Transactional Gravity: an introduction

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2025

Based on "**Gravity from transactions: fulfilling the entropic gravity program,**"

A. Schlatter and R. E. Kastner (2023). *J. Phys. Commun.* **7** 065009

DOI 10.1088/2399-6528/acd6d7

Part 1. The Transactional Formulation of QM

Part 2. The emergence of spacetime events & Einstein equations

Part 3. MOND modification arises through entropic considerations applied to invariance of the # of transactions as measured by thermal clocks

1. The Transactional Formulation of QM

- Based on the "absorber" or "Direct Action Theory" of electrodynamics (DAT), pioneered by Wheeler-Feynman and others
- Involves participation of absorbers along with emitters in giving rise to field-based forces and radiation.
- In the DAT, the basic field interaction is not the retarded field A_{ret} but is the time-symmetric

  field $\bar{A} = \frac{1}{2}(A_{ret} + A_{adv})$
- Classical version (WF): we get the observed effects of retarded radiation if charges actually generate $\bar{A}$ fields, and absorbing systems also generate $\bar{A}$ fields in response to the emitted fields. The absorbers' fields look like "free fields" from the standpoint of the emitter, and thereby account for radiation damping, which was a problem in the standard classical theory, which involves putting in an ad hoc 'free field' $A = \frac{1}{2}(A_{ret} - A_{adv})$

  In the DAT, the absorber response accounts for the apparent 'free field' and loss of energy by a radiating charge, in a natural way.

- Formally, in the WF DAT , the total field assumed to be acting on a charge i is the time-symmetric field from all other charges, i.e.:

$$A^{(DA)} = \underset{j \square i}{\square} \frac{1}{2}\left(A_{(j)}^{ret} + A_{(j)}^{adv}\right)$$

- The DAT also assumes that there are no true "free fields"; i.e., the *total* 'free field' is zero:

$$\underset{\forall j}{\square} \frac{1}{2}\left(A_{(j)}^{ret} - A_{(j)}^{adv}\right) = 0$$

- and therefore if we add this to $A^{(DA)}$, we get the standard expression with the formerly ad hoc 'free field' imposed by Dirac:

$$A = \underset{j \square i}{\square} A_{(j)}^{ret} + \frac{1}{2}\left(A_{(i)}^{ret} - A_{(i)}^{adv}\right)$$

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$$\underset{\forall j}{\square} \frac{1}{2}\left(A^{ret}_{(j)} - A^{adv}_{(j)}\right) = 0$$

In the DAT there is no independent mechanical system comprising the field A; there is only a direct interaction among charges

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$$A = \underset{j \square i}{\square} A^{ret}_{(j)} + \frac{1}{2}\left(A^{ret}_{(i)} - A^{adv}_{(i)}\right)$$

The Quantum Direct-Action Theory (QDAT)

- The fully quantum form of the DAT involves taking into account that:
  - (i) emitting charge is not "immune" from its own field as assumed in the classical DAT
  - (ii) there are negative energy solutions that need explicit handling
- The result of incorporating these is the Feynman propagator,

$D_F = \bar{D} + D_1$, where D_1 is the applicable 'free field' (D_1 is the even solution to the homogeneous equation)

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Crucially, in the QDAT, absorber response is *not universal* but contingent; basic probability of that occurring is the fine structure constant $\alpha \sim e^2$ where e is the electric charge or coupling constant.

- At the quantum level, or “QDAT”, we have two different kinds of field interactions: (i) unitary and (ii) non-unitary

- (i) takes place ubiquitously as the Coulomb interaction
- (ii) is contingent on absorber response, and yields real photons

(i) unitary interaction

The basic field interaction of the QDAT is the time-symmetric propagator commonly termed $\bar{D}$. It is the time-symmetric Green's function solution to the inhomogeneous equation for the electromagnetic field:

$$\nabla^2 G - \frac{1}{c^2}\frac{\partial^2 G}{dt^2} = -4\pi\delta(\boldsymbol{x} - \boldsymbol{x}')\delta(t - t')$$

The function $\bar{D}$ connects two charged currents, but does not define a temporal direction of propagation between them. It corresponds to a virtual (off-shell) photon.

