Title: On the Interplay Between General Relativity and Quantum Mechanics

Speakers: Roger Penrose

Series: Colloquium

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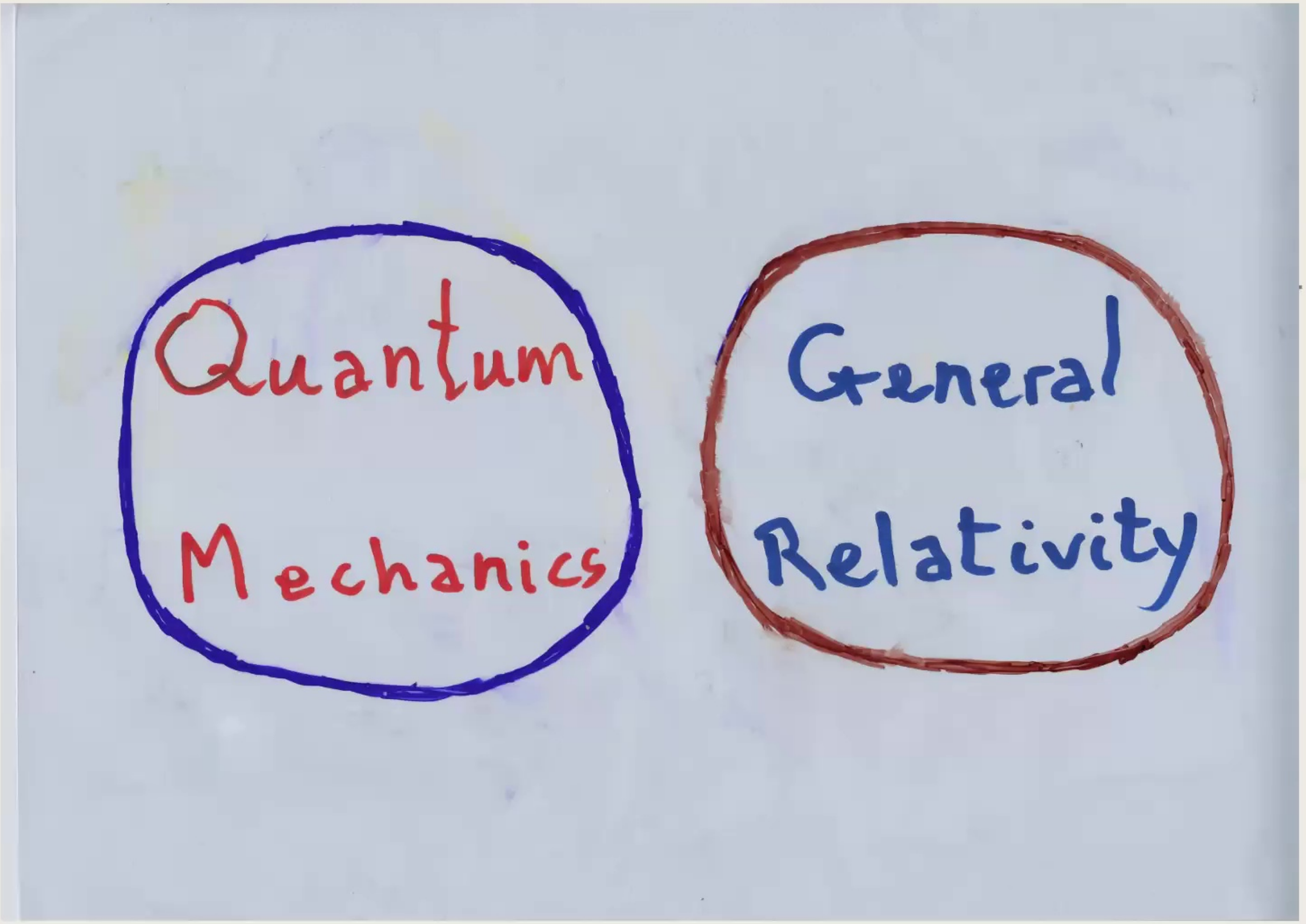
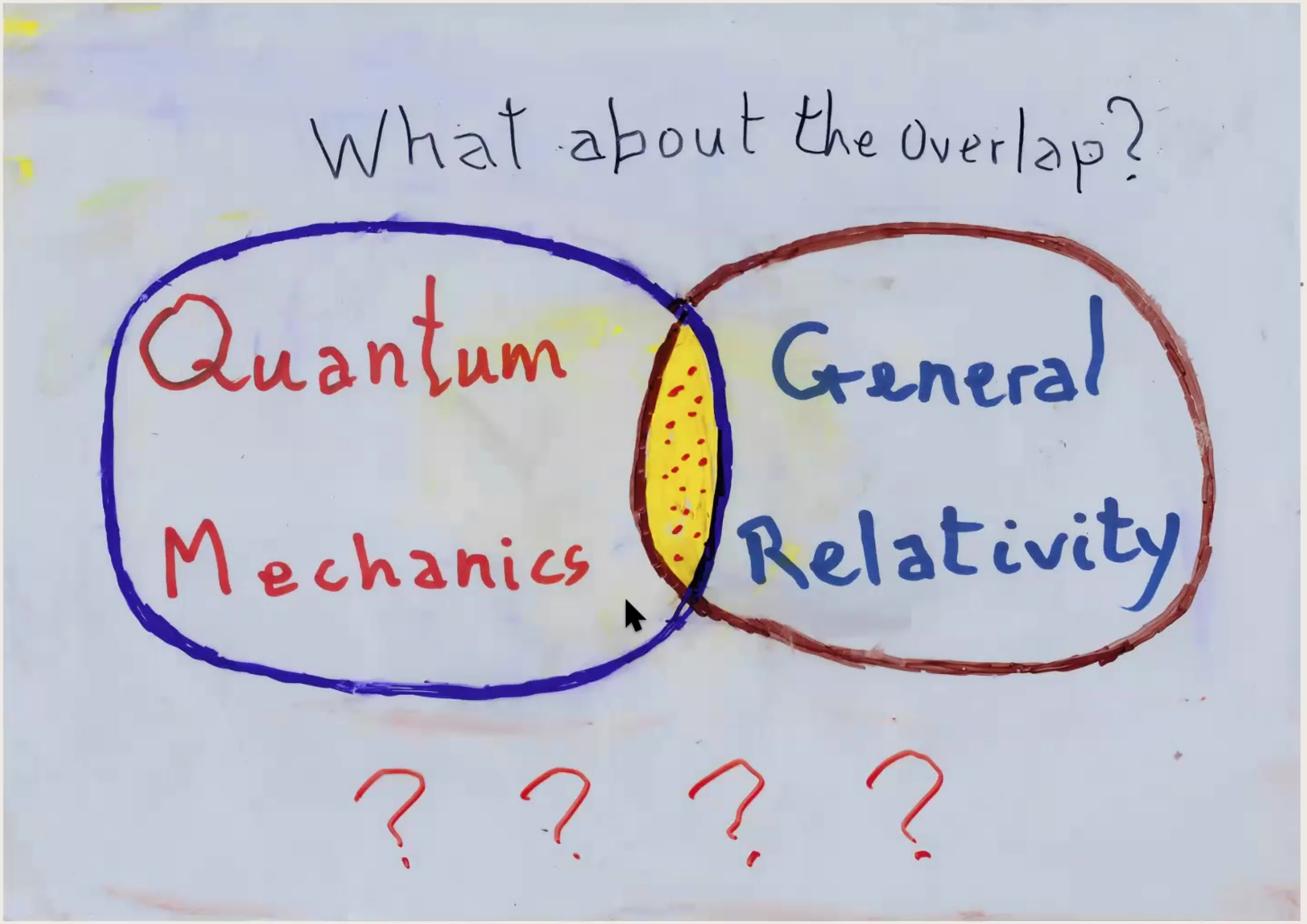
Abstract: There has been much theorizing on the question of how the procedures of quantum theory might modify general relativity, perhaps leading to a resolution of the problem of the space-time singularities of gravitational collapse. However, I shall argue that these procedures cannot, alone, resolve the space-time singularity issue. Instead, I shall maintain that considerations of relativity, both special and general, could well provide pointers to how the major conundrum of quantum mechanicsâ€”the collapse of the wave-functionâ€”may eventually be resolved, via curious retro-active aspects of quantum and classical reality.

Quantum Mechanics

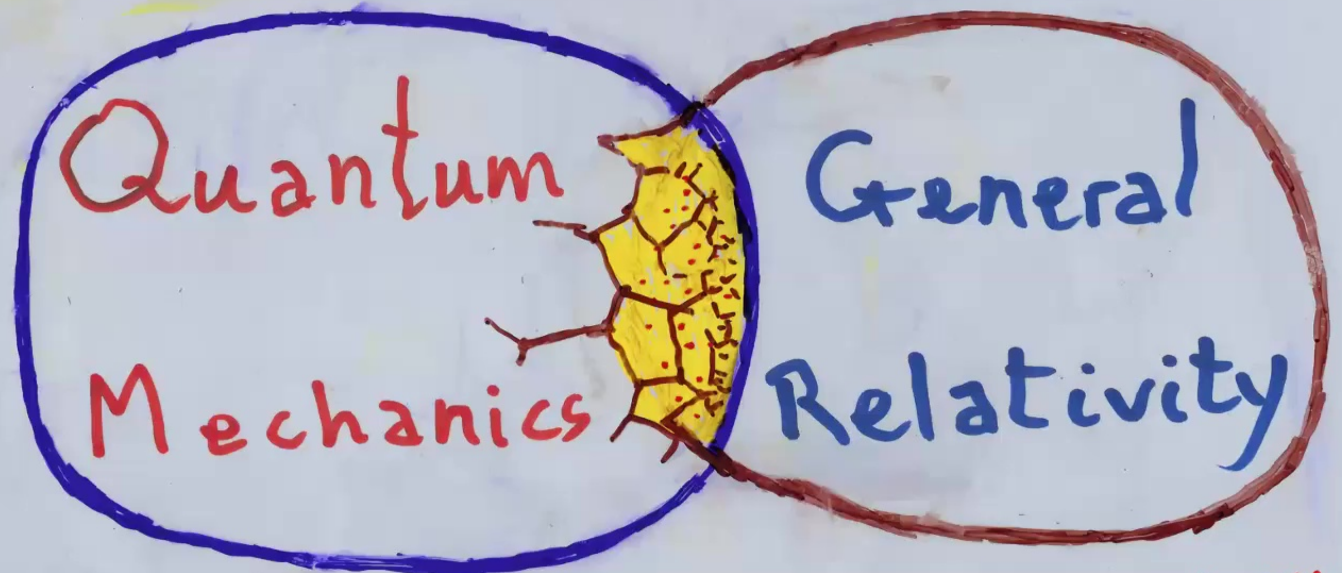
General Relativity


Quantum
Mechanics
General
Relativity


What about the overlap?
Quantum Mechanics
General Relativity
? ? ? ?

