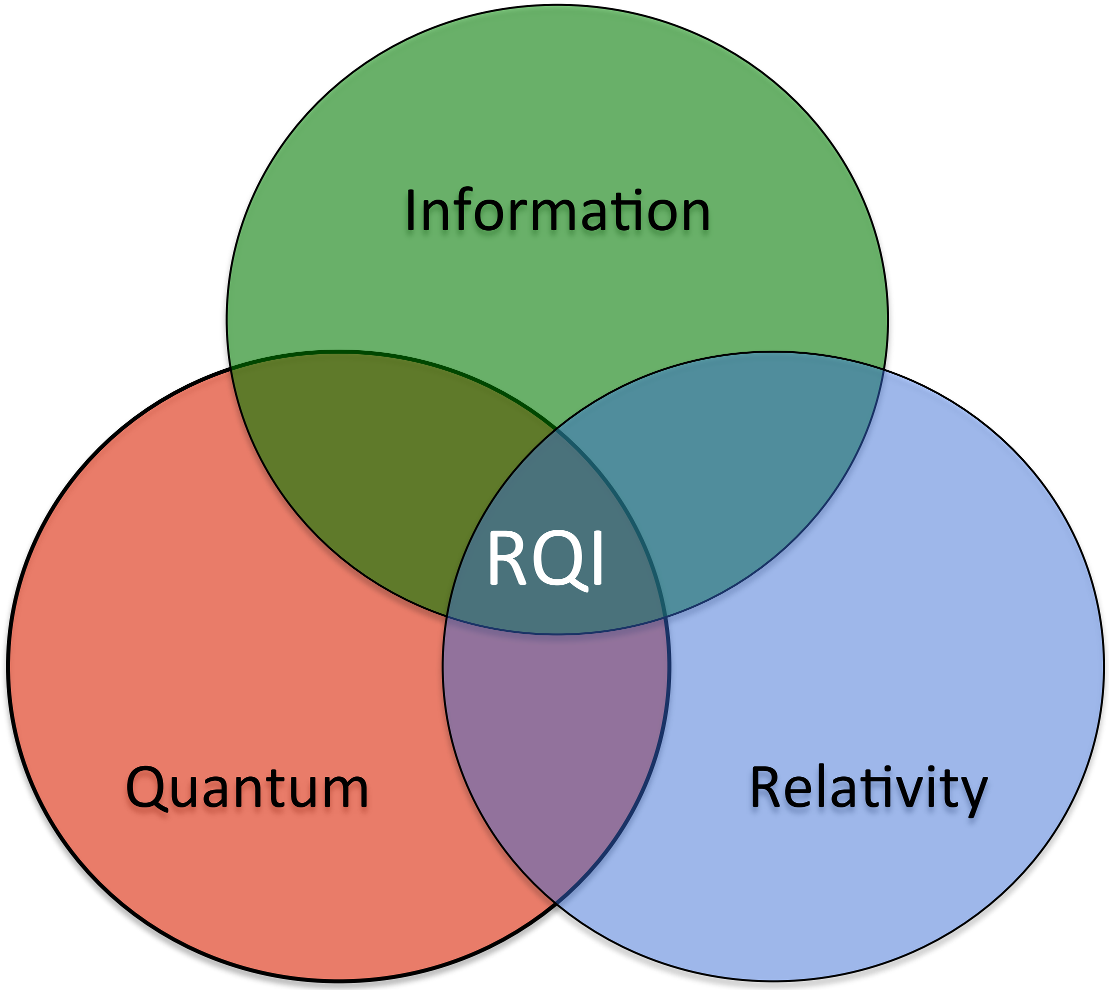
Quantum Leaks in Spacetime

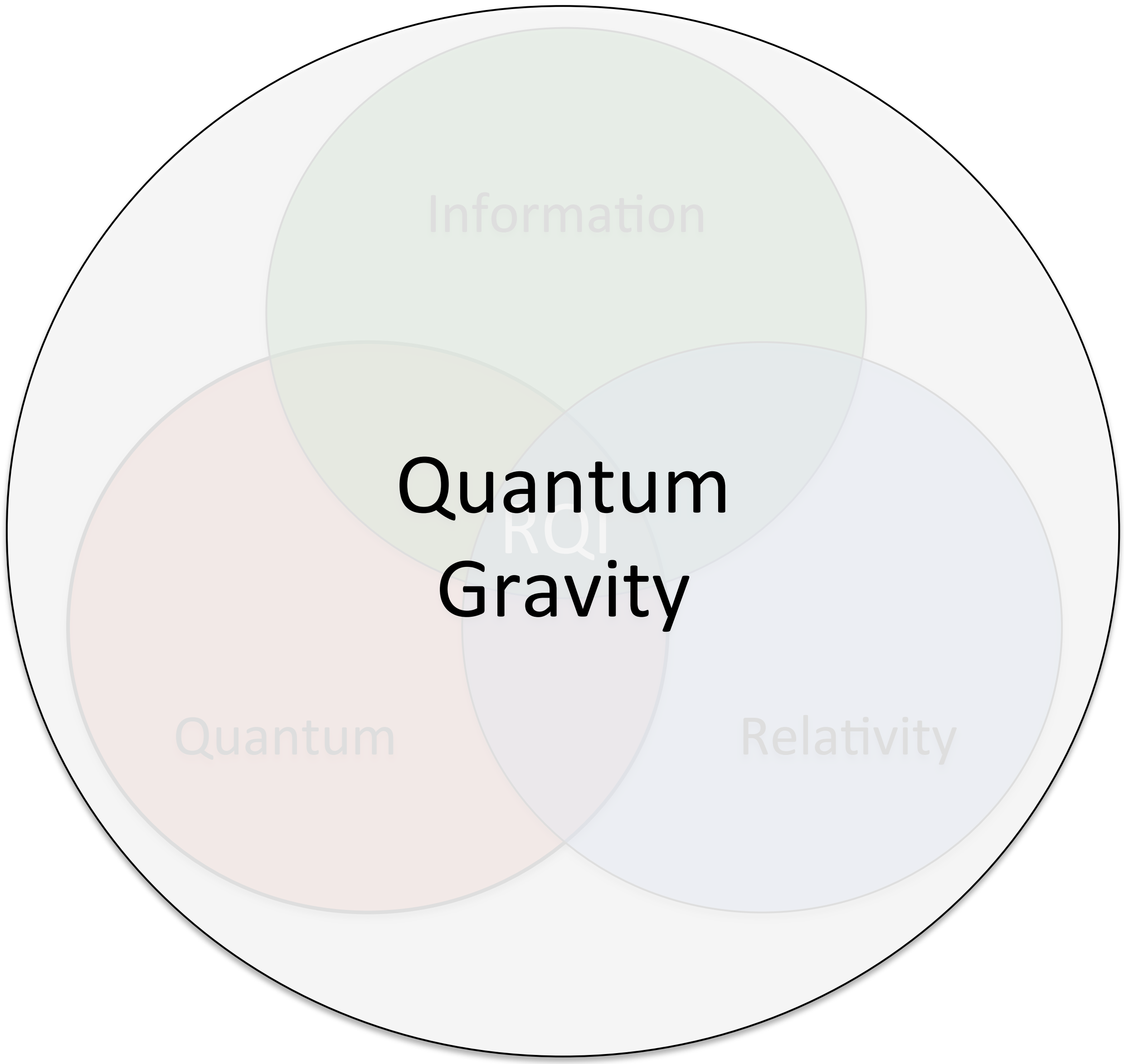
R.B. Mann

University of Waterloo

Relativistic Quantum Information



Relativistic Quantum Information



Why We Should Quantize Gravity

- The world is intrinsically quantum
  - Experiment strongly affirms QFT→ forces are quantum
  - Gravity should be the same as the other forces
- Classical/Quantum Hybrid models are inconsistent
  - Uncertainty principle in quantum sector violated on short time scales
- Thought experiments require it
  - CAT-type position experiments with a mass ➔ spacetime is in superposition➔ quantum spacetime

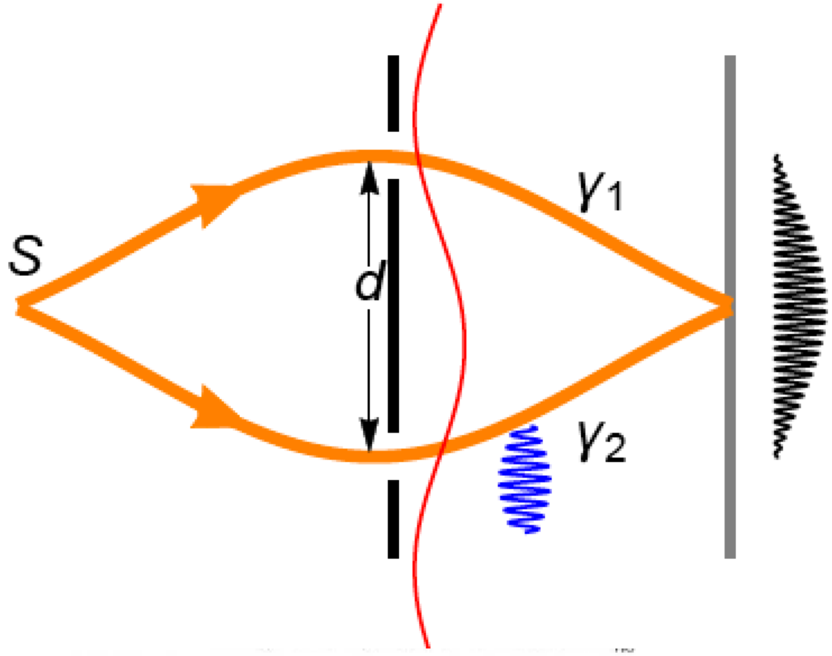
Why We Shouldn't Quantize Gravity

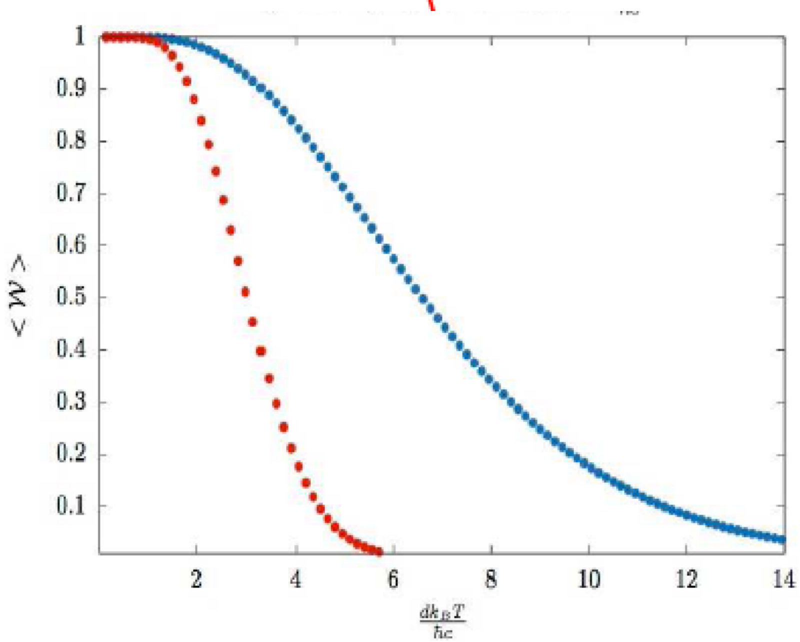
- The world is intrinsically geometric
  - All quantum theories require a spacetime background for their formulation (LQG not fully complete)
  - Observation strongly affirms this
- Hybrid quantum/classical models work if enough noise is present
  - Premature to rule out this approach
- Gravity cannot be shielded
  - Equivalence principle: all forms of matter couple to gravity the same way
    - → gravity perpetually `measures'
    - → gravity is perpetually `measured'

Is the universe fundamentally an open quantum system?

Double-slit Experiment

Samuel arXiv:1706.04401





$$P = P_{12} - P_1 - P_2$$

$$I = \langle W \rangle \left(\Psi_2^* \Psi_1 + \Psi_1^* \Psi_2 \right)$$

Fourier transform coefficients of the Wilson loop

$$\langle W \rangle = \exp\left[-\frac{e^2}{2\hbar c} \sum_l |\alpha_l|^2 \coth\left(\frac{\hbar \omega_l}{2 k_B T} \right) \right]$$

In a thermal bath of photons

$$\langle W \rangle = \exp\left[-\frac{e^2}{2\hbar c} \sum_l |\alpha_l|^2 \coth\left(\frac{\pi c \omega_l}{g} \right) \right]$$

In a constant gravitational field


Permeable
Information
How leaky is spacetime?

Finding Leaks

Quantum Detectors

S-Y Lin, B.L.Hu PRD73 (2006) 124018
PRD76 (2007) 064008

$$S_I = \lambda_0 \int d\tau \int d^4 x Q(\tau)\Phi(x)\delta^4\left(x^\mu - z^\mu(\tau)\right)$$

Vacuum

$$S = \frac{m_0}{2}\int d\tau\left[\left(\partial_\tau Q\right)^2 - \Omega_0^2 Q^2\right] - \int d^4 x\sqrt{-g}\,\frac{1}{2}\left(\nabla\Phi(x)\right)^2 + S_I$$

detector field interaction

Cavity

$$\hat{H} = \Omega_d \hat{a}_d^\dagger \hat{a}_d + \frac{dt}{d\tau}\sum_n \omega_n \hat{a}_n^\dagger \hat{a}_n + H_I$$

$$H_I = \lambda(\tau)(\hat{a}_d e^{-i\Omega\tau} + \hat{a}_d^\dagger e^{i\Omega\tau})\sum_n \left(\hat{a}_n u_n[x(\tau),t(\tau)] + \hat{a}_n^\dagger u_n^*[x(\tau),t(\tau)]\right)$$

Provide an operational means of probing the quantum character of spacetime

E.G. Brown, E. Martin-Martinez, N. Menicucci, RBM PRD87 (2013) 084062
D. Bruschi, A. Lee, I Fuentes J. Phys A46 (2013) 165303

In general linearly coupled – but see A. Sachs poster for Quadratic coupling

Hot Accelerating Detectors?

$$T = \frac{a}{2\pi}\left(\frac{\hbar}{k_B c}\right)$$

S.A. Fulling PRD7 (1973) 2850 P.C.W. Davies J Phys A8 (1975) 609 W. G. Unruh PRD14 (1976) 3251

- Unruh effect
  - Geometric Methods + Bogoliubov transformations
  - Eternally accelerating qubit coupled to a quantum field

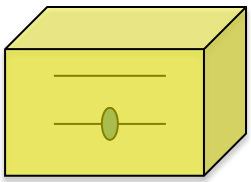
B. deWitt in *General Relativity: An Einstein Centenary Survey* (CUP 1980)

- Limitations
  - Highly idealized: eternal uniform acceleration, unbounded system, perturbative, model-dependent, …
- What we would like and need to know
  - Finite time and distance effects (cavities, switching)
  - Boundary conditions
  - Non-perturbative effects; non-equilibrium effects
  - Entanglement, Non-locality of correlations
- Interplay with curved spacetime and gravity?

