Models of wave function collapse, and their experimental tests ["Collapse Models"]

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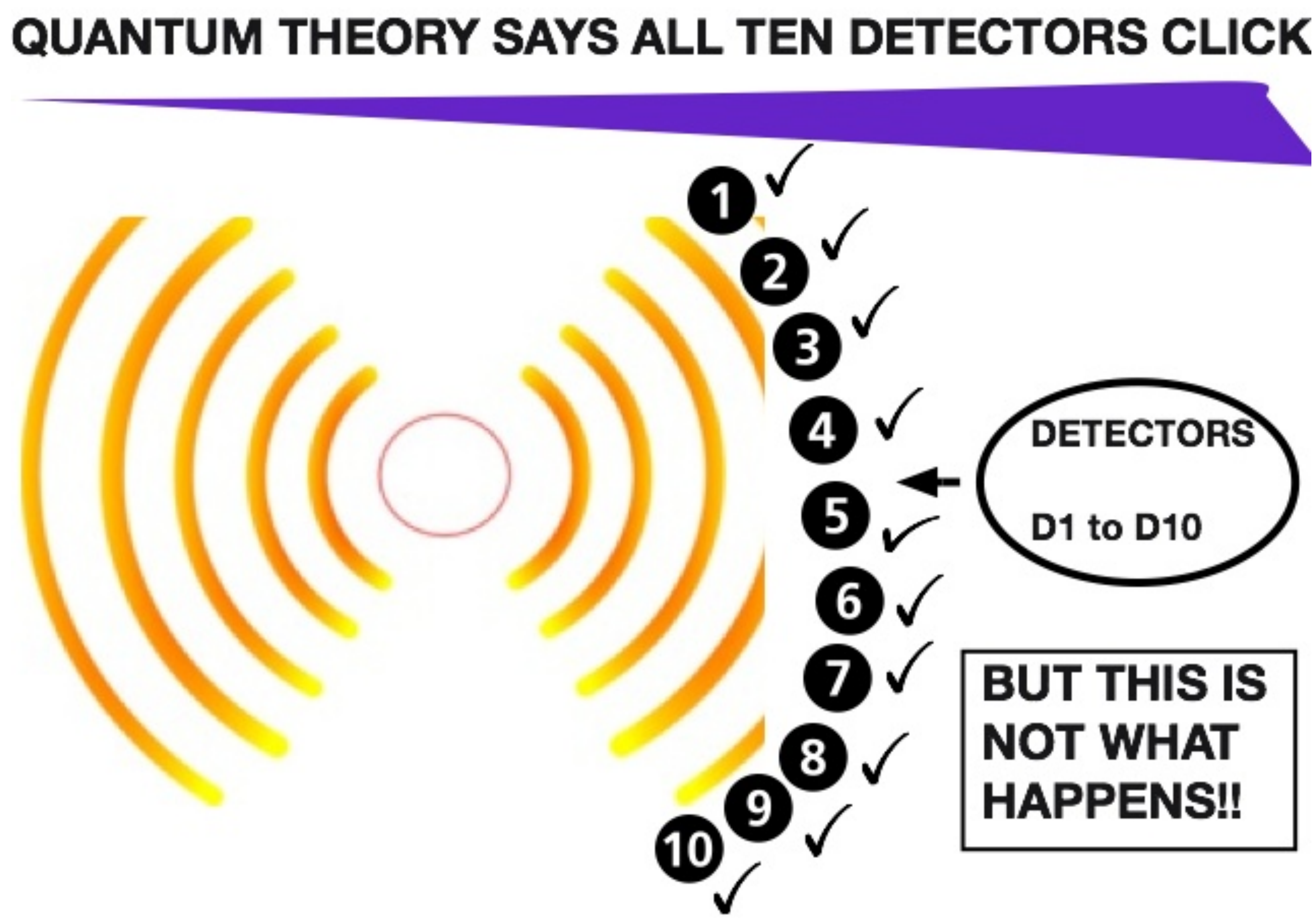
Reference:

Bassi, Lochan, Satin, Singh and Ulbricht
Reviews of Modern Physics 85 (2013) 471
[arXiv:1204.4325]

PLAN OF THE TALK

1. The quantum measurement problem
2. A possible solution: Continuous Spontaneous Localisation (CSL)
3. Possible origin of CSL?
4. Experimental tests of CSL

1. The quantum measurement problem

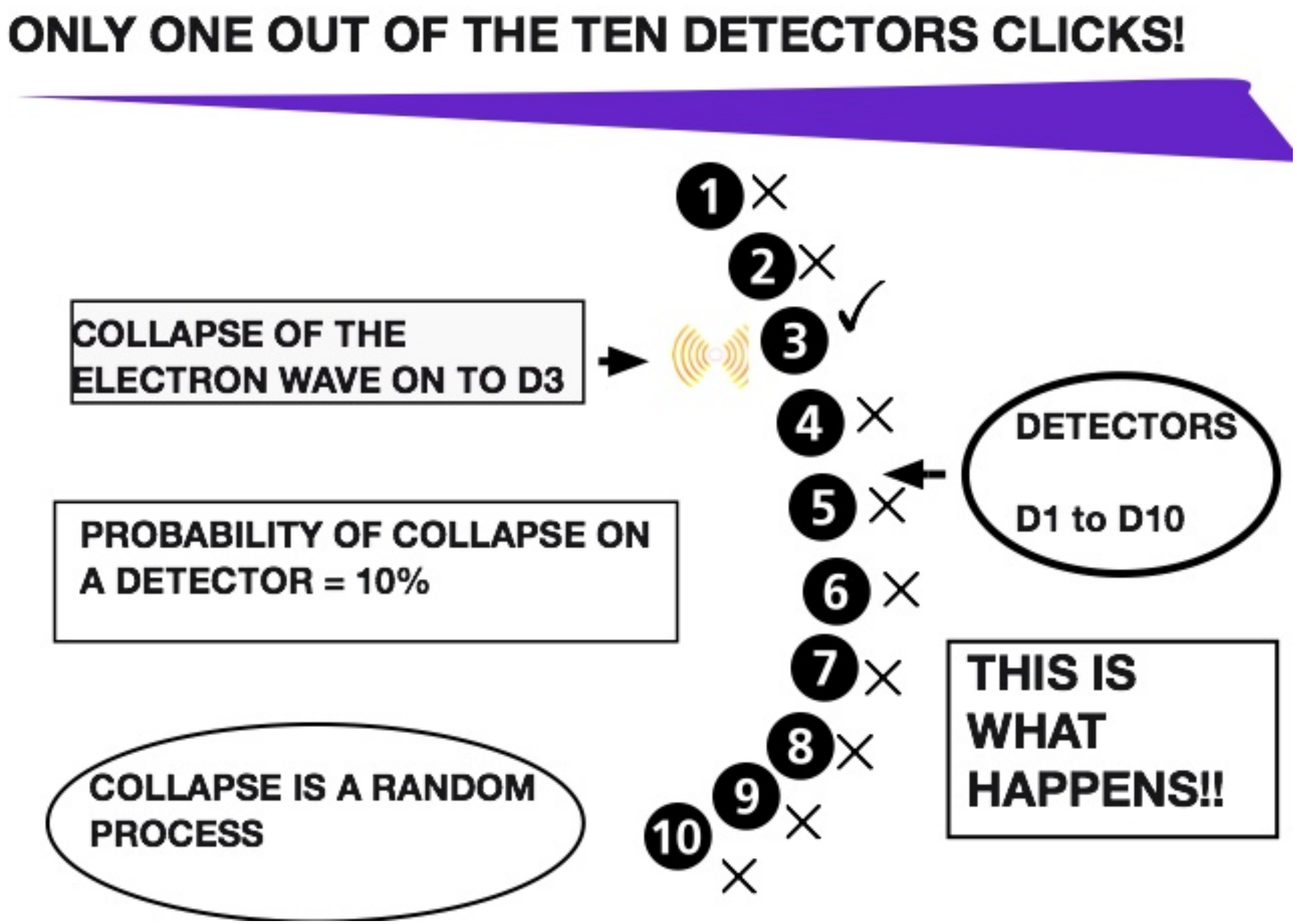


Prediction from quantum theory:

