# The Unruh effect: interpretation and relation to fundamental physics

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# Synopsis

**Introduction:** What is the Unruh effect

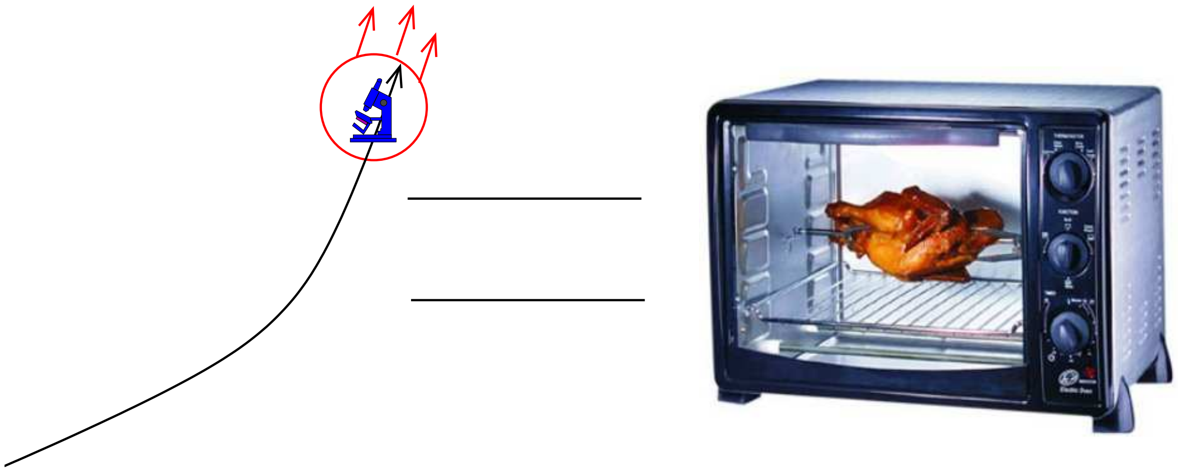
**Is it real?** Real, unreal, ”A coriolis force”

**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 accelleration 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 accellerating frame

$(\tau, t, x) \to \left(\sqrt{\rho}\tau, \zeta, \zeta/\sqrt{\rho} @ \rho_0\right)$ are not the same

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

Vacuum and creation+annihillation operators change

$$_M < 0|\hat{\phi}|0 >_M = \int \frac{d^3k}{\sqrt{E_k}} \left(a_k e^{ikx} + a^+_{-k} e^{-ikx}\right) \to$$

$$\to_R < 0|\hat{\phi}|0 >_R = \int \frac{d^3k}{\sqrt{E_k}} \left(a_{kR} K(kx) + a^+_{-kR} K(-kx)\right)$$

Since in QFT particle number not conserved and accelleration transformation breaks Lorentz symmetry, accellerating observers disagree on particle number Bogoliubov transformations $a^{+} \rightarrow \cos\theta a^{+} + \sin\theta a$ ,asymptotic states different

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

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

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).

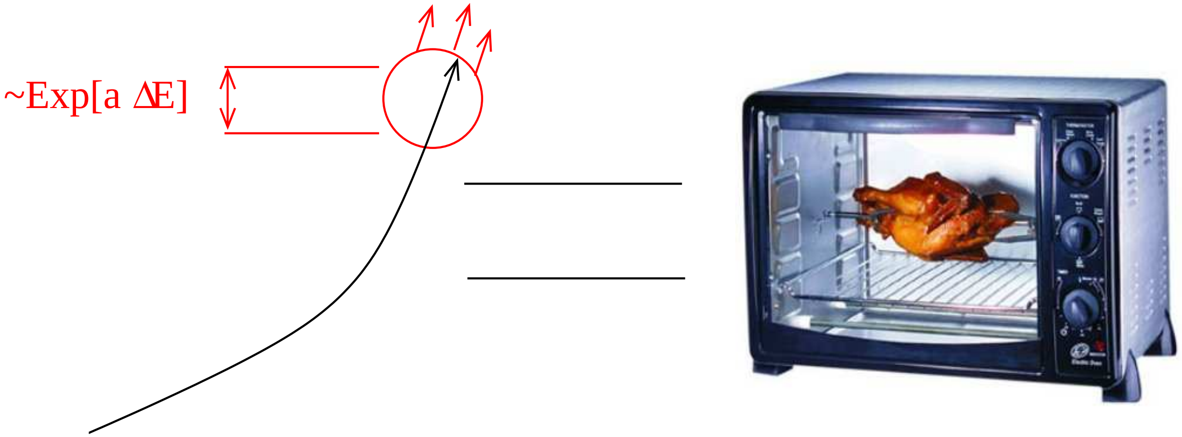
Not as discussed as the Hawking effect (Firewalls, new universes etc) But in a sense “weirder”
Quantum paradoxes (unitarity) same as for black holes, but they apply to something as everyday as accelleration.
Roughly threee interpretations

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

## The first view

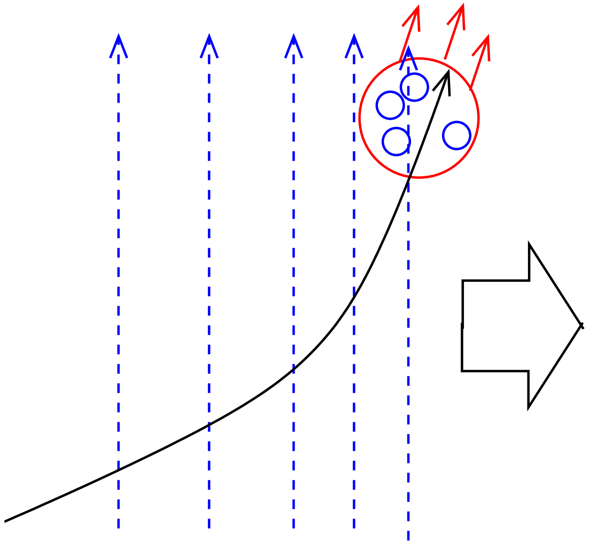
Unruh radiation is physical and contributes to the quantum evolution of a many-body system.

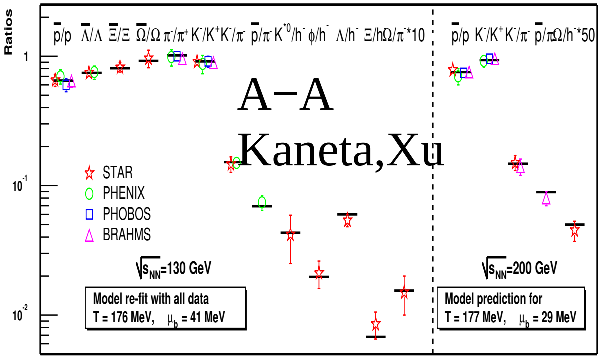
Experiments with accellerated detectors will see a thermal bath of radiation and thermalize with it.



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

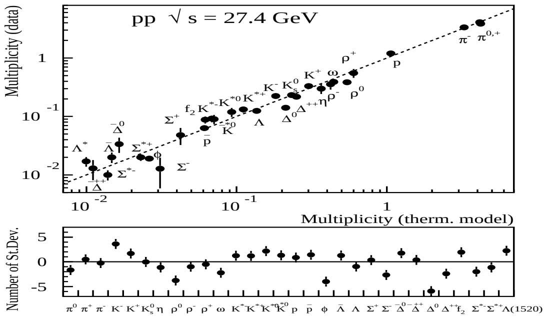
An intriguing proposal (Castorina, Kharzeev, Satz,Tuchin ) is that quantum probes in a strong semi-classical field (the "Color Glass condensate" in heavy ion collisions) will "instantly thermalize" due to Unruh radiation.