Oscillating Vacuum Detectors

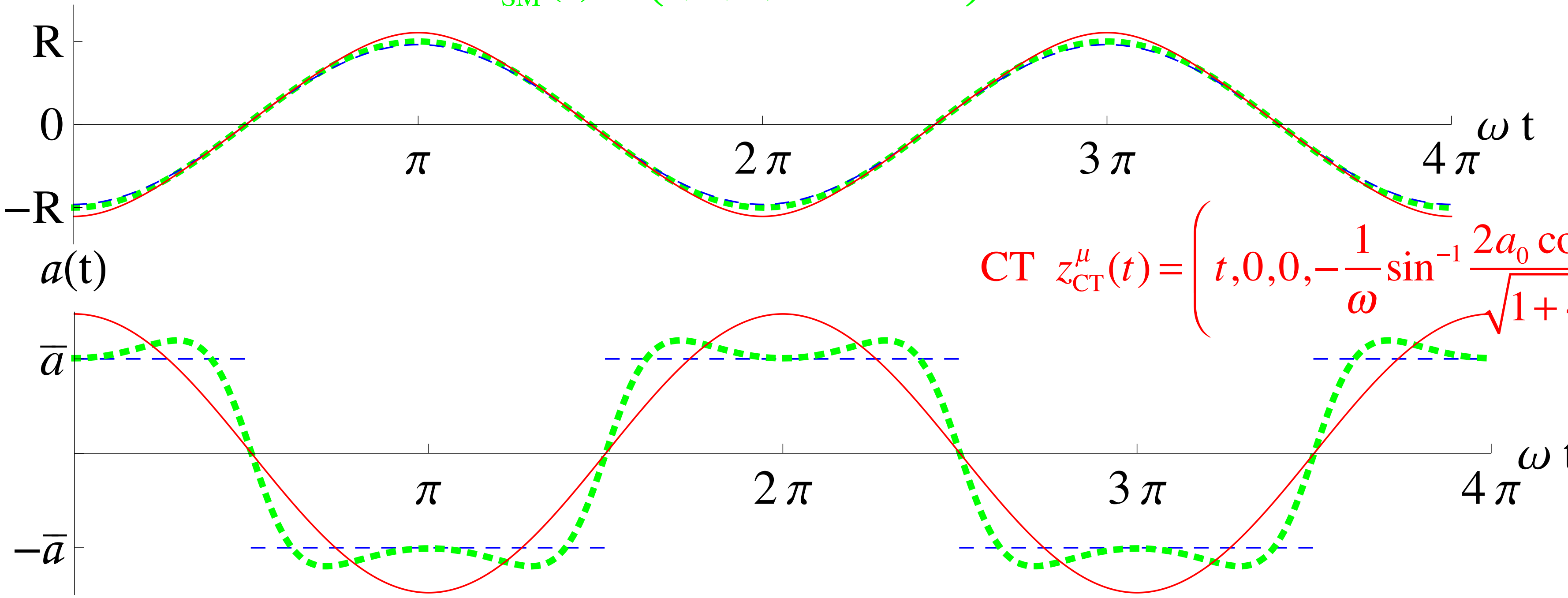
Non-uniform acc'n:
Ostapchuk/Lin/ RBM/Hu
JHEP 1207 (2012) 072

$$S=-\int d^4x\sqrt{-g}\,\frac{1}{2}\partial_\mu\Phi(x)\partial^\mu\Phi(x)$$



$$+\int d\tau\left\{\frac{m_0}{2}\left[\left(\partial_\tau Q\right)^2-\Omega_0^2Q^2\right]+\lambda_0\int d^4x\,Q(\tau)\Phi(x)\delta^4\left(x^\mu-z^\mu(\tau)\right)\right\}$$

SM $z^\mu_{\rm SM}(t)=\left(t,0,0,-R\cos\omega t\right)$

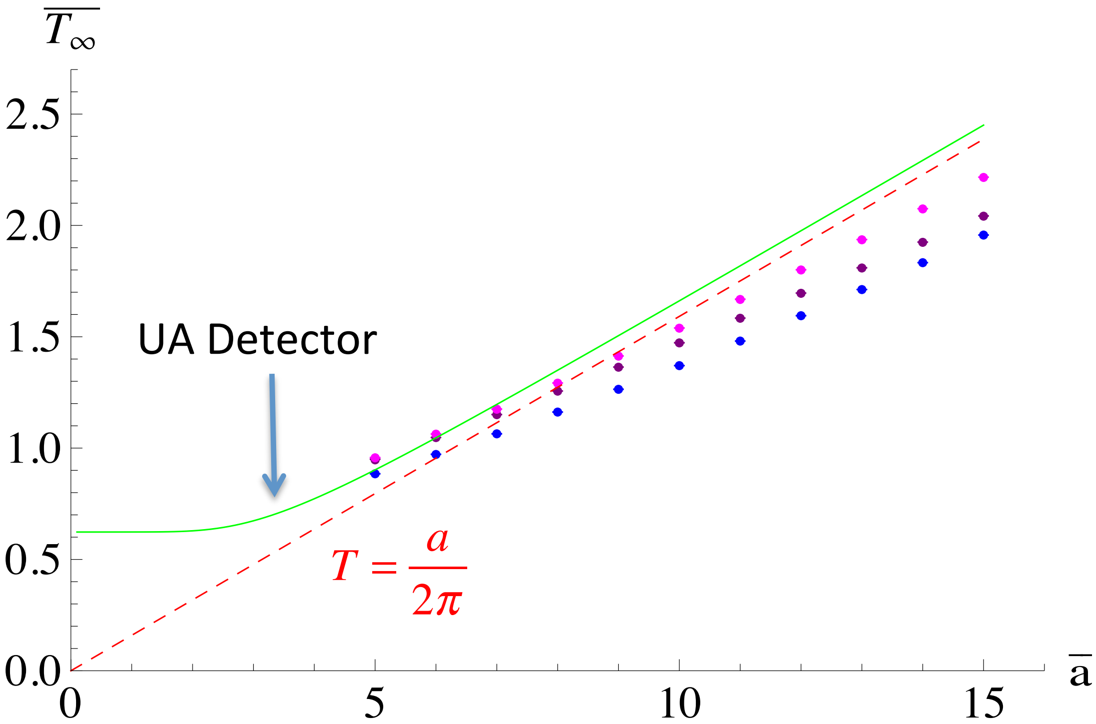


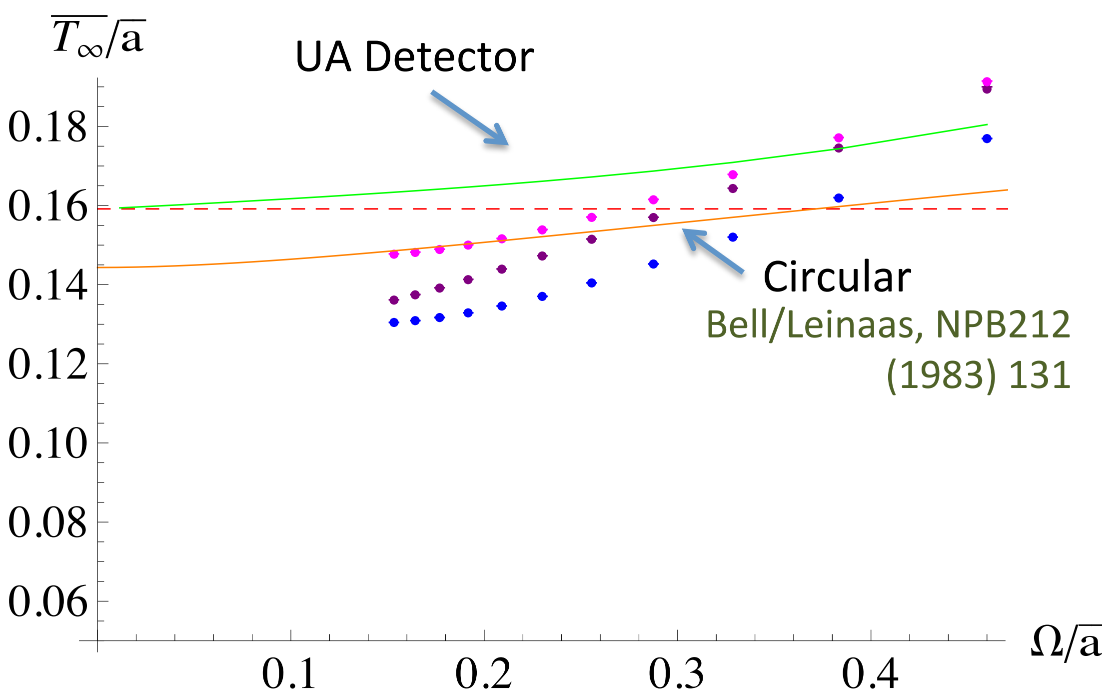
CT $z^\mu_{\rm CT}(t)=\left(t,0,0,-\frac{1}{\omega}\sin^{-1}\frac{2a_0\cos\omega t}{\sqrt{1+4a_0^2}}\right)$

AUA $z^\mu_{\rm AUA}(\tau)=\left(\frac{1}{a}\left[\sinh a\left(\tau-\frac{n\tau_p}{2}\right)+2n\sinh\frac{a\tau_p}{4}\right],0,0,\frac{(-1)^n}{a}\left[\cosh a\left(\tau-\frac{n\tau_p}{2}\right)+\left\{(-1)^n-1\right\}\cosh\frac{a\tau_p}{4}\right]\right)$

Results

Doukas/Lin/Hu/RBM JHEP 1311 (2013) 119





Effective Temperature

$$T_{\rm eff}(\tau) = \left[\frac{k_B}{\hbar\Omega_r}\ln\left(\frac{U(\tau)+\hbar/2}{U(\tau)-\hbar/2}\right)\right]^{-1} \to T_{\rm eff}(\infty) =$$

$$U(\tau) \equiv \sqrt{\langle \hat{P}^2(\tau)\rangle\langle \hat{Q}^2(\tau)\rangle - \langle \hat{Q}(\tau),\hat{P}(\tau)\rangle^2}$$

Average Acceleration $\quad \bar{a} \equiv \dfrac{\int_P a(\tau)d\tau}{\int_P d\tau}$

- CT worldline
- SM worldline
- AUA worldline

$$\omega = 20$$

$$\gamma \equiv \lambda_0^2 / 8\pi m_0 = 0.01$$

$$\Omega \equiv \sqrt{\Omega_r^2 - \gamma^2} = 2.3$$

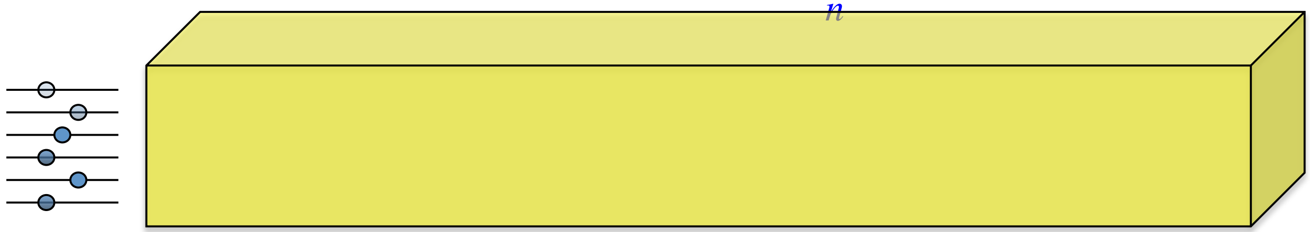
$$\Lambda = -\ln\frac{\hbar\Omega_R}{E_{\rm cutoff}} = 20$$

Cavity Detectors

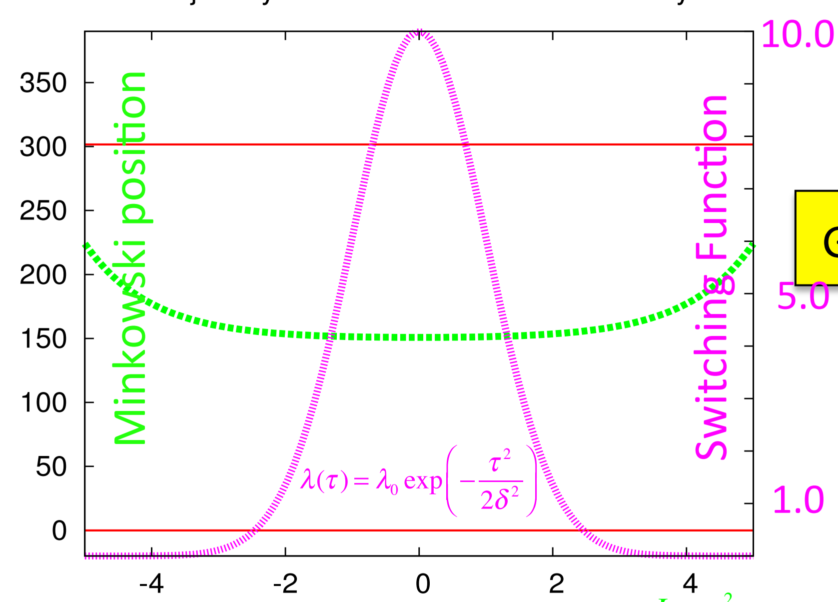
$$\hat{H} = \Omega_d \hat{a}_d^\dagger \hat{a}_d + \frac{dt}{d\tau} \sum_n \omega_n \hat{a}_n^\dagger \hat{a}_n$$

$$+ \lambda(\tau)(\hat{a}_d e^{-i\Omega\tau} + \hat{a}_d^\dagger e^{i\Omega\tau}) \sum_n \left(\hat{a}_n u_n[x(\tau),t(\tau)] + \hat{a}_n^\dagger u_n^*[x(\tau),t(\tau)] \right)$$

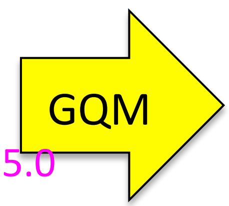
Brenna/Brown/Martin-Martinez/RBM
PRD88 (2013) 064031

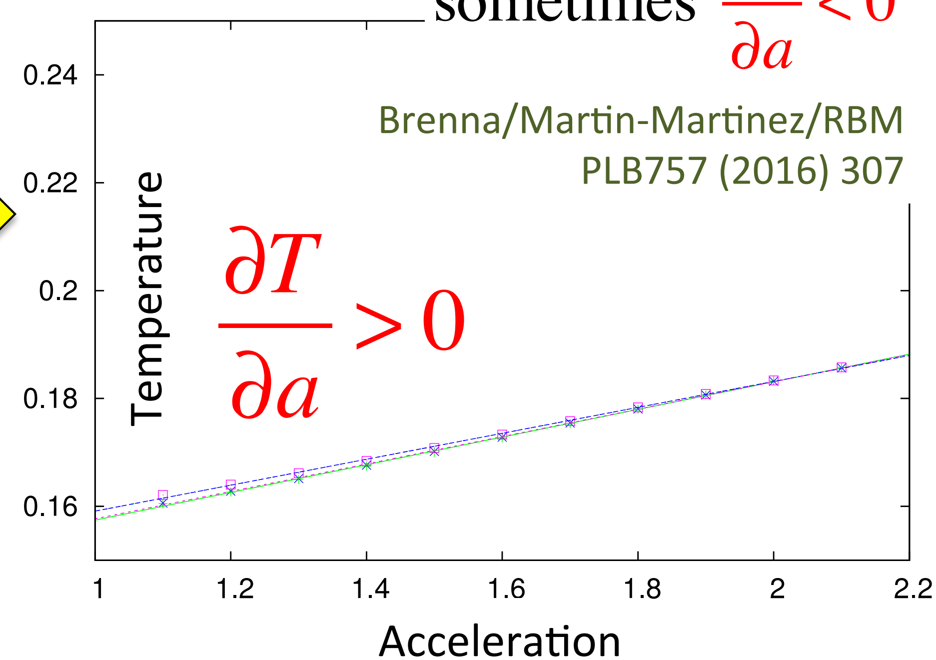


Trajectory of the Detector within the Cavity



$t(\tau) = c\sinh(a\tau)/a$ $x(\tau) = \frac{L}{2} + \frac{c^2}{a}[\cosh(a\tau) - 1]$