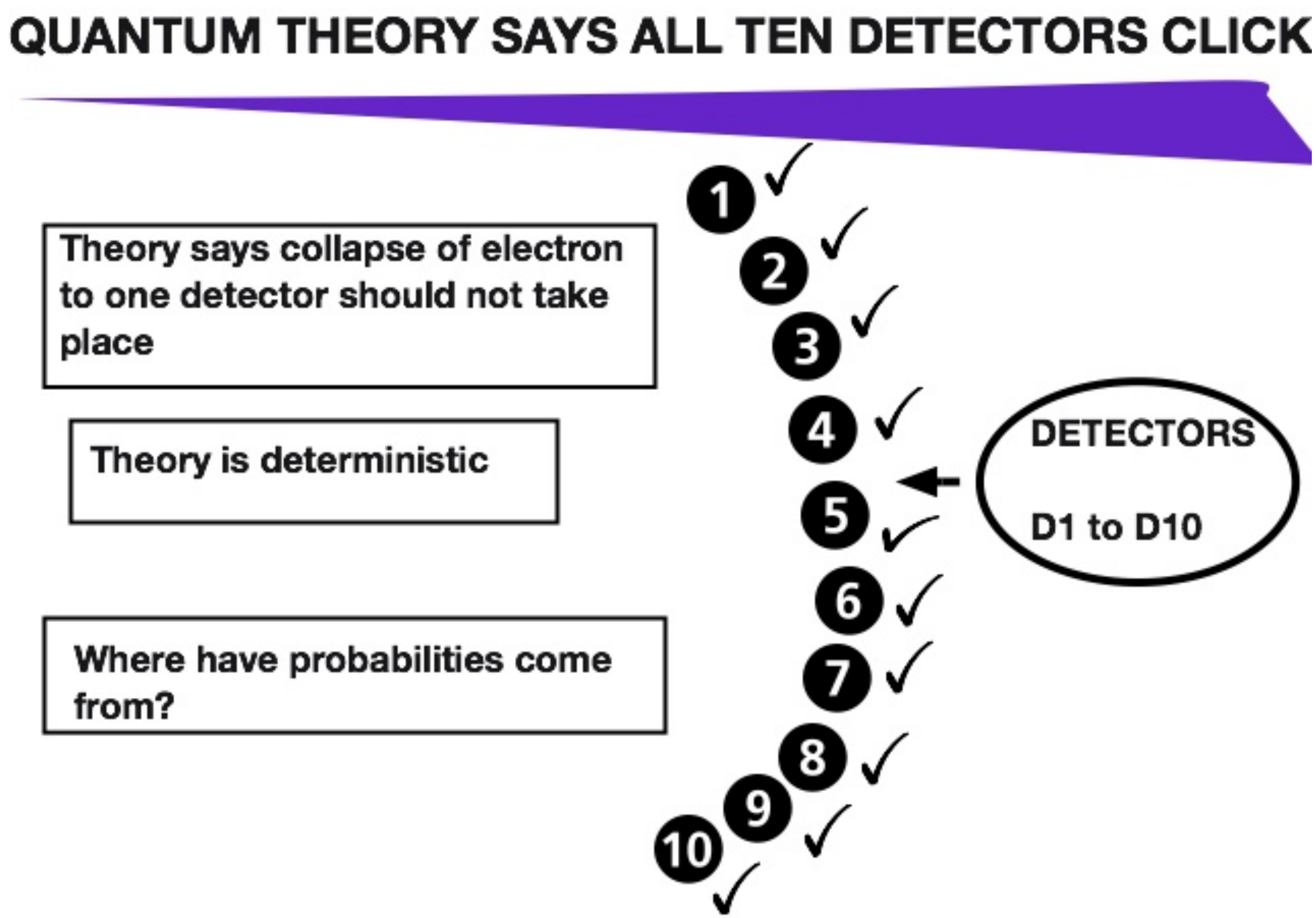
$$|\psi_e > \rightarrow |\psi_{e1} > |D_1 > + |\psi_{e2} > |D_2 > + |\psi_{e3} > |D_3 > + \ldots$$

Actual observation differs from the prediction:

$$|\psi_e> \rightarrow |\psi_{e3}> |D_3>$$



The quantum measurement problem:



Why is linearity lost,and that too, in a random fashion?

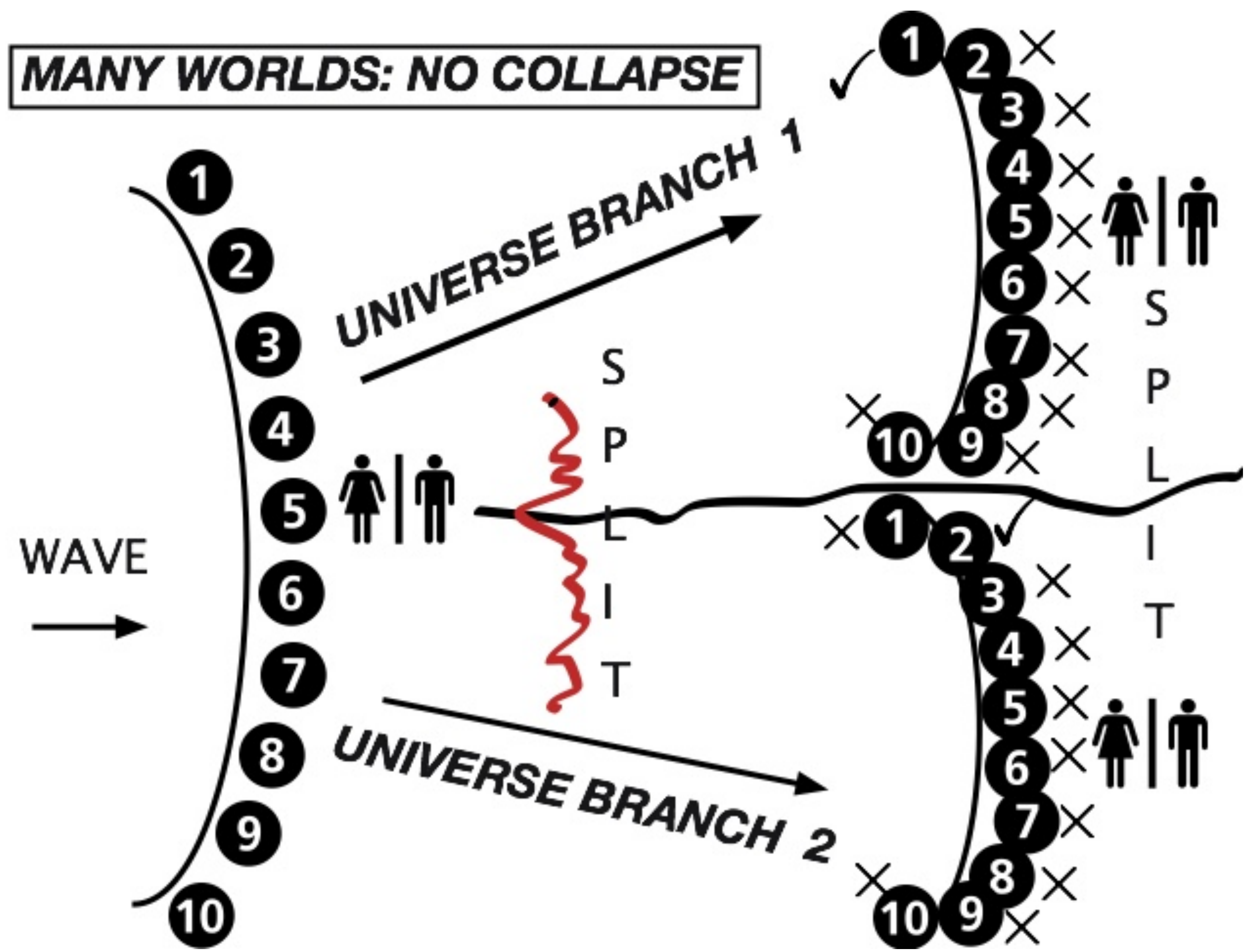
Where is the quantum-classical divide?

