Title: Making sense of semiclassical gravity

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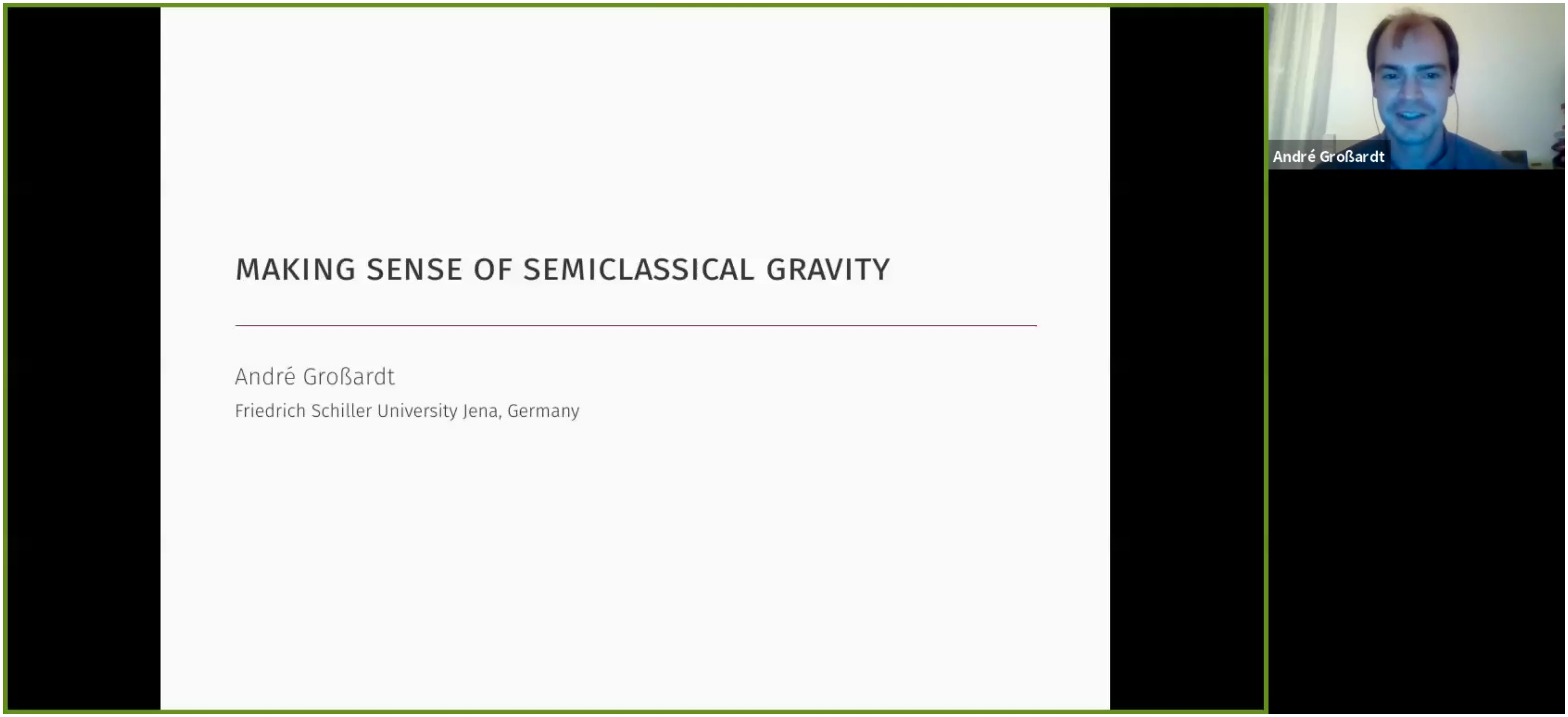
Abstract: In absence of both experimental evidence for and a fully understood theory of quantum gravity, the possibility that gravity might be fundamentally classical presents an option to be considered. Such a semiclassical theory also bears the potential to be part of an objective explanation for the emergence of classical measurement outcomes. Nonetheless, the possibility is mostly disregarded based on the grounds of arguments of consistency. I will discuss these arguments, attempting to present the broader picture of the constraints that need to be dealt with in order to formulate consistent semiclassical models of gravity, and the implications this has with regard to concrete proposals for theoretical models and

experimental tests of semiclassical versus quantized gravity.

