

The Unruh effect: interpretation and applications to neutrino physics



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Paper coming hopefully, in days

Synopsis

Introduction: What is the Unruh effect

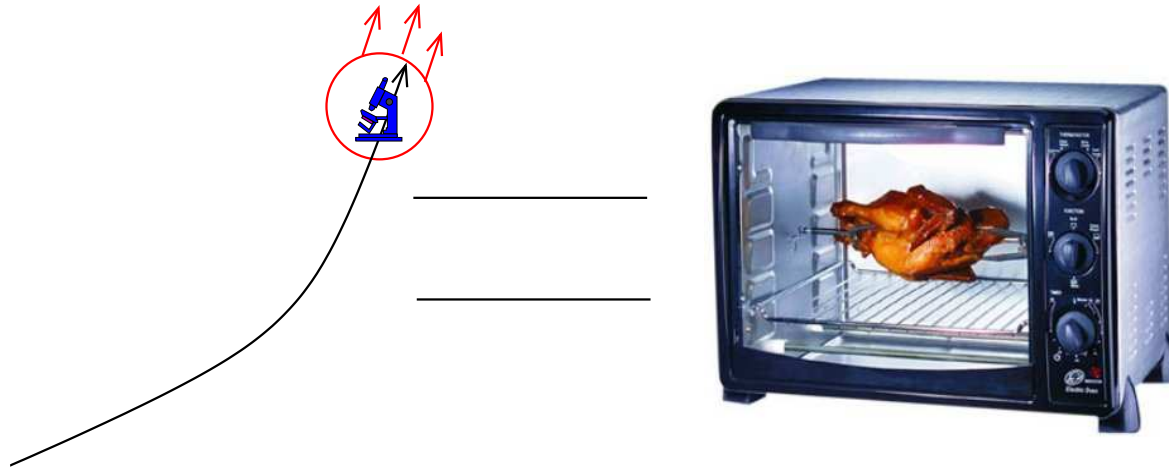
Is it real? Real, unreal, "A coriolis force"

The Unruh effect and fundamental QFT probing response to metric perturbation

Application The Unruh effect and neutrino masses

The Unruh effect: A short introduction

An accelerated detector in a Minkowski vacuum will see a thermal bath with a temperature $T = 2\pi a$.



- Required by the equivalence principle if Hawking radiation exists
- But as acceleration much more “mundane” than black holes, its existence is much more “subtle” and subject to interpretation

The Unruh effect: A short introduction

“Creation operator” for Minkowski space (creating solution of Klein-Gordon/Dirac equation) and one defined in accelerating frame $(\tau, t, x) \rightarrow (\sqrt{\rho}\tau, \zeta, \zeta/\sqrt{\rho} @ \rho_0)$ are not the same

$$\underbrace{\partial^2 + m^2}_{FT:a_p, |0\rangle_M} \rightarrow \underbrace{\frac{1}{2m\sqrt{\rho_0}} \left(\rho_0^2 \frac{\partial^2}{\partial \rho^2} + \rho_0 \left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} \right) + m^2 (\rho - \rho_0) \right)}_{FT:a_{Rp}, |0\rangle_R}$$

Vacuum and creation+annihilation operators change

$$\begin{aligned} {}_M \langle 0 | \hat{\phi} | 0 \rangle_M &= \int \frac{d^3k}{\sqrt{E_k}} (a_k e^{ikx} + a_{-k}^+ e^{-ikx}) \rightarrow \\ \rightarrow_R \langle 0 | \hat{\phi} | 0 \rangle_R &= \int \frac{d^3k}{\sqrt{E_k}} (a_{kR} K(kx) + a_{-kR}^+ K(-kx)) \end{aligned}$$

Since in QFT particle number not conserved and acceleration transformation breaks Lorentz symmetry, accelerating observers disagree on particle number

Straight-forward to show detector's probability of being in excited state from ground state is

$$P(p) = \left| \int d^3x_R \langle p | a_p | 0 \rangle_M \right|^2 \sim f_{FD/BE}(p, 2\pi T)$$

In other words, the Minkowski vacuum appears to the detector to be full of particles.

It is a straight-forward consequence of the view of particles are "irreducible representations of the Lorentz group" and quantization, proven in axiomatic QFT (Sewell et al).

Not as discussed as the Hawking effect (Firewalls, new universes etc) But in a sense “weirder”

Quantum paradoxes (unitarity) same as for black holes, but they apply to something as everyday as acceleration.

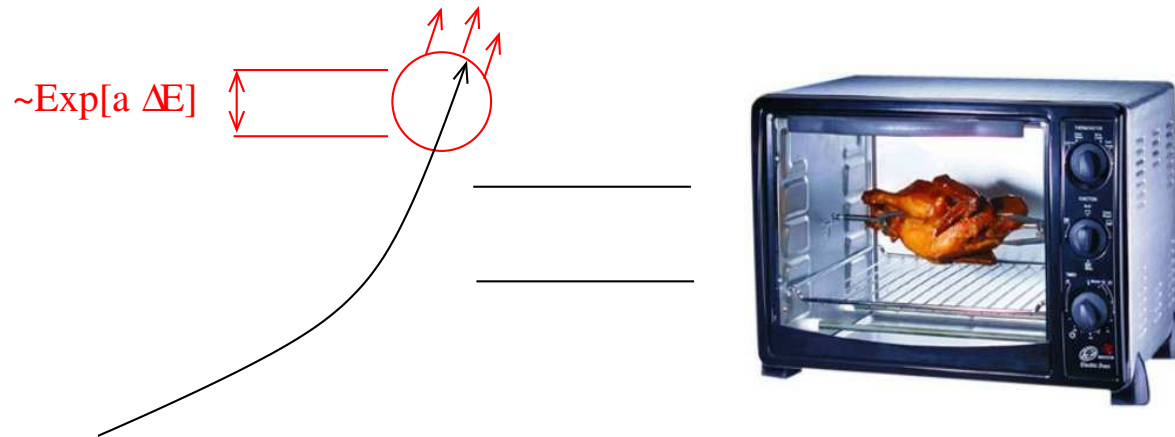
Roughly three interpretations

- It is “real” and “physical” Experimentally observable
- It is a mathematical artifact (Ford, O’Donnell)
- It is a “Coriolis force” (Matsas, Vanzella, Sudarsky, Suzuki, us)