Some Possible solutions:

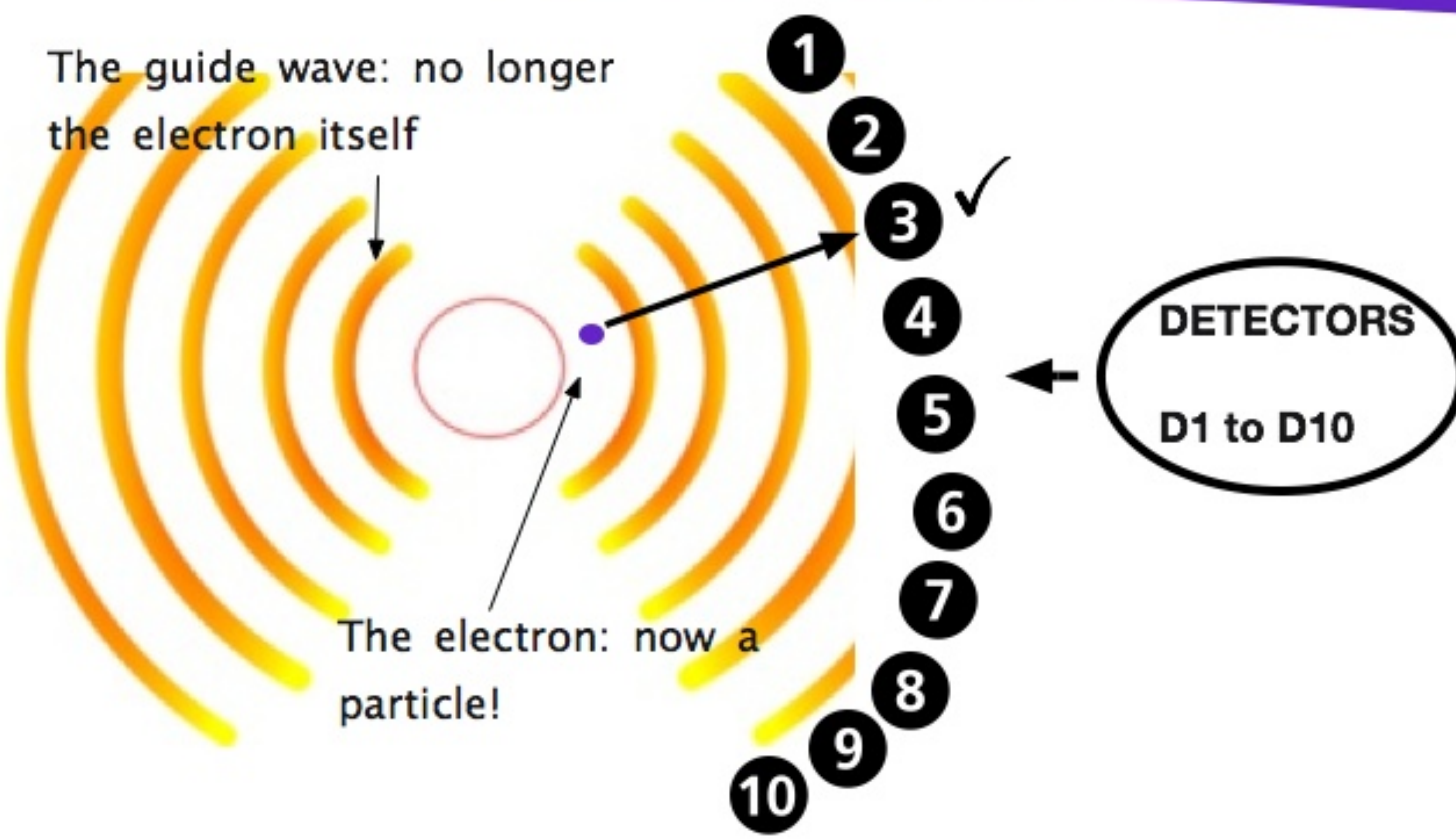
- Do not modify quantum theory, but change its interpretation.
  [Many worlds interpretation + decoherence]

- Do not modify quantum theory, but change its mathematical formulation.
  [Bohmian mechanics]

- Modify quantum theory: to a new universal dynamics
  [Collapse models]


MANY WORLDS: NO COLLAPSE
UNIVERSE BRANCH 1
UNIVERSE BRANCH 2
WAVE
SPLIT
SPLIT
1
2
3
4
5
6
7
8
9
10

BOHMIAN MECHANICS: ELECTRON HAS A DEFINITE PATH BUT WE DO NOT KNOW EXCATLY WHICH ONE!!



2. A possible solution: Continuous Spontaneous Localisation (CSL)

Quantum theory is not exact, but an approximation to a more general theory.

The principle of linear superposition is an approximate principle.

Quantum theory and classical mechanics are limiting cases of CSL.

Ghirardi, Rimini, Weber, Pearle 1980s]

SPONTANEOUS COLLAPSE : NO DETECTOR NEEDED

COLLAPSE OF THE WAVE DOES HAPPEN

BUT IT DOES NOT HAVE ANYTHING TO DO WITH DETECTORS

IT HAPPENS OF ITS OWN - SPONTANEOUSLY

SPONTANEOUS COLLAPSE : NO DETECTOR NEEDED

FOR SMALL OBJECTS LIKE ELECTRONS THE WAVE COLLAPSES AFTER A VERY VERY LONG TIME

FOR LARGE OBJECTS LIKE TABLES THE ASSOCIATED WAVE COLLAPSES EXTREMELY RAPIDLY

Constraints on modifying the Schrodinger equation

- Should have a nonlinear part, which breaks superposition.

- The nonlinear part should be stochastic, so as to allow random outcomes, and avoid faster than light-signalling.

- The nonlinear terms should be anti-Hermitean, if they have to cause collapse.

- The nonlinear equation should be such that the Born probability rule is recovered.

- There should be an amplification mechanism, so that the nonlinearity is negligible for microscopic systems.

Spontaneous Collapse

- A modified Schrodinger equation:

$$d\psi_t = \left[-\frac{i}{\hbar}H\,dt + \sqrt{\lambda}(q - \langle q\rangle_t)dW_t - \frac{\lambda}{2}(q - \langle q\rangle_t)^2 dt\right]\psi_t$$

$$\lambda = \frac{m}{m_0}\lambda_0$$

- Nonlinear, stochastic, gives Born probability rule

- Understanding position localization of macro-objects:

- Consider a free particle initially in a gaussian state, and substitute the wave-function in the modified equation.