A−A
Kaneta,Xu

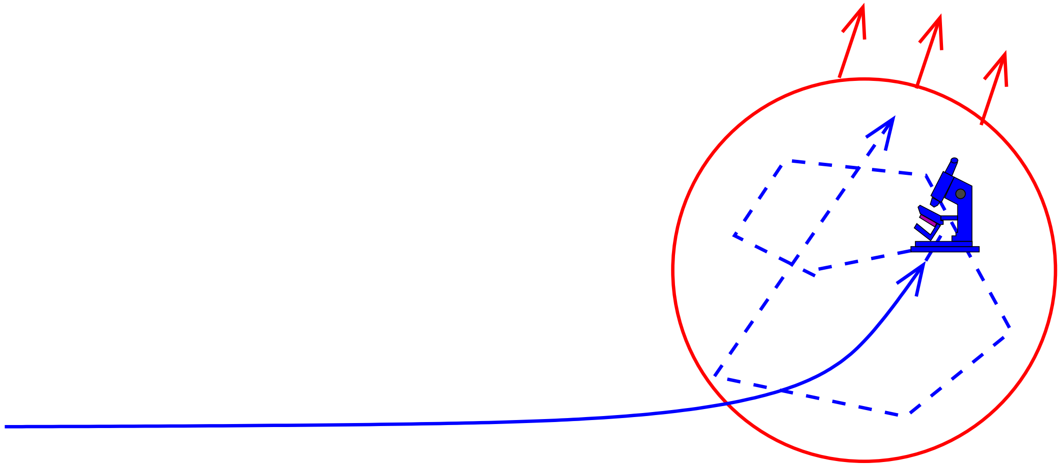
Smaller sizes (p−p,e−e)
Becattini

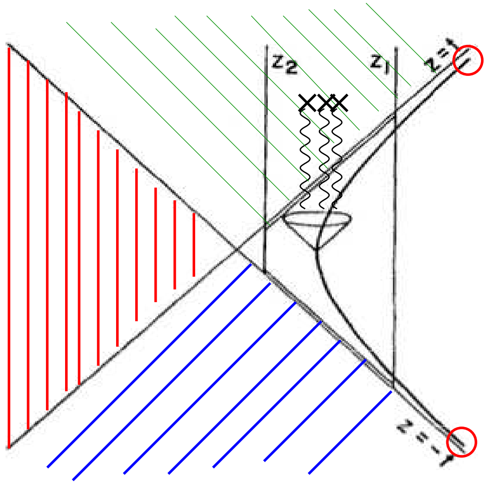


This has the power to explain why hadronic collisions look thermal, even in small systems .

## The second view

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





Boundary
conditions

Belinski et all ... effect critically depends on field behavior at boundary, no good quantization exists. But a lot of GR effects depend on boundary conditions at quantization, its the "non-unitary" bit of transformation (Belinski also does not believe in Hawking radiation)

Svajter, Padhanabhadan,Milgrom,... Quasi-thermal distributions for finite accellerations, IR effects, work in progress

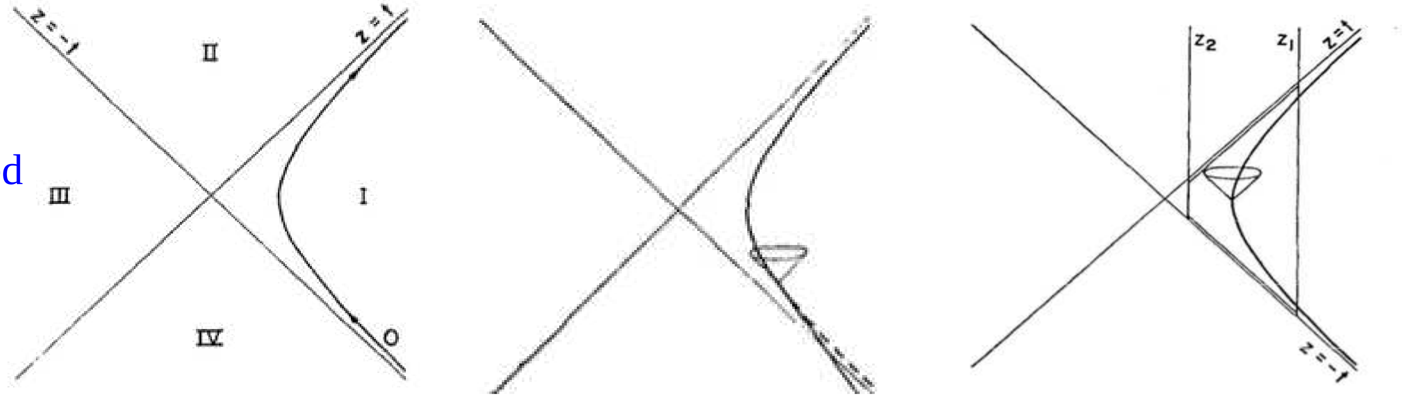
Which brings us to the third alternative: the Unruh effect as a Coriolis force (Boulware,Matsas,Vanzella,Sudarsky,Higuchi,Suzuki )

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

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

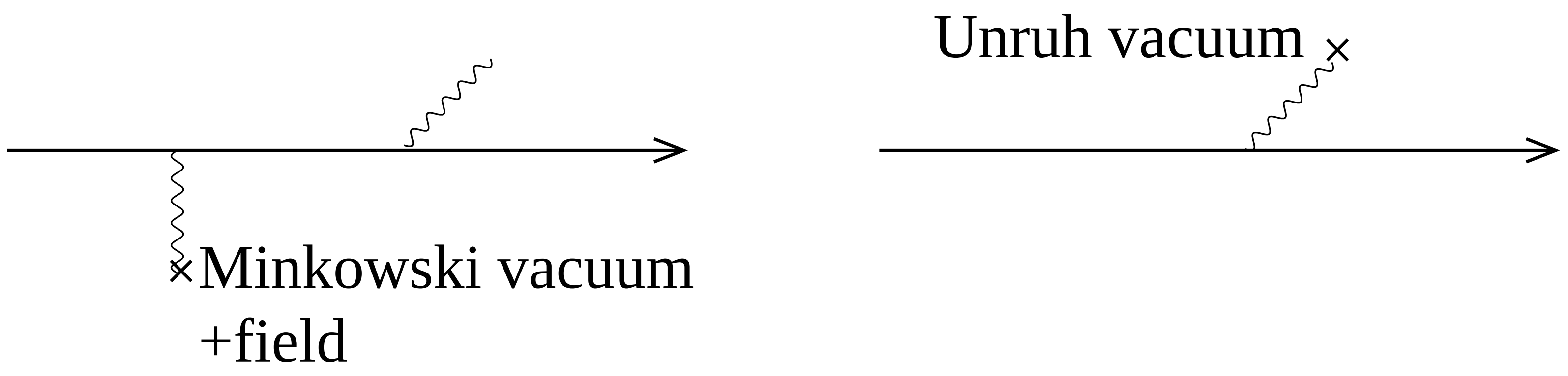
Both disagree on the interpretation but agree on the "physics": an observer interacting with a field.

Boulware
1982
Classical
accellerated
charge



Co-accelerating observer sees no field, an inertial observer sees Bremmstrahlung, as Bremmstrahlung from constant acceleration is beamed forward, ie primarily into the upper Rindler wedge ($t+z>0, t-z>0$ ) which is causally inaccessible to the co-accelerating observer. Moreover, the electromagnetic field seen by the co-accelerating observer constrained to the right Rindler wedge drops off as $1/r^2$ where r is the distance from the world line of the accelerating charge. The $1/r$ part is limited to a very small angle in the forward direction, in finite $\tau_{comoving}$ cant separated from the $1/r^2$ component. As leading order perturbative $\equiv$ classical...