The first view

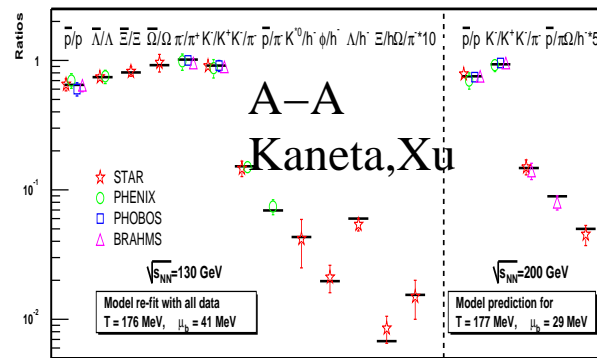
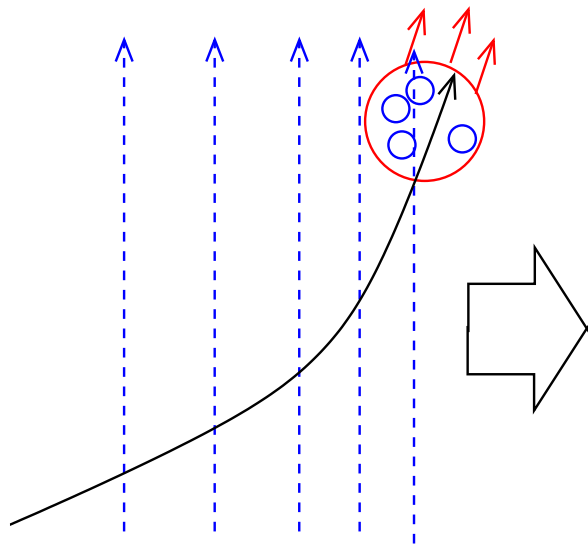
Unruh radiation is physical and contributes to the quantum evolution of a many-body system.

Experiments with accelerated detectors will see a thermal bath of radiation and thermalize with it.

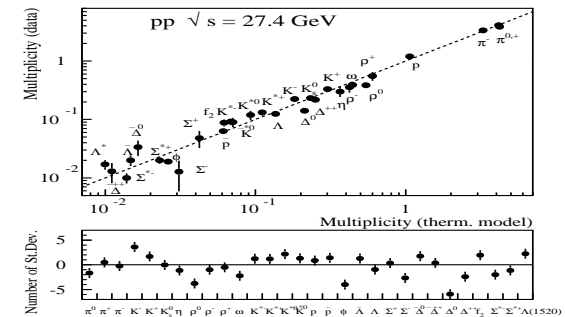


Typical setups involve 2-level system. But Unruh-calculation only, no inertial analysis

An intriguing proposal (Castorina, Kharzeev, Satz, Tuchin) is that quantum probes in a strong semi-classical field (the "Color Glass condensate" in heavy ion collisions) will "instantly thermalize" due to Unruh radiation.



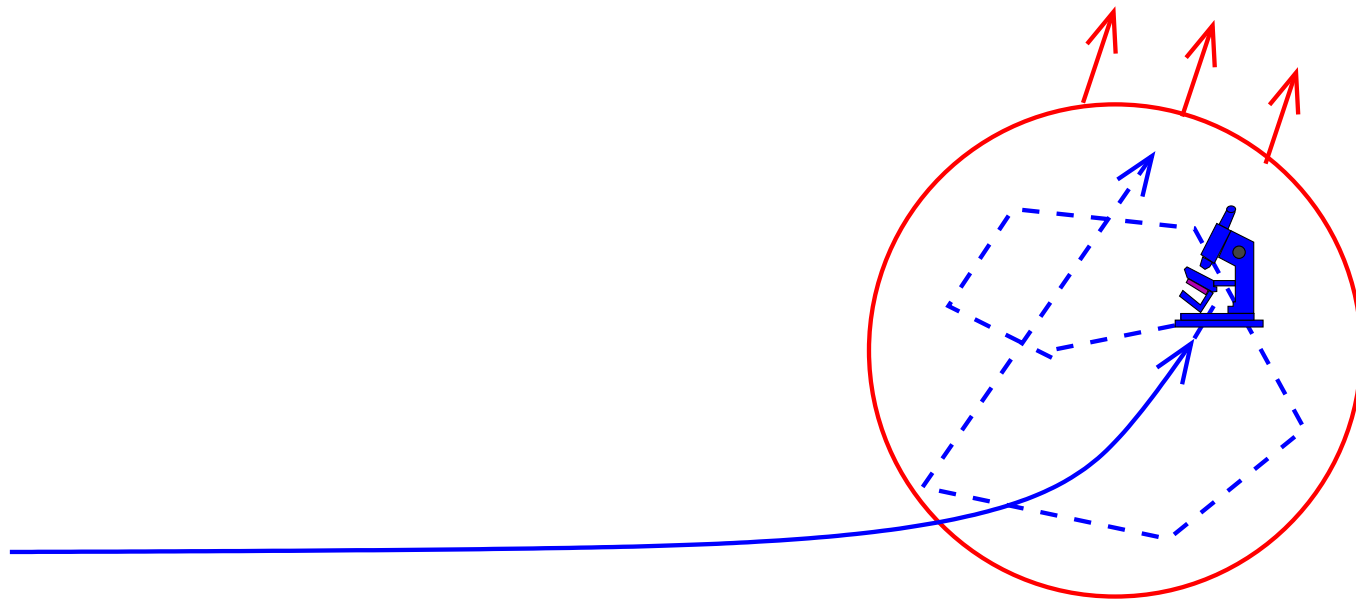
Smaller sizes (p-p, e-e)
Becattini



This has the power to explain why hadronic collisions look thermal, even in small systems .

The second view

An explicit calculation with a harmonic oscillator "detector" coupled to a scalar field (Ford, O'Connell , [quant-ph/0509151](#)) shows no radiation is perceived by asymptotic observer. However, detector still thermalizes and is effectively described by a Langrvan equation ([Fluctuation-dissipation theorem](#)).