In the QDAT, $\bar{D}$ describes the Coulomb force (generalizing to the Lorentz force, $\frac{dp_\alpha}{dt} = q\,F_{\alpha\beta}\,\frac{dx^\beta}{dt}$, at the relativistic level)

(ii) non-unitary interaction

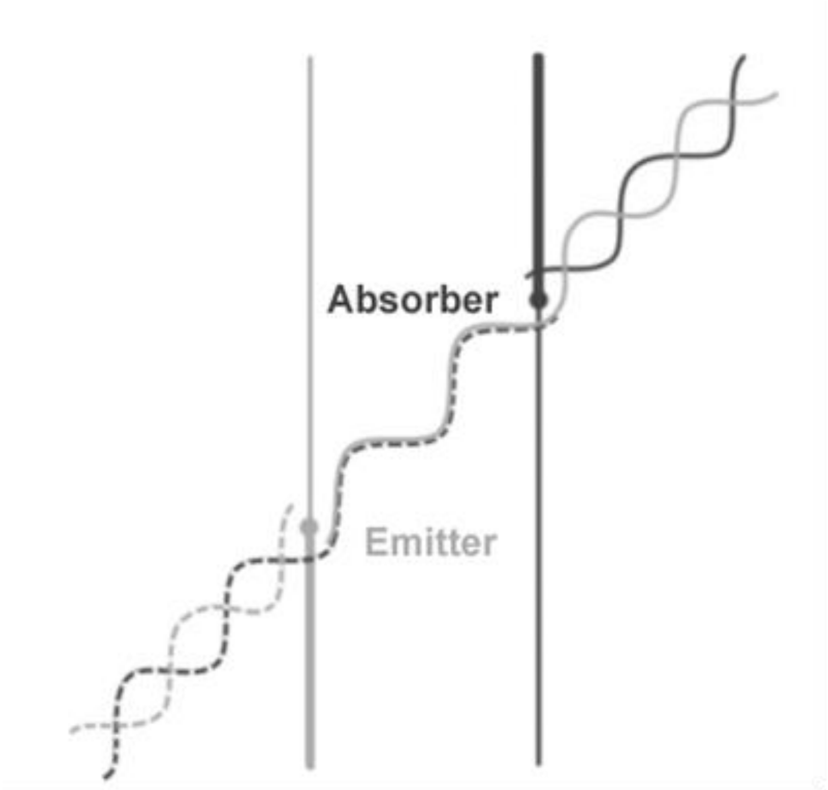
The basic unitary interaction transforms to a non-unitary interaction if absorber response occurs. This is the generation of a time-symmetric field from absorbers in response to an emitted field.

Absorber response gives rise to a free field D_1 that appears as a component in the Feynman propagator:

$$D_F = \bar{D} - \frac{i}{2} D_1$$

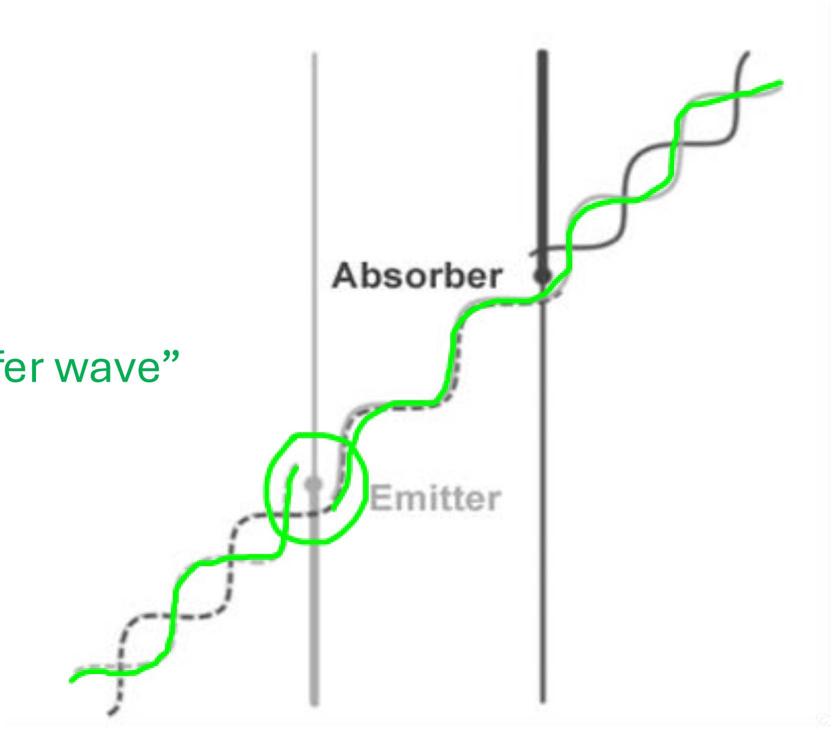
The D_1 term corresponds to an on-shell ("real") photon, while the entire D_F describes the photon propagating *from* an emitter *to* an absorber (limited to those endpoints). This is a radiative process, in contrast to the unitary interaction described by $\bar{D}$ which governs internal scattering processes.