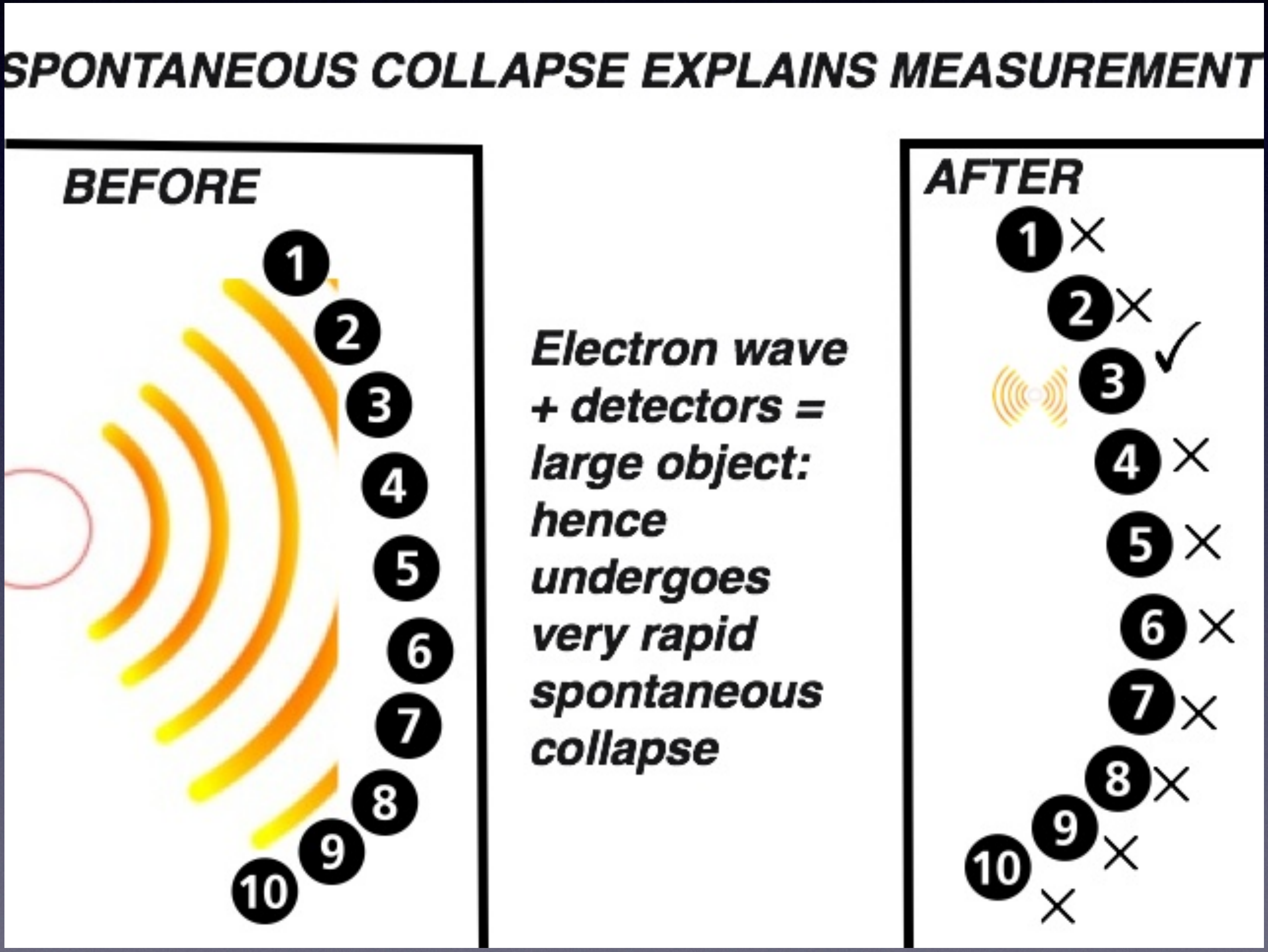
- The spread in the position and momentum reach asymptotic values:

$$\sigma_q(\infty) = \sqrt{\frac{\hbar}{m\omega}} \simeq \left(10^{-15}\sqrt{\frac{\mathrm{Kg}}{m}}\right)\,\mathrm{m}, \qquad \sigma_p(\infty) = \sqrt{\frac{\hbar m\omega}{2}} \simeq \left(10^{-19}\sqrt{\frac{m}{\mathrm{Kg}}}\right)\frac{\mathrm{Kg\ m}}{\mathrm{sec}}$$

$$\omega \;=\; 2\sqrt{\hbar\lambda_0/m_0} \;\simeq\; 10^{-5}\,\mathrm{s}^{-1}$$

•Thus localization models incorporate 'wavy' nature of quantum systems and 'particle' nature of classical objects in one single dynamical framework.

Spontaneous Collapse



- Understanding collapse of the wave-function

- Consider a two-state microscopic quantum system:

$$c_+|+\rangle + c_-|-\rangle$$

- interacting with a measuring apparatus $\mathcal{A}$
- Initial composite state $\Psi_0 = [c_+|+\rangle + c_-|+\rangle] \otimes \phi^{\mathrm{G}}$
- Standard quantum theory :

$$[c_+|+\rangle + c_-|-\rangle] \otimes \phi^G \quad \mapsto \quad c_+|+\rangle \otimes \phi_+ + c_-|-\rangle \otimes \phi_-$$

- In localization models:

$$\Psi_t = \frac{c_+|+\rangle \otimes \phi_+ + \epsilon_t c_-|-\rangle \otimes \phi_-}{\sqrt{1+\epsilon_t^2}}$$

$\epsilon(t)$ goes to the value $\epsilon(t) \ll 1$ with probability $|c_+|^2$

Outstanding Challenge

To develop a relativistic version of the collapse model

Why should the Schroedinger equation be modified?

[Various lines of reasoning suggest that the Schroedinger equation is approximate]

Deriving quantum theory from a deeper theory

- It is perhaps unsatisfactory to obtain quantum theory by `quantizing' its own [classical] limit.

TRACE DYNAMICS

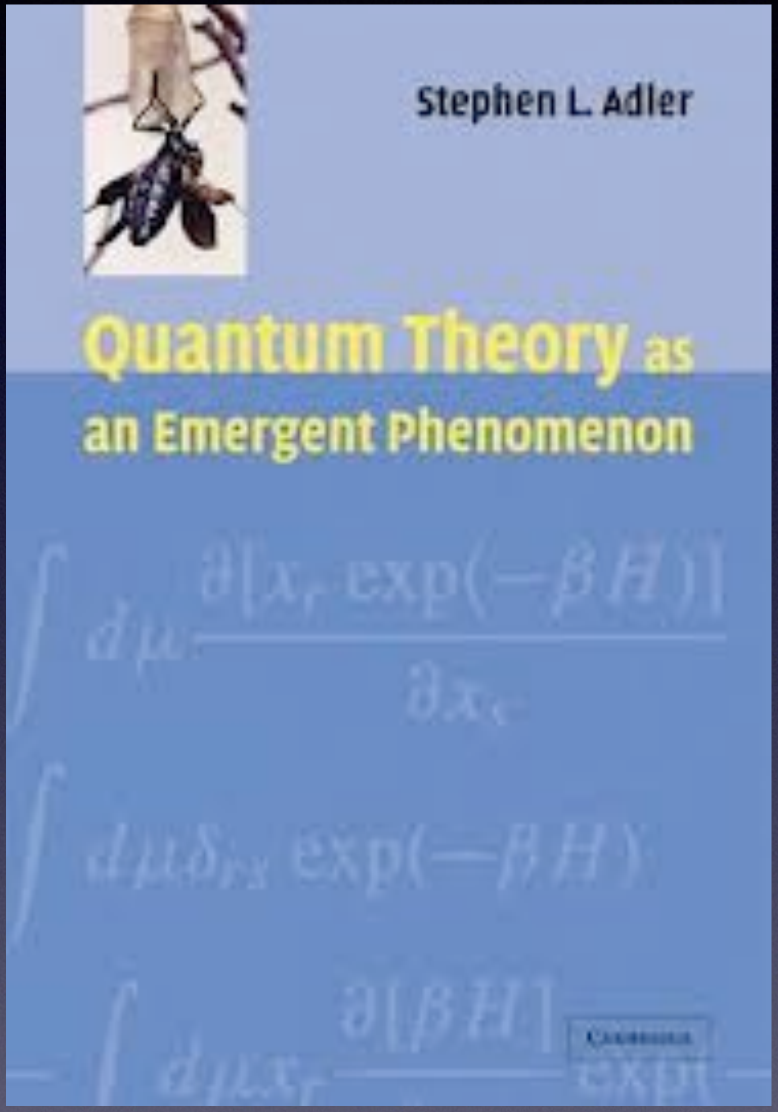
- One starts with a unitarily invariant classical theory of matrix dynamics.