Zoom Link: https://pitp.zoom.us/j/99590707415?pwd=MHFMZlhSMUdMbFFoMEFmQTIxSUhBQT09


MAKING SENSE OF SEMICLASSICAL GRAVITY
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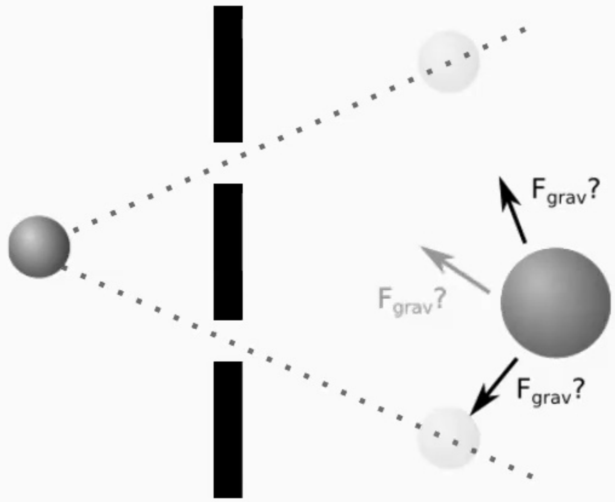
QUANTUM MATTER AS A SOURCE MASS FOR GRAVITY



What is the gravitational field of a superposition state?

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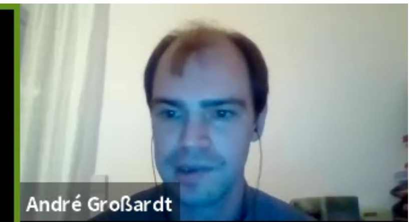

MEAN-FIELD SEMICLASSICAL GRAVITY

Semiclassical Einstein equations as a **fundamental** equation:

$$\boxed{R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = \frac{8\pi G}{c^4} \langle \hat{T}_{\mu\nu} \rangle}$$

Weak-field **nonrelativistic** limit:
$\nabla^2 V = 4\pi G \langle \psi |\, \hat{\rho}\, | \psi \rangle$ with $\hat{\rho} = m \hat{\psi}^\dagger \hat{\psi}$

Results in the **Schrödinger-Newton equation** (here for one particle)

$$\boxed{\mathrm{i}\hbar\, \dot{\psi}(t, \mathbf{r}) = \left(-\frac{\hbar^2}{2m} \nabla^2 - G m^2 \int \mathrm{d}^3 r' \, \frac{|\psi(t, \mathbf{r}')|^2}{|\mathbf{r} - \mathbf{r}'|} \right) \psi(t, \mathbf{r})}$$

$\Rightarrow$ **Nonlinear** Schrödinger equation
$\Rightarrow$ yields gravitational **self-interaction** of the wave function

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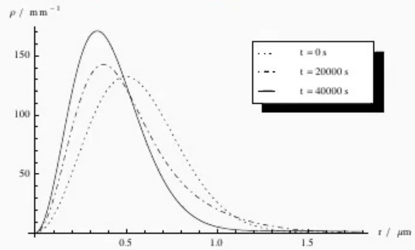
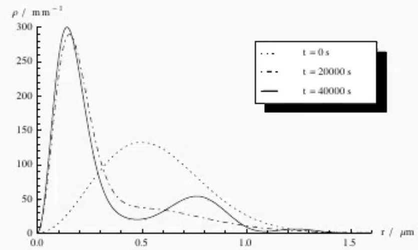
EXPERIMENTAL TESTS OF THE SCHRÖDINGER-NEWTON EQUATION

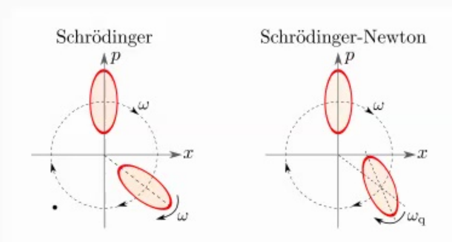
Free spreading of the wave function (interferometric tests):