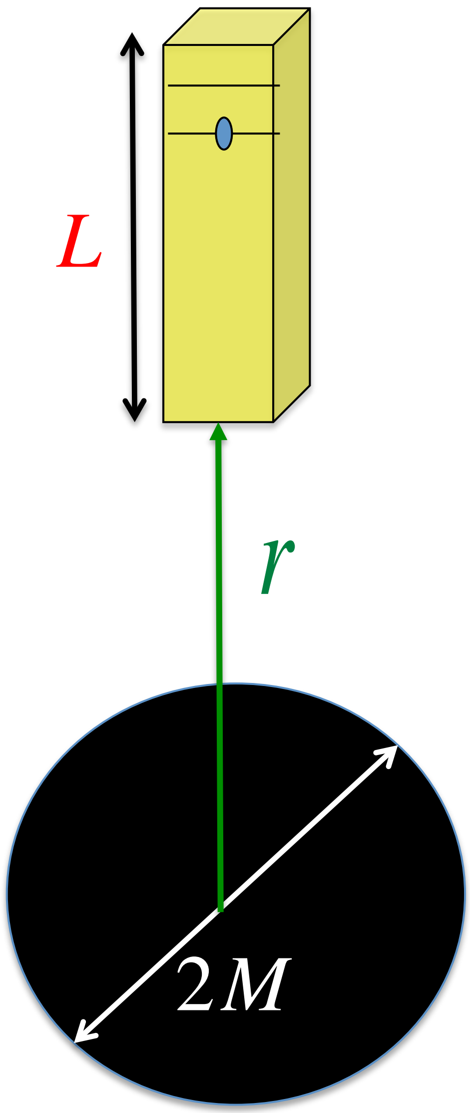
sometimes $\frac{\partial T}{\partial a} < 0$

Brenna/Martin-Martinez/RBM
PLB757 (2016) 307

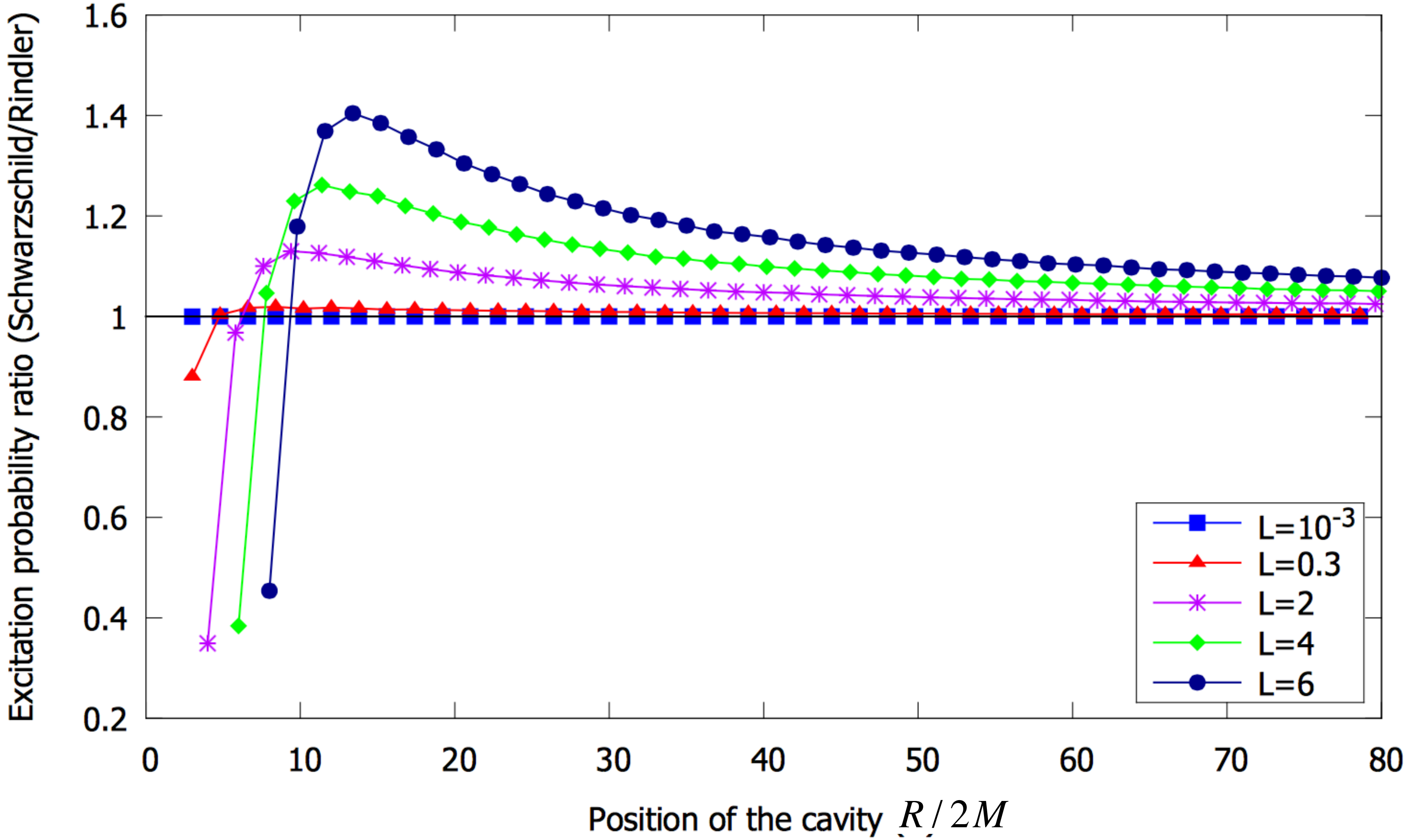
$$\frac{\partial T}{\partial a} > 0$$

Gravitating Cavity Detectors

Ahmadazadgan/Martin-Martinez/RBM
PRD89 (2014) 024013



- Consider a cavity that is static at some distance r from the black hole
- Compute excitation probability of a UdW detector as it falls through the cavity with zero initial speed as r is varied
- Compare to results in flat space where acceleration=gravity



- Smaller cavities, larger distances → small distinction

Detector Response Outside Black Holes

- BTZ Black holes
  - Static and Rotating
- Schwarzschild Black Holes
- Schwarzschild AdS Black Holes
- All for various boundary conditions, detector trajectories

Hodgkinson/Louko PRD86 (2012) 064031

Hodgkinson/Louko/Ottewill PRD89 (2014) 104002

Ng/ Hodgkinson/Louko/RBM/ Martin-Martinez PRD90 (2014) 064003

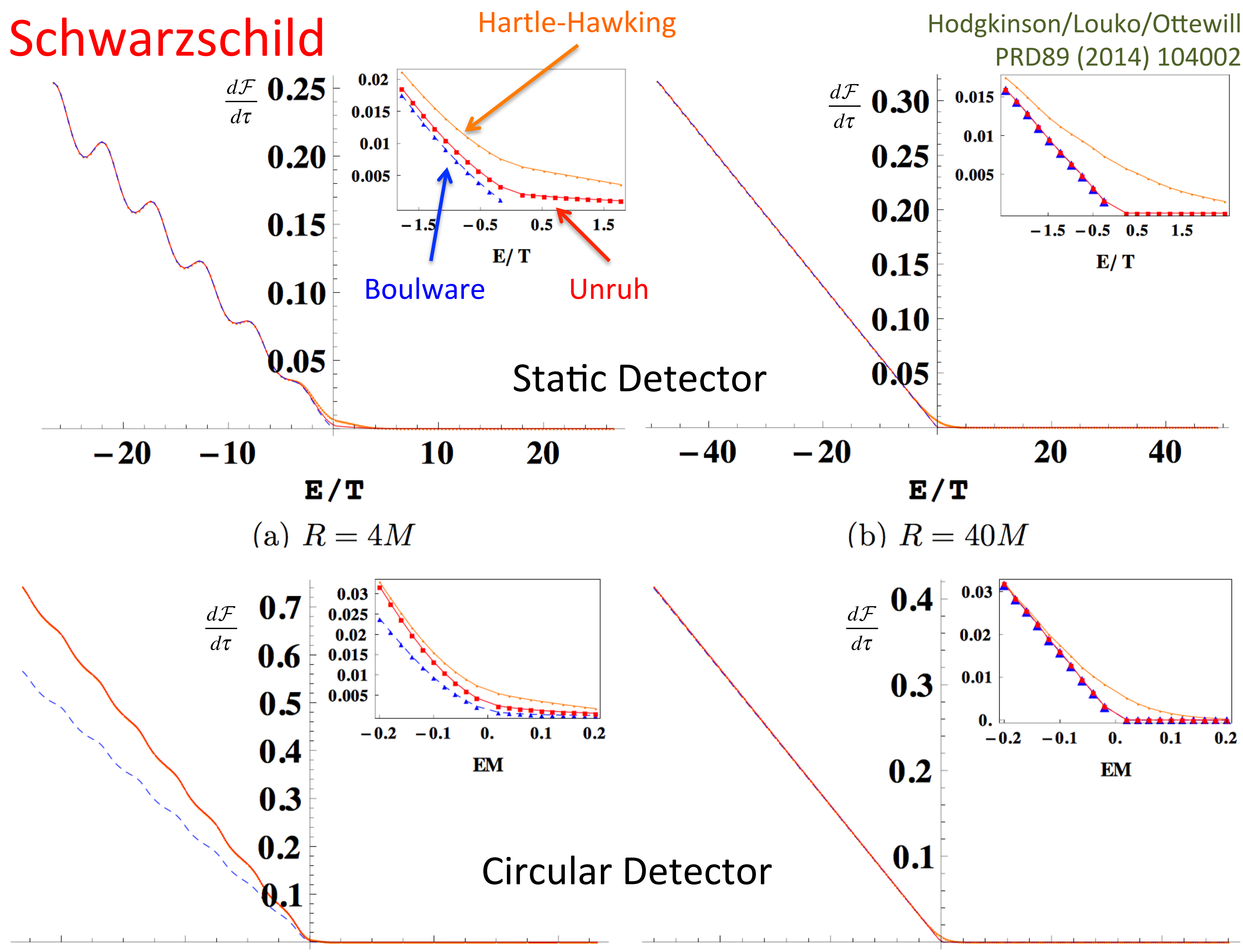
$$H_{\text{int}} = c\chi(\tau)\mu(\tau)\phi(x(\tau))$$

$$P(E) = c^2 \left|\langle 0_d|\mu(0)|E\rangle\right|^2 \mathcal{F}(E)$$

$$\mathcal{F}(E) = \Re\left[\int_{-\infty}^{\infty} du\,\chi(u)\int_0^{\infty} ds\,\chi(u-s)e^{-iEs}G^+(u,u-s)\right]$$

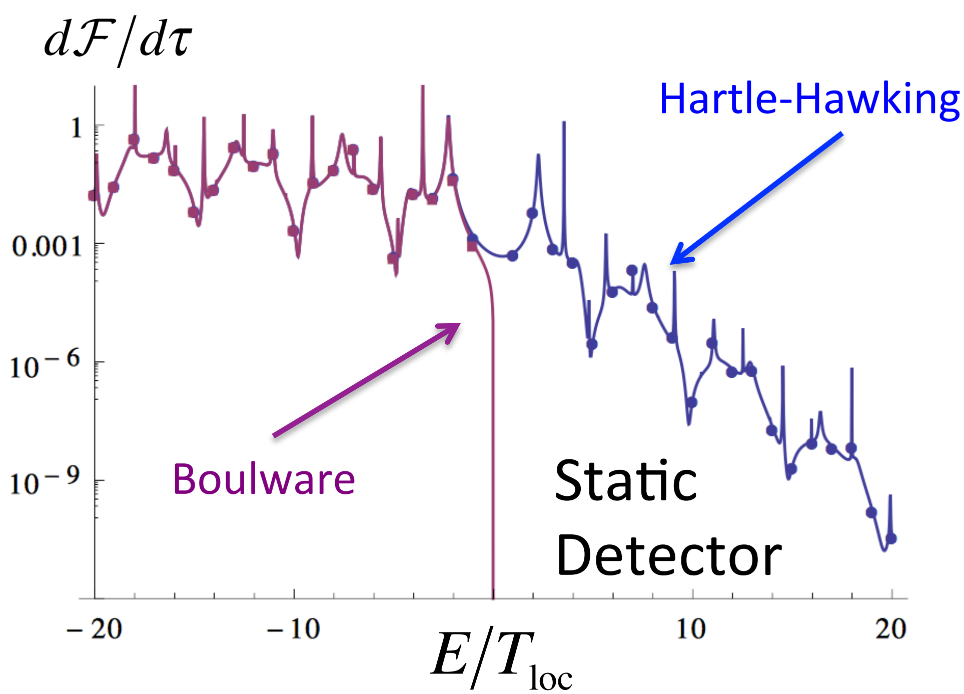
$$\frac{d\mathcal{F}}{d\tau}(E;M,\ell,\ldots) = \frac{1}{4} + 2\Re\left[\int_0^{\Delta\tau} ds\,e^{-iEs}G^+(\tau,\tau-s)\right]$$