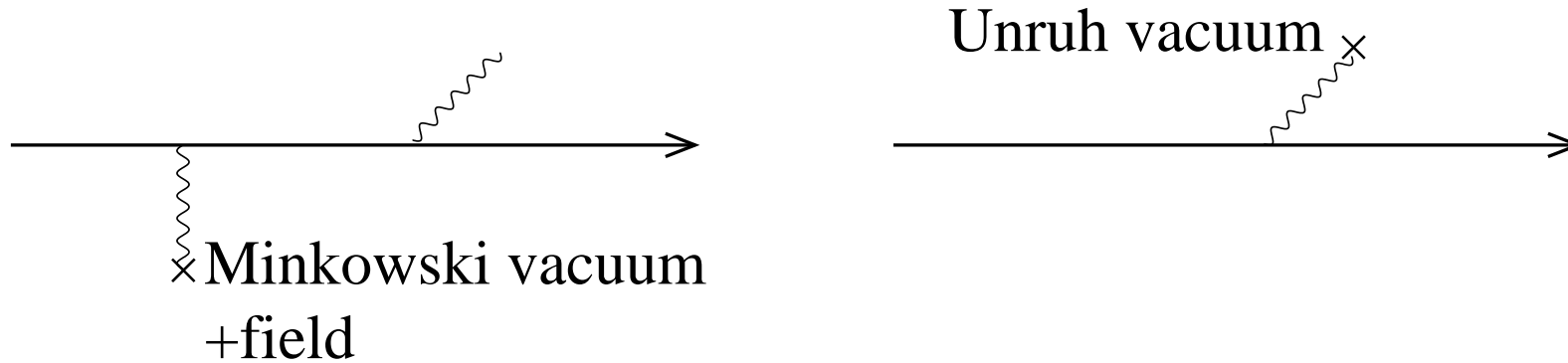
Which brings us to the third alternative: the Unruh effect as a Coriolis force
(Matsas, Vanzella, Sudarsky, Higuchi, Suzuki)

The inertial observer sees an accelerating probe which interacts with a classical field and occasionally radiates

The comoving observer sees a bath of low energy Unruh radiation, and occasional reinteractions

Both disagree on the interpretation but agree on the "physics": an observer interacting with a field.

This can be verified quantitatively



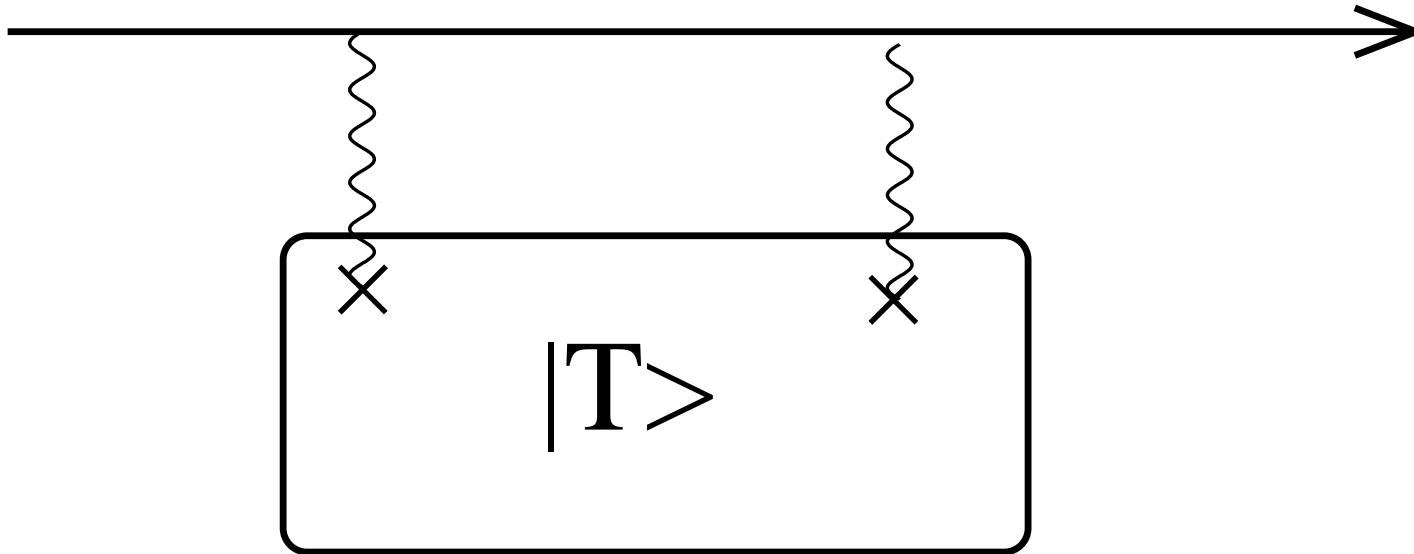
(Matsas, Vanzella, Sudarsky, Higuchi, Suzuki)

$$\Gamma_{RHS}^{Bremsstrahlung} \sim \frac{\tilde{m}_e a}{2\pi^{3/2} e^{\pi \tilde{\Delta m}}} G_{13}^{30} \left(\tilde{m}_e^2 \left| \begin{matrix} 1 \\ -1/2, 1/2 + i\tilde{\Delta m}, 1/2 - i\tilde{\Delta m} \end{matrix} \right. \right)$$

$$\Gamma_{RHS}^{Tree-level} \sim \int_{-\infty}^{+\infty} d\tilde{\omega} \frac{K_{i\tilde{\omega}+1/2}(\tilde{m}_e) K_{i\tilde{\omega}-1/2}(\tilde{m}_e)}{\cosh[\pi(\tilde{\omega} - \tilde{\Delta m})]}$$

To leading order in $\tilde{m} \times a$, g results match

There are a few caveats



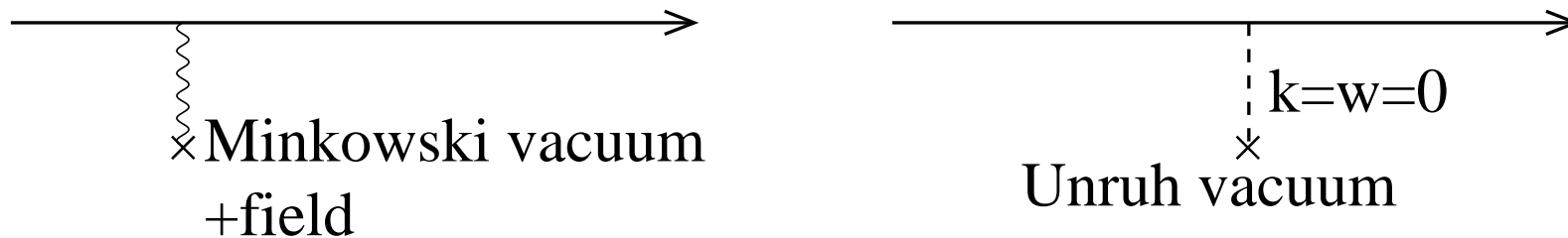
Only has been checked at tree level for certain theories (mismatch in orders explains part of disagreement with FOrd, O'Donnell)