This can be verified quantitatively (quantum leading order)



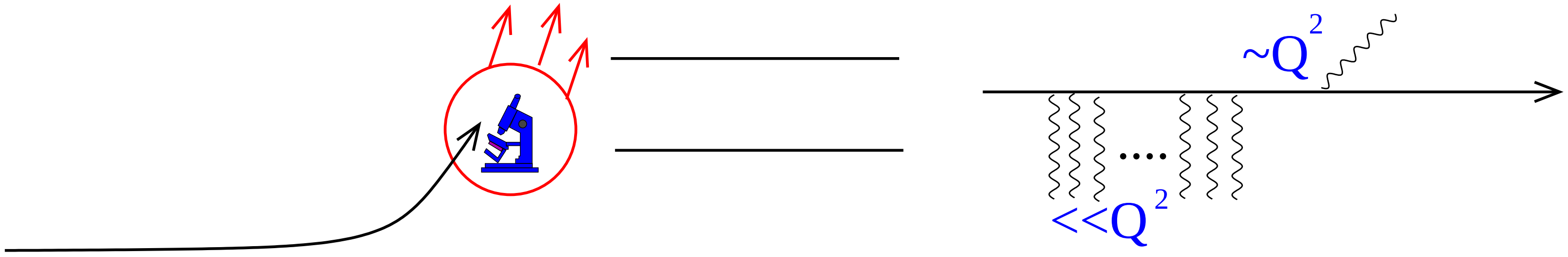
(Matsas,Vanzella,Sudarsky,Higuchi,Suzuki )

$$\Gamma_{RHS}^{Bremsstrahlung} \sim \frac{\tilde{m}_e a}{2\pi^{3/2} e^{\pi \widetilde{\Delta m}}} G^{3\,0}_{1\,3}\left(\tilde{m}_e^2 \middle| \begin{array}{c} 1 \\ -1/2\,,\ 1/2+i\widetilde{\Delta m}\,,\ 1/2-i\widetilde{\Delta m} \end{array}\right)$$

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

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

There are a few caveats: its not really Bremsstrahlung,more like Schwinger+Bremsstrahlung

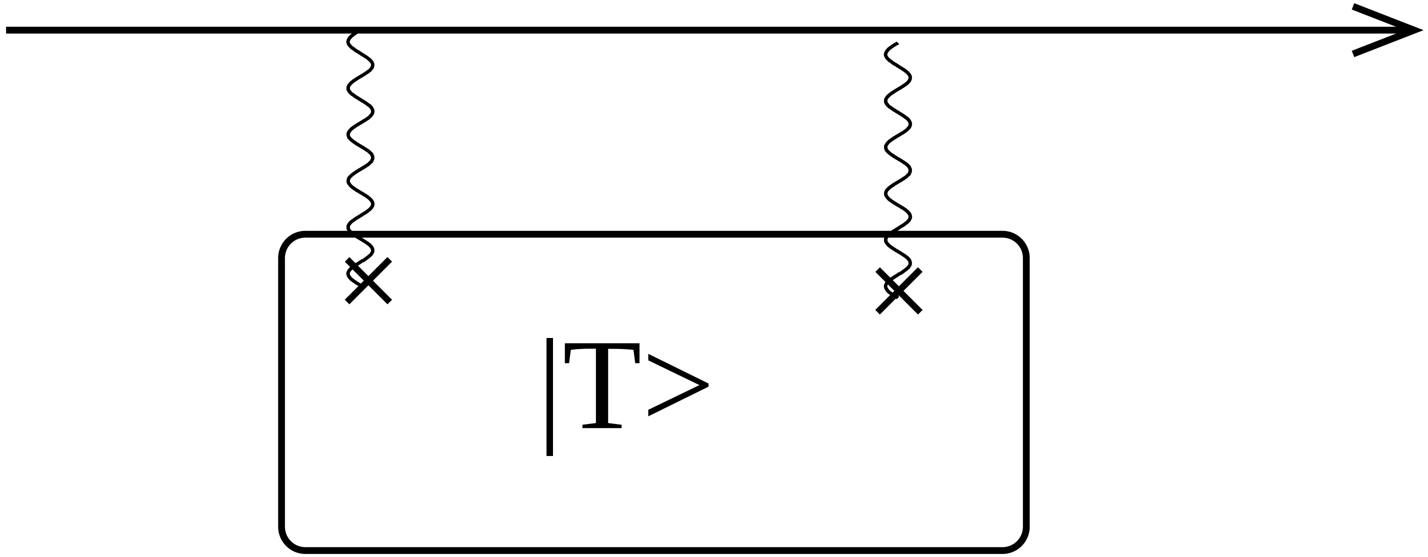


Need ”semiclassical approximation”, energy of each photon ≪ scattering scale (or this is just quantum scattering)

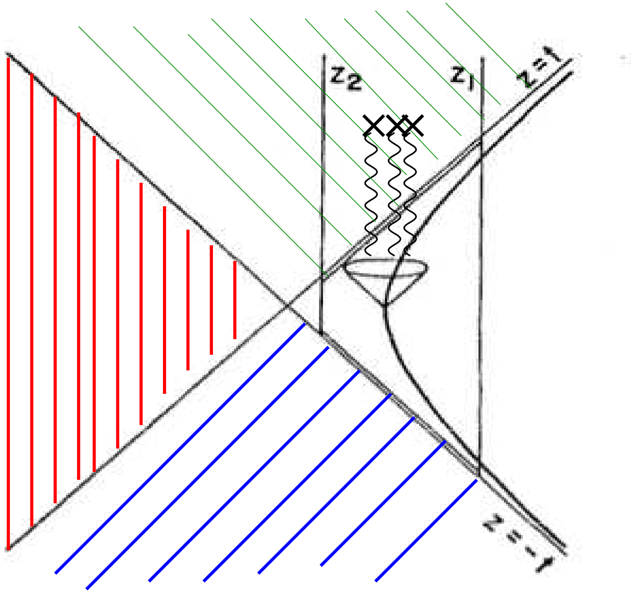
$$\left\langle \hat{J} \right\rangle \simeq \delta\left(x - v_0 t - \frac{1}{2}at^2\right) \Rightarrow \Delta x \ll \left(\nabla \vec{E}\right)^{-1} \Rightarrow \frac{\left|\nabla \vec{E}\right|}{\left|\vec{E}\right|} \ll |a|$$

This is the main barrier to studying this stuff experimentally! Need high intensity low frequency field wrt process studied

## There are a few caveats



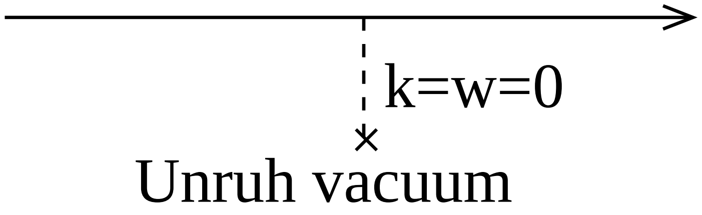
Only has been checked at tree level for certain theories (mismatch in orders explains part of disagreement with FOrd, O'Connell)
Not clear what will happen beyond leading order, when backreaction on the vacuum is included



Ongoing work with Henrique Truran. Could clarify thermalization physics
Can one relate entropy increase to tracing of DoFs over the horizon? Does the detector's finite frequency resolution, together with the configuration space profile in the Rindler frame induce decoherence? How is this related to entropy in the inertial frame?