the non-unitary interaction is a “transaction”

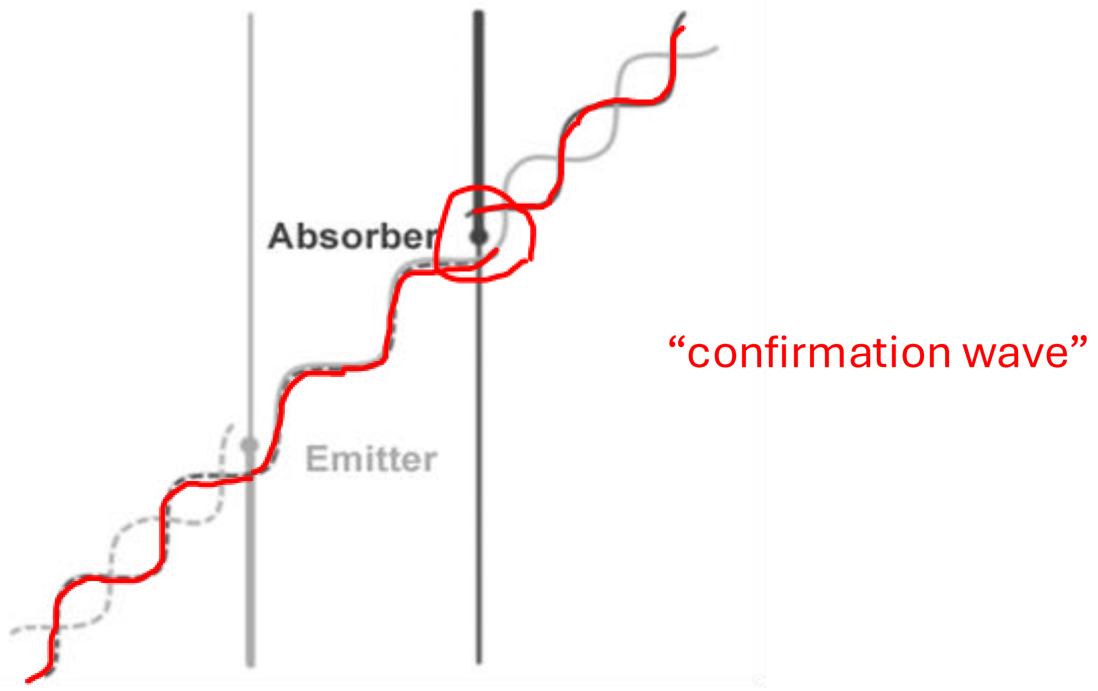


the $\overline{D}$ field from the emitter:

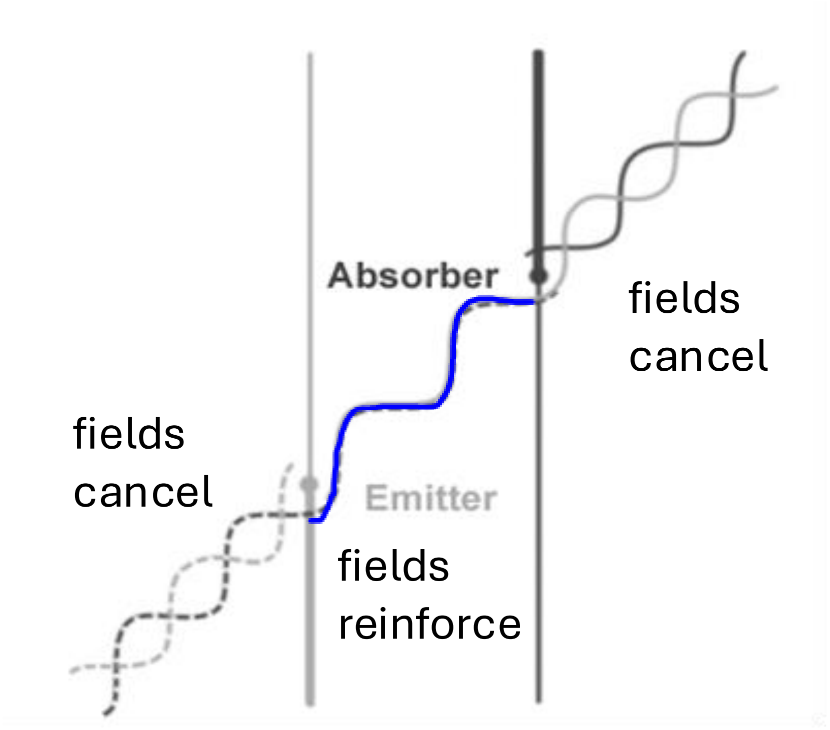
“offer wave”



the $\bar{D}$ field from the absorber:



Yields an effective D_1 field truncated to the interval between emitter and absorber, described by D_F



Transactions localize emitters and absorbers

- The Feynman propagator ties the real photon to a particular emitter and to its responding absorbers.
- For multiple responding absorbers and a single photon available for transfer, we have "collapse" to a single receiving absorber. This is in keeping with the non-unitarity of the process, which serves to define 'quantum measurement.'
- The transferred photon is therefore localized to that absorber, which becomes localized with it as a new bound state. The emitter is also localized in a transaction, since the momentum transferred by the photon provides information about the location of the emitter as well as the absorber. (Schlatter and Kastner, "A Model of Entropy Production," Scientific Reports 14, Article number: 30853 (2024)]

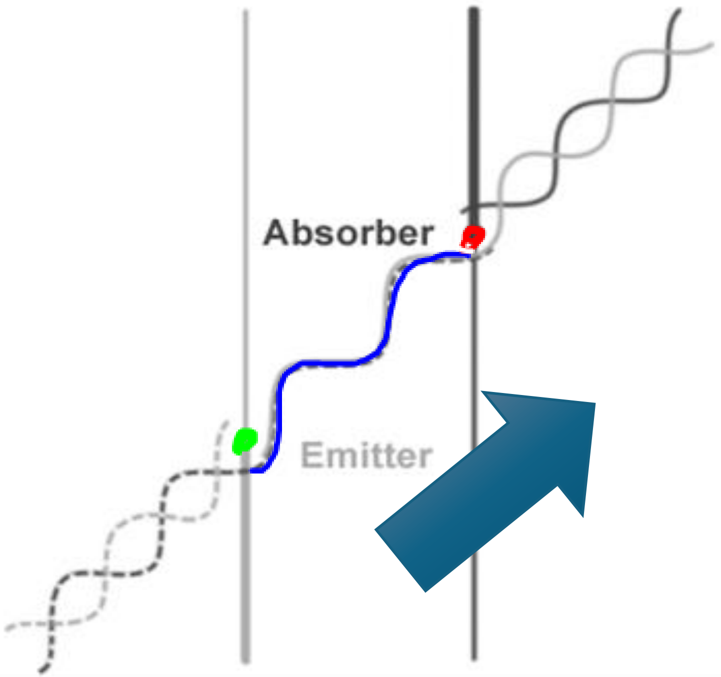
→ transactions localize matter systems

(to within expectation value <r> for a given atomic state)

A new spacetime interval is established through the actualized transaction:

- The emission event (past endpoint)
- The absorption event (present endpoint)
- The transferred photon defines a future-directed, invariant spacetime interval between the emission and absorption events (since absorption occurs after emission):

⇢ **we get an “arrow of time”**



- One often sees the term “field” defined as a “property of space”. This formulation is denied in the DAT. Specifically, fields are generated by sources and thus are not free-standing entities, nor do they require a medium to “travel in.”
- Instead, it is the matter sources that create the structured set of emission and absorption *events* comprising spacetime.
- this is a relational approach; “spacetime” is comprised of what Einstein called “point-coincidences”. Only that set of events is invariant; coordinate charts are covariant *descriptions* of those events, not substantive manifolds in themselves.