Not clear what will happen beyond leading order, when backreaction on the vacuum is included

Ongoing work with Henrique Truran. **Could clarify thermalization physics**

There are a few caveats

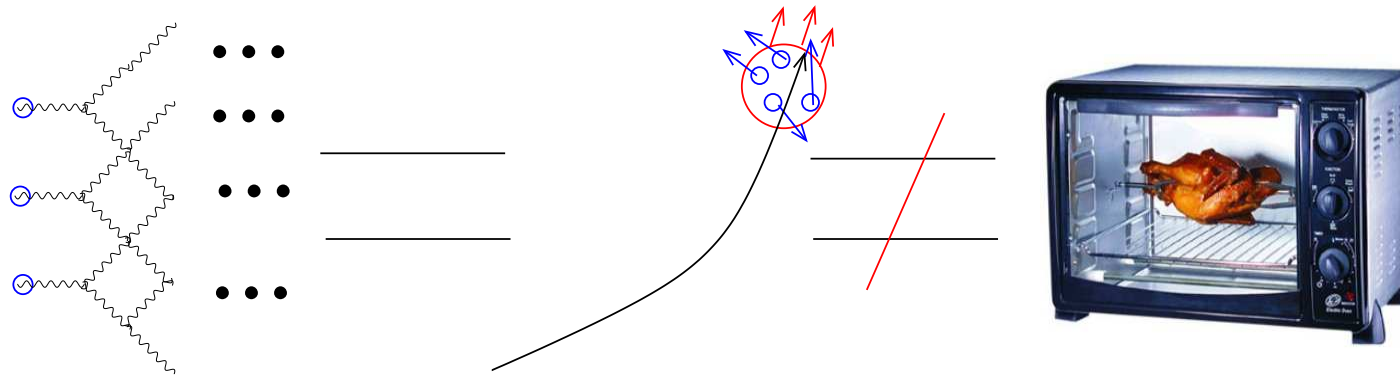
In the Infrared limit radiation undetectable "cannot detect a zero-wavenumber photon". True for QED, not necessarily scalar fields or CFTs



Related to equivalence principle (this is why a falling observer generally does not detect Hawking radiation at the horizon), but relies on field theory constraints outside gravitational physics (the Ward identity in QED)

Ongoing work with Henrique Truran. "Coriolis force" interpretation of Unruh effect not necessarily universal but applies to "real" theories. There might be a principle there!

The bad news: "Unruh thermalization" is not a magic spell which transforms your classically coherent system into a thermal bath in an instant.



- "Seeing a thermal vacuum" is not the same thing as interacting with it. The latter is higher order
- "Unruh thermalization" is, to leading order, nothing more than "bottom up thermalization" viewed in the comoving reference frame. Though **multi-body effects** could change things

But this makes the Unruh effect an interesting tool for fundamental QFT
The standard procedure: Scattering, which explores

$$\langle \phi_{initial} | M | \phi_{final} \rangle \quad , \quad M \sim M_{SM} + \frac{p^n}{\Lambda^n}$$

What happens when we: “Deform $g^{\mu\nu}$ ”, explore

$$\Delta L = g_{\mu\nu} f(\partial_\mu [A_\mu, \psi, \phi, \dots]) \rightarrow (g_{\mu\nu} + \Delta g_{\mu\nu}) f(\partial_\mu [A_\mu, \psi, \phi, \dots])$$

Usually nothing as accelerations required way too big... Ohsaku, Erbert, Zhukovsky have interesting papers on accelerated chiral symmetry restoration But $a \sim 200 \text{ MeV}$ a bit unrealistic That said, let us search!

Processes where the Unruh effect was found to be equivalent to perturbation theory... (Matsas, Vanzella, Sudarsky, Higuchi, Suzuki)

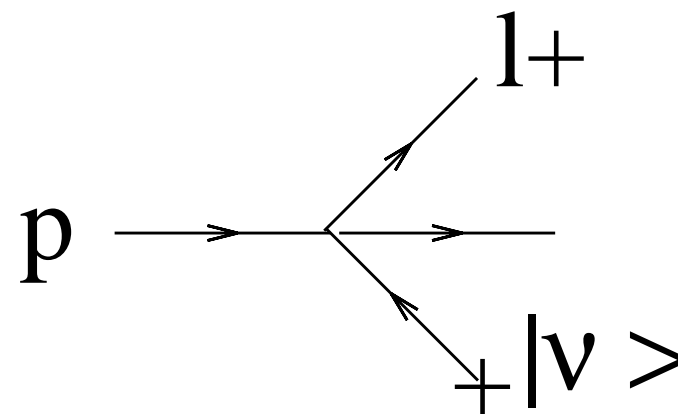
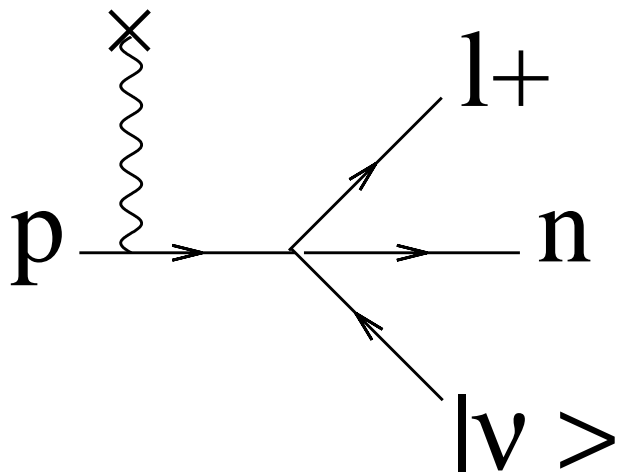
- Bremsstrahlung (QED)
- $e\nu \leftrightarrow e\nu$ scattering
- $p \leftrightarrow en\nu$ conversions

The latter are however interesting, since neutrino oscillations neglected here

Let us concentrate on this process $p \rightarrow n \nu e^+$

Inertial frame If you consider how the proton is being accelerated, EM/weak Bremsstrahlung

comoving frame Absorption of virtual electrons and neutrinos in the comoving frame



The problem!