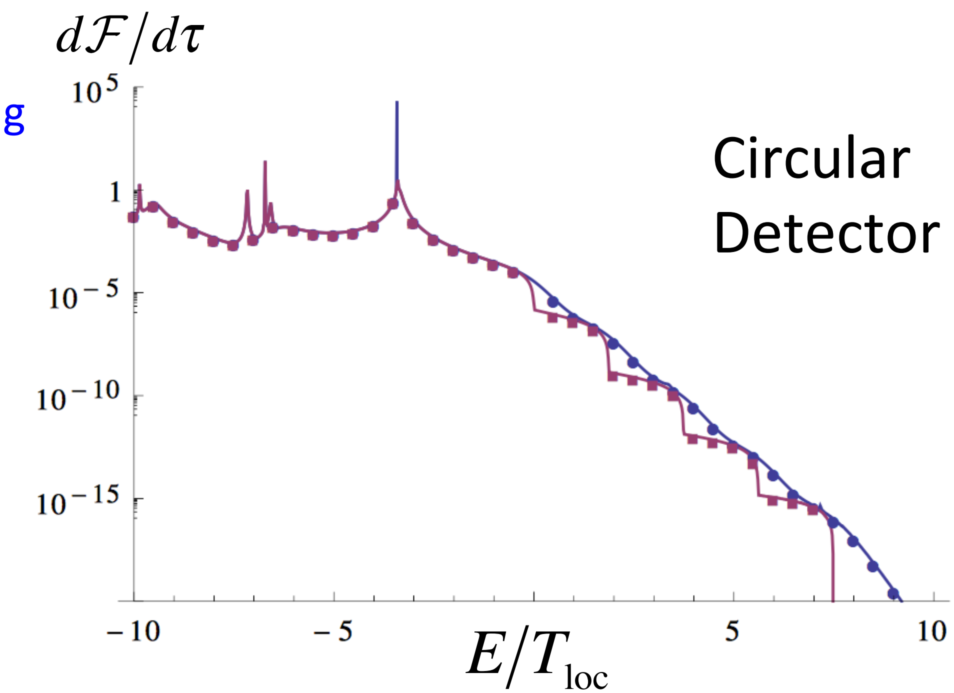
Detector Response Rate


Schwarzschild
Hartle-Hawking
Hodgkinson/Louko/Ottewill
PRD89 (2014) 104002
Boulware
Unruh
Static Detector
Circular Detector
dF/dτ
E/T
EM
(a) R = 4M
(b) R = 40M

Schwarzschild-AdS

Ng/ Hodgkinson/Louko/RBM/Martin-Martinez
PRD90 (2014) 064003





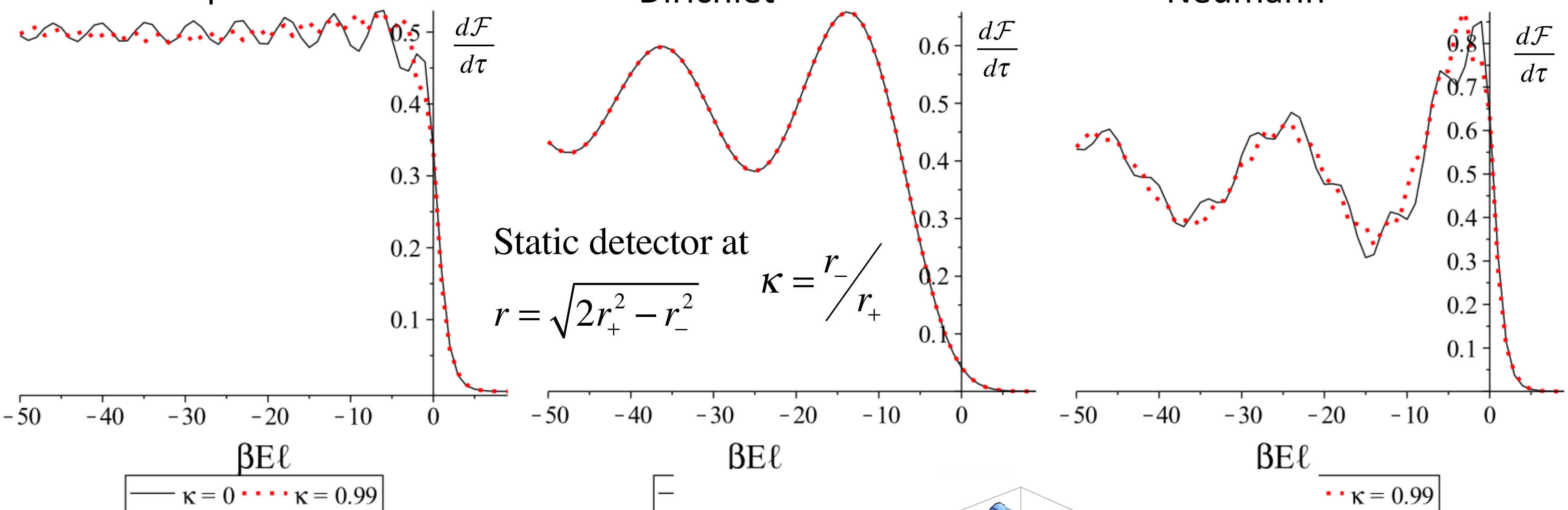
- Spikes due to Quasinormal mode resonances
- Visible only when black hole is much smaller than AdS length
- Peaks become higher and sharper as black hole size decreases

BTZ

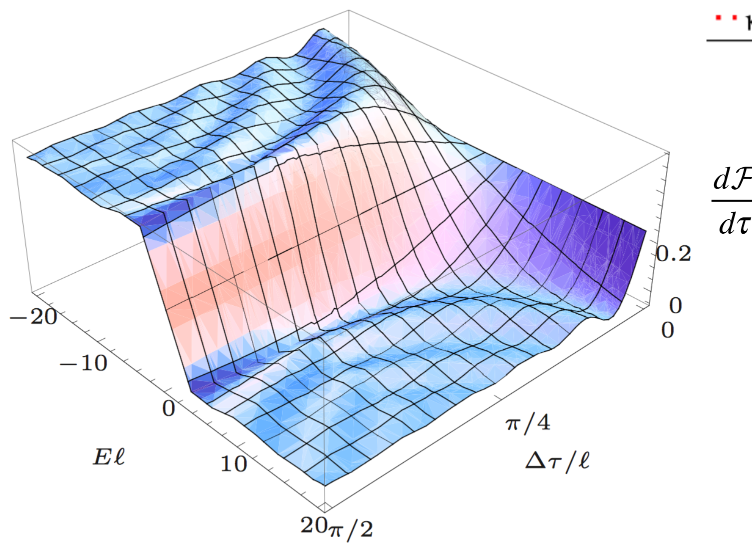
Hodgkinson/Louko PRD86 (2012) 064031

- Wightman function given by image sum not mode sum
- Can consider both rotating black holes and radially infalling detectors

Transparent Dirichlet Neumann



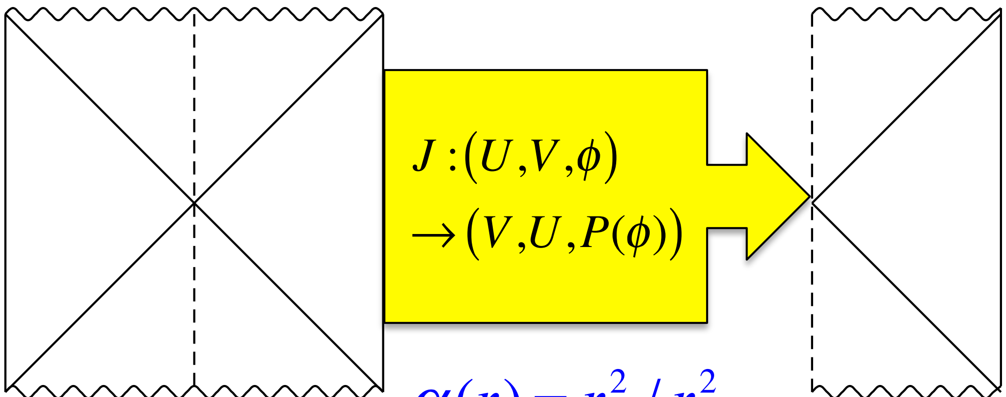
Radial infall excitation rate as a function of gap energy and time



See also Hodgkinson 1309.7281

Looking Inside Black Holes

Louko Lect.Notes Phys. 541:188 (2000)
Louko/RBM/Marolf CQG22 (2005) 1451



$\alpha(r) = r^2 / r_h^2$

BTZ Black Hole

BTZ Geon

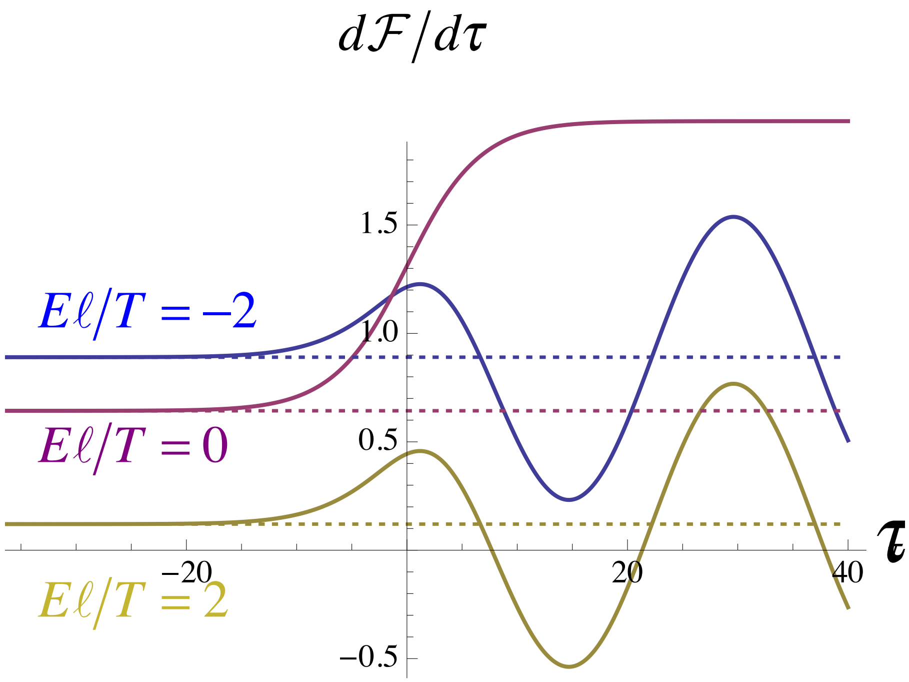
$$f(r) = \left(\frac{r^2}{\ell^2} - M\right)$$

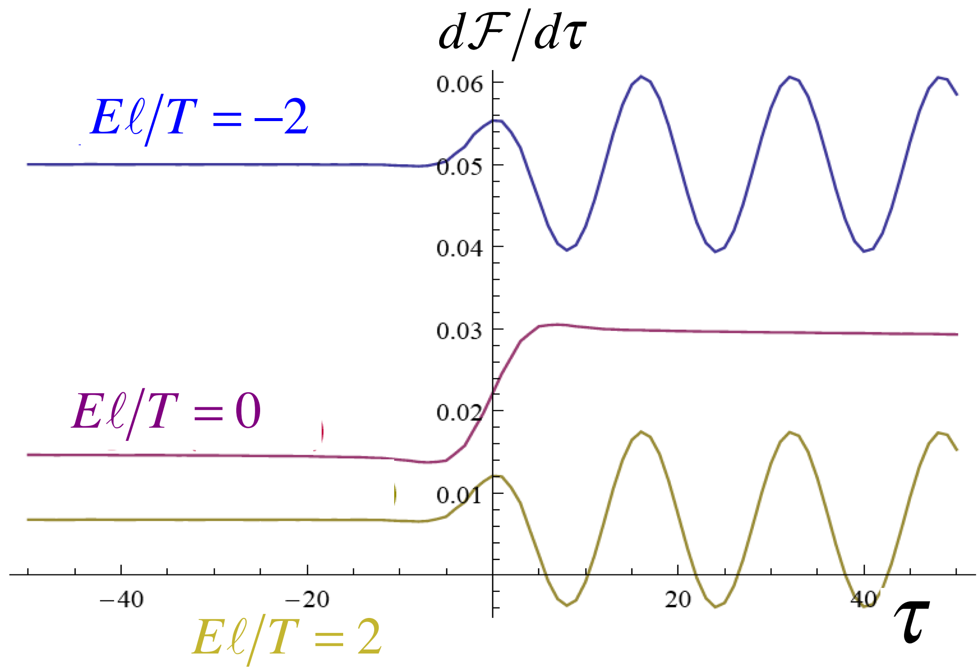
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + r^2 d\phi^2$$

$$= \frac{\ell^2\left[4\mathrm{d}U dV - M(1-UV)^2 d\phi^2\right]}{(1+UV)^2}$$

- No classical way of distinguishing these spacetimes
- Topological features hidden behind horizon
- But quantum fields probe all of spacetime
- Can a UdW detector `look' inside a black hole?

$$\frac{d\mathcal{F}}{d\tau}(E) = \frac{d\mathcal{F}}{d\tau}_{\mathrm{BTZ}}(E) + \Delta\frac{d\mathcal{F}}{d\tau}(E,\tau)_{\mathrm{geon}}$$





BTZ Geon

Smith/RBM CQG31 (2014) 082001

Schwarzschild Geon

Ng/RBM/Martin-Martinez
1706.08978

- Time dependence due to indefinite sign of Killing vector at origin
- Distinction vanishes at large distances and at past/future infinity

See K. Ng's poster for more detail

Entanglement Harvesting

- Quantum field correlations swapped with detectors

  Salton/RBM/Menicucci
  NJP17 (2015) 035001

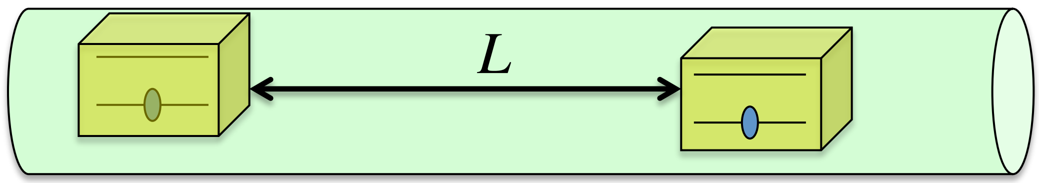
- Works even for spacelike separated detectors