(2) Entropic considerations applied to the emergent spacetime events lead to GR's metric structure

- A given reference frame defines a coordinate chart whose metric depends on the transactional effects of the matter sources of spacetime events/intervals
- Consider an entropic force $F = \frac{dS}{dx} T$
- Holographic principle: "space(time) is a storage device for information"; effects of mass contained in "volumes" are fully representable by "shells," surfaces, $\mathrm{A} = 4\pi R^2$
- Actualization of a test mass *m* within some distance $R \pm \{dx \in \lambda_C\}$ from a source mass *M* adds *m* to the shell at R and yields an entropy increase

$$dS = 2\pi \mathrm{k} \frac{dx}{\lambda_C} = 2\pi \mathrm{k} \frac{mc\ dx}{\hbar}$$

(dS quantifies energy transferred to actualize m to the shell at R per unit T)

- This leads us to Verlinde's account of the effective gravitational "force":

$$F_G(R,M) = \frac{dS}{dx} T(R,M)\ , \quad \text{where M is the source mass}$$

- Define T(R,M) through holographic principle: the energy $E = Mc^2$ available to actualize positions (through transactions) is contained within the surface $A = 4\pi R^2$.
- Position sizes defined by Planck area: $l_P^2 = \frac{G\hbar}{c^3}$. (Here, G can be taken as a conversion factor required to yield a length from the other physics constants; the value of G need not be assumed.)

We find T by first finding the number N of possible positions on the shell:

$$N(R) = \frac{4\pi R^2}{l_P^2} = \frac{4\pi R^2 c^3}{G\hbar}$$

and noting that T is defined by $E = \frac{1}{2} NkT$, we get

$$T = \frac{2Mc^2}{Nk} = \frac{2Mc^2 G\hbar}{4\pi R^2 kc^3} = \frac{G\hbar M}{2\pi kcR^2}$$

Note that taking the acceleration due to the entropic force, $g_R = \frac{GM}{R^2}$, leads to the Davies-Unruh T, i.e.:

$T_g = \frac{G\hbar M}{2\pi k c R^2} = \frac{\hbar g_R}{2\pi k c}$ - confirming consistency of the approach.

We can now use the previous result, $\frac{dS}{dx} = \frac{2\pi k c m}{\hbar}$

along with T_g in the entropic force expression: $F_g = \frac{dS}{dx} T_g$ to get

$$F_g(R, M, m) = \frac{dS(R, m)}{dR} T_g(R, M) = \frac{2\pi k c m}{\hbar} \frac{G\hbar M}{2\pi k c R^2} = \frac{GMm}{R^2}$$

which corresponds to the known expression for gravitational force.

Recall, however, that gravitation is not a real 'force' – this 'acceleration' is only what is measured relative to a flat coordinate chart. Thus, the effect is a reflection of the structure of actualized events due to matter sources such as M—i.e., it defines the applicable metric.

Obtaining the Einstein equations

Using the expression:

$$T_g = \frac{G\hbar M}{2\pi k c R^2} = \frac{\hbar g_R}{2\pi k c}$$

and substituting $E = Mc^2$ and $A = 4\pi R^2$ and solving for $g_R A_R$, we get

$$g_R A_R = \frac{4\pi G}{c^2} E$$

As R→ 0, the left hand side can be interpreted as the 00 component of the Ricci tensor; thus the above serves as the starting point for Einstein's equations...

Part 3. Emergence of Einstein equations with “MOND” correction

a “deeper” approach to Einstein equations based on ‘thermal time,’ as measured by thermal clocks, allows extraction of further results concerning deviations from Newtonian gravity.

These results correspond to the “MOND” corrections but are not *ad hoc*; they are derived by recognizing the invariance of the # of transactions per 4-volume, and enforcing correspondence between the thermal clocks of different observers.