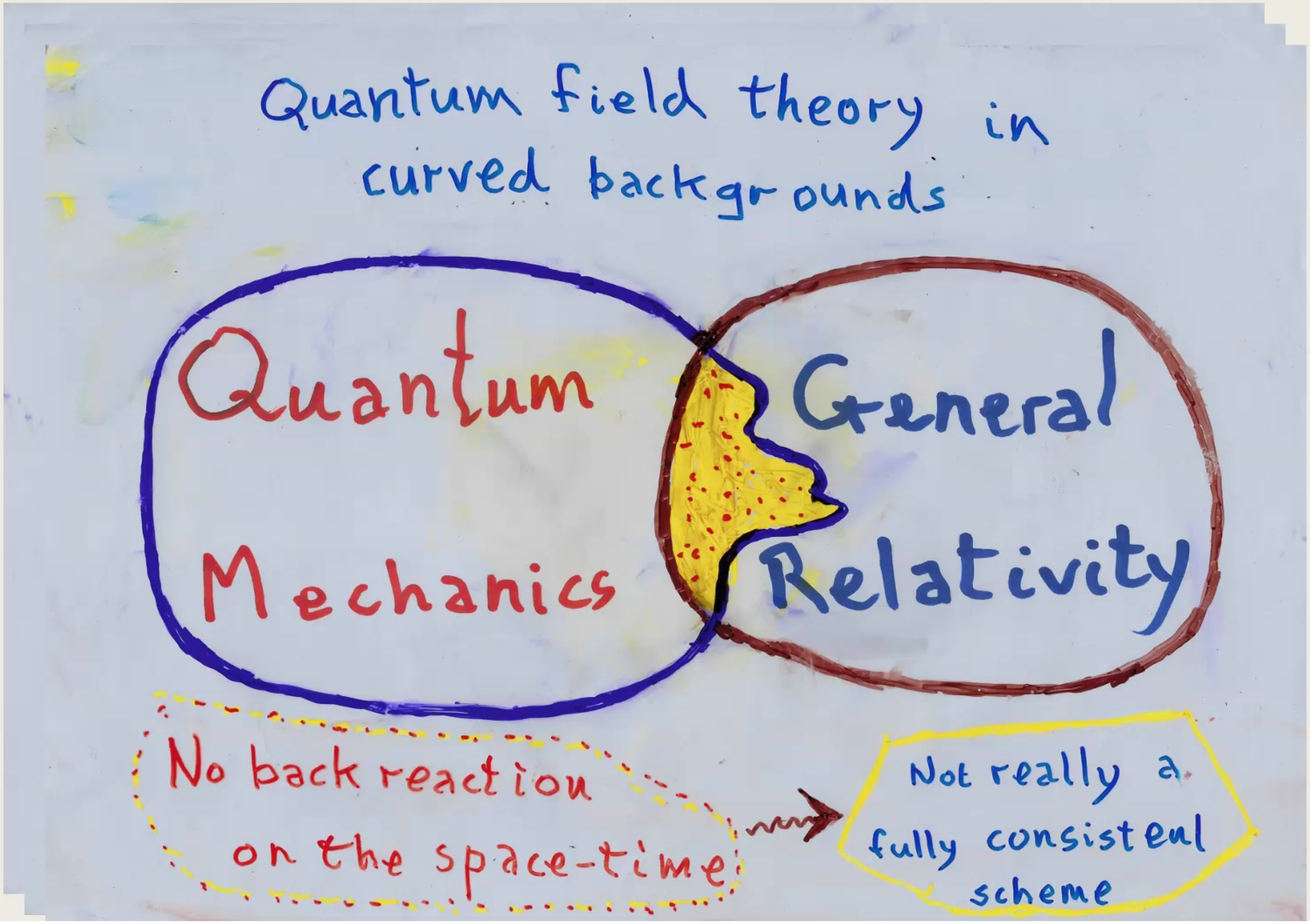
Graviton scatterings, Feynman graphs

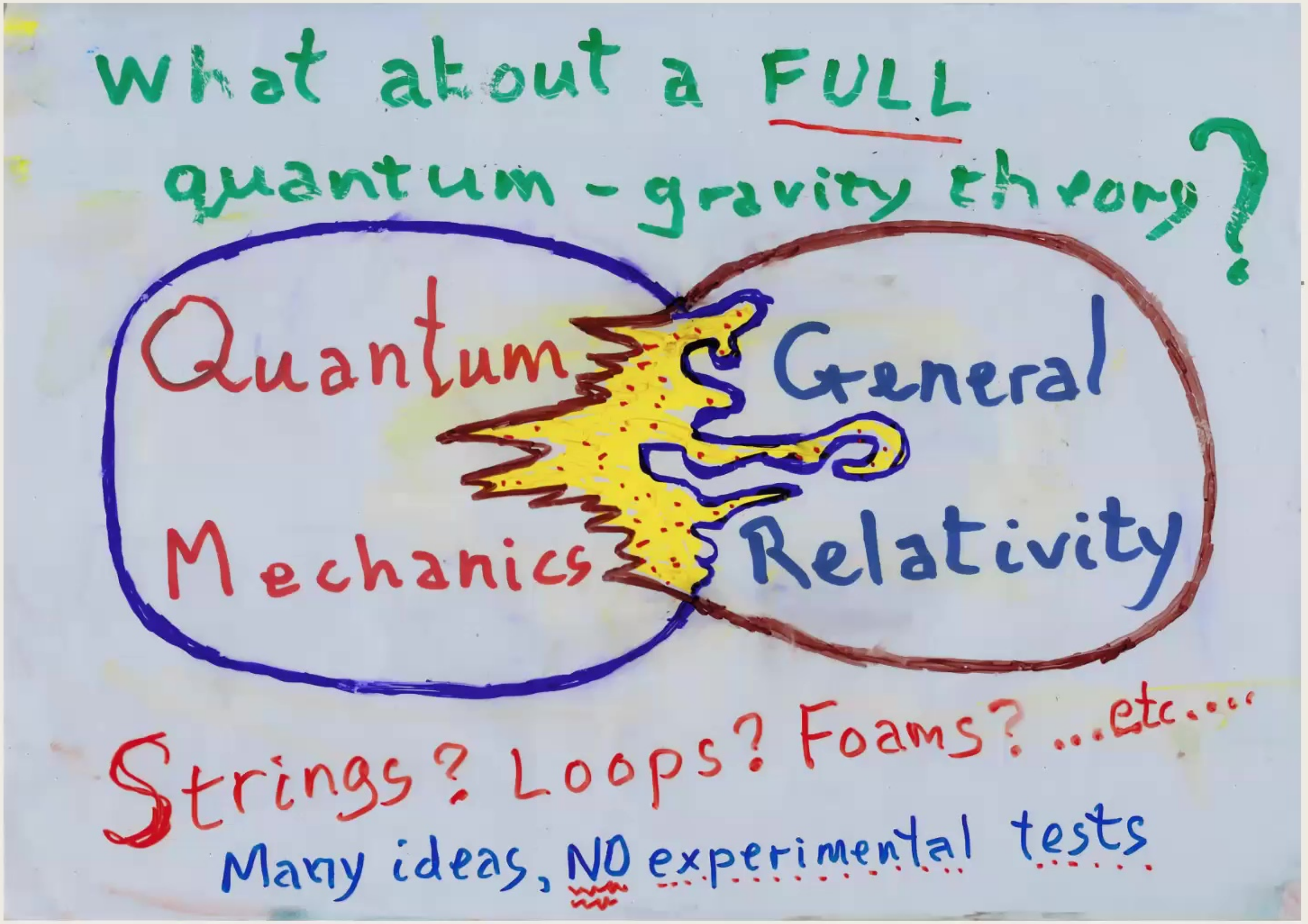
Feynman, de Witt, etc. etc.

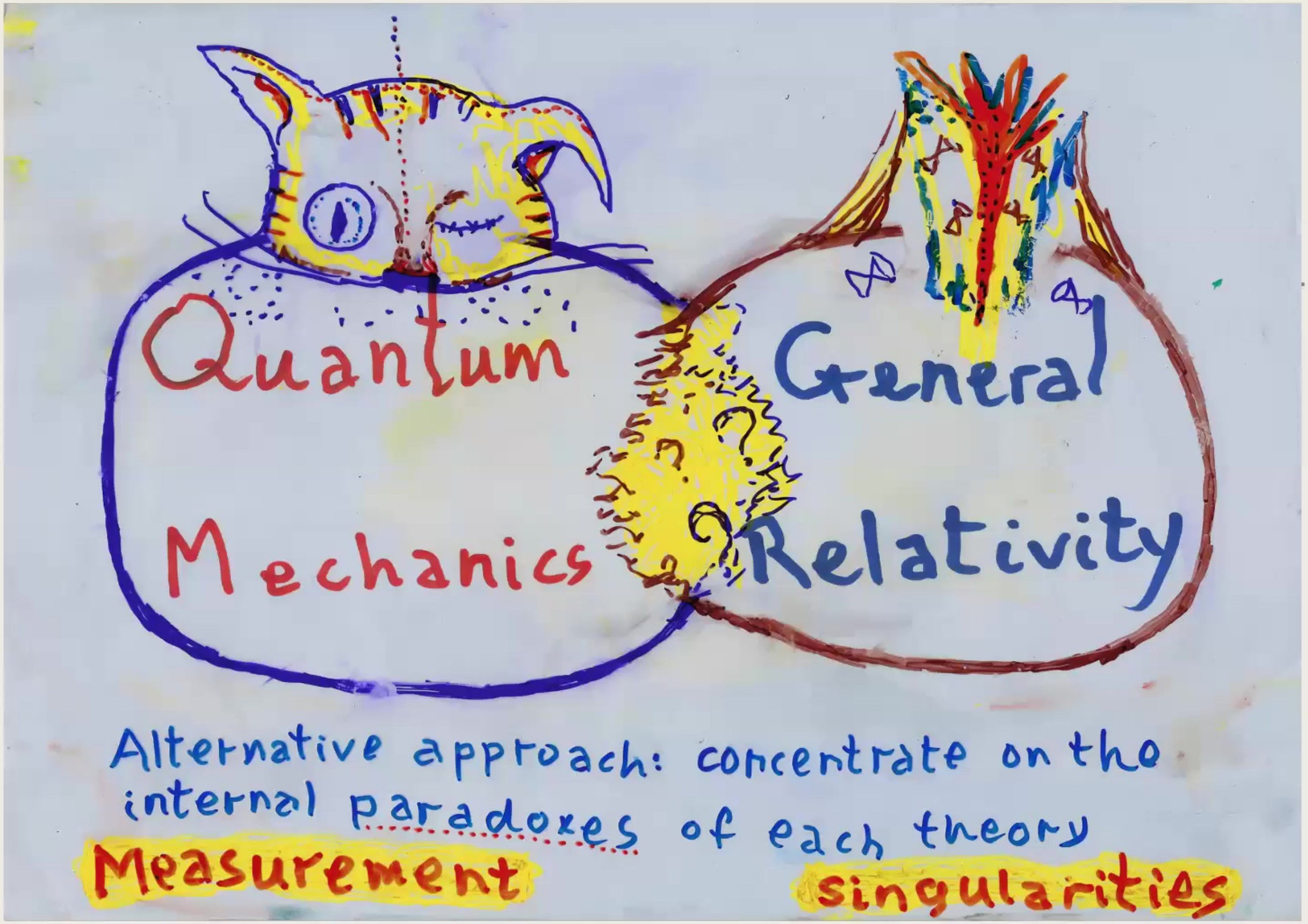


Very complicated (... but twistors ...). Actual curvature doesn't really come in. Divergences .... No black holes.

Lots of work, but we don't seem to learn anything of importance about the union.