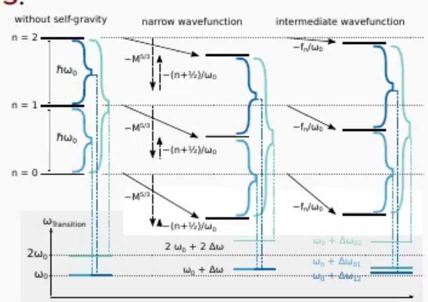




$\rho = 4\pi r^2\ |\psi|^2$ for masses of 7×10^9 u and 10^{10} u

Effects in **optomechanical systems**:





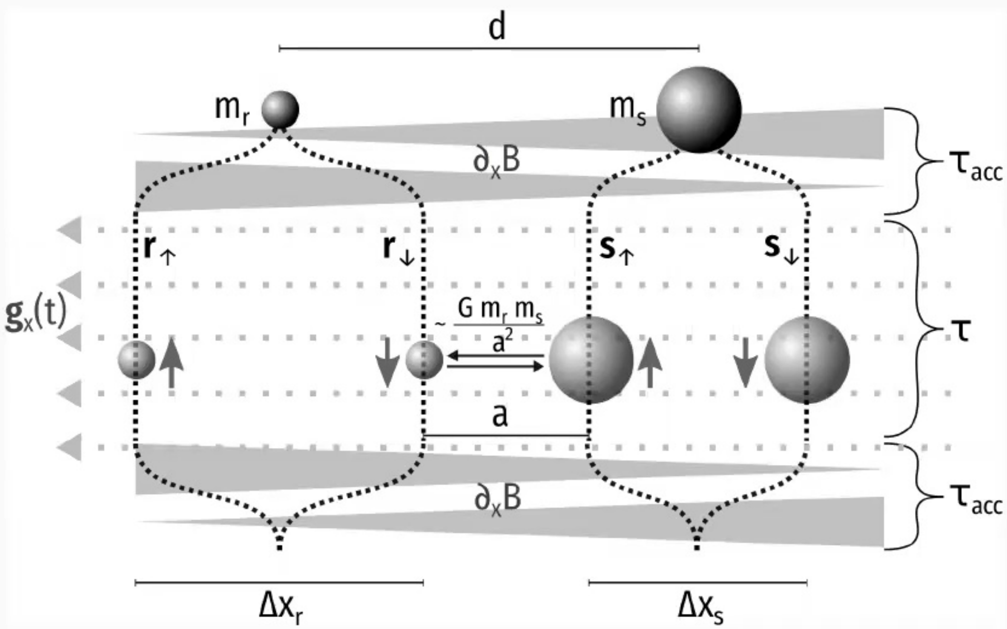
Yang et al. PRL 110 (2013) 170401

A.G. et al. PRD 93 (2016) 096003

GRAVITATIONAL ENTANGLEMENT OF SPIN-½ PARTICLES

Two adjacent Stern-Gerlach interferometers

Bose et al.: PRL 119 (2017) 240401



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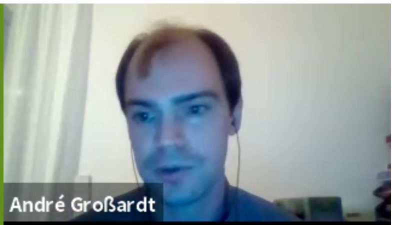

SEMICLASSICAL GRAVITY NEEDS WAVE FUNCTION COLLAPSE

No mean-field semiclassical gravity as a ρ-ontic theory:

- Massive superposition $|\psi_0\rangle = \frac{1}{\sqrt{2}}(|x_1\rangle + |x_2\rangle)$ will decohere like

$$\hat{\rho}_0 = |\psi_0\rangle\langle\psi_0| = \frac{1}{2}\begin{pmatrix} 1 & 1 \\ 1 & 1 \end{pmatrix} \longrightarrow \hat{\rho}_t \approx \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