Neutrinos are widely thought to oscillate, because weak Eigenstates do not coincide with mass Eigenstates

$$|\nu_{e,\mu,\tau}\rangle = \sum_i U_i^{e,\mu,\tau} \exp\left[i\sqrt{m_i^2 + p^2}\right] |i\rangle$$

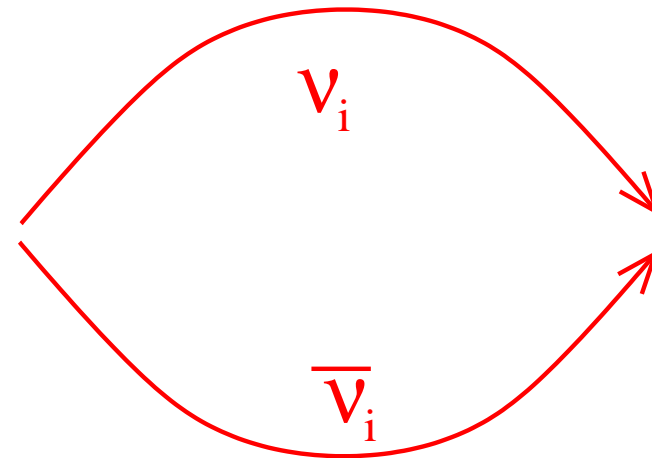
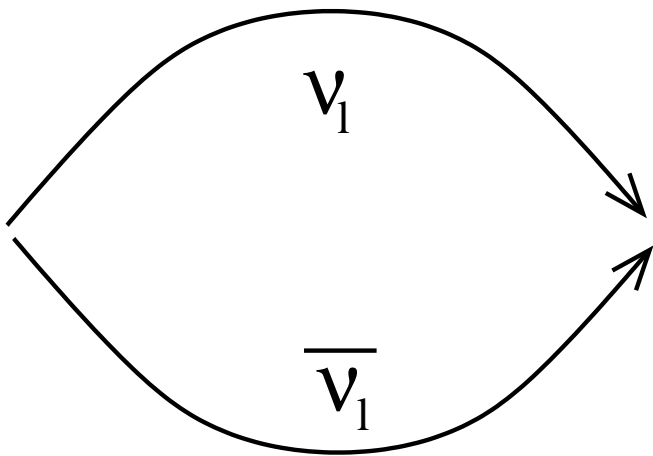
Equivalence calculations neglected oscillations, **Which is the most interesting part!**

Oscillations Sound "simple", and similar to Kaons, but its not!

- **Wigner:** Particles are representations of the Lorentz group, elementary particles are irreducible representations. $K^0, \overline{K}^0, K_{S,L}$ mass degenerate and composite
- Irreducible representations correspond to superselection rules: You cannot prepare a **superposition of protons and electrons** , why can you do it with neutrinoes?

Weinberg: Superselection rules are a red herring

One can easily extend any group (the Lorentz group to $SL(2, C)$) so superselection rules are broken and nothing else happens. But this refers to states, not to the vacuum. What does a neutrino vacuum look like?



Is it dominated by fluctuations of charge or mass Eigenstates? And who cares?!

Gravity does!

- Linear gravity couples to $T_{\mu\nu}$

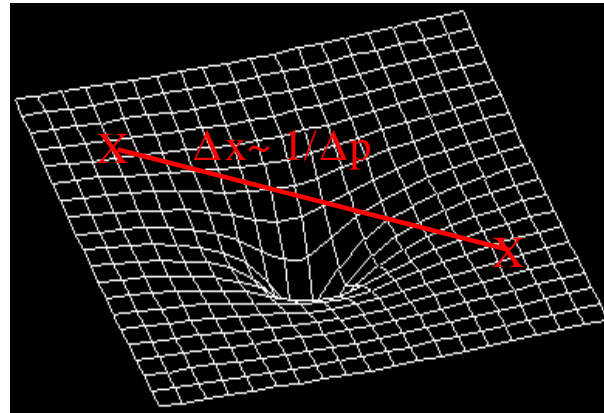
$$T_{\mu\nu} = \sum_{i=1\dots 3} [\bar{\psi}_i \gamma_\mu \partial_\nu \psi_i - g_{\mu\nu} (\bar{\psi}_i (\gamma_\alpha \partial^\alpha - m_i) \psi_i)] + \mathcal{O}(h, \psi^4)$$

- Neutrinos couple to charge Eigenstates

$$\hat{J}_{Ll}^\mu \simeq \sum_{j=1,\dots,3} U_{ij} (\bar{\psi}_{Lj} \gamma^\mu \psi_{Lj})$$

And this blatantly breaks the equivalence principle, **Albeit in an unobservable way**

The equivalence principle is compatible with semiclassical gravity

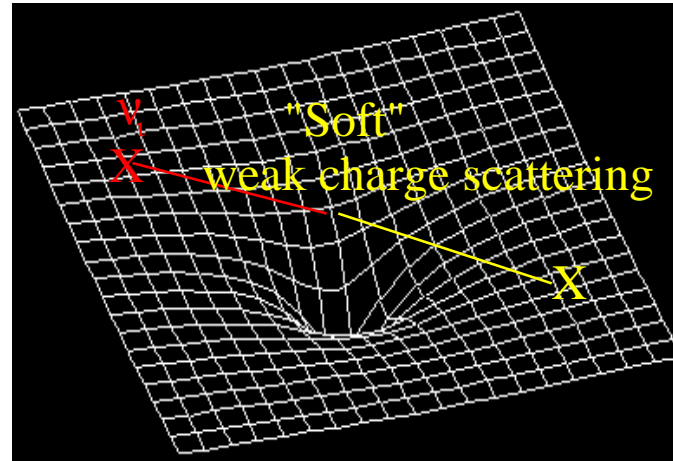


Only non-commuting observable with $T_{\mu\nu}$ is position : As long as

$$G \left(|T_{\mu\nu}| \xrightarrow[\text{measurement}]{} |T_{\mu\nu}| \right) \ll |R_{\mu\nu}|$$

we can assume a classical non-fluctuating spacetime. This is in fact the definition of $l_p \sim \sqrt{G} \sim 10^{19}$ GeV

Except for neutrinos!