## There are a few caveats

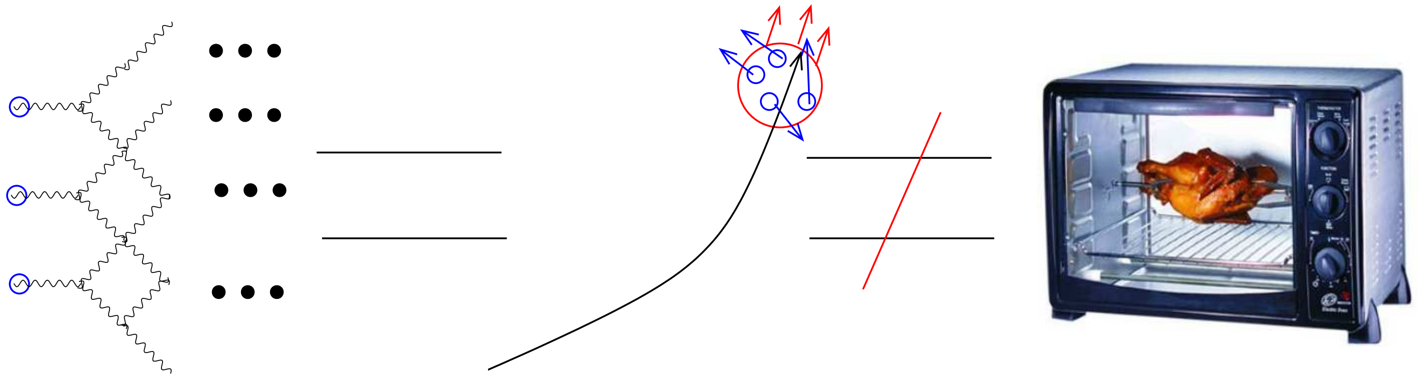
In the Infrared limit radiation undetectable ”cannot detect a zero-wavenumber photon . True for QED, not necessarily scalar fields or CFTs



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 <u>not</u> 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

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

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

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

Usually nothing as accellerations required <u>way too big</u>... Ohsaku,Erbert, Zhukovsky have interesting papers on accellerated chiral symmetry restoration But $a \sim 200$ MeV <u>a bit unrealistic</u> That said, let us search!

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

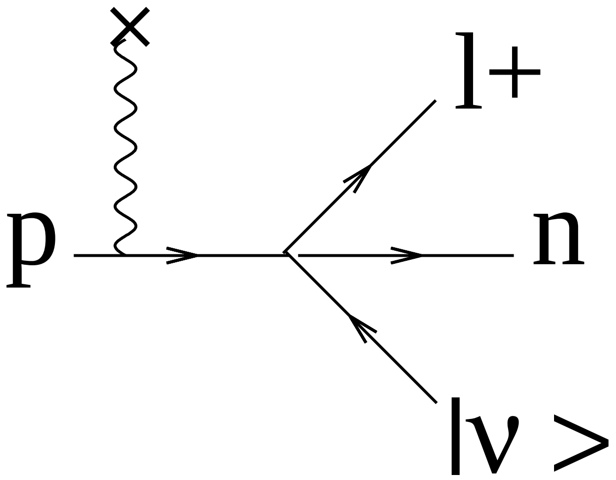
- Brehmsstrahlung (QED)
- $e\nu \leftrightarrow e\nu$ scattering
- $p \leftrightarrow en\nu$ convesions

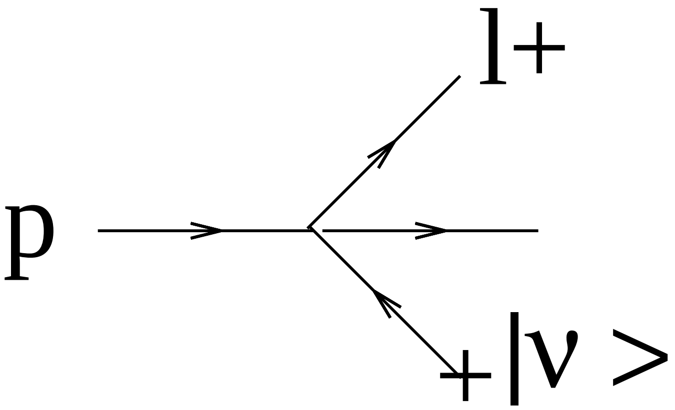
The latter are however interesting, since neutrino oscillations neglected here

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

**Inertial frame** If you consider how the proton is being accellerated, EM/weak Breamsstrahlung

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





## The problem!

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

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

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

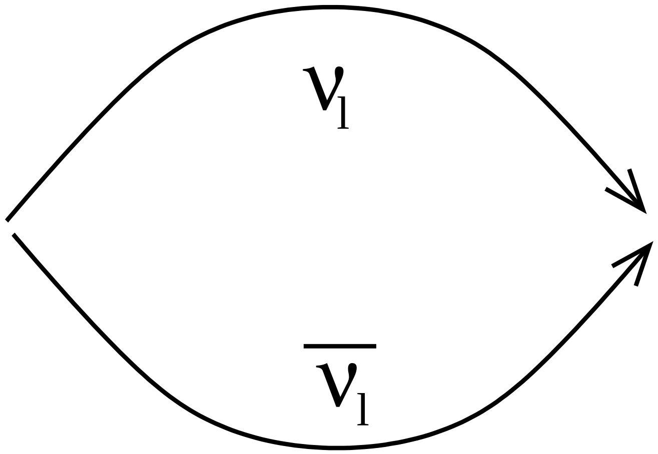
## Oscillations Sound "simple", and similar to Kaons, but its not!

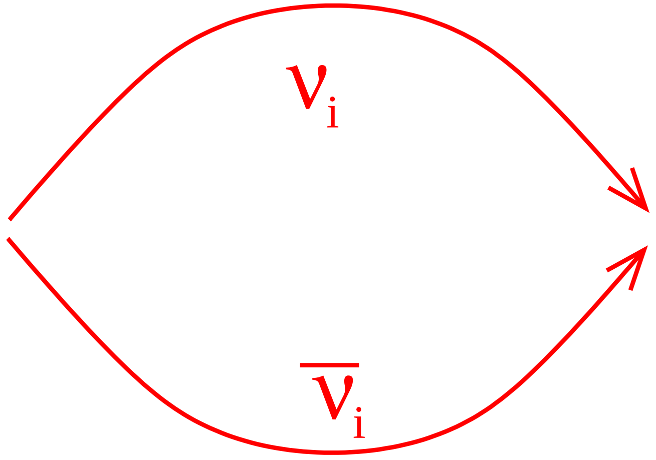
- Wigner: Particles are representations of the Lorentz group, elementary particles are irreducible representations. $K^0, \overline{K^0}, K_{S,L}$ mass degenerate and composite

- Irreducible representations correspond to superselection rules: You cannot prepare a superposition of protons and electrons (related to Coleman-Mandula theorem ), 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 $T_{\mu\nu}$

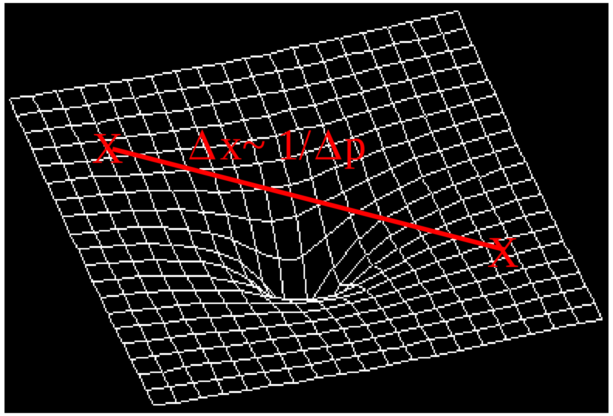
$$T_{\mu\nu} = \sum_{i=1\ldots3} \left[\overline{\psi_i}\gamma_\mu\partial_\nu\psi_i - g_{\mu\nu}\left(\overline{\psi}_i(\gamma_\alpha\partial^\alpha - m_i)\psi_i\right)\right] + \mathcal{O}\left(h,\psi^4\right)$$