- $\hat{T}_{\mu\nu} \approx \hat{m}(x) = m\,|x\rangle\langle x| \quad \Rightarrow \quad \rho(x) = \mathrm{Tr}\hat{\rho}_0\hat{m}(x) = \mathrm{Tr}\hat{\rho}_t\hat{m}(x)$
- Gravitates like equal mass distribution **regardless** of decoherence

not observed! (cf. Page & Geilker, 1981)

- $\hat{\rho}_t$ must be a mixture of **classical** (collapsed) states
- Dynamics of quantum states must be consistent with $\nabla^\mu G_{\mu\nu} = 0$

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WHAT IS SEMICLASSICAL GRAVITY?

- List of ingredients:
  1. Classical spacetime (pseudo-Riemannian 4-manifold)
  2. Quantum fields for matter (e. g. Standard Model)
  3. Optional: further degrees of freedom (“hidden variables”)
- Field dynamics described by QFT on curved spacetime
- For a full, consistent theory one needs:
  1. Right-hand side of Einstein’s equations
     (how does quantum matter source spacetime curvature?)
  2. Description of the **measurement process**
  3. Optional: dynamical laws for hidden variables

We do not have a full relativistic theory of semiclassical gravity yet

$\boxed{\text{not semiclassical gravity} \neq \text{perturbative quantum gravity}}$

neither is SCG ∪ PQG = all theories, nor necessarily SCG ∩ PQG $= \emptyset$

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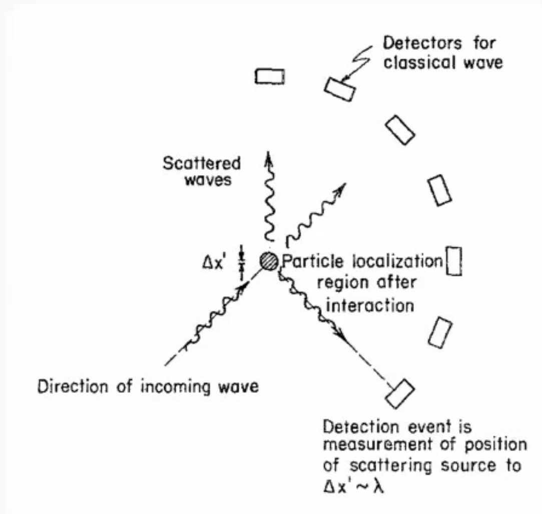
CONSISTENCY ARGUMENTS BASED ON WHICH-WAY INFORMATION

- **Which-way information via gravitational field?**
- Determine particle position for small Δp with classical gravitational wave, $\lambda p \ll 1$
- **Uncertainty $\Delta p \, \Delta x < 1$**

However:

- Uncertainty only corollary (Albers et al. 2008)
- Concrete proposal infeasible (Mattingly 2006)



Eppley & Hannah 1977

And: Mean-field semiclassical gravity does **not** transmit WWI

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VIOLATION OF UNCERTAINTY REQUIRES PLANCK MASS

Combine arguments by Eppley & Hannah, Mattingly, Albers et al.:

- Generate grav. wave: collide two objects of size λ with energy E
- Wave scattered of particle m at distance r: $E_{\mathrm{sc}} \sim \frac{E^2 m^2}{\lambda r^2}$
- Oscillator of M and L at distance R oscillates with: $E_{\mathrm{osc}} \sim \frac{M m^2 L^2 E^2}{\lambda^2 R^2 r^2}$
- For transition with prob. ~ 1 need $N \sim \omega_0 / E_{\mathrm{osc}}$ detectors:

$$M_{\mathrm{total}} \sim \frac{\omega_0 \lambda^2 R^2 r^2}{m^2 L^2 E^2} \gtrsim \frac{\omega_0 R^2 r^2}{m^2 E^2} \gtrsim \frac{\omega_0 R^2}{m^2}$$

