Title: Relativistic Quantum Information anRelativistic Quantum Optics: towards experiments to reveal quantum effects provoked by gravity

Date: Jun 26, 2012 02:50 PM

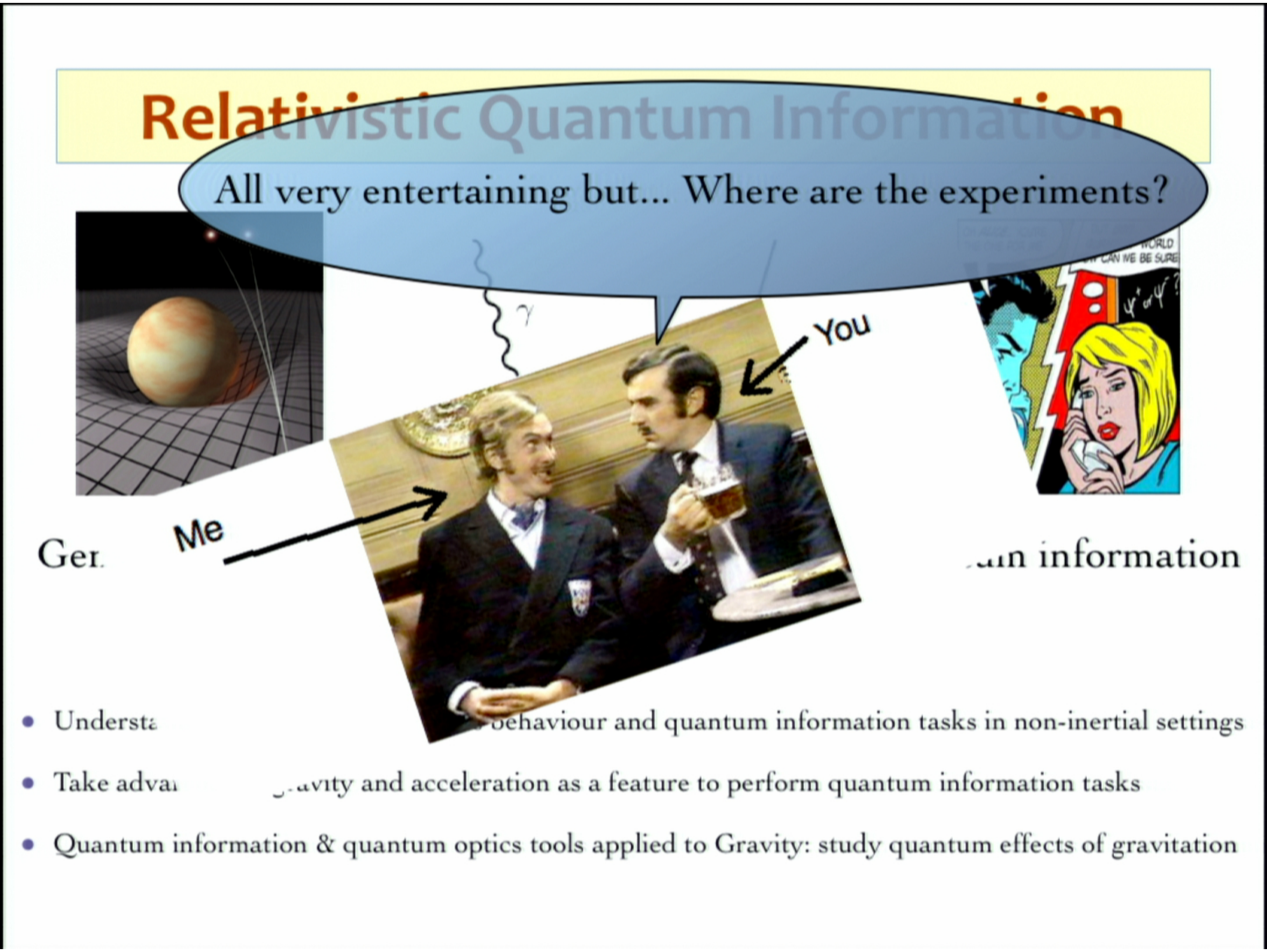
URL: http://pirsa.org/12060043

Abstract: We will explore different results on relativistic quantum information and general relativistic quantum optics whose aim is to provide scenarios where relativistic quantum effects can be experimentally accessible. Traditionally, relativistic quantum information has been far away from the experimental test, but the discipline is close to the transition point where experimental outcomes will soon arise. Not only to bestow experimental proof on long ago predicted but still undetected phenomena (such as the Unruh and Hawking effects), but also to provide insight into the relationship of general relativity and quantum theory, and to serve as a source of new quantum technologies.
We will show how it is possible to extract timelike and spacelike quantum correlations from the vacuum state of the field in a tabletop experiment, and how to use it to build a quantum memory. We will see how geometric phases can help to detect the Unruh effect and how to use what we learn from that setting to build a quantum thermometer. Finally we will discuss how quantum simulators can be applied to the study of quantum effects of gravity, and used to predict experimental scenarios way beyond current computational power of classical computers.

RQI and 'RQO': Towards Experiments

Eduardo Martín-Martínez,
IQC, Applied Mathematics, Physics & Astronomy
(University of Waterloo)

RQI-N 2012 - Perimeter Institute



Relativistic Quantum Information

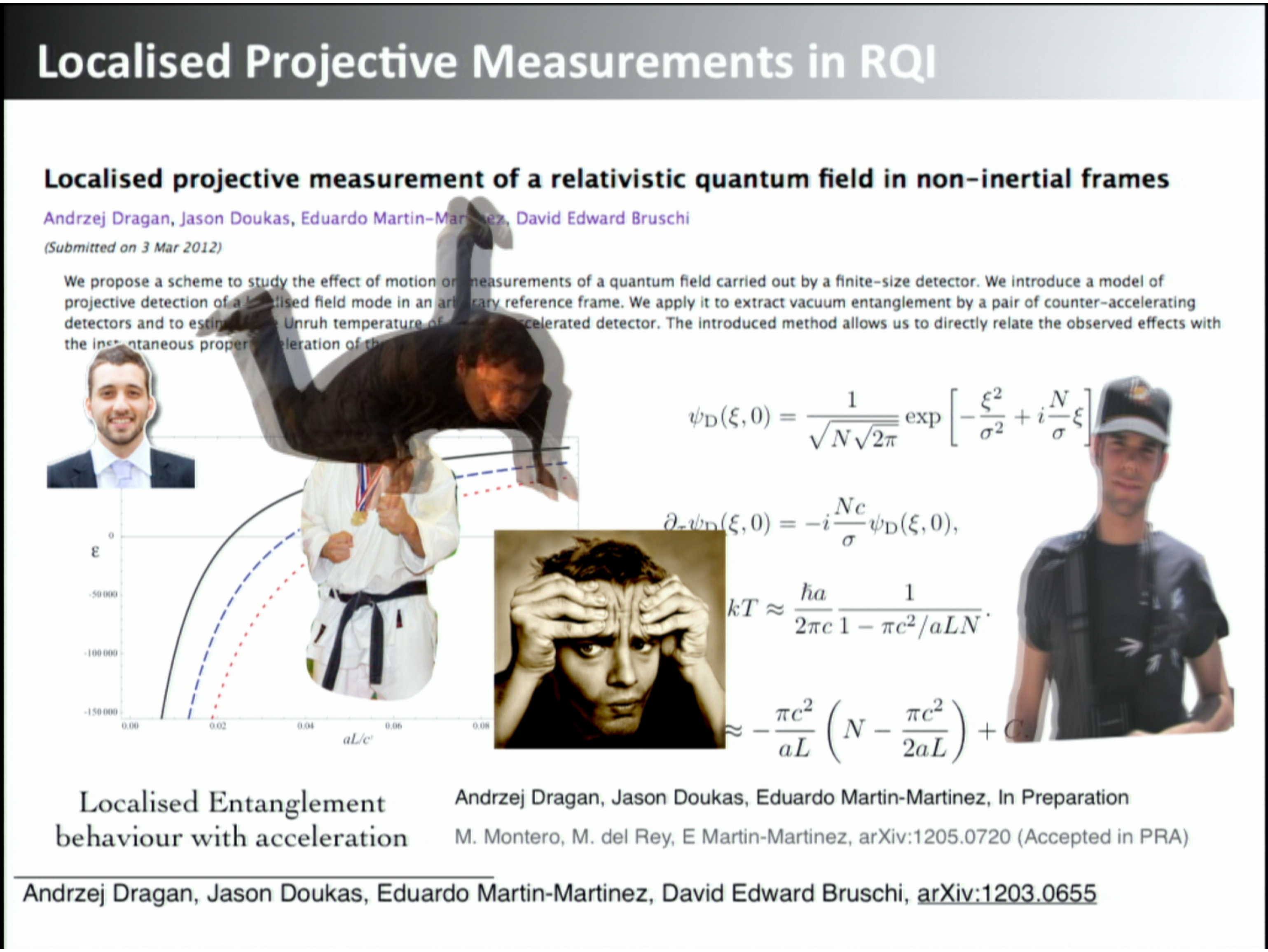
All very entertaining but... Where are the experiments?

Ger

ain information

- Understa
behaviour and quantum information tasks in non-inertial settings
- Take adva
avity and acceleration as a feature to perform quantum information tasks
- Quantum information & quantum optics tools applied to Gravity: study quantum effects of gravitation

Localised Projective Measurements in RQI



Localised projective measurement of a relativistic quantum field in non-inertial frames

Andrzej Dragan, Jason Doukas, Eduardo Martin-Mar ez, David Edward Bruschi

(Submitted on 3 Mar 2012)

We propose a scheme to study the effect of motion o neasurements of a quantum field carried out by a finite-size detector. We introduce a model of projective detection of a lised field mode in an ar rary reference frame. We apply it to extract vacuum entanglement by a pair of counter-accelerating detectors and to estim e Unruh temperature of celerated detector. The introduced method allows us to directly relate the observed effects with the ins ntaneous proper eleration of th

$$\psi_{\mathrm{D}}(\xi,0)=\frac{1}{\sqrt{N\sqrt{2\pi}}}\exp\left[-\frac{\xi^2}{\sigma^2}+i\frac{N}{\sigma}\xi\right]$$

$$\partial_\tau\psi_{\mathrm{D}}(\xi,0)=-i\frac{Nc}{\sigma}\psi_{\mathrm{D}}(\xi,0),$$