- Neutrinoes couple to charge Eigenstates

$$\hat{J}^{\mu}_{Ll} \simeq \sum_{j=1,..,3} U_{ij}\left(\overline{\psi_{L}}_j\gamma^\mu\psi_{Lj}\right)$$

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

# The equivalence principle is compatible with semiclassical gravity

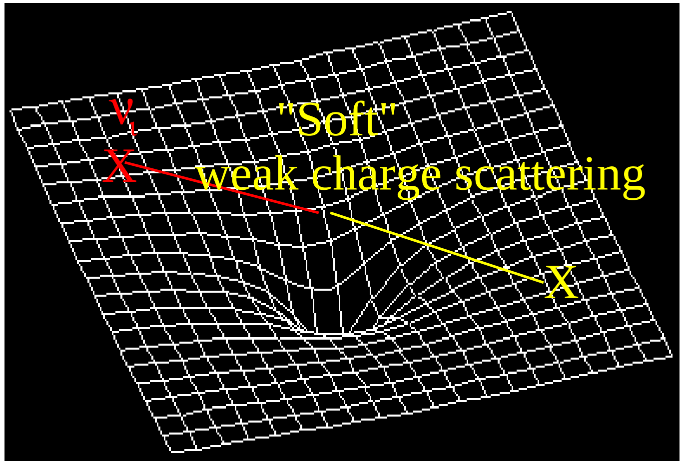


Only non-commuting observable with $T_{\mu\nu}$ is position : As long as

$$G\left( |T_{\mu\nu}| \underbrace{\rightarrow}_{measurement} |T_{\mu\nu}| \right) \ll |R_{\mu\nu}|$$

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 neutrinoes!



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

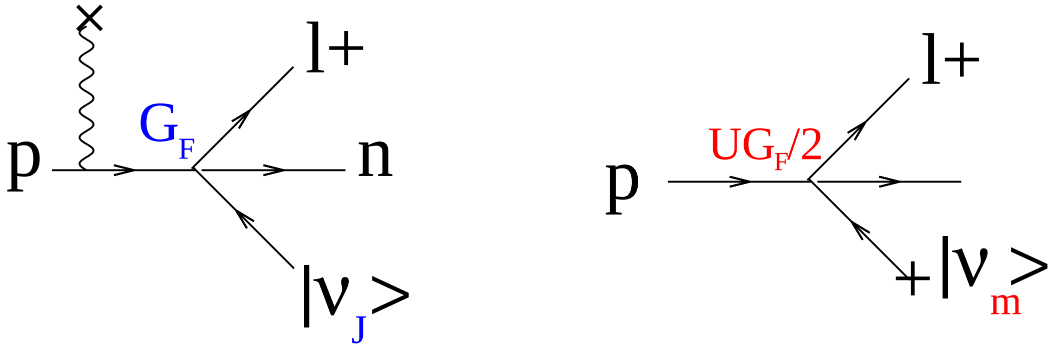
$$T_{\mu\nu}(\psi_{Li},\psi_{Ri}) \rightarrow \sum_j U_{ij} T_{\mu\nu}\left(\psi_{Lj},\psi_{Ri}\right)$$

Gravitational effect of oscillating neutrinos negligible but...

# The Unruh effect and oscillating neutrinoes

**Intertial frame** sees charge Eigenstates, since proton probes charge and neutrino produced at interaction.

**Comoving frame** sees mass Eigenstates, since antineutrino absorbed from Unruh bath (asymptotic mass state coming from "horizon")



The two are different by internal factor $U$ , not reconducible to a change of frame! This is a paradox!

Is it a problem? Phase space!

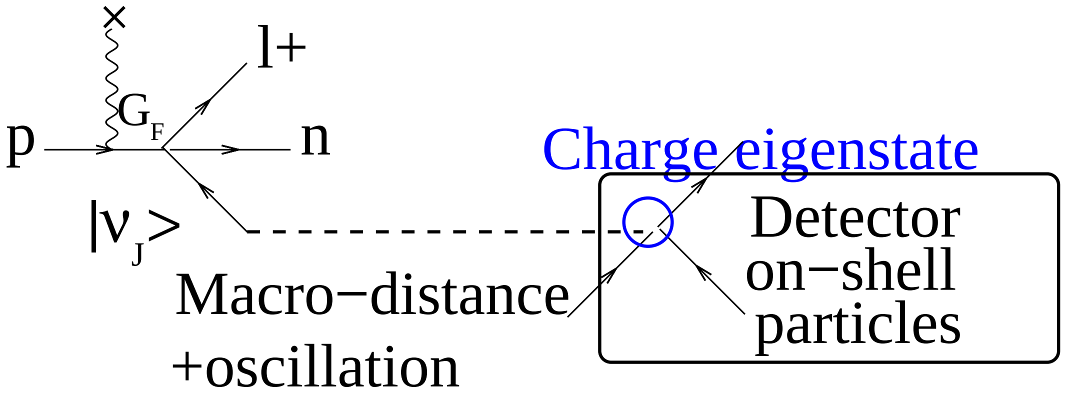
If Neutrinoes "on-shell", the same factor would appear in Minkowski frame since

$$\int d^4 k_{\nu_l} = \sum U^* U \int d^4 k_{\nu_i} \delta \left( k^2 - m_{\nu_i} \right)$$

The Minkowski mass state is projected out by the detector in Minkowski space in the same way as it is projected by the horizon in Rindler space...

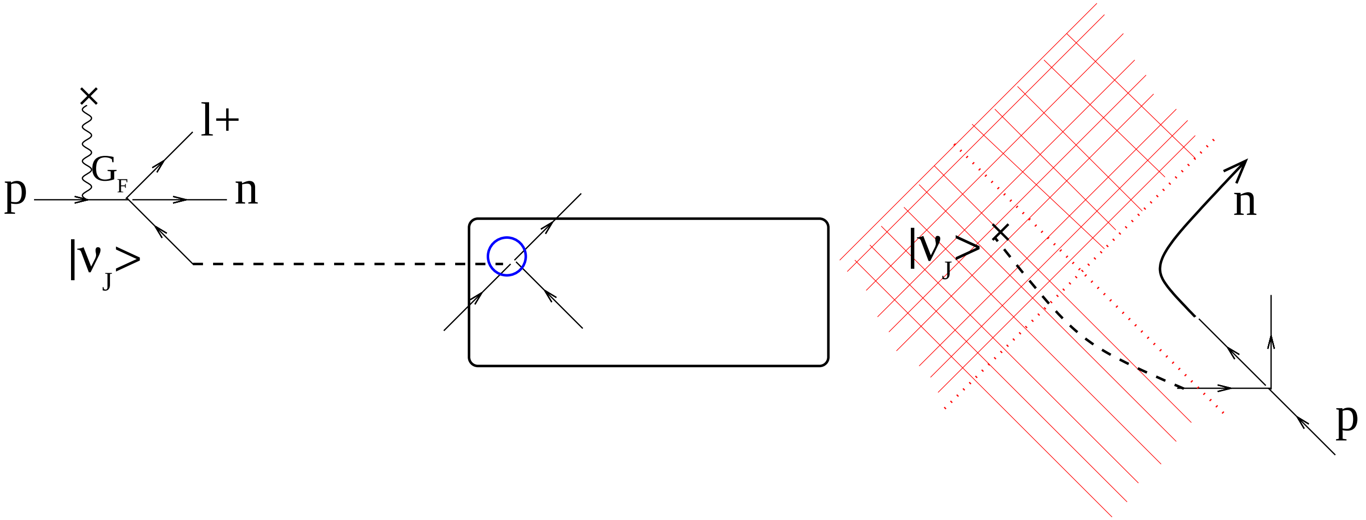
or is it?