Detecting neutrino charge-states will change $T_{\mu\nu}$ instantaneously, tension with GR in gravitating systems

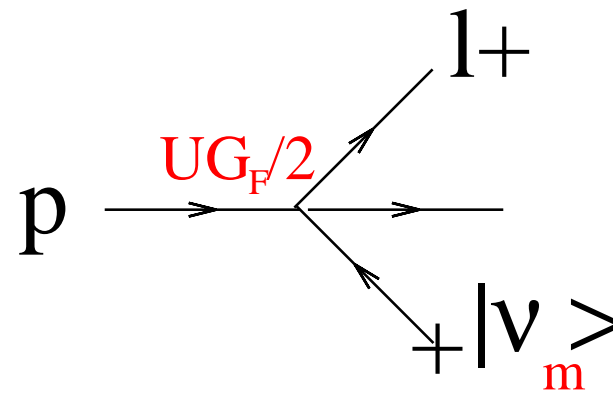
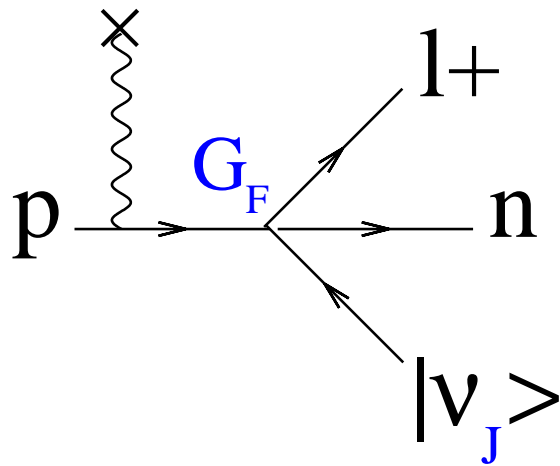
$$T_{\mu\nu}(\psi_{Li}, \psi_{Ri}) \rightarrow \sum_j U_{ij} T_{\mu\nu}(\psi_{Lj}, \psi_{Ri})$$

Gravitational effect of oscillating neutrinos negligible **but...**

The Unruh effect and oscillating neutrinos

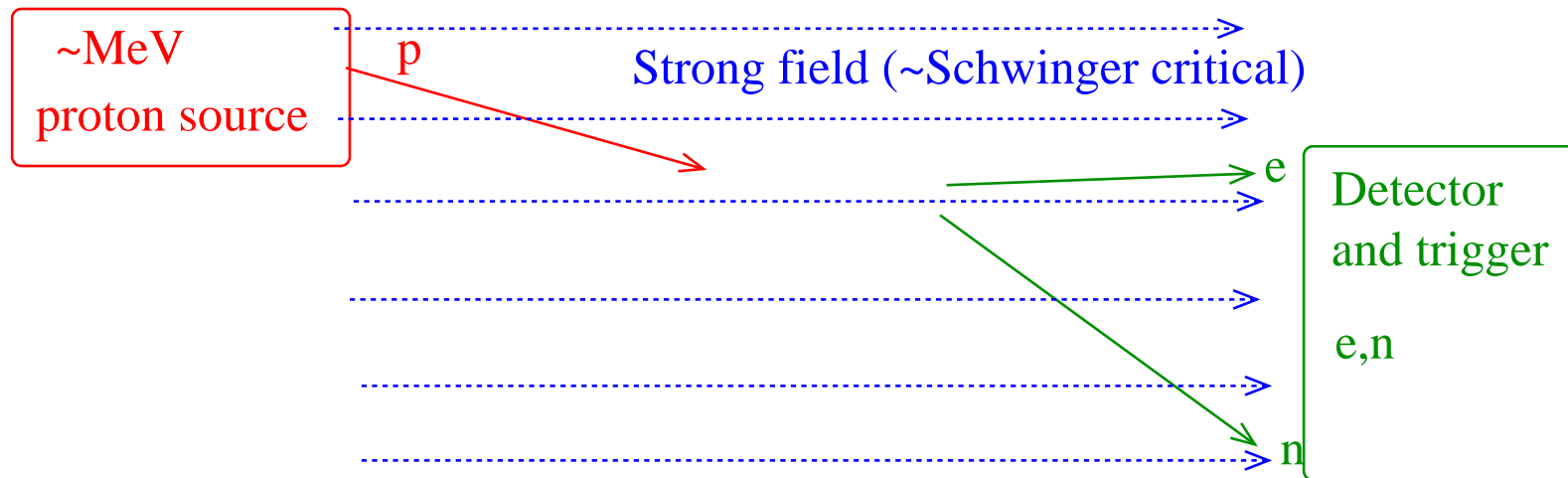
Inertial frame sees charge Eigenstates, since proton probes charge

Comoving frame sees mass Eigenstates, since thermal bath in free limit insensitive to charge

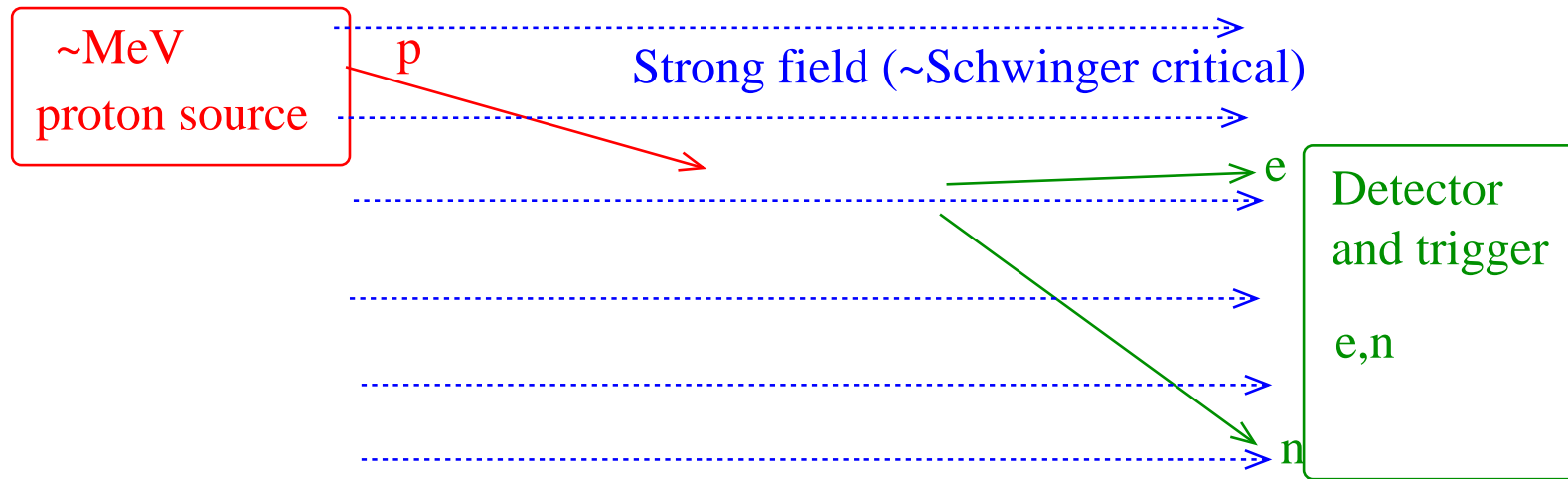


The two are not reconducible to a change of frame!