$$kT\approx\frac{\hbar a}{2\pi c}\frac{1}{1-\pi c^2/aLN}.$$

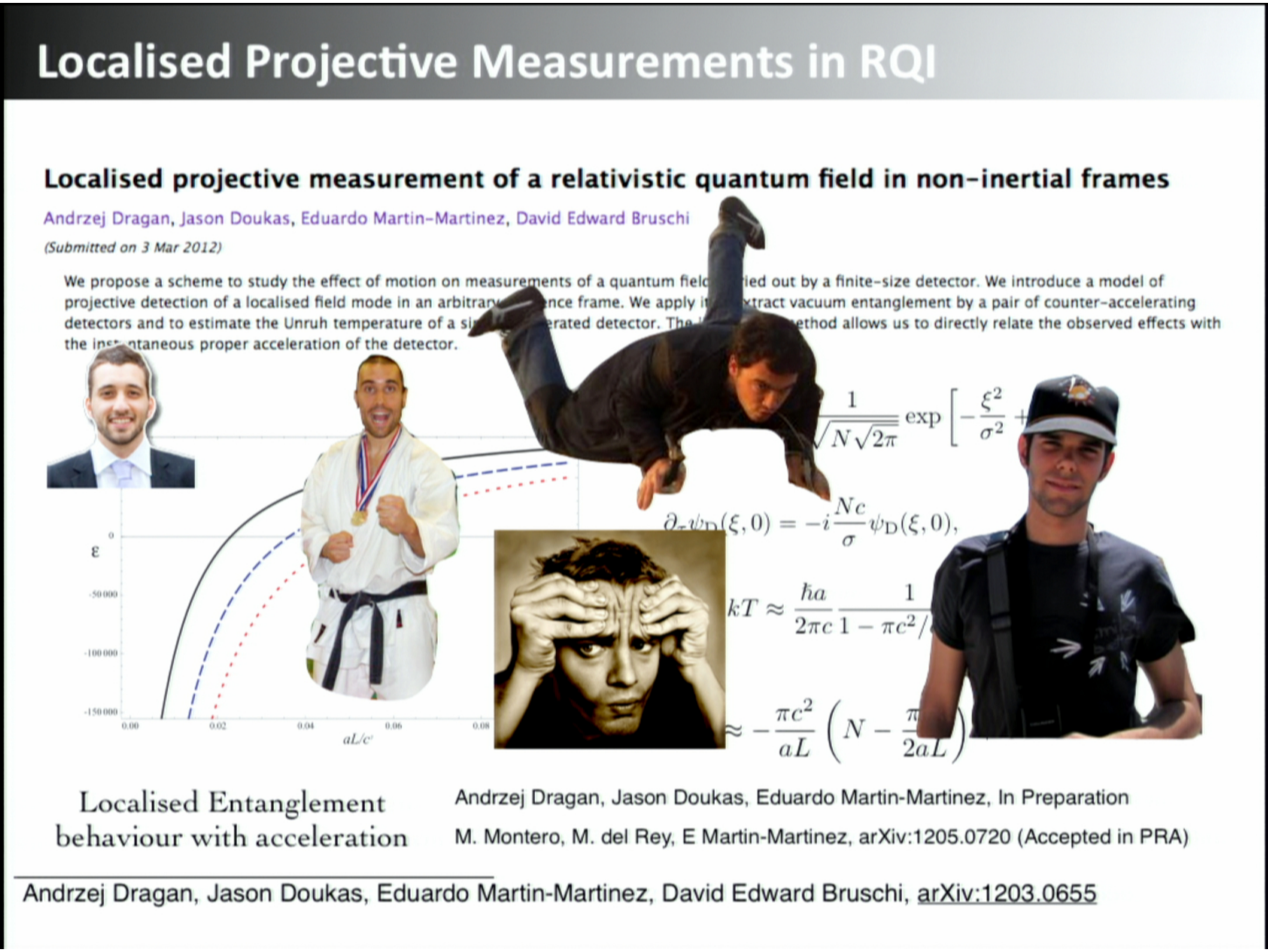
$$\approx-\frac{\pi c^2}{aL}\left(N-\frac{\pi c^2}{2aL}\right)+C$$

Localised Entanglement behaviour with acceleration

Andrzej Dragan, Jason Doukas, Eduardo Martin-Martinez, In Preparation

M. Montero, M. del Rey, E Martin-Martinez, arXiv:1205.0720 (Accepted in PRA)

Andrzej Dragan, Jason Doukas, Eduardo Martin-Martinez, David Edward Bruschi, arXiv:1203.0655



Localised Projective Measurements in RQI

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$$\approx-\frac{\pi c^2}{aL}\left(N-\frac{\pi}{2aL}\right)$$

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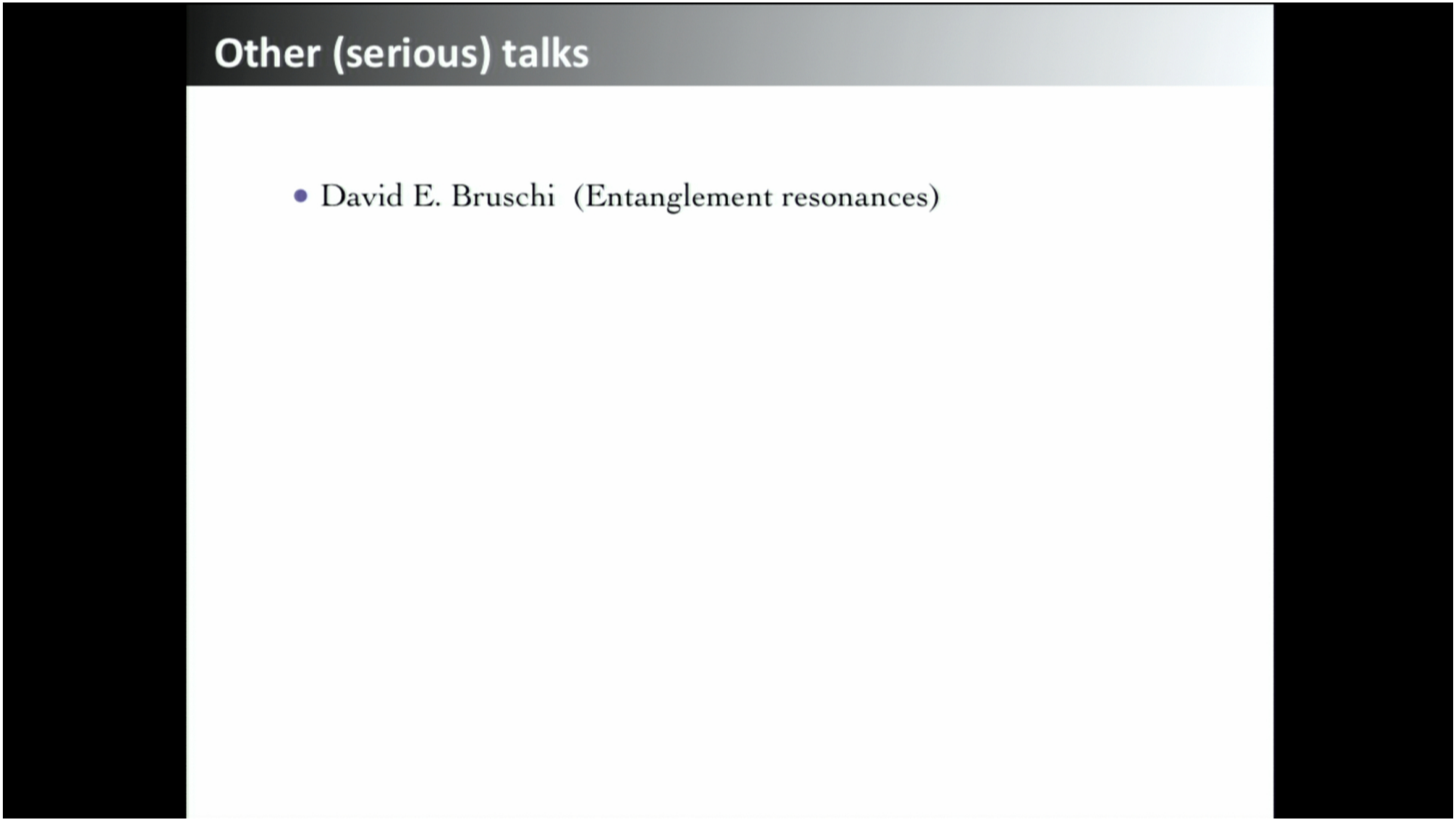
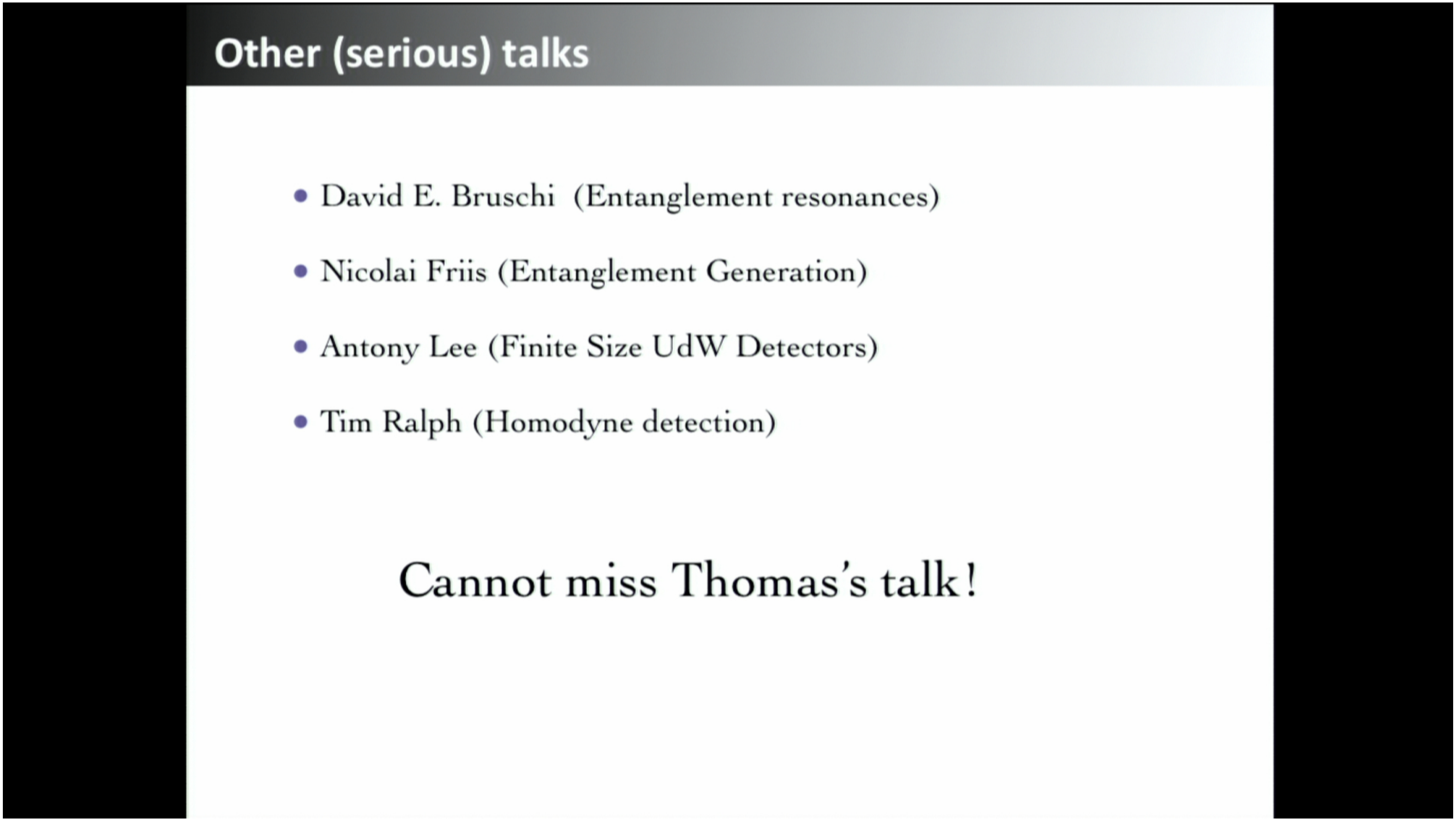


Other (serious) talks

- David E. Bruschi (Entanglement resonances)