- Detection requires $T \lesssim \omega_0$. Hawking-Unruh: $T \sim (m + M_{\mathrm{total}})/R^2$

$$\boxed{M_{\mathrm{total}} \gtrsim \frac{TR^2}{m^2} \sim \frac{m + M_{\mathrm{total}}}{m^2} \quad \Rightarrow \quad m \gtrsim 1}$$

Uncertainty not tested for $m \gtrsim m_{\mathrm{Planck}}$

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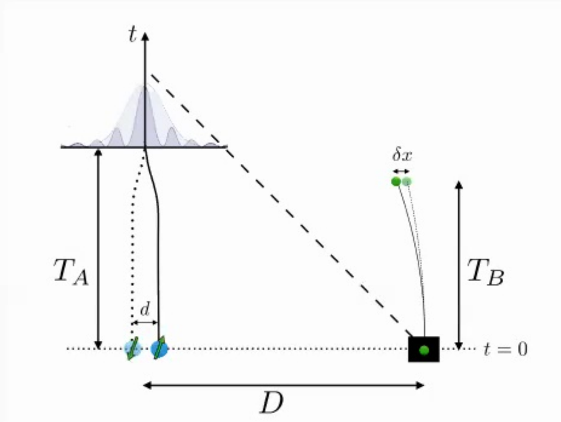
WHICH-WAY INFORMATION AND FTL SIGNALLING



Mari et al. 2016, Belenchia et al. 2018

- Quantum fluctuations of curvature $\Rightarrow \Delta x \sim 1$ **or** scatter particle: $\delta x \gtrsim r_S \gtrsim p \sim \frac{1}{\lambda} \gtrsim \frac{1}{\delta x}$

$$\boxed{\delta x > 1 \Rightarrow \mathcal{M}_A^n > D^n}$$

- $E \sim \left(\frac{\mathcal{M}_A^n}{T^{n+1}}\right)^2 T$ in form of class. GW **or** gravitons
WWI: $ET > 1$ **or** graviton

$$\boxed{\mathcal{M}_A^n < T^n < D^n}$$

Can Bob signal in $T < D$ by gaining WWI and decohering Alices state?

No need for quantization

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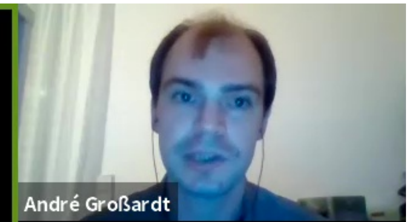

NONLINEARLITY AND FTL SIGNALLING (I)

Claim: **any deterministic nonlinearity in the Schrödinger equation leads to the possibility to send faster than light signals** (Gisin, 1989)

- E.g. entangled spin-$\frac{1}{2}$ particles:

$$\frac{1}{\sqrt{2}}\left(|\uparrow\rangle_A\,|\downarrow\rangle_B + |\downarrow\rangle_A\,|\uparrow\rangle_A\right) = \frac{1}{\sqrt{2}}\left(|+\rangle_A\,|+\rangle_B - |-\rangle_A\,|-\rangle_B\right)$$

  where $|\pm\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle \pm |\downarrow\rangle\right)$ are the σ_x eigenstates
- Measuring in σ_z or σ_x basis results in same density matrix after tracing over possible outcomes $|\uparrow\rangle_B$ and $|\downarrow\rangle_B$ or $|+\rangle_B$ and $|-\rangle_B$:

$$\boxed{\hat{\rho}_A = \frac{1}{2}\,|\uparrow\rangle\langle\uparrow| + \frac{1}{2}\,|\downarrow\rangle\langle\downarrow| = \frac{1}{2}\,|+\rangle\langle+| + \frac{1}{2}\,|-\rangle\langle-|}$$

equivalent mixtures (measurement at A independent of basis B) **remain equivalent** in a **linear** theory