The Unruh effect might move this from Gedanken-experiments to experiments



Same apparatus for Schwinger effect detection should also detect this, provided fast correlated ne^+ detection (to eliminate the "background", ie the Schwinger effect).



You don't need to detect neutrinos, which is great! Unfortunately μ, τ inaccessible. But can experimentally measure e rate and compare with inertial and comoving predictions. **Since they differ at least one is "wrong"**

Who is right? “minimalist” view

The Unruh effect is being explored for a variety of non-trivial theories, from Chiral symmetry breaking to the Higgs. Results are still controversial, but as relevant accelerations are ridiculous resolution wont come from experiment.

$$\Delta L = \mathcal{O}^d \rightarrow a_{required} \sim \langle \mathcal{O} \rangle^{1/d} \quad \mathcal{O} \text{ relevant operator}$$

neutrino mass is tiny $\sim eV$ at most,

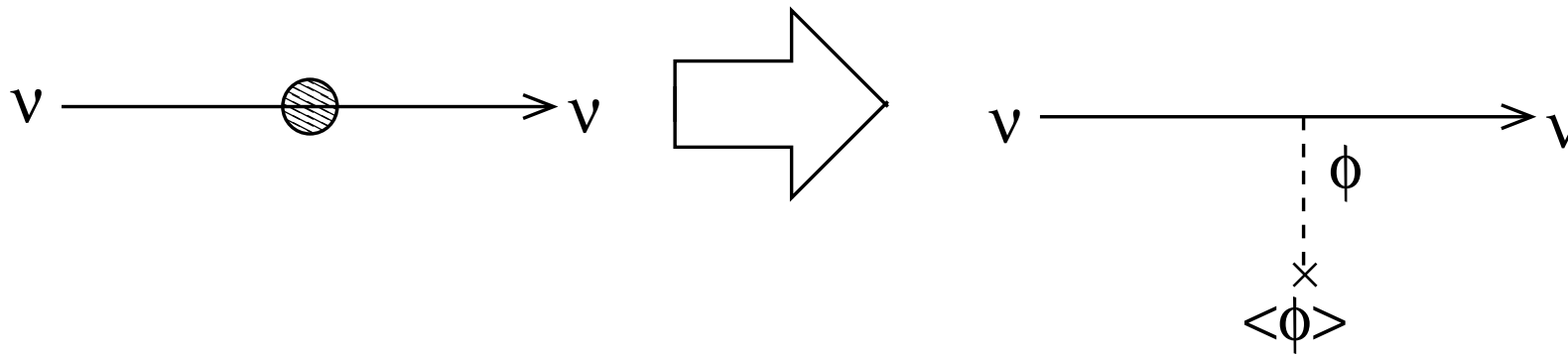
$$\Delta L = m\psi\bar{\psi} \sim eV^4$$

.
So Schwinger accelerations more than sufficient here.

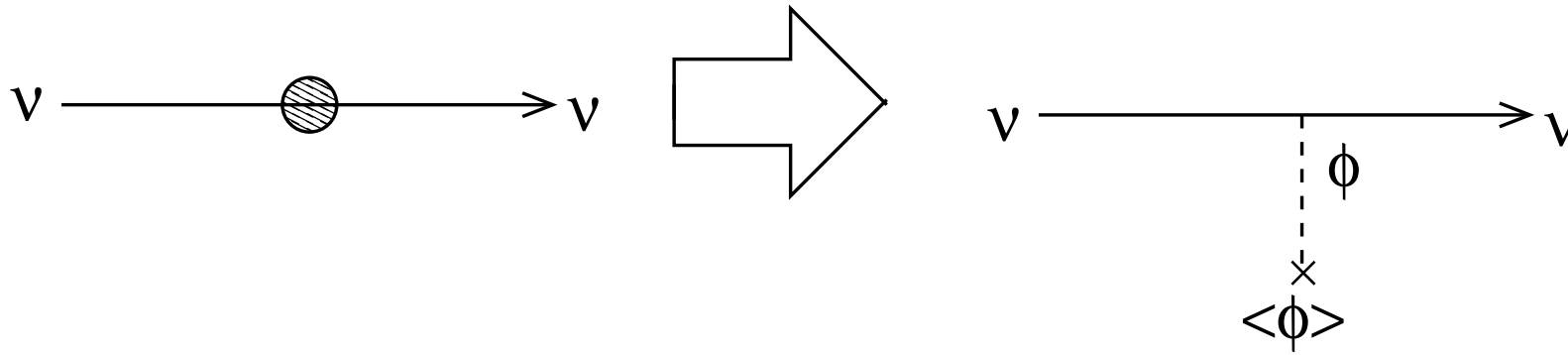
NB: leading order $a \times \tilde{m}$ used in Matsas and coauthors inadequate. **Virtuality of proton** corresponds to **thermal motion** in comoving frame. Work in progress

possible answer

Calculations done in "point-like fundamental mass" limit, but in standard model mass is an infrared operator.