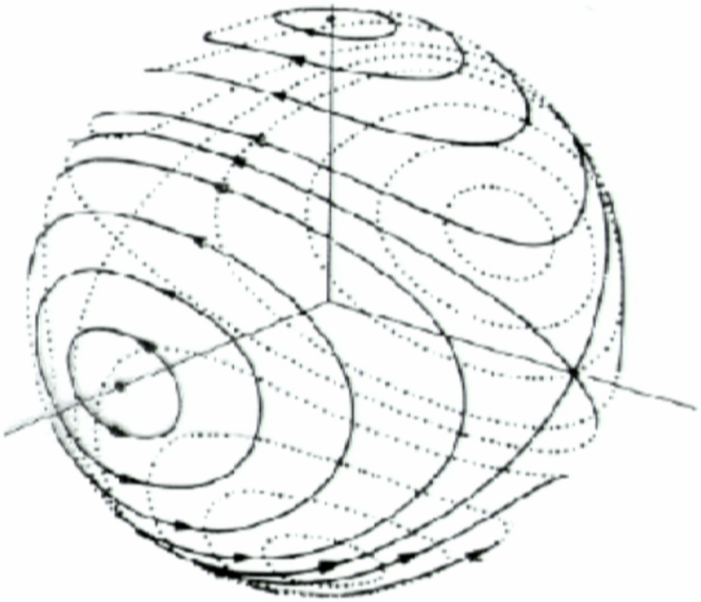


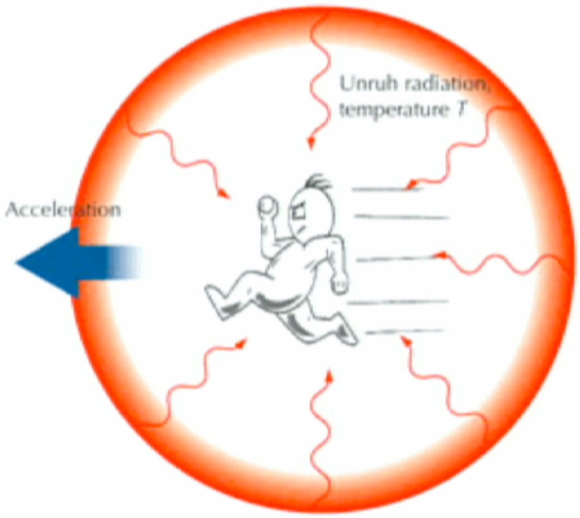
Other (serious) talks

- David E. Bruschi (Entanglement resonances)
- Nicolai Friis (Entanglement Generation)
- Antony Lee (Finite Size UdW Detectors)
- Tim Ralph (Homodyne detection)

Cannot miss Thomas's talk!

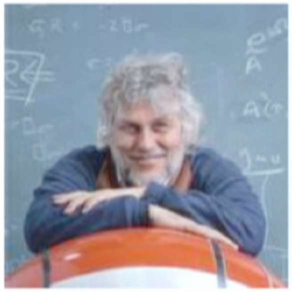
Berry's Phase and the Detection of the Unruh Effect





E. Martín-Martínez, I. Fuentes and R.B. Mann. Physical Review Letters 107, 131301 (2011)

What is the Unruh Effect?



Thermal response of "accelerated detectors" coupled to the (inertial) vacuum state of a quantum field

Geometrical Phases and adiabatic evolution

$$H(t) = H(R_1(t), \dots, R_k(t))$$

$R_1(t), \dots, R_k(t)$ Cyclicly and adiabatically varying parameters

$$|\psi\rangle \to e^{i\gamma} e^{i\phi} |\psi\rangle$$

$$i\gamma = \oint_R \boldsymbol{A} \cdot \mathrm{d}\boldsymbol{R} \qquad \boldsymbol{A} = \begin{pmatrix} \langle\psi(t)|\, \partial_{R_1} |\psi(t)\rangle \\ \langle\psi(t)|\, \partial_{R_2} |\psi(t)\rangle \\ \vdots \\ \langle\psi(t)|\, \partial_{R_k} |\psi(t)\rangle \end{pmatrix}$$

Main idea:

A detector moving through the space-time acquires a global Berry Phase

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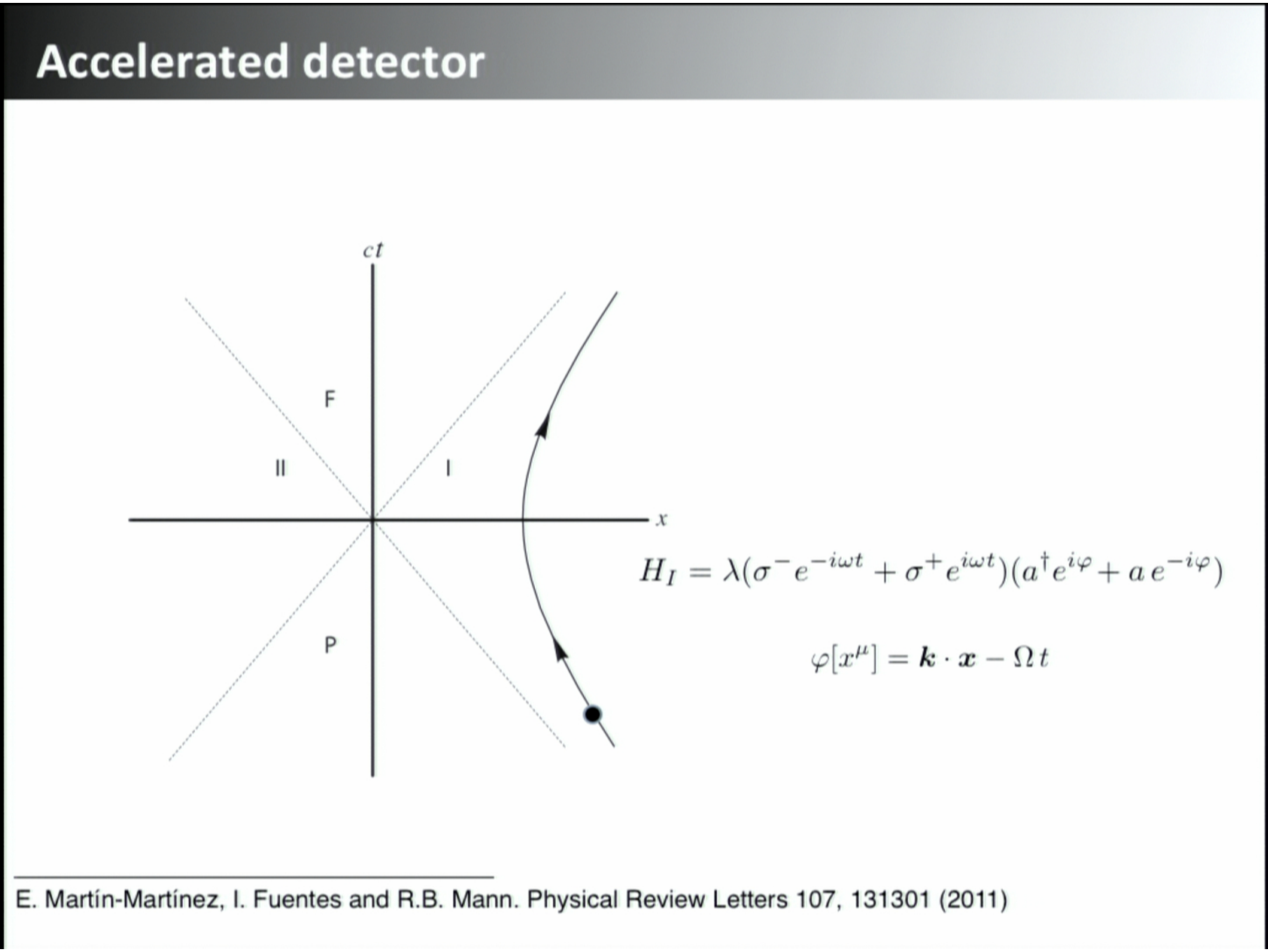
E. Martín-Martínez, I. Fuentes and R.B. Mann. Physical Review Letters 107, 131301 (2011)

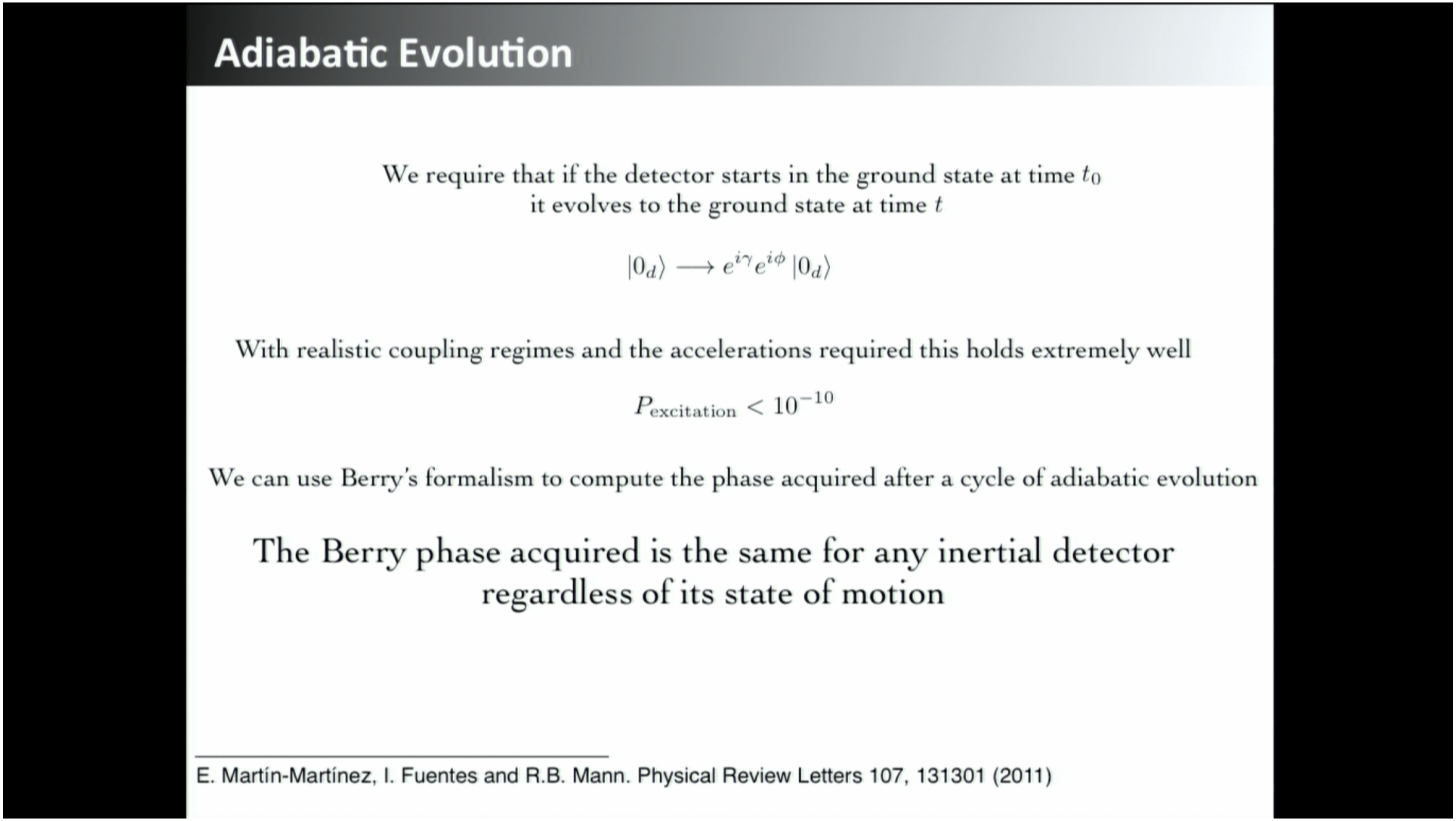


Accelerated detector

$$H_I = \lambda(\sigma^- e^{-i\omega t} + \sigma^+ e^{i\omega t})(a^\dagger e^{i\varphi} + a\, e^{-i\varphi})$$

$$\varphi[x^\mu] = \boldsymbol{k}\cdot\boldsymbol{x} - \Omega\, t$$

E. Martín-Martínez, I. Fuentes and R.B. Mann. Physical Review Letters 107, 131301 (2011)



Adiabatic Evolution

We require that if the detector starts in the ground state at time t_0
it evolves to the ground state at time t

$$|0_d\rangle \longrightarrow e^{i\gamma}e^{i\phi}\,|0_d\rangle$$

With realistic coupling regimes and the accelerations required this holds extremely well

$$P_{\text{excitation}} < 10^{-10}$$

We can use Berry's formalism to compute the phase acquired after a cycle of adiabatic evolution