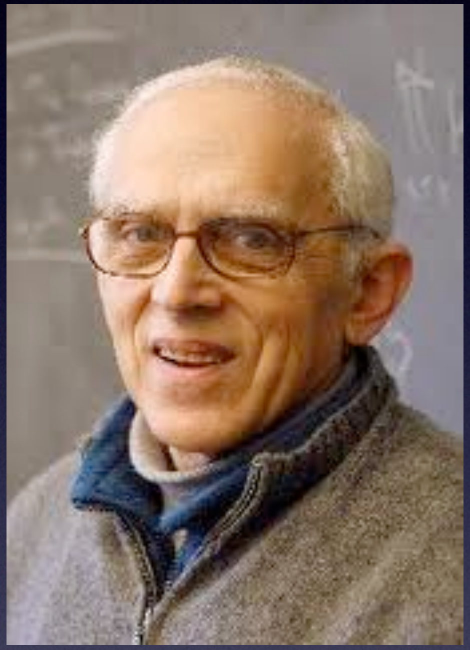
- Quantum theory is derived as an equilibrium statistical thermodynamics of this underlying theory.

- Brownian motion fluctuations around equilibrium provide a stochastic nonlinear modification of CSL kind.

Determinism+Randomness: Statistical Equlibrium + Fluctuations

TRACE DYNAMICS





Stephen Adler
(IAS, Princeton)

Time and collapse of the wave-function

- Incompleteness: Quantum theory depends on an external classical time.

- There ought to exist a reformulation of quantum theory which does not depend on classical time.

- Such a reformulation has been [partly] developed, and there is evidence that there are stochastic fluctuations around this reformulated theory, which imply a CSL type structure for modified quantum theory.

[TPS 2006; TPS 2009]
[Lochan & TPS 2011; Lochan, Satin & TPS, 2012; TPS 2012]

The problem of time in quantum theory

$$i\hbar\frac{\partial\psi}{\partial t} = H\psi$$

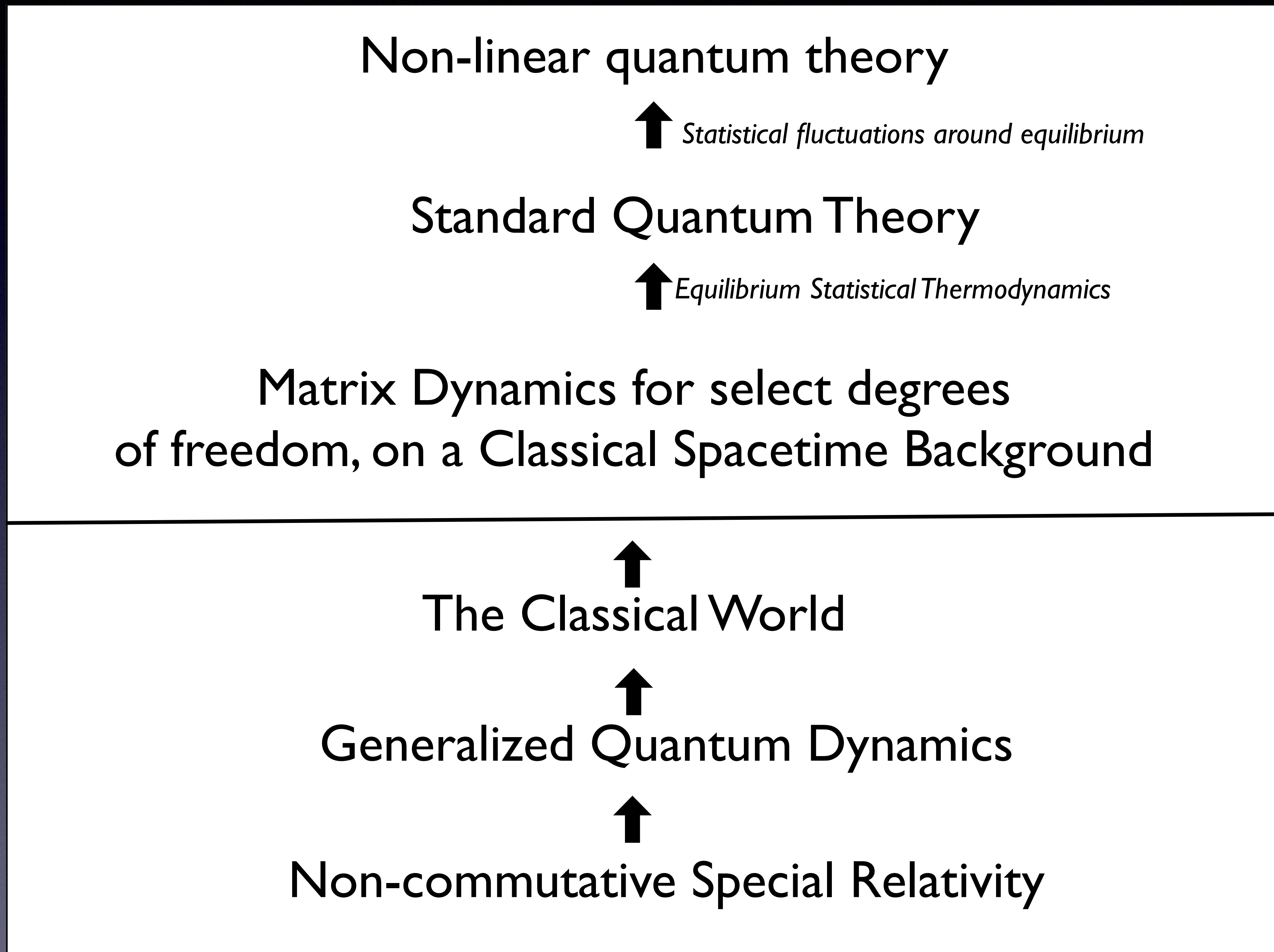
Part of a classical spacetime

Is produced by classical bodies

Are a limiting case of

Quantum theory depends on classical time.
Classical time comes from quantum theory!

Time and the quantum measurement problem



Gravity is responsible for collapse of wave-function

- There is a minimal fluctuation in the spacetime geometry produced by every object.

- When the wave-function describing the quantum state of this object propagates in this fluctuating spacetime, it loses coherence beyond a critical length after a critical time.