# Is it a problem? Phase space!



One must remember phase space integral $\equiv \sum$ Incoherent momentum Eigenstates
Reflects correlation between momentum Eigenstate and "large" (classical) detector (Coleman-Hepp ).

The neutrino never gets on-shell . It is observed as a charge Eigenstate , via (on-shell) interaction products. So if neutrino is a field, no phase space integral, treat neutrino as virtual particle (Akhmedov,Kopp, 1001.4815 ).



**Minkowski frame has detectors** ”large” (classical) objects that, in case of neutrinoes, measure charge Eigenstates

**Rindler frame has horizons** Boundary conditions specified in the free particle limit, projecting energy-momentum Eigenstates

Ambiguity tied to the fact that charge Eigenstates are never on-shell

## Possible caveat: Interference terms in both frames

$m_\nu \to 0$ 0 in the Minkowski frame is a kinematical approximation separating corrections of order $m_\nu/E_\nu \ll 1$

$m_\nu \to 0$ in the Rindler frame calculation removes mixing

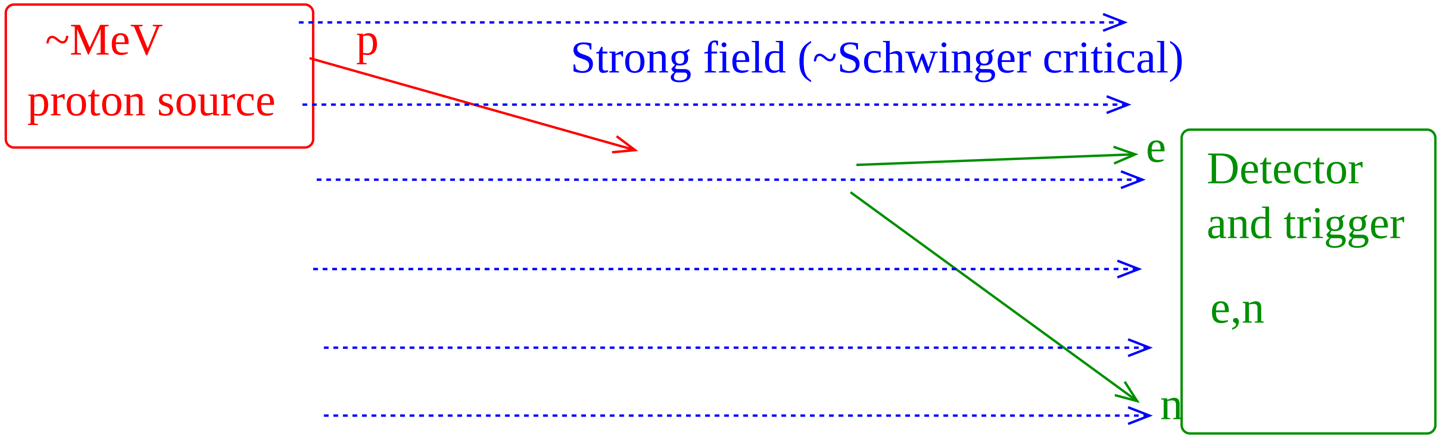
But Is this really correct? What happens when we add mass mixing in the Rindler frame too?

**Good news** Frames match! So are we wrong?

**Bad news** The KMS condition stops being satistifed, so the Rindler state is not a true thermal state! (As proven in axiomatic field theory)

A subtle but crucial point. Either the Rindler state is not a thermal state or QFT with neutrinoes not generally covariant!

# From Gedanken-experiments to experiments



~MeV

proton source

p

Strong field (~Schwinger critical)

e

n

Detector

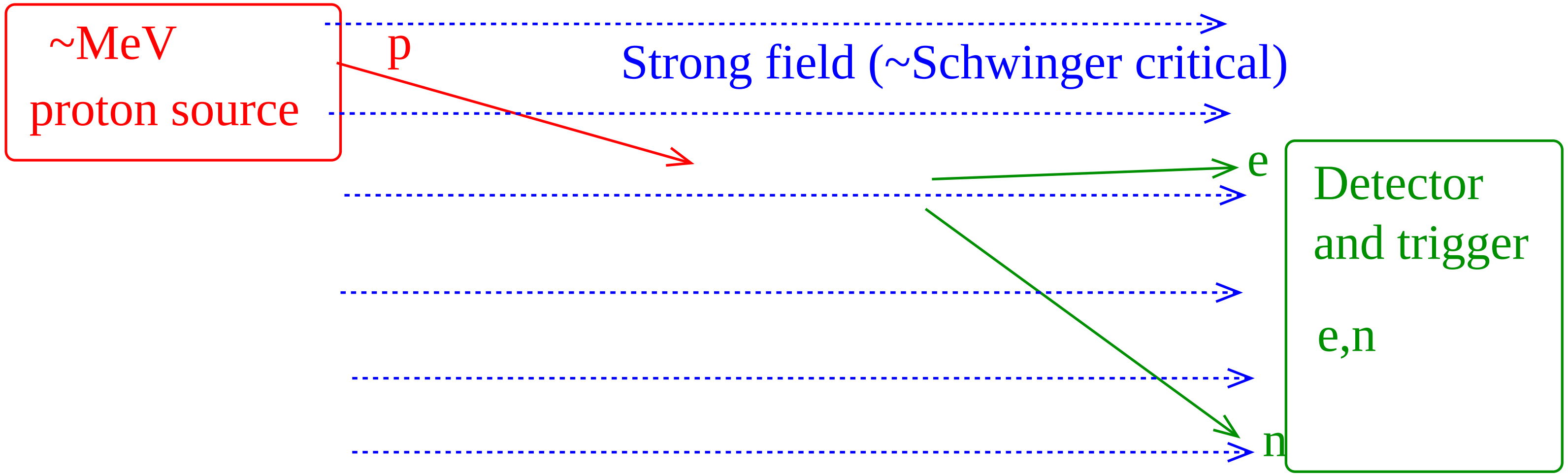
and trigger

e,n

Problem (fatal?) need powerful and uniform fields

$$\left|\nabla\vec{E}/\vec{E}\right| \ll m_n - m_p \sim |a| = em^{-1}\left|\vec{E}\right|$$

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



You dont need to detect neutrinoes, which is great! Unfortunately $\mu, \tau$ inaccesible. 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 accellerations are ridiculous resolution wont come from experiment.

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

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

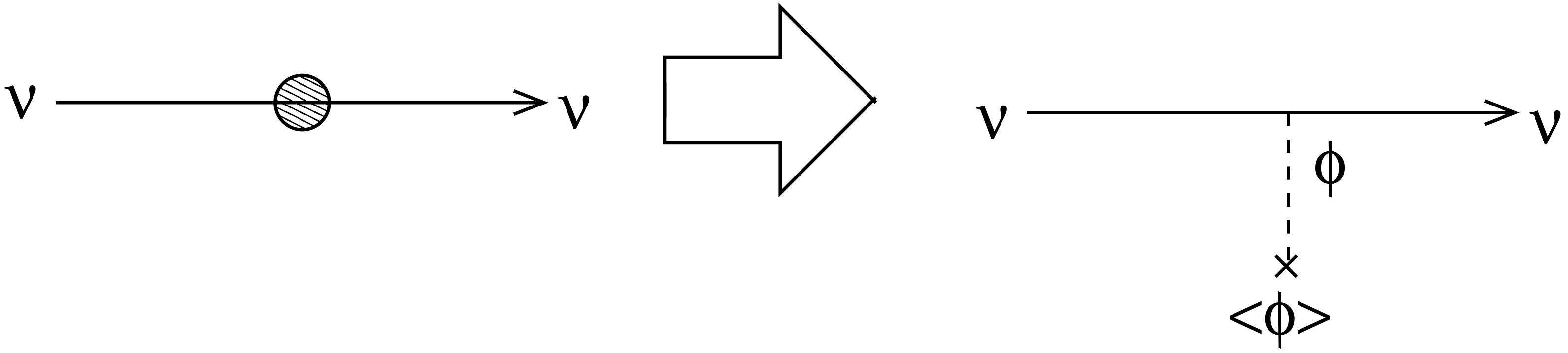
$$\Delta L = m\psi\overline{\psi} \sim eV^4$$

.