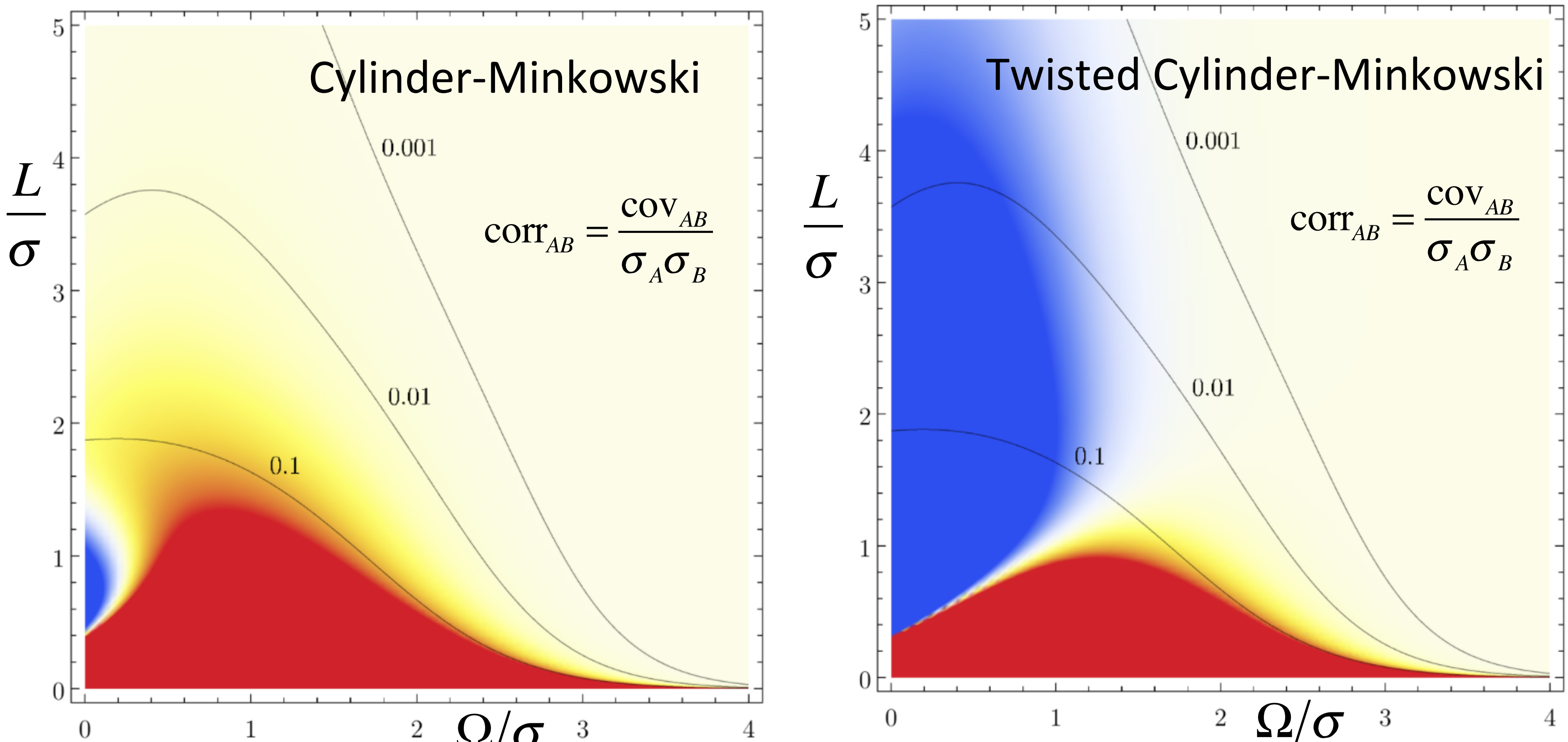
  Valentini PLA153 (1991) 321
  Reznik FndPhy 33 (2003) 167

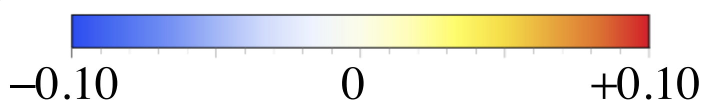
- Can be done sustainably → entanglement farming

  Martin-Martinez /Brown/Donnelly PRA88 (2013) 052310

- Applications (in principle)
  - Seismology Brown/Donnelly/Kempf/RBM/Martin-Martinez NJP16 (2014)105020
  - Rangefinding Salton/RBM/Menicucci NJP17 (2015) 035001
  - Quantum Key Distribution Ralph/Walk NJP17 (2015) 063008
  - Extraction from Atoms Pozas-Kerstjens /Martin-Martinez PRD94 (2016) 06407[illegible]
- Sensitive to spacetime geometry and topology



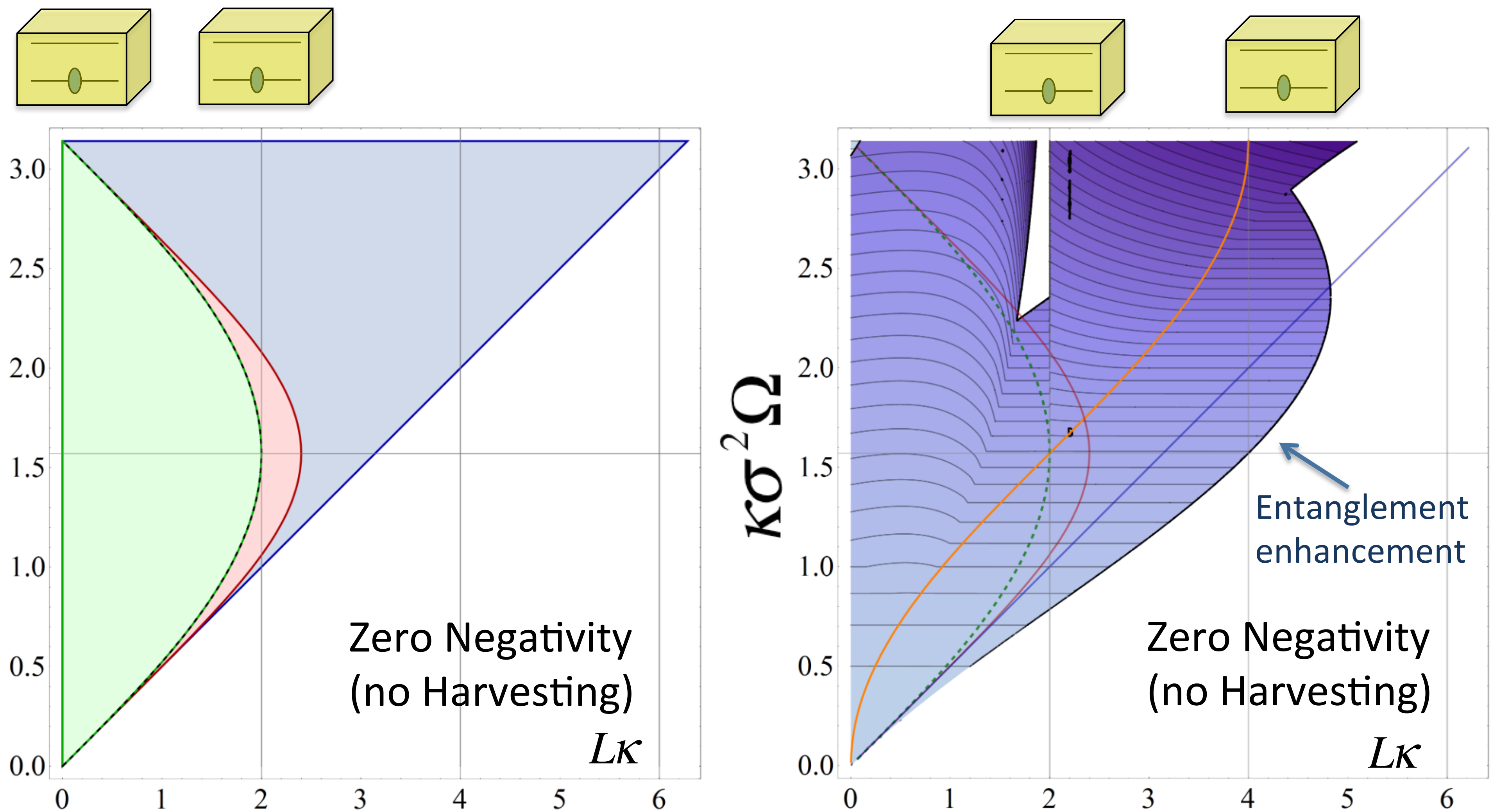




$$\mathrm{cov}_{AB} = \langle r_A r_B \rangle - \langle r_A \rangle \langle r_B \rangle$$

$$\sigma_A^2 = \mathrm{cov}_{AA} \qquad r \in \{0,1\}$$

Martin-Martinez /Smith/Terno PRD93 (2016) 044001



Parallel Acc'n or de Sitter

Inertial detectors in thermal Minkowski

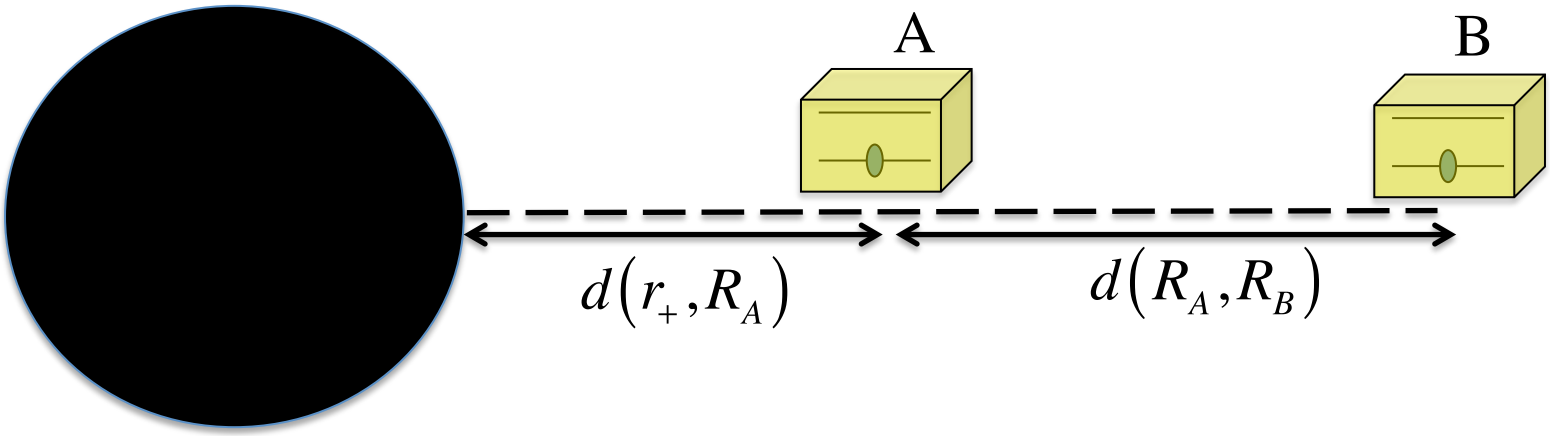
Inertial detectors in vacuum Minkowski

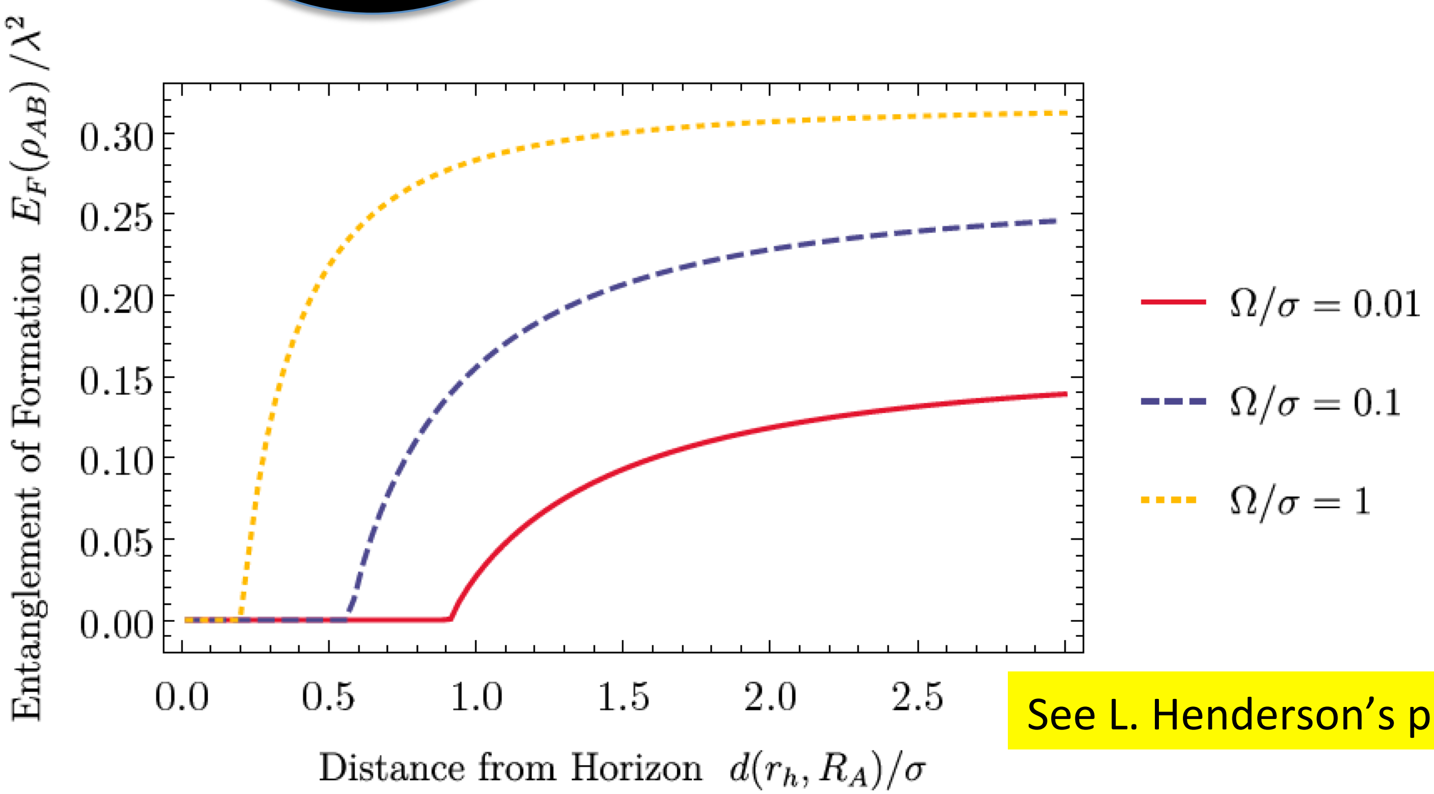
VerSteeg/Menicucci
PRD79 (2009) 044027

Salton/RBM/Menicucci
NJP17 (2015) 035001

Harvesting near a Black Hole

Henderson/Hennigar/Smith/Zhang/RBM

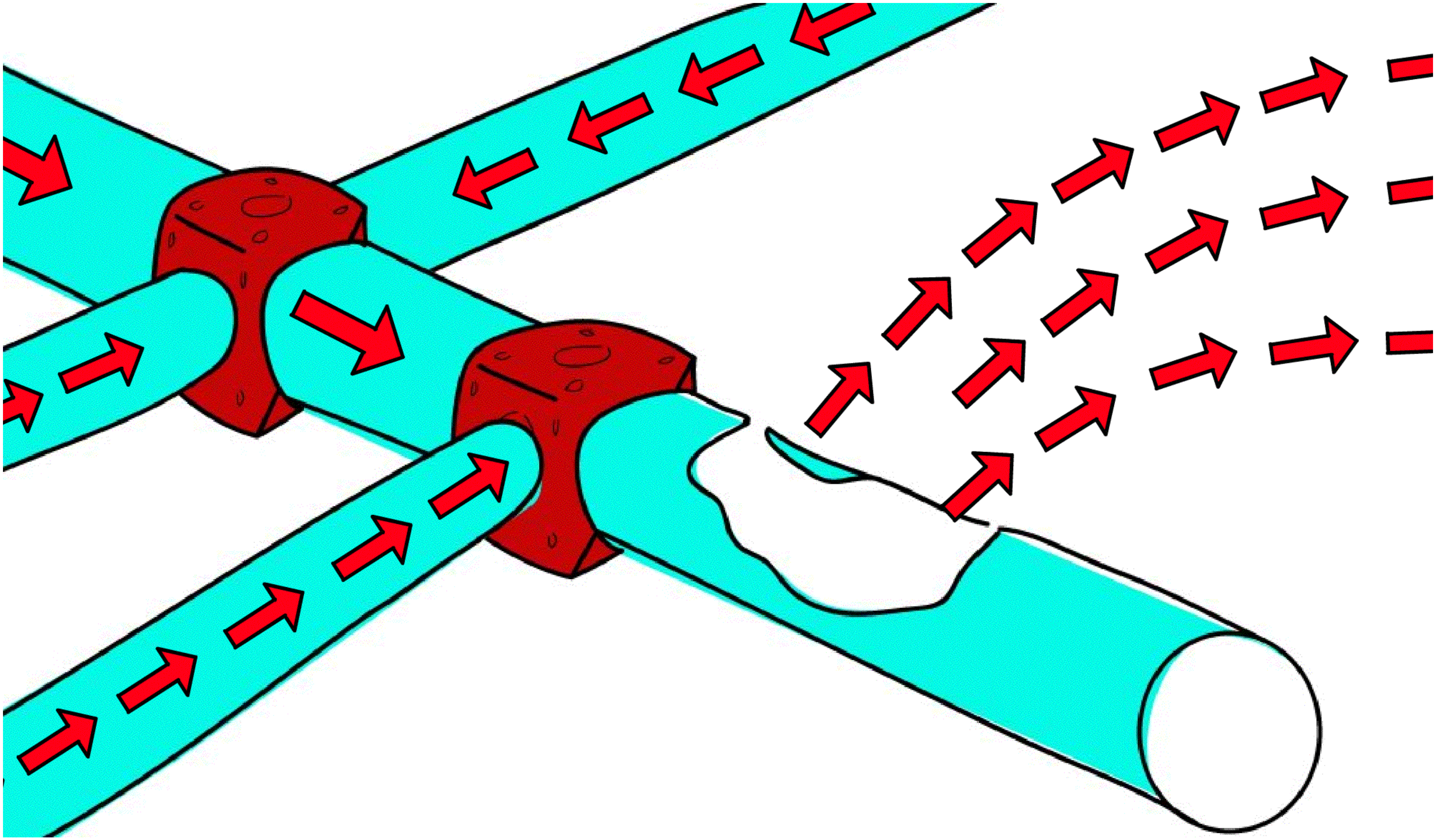




Hawking radiation inhibits entanglement harvesting

See L. Henderson's poster for more detail

Exploiting Leaks



(Future) Applications of Detectors

- Detectors in Shells
  - Can distinguish shell interiors from flat space

Ng/RBM/Martin-Martinez
PRD94 (2016) 104041

- Modulation of Unruh Radiation
  - Unruh effect can be enhanced or suppressed by a suitable choice of non-uniformly accelerated trajectory