- These scales are mass-dependent, and tally with CSL.

- There is some theoretical evidence that the stochastic mechanism for CSL comes from gravity.

Spacetime Fluctuations & Decoherence

(*Karolyhazy, Diosi)*

Principle: Minimum uncertainty in spacetime geometry: Modeled by a stochastic potential

- Karolyhazy: $\Delta s^3 \sim l_p^2\, s$: Modeled as colored noise

Stochastic Schrodinger equation:

$$i\hbar \frac{\partial}{\partial t}\psi(\mathbf{x},t) = \left(H + \int d^3x'\; f(\mathbf{x}')\;\gamma(\mathbf{x}',t)\right)\psi(\mathbf{x},t),$$

Karolyhazy: decoherence length and time:

$$a_c \gg R \implies \qquad \frac{\hbar^2}{G} \gg m^3 R \qquad : micro - region$$

$$a_c \approx R \implies \qquad \frac{\hbar^2}{G} \approx m^3 R \qquad : transition - region$$

$$a_c \ll R \implies \qquad \frac{\hbar^2}{G} \ll m^3 R \qquad : macro - region$$

- Micro: $$a_c \approx \frac{\hbar^2}{G} \frac{1}{m^3} = \left(\frac{L}{l_p}\right)^2 L; \qquad L = \frac{\hbar}{mc}$$

- Macro: $$a_c \approx \left(\frac{\hbar^2}{G}\right)^{1/3} \frac{R^{2/3}}{m} = \left(\frac{R}{l_p}\right)^{2/3} L$$

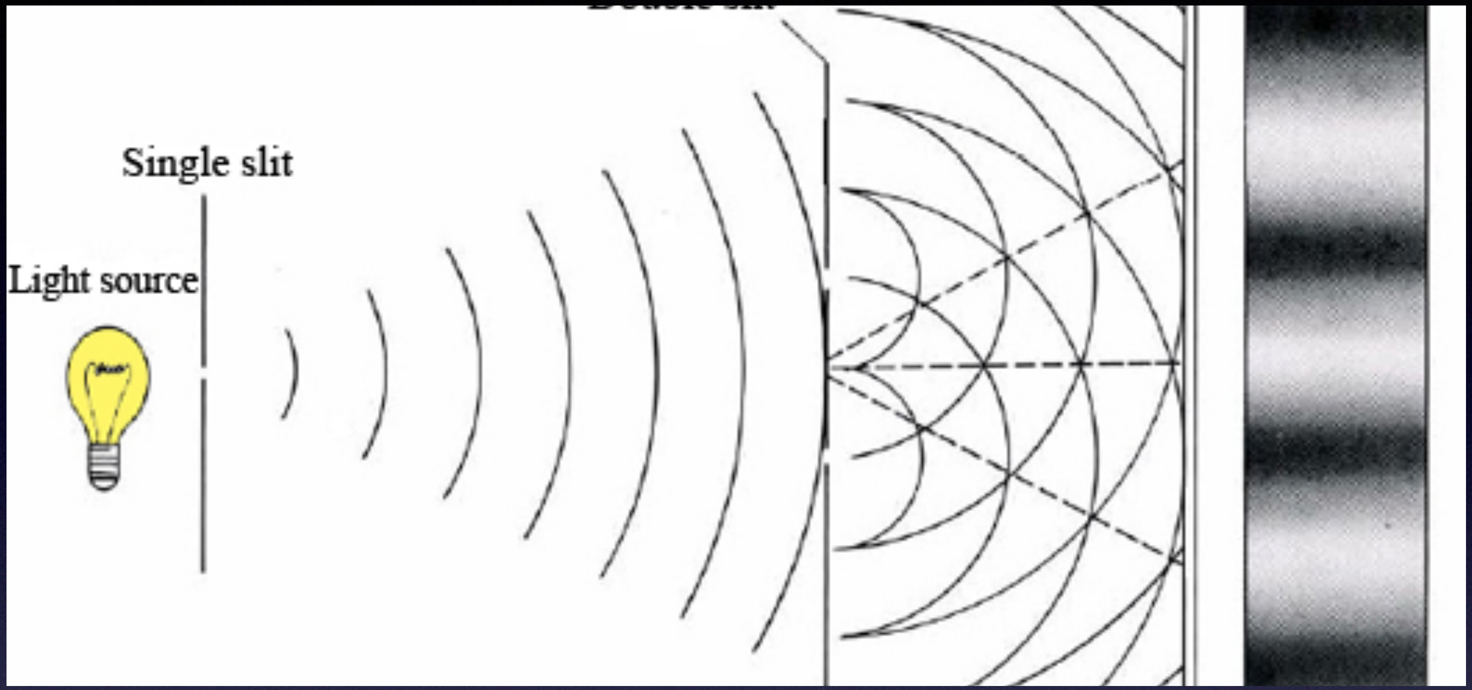
Experimental Tests of the Modified Equation

[Predictions differ from those of quantum theory in the mesoscopic regime]

Putting bounds on the collapse strength λ

- Testing superposition: interferometry and optomechanics
- CSL induced spectral line broadening
- Heating of ultra-cold atoms
- Anomalous Brownian motion
- Constraints from known laboratory physics
- Constraints from astrophysics and cosmology

Testing the superposition principle: interference



Double slit interference experiment

Successfully carried out for Helium ions, neutrons, atoms, and small molecules, thus establishing their wave nature and the principle of superposition for them

Towards Larger Particles

•Enormous technological challenges.

•Preparation of intense gas phase beams

•Preparation of spatial and temporal coherence of matter wave, followed by efficient detection.

•Pioneer experiment [Vienna, 1999]: C_{60} molecules [Fullerene: 700 nucleons] (far field diffraction from gratings)

•Current record: molecule with 10^4 nucleons. Aiming to push it to a million nucleons in the next few years.