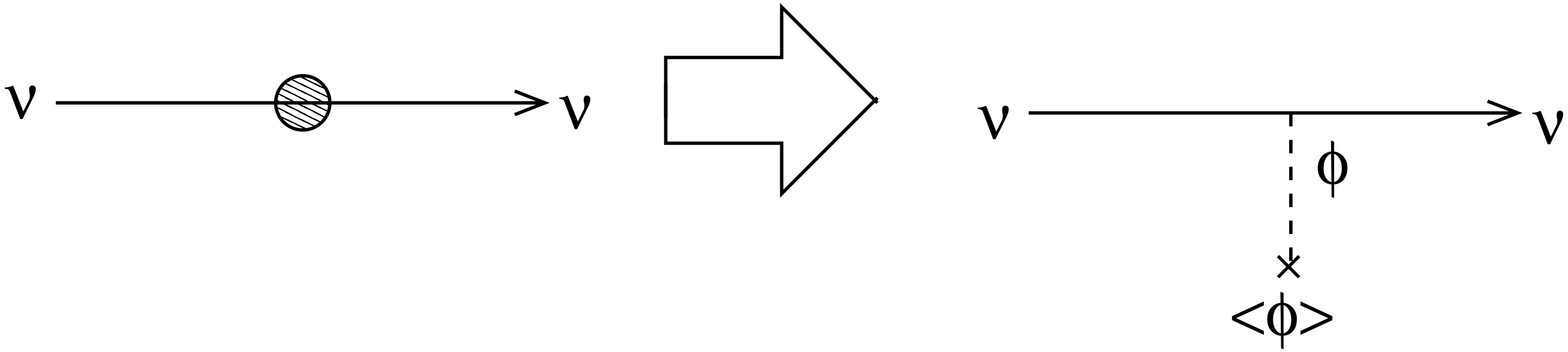
So Schwinger accellerations more than sufficient here.

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



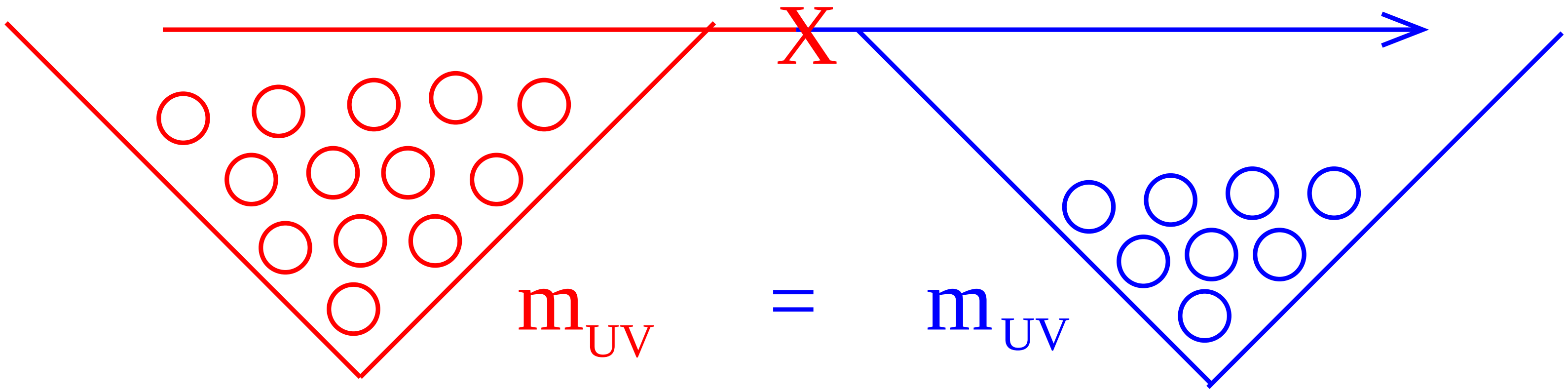
**Intertial frame** ”massive” particle aquires a form factor $\sim 1/\langle\phi^{\alpha}\rangle$
irrelevant for soft modes

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

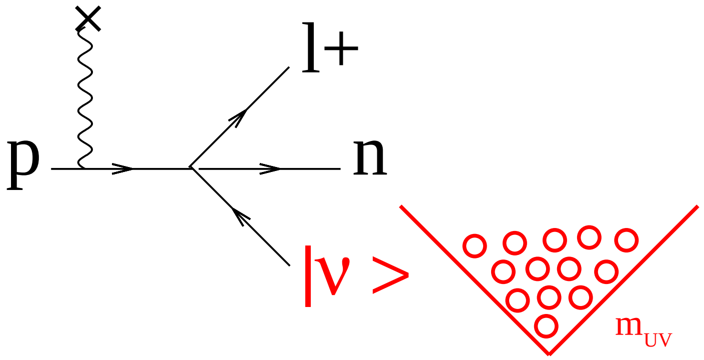
Inertial calculation more appropriate!

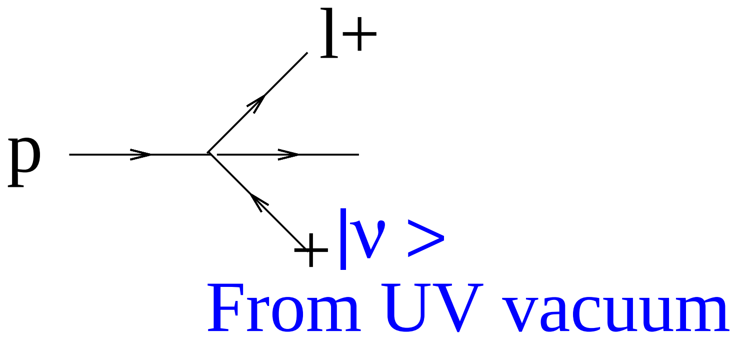
## Possible answer II

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.



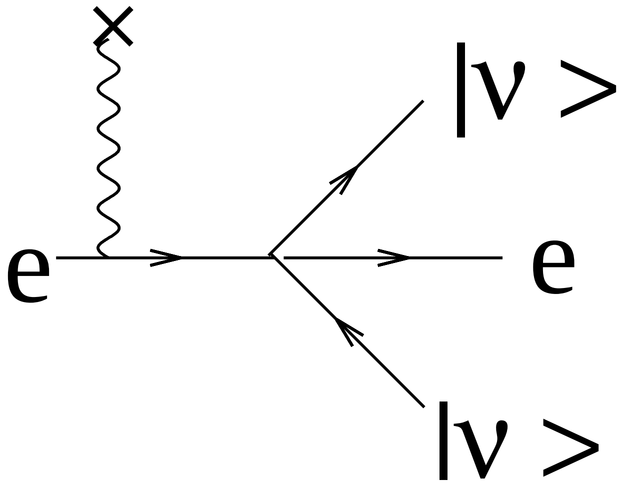
Masses generated by Fermi surface, oscillations by non-commutativity of neutrino charges

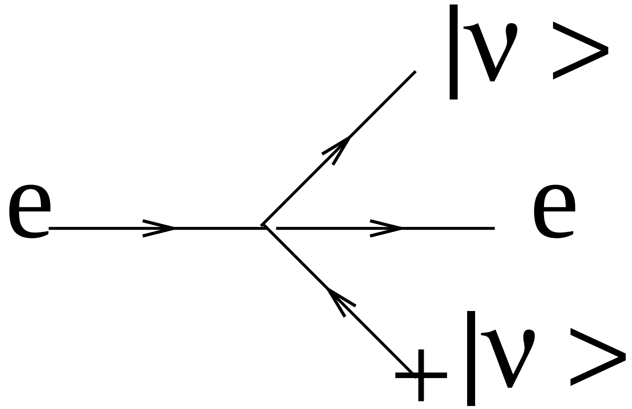




In this case , comoving calculation is “more” correct. The discrepancy w.r.t. inertial calculation gives mixing angles and mass differences (note the absolute values of mixing angles, not relative phases.