The point-like approximation breaks differently in different frames



Inertial frame "massive" particle acquires a form factor $\sim 1/\langle \phi^\alpha \rangle$
 irrelevant for soft modes

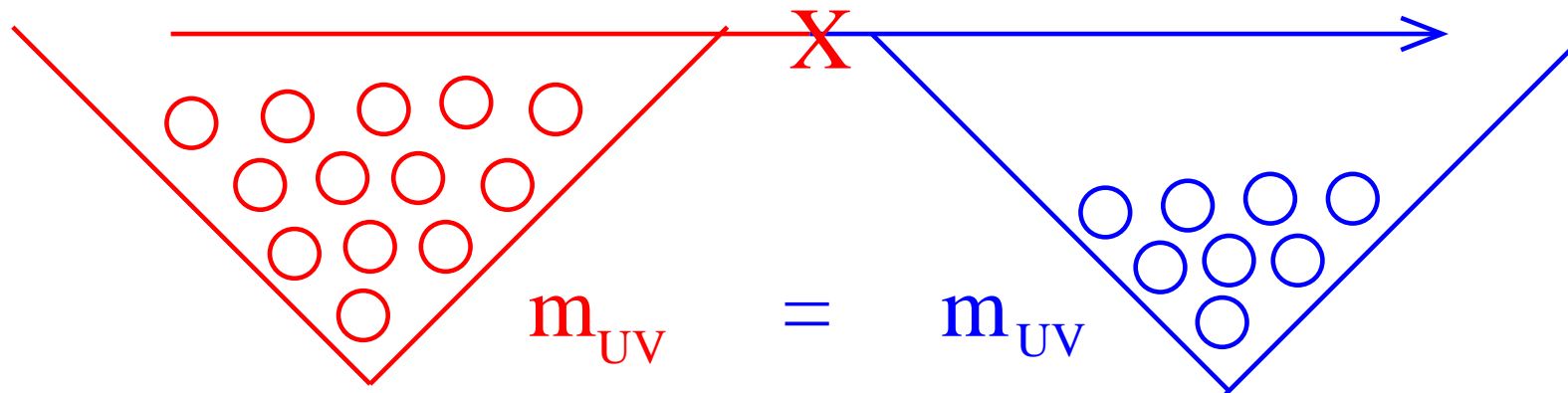
Comoving frame Condensate zero-modes transformed to Rindler frame.
 Condensate looks different! "to zero order", renormalized to higher
 temperature

Inertial calculation more appropriate!

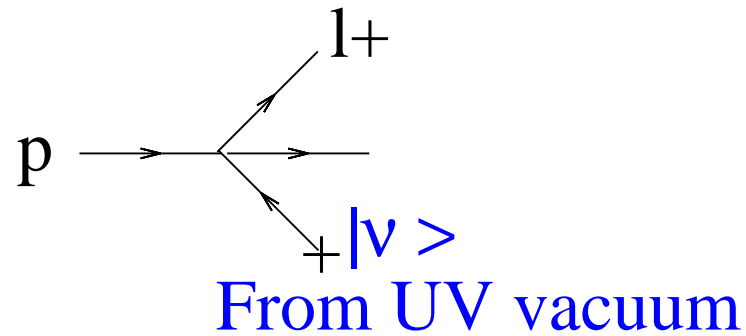
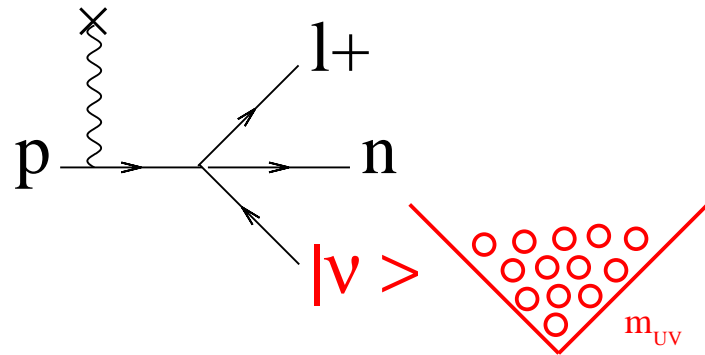
Possible answer II

What if the mass state is fundamental and the flavor state effective?

Not popular in the current consensus, but possible: [Bob McElrath](#) ,
oscillations from $CM\nu$ Fermi surface.

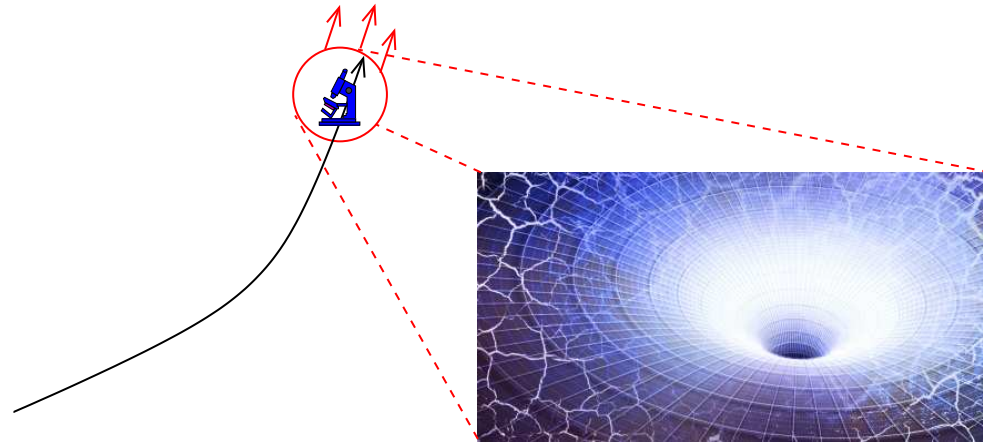


Masses generated by Fermi surface, oscillations by non-commutativity of neutrino charges



In this case , comoving calculation is “more” correct. The discrepancy w.r.t. inertial calculation gives mixing angles and mass differences (note the absolute values of mixing angles, not relative phases).

Possible answer III



QFT is about particles (representations of the Lorentz group) propagating on a manifold (spacetime). Neutrino oscillations seem to show a tension in this separation. A hint of QFT itself breaking down?

The Unruh effect gives an orthogonal way of "perturbing" QFT, as it perturbs the manifold, not the particles. For neutrinos, and only for them, this gives observable consequences. **Perhaps both predictions break down!**
Polarized beam/polarization detectors will also allow CPT tests

Conclusions

- Unruh effect as, if not more "mysterious" (shows tension between gravity and quantum mechanics) as Hawking radiation, but accessible
- For realistic quantum field theories, to leading order, it seems to be a "Coriolis force", tractable in the inertial frame by perturbative interactions. Not clear how universal is this equivalence or to what approximation does it hold.
- Neutrino oscillations presents a paradox for this picture. This paradox can be experimentally investigated.