Quantum field theory in curved backgrounds
Quantum Mechanics
General Relativity
No back reaction on the space-time
Not really a fully consistent scheme


What about a FULL
quantum-gravity theory?
Quantum
Mechanics
General
Relativity
Strings? Loops? Foams? ...etc....
Many ideas, NO experimental tests


Quantum
Mechanics
General
Relativity
Alternative approach: concentrate on the internal paradoxes of each theory
Measurement
singularities

Space-time Singularities

Cannot be a purely quantum-gravity problem. because:

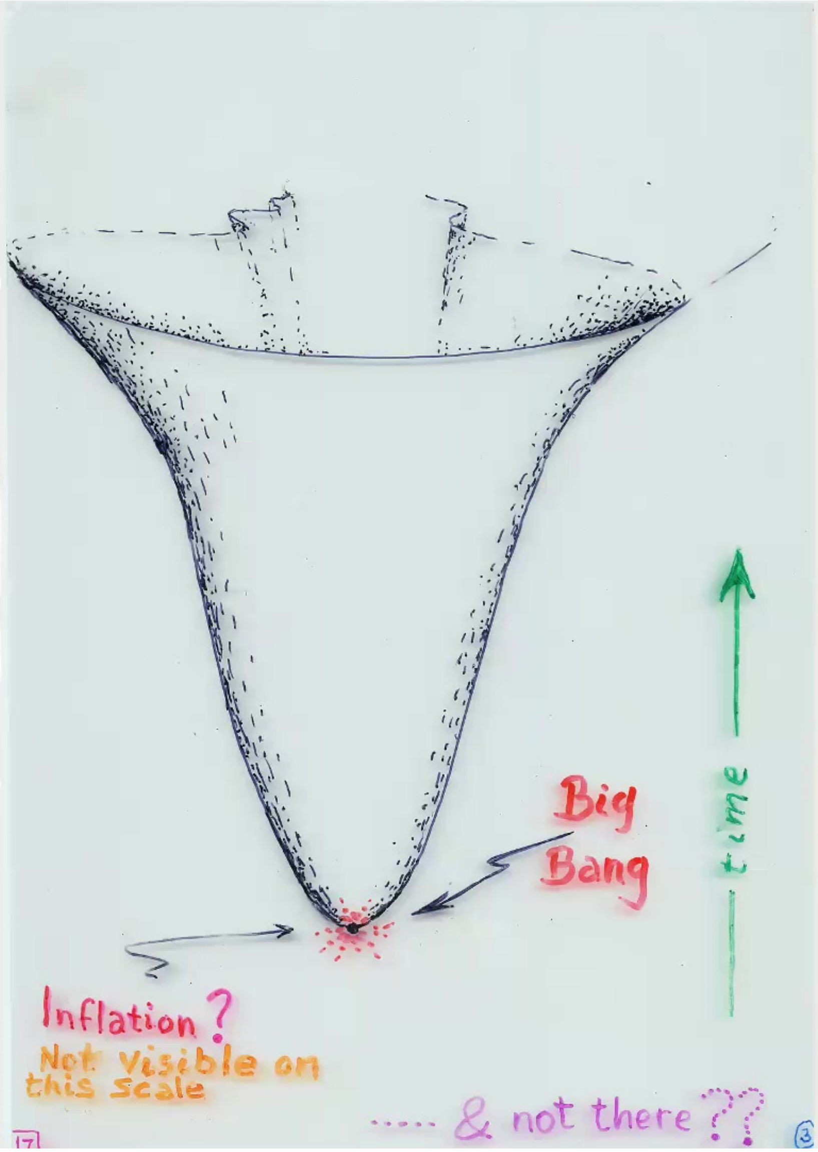
for singularities in black holes

Weyl curvature $\rightarrow \infty$

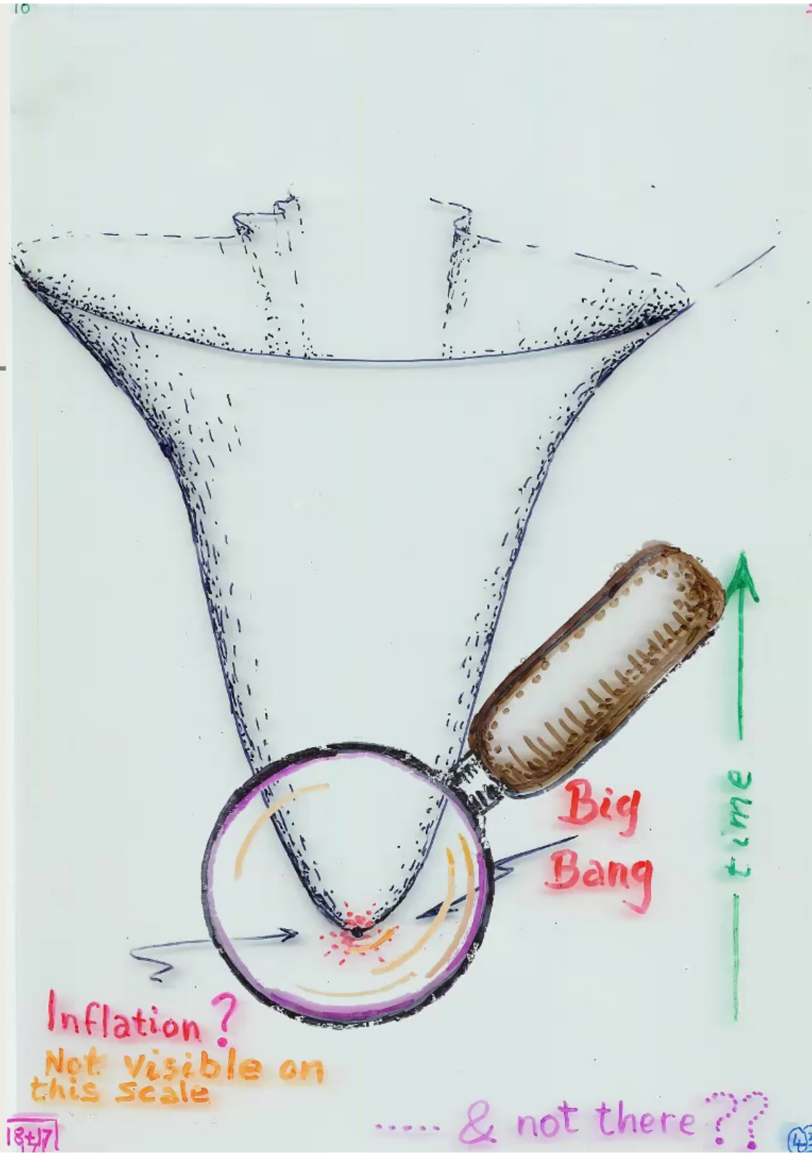
for the Big Bang

Weyl curvature $\rightarrow 0$

$\therefore$ Time-asymmetric theory!

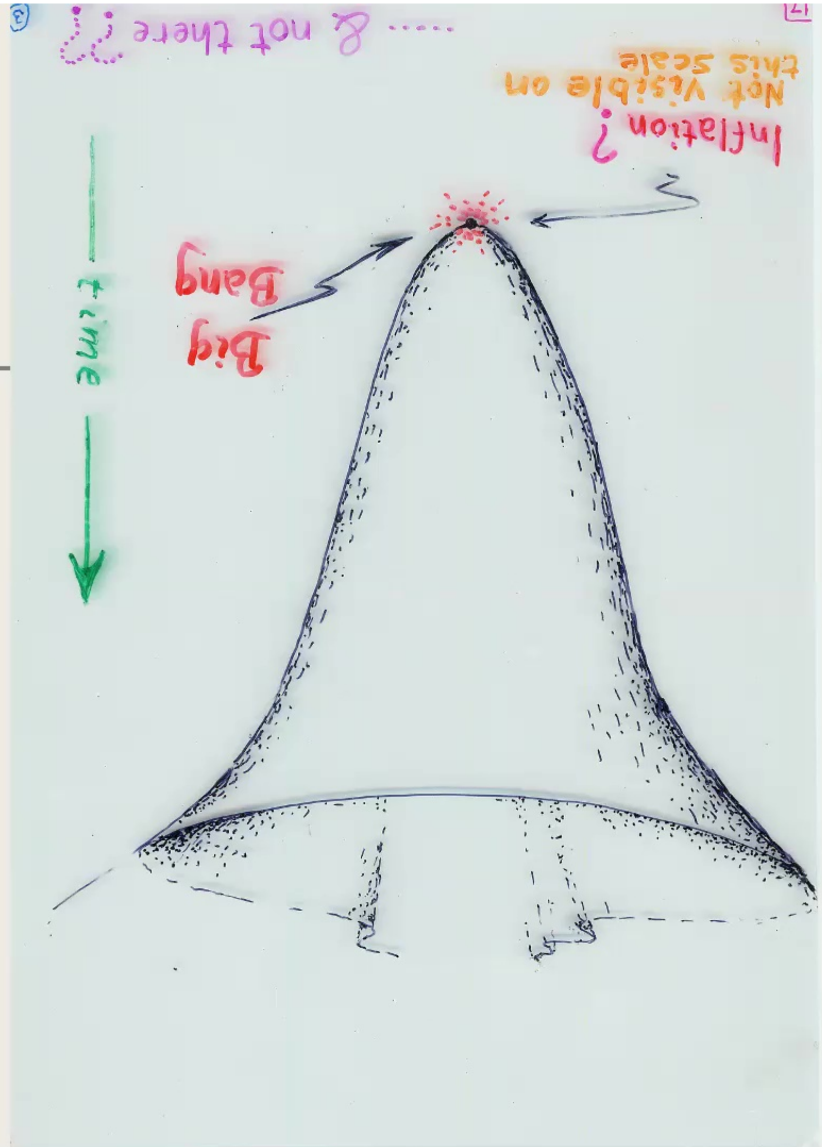


Big
Bang
time
Inflation?
Not visible on
this scale
..... & not there ??

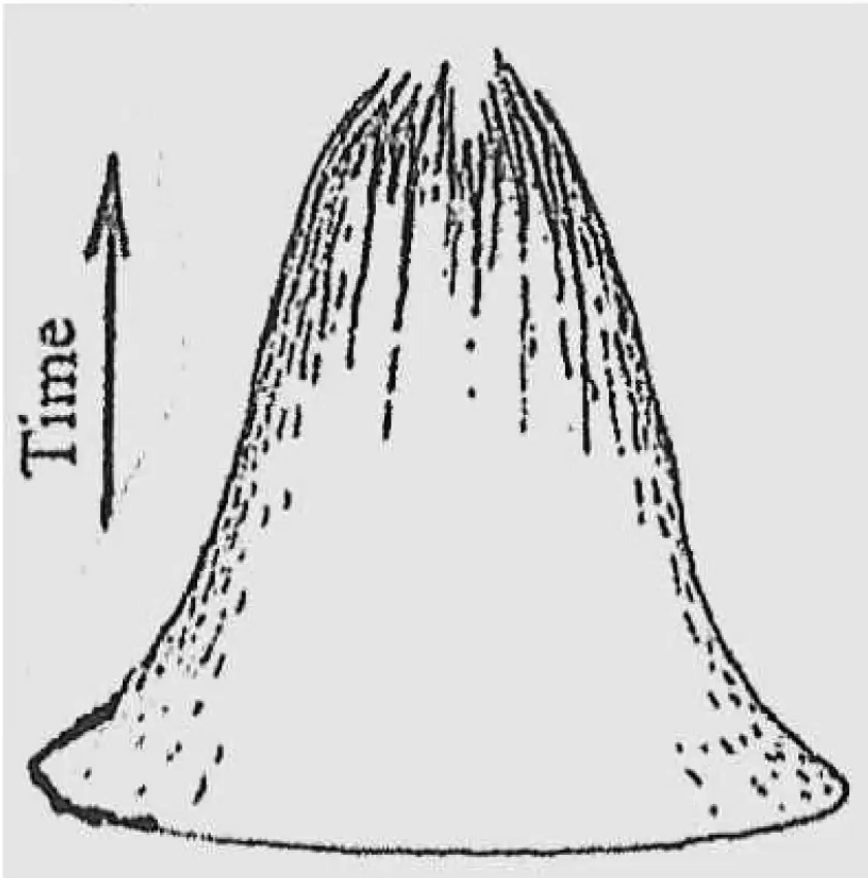


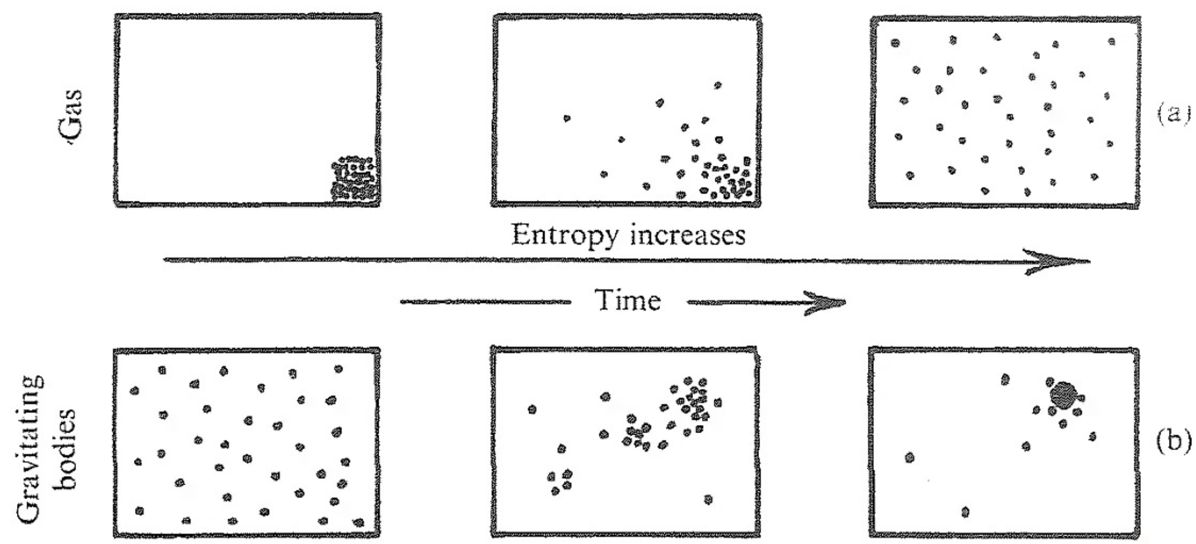
Big
Bang
time
Inflation ?
Not visible on
this scale
..... & not there ??