Gallery of molecules that show quantum interference

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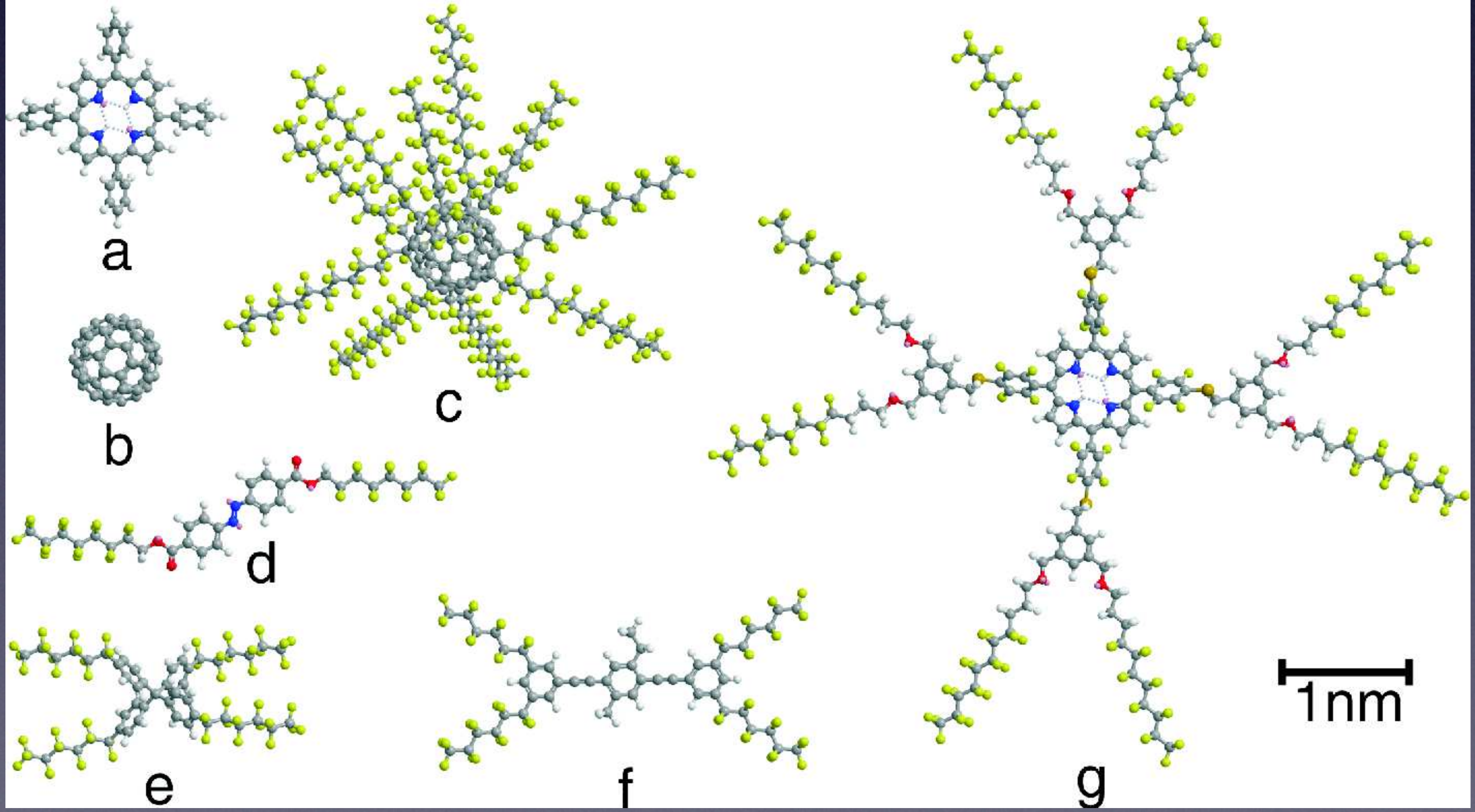


FIG. 7 Gallery of molecules that showed quantum interference in the KDTL interferometer. (a) Tetraphenylporphyrin (TPP); (b) C_{60} fullerene; (c) PFNS10, a carbon nanosphere with ten perfluroalkyl chains (Gerlich *et al.*, 2011); the variant PFNS8 with eight side arms was also used; (d) A perfluoroalkyl-functionalized diazobenzene (Gerlich *et al.*, 2007); (e) - (f) two structural isomers with equal chemical composition but different atomic arrangement (Tüxen *et al.*, 2010); (g) TPPF152, a TPP derivative with 152 fluorine atoms (Gerlich *et al.*, 2011).

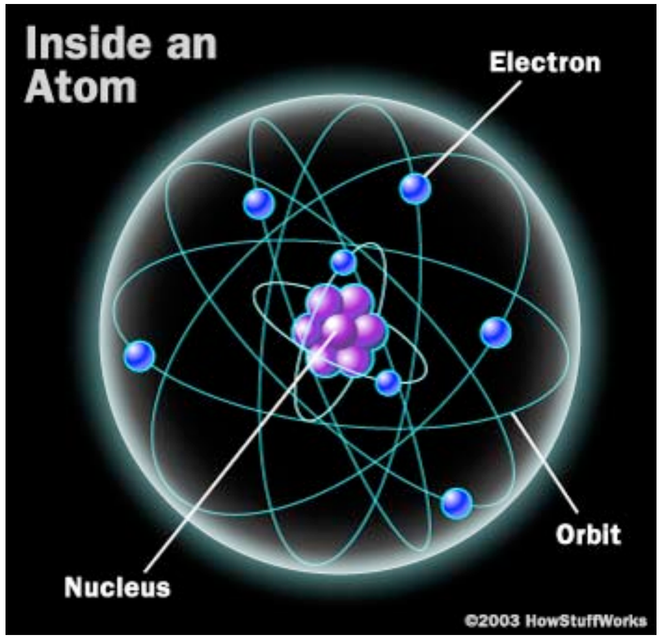
Will the principle hold for larger objects?

- Yes, according to quantum theory. No distinction between micro and macro world.

- But linear superposition of position states does not seem to hold in our day to day world! A table is never simultaneously `here' and `there'.

- Already superposition breaks down at the level of a dust grain : 10^{18} nucleons.

- What could be happening in the experimentally untested desert between 10^4 nucleons and 10^{18} nucleons?



Micro-world

Superposition holds

10^4 nucleons →

Meso-world

??

What could be happening here?

Macro-world

Superposition does not hold

← 10^{18} nucleons

•The Continuous Spontaneous Localization model assumes that the collapse constant

$$\lambda_{CSL} \sim 10^{-17}\mathrm{sec}^{-1}$$

•For the same CSL model Adler has proposed a higher value for the lower bound:

$$\lambda \sim 10^{-9}\mathrm{sec}^{-1}$$

Bounds from Interference Experiments

• Current interferometry experiments give an upper bound $\lambda < 10^{-5}\mathrm{sec}^{-1}$

•It has been suggested that interferometry experiments with particles having a million nucleons will be sensitive to Adler's value of λ

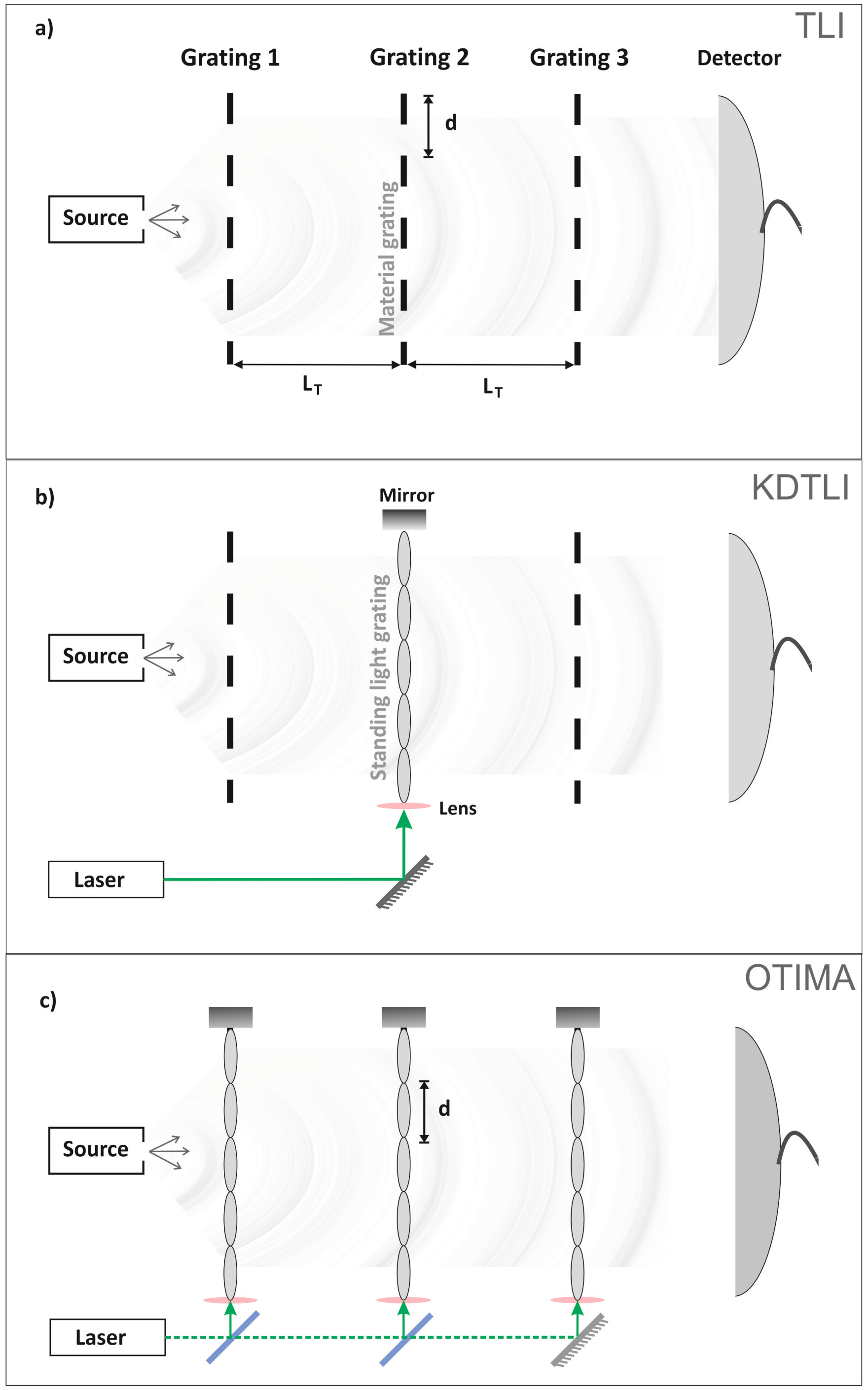
Decoherence: thermal decoherence and collisional decoh.