Ahmadzadagen/Kempf
1702.00472

See A. Ahmadzadegan's poster for more detail

- Black Hole Squeezers
  - QNMs of the Black hole can squeeze the vacuum, producing particles

Su/Ho/RBM/Ralph
1706.09117

See D. Su's poster for more detail

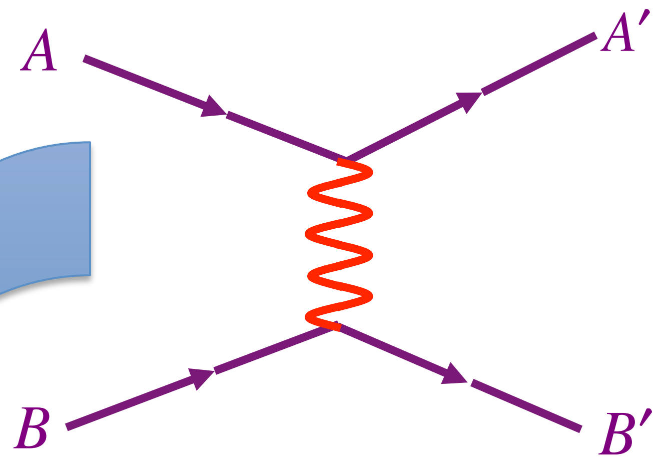
Gravitational Permeability of Information

Bassi/Grossardt/Ulbricht 1706.05677

- Gravity → decoherence of quantum matter
  - Thermal graviton background — Blencowe;Hu;Anastopoulos
  - Wavefunction collapse — Diosi/Penrose;Adler;Karolhazy
  - Minimal length effects — Kempf/Mangano/RBM;Das/Vagenas
  - Time Dilation decoherence — Zych/Costa/Pikovskii/Brukner/Ralph
- Matter → decoherence of quantum spacetime
  - Mini superspace models — Hawking;Zeh; Kiefer
- Indefinite Causal Order
  - Superpositions of causal order? — Oreshkov/Costa/Brukner
- Classical Channel Gravity?
  - Inhibition of gravitational entanglement — Kafri/Taylor/Milburn; Altimirano/Corona-Ugalde/Khosla/RBM/Milburn

Quantum Channel Model

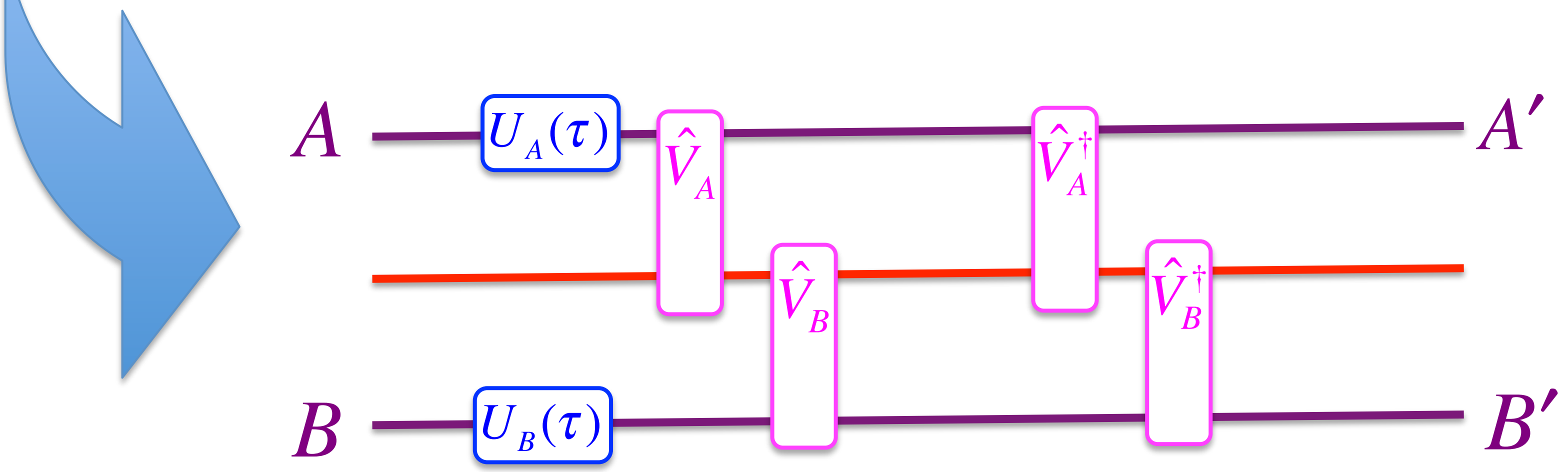
Kafri/Taylor
1311.4558



$$H = H_A + H_B + H_{AB}$$

$$U_A(\tau) = \exp\left(-itH_A\right) \quad \hat{V}_A = \exp\left(-i\sqrt{t}A\hat{x}\right)$$

$$U_B(\tau) = \exp\left(-itH_B\right) \quad \hat{V}_B = \exp\left(-i\sqrt{t}B\hat{p}\right)$$



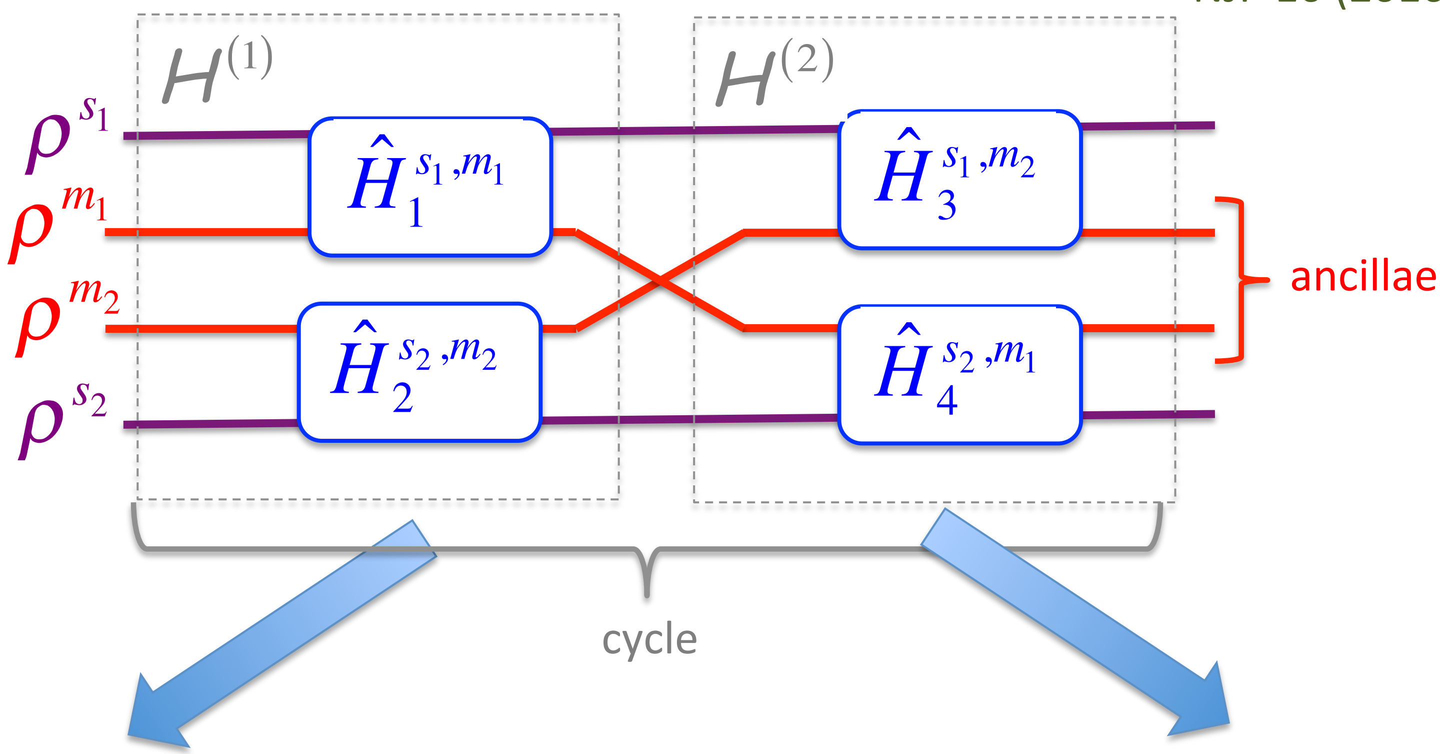
$$\hat{V}_A\hat{V}_B\hat{V}_A^\dagger\hat{V}_B^\dagger = \exp\left(-itAB\right)$$

Quantum Circuit Model of virtual particle exchange

$$\Rightarrow U_A U_B \hat{V}_A\hat{V}_B\hat{V}_A^\dagger\hat{V}_B^\dagger = \exp\left(-it\left(H_A + H_B + H_{AB}\right)\right)$$

Classical Channel Model

Kafri/Milburn/Taylor
NJP 16 (2016) 065020



Effective position measurements

$$H^{(1)} = \hat{H}_0 + g_1 \hat{x}^{s_1} \otimes \hat{p}_{m1} + g_2 \hat{x}^{s_2} \otimes \hat{p}_{m2}$$

Feedback of measurement result

$$H^{(2)} = \hat{H}_0 + g_1 \hat{Y}_1 + g_2 \hat{Y}_2$$

$$\hat{Y}_r = \hat{x}_m \otimes \hat{\mathcal{Y}}$$

An operator describing how the system absorbs feedback

Rapid repeated measurements in the continuum limit

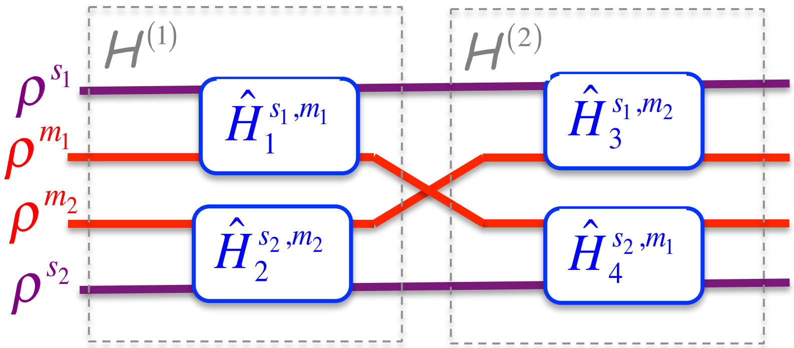
Classically Channeled Cosmology?

Altamirano/Corona-Ugalde/Khosla/
Milburn/RBM CQG34 (2017) 115007

- Basic Idea: Gravity couples to all forms of energy
  - All gravitational degrees of freedom are subject to repeated interaction with (unobservable) ancillae
  - These provide a perpetual measurement/feedback loop
- Cosmology: Scale factor is the only (position) degree of freedom
  - it should be subject to repeated interactions
- Need to obtain a master equation governing behaviour of the scale factor
  - Replaces standard approach in quantum cosmology

Effective Dynamics

Altimirano/Corona-Ugalde/Mann/Zych
New J. Phys. 19 013035
Grimmer/Leyden/Mann/Martin-Martinez
PRA94 032126



$$H^{(1)} = \hat{H}_0 + g_1 \hat{x}^{s_1} \otimes \hat{p}_{m1} + g_2 \hat{x}^{s_2} \otimes \hat{p}_{m2}$$

$$H^{(2)} = \hat{H}_0 + g_1 \hat{Y}_1 + g_2 \hat{Y}_2$$

Evolution of the density matrix

$$\rho_{sm}(t_{r+1}) = \prod_{i=p}^{1} \hat{U}_i(\tau')\rho_{sm}(t_r) \prod_{i=1}^{p} \hat{U}_i^{\dagger}(\tau')$$

State of the ancilla is Gaussian

$$\psi(x) = \langle \hat{x} | \psi \rangle = \frac{1}{(\pi\sigma)^{1/4}} e^{-\frac{x^2}{2\sigma}}$$

$$\hat{Y}_r = \hat{x}_m \otimes \hat{\mathcal{Y}}$$

Feedback the measured position

$$\frac{d\rho_s(t)}{dt} = \lim_{\tau\to 0, n\to\infty} \frac{\rho_s(t_{r+1}) - \rho_s(t_r)}{\tau}$$

$$D = \lim_{\tau\to 0 \sigma\to\infty} \tau\sigma$$

Master Equation

Governs system evolution between measurement + feedback

Contributes to the unitary dynamics of the system

$$\frac{d\rho_s(t)}{dt} = -i[H_0, \rho_s(t)] - \frac{i}{2}[\hat{\mathcal{Y}}, \hat{x}\rho_s(t) + \rho_s(t)\hat{x}]$$

$$-\frac{1}{4D}[\hat{x},[\hat{x},\rho_\tau^s(t_r)]] - \frac{D}{4}[\hat{\mathcal{Y}},[\hat{\mathcal{Y}},\rho_s(t)]]$$