Syncalibrating Clocks

- Margolus-Levitin show that for a given pure state the minimal time to reach an othogonal state is

$$\tau \sim \frac{h}{\bar{E}}.$$

- Analogy for photons: $\tau = \frac{1}{\nu} = \frac{h}{E}$.
- In case of low energy-photons in a thermal bath of temperature T: $\tau \sim \frac{h}{k_B T}$.
- Thematic similarity with thermal time-flow of Connes-Rovelli.
- In case of many bits and entropy S: $\tau \sim \frac{h}{S \cdot T}$.
- Principle of syncalibaration: Given time parameters t_1, t_2 then two clocks are syncalibrated (march in step, **agree on the # of transactions**) if:

$$\frac{dt_1}{\tau_1} = \frac{dt_2}{\tau_2}.$$

- Example: Tolman-Ehrenfest law for thermal equilibrium of temperature-field $T(x)$ on a Lorentz-manifold:

$$T(x_1)\sqrt{g_{00}(x_1)} = T(x_2)\sqrt{g_{00}(x_2)}.$$

- Einstein Equation as a result of syncalibrated clocks, a thermal clock and a light clock:

thermal time "velocity": $\frac{4}{h} k_B T_{g_R} \frac{c^2}{g_R} = \frac{c}{\pi^2} \quad \leftrightarrow \quad g_R\, A_R = \frac{4\pi G}{c^2} E, \quad (E = Mc^2).$

- For a sphere of test masses with $R(0) = R, \dot{R}(0) = 0, \ddot{R}(0) = g_R$

$$\ddot{V}_R(0) = \frac{4\pi G}{c^2} E.$$

- Taking densities and going to the limit $R \to 0$:

$$\frac{\ddot{V}_R}{V_R}(0) \xrightarrow{R\to 0} c^2 R_{00} \to R_{00} = \frac{4\pi G}{c^4} T_{00}.$$

- Equation has to hold for all initial velocities or, equivalently, for test masses at rest in all inertial reference frames, hence addition of momentum flow, or pressure components $T = tr(T_{\mu\nu})$:

$$R_{00} = \frac{8\pi G}{c^4}\left(T_{00} - \frac{1}{2} T \delta_{00}\right).$$

- Equation holds at every point in all inertial frames, therefore full equation holds (Baez, Wald).

- What about the three-momentum of the transacting photons? This corresponds to the Cosmological Constant, Λ

- Specifically, the number of photons per time passing through a surface of area $\sim R^2$ with momentum $p \sim \frac{1}{R}$. adds to the pressure term , and is proportional to the transaction (four-) density ϱ_γ:

$$\Lambda = 8\pi^2 l_P^2 \varrho_\gamma.$$

We may assume that EM-fields are (quasi)classical and oscillators are in coherent states. Hence the expectation of the number operator $\langle n \rangle_V$ follows a Poisson-distribution with $\lambda \sim \varrho_\gamma V$, which is Lorentz-invariant. This implies that a concrete realization of a “transaction-sprinkling“ does not result in a preferred foliation (Sorkin, Bombelli, Meyer).

- Consequently, in a FLRW-spacetime there holds with $R_P(t_U)$ denoting the particle horizon at the age of the universe t_U:

$\Lambda \sim \frac{1}{R_P^2(t_U)}$. as observed (see https://arxiv.org/pdf/2405.14803, A. Schlatter)

Galaxy Rotation (“Dark Matter“ effect)

- De Sitter space in static coordinates with $f(r) = \left(1 - \frac{r^2}{R_0^2}\right)$. We set $a_0 \stackrel{\text{def}}{=} \frac{a_\infty}{2}$ and define a de Sitter-entropy: $S_{dS}(r) = \frac{r}{R_0} S(r) = \frac{r}{R_0}\frac{k_B A_r}{2l_P^2}$ and corresponding acceleration $\mathrm{a}(r) \stackrel{\text{def}}{=} \frac{r}{R_0} a_0$.
- Adding a massive system M leads to $\tilde{f}(r) = \left(1 - \frac{r^2}{R_0^2} - \frac{R_S}{r}\right)$. The horizon is reduced and inspires us to calculate an effective entropy (E. Verlinde):

$$\bar{S}_{dS}(r) = S_{ds}(r) - \frac{4\pi c k_B M}{\hbar} r.$$

- Note that this entropy makes sense only in a region $r > r_0$ where $\bar{S}_{dS}(r)$>0. It turns out that

$$r_0 = \sqrt{\frac{MG}{a_0}}\,.$$

- Two observers, one in a static frame and the other comoving with the expansion, each have a thermal clock and they must be syncalibrated. The first observer sees effective acceleration $\bar{a}(r)$ and the other sees Newtonian gravitation with potential $\Phi(r)$. By the principle of syncalibration (and with increments dt_i effectly equal at astronomical scales):