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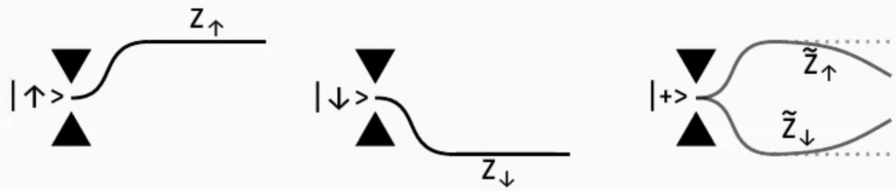
NONLINEARLITY AND FTL SIGNALLING (II)



- **Semiclassical gravity**: assume spin of particle A becomes entangled with its position (e.g. in magnetic field gradient)

$$|\uparrow\rangle \to |\uparrow\rangle \otimes |z_\uparrow(t)\rangle\,, \qquad |\downarrow\rangle \to |\downarrow\rangle \otimes |z_\downarrow(t)\rangle$$

- **However** in **superposition** states $|\pm\rangle$

$$|\pm\rangle = \frac{1}{\sqrt{2}}\left(|\uparrow\rangle \pm |\downarrow\rangle\right) \to \frac{1}{\sqrt{2}}\left(|\uparrow\rangle \otimes |\tilde{z}_\uparrow(t)\rangle \pm |\downarrow\rangle \otimes |\tilde{z}_\downarrow(t)\rangle\right)$$

with $\tilde{z}_{\uparrow\downarrow}(t) \approx z_{\uparrow\downarrow}(t) \pm \frac{Gm}{2} \int_0^t dt' \int_0^{t'} dt'' \, |z_\uparrow(t'') - z_\downarrow(t'')|^{-2}$

$\Rightarrow$ measurement outcomes at A **depend** on choice of basis at B

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NONLINEARLITY AND FTL SIGNALLING (III)

- Argument requires **projection postulate**: Bob's measurement projects on $|\uparrow\rangle_B$ or $|\downarrow\rangle_B$
- Prototype dynamical collapse based on Penrose criterion:
  - free parameter r_c
  - if superposition $\delta z > r_c$: collapse with rate $1/\tau \sim E_{\text{self-grav.}} \sim m^2/r_c$
- Approximate shift $\delta z \sim \frac{mt^2}{\Delta z^2}$ above limit from uncertainty (SQL):

$$\delta z^4 \gtrsim \frac{t^2}{m^2} \sim \frac{\delta z\, \Delta z^2}{m^3} \quad \Rightarrow \quad m^3 \gtrsim \frac{\Delta z^2}{\delta z^3} \gg \frac{1}{\delta z}$$

- Shift δz must be achieved in time $t < \tau$:

$$r_c \sim m^2 \tau \gtrsim m^2 t \sim \sqrt{m^3\, \delta z\, \Delta z^2} \gtrsim \frac{\Delta z^2}{\delta z} \gg \delta z$$

- Combined:

$$\boxed{r_c \gg 1/m^3}$$

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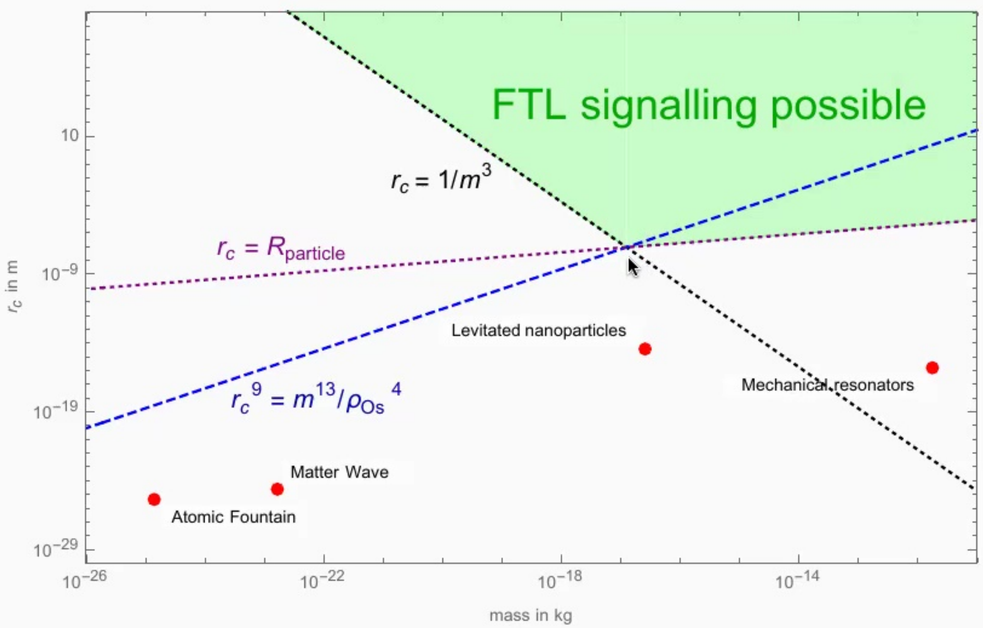
NONLINEARLITY AND FTL SIGNALLING (IV)