Governs how system responds to feedback

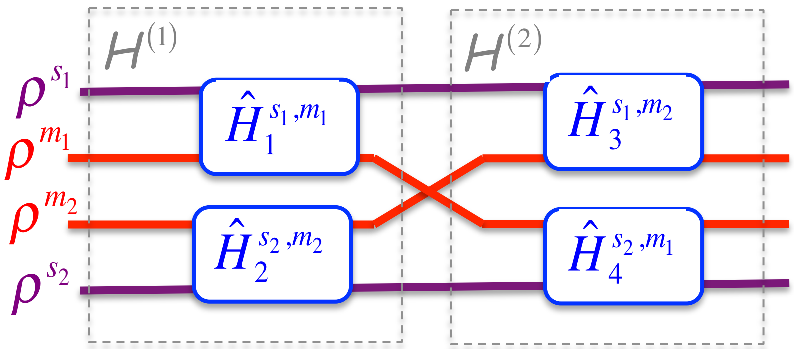
Governs strength of repeated weak measurement

See D. Grimmer's poster for QFT applications

$$\hat{Y}_i = K\hat{x}_{mi} \otimes \hat{x}^{s_{i+1}}$$

$$\frac{d\rho_{s_1 s_2}}{dt} = -\frac{i}{\hbar}[H_0 + V_0, \rho_{s_1 s_2}] - \left(\frac{1}{4D} + \frac{K^2 D}{4\hbar^2}\right)\sum_i \left[\hat{x}_i, [\hat{x}_i, \rho_{s_1 s_2}]\right]$$

Gravity's Master Equation?



$$H^{(1)} = \hat{H}_0 + g_1 \hat{x}^{s_1} \otimes \hat{p}_{m1} + g_2 \hat{x}^{s_2} \otimes \hat{p}_{m2}$$

$$H^{(2)} = \hat{H}_0 + g_1 \hat{x}^{s_1} \otimes \hat{x}_{m2} + g_2 \hat{x}^{s_2} \otimes \hat{x}_{m1}$$

Original unitary dynamics

$$\frac{d\rho_{s_1 s_2}}{dt} = -\frac{i}{\hbar}[H_0 + V_0, \rho_{s_1 s_2}] - \left(\frac{1}{4D} + \frac{K^2 D}{4\hbar^2}\right) \sum_i \left[\hat{x}_i, [\hat{x}_i, \rho_{s_1 s_2}]\right]$$

Additional effective unitary dynamics

Decoherence

Noisy Quantum Cosmology

Altamirano/Corona-Ugalde/Khosla/
Milburn/RBM CQG34 (2017) 115007

$$ds^2 = -N^2(t)a^2(t)dt^2 + a^2(t)\frac{dr^2}{1-kr^2} + a^2(t)r^2 d\Omega^2$$

Feedback measured value of the scale factor

$$\hat{H} = -\frac{\hat{\pi}^2}{4} - k\hat{a}^2 \qquad [\hat{a},\hat{\pi}] = i\hbar$$

$$\frac{d\hat{\rho}}{dt} = \frac{-i}{\hbar}\left[\frac{-\hat{\pi}^2}{4} - k\hat{a}^2, \hat{\rho}\right] - \left(\frac{k^2}{4\gamma\hbar^2} + \gamma\right)[\hat{a},[\hat{a},\hat{\rho}]]$$

Effective Metric

$$\langle ds^2 \rangle = -\langle a^2(t) \rangle dt^2 + \langle a^2(t) \rangle \left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right)$$

Interpreting the Noisy Solutions

$$\langle ds^2 \rangle = -\langle a^2(t) \rangle dt^2 + \langle a^2(t) \rangle \left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right)$$

$$t(\tau) = \int_0^\tau \mathrm{a}(\tau')d\tau'$$

Comoving time

$$= -\mathrm{a}^2 dt^2 + \mathrm{a}^2 \left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right) = -d\tau^2 + \mathrm{a}^2(\tau) \left(\frac{dr^2}{1-kr^2} + r^2 d\Omega^2 \right)$$

Observer can (in principle) determine evolution of $\mathrm{a}^2(\tau)$

Observer will infer from Einstein Eqs an effective Stress-Energy tensor $T_{\mu\nu}$

$$G_{\mu\nu}(\mathrm{a}^2) = 8\pi T_{\mu\nu}$$

Perfect fluid

$$T_\mu^\nu = \begin{pmatrix} -\rho & 0 & 0 & 0 \\ 0 & P & 0 & 0 \\ 0 & 0 & P & 0 \\ 0 & 0 & 0 & P \end{pmatrix}$$

Solutions depend on

$$\{\tau, k, \gamma, \langle \hat{a}^2 \rangle_0, \langle \hat{\pi}^2 \rangle_0, \langle \hat{a}\hat{\pi} + \hat{\pi}\hat{a} \rangle_0\}$$

$$P = w\rho$$

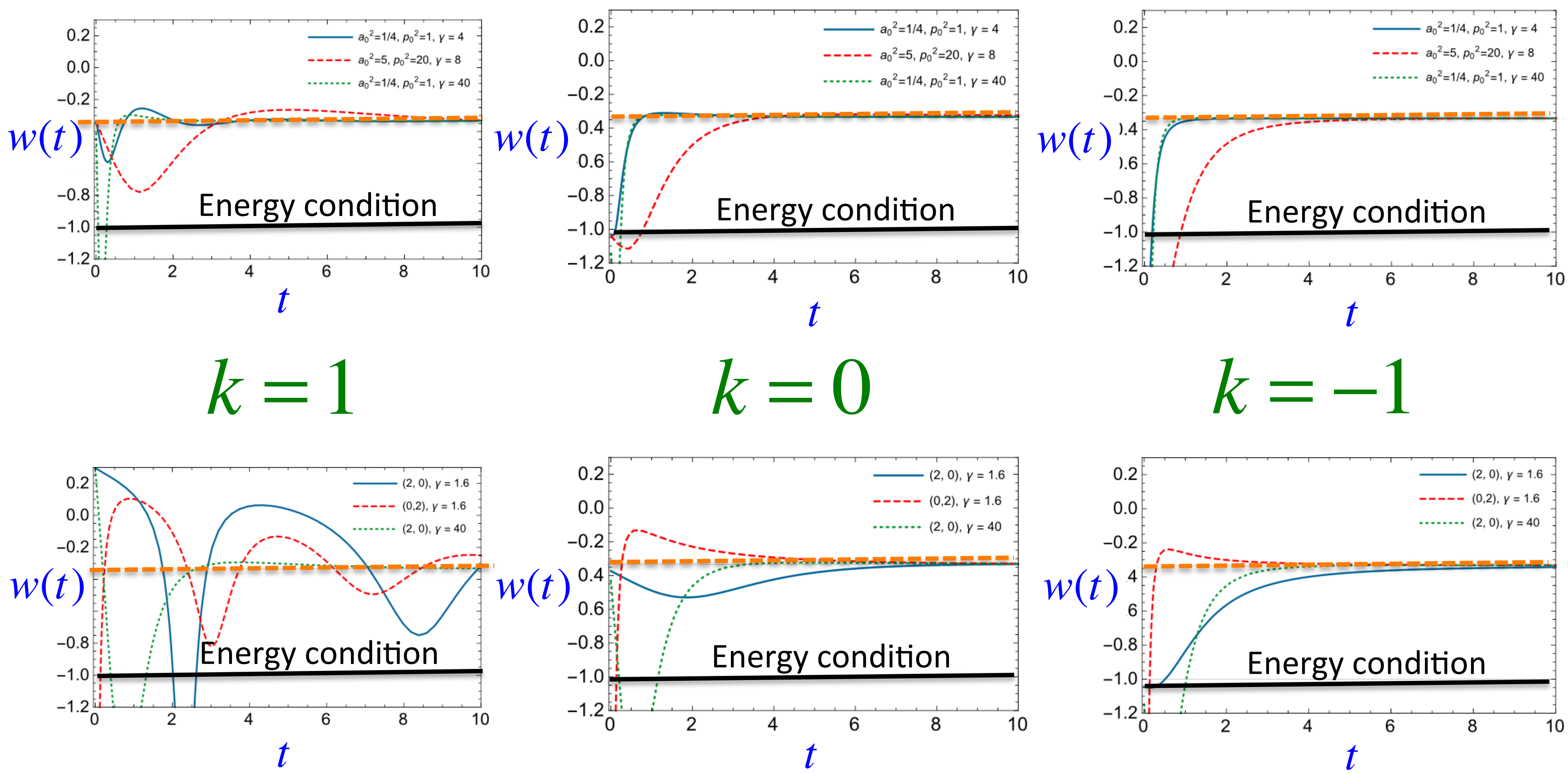
Equation of State

Eq of State

Initially Thermal State

$$4\langle \hat{a}^2 \rangle_0 = \langle \hat{\pi}^2 \rangle_0$$

$w = -1/3$ - - - - - - -



Initially Coherent State

$$\langle \hat{a}^2 \rangle_0 \langle \hat{\pi}^2 \rangle_0 - \frac{1}{4}\langle \hat{a}\hat{\pi} + \hat{\pi}\hat{a} \rangle_0 = 0$$

Dark Energy from Decoherence?

- Can generalize this model to include primordial matter

  Pascalie/Altamirano/RBM 1706.02312

  - Emergent dark fluid behaves as a curvature term in the Friedmann equations

    See N. Altamirano's poster for more detail

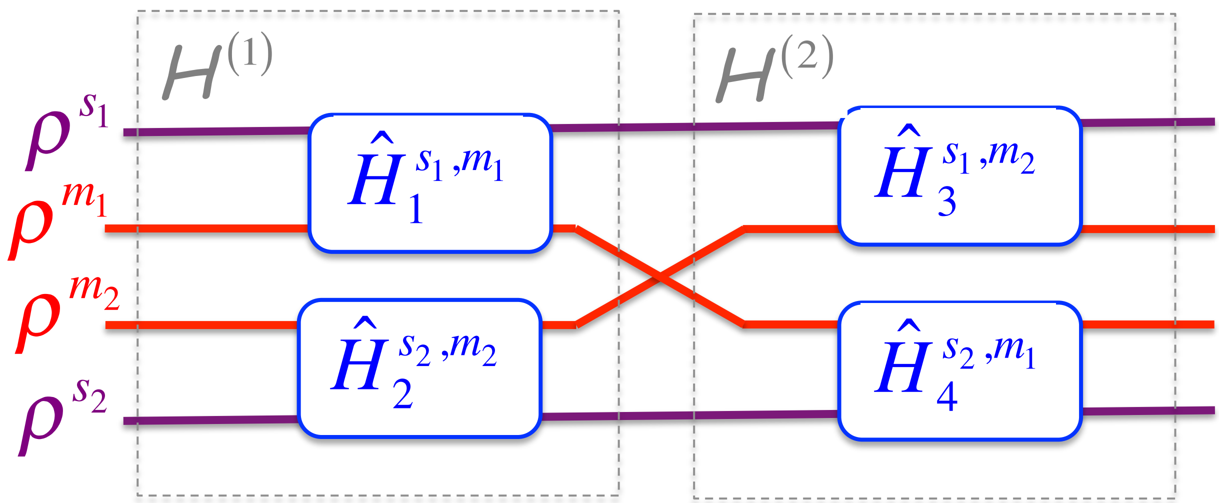
  - Can obtain an emergent cosmological constant

- Can incorporate many gravitational decoherence models into unimodular gravity
  - Energy non-conservation from quantum decoherence generates dark energy

Josset/Perez/Sudarsky PRL118 (2017) 021102

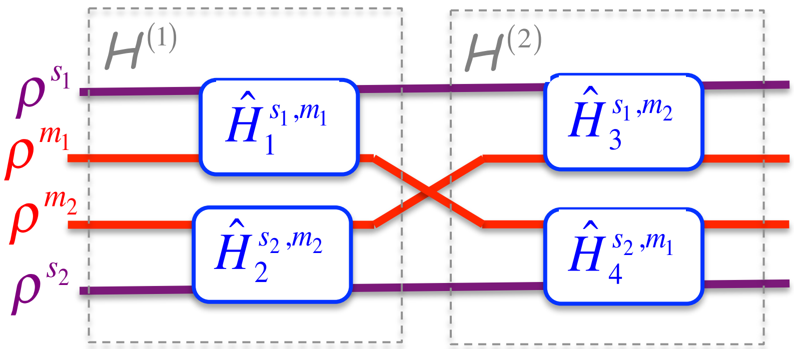
Plugging Leaks

Classically Channeled Gravity?



- Repeated measurement of ancilla dissipates information into environment
- Classical behaviour emerges when measurement is too strong for entanglement to develop
- Could gravity be this kind of emergent behaviour?

Gravity's Master Equation



$$H^{(1)} = \hat{H}_0 + g_1 \hat{x}^{s_1} \otimes \hat{p}_{m1} + g_2 \hat{x}^{s_2} \otimes \hat{p}_{m2}$$

$$H^{(2)} = \hat{H}_0 + g_1 \hat{x}^{s_1} \otimes \hat{x}_{m2} + g_2 \hat{x}^{s_2} \otimes \hat{x}_{m1}$$

Original unitary dynamics

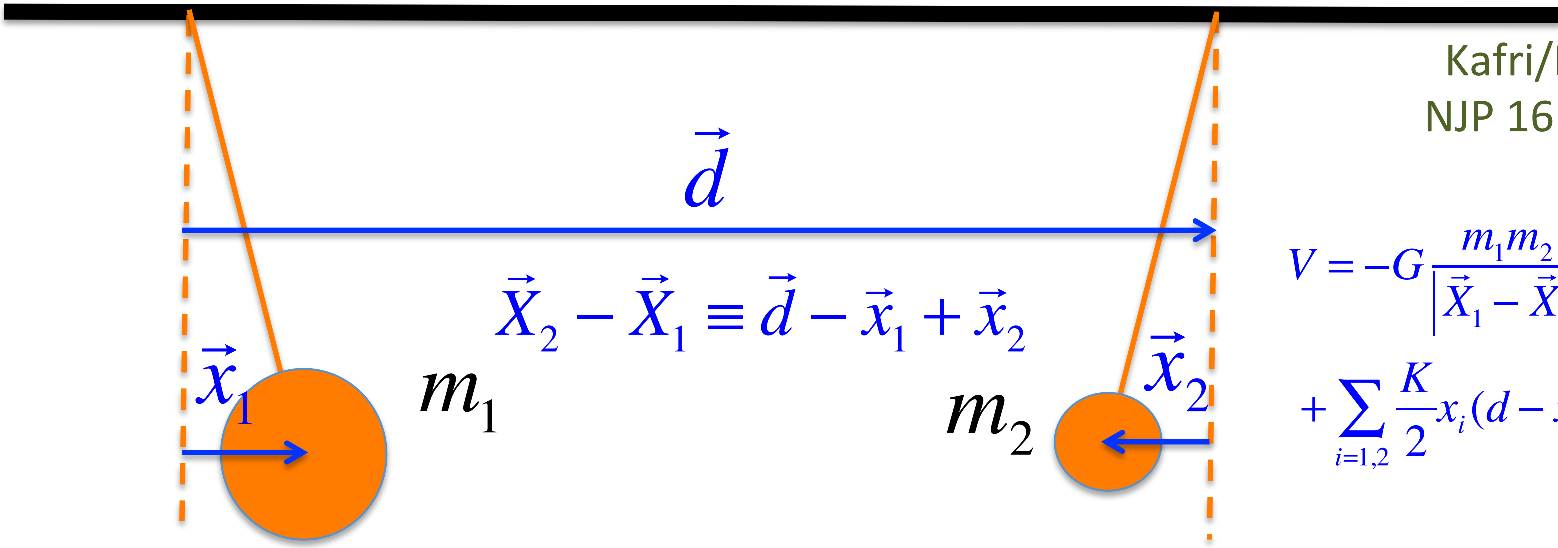
$$\frac{d\rho_{s_1 s_2}}{dt} = -\frac{i}{\hbar}[H_0 + V_0, \rho_{s_1 s_2}] - \left(\frac{1}{4D} + \frac{K^2 D}{4\hbar^2}\right) \sum_i \left[\hat{x}_i, [\hat{x}_i, \rho_{s_1 s_2}]\right]$$