CSL and matter-wave interferometry:

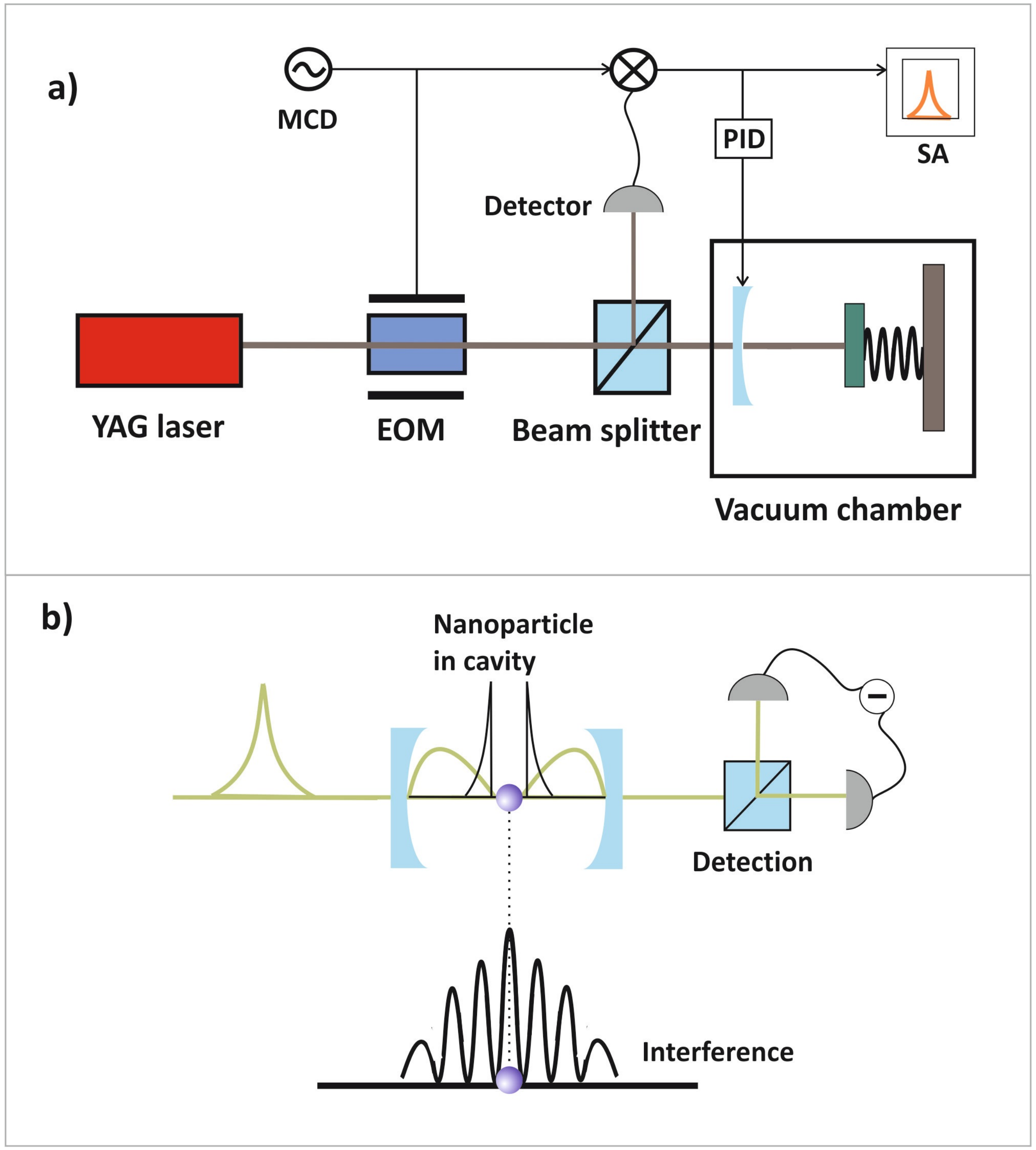
$$\frac{d}{dt}\rho_t = -\frac{i}{\hbar}[H, \rho_t] - \frac{1}{2}\sum_{i=1}^{n} \lambda_i [q_i, [q_i, \rho_t]].$$

$$\rho_t(x, y) = \rho_0(x, y) e^{-\lambda N (x-y)^2 t/2}.$$

Interferometers:



Optomechanics:



MERID

Anomalous Brownian Motion

- The stochastic hits in CSL predict a very tiny violation of momentum and energy conservation.

- Momentum violation results in an anomalous Brownian motion of a quantum particle subject to these hits.

- The estimated displacement of a micron sized sphere is of the order of its size, over a few seconds.

- This is in principle detectable at a pressure of about 10^{-11} Torr and temperature few Kelvin: ordinary Brownian motion and thermal effects are sufficiently suppressed.

[Collett and Pearle 2001; Bera et al. 2015]

Constraints from other physical prcesses

- No Decay of supercurrents in SQUIDS: $\lambda < 10^{-3}$
- No Proton decay: $\lambda < 10$
- Spontaneous X-ray emission from Germanium: $\lambda < 10^{-11}$
- Effect on rate of radiation from free electrons: $\lambda < 10^{-5}$

Constraints from astrophysics and cosmology

- Dissociation of cosmic hydrogen: $\lambda < 1$
- Heating of interstellar dust grains: $\lambda < 10^{-2}$
- Heating of intergalactic medium: $\lambda < 10^{-9}$
- Bound from spectral distortion of CMBR: $\lambda < 10^{-4}$

[Das, Lochan, Bassi]

- Generation of density perturbations during inflation

[Das et al. 2014, 2015]

SUMMARY

- The Schroedinger equation does not explain collapse of the wave function.

- A modified stochastic non-linear equation explains collapse, and is consistent with all known experiments.

- In the mesoscopic regime the predictions of this equation differ from those of the Schroedinger equation, and are being tested in the laboratory.

- The fundamental origins of this equation possibly have to do with gravity, and with the problem of time in quantum theory.

- The relativistic version remains to be developed.