$$T_{\bar{a}(r)}\, \bar{S}_{dS}(r) = T_{g(r)} S(r).$$

- This equation has a positive solution:

$$\bar{a}(r) = a_0 \Phi(r) \left(1 + \sqrt{1 + \frac{c^4}{MGa_0}} \right).$$

- There holds for $r = r_0 = \sqrt{\frac{MG}{a_0}}$:

$$\bar{a}(r_0) \sim a_0 = g(r_0),$$

and $\bar{a}(r)$ interpolates for $r > r_0$, until at astronomical distances $r \gg r_0$ there holds:

$$\bar{a}(r) \approx \frac{\sqrt{MGa_0}}{r}.$$

- It follows a Tully-Fisher type relation $v^\beta \sim M$ for galaxy rotation velocity and mass with $\beta = 4$:

$$v^2 = \sqrt{MGa_0}.$$

Conclusion: transactions dictate the 'rhythm of becoming' and naturally yield Einstein eqns with MOND corrections

- The acceleration g_R originates from a transaction and exchange of a photon, in which new spacetime events are created (leading to spacetime expansion)
- the exchanged photon acts as a 'light clock' syncalibrated with the thermal clock corresponding to T (enforcing invariance of the # of transactions). This identification yields the Davies-Unruh temperature $T \sim g_R$.
- The result $g_R A_R = \frac{4\pi G}{c^2} E$ generalizes to the full Einstein eqs.
- photon 3-momentum yields the cosmological constant Λ
- considering perspectives of 2 observers, static and co-moving with expansion, and syncalibrating their thermal clocks, yields the MOND correction:

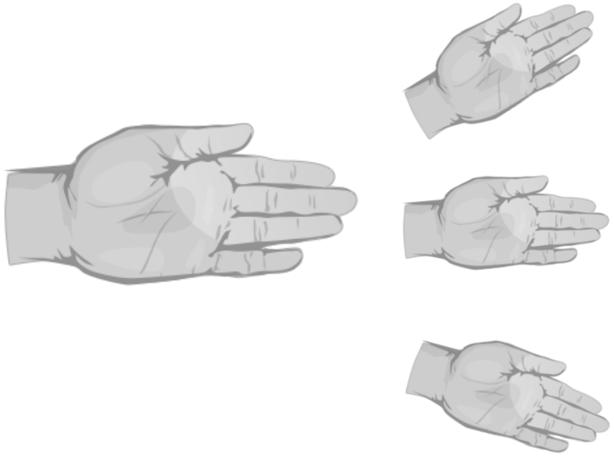
$$\bar{a}(r) \approx \frac{\sqrt{MGa_0}}{r}.$$

Thank you!

Supplemental materials

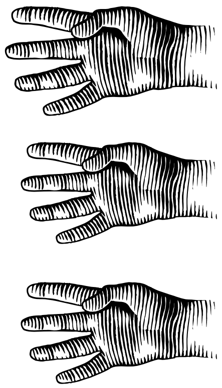
‘offer waves’ and ‘confirmation waves’

- in TI, the usual quantum state is called an ‘offer wave’ (OW)
- In general, it comprises separate smaller components that reach several different absorbers



The feature missing in the standard formulation: absorbers are active and respond to the emitter!

- each absorber's response to the component of the offer wave reaching it is called a 'confirmation wave' (CW). These are the 'advanced' (past-directed) solutions. They are neglected in the standard theory.