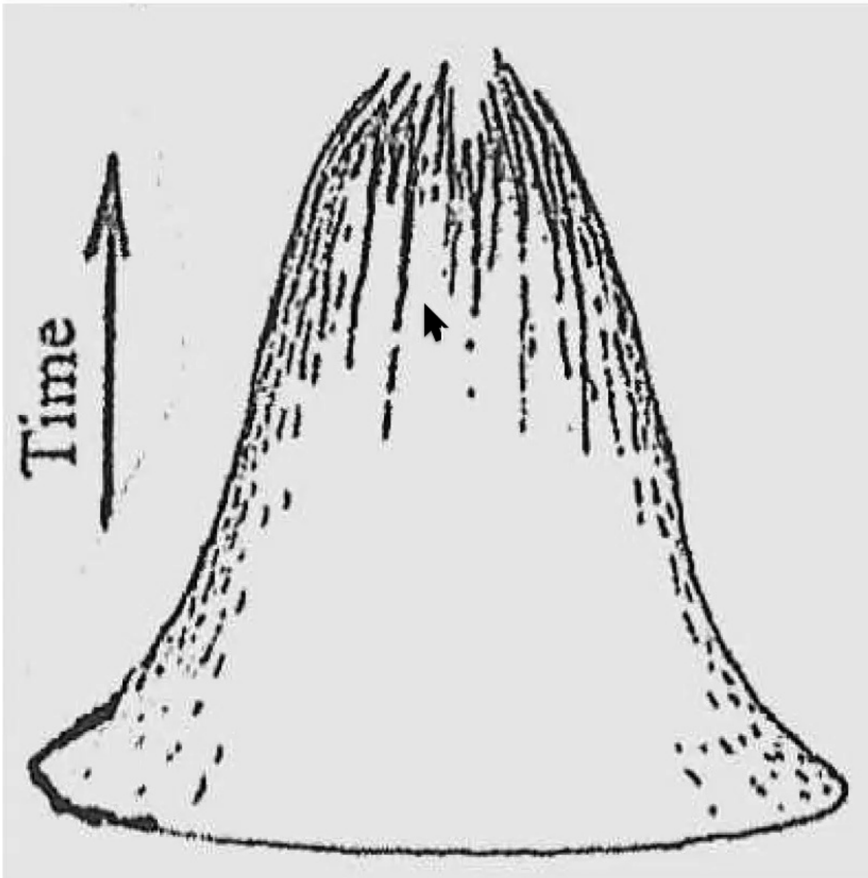

Inflation
Big Bang
19
5



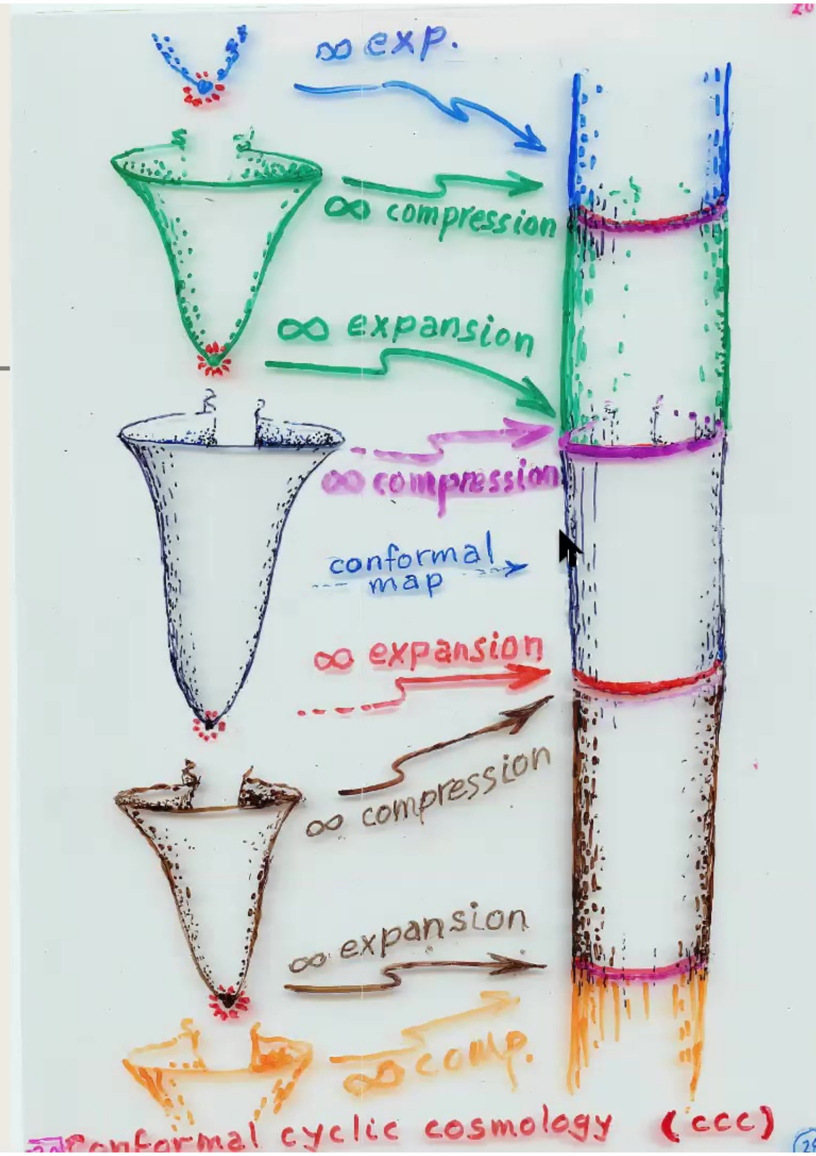
Inflation?
Not visible on this scale
..... & not there ??
Big Bang
time


Time

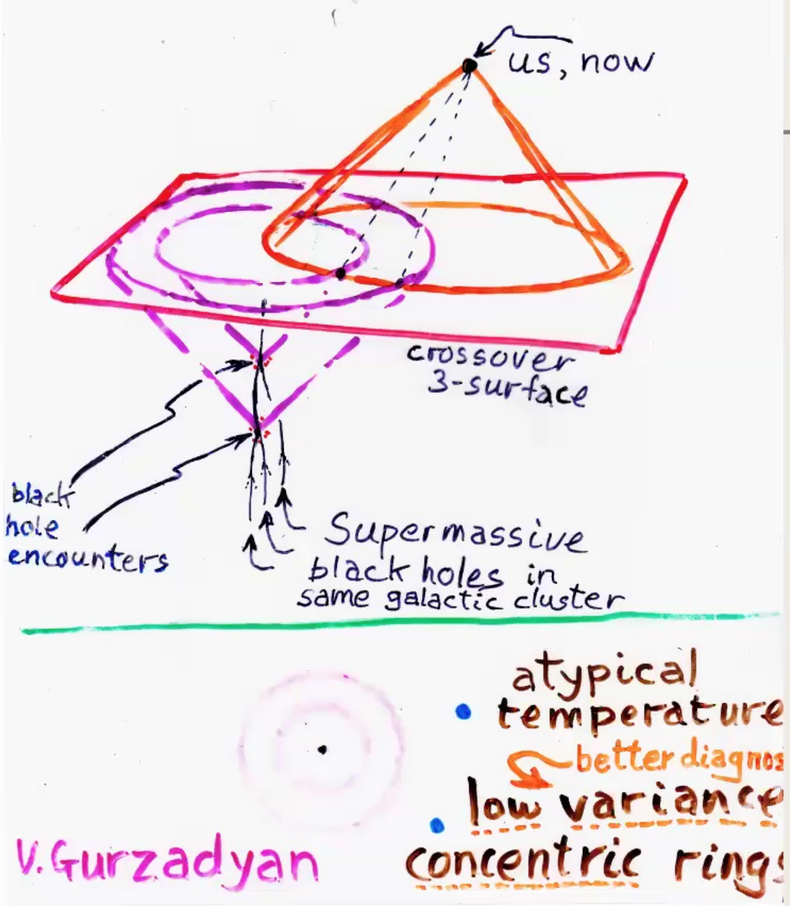

Gas
(a)
Entropy increases
Time
Gravitating bodies
(b)