The Berry phase acquired is the same for any inertial detector
regardless of its state of motion

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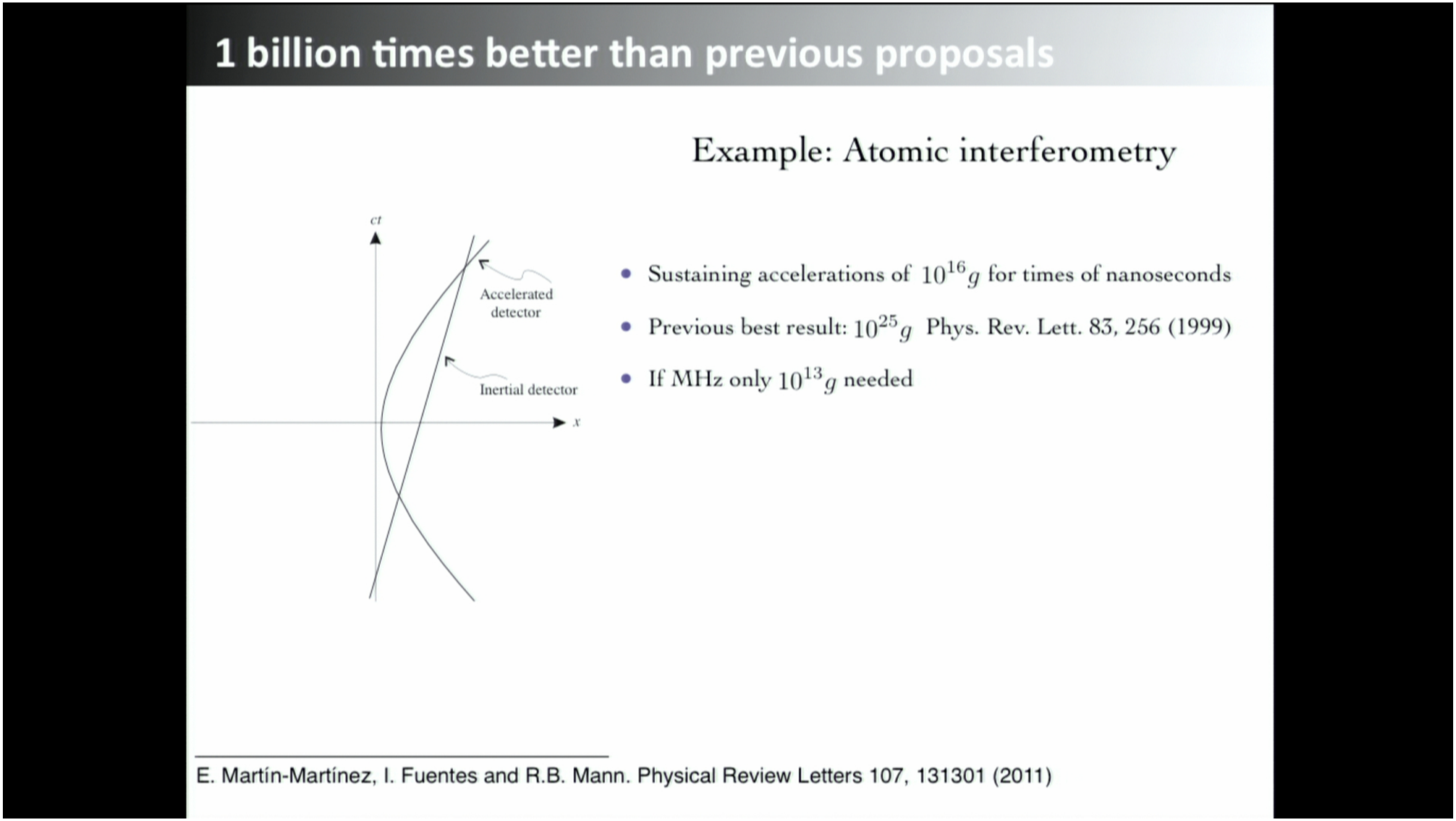
But it depends on the acceleration due to the Unruh effect

E. Martín-Martínez, I. Fuentes and R.B. Mann. Physical Review Letters 107, 131301 (2011)



1 billion times better than previous proposals

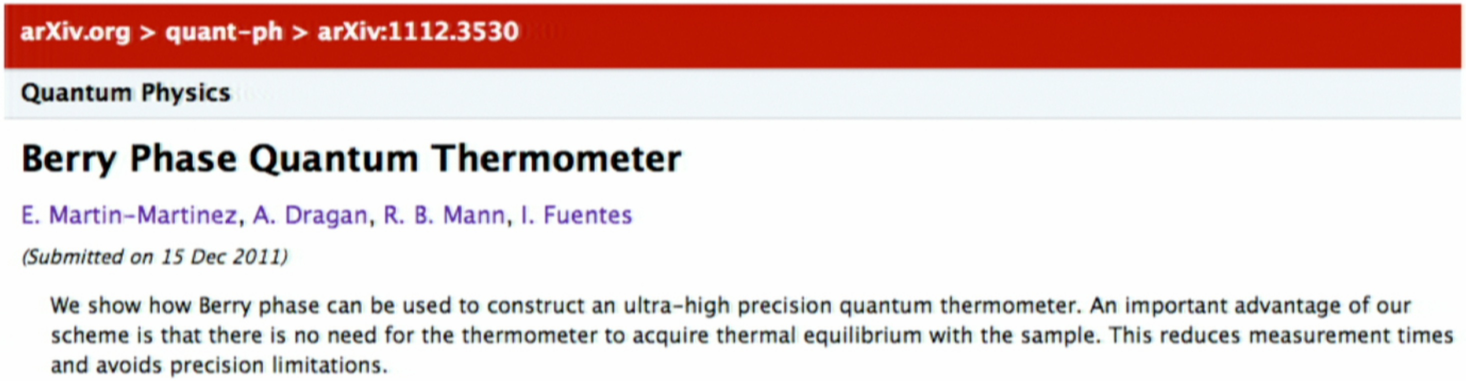
Example: Atomic interferometry

- Sustaining accelerations of $10^{16}g$ for times of nanoseconds
- Previous best result: $10^{25}g$ Phys. Rev. Lett. 83, 256 (1999)
- If MHz only $10^{13}g$ needed

E. Martín-Martínez, I. Fuentes and R.B. Mann. Physical Review Letters 107, 131301 (2011)

1 billion times better than previous proposals

$\gamma = \gamma(\rho_F)$ It can be used as a Thermometer that doesn't need to thermalise!



arXiv.org > quant-ph > arXiv:1112.3530

Quantum Physics

Berry Phase Quantum Thermometer

E. Martin-Martinez, A. Dragan, R. B. Mann, I. Fuentes

(Submitted on 15 Dec 2011)

We show how Berry phase can be used to construct an ultra-high precision quantum thermometer. An important advantage of our scheme is that there is no need for the thermometer to acquire thermal equilibrium with the sample. This reduces measurement times and avoids precision limitations.

Quantum simulation of Accelerated Detectors

M. del Rey, D. Porras and E. Martín-Martínez, Phys. Rev. A 85, 022511 (2012)

Quantum simulation of Accelerated Detectors

Why?
- Calculations related to the Unruh effect
- Non-perturbative analysis for strong couplings (accelerated atoms in cavities)
- Analyse possible many body effects

Some Previous Results

P. M. Alsing, J. P. Dowling, and G. J. Milburn, Phys. Rev. Lett. 94, 220401 (2005)

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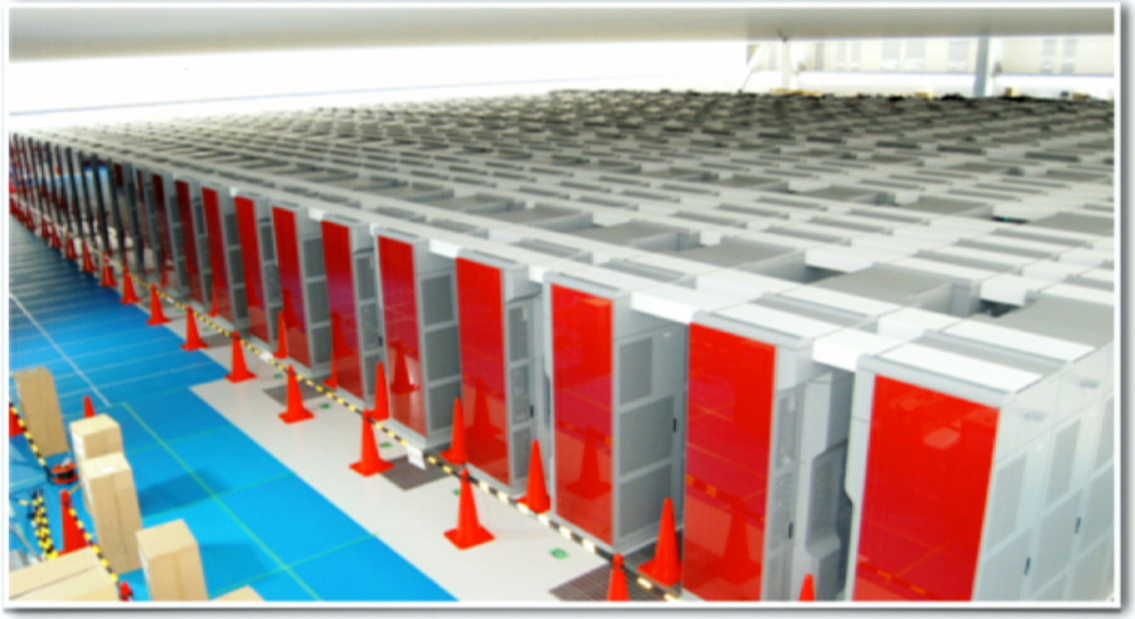
Spin models at K Computer



State of the art: <40 spins, dim $\mathcal{H} < 2^{40}$

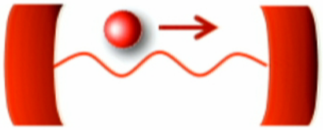
Modelling a cube of 7x7x7 spins will take 2^{343} variables

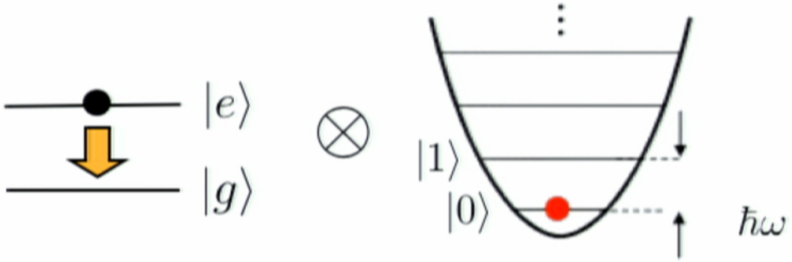
way bigger than the number of protons in the Universe!!!