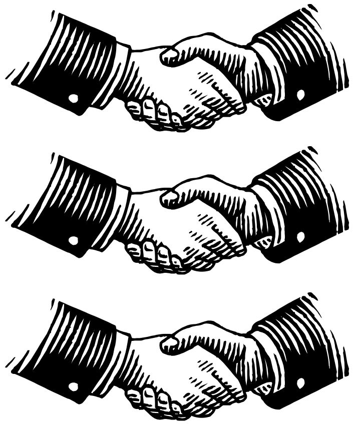


$\langle\Psi|A\rangle\langle A|$

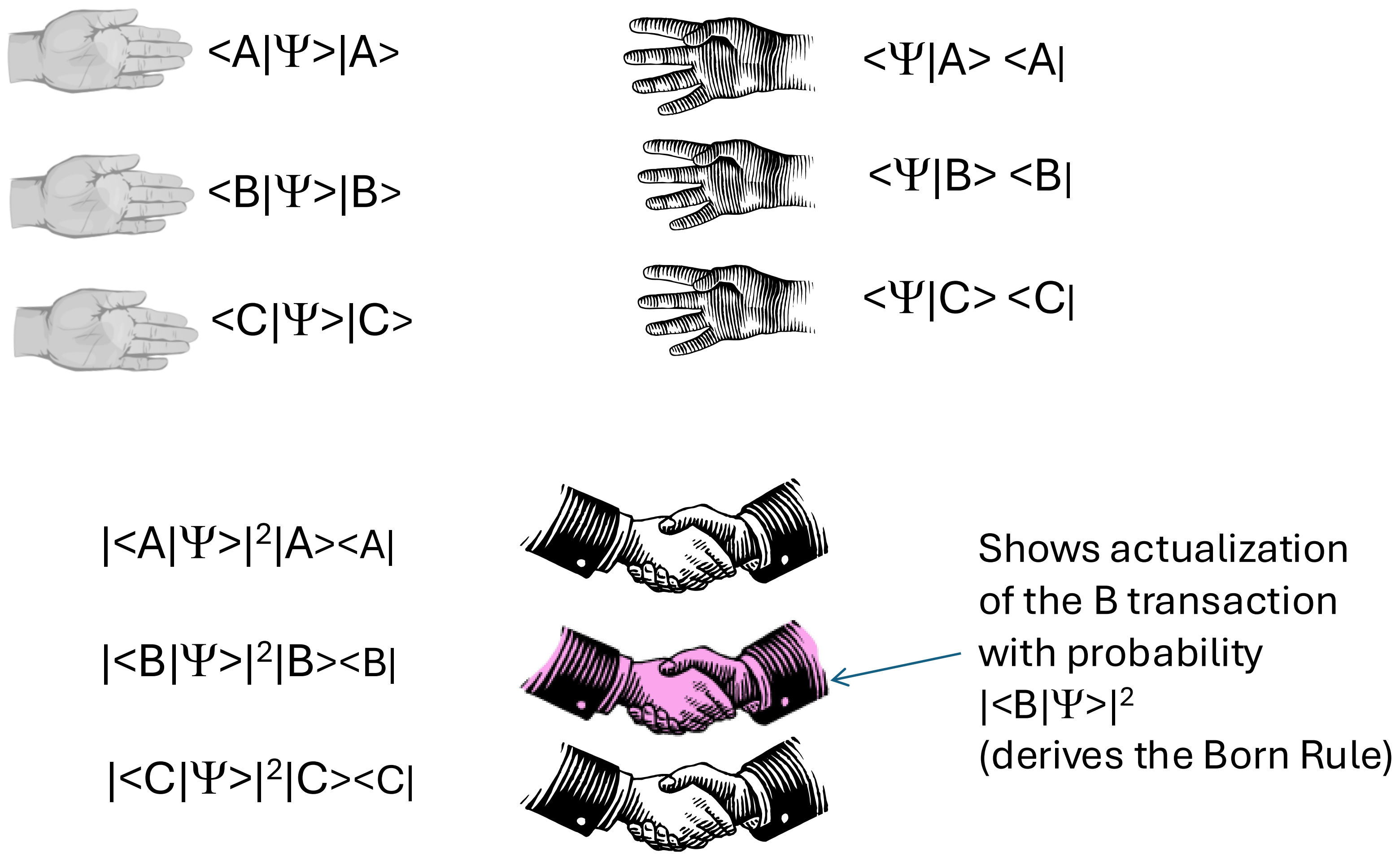
$\langle\Psi|B\rangle\langle B|$

$\langle\Psi|C\rangle\langle C|$

- the interaction of each OW and CW component is like a 'handshake'. Each is a possible 'transaction': a *possible* transfer of energy – but only one of these is actualized. This is 'quantum collapse'



Incipient transactions


<A|Ψ>|A>
<Ψ|A> <A|
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<Ψ|B> <B|
<C|Ψ>|C>
<Ψ|C> <C|
<A	Ψ>	2	A><A
<B	Ψ>	2	B><B
<C	Ψ>	2	C><C
Shows actualization
of the B transaction
with probability
<B	Ψ>	2
(derives the Born Rule)