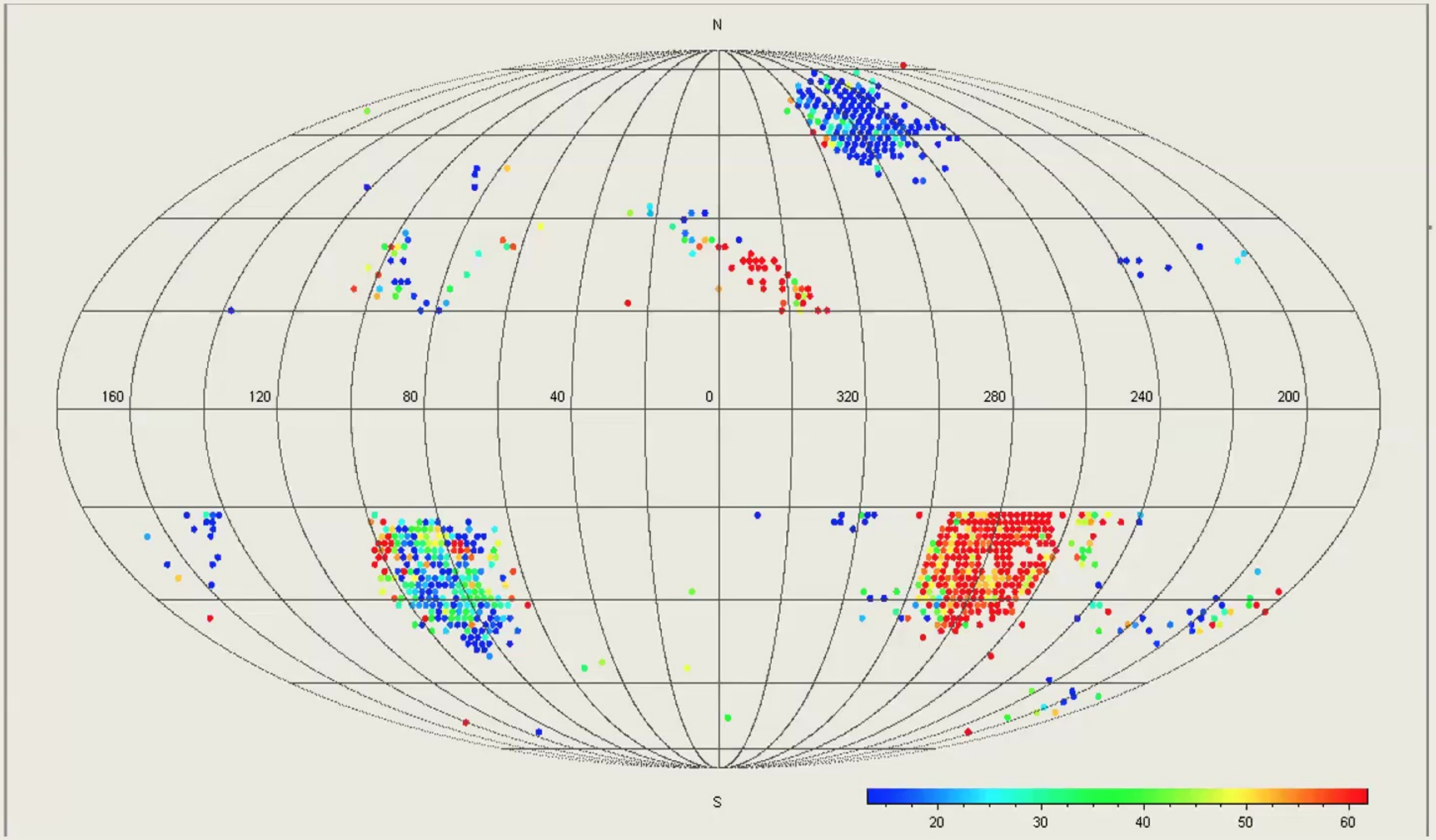

Time

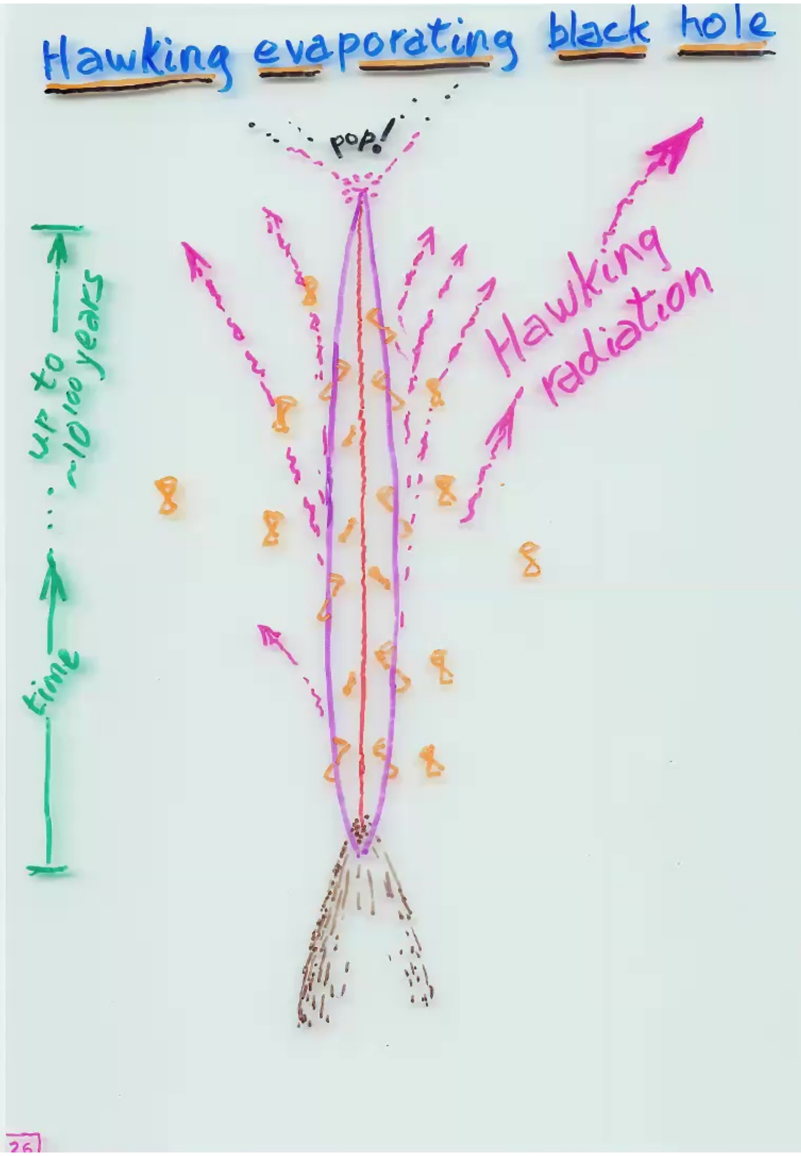

∞ compression
conformal map
∞ expansion

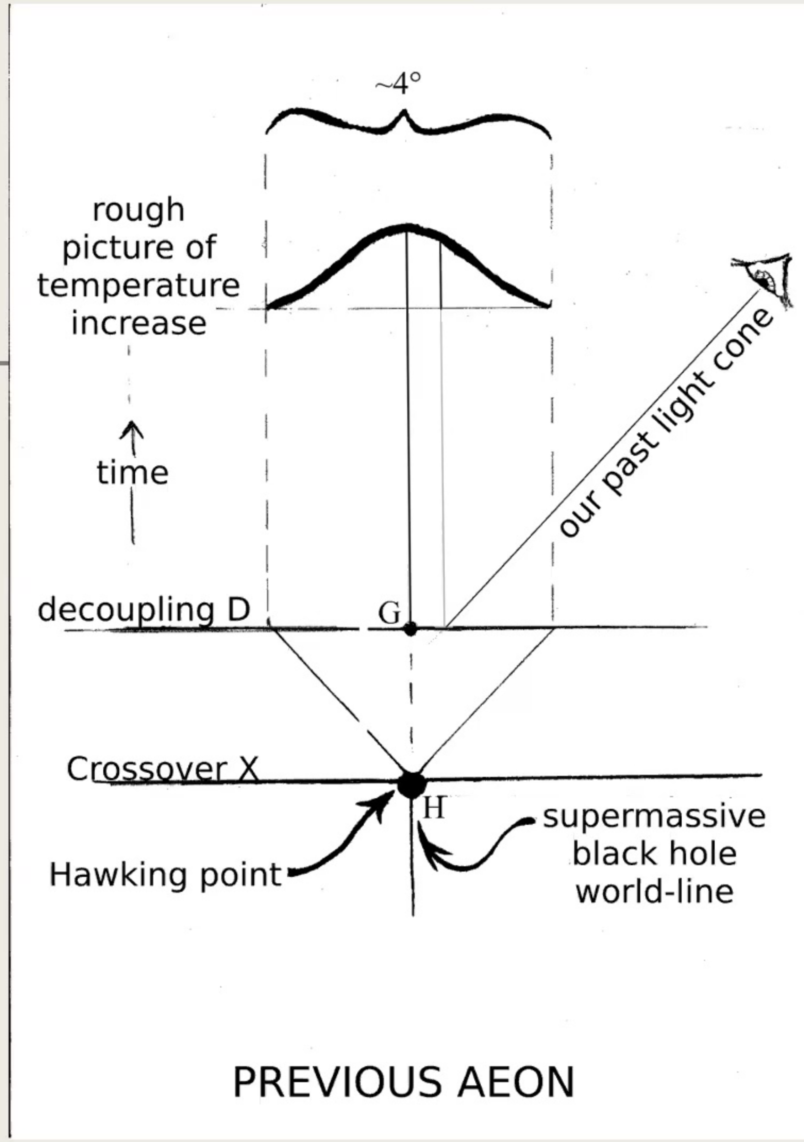

∞ exp.
∞ compression
∞ expansion
∞ compression
conformal map
∞ expansion
∞ compression
∞ expansion
∞ comp.
conformal cyclic cosmology (ccc)

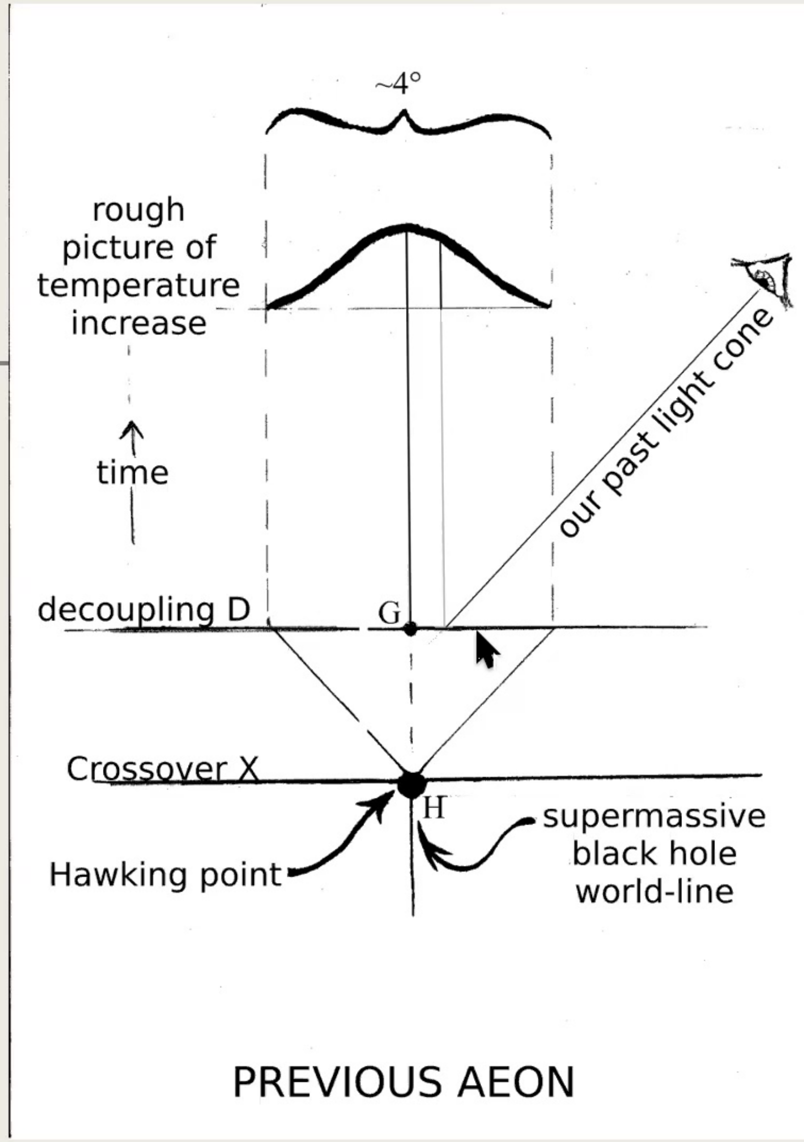
Can we "see" through into the aeon prior to ours?