M. del Rey, D. Porras and E. Martín-Martínez, ArXiv:1109.0209

Accelerated quantum emitter

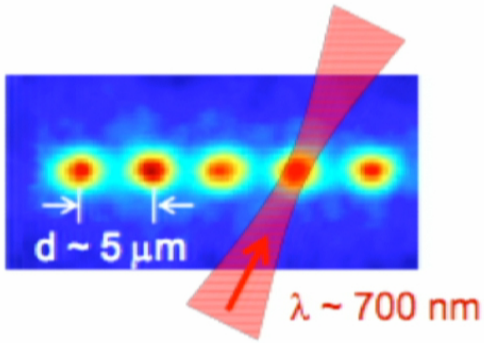
Consider an **accelerated emitter** interacting with a **single** electromagnetic **mode**

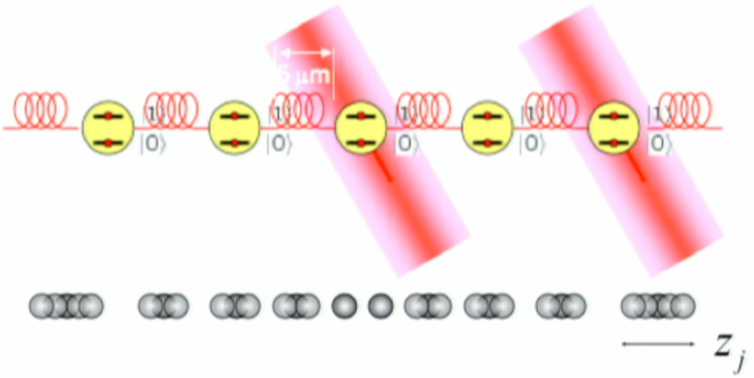




M. del Rey, D. Porras and E. Martín-Martínez, Phys. Rev. A 85, 022511 (2012)

Vibrational modes of an ion chain

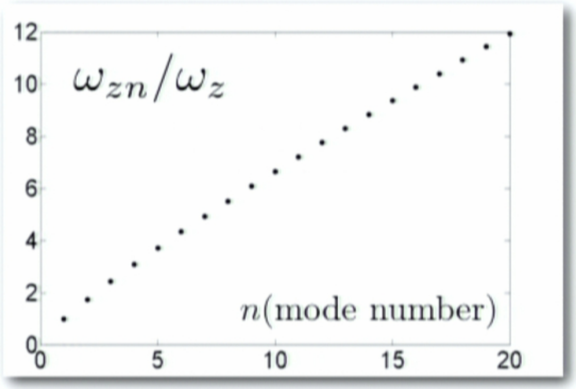




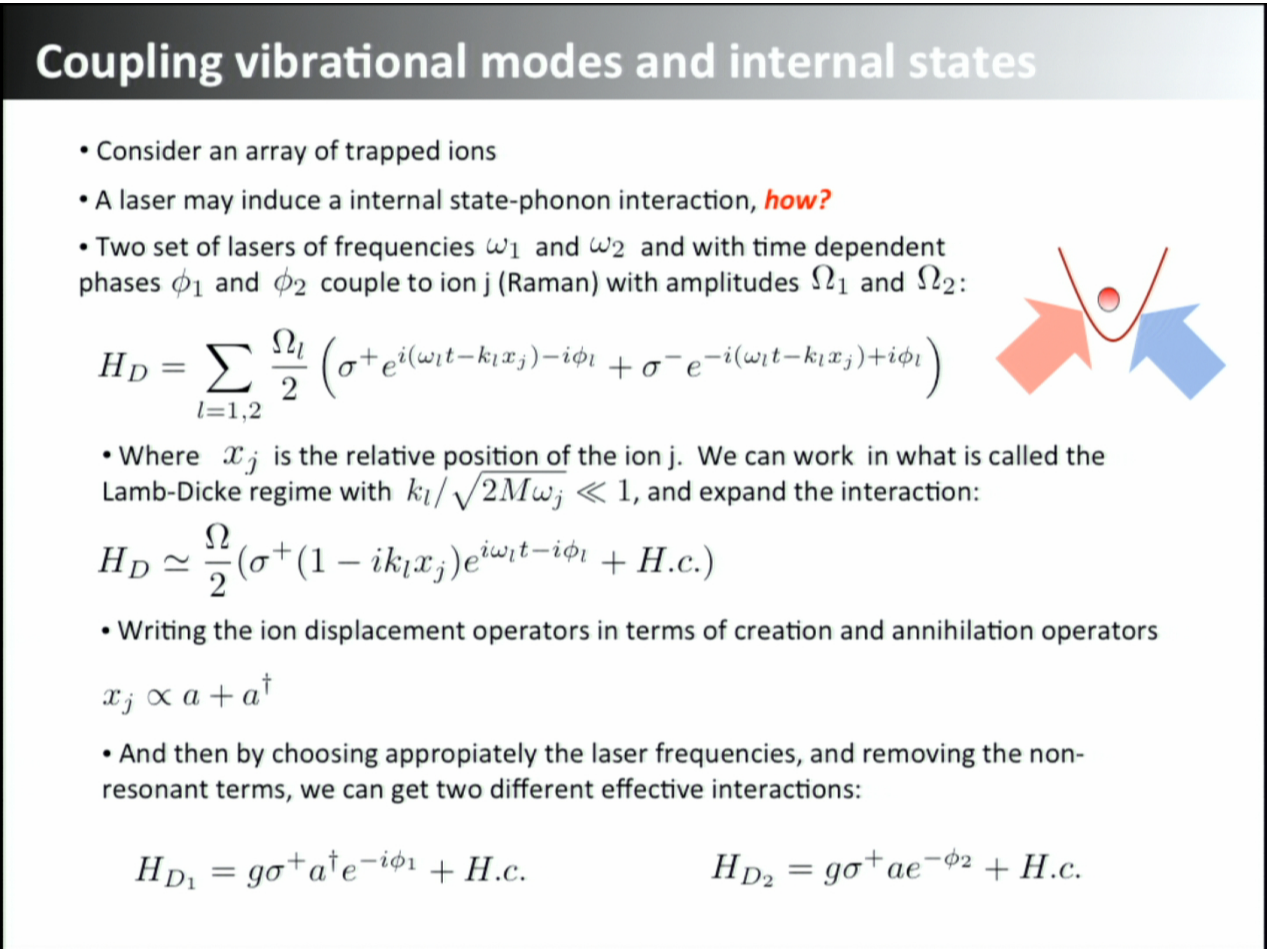
Longitudinal vibrations are analogous to acoustic phonons in solids

The parameters of the system can be tuned so these vibrations can be described as a Klein-Gordon 1-D field

$$H_z = \sum_n \omega_{zn} a^{\dagger}_{zn} a_{zn}$$



M. del Rey, D. Porras and E. Martín-Martínez, Phys. Rev. A 85, 022511 (2012)



Coupling vibrational modes and internal states

- Consider an array of trapped ions
- A laser may induce a internal state-phonon interaction, ***how?***
- Two set of lasers of frequencies ω_1 and ω_2 and with time dependent phases ϕ_1 and ϕ_2 couple to ion j (Raman) with amplitudes Ω_1 and Ω_2:

$$H_D = \sum_{l=1,2} \frac{\Omega_l}{2} \left(\sigma^+ e^{i(\omega_l t - k_l x_j) - i\phi_l} + \sigma^- e^{-i(\omega_l t - k_l x_j) + i\phi_l} \right)$$

- Where x_j is the relative position of the ion j. We can work in what is called the Lamb-Dicke regime with $k_l/\sqrt{2M\omega_j} \ll 1$, and expand the interaction:

$$H_D \simeq \frac{\Omega}{2}(\sigma^+(1 - ik_l x_j)e^{i\omega_l t - i\phi_l} + H.c.)$$

- Writing the ion displacement operators in terms of creation and annihilation operators

$$x_j \propto a + a^\dagger$$

- And then by choosing appropiately the laser frequencies, and removing the non-resonant terms, we can get two different effective interactions:

$$H_{D_1} = g\sigma^+ a^\dagger e^{-i\phi_1} + H.c. \qquad H_{D_2} = g\sigma^+ a e^{-\phi_2} + H.c.$$

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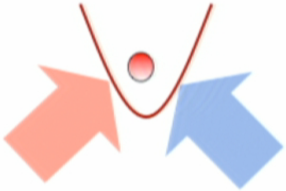

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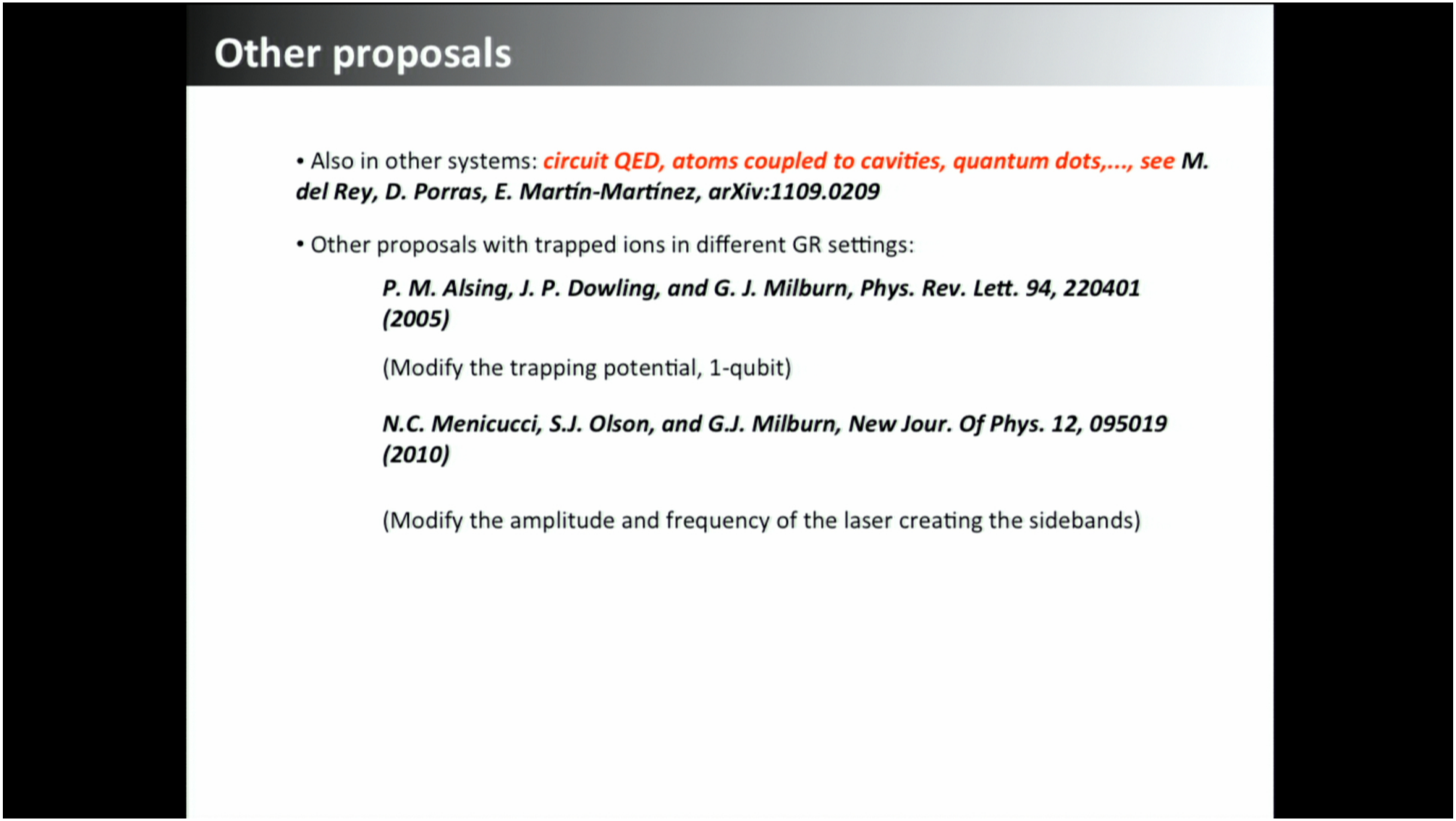


