively by, that of quantum mechanics wave function, contrary to many-years-anticipation: a new prediction, awaiting experimental test over and above the "Bohr-Einstein gedanken experiment."*

The EPR measurement

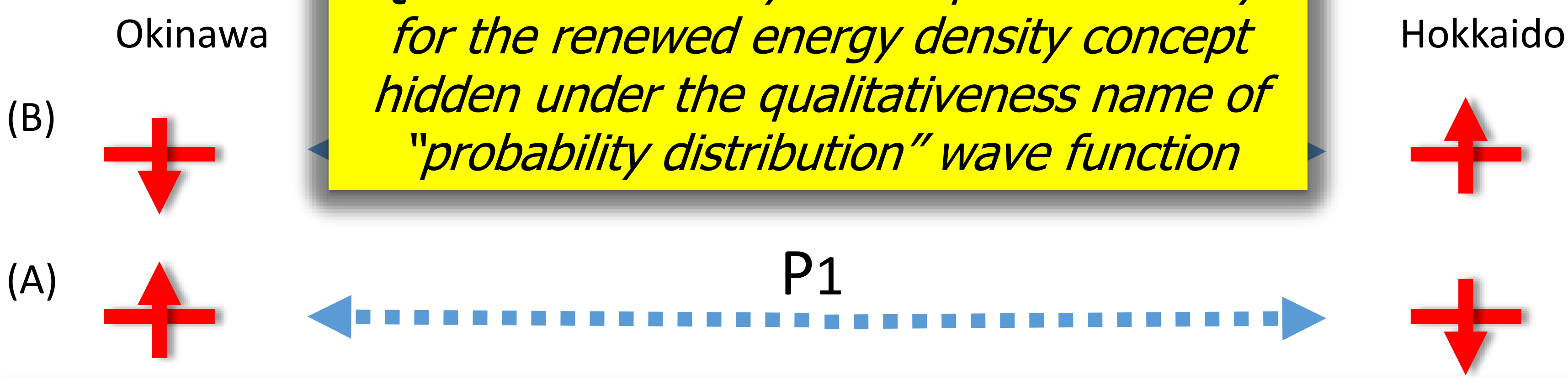
Quantum mechanics
①Stochastic
②Collapse of wave function over long distances occurs at super-light speed
③Causality is of no use