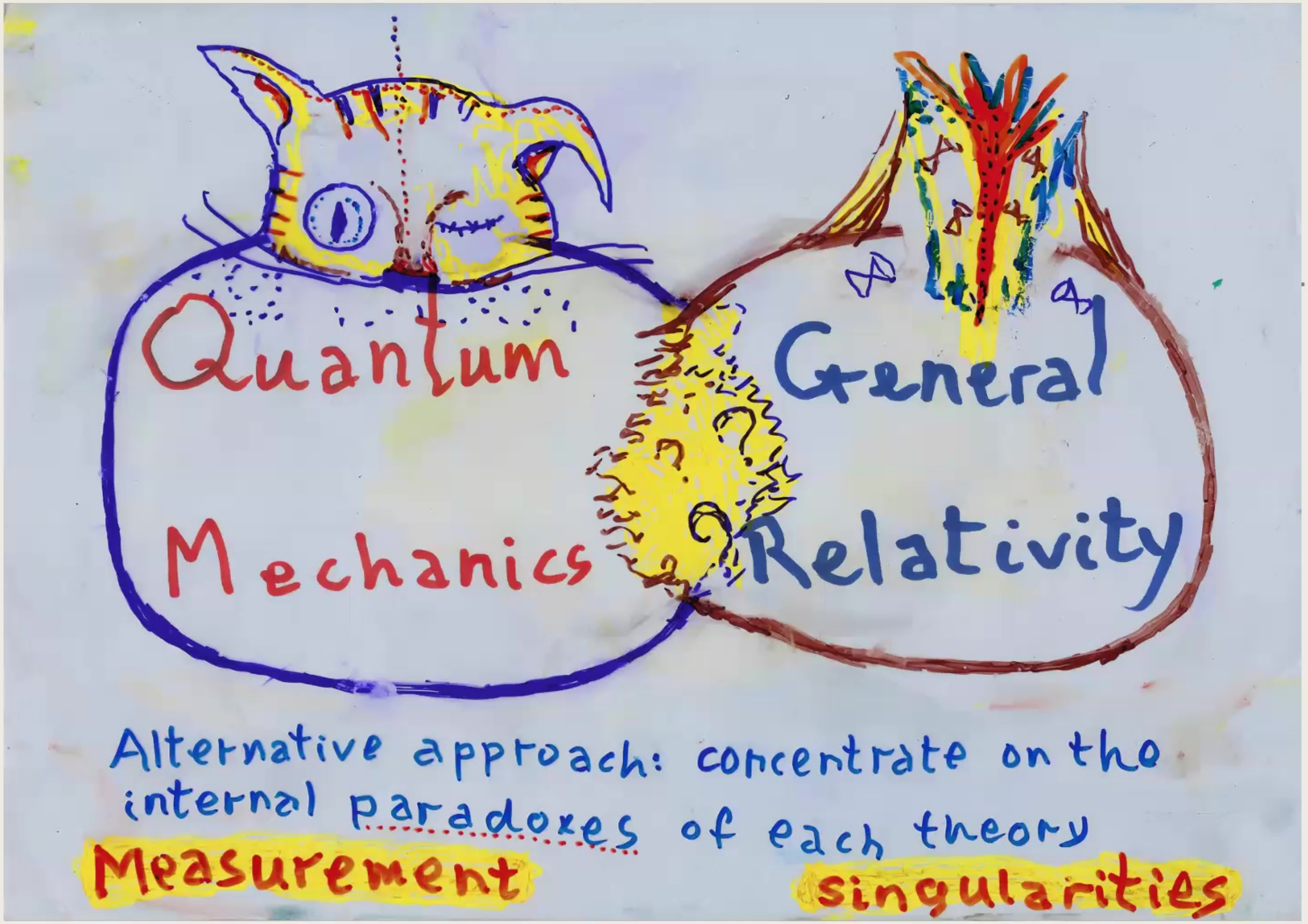



N
160
120
80
40
0
320
280
240
200
S
20
30
40
50
60


Hawking evaporating black hole
pop!
Hawking radiation
up to ~10^{100} years
time
26


~4°
rough picture of temperature increase
time
our past light cone
decoupling D
G
Crossover X
H
Hawking point
supermassive black hole world-line
PREVIOUS AEON


~4°
rough picture of temperature increase
time
our past light cone
decoupling D
G
Crossover X
H
Hawking point
supermassive black hole world-line
PREVIOUS AEON

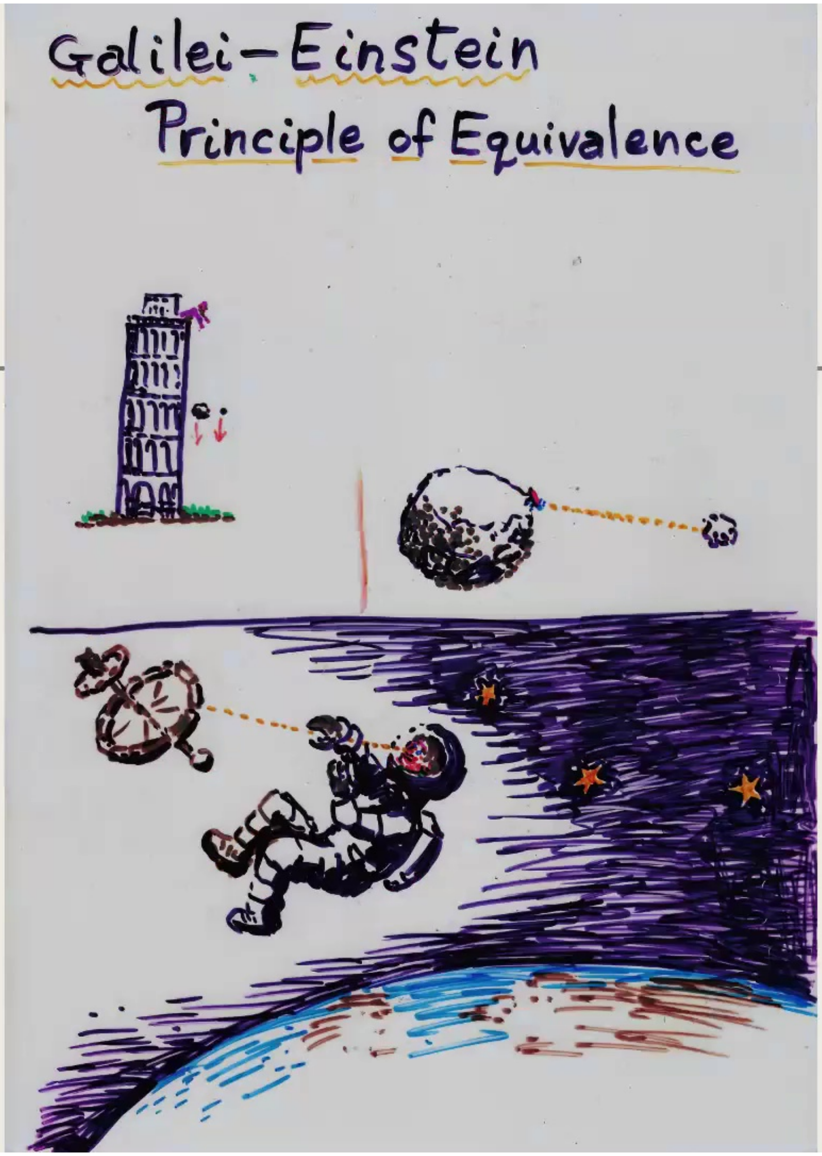

Quantum
Mechanics
General
Relativity
Alternative approach: concentrate on the internal paradoxes of each theory
Measurement
singularities

John S. Bell ("Against Measurement"*)

FAPP = For All Practical Purposes

"Suppose that when a formulation beyond FAPP is attempted, we find an unmovable finger obstinately pointing outside the subject, to the mind of the observer, to the Hindu scriptures, to God, or even only Gravitation? Would that not be very, very interesting?

*Physics World (1990)


Galilei-Einstein
Principle of Equivalence

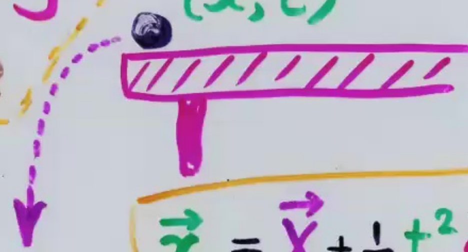
Principle of Equivalence and QM

(c = ∞) Const. grav. field $\vec{g}$

$(\vec{x}, t)$-system, fixed on table

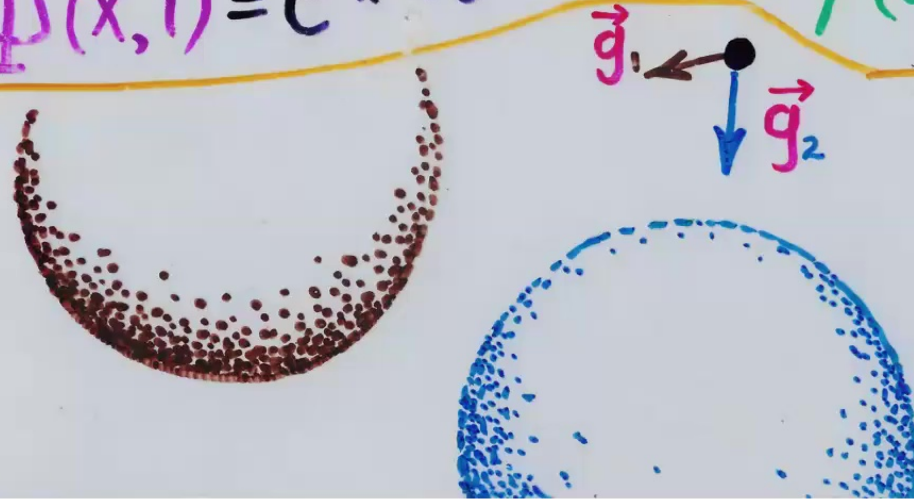
$(\vec{X}, t)$-syst. free fall, so grav. field = 0

$(\vec{X}, T)$



$$\vec{x} = \vec{X} + \tfrac{1}{2} t^2 \vec{g}$$
$$t = T$$

$$\Psi(\vec{X}, T) = e^{\frac{iM}{\hbar}\left(\frac{t^3 g^2}{6} - t\,\vec{x}\cdot\vec{g}\right)}\,\psi(\vec{x}, t)$$

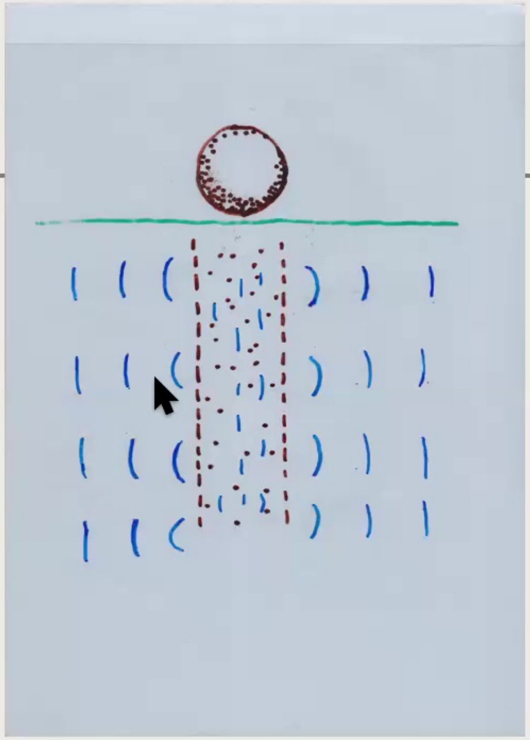


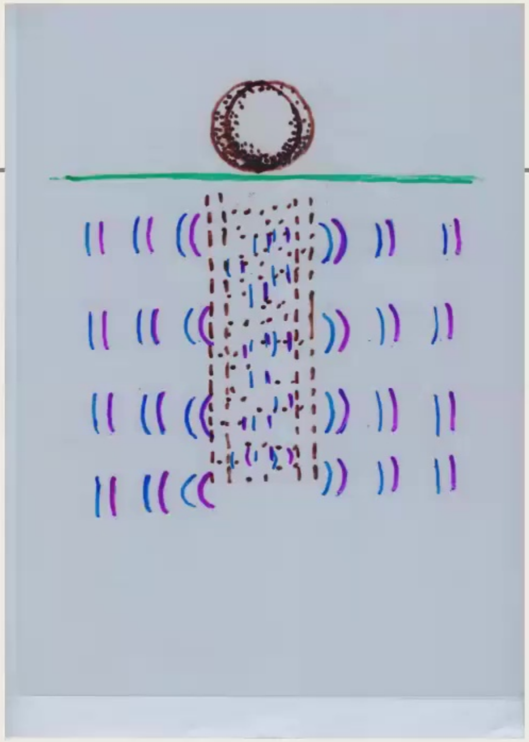
Colella
Overhauser
Werner

$c \to \infty$ limit of Unruh Vacuum

$$\int (\vec{g}_1 - \vec{g}_2)^2 d^3x = E_G$$

= grav. self-energy of difference mass distr





Diósi 1984, 1987, 1989 ....