Other proposals

- Also in other systems: ***circuit QED, atoms coupled to cavities, quantum dots,..., see M. del Rey, D. Porras, E. Martín-Martínez, arXiv:1109.0209***

- Other proposals with trapped ions in different GR settings:

  P. M. Alsing, J. P. Dowling, and G. J. Milburn, Phys. Rev. Lett. 94, 220401 (2005)

  (Modify the trapping potential, 1-qubit)

  N.C. Menicucci, S.J. Olson, and G.J. Milburn, New Jour. Of Phys. 12, 095019 (2010)

  (Modify the amplitude and frequency of the laser creating the sidebands)

The physics of an accelerated detector

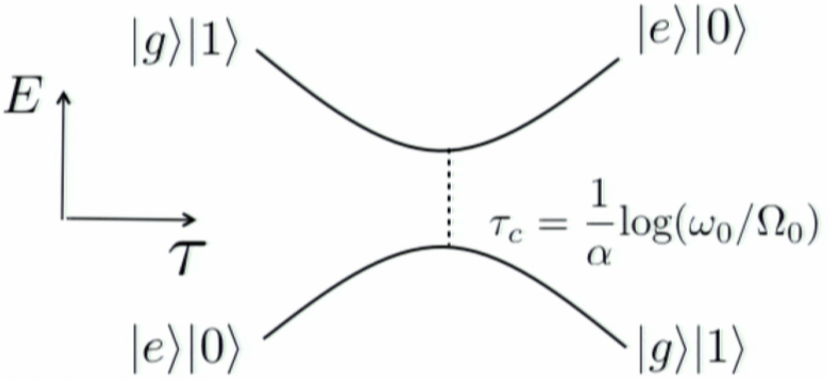
Non-equilibrium physics appears naturally in this problem

Recall that How would the simplest case (1 emitter) look like in the lab?

$$H(\tau) = g(\sigma^+ + \sigma^-)(a^\dagger + a) + \Omega_0 \sigma^+ \sigma^- + \omega_0 e^{-\alpha\tau} a^\dagger a$$

g couples: $|e\rangle|0\rangle \Leftrightarrow |g\rangle|1\rangle$

Landau-Zener-like problem (avoided level-crossing) $\Delta E(\tau) = \omega_0 e^{-\alpha\tau} - \Omega_0$

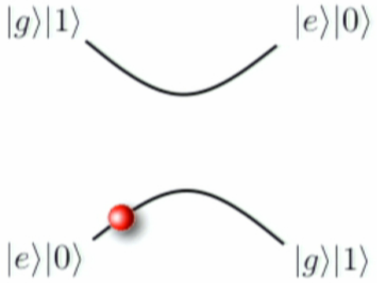


$$\tau_c = \frac{1}{\alpha}\log(\omega_0/\Omega_0)$$

M. del Rey, D. Porras and E. Martín-Martínez, Phys. Rev. A 85, 022511 (2012)

Landau-Zener model

Landau-Zener model (exactly solvable when energy difference is linear with time) using the parameters of the model adjusting the fact that



Our model $$\Delta E(\tau) = \omega_0 e^{-\alpha\tau} - \Omega_0$$

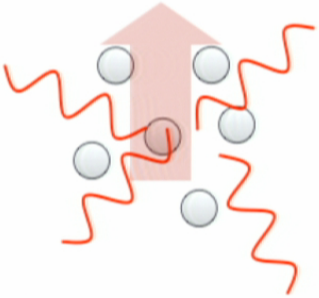
Landau-Zener $$\Delta E(\tau) = E_0 - \kappa\tau$$

M. del Rey, D. Porras and E. Martín-Martínez, Phys. Rev. A 85, 022511 (2012)

Conclusions and Open questions

We have shown that *current* experimental techniques can be used to implement quantum dynamics analog to the effective acceleration of a single relativistic particle.

We have established a connection between accelerated emitters and non-equilibrium phenomena (Landau-Zener transitions)



Work to come:
- Continuum.
- Arbitrary trajectories / time-dependent metrics.
- Simulating many modes, many emitters:
    - To some cases our model can be directly extended
    - We expect collective phenomena (Dicke superradiance) to play a role here.
    - Generation of multipartite correlations
    - Quantum phase transitions

$$H_I = \sum_{jm} g_{jm}(\sigma_j^+ e^{i\Omega\tau_j(\tau)} + \sigma_j^- e^{-i\Omega\tau_j(\tau)})(a_m^\dagger e^{i\phi_m(\tau)} + H.c.)$$

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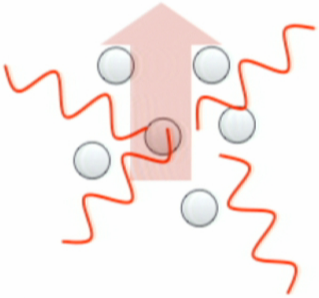

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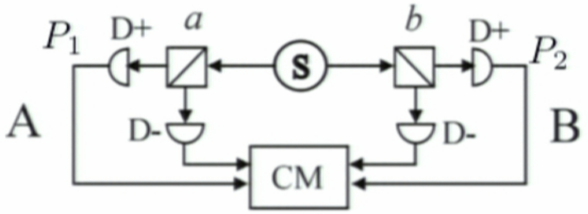
M. del Rey, D. Porras and E. Martín-Martínez, Phys. Rev. A 85, 022511 (2012)

The Aspect Experiment and the Unruh effect



$$|\Psi_{\text{EPR}}\rangle = \frac{1}{\sqrt{2}}[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle]$$

$$N_{\uparrow\uparrow} = \frac{1}{2}\sin^2(\theta_a - \theta_b)P_1P_2 \qquad N_{\downarrow\downarrow} = \frac{1}{2}\sin^2(\theta_a - \theta_b)P_1P_2$$

$$N_{\uparrow\downarrow} = \frac{1}{2}\cos^2(\theta_a - \theta_b)P_1P_2 \qquad N_{\downarrow\uparrow} = \frac{1}{2}\cos^2(\theta_a - \theta_b)P_1P_2$$

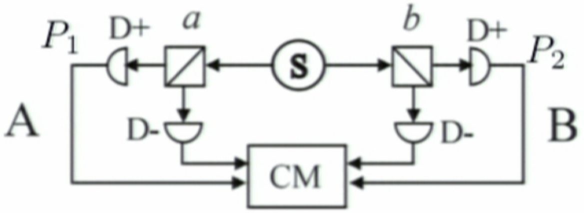
$$E_{\theta_a,\theta_b} = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}} = \cos[2(\theta_a - \theta_b)]$$

Local realism implies $S \equiv E_{\theta_a^1,\theta_b^1} - E_{\theta_a^1,\theta_b^2} + E_{\theta_a^2,\theta_b^1} + E_{\theta_a^2,\theta_b^2} \leq 2$

Quantum Mechanics gives $S = 2\sqrt{2}$

E. Martín-Martínez, M. del Rey and M. Montero (In preparation)

The Aspect Experiment and the Unruh effect



$$|\Psi_{\text{EPR}}\rangle = \frac{1}{\sqrt{2}}[|\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle]$$

$$N_{\uparrow\uparrow} = \frac{1}{2}\sin^2(\theta_a - \theta_b)P_1P_2 \qquad N_{\downarrow\downarrow} = \frac{1}{2}\sin^2(\theta_a - \theta_b)P_1P_2$$

$$N_{\uparrow\downarrow} = \frac{1}{2}\cos^2(\theta_a - \theta_b)P_1P_2 \qquad N_{\downarrow\uparrow} = \frac{1}{2}\cos^2(\theta_a - \theta_b)P_1P_2$$

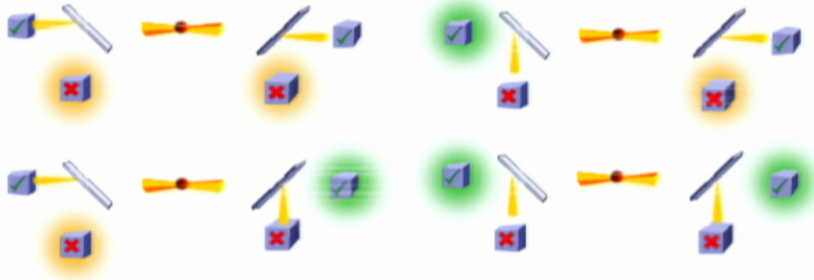
$$E_{\theta_a,\theta_b} = \frac{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} - N_{\uparrow\downarrow} - N_{\downarrow\uparrow}}{N_{\uparrow\uparrow} + N_{\downarrow\downarrow} + N_{\uparrow\downarrow} + N_{\downarrow\uparrow}} = \cos[2(\theta_a - \theta_b)]$$

Local realism implies $S \equiv E_{\theta_a^1,\theta_b^1} - E_{\theta_a^1,\theta_b^2} + E_{\theta_a^2,\theta_b^1} + E_{\theta_a^2,\theta_b^2} \leq 2$

Quantum Mechanics gives $S = 2\sqrt{2}$

E. Martín-Martínez, M. del Rey and M. Montero (In preparation)

The Aspect Experiment and the Unruh effect



Formalism: Spatially smeared UdW detectors

Uncorrelated noise: $S_a < S_0$ Degrades correlations, smaller

Correlated noise: $$S_a \approx \tanh^d\left(\frac{\hbar\Omega}{2K_B T_{\mathrm{U}}}\right) S_0$$

For the Aspect experiment $d = 2$

Where d seems to depend on the dimension of the maximally entangled state used

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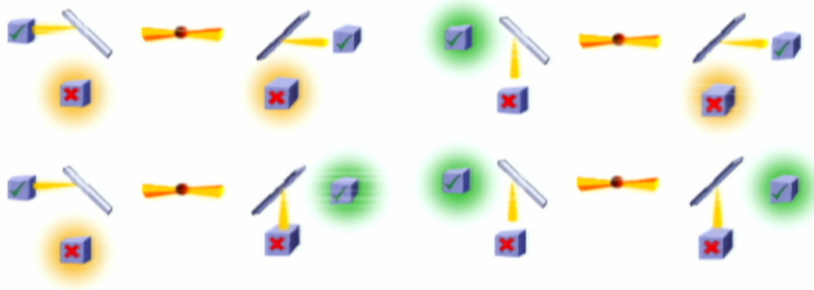
E. Martín-Martínez, M. del Rey and M. Montero (In preparation)