- Massive particles with $\Delta z < R$ have $\delta z \sim \rho\, \Delta z\, t^2 \;\Rightarrow\; r_c^9\, \rho^4 > m^{13}$



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IMPLICATIONS FOR SEMICLASSICAL GRAVITY

Mean field semiclassical gravity is **not** (yet) dead

- Direct test of SN self-gravity or entanglement test **equally** telling
- Are there ways of coupling **other** than $\langle\psi|\,\hat{T}_{\mu\nu}\,|\psi\rangle$?
- We have **no** compatible theory of measurement. Is there any?
- Can semiclassical gravity **itself** explain measurement?
  nonlinearity ✓ stochasticity (Born) **?** nonlocality (Bell) **?**

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HIDDEN VARIABLE MODELS OF SEMICLASSICAL GRAVITY

Hidden variables = measurement outcomes and source of gravity

- No actual model has been suggested.
- Simple nonrelativistic model: de Broglie-Bohm theory

$$\dot{\mathbf{q}}_i = f[\psi](t, \{\mathbf{q}_j\}) \qquad \mathrm{i}\dot{\psi}(t, \{\mathbf{r}_j\}) = (H_0 + V_g[\{\mathbf{q}_j\}])\psi(t, \{\mathbf{r}_j\})$$

For two particles:

$$\boxed{V_g = -\frac{Gm_1 m_2}{|\mathbf{r}_1 - \mathbf{q}_2|} - \frac{Gm_1 m_2}{|\mathbf{q}_1 - \mathbf{r}_2|}}$$

- Predicts entanglement (no self-force) just as quantized gravity

$$V_g = -\frac{Gm_1 m_2}{|\mathbf{r}_1 - \mathbf{r}_2|}$$

- **Semiclassical interpretation possible**
- Is there a relativistic generalization?

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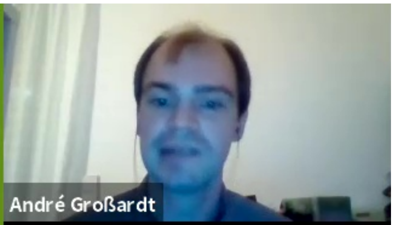

STOCHASTIC SEMICLASSICAL MODELS

Avoid conflicts with concepts of standard quantum mechanics

Tilloy & Diósi 2016: **CSL collapse as source of gravity**

- **Signal** (outcome of weak measurements of mass density) sources Newtonian gravitational potential
- **Requires collapse models** and **relativistic generalization difficult**

Albers et al. 2008 + Oppenheim 2018: **Hybrid cq-theories**

- **Ensembles** of spacetimes as cq-states, full GR (ADM formalism)
- Problem of **individual measurements**: semiclassical (as defined)?
- Full equations of motion **nonlinear**: problem with FTL signalling?
- Maybe **mean field + collapse** in disguise?

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(SORT OF A) CONCLUSION

Skepticism about semiclassical gravity may be justified **but** better based on difficult incorporation of collapse, **not** alleged paradoxes

- Little to do with gravity
- Instead same issue that troubles collapse models, Bohmian mechanics, attempts to describe quantum mechanics as an emergent theory:

Conflict between quantum **nonlocality** and **Lorentz covariance**

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