Penrose 1986, 1993, 1996, 2014 ...

OR = "objective reduction of state

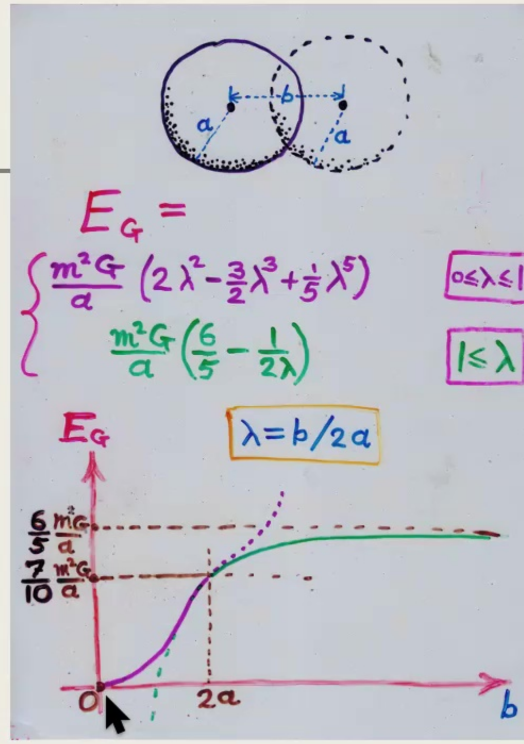
E_G = gravitational self-energy of the difference between the two mass distributions of a superposition of a body in two distinct locations.

(For a rigid translation, E_G = energy of displacing one instance of the body away from the gravitational field of the other.)

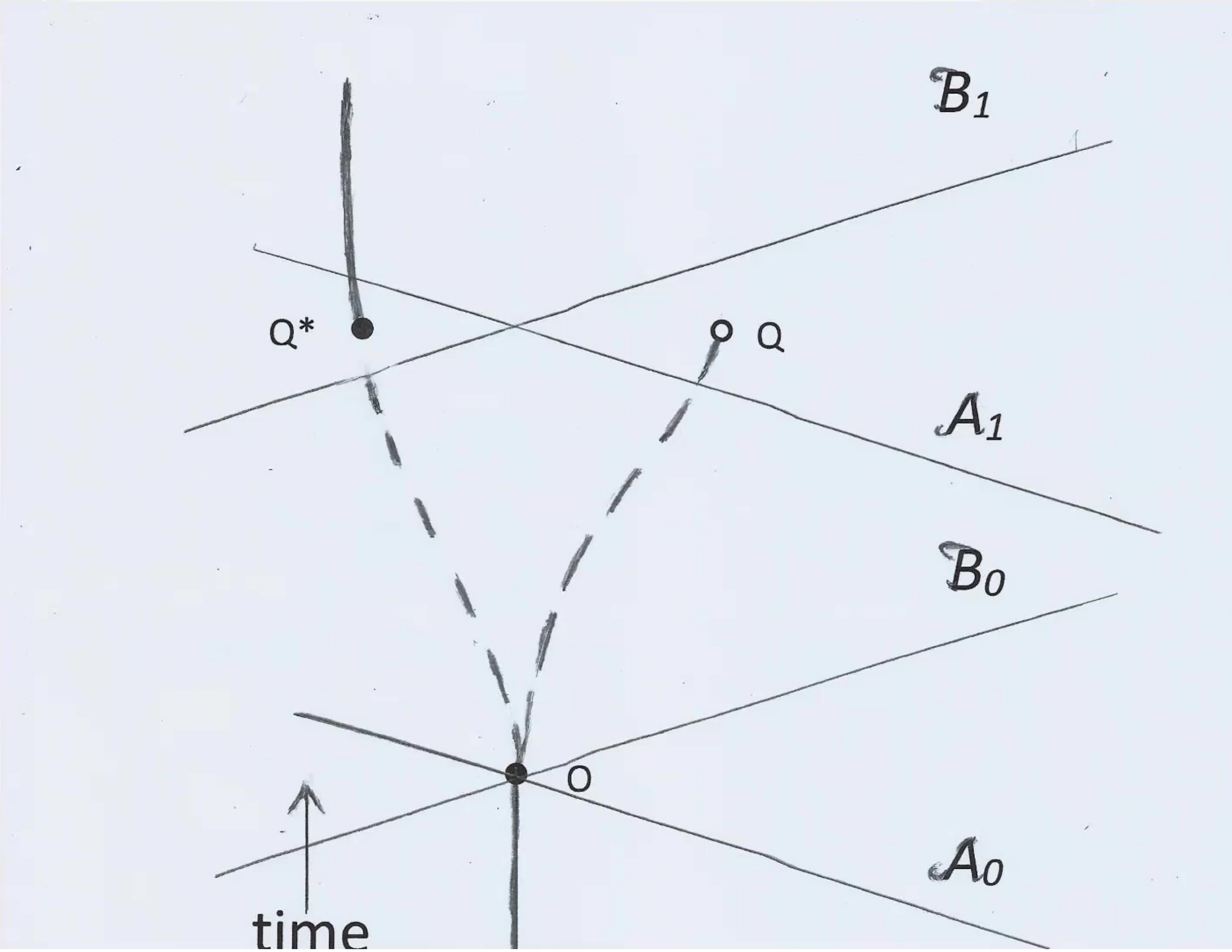
Average collapse time $\approx \dfrac{\hbar}{E_G}$

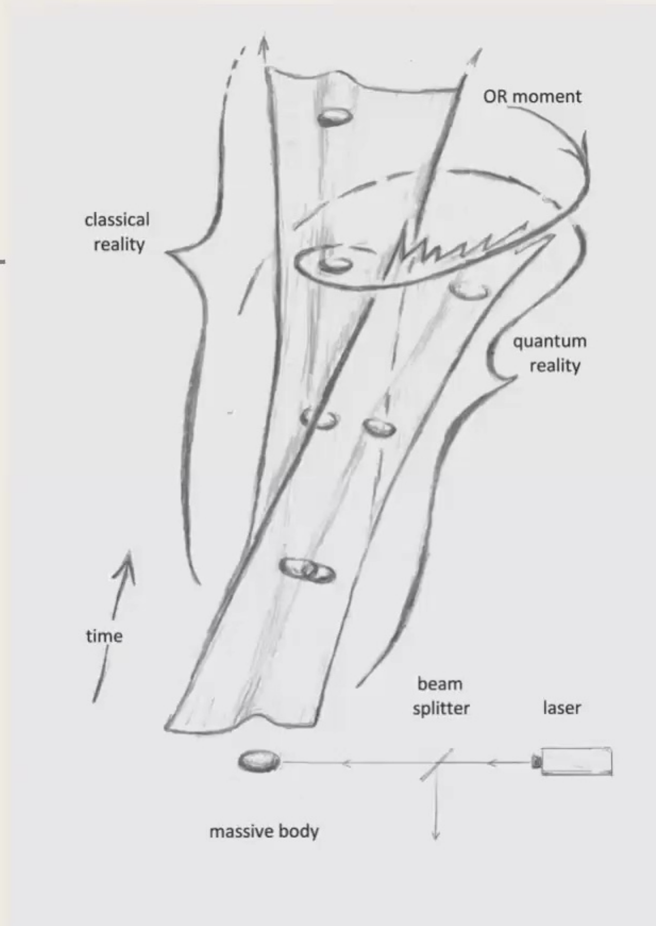
unknown constant!

Comes from Heisenberg time/energy uncertainty (like the decay of an unstable particle or



a
b
a
$E_G =$
$\frac{m^2 G}{a}\left(2\lambda^2 - \frac{3}{2}\lambda^3 + \frac{1}{5}\lambda^5\right)$
$0 \le \lambda \le 1$
$\frac{m^2 G}{a}\left(\frac{6}{5} - \frac{1}{2\lambda}\right)$
$1 \le \lambda$
E_G
$\lambda = b/2a$
$\frac{6}{5}\frac{m^2G}{a}$
$\frac{7}{10}\frac{m^2G}{a}$
0
2a
b


$\mathcal{B}_1$
Q*
Q
$\mathcal{A}_1$
$\mathcal{B}_0$
O
$\mathcal{A}_0$
time


OR moment
classical
reality
quantum
reality
time
beam
splitter
laser
massive body

Physical reality?

- **Classical Reality**

One can ask, of a system "What is your state?" and it can correctly answer "My state is X"

- **Quantum Reality**

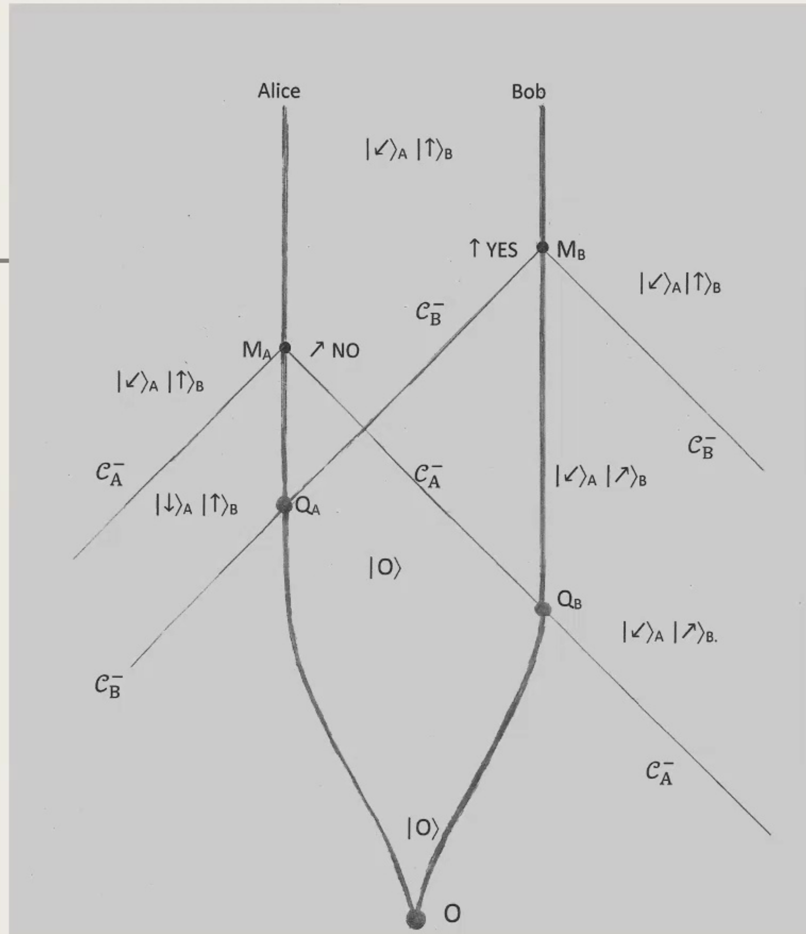
One can only sugest to a system "Is your state X" and if you are correct, the system replies, with certainty "Yes, my state is indeed X"

Quantum Reality

by Einstein's dictum

If, without in any way disturbing a system, we can predict with certainty (i.e. with probability unity) the value of a physical quantity, then there exists an element of physical reality corresponding to this physical quantity.

Albert Einstein 1935


Alice
Bob
|↙⟩A |↑⟩B
↑ YES
MB
|↙⟩A|↑⟩B
$\mathcal{C}_B^-$
MA
↗ NO
|↙⟩A |↑⟩B
$\mathcal{C}_B^-$
$\mathcal{C}_A^-$
$\mathcal{C}_A^-$
|↙⟩A |↗⟩B
|↓⟩A |↑⟩B
QA
|O⟩
QB
|↙⟩A |↗⟩B.
$\mathcal{C}_B^-$
$\mathcal{C}_A^-$
|O⟩
O

Can OR depend on the amplitudes?