Tachibana (new theory)
predicts deterministically

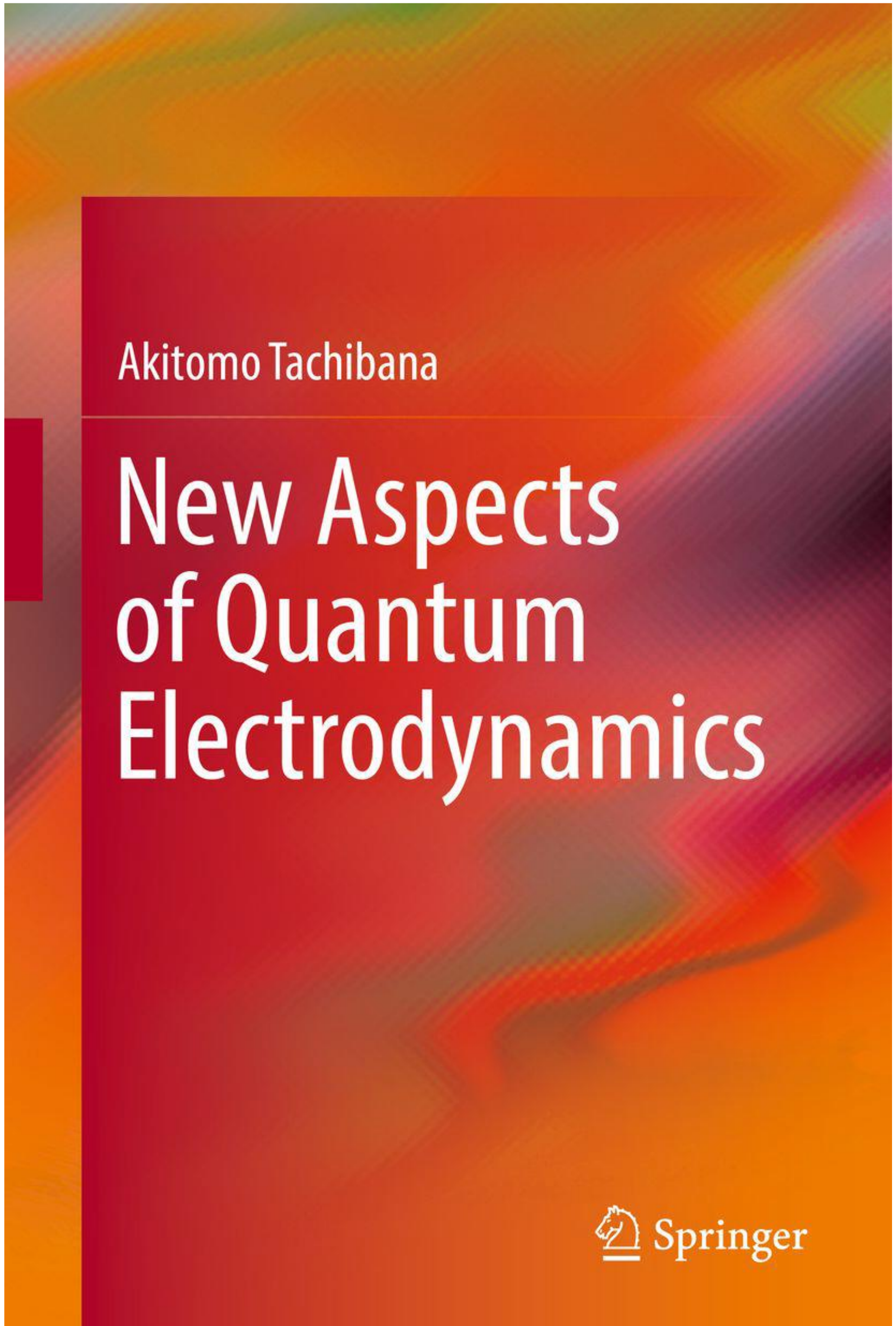


$t = t_1, t_2, \ldots$

Quantum Electrodynamics paves the way for the renewed energy density concept hidden under the qualitativeness name of "probability distribution" wave function



Entangled mutually exclusive events (A) and (B) are stochastic by Quantum Mechanics, but predicted deterministically by Quantum Electrodynamics



and more ...

Akitomo Tachibana

New Aspects of Quantum Electrodynamics

- ▶ Makes use of abundant figures to help the reader grasp ideas quickly
- ▶ Includes many equations to help the reader to follow the logic step by step
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- Theory
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- Measurement problem
  - Quantum mechanics (QM) vs Quantum Electrodynamics (QED)
  - Double-slit phenomenon, EPR measurement, and more …
- Conclusion

Measurement problem

■Correct theory of the double-slit phenomenon：
Quantum Electrodynamics (QED)

■Correct quantum theoretical view of the double-slit phenomenon：
Relativistic Quantum Field Theory (QFT)

CONCLUSIONS

- 1st : We apply the Alpha oscillator theory to Quantum Electrodynamics (QED) and formulate the dual Cauchy problem and predict the double-slit phenomenon: “Even if with the same initial condition given, different spots on the screen should be predicted deterministically with no introduction of hidden variables,” which resolves the “Mystery of Quantum Mechanics (Feynman).”

- 2nd : The interference pattern is similar to, but cannot be reproduced quantitatively by, that of Quantum Mechanics wave function, contrary to many-years-anticipation. This is a new prediction, awaiting experimental test over and above the “Bohr-Einstein gedanken experiment.”

- 3rd : Application of this theory to entanglement known by the Einstein-Podolsky-Rosen (EPR) measurement predicts its determinism in a new complete form.

Thank you for your attention!