The Aspect Experiment and the Unruh effect



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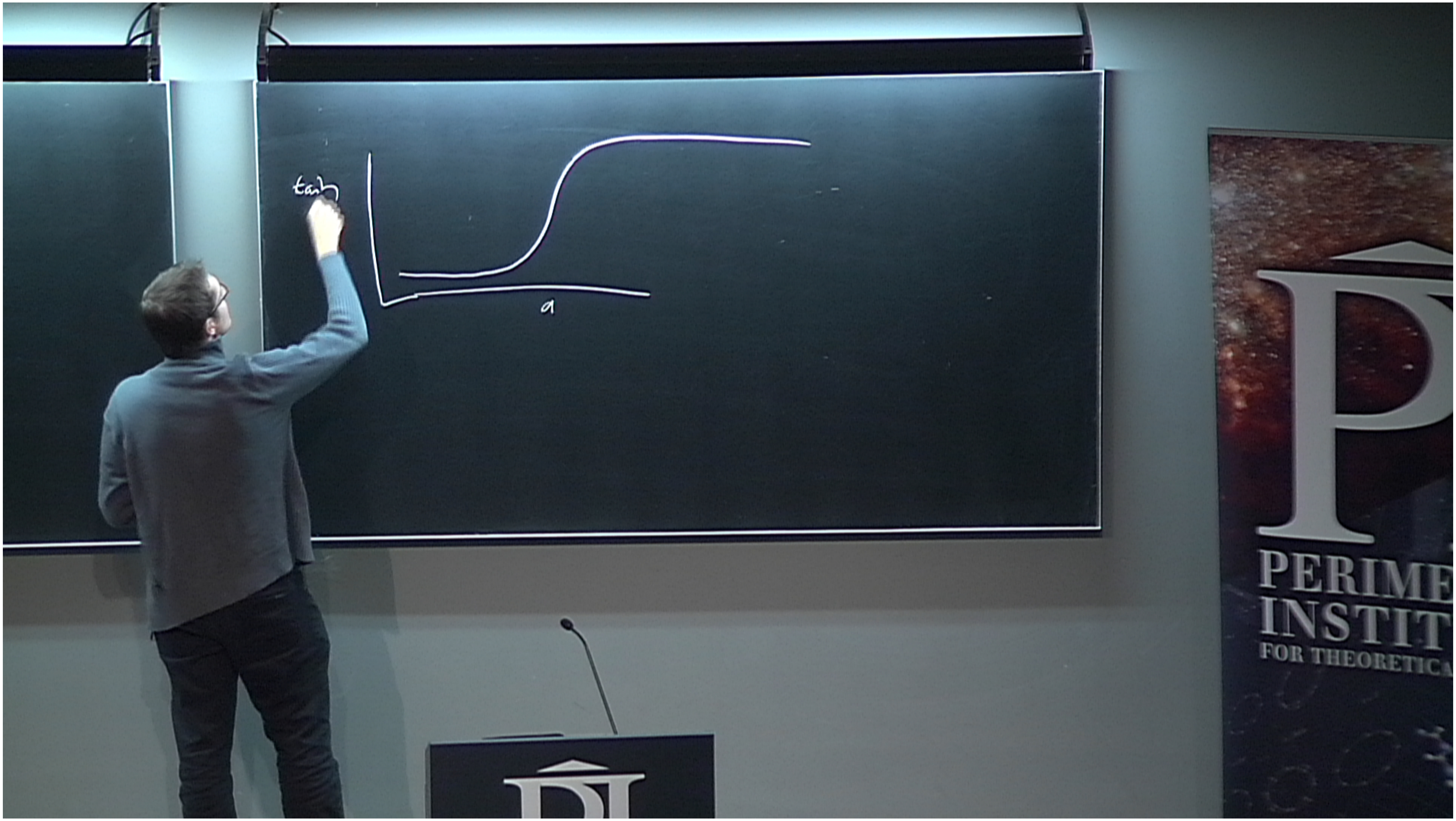
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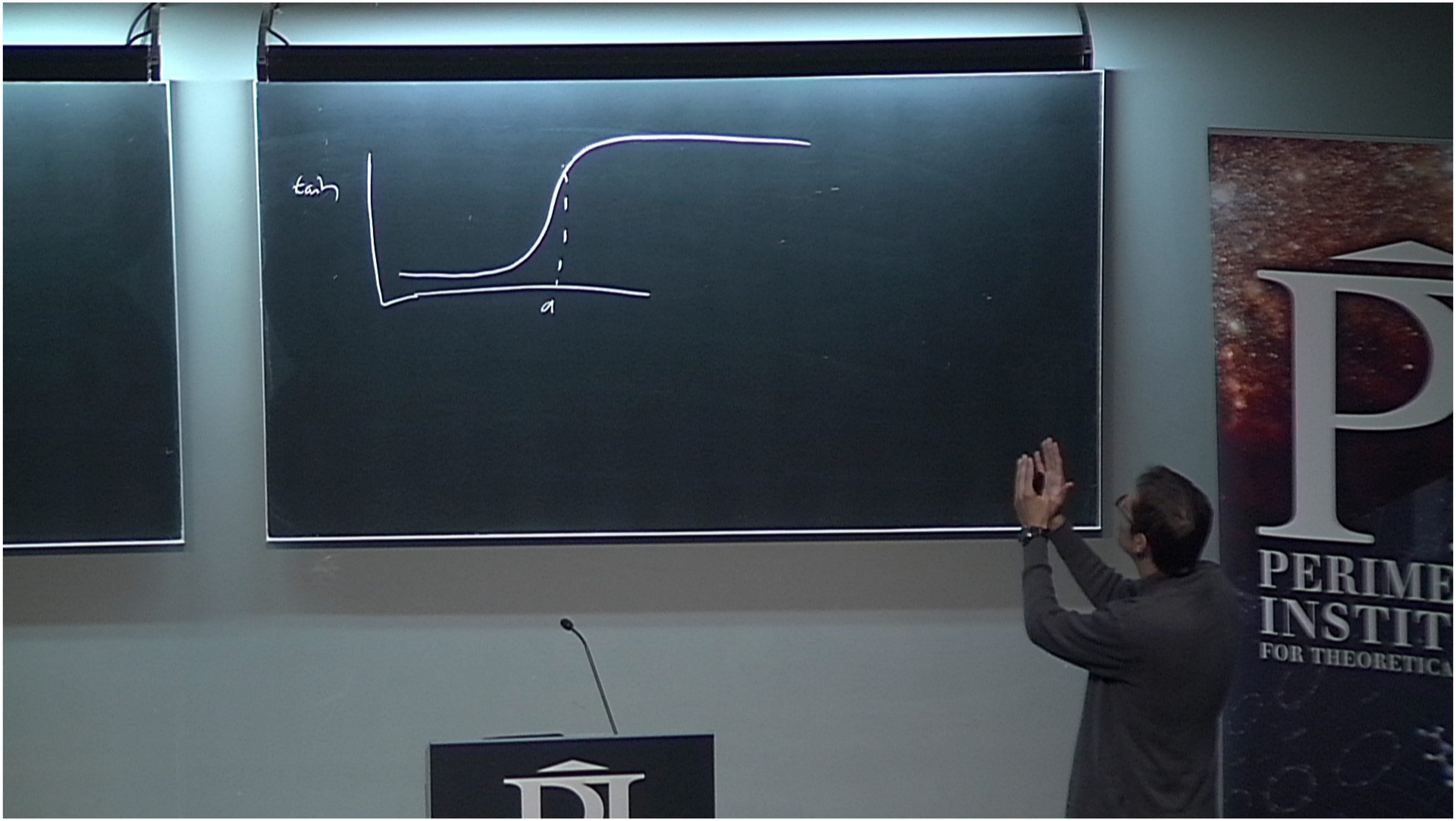
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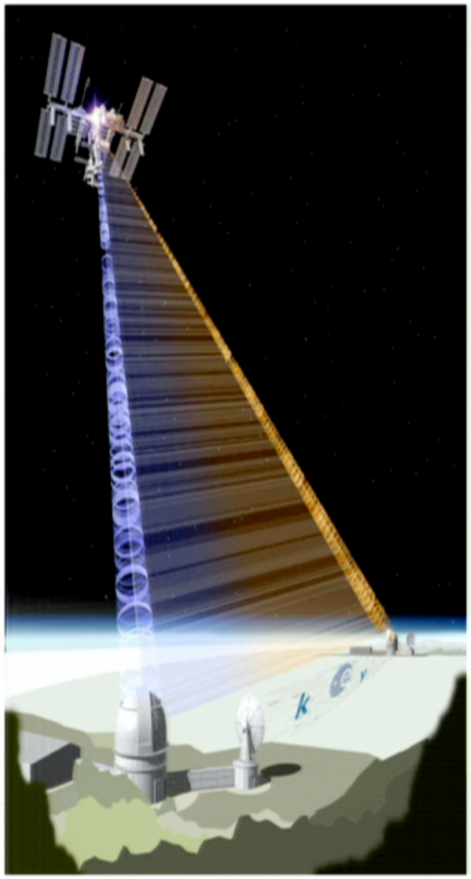
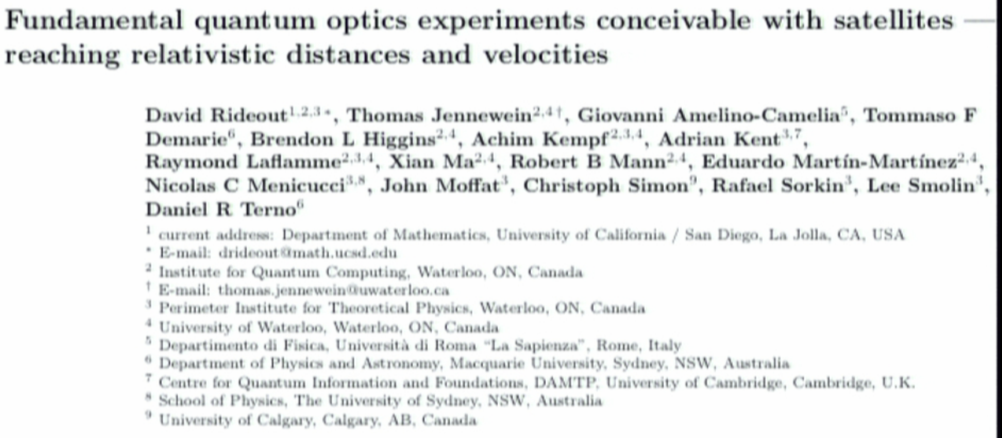
Satellite-based experiments





Fundamental quantum optics experiments conceivable with satellites — reaching relativistic distances and velocities

David Rideout[1,2,3*], Thomas Jennewein[2,4†], Giovanni Amelino-Camelia[5], Tommaso F Demarie[6], Brendon L Higgins[2,4], Achim Kempf[2,3,4], Adrian Kent[3,7], Raymond Laflamme[2,3,4], Xian Ma[2,4], Robert B Mann[2,4], Eduardo Martín-Martínez[2,4], Nicolas C Menicucci[3,8], John Moffat[3], Christoph Simon[9], Rafael Sorkin[3], Lee Smolin[3], Daniel R Terno[6]

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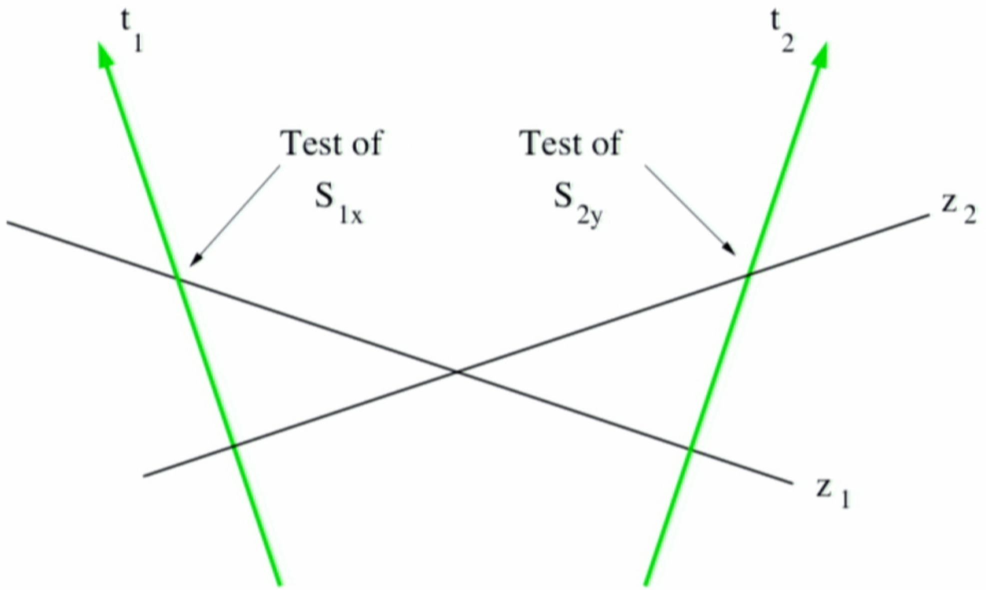
[8] School of Physics, The University of Sydney, NSW, Australia
[9] University of Calgary, Calgary, AB, Canada