~ Donadi argument

$$|\nearrow\rangle_B = \alpha|\uparrow\rangle_B + \beta|\downarrow\rangle_B$$

$$\text{or } \bar{\beta}|\uparrow\rangle_B - \bar{\alpha}|\downarrow\rangle_B$$

Alice meaures

Take it all in one plane

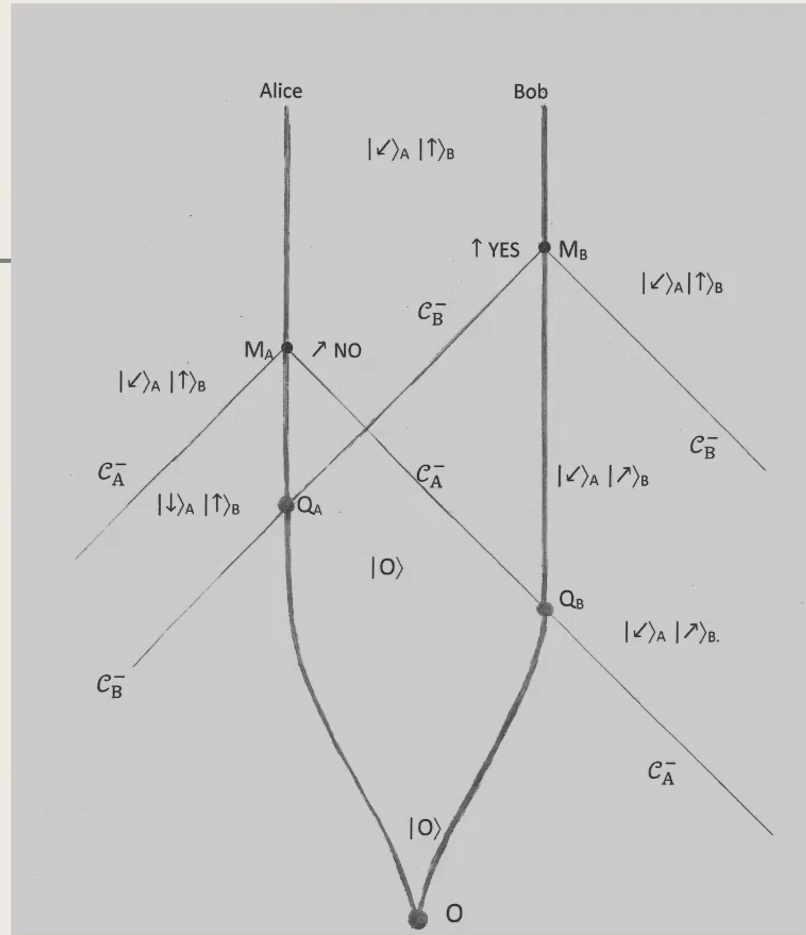
$$\alpha = \cos\frac{\theta}{2}, \quad \beta = \sin\frac{\theta}{2}$$

$q_\beta(t)$ = prob. of OR having taken place within time t

(in any case invariant under $(\alpha,\beta)\to(-\beta,\alpha)$)

Note: direct measurement gives $\frac{1}{2}q$

$\boxed{\text{Problem for CSL models, where } (\alpha,\beta) \text{ evolves stochastically} \to \sim (1,0) \text{ or } (0,1)}$



Alice
Bob
$|\swarrow\rangle_A\,|\uparrow\rangle_B$
↑ YES
M_B
$|\swarrow\rangle_A|\uparrow\rangle_B$
$\mathcal{C}_B^-$
M_A
↗ NO
$|\swarrow\rangle_A\,|\uparrow\rangle_B$
$\mathcal{C}_B^-$
$\mathcal{C}_A^-$
$\mathcal{C}_A^-$
$|\swarrow\rangle_A\,|\nearrow\rangle_B$
$|\downarrow\rangle_A\,|\uparrow\rangle_B$
Q_A
$|O\rangle$
Q_B
$|\swarrow\rangle_A\,|\nearrow\rangle_B.$
$\mathcal{C}_B^-$
$\mathcal{C}_A^-$
$|O\rangle$
O

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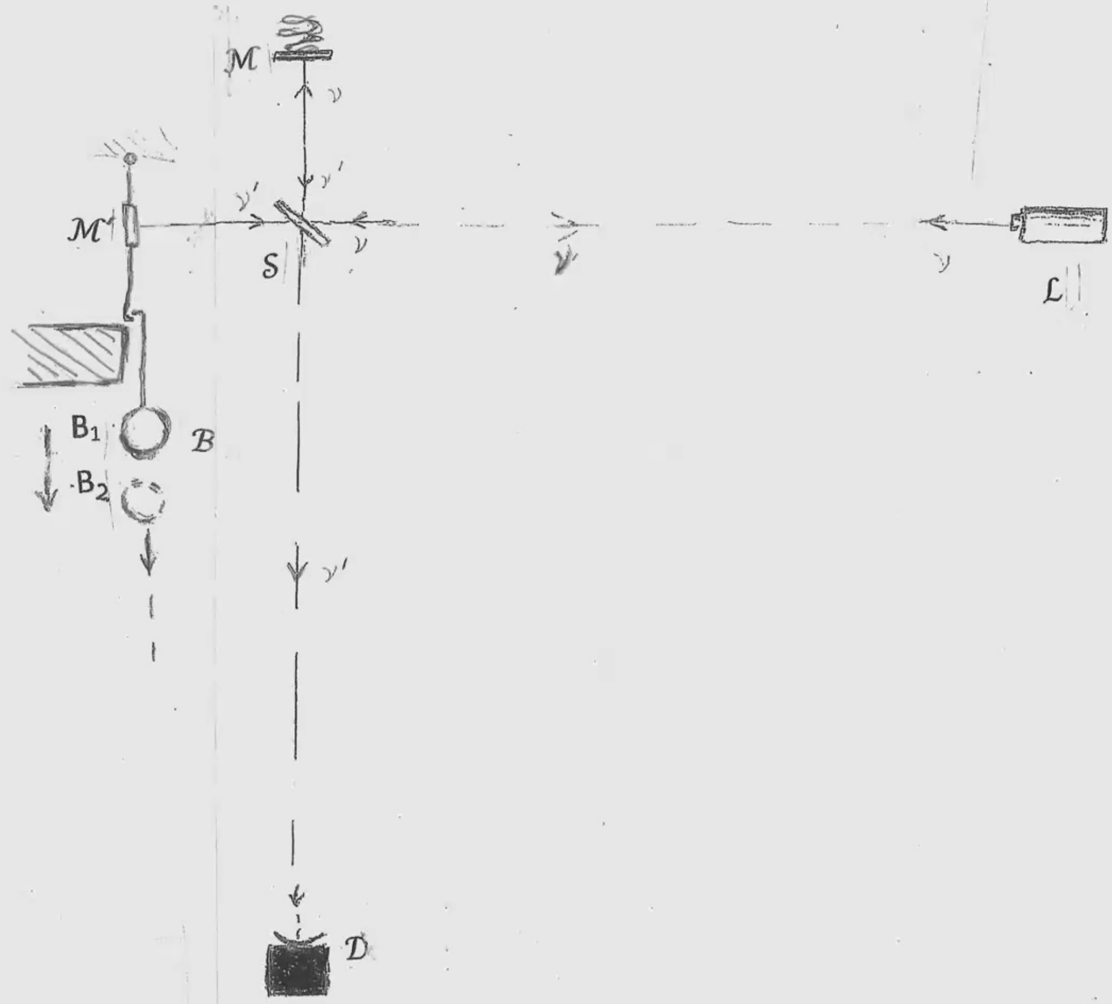
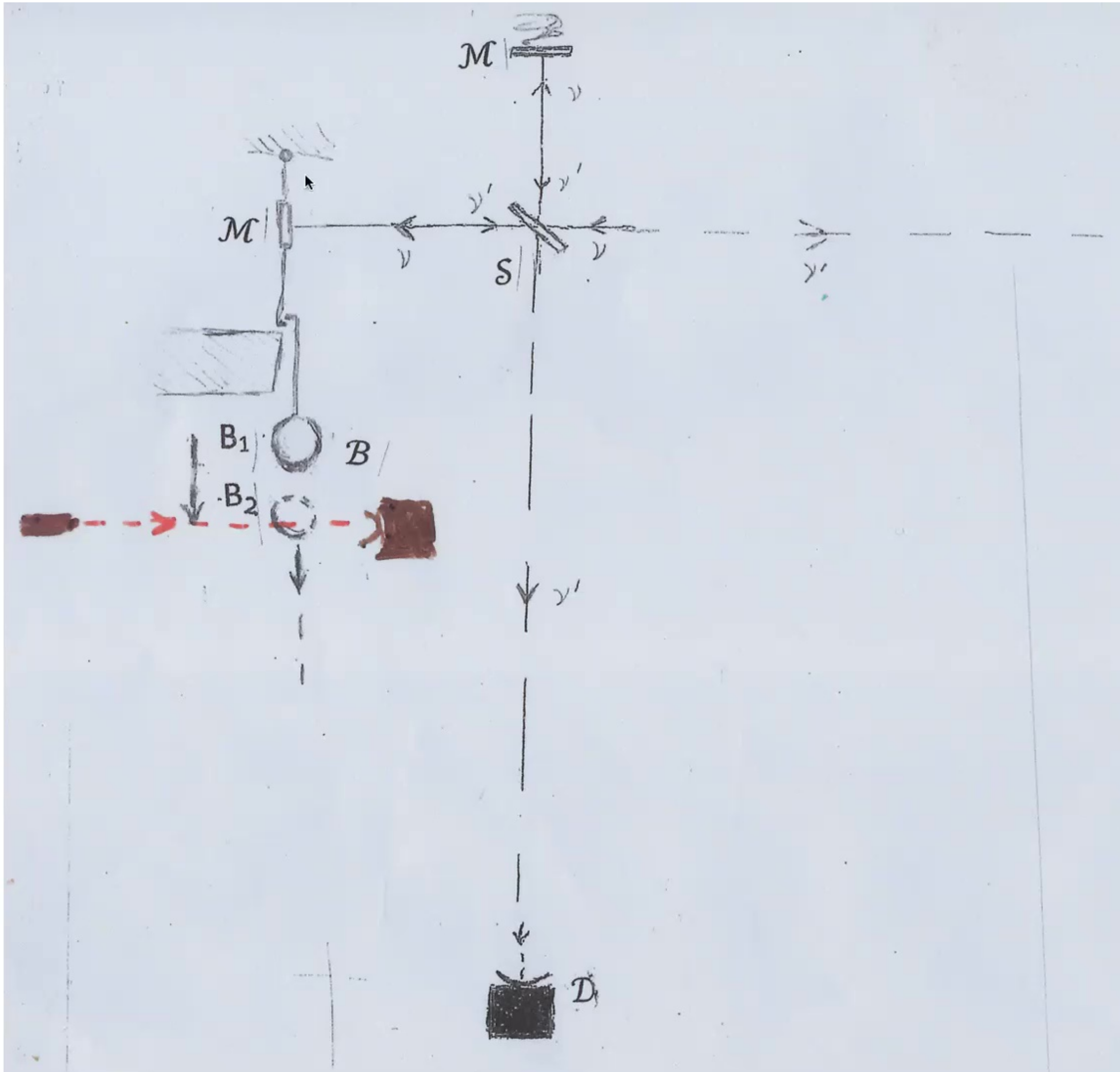

M
M'
S
L
B1
B2
B
D



M
ν
ν'
M
ν'
S
ν
ν
ν'
B1
B
B2
ν'
D