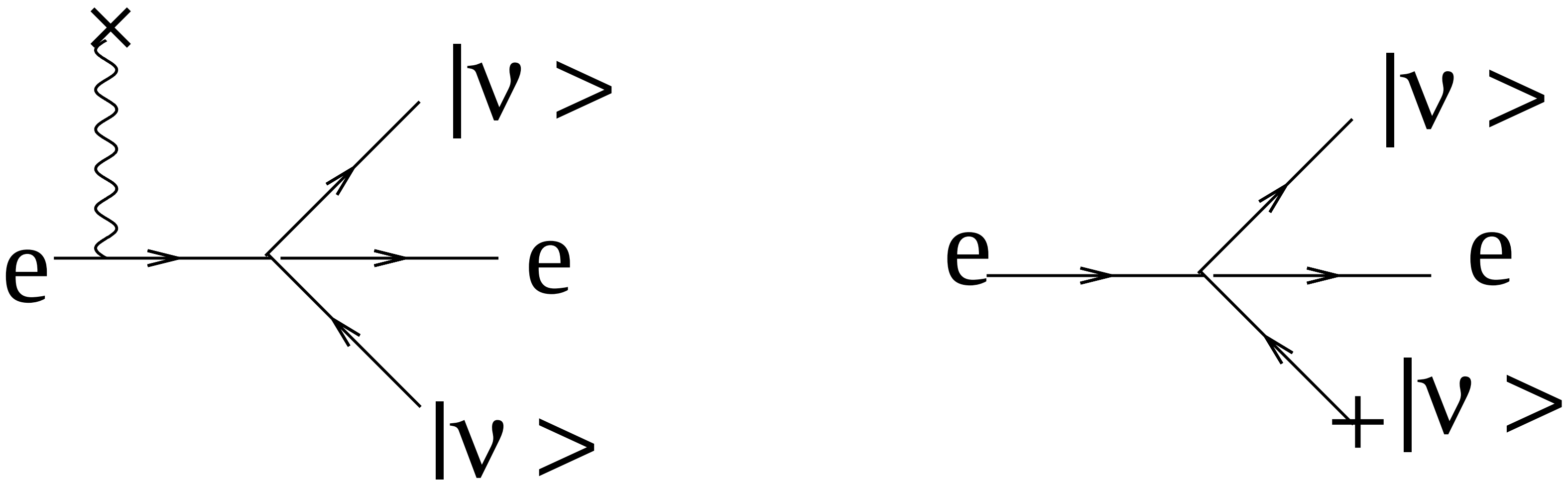
# Alternatively: A neutral current process





Big disadvantage: Need to detect neutrino! (basically you measure neutrino production in an electron beam). But "cheap" reactor detectors in development (also in Brazil).

## Alternatively: A neutral current process

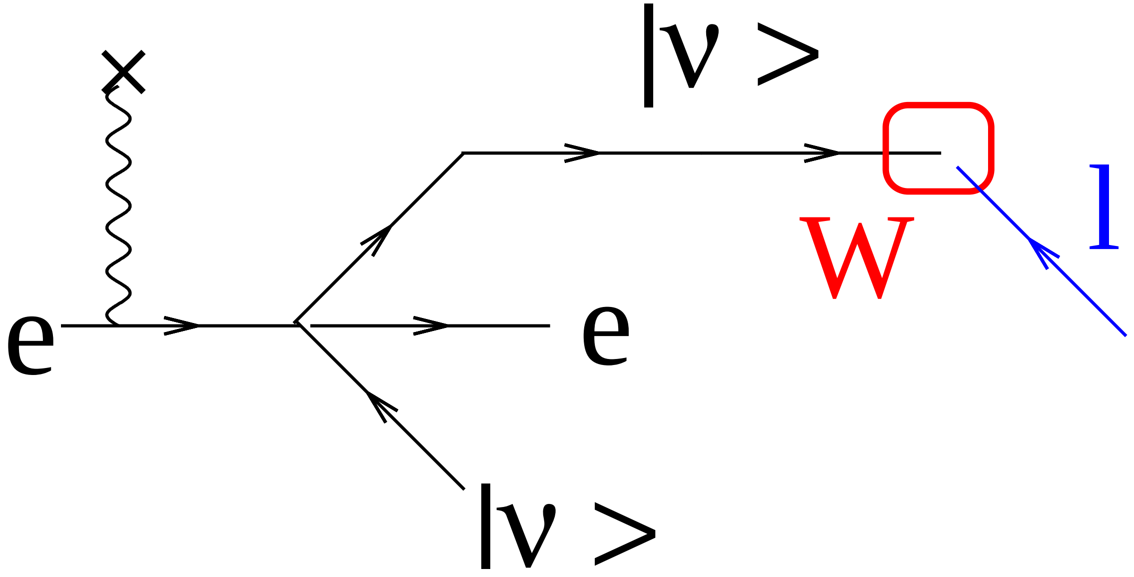


Big advantage: scales for field strenght dramatically lower

$$\left|\nabla\vec{E}/\vec{E}\right| \ll m_\nu \sim |a| = e m_e^{-1} \left|\vec{E}\right|$$

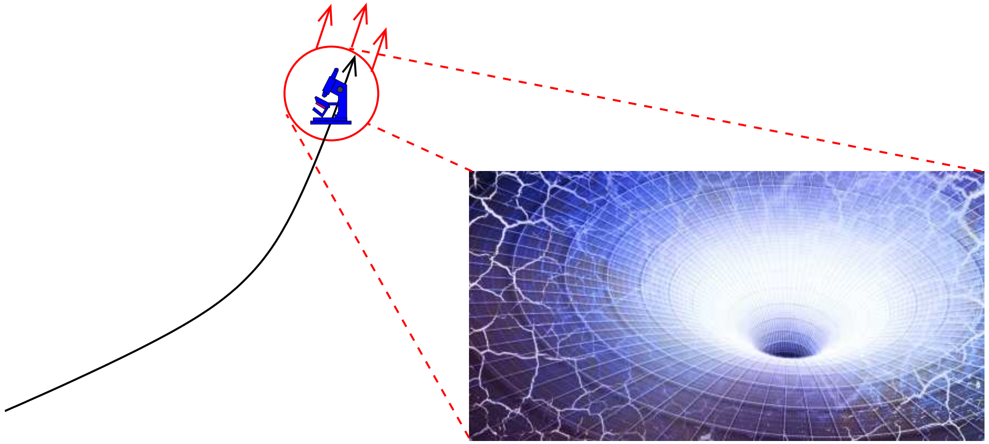
Synchrotron lab high-luminosity accellerator might work!

## Alternatively: A neutral current process



Another disadvantage: Possibly no paradox since neutral process, produces $\nu\overline{\nu} = \nu_i U_{ij} U^{+}_{jk} \overline{\nu_k}$ , which then interacts in detector via charged current. coherence of process not clear (Smirnov,Zatsepin,MPL A7 (1992) 1272-1280 ). At most, varying $a$ will give direct neutrino mass measurement!

# Bottom line



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 neutrinoes, 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.