Thomas Jennewein's talk

Satellite-based experiments

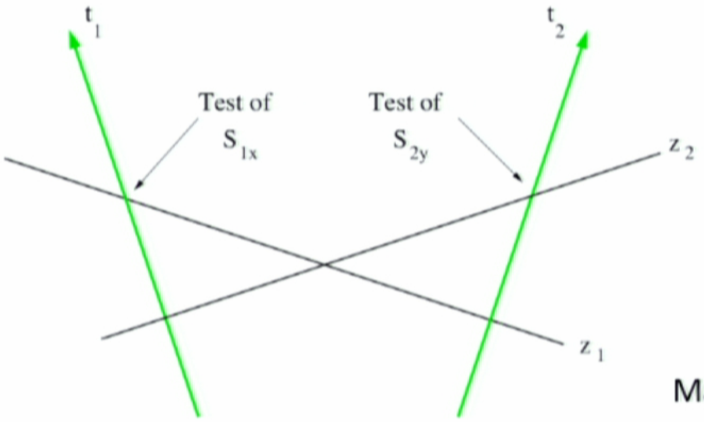
Bell test with detectors in relative motion

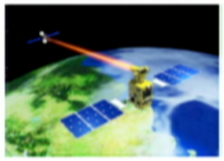


Who measures first? (Interpretational implications)

Satellite-based experiments

Bell test with detectors in relative motion





LEO Satellites: $15\ \mathrm{km}\cdot\mathrm{s}^{-1}$

Time shift: $\dfrac{\Delta t}{x} \approx 166\ \mathrm{ps}\cdot\mathrm{km}^{-1}$

Minimal separation $\approx 60 - 1000\ \mathrm{km}$

Maximum achievable separation (LEO) $\approx 1500\ \mathrm{km}$

Synchronicity requirement $\approx 250\ \mathrm{ns}$

Who measures first? (Interpretational implications)

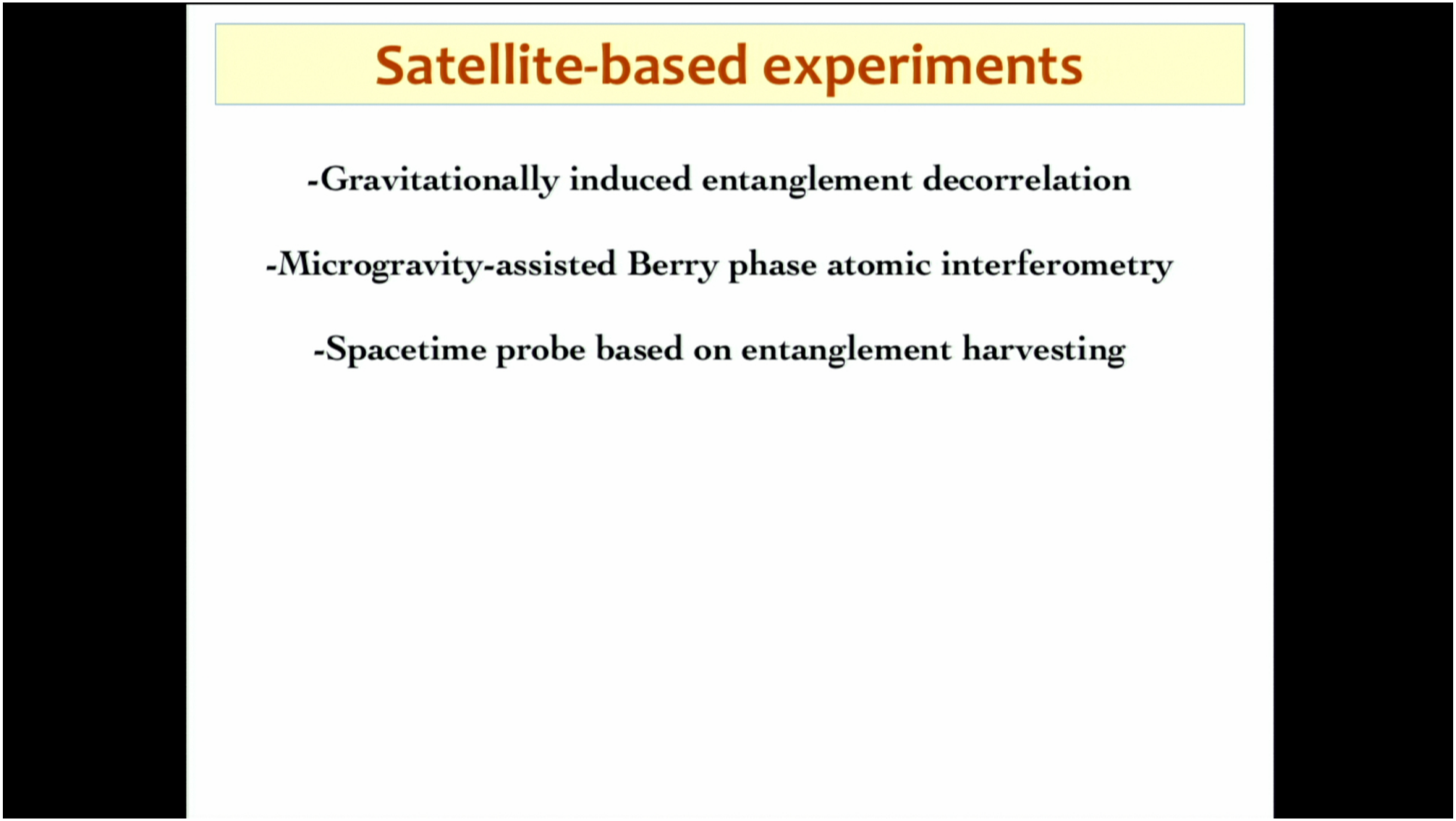
Satellite-based experiments

Fundamental tests:

-Fermi Problem
-Extraction of spacelike entanglement

We would like to maximise spacelike separation times

Kind of experiment	**Typical distances R**	**Space-like separation times $R/c \geq T$**	**Feasibility**
Tabletop	$\approx 1\,\mathrm{m}$	$\approx 3\,\mathrm{ns}$	–
Earthbound	$\sim 10\,\mathrm{km}$	$\approx 30\,\mu\mathrm{s}$	Possibly with superconducting qubits [77]
LEO satellite-based	$\sim 1000\,\mathrm{km}$	$\approx 3\,\mathrm{ms}$	Barely feasible with ions [78]
GEO satellite-based	$\approx 36{,}000\,\mathrm{km}$	$\approx 0.1\,\mathrm{s}$	Well feasible with ions/atoms
Moon-Earth	$\approx 380{,}000\,\mathrm{km}$	$\approx 1\,\mathrm{s}$	Feasible with macroscopic detectors
Solar System	$\sim 1\,\mathrm{a.u.}$	$\approx 500\,\mathrm{s}$	Well feasible with macroscopic detectors

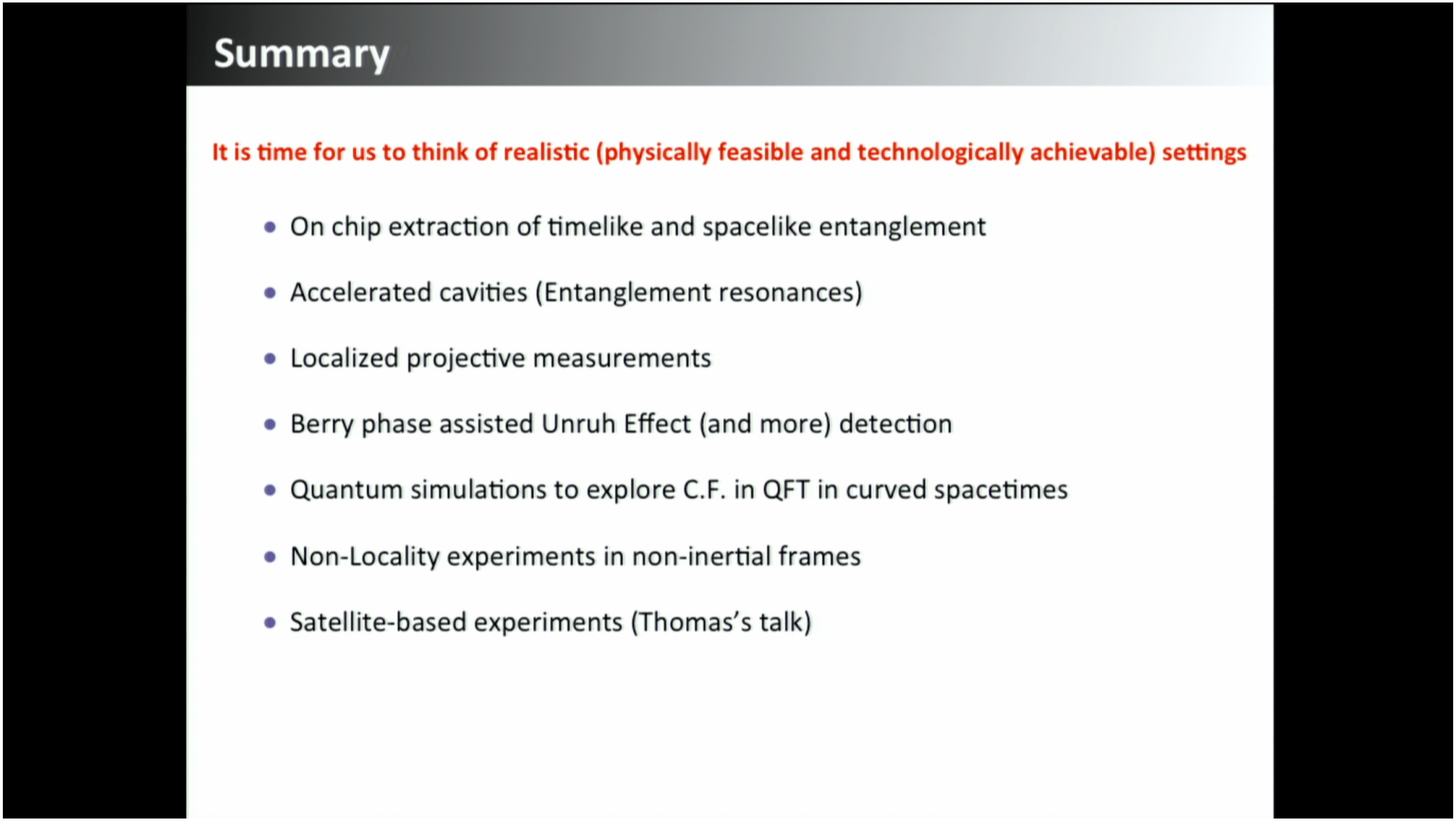


Satellite-based experiments

-Gravitationally induced entanglement decorrelation

-Microgravity-assisted Berry phase atomic interferometry

-Spacetime probe based on entanglement harvesting



Summary

It is time for us to think of realistic (physically feasible and technologically achievable) settings

- On chip extraction of timelike and spacelike entanglement
- Accelerated cavities (Entanglement resonances)
- Localized projective measurements
- Berry phase assisted Unruh Effect (and more) detection
- Quantum simulations to explore C.F. in QFT in curved spacetimes
- Non-Locality experiments in non-inertial frames
- Satellite-based experiments (Thomas's talk)