Additional effective unitary dynamics

Decoherence

Classically Channeled Newtonian Gravity

Kafri/Milburn/Taylor
NJP 16 (2016) 065020



$$V = -G\frac{m_1 m_2}{|\vec{X}_1 - \vec{X}_2|} \approx \text{const}$$

$$+\sum_{i=1,2}\frac{K}{2}x_i(d-x_i) - Kx_1x_2 + \mathcal{O}(x_i^3)$$

$$\frac{d\rho(t)}{dt} = -i[H_0 + \sum_i \hat{\Omega}_i - K\hat{x}_1\hat{x}_2, \rho(t)] - \left(\frac{1}{4D} + \frac{K^2 D}{4}\right)\sum_i\left[\hat{x}_i,\left[\hat{x}_i,\rho(t)\right]\right]$$

$$K = 2\frac{Gm_1m_2}{d^3} \quad \Omega_i = \frac{K}{2}x_i(d-x_i) \quad \hat{\Omega}_i - K\,\hat{x}_1\,\hat{x}_2 \approx -G\frac{m_1m_2}{|d+x_1+x_2|}$$

Minimize Noise:

$D = K/2$

$$\frac{d\rho(t)}{dt} = -i[H_G, \rho(t)] - \sum_{i=1}^{2} K\delta_{ij}\left[\hat{x}_i,\left[\hat{x}_j,\rho(t)\right]\right]$$

Master Equation for Weak Newtonian Gravity

Testing CCG?

$$\frac{d\rho(t)}{dt} = -i[H_G, \rho(t)] - \sum_{i=1}^{2} K\delta_{ij}\left[\hat{x}_i, \left[\hat{x}_j, \rho(t)\right]\right]$$

- If 2 bodies are Gaussian, Master equation can never entangle them
- Conversely, weaker decoherence will yield an entangled ground state

Same rate of Gravitational Decoherence as in Diosi model

Diosi, J. Phys. Conf. Ser. **306** 012006 (2011).

Temperature of decohering noise

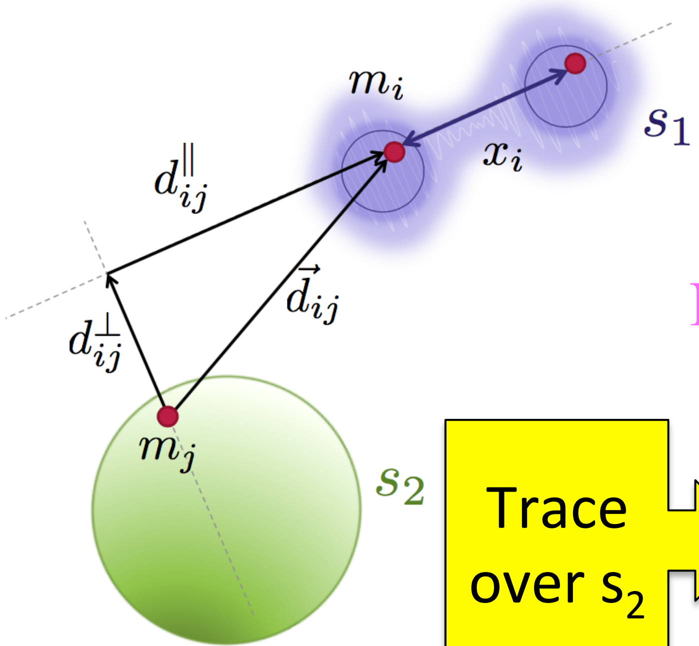
$$T_{grav} = Q\frac{G\hbar m}{\omega d^3} \sim 10^{-9} \ {}^{o}\mathrm{K}$$

- Clock Decoherence?
  - An array of N clocks will have a minimum dephasing rate
  - Gravitational redshift undergoes dephasing
  - Very difficult to test

Altamirano/Khosla PRA95 (2017) 052116

Generalize to Macroscopic (Rigid) Bodies

Altamirano/Corona-Ugalde/
Mann/Zych 1612.07735



$$\Gamma_{ij} \equiv \frac{1}{4D} + \frac{K_{ij}^2 D}{4\hbar^2} M \qquad K_{ij} \equiv 2Gm_i m_j \frac{(d_{ij}^{\parallel})^2 - \frac{1}{2}(d_{ij}^{\perp})^2}{d_{ij}^5}$$

Trace over s_2

$$\frac{d\rho_{s_1}}{dt} = -i\Big[H_0 - G\frac{M_1 M_2}{|r_1 - r_2|}, \rho_{s_1}\Big] - \Big(2\sum_{i<j=1}^{N_1} \Gamma_{ij} + \sum_{i=1}^{N_1} \sum_{j=N_1+1}^{N_1+N_2} \Gamma_{ij}\Big)[\hat{r}_1,[\hat{r}_1,\rho_{s_1}]]$$

Atom + Earth

$$\Gamma_{KTM}^{min} \geq \frac{3}{4}\left(\frac{6}{7}\right)^3 \frac{GMm}{\hbar R^3} \Delta x^2$$

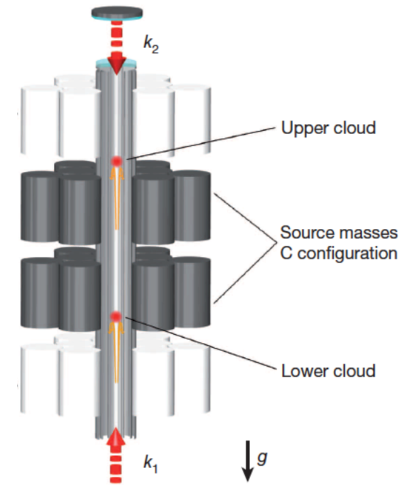
Max Visibility

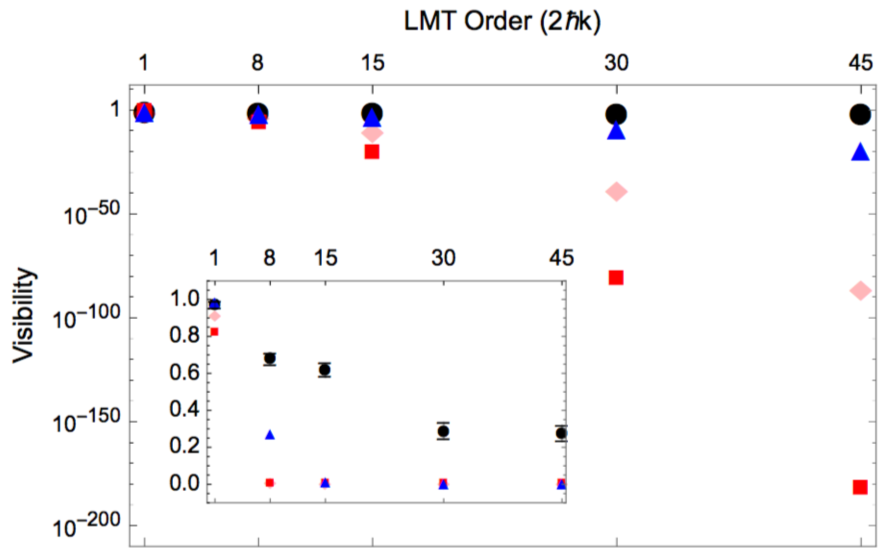
$$V_{KTM}^{max} = e^{-\frac{2}{3} C \frac{G\hbar M_{\oplus}}{m R_{\oplus}^3} (2Nk)^2 T^3}$$

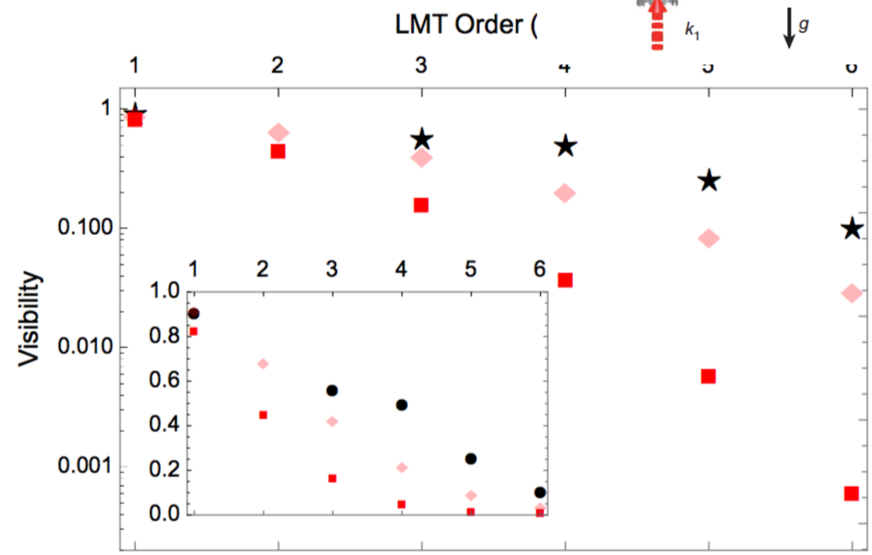
Gravity is not a Pairwise Classical Channel

$$V_{KTM}^{max} = e^{-\frac{2}{3}C\frac{G\hbar M_{\oplus}}{mR_{\oplus}^3}(2Nk)^2T^3}$$

Vertical separation of atom wave-packets over time T: $\Delta x(t) = \frac{2N\hbar kT}{m}$







● Kovachi data ▲ KTM 0.1 reduced $C = 0.1$ * Sugarbaker data ■ KTM $C = 1$ ◆ KTM multi–particle $C = 0.47$

$M_{\oplus} = 6 \cdot 10^{24}$ kg

$R_{\oplus} = 6 \cdot 10^{3}$ km

$\frac{\hbar k}{m} = 5.8$ mm/s

$m = 1.4 \cdot 10^{-25}$ kg ^{87}Rb

T = 1.15 s (Sugarbaker)

T = 1.04 s (Kovachy et.al.)

Kovachy et.al. Nature **528** 530--533 (2015)

Sugarbaker *Atom interferometry in a 10 m fountain*, (Ph.D. thesis, 2014)

See P. Corona-Ugalde's poster for more detail

Understanding Leaks

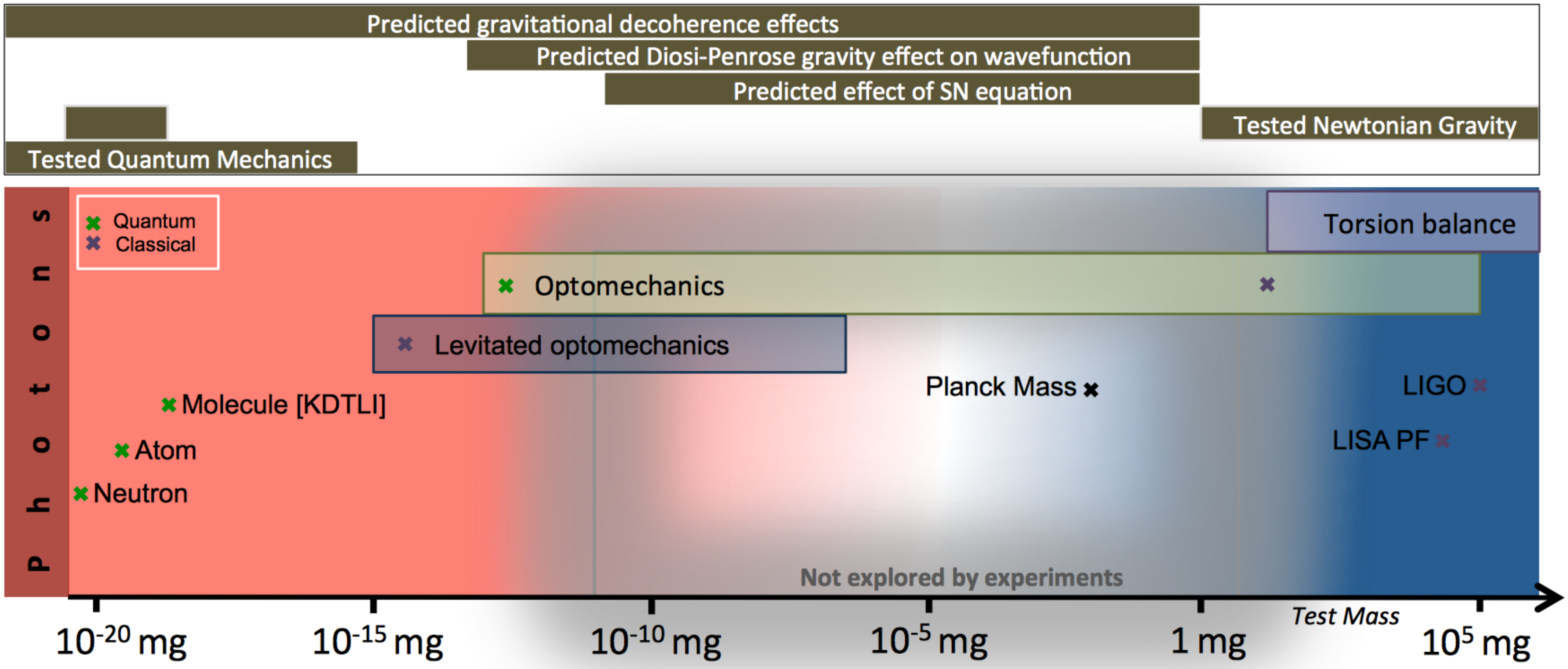
Questions we need to ask

- Is gravity an intrinsically open quantum system?
- Is spacetime evolution fundamentally non-unitary?
- Is gravity essential for quantum → classical ?
- Does gravity emerge from repeated quantum interactions/measurements?
- How permeable is quantum gravitational information?
  - How do we quantify this permeability?
  - How do we test for it?

Exploring Gravitational Leakage

- Explore simple models
  - Quantum cosmology
  - Mini-superspace models
  - Black hole radiation and information paradox
- Build a consistent Newtonian theory
  - KTM model; Schroedinger/Newton equation; Diosi/Tilloy model
  - Can Newtonian gravity emerge from repeated measurement?
- Build a consistent relativistic theory
  - Generalizations of string theory, LQG?

Plenty of Scope for Testing



Bassi/Grossardt/Ulbricht 1706.05677